International Committee for Future Accelerators
Sponsored by the Particles and Fields Commission of IUPAP

Beam Dynamics Newsletter

No. 38

Issue Editor:
I. S. Ko

Editor in Chief:
W. Chou

December 2005

Contents

1 Forward

1.1 From the Chairman

Weiren Chou, Fermilab
mail to: chou@fnal.gov

An *ICFA Seminar* was held from September 28 to October 1, 2005 at the Center for High Energy Physics, Kyungpook National University, Daegu, Korea. This Seminar takes place every three years and brings together government officials involved in strategic decisions for High Energy Physics (HEP), representatives of the major funding agencies, the directors of major HEP laboratories, and leading scientists from all of the regions in which there is HEP activity. Most of the presentations at this Seminar have been posted on the web: http://chep.knu.ac.kr/ICFA-Seminar/program.php. I encourage you to take a look at these excellent talks by well-known physicists in the field.

During the Seminar, there was a meeting to discuss an important topic: the future of ICFA. When ICFA was created nearly 30 years ago in 1976 by the International Union of Pure and Applied Physics (IUPAP) Commission 11 (Particle and Fields), its first aim was "*To promote international collaboration in all phases of the construction and exploitation of very high energy accelerators*." Since then, it has played a critical role in promoting energy frontier machines such as the SSC, LHC and most recently the ILC. However, the particle physics field is changing; non-accelerator physics is becoming a larger part of particle physics, and the field is no longer as dominated by large accelerators as three decades ago. Many accelerators are now facilities for neutron science, synchrotron radiation science and proton therapy. Some laboratories, e.g. SLAC and DESY, which in the past worked almost exclusively on particle physics, are now active in a much broader range of physics. These changes lead to the question of whether ICFA itself should change. No conclusion was reached at this ICFA meeting. The discussion will be continued at future ICFA meetings.

The year 2005 has been an active year for this Panel.

- We organized five Advanced Beam Dynamics Workshops (ABDWs), two jointly with the Advanced and Novel Accelerators Panel: 32nd "*ERL2005*," 34th "*HPSL2005*," 35th "*Physics and Applications of High Brightness Electron Beams*," 36th "*Nanobeam2005*" and 38th "*LBI-LPA 2005*."
- We also sponsored several ICFA Mini-Workshops, which were organized respectively by the Future Light Sources Working Group, High Luminosity e+e− Colliders Working Group and High Intensity Hadron Beams Working Group.
- We published three issues of the ICFA Beam Dynamics Newsletter: No. 36 (April), 37 (August) and 38 (this issue).
- We made a proposal to ICFA and JACoW for future ABDWs (beginning in 2006) to join the JACoW collaboration for online publication of workshop proceedings. The proposal was approved. From now on, we will be able to share

JACoW's vast database of more than 9,000 authors' names. All papers published by these people at the JACoW conferences (including future ICFA workshops) can be searched using JACoW. The 37th "*FLS2006*" and 39th "*HB2006*" will be the first two ICFA workshops as JACoW members.

- We initiated the *World Accelerator Catalogue* project. This is an online database and will be completed in 2006. We received strong support from most of the laboratory directors, who provided us with the names of contact persons for each accelerator in their laboratories.
- In collaboration with the ILC GDE and ILCSC, we are helping organize an *International Accelerator School for Linear Colliders*. This school will take place May 19 – 27, 2006 at Sokendai, Japan. More details can be found in Section 3.1 of this newsletter.

These achievements are the results of the hard work of all Panel members. I am particularly thankful to these colleagues because all of them carry out their ICFA responsibilities on a voluntary basis. Their ICFA activities are an addition to their already busy daily schedule. Many of them work at night or weekends on ICFA related activities. We owe them a great deal if we imagine how this field would look like without ICFA and its panels.

The Editor of this issue is Professor In Soo Ko, a panel member and Director of the Pohang Accelerator Laboratory (PAL) in Korea. I'd like to express my gratitude to him for having collected a number of interesting articles and produced a well-organized fine Newsletter.

1.2 From the Editor

In Soo Ko, Pohang Accelerator Laboratory
mail to: isko@postech.ac.kr

In this Newsletter, there is a special session dedicated to the electron bunch compression. This topic becomes very important in the field of linac-based free electron lasers and eventually ILC linac as well. Detailed mechanism of electron bunch length compression is covered by M. Dohlus and T. Limberg of DESY, and P. Emma of SLAC. Microbunching instability due to bunch compression which degrades FEL lasing is described by Z. Huang and J. Wu of SLAC, and T. Shaftan of BNL. I thank all authors for their contributions to this issue of Newsletter. I miss the third article on the bunch compression scheme for ILC that was not submitted on time. It will appear in the next issue of the Nesletter.

In the ILC section, we have a detailed plan for ILC School scheduled on May 19-27, 2006 at Sokendai, Hayama, Japan.

There are several activity reports including one from South Africa. We have an excellent and rare chance to hear voices from African physicists. One interesting issue is a suggestion of the creation of International Science Center including African Synchrotron Radiation Facility, which reminds me SESAME project.

2 Letters to the Editor

2.1 Report of the World Conference on Physics and Sustainable Development

Sameen Ahmed KHAN
rohelakhan@yahoo.com, http://www.geocities.com/rohelakhan/
Middle East College of Information Technology (MECIT)
The Technowledge Corridor, Knowledge Oasis Muscat
Post Box No. 79, Al Rusayl, Postal Code: 124
Muscat, **Sultanate of Oman**

2.1.1 World Conference on Physics and Sustainable Development

The *World Conference on Physics and Sustainable Development* (WCPSD), a landmark event organized to celebrate the International Year of Physics, was held during 31 October – 3 November 2005, at the International Conference Centre in Durban, South Africa. The Conference brought together, students, educators, scholars, representatives and decision-makers from numerous government and non-government agencies around the world, who formulated a plan aimed at resolving the challenges posed by sustainable development. Physics has made numerous contributions to the global economy in areas such as electronics, materials and computer technology, and to health through x-rays, synchrotron radiation, magnetic resonance imaging and nuclear medicine. However, these revolutionary technologies have been of greater benefit to people in the developed world than in the developing world. The Durban Conference was, in the words of Dr. Edmund Zingu, President of the South African Institute of Physics, "*an attempt to re-direct the attention and efforts of physicists towards the Millennium Development Goals*", endorsed by world leaders at the United Nations Millennium Summit in September 2000. The conference served as the first global forum to focus the physics community on development goals and to create new mechanisms of cooperation toward their achievement. It created an intellectual platform for an assessment of physics in development and the role it can play for sustainable development, particularly in the emerging and the developing countries. Participants from developed and developing nations examined the contributions that physics has made to society in the past in order to formulate and sharpen action-oriented plans for the contributions that it can and should make in future.

The above Conference was a follow-up on the 1999 UNESCO-ICSU World Conference on Science, which sought to strengthen the ties between science and society, as well as the broader UN World Summit on Sustainable Development that took place in Johannesburg in 2002. This Conference was cosponsored by several international organizations including: *International/World Year of Physics*, UNESCO; the Abdus Salam International Centre for Theoretical Physics (ICTP); the International Union of Pure and Applied Physics (IUPAP); and the South African Institute of Physics (SAIP). About five-hundred physicists participated. Importantly there were several observers/representatives from numerous agencies including, American Physical Society; European Laboratory for Particle Physics (CERN) in Geneva, European

Physical Society, IAEA, IUPAP, UNESCO, World Bank and several of the African organizations.

WCPSD was preceded by the *25th General Assembly* of the IUPAP in Cape Town. It is the first time that the General Assembly (held once in three years) was held in the Continent of Africa; and the second time that it was held outside of USA/Canada and Europe (held once in Asia; in Japan in 1993). WCPSD was immediately followed by two major Physics events in Durban: *US-Africa Advanced Studies Institute on Photon Interactions with Atoms and Molecules* and the *IAEA Technical Meeting on Accelerator-based Physics for sustaining the flow of Technology and Skills*.

WCPSD was much different from most of the other conferences, where the individual presentations of one's own research are the chief focus. WCPSD laid a great emphasis on chalking out programmes to work towards sustainable development. The Conference covered the following four focal themes:

1. **Physics Education**
   (330 registered participants)

2. **Energy & Environment**
   (80 registered participants)

3. **Physics & Economic Development**
   (52 registered participants)

4. **Physics & Health**
   (47 registered participants)

Besides there were about thirty participants involved in coordination and organizing. The Conference was inaugurated by His Excellency, Mosibudi MANGNENA, Minister of Science and Technology, South Africa. A welcome civic reception & banquet was held on the first day by the Mayor Councilor Obed MLABA. The first day consisted of a Plenary Session with presentations by the Organizers, Keynote Speakers and the Programme Chairs of each theme. The second day was devoted to active discussions among the sub-groups under each of the four themes. A brief summary of each of the four is outlined below.

An urgent need was felt to strengthen the *Physics Education*. Physicists pledged to make high-quality physics resources widely available in developing countries by establishing a website along with Resource Centres in Africa, Asia and Latin America. These will prepare instructional materials and model workshops for teacher trainers in Asia, Latin America and Africa. The resulting resource material will be made available on the web. A multidisciplinary mobile science team will also be created to provide online support.

Under the umbrella of *Energy and Environment*, efforts to enhance efficiency and reduce pollution in transportation will include investigating new battery technologies and improved internal combustion technology for hybrid application. Teams will develop solar photovoltaic technologies, including new and environmentally-friendly processes for generating and storing electricity. Efforts shall be made to enhance the usage of wind power.

The focal theme, *Physics & Economic Development*, drew a lot of attention with active participation from representatives of UNESCO, IAEA, IUPAP, World Bank, among others. This working group has come up with a series of recommendations and initiatives on how to strengthen Research and Development (R&D). Physics makes a vital contribution to the economy. It was pointed out that physics-based industries account for 43% of manufacturing employment in the United Kingdom. A Training Facility for Physicists in Economic Development is proposed, which shall provide training in entrepreneurship and related skills. The group further proposed to launch a joint research project on nanoscience and nanotechnology with a focus on clean water, air and energy. It proposes an integrated approach to strengthen R&D in nanosciences and help turn nanotechnologies into commercially viable products for the benefit of society, in the developing countries. An online network devoted to physics and agriculture was also proposed. Most members of this group will be following up with laboratory work and liaison with the industry. The group also urged the creation of International/Regional Science Centres (including the AfSRF: *African Synchrotron Radiation Facility*) in the developing countries.

Under the fourth and final theme, *Physics & Health*, educational resources will be made available through the Physics and Engineering Resources for Healthcare Development (PERHD) website, sponsored by the World Conference. Further projects include creating a network of training centres in physics of radiation therapy using shared resources from institutions around the world and providing guidelines to elaborate educational programmes in medical physics.

The Conference had about 200 Poster Presentations, displayed for two days. The third and the last day was devoted to the presentations of the summaries of the deliberations of each of the sub-groups on the preceding day. There shall be some follow-up meetings to review the progress of the deliberations and proposals during the WCPSD. An interesting item in the Conference was *The Lab in a Lorry*. This mobile laboratory is a partnership between the Schlumberger Foundation and the Institute of Physics, UK. It is contributing to popularizing physics among school students and in creating a general awareness.

In the conference the accelerators and accelerator facilities were mentioned in the context of the sustainable development. The role of accelerator facilities in the arena of international cooperation was extensively covered. Further details about the WCPSD are available at, http://www.wcpsd.org/

2.1.2 References

1. 31 October - 02 November 2005, **World Conference on Physics and Sustainable Development (WCPSD),** Durban, South Africa, http://www.wcpsd.org/
2. 6-8 September 2000, **United Nations Millennium Summit**, http://www.un.org/millennium/summit.htm
3. 26 June - 1 July 1999, **UNESCO-ICSU World Conference on Science**, Budapest, Hungary, http://www.unesco.org/science/wcs/
4. 26 August – 4 September 2002, **The United Nations World Summit on Sustainable Development**, Johannesburg, South Africa, http://www.un.org/events/wssd/
5. The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, http://www.ictp.it/
6. The International Union of Pure and Applied Physics (IUPAP), http://www.iupap.org/
7. The South African Institute of Physics (SAIP), http://www.saip.org.za/

8. 26-28 October 2005, **IUPAP 25th General Assembly**, Cape Town, South Africa, http://www.saip.org.za/iupap/ga2005/index.html
9. 3-12 November 2005, **US-Africa Advanced Studies Institute on Photon Interactions with Atoms and Molecules**, Durban, South Africa, http://www.africanlasercentre.org/USAfricanPhotonInteractions.asp
10. 7–10 November 2005, **The IAEA Technical Meeting on Accelerator-based Physics for Sustaining the flow of Technology and Skills,** Durban, South Africa, http://www.iaeameeting.tlabs.ac.za/Iaea/Introduction.htm
11. *The Importance of Physics in the UK Economy*, Institute of Physics, UK (March 2003).
12. *The Lab in a Lorry***,** http://www.labinalorry.org.uk/

3 International Linear Collider (ILC)

3.1 International Accelerator School for Linear Colliders

Barry Barish, Weiren Chou and Shin-ichi Kurokawa
mail to: barish@ligo.caltech.edu, chou@fnal.gov, shin-ichi.kurokawa@kek.jp

We are pleased to announce the *International Accelerator School for Linear Colliders.* This school is organized jointly by the International Linear Collider (ILC) Global Design Effort (GDE), the International Linear Collider Steering Committee (ILCSC) and the International Committee for Future Accelerators (ICFA) Beam Dynamics Panel. It will take place at Sokendai (a graduate university about 70 km south of Tokyo), Hayama, Japan from May 19 – 27, 2006. The school is sponsored by the U.S. Department of Energy (DOE) Office of Science, Fermilab, SLAC, CERN, DESY, KEK, PPARC, INFN and CARE/ELAN.

We will offer an 8-day program, with 6 days of lectures on accelerators at Sokendai and 2 days for a site visit to KEK, where lectures on detectors and physics will be given. The KEK part of the program is optional. The program also includes a half-day field trip to Kamakura, a historical town where Shogun had the government in the 13th – 14th centuries.

There will be a total of 20 lectures covering both basic accelerator topics (e.g. synchrotrons, linacs, superconductivity, beam-beam interactions, etc.) and advanced topics. Most of the advanced topics will be focused on the ILC (e.g., sources, bunch compressor, damping ring, superconducting RF linac, beam delivery, instrumentation, feedback, conventional facilities and operations). There will also be a lecture dedicated to room temperature RF and the Compact Linear Collider (CLIC). In addition, there will be a special lecture on the Accelerator Test Facility (ATF) at KEK, where students can work on a real accelerator. All lectures will run in sequence. (There will be no parallel sessions.) A complete description of the program is attached. There will be homework but no examinations or university credits.

We encourage young physicists (graduate students, post doctoral fellows, junior researchers) to apply. In particular we welcome those physicists who are considering changing their career from experimental physics to accelerator physics. The school will accept up to a maximum of 80 students from around the world. All students will receive financial aid for covering the expenses for attending this school (including airfare, lodging, meals, local transportation and school supplies). There will be no registration fee. Each applicant should complete the online registration form (which can be found at www.linearcollider.org/school) and send us a curriculum vita as well as a recommendation letter from his/her supervisor (in electronic form, either PDF or MS WORD). The deadline for application is February 15, 2006. For more information, please contact:

Yoko Hayashi
KEK
1-1 Oho, Tsukuba, Ibaraki
305-0801 Japan
Phone: +81-29-864-5214
Fax: +81-29-864-3182
E-mail: ilc-school@milk.kek.jp

Organizing Committee
Barry Barish (GDE/Caltech, Chair)
Shin-ichi Kurokawa (ILCSC/KEK)
Weiren Chou (ICFA BD Panel/Fermilab)
Jean-Pierre Delahaye (CERN)
Rolf-Dieter Heuer (DESY)
In Soo Ko (PAL)
Kaoru Yokoya (KEK)
Alex Chao (SLAC)
Paul Grannis (US DOE)

Curriculum Committee
Weiren Chou (Fermilab, Chair)
Alex Chao (SLAC)
Michiko Minty (DESY)
Carlo Pagani (Milano)
Junji Urakawa (KEK)
Jie Gao (IHEP/China)
Eun-San Kim (PAL)

Local Committee
Shin-ichi Kurokawa (KEK, Chair)
Junji Urakawa (KEK)
Kaoru Yokoya (KEK)
Satoru Yamashita (U. of Tokyo)

International Accelerator School for Linear Colliders – Curriculum (v.6, 11/30/2005)

May 19-27, 2006, Sokendai, Hayama, Japan

Daily Schedule

Breakfast	08:00 – 09:00
Morning	09:00 – 12:30, including ½-hour break
Lunch	12:30 – 14:00
Afternoon	14:00 – 17:30, including ½-hour break
Dinner	17:30 – 19:00
Evening	19:00 – 20:30

List of Courses

	Morning	Afternoon	Evening
May 19		*Arrival, registration*	*Rest*
May 20	Introduction I & II	Sources; Bunch compressors	Tutorial & homework
May 21	Damping ring basics	Damping ring design	Tutorial & homework
May 22	ILC linac basics; ILC linac beam dynamics	*Field trip to Kamakura*	*Free time*
May 23	High power RF; SRF basics	SRF cavity technology	Tutorial & homework
May 24	ILC cryomodule; Room-temperature RF	Beam delivery; Beam-beam interaction	Tutorial & homework
May 25	Instrumentation & feedback	Conventional facilities; Operations	Tutorial & homework
May 26 (*)	*Sokendai – KEK*	KEK tour	*Free time*
May 27 (*)	Detectors; Physics	ATF; Site visit to ATF	*Free time*
May 28	*Departure*		

(*) Courses at KEK are optional. Students may choose to leave on May 26. Accommodation will be at KEK on May 26 and 27.

Program

	Saturday, May 20	Sunday, May 21	Monday, May 22	Tuesday, May 23
Morning 09:00 – 12:30	Opening remarks (10) Lecture 1 – Introduction I (90) • Why LC • What's ILC • Layout of ILC • Overview of issues Lecture 2 – Introduction II (90) • Parameter choices & optimization	Lecture 5 – Damping ring basics (180) • Betatron motion • Synchrotron motion • Beam energy • Beam emittance • Radiation damping • Intrabeam scattering	Lecture 7 – ILC Linac basics (90) • Linac basic principles • SW linacs and structures • SRF parameter constraints • Beam loading and coupling • Lorentz force detuning Lecture 8 – ILC Linac beam dynamics (90) • Lattice layout • Beam quality preservation o RF field stability o Wakefield and dampers o HOMs o Alignment tolerances o Vibration problems o Beam based alignment	Lecture 9 – High power RF (60) • RF system overview • Modulators • Klystrons • RF distribution Lecture 10 – SRF basics (120) • Superconductivity basics • SRF peculiarities • Cavity design criteria • Various constraints • ILC BCD Cavity
Afternoon 14:00 – 17:30	Lecture 3 – Sources (120) • e- gun • e+ sources • Polarized sources Lecture 4 – Bunch compressors (60) • Bunch compressors • Spin rotator	Lecture 6 – Damping ring design (180) • Options • Lattice • Parameter optimization • Machine acceptance • E-cloud, space charge and instability issues • Wigglers • Kickers and other technical systems	Field trip to Kamakura	Lecture 11 – SRF cavity technology (180) • Material issues • Cavity fabrication and tuning • Surface preparation • Gradient limit and spread • Power Coupler • HOM Couplers • Slow and fast tuner • Path to ILC
Evening 19:00 – 20:30	Tutorial & homework	Tutorial & homework	Free time T	utorial & homework

Program (cont'd)

	Wednesday, May 24	Thursday, May 25	Friday, May 26	Saturday, May 27
Morning 09:00 – 12:30	Lecture 12 – ILC cryomodule (60) • ILC cryogenics and rational • ILC cryomodule concept Lecture 13 – Room-temperature RF (120) • Room temperature cavity and gradient limit • CLIC design	Lecture 16 – Instrumentation & feedback (180) • Beam monitoring • Precision instrumentation • Feedback systems	Bus from Sokendai to KEK	Lecture 19 – Detectors (90) • ILC detectors Lecture 20 – Physics (90) • ILC physics • Physics beyond 1 TeV • e-e- and □-□ options • ILC and XFEL
Afternoon 14:00 – 17:30	Lecture 14 – Beam delivery (120) • Beam delivery system overview • Collimation • Machine-detector interface, shielding and beam dump • Beam monitoring and control at final focus Lecture 15 – Beam-beam (60) • Beam-beam interaction	Lecture 17 – Conventional facilities (90) • Overview • Tunneling • Site requirement Lecture 18 – Operations (90) • Reliability • Availability • Remote control and global network Closing remarks and student awards ceremony (20)	KEK tour • B-Factory • Photon Factory • SRF • J-PARC (KEK site) • FFAG	Special lecture – ATF (90) • Machine introduction • Machine performance • ATF2 and R&D plan • Diagnostics Site visit to ATF
Evening 19:00 – 20:30	Tutorial & homework	Tutorial & homework	Free time	Free time

4 Bunch Compression for Linac-based FELs

4.1 Electron Bunch Length Compression

M. Dohlus, T. Limberg, DESY and P. Emma, SLAC
mail to: emma@slac.stanford.edu

4.1.1 Introduction

Future 4th-generation light sources, especially linac-based free-electron lasers, will require very short bunches (< 100 fs) of high-brightness electron beams with peak currents of the order of kilo-Amperes. These bunches cannot be produced directly in guns because space charge forces would destroy the brilliance within a short distance. So we must start with a low intensity bunch with peak current of a few tens of Amperes, accelerate to energies where the space charge forces are weakened sufficiently by the $1/\gamma^2$ scaling, and then compress the bunch length to increase the peak current.

