ICFA Beam Dynamics Newsletter, No. 21

Editors in chief
K. Hirata and J.M. Jowett

Editors
W. Chou, S. Ivanov, H. Mais, J. Wei, D.H. Whittum, and C. Zhang

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1: Forewords

1.1 Foreword

John M. Jowett John.Jowett@cern.ch CERN

This newsletter is the first to be prepared by Jie Wei, one of the recently appointed editors. Besides the usual variety of material, Jie has chosen to give it a special and very timely focus on "Next-Generation High-Intensity Applications".

Regular readers may have been disappointed by the fact that no issue appeared in December 1999. This meant that some announcements that would have been included in that issue are now out of date. We hope that the affected authors and our readers will accept our apologies for this. Still, we ask everyone to remember that the editors of each issue donate their spare time on an entirely voluntary basis as a service to the beam dynamics community and that they have few resources to help them in the task.

Their main resource, in fact, is the other members of that community and their willingness to spend a little time communicating with their colleagues. The newsletter is unique in providing informal and open contact that is quite complementary to the traditional, but more formal, channels of scientific publication. Although it gets easier all the time, it is still worth mentioning that we try particularly hard to be truly international and reach our colleagues everywhere on the planet. Please think about what you can contribute to the newsletter!

1.2 From the Editor

Jie Wei Wei1@bnl.gov Brookhaven National Laboratory

When I first took the charge of editing this issue of Newsletter, it occurred to me that Andy Sessler would be among the best few persons to write a profound "letter to editors". Indeed, Andy's letter "Absent: A Plan for High Energy Physics" generated many discussions and debate even before its formal publication. Here, the response from George Trilling is one example.

I met Andy about ten years ago. On and off for several years, we worked together with Xiao-Ping Li on the topic of crystalline beams at our spare times, some times during Andy's visit to BNL while he was serving the trustee service of the Associate University Inc., some times during our visit to LBL, and most often when we both attend some conference or workshop. I vividly remembered the days when we struggled through the theory of general relativity to derive the equations of motion in the beam rest frame. On those frustrating time, Andy would tell us many stories and jokes. Once he told us how in the 60's he spend one evening per week at the home of Kelvin Neil's, drinking beer while working on the now famous resistive wall instability problem. Around that time, that work was considered useless. Of course, today the concept of crystalline beams still sounds crazy and useless to many people. But Andy's spirit and attitude to life has deeply impressed and inspired me, and in years influenced me forever.

This issue contains a special theme "Next Generation High Intensity Applications". With the recent addition of Neutrino Factory studies at many places including Europe, US, and Japan, this area has become increasingly active. Among the nine contributions of this section, Spallation Neutron Source (SNS) is the first and only funded project. However, the path is far from smooth. As the first of its kind, we debated between Rapid-Cycling-Synchrotrons and Accumulator Ring concept for the ring, and between normal conducting and superconducting RF technology for the linac. Now second year in construction, we finally come to a design that is technically sound and economically acceptable. The successful completion of SNS would be a great encouragement to our community.

Finally, I would like to thank my colleague Dr. Nuria Catalan-Lasheras for numerous helps in making this issue possible. When it seems impossible to convert figures in various formats into the required .EPS form, Nuria always does the magic.

2: Letters to the Editors

2.1 From A. M. Sessler: Absent: A Plan for High Energy Physics

Andrew M. Sessler amsessler@lbl.gov Lawrence Berkeley Laboratory

In 1993, when the SSC was stopped, we all knew it was a disaster for High Energy Physics (HEP), but we were confident that by the turn of the century, HEP would be back on track. Now, here we are, at the turn of the century, maybe not in "disaster mode", but certainly experiencing a malaise, an ever-decreasing budget, and no accepted plan for the future. We had better develop a Plan.

If we look at some other fields we can see how important it is to have a plan. Fusion energy has suffered a decrease from 471M$/year in FY'84 to 230M$/year in FY'99 while subject to severe criticism in the Congress for having no plan. Now, and after many committees, and acceptance by the community, at a Snowmass Gathering, such a plan has been developed and the funding is starting to grow. Astronomy, on the other hand, has for very many years had a mechanism for developing an accepted plan; namely each decade (and they are now starting their fifth) they produce a prioritized list of desired new facilities. The funding of the field has been generous (no doubt, also, because of the excitement of astronomy, but HEP is also exciting), as ever-new telescopes, terrestrial and in space, are constructed and operated.

It is dangerous to think that the support for HEP will just stay up, or even grow, that federal monies will continue to arrive, supporting one good thing after another, even in the absence of a master plan. (We might experience the disaster that befell fusion!) True, we high-energy physicists are busy with some very fine things: the Tevatron (both collider and fixed target experiments), the B-Factory, CESR, some experiments at the AGS, international activities at LEP and DESY, and our university activities including the vital function of teaching and training future high-energy physicists. And, not to be forgotten, there is the planning and construction (both machine and experiments) for the LHC. But beyond that there is a great void of facilities, facilities needed for advancing our science.

Should we build an NLC? Should we build a Neutrino Factory? Should we build a Super-LHC? Should we build a Muon Collider? Should we do something else? We need, in my view, to develop a Plan. Absent that, we will not experience any increase in HEP funds and, very likely, experience a steady decrease in funding (as we have been experiencing in recent years as inflation, and especially "scientific inflation"; i.e., more expensive apparatus and more difficult experiments, has eaten into our budget by a significant amount). To be precise, from FY'93 until FY'00 the growth has only been 2% per year. Even in this year (FY'01), a year of "a historic science and technology budget", when, for example, the National Science Foundation has a proposed 17% increase in its budget, the proposed budget for HEP increases by only 2%, i.e., once again, less than inflation.

In this day and age, and with the new facilities costing so much, international cooperation is demanded, but we need a new major facility in the United States. And I am sure that Europe and Japan understands, and supports, such a desire for it is only with strong national programs that HEP will flourish any place in the world. One can't help but discern a dangerous trend when the fore-front colliders in e-p, e-e, and p-p are all in Europe; namely, HERA, LEP, LHC.

Who should form such a Plan? What form should a Plan take? Let us consider the first question first. The Plan could come from the community (as is the case in Astronomy) or it could start with the funding agencies and the major laboratory directors (as was the case in fusion). I have urged that the community have a Snowmass Gathering as soon as is possible; namely in 2001, and with the focus to be on new facilities. I am pleased to be able to say that both the DPB and the DPF have accepted this proposal. In order to move things along, and you quite understand that I feel strongly that we must move along, I suggest that HEP go into the Snowmass Gathering with a Draft Plan on the table.

The DOE, the NSF, HEPAP, and the major laboratory directors could develop that Draft Plan. Perhaps that can be accomplished through a select sub-panel of HEPAP jointly sponsored by the DOE and the NSF. This panel should include major laboratory directors (so we get one plan; not many), selected physicists (especially from universities), and foreign representation, at the highest levels, from KEK, CERN / ECFA, and ICFA. Major laboratory cooperation, and international co-operation, is essential, these days, for progress in HEP. That cooperation needs to be invoked right at the beginning. (Remember what happened to the SSC when the US tried to develop international cooperation at a late stage.) There is plenty of time, in the next year and a half, for all of this to be done. Then, out of Snowmass could emerge a Plan for HEP endorsed by all the major players and most, if not all, of high-energy physicists.

Now, what should be in the Plan? It, first of all, must make the case for continued effort in HEP, and for major new, science-driven facilities, in the US. These arguments have to be compelling to other physicists; even to other scientists. It should list, then, the various facilities and activities which might be considered for the future of HEP and, most importantly, the scientific question that each will be able to address. This list must include adequate use of the present and planned facilities, as well as non-accelerator activities. Questions that must be addressed include the timing for construction of new facilities (related to when we will obtain what physics information) as well as the energy scale appropriate to new facilities (what does the physics need).

Then, the Plan needs to make budget projections. Perhaps these should be made at three levels: high, a vigorous program; medium, a program that significantly moves the science along; low, the present level of funding. Then for each of these, extending for, say, ten years, we should develop a balanced HEP program, including goals and spending profiles. (Since we don't have CDR's for the new facilities we need to adopt "working cost estimates" for this exercise.) Notice that I don't consider one future facility an adequate plan. (That, you will recall, is what happened to fusion where the only item in the future was ITER and when the cost was too high for the US Congress, the field was thrown into disarray. Actually, there were many other proposals "on the table", but no agreed upon plan.) The Plan must include alternatives (especially as the Plan will be considered by the OMB and the Congress and we know they want to see alternatives).

I suspect that for the case of the first and second budget projections we shall see that we can "afford" (i.e., is consistent with proper use of the Tevatron, the LHC, and non-accelerator experiments, etc.) quite a number of new facilities– maybe all that are presently being considered (but spread out over time). Probably, for the third projection we will have to make some hard choices, but the whole point of the process; namely, the development of a Plan is to increase the budget from its present level.

The Plan, once it is developed and accepted by the HEP community, must be "sold" to our colleagues in other branches of physics (perhaps through the American Physical Society), and also "sold" to the general scientific community (perhaps through the National Academy of Sciences). The Plan must be accepted by the DOE (not only within the Office of Science, but right up to the Secretary) and by the NSF (not only in the Physics Division, but right up to the Board). Probably this "acceptance" is at one of the three budget levels. Next the Plan must be "sold" to the OMB; that is, they must agree to include it in the President's Budget. Finally, approval by Congress is needed. It is a long route, but we better start now.

The US, as a whole, is presently experiencing a budget surplus; now is the time to "get in line";

without a Plan we aren't even on the right street.

Andrew M. Sessler

Lawrence Berkeley Laboratory

2.2 From G. Trilling: Response to the Letter of A. M. Sessler

George Trilling `trilling@mh1.lbl.gov` Lawrence Berkeley Laboratory

Dear Andy,

I read with interest your message for the ICFA newsletter. While I agree that a plan would be helpful, I believe that you present an oversimplified view of the challenges facing HEP and particularly U.S. HEP. The real problem, in my opinion, is that the accelerator-based physics that we are used to doing is running into a fundamental financial barrier. It is that barrier, coupled with political obstacles to large scale international collaboration in facility construction, (and not our collective laziness) that is preventing the formulation of a credible plan. Let me expand on these notions.

In my view, it will be extremely difficult to sell our government and our non-HEP scientist colleagues proposals for U.S. funding to build facilities whose costs are significantly higher than a figure appropriately related to the size of our base program. Specifically I believe that a figure about two times the annual U.S. HEP budget approximates the maximum cost of a major facility that, with enough U.S. HEP community support, can be proposed and eventually accepted by our government. This amounts to a facility cost of 1.5 to 2 billion dollars. Such a facility cost spread over, say 8 years, would imply an added level of funding of $\sim$25% which could probably be accepted without too much criticism from the rest of the scientific community. If one looks at what has recently been built here and even in Europe, the projects do satisfy that constraint: SNS, the Main Injector and PEPII, RHIC, LEP, and the CERN funding for LHC (where here I use the yearly CERN funding to determine my scale). The sole recent exception that I know about is the SSC, and we saw what happened in that case. I believe that the only way that the U.S. would support the construction of an HEP facility of much higher cost would be on the basis of so compelling a scientific case that our biology, astronomy, and condensed matter friends would be willing to sacrifice part of their support to see it built. This did not happen for the SSC, and I am skeptical that it will happen in the future. Unfortunately early cost estimates for an NLC of 500 GeV energy (half of the Gilman Panel lower limit) are much larger than the above suggested limit. Perhaps there are projects that do satisfy the above limit, and that will be powerful additions to the list of U.S. HEP facilities; but, speaking for myself, I do not know of such projects whose costs, parameters, and benefits are as yet well enough understood (and in the case of costs, low enough) to incorporate them, except as R&D endeavors, into a realistic Plan.

In spite of the rather bleak picture that I am painting, there is a real way to move to multi-billion dollar facilities, namely to operate from a much larger base, World HEP rather than U.S. HEP. You did mention international collaboration in your note, but without noting the significant change of attitude that may be required to make such collaboration in large facility construction a useful reality. International participation in the LHC machine, including the U.S., is a good start in this direction, but is only a limited example of what is needed in the future, since the U.S. is contributing only about 5 - 10% of the cost of the machine. To be effective in substantially reducing costs to any one region, the other regions would have to contribute much larger fractions, somewhat analogously to a global version of CERN.

In order for such international collaboration to foster facilities that are beyond the funding capabilities of any one country or region, there will, as I mentioned above, have to be a change of attitude in both HEP leadership and funding agencies in all of the regions. There will have to be a recognition that, in the long run, the further progress of accelerator-based HEP demands from the leadership and the funding agencies a much broader outlook than one just focused on the immediate interests of a particular Lab in a particular region. There will, in my view, have to be acceptance of two basic principles:

1) Groups in all regions can and should benefit from collaborating and contributing to the construction of a new facility, even if sited in another region. There should be global collaboration in the planning for such facilities.

2) To maintain the strength and interest of the various regions, it is essential that new facility projects be distributed throughout the various regions. This is of course essential if governments and funding agencies are to see the benefits of such international collaboration.

The second item will require willingness to make some sacrifice of the immediate interests of particular Labs in exchange for the benefit of long-term global collaboration and global funding. That is where the change of attitude may be needed.

Somehow the kind of breadth and wisdom that led to CERN's founding by the European community will be required on a global scale if we are to progress in a serious way to facilities beyond the LHC. If this were to happen, then we could write some real plans, and even hope to command the funding support to bring them to reality.

George Trilling

2.3 From J. M. Jowett: About the MAD Program

John M. Jowett `John.Jowett@cern.ch` CERN

Dear Jie,

The program MAD (for "Methodical Accelerator Design") is one of the most widely used tools in the world-wide accelerator and beam dynamics community. The bulk of the very substantial conceptual, mathematical and programming effort required to create, maintain and develop it since its beginnings in the early 1980s has been undertaken by Chris Iselin at CERN. A number of other people have, of course, contributed both ideas and program code at various times.

At present, most users know MAD Version 8 (MAD8). This is now a very large Fortran program that allows them to design accelerator lattices, compute their optics, track particles and evaluate numerous physical effects. MAD's standard input language (SIF) has been widely adopted as a canonical way to describe accelerator structures.

Chris recently retired from CERN and might well have been content to leave the community with a more-or-less frozen MAD Version 8, in excellent shape and surely capable of serving us well for many years to come. However, his standards being higher than that, he has also left us with a new MAD, Version 9 (MAD9).

Version 9 is a complete re-write of MAD in the C++ language. Chris has built on the experience gained with earlier incarnations of MAD to produce an even better structured program, systematically exploiting object-oriented techniques. A keystone of the structure is the CLASSIC library of classes for accelerator physics (that he was also largely responsible for developing).

MAD9 is currently being tested here at CERN, mainly in the framework of applications to the LHC, but we hope that its use will spread to other machines as quickly as possible. The plan is that, very soon, all LHC optics work will be done with MAD9.

Some of the capabilities of Version 8 are still lacking but we are working to provide all the essential features or improved versions of them. However we intend to avoid the tendency to "bolt-on" other programs as happened to some extent with MAD8. Thus, for example, the "HARMON" and "BMPM" modules no longer appear in those forms.

In the meantime, no-one need worry about adopting MAD9 for their work: if they still need to use MAD8 for some specific calculation, MAD9 can always generate a MAD8 description of their machine.

Among the improvements already present in MAD Version 9 are:

1. Support for multiple beam-lines simultaneously, facilitating, for example, matching constraints that couple the two rings of a two-ring collider.

2. Much improved Lie-algebraic map calculations.

3. A uniform method and format for extracting many kinds of structured data from MAD for use with other programs.

4. An improved and more consistent input language.

Schematically, we distinguish two broad approaches to extending MAD9's capabilities. The first is the *deep* mode, requiring programming in C++ and an understanding of the internals of the program. This has already proved its worth in the development of space-charge simulations at the Paul Scherrer Institute (PSI).

On the other hand, a lot of attention is being paid to the *shallow* mode in which MAD9 exchanges *structured* data with other programs or environments (spreadsheets, Mathematica, graphical displays, . . .) via, say, files or pipes. Such exchanges can be one-way or two-way and open up many possibilities.

The Accelerator Physics group of the SL Division at CERN will continue to take principal responsibility for developing MAD although collaborations with other institutions are taking shape. The principal source of information about the program is the MAD Home Page

`http://wwwslap.cern.ch/mad`

This page has recently been enhanced with access to various other resources concerning MAD and should evolve quite rapidly in future. In addition we plan to report on further developments in future editions of this newsletter.

Yours sincerely,

John Jowett

2.4 From I. Pogorelsky: Andrei Amatuni

Igor Pogorelsky `igor@bnl.gov` Brookhaven National Laboratory

Dear Editor,

Andrei Amatuni died from a heart attack last October while flying to an international workshop on "New Visions in Laser-Beam Interactions" to present a new laser method of electron acceleration and a talk on a coronary angiography. Amatuni was born in 1928 in Leningrad. In 1938 at the height of the Stalin repression, his father, Tsolak Amatuni, was falsely accused of sabotage and being in the "Trotski group" and executed. Ten-year-old Andrei was exiled with his mother to the deserts of Turkmenistan. The only positive recollections from that period were brilliant teachers in the local elementary school- professors from Moscow and Leningrad universities apparently suffering the same poor fate. This is how his passion for science was seeded. During World War II, Andrei managed to find refuge with his relatives in Armenia where in 1945 he graduated from high school. He was a bright student, and in spite of his "suspicious" past he was admitted to Moscow University where he graduated from the Physics Department in 1950. However, until posthumous "rehabilitation" of his father name in 1956, Andrei could not find a permanent job. He made his living by teaching courses in Armenian schools, but continued theoretical research on his own. In 1956 he was able to return to his Alma Mater where that same year he published three noteworthy papers on the quantum theory of anti-ferromagnetism and defended his Ph.D. thesis. In 1957 he returned to Yerevan as a Head of the Theoretical Laboratory at the Physics Institute. He worked on the design of the 6 GeV Yerevan synchrotron biggest in the USSR and obtained several fundamental results in theory of x-ray transition radiation. Since the mid 60s, partially stimulated by a one year term at CERN, Amatuni shifted his scientific interests to High-Energy Physics. He published papers on application of functional analysis methods to non-linear theory of S-Matrix, theory of complex momenta applied to high energy photo- and electro-production processes, and parastatistics in particle physics. Several of his findings were confirmed experimentally at the Yerevan Synchrotron and elsewhere. His professional career developed with equal success. He was appointed Deputy Director of Yerevan Physics Institute from 1964-73, and Director from 1973-92. During these three decades he initiated in his institute new directions in theoretical and experimental research including: physics of accelerators and cosmic rays, in applied and computational physics. He developed collaborations with the leading High Energy Physics centers in the former USSR and abroad (CERN, DESY, FNAL, SLAC, LBL, CEBAF and others). Amatuni devoted a large portion of his time to teaching and popularization of science. For almost 40 years he taught advanced graduate courses in theoretical physics. In the 70s he established a "School of Young Physicists"—affiliated with the Yerevan Physics Institute an extracurricular school of physics and mathematics for the high school students. Building closer ties between fundamental science and industry, he was among the first to promote accelerator driven transmutation of nuclear waste (in particular for the Armenian Nuclear Power Plant), the application of radioactive isotopes and electron accelerators in medicine and agriculture, the application of synchrotron radiation in medicine, biology, microelectronics, and the application of high current electron accelerators to production of artificial diamonds.

He organized a number of international conferences and schools such as the Nor Amberd School of Physics in the early sixties, and conferences on Transition Radiation and on New Methods of Acceleration held in Armenia. For nearly two decades he was a member of the USSR-US Joint Coordinating Committee on Fundamental Properties of Matter (JCC-FPM). During 1992-1995 he was a member of the International Committee on Future Accelerators (ICFA). His high official position, diverse activities and responsibilities never distracted him from active engagement in fundamental research. He made numerous contributions in different areas of theoretical physics including: solid state physics, theory of x-ray transition radiation, theory and phenomenology of elementary particles, theory of new methods of particle acceleration. Among his most noteworthy results is the theoretical discovery in the early 80s of the non-linear phenomena of self-acceleration and self-focusing of electron bunches by plasma wake fields. After relinquishing most of his long term administrative responsibilities, his last years were especially diverse and productive in science. He started to work on the theory of nonlinear interactions of charged particles with intense beams of electromagnetic radiation and/or plasmas and on practical application of these results to new methods of charged particle acceleration.

Apart from being a distinguished scientist, he loved literature, classical music, history and art, he was a great father and grandfather, a scientist and a teacher and an extraordinarily nice person. He will be gratefully remembered by those who knew him personally most probably for his endless optimism, friendliness, infinite kindness that were so naturally combined with his integrity, wisdom and intellect. He will be especially missed by his wife, daughter, son whom he named for his father Tsolak, and grandchildren.

Igor Pogorelsky

Brookhaven National Laboratory

3: Special Section - Next-Generation High-Intensity Applications: Issues, Challenges, and Status

3.1 Spallation Neutron Source (SNS)

R. Keller	r_keller@lbl.gov	Lawence Berkeley Laboratory
J. Staples	jwstaples@lbl.gov	Lawence Berkeley Laboratory
J. Stovall	jstovall@lanl.gov	Los Alamos National Laboratory
R. Sundelin	sundelin@jlab.org	Thomas Jefferson Laboratory
J. Wei	wei1@bnl.gov	Brookhaven National Laboratory

The Spallation Neutron Source (SNS) is designed to meet the growing need for new tools that will deepen our understanding in materials science, life science, chemistry, fundamental and nuclear physics, earth and environmental sciences, and engineering sciences. The SNS is based on an accelerator producing an average beam power of 2 MW at a repetition rate of 60 Hz. The project is presently in its second year of construction. The accelerator complex consists of a Front End (ion source, Low Energy Beam Transport, RFQ, Medium Energy Beam Transport), a linac, a High Energy Beam Transport, an accumulator ring, and a Ring-Target Beam Transport, as shown in Figure 3.1.

The SNS Linac will be comprised of 3 distinct types of accelerating structures. A 402.25 MHz drift-tube linac, which will accelerate the beam from 2.5 to 87 MeV, followed by an 805 MHz side-coupled linac which will further accelerate the beam to 186 MeV. Finally a superconducting linac will accelerate the beam to its final energy of 1 GeV. At "press time" the final linac architecture, rf power topology and control philosophy are still under discussion. A detailed description of the linac design and its expected performance will be presented in a future issue of this newsletter. The following sections summarize design studies on the Front End, linac superconducting cavity, and the ring.

3.1.1 Ion Source and LEBT

Roderich. Keller r_keller@lbl.gov LBNL Berkeley

(Co-authors: R. Thomae, M. Leitner, J. Reijonen, D. Cheng, J. Staples, K. N. Leung, A. Ratti, J. Greer, and R. Gough.)

3.1.1.1 Introduction

With the adoption of a 2-MW average beam-power scenario for the SNS Accelerator Systems, the Front-End Systems (FES) are required to deliver a 52-mA H^- beam to the Drift-Tube Linac. Consistent with this requirement the first two FES subsystems, Ion Source and Low-Energy Beam-Transport line (LEBT), are being designed to produce a 65-mA beam of 65 keV energy at 6% duty factor with a narrow transverse rms-emittance of 0.2 π mm mrad, normalized. It is the combination of these performance parameters, together with a desired time-between-maintenance of 504 hours, that clearly aims beyond the state-of-the-art; even though, for example, much higher H^- current values had already been reached by the SSC ion source [1]. The path of development at LBNL towards the stated performance goals goes through a series of demonstration experiments with a so-called R&D Ion Source in various configurations, a Startup Ion-Source/LEBT System aiming

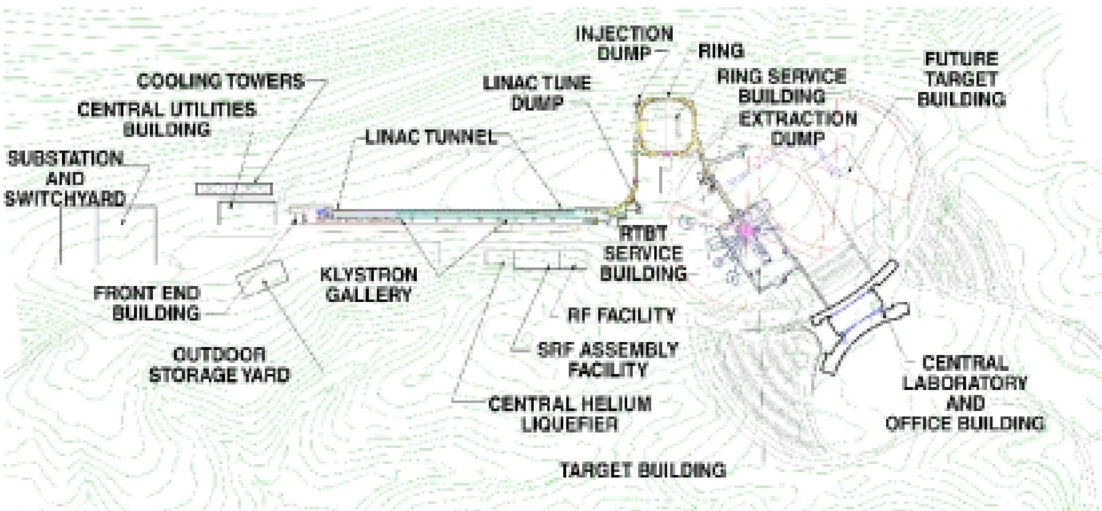

Figure 3.1: Schematic layout of the Spallation Neutron Source.

at 35-mA beam current, and lastly a 65-mA Production System. The beam-current goal of 65 mA was set in order to fulfill the 52-mA requirement at the end of the MEBT structure under the conservative assumption of 20% beam loss in the RFQ. A schematic of the Startup configuration is shown in Fig. 3.2.

For the ion source a well-proven multicusp (“bucket”) discharge vessel was chosen that includes a magnetic dipole filter to separate two plasma regions and relies on the volume-production process for H^- generation, assisted by minimal cesium coating of the surfaces surrounding the second plasma region, near the outlet aperture. To avoid severe lifetime limitations as well as contamination of the inner surfaces by condensed refractory metal associated with the use of cathode filaments, the discharge is driven by rf power at 2-MHz frequency, coupled inductively by an immersed antenna. The extracted beam always contains a significant amount of electrons, and these electrons are separated from the ion beam in the extraction gap and deposited on a special ’dumping’ electrode at rather low energy. In this way, the electron space charge is removed from the ion beam as soon as the beam is formed, and the power load on the dumping electrode is low, compared to separation at full beam energy. The LEBT has three main functions: to extract the ion beam from the plasma generator, match it into the subsequent RFQ accelerator, described elsewhere [2], and lastly to chop the beam into mini pulses of about 600 ns duration.

A fully electrostatic LEBT [3] had been previously developed and successfully operated with a 30-mA, 40-keV proton beam and served as a model for the SNS LEBT. Even though a magnetic LEBT might also have provided proper matching to the RFQ, the inclusion of a fast chopping system in combination with the issue of partial, time-varying, space-charge compensation often encountered with magnetic systems directed us towards a fully electrostatic configuration. The design of the electrode contours is based on IGUN [4] simulations, using the code in a novel way to include finite ion temperatures as well as the space charge created by the electron population in the extraction gap. The deflecting action of the chopper electrodes which together form the center part of an einzel lens and also serve as electrostatic steerers, was verified using the code LATTICE. Presently, the Startup Ion-Source/LEBT is being commissioned at the LBNL Integrated Testing Facility for the SNS Front End Systems. The Production System is being designed and fabricated in parallel and will be operated at first on a separate test stand and later on in the Integrated Testing Facility. The Front-End Systems will be entirely commissioned at Berkeley Lab and then shipped to the SNS Facility at Oak Ridge in the spring of 2002.

3.1.1.2 Ion source

The ion source type chosen for the SNS Front-End Systems was developed from a successful line of ion sources serving the Neutral Injection and later the High-Energy Accelerator communities. The volume-production process of H^- generation was given preference over surface production because of the danger of sparking in the extraction gap caused by copious amounts of cesium associated with the latter process. The cesium enhancement to the volume-production process utilizes only minute amounts of cesium which are not even visible upon source disassembly and have never given rise to excessive sparking during the tests with the R&D Ion Source. Cesium enhancement reduces the amount of rf power needed to create a certain plasma density by about a factor of three and at the same time reduces the amount of electrons in the discharge, and therefore in the ion beam, by an even larger factor. Cesium is introduced into the plasma generator in the form of the $Cs_2\,Cr\,O_4$ compound stored on the inside of a heated collar in small “getter” containers that open up at elevated temperatures. The collar temperature is adjusted by passing heated gas through a steel tube connected to the collar and monitored by a thermocouple. The R&D Ion Source was able to generate an ion beam with a square-shaped current pulse of 43 mA amplitude

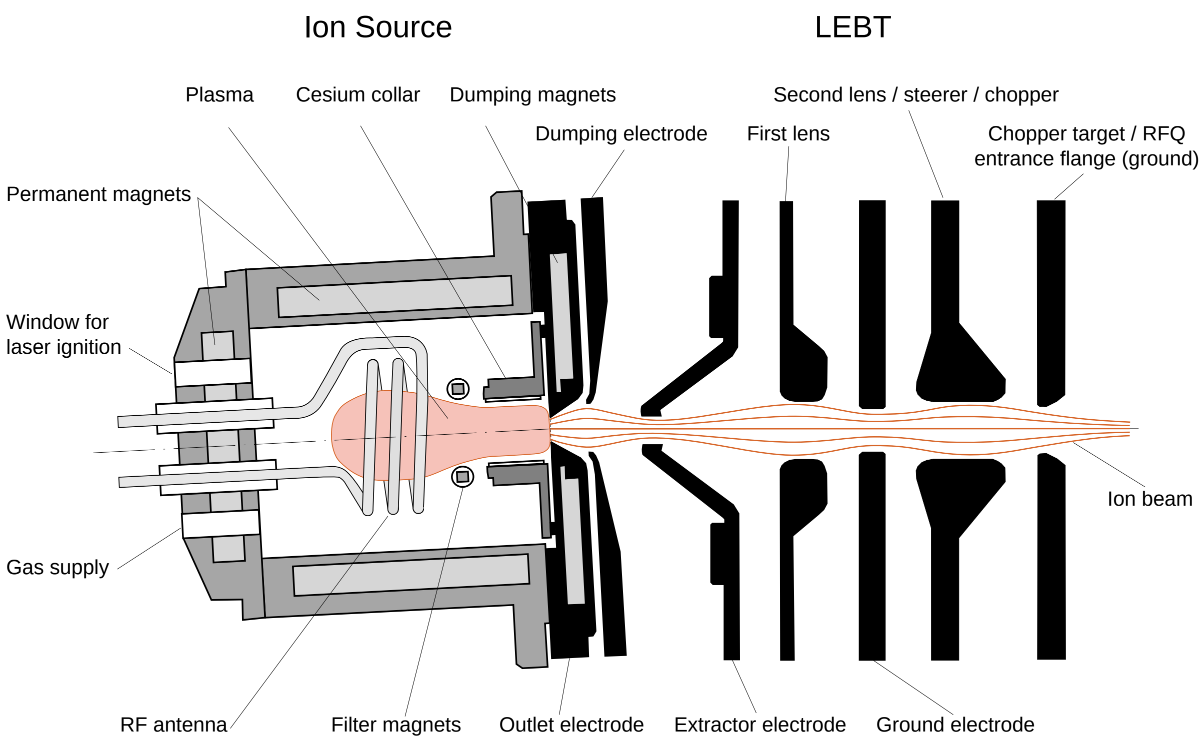

Figure 3.2: Schematic of Startup Ion-Source and Startup LEBT. Note that the actual filter and electron-dumping magnetic fields are oriented orthogonally to the illustration plane. The size of the ion beam is greatly exaggerated in this schematic to emphasize the focusing action of the double-lens system.

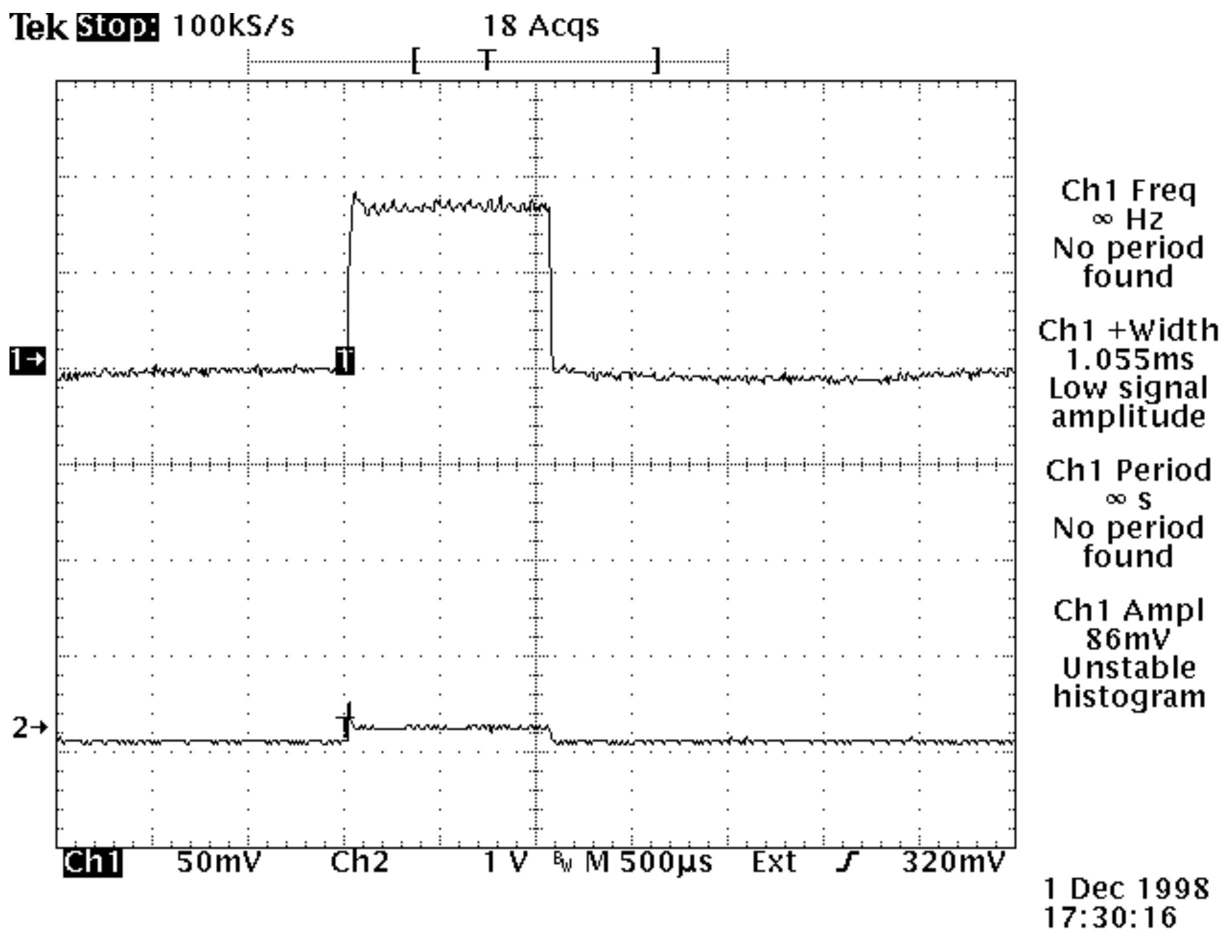

Figure 3.3: 43-mA ion-beam pulse (upper signal, 25 mA/div) from the R&D Ion Source at 12% duty factor. The discharge was cesium enhanced, but the source was not equipped with an electron-separating magnetic field or a dumping electrode. The electrons in the extracted beam were separated from the ions inside the Faraday cup and reached a current of 90 mA (lower signal, 500 mA/div).

at 30 kW peak rf power and 12% duty factor, see Fig. 3.3. At 45 kW rf power, the same source produced an ion beam pulse of 70 mA peak amplitude that sloped down to 35 mA during the 1-ms pulse duration. The measured electron current started at about 200 mA in this case and sloped up to 225 mA towards the end of the pulse.

Antenna lifetime is a very important issue for the SNS Front End because it will determine the time-between-services for the entire system. Previously employed porcelain-coated copper antennas exhibited somewhat erratic performance, typically caused by small cracks in the coating that during operation developed into hot spots, anchoring plasma arcs that eroded the copper tubes. The most recent antenna design consists of a water-cooled titanium or stainless-steel tube inserted into a quartz tube for protection. Such an antenna was subjected to a 530-hour test inside a standard multicusp rf plasma generator, operated with hydrogen at 3-kW cw power, and subsequently, without servicing, to 300 hours more of short-pulsed operation. The quartz tube held up very well under these conditions, suggesting that the 504-hour lifetime can be reached with the SNS Production Ion-Source. The Startup Ion-Source is currently being commissioned at the LBNL Integrated Testing Facility and operated in connection with the Startup LEBT. So far, a maximum ion beam current of 20 mA has been measured downstream of the LEBT, without using any cesium enhancement. This ion source is essentially built from stainless steel and incorporates an electron-dumping magnet field and a dumping electrode. The entire source assembly is tilted with respect to the LEBT axis to compensate for the steering action that the dumping field exercises on the ion beam. The tilt angle can be adjusted between 0 and 7 degrees without breaking vacuum. The Production Ion-Source will essentially be a copy of the Startup Source, with the exception of the cesium-collar design which will have to be modified to attain the optimum temperature at a peak discharge power of approximately 60 kW.

3.1.1.3 LEBT

As stated above, the SNS Front-End LEBT is derived from an earlier proton LEBT design that had shown good agreement between simulated and measured beam parameters. Changes were made not only to the inner electrode contours but also to the mechanical layout of the vacuum chamber and high-voltage insulators, keeping only one major insulator to separate the ion-source and ground potentials along the air-to-vacuum interface, see Fig. 3.4. All other insulators that separate LEBT electrodes on different potentials are plain ceramic rods glued to stainless-steel end pieces. This design uses less length than a conventional multi-ring design and thus provides increased pumping speed near the system axis. The second einzel lens (second-last electrode in beam direction) is split into four quadrants to allow the application of pulsed chopping waveforms as well as dc steering voltages. The last LEBT electrode is part of the RFQ entrance wall and on its upstream side carries a diagnostic electrode made again from four insulated quadrants. Chopping waveforms of about 2.5-kV amplitude and 295-ns duration are applied between two opposing groups of adjacent quadrants, rotating the assignments by 90° from pulse to pulse. This pattern causes the chopped beam to be deflected alternatingly towards each one of the four separation zones between the diagnostic-electrode quadrants, oriented under 45-degree angles with respect to the RFQ vanes. In this way, any parts of the beam that are not intercepted by the diagnostic electrode are prevented from hitting the RFQ vanes themselves whose accurate shapes could otherwise slowly be eroded.

Chopping tests performed on the 40-keV proton beam line indicate that 50-ns rise and fall times can be expected from the SNS LEBT chopper.

Independently of the chopping waveforms, dc steering voltages can be applied between opposing quadrants of the second einzel lens to adjust the beam tilt angle. In addition, the entire LEBT vacuum chamber together with the ion source can be transversely shifted under vacuum with respect to the RFQ axis to correct any positional beam offset. The diagnostic electrode will be helpful in detecting such offsets by measuring the difference in currents on the two quadrants between whom the chopped beam is directed during a given pulse. Under good alignment conditions, the sum of these current signals will be proportional to the total ion beam current delivered by the LEBT and can be used to monitor this quantity.

The 2-d code IGUN was used to simulate the ion beam in developing the electrode layout for the Production LEBT. IGUN assumes cylindrical symmetry, is rather easy to set up and run on a personal computer, and has proven to produce reliable results [5], but it appears to exhibit a functional error in cases such as the SNS ion-source extraction system when a finite ion temperature is chosen among the input conditions, leading to unrealistic splits of the output emittance and overly chaotic arrangement of the beam trajectories near the axis. Detailed studies proved that these effects are directly related to an anomalous curvature of the equipotential surface ('meniscus') that separates ion-source plasma and beam. To overcome this problem, zero ion-temperature conditions are applied at first when the plasma meniscus shape is being calculated, resulting in a smoothly curved shape. The simulation problem is then split at the equipotential surface 0.2 keV

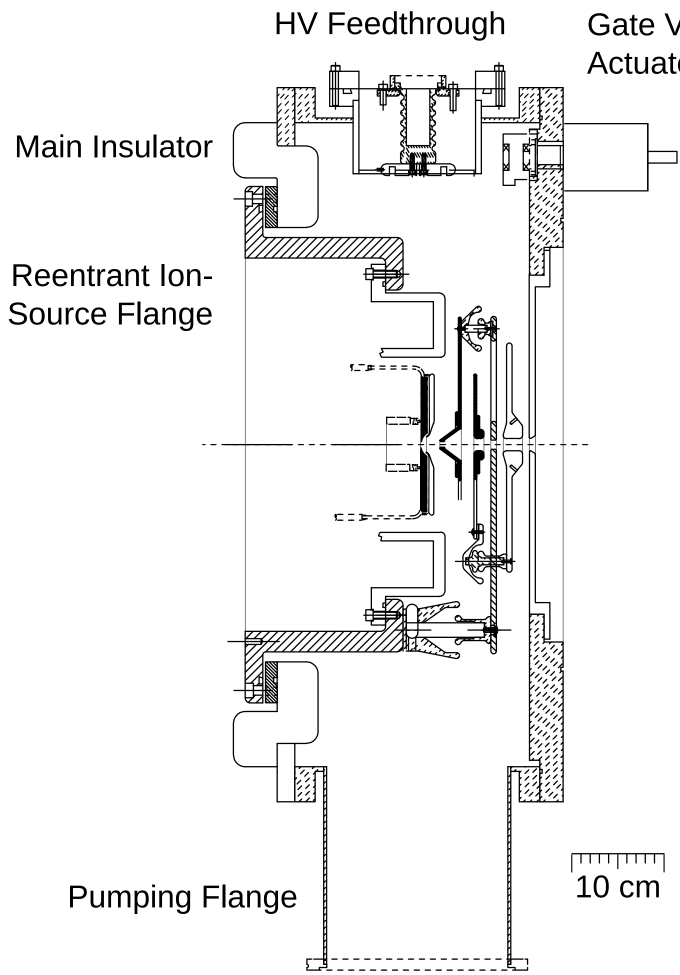

Figure 3.4: Startup LEBT being mounted inside the vacuum chamber. Three 500-l turbo pumps are installed around the chamber perimeter.

above meniscus potential, and transverse angles corresponding to the assumed ion temperature are added to the resulting output trajectories, alternating between radially outward, unchanged, and inward directions. These trajectories are then introduced into a second simulation run. Another complication is caused by the presence of electrons with an asymmetric density profile in the extracted ion beam, due to the dumping magnetic field. The LBNL approach [6] in dealing with this issue consists in adding the effective space charge of the electrons to the ion-beam current for the upstream region of the extraction gap, calculating an intermediate equipotential surface where the electrons are believed to have been removed by the dumping field, and then continuing in a third run with reduced current, representing the ions alone. The question with this approach is which exact current value to ascribe to the electrons, because their axial velocities will gradually decrease to zero over the region of interest. To resolve this issue, we empirically calibrated this process by comparing a measured emittance with simulation results for the Startup LEBT at 8-mA ion-beam current. It turned out that an electron current higher by a factor of 6 than the ion current led to good agreement with the measured emittance size and Twiss parameters in this case where no cesium was used in the ion source. For operation with cesium, no measured emittance values are yet available, but a reduction of electron current by a factor of 6, resulting in a 1:1 ratio between electron and ion currents, appears reasonable. By varying this ratio in test runs, we established that the value is rather uncritical and that any residual effects caused by an incorrectly assumed value can easily be corrected by varying the potential of the extractor electrode to adjust the voltage in the main extraction gap. The Production LEBT has to handle a beam current of 65 mA. To accommodate the additional space charge as compared to the Startup LEBT, the entrance-section design of the Production LEBT is widened, whereas the exit part with the second lens is kept unchanged, allowing to rely on the established operational parameters of the chopping system.

Other details of the electrode shapes are modified as well, leading to the design shown in Fig. 3.5. The predicted transverse normalized rms emittance for the Production LEBT is 0.10π mm mrad, two times smaller than the allocated emittance budget, when the correct Twiss parameters are obtained at the RFQ entrance plane. This factor of two provides a reasonable cushion in view of possible discrepancies between simulations and the actual beam emittance, caused, for example, by the dumping magnetic dipole field whose effects are not considered in the 2-dimensional calculations.

3.1.2 RFQ and MEBT

John Staples `staples@lbl.gov` LBNL

LBNL is providing the Front End Systems (FES) for the five-laboratory Spallation Neutron Source (SNS) collaboration. The FES comprises the ion source, LEBT, RFQ, MEBT, and computer controls specific to the front end.

The FES provides a 2.5 MeV H^- beam at a peak current of 56 mA to the entrance of the DTL. The RFQ accelerates the H^- beam from 65 keV from the ion source to 2.5 MeV, to be subsequently accelerated to full energy by the linac system. the RFQ bunches the cw beam at 402.5 MHz and matches the 402.5 MHz frequency of the first linac sections. The MEBT provides room for the fast (<10 nsec) chopper that provides a 250 nsec gap for the ring extraction kicker. The high-energy section of the linac continues acceleration at 805 MHz. The RFQ operates at a beam duty factor of 6% and is 3.7 meters long.

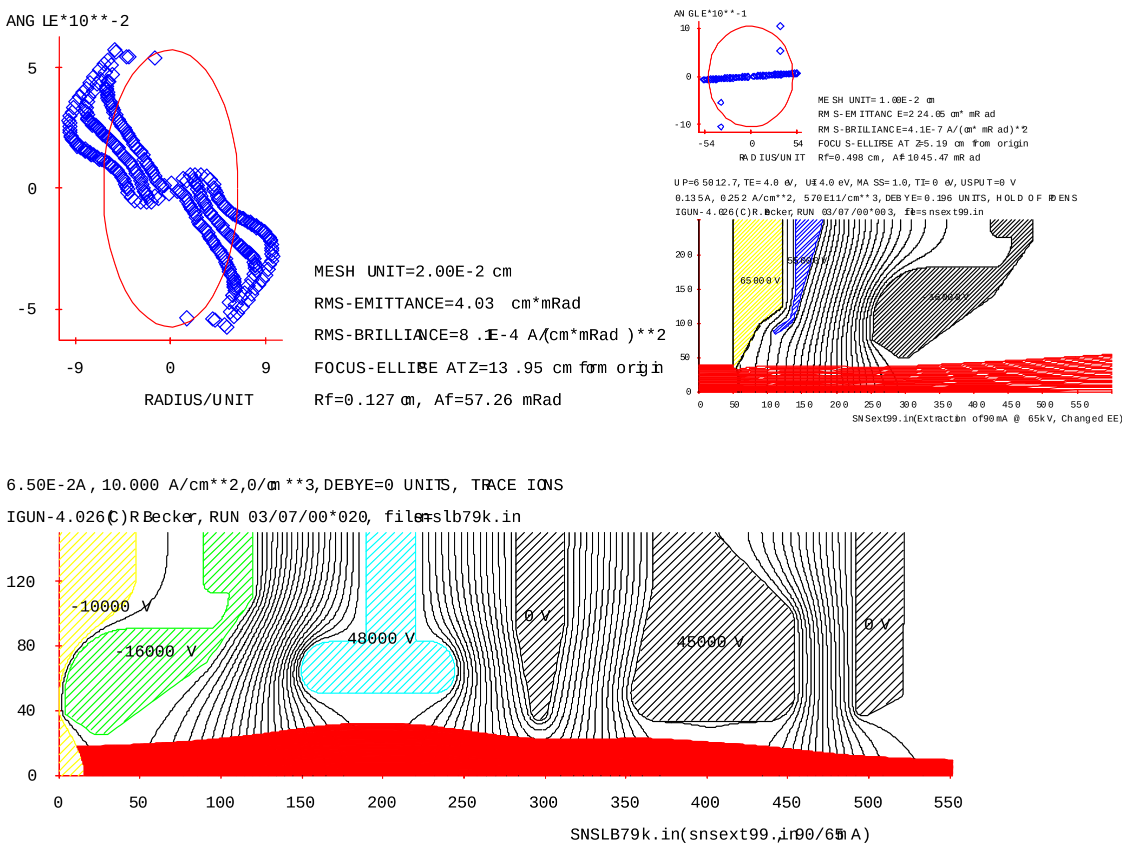

Figure 3.5: Production LEBT with beam trajectories simulated by IGUN. Assumed beam currents are 90 mA in the first part of the extraction gap and 65 mA elsewhere. The Twiss parameters in the exit plane are α =1.68 and β=0.090 m, with a normalized rms emittance (converted to x/x' equivalent) of 0.093 π mm mrad.

Table 3.1: Key RFQ Parameters

Item	Value	Units
Input Energy	65	keV
Output Energy	2.5	MeV
Frequency	402.5	MHz
Length	3.72	meters
Nominal Aperture r_0	3.51	mm
Surface field	1.85	kilpatrick
Peak rms structure power	630	kW

3.1.2.1 The Radio Frequency Quadrupole (RFQ) accelerator

The RFQ beam dynamics design consists of the usual four sections: the radial matcher, the shaper, the buncher and the accelerator sections. Table 3.1 lists some key RFQ parameters.