To compress a bunch longitudinally, the time of flight through some section must be shorter for the tail of the bunch than it is for the head. The usual technique starts out by introducing a correlation between the longitudinal position of the particles in the bunch and their energy using a radio frequency (RF) accelerating system.

Utilizing the resulting velocity spread and time of flight differences in a drift is called ‘ballistic bunching’, while inside of an RF section it is named ‘velocity bunching’. A principle problem of these methods stems from the fact that the higher the peak current after compression, the higher the beam energy must be to avoid damaging space charge effects, and the higher beam energy means smaller velocity differences.

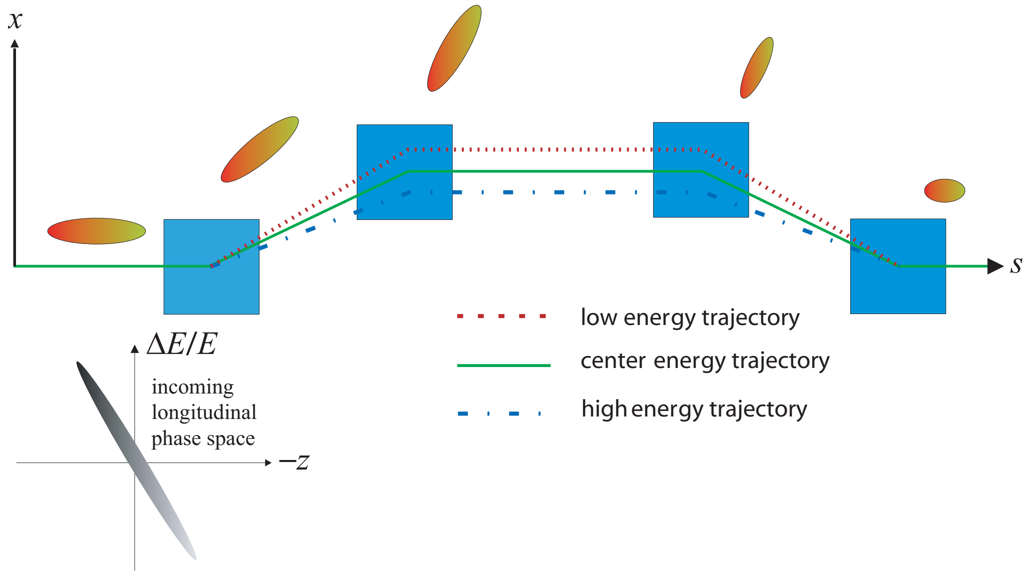


Figure 1: Longitudinal bunch compression in a simple 4-bending-magnet chicane.

If path length differences in a dispersive section, like a magnetic chicane, are used to bring the particles closer together in time, the velocity spread can be zero. Figure 1 illustrates the principle: an energy chirp, an (ideal) linear correlation between energy and longitudinal bunch position is introduced, lowering the particle energy in the head of the bunch and increasing it in the tail. The different path lengths through a dispersive section, made up from four dipole magnets, then compress the bunch length.

The principle problem here is that short bunches on curved trajectories will emit Coherent Synchrotron Radiation (CSR). The resulting energy loss varies along the bunch length; it increases energy spread and transverse emittance and may even disturb the compression process itself.

4.1.2 Dispersive Beamlines

In general, any curved beam line section introduces a path length difference for particles with a relative energy (momentum) deviation δ:

$$\Delta z = \eta_s(\delta)\cdot\delta = R_{56}\cdot\delta + T_{566}\cdot\delta^2 + U_{5666}\cdot\delta^3 + \cdots \qquad (1)$$

with η_s being the longitudinal dispersion. The coefficient R_{56} can be termed linear longitudinal dispersion (just as R_{16} is described as linear horizontal dispersion) and is usually the leading term for bunch compression. In the following, we present some examples of dispersive beam line sections suitable for magnetic bunch compressors.

4.1.2.1 *A simple bending magnet chicane*

The simplest and most common magnetic compressor is the 3- or 4-dipole magnetic chicane. Four dipoles, instead of the minimum of three, are typically used to provide a central drift space for beam diagnostics (beam position monitor, profile monitor, collimator, etc.). As an example we take the 'Zeuthen Chicane', a benchmark layout used for CSR calculation comparisons at the January 2002 ICFA Beam Dynamics Mini-Workshop at Zeuthen near Berlin [1]. Figure 2 shows the chicane layout and Table 1 lists the parameters. The parameters are close to actual compressor chicanes designed for the LCLS [2] or the European XFEL [3] project.

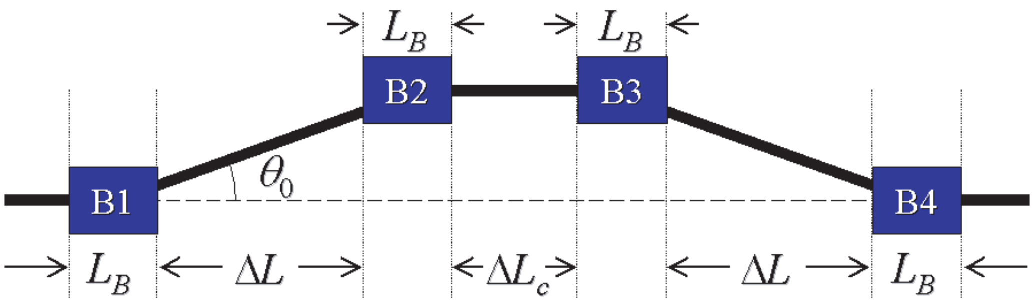


Figure 2: A simple bending magnet chicane: The benchmark chicane of the Zeuthen 2002 ICFA Workshop [1].

The physical length of each magnet is L_B, the nominal bending angle is θ_0 (for the reference particle), and the drift distance between dipoles is ΔL. With rectangular magnets the chicane is achromatic to all orders, making it an attractive design.

Table 1: Parameters for the Benchmark Chicane of the Zeuthen 2002 Workshop.

Parameter	Symbol	Value	Unit
Bend magnet length (projected)	L_B	0.5	m
Drift length B1-B2 and B3-B4 (projected)	ΔL	5.0	m
Drift length B2-B3	ΔL_c	1.0	m
Bend radius of each dipole magnet	ρ	10.3	m
Bending angle	θ_0	2.77	deg
Momentum compaction	R_{56}	–25	mm
2nd order momentum compaction	T_{566}	+38	mm
Total projected length of chicane	L_T	13.0	m
Effective total chicane length ($L_T - \Delta L_C$)	L_{act}	12.0	m
Bunch charge	q	1	nC
Electron energy	E	5	GeV
Initial bunch length	σ_i	200	μm
Final bunch length	σ_f	20	μm

The additional path length, Δs, of a particle passing through a chicane with small bending angle ($|\theta_0| \ll 1$), taken with respect to a straight trajectory (*i.e.*, with chicane switched off), can be approximated by

$$\Delta s \approx \theta_0^2\left(\Delta L + \frac{2}{3}L_B\right). \tag{2}$$

The compression coefficients are made clear by expanding θ^2 in terms of a small relative energy deviation, $\delta \equiv \Delta E / E$, with $\theta^2 = \theta_0^2/(1+\delta)^2 = \theta_0^2(1-2\delta+3\delta^2-4\delta^3+\cdots)$. The linear term is then identified as

$$R_{56} \approx -2\theta_0^2\left(\Delta L + \frac{2}{3}L_B\right) = -2\theta_0^2\left(\frac{1}{2}L_{act} - \frac{4}{3}L_B\right), \tag{3}$$

where L_{act} is the active chicane length, $L_{act} = L_T - \Delta L_c$ and we assume a coordinate system with the head of the bunch at $z < 0$.

The zeroth-order (Δs), second-order (T_{566}) and 3rd-order (U_{5666}) factors are clearly related to the R_{56} as

$$\Delta s \approx -\frac{R_{56}}{2}, \quad T_{566} \approx -\frac{3}{2}R_{56}, \quad U_{5666} \approx 2R_{56}, \tag{4}$$

and similarly for higher orders. This expansion is valid for all compression systems without significant bend-plane focusing (*i.e.*, without quadrupole magnets).

4.1.2.2 *S-chicanes, double chicanes, arcs, and wigglers*

In addition to the standard four-dipole chicane, various other compressor types exist, which offer some flexibility in system characteristics. For example, an S-chicane offers some potential compensation of CSR-induced projected emittance growth, since, as Fig. 3 shows, it can be thought of as the simplest double chicane (see next paragraph). The R_{56} of an S-chicane consisting of six bends of equal bending angles (the two superfluous bends in the center of the sketch are not counted here, but are included simply to clarify the double chicane nature of an S-chicane) is:

$$R_{56} \approx -2\theta_0^2\left(\frac{1}{2}L_{act} - 2L_B\right). \tag{5}$$

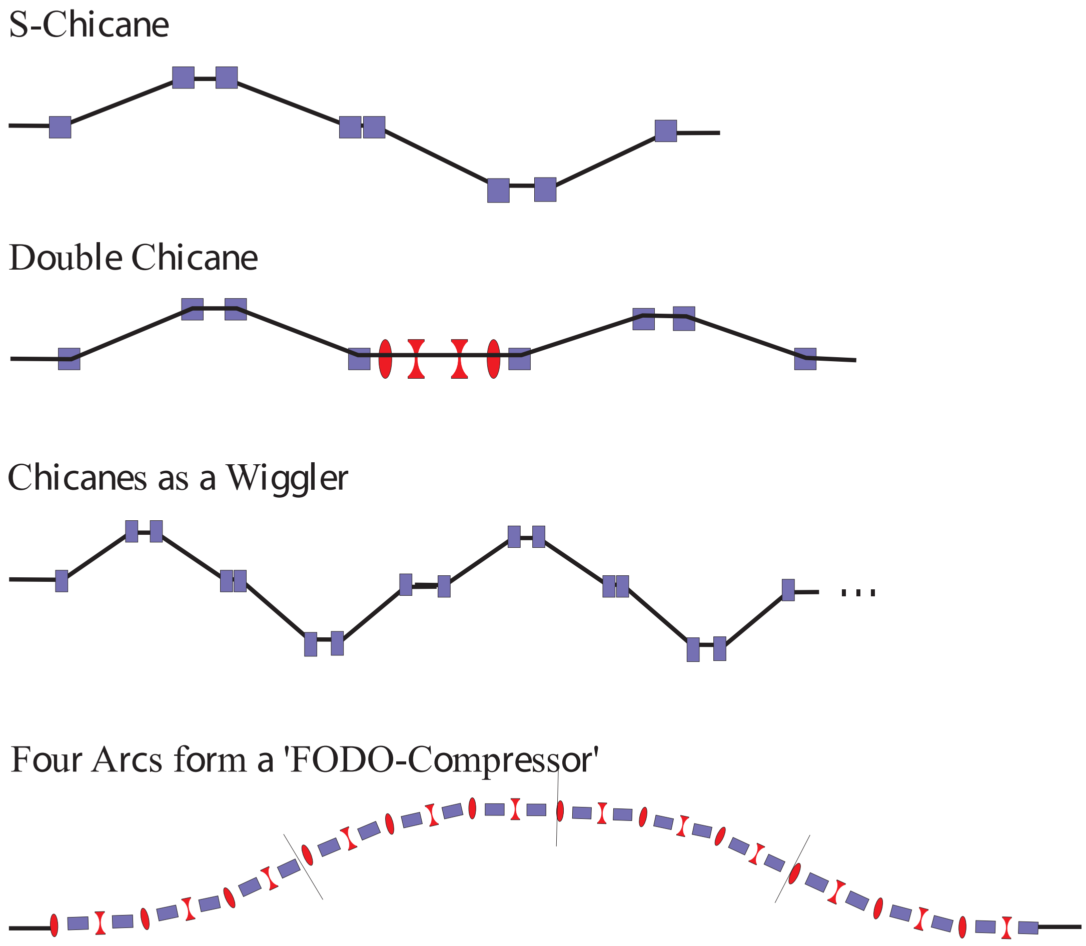
For chicanes where $L_B \ll L_T$ the R_{56} value is the same as for a simple chicane with equal active length and equal magnet bend angle.

The second layout of Fig. 3 shows a double chicane. Its R_{56} is simply the sum of the R_{56} values for each chicane. The second chicane is weaker to compress to higher charge densities in a weaker bending system in order to minimize emittance growth due to CSR. A further advantage in this case is the possibility to compensate projected emittance growth (see section 4.1.5) by optimizing the phase advance of the optics between the chicanes [4,5]. The emittance growth compensation is only effective if the longitudinal bunch shape is unchanged, although compressed, across the system.

Longer wiggler systems can also be formed, as shown in the third layout of Fig. 3, when a large R_{56} value is required. The use of a normal chicane in this situation may produce a very large peak bend-plane dispersion R_{16}, which will generate an unacceptably large transverse beam size. Such a long wiggler is useful in a linear collider where required R_{56} levels can be more than ten-times that of typical FEL values. It is also possible to locate quadrupole magnets between dipole magnets where the dispersion passes through zero, allowing continuous focusing across these long systems [6].

Arc beamline sections, as shown in the fourth layout of Fig. 3, can also be used as compressors. Typically these have opposite sign R_{56} values, which allows the possibility to compress a bunch which has an opposite sign energy chirp, such as produced by a strong longitudinal wakefield [7]. The R_{56} value can be conveniently adjusted by varying the betatron phase advance per cell in the bend plane. These systems are not used widely in FELs because they produce chromatic aberrations, introduce large beamline geometry excursions, and require many well aligned components. The R_{56} of a long FODO-cell arc with bend-plane phase advance per cell μ, total length L_T, total bend angle θ_T, and N_c FODO cells is approximately given by

$$R_{56} \approx \frac{\theta_T^2 L_T}{4N_c^2 \sin^2(\mu/2)}. \tag{6}$$



S-Chicane

Double Chicane

Chicanes as a Wiggler

Four Arcs form a 'FODO-Compressor'

Figure 3: Different types of magnetic compressor beamlines.

4.1.3 Compressing the Bunch

In the following chapter we go through the steps of relativistic electron bunch compression using dispersive beam line sections: the bunch is accelerated at an off-crest RF phase, thereby introducing an energy chirp (correlated energy spread along the bunch length), then it traverses a bending section, such as a chicane. We derive some useful approximations in a linear compression model and discuss higher order effects and their possible compensations qualitatively.

4.1.3.1 *RF acceleration*

The energy of a particle after acceleration in an RF section with phase ϕ and peak RF voltage V (ignoring a possible small initial energy), is given by

$$E(z_0) = eV\cos(\phi + kz_0), \tag{7}$$

where z_0 is the longitudinal position in the bunch, $E = E(0)$ the beam energy, and k the RF wavenumber ($k = 2\pi/\lambda$). Self-fields of the bunch are not taken into account here.

The RF phase is defined with maximum acceleration at $\phi = 0$, and its sign is such that the bunch head is at a lower energy than the bunch tail for $\pi < \phi < 0$. The head of the bunch is in the direction $z_0 < 0$, which makes the R_{56} value of a chicane a negative number.

Expanding Eq. (7):

$$E(z_0) = E\big(1 + p' \cdot z_0 + \frac{1}{2} p'' \cdot z_0^2 + \frac{1}{6} p''' \cdot z_0^3 + \mathcal{O}(z_0^4)\big), \tag{8}$$

and defining the linear term as the energy ‘chirp’ factor *h*,

$$h \equiv p' = -\frac{eV}{E} k \sin\phi, \tag{9}$$

makes the linear ($|kz_0| \ll 1$) relative energy deviation of a particle at longitudinal position z_0 within the bunch simply $\Delta E / E \equiv \delta = h z_0$.

4.1.3.2 *Compression in linear approximation*

At the end of a linac which induces an energy chirp *h* (see Eq. (9)), the mapping of longitudinal position and relative energy deviation of an ultra-relativistic particle is

$$\begin{aligned} z_1 &= z_0, \\ \delta_1 &= h z_0 + \delta_i, \end{aligned} \tag{10}$$

where $\delta_i \equiv \Delta E_i / E$ by definition is not correlated along the bunch length. It is the contribution to the net energy spread at this point which is due to the initial (random) intrinsic energy spread within the beam.

After a bend section with longitudinal dispersion R_{56}, and ignoring higher order terms, we have the mapping

$$\begin{aligned} z_2 &= z_1 + R_{56}\delta_1 = z_0 + R_{56}(\delta_i + h z_0), \\ \delta_2 &= \delta_1 = h z_0 + \delta_i. \end{aligned} \tag{11}$$

We ignore radiation effects and bunch interactions with the vacuum chamber walls, and assume that the particle energy has not been changed in the bend system. Rewriting z_2 we have

$$z_2 = (1 + hR_{56}) z_0 + R_{56}\delta_i. \tag{12}$$

Taking an ensemble average over all particles in the bunch using the notation $\langle \ldots \rangle$, and using our definition $\langle z_0 \delta_i \rangle = 0$, the second moment of the distribution ($\sigma_{z_2} \equiv \langle z_2^2 \rangle^{1/2}$) is the final rms bunch length

$$\sigma_{z_2} = \sqrt{(1 + hR_{56})^2 \sigma_{z_0}^2 + R_{56}^2 \sigma_{\delta_i}^2}, \tag{13}$$

where $\sigma_{z_0} \equiv \langle z_0^2 \rangle^{1/2}$ is the initial rms bunch length, and $\sigma_{\delta_i} \equiv \langle \delta_i^2 \rangle^{1/2}$ is the rms relative intrinsic energy spread (uncorrelated component) at energy E.

For 'full' compression where $1 + hR_{56} = 0$, the final bunch length is limited by the product of intrinsic energy spread, σ_{δ_i}, and the R_{56} of the compressor:

$$\check{\sigma}_{z_2} \approx |R_{56}|\sigma_{\delta_i}. \tag{14}$$

For substantial initial energy spread, as in the case of a linear collider where the beam is extracted from a storage ring, this is indeed the limiting issue and the value of R_{56} must be chosen small enough to allow the necessary compression.

In FEL applications, with a high-brightness RF-photocathode source, the intrinsic energy spread is extremely small and the bunch length is simply scaled from its original length as

$$\sigma_{z_2} \approx |1 + hR_{56}|\sigma_{z_0} = \sigma_{z_0}/C, \tag{15}$$

where C is the compression factor, $C \equiv \sigma_{z_0}/\sigma_{z_2}$, with typically $C \gg 1$. The limit to very short bunches in this case is typically due to higher order aberrations in the longitudinal phase space, which will be discussed in the next chapter.

In addition to bunch length compression, the intrinsic (uncorrelated) relative energy spread is magnified by the compression factor: $\sigma_{\delta_f} = C\sigma_{\delta_i}$, preserving the longitudinal emittance. In FEL applications this final intrinsic energy spread can be as important as the transverse emittance.

4.1.3.3 *Non-linearities in bunch compression*

The non-linearities of both the accelerating RF fields and the longitudinal dispersion can distort the longitudinal phase space. An example is the evolution of longitudinal phase space during bunch compression shown in Fig. 4, after a linac section and magnetic chicane. The non-linearity of the fundamental RF frequency is already visible before compression as a curvature in the energy chirp (left plots). After compression, the non-linearity of the chirp, together with the T_{566} of the chicane, dominates the shape of the bunch in phase space and a sharp spike develops at the head of the charge distribution with a width depending on the intrinsic energy spread (center plots). This spike can also lead to a local transverse emittance dilution [8], as described in the next sections.

Note that for a chicane, or any simple compressor with no quadrupoles, both effects (the non-linear chirp and the T_{566}) add to the spike. This is because all compressors have $T_{566} > 0$, and a chicane always has $R_{56} < 0$, which when accelerating forces a phase $\pi/2 < \phi < 0$ (*i.e.*, $h > 0$). With this simple system there are no free parameters to compensate the spike, except to limit the compression.

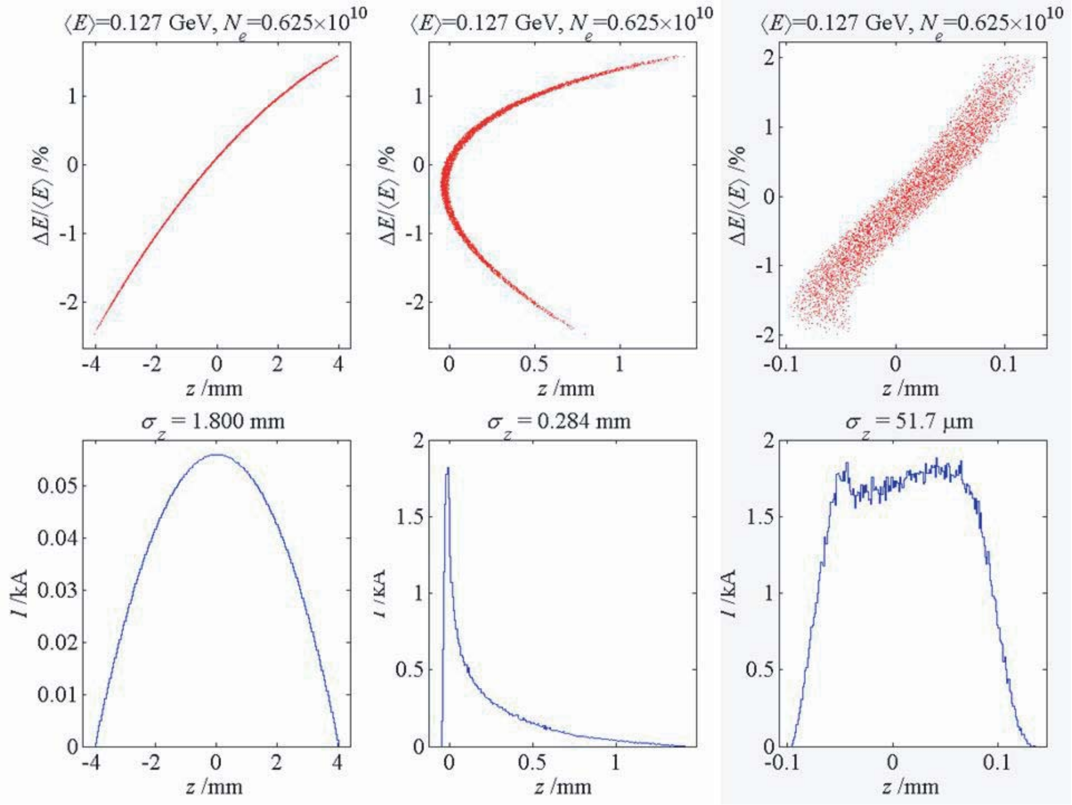


Figure 4: Longitudinal phase space and bunch current distribution before (left two plots) and after (center two plots) a bunch compressor chicane. The right two plots show the phase space after the chicane if a 3rd-harmonic RF section is used to compensate the non-linearities of the fundamental frequency and magnetic chicane. The R_{56} is increased here to achieve the same 1.8-kA peak current.