The RFQ has a total of 449 cells and is 372 cm long, or about 5 free-space wavelengths. Fig. 3.6 shows a macroparticle simulation of the beam through the RFQ (x-spread on top, phase spread in the center, and energy spread on bottom), along with demarcation lines showing the four beam physics subsections: the radial matcher (RM), the shaper (SM), the gentle buncher (GB) and the accelerator (AC) sections. In addition, the fractions at the bottom indicate the position of the junctions between the four 93 cm long physical modules. The gray core contains 50% of the beam, the black surround 90%, and the colored area last 10% of the beam.

Input Matching A LEBT with two electrostatic einzel lenses matches the input Twiss parameters α and β (the beam is cylindrically symmetric in both x and x') into the RFQ. The electrostatic LEBT allows a transverse beam chopper to be used by splitting the second lens into four quadrants and applying a chopping waveform to the quadrants.

Even though the default design parameters call for an 80% RFQ acceleration efficiency (56 mA out with 70 mA in), simulations with a normalized rms input emittance of 0.2 π mm-mrad indicate that the transmission efficiency is 92% at 56 mA output beam current.

Cavity Configuration The RFQ operates at the TE_{120} quadrupole mode cutoff frequency, with resonant end sections that satisfy termination boundary conditions that allow a flat voltage distribution along the entire structure.

The 4-vane RFQ is excited in the TE_{120} mode, producing a time-varying quadrupole electric field along the axis. This quadrupole field imposes an alternate gradient (strong) focusing force on the beam with period length $\beta\lambda$, where λ is the free-space wavelength of the r.f. excitation.

In a circular waveguide the TE_{120} cutoff frequency is significantly above the lowest TE_{110} dipole mode frequency, but, in an RFQ, the loading effect of the vanes brings the TE_{110} and TE_{120} mode frequencies into near coincidence. Mode mixing can occur when mechanical asymmetry drives the TE_{110} mode when its frequency is near the TE_{120} mode, producing dipole fields on axis, which deflect the beam off-center.

The dipole mode frequency is moved 35 MHz above the quadrupole mode frequency by a transverse stabilizing technique developed at KEK for the JHC high duty-factor RFQ [9] using so-called pi-mode stabilizers, which can be easily water-cooled. Fig. 3.7 shows pi-mode stabilizers running straight across the RFQ cavity, through holes in adjacent vanes. The rods are placed in the RFQ in pairs, of alternating horizontal and vertical orientation.

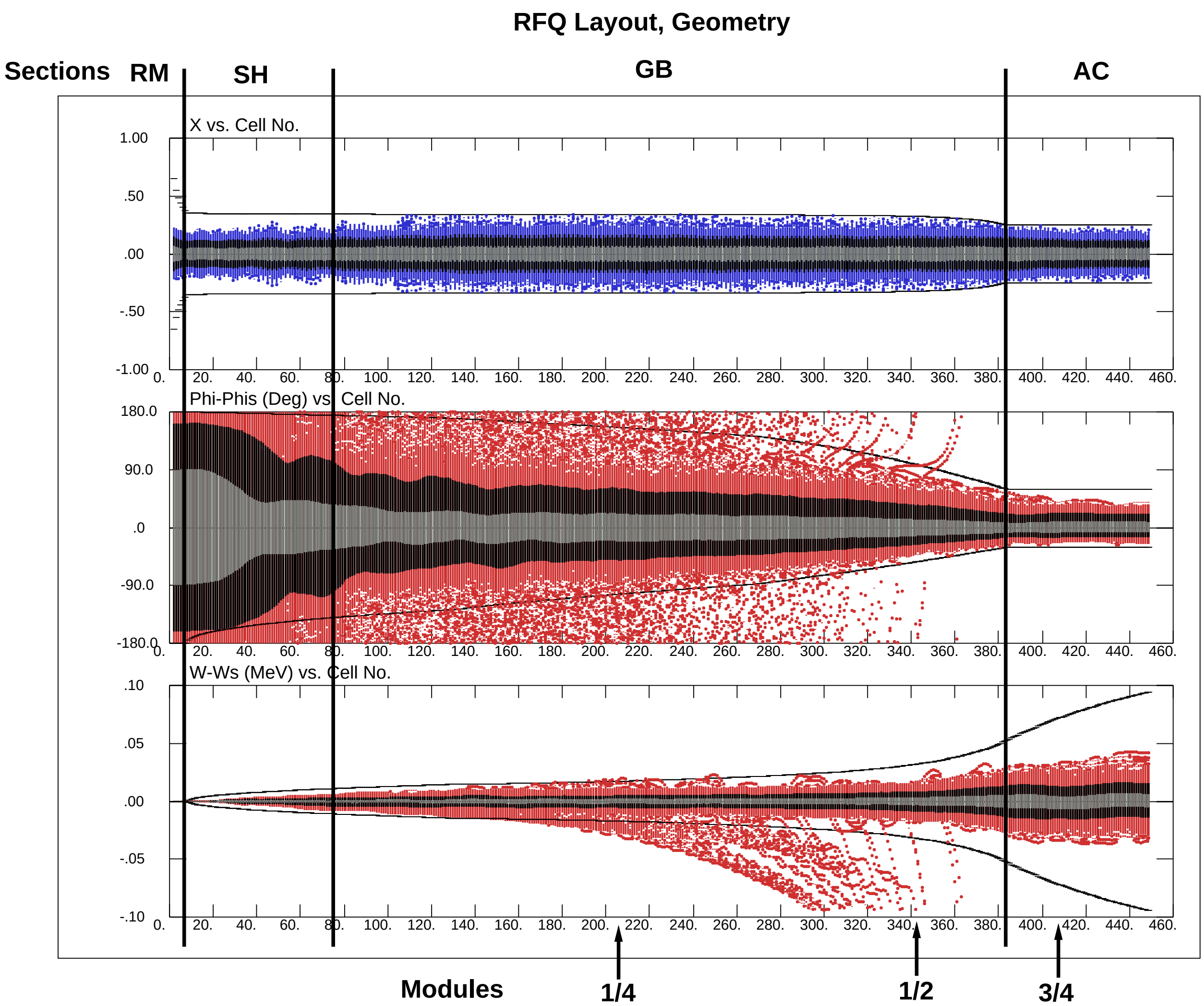

Figure 3.6: Transverse and longitudinal bunch widths, RFQ and module sections

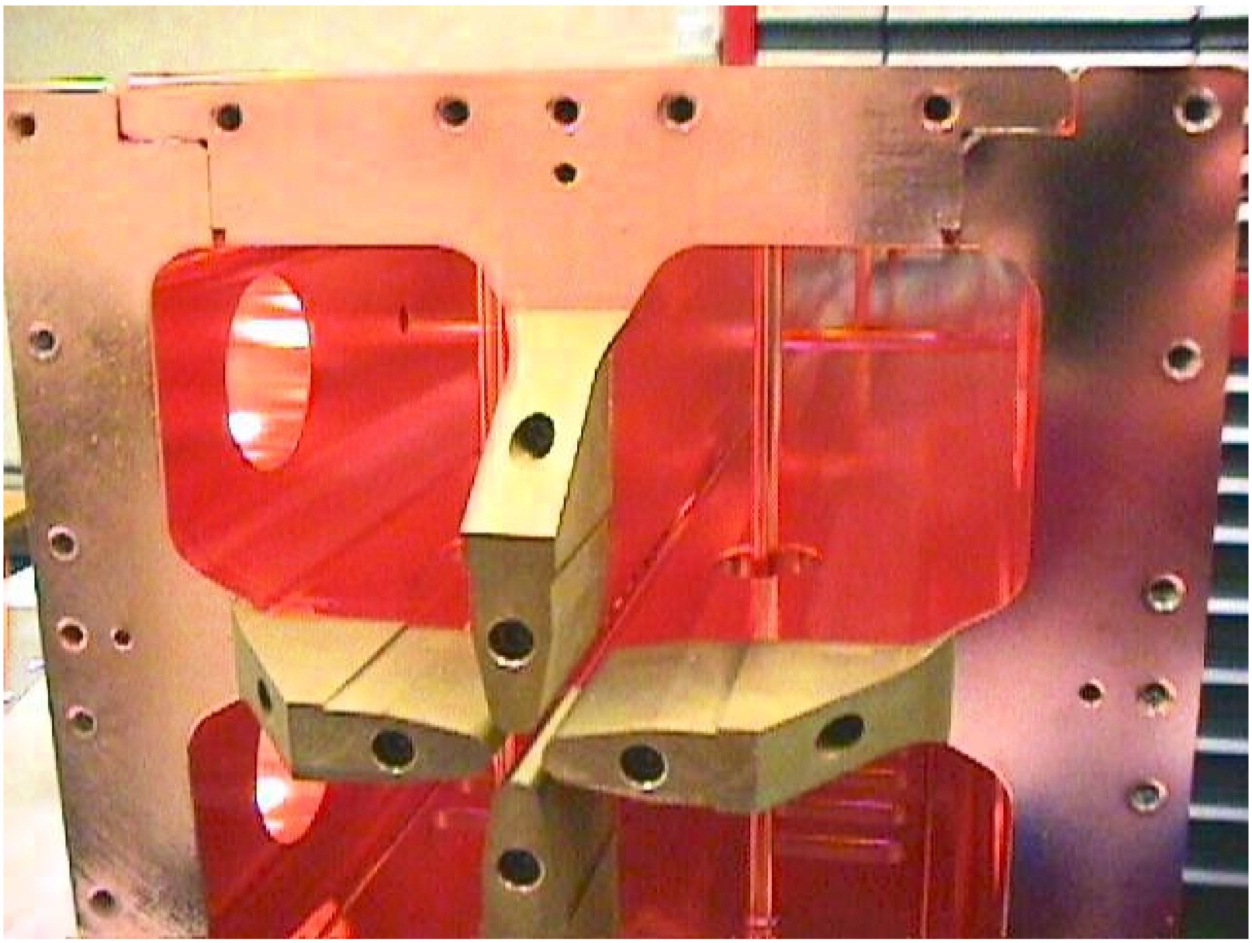

Figure 3.7: Pi-mode stabilizer rods within RFQ structure

Table 3.2: Key MEBT Parameters

Item	Value	Units
Length	3.62	meters
Peak output current	56	mA
Number of quadrupoles	14	
Number of rf cavities	4	
Transverse output emittance	0.27	π mm-mrad, norm, rms
Longitudinal output emittance	126	π keV-deg, rms

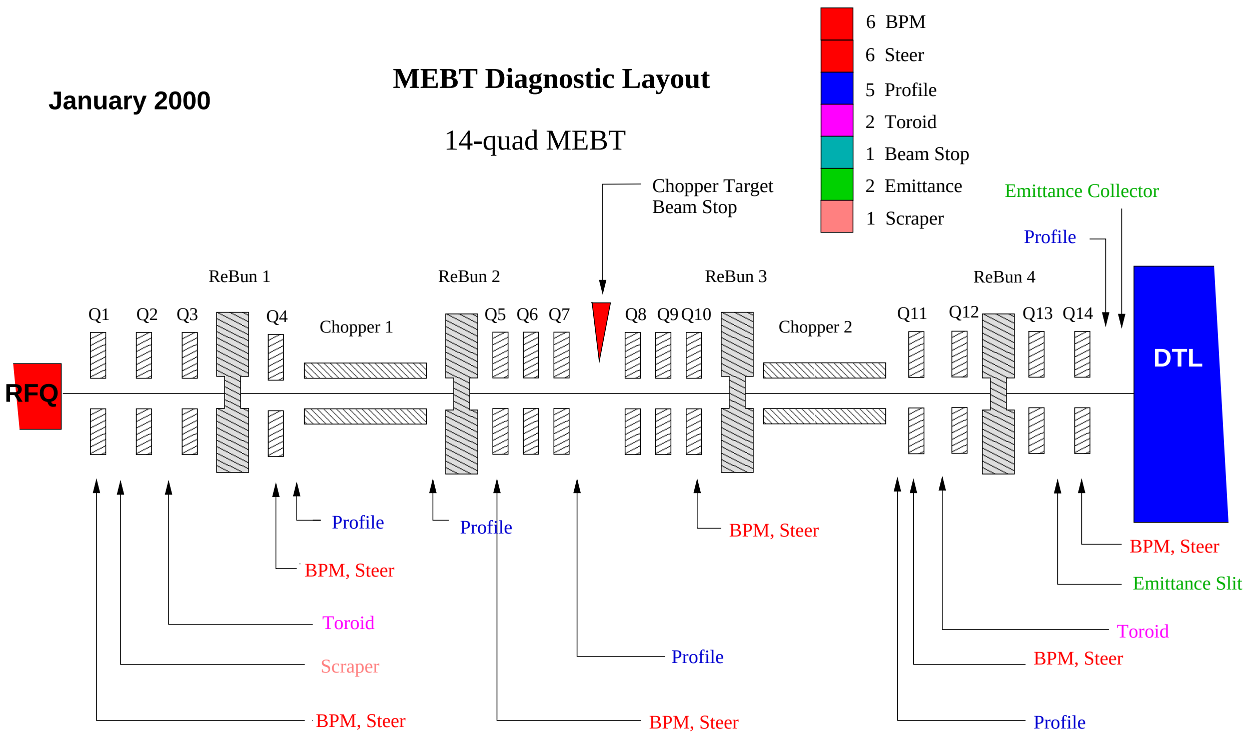

Figure 3.8: MEBT logical layout and diagnostics complement

3.1.2.2 Medium Energy Beam Transport (MEBT)

The MEBT transports the 56 mA, 2.5 MeV H^- beam from the RFQ exit to the DTL entrance and accommodates the fast chopper. In addition, the MEBT includes diagnostic instruments that provide real-time, non-intercepting information of various beam parameters. Additional intercepting diagnostics are also provided, to be used for commissioning and off-line beam measurements.

The MEBT comprises an input matching section of four quadrupoles, a symmetric center section comprising a chopper and a focusing quadrupole triplet, the chopper target, followed by a symmetric focusing triplet and antichopper, identical to the chopper, and finally a four quadrupole output matching section. Fig. 3.8 shows the logical layout of the MEBT and Table 3.2 lists some key MEBT parameters.

Design Issues A 56 mA, 2.5 MeV, bunched H^- beam with a nominal normalized rms emittance of 0.20-0.25 π mm-mrad has significant nonlinear space charge forces tending to defocus the beam and increase the emittance of the beam.

To minimize the effects of space charge, the external focusing forces are kept as large as practical to dominate the nonlinear space charge forces arising from the nonlinear distribution of charge in the beam itself. However, spaces must be provided for the traveling-wave choppers, and the lattice is therefore somewhat irregular. To match the beam across the 62 cm drifts containing the choppers, the phase advance from the RFQ is adiabatically (as much as possible) reduced in the first four quadrupole section, followed by transverse compression of the beam vertically at the chopper target. The second half of the MEBT is essentially a mirror image of the first half, matching the beam into the DTL.

The four rebuncher cavities maintain the bunch length short enough so that longitudinal nonlinearity due to the sinusoidal waveform does not significantly filament the longitudinal phase space distribution. The bunch length is allowed to expand slightly, reducing the charge density, but not so large as to experience significant rebuncher waveform nonlinearity. In addition, the beam size is kept as small and round as possible at the cavity gaps so not to couple asymmetrically to the gap fringe field.

The emittance growth due to the finite rise/fall time of the chopper waveform is minimized by the presence of the antichopper, which returns partially chopped beam during the 10 nsec transition time back to the axis, so that the envelope of partially chopped bunches is always contained with the envelope of the unchopped beam. Macroparticle simulations of partially chopped beam through the rest of the linac indicate that the transversely asymmetric distribution of a partially chopped pulse does not result in growth of the beam outside the normal (unchopped) beam envelope.

MEBT Chopper The ring requires at least a 250 nsec gap in the accumulated circulating beam for the extraction kicker magnet to rise. The amount of beam in the gap must be less than 10^{-4} of the total beam to reduce the activation of the extraction Lambertson septum magnet.

The beam will be prechopped in the LEBT with a rise/fall time of less than 50 nsec with a square wave with a duty factor of 65% at a rate of 1.188 MHz, and the MEBT chopper will clean up the transitions with a rise/fall time of less than 10 nsec, and will increase the beam on/off intensity ratio to at least 10^4:1.

Beam simulations at LANL and BNL indicate that partially chopped bunches, resulting from a 10 nsec transition, as long as their extent is contained within the envelope of an unchopped bunch, will be accelerated through the linac without additional loss.

MEBT Chopper Target The MEBT chopper is a “clean up” chopper, sharpening up the rise/fall time of the LEBT chopper, and increasing the on/off intensity ratio of the chopped beam.

The rise/fall time of the LEBT chopper will be less than 50 nsec, and conceivably as short as 20 nsec. To achieve a 10 nsec rise time, the MEBT chopper cleans up the ends of the chopped pulse, delivering 2.5 MeV beam to the MEBT chopper target in approximately 2000 50 nsec triangular-shaped pulses during the 1 msec beam pulse. The peak power of a 56 mA, 2.5 keV beam is 140 kW, and the average power of the beam on the target is less than 500 watts. The rms beam spot size on the target is σ_x = 0.41 cm by σ_y = 0.18 cm. The maximum power density during the peak of the 50 nsec triangular pulse is 140 kW/$2\pi\sigma_x\sigma_y$ = 302 kW/cm^2 at the core of the beam.

The target material is a molybdenum alloy, TZM. ANSYS calculations indicate that, with a 30% derating of the 95 ksi yield to give a margin for fatigue fracture, that the temperature rise during a 1 msec beam pulse results in a factor of two margin below the derated yield stress limit. The temperature rise during a 50 nsec micropulse is less than 2° C, and the 500 watt steady-state heat load is easily accommodated with a microchannel water cooling system embedded in the target. The beam strikes the target at an angle 75° from the normal, and the lifetime of the target due to sputtering damage is expected to be several years. The peak surface temperature of the target is 122°C, and is about 90°C in the pressurized water channel after steady-state has been reached

Quadrupoles The quadrupoles are based on the LEDA quadrupoles, which have been prototyped and measured. The quadrupoles are split about both the horizontal and vertical midlines, and will be assembled around the beam pipe. In addition, six of the quadrupoles have BPMs within the quadrupole bore and steering windings on the return yokes. The sextupole component which is excited when the steering coils are activated has been determined with ANSYS simulations and its effect on the beam emittance was reported above. The n=6 (dodecapole) component has also been determined by ANSYS simulations, and its amplitude is three orders of magnitude below that which would cause noticeable emittance growth in the MEBT.

Rebuncher Cavities The four rebuncher cavities are reentrant, and are thinned out near the axis to save space. At larger radii, the cavities are expanded out along the beam axis to increase the cavity stored energy and to avoid parallel surfaces which are prone to multipacting.

The cavity aperture radius is 1.5 cm for the first and fourth cavities, 1.8 cm for the second and third cavities. The four cavities have maximum energy gain ($e \int E_0 T dL$) of 75, 45, 49 and 120 keV, respectively, with the two cavities in the center with the larger bore radius having the lowest required gradients.

MEBT Design Procedure The configuration chosen early for the SNS MEBT is the chopper-antichopper solution for the reasons stated above: its inherent symmetry allows more latitude for partially chopped bunches and more immunity for ringing in the chopper power supplies, as long as the power supplies themselves are matched. The challenge of this approach is the high power density on the chopper target.

The analysis procedure involves optimizing the Twiss parameters through the MEBT with envelope codes such as TRACE3D, and then fine-tuning and optimizing the parameters with macroparticle simulation codes such as PARMILA. In all cases, the input beam distribution is derived from simulations of the RFQ with an 8-term version of PARMTEQ. The beam is then further propagated through the first 20 MeV tank of the DTL with PARMILA, to verify the quality of matching between the RFQ, the MEBT and the DTL. The beam emittance at the end of the DTL is used as a criterion for good matching conditions throughout the MEBT.

Practical engineering considerations play a large role in the design of the MEBT. The components, such as the quadrupoles, beam diagnostics and rebuncher cavities must be physically realizable, with flanges and vacuum ports. In addition, due to the high beam current, the beam pipe is as symmetric and continuous as possible, to minimize interaction with the beam. The aperture is large enough to intercept no beam and to provide adequate vacuum conductance.

The LBNL MEBT design has been validated by the LANL beam dynamics group, who continue macroparticle simulations with ensembles generated at the RFQ entrance, carried through the MEBT and then through the rest of the linac. The simulations using the same particle ensembles are continued through the HEBT and the accumulator ring by BNL. In this manner, a complete end-to-end simulation is accomplished, including errors in all components of the accelerator. The LANL beam physics group has played an important role in the development and refinement of the MEBT beam physics design.

(The work of the previous two sections is supported by the Director, Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.)

3.1.3 Superconducting Cavities

R. Sundelin `sundelin@jlab.org` Thomas Jefferson Laboratory

The Spallation Neutron Source is in the final stages of changing the technology for the linac, between 185 MeV and 1000 MeV, from normal-conducting copper at room temperature to superconducting niobium at 2.1°K. This change will provide lower operating costs, higher availability, and potential upgrades in beam power.

Superconducting cavities differ from normal-conducting cavities primarily by exhibiting Q_0 values of several times 10^9, rather than several times 10^4, which is partially offset by a Carnot efficiency around 10^{-3} for the superconducting cavities. This leads to the greatest advantage for CW accelerators, and is near the break-even point for accelerators such as the SNS linac, which has an RF duty cycle of 7%. At a 7% duty cycle, the normal-conducting cavity fields are limited by the ability to conduct heat away from the copper, so the superconducting linac can be appreciably shorter. The shorter linac, with reduced parts count and the option of including a "hot spare," improves the availability.

Unlike a normal-conducting copper cavity, which has a well defined upper accelerating field determined by the ability to remove heat (the limitation switches to field emission and sparking at much shorter duty cycles), a superconducting cavity is limited by the worst defect on its surface. The limitation may be either field emission or thermo-magnetic quench. The field emission limitation is the same mechanism as in normal-conducting cavities, except that the RF-accelerated field emitted electrons bombard the surface, and can overload the refrigerator or initiate a thermo-magnetic quench. The field emitters are normally defects with a Fowler-Nordheim enhancement coefficient in the vicinity of 50 (i.e., they emit at 0.02 times the field at which a defect-free surface emits). A thermo-magnetic quench is caused by a defect which is either normal-conducting, or which becomes normal-conducting at an anomalously low RF magnetic field. Such defects are typically one micron in diameter. The heat they generate causes the temperature of the surrounding niobium to exceed its critical temperature (9°K), and this creates a run-away situation because more heat is generated by the normal-conducting niobium. Use of niobium with thermal conductivity at 2.1°K of 300 times its thermal conductivity at room temperature keeps the thermo-magnetic quenches from being the predominant limitation. Since the defects are randomly distributed in location and size, no two cavities have the same maximum operating gradient capability.

Other important considerations in the design of a superconducting cavity are that the ambient magnetic field be reduced to about 0.5 mT to avoid a significant Q reduction due to frozen-in flux. The cavity needs to be capable of being tuned by deformation while cold, without being overly susceptible to microphonics or Lorentz force detuning, and the amount of niobium used to accomplish this needs to be controlled to control the cost. The shape needs to be such that the cavity can be formed by electron beam welding, and be readily chemically cleaned and rinsed. The cell shape needs to minimize the ratio of the peak surface electric field to the accelerating field, and of the peak surface magnetic field to the accelerating field. The coupling between cells needs to be adequate to maintain a flat field profile. The minimum beam pipe diameter needs to avoid intercepting any appreciable amount of the beam. The number of cells in a cavity needs to be relatively small, since only a small number of cell lengths can be used (due to manufacturing requirements; two for the SNS), and the phase slip of the beam with respect to the cavity length needs to be relatively small or the cavity efficiency drops unacceptably. The cavity cell must not support either one- or two-point multipacting to the extent that processing the multipacting barriers is impossible, or takes an unacceptable length of time. The cavity must not be inelastically deformed by external helium pressure during the refrigerator cool-down, during which time the pressure is somewhat above atmospheric. The non-pi modes of the fundamental passband must avoid being at sidebands of the frequency at which the beam is notched for injection into the ring. The input coupler must deliver the requisite power to the beam without creating an unacceptable heat load, without multipacting, and without window arcing. The higher order modes which are induced by the beam must be damped adequately so that they do not destroy the beam, or unacceptably increase its emittance.

As one may deduce from the preceding discussions, it is essential that the surface of a superconducting cavity be extraordinarily clean. High pressure rinsing has advanced the state of the art so that peak surface electric fields of 25 to 30 MV/m can now be achieved, compared with the 10 to 14 MV/m available with the previous state of the art. The intrinsic limit of a superconducting cavity is imposed by the ability of the superconductor to support an RF magnetic field without breaking the Cooper pairs that provide the superconductivity; the intrinsic magnetic field limit occurs at a peak surface electric field of around 70 MV/m (for the SNS cavity shape), which is well above the present state of the art. Further improvements in the state of the art are expected to increase the fields available in the superconducting cavities. When such improvements become available, the cavities can be removed a few at a time, treated with the improved process, and reinstalled.

3.1.4 Accumulator Ring

J. Wei wei1@bnl.gov Brookhaven National Laboratory

During the past year, several studies have been performed at the Brookhaven National Laboratory to explore optimum scenario for the SNS ring used to accumulate proton bunch. The first study is on an alternative scheme based on Rapid-Cycling-Synchrotrons (RCS) [10], generally believed to be more cost-effective than a full-energy LINAC-accumulator ring design (LAR) [11]. The study, on the contrary, led to the conclusion that stringent beam loss limit of a 2 MW-source requires a design of the RCS rings that are technically challenging and consequently less cost-effective [12]. After reaching this conclusion, our physics group re-focused on design optimization of the present full-energy LINAC-accumulator ring [13]. The original all-FODO lattice was changed to a FODO-arc/doublet-straight hybrid lattice. By improving arc-straight matching, the ring acceptance is increased by more than 50%, and the uninterrupted straight section is increased to 12.5 m, thus making ring injection robust and also significantly increasing collimation efficiency. Finally, the ring is designed to be flexible to accommodate output energy variation of the Linac and potential gradient improvement of the linac superconducting RF cavities.

3.1.4.1 Rapid-Cycling-Synchrotron alternative design

The nominal accelerator complex (LAR) consists of the source and the front end, a 1 GeV full-energy LINAC, a single accumulator ring and its transfer lines, and the target. The RCS design consists of a 400 MeV LINAC injecting into two synchrotrons, each accelerating beam pulses of 1.04×10^{14} protons at a repetition rate of 30 Hz from 400 MeV to 2 GeV, producing a combined beam power of 2 MW. The two synchrotrons are vertically stacked sharing the same tunnel.

The primary challenge to the RCS design is to minimize the radio-activation caused by uncontrolled beam loss. Among the existing RCS machines, typical beam loss ranges from several to tens of percent. Major beam loss usually occurs at injection and the initial ramping stage (first 5 ms). These beam losses are typically attributed to a high space change tune shift (0.5 or larger), limited physical and momentum acceptance, and large magnetic field errors. The SNS synchrotrons are designed with practically achievable large acceptance so that beam space charge tune shift remains about 0.2. The use of programmable ramping moderates the required RF voltage and ramp rate, resulting in a reasonable machine circumference and a tolerable eddy-current induced magnet errors. Lengths of the magnets are chosen to avoid excessive error due to saturation fringe field.

Effective collection of the beam halo is essential for maintaining a low uncontrolled beam loss. To facilitate the momentum cleaning and multi-stage collimation systems, a wide momentum acceptance (full beam plus $\pm 2\%$ in $\Delta p/p$) is chosen. This allows cleaning of the momentum halo using a multi-turn beam gap kicker system. With the collimation system designed to be more than 90% efficient, the total allowed beam loss is at 1% level.

Flexibility is another important aspect considered in the design. A matched FODO/doublet hybrid lattice is chosen so that chromatic and resonance correction can be done mainly in the FODO arcs, while long uninterrupted doublet straight sections allow flexible modular operation (injection painting independent of lattice tuning, long uninterrupted straight section, balanced RF cavity arrangement, etc.). Since the FODO arc and doublet straight section are optically matched, a low amplitude (β_{max}) is achieved for the given cell length, thus confining the beam size.

In summary, in order to build a RCS machine that will perform to the stringent beam loss limit required by the high-intensity, high power operational scenario, we must meet the following challenges:

- cleaning of ramping and RF capture beam loss
- development of programmable magnet power supply
- construction of large-bore magnets with laminated coils
- construction of large-aperture vacuum chambers with RF shielding
- control of magnetic field errors due to ramping eddy current and saturation
- need for separate quadrupole magnets for eddy current mismatch compensation
- instabilities (head-tail, e-p like (PSR), etc.)
- achievement of desired beam distribution at the target

3.1.4.2 Low-loss accumulator ring design optimization

After reaching the conclusion that an RCS design for a 2 MW Spallation Neutron Source is less cost-effective in comparison with a full energy LINAC-accumulator ring design, our physics group re-focused on design optimization of the present ring.

Reliability and maintainability are of primary importance to the SNS facility. Hands-on maintenance for the accumulator ring demands an average radio-activation at or below 1 – 2 mSv/hour 30 cm from the machine device. The corresponding uncontrolled beam loss is 10^{-4} for a 1 GeV beam.

To achieve this goal, the SNS ring design avoids common practices that lead to heavy beam loss: The beam is painted to a quasi-uniform distribution to keep space-charge tune shift below 0.15. A transverse acceptance/emittance ratio of about 3 allows the beam tail and beam halo to be cleaned by the collimation system before hitting the rest of the ring. A stationary RF bucket confines the beam to within 70% of its momentum acceptance ($\Delta p/p = \pm 1\%$), while the machine vacuum chamber provides a full momentum aperture of ±2% in $\Delta p/p$. The layout and magnetic field at injection are designed to prevent premature H^- and H^0 stripping and excessive foil hitting. A moderate main magnet field avoids saturation effects, and shimmed pole tip ends in both dipole and quadrupole magnets help compensate fringe field effects. Finally, vacuum chambers are coated, chamber steps are tapered, and injection beam momentum is broadened to avoid instabilities [23, 22, 24].

Efficient beam halo collection is essential for maintaining a low uncontrolled beam loss [16]. To facilitate multi-stage collimation and momentum cleaning using a multi-turn beam gap kicker system [17], a wide transverse and momentum acceptance is essential. With the collimation system designed to be more than 90% efficient, the total allowed beam loss on the collimators [21] is about 10^{-3}.

Flexibility is another important design goal. A matched FODO/doublet lattice is chosen because FODO arcs allow easy chromatic and resonance correction, while long uninterrupted doublet straights make the arrangement of injection modules independent of lattice tuning, and allow for optimal placement of collimators for phase-space collimation [16].

To address the issue of engineering reliability, collimators and machine hardware are designed to withstand an average 10^{-2} beam power. In addition, the machine is designed to withstand a couple of full beam pulses for commissioning and emergency handling.

As shown in Fig. 3.9, the ring has a four-fold symmetry consisting of four straight sections

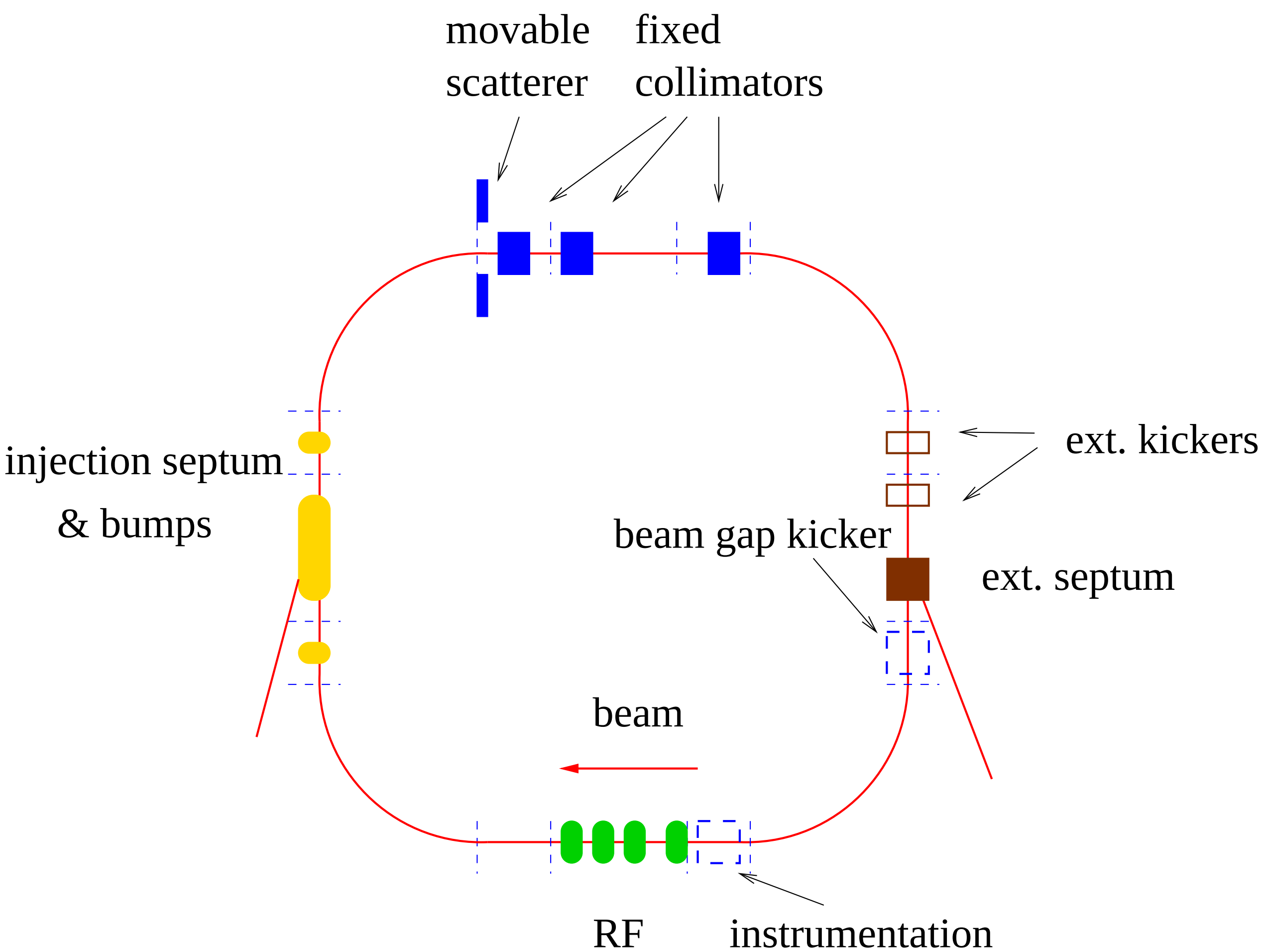

Figure 3.9: Schematic layout of the LINAC-accumulator ring indicating sections for injection, collimation, beam gap cleaning, RF system, instrumentation, and extraction.

intended for injection, beam collimation, RF system and beam instrumentation, and extraction. Chopped H^- beams are injected through charge exchange painting process to the ring, accumulated for 1225 turns, and then extracted with fast kickers.

FODO/Doublet hybrid lattice Key issues of the ring lattice design are adequate transverse and momentum acceptance for beam-tail development control and collimation, easiness for chromatic and resonant correction, and flexibility for injection, extraction, and collimation arrangement. We have been studying the benefit of an alternative lattice, the so-called hybrid lattice [15, 14] consisting of FODO structure in the arcs but doublets in the straight sections. The FODO arcs are ideal for chromatic and resonance correction. The long uninterrupted straight sections are flexible to accommodate injection, collimation, and extraction schemes which are essentially independent of lattice tuning, reducing the need for extra-large bore (31 cm inscribed diameter) quadrupoles and sextupoles. As shown in Fig. 3.10, the arc and straight sections are optically matched, increas-

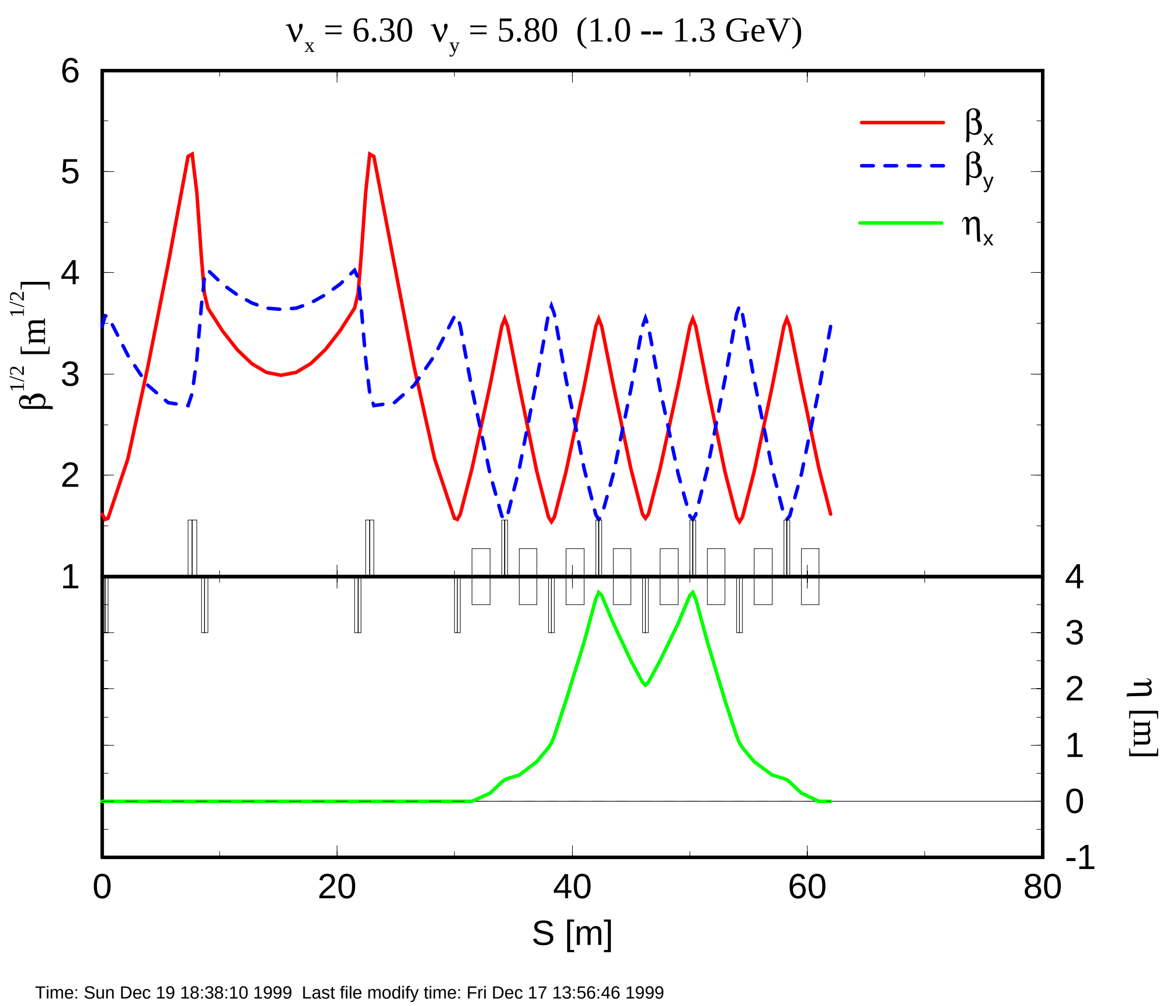

Figure 3.10: An alternative SNS Ring hybrid lattice with FODO arc and doublet straight sections.

ing the total ring acceptance from previously about 360 πmm·mr to 480 πmm·mr. Furthermore, the transverse tunes are fully adjustable and are planned to be split to minimize coupling and to reduce the beam envelope variation (i.e. β_{max}/β_{min} ratio). Chromatic sextupoles are introduced to control chromaticity, to minimize off-momentum optics mismatch, and to improve dynamic acceptance and momentum acceptance.

Magnet fringe field With the SNS ring, the magnet aperture (17 cm dipole gap, 21 to 31 cm quadrupole inscribed diameter) is relatively large to provide adequate acceptance for the painted beam (about 120 π mm mr full unnormalized emittance). The magnet length (from 0.5 to 1.5 m), on the other hand, is relative short in a ring of moderate circumference. The effect of magnet fringe field is significant.

Impact from the transverse magnetic field component is evaluated by many computer tracking and simulation codes using multipole series expansions. Magnet pole tips are shaped to minimize the local contribution of the leading multipoles allowed by the magnet symmetry. On the other hand, impact from the longitudinal component of the magnetic field is often negligible especially for rings of larger circumference (e.g., RHIC, LHC). The relative magnitude of this longitudinal-component contribution is estimated by a "theorem" [25] to be the ratio of beam transverse emittance ϵ to the magnet length L. For machines like RHIC or LHC, the quantity ϵ/L is of the order of 10^{-7} or smaller. For SNS ring, however, ϵ/L is about 10^{-3}, comparable to the contribution from the transverse components. Octupole corrector families [26] are designed for global compensation. Table 3.3 lists expected tune shifts from various mechanisms indicating their impact to the beam.

Table 3.3: Tune shift produced by various machanisms

Mechanism	Full tune spread
Space charge	0.15
Chromaticity	±0.08
Kinematic nonlinearity	0.001
Fringe field (hard edge)	0.025
Uncompensated ring magnet error	±0.02
Compensated ring magnet error	±0.002
Injection fixed chicane	0.004
Injection painting bump	0.001

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3.2 JHF Activities and KEK/JAERI Joint Project

S. Machida shinji.machida@kek.jp KEK
National Laboratory for High Energy Physics
Y. Mori yoshiharu.mori@kek.jp KEK
National Laboratory for High Energy Physics

Since two high intensity accelerator projects, the Japan Hadron Project (JHF) at KEK and the Neutron Science Project (NSP) at JAERI, were merged last fall, refinement of machine parameters and R&D in accelerator components are continued. Hereafter, we call it the KEK/JAERI Joint Project for high intensity proton accelerator facility (shortly Joint Project.)

One of visible changes of the parameters is a footprint of the 50 GeV Proton Synchrotron (PS). In order to locate it well fit in the new site at JAERI, a threefold symmetry lattice is adopted instead of rectangular shape with two long and two short straight sections proposed before. The arc section consists of eight 3-DOFO modules with two missing bends in the middle cell. The phase advance of around 270 degrees per module enables the imaginary transition energy as well as the dispersion free straight section.

The average beam current of the 50 GeV PS, when it utilizes resonant slow extraction, is 15 μA with a repetition rate of 0.3 Hz and can be up to 20 μA with faster repetition of single-turn fast extraction. That of 3 GeV PS is 333 μA with 25 Hz operation, which makes the beam power of both synchrotrons 1 MW.

The construction of the first part of linac has started at KEK which was originally approved as a part of JHF. It consists of ion source, 3 MeV RFQ, 50 MeV DTL, and Separated DTL up to 60 MeV. After the beam commissioning, the whole system will be moved to JAERI.

The 50 GeV PS (or even 3 GeV PS) of the Joint Project will be appropriate as a proton driver of a neutrino factory, which draws a growing attention for last few years. Discussions have been started on the upgrade path of the 50 GeV PS with double or even four times as large beam current although the present baseline parameters well satisfy requirements of a neutrino factory to begin with. The new site for the Joint Project at JAERI can accommodate an accelerator complex up to a 50 GeV muon storage ring.

As a phase rotator of muon beams right after a muon decay section, an accelerator which follows, and a future high repetition ($\sim$1 kHz) proton driver, among others, a study of Fixed Field Alternating Gradient (FFAG) synchrotron is going on at KEK. The first proton model of 1 MeV output energy with 1 kHz repetition rate has been commissioned this March. Although the diameter of that machine is only 2.5 m, it has all the components that are necessary for a modern large scale accelerator.

At the moment, we confirmed that an injected beam is circulating at the inner orbit. The RF acceleration with a broad band Magnetic Alloy (MA) cavity will be applied soon. We plan to have a wide variety of beam dynamics study in a couple of years. The design and R&D of a 200 MeV FFAG have been initiated as the next stage of the FFAG study. An ultra-high gradient cavity with new ferrite material is under development for a phase rotator in parallel.

3.3 Studies at RAL towards a European Spallation Source and a Neutrino Factory Proton Driver (NFPD)

G.H.Rees G.H.Rees@rl.ac.uk Rutherford Appleton Laboratory, UK
C.R.Prior C.R.Prior@rl.ac.uk Rutherford Appleton Laboratory, UK

A reference design for the ESS has been described in the ICFA Newsletter, No. 20, of August, 1999. There have been some further developments for the 5 MW, 50 Hz source since that time, both for the 1.334 GeV linac and for the two associated accumulator rings. These developments are described in the next section, which also includes some details of a rapid cycling synchrotron option (RCS) that had earlier been discarded in favor of the linac-accumulator rings (LAR). The power levels and operating frequency for a Neutrino Factory Proton Driver (NFPD) are comparable to those for the ESS and a similar comparison between LAR and RCS options may be made. The NFPD has the additional requirements, however, of 1 ns rms bunch durations and this influences the choice between the options.

3.3.1 ESS

Studies have continued for the revised linac frequencies of 280 and 560 MHz. End to end simulations, in the absence of machine errors, show total rms emittance growths of 10.5% in the transverse planes and 5% in the longitudinal plane, but with an additional 7% for the latter while the beam debunches ahead of energy correcting cavities. These consist of two coupled cavity linac (CCL) cavities, each providing a peak voltage of 6 MV, and their distance from the end of the linac is approximately 72.0 m. The peak linac current is 114 mA after funneling at 20 MeV. The low energy stages consist of a 2.5 MeV RFQ, chopper section and a 2.5 to 20 MeV drift tube linac (DTL). The chopper sections are 1.6 m in length and exhibit no rms emittance growth, while the DTLs are operated at a synchronous phase angle of -42^o to limit the non-linearity of the longitudinal motion. Consideration is also being given to replacing the 20 to 100 MeV CCDTL section by a 560 MHz DTL.

Maximum tolerances specified for the linac rf generators are ±0.5% and $\pm0.5^o$ in amplitude and phase, respectively, and these result, in the worst case, to output phase errors of up to 3^o. The momentum error is corrected at the correction cavities but a 3^o phase error introduces a new fractional momentum error of $\pm3.3\ 10^{-4}$. Phase ramping of the correction cavities is provided up to values of $\pm18^o$ to sweep the output beam momentum from a fractional momentum offset of zero to 4×10^{-3}. Misalignment and quadrupole errors enhance the transverse emittances, and the final normalized transverse rms emittances are approximately 0.35(π) μrad.m.

A superconducting linac (SCL) has also been considered to replace the CCL. Cavity shapes have been optimized to minimize the cavity fields for six cell units at 560 MHz. Limits are set by the power in the input couplers, and not by the peak fields, due to the relatively long cavities and the high level of beam current. The overall linac length is not very different from the room temperature case, resulting in a cost increase. This situation may change in the future, however, if higher power input couplers become available. Tracking simulations for the SCL give similar results to those for the CCL for the case of similar errors. There may be larger rf system errors, however, unless separate rf generators are used for each cavity, which will also result in increased costs.

For the accumulator rings, the circumference has been increased to reduce the number of injected turns and hence to reduce the number of proton foil traverses and foil temperature. The previous lattice has been modified by adding a straight section in each superperiod, with an increase in radius from 26.0 to 35.0 m. Injection is improved by increasing the chopping duty cycle from 60 to 70% and by reducing the normalized dispersion at the stripping foil to 1.6 $m^{\frac{1}{2}}$. These, together with the fewer number of injected turns, reduce the average number of foil hits on subsequent turns to about two. The three adjacent straight sections in the revised superperiod simplify the design of the betatron collimation system.

The RCS option consisted of an 800 MeV injector linac and two 3 GeV, 25 Hz synchrotrons accelerating beam in alternate half cycles to provide a 50 Hz beam for the two target stations. The number of particles per pulse in each ring is approximately 2×10^{14}, and the dual harmonic acceleration systems use the harmonic numbers 2 and 4. The peak beam loading power at mid-cycle is approximately 5 MW for each ring, and longitudinal stability is obtained by using relatively large bunch areas of 5 eV sec per bunch. Costs for the RCS option were estimated at a little more than those for the LAR option, and this, together with the added complexity, led to the final choice for the LAR.

3.3.2 Neutrino Factory Proton Driver (NFPD)

Specifications for a NFPD have been set at 4 MW beam power, 50 or 100 Hz repetition frequency, proton kinetic energies in the range 2 to 30 GeV and 2 to 12 beam bunches per pulse, with final bunch durations of 1 ns rms. Studies at RAL have concentrated on synchrotron options in the energy range 5 to 15 GeV, but RAL also collaborates with CERN on the design of the accumulator ring for a 2 GeV, LAR option.

As an initial study point, an energy of 5 GeV has been selected for the synchrotron option as this is the lowest energy at which it appears practical to achieve the specified final bunch durations. A low linac injection energy of 180 MeV has been chosen to assist in achieving this feature. The possibility of a common linac injector for a neutrino factory and a spallation neutron source has also been considered, but the gain would not be great for the synchrotron scheme proposed as the common linac energy would be small compared with the output energy of the spallation source linac. There also appears incompatibility between the LAR option and a spallation source linac because very different chopping duty cycles are required for the two sources.

The scheme proposed for a 5 GeV synchrotron option is the use of a 180 MeV H^- linac to feed two 50 Hz, 1.2 GeV proton synchrotrons, operating almost in phase; together these feed two 25 Hz, 5 GeV synchrotrons in alternate cycles. The combined output from the two 5 GeV rings is at 50 Hz, after the bunches have been compressed to the 1 ns rms bunch durations.

The low linac injection energy is adopted to minimize ($\sim$1 eV sec) the longitudinal bunch areas. Two bunches per ring are proposed for the 1.2 GeV synchrotrons in a $h = 2$ rf system, and four per ring for the 5 GeV rings in a $h = 8$ rf system, but assisted with a $h = 24$ system for the final bunch compression. Peak voltages required are 275 kV, 575 kV and 490 kV for the $h = 2$, 8 and 24 systems, respectively. Magnet lattices have been designed for the synchrotrons; those for the 1.2 GeV rings are very similar to those proposed for the ESS accumulator rings, while those for the 5 GeV rings employ missing magnet doublet cells, with the value for gamma transition set at 6.5, above but close to the value for gamma of 6.33 for 5 GeV protons. The lattice for the 5 GeV ring is very insensitive to gamma transition reduction due to transverse space charge forces. Tracking studies indicate that the 1 ns rms bunch durations may be achieved, but more detailed studies are required to confirm this fact. In particular, correction for the non-linear component of the momentum compaction requires to be evaluated.

A similar scheme to the one described may be used for a final energy of 15 GeV. In this case, a linac energy of 180 MeV may again be used, but now feeding two 25 Hz, 3 GeV rings, operating almost in phase; together these feed two 12.5 Hz, 15 GeV rings in alternate cycles to provide 25 Hz pulses at the high power target. The number of particles per pulse in the 15 GeV rings is 6.7×10^{13}, which may be compared with the 10^{14} per ring for the 5 GeV scheme. Use of the ISR tunnel at CERN may be considered for the 15 GeV rings but CERN also considers for this location a slower cycling option at the higher energy of 30 GeV.

The various synchrotron options may be compared with the 2 GeV LAR option. The final bunch durations of 1 ns rms are more readily achieved in the synchrotrons, and this specification has been relaxed to 1.5 ns rms for the LAR. Other difficult features for the 2 GeV LAR are the high power for the chopper collimators, the low momentum spread allowed in the accumulator ring, a factor of four less than for the ESS accumulators, and very high transverse space charge tune shifts in a separate compressor ring (both to be located in the ISR tunnel together with an injection collimation line). The low momentum spread in the LAR infers very tight tolerances for the rf generators in the 2 GeV injector linac. Finally, it is noted that target considerations appear to favor higher values for the product of the target energy and the repetition frequency, for a given beam power. This may give some bias towards the synchrotron options.

3.4 European Neutrino Factory Studies at CERN

H. Schonauer `horst.schonauer@cern.ch` CERN

The activity of the Neutrino Factory Working Group for Accelerator Aspects at CERN (NFWG) has begun in May 1999, following a mandate issued by the Director of Accelerators K. Hübner. Some of the present goals were specified at the NuFAct'99 workshop (Lyon - July 1999), like a proton beam power on target of 4 MW, possibly allowing a production of $\sim 10^{21}$ μ/year at 50 GeV.

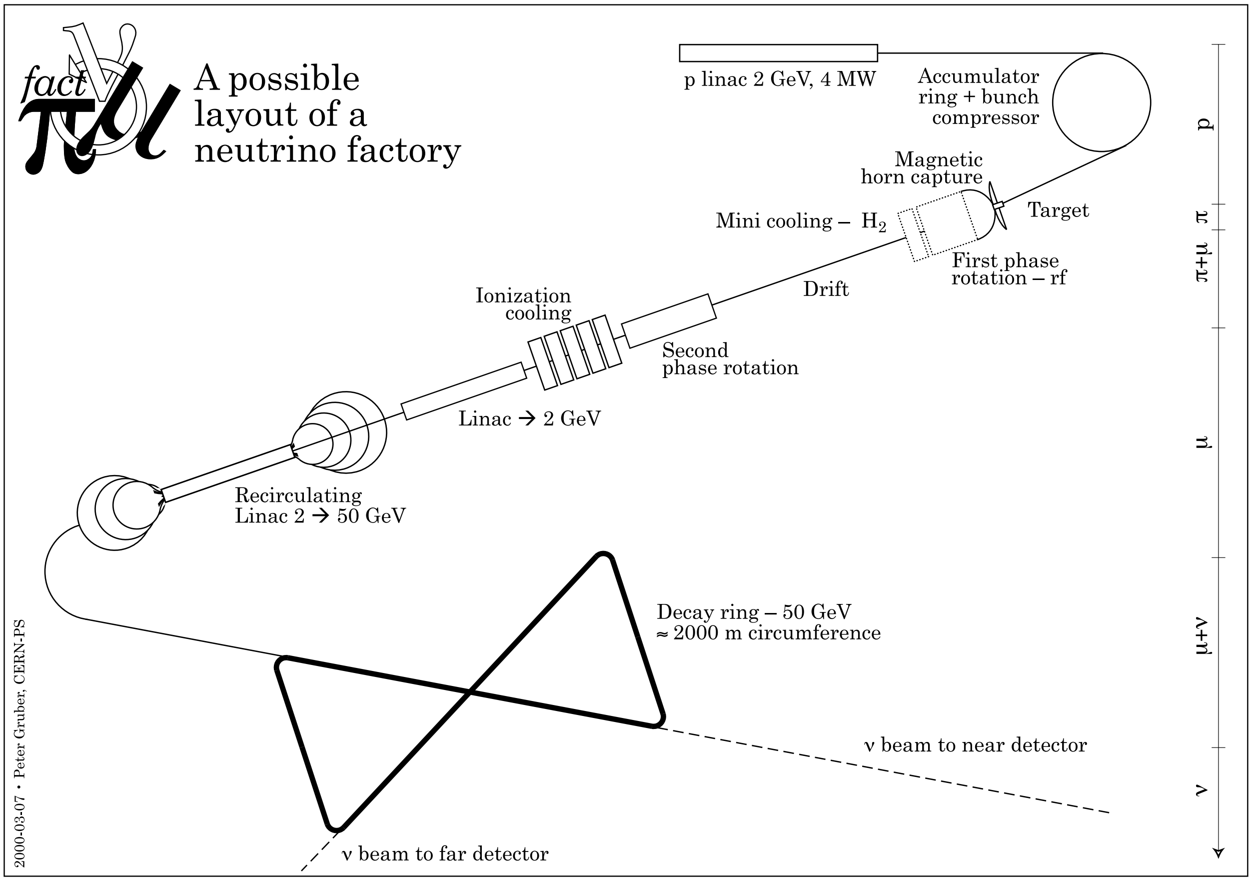

Figure 3.11: Possible layout of an European Neutrino Factory.

3.4.1 Proton Drivers

In view of the uncertainty of some crucial specifications like pulse repetition rate and to be prepared for possible evolutions, a three-fold way has been chosen for the studies of 4 MW proton drivers (in the order of increasing energy/decreasing repetition frequency):

1. A CERN-specific 2 GeV / 100 Hz scenario combining the 2 GeV Superconducting Proton Linac (SPL) based on recycled LEP cavities and studied since 1996 as injector for the CERN PS with an accumulator and a compressor ring in the ISR tunnel ($C = 942$ m). Both rings hold 12 bunches ($h = 24$) in high γ_t lattices ensuring fast debunching of the linac microbunches in the accumulator as well as very fast rotation (~ 7 turns) in the compressor. The feasibility of H^- injection (600 turns) and of the final bunch rotation including the space-charge dependence of the slip-factor has been shown. The accumulator lattice is designed, the intersecting compressor is being studied. More refined simulations including the effect of space charge on momentum compaction and of the microwave instability are planned.
2. A 5 GeV / 50 Hz and, recently, also a 15 GeV/25 Hz scenario was investigated at RAL in the frame of a collaboration - cf. the contribution of G.H.Rees and C.R. Prior.

3. For the case that slow repetition rates will ultimately be needed, we opted for a 30 GeV / 8 Hz configuration (upgradable to 8 MW / 15 Hz by adding a second ring), using the ISR tunnel for the driver. Eight bunches are accelerated by a h=32 RF system in a high γ_t (~ 40) lattice providing naturally short bunches without compression at top energy. The feasibility of the approach has been demonstrated by tracking studies including resonant longitudinal impedances. The driver is filled on a 60 ms, 2.2 GeV, flat bottom by four batches from a 1/4 size 50 Hz booster similar to the AUSTRON design. A 150 MeV H^- linac (nearly identical to the RAL/ESS design) completes the chain.

3.4.2 Target Work

A number of ideas are being under consideration which in principle should allow to dispose of the power deposited in the target by an up to 4 MW proton beam. The crucial problems are mechanical movements in high magnet fields, heat transfer, material stress, radiation damage and radioactivity confinement. Most of the work is at present being done in the US and at some European laboratories outside CERN. A group of CERN physicists with experience and knowledge in pion production solid and molten targets technology, beam dumps, safety, radioactivity inventory and shielding is being set up and shall assure the contact face to the external laboratories.

3.4.3 Pion/Muon Collection, Bunch Compression, Cooling

The main activities concentrate on:

- Study of an induction linac scenario adapted to the 2GeV linac. Pions generated by 2 GeV protons are collected from the target using a tapered solenoid (max. $B = 20$ T). The target consists of 2.6 cm of Hg, i.e. 20% of one interaction length). After the tapered collection solenoid region, the solenoid is continued for 200 m with a diameter of 60 cm, where the pions decay to muons and the correlation of energy with time is developed. An induction linac is then applied for the correction of the momentum spread to an average value of 200 MeV/c. The beam is focused in the induction linac by solenoids producing 1.4 T average field between the high voltage gaps. The electric field is taken from SUPERFISH simulations assuming an electrostatic gap, with the gradient limited to $\pm$ 2 MV/m, which combined with a total length of 50 m allows muons to be captured with an energy spread of $\pm$ 100 MeV. The maximum internal diameter is continued through the induction linac at 60cm, which combined with the solenoid strength, limits the beam output emittance. With 4 MW, 2 GeV proton beam ($\sim 10^{23}$ proton/year) on a Hg target (of 30 cm length) the resulting muon per proton number of 0.019 corresponds to 2.4×10^{21} μ/year in a 10^7 s year. The output emittance is 14 mm rad (rms normalized) and the RMS momentum spread less than 4%. The bunch length would be $\sim$ 0.3 μs. The beam dynamics simulations have been performed using ICOOL, a code developed in BNL specifically for the study of the cooling of muon beams.
- A 44 MHz RF scenario, matching the capabilities of a low energy proton driver. The simulation uses the same target data as for the induction linac. After the target the pions decay in a 30 m long channel focused by a 1.8 Tesla solenoid. A its end the particles within the energy range 100 – 300 MeV are captured in a series of 44 MHz cavities and their energy spread reduced by a factor two. A first cooling stage, employing the same RF cavities, reduces the transverse emittances by a factor 0.6; thereafter the beam is accelerated to an average energy of 300 MeV. The beam phase width as well as the reduced physical dimensions of the beam allows to employ an 88 MHz cavity cooling system that will reduce the transverse normalized emittance to the required 15 π mm (re-circulator acceptance). The system will be

continued at 88 MHz, at 176 MHz and finally at 352 MHz until the final energy of 2 GeV is reached. The muon yield of this system corresponds to 0.0156 μ/proton, and again assuming 10^{23} proton/year, this system would produce 1.6×10^{21} μ/year. If we remove the production mechanism from the count this system gives 0.09 μ/π collected in a 30 cm radius.

What makes this RF scenario attractive is its use of existing technology, e.g. that of the CERN PS 40MHz cavity. Results of exploratory SFH runs for a 44 MHz normal-conducting cavity of 30 cm bore radius are encouraging (1.6 MW power required for 2 MV/m). This cavity could accommodate a solenoid around the chamber. Preliminary estimations of the power losses for 2 MV/m at 44 MHz and 4 MV/m at 88 MHz give a figure of 10 MW for the entire phase rotation and cooling system for the 100 Hz pulse rate of the 2 GeV proton driver. A choice in favour of a low energy proton driver will depend both upon the existence of such an optimized scheme and on the demonstration of the production of an adequate flux of pions/muons by low energy protons (result expected from the HARP experiment planned at the CERN PS).

3.4.4 Muon Storage Ring and Recirculating Linac Accelerators

A design tool for a muon storage ring and recirculating linear accelerators in form of Mathematica packages was created and applied to a number of scenarios. It provides the initial values for precise matching and tracking with MAD. The CERN scenario assumes 50 GeV muon energy, 10^{14} muons/s at the entrance of the triangular storage ring ($C = 2$ km), two long straight sections feeding neutrinos to detectors at 1000 and 3000 km distance with a muon beam divergence of less than 0.2 mrad. Tracking tens of thousand electrons, created in the long straight by muon decay, for a fraction of a turn indicates that the energy, deposited at the beginning of the arcs, causes a local enhancement of the average power by less than an order of magnitude.

A collaboration for the design of the recirculating linear accelerators that accelerate the muon beams from 2 to 10, and from 10 to 50 GeV, respectively, in four passes, was established with C.E.A. in Gif-sur-Yvette, France.

3.4.5 General Activities

The theory of the transverse and longitudinal emittance blow-up during pion to muon decay has been established. It explains the mechanism of the blow-up, gives its magnitude, prescribes the pion emittance to be collected, the intensity of the solenoidal field and suggests that momentum collection may be more effective if it starts 10 m from the target. Further developments including RF fields and other magnetic systems are planned.

3.5 Feasibility Study of Neutrino Source Based on Muon Storage Ring

N. Holtkamp `holtkamp@fnal.gov` Fermi National Accelerator Laboratory

S. Geer `sgeer@fnal.gov` Fermi National Accelerator Laboratory

One of the first applications of an intense muon source could be a muon storage ring. The muon beam is injected into the ring and decays while circulating. The neutrinos from the decay muons form a very intense and well collimated beam (ν_e,ν_μ) that could be used for future neutrino experiments. The idea for such a neutrino source has been described many times [1], but only recently with the progress on ionization cooling concepts being made within the muon collider/neutrino source collaboration, such a source seems feasible. With a new proton driver and a target that can withstand the intense radiation and the power density from the impinging proton beam, the source will produce enough muons through pion decay to achieve approximately $2{\times}10^{20}$ muons decaying into neutrinos in one of the straight sections of the storage ring. In order to achieve this goal very efficient and large aperture focusing and rf accelerating systems have to be developed. The biggest advantage though comes from the fact, that the transverse emittance for a neutrino source has to be reduced by only a factor of approximately ten in both transverse dimensions. The longitudinal emittance coming from the source is of no importance, which makes longitudinal cooling unnecessary. Following the goal of $2{\times}10^{20}$ muons/year decaying in one straight section an attempt has been made to investigate the technical feasibility of such a facility as a whole.

3.5.1 Introduction

A muon storage ring as a source of intense neutrino beams supersedes a standard neutrino source in many ways. Classical neutrino sources have long decay channels which are used to generate $\bar{\nu}_{\mu,\tau,e}$, $\nu_{\mu,\tau,e}$ beams from pions coming from a target that is hit with an intense proton. In a muon storage ring the muons circulate after injection until they decay. A fraction of these muons will decay in the straight section, which will produce an intense, very well collimated and clean ν_e,$\bar{\nu}_e$ beam.

3.5.1.1 Physics program

Recent measurements of atmospheric muon neutrino (ν_μ) fluxes from the Super-Kamiokande (SuperK) collaboration have shown an azimuth-dependent ($\rightarrow$ baseline dependent) depletion that strongly suggests neutrino oscillations of the type $\nu_\mu \rightarrow \nu_x$. Since the atmospheric ne flux is not similarly depleted, nx cannot be ne and must therefore be either ν_τ, or ν_s (a sterile neutrino). These observations have inspired many theoretical papers, several neutrino oscillation experiment proposals, and much interest in the physics community. This interest is well motivated. Understanding the neutrino-mass hierarchy and the mixing matrix that drives flavor oscillations, may provide clues that lead to a deeper understanding of physics at very high mass-scales and insights into the physics associated with the existence of more than one lepton flavor. Hence, there is a strong incentive to find a way of measuring the neutrino flavor mixing matrix, confirm the oscillation scheme (three-flavor mixing, four-flavor, ν-flavor?), and determine which mass eigenstate is the heaviest (and which is the lightest). This will require a further generation of accelerator based experiments beyond those currently proposed.

High energy neutrino beams are currently produced by creating a beam of charged pions that decay in a long channel pointing in the desired direction. This results in a beam of muon neutrinos ($\pi^+ \rightarrow \mu^+ + \nu_\mu$) or muon anti-neutrinos ($\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$). In the future, to adequately unravel the mixing matrix, we will need ne and $\bar{\nu}_e$ (as well as ν_μ and $\bar{\nu}_\mu$) beams. To illustrate this, consider neutrino oscillations within the framework of three-flavor mixing, and adopt the simplifying approximation that only the leading oscillations contribute (those driven by the largest Δm^2_{ij} defined as Δm^2_{32} equiv $\Delta m^2_3 - \Delta m^2_2$, where m_i is the mass associated with mass eigenstate i. The probability that a neutrino of energy E (GeV) and flavor α oscillates into a neutrino of flavor β whilst traversing a distance L (km) is given by:

$$
\begin{aligned}
P(\nu_e \rightarrow \nu_\mu) &= \sin^2(\theta_{23}); \sin^2(2\theta_{13}); \sin^2\left(1.267\Delta m^2_{32} L/E\right) \\
P(\nu_e \rightarrow \nu_\tau) &= \sin^2(\theta_{23}); \sin^2(2\theta_{13}); \sin^2\left(1.267\Delta m^2_{32} L/E\right)\ lll \\
P(\nu_\mu \rightarrow \nu_\tau) &= \sin^2(\theta_{13}); \sin^2(2\theta_{23}); \sin^2\left(1.267\Delta m^2_{32} L/E\right)
\end{aligned}
\tag{3.1}
$$

Each of the oscillation probabilities depend on Δm^2_{32} and two mixing angles θ_{ij}. To adequately determine all the qij and sort out the various factors contributing to the $P(\nu_\alpha \to \nu_\beta)$ will require ne as well as ν_μ beams! In addition, there is a bonus in using ne beams since electron neutrinos can elastically forward scatter off electrons in matter by the charged current (CC) interaction. This introduces a term in the mixing matrix corresponding to $\nu_e \to \nu_e$ transitions that is not present for neutrinos of other flavors. Hence, if electron-neutrinos travel sufficiently far through the Earth, matter effects modify the oscillation probabilities. This modification depends on the sign of Δm^2_{32}, and provides a unique way of measuring which mass eigenstate is heaviest, which is lightest! We conclude that if we can find a way of producing ne beams of sufficient intensity, we are highly motivated to do so. The obvious way to attempt to produce high energy ne beams is to exploit muon decays. Since muons live 100 times longer than pions, we need to avoid using a linear decay channel, which would be impractically long for high energy muons. The solution is to use a muon storage ring with long straight sections, one of which points in the desired direction. This yields a neutrino beam consisting of 50% ν_e and 50% $\bar{\nu}_\mu$ if μ^+ are stored, or 50% ν_μ and 50% $\bar{\nu}_e$ if μ^- are stored. Using a storage ring to produce secondary beams of $\mu^\pm$, $e^\pm$, $\bar{\pi}$ and ν was proposed by Koshkarev [2] in 1974. The idea (also ascribed to [3] and Collins [4]) therefore dates back to the early days of the ISR at CERN. The key questions that need to be addressed in order to produce a viable proposal for the production of secondary beams by this method are:

- How can enough particles be stored?
- How can their phase-space be compressed to produce sufficiently intense beams for physics?

The calculated beam fluxes using the Koshkarev scheme were too low to motivate the construction of a secondary beam storage ring. A viable solution to the key question (how to make sufficiently intense beams) was implemented at the beginning of the 1980's for antiproton production, leading directly to the CERN proton-antiproton collider and the discovery of the weak Intermediate Vector Bosons. The solution to the intensity question involved using lithium lenses to collect as many negative particles as possible, and stochastic cooling to reduce the phase-space of the $\bar{p}$ beam before acceleration. In 1980 it was suggested [5] that the negative particle collection ring (the Debuncher) at the proposed Fermilab antiproton source could be used to provide a neutrino beam downstream of one of its long straight sections. The Debuncher collects negative pions (as well as antiprotons) which decay to produce a flux of captured negative muons. The muon flux in the Debuncher was subsequently measured and found to be modest. The short baseline neutrino oscillation experiment proposal (P860 [6]) that was developed following these ideas was not approved ... the problem of intensity had not been solved! In order to make progress we need a method of cooling muon beams and a way of producing more muons. Stochastic cooling cannot be used since the cooling time is much longer than the muon lifetime. Ionization cooling was proposed as a possible solution (see [7]). A way of collecting more pions (that subsequently decay into muons) using a very high-field solenoid was proposed by Djilkibaev and Lobashev [8] in 1989. Thus by the end of the 1980's the conceptual ingredients required for very intense muon sources were in place, but the technical details had not been developed. Fortunately in the 1990's the desire to exploit an intense muon source to produce muon beams for a high energy muon collider motivated the formation of an R&D collaboration (The Muon Collider Collaboration). This has resulted in a more complete technical understanding of the design of an intense muon source [9]. In 1997 it was proposed [10] to use a muon collider type muon source, together with a dedicated muon storage ring with long straight sections, to produce a very intense neutrino source. It was shown that this "neutrino factory" was sufficiently intense to produce thousands of events per year in a reasonably sized detector on the other side of the earth ! The intensity problem had been solved ! In addition, it was shown that the ring could be tilted at large angles to provide beams for very long (trans-earth) neutrino oscillation experiments, and that muon polarization could in principle be exploited to turn on/off the initial ne flux [10]. This proposal came at a time of increasing interest in neutrino oscillation experiments due to the SuperK results, and also at a time when the particle physics community was/is considering possible facilities needed at its laboratories in the future [11]. Thus, the neutrino factory concept quickly caught the imagination of the physics community, and the interest of its laboratory directors. This interest led to the first NUFACT workshop at Lyon in 1999, and a request from the Fermilab directorate for a 6 month technical study [12] to explore an explicit neutrino factory design and identify the associated R&D issues, together with a parallel 6 month physics study [13] to explore the physics potential of a neutrino factory as a function of its energy, intensity, and the baseline for oscillation experiments.

3.5.1.2 Accelerator facility

Table 3.4: Charge for the purpose of the feasibility study initiated by Fermilab.

1. A design concept for a muon storage ring and associated support facilities that could, with reasonable assurance, meet performance goals required to support a compelling neutrino based research program.
2. Identification of the likely cost drivers within such a facility.
3. Identification of an R&D program that would be required to address key areas of technological uncertainty and cost/performance optimization within this design, and that would, upon successful completion, allow one to move with confidence into the conceptual design stage of such a facility.
4. Identification of any specific environmental, safety, and health issues that will require our attention.

Table 3.5: Set of parameters chosen for the feasibility study.

Energy of the Storage Ring	50	GeV
Number of Neutrinos/straight section	$2{\times}10^{20}$	1/year
no polarization		
capability to switch between μ^+ and μ^-		
Baseline for facility FERMI to SLAC/LBNL		

If the m-beam divergence in the straight section is small compared to the decay angle, the opening angle of the neutrino beam is completely dominated by the decay kinematics. Given the energy of the muons this angle basically equals $1/\gamma_{muon}$. From the requirement to have the divergence of the muon beam in the straight section to be small compared to the divergence of the neutrino beam, a goal emittance for the muon source can easily be defined.

In the simplest version of a racetrack shaped storage ring with two long straight sections, almost one third of the muons will decay in each straight. Given the large number of different and technically demanding sub-systems required for such a facility the charge for the feasibility study was focused on basic questions one would have to answer for such an accelerator facility (see Table 3.4. Given the large variety of possibilities for short (500 km), long (3000 km) and very long baseline (> 8000 km) experiments and based on somewhat preliminary assumption in September 1999 on the potential physics goal, a number of boundary conditions had to be

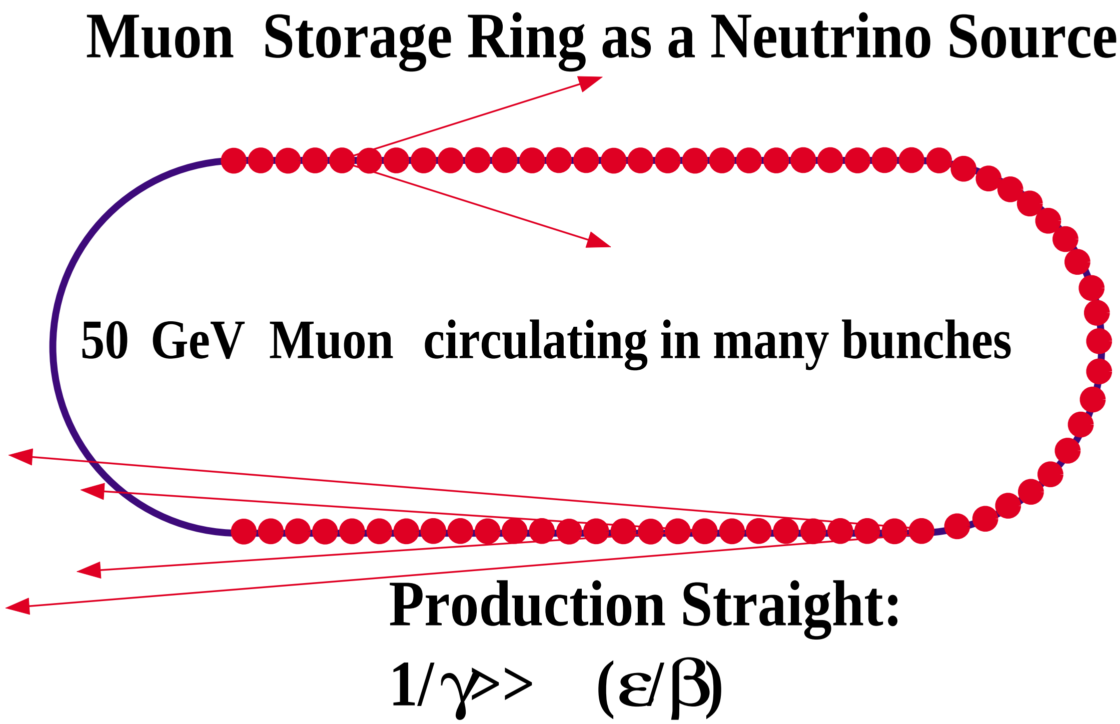

Figure 3.12: Sketch of a Muon storage ring with two long straight sections.

taken into account, before a specific set of accelerator parameters was picked. The final list is given in Table 3.5. This table together with a number of assumptions (see Table 3.6, that were made defined a set of specifications for the accelerator complex. These specifications are given in Table 3.8. Nevertheless many of these parameters were based on an earlier study [14]. It was also recognized very early, that because of the high energy (50 GeV) and high average current with 6×10^{20} muons per year in 2×10^{7} seconds the average beam power would be 240 kW. This would be one of the highest pulsed power lepton beams in the world. The basic sketch as well as a list of storage ring parameters being picked for this study is given in Figure 3.12 and Table 3.7. The acceptance of the storage ring is designed for 3σ of 3.2 πmm·mr. This allows a total emittance growth of approximately a factor of 2 in the accelerating systems once the muon beam has been cooled down to the goal value of 1.6 πmm·mr. The straight section pointing towards the west coast would have the large β-functions to provide the smallest possible opening angle for neutrino beam. The upward pointing straight section would feed a surface experiment with a very intense neutrino beam. In order to correct the nonlinear and off-energy beam dynamics, the b-function is significantly smaller ($\approx$ 150 m).

3.5.2 General Layout

The footprint of the total facility is comparatively small and fits easily under several existing laboratory sites. This is considered a big advantage compared to other large scale accelerator studies going on. A sketch which is basically made to scale is shown in Figure 3.13. The largest subsystems are the accelerating linacs and recirculating accelerators (RLA1 and RLA2). The total area required in order to provide a 50 GeV muon beam to a storage ring is approximately 1.0 $\sim$ 2.0 km. The philosophy behind this layout is, that bending between the different subsystems is minimized, which will minimize muon loss because of the large transverse emittance that will have to be trans-

Table 3.6: List of basic assumptions made for this feasibility study.

1. Given the experience in the simulations being done for the Muon Collider and based on an earlier paper on this subject a reasonable assumption had to be made for the number of muons one could expect per incident proton on target. This would have to include all the decay losses and the beam loss during cooling and acceleration.
2. Because this is a pulsed accelerator the average current that has to be accelerated to achieve the 2×10^{20} neutrinos/year, critically depends on the total operating time. More operating time reduces the investment cost on the high power rf systems. An optimistic assumption here led to 2×10^{7} sec/year assumed for the purpose of this study.
3. The intense proton source being considered would be based on the results of the design study going on at Fermilab.

Table 3.7: Parameters for the 50 GeV storage Ring.

Energy	GeV	50
decay ratio per straight	%	39
Designed for inv. Emittance	πm·rad	0.0032
Emittance at cooling exit	πm·rad	0.0016
β in straight	m	440
N_μ/pulse	10^{12}	6
typical decay angle of $\mu = 1/\gamma$	mrad	2.0
Beam angle $(\sqrt{\epsilon/\beta_o}) = (\sqrt{\epsilon\gamma})$	mrad	0.2
Lifetime $c\gamma\tau$	m	3×10^{5}
$\gamma = (1-\alpha^2)/\beta$		

Table 3.8: Parameters for the facility following from Table 3.4 and Table 3.6.

1. Given the ongoing study at Fermilab for a fast cycling proton synchrotron (15 Hz) with 16 GeV extraction energy, the number of protons per pulse required on target is at least 2×10^{13}. This as approximately 1 MW beam power on target.
2. The transverse emittance of the muon beam after the cooling channel has to be small enough, in order to have the beam divergence in the straight section to be less then 1/10 of the decay angle, which is $1/\gamma = 2$ mrad. At an invariant emittance of $\gamma\epsilon = 1.6$ πmm·rad the β-function would be 400 m. This seemed reasonable.
3. Following the assumption of having ten protons per one muon injected in the storage ring, 2×10^{12} muons per pulse are required after the cooling channel and have to be accelerated.
4. Abandoning polarization for this study had two advantages. The very low frequency rf system that was proposed directly after the target is not necessary, because forward and backward polarized pions do not have to preserve their correlation in longitudinal phase space. For the same reason the proton bunch length in the proton accelerator could go up to 3 nsec instead of 1 nsec, which is a significant relief.
5. Fermilab to SLAC/LBNL with a distance of 3000 km defines the slope of the storage ring with respect to the earth surface, which is 22% or 13 deg in our case. Gentle enough to think of conventional installation methods.

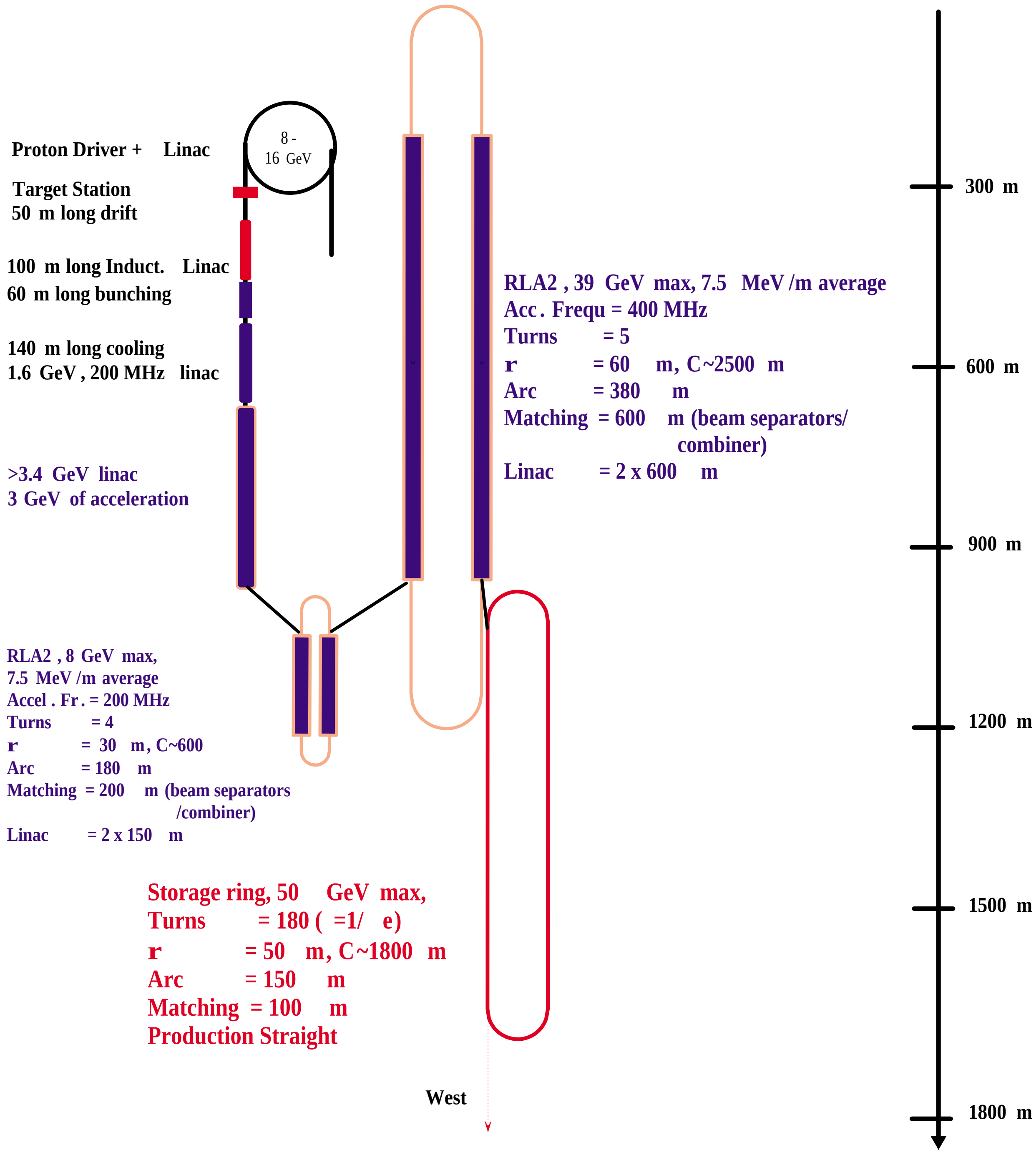

Figure 3.13: Footprint (to scale) of the whole facility.

ported. The same number of passes through each linac of the RLA's is another criterion that was applied to make the beam loading equal and the rf system requirement the same for both sides. Coming out of the last RLA, the muon beam would be gently bent downwards into the storage ring tunnel and injected into the straight section pointing to the long baseline experiment. Another remarkable result of this layout, given the earlier boundary conditions, is that the direction the proton beam hits the target d defines the direction of the neutrino beam going to the experiment. Therefore once the location of the detector is fixed, the layout is constraint, or one of the boundary conditions have to be given up, which will most probably increase cost or decrease performance.

3.5.3 Subsystems

The different subsystems of such a Neutrino Factory in principle are very similar to what is required for a Muon Collider, although not identical and in many ways not as demanding. The relaxation of having the muons in each pulse distributed over many bunches together with the reduced transverse cooling being required, are the most obvious ones. The beam dynamics and performance of these subsystems is described in another paper [15], while here the main focus is on technical feasibility.

3.5.3.1 The proton driver

The design of an intense proton source as part of a possible upgrade within the baseline program at Fermilab is under investigation [16]. A fast cycling synchrotron operating at 16 GeV is under study, which produces a high power proton beam, with four bunches per pulse at a repetition rate of 15 Hz. Given the infrastructure at Fermilab, the existing linac in combination with a minor upgrade program would be capable of providing enough protons for injection. In the course of the study two things became evident: 1) The required proton intensity is more likely to be $3{\times}10^{12}$ per pulse due to smaller efficiency of the low Z target and, 2) this intensity can be distributed over four bunches but not more, given the limitation of the induction linac (being used later on in the accelerator chain) that has to produce a number of high voltage pulse within one acceleration cycle of the synchrotron ($\approx 2\ \mu$sec). Given the advantages of a low Z target (see later in this paragraph) the optimization showed in addition that there is a 15-20% advantage in the pion yield per unit proton beam power as the energy of the protons drop. From the engineering point of view and given the higher yield, a lower energy proton driver would be therefore be preferable. It became also quite clear, that proton synchrotron is one of the larger consumers of wall plug power within the facility.

3.5.3.2 The target

Extensive studies on target yield as well as on radiation damage are performed. The basic system considered as a first generation target consists of a strained graphite rod, which would operate at approximately 2200 C°[18]. The advantages of graphite are the lower atomic number and the capability of withstanding very high thermal and mechanical stress. While the power deposited in the target per incident beam power goes down by a factor of five, the yield only drops by about 1.5. The target would be radiation cooled and based on present knowledge would have to be exchanged every 3 month. An intense R&D program together with the collaborating institutions is necessary to justify these statements. The design of the 20 Tesla capture solenoid is a technical enterprise by itself. The combination of a 11 Tesla superconducting coil with an 8 Tesla normal conducting coil set additional constraints on feasibility. The nc coil requires approximately 10 MW dc power and the lifetime is limited to about 2500 hours because of erosion due to excessive cooling requirements [19]. The target area, remote handling procedures and the facilities are very similar to what has been proposed for the Spallation Neutron Source in Oak Ridge. Having a solid target even reduces the operational risk [18].

3.5.3.3 The phase rotation

In order to reduce the energy spread of the muon beam, the muons have to be rotated in phase space. The 50 meter long decay channel is not only used to let the pions decay into muons but also to develop a correlated energy spread along the muon bunch. With a total length of more than 200 nsec per bunch, each of the four bunches coming from the target should be de-accelerated at the head and accelerated at the tail [20]. An induction linac naturally provides voltage pulses of that order while rf cavities with a low enough frequency either become excessively large or too power intensive. A 100 meter long induction linac operating at 15 Hz with 4 pulses per cycle and a not yet achieved gradient of -1 to 1 MV/m (2MV/m total) would be required. A sketch of an induction cell together with a superconducting coil operating at 1.3-3 Tesla is shown in Figure 3.14. Coming out of the decay channel the required beam aperture is 60 cm, which dominates the core size. Each unit it approximately one meter long and driven by an individual power supply [20][21]. The accelerating gradient is large compared to existing induction linacs and certainly an R&D item. Technical feasibility on the other hand is less of a concern than investment cost, power consumption and reliability.

3.5.3.4 Mini cooling, bunching and the cooling channel

Mini cooling and re-bunching of the muon beam after the phase rotation is the first intrinsically non-efficient step. Four muon pulses with a length of about 200 nsec each drift through a long liquid hydrogen absorber into high gradient cavities and then further on into the cooling channel. While mini-cooling reduces the transverse emittance by about 50% the cooling channel has to reduce the emittance by almost an order of magnitude. The high gradient 200 MHz cavities have to reaccelerate and focus the longitudinally growing muon bunch while strong alternating solenoids with up to 5 Tesla on axis produce small enough b-functions for transverse cooling[23]. The main challenge here is certainly the unrivaled gradient in a normal conducting cavity at 200 MHz and the source that is necessary to provide enough peak power at this frequency [24]. The high field superconducting coils on the other hand are more than challenging due to the very large stored energy and the enormous forces (2000 tons) they have to sustain[22].

3.5.3.5 The acceleration

Coming out of the cooling channel, the muons have a kinetic energy of about 110 MeV and have to be accelerated to 50 GeV. The transverse invariant emittance is ideally 1.6 πmm·mr. The longitudinal phase space is diluted due to scattering as well as energy and position dependent drift differences. In order to capture the beam the first part of the acceleration can only be done in a low frequency high gradient rf system operating far off crest to form a stable bucket. 200 MHz is the minimum possible frequency because that is the bunching frequency used early on after phase rotation. The main difference here is, that distributed focusing (solenoids or quads) can be used, which makes the use of superconducting rf possible. Shown in Figure 3.13 is a 3 GeV linac which gradually increase the phase angle for acceleration. Afterwards two cascaded recirculating linacs boost the energy to 50 GeV. The large energy spread of the beam in combination with the large beam size requires long matching sections in order to go into and out of the arcs. For this reason the second RLA dominates the required real estate. The number of recirculations is limited by the fact, that the separation from turn to turn becomes more difficult as the number of turns increases

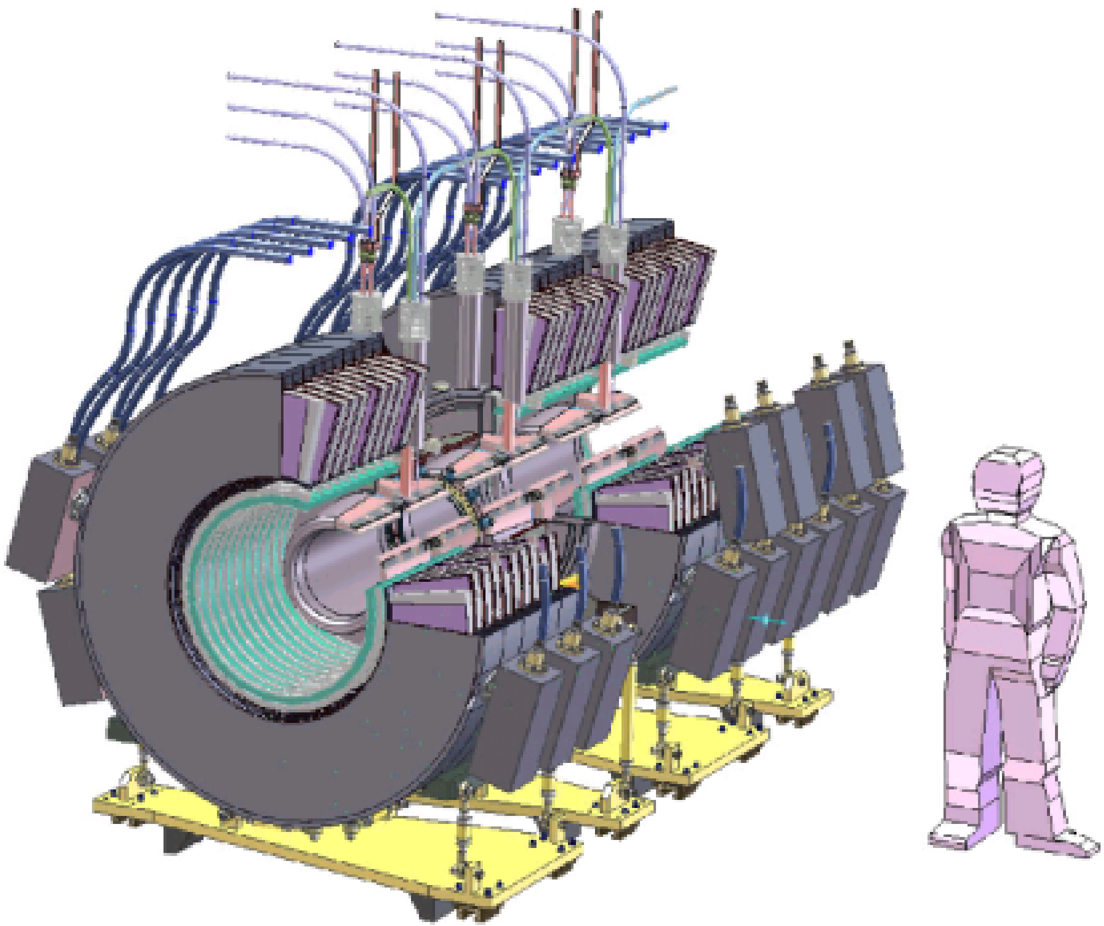

Figure 3.14: Sketch of an induction cell with integrated sc 3 T coils.

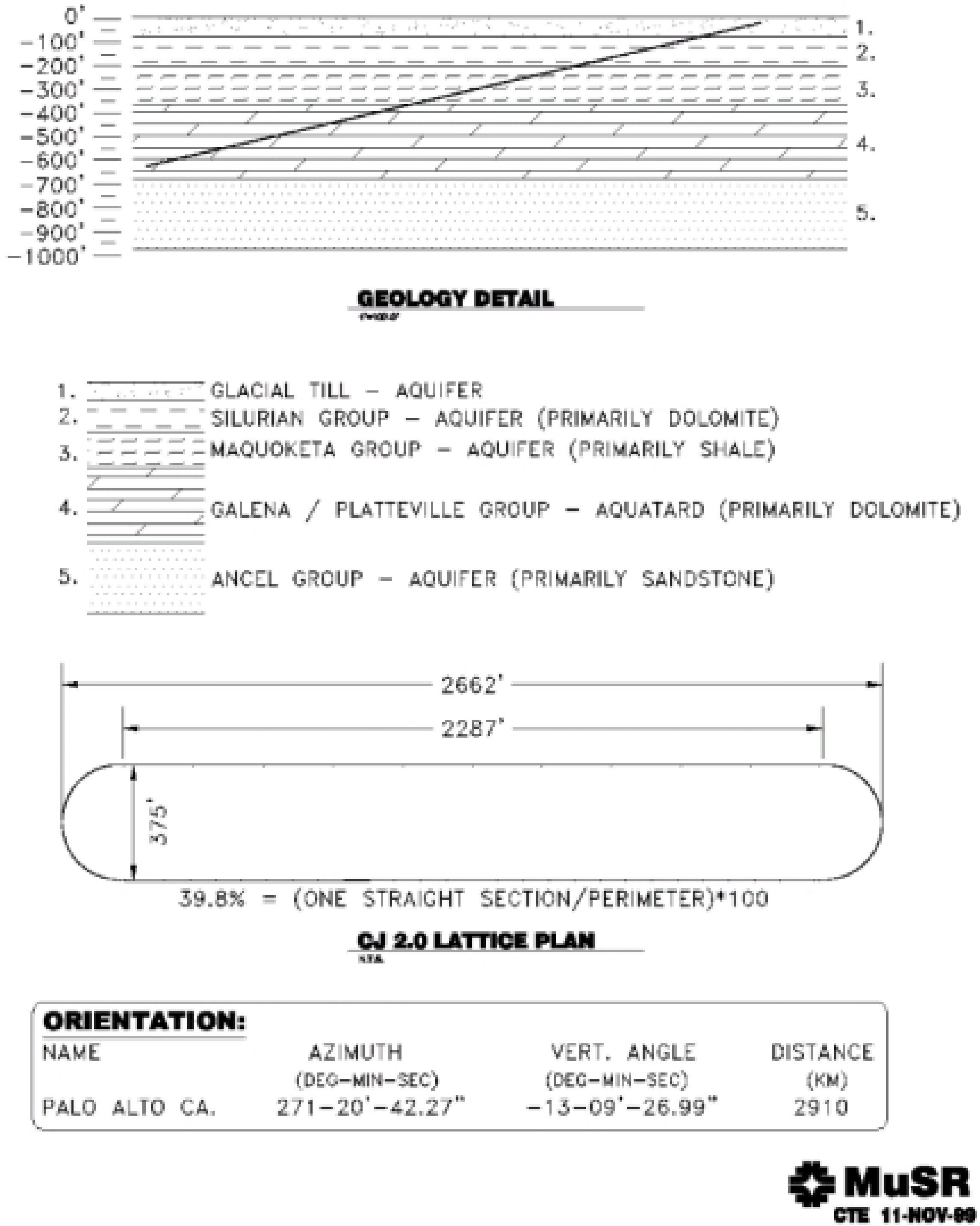

Figure 3.15: Layout of the Muon storage ring under the Fermilab site taking geological boundary conditions into account.

[25]. Developing the low frequency high gradient superconducting cavities for these accelerators is clearly a high priority item. Based on the technology at CERN, where sputtered niobium on copper cavities are use for acceleration at 350 and 400 MHz, this seems feasible, but has not been demonstrated yet. The first linac as well as RLA1 is based on 200 MHz rf. RLA2 though would have twice the frequency (400 MHz) in order to save investment and operational cost. The rf power sources, that would be used to drive these cavities have to be developed as well. Providing peak power at low frequency using standard technology leads to excessively large structures. Multi-beam klystrons are on possibility to avoid such pitfalls [26].

3.5.3.6 The storage ring

The muon storage represents neither a cost driver not a real technological issue, given the boundary conditions from Table 3.8. The racetrack shape with the superconducting 6 T arcs brings the efficiency per straight to almost 40% (40% of all muons decay per straight). The circumference is about 1800 meters and given the angle of 13°, the ring dips 260 m into the earth on one side. The available depth for reasonably good tunneling conditions in that sense is the only real site dependent part of this study. A sketch of the geology under the Fermilab site demonstrates the boundary conditions. Starting almost at the surface of the earth the ring goes down to the top of the underlying aquifer which should be avoided to largely increased tunneling cost (compare Figure 3.16). Maximizing the yield from each straight section on the other hand asks for maxi-mum circumference. The gain that can be made by following this philosophy is shown in Figure 3.16. Bending magnets with a field larger than 6 Tesla do not significantly increase the yield but are technically more challenging, given the fact that a large aperture is required: a) for the beam due to the large emittance, b) due to the tungsten shield to protect the magnet from decay electrons. As a result of this study, the storage ring certainly seems not to be an R&D issue at all.