A higher harmonic RF system can be used to compensate the non-linearities of the fundamental frequency system and the higher order longitudinal dispersion in the magnetic chicanes. A simulation of such a compensation using a 3rd harmonic RF is shown on the right side of Fig. 4. The RF phase of the harmonic section ($n = 3$) is set to the decelerating crest ($\phi_3 = \pi$) to compensate the 2nd-order curvature with a reasonable peak voltage of 16 MV in this case. Most FEL projects under design presently use a similar scheme to keep the longitudinal phase space as linear as possible throughout bunch compression.

To linearize longitudinal phase space, a working point for RF phases and amplitudes must be found for the fundamental frequency and the n^{th} harmonic system ($n = 3$ for the European XFEL and $n = 4$ for the LCLS). The relation between the normalized RF amplitudes $a_{1,n} = eV_{1,n} / E$ and phases $\phi_{1,n}$ and the particle energy and its derivatives according to Eq. (8) is given in Eq. (16):

$$\begin{pmatrix} 1 & 0 & 1 & 0 \\ 0 & -k & 0 & -(nk) \\ -k^2 & 0 & -(nk)^2 & 0 \\ 0 & k^3 & 0 & (nk)^3 \end{pmatrix} \begin{pmatrix} a_1 \cos(\phi_1) \\ a_1 \sin(\phi_1) \\ a_n \cos(\phi_n) \\ a_n \sin(\phi_n) \end{pmatrix} = \begin{pmatrix} 1 \\ p' \\ p'' \\ p''' \end{pmatrix}. \tag{16}$$

Using this equation and Eq. (1), one can write Eq. (10) and (11) to higher order, require a certain beam energy and chirp and, at least for a compression system with one linac and a single chicane, calculate analytically the amplitudes and phases which set the quadratic term of the chirp to zero [9].

In realistic bunch compression schemes with multiple compression stages, intermediate booster RF, wakefields, and space charge effects, this can serve only as a starting point for the optimization of the bunch compression RF parameters. For the optimization of realistic cases, numerical simulation tools like the 2D *LiTrack* code [10] can be employed. Eq. (16) proves very useful to perform these optimizations, supplying a method to change phase space curvature in second and third order in a controlled manner while keeping the beam energy and the chirp constant.

4.1.3.4 *Stability of compression*

The final rms bunch length, as given by Eq. (15), in the case where the intrinsic energy spread is extremely small, can be quite sensitive to the energy chirp and thus to the precise RF phase. The relative change in final bunch length as a function of small RF phase variations, $\Delta\phi$, is given by

$$\frac{\Delta\sigma_z}{\sigma_z} \approx (1-C)\cdot\left(3\tan\phi+\frac{1}{\tan\phi}\right)\cdot\Delta\phi. \tag{17}$$

For high compression factors ($C \gg 1$) and acceleration not too far off crest ($|\phi| \ll 1$ and $\phi \neq 0$), this simplifies to

$$\frac{\Delta\sigma_z}{\sigma_z} \approx -C\cdot\frac{\Delta\phi}{\phi}. \tag{18}$$

To keep the peak current after compression stable to $\pm 10\%$ when compressing by a factor of $C = 100$ at an RF phase of -10°, the phase needs to be stable within ±0.01 degrees. This result applies to a single off-crest phased linac and chicane compressor. Multi-stage compression systems can be made less sensitive.

In the presence of a higher harmonic RF system, RF amplitudes and phases can be optimized to reduce phase sensitivity by more than an order of magnitude as described in [11]. In the case of the European XFEL, the optimal RF settings for phase insensitivity require a considerably larger amplitude for the 3rd harmonic RF than would be obtained simply by linearizing the compression process.

If longitudinal wakefields contribute significantly to the chirp, such as for an S-band normal-conducting linac, tight control of pulse-to-pulse charge stability is also required.

4.1.4 Self-Field Effects

A SASE-FEL driver linac has to provide bunches of such ultra-high brilliance and charge density that the interaction with their own electromagnetic field (self-field) in an undulator magnet is strong enough to start the SASE process from shot noise. This ability to produce strong self-fields can severely deteriorate the brilliance in the magnetic chicanes used for bunch compression. Although they are normally designed to avoid coupling from incoming energy deviations to transverse phase space, for example, R_{16} and R_{26} and higher order terms will be zero, or at least small, particle energy changes inside the chicanes due to self-fields like coherent synchrotron radiation or space charge fields may cause transverse emittance growth. In the following chapter, we will give an overview of self-fields, discuss emittance growth mechanisms, and provide numerical examples.

In a rigid bunch in linear motion with the velocity of light, the head particles influence the tail via diffraction and multiple diffraction of their primary field, *e.g.*, via the usual geometry wakes.

The curved motion of charged particles due to magnetic guiding fields causes radiation of electro-magnetic waves, so that head and tail particles can interact. Tail-head effects are usually much stronger as most of the power is radiated into the forward direction.

Most investigations of radiation effects assume free space conditions. The presence of perfect electric conducting boundary conditions (PEC) is taken into account for a few cases: parallel plates (see section 4.1.4.5), toroidal chambers [12], and for a simplified model of the wave equations (paraxial approximation [13,14]).

So far there is no usable method for the calculation of scattering objects that might cause significant energy propagation into the backward direction. It will be shown later that resistive wall effects are not generally negligible for the design of bunch compressors. The general treatment of such effects is unsolved even for linear motion. Resistive wall fields can be calculated for linear motion in cylindrical structures [15] and circular motion in toroidal chambers [12]. In principle, the calculation for curved trajectories between parallel plates could be done. All field calculations for resistive walls are done in the frequency domain so that they cannot directly be used for self-consistent particle tracking.

The usual assumption is that space charge effects scale with $1/\gamma^2$ for particles in constant linear motion. This is true if all particles of a bunch have the same constant velocity and direction, but the desired bunch compression is in contradiction to this condition. Even if the compression is so slow and gentle that no electromagnetic fields are radiated, the energy of the electromagnetic field, which travels with the beam, changes and the kinetic energies of the particles as well.

4.1.4.1 *Space charge effects for steady state linear motion*

For a round Gaussian beam with an rms length σ_z and an rms radius σ_r, the longitudinal field in free space is [16]

$$E_z(r=0,z,t) = -\frac{1}{4\pi\varepsilon_0}\frac{1}{\gamma\sigma_r}\int \lambda'(z-vt+x)F\left(\frac{x\gamma}{\sigma_r}\right)dx, \tag{19}$$

with

$$F(\xi) = \sqrt{\frac{\pi}{2}}\exp\left(\frac{\xi^2}{2}\right)\left[1-\operatorname{erf}\left(\frac{\xi}{\sqrt{2}}\right)\right] \approx \frac{1}{\sqrt{1+\xi^2}} \quad \text{for } |\xi| \gg 1. \tag{20}$$

The impedance per length for a wave-number k is given by

$$Z' = \frac{Z_0}{4\pi} \frac{jk}{(\gamma\beta)^2} H\Big(\frac{k\sigma_r}{\gamma\beta}\Big), \tag{21}$$

with

$$H(\xi) = \int \exp(-j\xi x) F(x) dx \approx 2 \ln |\xi|, \quad \text{for } |\xi| \ll 1. \tag{22}$$

The influence of a vacuum chamber with radius R can be neglected if $kR/\gamma \gg 1$.

For free space, the bunch in Table 1 (final bunch length) sees a maximum space charge field of 100 kV/m at 500 MeV and 1 kV/m at 5 GeV.

4.1.4.2 *Compression work*

For the same Gaussian beam as above, we calculate a lower limit for the exchange of kinetic energy and electro-magnetic field energy in the longitudinal plane for the case of adiabatic compression. In a beam pipe with radius R, the electromagnetic field energy is approximately:

$$W \approx \frac{e^2}{4\pi^{3/2}\varepsilon_0 \sigma_z} \ln \frac{R}{1.5 \cdot \sigma_r}. \tag{23}$$

If the beam is compressed from σ_{z_1} to $\sigma_{z_2} = \sigma_{z_1}/C$, C being the compression factor, and the transverse beam dimensions are equal before and after compression, then the beam loses kinetic energy: $\Delta W = W_2 - W_2 = (C-1)W_1$.

This is a lower limit, which depends on the assumption of a beam pipe with a certain radius. This lower limit is not necessarily negligible compared to synchrotron radiation energy loss in free space.

For the example of the ‘Zeuthen Chicane’ (see chapter 2.1) with a beam pipe radius of 1 cm and an average beam radius of 30 μm (at 5 GeV), we have a total loss of kinetic energy of 1.2 mJ.

4.1.4.3 *Coherent and incoherent synchrotron radiation in steady state circular motion*

We assume a thin Gaussian bunch of N positrons with constant longitudinal rms dimension σ_z on an orbit with radius ρ in stationary circular motion. The total radiated power as function of the bunch length is sketched in Fig. 5. The abscissa of the diagram in Fig. 5 is normalized to $\sigma_0 = \rho/\gamma^3$ (which is about a quarter of the critical photon wavelength).

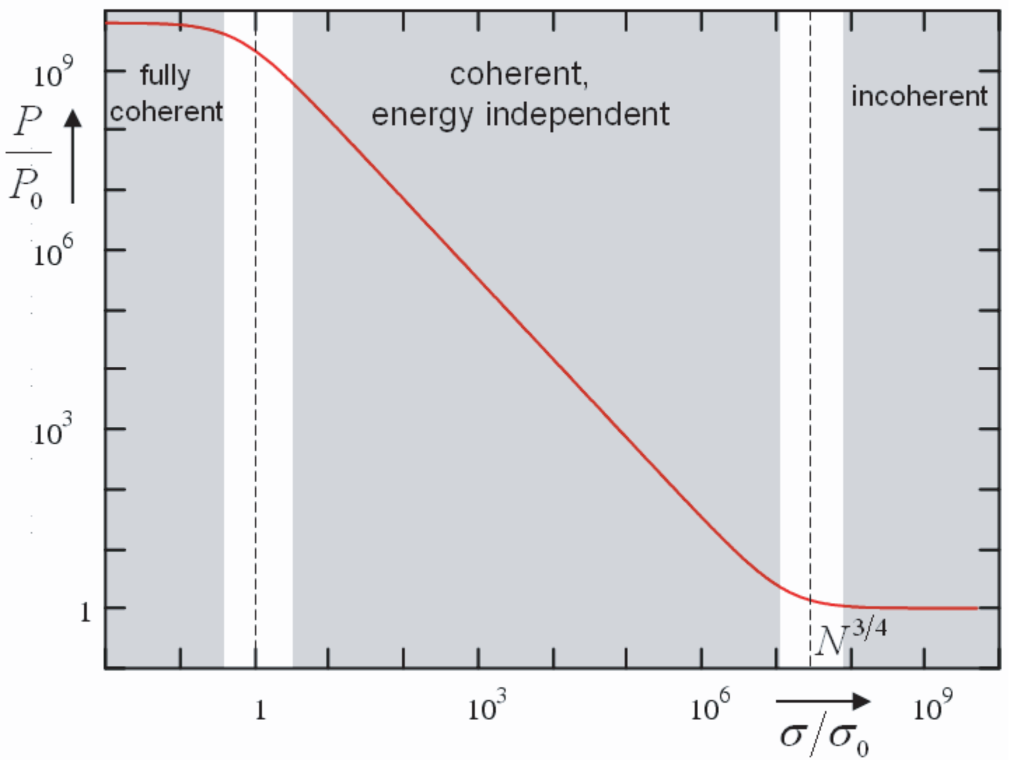


Figure 5: Regimes of fully coherent, energy-independent coherent and incoherent radiation.

Three regimes can be distinguished (small transition regimes are neglected). If the longitudinal distance between individual particles is sufficiently large, they radiate independently, or incoherently, so that the power

$$P_0 = N \frac{1}{6\pi} \frac{e^2 c}{\varepsilon_0} \frac{\gamma^4}{\rho^2} \tag{24}$$

is N times the power radiated by one electron. In the other extreme, particles in a longitudinal range smaller as σ_0 radiate fully coherent, independent of the fine structure of the longitudinal distribution. In this regime of fully coherent radiation, the particles radiate as one point charge with a power of:

$$P_f = N^2 \frac{1}{6\pi} \frac{e^2 c}{\varepsilon_0} \frac{\gamma^4}{\rho^2}, \tag{25}$$

which is N times the power of the incoherent radiation. Between these two extremes is a regime of coherent radiation with $P \propto N^2$ that does not depend on the energy γ, but on the rms bunch length σ_z

The power of the coherent, but energy independent radiation is

$$P_{csr} = N^2 x \frac{e^2 c}{\varepsilon_0} \frac{1}{\rho^{2/3} \sigma_z^{4/3}}, \quad \text{with } x = \frac{\Gamma(5/6)}{4\pi^{3/2}} \frac{1}{\sqrt[3]{6}} \approx 0.0279. \tag{26}$$

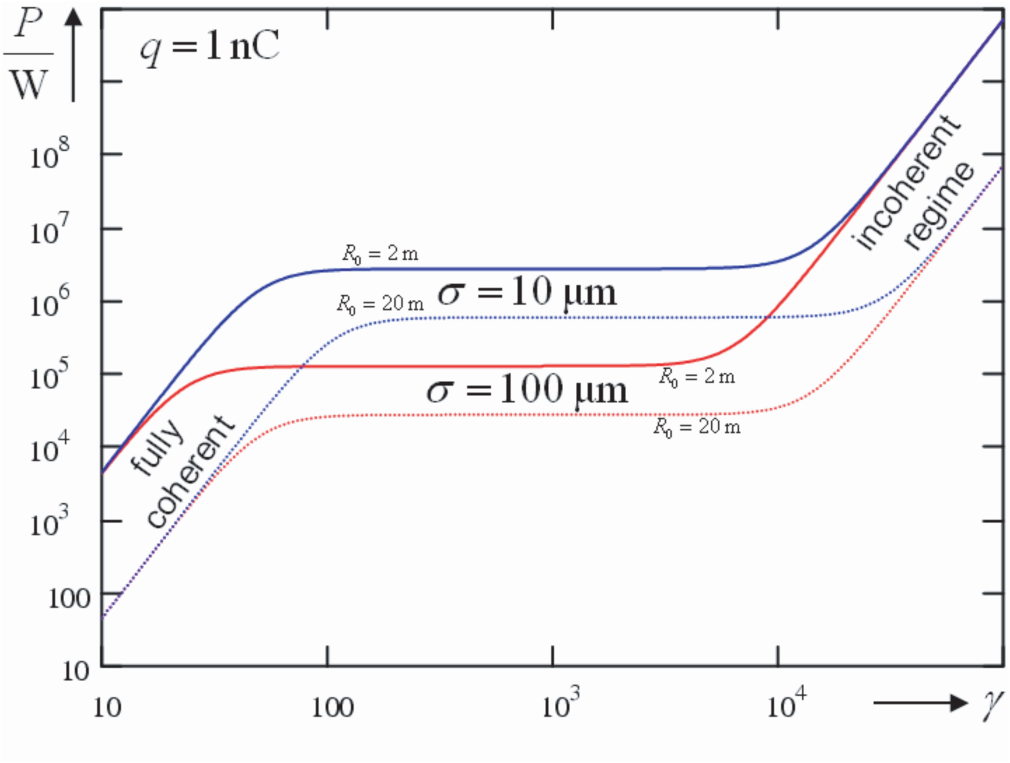


Figure 6: Radiated power versus energy of a bunch with the charge of 1 nC.

Therefore the transition to the incoherent regime is approximately at $\sigma_z = N^{3/4}\sigma_0$. Fig. 6 shows the radiated power as function of the energy for a Gaussian bunch with 1 nC charge. Curvature radii between 2 and 20 m and bunch lengths of the order of 10 to 100 μm are typical for the XFEL and LCLS bunch compressors. The choice of the energy for a bunch compression stage is a compromise between radiation and effects which scale with $q/\sigma_z\gamma^2$. This leads usually to a working point in the regime of energy independent coherent radiation.

For the Zeuthen example from chapter 2.1, we find a radiated power of 378 kW (for the final bunch length) and an energy loss of 0.6 mJ, assuming steady state conditions along the last bend.

4.1.4.4 *Transient CSR effects*

The time constants of transients can be estimated with a two-particle model. We assume both particles travel with the velocity $v = \beta c$ along the same trajectory $\mathbf{r}(s)$ which is pieced together from a semi-infinite line, an arc with curvature radius and a consecutive semi-infinite line. (This case is discussed in detail in [17].) The temporal distance between head and tail particle is Δ / v and the retarded distance is $\|\mathbf{r}(vt) - \mathbf{r}(vt' + \Delta)\| = c(t - t')$ is $\Delta/(1-\beta) \approx 2\gamma^2\Delta$ before the leading particle reaches the arc. Suppose the arc is long enough, the interaction is stationary again when the leading particle is still in the arc while the retarded tail just enters. This happens in the ultra-relativistic limit for the retarded distance $L_\Delta = \sqrt[3]{24\rho^2\Delta}$. The stationary process on the second semi-infinite line is reached when the retarded tail particle leaves the arc. This is observed by the head at the distance $\Delta/(1-\beta)$ to the end point of the arc.

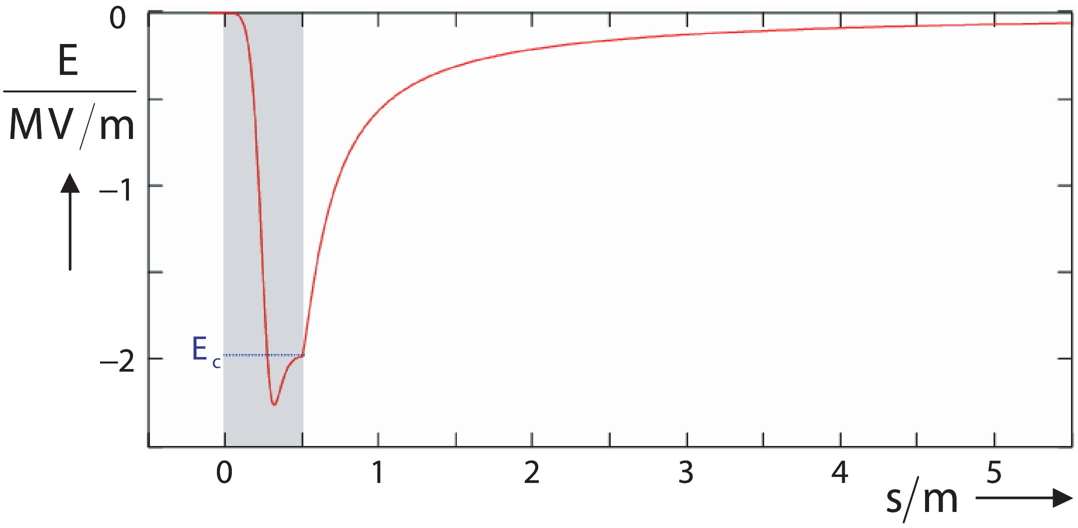


Figure 7: Longitudinal electrical field in the center of a spherical bunch that travels through a bending magnet. The field is plotted as function of the bunch position. (Bunch charge: 1 nC, bunch length: 20 μm, bending radius: 10 m).

Fig. 7 shows the longitudinal field in the center of a spherical Gaussian bunch that travels through a bend. For this case the characteristic length $L_{\sigma_z} = \sqrt[3]{24\rho^2\sigma_z}$ is 0.36 m so that the steady state condition is hardly reached. The asymptotic behaviour of the decay after the bend in ultra-relativistic limit is

$$E = -\lambda/(4\pi\varepsilon_0 D), \tag{27}$$

with D the distance to the exit and λ the 1D charge density. Figs. 8 and 9 show the normalized longitudinal field of an ultra-relativistic thin Gaussian bunch in the transition from linear to circular motion or otherwise. The field is normalized to

$$E_c = \frac{1}{\sqrt[3]{3}(2\pi)^{3/2}} \frac{1}{\rho^{2/3}\sigma_z^{4/3}} \frac{q}{\varepsilon_0} \tag{28}$$

which is approximately the steady state field in the center of the bunch. For the example in section 4.1.2.1, this field is 2 MV/m for the final bunch length.