3.5.4 Summary

This is preliminary summary of the feasibility study on a muon storage ring used as a new intense source for long baseline neutrino beams. The study is done in close collaboration with the Neutrino Source/Muon Collider collaboration and has focused much more closely on the engineering aspects of such a facility. As a result, many R&D issues have been identified. All of them seem solvable if an aggressive R&D program could be started, but it would have to happen almost simultaneously. All of these solutions are extrapolations of existing and well understood technologies. One of the real challenging subjects, the beam diagnostics, which will be crucial for the performance especially of the cooling channel, has not been addressed. Here really new inventions are required.

Acknowledgement We would like to thank all the contributors to this study for the enthusiasm they have shown. Especially I want to thank Robert Palmer who contributed many of the ideas that were used as the basis of this study. Andy Sessler, for focusing the Neutrino Source/Muon Collider collaboration on this subject and Jonathan Wurtele and Mike Zisman for organizing the simulation effort for the cooling channel. I want the thank the contributors from the different laboratories (INP, Protvino, TJNAF, Oak Ridge, Michigan State University, National High Magnetic Field Laboratory etc) and their management for their support and interest. (Presenting the list of names would be too long.) I also would like to express my gratitude to the Fermilab management for their support and for giving me the opportunity to organize this study.

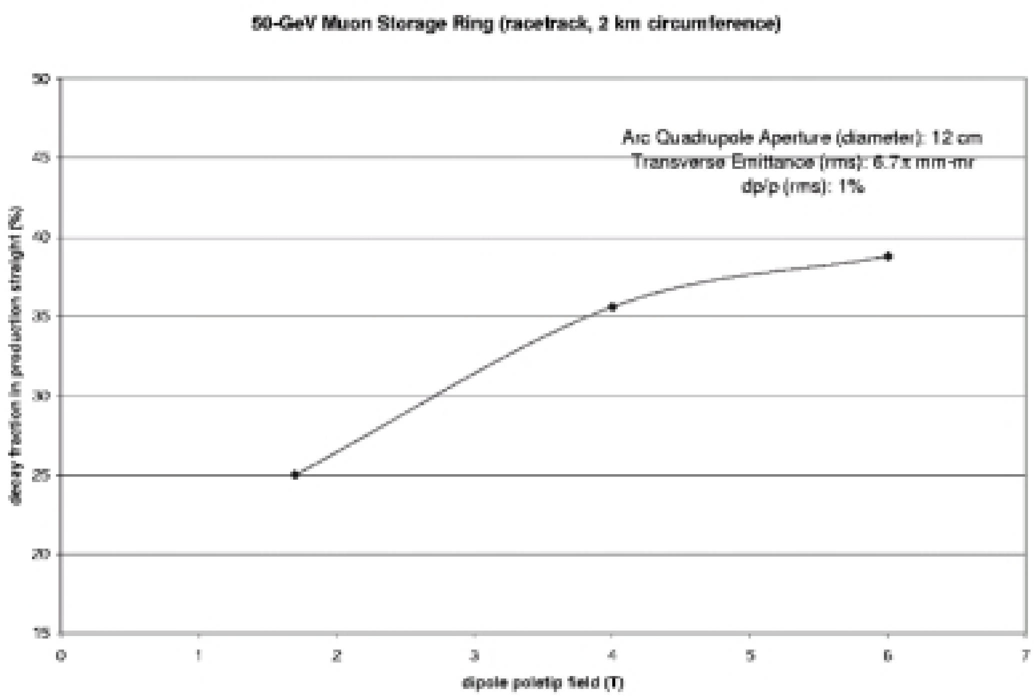

Figure 3.16: Muon yield versus bend strength assuming the maximum depth to be used for the storage ring tunnel at angle of 13°.

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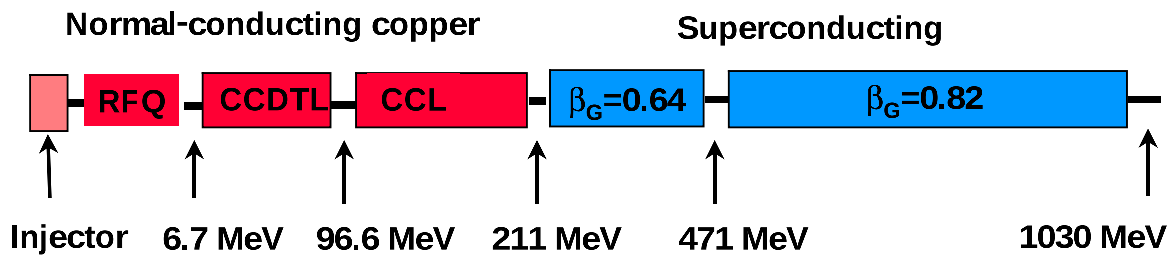

Figure 3.17: Block diagram of the APT linac.

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3.6 Accelerator Production of Tritium (APT) and Beam Halo

T. Wangler twangler@lanl.gov Los Alamos National Laboratory

During the past 5 years, the DOE has supported a program to develop a high-intensity proton linear-accelerator design, called Accelerator Production of Tritium (APT). In December of 1998, the Secretary of Energy announced that commercial light water reactors will be the primary tritium supply technology. The Secretary designated the APT as the backup technology for tritium supply. Fig. 3.17 shows a block diagram of the APT linac, showing a low-energy normal-conducting proton linac that accelerates the beam to 211 MeV, followed by two sections of a superconducting linac. The APT final energy of 1030 MeV is comparable to the final energy of the 800-MeV LANSCE proton linac at Los Alamos. However, APT delivers a continuous or CW beam current of 100 mA, which is 100 times the average beam current of LANSCE. The beam power is also about 100 times greater than LANSCE, which, at present, is the world's most powerful linac. Because of the large average beam current, one of the most important features of the APT design is the emphasis on designing for low beam loss to limit the potential radio-activation of the accelerator. This requirement is driven by the desire for high availability, to enable the operations personnel to be able to carry out routine maintenance without being constrained by the high activation levels along the machine.

The APT beam-dynamics design goal was to limit the beam loss, especially above 100 MeV where the radio-activation concerns are greatest, to less than 0.1 nA/m. This is comparable to the loss rate throughout most of the LANSCE linac, where essentially unconstrained hands-on maintenance is possible. The analyses of the APT design provide strong evidence that this goal has been achieved for two reasons. First, the APT design avoids the most important beam-loss mechanisms of the LANSCE linac. Second, the basic physics of beam-halo formation has been studied and the main halo mechanism has now been identified. As a result, APT design choices have been made to minimize the beam halo For many years after the LANSCE linac produced its first beam in 1972, the causes of the beam halo at LANSCE remained a mystery. From theoretical studies over the past several years at Los Alamos and elsewhere, the nonlinear and time-dependent space-charge force associated with a mismatched beam has been identified as a major source of beam-halo formation. Beam mismatch occurs when the beam size deviates from the optimal size needed to balance the focusing forces from the quadrupole magnets and the defocusing forces produced by space charge and the beam emittance. Beam mismatch excites collective modes in the beam; these modes produce rms envelope oscillations that resonate parametrically with the transverse (betatron) or longitudinal oscillations of certain beam particles. This interaction drives those particles to larger amplitudes. Numerical solutions to simple particle-core models have provided predictions for the halo properties, including approximate scaling formulas for the maximum halo amplitude.

3.7 Accelerator in Energy: Recent Development of an Accelerator-Driven System (ADS)

Hiroshi Takahashi `Takahash@bnl.gov` Brookhaven National Laboratory

I describe the recent development of an accelerator-driven reactor for producing energy, and for transmuting minor actinides and long-lived fission products. To run these reactors in a slightly subcritical condition rather than at deep criticality, the proton accelerator can be a low-powered cyclotron which requires only a small building and site; hence, the cost of generating electricity by this system becomes inexpensive. To get a higher beam current for a circular accelerator, a fixed field alternating gradient (FFAG) synchrotron can be used for driving the subcritical reactor without jeopardizing the reduction of the shock wave created by manipulating the pulsed-mode operation. The induction FFAG is discussed. To reduce the energy costs of transmuting long-lived fission products (LLFPs) such as Tc-99, and I-129, I reconsider the old concept of depositing of them into outer space by not rocket but by an ions thruster.

3.7.1 Introduction

At the last JAERI symposium [1], under the title of “The Role of Accelerator Technology in Nuclear Fuel Cycle”, I discussed the historical development of the use of an accelerator in nuclear-energy production, such as Lawrence’s material testing accelerator projects (MTA). I also mentioned Lewis’s proposal for producing the fissile materials for the CANDU reactor, the accelerator breeder including the light water fuel regenerator [2] in the International Nuclear Fuel Cycle Evaluation (INFCE) in 1977, all of which use a high-power linear accelerator. Furthermore we described a transmutor of minor actinides driven by a small cyclotron accelerator [3], and the production of secondary particles, such as muons and antiprotons. In the last few years, this field has grown extensively due to the application of accelerator technology for solving the problem of high-level radioactive waste, and for nuclear-energy production; this growth was aided by progress in the development of a high-intensity proton accelerator, for applications in the scientific field of neutron scattering, and for medical use.

To solve the problem of disposing of high-level radioactive waste, the use of transmutors of minor actinides and long-lived fission products(LLFP) driven by an accelerator has been of considerable interest to the nuclear-energy community, along with the projects of deep geological storage of waste in repositories like Yucca Mt. The Department of Energy in the United States conducted a roadmap study for planning the accelerator transmutation of waste (ATW) projects [4].

To promote nuclear energy as a future alternative energy source to fossil fuel, the front end of the fuel cycle such, as the production of fissile fuel from the fertile material, is very important as well as the ATW. A high burn-up of the fuel is essential for saving fissile fuel and for getting a higher plant factor both of which reduce the costs of electricity generation. Along with the safer operation conferred by the slightly subcritical operation of the fast reactor [5], these are the key components to ensure competitive economic success. This approach also is pursued in areas of the world that are not affluent in their fossil fuel resources.

Although, the fast breeder using the liquid Na-cooled reactor (LMFBR) was developed to get a high breeding gain, the cost of the electricity it generated was 1.5 times higher than that of the LWR; this is too expensive, so the emphasis shifted to low-cost generation of electricity rather than pursuing a high breeding gain, which is not urgently required due to the slow growth of nuclear-energy production. However, to keep alive the alternative option of using nuclear energy rather than fossil fuel, which might itself become expensive, such studies have continued. For the LMFBR, to get a high neutron economy, a harder neutron energy spectrum is desirable, so using a non-chemical reactive heavy-metal coolant like Pb [6], Pb-Bi instead of the chemically active Na has been explored. Also, operating a subcritical condition driven by a proton accelerator has been studied to achieve a high level of safety and give greater flexibility in choosing the fuel's composition and the structural materials. As I proposed, to run this reactor in the slightly subcritical condition of $k = 0.99$ or 0.98 [7] requires only a small-powered proton accelerator, such as a cyclotron, which can accelerate protons in a continuous wave (CW) mode, and so eliminate problems due to shock wave created by the pulsed-mode operation (discussed in a later section).

3.7.2 Light Water Reactor with Hard Neutron Energy Spectrum

Recently, a light water reactor with a hard neutron energy spectrum [8] was extensively examined as the next generation of the LWRs following the ABWR and APWR. The elimination of excess plutonium created by LWRs and by the military is vital to lowering concerns about the proliferation of fissile material. Using mixed fuel in LWRs has been frequently practiced. But this creates more of the higher minor actinides and it is difficult to achieve more than 2 cycles of fuel burn-up due to their presence.

When the water and plutonium fuel lattice is tightened in the LWR lattice, the neutron- energy spectrum becomes harder, although not as hard as in the LMFBR; however, this reduces neutron capture in the LWR, and so stainless-steel can be used for the cladding materials. A high burn-up can be obtained, and also a high conversion ratio greatly conserves the fissile material.

In the NERI program we are studying the Pu-fueled tight lattice LWR with a hard neutron-energy spectrum. This reactor uses thorium fertile material instead of uranium which lowers the production of minor actinides and effectively transmutes excess plutonium and minor actinides. Although the larger neutron capture by thorium compared with uranium-238 increases the required inventory of plutonium, the initial excess reactivity is reduced due to the lower fission cross-section of Th-232 in the harder neutron-energy spectrum. Furthermore, although using uranium as the fertile material increases reactivity as burn-up increases and thereby results in introducing burnable poison, employing thorium reduces the amount of the burnable poison due to a lesser rise in reactivity as burn-up increases; it also raises the conversion factor, and results in a higher burn up capability.

The sharp increase of the fission cross-section of Pu-239 as the neutron energy increases tends to generate a positive water-coolant void coefficient .To suppress this, it was proposed having a pancake-type flatted core, and void-channel assemblies in the core design, similar to the LMFBR design; however, this reduces neutron economy due to the large leakage of neutrons from the core, and it is hard to get a high conversion ratio. Also as frequent fuel exchanges are needed, it lowers the plant factor and generates a fuel volume of spent fuel. Because the fission cross-section in the U-233 fuel is not sharp, the positive water-coolant void coefficient is reduced a little, which is beneficial for obtaining a higher neutron economy by lowering the neutron leakage from the core; neutron economy can be somewhat improved above that of the Pu and U-238 fuel cycles.

By operating the above reactor in a subcritical condition, with a solid core not a neutron-leaky core as is entailed with a flattened core or with a void channel assembly, it can operate without the risk of criticality. Since this is not a neutron-leaky core, it has a higher neutron economy and gives a high conversion ratio and high burn-up of the fuels. We suggested running the reactor in a slightly subcritical condition, with control rods to regulate a changes in burn-up reactivity.

In our LWR fuel regenerator studied in the INFCE program, the spent fuel is used so that the multiplication factor, k, is small and a high-powered proton accelerator like a linear accelerator is required. As studied in this program, using a high concentration of plutonium fuel can maintain the k values close to one in a large burn-up; then, this reactor can be operated with a small-powered circular accelerator like a cyclotron or fixed field alternating gradient (FFAG) which are far cheaper than an expensive linear accelerator. A modular-type reactor system driven by multiple small-powered accelerators is more reliable for energy production than reactors driven by a high-power linear accelerator, and can compete with alternative energy-producing systems .

3.7.3 Proton Accelerator

By operating a hard-neutron-spectrum reactor in a subcritical condition, fuel and cladding materials can be chosen with great flexibility without sacrificing the criticality safety associated with the positive coolant-void coefficients. This might contribute to low-cost generation of electricity, and could become competitive as an alternative generator of electricity. The linear accelerator, which can accelerator a high beam current, was promoted in earlier stages, and the control of reactor power by accelerator power was advocated to get rid of the control rods to compensate for fuel burn-up.

Generating only a low-power beam to run the reactor is not economical because it imposes a limit on the full capabilities of an expensive accelerator. Furthermore, although the large-powered accelerator is capable of quickly generating fissile material and tritium, as we designed in the Accelerator production of tritium (APT), it is not suitable from a non-proliferation point of view. Recently, the reliability of the accelerator for driving a subcritical reactor has been discussed. To generate electricity for residential and industrial use, its reliability must be firmly established, in contrast to its use for physics experiments which are more forgiving of any such lapses.

Although extensive reliability of an accelerator can be ensured by reducing the electric field in the acceleration cavity, a subcritical reactor driven with multiple accelerators has higher reliability than one driven by a single accelerator. When one of the multiple accelerators shuts off delivery of the beam, the reactor's power will be reduced to a lower level; power-generation systems composed of multi-modular-type reactors and multiple accelerators can provide high reliability in generating electricity. Our old proposal for driving many reactors from a single high-powered accelerator by splitting the beam should not be adopted until very high reliability can be attained in accelerator operation.

Presently, a 660 MeV 1.5 mA CW cyclotron has been operating, generating spallation neutrons at PSI at Switzerland. A higher beam current of more than 10 mA at 1GeV can be achieved by properly designing the cyclotron.

3.7.3.1 Fixed-Field Alternating-Gradient accelerators (FFAG) [9]

Recently, the use of a rapid-cycling proton synchrotron was considered to obtain a high intensity proton beam for generating spallation neutrons, for neutrino oscillation experiments, and for a muon- muon collider.

To accelerate the charged beam with a higher intensity, a Fixed Field Alternate Gradient (FFAG) Synchrotron was proposed. The FFAG was invented by Ohkawa [10], Symon [11], and Kolomensy [12] in 1950, and successfully applied to an electron accelerator in the MURA project. The FFAG is a multi-orbit synchrotron(MOS), and larger beam current can be accelerated from it than from a single orbit synchrotron.

Ruggiero et al [13] suggested a usage of the FFAG into which protons are injected using a linear-induction accelerator. Since a linear induction accelerator can accelerate a high-intensity proton beam, this approach avoids the stripping of electrons by the foil. However, the accelerator's induction cell is used only once to accelerate the pulsed beam; the usability of an induction cell is limited, and the accelerator building must be a long one, similar to the linear RF accelerator.

The FFAG synchrotron does not deliver continuous wave (CW) acceleration like the cyclotron, but rather, a pulsed acceleration, so that a subcritical reactor driven by this FFAG gets a shock wave for each pulse of proton beam injected. But the recent development of a for high permeability magnetic alloy at KEK for the JHF project enabled us to obtain an elongated beam pulse with a much higher frequency, so that the magnitude of the shock wave created in the subcritical reactor becomes small, the deterioration of the materials will thereby be reduced, and electricity can be generated without fluctuations. An acceleration cavity with loaded with ordinary ferrite can yield at most, 10 KV/m or so, but the new type of high-gradient RF cavity using this high permeability magnetic alloy can successfully achieve a 100 KV/m field.

3.7.3.2 Induction FFAG

Recently, Kishiro and Takayama [14] proposed having a circular induction accelerator; that allows the efficient use of induction acceleration by repeatedly using an induction cell by circulating the beam. Thus, the accelerator be designed as a compact one.

The induction accelerator was studied with a view to accelerating a very high peak electron current for the free electron laser, and also to accelerate ultrahigh intensity heavy ions for inertial fusion applications; the latter proposes 50-100 turns to get more than KA. Induction acceleration for protons might be possible with a turn number of 2×10^4. To get a high intensity of beam, a beam bucket can be created using the power supply (modulator) with frequency of 100 kHz – 1 MHz.

This circular induction accelerator uses a single track, but, by employing a multi-track orbit trajectory in the FFAG's magnetic field, the space-charge limitation can be extended further. In regular FFAG acceleration, the particles are accelerated and modulated by RF. Induction acceleration, which can create a higher acceleration field than can RF acceleration, might be more efficient than a FFAG with RF acceleration.

Since the induction-accelerator system does not have an associated wake field in the RF cavity, the beam's track is not disturbed and each train of the beam is independent. In the case of induction acceleration, since it does not involve breakdown of the electric fields in the cavity, its reliability might be increased more than in RF acceleration, although each beam's track must be stabilized. The beam current in the proton accelerator is much smaller than the electron machine. But in CW operation, using a super-conduction cavity entails the wake field having a longer lifetime; the beam then might be disturbed by this wake field.

The IFFAG is not CW machine like the cyclotron. A shock wave will be created in the subcritical assembly by pulsed operation, but its magnitude can be reduced by pulsing it at a high repetition rate of more than a kilo hertz in contrast to the conventional synchrotron, and by elongating the pulse length.

In our Induction Fixed Field Alternating Gradient (FFAG) synchrotron a modulator regulates those changes in acceleration that are carried out by RF in the regular FFAG by the induction cell.

3.7.4 Spallation Target

Successful experiments in neutron scattering using the pulsed spallation neutron source are promoting high-power spallation neutron projects in Japan and the United States. To produce pulsed neutrons with a short width, mercury which has larger neutron capture than Pb will be used as the target material. To accommodate the shock wave created by the short pulsed spallation reactions, many tests are being conducted using the alternate gradient synchrotron (AGS). These studies provide many important data applicable to designing the CW target used for the accelerator-driven system; consequently, these projects offer excellent opportunities for collaborations between the two technical fields of nuclear reactor technology and accelerator technology which is very important in both disciplines, although the shock problem in the latter is less vital because of using the high-frequency pulsed mode acceleration in the FFAG (discussed in a later section).

For accelerator driven system (ADS), the Pb-Bi eutectic will be used as target material. Since, for getting spallation neutrons, it is not necessary to have a high temperature target. This approach can reduce the corrosion of the container vessel by high temperature Pb-Bi, which is being considered to use as the coolant.

3.7.5 Disposal of Long-Lived Fission Products to Outer Space using an Ion Thruster [15]

Transmutation of the LLFPs requires a substantial number of neutrons, especially when not only long lived one, but also the whole isotopes with the same Z number as LLFPs are transmuted by neutron capture. Thus, transmutation using the neutrons produced in a critical reactor is not an efficient process.

The National Aeronautical and Space Administration (NASA) studied the possibility of disposing of HLW using the space shuttle [16], but this requires a large amount of energy. Instead of using a rocket to generate the escape velocity, by ejecting LLFPs with the escape velocity using an accelerator, we can reduce substantially the energy needed for their disposal. To uniformly disperse the LLFPs into outer solar space from the parking orbit requires an earth escape velocity (V_{EE}) = 42.07 km/sec.

Instead of dispersing the LLFPs uniformly in outer space, if we disperse them uniformly in the plane of the earth's orbit, then the velocity required is reduced from 42.07 km/sec to $(\sqrt{2} - 1)V_{EE} = 12.32$ km/sec. When the isotopes are not separated, the power required to dispose uniformly in outer space or in the earth orbit plane of all the LLFPs elements produced by one 1-GWe LWR is, respectively, 8.5 kW and 0.73 kW.

These energies are far smaller than that required to transmute the LLFPs by spallation neutrons where the neutrons are multiplied by the subcritical assembly, which is in the order of a few 10s of MW.

Although the energy required to accelerate the LLFPs is not very great, the current to dispose of the isotropic and elemental LLFPs ions is large. The total current for the accelerated isotopes and elements is, respectively, about 2.2 and 8.2 amperes. When the charged ions are ejected into outer space, the magnetic field in solar space might trap the charged ions so that the LLFPs would not be disposed into the outer solar system. To prevent this trapping, the charged ions should be neutralized in the same way as is done for neutral-beam injection in the magnetic fusion reactor.

Instead of using a static accelerator with a neutralizer, ions thrusters which were developed for space propulsion have the capability to dispose of the LLFPs. Electrojet thrusters(EJTs) have been studied by the Russian and European space agencies. Among the most advanced types which may be used for making sufficiently strong EJTs, are the stationary plasma thrusters (SPTs) of the Russian "Fakel" ("Torch") developmental and design office, and the Ion EJT of the EAS-XX type that is being developed at present in Europe. Their electric power is reasonably high, and the life time of thrusters is 2-3 years. Also their efficiency is high so that the electric power required to dispose of the LLFP can be lowered substantially. This is especially true for the Ion EJET of EAS-XX, where the maximum electric power is 6.3 KW and the specific power is 35-60 Km/sec; the efficiency of the EJT is up to 88% and its operating life time is 15000 hours. These are almost the same specifications as we proposed for accelerator for disposing of the LLFPs which are generated by a 1 GWe LWR. Hence, although the LLFP ions are different from the ones used for the ion thruster, we can apply the technology of an ions thruster for material improvement. A high-current ion thruster for many different kinds of ions was developed by Wilbur's group [17].

There is much concern about the possibility of a failure when launching LLFPs from the earth. NASA extensively studied the shielding of the rad wastes which will be loaded into the space shuttle to protect the astronauts. Experiments were performed by dropping the capsule with its heavy shield material on to hard-and soft-ground surfaces; damage to the payload was examined for evaluating the impact of the payload in a launching failure. In contrast to the previous studies for disposing of whole rad waste, our payload is only LLFPs and it has no short-lived fission products(SLFP), such as Cs-137 and Sr-99, nor minor actinides; thus, radioactivity is far smaller than in these radwastes.

The radioactivity of LLFPs generated by running a 1 GW power plant for 1 year is less than the radioactive material Pu-238 that was used for the Cassini mission. The radioisotope thermoelectric generator (RTG) of Pu-238 produces 265 watts, and the radioactivity of this Pu-238 is about 1000 Curies which is higher than the about 500 Curies of our LLFPs.

3.7.6 Conclusion

The accelerators which were developed in the last few decades can give a high neutron economy for nuclear reactors without jeopardizing critical safety and also can allow flexibility in choosing the a fuel and structure materials for high performance for nuclear-energy production. The LWR with a hard neutron-energy spectrum can be run in a slightly subcritical condition similar to the LWR fuel regenerator in the INFCE study for high burn-up and also for transmuting the minor actinides and long-lived fission products. Thorium fertile material instead of uranium-238 provides better neutronic characteristics and also a more proliferation-resistant fuel-cycle than the Pu-U-238 fuel cycle. A circular accelerator, such as a cyclotron or FFAG which are cheaper than the linear accelerator, can be used for driving the slightly subcritical reactor at reasonable cost. The disposition of long-lived fission products by using the ions thruster can conserve the energy required to transmute them by neutron absorption, although this approach still needs public acceptance.

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3.8 Particle Accelerator Technology and the Elimination of Nuclear Waste

Jean-Pierre Revol Jean.Pierre.Revol@cern.ch CERN

Progress in particle accelerator technology makes it possible to use a proton accelerator to eliminate nuclear waste efficiently. The Energy Amplifier (EA) proposed by Carlo Rubbia and his group is a subcritical fast neutron system driven by a proton accelerator. It is particularly attractive for destroying, through fission, transuranic elements produced by present nuclear reactors. The EA could also transform efficiently and at minimal cost long-lived fission fragments using the concept of Adiabatic Resonance Crossing (ARC) recently tested at CERN with the TARC experiment. The ARC concept can be extended to several other domains of application (production of radioactive isotopes for medicine and industry, neutron research applications, etc.).

3.8.1 Introduction

The research work presented here is an exceptional contribution for a laboratory such as CERN, in principle devoted entirely to fundamental research. However, the Energy Amplifier (EA) [1] is an innovative approach to nuclear energy, and it should come as no surprise that such an innovation results from fundamental research which has always been a main driving engine of innovation. Examples are legion and well known; one of the most recent, the World-Wide Web, was invented at CERN and not by the much more powerful and resourceful computer industry. Because particle physicists, interested in discovering the ultimate structure of matter, have pushed particle accelerator technology as far as they have, it is possible today to consider using a proton accelerator to drive a new type of nuclear system, with very attractive properties. Today, the world is facing an extremely difficult challenge, that of producing sufficient energy to sustain economic growth without ruining the ecological equilibrium of the planet. The massive use of fossil fuels has allowed the Western World to reach an unprecedented level of wealth. Unfortunately, if the rest of the Earth's population were to carry out the same energy policy, the entire planet would be in serious trouble. There is, therefore, a moral obligation for developed countries to provide new energy sources for the entire world in order to minimize global warming and other pollution effects. If an acceptable solution is found, it will certainly be the result of systematic R&D and in this context, nuclear energy should be part of this R&D. The present nuclear energy programme is meeting growing public opposition world-wide because of three main reasons: (a) the association with military use and the fear of nuclear weapon proliferation; (b) the fear of accidents such as Chernobyl (1986 prompt-supercritical reactivity excursion) and Three Mile Island (1979 loss-of-coolant accident resulting in a core meltdown); (c) the issue of the back-end of the fuel cycle (nuclear waste management: at this time only deep geological storage is seriously envisaged). Obviously, nuclear power, without these drawbacks would be ideal as it does not release greenhouse gases nor other chemical pollutants (NOx, SOx, etc.), nor dust particles, nor even radioactive particles as coal ashes do. Therefore, the real question facing scientists today is: Is it possible to transform nuclear energy production in such a way as to make it acceptable to society? Nuclear energy is a domain that has essentially seen no significant fundamental R&D since the end of the 1950s when the first civil power plants came into operation. There have been many technological improvements, mainly with the purpose of improving safety. However, we have seen that even these were not sufficient. The concept of the EA was proposed by C. Rubbia and his group specifically as an answer to the concerns raised by current nuclear energy production. The present EA version is optimized for the elimination of the nuclear waste, as it is considered to be the most pressing issue in the Western World. In developing countries such as China and India, where there is virtually no nuclear waste,

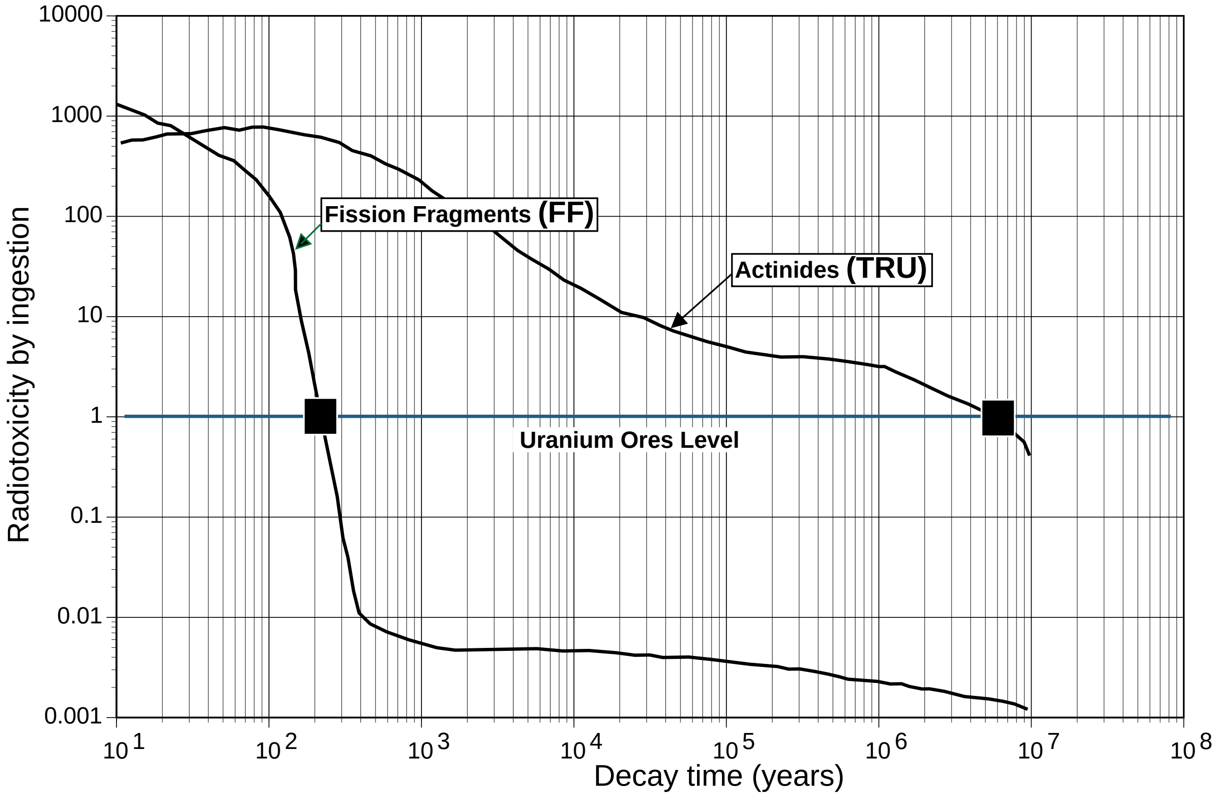


Figure 3.18: Time evolution of the potential radiotoxicity (relative to uranium ore) of the two main components of nuclear waste for PWR spent fuel, obtained with the ORIGEN2 code.

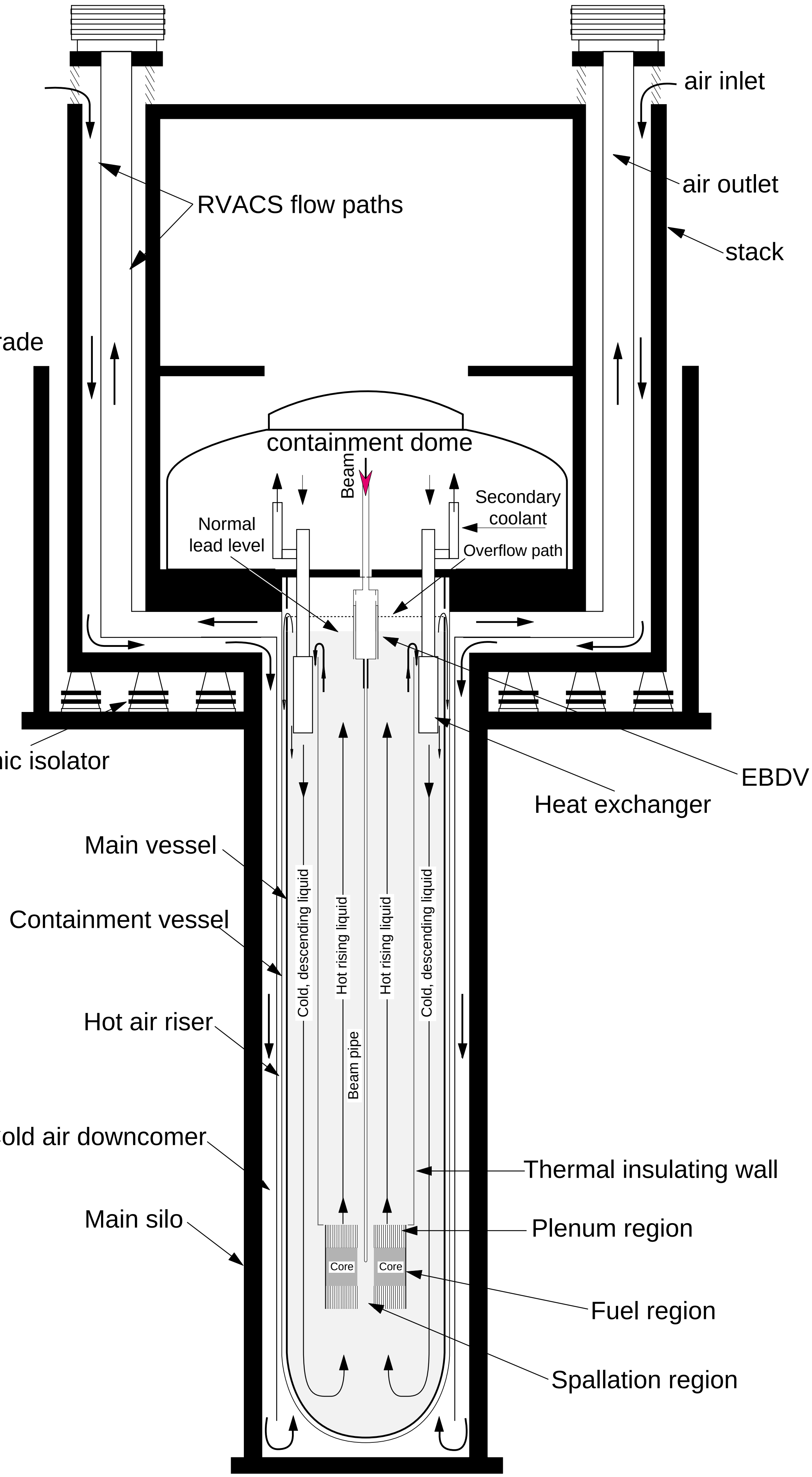
a version of the EA optimized for energy production, adapted to the detailed needs of the country and with minimized waste production, is the more appropriate solution. It is interesting to note that the Chinese Government has just approved the first phase of an R&D project on an EA system for energy production.

3.8.2 Nuclear Waste

Transuranic elements (TRU) and fission fragments (FF) are the two main components of nuclear waste representing respectively 1.1% and 4% of spent nuclear fuel. TRU, which are produced by neutron capture in the fuel eventually followed by decay, can only be destroyed by fission, while FF can only be destroyed by neutron capture; therefore, different methods will have to be used to eliminate them. As the long term radiotoxicity of waste (Fig. 3.18) is clearly dominated by TRU, the EA has been designed to destroy them with the highest efficiency.

3.8.3 The Energy Amplifier

The Energy Amplifier is a subcritical system, driven by a proton accelerator and using fast neutrons (Fig. 3.19). A complete description of all the features of the EA can be found in Ref. [1]. One of the main characteristics is the presence of 10^4 tons of molten lead used as a target for the protons to produce neutrons by spallation, as a neutron moderator, as a coolant to extract heat by natural convection and as a radioactivity containment medium.


air inlet
air outlet
stack
RVACS flow paths
grade
containment dome
Beam
Secondary
coolant
Normal
lead level
Overflow path
Seismic isolator
EBDV
Heat exchanger
Main vessel
Containment vessel
Hot air riser
Cold air downcomer
Main silo
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Hot rising liquid
Cold, descending liquid
Beam pipe
Thermal insulating wall
Plenum region
Core
Core
Fuel region
Spallation region

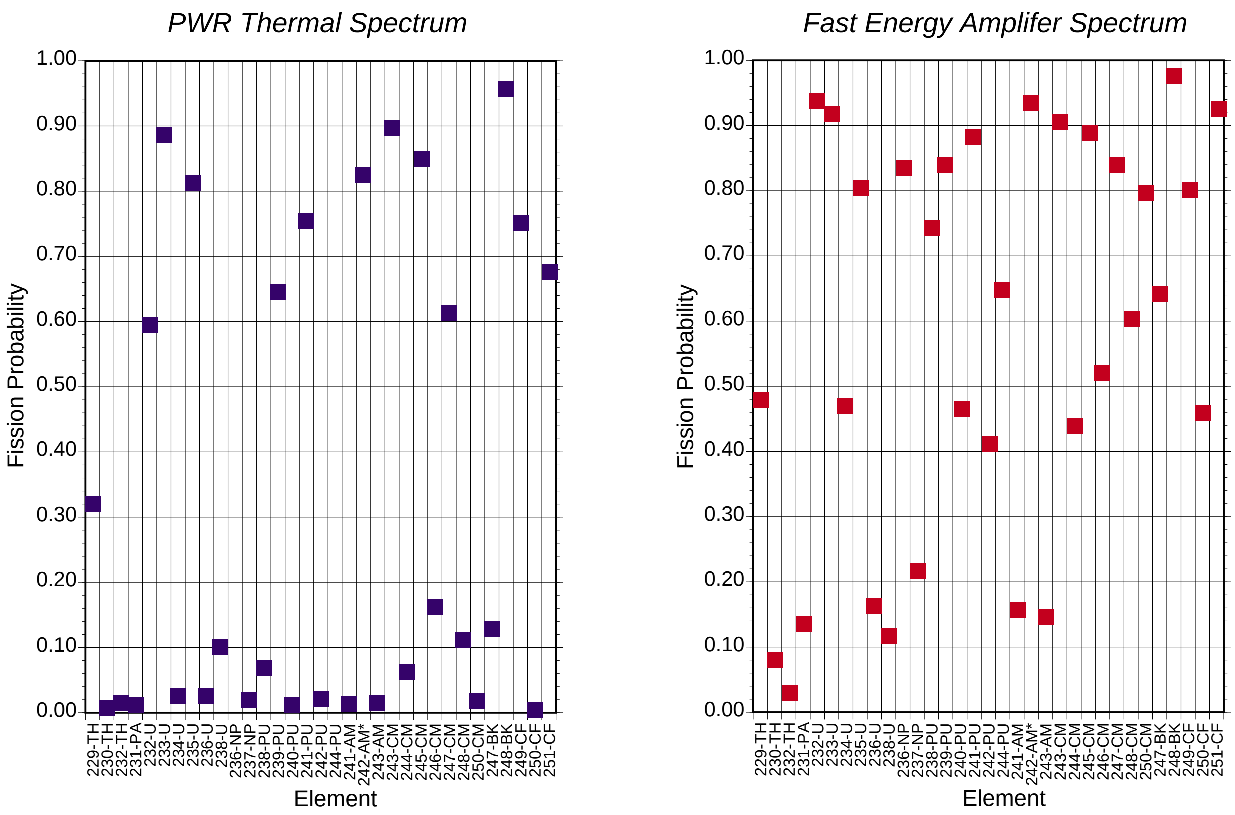

Figure 3.20: Comparison of fission and capture probabilities of actinides for thermal and fast neutron fluxes.

3.8.3.1 Why fast neutrons?

The choice of lead as a neutron moderator to obtain the hardest possible neutron energy spectrum is deliberate. This is dictated by the need to optimize the fission probability of TRU. Indeed, in the fast neutron flux provided by the EA all TRU can undergo fission, a process which eliminates them, while in a PWR thermal neutron flux many TRU do not fission and thus accumulate as waste (Fig. 3.20). In addition, as the capture cross section of neutrons on FF is smaller for fast neutrons than for thermal neutrons (Fig. 3.21), and since neutron capture on FF is the main limitation to long burnups, in a fast neutron system the efficiency with which the fuel can be used will be much higher than in a PWR. Typically it is hoped to reach burnups of 150 GW$\times$day/t (a burnup of 200 GW$\times$day/t was achieved in the fast EBR2 system at Argonne National Laboratory).

3.8.3.2 Subcriticality and the accelerator

The proposed system [1] has a neutron multiplication coefficient (k) of 0.98. The sustainability of the nuclear fission reactions is made possible because of the presence of an external source of neutrons provided by the proton beam. The working point is far below criticality, which ensures that the system remains subcritical at all times, implying that, by construction, accidents of the Chernobyl type are impossible. The traditional k_{eff} of the system itself (with beam turned off) is even smaller than k (of the order of 0.97). The energy amplification in the system, defined as the ratio between the energy produced in the EA and the energy provided by the beam, can be parametrized as $G_0/(1-k)$, where G_0 is a constant characterizing the spallation process. This aspect of the system has been studied in the FEAT experiment [2] at CERN where it was shown that

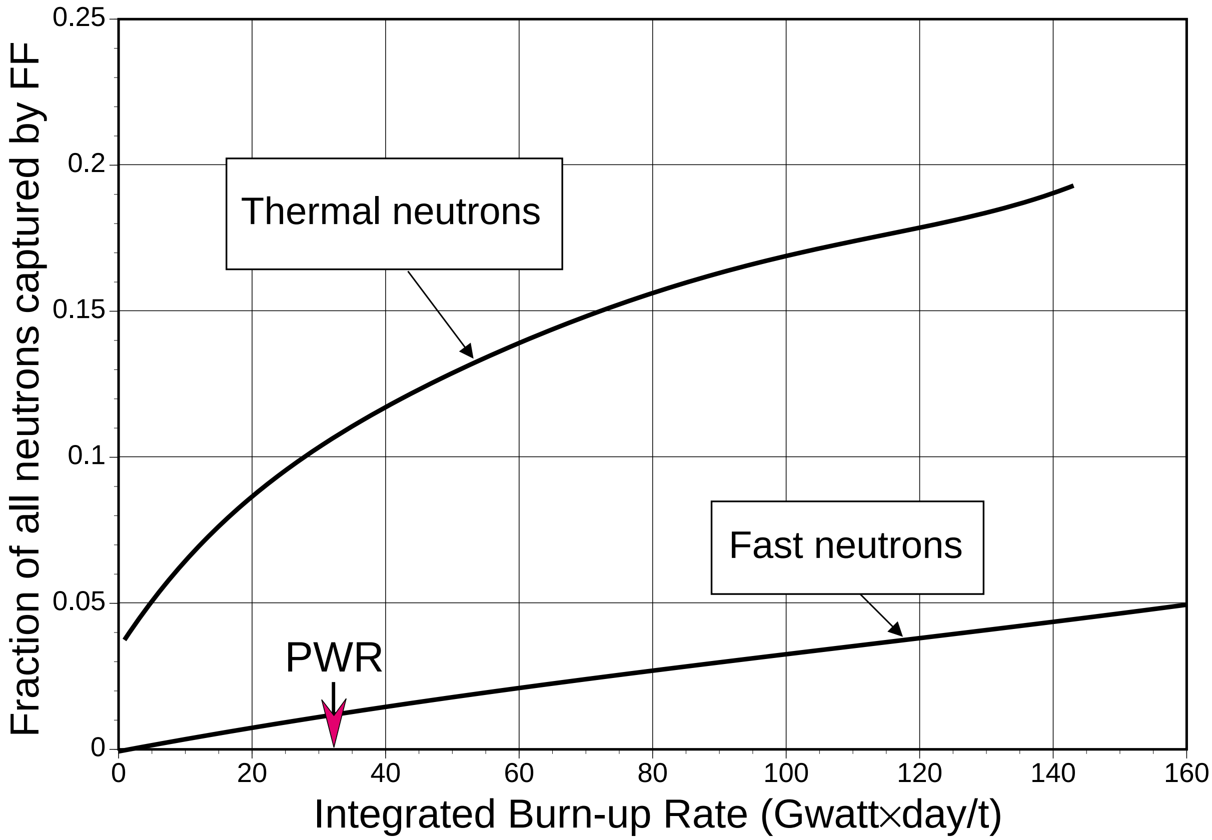

Figure 3.21: Fraction of neutron captures on fission fragments (FF) for thermal and fast neutron fluxes, as a function of burnup. The maximum burnup for a PWR is indicated. For the EA the burnup is expected to reach 150 Gwattxday/ton.

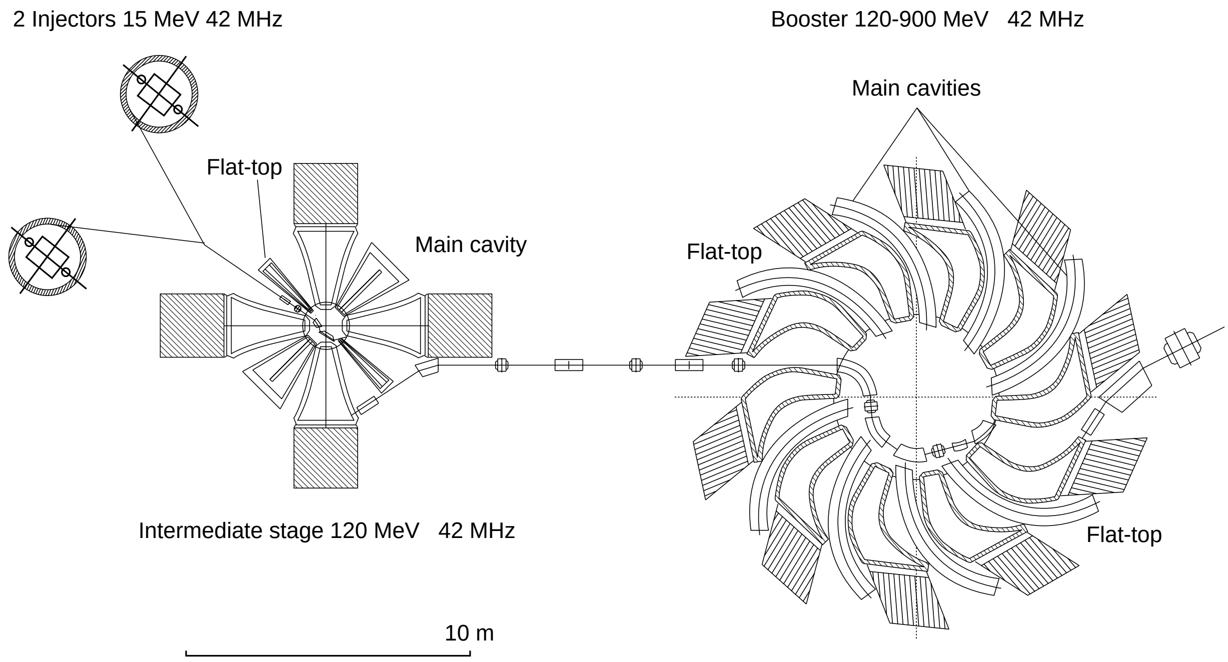

Figure 3.22: The full cyclotron high intensity accelerator layout proposed to drive a $k = 0.98$ EA [1].

this energy gain is well understood and that, not only is it independent of the proton beam intensity, but it is also independent of the beam kinetic energy if above about 900 MeV. This fortunate feature means that the accelerator can be of relatively modest size (Fig. 3.22). All experts agree that the present accelerator technology can provide the required beam power (10 to 20 mA at 1 GeV) with either linac or cyclotron solutions [3]. Examples already exist of high power accelerators which are planned or have been considered in various parts of the world:

- the PSI (Switzerland) cyclotron now running at 1.4 mA, 590 MeV, 0.826 MW [4];
- the proton linac for the Los Alamos Neutron Science Centre (LANSCE) running up to 1.5 mA, 0.8 GeV and 1 MW of average power [5];
- both the USA and Europe had projects to build linacs to produce tritium: (TRISPAL at CEA (France): 600 MeV, 40 mA, 24 MW and LANL (USA): 1 GeV, 100 mA, 100 MW). Even though tritium is no longer officially on the agenda, accelerator developments are continuing;
- Japan is also considering a high intensity proton source as part of their new Neutron Science Project [6]. The system needed to drive an EA represents only a reasonable extrapolation of what has already been achieved in current accelerator technology.

In practice, the choice of accelerator technology may be coupled with the strategy for the EA system. If the strategy is to destroy waste on a nuclear power plant site, then the cyclotron with its smaller size (Figure 5) has a clear advantage (it is easier not to have to extend the power plant site, and easier for control and safety of the accelerator, cost effectiveness). Several other technical advantages can be found in favour of the cyclotron as compared to a linac:

- One can achieve high efficiency (50%), as the current in RF cavities would be about 100 times (100 turns) the extraction current, implying that most power is in the RF cavities (which have reached 70% efficiency), keeping the losses relatively small.

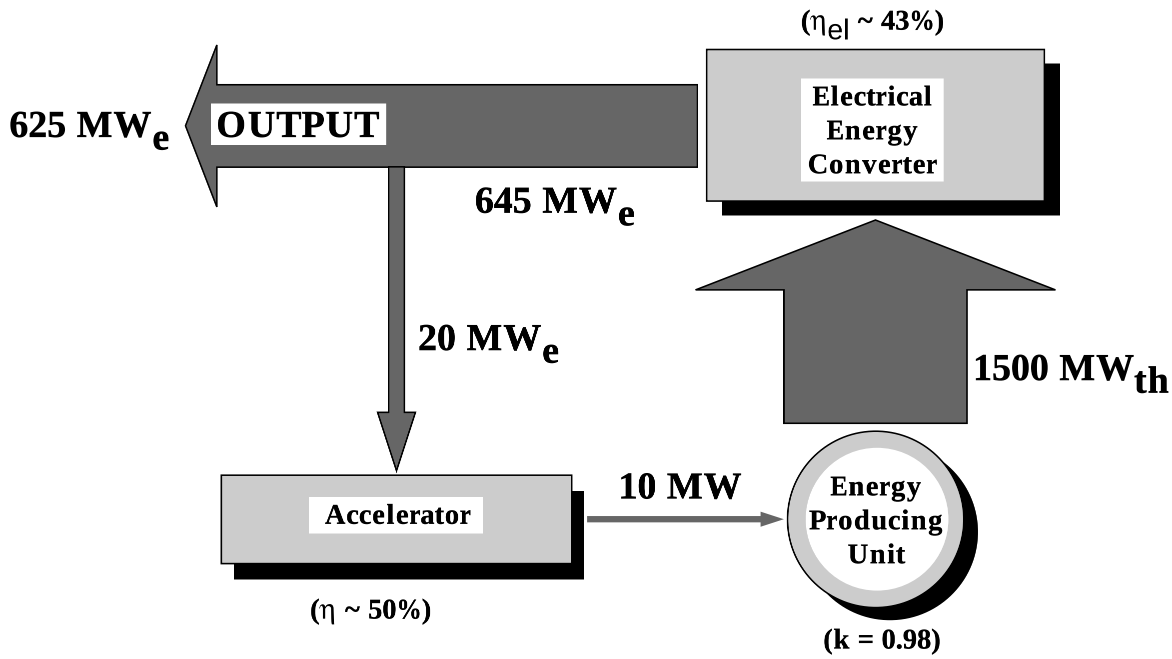

Figure 3.23: The energy amplification scheme in the standard EA system as proposed in Ref. [1].

- There is no need for SC cavities, keeping the technology simple.
- The reliability may be better than in linacs which need many more control elements (reliability decreases strongly with an increase in the number of parts).
- In a warm linac the small aperture is a problem for the beam losses, which in addition are not localized (a superconducting linac is difficult below 400 MeV because of the problem of making short niobium-coated superconducting cavities). In cyclotrons, beam losses are expected to be small and localized. Machine elements are accessible as soon as it comes to a halt (this is the case at PSI).

An important achievement of the FEAT experiment was the validation of the innovative simulation developed by the EET group at CERN of energy amplification in accelerator driven subcritical systems. This gives confidence in the choice of the main parameters of a system where less than 5% of the electric power needs to be recirculated during its operation (Fig. 3.23).

3.8.3.3 Destruction of nuclear waste: TRU

The general strategy consists of using as fuel thorium mixed with TRU as opposed to uranium with plutonium as proposed in fast critical reactors, such as SuperPhenix. The availability of an external neutron source, thanks to the accelerator, and the availability of a fast neutron energy spectrum, thanks to the choice of lead as moderator, allows the sustained operation of a subcritical device with wide flexibility in the choice of fuel. Pure thorium does not fission, but it is ^{233}U bred from ^{232}Th which can produce energy through fission. In practice, seeds are needed to provide fissions at the startup of the system, and for this purpose any fissionable element will do: ^{233}U from a previous EA fuel load or ^{235}U extracted from natural uranium or military ^{239}Pu or simply TRU, which is precisely the main component of the waste we wish to destroy. Therefore, it is possible, in an EA, to destroy TRU by fission, a process which produces energy and makes the method economically

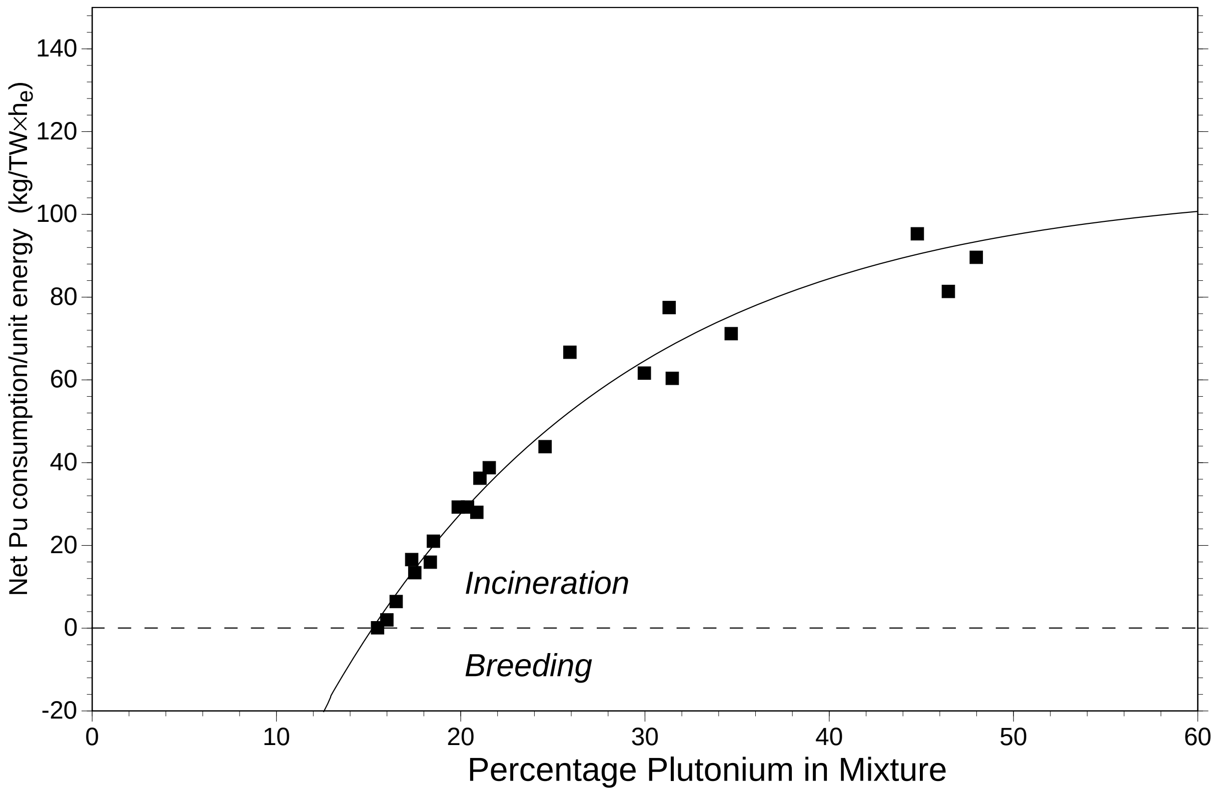

Figure 3.24: Net plutonium consumption per unit energy in a uranium-plutonium fast breeder (CAPRA [7]) as a function of plutonium concentration. Note that the unit is kg/TW×h electric and not thermal.

attractive. TRU represent potentially about 40% of the energy that a PWR delivers while producing these TRU. Thorium is an attractive fuel because it exists in relatively large quantities in the Earth's crust (at least five times more abundant than uranium), it is isotopically pure (no enrichment is needed), all of it is used in the EA as compared to only 0.7% of ^{235}U in a PWR and it is about 5 neutron captures away from the TRU one wants to destroy, ensuring that it can work in a mode where it destroys more TRU than it produces.

It is easy to see why a thorium system would be much more practical than a uranium system for the destruction of TRU. The high equilibrium concentration (15%) of plutonium in uranium type systems (Fig. 3.24) forces the use of extremely large plutonium enrichment, which would make these systems extremely dangerous, while in an EA, equilibrium concentrations of the order of 10^{-5} (Fig. 3.25) naturally ensure a high burning rate for reasonable TRU concentrations. A study [8] carried out for the Spanish Government, based on a practical example, showed that a 1500 MW$_{th}$ EA could destroy a net amount of 34 kg of TRU per TW×h$_{th}$ of thermal energy produced. In comparison, a PWR, on the contrary, produces 14 kg of TRU per TW×h$_{th}$. It is expected that the reprocessing needed to extract TRU from spent fuel should be much simpler than what is needed to extract plutonium from spent fuel for MOX, as performed in the La Hague factory (PUREX process). A pyrolectric reprocessing method [9] developed at the Argonne Laboratory in the United States collects all TRU on a single electrode; this is sufficient since all of them fission and do not need to be separated from one another.

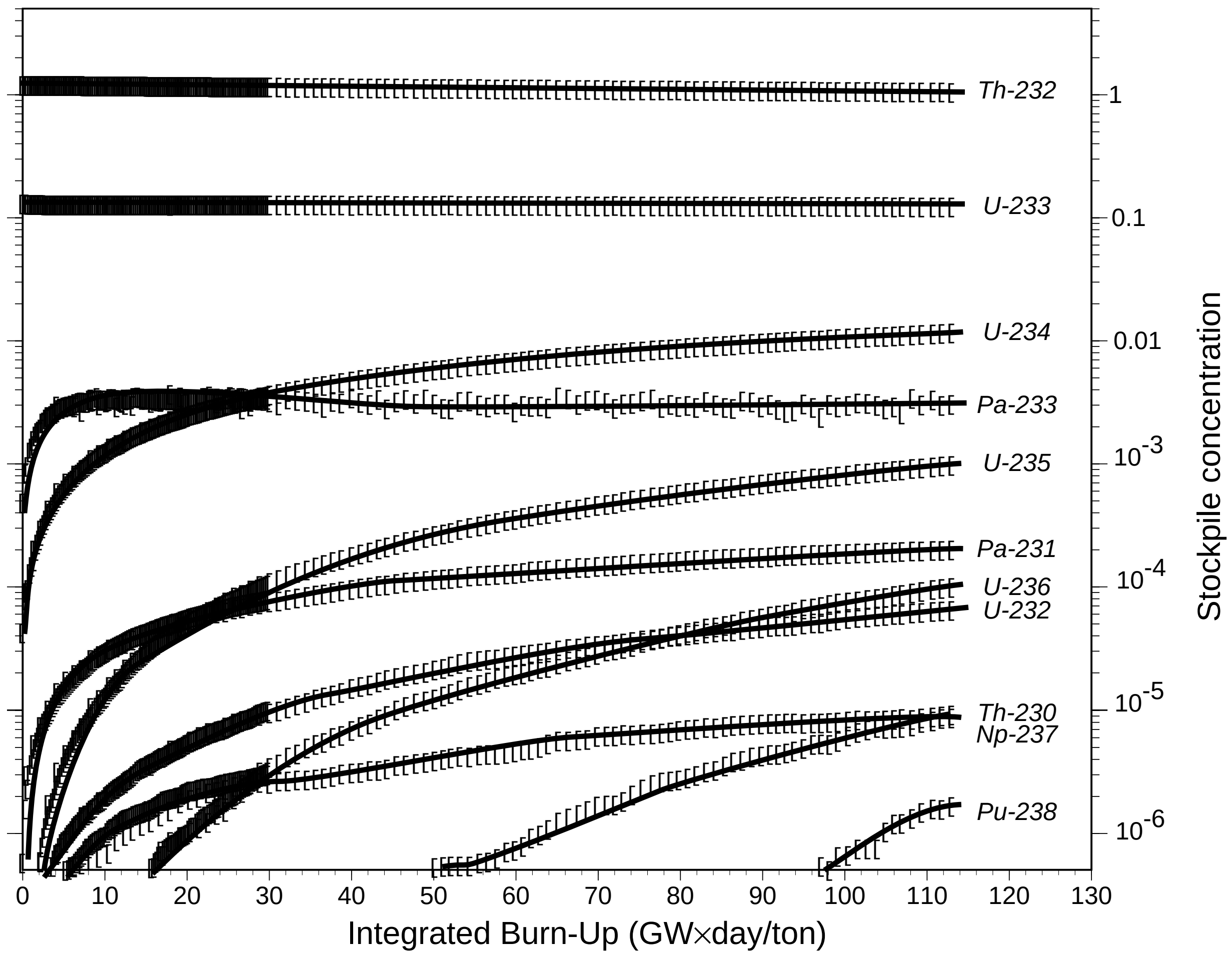

Figure 3.25: Evolution as a function of burnup of the stockpile of the main elements present in the EA fuel [1].

3.8.3.4 Why not a critical system using thorium?

Critical reactors using thorium fuel have worked in the past [10], motivated by the prospect of a high neutron yield per neutron absorbed which ^{233}U offers over the whole neutron energy range, only slightly surpassed by ^{239}Pu for fast neutrons. However, there is a price to pay for breeding ^{233}U. It is the production of ^{233}Pa which has a large neutron capture cross-section and must be compensated by a higher enrichment in fissile material. Also, ^{233}U fissions produce more ^{135}Xe (direct yield 1.4% for ^{233}U versus 0.3% for ^{235}U) and samarium precursors (^{147}Nd, ^{149}Pm) than ^{235}U. These isotopes represent a significant fraction of the total neutron absorption by fission products. At mid-cycle they account for more than 50% of the total fission product absorption.

Finally, the effective fraction of delayed neutrons (β_{eff}) of ^{233}U is less than half of that of ^{235}U, leading to a smaller safety margin. This goes against our strategy of a different approach to safety in the choice of a subcritical system. In a critical system, the effective neutron multiplication coefficient (k) is maintained equal to one by active control and feedback. The resulting safety of the system is then defined in terms of the probability for the system to become (or not to become) supercritical (k >1), as happened in Chernobyl in 1986. The probability of such an accident occurring may be very small, but is not zero. In a subcritical system, the effective neutron multiplication coefficient is smaller than one by construction. Therefore, the resulting safety aspect is a deterministic one. The system is and remains subcritical at all times and Chernobyl type accidents are simply impossible. Furthermore, the availability of an external neutron source in an EA allows greater flexibility in the choice of fuel than in a critical system, particularly relevant for TRU burning.

3.8.3.5 Destruction of nuclear waste: Long-Lived Fission Fragments (LLFF)

In a system such as the EA, where TRU are destroyed, the long term ($\geq$ 500 years) radiotoxicity of the waste becomes dominated by LLFF (Fig. 3.26). This residual level of radiotoxicity could perhaps be tolerated, since it is lower than the level of radiotoxicity of coal ashes corresponding to the production of the same quantity of energy. However, since the main LLFF (^{99}Tc and ^{129}I) can be soluble in water and therefore have a non-zero probability over a time-scale of million of years of contaminating the biological chain with hard-to-predict long term effects, it may be wise to destroy them also. In order to provide such an option, Carlo Rubbia has proposed to use Adiabatic Resonance Crossing (ARC) [12] (Fig. 3.27) to enhance the neutron capture probability, turning for instance a 2.1×10^5 year half-life ^{99}Tc into ^{100}Tc decaying quickly ($t_{1/2} \sim$ 15.8 s) into stable ^{100}Ru. The TARC experiment at CERN [13] has shown that one can indeed use the peculiar (small elastic collision length $\lambda \sim 3$ cm and small elastic $\Delta E/E$) kinematic of neutrons in pure lead (the most transparent to neutrons of all heavy elements) to maximize the neutron capture probability, making optimum use of prominent resonances in the neutron capture cross-section. Note that ^{129}I and ^{99}Tc which were studied in TARC represent 95% of the LLFF volume. The results from TARC imply that one could actually destroy ^{99}Tc and ^{129}I in the lead in the vicinity of the EA core, where conditions are such that one can destroy about twice as much of these elements as is produced over the same time period in the EA core. This possibility to transmute LLFF in a parasitic mode, around an EA core, may be an additional incentive to eliminate LLFF, a process which, unlike the elimination of TRU producing energy, does not pay.

3.8.3.6 Medical applications

A second important application domain of ARC is the production of radioisotopes for medical applications [12]. The same technique (TARC), which is very efficient for destroying fission frag-

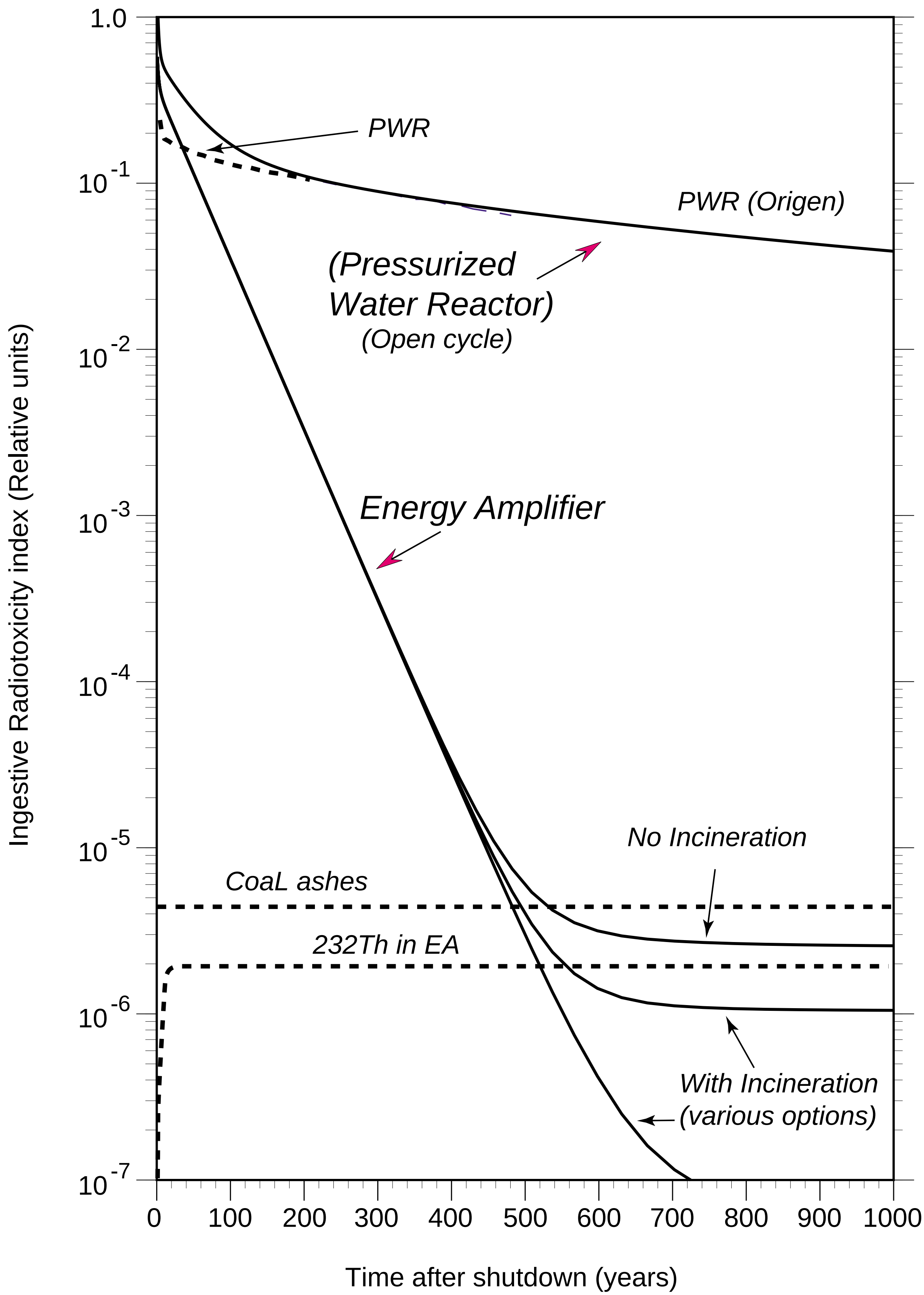

Figure 3.26: Evolution of the potential radiotoxicity of nuclear waste for PWR, EA and coal burning power station, showing that in the EA, the long-term radiotoxicity can be 4 orders of magnitude smaller than in a PWR in open cycle and is dominated by LLFF if no further incineration is performed (adapted from Ref. [11]).

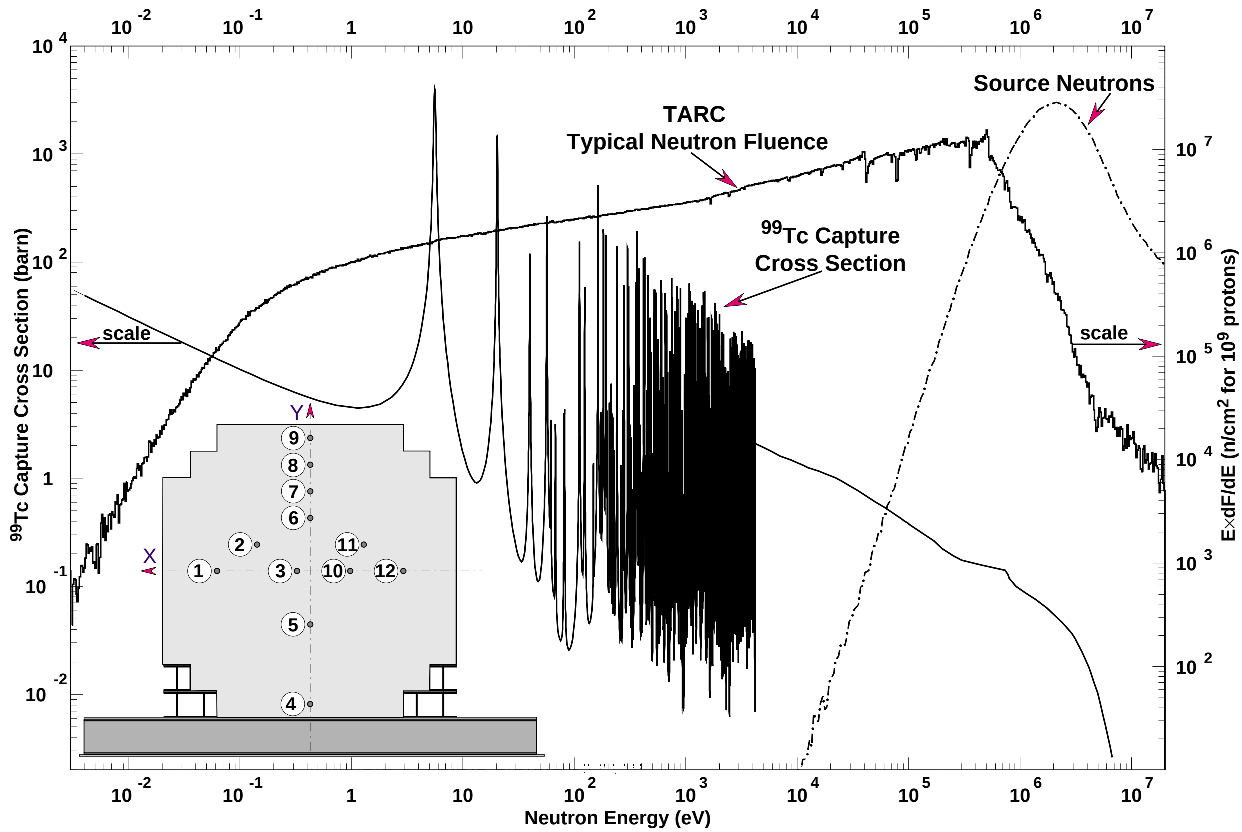

Figure 3.27: Illustration of the Adiabatic Resonance Crossing principle, showing how the presence of lead transforms the spallation neutron energy distribution into a flat flux distribution of slowing down neutrons, with iso-lethargic steps smaller than the width of cross-section resonances where they will be captured with high probability. A sketch of the 334 ton TARC lead volume is also shown.

ments can also be used to induce any other type of nuclear transmutation (ie. radioisotope production), providing an attractive alternative to production with nuclear reactors. A relatively small system free of all the complications of running a critical nuclear reactor has many advantages, as it would:

- favour local radioisotope production thanks to the small size of the system (activator on the hospital site);
- favour the possibility of using shorter-lived isotopes, resulting in a much smaller dose to the patient [example: ^{128}I (25m) instead of ^{131}I (8j)];
- avoid long (costly) transportation allowing smaller doses at the production site;
- allow flexibility in the choice of neutron source according to need: high intensity accelerators (cyclotron) [industrial production of ^{99m}Tc ($t_{1/2} = 6$ h) from the decay of ^{99}Mo ($t_{1/2} = 65$ h)] to radioactive neutron sources [low activity applications]. In TARC, we successfully tested the idea of using natural molybdenum which contains 24.13% of stable ^{98}Mo to produce ^{99}Mo simply by neutron capture, instead of extracting ^{99}Mo from the spent fuel of a nuclear reactor.

These applications were considered sufficiently important that CERN has now obtained a patent [14] on medical radioisotope production based on ARC.

3.8.4 Conclusion

One should not forget that fundamental research is a strong driving force in innovation and that it can lead to potential solutions of some of the most difficult problems facing our society at the beginning of the third millennium. In particular, nuclear energy could make an important contribution to the solution to the energy problem and it would be a mistake to exclude it, a priori, from fundamental R&D. The Energy Amplifier, based on physics principles well established by dedicated experiments at CERN, is the result of an optimization made possible by the use of an innovative simulation code validated in these experiments (FEAT and TARC). This experimental programme has generated new applications in various fields: medical applications for which CERN now owns a patent, research with the approved CERN TOF facility [15], and other surprising ideas such as a nuclear engine [16] for deep space exploration. All of which come as an additional reward for those who have been involved in this project.

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3.9 High-Power Proton Accelerator Studies in France

Jean-Michel Lagniel jmlagniel@cea.fr CEA-Saclay

(for the CEA-CNRS collaboration, CEA-Saclay, DSM-DAPNIA-SEA, 91191 Gif-sur-Yvette Cedex, France)

3.9.1 Introduction

Teams from the two French research agencies CEA and CNRS are working on high-intensity high-duty factor proton, H^- and deuteron linear accelerators. The studies and R&D programs are motivated by several applications such as transmutation of radioactive waste, spallation neutron sources, material irradiation facilities, production of radioactive ion beams, neutrino and muon facilities. The strategy of the French institutions has been to: select the R&D programs with a maximum overlap on the different projects; concentrate the effort on a limited number of subjects; develop strong European and International collaborations as well as partnerships with Industry. The CEA-CNRS team of accelerator physicist and engineers is then working for several years on the (1) Construction of IPHI (injector of protons with high intensity), a prototype for beams with up to 100 mA at 10 MeV and high duty cycle (up to cw), (2) Fabrication and test of $\beta < 1$ Superconducting RF cavities, (3) Development of powerful tools for linac designs and beam dynamics studies.

3.9.2 Motivations

Proton and deuteron accelerators with average beam power greater than 1 MW are studied all over the world for numerous applications, mainly because they are more and more considered as ideal sources of neutrons and secondary particle. Accelerator driven neutron sources are specially interesting to obtain high flux, broad energy spectra, cw or pulsed mode for time of flight measurements, as well as for safety reasons associated with fast shut-down capabilities ...

In France, the CEA (Commissariat à l'Energie Atomique) has studied the TRISPAL project for tritium production from 1992 to 1998. A detailed design of a 24 MW beam power proton linac (40 mA, 600 MeV, cw) has been done to produce high flux of spallation neutrons used to transmute ^{6}Li into tritium. The CEA-Saclay team is involved since several years in the IFMIF project (International Fusion Material Irradiation Facility). The aim of this IEA (International Energy Agency) activity is the design of a high-flux neutron source with an energy spectrum peaked near 14 MeV for research and development on materials for the next generation of fusion reactors. The IFMIF team has the particularity to rally a broad community of scientists from different fields (accelerator, Li-target, test facility, users, design integration) and coming from the European Community, Japan and the United States of America, with the Russian Federation as an associate member. The confrontation of ideas with high level scientists from different laboratories is very fruitful and the work shared with European, Japanese, American and Russian colleagues is highly appreciated. The IFMIF facility is based on two 125 mA, 35-40 MeV, cw deuteron linacs. A full description of the work done during the IFMIF Conceptual Design Activity (CDA) can be found in the "IFMIF Conceptual Design Activity final report" (edited by M. Martone, ENEA Frascati Report). After a period of engineering design activities the project enters now in a "Key Engineering Phase" (KEP) for 3 years. The CEA is also involved in the European Spallation Source (ESS) project. For this 5 MW spallation neutron source, [1] CEA-Saclay participates to the R&D program for the 1.33 GeV, 107 mA H^- peak current, 6% duty cycle linac. This contribution concerns the development of an ECR H^- ion source, beam diagnostics and the conceptual design of the accelerating structures including the evaluation of a superconducting cavity option for the high energy part of the linac. The two French research agencies, CEA and CNRS-IN2P3 (Centre National de la Recherche Scientifique - Institut National de Physique Nucléaire et de Physique des Particules), have started an evaluation program on the accelerator driven transmutation of waste (ADTW) technologies. In such systems, spallation neutrons are used to transmute long-lived nuclei with a high radio-toxicity into short lived or stable nuclei. The accelerator is coupled with a sub-critical target where are located the minor actinides and/or fission products to transmute [2]. A beam power of 20 MW or more is needed, 20 - 50 mA cw proton beams must then be accelerated by a linac up to an 600 - 1200 MeV energy range. The choice of the beam intensity and energy must result of a complex optimization of the whole system and the design must take into account the severe constraints on the accelerator availability and on the acceptable beam losses. CEA and CNRS have also strong interests for the studies of the next generation of radio-active ion beam facilities as well as new projects of high energy physics with neutrino and muon beams also based on high power particle accelerators.

A significant R&D program has then been undertaken by a CEA-CNRS (IN2P3) collaboration in order to optimize the design of the high-power proton linacs needed as drivers for the different applications. This program includes the construction of a high intensity (up to 100 mA), cw, 10 MeV, prototype (IPHI, section 3), the fabrication and test of $\beta < 1$ superconducting RF (SRF) cavities (section 4) and computer code developments for linac designs and beam dynamics studies (section 5).

3.9.3 IPHI (Injector of Protons with High Intensity)

IPHI (“Injecteur de Protons Haute Intensité”, see Fig. 3.28) is the name of the CEA-CNRS R&D program undertaken since 1997 on the front end of high-power linacs. The objective is to accumulate experience in this difficult part of the accelerator in order to optimize the whole machine in terms of performances, cost and reliability-availability. The IPHI programm is undertaken to (1) validate the beam dynamics codes in the low-energy sections where space-charge effects are dominant, (2) measure a real beam distribution at an energy where halo considerations become crucial to be able to optimize a high-energy linac, (3) define the technological choices and adequacy of design codes, (4) have realistic estimations on reliability-availability, cost of the components and ability of the manufacturers to build them. The project aim is to build a 10 MeV “Injector for Protons with High Intensity” (up to 100 mA) with a duty cycle up to 100% (up to 1 MW beam power). The first stage is the High-Intensity Light-Ion Source SILHI designed to produce high-intensity proton or deuteron beams at 95 kV (Fig. 3.29). This 2.45 GHz ECR source is now at a high performance level [3]. Table 3.9 gives the present performances (status with consistent values except when specified).

A long test has been done at the end of 1999 to measure the availability of the source. SILHI has been operated days and nights during 104 hours (5 days) at the nominal energy (95 keV) with a 75 mA cw beam. An availability of 99.96% has been obtained with only one beam trip just after the cold start Monday morning. The beam stopped during 2’30” due to a spark. This excellent result has been obtained thanks to a relentless work of the SILHI Team and fruitful collaborations with experts from several Laboratories (CEA-Grenoble, Los Alamos National Laboratory, INFN-LNS...). It is especially important with respect to the severe limitation of the number of beam trips requested by accelerator driven sub-critical reactors. No damage is observed on the new HV extraction electrodes after more than 600 hours of cw operation in the 80-100 mA range. The stability and reproducibility of the beam are excellent. The present work on SILHI is mainly devoted

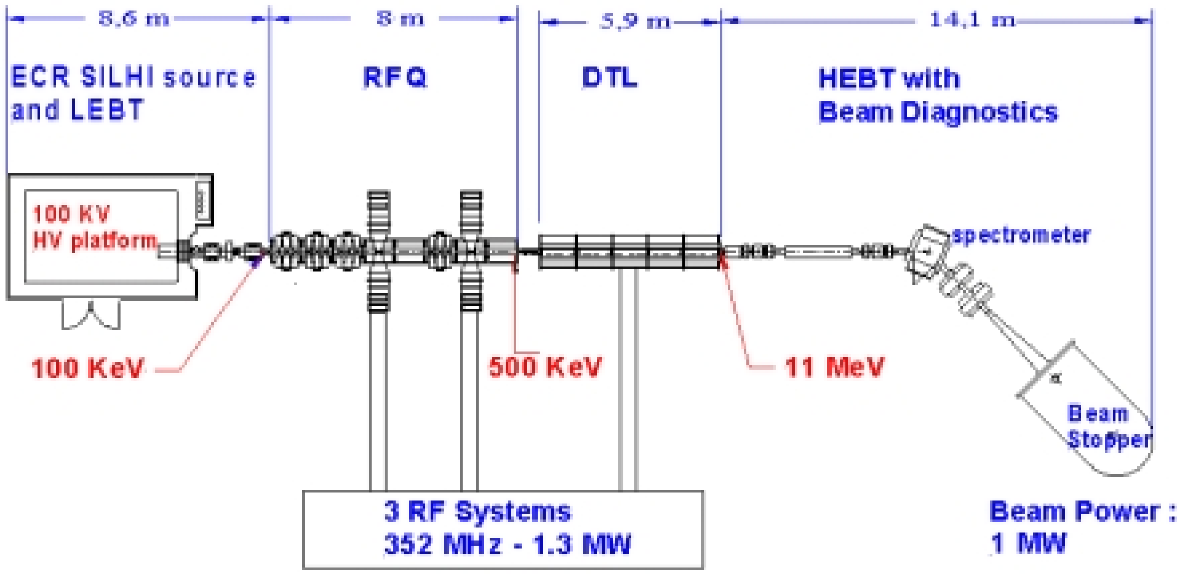

Figure 3.28: Layout of the IPHI project.

Table 3.9: Status of the SILHI source

Parameters	Design	Status
Energy [keV]	95	95
Proton current CW [mA]	100	111
Proton fraction [%]	> 90	88
Extraction aperture [mm]	10	8
Forward RF power [W]	1200	850
Hydrogen mass flow [sccm]	< 10	~ 2.0
r-r' rms norm. emit (LEBT) [πmm mrad]	0.20	0.11 (75 mA)

Figure 3.29: The high-intensity ECR source SILHI, LEBT and emittance measurement unit.

Table 3.10: IPHI RFQ main parameters

Length	8 m
Vane voltage	87.34 to 122.82 kV (1.7 Kp)
R_0 (mean aperture)	3.69 to 5.27 mm
r/R_0	0.85
a	3.56 to 4.41 mm
m	1.0 to 1.735
Input trans. Emit.	0.25 πmm mrad (rms norm)
Output trans. Emit.	0.25 πmm mrad (rms norm)
Output long. Emit.	0.18 MeV deg (rms norm)
Transmission (100 mA)	99.4% for 1.8 Kp
	99.3% for 1.7 Kp
	97.3% for 1.6 Kp

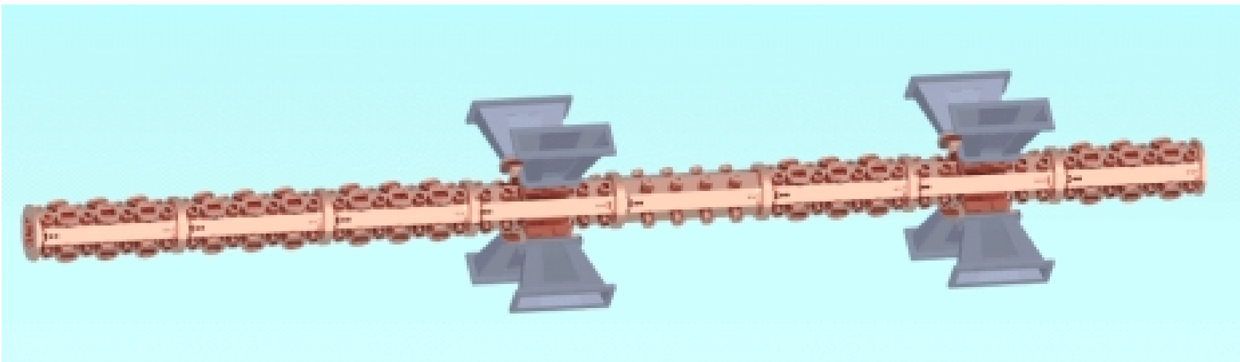

Figure 3.30: Computer view of the IPHI RFQ cavity (8 x 1m long)

to the development of new diagnostics, including a non-interceptive beam-profile measurement system. A new ECR source is also under construction at Saclay for the production of H^- beams in the framework of the ESS project. It is expected that the ECR technique will give both high performances and availability as demonstrated for the production of protons. The ECR source time of life must be actually better than those achieved using a filament or antenna to create the plasma. Table 3.10 gives the main parameters of the 5 MeV RFQ designed to maintain a very high beam transmission with a relatively low maximum electric field. The optimization of the beam dynamics has been done using a large set of codes developed at Saclay (codes for parameter optimization and TOUTATIS for multiparticle beam dynamics), LANL (PARMTEQ) and MRTI (LIDOS). A deep analysis the different models used in these codes is underway and the beam dynamics simulations will be validated by the measurements done with IPHI.

The engineering design (thermo-mechanical analysis, optimization of the geometry ...) has been done and several prototypes have been built to validate the construction process of the cavity. The 8 1 m long segments which will be assembled to form the RFQ cavity (Fig. 3.30) have been ordered in 1999. The first segment will be constructed at the end of 2000. Several parts of the RF systems have been also ordered last year (RF windows ...) and the low RF power mock-up shown in Fig. 3.31 has been built. It is now used to develop the RF field measurement system and optimize the RF tuning procedure. The first beam acceleration in the IPHI RFQ is scheduled end 2002.

For the design of the DTL, a full 3D magnetic analysis of the low energy quadrupoles (around

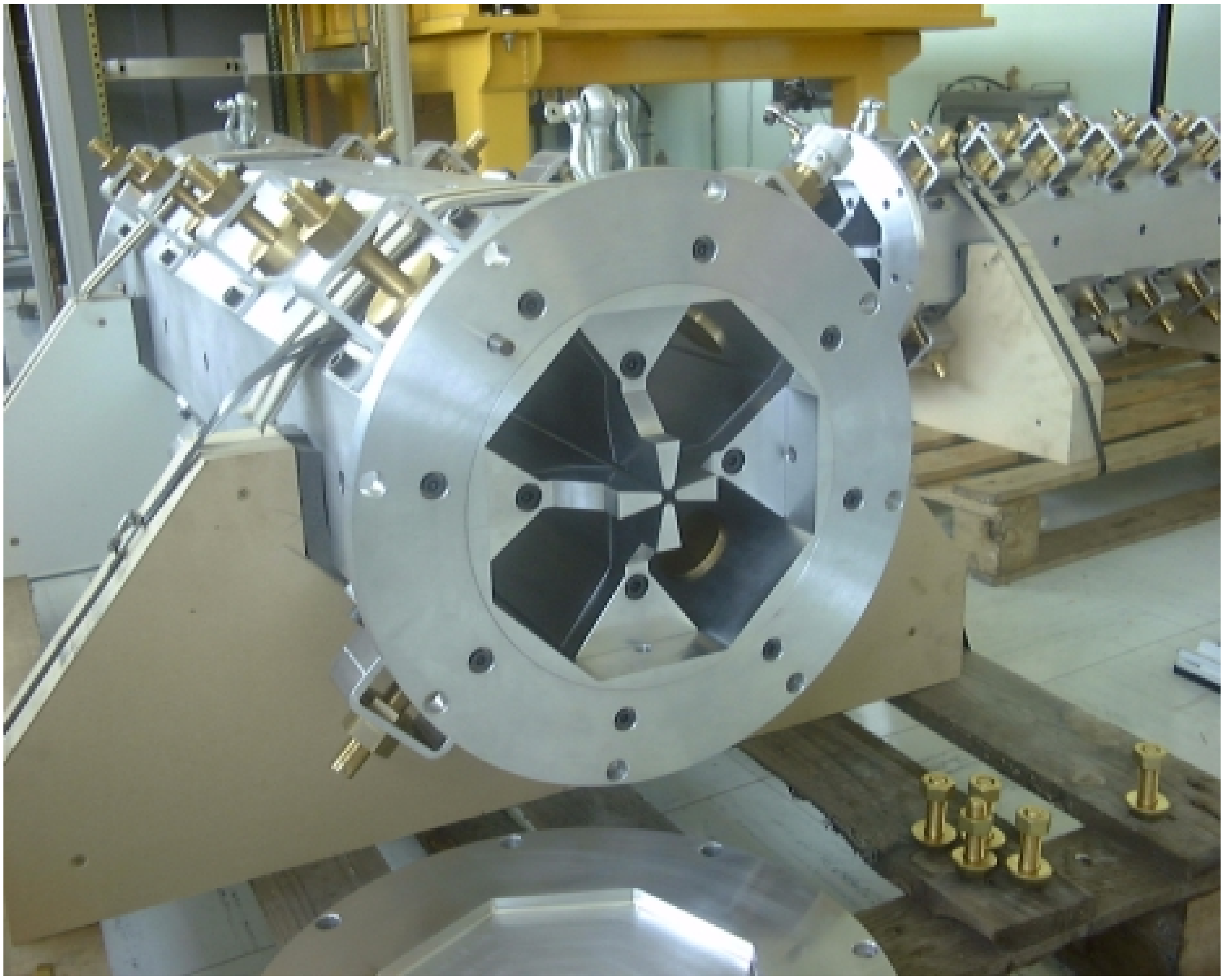

Figure 3.31: Mockup of the IPHI RFQ

Figure 3.32: Two types of quadrupoles for the IPHI DTL

5 MeV) has been done. The field non-linearities have been calculated taking into account the surrounding quadrupoles. The construction of a short tank (4 cells) is progressing for high-power tests starting at the end of this year to demonstrate the capability to work in cw mode. The engineering design of the drift tube has been done with AES (Advanced Energy System) and two types of quadrupoles will be tested (Fig. 3.32) in the short tank in collaboration with CERN. A positive decision for the construction of a 10 MeV tank is expected in the near future.

3.9.4 SRF Cavity Studies

A strong R&D effort on $\beta < 1$ SRF cavities is justified by the fact that this technology brings important advantages, the most obvious being economical. Actually, the high RF to beam power efficiency (almost 100%) significantly reduces the operation cost and the investment cost can be slightly reduced. Standard copper RF cavities typically operate at 1.5 MeV/m with a shunt impedance around 35 MW/m. A 1 GeV linac is then $\sim$ 670 m long and 43 MW of RF is lost in the copper ($\sim$ 70 MW from the plug). Only a few Watts are lost for input power levels of hundreds of kilowatts in SRF cavities. Although a dissipation at the liquid helium temperature, even taking in account Carnot efficiency, AC losses are still negligible compared to room temperature structures. SRF cavities offering higher gradients can also allow an accelerator length reduction. Accelerating fields of 10 MeV/m are foreseen as compared to around 1.5 MeV/m for copper cavities. The only drawback of superconducting cavities is the use of cryogenics but this technology has already proven to be quite well mastered on several large machines worldwide.

An important know-how in the SRF cavity domain has been obtained by the CEA - CNRS-IN2P3 collaboration (CEA-Saclay, IPN-Orsay and LAL) and by the French industry (CERCA...) thanks to several studies and constructions done for the TESLA-TTF electron linac. This expertise is obviously very useful in the high-power proton linac field for which the $\beta < 1$ SRF cavity technologies are developed.

Cavities Preliminary studies have been done in 1996 by a LANL - CEA-Saclay team to demonstrate that beam losses as high as 10^{16} p/cm^2/s do not affect the superconducting properties of niobium cavities. In 1997, four 700 MHz single-cell cavities ($\beta = 0.48$ and 0.64) were successfully built and tested by LANL. Several single cell 704 MHz $\beta = 0.6$ Nb cavities have been made by CERCA for the CEA-CNRS collaboration and tested at low RF power. The superconducting cavities are of standard elliptical shape used for electron machines, but squeezed to take in account the non-relativistic velocity of the protons. Consequently, the ratio of the surface magnetic field to the accelerating field (B_{peak}/E_{acc}) is enhanced in comparison with a $\beta = 1$ cavity by almost a factor of 2. Hence, the performance aimed at ($B_{peak} = 75$ mT in the prototype case), considering the required reliability, is at the same level that for very high gradient machines (the design field for the future electron-positron collider TESLA is 100 mT). This definitely imposes the use of bulk niobium cavities at high frequency (704 MHz in our case) and rules out other choices like the sputtered niobium on copper technique (which performance is barely limited today to 25 mT with losses at least 10 times higher). The cryogenic losses, although only weighing about 10% of the total AC losses, have to be reduced for cost savings during operation. First results obtained at Saclay on a $\beta = 0.65$ single-cell cavity are very promising. Excellent performances have been achieved, exceeding the design point with enough margins, and justifying the above choices (Fig. 3.33). These have yet to be confirmed on optimized multicell cavities for both b values. “CRYHOLAB”, a horizontal cryostat built by CEA and CNRS, will be available this year to test these multicell cavities.

Couplers The main power coupler has to deliver 300 kW of continuous RF power from the RF source at room temperature down to the cavity at cryogenic temperature. It is a very delicate part to design, bearing in mind the desired reliability and robustness. Although recent progress in most laboratories have been achieved in high power handling on superconducting machines (KEK in Japan, CERN in Europe and Cornell in US have demonstrated more than 300 kW CW), the design of such a coupler is still a challenge. Work has been started at CEA-Saclay in collaboration with the Los Alamos National Laboratory (LANL, USA). The goal is to design and build a 300 kW power coupler at 700 MHz.

Cryomodule Cavity and power coupler should be integrated in a cryostat to form a cryomodule. This is a rather skilled operation involving complete mechanical and thermal calculations, as well as magnetic shielding, cryogenic cold box and vacuum system designs. Furthermore, the assembly procedure inside a class 10 clean room should be very carefully analyzed: Cavity performance might be completely ruined if mounting is not done properly. Integrated cryogenic cooling schemes of the different parts (cavities, couplers and thermal shield) have to be optimized taking in account the cryogenic plant requirements. The final test of the cryomodule should give the overall cryogenic losses at the nominal power value.

High-power test of a fully equipped cryomodule The aim the CEA-CNRS team associated with INFN in Italy is now to design a cryomodule fully equipped with its cavities, high-power couplers and cryogenic connections, to measure the real cryogenic losses of this system and to

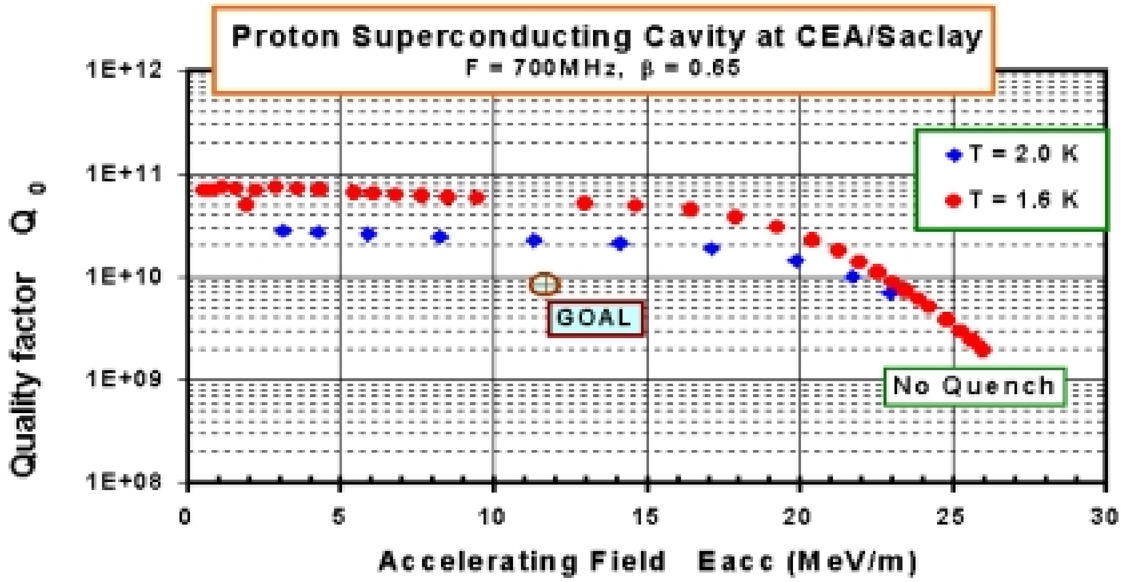

Figure 3.33: Q_0 vs. E_{acc} plot for a single-cell niobium cavity for proton. (Note that the obtained performance by far exceeds the design goal)

reach high accelerating fields. If the cryogenic tests are successful at high RF power the know-how should be transferred to European industrials for future production.

3.9.5 Beam Dynamics and Linac Design

Linked with the R&D efforts on the front end and SRF cavity technologies, beam dynamics studies including errors on both beam and accelerator parameters have to be done to choose the linac design. The aim is to optimize several basic parameters such as - type and length of the focusing periods, - accelerating fields - choice of the quadrupoles type (SC or room temperature) - size of the beam aperture - transition energy to start the use of SRF cavities... The goal of this optimization is to find the best compromise between beam dynamics and low beam losses, reliability and costs (construction plus operation including manpower). The knowledge gained throw the R&D programs are obviously essential to make the right choices.