4.1.4.5 *Shielding*

The normalized longitudinal CSR field along a Gaussian bunch in steady state circular motion between perfect electric conducting planes with gap height h is shown in Fig. 10 for different shielding parameters $x = h/\sqrt[3]{\rho\sigma_z^2}$. The coherently radiated power is $P = S(x)\cdot P_c$, with the shielding function $S(x)$ that is plotted in Fig. 11 and P_c the free space radiation according to Eq. (26).

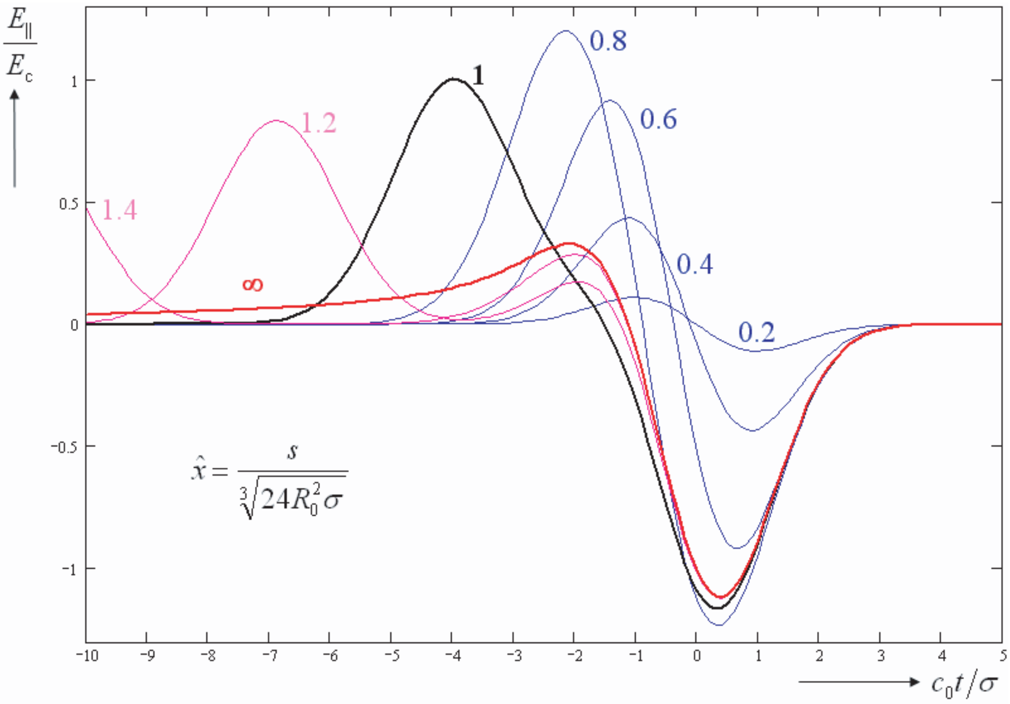


Figure 8: Transient CSR field: Injection

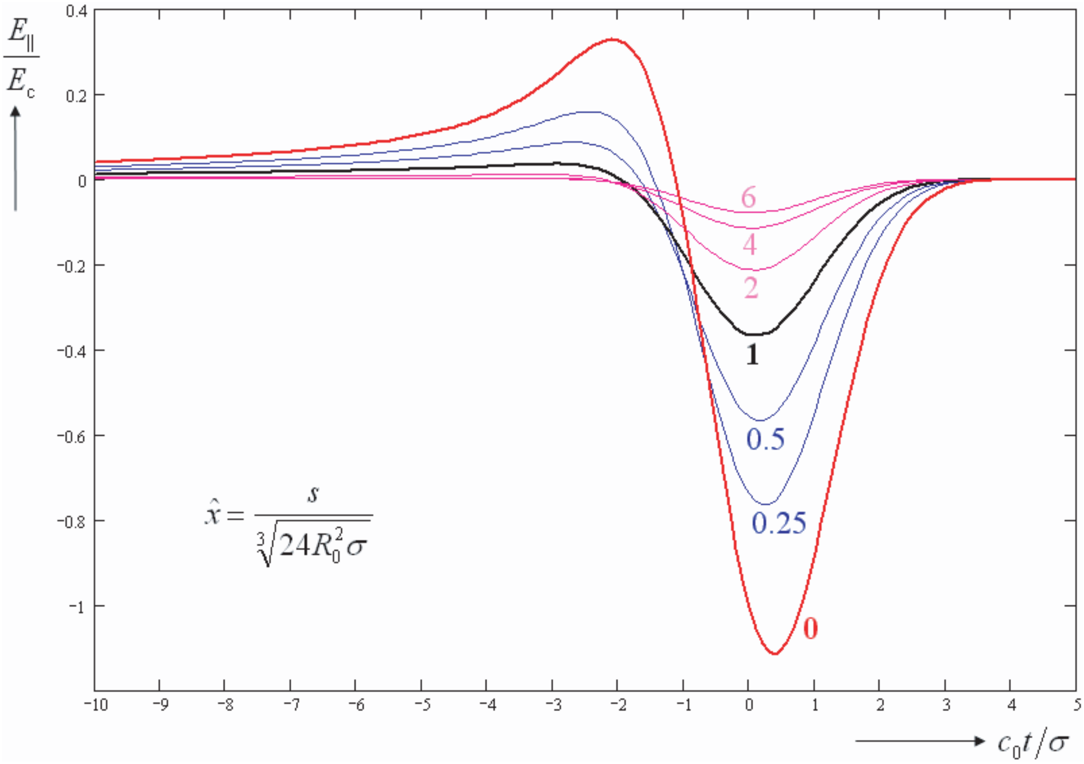


Figure 9: Transient CSR field: Ejection

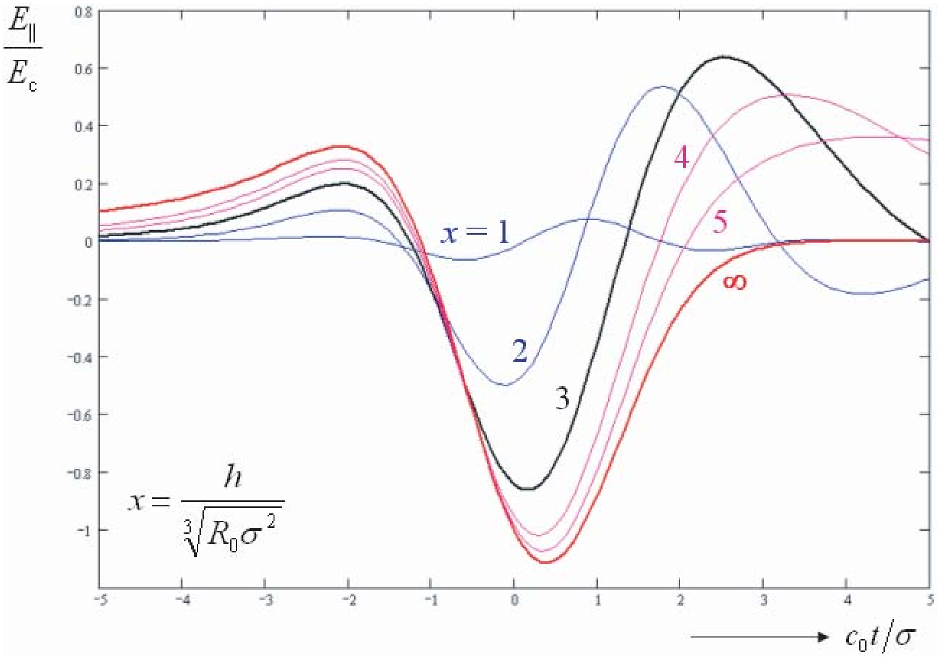


Figure 10: Shielding of circular motion CSR.

For a significant shielding of radiation the gap has to be $\sqrt[3]{\rho\sigma_z^2}$ or smaller. It is difficult to shield CSR completely, as the gap widths for the final (compressed) bunch length is so small that resistive wall wakes are intolerable (*e.g.*, for a bending radius at the chicane exit of $\rho = 10$ m, $x \le 1$, and a bunch length of $\sigma_z = 20$ μm, the gap must be smaller than 1.6 mm). On the other hand it is difficult to avoid shielding effects (*e.g.*, for a bending radius at the chicane entrance of $\rho = 10$ m, $x > 3$, and a bunch length of $\sigma_z = 200$ μm, the gap must be wider than 22 mm). It might be possible to design a 1-stage bunch compression system with parameters similar to the benchmark example, avoiding shielding effects according to Fig. 11, but it is nearly impossible to design a double chicane (see Fig. 3) with a compression ratio of about hundred without significant differences in the shielding characteristics for the two chicanes. This reduces the emittance compensation potential which balances free space field effects.

To judge for instance the shielding characteristic of a chicane, the steady state shielding criterion is not sufficient. Figure 12 shows the longitudinal electric field observed by a particle in the center of a distribution that is tracked through a bunch compressor. The solid line is calculated without shielding, the dashed line is for shielding by horizontal PEC planes. The energy loss is dominated by transients in drifts, especially downstream of magnet 3, which is even more clearly shown in Fig. 13. It is obvious that the field strength in the last magnets is stronger as the bunch length is reduced.

The shielded field strength in magnets 2, 3 and 4 is similar to that in free space as expected from the steady state criterion. The transient regimes in the drift downstream of the magnets is similar to the free space calculation close to the magnet, but further down the drift shielding is stronger than expected.

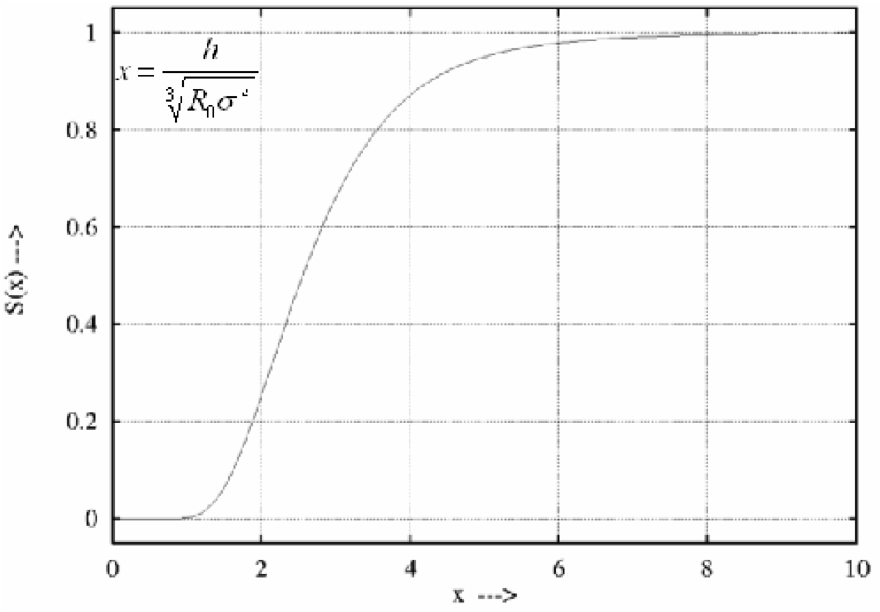


Figure 11: Shielding function.

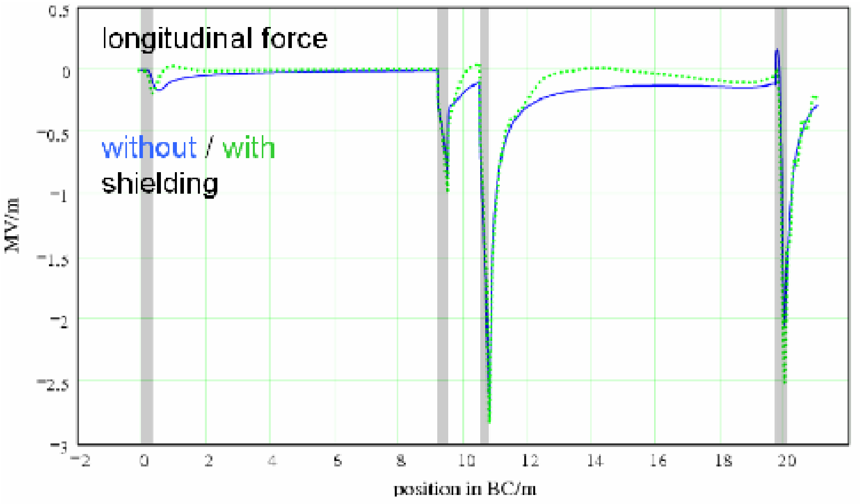


Figure 12: Shielding in a real BC.

The PEC planes act a dispersive wave guide system where fields propagate with less than the speed of light. The group velocities of waveguide modes v_g are related to cut-off frequencies ω_c by

$$\frac{v_g}{c} = \sqrt{1 - (\frac{\omega_c}{\omega})^2}. \tag{29}$$

Therefore the coherently radiated fields from the bends are not able to follow the beam. The beam escapes from the radiated field if

$$ct - v_g t > \sigma_z. \tag{30}$$

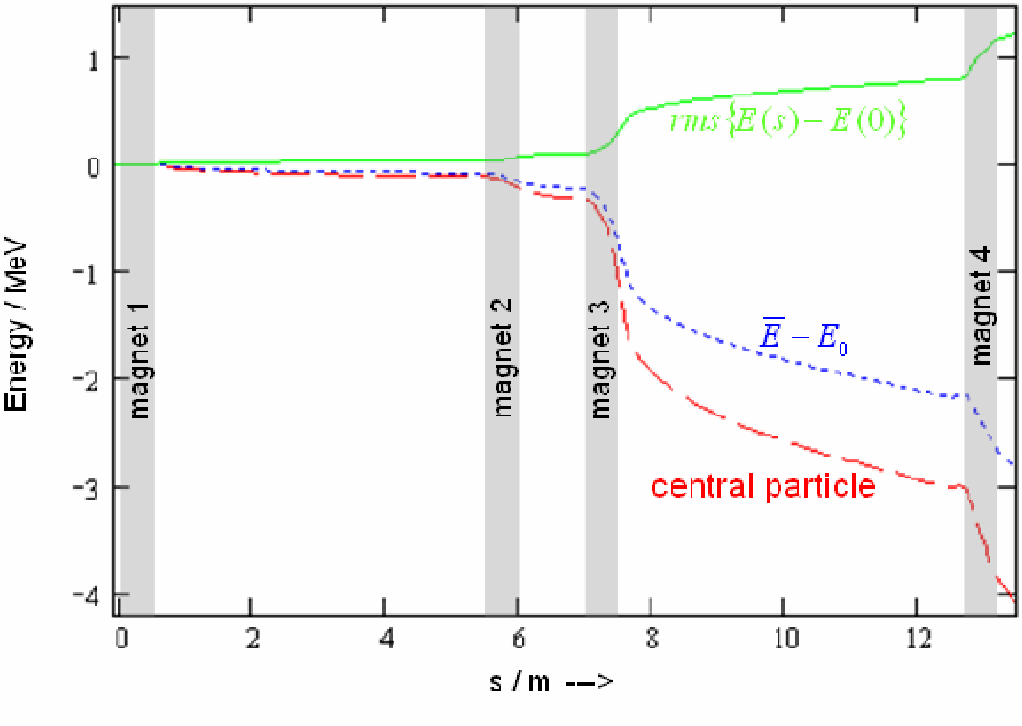


Figure 13: Energy and energy spread along the bunch compressor. Red: particle in center of distribution, blue: averaged energy, green: rms energy spread induced after the entrance of the chicane.

With the rms frequency of the bunch $\omega_{rms} = c/\sigma_z$ and the lowest cut-off frequency $\omega_c = \pi c/h$ of the shielding planes one finds that this condition is fulfilled for distances larger than

$$ct \approx \frac{2}{\pi^2}\frac{h^2}{\sigma_z}. \tag{31}$$

For example, in Fig. 12 this condition is fulfilled approximately one meter after the 3rd magnet (with a gap height $h = 1$ cm and a bunch length of $\sigma_z = 20$ μm).

While the beam approaches the last magnet the absolute field strength increases again. This is not due to radiation but caused by the compression of the transverse beam dimensions.

4.1.4.6 *Resistive wall wakes*

For simplicity, we assume a round beam pipe with an impedance per length of:

$$Z'(k) = \frac{1}{2\pi R}\cdot\frac{Z_s(k)}{(1 + jk\frac{R}{2}\frac{Z_s(k)}{Z_0})} \tag{32}$$

with the surface impedance $Z_s(k)$ and the radius of beam pipe R. For a metallic pipe, the surface impedance is given by

$$Z_s(k) = \sqrt{jkZ_0 / \kappa}, \tag{33}$$

κ being the conductivity. Fig. 14 shows the resistive wall wake of a 1 nC bunch in a round copper beam pipe.

For the example of the 'Zeuthen Chicane' (see section 4.1.2.1), the strength of the resistive wall wake assuming parallel copper plates 1-cm apart (or a beam pipe with 5-mm radius) for the final bunch length is up to 0.1 MV/m.

4.1.5 Emittance Growth

Transverse emittance is a measure of the phase space area, occupied by the bulk of the particles, projected onto one transverse plane:

$$\varepsilon^2 = \langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2. \tag{34}$$

For a reasonable particle distribution which is centered on the longitudinal axis, as for instance in a storage ring collider, this quantity is clear.

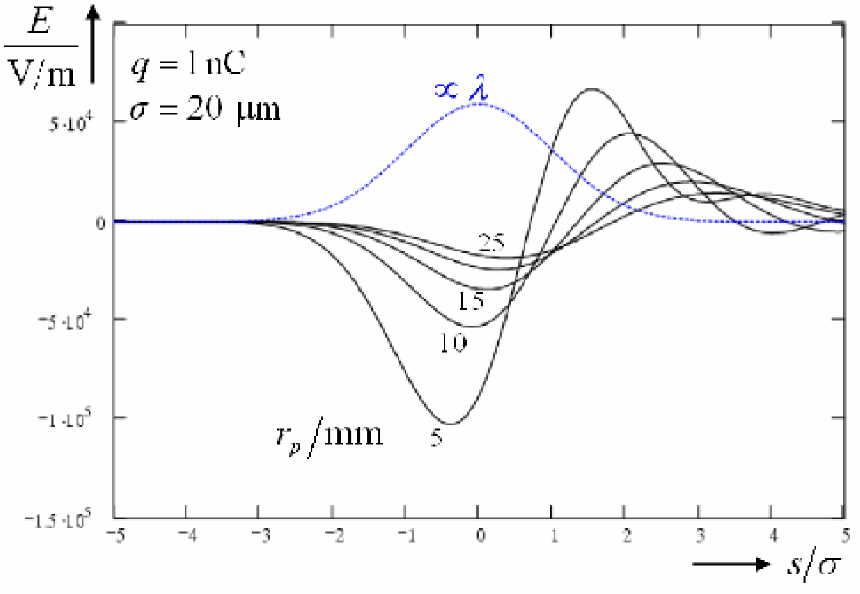


Figure 14: Resistive wall wake for a Gaussian bunch in a round copper pipe.

In a linac, however, wakefields and CSR fields tend to produce varying transverse offsets along the bunch, and 'banana' shaped bunches with long transverse tails may be the result. To characterize the ability of such a bunch to drive, for instance, a SASE FEL, the transverse emittance for longitudinal slices along the bunch, the *slice* emittance, is defined. The overall bunch-length integrated emittance is important because it is the measurable quantity for many beam diagnostics, and is referred to as the *projected* emittance.

4.1.5.1 *Projected emittance*

A simple model for projected emittance growth assumes that the phase space of the longitudinal beam slices are unperturbed, but their centroids $x_c(s)$, $x'_c(s)$ have shifted.

The second moments of the full bunch can then be expressed as superpositions of the second moments of the centroids and those of the unperturbed distribution, described by the Twiss parameters, α and β, and the initial emittance, ε_0.

$$\langle x^2\rangle = \langle x_c^2\rangle + \varepsilon_0\beta,\ \ \langle xx'\rangle = \langle x_c x_c'\rangle - \varepsilon_0\alpha,\ \ \langle x'^2\rangle = \langle x_c'^2\rangle + \varepsilon_0(1+\alpha^2)/\beta \qquad (35)$$

A simple estimate is given by the case where (for example) a CSR-induced bunch-length correlated energy spread ΔE_{rms} is generated over the last bending magnet of a chicane. We assume a short magnet with bending angle θ. The energy spread induces mostly an angular spread $\Delta x'_{rms} = |\theta|\,\Delta E_{rms}/E$ after the bend, producing a final projected emittance of

$$\varepsilon = \sqrt{\varepsilon_0^2 + \varepsilon_0\beta(\theta\Delta E_{rms}/E)^2}\ , \qquad (36)$$

which suggests a small (horizontal) β-function in that region of the chicane. A detailed study for realistic cases can be found in [5]

In addition to these more subtle self-field effects, more common mechanisms for projected emittance growth may also occur, such as imperfect dipole magnet field quality. The sensitivity involved here is appreciated by considering the 'Zeuthen Chicane', where the initial bend-plane beam size is 75 μm, growing to 2 mm at chicane center, and returning to 25 μm at the end of the chicane. This is equivalent to a factor of 1500 projected emittance growth at chicane center, and the expectation that a perfect chicane will completely restore the emittance by its finish. In fact a slight transverse magnetic field gradient, especially in the center two bends, can break the achromaticity and produce significant emittance growth. The large transverse beam size in the center magnets will sample any field non-uniformity and set a tight field quality tolerance on these magnets. The tolerance on the relative quadrupole field component of the center bends is

$$\left|\frac{b_1}{b_0}\right| < \frac{r_0\sqrt{2\Delta\varepsilon}}{|\theta_0\eta|\,\sigma_\delta\sqrt{\beta}}, \qquad (37)$$

where b_1/b_0 is the quadrupole field, evaluated at a radius r_0, normalized to the nominal dipole field, $\Delta\varepsilon$ is the tolerable emittance increase (e.g., 2% of ε_0), β and η are the bend-plane beta and dispersion functions, respectively, in the magnet, and θ_0 is the nominal magnet bend angle. With the parameters from Table 1, and $\beta \approx 20\,\mathrm{m}$, $\eta \approx \theta_0(\Delta L + L_B) \approx 266\,\mathrm{mm}$, and an rms energy spread $\sigma_\delta \approx 0.72\%$, the relative quadrupole field tolerance is a demanding level of $|b_1/b_0| < 5\times10^{-5}$ at $r_0 = 10$ mm. Such a field error will generate residual dispersion beyond the chicane and can be corrected by including weak correction quadrupoles in the chicane.