An important effort is also devoted to the analysis and improvement of the codes to achieve a high precision in these beam dynamics calculations. In this domain as well as for the R&D programs a strong and fruitful collaboration is organized with several laboratories over the world, particularly with LANL in USA and INFN in Italy.

Fig. 3.34 gives a typical layout of high-power proton linac. The front end, starting from the proton source up to an energy of about 10 MeV corresponds to the IPHI prototype. Above 100 MeV the superconducting cavities represent the longest part of the accelerator to bring the protons up to the final energy (450 MeV or more for a waste transmutation demonstrator, around 1 GeV to reach a high spallation efficiency). The high energy part is designed by the CEA-CNRS-INFN collaboration using superconducting bulk niobium cavities at the second harmonic frequency of 704 MHz and working at the superfluid helium temperature of 2 K. This enables running at high accelerating fields ($E_{acc} > 10$ MeV/m) while keeping very low RF losses (Quality factors Q_0 above 8×10^9 are achievable). A single power coupler will feed each cavity. A string of two cavities with

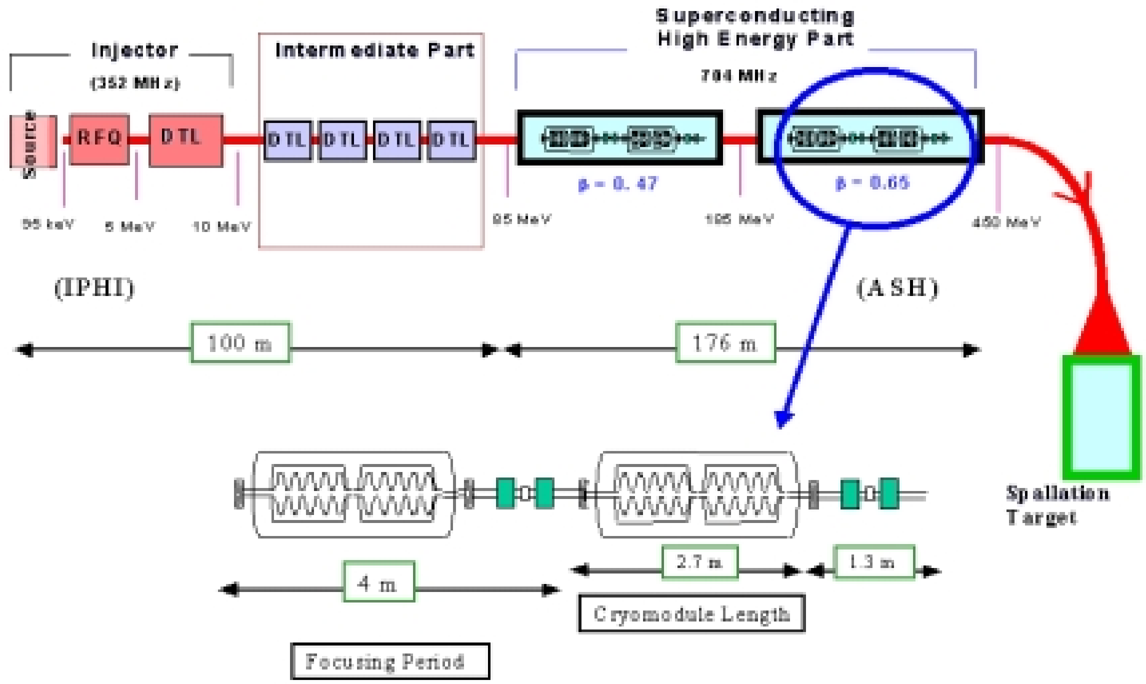

Figure 3.34: Layout of a High Power Proton Accelerator

their main coupler will be assembled inside a clean room to form a cryomodule. Beam focusing will be done using doublets of room temperature quadrupoles located in between the cryomodules leading to a lattice period of 4 meters. The superconducting part can be divided in two sections, each section corresponding to a different geometric β value ($\beta = 0.47$ and $\beta = 0.65$ in the present design).

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3.10 Multi-Application Facility Using a High-Power Proton Accelerator

Jean-Michel Lagniel `jmlagniel@cea.fr` CEA-Saclay

(for the CEA-CNRS collaboration, CEA-Saclay, DSM-DAPNIA-SEA, 91191 Gif-sur-Yvette Cedex, France)

Numerous experts of a working group set up by the Haut Commissaire of the CEA in 1999 have participated to this study. The present document is based on a work done by Jean-Louis Laclare, chairman of this working group.

3.10.1 Foreword

Over the last 70 years, accelerators have become indispensable tools to progress in applied and fundamental research in disciplines as varied as:

- nuclear physics,
- particle physics,
- condensed matter,
- life sciences,
- radiotherapy,
- the environment,
- hybrid reactors and nuclear waste transmutation, etc.

Throughout this period fantastic progress has been made in accelerator physics and associated techniques to meet the ever increasing demands of the different sectors of research. Meanwhile, innovations in the techniques used enabled the emergence of new domains of science (Technology-driven Science), opening up new and unanticipated fields of exploration. The achievements of science and progress in research and development work on accelerators are thus closely linked.

The accelerators used for particle physics are highly specialised. They have also become gigantic and accordingly costly. Their design, construction and operation thus necessitate international collaboration (at European if not intercontinental levels). The same trend is apparent in all the increasingly numerous disciplines where accelerators are used. Large projects have become the rule, with costs counted in billions of Euros. At least 20 years separate the first expression of needs from the beginning of operation of the installations. In all these disciplines, as in particle physics, international collaboration is a necessity. However, in view of the number of such projects, international collaboration is likely to be no longer sufficient. It is now, in addition, necessary to analyse possible synergies between projects and to assess the possibility of sharing multi-purpose installations. Clearly, the goal is to maximise scientific production (without compromising the quality) while minimising resources.

Over the last 10 years, in-depth studies have been carried out on the feasibility of high-power proton accelerators capable of producing beams of several tens of MW. With heavy targets, such beams can produce extremely intense spallation neutron flux levels. At the present time, a whole series of applications could benefit from the performance of this new generation of high-power proton accelerators:

- spallation neutron sources for condensed matter studies,
- hybrid reactors for waste transmutation,
- neutrino and muon factories,
- technological irradiation tool,

- production of radioactive ion beams,
- production of radioisotopes, etc.

The scientific objectives of the above applications are reviewed in section II. It identifies a broad overlap in terms of primary proton beam specifications and point out the possibility of combining a number of these applications on the same site with a single accelerator. The concept of a multi-application installation makes substantial savings feasible. This idea is not a new one, but has already been proposed in a Japanese project (Neutron Science Project which became the Joint Project) as well as the Korean project (KOMAC). The process did not go as far for the ESS project. As it stands, the project priority is the study of condensed matter with pulsed beams of spallation neutrons. The design report refers to the provision of parasitic experimental facilities devoted to nuclear physics and muon production. The possibility is also raised of adding experimental devices for neutrinos and the irradiation of materials. Similarly the “SIRIUS” project at the Rutherford Laboratory ISIS spallation neutron source is dedicated to the production of radioactive ions for nuclear physics purposes.

3.10.2 Objectives of Fundamental and Applied Research

3.10.2.1 Study of condensed matter by spallation neutron scattering

Due to the characteristics of the neutron (spin, absence of electrical charge, mass, and wavelength to energy relationship) and to its interaction (nuclear and magnetic) with atoms, the scattering of thermal neutrons is a particularly important technique to study the structure and the dynamics of condensed matter. It concerns both the arrangement and movement of atoms in solids and liquids, as well as the heterogeneity of materials at micrometric and nanometric scales, or microscopic magnetism.

With the ILL in Grenoble, SINQ in Switzerland, ISIS at Rutherford and several national reactors in operation, Europe will have the most effective set of neutron sources for many years to come. However, thought must be given to the years 2010 to 2015 in view of the probable decommissioning of a number of research reactors and the appearance of spallation sources substantially more powerful than the best research reactors. The potential of the neutron scattering technique is currently limited by neutron flux but it is hardly conceivable to build a reactor of substantially higher power and flux (e.g. ten times greater) than the existing ILL.

On the other hand pulsed spallation sources can produce neutrons with a pulse luminosity far higher than the best existing continuous sources (reactors) while offering far lower total power and energy dissipation. It is also important to bear in mind that the spallation source instrumentation is fundamentally different to that of a reactor. The spectrometers are fixed, the neutrons impinging on the sample arrive in the form of pulses (generally “white” or polychromatic) and the scattered neutrons are analysed in terms of wavelength by the time of flight method. In a reactor, a continuous monochromatic beam is usually chosen and the detection is by angular dispersion. The data are analysed differently and are more complex in the case of experiment with spallation sources. It is therefore possible to anticipate the creation of powerful 50 Hz and 10 Hz spallation sources offering major advances in the study of isotropic matter (polycrystallised systems, liquids and amorphous substances, polymers and colloids), hence in the field of chemistry and materials. The great penetration depth of neutrons will make for example possible to monitor in situ structural changes, for instance associated with an ageing phenomenon, industrial processes (shaping of metals and polymers), or the structural mapping of complex materials with a resolution of 0.1 mm (analysis of phases, residual stresses and crystallographic texture). With powder diffraction, it should be possible to achieve resolutions corresponding to the best synchrotron radiation sources, but with greater sensitivity to light elements and, of course, the obtaining of magnetic structures. Finally, spallation sources should provide unique information in vibrational spectroscopy, notably by the use of epithermal neutrons.

The recent international projects concerning high-flux neutron sources are then based on the pulsed spallation technique:

- SNS in the USA (to be commissioned in 2006),
- Joint project in Japan (construction to begin in 2001),
- ESS "European Spallation Source" in Europe, a project in the design phase which associates 14 Laboratories and 8 European countries.

Power levels in the 2 to 5 MW range are planned for the new installations (to be compared to 57 MW for the ILL high-flux reactor and 200 kW for ISIS, the most powerful existing spallation source). An installation of the ESS type will make possible a gain of one to two orders of magnitude in the flux and luminosity in the neutron pulse compared to the constant flux given by the ILL.

The ESS spallation source would feature:

- a 1.3 GeV, 5 MW linear accelerator producing 1 ms long H^- pulses,
- two rings to compress the pulse from 1 ms to 1 microsecond,
- two spallation neutron targets using mercury, with a repetition frequency of 50 Hz for thermal or epithermal neutrons and/or 10 Hz for cold neutrons respectively.

The neutrons will then be guided towards the experimental devices.

3.10.2.2 *Production of radioactive ion beams*

Research in the field of nuclear physics associated with the study of these extreme states of the nucleus will be the priority for many years to come.

According to the Megascience forum of the OECD (working group on nuclear physics, January 1999), the scientific incentive can be summarised as follows: To establish the theory of nuclear structure, scientists need to study the properties of a large number of different nuclei without restricting themselves to those which exist in stable form in our environment and constitute only around 10% of all the possible nuclei. Once produced, exotic nuclei (with a high number of nucleons or an unconventional proton/neutron ratio) are typically unstable, have a limited life time and disintegrate (radioactivity). They firstly constitute an excellent means of studying the fundamental interaction between nucleons, and secondly, beams of radioactive nuclei offer new possibilities for advanced research in astrophysics (explosions of supernovas, novas, X-ray bursters, neutron stars, and even the spectacular gamma-ray bursters which could constitute the most violent and most energetic phenomena since the big bang) and in particle physics (enabling extremely rigorous tests to be carried out on predictions of the standard low energy model).

Rare and highly unstable nuclei (as distant as possible from the valley of stability) can be produced by bombarding heavy metal targets with an intense flux of spallation neutrons. In the ISOL (Isotope Separation On Line) scenario envisaged, the neutrons are produced by an intense beam of protons (preferred to deuterons). Two major projects are planned:

- In Japan, the ”Joint Project” multidisciplinary installation plan to devote part of its beams to the production of radioactive nuclei for a dedicated experimental facility with a fishbone and post-accelerator.

- In the USA, the future SNS spallation source accelerator can be used, to a certain extent, for the production of radioactive nuclei.

- In Europe, as part of EURISOL, a working group was assigned to identify the research and development work to be promoted in the different fields involved: primary beam, target and accelerator, as a first objective.

In this context a progression by stages has been proposed by GANIL:

- SPIRAL in the short term,

- SPIRAL II in the medium term, with the addition of a cyclotron accelerating 50 MeV deuterons upstream of a production target,

- The installation of high performance (flux 104 times greater than those of SPIRAL) using no longer SPIRAL but a linear accelerator system with protons or deuterons of 100 MeV per nucleon.

This could be in service by 2010 with, as an intermediate phase, a study of details completed in 2004. In this sequence the use of a 1.3 GeV proton linear accelerator supplying 1 MW beam and comparable to that envisaged to serve other fields of research would provide an additional gain of two orders of magnitude as concerns flux. A time structure with a 50 Hz pulse rate is tolerable.

3.10.2.3 Hybrid reactors and the transmutation of nuclear waste

Hybrid reactors are based on the use of an additional source of neutrons, outside the core of a nuclear reactor. It is generally accepted that the use of a high-intensity proton accelerator is the most effective means of creating an external source of this type. This approach offers a degree of liberty in the choice of the fissile core: by allowing operation under sub-critical conditions, it provides freedom from neutronic constraints in terms of reactivity control or neutron balance. This constitutes a specific advantage in the transmutation of nuclear waste, minor actinides and certain long-lived fission products. These subjects of research constitute some of the major issues being studied in France in accordance with the law of 1991. In addition, such reactors would have advantages such a higher burnup and the fact that core composition and geometry would become less critical.

The excess of available neutrons makes it possible to envisage:

- the use of new fuels (thorium),

- the transmutation of nuclear waste, minor actinides and long-lived fission products, thus greatly reducing their radiotoxicity by fast neutron spectrum fission.

These subjects of research are major issues for France.

The research and development work in hand should lead to a new generation of linear proton accelerators capable of meeting extremely stringent beam power requirements of up to 5 to 50, if not 100 MW, i.e. 10 to 100 times better than the best existing machines (LAMPF at LANL or SINQ at PSI). It would also be necessary to provide far higher standards of reliability and maintainability for industrial operation (“ADS quality”: minimum activation of structures, ease of maintenance, rapid intervention, high availability, excellent overall reliability to limit thermal/mechanical fatigue of equipment and hence its life time: probably not more than 100 unscheduled beam interruptions per year).

To obtain an industrial system in the longer term, it would be necessary to proceed by stages. The demonstrator stage should include a proton accelerator of an energy in the region of 1 GeV and an initial power of 5 MW extendable to 20 MW in a subsequent phase. It must be mentioned that the design approach adopted for the accelerator should make it possible to evolve from the demonstrator stage to the industrial prototype stage. Only a linear accelerator can reach the beam powers required. The cyclotron option, limited to a maximum of a few megawatts per unit, would be studied only in the case where a series of accelerators must be used to create the external neutron source. For the target material, lead-bismuth is preferred. Intense research and development activity is in progress to design the reactor, in collaboration mainly with Italy, Belgium and nuclear industry. A number of options remain open.

This application could benefit greatly from a linear proton accelerator developed simultaneously for other applications. To provide sufficient compatibility with other applications, a hybrid reactor must be able to operate in the pulsed regime. It would, in fact, appear that operation at 50 Hz with pulses of constant peak intensity and variable length (typically 100 mA for 1 ms for 5 MW at 1 GeV) is extremely advantageous in a number of respects:

- measurement of proton beam parameters,
- power adjustment and setting,
- RF adjustment,
- reactor diagnosis (measurement of k_{eff})

It remains to be determined whether, under certain conditions, pulsed operation at 50 Hz is not liable to encourage power fluctuations in the core. The question has been raised and needs to be studied.

Existing projects and programmes include:

- ATW Los Alamos with a special effort concerning:
- accelerators, already initiated on the occasion of APT and re-usable for the new project,
- research and development work on the Pb-Bi target, in collaboration with Russia.
- Joint Project at Tokaï which offers 0.8 MW of proton-beam power for the transmutation experiments.
- TRASCO, a 30 MW project in Italy.

Mention should also be made of the work of the “minister’s advisors group on accelerator-driven systems” and that of the Gédéon consortium which coordinates the basic research and development work in France.

3.10.2.4 Technological irradiation tool

Since the introduction of nuclear technology, experimental reactors have been successfully used as irradiation tools for technological purposes. With power ratings of less than 100 MW and frequently using an MTR fuel enriched with ^{235}U, such installations routinely supply maximum neutron fluxes of a few 10^{14} n cm^{-2}s^{-1} both in the thermal range and the fast range above 1 MeV. The level of damage is limited to a few displacements per atom per year.

The development of new materials for nuclear equipment, designed for better performance and longer life time, constitutes an issue of major importance. It is necessary to attain neutron fluxes of some 10^{15} n cm^{-2}s^{-1} in both the thermal and fast ranges, as well as an annual damage of a few tens of displacements per atom. The spallation of sufficiently intense beam of protons on a target of heavy metal should make it possible to achieve these objectives.

Of the different factors involved in selecting a spallation installation for producing neutrons for technological irradiation purposes, the energy and current of the proton beam, the spallation material and the operating temperature constitute parameters whose determination is essential for achieving the objectives. Furthermore, an irradiation tool for experimental purposes must offer high operating flexibility and ease of access to the irradiation devices and the installations must not require lengthy maintenance. Although the number of neutrons emitted per proton increases as a linear function of the energy of the proton, the ratio of the proton energy to the number of neutrons emitted no longer falls and reaches an asymptotic value at around 1.2 to 1.4 GeV. This is why proton energy can be set at around 1.3 GeV. The penetration depth of protons at this energy is consistent with the usual height of experimental irradiation devices.

For the SNS and ESS projects, mercury has been chosen as the spallation material. The reasons for this choice are easy to understand: mercury, being liquid at room temperature, is highly suitable for an experimental installation subject to frequent interruptions required by the users. However, as a result of synergy with the work carried out on hybrid systems, it would be perfectly possible to initially opt for a Pb-Bi target for the irradiation tool. The required proton-beam power is 10 MW and the density at the window attains 58 μAcm^{-2}. The irradiation devices are placed around the spallation zone at a distance of 12.5 cm. This buffer zone of 12.5 cm enables amplification of the neutron source by n, xn reactions and shields the devices to be irradiated from the protons. The irradiation zone is physically separated from the spallation zone and the buffer zone. In the spallation zone and the buffer zone, the material is liquid, while in the irradiation zone, the material into which the experimental devices are introduced consists of solid, structured lead. Apart from the possibility of obtaining high neutron flux levels, this mode of neutron production only requires fissile material inventories strictly limited to the requirements of technological analysis. This type of installation operates at a very low k_{eff}, determined by the scale of the experimental programme. Amplification of the spallation neutron source by fissions in experimental fuels can only be limited and the energy released by this amplification is nearly all deposited within the experimental device.

If a technical analysis were carried out, it would probably indicate that further synergy would seem achievable as concerns the target that could be shared between the irradiation tool and the production of radioactive nuclei for instance. This would lead to the adoption of a multipurpose target with outputs dedicated to each of the applications.

3.10.2.5 Neutrino plants

Neutrinos play a crucial role in particle physics and astrophysics. Being neutral and sensitive to weak interactions only, it is very difficult to study them. On the other hand, these properties make them excellent tools for studying the core of the sun, explosions of supernovas and the outer reaches of the universe.

The question of their mass is fundamental for numerous reasons:

- without mass, they would be the only fermions to be so,
- in certain grand unified theories, they have mass and there are relationships between their mass and that of the quarks associated with them,
- having mass, they could contribute significantly to the black matter of the universe.

Up to now, attempts to measure their mass directly have only resulted in establishing the upper limits. One indirect method of measurement consists of detecting the oscillation phenomenon between different species of neutrinos, this phenomenon only being possible if they have mass.

There are a number of signs that such oscillations exist: deficit of neutrinos originating from the sun (CHLORINE, GALLEX, SAGE, SUPERKAMIOKANDE), deficit of neutrinos in the atmosphere (SUPERKAMIOKANDE), excess of antineutrinos of the electron type observed at LAMPF by LSND.

At the present time, neutrinos are produced with circular high-energy proton accelerators. There are projects at CERN, FERMILAB and KEK to feed these neutrinos to experiment installations thousands of kilometres away (GRAN SASSO laboratory in Europe, SOUDAN mine in the USA and the KAMIOKA mine in Japan), to access the appropriate oscillation parameter domain (mixing angles and masses).

However, the accessible flux levels remain low and limit the research goals. In addition, the neutrinos produced are mainly of the muon type. The exact determination of the oscillation parameters of neutrinos requires elaborated statistics and systematic study of the different types of neutrinos. If the neutrinos have mass, it is to be expected that there will be a lepton mix matrix, similar to that of quarks and capable of giving rise to new CP violation phenomena. The detailed study of masses and the mixing of neutrinos requires flux intensities greater by a number of orders of magnitude than those currently available.

In this context, a new system for producing neutrinos with flux levels of around 1020 per year is being studied in the major particle physics laboratories. It is based on the use of a storage ring for muons whose disintegrations would supply (anti)neutrinos of both the muon and electron types. The production of muons is often based on an installation comprising a very high intensity proton linear accelerator (beam of 2 GeV, 2 mA, 4 MW, pulsed for the CERN project), a proton accumulation ring, a production target, a linear accelerator for pre-accelerating the muons resulting from disintegration of pions, a recirculator using the CEBAF principle, and the storage ring.

In addition to the development work necessary for the high-intensity proton linear accelerator, an important feasibility issue remains to be resolved relating to the collection and cooling of muons. This will require a number of years of research and development work, which has led CERN to see the neutrino plant as a post-LHC option. Furthermore, the concept of a neutrino plant fits in nicely with a longer term project for a circular muon collider making it possible to reach as yet unattained energies at the centre of mass (in the region of 10 TeV) with equipment of a size comparable to that of the LEP.

3.10.3 Technical Options Answering the Specifications

3.10.3.1 Summary of specifications

The most powerful existing proton accelerators are of either the cyclotron type (SIN - PSI at Zurich) or the linear accelerator type (LAMPF at Los Alamos). Both are limited to 1 MW. Ta-

Table 3.11: Power, energy, and current comparison of proton accelerator facilities for applications.

Use	Max. Beam Power	Energy	Average Current
Condensed Matter	5 MW	1.3 GeV	3.75 mA
Radioactive Beams	$>$ 200 kW	$>$ 200 MeV	$\sim$ 1 mA
Hybrid Systems			
100 MWth demonstrator	$\sim$ 5 MW	$\sim$ 600 MeV	$\sim$ 10 mA
Industrial system	$\sim$ 50 MW	$\sim$ 1 GeV	$\sim$ 50 mA
Irradiation Tool	10 - 40 MW	$\sim$ 1 GeV	$\sim$ 10 - 40 mA
Muons-Neutrinos	4 MW	2 GeV	2 mA

ble 3.11 indicates tipical power, energy and current levels required of the accelerator for the different uses discussed above.

The power levels required can reach 50 MW for one application, and are far higher than those of existing equipment. This factor of 50 justifies the intense research and development work that has been carried out for many years.

3.10.3.2 Cyclotron

These accelerators are limited to intensities of a few mA dc and energies below 1 GeV, i.e. well below the specifications. For reasons of compactness, they combine the functions of guiding and focusing (weak) and are very sensitive to space charge effects. The separation of the orbit between successive turns, which is necessary to limit losses, requires extremely high acceleration rates and the installation of high-powered cavities between the magnetic sectors. The PSI cyclotron has an energy level of approximately 600 MeV. It is currently limited to current levels of around 1 mA (600 kW routinely and 1 MW maximum) at the target. Using the PSI machine as a basis, it is possible to extrapolate the parameters of cyclotron that would possibly deliver a few MW. However, 10 MW seems out of range. It might be possible to combine a number of cyclotrons to increase the intensity at the target. This approach would require the use of dozens of units for an industrial system (which would give rise to reliability issues). It could in no case be satisfactory for applications requiring a pulsed beam, as for instance in the case of the study of condensed matter by scattering of spallation neutrons.

3.10.3.3 Linear accelerator

The linear accelerator is the only type of equipment with which the high intensities required can be reached. Space charge sets the limit at low energy and the RFQ (Radio Frequency Quadrupole), part of the pre-injector, can accept up to 100 mA continuously (i.e. 100 MW after acceleration to 1 GeV) as has been experimentally demonstrated with LEDA (Low Energy Demonstration Accelerator) at Los Alamos. The IPHI programme (CNRS-CEA) has been started at Saclay on a comparable basis to that of LEDA.

3.10.3.4 Reliability

As concerns reliability, the hybrid reactor application is by far the most demanding as it requires a very limited number of unscheduled beam interruptions: of the order of 100 per year at maximum provided the target and reactor designs are optimised for this. In comparison, the specification for the study of condensed matter by neutron scattering is relaxed with several hundreds. The statistics for linear accelerators and cyclotrons in operation give similar results, amounting to some 10,000 interruptions per year for both types of installation, i.e. some two orders of magnitude higher than the specifications. It is evident that the equipment involved was not designed according to reliability criteria. At the time, this criterion was far less important than energy, current, capital and operating cost etc. More recently, high levels of reliability have been demanded for the synchrotron light rings of the third generation, which have achieved a mean time between failures of around 20 hours, with no great incentive to improve on these figures as the interval between two injections is 12 to 24 hours. On the basis of this data, a figure of 300 unscheduled interruptions per year is obtained. Means are available of doing substantially better and thus meeting the objective of one hundred. The extreme importance of the quality of the electricity supply to the site must be noted. On the reactors and targets side, efforts must be pursued in parallel to achieve greater tolerance if possible.

3.10.3.5 Beam time structure

The time structure of the proton beam from a linear accelerator can be adjusted according to user demand. This can be illustrated by the example of a beam power of 5 MW, supplied at an energy level of 1 GeV, in the form of a 1 ms pulse, with a repetition period of 20 ms (frequency of 50 Hz).

According to this example it is then possible to establish:

- an average current of 5 mA (beam power to proton energy quotient).
- a peak current of 100 mA by averaging only during the 1 ms of the pulse with beam. In fact, during the 1 ms pulse, the beam is divided into bunches of approximately 80 ps, which repeat at the accelerating radiofrequency frequency of 352.2 MHz, with the result that the bunches are 2840 ps apart. This microstructure is always present in the beam. It corresponds to the alignment of the particles with the RF acceleration phases.
- a peak-to-peak current of 3.5 A by averaging over the length of the bunches.

3.10.4 Multipurpose Facility

3.10.4.1 Example of operation for the linear accelerator

As all the applications in question (probably including the hybrid reactor) can operate in the pulsed regime, it will be possible to meet the requirements of applications with a single accelerator saving both construction and operation costs. For this to be possible at 50 Hz, series of pulses can be distributed over a 20 ms period, each pulse being formed (with identical peak current) to supply the needs of a given application at the required power level (by adjusting the pulse duration).

By way of an example, with a 1 GeV linear accelerator supplying 100 mA peak current (i.e. 5 MW per ms of beam), it is possible, with a 20 ms period, to provide the following pulse sequence:

- 1 ms of H^- = 5 MW for two compression rings for the study of condensed matter by scattering of spallation neutrons,
- 0.2 ms of protons = 1 MW for production of radioactive nuclei,
- 1 ms of protons = 5 MW for the hybrid demonstrator,
- 2 ms of protons = 10 MW for the irradiation tool,
- 0.8 ms of H^- = 4 MW for the neutrino plant.

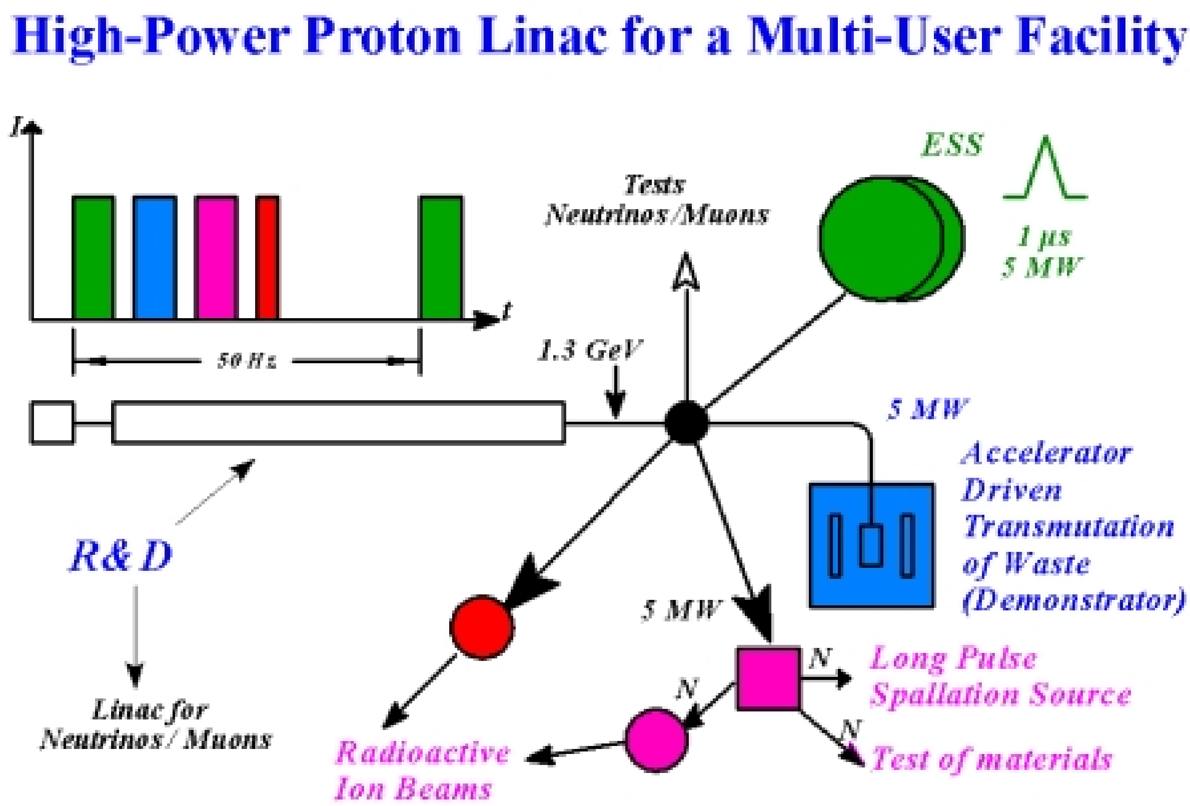

Figure 3.35: Schematic layout of a multi-application facility using a high-power proton accelerator.)

In this example, the accelerator supplies a total beam power of 25 MW with a duty cycle of 25%. The interval between successive pulses must be sufficient to operate fast-acting switching magnets without loss of particles.

3.10.4.2 Features of accelerator

The accelerator would include:

- two sources:
- a proton source for the majority of the applications,
- an H^- ion source specific to the spallation neutron source and the neutrino plant,
- low-energy beam transport, from the sources and up to approximately 100 keV,
- an RFQ (Radio Frequency Quadrupole) for preaccelerating the beams up to about 5 MeV,
- a succession of hot cavities of the DTL (Drift Tube Linac) type installed downstream the RFQ to make the transition to an energy level of around 100 MeV,
- a succession of superconducting cavities to raise the particles to the final energy level with high accelerator gradients of around 10 MV/m so as to obtain a high yield and keep the length of the accelerator short,

- a high-energy transport and distribution system used to direct the beam to the different targets of the users, via compressor rings as appropriate.

3.10.4.3 Special equipment

Special equipment for the different applications is installed further downstream.

The spallation neutrons for the study of condensed matter are produced in two targets, around which are arranged moderators and the various neutron guides leading to the experiment areas. The first target specialised for long wavelengths operates at 10 Hz (1 pulse out of 5), the 1 ms pulses being directly supplied by the accelerator. The second target, specialised in short wavelengths, requires prior compression of the pulses from 1 ms to 1 microsecond (4 pulses out of 5) in the accumulator rings.

Radioactive nuclei, derived from the production target, are either used without further treatment after separation, or are post-accelerated by means of a cyclotron or a linear accelerator with an RFQ type pre-injector. The experimental areas comprise mass separators and high-resolution detectors.

The hybrid demonstrator and the irradiation tool both have a sub-critical reactor with all the necessary experimental equipment.

The production of intense beams of neutrinos requires a complex set-up. The H^- pulse from the accelerator must be previously shaped (accumulation and compression rings) before being sent to the pion/muon production target. Downstream of the pion/muon production target, there is a recirculation accelerator of the CEBAF type and the storage ring in which the muons disintegrate into neutrinos.

In a multipurpose installation of the type envisaged, the infrastructure (buildings, power lines, utilities etc.) and personnel safety aspects will deserve special attention.

3.10.5 Conclusion

There are excellent scientific, technical and economic reasons for studying in detail a European multi-application installation project based on a high-power proton accelerator. Such an installation could be operational around 2010-2015 and serve for a number of decades:

- a hybrid reactor demonstrator,
- means of studying condensed matter by the scattering of spallation neutrons,
- a technological irradiation tool,
- a facility for nuclear physics with beams of radioactive nuclei, etc.

The installation could constitute a European centre of excellence in the field of neutronics, where large numbers of scientific and technical executives could be trained.

It is time to organise a large European collaboration for the feasibility study and conception phase of such a project. During this phase, the project team could:

- review the different beam needs of the different applications,
- analyse their compatibility,
- define the scope of a site-independent project and obtain the corresponding specifications for the facility subsystems: infrastructures, accelerators, experimental instruments,

- select the most appropriate options regarding scientific, technical, organisational and administrative aspects,
- estimate the costs for construction, operation and the needs in manpower,
- propose a time schedule and the associated multi-annual budget,
- propose a type of organisation and statutes,
- draw up the specifications for the site.

The study finalised by a conceptual design report could be sufficiently detailed to minimise contingencies on those parts of the project having a large potential impact in terms of performances, costs or delays.

Table 3.12: Summary of Mega-Watt High-Intensity Facilities.

	Energy [GeV]	Current [mA]	Rep.-rate [Hz]	Ave. power [MW]	Type
SNS	1	2	60	2	LAR
ESS	1.33	1.9	50	2.5	LAR
JHP	3	0.33	25	1	RCS
CERN NFPD	2	2	100	4	LAR
RAL NFPD	5	0.4	25	2	RCS
FNAL NFPD	16	0.25	15	2	RCS
CERN EA	1	10 – 20	CW	10 – 20	Cyclotron
APT	1.03	100	CW	103	linac
TRISPAL	0.6	40	CW	24	linac
ADTW	0.6 – 1.2	20 – 50	CW	> 20	linac
μ-collider driver	30	0.25	15	7.0	RCS

3.11 Summary of Mega-Watt High-Intensity Facilities

Jie Wei `wei1@bnl.gov` Brookhaven National Laboratory

Table 3.12 summarizes some of the Mega-Watt applications discussed in this special section. The average beam power is for each ring in the case of dual-ring design.

4.1 Summary of the Workshop on Beam-beam Effects in Large Hadron Colliders (LHC99)

Werner Herr Werner.Herr@cern.ch CERN, SL Division

The international workshop on beam-beam effects in large hadron colliders (LHC99) took place at CERN from the 12th to 16th of April 1999. The members of the local organizing committee were J. Gareyte, W. Herr, E. Keil and F. Ruggiero. It was attended by 43 participants from 13 institutes. The scenario was prepared by 7 plenary talks on experience with beam-beam effects in existing colliders. In the following, the issues were discussed in two working groups. One on weak-strong beam-beam effects chaired by E. Keil (CERN) and another one on strong-strong beam-beam effects, chaired by K. Yokoya (KEK). In these working groups 14 formal presentations were made to initiate the discussions. All presentations together with the summaries from the chairmen of the working groups are compiled into the proceedings of the workshop (CERN-SL-99-039 (AP), edited by J. Poole and F. Zimmermann). The proceedings and further details on the workshop and LHC beam-beam studies can be accessed through the following web pages:

http://wwwslap.cern.ch/collective/bb-workshop99/

and

http://wwwslap.cern.ch/collective/lhcbb/

4.1.1 Incoherent and Weak-Strong Beam-Beam Effects

The working group on incoherent effects was coordinated by E.Keil (CERN) and the discussions were organized around the following topics: measurable quantities and instrumentation, experiments and simulation.

A consensus was reached on the necessity to have a good instrumentation, possibly bunch by bunch, for the relevant parameters such as tunes, luminosity, beam size and beam lifetime. The vital question how the dynamic aperture is affected by beam-beam effects was studied in simulations by different people and with different programs. The tune space occupied by the tune spread due to the non-linear beam-beam interaction is quantified with tune footprints and the effects of the crossing angle and PACMAN bunches can be demonstrated. The dynamic aperture due to field errors in the presence of beam-beam interactions was studied independently by three people and the possible excitation of synchro betatron resonances due to the crossing angle and finite dispersion was evaluated in a separate study. It was generally agreed that a crossing angle of 300 microradian is the minimum for the present optics parameters to ensure sufficient aperture.

4.1.2 Coherent and Strong-Strong Beam-Beam Effects

The working group on coherent effects was coordinated by K. Yokoya (KEK). The main topics for discussion were a general understanding of coherent beam-beam modes and their observation, problems related to the parasitic crossings at the LHC and simulation techniques. The existence of coherent beam-beam modes was clearly demonstrated by measurements at LEP in electron positron collisions. Y. Alexahin presented his recent theoretical work on coherent oscillations of non-rigid bunches based on the Vlasov equation. He demonstrated that for the LHC parameters the frequency of the pi-mode is shifted outside the incoherent tune spread with the loss of Landau damping as a consequence. During the workshop A. Hofmann suggested to decouple the two beams by different betatron tunes. It was demonstrated that for a sufficiently large tune split in the order of the beam-beam parameter, the Landau damping is restored. The further complication of beam-beam modes with parasitic collisions and a large number of bunches will be studied.

The parasitic collisions change the orbit of the bunches and as a consequence of the gaps in the bunch train (PACMAN bunches), the orbit distortions are different from bunch to bunch. This causes orbit offsets at the interaction point which do not strongly affect the luminosity but may result in secondary effects, such as bad lifetime. The size of these distortions can be computed for all nearly 3000 bunches in each beam by a self-consistent orbit calculation, including the beam-beam kicks. They are estimated to be about 10 to 20 percent of the transverse beam size. The question what offsets can be tolerated will be studied in simulations and experiments.

4.2 Summary of Workshop on LHC Interaction Region Correction Systems

J. Wei wei1@bnl.gov Brookhaven National Laboratory
J. Strait strait@fnal.gov Fermi National Laboratory
J.-P. Koutchouk jean-pierre.koutchouk@cern.ch CERN
T. Taylor thomas.taylor@cern.ch CERN
W. Fischer wfischer@bnl.gov Brookhaven National Laboratory

The Workshop on LHC Interaction Region Correction Systems was held at Brookhaven National Laboratory, New York, on 6 and 7 May 1999. The workshop was attended by 25 representatives from CERN, FNAL, KEK, BNL, and other institutions and universities. The workshop had three individual sessions: Magnet field quality, Global correction, and Local correction.

The performance of the Large Hadron Collider (LHC) at collision energy is limited by the field quality of the interaction region quadrupoles and dipoles. This workshop addressed the interaction region magnet field quality, to reviewed the principles and efficiency of correction schemes, and to finalized a compensation plan and corrector layout for the LHC interaction region. The workshop scope will covered FNAL and KEK built quadrupoles, BNL built separation dipoles, and European interaction region correctors.

The session on Field Quality Issues, chaired by J. Strait (FNAL), discussed the progress made by KEK and FNAL in achieving the best possible field quality in the interaction region quadrupoles. The effect of field errors were considered by analyzing simulation studies. Attention was given to the uncertainties in predicting and measuring field errors.

The session on Global Correction, chaired by J.-P. Koutchouk (CERN), considered methods of reducing the nonlinearity of an LHC like accelerator. Methods discussed were the minimization of one-turn map coefficients and the minimization of resonance driving terms. The session also discussed magnet sorting, the crossing angle dependence of the dynamic aperture and operational experience from LEP.

The session on Local Correction, chaired by T. Taylor (CERN), discussed the location, strength and effectiveness of multipole correctors in the interaction regions for both, proton and heavy ion operation. Discussions were based on technical feasibility considerations and dynamic aperture requirements. Work on linear corrections in the interaction regions was reviewed.

4.2.1 Proposed IR Corrector Layout and Plan

The proposed layout and content for the interaction region corrector packages is shown in Fig. 4.1.

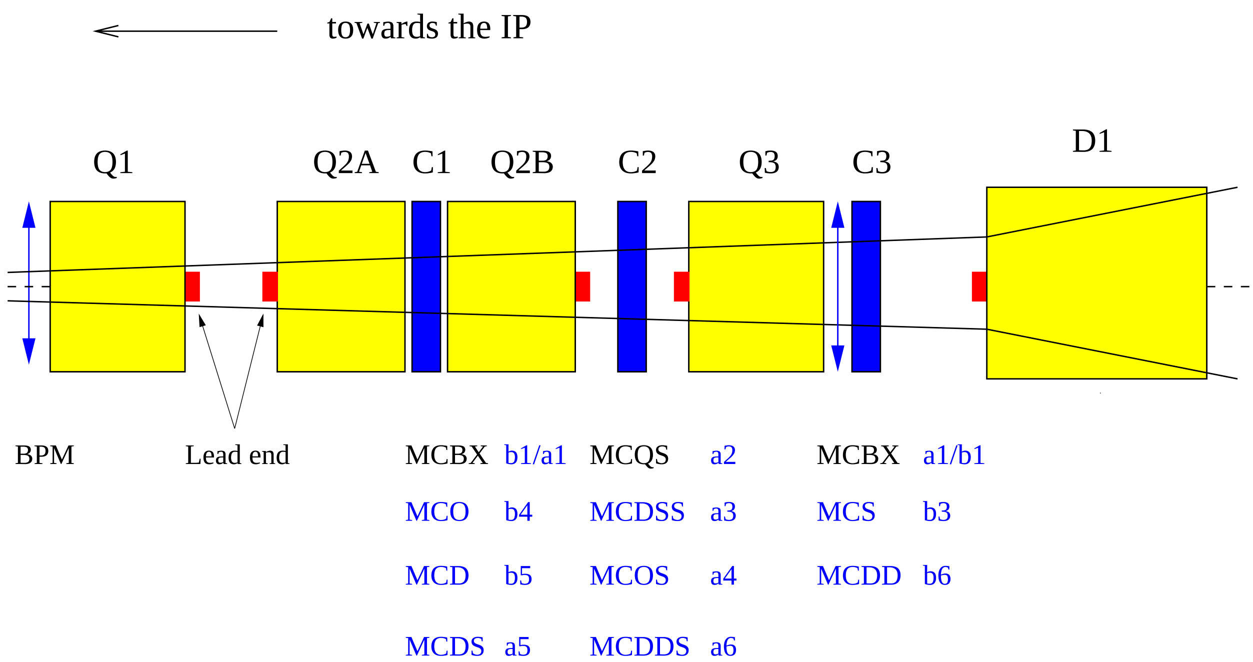

Figure 4.1: Schematic layout of the proposed LHC inner triplet region correction packages.

1. Corrector layout for all the 8 inner triplets of the 4 interaction region are identical. This allows constructional and operational flexibility, allowing sorting practice at late stage of construction.

2. Correctors at IP2 are mainly useful during the heavy ion operation when the β^* at IP2 is low. Correctors at IP2 and IP8 may also be used for global correction. Initially, one may choose not to power IP8 correctors until needed.

3. Each inner triplet contains 3 corrector packages: package C1 located between Q2A and Q2B contains five elements: b_1, a_1, b_4, b_5, and a_5; package C2 located between Q2B and Q3 contains four elements: a_2, a_3, a_4, and a_6; package C3 located between Q3 and D1 contains four elements: b_1, a_1, b_3, and b_6.

4. The strengths designed for each correction element is given in Table 1. Tentatively, the strengths for $n > 2$ multipoles are set here as twice the maximum strength used to locally compensate the lumped multipole errors of IR inner triplet quadrupoles built by FNAL (reference table version 2.0) and KEK (reference table version 3.0), cold D1 built by BNL (reference table version 1.0), and warm D1 (reference table version 1.0). (It was decided that these strength should be moderately chosen to maximize their effectiveness.)

5. The strength for $n = 1, 2$ elements are chosen to be as much as practically achievable.

6. Due to the strong b_6 correction needed, more space is reserved for its coil winding. Therefore, the package C3 that contains b_6 correction element has only two nonlinear ($n > 2$) layers, while both C1 and C2 have three nonlinear layers.

7. The design strength will be finalized by the end of year 1999 after further measurement is made on the IR magnet prototypes and after further feasibility study is performed on the corrector spool piece design.

Table 4.1: Proposed IR corrector package contents and strength. The strength is integrated over the length of the correction element normalized at the reference radius of 17 mm. Each inner IR triplet contains one of each type of correction element. The magnetic length of each element is 0.5 m.

n	b_n strength	a_n strength	Unit
1	3.0	3.0	[T]
2	–	0.51	[T]
3	0.029	0.068	[T]
4	0.027	0.068	[T]
5	0.012	0.012	[T]
6	0.025	0.010	[T]

4.2.2 Other Issues

Consensus is reached on other issues at the workshop pertaining to IR compensation and operation:

1. Updated error tables for IR inner triplet quadrupoles and warm D1 dipoles are needed before the end of September 1999 for the final determination of the IR corrector strength.

2. During the LHC operation, a "threshold" (e.g. 10% of the maximum strength) may be set for the powering of IR correctors below which correctors will not be activated.

3. The orientation of the IR inner triplet quadrupoles and cold D1 is shown in Fig. 1. This arrangement reduces the requirements on the IR corrector power supply strengths.

4. Magnetic tuning shims are not planned to be used for any LHC IR magnets due to mechanical difficulties and uncertainty in magnet multipole errors.

5. In general, sorting on IR magnets, correctors, and assemblies is encouraged during all stages of construction to optimize the performance and to minimize the corrector power supply requirements. Decision on IR corrector layout, however, is made independent of sorting consideration, since sorting is often constraint by real world issues like planning, assembly and installation schedule, as well as other more "fundamental" needs.

6. Options for global correction will be evaluated in the future to determine the corrector candidates and their locations, preferably in regions where the counter-rotating beams are separated.

7. Impacts from magnetic errors of multipole order higher than $n = 10$ appear to influence the dynamic aperture when the betatron amplitude is larger than 10σ in the presence of the design crossing angle. In practical operation, however, these higher order impacts are likely to be negligible due to their strong amplitude dependence, when the actual dynamic aperture is below 10σ.

8. Alignment of IR magnet coldmasses and assemblies is crucial to the collision performance. Reference misalignment tables will be established for the IR magnets and correctors.

4.3 Workshop on Instabilities of High Intensity Hadron Beams in Rings

T. Roser `roser@bnl.gov` Brookhaven National Laboratory

S.Y. Zhang syzhang@bnl.gov Brookhaven National Laboratory

Hadron beams with intensities exceeding present performance records are a central feature of many planned and proposed new facilities, such as SNS, ESS, JHF, NSP at JAERI, and the Muon-Collider proton driver, as well as of possible upgrades of existing facilities, such as the AGS as proton driver and CERN-PS as spallation driving facility. To examine the beam dynamics of these high intensity machines, the Workshop on Instabilities of High Intensity Hadron Beams in Rings has been held at Brookhaven National Laboratory from June 28 to July 1, 1999.

The workshop was devoted to:

1. Instability issues associated with high intensity beams.
2. Evaluate beam instabilities in the SNS storage ring, proton driver of a muon collider, and other hadron facilities.
3. Develop understanding of instability issues from comparison of theoretical models and machine measurements.

The workshop consisted of invited talks and three working groups on impedance issues, instability thresholds and damping, and the production of intense short bunches.

Although the main focus of the workshop was on high intensity hadron machines operating below or around transition energy, instability issues from other machines were also included.

Prior to the workshop, a set of topics was developed and circulated within the potential attendants of the workshop. During the workshop these topics were used as the guidance for the working group discussions. These workshop topics are:

1. Impedance sessions:
   - High intensity proton rings will require large apertures. Are impedance calculations reliable for large vacuum chambers, large steps, and large aperture kickers?
   - Is it beneficial to have the rf shielding or vacuum chamber follow the betatron envelope?
   - What is the impedance of ceramic chambers with or without metallic strips?
   - Is it beneficial to reduce the broad band impedance to a few Ohm for high intensity proton machines?
   - How do ferrite window frame, C frame, traveling wave, and stripline kickers compare in terms of impedance and engineering requirements?
   - Is it practical and/or useful to compensate the longitudinal space charge impedance?
   - What are the best methods to measure longitudinal and transverse impedances?
   - What are the key issues for the impedance budget for a) high power, b) high peak current (short bunch), c) very low loss hadron machines?
2. Instability sessions:
   - Stability against longitudinal microwave instability at high intensity: is a large momentum spread sufficient to stabilize the beam?

- Transverse stability at high intensity: what is the effect of space charge?
- What is an appropriate description of fast transverse instabilities for long bunches and large space charge tune shifts?
- What is an appropriate description of fast transverse instabilities for short bunches and very large space charge tune shifts?
- What is the effect of uneven longitudinal phase space distributions?
- Do space charge stabilized ”hot spots” exist and do they affect overall beam stability?
- e-p instability: How to identify it and how to cure it.