Similarly, the relative sextupole field tolerance is

$$\left|\frac{b_2}{b_0}\right| < \frac{r_0^2\sqrt{\Delta\varepsilon}}{|\theta_0|\eta^2\sigma_\delta^2\sqrt{\beta}}, \qquad (38)$$

or in this case $|b_2/b_0| < 2\times10^{-4}$ at $r_0 = 10$ mm, also requiring great care in dipole magnet fabrication.

4.1.5.2 *Simple estimation of CSR projected emittance growth*

An example is the Zeuthen benchmark chicane (see Table 1). The mean CSR-induced energy loss per particle is given by Eq. (26) as

$$\Delta E_{mean} = P_{csr}\cdot\frac{L_B}{cN} \approx 0.6\text{ MeV}. \qquad (38)$$

The rms energy spread for a Gaussian bunch is approximately

$$\Delta E_{rms} \approx 0.7\cdot\Delta E_{mean} \approx 0.4\text{ MeV}. \qquad (40)$$

The (normalized) emittance at the chicane entrance is $\gamma\varepsilon_0 = 1$ μm and the β-function in the 4th bend magnet is about five meters. With the rough estimate from Eq. (36) we predict a final projected emittance of $1.3\varepsilon_0$ at a beam energy of 5 GeV (and $3\varepsilon_0$ at 500 MeV).

Benchmark calculations with different codes at the workshop yielded between $1.4\varepsilon_0$ and $1.6\varepsilon_0$. The codes include effects from the full chicane, while Eq. (36) is only for the final, but typically dominant bend. For the projected emittance at $E = 500$ MeV, the codes yield around $5\varepsilon_0$.

A remark to the scaling with energy: R_{56} and compression factor are kept constant. The CSR fields are independent of beam energy, so their relative strength scales with the inverse beam energy and the impact on transverse emittance is stronger at the lower energy. With a different scaling, keeping the absolute chirp $h\cdot E$ constant, the emittance growth becomes almost independent of beam energy.

4.1.5.3 *Slice emittance*

The time-sliced emittance can be increased by two effects:

- Inside the compressor chicane the slice will sample the non-linearities of the longitudinal CSR field. When the bunch is deflected in a bend, a longitudinal slice of particles does not stay perpendicular to the momentum; it is yawed with respect to the momentum axis. Assuming no bend-plane focussing, and a convergent incoming beam with a waist inside the chicane, the projected length of a slice with an initial length of zero is

$$\sigma_{proj} = \sqrt{\varepsilon_0\beta_w}\sqrt{\left(\frac{R_{52} - s_w R_{51}}{\beta_w}\right)^2 + R_{51}^2}, \qquad (41)$$

with β_w the β-function at the waist, s_w the distance between chicane entry and waist, and R_{51} and R_{52} the usual transport matrix coefficients from start of chicane to any point within [5]. For a four-dipole chicane, $|(R_{52} - s_w R_{51}) / \beta_w|$ is small in the region from the end of the third to the fourth magnets, where strong CSR fields occur, if the horizontal optical waist is positioned there. Further reduction of slice emittance growth can be achieved by minimizing β_w.

- The non-linear variation of the longitudinal and transverse CSR fields, as a function of transverse position, contributes to slice emittance growth, even if the projected slice length is small, such as inside and downstream of the last bending magnet.

4.1.6 Numerical CSR Models

In real bunch compressors, neither in arcs nor in the drifts between, is the steady state condition ever reached. A precise calculation of particle dynamics in the presence of CSR fields has to consider the spatial and temporal dependency of electromagnetic fields that are generated on arcs and lines in a bunch compression system by a bunch that changes its shape during compression. Essentially two types of approaches are presently used for the calculation of particle distributions on curved trajectories with CSR: The 1-D approach, such as used by the tracking code *Elegant* [18], uses a simplified model for the calculation of longitudinal forces. It neglects transverse forces as well as transverse beam dimensions and assumes that the longitudinal distribution is unchanged at retarded times. A ‘renormalized’ Coulomb term is used to extract the field singularity in the 1-D beam. The sub-bunch approach uses a set of 3-D charge distributions, *e.g.*, time-independent Gaussian, to approximate the source distribution. The physical model of the sub-bunch method is complete, but the resolution of phase space modelling is severely limited by the numerical effort for the field calculation of all point to point interactions. It should be mentioned that in many cases even a perturbation calculation is sufficient where the electromagnetic field of the ideal distribution is used to calculate the forces that are used for particle tracking.

4.1.7 Acknowledgments

The work was supported in part by the U.S. Department of Energy, contract DE-AC02-76SF00515.

4.1.8 References

1. ICFA Beam Dynamics Mini Workshop (Future Light Sources Sub-Panel), *Coherent Synchrotron Radiation and Its Impact on the Dynamics of High Brightness Electron Beams*, January 14-18, 2002, DESY-Zeuthen (Berlin, GERMANY). http://www.desy.de/csr/csr_workshop_2002/csr_workshop_2002_index.html
2. *LCLS CDR*, SLAC Report No. SLAC-R-593, 2002.
3. *TESLA TDR*, DESY Report No. DESY-2001-011, 2001.
4. P. Emma, R. Brinkmann, PAC’97, Vancouver, B.C., Canada, 1997.
5. M. Dohlus, T. Limberg: *Impact of Optics on CSR-Related Emittance-Growth in Bunch Compressor Chicanes*, PAC’05, Knoxville, TN, 2005.

6. T. Raubenheimer, *et al.*, PAC'93, Washington, D.C., 1993.
7. K.L.F. Bane, *et al.*, APAC'98, Tsukuba, Japan, 1998.
8. R. Li, *Analysis and Simulation on the Enhancement of the CSR Effects*, XX International Linac Conf., Monterey, CA, Aug. 2000.
9. K. Floetmann, T. Limberg, Ph. Piot, *Generation of Ultrashort Electron Bunches by cancellation of nonlinear distortions in the longitudinal phase space*, TESLA-FEL Report 6, 2001, DESY.
10. K.L.F. Bane and P. Emma, *LiTrack: A Fast Longitudinal Phase Space Tracking Code with Graphical User Interface*, PAC'05, Knoxville, TN, 2005.
11. M. Dohlus, T. Limberg: *Bunch Compression Stability Dependence on RF Parameters*, FEL'05, Stanford, CA, 2005.
12. R. Warnock, P. Morton: *Fields excited by a beam in a smooth toroidal chamber*, SLAC-PUB-4562, March 1988.
13. G.V. Stupakov, I.A. Kotelnikov: *Shielding and synchrotron radiation in toroidal waveguide*, Phys. Rev. ST Accel. Beams 6, 034401 (2003).
14. T. Agoh and K. Yokoya: *Calculation of coherent synchrotron radiation using mesh*, Phys. Rev. ST Accel. Beams 7, 054403 (2004).
15. K. Yokoya: *Resistive wall wake functions for arbitrary pipe cross section*, PAC 1993, Vol.5, p. 3441-3443.
16. M. Dohlus, A. Kabel, T. Limberg: *Coherent Effects of a Macro-Bunch in an Undulator*, Nucl. Instr. And Meth. A 445 (2000), p. 84-89.
17. E. Saldin, E. Schneidmiller, M. Yurkow: *Coherent Radiation of an Electron Bunch Moving in an Arc of a Circle*, TESLA-FEL-96-14, 1996.
18. M. Borland, *Elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation*, APS LS-287, Sep. 2000.

4.2 Microbunching instability due to bunch compression

Zhirong Huang, Juhao Wu (SLAC)
Timur Shaftan (BNL)
mail to: zrh@slac.stanford.edu

4.2.1 Introduction

Magnetic bunch compressors are designed to increase the peak current while maintaining the transverse and longitudinal emittances in order to drive a short-wavelength free electron laser (FEL). Recently, several linac-based FEL experiments observe self-developing micro-structures in the longitudinal phase space of electron bunches undergoing strong compression [1-3]. In the mean time, computer simulations of coherent synchrotron radiation (CSR) effects in bunch compressors illustrate that a CSR-driven microbunching instability may significantly amplify small longitudinal density and energy modulations and hence degrade the beam quality [4]. Various theoretical models have since been developed to describe this instability [5-8]. It is also pointed out that the microbunching instability may be driven strongly by the longitudinal space charge (LSC) field [9,10] and by the linac wakefield [11] in the accelerator, leading to a very large overall gain of a two-stage compression system such as found in the Linac Coherent Light Source (LCLS) [12].

This paper reviews theory and simulations of microbunching instability due to bunch compression, the proposed method to suppress its effects for short-wavelength FELs, and experimental characterizations of beam modulations in linear accelerators. A related topic of interests is microbunching instability in storage rings, which has been reported in the previous ICFA beam dynamics newsletter No. 35 (http://www-bd.fnal.gov/icfabd/Newsletter35.pdf).

4.2.2 Sources of Initial Beam Modulations

The high-brightness electron beams required for a short-wavelength FEL are generated by photocathode rf guns. Electron density modulations will be produced during the photoemission process since the typical drive laser intensity profile is not smooth. In fact, the laser intensity modulation may even be enhanced when a flat-top temporal distribution is desired to mitigate the space charge induced emittance growth, as demonstrated by recent experimental studies of temporal pulse shaping techniques [13]. The initial bunch current spectrum may be characterized by a bunching factor

$$b_0(k_0) = \frac{1}{Nec}\int I_0(z_0)e^{-ik_0z_0}dz_0 \ , \qquad (1)$$

where $I_0(z_0)$ is the initial current profile as a function of the longitudinal position z_0 (with the bunch head at $z_0 > 0$), $\lambda_0 = 2\pi/k_0$ is the initial modulation wavelength under considerations, and N is the total number of electrons. At relatively low beam energies in the gun section, the electrons repel each other in the higher density regions and initiate the space charge oscillation between density and energy modulations. The initial density modulation may be reduced at the expense of the increased energy modulation. This process will be further discussed in Sec. 4.2.4.1.

In addition to any residual density and energy modulations created by the non-smooth laser profile, the electron density modulation can be caused by shot noise fluctuations as well. Since the gain bandwidth of the microbunching instability is very broad as discussed below, the shot noise bunching is on the order of $1/\sqrt{N_\lambda}$, where N_λ is the number of electrons per modulation wavelength.

4.2.3 Theory

4.2.3.1 *Gain mechanism*

The mechanism for microbunching instability is similar to that in a klystron amplifier [9,5]. A high-brightness electron beam with a small amount of density modulation can create longitudinal self-fields that lead to beam energy modulation as shown in Fig. 1. Since a magnetic bunch compressor (usually a chicane) introduces path length dependence on energy, the induced energy modulation is then converted to additional density modulation that can be much larger than the initial density modulation. This amplification process (the gain in microbunching) is accompanied by a growth of energy modulation and a possible growth of emittance if significant energy modulation is induced in a dispersive region such as the chicane. Thus, the instability can be harmful to short-wavelength FEL performance by degrading the beam quality.

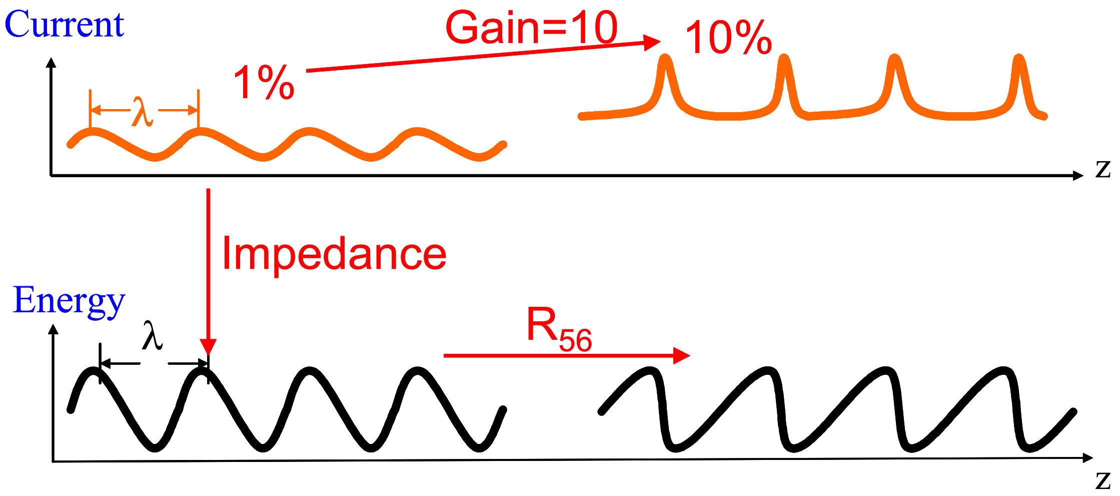


Figure 1: An illustration of microbunching instability in a bunch compressor.

It is typical to assume that modulation wavelengths are much shorter than the electron bunch length, and that density modulation amplitudes are much smaller than the average current. Under these assumptions, the amplitude of the density modulation at each wavelength grows independently and is characterized by a gain spectrum G(k_0) of the accelerator system:

$$G(k_0)=\left|\frac{b_f(k_f)}{b_0(k_0)}\right| , \tag{2}$$

where $b_f(k_f)$ is the final bunching factor for the compressed wavenumber k_f corresponding to k_0.

In what follows, we further divide the self-fields into two categories: the self-fields created upstream of the bunch compressors such as the LSC field and linac wakefields, and the self-fields created during the compression process such as CSR. Although the gain mechanism is the same for all impedance sources, the treatment of CSR instability is more complicated due to the coupling of transverse and longitudinal motions in a bunch compressor.

4.2.3.2 *Microbunching gain due to LSC and wakfields upstream of the compressor*

Any wakefield upstream of a bunch compressor can contribute to beam energy modulation. For very short modulation wavelengths under considerations, we can neglect effects of vacuum chamber and use the free-space LSC impedance per unit length (see, e.g., Ref. [14,15])

$$Z_{LSC}(k_0)=\frac{iZ_0}{\pi k_0 r_b^2}\left[1-\frac{k_0 r_b}{\gamma}K_1\left(\frac{k_0 r_b}{\gamma}\right)\right]\approx\frac{iZ_0 k_0}{4\pi\gamma^2}\left(1+2\ln\frac{\gamma}{k_0 r_b}\right) \text{, when } \frac{k_0 r_b}{\gamma}<<1 , \tag{3}$$

where $Z_0 = 377\ \Omega$ is the free space impedance, r_b is the beam radius of a uniform cross section, and K_1 is the modified Bessel function. The high-frequency behaviour of the geometric impedance in a periodic accelerating structure is [16]

$$Z_{Linac}(k_0) = \frac{iZ_0}{\pi k_0 a^2} \ , \tag{4}$$

where a is the average iris radius of the accelerating structure. Note that both LSC and the high-frequency linac impedance are imaginary, indicating redistribution of beam energy without any net energy loss. The LSC impedance is the dominant contribution to the microbunching instability at very high frequencies when $ka/\gamma >> 1$ [10].

At about 100 MeV or higher beam energies, the electron density modulation is basically frozen in the linac, and the energy modulation accumulates according to

$$\Delta\gamma_m(k_0) = -\frac{I_0 b_0(k_0)}{I_A}\int_0^L ds \frac{4\pi Z(k_0;s)}{Z_0} \ , \tag{5}$$

where $I_A \approx 17$ kA is the Alfven current, $Z = Z_{LSC} + Z_{Linac}$ is the total impedance, and s is the bunch position along the accelerator beam line, and L is the total length of the linac.

The accumulated energy modulation is then converted to additional density modulation by a bunch compressor with the momentum compaction R_{56}. For a gaussian energy distribution with the intrinsic rms energy spread $\sigma_\delta = \sigma_\gamma/\gamma_b$ prior to the bunch compressor (at energy $\gamma_b mc^2$), the gain in density modulation after the compressor is [9]

$$G \approx \frac{I_0}{\gamma_b I_A}\left| k_f R_{56}\int_0^L ds \frac{4\pi Z(k_0;s)}{Z_0}\right| \exp\left(-\frac{k_f^2 R_{56}^2 \sigma_\delta^2}{2}\right) \ . \tag{6}$$

Here $k_f = k_0/(1+hR_{56})$ is the compressed modulation wavenumber, and $h<0$ is the linear energy chirp in front of the compressor (relative energy correlation divided by the bunch length). The gain typically peaks when $k_f R_{56}\sigma_\delta \approx 1$, and is exponentially suppressed at shorter modulation wavelengths. Since the LSC impedance scales almost linearly with k_0, the maximum LSC-induced microbunching gain scales as $\sigma_\delta^{-2} R_{56}^{-1}$ and depends sensitively on the intrinsic energy spread.

4.2.3.3 *Microbunching gain due to CSR in a compressor chicane*

The electron density modulation is a source of CSR emission in a bunch compressor chicane. The resulting energy modulation due to the CSR force in one dipole can be converted into additional density modulation at the next dipole, giving rise to the CSR instability inside a bunch compressor. For modulation wavelengths much shorter than the electron bunch length, we can neglect shielding effects of conducting walls and transient effects associated with short bends to employ the longitudinal CSR impedance for a line charge model [17,18]:

$$Z_{CSR}(k;s) = (1.63 + 0.94i)\frac{Z_0 k^{1/3}}{4\pi\rho(s)^{2/3}} \ , \tag{7}$$

where $\rho(s)$ is the bending radius at a distance s from the beginning of the bunching compressor. The Effective longitudinal CSR force for a bunch with the finite transverse extend is discussed in Ref. [19,20].

However, the density modulation is no longer frozen in the chicane. In fact, the longitudinal motion in a dipole is coupled to the horizontal motion, and the density modulation is subject to emittance damping when the path length spread due to a finite beam size is comparable to the reduced modulation wavelength [5], i.e.,

$$\frac{L_d}{\rho}\sqrt{\varepsilon_0\beta_0} \approx \frac{\lambda}{2\pi} \ . \tag{8}$$

Here L_d is the length of the dipole, β_0 is the initial beta function, and ε_0 is the transverse emittance. Taking into account the emittance effect and changes of modulation wavelengths due to compression, the CSR microbunching is governed by an integral equation as [6,7]

$$b(k(s);s) = b_0(k(s);s) + \int_0^s d\tau K(\tau,s) b(k(\tau);\tau) \ , \tag{9}$$

where the kernel is

$$K(\tau,s) = ik(s)R_{56}(\tau \to s)\frac{I(\tau)Z_{CSR}(k(\tau);\tau)}{\gamma_b I_A}\exp\left[-\frac{k_0^2 U^2(s,\tau)\sigma_\delta^2}{2}\right]$$

$$\times\exp\left[-\frac{k_0^2\varepsilon_0\beta_0}{2}\left(V(s,\tau)-\frac{\alpha_0}{\beta_0}W(s,\tau)\right)^2-\frac{k_0^2\varepsilon_0}{2\beta_0}W^2(s,\tau)\right], \tag{10}$$

$k(\tau)/B(\tau) = k(s)/B(s) = k_0$, $B(s) = (1+hR_{56}(s))^{-1}$, $I(\tau) = I_0 B(\tau)$ is the peak current at the location τ, α_0 is the initial Twiss parameter, and

$$U(s,\tau) = B(s)R_{56}(s) - B(\tau)R_{56}(\tau),$$

$$V(s,\tau) = B(s)R_{51}(s) - B(\tau)R_{51}(\tau),$$

$$W(s,\tau) = B(s)R_{52}(s) - B(\tau)R_{52}(\tau). \tag{11}$$

For typical four-dipole chicanes, the integral equation can be solved by an iterative method to obtain analytical formulas for the final gain [7]. The results are compared to two numerical tracking codes (*ELEGANT* [21] and CSR_calc [22]) for a benchmark chicane (see http://www.desy.de/csr/ for more details) as shown in Fig. 2 [23].

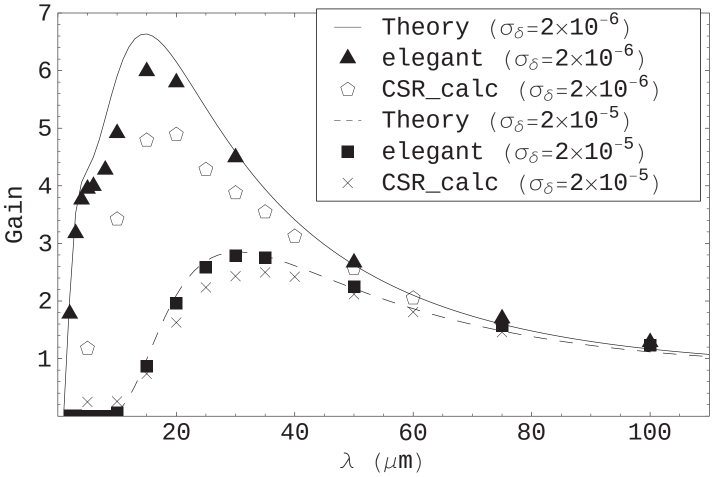


Figure 2: CSR microbunching gain for a benchmark chicane as a function of the initial modulation wavelength for $\gamma\varepsilon_0 = 1\ \mu\text{m}$ at 5 GeV.

4.2.3.4 *Landau damping with a laser heater*

When more than one bunch compressors are present in the accelerator, the overall gain is the product of individual compressor gains that includes LSC, CSR and linac wakefield effects. For the very small uncorrelated energy spread generated from a photocathode rf gun (with a measured rms value of 3 to 4 keV [24]), the peak overall gain can be very large (>1000) for a two-stage compression system found in typical x-ray FEL designs and can even significantly amplify the electron shot noise. The gain is usually dominated by the LSC effect as the CSR microbunching is subject to emittance damping discussed above. Thus, the only effective way to suppress the large gain is to increase the uncorrelated energy spread before compressing the bunch. Ref. [10] suggests a laser heater that makes use of resonant laser-electron interaction in a short undulator to induce rapid energy modulation at the optical frequency as an effective energy spread for Landau damping. For an undulator with a strength parameter K and a length of L_u, the amplitude of the energy modulation at the resonant laser wavelength is

$$\Delta\gamma_L = \sqrt{\frac{P_L}{P_0}}\frac{KL_u}{\gamma_0\sigma_r}\left[\mathrm{J}_0\left(\frac{K^2}{4+2K^2}\right)-\mathrm{J}_1\left(\frac{K^2}{4+2K^2}\right)\right]\exp(-\frac{r^2}{4\sigma_r^2})\ , \tag{12}$$

where P_L is the laser peak power, $P_0 \approx 8.7$ GW, J_0 and J_1 are the usual Bessel functions associated with a planar undulator, and σ_r is the rms laser spot size in the undulator.

For the LCLS X-ray FEL operated at the radiation wavelength of 1.5 Å, the uncorrelated rms energy spread can be increased from about 3 keV produced by the rf gun to about 40 keV without degrading the FEL performance. The LCLS laser heater is designed in a small magnetic chicane near the end of the photoinjector at 135 MeV as shown in Fig. 3 [12], with a total undulator length of about 0.5 m. The laser rms spot size is chosen to match the electron rms transverse beam size in order to generate a more Gaussian-like energy profile for effective Landau damping. The modest amount of the laser power ($P_L \approx 1$ MW) is provided by the 800-nm Ti:sapphire laser that drives the photocathode rf gun. In addition to easy optical access, the chicane provides a useful temporal washing effect (due to transverse and longitudinal coupling) that completely

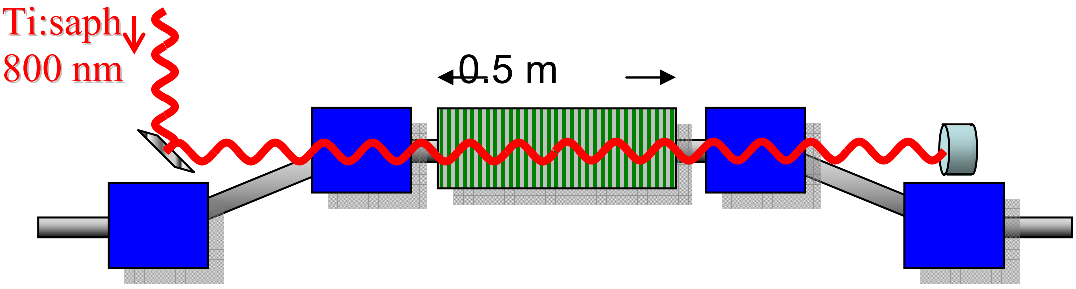


Figure 3: Layout of the LCLS laser heater inside a magnetic chicane at the injector end ($\gamma_0 mc^2$ = 135 MeV).

smears the laser-induced 800 nm energy modulation. The induced emittance growth due to the energy change in the chicane is negligible. The overall microbunching gain can be reduced to a tolerable level determined by beam dynamics simulations to be discussed next. A similar laser heater has also been adopted by the FERMI FEL project at Trieste [25].

4.2.4 Simulations

The detrimental effects of microbunching instability in bunch compressors are first illustrated by computer simulations [4]. Since the modulation wavelengths are generally small compared to the electron bunch length, the simulations require a longitudinal bin size much smaller than the wavelength and hence typically use a million or more macroparticles. Even with the use of quiet loading algorithms such as the Halton sequence, numerical noise remains an issue in start-to-end simulations and must be controlled to an acceptable level. We discuss some of these issues here and the start-to-end LCLS simulations that demonstrate the function of the laser heater and set the tolerable drive laser modulation amplitudes.

4.2.4.1 *Injector simulations*

As mentioned in Sec. 1.1.2, LSC can not be described by a simple impedance element at the low energy injector region due to space charge oscillation dynamics. Such an oscillation will convert density modulation into energy modulation and vice versa. For a relativistic beam in a drift space, we can estimate the space charge oscillation frequency as [14,15]

$$\omega_{sc} = c\left[\frac{I_0}{\gamma^3 I_A} k_0 \frac{4\pi\left|Z_{LSC}(k_0)\right|}{Z_0}\right]^{1/2} \le \frac{2c}{r_b}\left(\frac{I_0}{\gamma^3 I_A}\right)^{1/2} \equiv \omega_p, \qquad (13)$$

where ω_p is the plasma frequency. For example, if r_b = 200 μm, I_0 = 100 A, and the modulation wavelength $\lambda_0 \in [50, 300]$ μm, the space charge oscillation distance is about 1.5 to 3.5 m for a 10 MeV beam, and increases to 10 to 45 m for a *30* MeV beam. Thus, space charge oscillation can be important at lower beam energies but becomes insignificant at higher energies for a given beam line. The space charge oscillation dynamics taking into account the transverse beam profile is analyzed recently in Refs.

[26,27], and the effect of acceleration can be included by generalizing the integral equation for the CSR microbunching described above [28,27].

Nevertheless, full space charge simulations using *PARMELA* [29] or *ASTRA* [30] (including both longitudinal and transverse effects) are necessary to quantify the evolution of the electron density and energy modulations in the injector region. Both *PARMELA* and *ASTRA* space-charge simulations of the LCLS photoinjector show that the initial density modulation caused by the drive laser is only reduced by a factor of a few (3-6) at the end of the injector for a wide spectral range (from 25 μm to 300 μm), while noticeable energy modulation is accumulated [28]. The modulated beams after the injector simulation can then be used by *ELEGANT* for the main linac simulation. Note that much stronger damping of the initial density modulation in the TESLA Test Facility injector simulations has been reported in Ref. [31], although the origin of the damping mechanism is not well-understood.

4.2.4.2 *Linac simulations*

ELEGANT supplies two beamline elements that simulate the longitudinal CSR effect. One is a drift element and the other is a bending magnet. The CSR model used by *ELEGANT* is based on the energy change of an arbitrary line-charge distribution as a function of the bunch position in a dipole magnet [17,18], together with the proper treatment of transient effects including the drift space [32,33]. The CSR-induced energy change in both magnet and drift space is implemented in a kick-transport-kick algorithm. More details about how to split the magnets and how to choose the canonical integrator are discussed in Ref. [34]. One difficulty in these computations comes from noise in the linear density histogram due to the use of a finite number of particles and a large number of bins. This is a particular problem when taking derivative of the line density. Smoothing, e.g., Savitzky-Golay smoothing filter, is used to overcome this problem, at the expense of some loss of information. Therefore, it is necessary to vary both the number of particles and the amount of smoothing until numerical convergence is obtained in the simulations.

ELEGANT supplies two similar beamline elements for the LSC effect. One is a drift element and the other is an rf cavity that also includes structure wakefields. The 1-D LSC impedance of Eq. (3) is used in a kick-drift-kick (or kick-accelerate-kick) algorithm. The distance l between kicks must be set properly to get a valid result. Normally, one sets $l << c/\omega_p$. The drift element automatically selects the drift distance, using $l = 0.1c/\omega_p$. The acceleration element requires the user to specify the number of parts to split the cavity into, and simply checks that $l \leq 0.1c/\omega_p$. For the case with acceleration, $l \leq 0.1\gamma/(d\gamma/ds)$ ensures that the momentum does not change too much between kicks. For a Gaussian or a parabolic transverse beam distribution, the effective beam radius is fitted as $r_b \approx 1.7(\sigma_x+\sigma_y)/2$ in Eq. (3), where σ_x and σ_y are the rms beam sizes in the transverse planes. Fast Fourier transformation (FFT) of the current histogram is then taken. A low-pass filter is normally used to control the high-frequency noise. The cutoff frequency and slope of the filter are specified by users. Generally, the number of bins is chosen such that the frequencies of interest are less than $0.2\ F_n$, where F_n is the Nyquist frequency. The low-pass filter is then set to remove frequencies above $0.4\ F_n$. The (filtered or unfiltered) FFT of the current is then multiplied by the impedance, and the result is inversely Fourier transformed. This gives the voltage as a function of bin in the original current histogram. This voltage can be applied to each particle, with interpolation between bins to make a smoother result. The

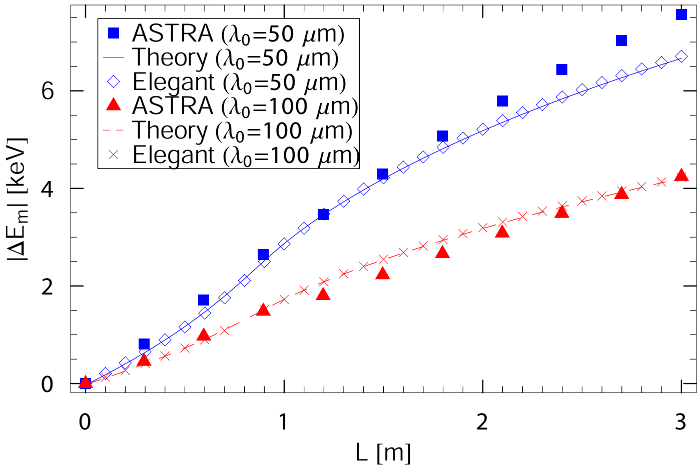


Figure 4: LSC-induced energy modulation amplitude as a function of the drift distance L for a 120-MeV, 120-A beam with a ±5% initial density modulation at 50 μm and 100 μm modulation wavelengths.

LSC-induced energy modulations in *ELEGANT* are compared to *ASTRA* simulations and analytical results (i.e., Eq. (4)) as shown in Fig. 4 [12].

4.2.4.3 *Discussion of simulation results*

To illustrate how the microbunching instability may degrade the beam qualities, and to demonstrate the function of the laser-heater in suppressing the instability, Fig. 5 shows a typical longitudinal phase space comparison at the end of the LCLS accelerator with and without the laser-heater for an initial ±8% laser intensity modulation at λ_0 = 150 μm [35]. The start-to-end simulations are carried out by *ASTRA* for the injector and *ELEGANT* for the linac, with a separate tracking code for the resonant laser-electron interaction to simulate the heating process prior to the *ELEGANT* runs. Without the laser heater, the very large final energy modulation (with the compressed wavelength of about 3 μm) due to the microbunching instability becomes effective slice energy spread for the FEL. As shown on the left plot of Fig. 6, such a large slice energy spread will degrade the FEL gain. The laser heater clearly limits the instability gain as well as the final slice rms relative energy spread to about 1.0×10^{-4}, which has a negligible effect on the LCLS performance. In the absence of the laser heater, the significant energy modulation induced by CSR in dipoles can couple to the growth of the slice horizontal emittance and further affect the FEL operation, while the slice emittance is entirely unaffected when the laser heater is on (see the right plot of Fig. 6). Similar conclusions can be made for other modulation wavelengths.

In fact, even though the high-frequency gain is significantly suppressed by the increased energy spread due to the laser heater, there are residual modulations at longer wavelengths, which are still visible on the right side of Fig. 5. This sets the initial tolerable density modulation amplitude to be about ±8% at 150 μm. Since the gain is broad and is relatively insensitive to initial wavelengths between 50 μm to 300 μm, the maximum laser intensity modulation amplitude at the cathode is determined to be about 5% (rms) in order for the laser-heater suppressed microbunching to not affect the LCLS FEL [35].

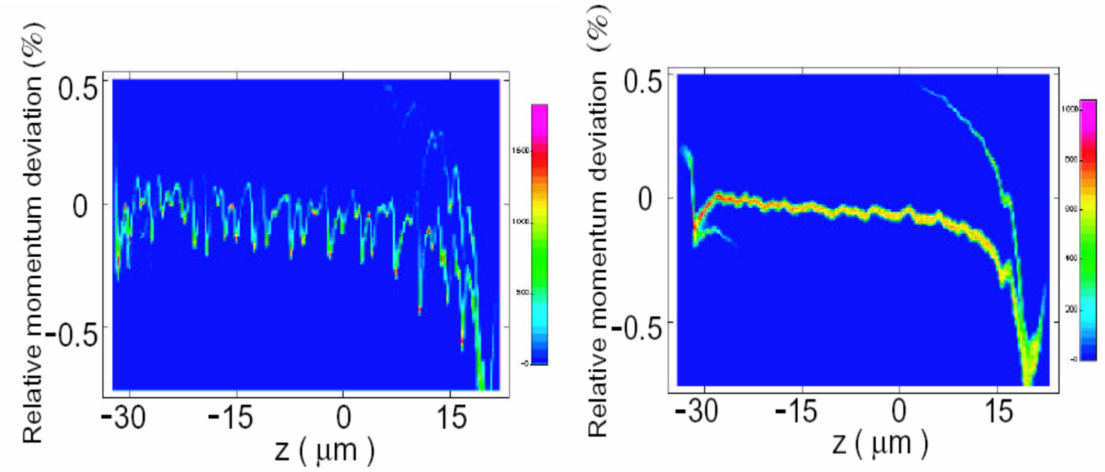


Figure 5: Longitudinal phase space distribution at the entrance of the LCLS undulator for an initial ±8% laser intensity modulation at $\lambda_0 = 150\ \mu$m in the start-to-end simulation without the laser-heater (left plot) and with the laser heater (right plot).

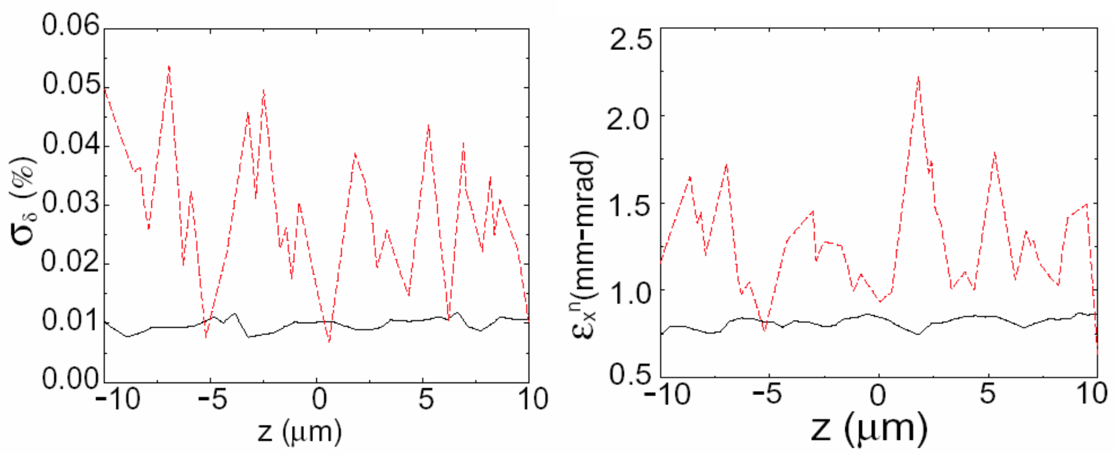


Figure 6: Slice rms relative energy spread σ_δ (left plot) and slice normalized emittance ε_x^n (right plot) at the entrance of the LCLS undulator for an initial ±8% laser intensity modulation at $\lambda_0 = 150\ \mu$m in the start-to-end simulation. Solid curve stands for the result with the laser-heater; and dashed curve for the result without the laser-heater.

4.2.5 Experimental Observations and Analyses

Due to the extremely short time scales associated with compressed bunches, longitudinal phase space characterizations usually rely on measurements of chirped beam energy spectra. Up to date quite a few linac-based FEL facilities report a self-developing microstructure when the bunch undergoes strong compression [1-3].

In energy-recovery accelerators the microstructure is observed at Jefferson Lab IR-demo FEL during compression experiments [1]. While approaching the maximum compression the bunch energy profile started to show a fine structure; such effect is systematically enhanced as the charge per bunch is increased.

More recently strong break-up of energy spectrum near the phase of maximum compression is observed at the Accelerator Test Facility (BNL) [36]. Currently this effect is being studied experimentally and in simulations.

At the commissioning stage of Deep Ultraviolet FEL (DUV-FEL at NSLS, BNL) and TESLA Test Facility (TTF-1 at DESY), strong modulations of the chirped bunch energy spectra are observed and analyzed [2,3] (see Fig. 7). The chirp (or the linearly correlated energy spread) is provided by running one of the accelerating sections off the crest of the accelerating voltage. The local brightness in the image is linearly proportional to the local amount of charge. The horizontal coordinate of the beam image scales with energy; the position of the image centroid is defined by the average beam energy. Electrons, located in the head (tail) of the bunch, gain (lose) energy while traveling through the accelerator section, but the energy of the beam centroid stays constant. Therefore the bunch gets dispersed along the horizontal axis of the monitor and the head (tail) of the bunch gets mapped on the right (left) side of the monitor screen. This setup is a particular implementation of the so-called ‘‘zero-phasing’’ method of bunch length measurement [37].

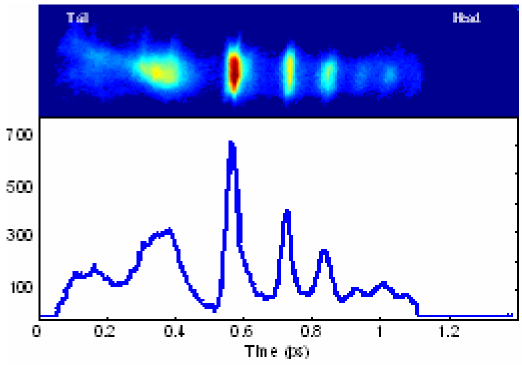


Figure 7: Example of the beam energy spectrum measurement at the DUV-FEL (BNL). Modulated beam image after spectrometer (upper plot), vertical axes is Y-coordinate; horizontal one is proportional to the beam energy. Bottom figure: “zero-phasing” projection of the beam on upper plot, horizontal axis is scaled in picoseconds.

The experiments at TTF include changes of the compressor strength by varying the amount of energy chirp, variation of charge per bunch and tomographic reconstruction of the longitudinal phase space [38]. The measurements show that the structure appears only when the beam is compressed; at the same time the chicane itself does not impose any structure when the beam passes the chicane without energy chirp.

At the TTF among the different sources of wakefields a possible mechanism based on the CSR self-interaction in the bunch compressor is considered [39]. Calculations with TraFiC^4 code [40] indicate that the CSR force has the strength to yield the energy redistribution similar to the measurements. It is shown that, if non-linearities such as the curvature of the accelerating RF sections are significant, compression would produce non-Gaussian and locally peaked distributions. For such types of distributions, CSR effects can be much stronger compared to Gaussian distributions with the same rms bunch lengthes. The LSC microbunching instability is also considered as a possible candidate for the strong distortions of longitudinal phase space [9].

Another way of interpreting sharp spikes in the energy spectrum is discussed in Ref. [15]. After strong compression significant beam energy modulation may be induced

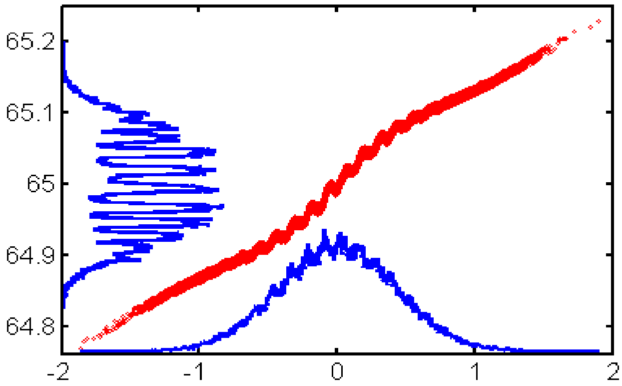


Figure 8: Illustration of electron bunch longitudinal phase space. Abscissa is time (ps), ordinate is energy (MeV). Beam energy modulation along the chirped bunch leads to deeply modulated energy spectra.

during the off-crest acceleration before the energy spectrometer for a small initial density modulation,. The projection of this energy-modulated phase space onto energy axis (chirped energy spectrum) can exhibit sharp spikes similar to that observed in the experiments (see Fig. 8).

To determine whether the energy modulation or the density bunching dominates the observed structure (such as in Fig. 7), two additional experiments are performed at the DUV FEL [41].