3. Short bunches session:

- For the muon collider proton driver, short bunches with 1 ns rms length and 5e13 protons at about 20 GeV are required. How can this be achieved and what techniques are most promising (operation near transition, bunch rotation, high rf voltage, ...)?
- What are the requirements on impedance?
- What are the relevant stability criteria and growth rates?
- What can be learned from the experience with short electron bunches?

Very active discussions have produced ample results, which are included in the summaries for the working groups. As expected, some issues in the topics have been resolved, but most of the issues are still lack of clear cut solutions. The discussions will continue, beyond the workshop time period.

The Organizing Committee of the workshop was:
J. Alonso(ORNL),
C. Ankenbrandt(Fermilab),
R. Cappi(CERN),
A. Chao(SLAC),
W. Chou(Fermilab),
R. Macek(LANL),
Y. Mori(KEK),
G. Rees(RAL),
T. Roser(Chair),
F. Ruggiero(CERN),
W.T. Weng(BNL),
S.Y. Zhang(Co-chair).
Mary Campbell served as the secretary of the workshop.

The active supports for the workshop given by the SNS project and the Brookhaven National Laboratory are greatly appreciated.

4.4 Japan-Italy Symposium on beam Physics Related to High Luminosity Meson Factories

K. Hirata Kohji.Hirata@kek.jp SKD, the Graduate University for Advanced Studies/KEK
M. Serio Mario.Serio@lnf.infn.it LNF-INFN

The symposium was held in LNF (Laboratori Nazionali di Frascati) on 16 and 17 December 1999. The focus was mainly on the operational experiences on DAΦNE and KEKB but some discussion on the higher luminosity was made, too. The symposium was planned by K. Hirata, based on the agreement on a collaboration between KEK and LNF. The travel was supported by Japan Society for the Promotion of Science.

The agreement was made beween G. Vignola(LNF) and K. Takata (KEK), directors of accelerator divisions in 1996. Not much was done, however, until this symposium. The symposium was also delayed a lot mainly because of the late approval of the budget. Originally, it was planned to be held before the operations of DAΦNE and KEKB. Nevertheless, it was a very useful and interesting symposium.

In the talks, the difficulties of the high luminosity machines are reviewed based on the operation experiences of DAΦNE and KEKB. Also, discussions on the higher luminosity were made. It was agreed that this symposium should be continued and Hirata and Serio will serve as coordinators.

The program and the slides shown in the symposium are available through the following site.

http://wwwsis.lnf.infn.it/jsps/

4.5 7-th Accelerator Physics Symposium in China

Z.Y. Guo guozy@alpha02.ihep.ac.cn IHEP, Beijing

The 7-th Accelerator Physics Symposium was held from 26 July to August 1, 1999 in a beautiful mountain area - Jingbo Lake of Heilongjiang Province in China sponsored by the Particle Accelerator Society of China (PASC). About 50 participants from universities and research laboratories across the country attended this symposium, in which 66 papers were accepted and 48 papers were reported. In the symposium, a method of Lie algebra for achromatic analysis, a method of normal form for beam-beam effect and a study on nonlinear effect for proton linac were introduced; the foreign particle instabilities in storage ring are discussed including the beam-photoelectron instability in Beijing Electron Positron Collider (BEPC), the ion effect in Hefei Synchrotron Radiation Light Source (HSRLS), the dust effect in BEPC and the beam life time issues in storage rings; some RF structure studies like CCDTL, back forward traveling wave and X-band for linac are described; the recent studies of beam-beam interaction in collider were presented; the beam phenomena in operation of BEPC, HSRSL and Langzhou Heavy Ion Facility are reviewed; the physics design of Shanghai Synchrotron Radiation Facility (SSRF), HSRLS upgrade plan and Langzhou heavy ion cooling ring project were reported. The advanced problems like physics of free electron laser, high intensity proton linac and plasma focus were touched in the symposium. It was proposed that the cooperation among the laboratories throughout the country should be promoted and a few mini workshop would be held in future.

Reported by Z.Y. Guo, Y.Z. Lin, and Z.P. Liu

4.6 Activities of the Neutrino Factory and Muon Collider Collaboration

Andrew M. Sessler amsessler@lbl.gov Lawrence Berkeley Laboratory

For a number of years the Muon Collider Collaboration has been working towards establishing the feasibility of a muon collider. Recently, as a result of the new results from Super K, which clearly indicate the existence of neutrino oscillations, and increased confidence in the production and manipulation of muon beams coming from the work of the last few years, the collaboration has considered the building of a storage ring as the first step towards a collider. Such a ring would be very interesting, for particle physics, in its own right, while being considerably easier to build than a collider. In light of this development, the Collaboration has re-named itself (as above; Muon Collaboration for short).

A muon storage ring (10-50 GeV) that can produce a directed beam of intense neutrinos (10^{20} -10^{21} per year) for both domestic and intercontinental experiments (base line of as much as 5,000 km). Such a device requires a powerful proton source (1-4 MW), muon capture, manipulation, cooling, acceleration, and storage. The beam dynamics issues are very extensive and the Muon Collaboration is desirous of new members.

Information about the Collaboration can be found at

http://www.cap.bnl.gov/mumu/

Two upcoming meetings may interest the reader. There is a Collaboration meeting planned for Catalina Island (near LA), May 17-19, 2000 and a Neutrino Factory Workshop, NuFACT00, Monterey, May 22-26, 2000. The NuFACT00 Workshop, chaired by Stan Wojcicki and Jonathan Wurtele, is the second in a series. It is not organized by the collaboration, and will be, as was the first workshop, held in Lyon last July, devoted to the physics (particle physics, detector physics, machine physics) of neutrino factories. Participants are welcome (links to the NuFACT00 workshop should be available soon at the url above).
Andrew M. Sessler
Jonathan Wurtele

4.7 Workshop on Very Rapid Cycling Acceleration with FFAG Synchrotrons (FFAG99)

Yoshiharu Mori Yoshiharu.Mori@kek.jp KEK

The workshop on very rapid cycling beam acceleration with FFAG synchrotrons (FFAG99) was held at KEK-Tsukuba from Dec. 6 to 8 in 1999 with more than 30 participants. The purposes of the workshop were, 1) to discuss its directions such as a proton driver for a muon collider, an accelerator driven system for nuclear energy, etc, 2) to discuss its direction such as a very rapid cycling acceleration for muon phase rotation and acceleration, 3) to establish design principles with modern accelerator technology such as a high gradient accelerating cavity, and 4) to study beams under extreme regime such as a high repetition and high intensity operation in highly non-linear magnetic field. The topics which have been covered in this workshop were including, proton driver, and spallation neutron sources for material sciences and accelerator driven system for nuclear energy such as a high current machine, accelerator at industrial scene including medical use with its very stable operation, energy breeder with its extreme high power efficiency, muon acceleration and storage ring, and neutrino factory as a versatile beam transport. As for FFAG machine designing, lattice design principle with modern concept for scaling and non-scaling FFAG, computational tools to track particles in a small machine, operational scenario aiming high current, pursuit of high power efficiency, a high gradient accelerating cavity, possible scheme for muon phase rotation, feasibility and problems for muon acceleration, development of very high field gradient RF cavity, and dynamic aperture have been discussed. Among them, intense discussions on the POP (proof-of-principle) FFAG synchrotron for proton acceleration (PoP FFAG), which is under development at KEK have been carried out. The next workshop (FFAG00) will be held also at Tsukuba in June, 2000.

Information about the FFAG study can be found at

`http://hadron.tanashi.kek.jp/FFAG/`

Yoshiharu Mori, Prof.

4.8 Beam Physics School in India

Srinivas Krishnagopal `skrishna@cat.ernet.in` India

The Fourth School on the Physics of Beams was held at the Centre for Advanced Technology (CAT), Indore, India, from 27 December 1999 to 7 January 2000. This was the fourth in a series of schools funded by the Department of Science and Technology (DST), with the aim of disseminating more widely in India, knowledge of, and interest in, beam physics.

The format of the School included core topics, that were covered in 4-5 lecture hours, and advanced topics that were in the form of 2 hour seminars. The School commenced with an overview of beam physics by Kohji Hirata. He gave a very good pep talk on why beam physics is an exciting field of research, particularly for young students, including those wanting to do theory. Core topics covered included: (i) introduction to accelerators and storage rings (by S. Krishnagopal, CAT); (ii) introduction to cyclotrons (V. S. Pandit, VECC, Calcutta); (iii) linear accelerators (R. G. Pillay, TIFR, Mumbai); (iv) nonlinear dynamics (A. Khare, IoP, Bhubaneshwar); (v) free-electron lasers (P. Jha, Lucknow University). Advanced topics covered included: (i) synchrotron radiation sources (G. Singh, CAT); (ii) applications of synchrotron radiation (R. V. Nandedkar, CAT); (iii) quantum aspects of beam physics (R. Jagannathan, IMSc, Chennai); (iv) overview of high-energy theory (G. Rajsekaran, IMSc, Chennai). We had planned have advanced lectures on laser-plasma acceleration, but unfortunately could not make it this year. Students were also briefed on the various accelerator labs. and projects in the country.

There were 28 students at the School, representing 14 universities and 3 national laboratories from around the country. One of the nice features of this School is that everything is done in the CAT guest-house, under one roof: the rooms, lecture hall, mess. Having everyone under one roof, all the time, makes for excellent interaction amongst the students, and between the students and the lecturers. This helped enormously in getting questions answered outside the class-room, and in discussing physics of all sorts. There was a one-hour tutorial session scheduled every day, but more useful were the many-hour tutorial sessions that ran most of the nights, often up to midnight. These were informal, and very productive.

As in the last School, there were also a few laboratory experiments, just to give the students a feel for the things they learnt in class. Three experiments were organized: (a) characterization and assembly of NdFeB magnets for an FEL undulator; (b) study of modes in RF structures using SUPERFISH; (c) characterization of a beam position monitor, as well as of a pulse-forming network.

The students were divided into four groups, and, along with a visit to the INDUS synchrotron source, the students were rotated amongst the four activities over four afternoons.

There were a number of social activities. A couple of dinners out, a visit (now becoming almost mandatory for the School) to a local Rajasthani theme park, which was hugely enjoyed, and a hiking trip in the nearby mountains, after which we also played a cricket match against the local talent (which we unfortunately lost).

The feedback received from the students at the end of the School was very positive. All felt that the School had been a good experience: they had enjoyed themselves and had learnt a bit about beam physics. Particularly appreciated were the laboratory sessions, where they got a real “feel” for beam physics, and the night tutorials, where they could discuss their doubts in a more informal atmosphere. About half the students expressed interest in doing a summer project in beam physics, and possibly taking up a career in beam physics. A number of them have applied for the Summer Research Programme that we conduct at CAT during the summer, where they will have a chance to do a two month project in beam physics.

This was the last School in the cycle of three funded by DST. However we have been strongly urged to continue the School, and approach DST for funding the next cycle of three Schools. This we will be doing shortly.

5.1 Problems of Electron Cooling of High Brightness Ion Beams

V. Parkhomchuk BINP, Novosibirsk, Russia
L. Hermansson
D. Reistad dag.reistad@tsl.uu.se TSL, Uppsala, Sweden

Electron cooling is used to increase the brightness of stored (anti)proton and ion beams by reducing their six-dimensional phase space volume. Some effects, which are limiting the attainable stored beam currents due to interaction between the stored beam and the cooling electron beam, have been observed in several currently operating ion storage rings with electron cooling systems. It seems likely that these effects occur due to the same, so-called "electron heating" phenomenon, which has been discussed with relation to the CELSIUS ring in Uppsala, Sweden. In this report we present some new experimental results and theoretical ideas of "electron heating" to stimulate a wider discussion on this interesting subject.

5.1.1 Observed Limitation of Ion Beam Intensity

Quick loss of ions from electron cooled beams just after injection was observed as soon as the electron cooler was turned on for the first time at CELSIUS in 1990. The effect was nicknamed "electron heating" [1]. Similar effects have been observed at the IUCF Cooler [2] and at COSY Julich [3]. All these cooler rings inject protons of 40 - 50 MeV. Lifetimes of only a few seconds are observed for 2 - 5 mA electron cooled proton beams of this energy. Without electron cooling the proton beam lifetime is $\tau_{no\ cooling}$ ~200 - 400 s, which is close to estimates based on multiple scattering of the protons on the residual gas in the vacuum chamber.

On the other hand, after injection and cooling in CELSIUS of a proton beam of very small current, the beam lifetime has been observed to be limited only by single scattering of the protons on the residual gas, and is several times larger than that, which is observed without electron cooling, due to multiple scattering of the beam particles (by the factor of ($\sim ln(1/\theta_{max,aperture})$)). For example, the lifetime of a 0.1 mA electron cooled proton beam at CELSIUS is about $\tau_{single\ scattering} \sim 1000$ s.

At CELSIUS, the diameter of the electron beam (20 mm) is often smaller than the uncooled stored beam size, particularly at the injection energy. It was an early idea that the observed short initial lifetime of electron cooled beams at CELSIUS was due to the non-linear electric field outside of electron beam and the weak cooling of protons with large betatron amplitudes. If however the diameter of the electron beam were determining the maximum betatron amplitude, which could be electron cooled at CELSIUS, then electron cooling would only work for particles with betatron amplitudes, which are less than A_c. This would correspond to a lifetime of the cooled beam of only

$$\tau_{singlescattering}\left(\frac{A_c}{A_{max}}\right)^2 = 0.02\tau_{nocooling}\ln\left(\frac{1}{\theta_{max}}\right) \sim 0.1\tau_{nocooling} \sim 20-40\mathrm{s}.$$

The observed good lifetimes of low-intensity cooled beams show absolutely that electron cooling works over the whole aperture.

It seems that coherent interaction of the intensive ion beam with the electron beam is a more realistic explanation [4]. Experiments with detuned cooling, in which the electron energy has been set far away from the correct energy for cooling, have shown that the losses take place without cooling too. This means that the simple idea that losses occur because after cooling the ion beam gets too low momentum spread resulting in the development of coherent instability does not explain the observed effects. Only the presence of the electron beam on the ion beam orbit is sufficient to create the problem.

Fig. 5.1 shows losses during accumulation of 180 MeV protons at CELSIUS. The reader can see that the proton current has a threshold value near 2 mA. For beam currents exceeding 2 mA the losses increase very rapidly and the maximum accumulated current of 3 - 5 mA corresponds to equilibrium between accumulation and loss rates.

5.1.2 Simplified Theoretical Model of Heating

Let us assume that a cloud of ions is performing coherent oscillations inside the ion beam. The oscillation energy is transferred between kinetic energy of the moving ion cloud and potential energy from the electric field of the perturbed space charge of the ion beam. The plasma oscillation energy can be written

$$W = \left(\frac{MV^2}{2} + \frac{M\omega_p^2 X^2}{2} \right) * N_i \qquad (5.1)$$

where $\omega_p = \sqrt{n_i (Ze)^2/\epsilon_0 M}$ is the plasma frequency of the ion cloud, X is the displacement of the cloud from its equilibrium position, V is its velocity, M is the ion mass, N_i the number of ions in the cloud, n_i is the ion density, and ϵ_0 the permittivity of free space. Outside the cooling section the ion cloud performs such plasma oscillations keeping W constant.

During the motion inside the electron beam, the electric field of the ion cloud is transiently neutralized by the space charge of the electron beam. This is provided that $\tau\omega_e >> 1$ where τ is the ion interaction time with the cooling electron beam and $\omega_e = \sqrt{n_e e^2/\epsilon_0 m}$ is the electron plasma frequency (n_e is the electron density and m is the mass of the electron). This condition means that shifts of electrons quickly neutralize the electric field, which is produced by the ion beam fluctuation (Debye screening).

The acceleration of the electrons to the velocity of the ion cloud takes some energy away from the oscillation, and thus has a damping effect:

$$\left(\frac{\delta W}{N_i} \right)_{damping} = -g \cdot Z \frac{mV^2}{2}. \qquad (5.2)$$

Here, g is a numerical factor reflecting delicate details of the interaction kinetics. For pure non-elastic interaction $g = 1$, for elastic impact g may be up to 4.

The neutralization has however also an antidamping effect on the plasma oscillation of the ion cloud. This is because the moving ion cloud does not see the restoring force of the plasma oscillation during the interval while it is neutralized by the electrons, so it drifts to an (on average) larger amplitude, see fig. 5.2.

$$\left(\frac{\delta W}{N_i} \right)_{antidamping} = \frac{M\omega_p^2}{2} \Delta X^2 \qquad (5.3)$$

Here, $\Delta X = V * \tau$ is the amplitude of the displacement developed during the time of flight of the cooling section τ. It is easy to see that the antidamping ("heating") overcomes the damping if

$$\omega_p^2 > g \frac{Zm}{M\tau^2}. \qquad (5.4)$$

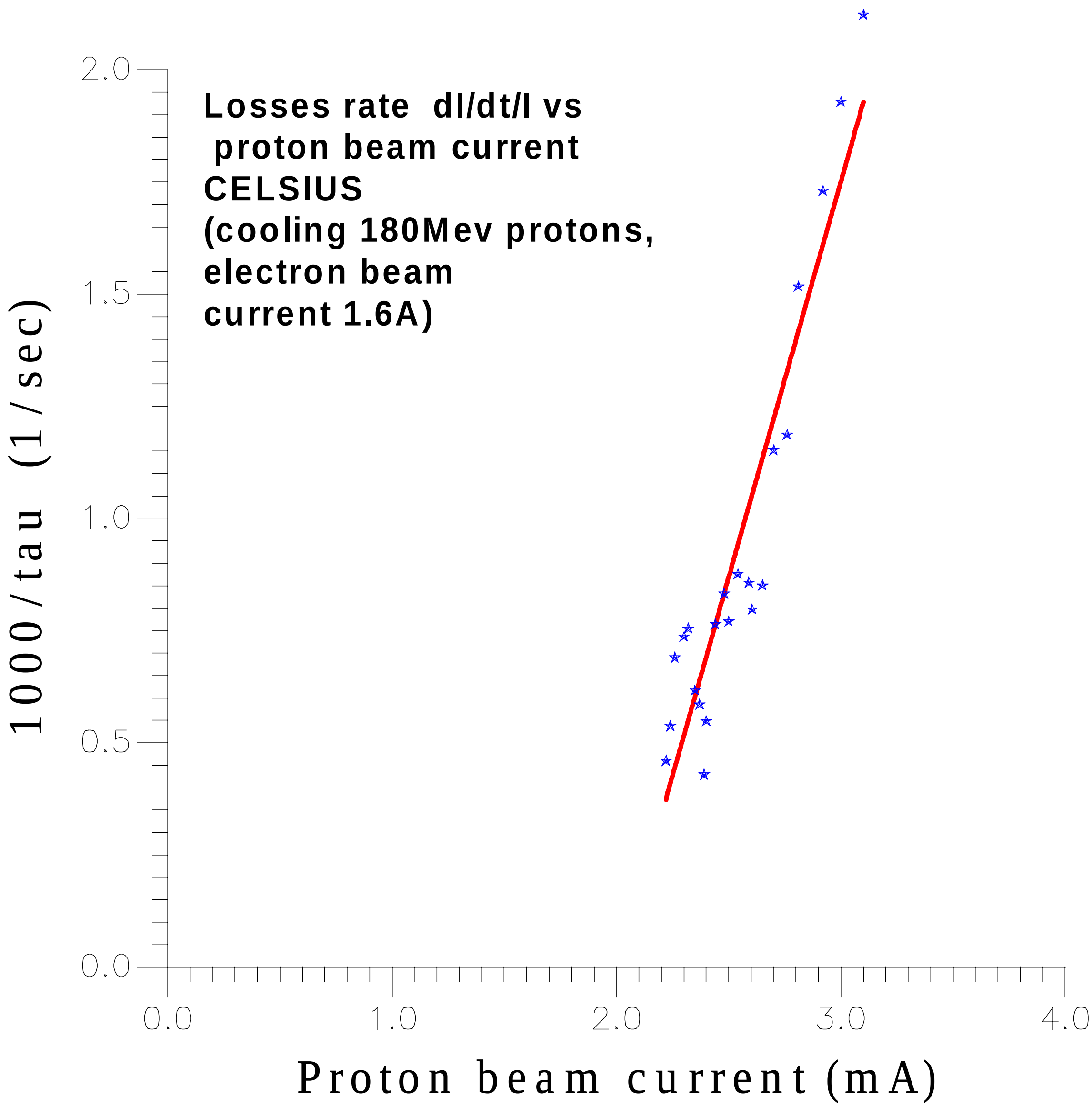

Figure 5.1: The losses of proton beam vs. proton beam current.

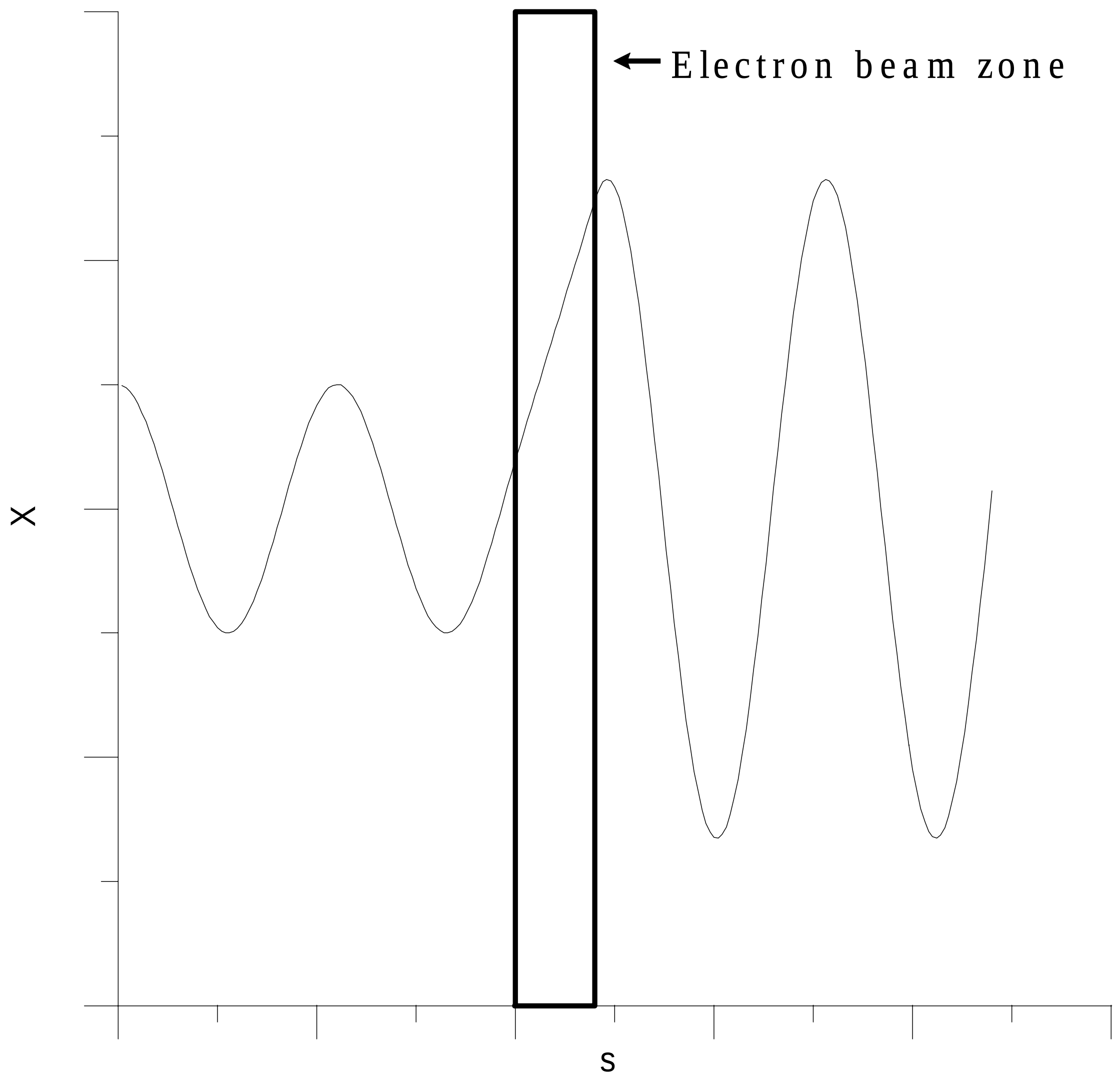

Figure 5.2: Simplified model of “electron heating”. The beam travels from the left to the right in the figure. A cloud of ions performs transverse or longitudinal plasma oscillations. Inside the electron beam, the restoring force disappears because the electrical fields are neutralized by the electrons, thus the ion cloud drifts to a larger plasma oscillation amplitude.

Or, if we define the frequency of electron oscillations in the ion beam the space charge field $\omega_{ei} = \sqrt{e^2 Z n_i / \epsilon_0 m}$, the condition for stability gets the following very nice form:

$$\tau^2 \omega_{ei}^2 < g. \tag{5.5}$$

It means that if the phase shift over the cooling region of the electron plasma oscillations in the ion beam space charge field becomes larger than $\sqrt{g}$ the antidamping overcomes damping and instead of cooling we will see heating of intensive ion beam!

5.1.3 Conclusions

The above treatment of electron heating is a sketch, made to indicate in which direction the explanation for electron heating has to be searched. As the model is presented here, the phenomenon should saturate as soon as the condition $\tau\omega_e >> 1$ is met; a further increase of the electron current should not make things worse. This is contrary to experience at CELSIUS, which is that the ion beam lifetime (with detuned electron energy) varies as I_e^{-1}. This will be addressed in a more complete model, which will include a full treatment of the electron as well as the ion oscillations in the perturbed space charge field of both beams. The phenomenon of electron heating is similar to beam-beam effects in colliders. As in colliders, the condition for stability is to have a small enough plasma oscillation phase shift over the interaction region (eq. 5). If the model of electron heating as described here turns out to be correct, then it is obvious from eq. 5 that the length of electron cooling systems should not be made too great. It is better to make electron cooling systems short, and to compensate their short length with a higher electron current.

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5.2 Accelerator Physics Issues of a 5 TeV Wakefield Collider

C. Chiu chiu@physics.utexas.edu UT-Austin, Dept of Physics, Institute of Fusion Studies

S. Cheshkov cheshkov@physics.utexas.edu UT-Austin, Dept of Physics, Institute of Fusion Studies

T. Tajima tajima1@llnl.gov UT-Austin, Dept of Physics
Inst of Fusion Studies/LLNL

In pursuit of the next energy front, a laser-based wakefield linear collider at 5 TeV has been considered for which many wakefield units are needed to reach the desired energy. Also the collider demands an extremely small emittance and thus extremely precise beam handling. Based on computer simulations of a multistage system which includes magnets and jitters, we continue the ongoing investigation of the sensitivity and the resilience of the system to non-ideal elements. We have found that for a fixed final energy of the beam, the final emittance is inversely proportional to the total number of stages. Thus it is desirable to work with superunits, where each superunit consists of closely spaced short tubes and there is a large gap between each pair of the adjacent superunits. We present an illustrative case with the Gaussian width of the transverse jitters $\sigma_D = 0.1\mu$ where the beam emittance is under control.

5.2.1 A Collider Model of LWFA with Magnets

In pursuit of the next energy front at 5 TeV, a laser-based wakefield linear collider has been considered [1, 2, 3]. In order to evaluate the potentiality of this approach and to identify the crucial physical and technological problems associated with this, a systems approach through the accelerator map has been investigated. This communication gives a brief report of our recent results. We defer to a more extensive treatment of our work to a future publication[4].

Since it is necessary to stage many wakefield units in order to reach the desired energy, such an accelerator system is composed of many stages. The properties of the accelerator depend on how this works as a system. In particular, as the collider demands extremely high luminosity consistent with its high energy, it also demands extremely small emittance and thus extremely precise beam handling. The analysis of beam dynamics in the multistage collider system that contains jitters and noises is thus needed to investigate the sensitivity and resilience of the system to the non-ideal elements.

There are mainly two approaches in generating laser-plasma wakefields. First the creation of the wakefield by passing a laser pulse through a uniform plasma. The other is to have the wakefield created within a plasma channel which is imbedded in a uniform plasma medium (see for example: Ref. [5]). The latter approach is much difficult to achieve in the laboratory. There has been active and exciting research in this direction. Nevertheless it is still in its early stage of the development. See for example Ref. [6] and references cited therein.

From the theoretical point of view, using plasma channels may substantially improve the resilience of accelerator system [2]. Our present report will focus on the first approach using the uniform plasma medium. We defer discussions on the plasma channel approach again to Ref. [4].

5.2.1.1 Longitudinal motion of beam particles

Wakefield acceleration: Consider the passage of a laser pulse through a uniform plasma medium along the z-direction. There are wakefield plasma waves trailing behind the pulse. For the case where the laser pulse has some specified shape and its length is about the wavelength of the plasma wave, trailing wakefields may be described by: [7]

$$E_z \propto -\cos\zeta \;\text{ and }\; E_x \propto +x\sin\zeta, \text{ with } \zeta = k_p(z - v_p t), \tag{5.6}$$

where v_p and k_p are the speed and the wave number of the plasma waves. Neglecting correlation between the x- and the y-directions, we work with one of the transverse components, which we have chosen to be the x-component. Consider a beam electron placed in the quarter-wave region:

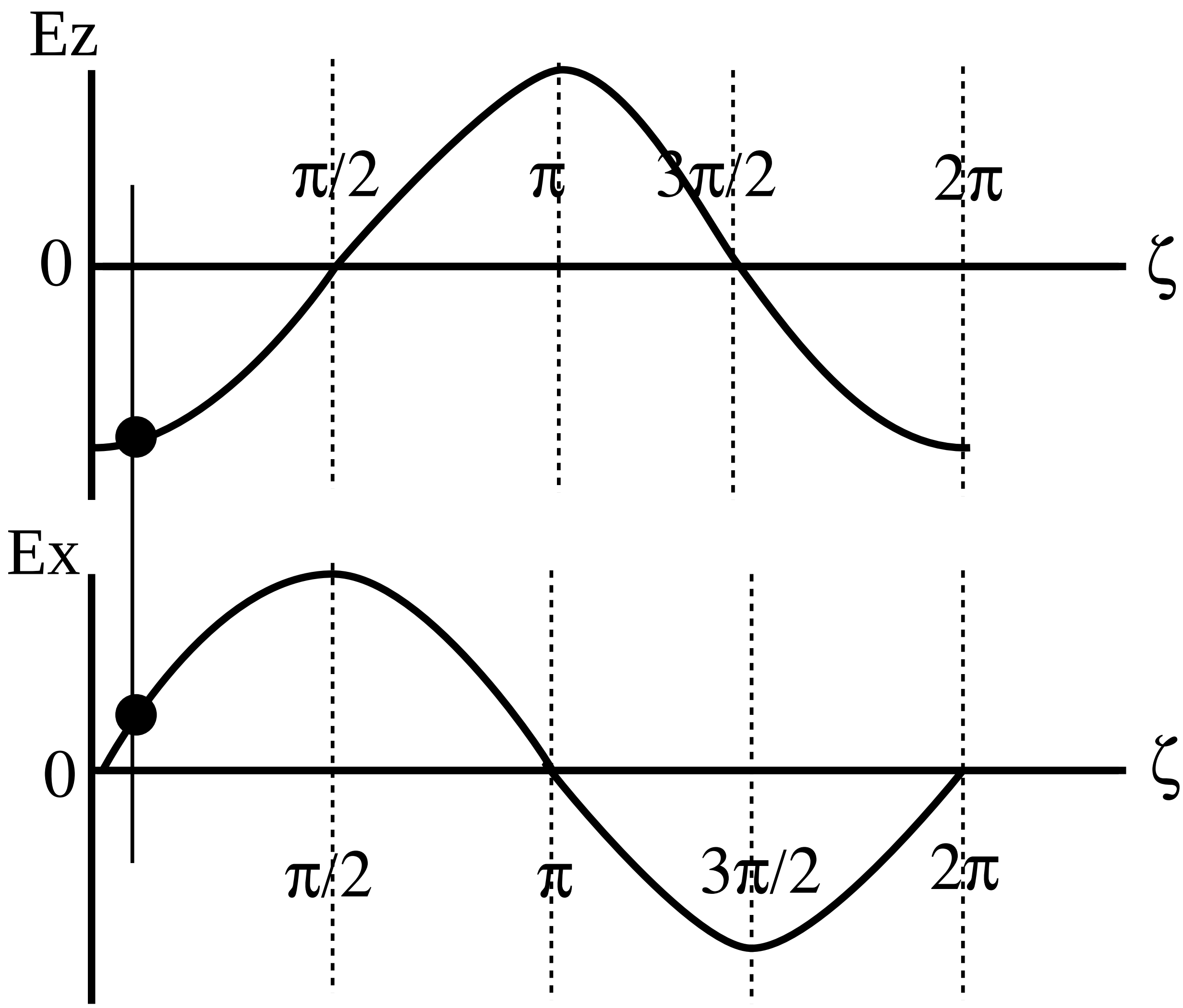

Figure 5.3: Sinusoidal oscillations of the longitudinal and the transverse components of wakefield as a function of the phase angle ζ.

$0 < \zeta < \pi/2$, with a positive x-coordinate. The situation is shown in Fig. 5.3. Since the electron is negatively charged, there will be a force to accelerate it in the positive z-direction and also a force acting on it pointing toward the origin, which focuses the beam in the transverse direction.

Longitudinal phases: The accelerator consists of a series of tubes aligned along the z-axis see Fig. 5.4. First consider the acceleration within one tube. In order to accelerate beam electrons within the quarter-wave region, the longitudinal spread of the beam must be small compared to a quarter of the wavelength, which we shall assume is the case. The variables z and t in eq.(5.6) may be defined with respect to any reference point fixed in space and time. For the time being we assume that the longitudinal coordinate of the tube is fixed in the laboratory frame. Let the variable z be defined with respect to the left-end of the tube, and the variable t defined with respect to the time when the center of the beam passes by the same left-end. The phase of the traveling plasma wave within the tube can now be written as

$$\Psi_p = \Psi_s + k_p(z - v_p t), \tag{5.7}$$

where Ψ_s is the phase of the plasma wave at $z = 0, \text{and}\, t = 0$. Since the beam electrons are moving with essentially the speed of light, the coordinate of the center of the beam relative to the

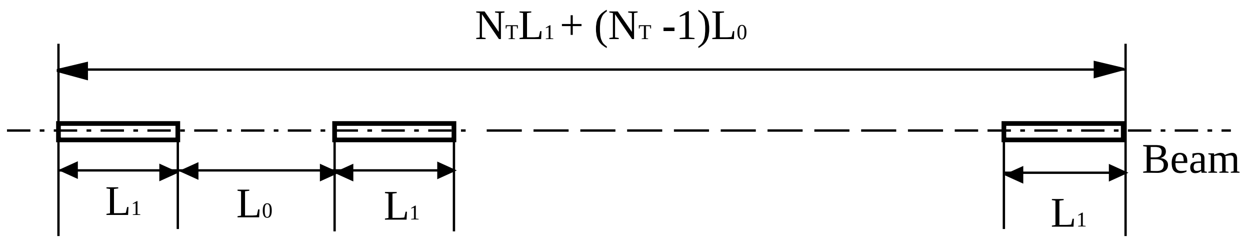

Figure 5.4: The layout of the aligned tubes in a laser-wakefield accelerator.

left end is given by z=ct. At z and t, the phase of the center of the beam is given by

$$\Psi_c = \Psi_s + k_p(z_c - v_p t) = \Psi_s + k_p(c - v_p)t. \tag{5.8}$$

Thus relative to the plasma wave, the electron's phase slips forward. Accelerating through a full tube-length L_1, the electron's phase slips by

$$\Delta = \Psi_c(z = L_1, t = L_1/c) - \Psi_s = k_p(c - v_p)L_1/c \approx \frac{k_p L_1}{2\gamma_p^2} \tag{5.9}$$

To stay within the quarter-wave interval, for $\Psi_s = 0$, the maximum value of Δ is $\pi/2$.

Longitudinal Lorentz factors: We take a closer look at the quantity γ_p. Consider the passage of a photon with a frequency ω and the wave number k through a plasma medium which has a plasma frequency ω_p. There is the following well known dispersion relation

$$\omega^2 = \omega_p^2 + k^2 c^2. \tag{5.10}$$

The photon in the plasma medium may be regarded as a dressed photon [8], which has a rest mass $m_\gamma = h\omega_p/(2\pi c^2)$, where h is the Planck constant. Within the plasma medium, the energy-momentum relation is given by $E_\gamma^2 = m_\gamma^2 c^4 + p_\gamma^2 c^2$ with $E_\gamma = \omega h/2\pi$ and $p_\gamma = kh/2\pi$. The velocity of the dressed photon is given by $v = p_\gamma c/E_\gamma = kc^2/\omega$. Extending to the case of a laser pulse, v is to be replaced by the group velocity of the pulse v_g, and the corresponding Lorenz factor, which is the ratio of the total energy to the rest energy, is given by $\gamma_g = [1 - (v_g/c)^2]^{-1/2} = [1 - (kc/\omega)^2]^{-1/2} = \omega/\omega_p$. According to the laser-wakefield wave theory, v_p, the propagating speed of the wakefield is identical to the group velocity of the laser-pulse, or

$$\gamma_p = \gamma_g = \frac{\omega}{\omega_p}. \tag{5.11}$$

Longitudinal equation of motion: For the longitudinal motion of accelerating electrons, there are two independent variables for each electron, which are its Lorenz factor γ and its phase Ψ. Based on the Lorenz force and the ponderomotive force created by the laser pulse, following the notions of Ref. [1], the equations of motion are given by

$$\frac{d\gamma}{dz} \approx k_p \Phi_0 \cos\Psi, \text{ and } \frac{d\Psi}{dz} \approx k_p\left(1 - \frac{\beta_p}{\beta}\right) \approx \frac{k_p}{2\gamma_p^2}\,, \tag{5.12}$$

where $\Phi_0 = \frac{\pi a_0^2}{4}$, which is proportional to the intensity of the laser pulse with $a_0 = eA/(mc^2)$ being the normalized vector potential.

Energy gain and its maximum value: Upon integrating over z, the increase in the Lorenz factor after traversing through one tube is given by:

$$\Delta\gamma = \Delta\gamma_{max}\left[sin(\Psi_s + \Delta) - sin\Psi_s\right], \text{ with } \Delta\gamma_{max} = 2\gamma_p^2\Phi_0. \tag{5.13}$$

The parameter values assumed are as follows..

- For the laser pulse, we take $a_0 = 0.5$, which gives $\Phi_0 = 0.2$.
- The plasma density $n = 10^{17}\text{cm}^{-3}$. This gives the plasma frequency $\omega_p = [ne^2/(\epsilon_0 m)]^{1/2} = 1.8 \times 10^{13} sec^{-1}$, the wave number of the plasma waves $k_p = \omega_p/v_p \approx \omega_p/c \approx 6 \times 10^4\ \text{m}^{-1}$, and the corresponding wavelength $\lambda_p \approx 100\mu$.
- We take $\gamma_p = 100$. From eq.(5.11), the corresponding laser frequency $\omega = \gamma_p\omega_p = 1.8 \times 10^{15} Hz$, which has a period of about 3 fsec and a wavelength $\lambda = \frac{2\pi c}{\omega} \approx 1\mu$.
- Consider the case where $\Psi_s = 0$ and where the phase slippage is maximum. This leads to $\Delta_{max} = \Psi - \Psi_p = \pi/2$. From eq.(5.9) the corresponding tube-length is given by

$$L_1 = \frac{2\gamma_p^2\Delta_{max}}{k_p} = \frac{\pi\gamma_p^2}{k_p} \approx 0.5m. \tag{5.14}$$

  After passing through one tube, from eq.(5.13) the corresponding energy gain by an electron (having the rest mass energy $mc^2 \approx 0.5MeV$) is given by

$$\Delta\gamma_{max}mc^2 = 2\gamma_p^2\Phi_0 mc^2 \approx 2\ \text{GeV}. \tag{5.15}$$

Initial conditions: We now turn to a multistage system. We assume initially there are spreads both in the longitudinal coordinate or the initial longitudinal phase Ψ, and in the energy or the initial Lorenz factor γ. Denote the initial phase of the plasma wave at the moment when the center of the beam passes by the left end of the tube by Ψ_s, and the initial phase of each accelerating beam particle defined relative to the center of the beam, by $\delta\Psi$. (Here the particle label is suppressed.) The latter is a stochastic number generated by the computer based on a normalized Gaussian distribution with a width σ_Ψ. The spread in the Lorenz factor of beam particles $\delta\gamma$ (again the particle label is suppressed) is also assumed to be Gaussian distributed, which centers at the initial mean energy, or the initial mean Lorentz factor γ and has a width σ_γ.

Longitudinal recurrence relations: Denote $\delta\Psi_n$ and $\delta\gamma_n$ to be the spreads of each beam electron (again the particle label is suppressed). Their evolution through the multistage system can now be obtained through following two recurrence relations. From the nth stage to the $n+1$th stage, they are given by

$$\delta\Psi_{n+1} = \delta\Psi_n, \tag{5.16}$$

$$\delta\gamma_{n+1} = \Delta\gamma_{max}\left[\cos\left(\Psi_s + \Delta\right) - \cos\Psi_s\right]\delta\Psi_n + \delta\gamma_n \tag{5.17}$$

So far we assume the longitudinal coordinate of the tube is rigidly fixed, which implies that the longitudinal initial phase Ψ_s for each tube is fixed at a known value. If there is a longitudinal jitter, one may replace Ψ_s by $\Psi_{s0} + \delta\Psi_s$, where Ψ_{s0} may be predetermined and $\delta\Psi_s$ varies from stage to stage. Since the uncertainty due to the latter does not accumulate from one stage to the next, the error involved here is not important and has been neglected in the present work.

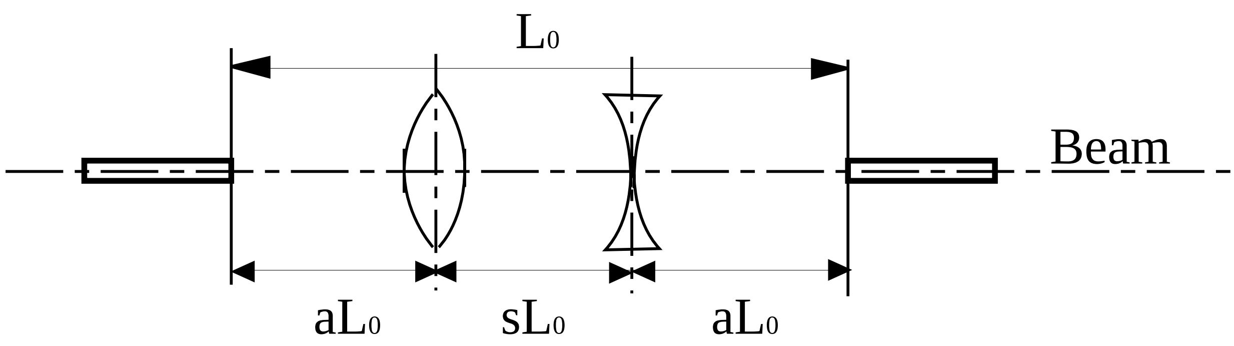

Figure 5.5: The layout of a quadrupole doublet within a gap.

5.2.1.2 Transverse motion of beam particles

Transverse equations of motion: In the transverse direction, at each stage, the equation of motion for each beam particle is given by

$$x'' \equiv \frac{dx^2}{dz^2} = \frac{F_x}{mc^2} = -\Omega^2 x,\ \ \Omega = \sqrt{\frac{\Phi_0}{\gamma}\frac{2}{k_p r_s}}\sqrt{sin\Psi} \tag{5.18}$$

where r_s is the radius of the mean cross section of the beam, and γ the beam particle energy. The quantity Ψ is the phase of the beam particle, which may be written as $\Psi = \Psi_c + \delta\Psi$, with Ψ_c being the phase of the center of the beam defined in eq.(5.8). As the electron being accelerated within the tube, the phase of the center of the accelerating beam electron varies from Ψ_s to $\Psi_s + \Delta$. Averaging over the full tube-length, in Ref. [1] the approximation $< \sin\Psi > \approx (1 + \delta\Psi)/4$ was assumed. We adopt the same approximation form in the present work [9].

Transverse jitters and equations of motion: We assume there are jitters in the transverse directions. At each stage, a random number is generated based on a normalized Gaussian distribution with a width σ_D. Denote the jitter displacement in the x-direction by D. This leads to the following recurrence relation,

$$\begin{pmatrix} x_{n+1} \\ x'_{n+1} \end{pmatrix} = M_{wk} M_{gap} \begin{pmatrix} x_n - D \\ x'_n \end{pmatrix} + \begin{pmatrix} D \\ 0 \end{pmatrix} \tag{5.19}$$

with

$$M_{wk} = \begin{bmatrix} \cos\theta & \frac{1}{\Omega}\sin\theta \\ -\Omega\sin\theta & \cos\theta \end{bmatrix},\ \theta = \Omega\tau,\ \tau = \frac{\Delta}{\omega_s},\ \omega_s = \frac{1}{2\gamma_p^2}. \tag{5.20}$$

Taking into account a free drift over length of L_0,

$$M_{gap} = S(L) = \begin{bmatrix} 1 & L_0 \\ 0 & 1 \end{bmatrix}. \tag{5.21}$$

Magnets: The layout with magnets is schematically illustrated in Fig. 5.5. Within the gap there is a pair of quadrupoles separated by a distance sL_0. And the distance between each of the magnets to the corresponding end of the tube is given by aL_0. For the matrix M_{gap}, the following replacement is made to account for the presence of the magnets:

$$M_{gap} \to S(aL_0)M(f)S(sL_0)M(-f)S(aL_0) = \begin{bmatrix} 1 + \frac{s}{b} - \frac{as}{b^2} & [1 - \frac{a^2 s}{b^2}]L_0 \\ -\frac{s}{b^2 L_0} & 1 - \frac{s}{b} - \frac{as}{b^2} \end{bmatrix} \tag{5.22}$$

with $b = f/L_0$, where f is the magnitude of the focal length which is assumed to be the same for both the convergent and the divergent quadrupoles.

5.2.2 Degradation of Emittance due to Jitters for 1250- and 5000-Stages

Our present investigation is mainly on the issue of emittance degradation due to the positional jitter of either the driver (laser) or the accelerating medium (the tube and/or the plasma). A systems code of a multistage collider is utilized to investigate the effect on the emittance. The emittance, to be more specific, the transverse emittance in the x-direction is defined by

$$\epsilon_x = \sqrt{(\sigma_x \sigma_{x'})^2 - c_{xx'}^2}, \tag{5.23}$$

$$\text{where } \sigma_i = \sqrt{< i^2 > - < i >^2} \text{ and } c_{ij} =< ij > - < i >< j > . \tag{5.24}$$

The initial beam energy is assumed to be at 0.5 TeV or $\gamma = 10^6$, and ϵ_x, the initial emittance in the x-direction at 2.2nm. The emittance of all the results shown in this work is that in the x-direction.

Degradation of emittance due to jitters Fig. 5.6 shows the growth of emittance ϵ_x as the beam is traversing through the system at 2.5 TeV.

- The 1250 stage case: Here the energy gain per tube is 2GeV. The corresponding slipping phase (see eq. (5.9) is at its maximum value $\frac{\pi}{2}$. As shown in the figure,

* Curve I is for the case where jitters are absent. Here the emittance stays at initial value of 2.2nm throughout the entire process.

* Curve I' is for the case with jitters where the Gaussian width $\sigma_D = 0.5\mu$. Notice the final emittance is increased from its initial value by about a factor of 7000.

- The 5000 stage case: Here the energy gain per tube is 0.5 GeV, so the final energy of the beam is at again 2.5 TeV. The situation is also illustrated in Fig. 5.6.

* Curve II is for the case when jitters are absent. As for curve I, emittance here again stays the same throughout the process. So curve II is essentially the same as curve I.

* Curve II' is when there are jitters with a Gaussian width $\sigma_D = 0.5\mu$ jitters. Here the final emittance grows by about a factor of 400.

The emittance curves for the two cases considered with the magnetic fields properly adjusted are given by I" and II". Here magnets help to reduce the final emittance by about a factor of 4.

A salient feature: The two curves I' and II' displayed in Fig. 5.6 have illustrated the following important point. Consider the situation where the final beam energy is fixed, one may improve the emittance control of the system by increasing the number of units.

5.2.3 Emittance vs Total Number of Stages, N_T

Because the emittance degradation may be ameliorated with shorter stage-length (and thus more stages), it is of interest to see cases of very large number of stages. We have made a systematic study of the dependence of final emittance of the beam particles on the total number of stages, ranging from 1.25K to 500K at the final beam energy of 2.5 TeV. The situation is illustrated in Fig. 5.7. Consider first Fig. 5.7a, the top plot. Here the gap width is set to be 10 times the tube-length.