The goal of the first experiment is to study the sensitivity of the modulation to beam size changes along the zero-phasing section of the accelerator after the bunch compressor. Adjusting quadrupoles in the transport line after the chicane, three focusing solutions are established and provide three different beam envelopes (0.25, 0.5, 1.0 mm average rms beam size along the transport line). It is explicitly shown that the strong modulation, present when the beam size is small, almost vanishes at a larger beam cross section. The observed structure, if caused by strong density modulations, should not be very sensitive to changes in transverse beam dimensions after compression. On the contrary, LSC-induced energy modulations in the linac can have a strong dependence on the beam size for the DUV-FEL parameters.

In the next experiment CTR power is measured from electron bunches with drastically different modulation amplitudes (given by different beam sizes along the zero-phasing section) under the same experimental conditions. Measured values of power for various CTR wavelength ranges do not differ for the two cases, indicating that the spectral content of density modulation is the same in both cases. These experiments confirm that the observed structure is dominated by energy modulation instead of current modulation.

To determine the range of modulation frequencies and amplitudes, another experiment is performed [42]. This time the energy of the bunch is varied, and a set of "zero-phasing" images are recorded. Initial analysis of the results shows major difference in frequency and amplitude content of the structure at different energies. For instance, the number of spikes (and the modulation wavelength) in a "zero-phasing" image is found linearly proportional to the beam energy. The modulation amplitude increases as the beam energy is decreased, in general agreement with the energy dependence of the LSC impedance discussed in Sec. 4.2.3.2. The experimental data are

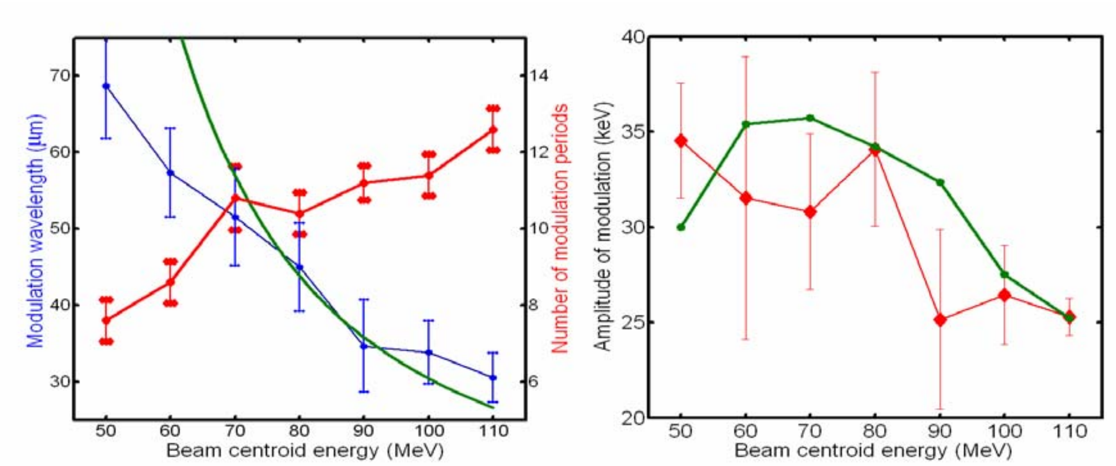


Figure 9: Dependence of modulation wavelength (left plot) and modulation amplitude (right plot) on energy. Red and blue traces correspond to the measured data; green traces correspond to analytic calculation (left plot) and simulation result (right plot).

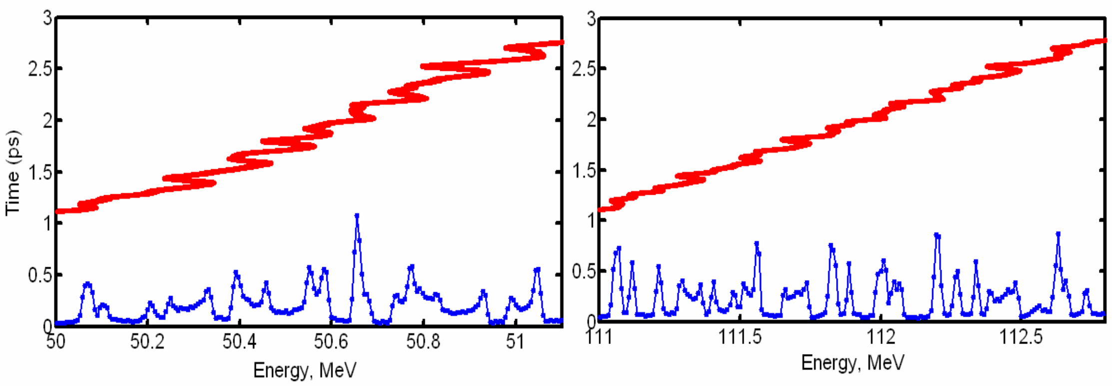


Figure 10: Simulated phase space at the end of the accelerator for two different energies (50 and 110 MeV).

then processed and dependences of the modulation wavelength and amplitude are compared with the analytic calculation and simulations, yielding a reasonable agreement (see Fig. 9). The numerical simulations, implemented in *MATLAB* [42], use the same LSC computation algorithm as described in Sec. 4.2.4.2.

Note that the observed amplitude of final energy modulation is in the range of 20–40 keV, which exceeds the expected intrinsic energy spread (less than 10 keV for this experiment) by a large factor. Simulations also demonstrate that reconstructed amplitudes of energy modulation (Fig. 10) correspond to about 3% of initial density modulations [42], comparable with the measured intensity fluctuations of the DUV-FEL rf gun drive laser pulse. Thus, nonuniformities in the longitudinal density profile in the range of only a few percent can cause strong energy modulations due to the action of the space charge force.

In the DUV-FEL accelerator the strong energy modulation occurs while a beam with a modest peak current (~200 A) travels along the accelerator of only 15 m. For much longer accelerators with two-stages of compression such as proposed for short-wavelength FELs, this effect can be much stronger and can lead to a significant microbunching instability that degrades the electron beam quality beyond the FEL tolerance. Therefore, these experimental results and their analysis warrant controlled increase of the intrinsic energy spread by a laser heater to suppress the microbunching instability.

4.2.6 Acknowledgments

The authors would like to acknowledge collaborative work with M. Borland, P. Emma, W. Graves, K.-J. Kim, C. Limborg, H. Loos, B. Sheehy, G. Stupakov, J. Welch, L.-H. Yu on this subject. Our research is supported by Department of Energy contracts DE--AC02--76SF00515 and DE-AC02-76CH00016.

4.2.7 References

1. Ph. Piot et al., in Proc. of EPAC2000, 1546 (2000).
2. W. Graves et al., in Proc. of PAC2001, 2224 (2001).
3. M. Hüning, Ph. Piot and H. Schlarb, Nucl. Instrum. Meth. A **475**, 348 (2001).
4. M. Borland et al., in Proc. of PAC2001, 2707 (2001); Nucl. Instrum. Meth. A **483**, 268 (2002).
5. E. Saldin, E. Schneidmiller, and M. Yurkov, Nucl. Instrum. Meth. A **490**, 1 (2002).
6. S. Heifets, G. Stupakov, and S. Krinsky, Phys. Rev. ST Accel. Beams **5**, 064401 (2002); 129902 (2002).
7. Z. Huang and K.-J. Kim, Phys. Rev. ST Accel. Beams **5**, 074401 (2002); 129903 (2002).
8. S. Reiche and J. B. Rosenzweig, Phys. Rev. ST Accel. Beams **6**, 040702 (2003).
9. E. Saldin, E. Schneidmiller, and M. Yurkov, Nucl. Instrum. Meth. A **483**, 516 (2002).
10. E. Saldin, E. Schneidmiller, and M. Yurkov, Nucl. Instrum. Meth. A **528**, 355 (2004).
11. Z. Huang et al., in Proc. of PAC2003, 3140 (2003).
12. Z. Huang et al., Phys. Rev. ST Accel. Beams **7**, 074401 (2004).
13. H. Loos et al., in Proc. of PAC2005, 642 (2005).
14. J. Rosenzweig et al., DESY TESLA-FEL-96-15 (1996).
15. Z. Huang and T. Shaftan, Nucl. Instrum. Meth. A **528**, 345 (2004)
16. R. Gluckstern, Phys. Rev. D **39**, 2780 (1989).
17. J. Murphy, S. Krinsky, and R. Gluckstern, in Proc. of PAC1995, 2980 (1995).
18. Y. Derbenev et al., DESY TESLA-FEL-95-05 (1995).
19. M. Dohlus, presented at *The CSR workshop*, Zeuthen, Germany, 2002 (http://www.desy.de/csr/).
20. R. Li, JLAB-TN-05-046 (2005).
21. M. Borland, ANL Advanced Photon Source Report No. LS-287 (2000).
22. P. Emma, CSR_calc code.
23. Z. Huang et al., Nucl. Instrum. Meth. A **507**, 318 (2003).
24. M. Hüning and H. Schlarb, in Proc. Of PAC2003, 2074 (2003).
25. S. Di Mitri et al., in Proc. of FEL2005 (2005).
26. G. Geloni et al., Nucl. Instrum. Meth. A **554**, 20 (2005).
27. J. Wu, Z. Huang, and P. Emma, SLAC-PUB-11448, in Proc. of FEL2005 (2005).
28. C. Limborg et al., in Proc. of EPAC2004, 1506 (2004).
29. L.Young and J.Billen , PARMELA code.
30. K.Floettmann, ASTRA code (https://www.desy.de/~mpyflo/).
31. Y.-J. Kim, D. Son, Y. Kim, Nucl. Instrum. Meth. A **528**, 427 (2004).
32. E. Saldin, E. Schneidmiller, and M. Yurkov, Nucl. Instrum. Meth. A **398**, 373 (1997).
33. G. Stupakov and P. Emma, in Proc. of EPAC2002, 1479 (2002).
34. M. Borland, Phys. Rev. ST Accel. Beams **4**, 070701 (2001).
35. J. Wu et al., in Proc. of LINAC2004, 390 (2004).

36. G. Andonian, presented at *The Physics and Applications of High Brightness Electron Beams,* Erice, Italy, 2005 (http://www.physics.ucla.edu/PAHBEB2005/talks/10_oct_2005/wg_2/g_andonian.pdf).
37. D. Wang, G. Krafft, and C. Sinclair, Phys. Rev. E **57**, 2283 (1998).
38. M. Hüning, in Proc. of DIPAC2001, 56 (2001).
39. T. Limberg, Ph. Piot, and E.A. Schneidmiller, Nucl. Instrum. Meth. A **475**, 353 (2001).
40. M. Dohlus, A. Kabel, and T. Limborg, Nucl. Instrum. Meth. A **445**, 338 (2000).
41. T. Shaftan et al., Nucl. Instrum. Meth. A **528**, 397 (2004).
42. T. Shaftan and Z. Huang, Phys. Rev. ST Accel. Beams **7**, 080702 (2004).

5 Workshop and Conference Reports

5.1 15th ICFA Beam Dynamics Mini -Workshop on Low Level RF

Trevor Linnecar, CERN
mail to: Trevor.Linnecar@cern.ch

5.1.1 Introduction

This workshop (http://cern.ch/LLRF05) on low-level RF, held at CERN, Geneva in Oct. 2005 was the second in a series initiated at Jefferson Lab, USA, (http://www.jlab.org/intralab/calendar/archive01/LLRF) four years ago. The Jefferson workshop, concentrating mainly on low-level techniques as applied to Superconducting Linacs had made it clear that digital techniques to implement beam and cavity servo systems could offer considerable power and flexibility and indeed different projects in this area had already been started. In the intervening years digital implementations, while not excluding interesting analogue solutions, have blossomed and operational results have been obtained on different accelerators. This, together with the unprecedented requirements for low-level control posed by future projects, made a second workshop, where ideas, implementations and new requirements could be discussed and compared, urgent. In addition it would be very useful to share experience between linac and synchrotron projects.

5.1.2 Workshop Organization and Statistics

The three and a half days were split into half-day sessions comprising five talk sessions and two working group sessions. There were no parallel talk sessions to allow participants to hear all talks. A parallel poster session, with posters on view for two days, was organized. A specific period, 1.5 hours, was set aside for discussion of the posters with the authors present. There were a total of 43 talks and 17 posters. The talks were of three types: review (8 talks of 25 minutes), specific (32 talks of 15 minutes), and tutorial (3 talks of 45 minutes). Five minutes for questions and discussion were allocated after each talk. The tutorials were used as a way of introducing recent established methods, techniques and ideas, to the audience as a whole. Four working groups were organized, a) Synchrotrons and LHC, b) Linacs, c) System Modeling, and

d) Hardware, and these took place in parallel during the two sessions allocated. Short oral presentations (20) were also given in these sessions. During the last, closing session, the working group convenors summarized the activities in their groups and a poster summary was given. On the last afternoon a visit to some CERN installations was organized.

While there will be no written proceedings from this workshop, a CD containing all talks and posters will be sent to participants. All information concerning the workshop, including names of registrants, chairmen, convenors, and the timetable and all talks and posters are available at the LLRF05 site.

There were 125 participants, split between the three continents, America (37), Asia (9) and Europe (79) and covering 14 countries and 34 different institutes.

5.1.3 Workshop Summary

It is not possible to report here all the very interesting talks and posters, covering a very broad range of subjects, which were presented at the workshop. Nonetheless a brief summary follows to give the flavour of the workshop. As mentioned above all presentations can be accessed on the web-site.

The low-level systems that need to be designed for RF control do not vary in great detail between accelerators. The beam dynamics in the different machines is well understood and the methods using different feed-back loops and feed-forward to keep control of the beam are well understood. The challenges that arise now come from the very stiff RF amplitude and phase requirements, ± 0.01% in RF amplitude and 0.1° in phase, the stability of the timing reference systems, 10 femtoseconds over kilometers, and from the push to very intense beams that new projects often require. The effects of beam loading from the latter, especially with uneven filling patterns, have to be carefully controlled to prevent collision point movement and coupled bunch instabilities on the beam. Overview and review talks from the different laboratories represented made these points very clear.

Even if the systems themselves are fairly well defined, this is not true for the actual hardware and software designs of the systems themselves; here the different talks showed a variety of solutions. Although purely analogue techniques for implementing low-level RF systems are still envisaged for new projects, they are very much in the minority. Analogue electronics still has its place in the RF front ends and also in situations when fast feedback with small loop group delay is required. In this workshop 28 different laboratories covering both linacs and synchrotrons presented systems based primarily on digital techniques and only one laboratory was still hesitating between an analogue or digital system. The digital designs themselves vary from FPGA implementations (field programmable gate arrays) to DSP implementations (digital signal processing chips) and different combinations of the two, usually with DDS (direct digital synthesizers) as the RF source. The same diversity is true of the hardware platforms though variations of the VME/VXI chassis tended to be predominant.

The design of the complex digital hardware and the algorithms implemented in the FPGA or DSP software can be more easily verified by suitable design techniques and by simulation. Several papers at the workshop described simulation tools and their use. Often these were based on Matlab / Simulink. Cavity and klystron modeling based on measurement data, or analogue models, are used to provide “black boxes” for the simulation. An extension is to provide dynamic models. Beam instability modeling is also in good shape. Simulation is an area into which considerable effort is being placed and results are very encouraging. For the software development itself this depends very much on the hardware implementation but serious attempts are being made to provide architectures which allow simple porting between chips.

As can be seen the field is expanding rapidly and many implementation solutions are being found in the different laboratories. Hopefully some common ideas can be used in the future and to this end it was decided at the workshop to set up a web-site or e-mail list for ideas to be communicated – Dayle Kotturi of SLAC offered to take this on.

Other items covered in the talks and posters included the following. Reference distribution as mentioned above – here coaxial cables still have their place although for future requirements where femtosecond stability is needed, optical solutions are probably necessary. The need for post-mortem facilities and beam-abort control implies a design with sufficient monitoring buffers, but also with good software analysis behind - this was mentioned in several talks. Phase noise measurements, noise from phase detectors, from amplifiers, and cryogenic systems were also important subjects, as were the issues of noise and stability introduced by operating klystrons near saturation. For the latter linearisation techniques were discussed. Precision low-noise instrumentation was also presented. Ponderomotive forces, microphonics and techniques for their measurement and control, including adaptive algorithms, continue to be studied.

Working group one was dedicated to synchrotrons, in particular the LHC. Issues that arose included the control of RF noise and the production of controlled longitudinal emittance blow-up with no tails in the distribution halo. The possibility of using klystron linearisarion to increase small signal gain when approaching saturation, phase detector noise floors and the necessary purity of the signal sources, were mentioned as important issues for beam lifetime in store. The significance of narrowband as opposed to white noise and the mechanisms whereby this can cause beam loss were also debated. Some time was also allocated to diagnostics, the analysis and understanding of the flood of data that can come after an abort and the incorporation of beam inhibits.

Working group two attacked different issues in the LINAC domain. There are ~ 15 separate linac developments for LLRF identified. Frequently, reference line stability is a major issue with femtosecond accuracy required from the source to the different RF stations and experiments. A conceptual design for the ILC LLRF has already been studied and proposed. For the SNS it was noted that online RF/beam response measurements would be beneficial.

Working group three examined simulation and modeling in more detail, hearing new presentations as well as looking again at the talks mentioned above. They discussed the different attempts to model the RF components both statically and dynamically noting the need for accurate modeling and simulation to attain the extremely high control precision required. Simulations must also now take account of adaptive feedforward, amplifier pre-compensation and gain scheduling. They discussed automation and the resulting benefits to operation from reduced down-time and operator work-load. They also looked at the ILC proposal, noting the compact low-cost hardware suggested.

Working group four looked at hardware platforms noting the lack of consensus here. They discussed procedures for choosing the analogue to digital converter and the apparent slowdown in performance improvement of these devices in general. They concluded that FPGAs are the chip of choice for most new large systems but that the DSP could be catching up. The hardware solutions to reference line requirements still use coaxial cable but the suggestion is that SNS will be the last machine with this choice, FELs and the like needing femtosecond stability.

5.1.4 General Summary

A large international community is working in the area of low-level RF, an area which is moving very quickly. Although the basic LLRF requirement is the same everywhere, the number of hardware and software implementations is as great as the number of accelerator laboratories. At this time it is impossible to have a consensus as to the best design practices. As a consequence there is a clear need for regular workshops to try and compare the operational results as designs are tried out on accelerators, and to keep a close watch on new developments. The interval between the first and second workshop was probably too long and it was proposed that a third workshop be organized in two years time. This will take place on the American continent and Mark Champion (SNS) has agreed to follow this up. A fourth in four or five years taking place in Poland is also a strong possibility.

Scientific Programme Committee

Kazunori Akai (KEK) Larry Doolittle (LBNL) Trevor Linnecar (CERN): Chair

Mike Brennan (BNL) Roland Garoby (CERN) Patricia Shinnie, (CERN): Secretary

Mark Champion (SNS) Curt Hovater (JLab) Stefan Simrock (DESY)

Brian Chase (FNAL) Matthias Liepe (Cornell) Dmitry Teytelman (SLAC)

Local Organizing Committee (CERN)

Maria Elena Angoletta Roland Garoby Flemming Pedersen: Chair

Philippe Baudrenghien Lydia Ghilardi: Secretary Patricia Shinnie

Alfred Blas Trevor Linnecar

5.2 Nanobeam2005

Akira Noda
Institute for Chemical Research, Kyoto University
mailto: noda@kyticr.kuicr.kyoto-u.ac.jp

As the 36th ICFA Beam Dynamics Workshop, an international workshop Nanobeam2005 was held at Kyoto University, Uji-campus for the period from the 17th to 21st, October, 2005 by co-operation among Institute for Chemical Research and Yukawa Institute for Theoretical Physics, Kyoto University and High Energy Accelerator Research Organization (KEK) co-chaired by myself and Prof. Junji Urakawa at KEK. The following committee members took their role for the workshop and I would like to present my sincere thanks for their cooperation.

International Advisory Committee

P.Debu(CEA/Saclay)
D.Burke (SLAC)
J.P.Delahaye (CERN)
S.Holmes(FNAL)
S.Ozaki(BNL)
S.I.Kurokawa(KEK)
S.Myers(CERN)
A.Skrinsky(BINP)
D.Trines(DESY)
A.Wrulich(PSI)
N.Sasao(Kyoto U.)
Y.Kamiya(KEK)
ICFA Beam Dynamics Panel

International Program and Organizing Committee

R.Assmann(CERN)
A.Bay(Lausanne U.)
G.Blair(Royal Holloway)
R.Brinkmann(DESY)
P. Burrows(QMUL)
B.Dehning(CERN)
J.G.Dugan(Cornell U.)
Jie Gao(IHEP)
M.Harrison(BNL)
M.Hildreth(NotreDame U.)
K.J.Kim(ANL)
N.Kumagai(SPring-8)
M.Mayoud(CERN)
O.Napoly(CEA/Saclay)
A.Noda(Kyoto U.)
T.Raubenheimer(SLAC)
L.Rivkin(PSI)
S.Russenschuck(CERN)
A.Seryi(SLAC)
T.Shintake(RIKEN)
V.Shiltsev(FNAL)
D.Angal-Kalinin(Daresbury)
S.Mishra(FNAL)
J.Urakawa(KEK)
V.Telnov (BINP)
N.Toge (KEK)
N.Walker(DESY)
K.Yokoya(KEK)
L.Zhang(ESRF)
F.Zimmermann(CERN)
A.Wolski(LBNL)

Local Organizing Committee

A.Noda(Kyoto U.) J.Urakawa (KEK) (Chairmen)
Y.Iwashita(Kyoto U.) T.Tauchi (KEK) (Scientific Secretariat)
T.Shirai(Kyoto U.) T.Nomura(Kyoto U.)
M.Kumada(NIRS) Y.Honda(KEK)
T.Sanuki(U. Tokyo) T.Yamazaki(Kyoto U.)
H.Ohgaki(Kyoto U.) K. Masuda(Kyoto U.)