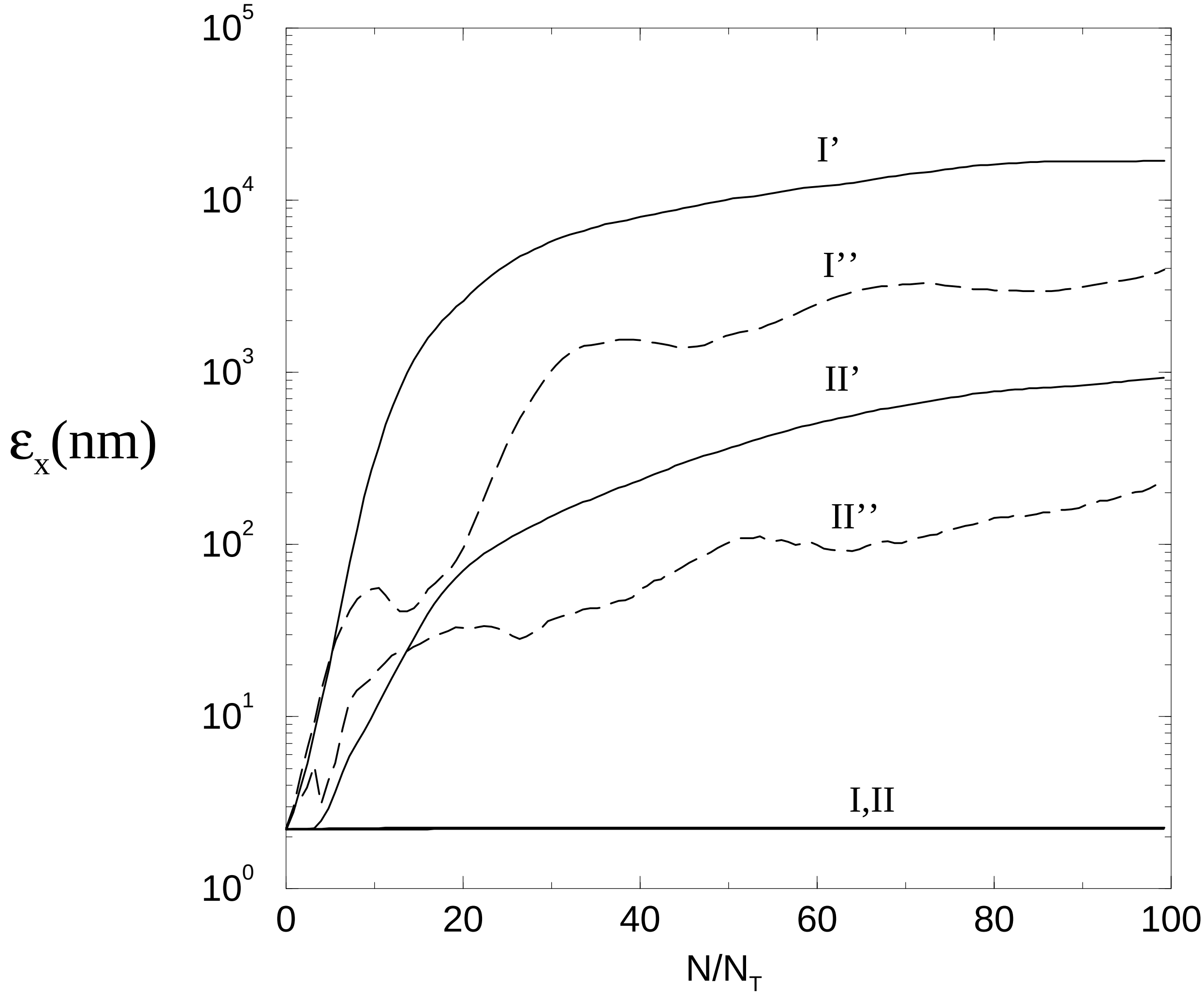

Figure 5.6: Emittance versus the percentage of the total stages traversed at 2.5 TeV

• Configuration one with 1250 stages. I: No jitters; I': $\sigma_D = 0.5\mu$ and $B = 0$ I'':$\sigma_D = 0.5\mu$ and B adjusted.

• Configuration two with 5000 stages. II: No jitters; II': $\sigma_D = 0.5\mu$ and $B = 0$ II'':$\sigma_D = 0.5\mu$ and B adjusted.

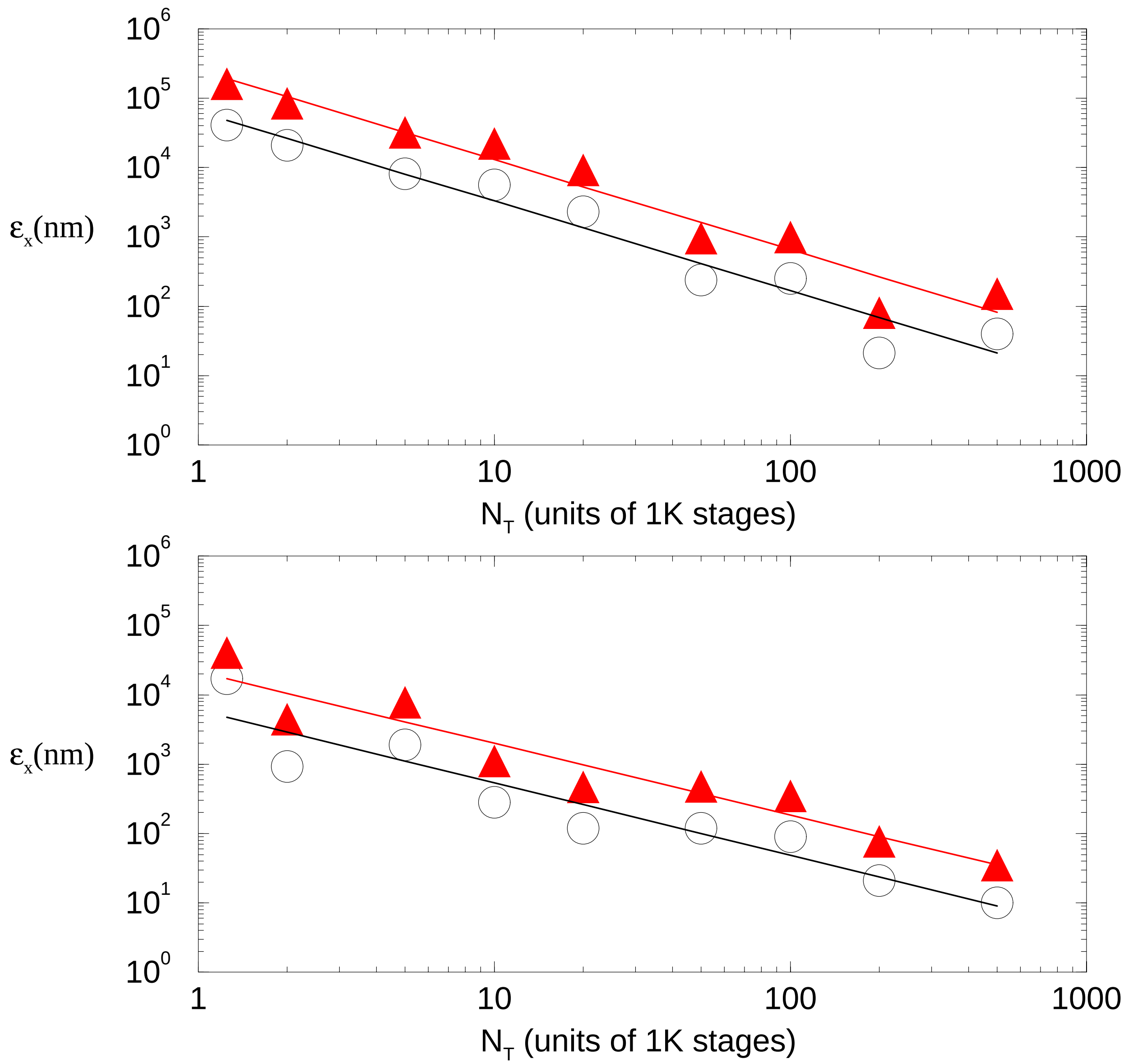

Figure 5.7: Emittance versus the total number of stages N_T at 2.5 TeV.
• a. Gap: $L_0 = 10L_1$, Jitters: $\sigma_D = 1\mu$ (triangles), $\sigma_D = 0.5\mu$ (circles).
• b. Gap $L_0 = L_1$, Jitters: $\sigma_D = 1\mu$ (triangles), $\sigma_D = 0.5\mu$ (circles).

- The triangles in this plot represent the case, where the jitter parameter $\sigma_D = 1\mu$. The plot is emittance versus the total number of stages, N_T. Notice that it is a log-log plot. The points are approximately along a straight line.
- The circles in the top plot are for the case where the jitters are reduced to $\sigma_D = 0.5\mu$. Here the emittance is lowered. The linear behavior and the slope are about the same as the case of the triangles.

For both cases considered, the empirical relation,

$$\epsilon_x \propto \frac{1}{N_T} \tag{5.25}$$

is approximately satisfied.

Fig. 5.7b is for the configuration where the gap-width equals the tube-length. Again the cases with $\sigma_D = 1\mu$ and $\sigma_D = 0.5\mu$ are included. Comparing to Fig. 5.7a, one sees that the over-all linear behavior is maintained. Notice the trend is that as the gap-width is reduced the final-emittance is reduced. Here the reduction factor is about 8.

Origin of the $1/N_T$ dependence: One may arrive at the $1/N_T$ dependence based on a random walk picture together with a plausible assumption. Here is the reasoning. The transverse emittance of interest is proportional to the mean area of the phase space, which is the space: x-p_x. Consider doing a random walk along the x-direction. Here the step-size is kept fixed and each step can either be positive or negative. After N_T steps, the mean displacement will be given by

$$\Delta x \propto \sqrt{N_T} \times stepsize \tag{5.26}$$

The amount of the energy gain as the beam particle traverses through the accelerator system is proportional to the total length of all the tubes of the system. Denote this total length by L_T. Since in the present work the total energy gain is fixed, so total length is a constant, i.e. $L_T = N_T L_1 = constant$. This implies that the length of one single tube is inversely proportional to the total number N_T. Now we make the plausible assumption that the random walk step-size in the x-direction is proportional to the tube length, L_1. (This could be the case, for instance, if the stepsize is correlated to the betatron phase space rotation. We will defer the investigation on this point to the future.) This assumption leads to

$$stepsize \propto L_1 = \frac{L_T}{N_T} \approx \frac{const}{N_T} \tag{5.27}$$

Equations (5.26) and (5.27) together imply that Δx is proportional to $\frac{1}{\sqrt{N_T}}$. Similarly assuming for one stage, the jitter in p_x is proportional to L_1, one expects that Δp_x should also be proportional to $\frac{1}{\sqrt{N_T}}$, in turn the inverse law for the final emittance, i.e. $\epsilon_x \propto \Delta x \Delta p_x \propto 1/N_T$.

Intermediate emittance vs percentage of system traversed: Now let us keep N_T fixed. Using the same random walk interpretation, after passing through N stages, where $N < N_T$, one expects $\Delta x \propto \sqrt{N}$ and $\Delta p_x \propto \sqrt{N}$. So

$$\epsilon_x \propto \sqrt{N} \times \sqrt{N} = N \tag{5.28}$$

Fig. 5.8 are plots of the intermediate emittance as a function of the fraction of the total system traversed. It is for the setup where the total number of stages $N_T = 50K$. The curves illustrate the situations with and without the inclusion of a spread in energy and also a spread in the longitudinal phase. The top curve corresponds to the case where both spreads are included. The approximate linear behavior of the top curve supports the present prediction.

5.2.4 Super-Units and Magnets

With the scenario of having a very large number of stages, in each acceleration stage particles do not experience a large phase slippage. Thus it allows a second or more stages without adjusting the phase of the laser pulse. This permits to introduce superunits. Between two such superunits, there is the need for injecting fresh laser and resynchronization of the beam and the laser, and placing magnets over a certain period of length in order to maintain the quality of the beam. They all require large gaps, say, of the order of 1m. So we consider a mixed configuration, where there are super-units with short tubes closely spaced interspersed by large gaps. We present the following illustrative system:

- Total energy: 2.5 TeV, which is used as each of the two arms of 5 TeV collider.
- Total number of superunits (SU): 500
- One super-unit (SU):

* 100 stages per SU,
* gap = tube = 0.83 cm.

- Transverse jitters between adjacent tubes: 0.1μ
- Size of the large-gap between two adjacent super-units: 1m
- Length of the accelerator: about 1300 m.

Fig. 5.10 shows the emittance vs percentage of the total stages for a superunit-largegap-system. Cases considered are as follows.

- Case a. No magnets, with jitters: $\sigma_D = 0.1\mu$.
- Case b. With magnets between the super-units and with jitters: $\sigma_D = 0.1\mu$.
- Case c. No magnets, with jitters $\sigma_D = 0.2\mu$ for comparison.

Case b is the showcase, where emittance is well under control throughout the acceleration. Without magnets as in case a, the final emittance is increased by about a factor of 3 which is still tolerable. Case c shows that as the Gaussian width of the jitters is doubled, it leads to a substantial growth in the emittance.

Focusing effect of magnets: The focusing effect of magnets for the present system is illustrated in Fig. 5.11. Case a shows the final transverse phase space without magnets, and case b the transverse phase space with magnets.

5.2.5 Summary

Our investigation on a possible 5 TeV linear collider has focused on the crucial issue of the emittance degradation due to the positional jitter of either the driver (the laser) or the accelerator medium (the tube and/or the plasma). In pursuit of a possible accelerator system that allows a consistent requirements for the collider, we suggest a particular scenario to have a fairly large number of stages in order to control the emittance degradation. As the number of stages increases, each stage allows less betatron phase space rotation. This gives the plausible origin for the inverse-law relation.

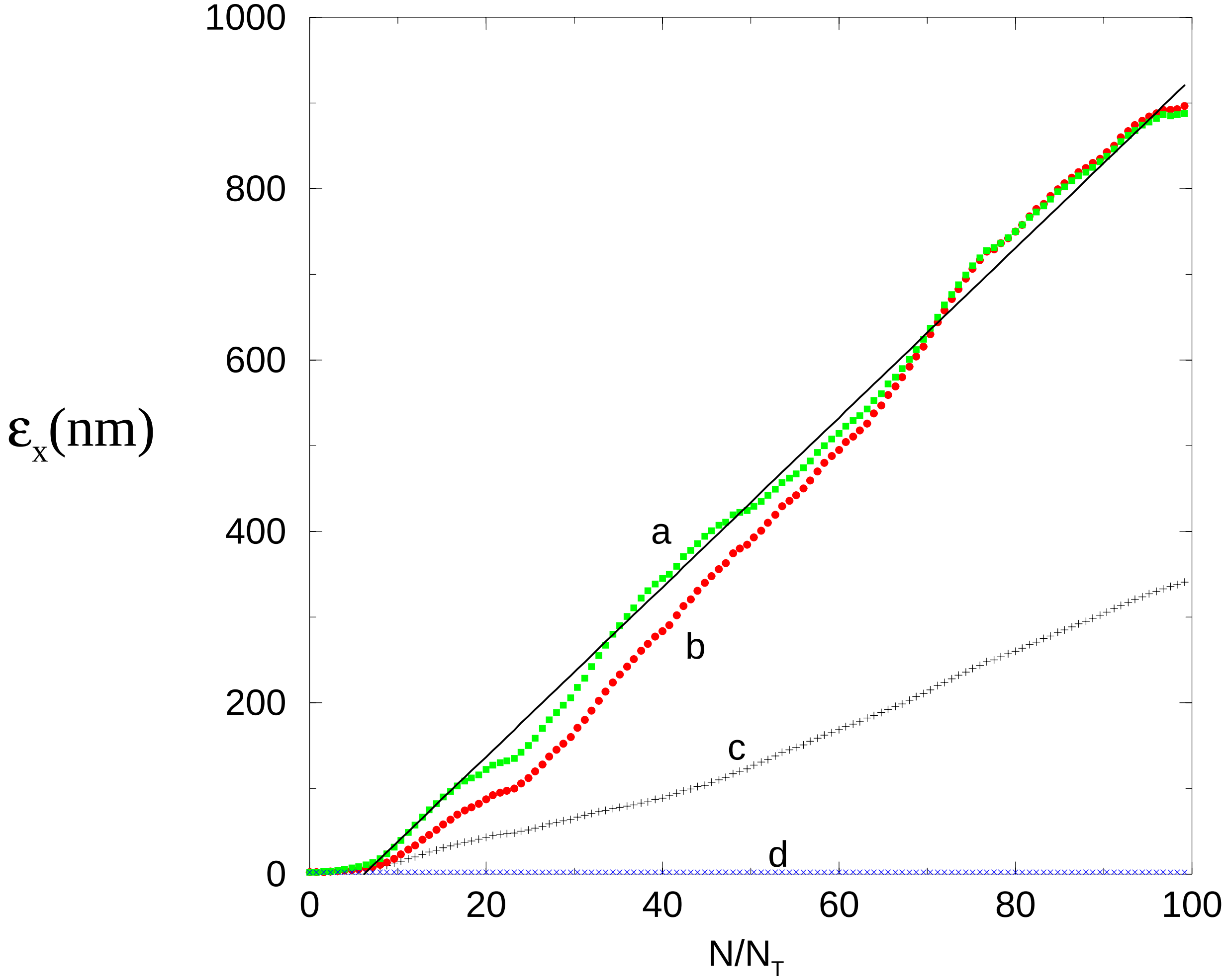

Figure 5.8: Emittance versus the fraction of total stages traversed at 2.5 TeV, with jitters $\sigma_D = 1\mu$.

- a. Energy spread $\delta\gamma = 10^4$, phase spread $\delta\Psi = 0.01$. The straight line is a fit to curve a. It illustrates that for large N, $\epsilon_x \propto N$.
- b. Energy spread $\delta\gamma = 0$, phase spread $\delta\Psi = 0.01$.
- c. Energy spread $\delta\gamma = 10^4$, phase spread $\delta\Psi = 0$.
- d. Energy spread $\delta\gamma = 0$, phase spread $\delta\Psi = 0$.

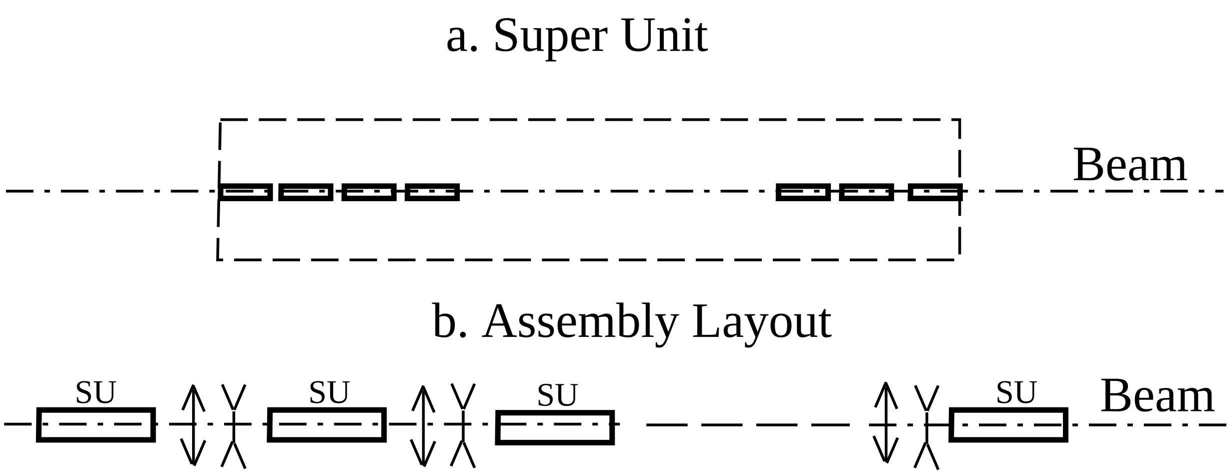

Figure 5.9: The assembly of superunits.
• a. A superunit
• b. The layout with superunits, large gaps and magnets.

- Our illustrative system is to be used as each of the two arms of the 5TeV Collider. Among other things, the system includes, superunits, magnets and jitters. A systems code of a multi-staged collider with laser driven wakefield acceleration is utilized to investigate the effect on the emittance in the transverse direction.

- Our study shows the emittance degradation depends upon several parameters, one of which is the length of each unit (and thus the total number of units) of accelerating stages. This dependence leads to a unique new strategy (somewhat counterintuitive one) to adopt a large number of very short units. We have shown that this strategy can improve the resilience against the jitter-induced emittance degradation, over the previous strawman model which allows the beam electrons to accelerate over the maximum length before slipping away from the quarter-wave-region.

- When we have a very short individual stage such as 1cm, such a stage may be conceived to be made up of a "chip" unit of laser (with an appropriate accelerating structure such as a channel within it). Thus the entire system is composed of a stack of laser chips.

Acknewledgement: The results of this work was presented at the APS Centennial meeting in Atlanta, Georgia, in March 1999. We thank Mike Downer and also colleagues and students in his experimental group for valuable discussions. This work is supported in part by the US Department of Energy (DOE) and Japan Atomic Energy Research Institute (JAERI).

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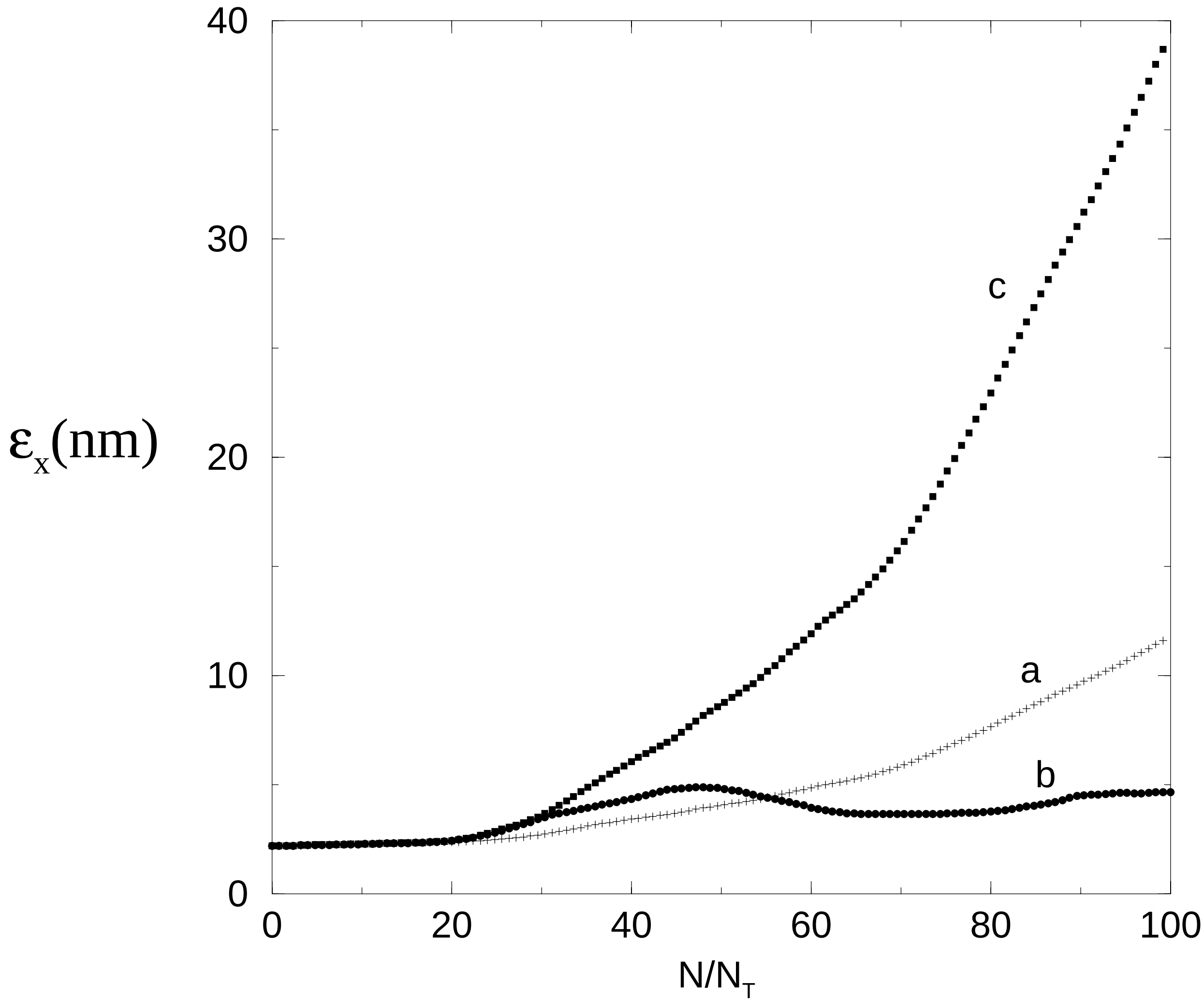

Figure 5.10: Emittance versus the percentage of total stages traversed at 2.5 TeV for an accelerator with a total of 500 superunits, where there are 100 stages per superunit.

- a. $B = 0$, $\sigma_D = 0.1\mu$
- b. B adjusted, $\sigma_D = 0.1\mu$, the present illustrative case.
- c. $B = 0$, $\sigma_D = 0.2\mu$

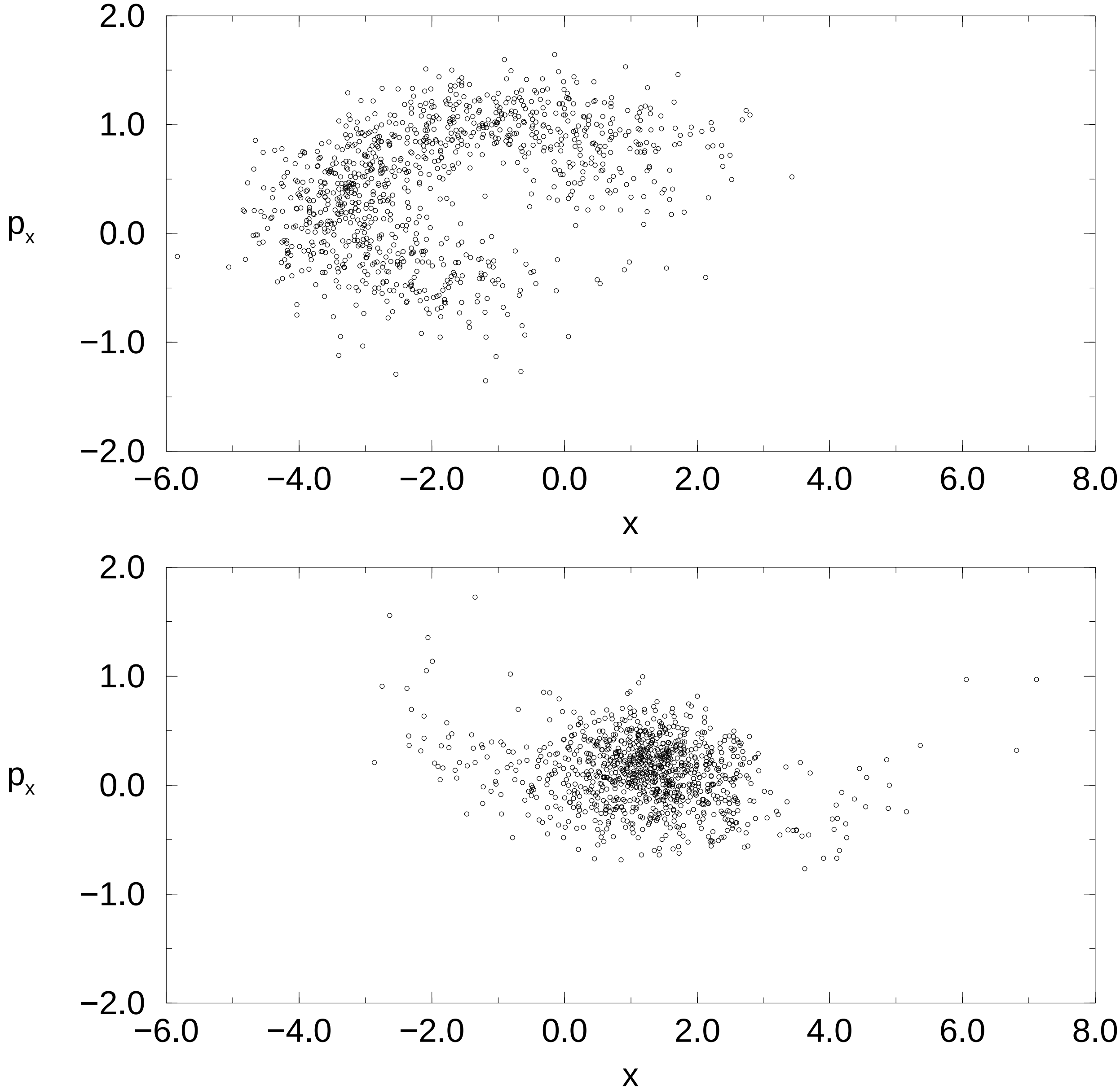

Figure 5.11: The phase space plot: p_x versus x for case a and case b illustrated in Fig. 5.10.
• a. $B = 0$, $\sigma_D = 0.1\mu$
• b. B adjusted, $\sigma_D = 0.1\mu$, the present illustrative case.

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[9] In Ref. [4] following approximation was considered, where one expanded $\sin\Psi$ to first order in $\delta\Psi$ and replaced the phase Ψ by the mid-point phase value: $\Psi_m = \Psi_s + 0.5\Delta$. It led to the approximate identity for the average: $<\sin\Psi>\approx<\sin(\Psi_m+\delta\Psi)>\approx\sin\Psi_m+\cos\Psi_m\delta\Psi$. It turned out that for total number of stages greater than 2000, behavior of emittance of the present paper obtained based on the approximation $<\sin\Psi>\approx(1+\delta\Psi)/4$ is qualitatively similar to that in Ref. [4] for the case where $\Psi_s\approx 0.15$.

5.3 New Doctoral Theses in Beam Dynamics

5.3.1 Mauro Pivi

Author: Mauro Pivi (mauro.pivi@cern.ch), European Center for Nuclear Research, LHC Vacuum Group, Geneve, Switzerland

Institution: CERN

Title: Beam induced electron multipacting in the CERN Large Hadron Collider accelerator LHC

Date: February 2000.

Supervisor: Prof. E. Chiavassa (CHIAVASSA@to.infn.it), Teacher of Nuclear Physics, University of Sciences, Mathematics and Physics of Torino (Turin) - Italy.

Supervisor: Dr. Oswald Grobner (Oswald.Grobner@cern.ch), CERN - LHC Vacuum Group Leader, 1211 Geneve 23 Switzerland.

Reference http://wwwslap.cern.ch/collective/electron-cloud/electron-cloud.html

Abstract: Electron multiplication driven by the electric field of the proton bunches is expected to occur in the Large Hadron Collider (LHC), according to previous studies performed at CERN with two computer simulation codes. Electrons, secondary electrons and photoelectrons created by the beam will be accelerated in the electric field of the proton beam and will produce a large heat load at the surface, space charge in the chamber, coupling between the electrons and the beam and a pressure increase, which ultimately could cause the loss of the proton beam. It is, therefore, fundamental to study the phenomenon. The Ph.D. thesis work included studies and planning for the laboratory experimental setup to reproduce the electron multipacting induced by radio frequency, performing data aquisition and analysis, modelization and simulations of the phenomenon, furthermore, to study the parameters influencing the effect, such as vacuum

chamber material, cleaning, surface treatments, to better understand multipacting and determine the most effective ways to avoid this critical effect for the LHC accelerator.

For this reason, a travelling-wave multi-wire chamber and a 100 MHz resonant cavity have been built to study and in particular to reproduce multipacting using radiofrequency pulses to simulate the effect of the proton beam on the electrons. I have determined experimentally the multipacting dependence on the RF pulse parameters in the TW multi-wire chamber (simulating the proton beam parameters). I have studied and built an electron energy spectrum analyzer, concentric hemisphere type, which has been used to measure the energy distribution of the electrons hitting the surface of the experimental chamber during multipacting. To validate the LHC multipacting computer simulation code developed at CERN, the program was adapted to the TW experimental set-up. The simulations performed for the TW chamber are in good agreement with the experimental data, giving confidence on the LHC multipacting computer code. In addition a computer model for multipacting in the TW chamber was studied.

The critical secondary electron yield SEYcrit is a crucial parameter for LHC, all the efforts are aimed at reducing the effective secondary electron yield (SEY) below this value. An electron cloud builds-up if $\mathrm{SEY} > \mathrm{SEY}_{crit}$, while decreases exponentially if $\mathrm{SEY} < \mathrm{SEY}_{crit}$. I have estimated SEY_{crit} for the experimental TW chamber, where the same effect occurs. The effective SEY decreases during multipacting and electron bombardment, an effect known as conditioning or scrubbing. Beam scrubbing, by means of the energetic multipacting electrons, is one of the most effective ways of cleaning in situ the beam screen surface for LHC. I have determined the decrease of the multipacting as a function of the electron dose; I have estimated the scrubbing time for LHC, which is necessary to decrease the secondary yield below SEYcrit both at LHC nominal beam parameters and during the first year of operation with reduced beam intensity. Moreover, I have designed and built a system to measure the SEY directly in the multi-wire chamber.

Auger analysis of the surface shows that two simultaneous effects take place on samples exposed to multipacting: the removal from the surface of contaminants causing an high secondary yield and the building-up of a carbon layer, with a low SEY.

Besides the in situ beam-scrubbing scenario for LHC, other possible remedies were studied aimed suppressing multipacting in the most effective way and as permanently as possible. After bake-out of the chamber the scrubbing time could be reduced by about one order of magnitude. A novel plasma RF discharge treatment using Freon11 (CCl3F), which I have tested both on a stainless steel and on a copper surface, was found to be very effective in quickly eliminating multipacting. After fitting a TiZrV (NEG) coated rolled sheet in the TW chamber, I have verified the disappearance of multipacting, due to the NEG activation. This effect seems nearly permanent for the NEG. In addition, a complete suppression of the electron multiplication can be achieved with an axial solenoid magnetic field of only few Gauss. A 100 MHz resonant cavity was built to study multipacting with higher field level than in the travelling-wave chamber; I have tested the system and measured the multipacting.

Finally, I took part in the recent measurements in the SPS accelerator at CERN with an LHC-type proton beam, where multipacting was unambiguously observed during dedicated machine development sessions (MD) for LHC. An extensive program is underway at CERN for the next MD period in the SPS in order to evaluate the possible remedies, like the freon plasma treatment, the activation of the TiZrV coating and the solenoid magnetic field, which were tested by the recent studies, and to determine the most effective way to avoid the detrimental effect of the electron-cloud in the LHC accelerator.

6: Forthcoming Beam Dynamics Events

6.1 Joint CERN-JAPAN-JINR-Russia-USA Accelerator School

Nadezhda Tokareva `tokareva@sunse.jinr.ru` JINR

July 1 - 14 2000, Russia
JAS'2000
on board the ship along the Volga river

Joint CERN-Japan-JINR-Russia-USA Accelerator School will organize a course on Frontiers of Accelerator Technology: High Quality Beams, (JAS'2000). The School will take place in Russia on a river-boat between St. Petersburg and Moscow from 1 to 10 July 2000 and will continue at the Joint Institute for Nuclear Research, Dubna, Moscow Region, from 11 to 14 July 2000. This international program provides an excellent educational opportunity for graduate students, post-docs, research scientists and engineers in university departments which use particle accelerators and in manufacturing companies which specialize in equipment for accelerators in this important and growing field. The School consists of approximately 9 working days of intensive lectures and mini-courses on the wide range of technologies that form the base of the beam/accelerator field. In particular the school will focus on the physics and technology of attaining high quality particle and photon beams for scientific research and for industrial applications.

The School is supported by the Ministry for Science and Technologies of the Russian Federation, the Ministry for Atomic Energy of the Russian Federation and the Russian Academy of Sciences.

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For further information please contact JINR Organizing Committee:
jas200@sunse.jinr.ru
or visit the School Web site:

`http://sunse.jinr.ru/jas2000.html`

6.2 US Particle Accelerator School

SY Lee `uspas@fnal.gov` USPAS

June 5-16, 2000
USPAS
Stony Brook, New York

The USPAS is offering undergraduate, graduate and special topical courses in beams physics and technologies from June 5-16, 2000 at SUNY at Stony Brook on Long Island, New York. Students have the opportunity to earn 3 semester hours of credit by taking one two-week course or two one-week courses. The deadline of application at a lower registration fee is April 7, 2000. Financial support is available.

Please provide this information to your colleagues, students, and staff scientists. For an application or for more information, please contact the USPAS Office (uspas@fnal.gov, phone 630-840-3896), or visit our website

`http://fnalpubs.fnal.gov/uspas`

for on-line-application.

7: Announcements of the beam Dynamics Panel

7.1 Advanced ICFA Beam Dynamics Workshops

7.1.1 18th ICFA Advanced Beam Dynamics Workshop on Quantum Aspects of Beam Physics

Pisin Chen chen@slac.stanford.edu SLAC

The 18th ICFA Advanced Beam Dynamics Workshop
on
QUANTUM ASPECTS OF BEAM PHYSICS
Capri, Italy
October 10-15, 2000

The 18th ICFA Beam Dynamics Workshop on “Quantum Aspects of Beam Physics” will be held in Capri, Italy from Oct. 15 to 20, 2000. This is a follow-up to the historic first meeting held in Monterey, California, in 1998. During the first workshop, more than 100 outstanding experts in beam physics, particle physics, nuclear physics, atomic physics, condensed matter physics, and astrophysics from around the world gathered to explore the frontiers of quantum effects in beam physics. The landscape was surveyed, the water charted, and new directions defined. This inspiring meeting has now been documented in the 800-page conference proceedings under the same title (“Quantum Aspects of Beam Physics”, ed. P. Chen, World Scientific, 1999.).

Encouraged by the success and by the popular demand, we have decided to hold the second workshop later this year. A proposed organization, schedule, preliminary topics, working group chairs, and plenary session of the workshop are attached in the following for your information. While we did cover related astrophysics issues in the Monterey meeting, this time we decide to formally recognize it as a separate topic: “Astro-Beam Physics”. This is a very broad area that intends to apply our knowledge of high energy, high density beam physics to astrophysical phenomena. We look forward to exciting exchanges on this new topic as well as the other five very warmly discussed topics of the last workshop.

As the workshop is by invitation only, please send your inquiry to

Dr. Stefania Petracca (qabp2k@sa.infn.it)
University of Sannio
Benevento, Italy

for additional information and a formal invitation.

Pisin Chen, Chairman
International Workshop on Quantum Aspects of Beam Physics

http://qabp2k.sa.infn.it

Title: The 18th Advanced ICFA Beam Dynamics Workshop: ”Quantum Aspects of Beam Physics”.

Time and Place: Oct. 15-20, 2000, Capri, Italy

Estimated Attendance: 100

International Advisory Committee:

N. Cabibbo	(Rome),
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E. Picasso	(Pisa),
A. Sessler	(LBL),
A. Skrinsky	(BINP),
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E. Uggerhoj	(Aarhus),
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S. De Nicola	(Napoli),
S. De Siena	(Salerno),
R. Fedele	(Napoli),
K. Hirata	(Sokendai/KE),
L. Palumbo	(Rome),
S. Petracca	(Sannio)

Working Group Topics:

1. Quantum Fluctuations in Beam Dynamics (Group A)
2. Photon-Electron Interaction in Beam Handling (Group B)
3. Physics of Condensed Beams (Group B)
4. Beam Phenomena under Strong Fields (Group C)

5. Astro-Beam Physics (Group C)

6. Quantum Methodologies in Beam Physics (Group D)

Plenary Session:

1. R. Ruth*(SLAC): "Ultimate Limits on Beam Phase Space"
2. C. Hill (Fermilab): "A New Diffractive Quantum Limit in Particle Beam Focusing"
3. C. Pellegrini (UCLA): "Quantum Fluctuations in SASE FEL"
4. S. Chattopahdyay (LBL): "Ultra-Short Beam Slicing and Tests of Quantum Mechanics"
5. W. Ertmer(Hannover): "Bose-Einstein Condensate and Atom Laser"
6. R. Chiao (UC Berkeley): "The Weakly-Interacting Photon Gas in Two-Dimensions: Bose-Einstein Condensation, Superfluidity, and Vortices"
7. J. Wei(BNL): "Crystaline Beams"
8. E. Uggerhoj (Aarhus): "Recent Results in Crystal Channeling Experiments"
9. S. Klein (LBL): "Nonlinear QED Effects in Heavy Ion Collisions"
10. J. Leinaas (Oslo): "Unruh Effect in Storage Rings"
11. I. Mirabel*(Saclay): "The Nature of Astrophysical Jets"
12. Y. Takahashi (Huntsville): "Photonic Acceleration and Ultra-High Energy Cosmic Rays"
13. R. Fedele (Napoli): "Landau Damping in Nonlinear Schroedinger Equations"
14. P. Chen (SLAC): "Supersymmetry in Beam Dynamics"

$*$ To be confirmed

7.1.2 ICFA Workshop on High Intensity High Brightness Hadron Beams

There will be an ICFA workshop from October 2 to 6, 2000 at Fermilab on the subject of "High Intensity and High Brightness Hadron Beams." It will discuss a broad range of topics associated with such type of beams, e.g., review of existing hadron machines and overview of planned machines/projects, beam dynamics, technical design issues, technical system performance, applications in high energy physics, nuclear physics, heavy ion fusion, nuclear industry, energy industry and other fields. Advanced planning is taking place for this workshop pending DOE approval.

This workshop is co-sponsored by Fermilab and the KEK. For more information, please contact:
Weiren Chou, workshop co-chairman, Fermilab, 630-840-5489, choufnal.gov
Yoshiharu Mori, workshop co-chairman, KEK, 81-424-699577, yoshiharu.morikek.jp

For administrative information, please contact:
Cynthia Sazama, Fermilab, P.O. Box 500, Batavia, IL 60510, USA, fax: 630-840-8589, e-mail: sazamafnal.gov

7.2 ICFA Beam Dynamics Newsletter

Editors in chief

Kohji Hirata (kohji.hirata@kek.jp) and John M. Jowett (John.Jowett@cern.ch)

Editors

Weiren Chou (chou@adcon.fnal.gov),
Sergei Ivanov (ivanov_s@mx.ihep.su),
Helmut Mais (mais@mail.desy.de),
Jie Wei (wei1@bnl.gov),
David H. Whittum (whittum@SLAC.Stanford.EDU),
Chuang Zhang (zhangc@bepc3.ihep.ac.cn)

7.2.1 Aim of the Newsletter

The ICFA Beam Dynamics Newsletter is intended as a channel for describing unsolved problems and highlighting important ongoing works, and not as substitute for journal articles and conference proceedings which usually describe completed work. It is published by the ICFA Beam Dynamics Panel, one of whose missions is to encourage international collaboration in beam dynamics.

7.2.2 Categories of the Articles

It is published every April, August and December. The deadlines are 15 March, 15 July and 15 November, respectively.

The categories of articles in the newsletter are the following:

1. Announcements from the panel
2. Reports of Beam Dynamics Activity of a group
3. Reports of Beam Dynamics related workshops and meetings
4. Announcements of future Beam Dynamics related international workshops and meetings.

   Those who want to use newsletter to announce their workshops etc can do so. Articles should typically fit within half a page and include descriptions of the subject, date, place and details of the contact person.
5. Review of Beam Dynamics Problems

   This is a place to put forward unsolved problems and not to be used as the achievement report. Clear and short highlights on the problem is encouraged.
6. Letters to the editor

   It is a forum open to everyone. Anybody can show his/her opinion on the beam dynamics and related activities, by sending it to one of the editors. The editors keep the right to reject a contribution.
7. New Doctoral Theses in Beam Dynamics

   Please send announcements to the editors including the following items (as a minimum):

   (a) Name, email address and affiliation of the author,
   (b) Name, email address and affiliation of the supervisor,
   (c) Name of the institution awarding the degree,

(d) The title of the thesis or dissertation.

(e) Date of award of degree. (For a while, we accept the thesis awarded within one year before the publication of the newsletter.)

(f) A *short* abstract of the thesis is also very desirable.

8. Editorial

All articles except for 6) and 7) are by invitation only. The editors request an article following a recommendation by panel members. **Those who wish to submit an article are encouraged to contact a nearby panel member**.

The manuscript should be sent to one of the editors as a LaTeX file or plain text. The former is encouraged and authors are asked to follow the instructions below.

Each article should have the title, author's name(s) and his/her/their e-mail address(es).

7.2.3 How to Prepare the Manuscript

Here, the *minimum* preparation is explained, which helps the editors a lot. The full instruction can be found in WWW at

`http://www-acc-theory.kek.jp/ICFA/instruction.html`

where you can find the template also.

Please follow the following:

- Do not put comments (%) when sending the manuscript through e-mail. Instead, you can use `\comm` as `\comm{your comments}`. It is defined as \newcommand\comm[1]{}.
- Start with `\section{title of your article}`. **It is essential**.
- Then put your name, e-mail address and affiliation.
- It is *useless to include any visual formatting commands* (such as vertical or horizontal spacing, centering, tabs, etc.).
- Do not define new commands.
- Avoid TEXcommands that are not part of standard LATEX. These include the likes of `\def`, `\centerline`, `\align`, ...
- Please keep figures to a minimum. The preferred graphics format is Encapsulated Postscript (EPS) files.

7.2.3.1 Regular Correspondents

Since it is impossible for the editors and panel members to watch always what is going on all around the world, we have started to have *Regular Correspondents*. They are expected to find interesting activities and appropriate persons to report them and/or report them by themselves. We hope that we will have a "compact and complete" list covering all over the world eventually. The present *Regular Correspondents* are as follows

Liu Lin (liu@ns.lnls.br)	LNLS	Brazil
S. Krishnagopal (skrishna@cat.ernet.in)	CAT	India
Ian C. Hsu (ichsu@ins.nthu.edu.tw)	SRRC	Taiwan

We are calling for more volunteers as *Regular Correspondents*.

7.2.4 Distribution

The ICFA Beam Dynamics Newsletters are distributed through the following distributors:

W. Chou	chou@adcon.fnal.gov	North and South Americas
Helmut Mais	mais@mail.desy.de	Europe* and Africa
Susumu Kamada	Susumu.Kamada@kek.jp	Asia** and Pacific

(*) including former Soviet Union.
(**) For mainland China, Chuang Zhang (`zhangc@bepc5.ihep.ac.cn`) takes care of the distribution with Ms. Su Ping, Secretariat of PASC, P.O.Box 918, Beijing 100039, China.

It can be distributed on a personal basis. Those who want to receive it regularly can ask the distributor to do so. In order to reduce the distribution cost, however, please use WWW as much as possible. (See below).

7.3 World-Wide Web

The home page of the ICFA Beam Dynamics Panel is at the address

`http://www-acc-theory.kek.jp/ICFA/icfa.html`

(which happens to be in Japan). For reasons of access speed, there are mirror sites for Europe and the USA at

`http://wwwslap.cern.ch/icfa/`
`http://www.slac.stanford.edu/grp/arb/dhw/dpb/icfa/icfa.html`

All three sites are essentially identical and provide access to the Newsletters, Future Workshops, and other information useful to accelerator physicists. There are links to information of local interest for each area.

7.4 ICFA Beam Dynamics Panel Organization

The mission of ICFA Beam Dynamics Panel is *to encourage and promote international collaboration on beam dynamics studies for present and future accelerators*. For this purpose, we publish *ICFA Beam Dynamics Newsletters* three times a year, we sponsor *Advanced ICFA Beam Dynamics Workshops* and *ICFA Beam Dynamics Mini-Workshops*, and we organize *Working Groups* in the panel to promote several important issues.

Chairman K. Hirata

Chief Editors of ICFA Beam Dynamics Newsletter K. Hirata and J. M. Jowett

Editors of ICFA Beam Dynamics Newsletter W. Chou, S. Ivanov, H. Mais, J. Wei, D.H. Whittum, and C. Zhang

Distributers of ICFA Beam Dynamics Newsletter W. Chou, H. Mais, S. Kamada

Leader and Subleader of Future Light Source Working Group K. J. Kim and J. L. Laclare

Leader and Subleader of Tau-Charm factory Working Group E. A. Perelstein and C. Zhang

Leader of High-Brightness Hadron Beams Working Group W. Chou

WWW keeper K. Hirata, J. M. Jowett and D.H. Whittum

Panel Members

Pisin Chen (chen@slac.stanford.edu)	SLAC
Weiren Chou (chou@adcon.fnal.gov)	Fermilab
Yoshihiro Funakoshi (yoshihiro.funakoshi@kek.jp)	KEK
Kohji Hirata (kohji.hirata@kek.jp)	Sokendai/KEK
Albert Hofmann (Albert.Hofmann@cern.ch)	CERN
Ingo Hofmann (I.Hofmann@gsi.DE)	GSI
Sergei Ivanov (ivanov_s@mx.ihep.su)	IHEP (Protvino)
John M. Jowett (John.Jowett@cern.ch)	CERN
Kwang-Je Kim (kwangje@aps.anl.gov)	LBNL
Jean-Louis Laclare (laclare@dapnia.cea.fr)	SOLEIL
Helmut Mais (mais@mail.desy.de)	DESY
Luigi Palumbo (lpalumbo@frascati.infn.it)	Univ.Rome/LNF-INFN
Claudio Pellegrini (claudio@vesta.physics.ucla.edu)	UCLA
Elcuno A. Perelstein (perel@ljap12.jinr.dubna.su)	JINR
Dmitri Pestrikov (pestrikov@inp.nsk.su)	BINP
Jie Wei (wei1@bnl.gov)	BNL
David H. Whittum (whittum@SLAC.Stanford.EDU)	SLAC
Chuang Zhang (zhangc@bepc3.ihep.ac.cn)	IHEP(Beijing)