This workshop is sponsored by the 21st Century Center of Excellence-Center for Diversity and Universality in Physics-. Research and developments for realization of linear collider in order to reach high energy limit to clarify the elementary particles are the main subject of the workshop. In addition, the presentations dealing with the application of such Research and Developments in accelerator and beam physics to other fields are also included considering the fact that the workshop site is at Institute for Chemical Research. Such a program stimulated active discussions among researchers in different fields and received good remarks from participants to have obtained valuable information and human relations.

Toward the realization of ILC (International Linear Collider), based on the international committee decision to adopt super conducting technology, steady research results are presented. The plenary talks are as follows.

Plenary Talks

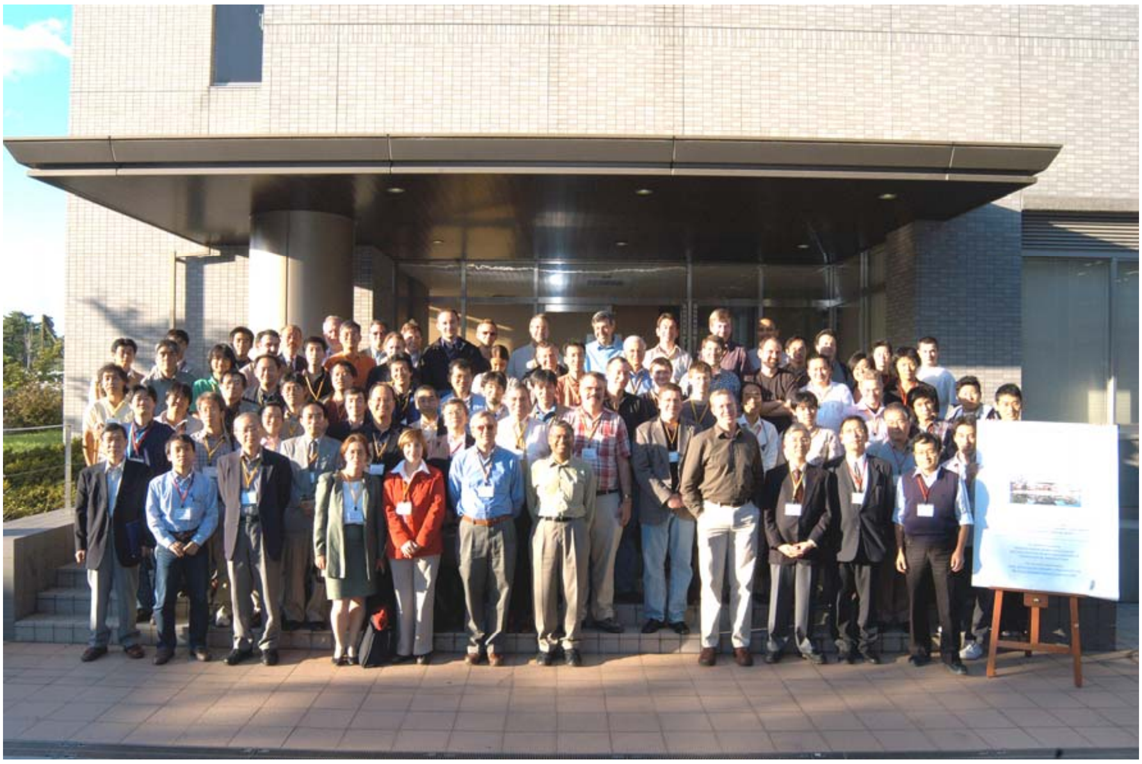
F. Zimmermann (CERN) :	Summary of Nanobeam 2002 and Expectation 'Stability and Ground Motion Issues in CLIC'
K.Yokoya (KEK) :	Status of ILC
A. Seryi (SLAC) :	Issues on Stability and Ground Motion in ILC
G.Blair (Royal Holloway) :	Test Facility for Final Focus Beam Line of ILC
T. Yamazaki (Kyoto U.):	Frontiers of Light Source
D. Urner (U. Oxford):	The StaFF (Stabilization of the Final Focus of the ILC) Project
S. Isoda (Kyoto U.):	Electron microscope as a nano-beam analyzer
H. Murayama (UC Berkeley):	Frontiers of high energy physics at LHC and ILC
K.Kataoka (U. Tokyo) :	Nanomaterial and its Medical Use
Y. Kobayashi (JAEA):	Study of cellular radiation response using heavy-ion microbeams
W. Yokota (JAEA):	Microbeam system for heavy ions from cyclotron to irradiate living cells
H. Tanaka:	Stabilization of Stored Beam in the SPring-8 Storage Ring -- Towards Maximizing the Light Source Performance --.

In addition, the following working groups are organized

- **Laser Wire Mini-Workshop**
    - WG1: Laser Wire (Conveners: Dr. G. Blair, Dr. J. Frish, Dr. N. Sasao)
- **BDS&FFIR of Linear Collider**
    - WG2a: BDS-design and interaction region (Conveners:Dr.Angal-Kalinin, Dr. A. Seryi, Dr. S. Kuroda)
    - WG2b: Stabilization and beam control (Conveners: Dr. P.N. Burrows, Dr. T. Tenenbaum, Dr. R. Sugawara)
    - WG2c: Future R&D Plans (Conveners: Dr. F. Zimmerman, Dr. M. Ross, Dr. M. Kuriki)
    - WG2d: Final Focus Q-magnet (Conveners: Dr. F. Kircher, Dr. B. Parker, Dr. M. Kumada)
- **Nanobeam Sources and Applications**
    - WG3a: Low emittance sources (Conveners: Dr. F. Stephan, Dr. J. Lewellen, Dr. J. Clendenin, Dr. K. Masuda)
        - Low emittance electron sources
            - normal-conducting and super-conducting rf guns

        - thermionic rf guns and dc guns
        - microscopes
        - photocathode materials
        - other electron emitters; needle cathode, diamond as a secondary-emission-based cathode
        - thermal emittance measurement
        - modeling
- WG3b: FELs/Radiation sources (Conveners: Dr. G.N. Kulipanov, Dr. M. Couprie, Dr. H. Ogaki)
    - Beam quality for the FELs
        - for oscillator FELs
        - for SASE and HGHG FELs
    - SR sources
        - low emittance lattice
        - short electron bunch, short pulse radiation
    - New radiation sources
        - ERL
        - PXR, Laser compton
        - isochronous ring
    - Beam diagnostics & stabilization (electron and photon beam)
- WG3c: Other Sources (Conveners: Dr. Y. Jeong, Dr. X. Wang, Dr. H. Hanaki)
    - Ion beam
        - microbeam
        - cyclotron, storage ring, cooler ring
    - Related topics from nano-technology
        - lithograpy, micro machning, MEMS, neutron
- WG4: Physics with High intensity lasers (Conveners: Dr. J. Gronberg, Dr. T. Takahashi)

In total 104 people from 9 countries participated (63 from Japan, 15 from United States, 7 from United Kingdom, 7 from Germany, 4 from Russia, 3 from France, 3 from Korea, 1 from Switzerland and 1 from Spain). The group photo of workshop participants is shown below. Next workshop is agreed to be organized in Russia after 3 years following the present one.



5.3 Report on the Mini-Workshop on "The Frontier of Short Bunches in Storage Rings"

Mario Serio
INFN - Laboratori Nazionali di Frascati, C.P. 13, 00044 Frascati (RM)
mail to; Mario.Serio@LNF.INFN.IT

The ICFA mini-workshop "The Frontier of Short Bunches in Storage Rings", was held on 7-8 November 2005 at INFN - Laboratori Nazionali di Frascati, under the aegis of the ICFA Beam Dynamics Panel. The scope of the workshop was to discuss the issues of very short bunches in synchrotron light sources and e+e- colliders.

The synchrotron light community is interested since bunches in the millimeter scale are necessary for time-resolved experiments and for stable production of coherent synchrotron radiation. Moreover, since short bunches at the Interaction Point of colliders allow to lower the β*, possibly gaining correspondingly in luminosity, techniques to shorten the bunches in storage rings are of interest for the super-factory community.

In fact, the organization of this workshop stemmed from the desire to submit to the accelerator community the idea of "Strong RF Focusing", thought for an evolutionary

DAFNE collider (see D. Alesini et al., "Proposal of a Bunch Length Modulation Experiment in DAFNE", LNF 05-04 (IR), www.lnf.infn.it/sis/preprint/pdf/LNF-05-4%28IR%29.pdf and C. Biscari et al., PAC 05, ROAA003).

In spite of the short advice, the participation was numerous and well balanced. We had 24 talks and 48 participants from France, Germany, Italy, Japan, Jordan, Russia, Switzerland, Great Britain and USA, representing ESRF, SOLEIL, BESSY 2, INFN-LNF and Pisa, Sincrotrone di Trieste, KEK, SESAME, BINP, CERN, DIAMOND, APS, CESR, JLAB, LBNL, NSLS/BNL and SLAC.

The workshop was organized in four sessions during two days. The first and the last session were devoted to an overview of present and foreseen activities. The second session dealt with Lattice, Dynamic aperture, Lifetime and Beam-Beam effect. The third session was devoted to Diagnostics, RF Design, Impedance, Coherent Radiation and Bunch Lengthening.

Activities and plans from all represented Laboratories were reviewed and discussed during this very interesting workshop.

The concluding remarks were made by Andrew Hutton (JLAB), who, standing the growing interest toward short bunches in storage rings, proposed to re-iterate in about one year this meeting, possibly hosted by a lab in the USA and to create an international collaboration on short electron bunches to coordinate the experimental activities at various suitable facilities, sharing as much as possible the diagnostics techniques and the simulation tools. The Organizing Committee agreed to explore this possibility in the near future.

The complete program with links to the presentation is available at the web page http://www.lnf.infn.it/conference/sbsr05/prog.html

5.4 Experimental Physics Controls Experts Meet in Geneva

Axel Daneels, CERN
mail to: Axel.Daneels@cern.ch

5.4.1 Introduction

From 10 - 15 Oct 2005, the "European Organization for Nuclear Research" (CERN) and the "Centre de Recherches en Physique des Plasmas" (CRPP) of the "École Polytechnique Fédérale de Lausanne" (EPFL), hosted the EUROPHYSICS conference ICALEPCS'2005, the tenth "International Conference on Accelerator and Large Experimental Physics Control Systems" at the "Geneva International Conference Centre" (CICG).

ICALEPCS is the prime conference in the field of controls of experimental physics facilities: particle accelerators and detectors, optical and radio telescopes, thermo-nuclear fusion, lasers, nuclear reactors, gravitational antennas, etc. The initiative to create this series of biennial conferences was taken end 1985. Until then experimental physics controls, and in particular accelerator controls, was not allotted more than a session in more general purpose conferences (e.g. the EPS Conference on Computing in Accelerator Design and Operation, Berlin, Sept. 1983) or a workshop in the context of a specific facility (e.g. for the National Synchrotron Light Source at BNL, Jan. 1985, and the Proton Storage Ring and Ground Test Accelerator at LANL, Oct. 1985). Considering the pervasive growth of controls in the accelerators, it was felt that this topic deserved a full-fledged conference. An initial group of six laboratories, namely CERN (Geneva), GANIL (Caen), HMI (Berlin), KFA (Jülich), LANL (Los Alamos), and PSI (Villigen) were then called in to create the group on Experimental Physics Control Systems (EPCS) within the European Physical Society (EPS) (1986) with the purpose, amongst others, to patronize these conferences. In a next step, CERN offered to organize the first ICALEPCS in 1987.

The ICALEPCS circulate around the globe: Europe, America and Asia. The conferences are, as a rule, co-organized by the *European Physical Society's* (EPS) interdivisional group on *Experimental Physics Control Systems* (EPCS) and are held under the auspices of:

- the *European Physical Society* (EPS),
- the *Institute of Electrical and Electronics Engineers* (IEEE) through its *Nuclear and Plasma Science Society* (NPSS),
- the *Association of Asia Pacific Physics Societies* (AAPPS),
- the *American Physical Society* (APS),
- the *International Federation of Automatic Control* (IFAC),
- the *International Federation for Information Processing* (IFIP) through its *Technical Committee on Computer Applications in Technology* (TC5).

5.4.2 ICALEPCS'2005

As the first ICALEPCS was held in Switzerland, in Villars-sur-Ollon, in 1987 it was felt that for its tenth event it should be held again in Switzerland. Geneva was selected because of its central location in Europe amidst a large number of experimental physics facilities (CERN, CRPP, PSI, LAPP, ESRF, ITER … to name a few that are within a stone's throw). CERN, which is currently constructing the "*Large Hadron Collider*": (LHC) and its experiments, is a major producer of such control systems, as are scientists at the CRPP-EPFL, who are in the Swiss Association in the European Fusion Programme and collaborate in the JET and ITER fusion projects. CERN and CRPP-EPFL were thus quite naturally perfect organizers for this event.

ICALEPCS2005 covered all domains of controls and operation: too many to be covered at each conference. Therefore, besides the recurrent ***Status Report,*** this year's event focused issues of current concern in the community: ***Process Tuning, Automation and Synchronization***, ***Security and Other Major Challenges***, ***Development Approaches***, ***Hardware Technology Evolution***, ***Software Technology Evolution***, ***Operational Issues*** and ***Dealing with Evolution***

ICALEPCS'2005 was particularly auspicious: it fell in the year that UNESCO has declared the *World-Year of Physics*, and in addition, being hosted in Geneva, it received a strong support from the Swiss Federal Government, the Republic and Canton of Geneva and the French Authorities of the Département de Haute Savoie. The attendance was particularly high with in the 450 delegates representing 160 Organisations (laboratories, universities and industrial companies) from 27 countries spread over Europe, America, Asia and Oceania (Australia).

5.4.3 ICALEPCS'2007

ICALEPCS'2007 will be held in Knoxville (Tennessee, USA), jointly hosted by Dave Gurd (SNS, Oak Ridge National Laboratory, Oak Ridge, USA) and Karen White

(Thomas Jefferson National Accelerator Facility, Newport News, USA). Watch the ICALEPCS Website for details on this event. For more details:

- on the series of ICALEPCS in general, see its Website. http://www.icalepcs.org/;
- on ICALEPCS'2005, see http://icalepcs2005.web.cern.ch/Icalepcs2005/ .

6 Forthcoming Beam Dynamics Events

6.1 37th ICFA Advanced Beam Dynamics Workshop on Future Light Sources

Place and date: DESY, Hamburg, Germany, May 15-10, 2006

Christel Övermann
DESY, Notkestr. 85,22607 Hamburg, Germany
mail to: christel.oevermann@desy.de

6.1.1 Topics

The workshop intends to review and discuss all kinds of modern accelerator-based light sources for wavelengths ranging from the infrared to X-rays. The program will consist of a few plenary summary talks and working group sessions with sufficient time for presentations and discussions, thus keeping the spirit of the workshop format. Working groups will be dedicated to various types of radiation sources like ERLs, FELs and storage rings as well as to critical technological aspects like diagnostics, electron sources, numerical simulations, short-pulse generation and stability issues.

6.1.2 Committees

Workshop Chairmen: Kwang-Je Kim (Argonne Natl. Lab.)
Jörg Rossbach (Hamburg Univ. and DESY)

Program Committee:

R. Bakker (PSI)
W. Decking (DESY)- Chair
P. Emma (SLAC)
G. Hoffstätter (Cornell Univ.)
H. Kitamura (SPring-8)
I.S. Ko (POSTECH)
T. Limberg (DESY)
L. Merminga (Jefferson Lab.)
A. Meseck (BESSY)
D. Robin (LBL)
R. Walker (Diamond Light Source)

Local Organizing Committee:

C. Kluth (DESY)
T. Limberg (DESY)
M. Marx (DESY)
S. Mette (DESY)
I. Nikodem (DESY)
C. Övermann (DESY) - Chair
B. Poljancewicz (DESY)

Y. Wu (Duke Univ.)
S. Zholents, LBL

6.1.3 Contact

Further information can be found on the workshop homepage at:
http://fls2006.desy.de

6.2 The 39th ICFA Advanced Beam Dynamics Workshop: High Intensity High Brightness Hadron Beams

Place and date: EPOCHAL International Congress Center / Tsukuba City, Japan, May 29-June 2, 2006

Yong Ho Chin (KEK) and Hiroshi Yoshikawa (JAEA)
mail to: hb2006@kek.jp

6.2.1 General Information

The 39th ICFA Advanced Beam Dynamics Workshop, “High Intensity High Brightness Hadron Beams, HB2006”, will be held at the EPOCHAL International Congress Center in Tsukuba City, Japan, near KEK on May 29-June 2, 2006. This Workshop is co-sponsored by KEK and JAEA (previously JAERI).

The themes of this workshop follow closely those of the previously held two workshops in the same series: ICFA-HB2002 (April 8-12, 2002 at Fermi-lab, USA) and ICFA-HB2004 (October 18-22, 2004, in Bensheim, Germany), which cover a wide range of issues associated with high intensity hadron beams. This time, however, since the commissioning of SNS will be already started by the time of the workshop and the construction of J-PARC linac will be nearly completed, more emphasis on J-PARC and SNS will be made as on-going major projects of the hadron machines.

The first and the last days are devoted to the plenary sessions for opening, reviews and working group summaries. The middle three days are dedicated to the working activities. The subjects of the working groups may include

A. Beam Instabilities and their cures
B. Space-charge theory, simulations, and experiments
C. Beam diagnostics, collimation, injection/extraction and targetry
D. Beam cooling and intra-beam scattering
E. High intensity linacs / Proton drivers
F. FFAG and other advanced techniques
G. Commissioning strategies and procedures

Parallel invited sessions will be held in the morning for each topic and will be moved to the working sessions for the same topic in the afternoon. The working sessions will contain organized discussions as well as contributed papers, which will be selected from submitted abstracts by the session conveners. We encourage submission of contributed oral talks to be presented in the working sessions. Workshop proceedings containing all invited and contributed papers will be published on the JACoW web site, as well as its hard-copies and CDs will be published from KEK.

Details of the HB2006 Workshop appear on the web at http://hb2006.kek.jp/.

Please direct all the inquiries concerning this workshop to the e-mail address of the workshop secretariat; hb2006@kek.jp. Your e-mail will be forwarded to the most appropriate personnel for your inquiry.

6.2.2 Scientific Program and Workshop Schedule:

The present plan of the program is as follows: The first and the last days are devoted to the plenary sessions for opening, reviews and working group summaries. The middle three days are dedicated to the working activities. Two or three topics are picked up per day as the working subjects and a room will be allocated to each topic. Parallel invited sessions for those topics will be held in the morning and will be moved to the working sessions for the same topic in the afternoon. The working sessions will contain organized discussions as well as contributed papers, which will be selected from submitted abstracts by the Program Committee and session conveners. The J-PARC tour is planned in the afternoon of the last day. The Banquet will be held on Wednesday evening.

	Monday	Tuesday	Wednesday	Thursday	Friday
AM	Plenary	Invited Parallel	Invited Parallel	Invited Parallel	Plenary
PM	Plenary	Work Session.	Work Session.	Work Session.	Tour

The subjects of the working groups may include

A. Beam Instabilities and their cures
B. Space-charge theory, simulations, and experiments
C. Beam diagnostics, collimation, injection/extraction and targetry
D. Beam cooling and intra-beam scattering
E. High intensity linacs / Proton drivers
F. FFAG and other advanced techniques
G. Commissioning strategies and procedures

6.2.3 Submission of Abstracts for Contributed Papers

We encourage submission of contributed oral talks to be presented in the working sessions. Due to time limitations in the working sessions, the acceptance of contributed oral papers is subject to approval by the Program Committee and session conveners. The authors selected for presentation of contributed papers will be notified as soon as possible. The abstracts will be accepted from January 2006 (after our database server becomes ready). Further details on abstract submission will appear on this website in due time. The deadline for the abstract submission for contributed papers is March 17, 2006.

6.2.4 The Workshop Proceedings

The ICFA Advanced Beam Dynamics Workshop series joined the JACoW in July 2005. Workshop proceedings containing all invited and contributed papers will be available on the JACoW web site, as well as its hard-copies and CDs will be published from KEK. Authors are requested to submit the paper in Postscript format (and other original files following the JACoW standard) and its camera-ready copy at the conference. Details for paper submission will be published on our website in due time.

6.2.5 The registration fee

30,000 Yen (about 270 USD) for early registration
35,000 Yen (about 320 USD) for late registration

Registration will be accepted after early February, 2006. Payment by a credit card via web will be available. Further details will appear on this website in due time.

6.2.6 The Workshop Site

EPOCHAL International Congress Center in Tsukuba City

http://www.epochal.or.jp/english/index.html

Plenary: Hall 200
Invited Parallels and Working sessions: Room 201B, 202A and 202B

6.2.7 The Workshop Hotel

A number of rooms were booked at Okura Frontier Hotel Tsukuba and Okura Frontier Hotel Tsukuba Epochal. Both of them are within walking distance from the Workshop Site.

http://www.okura-tsukuba.co.jp/english/index.html

Room charge for a single room - about 80 USD
Room charge for a twin room for two persons- about 150 USD
Both of them include tax and service charges but no breakfast.

The internet access is available from each room for free of charge. Breakfast not included. Further details on the workshop discount rates and reservation procedure will appear on this website in due time.

6.2.8 Important Dates

Early October, 2005: Distribution of the 1st Announcement
January, 2006: Distribution of the 2nd Announcement
January, 2006: Commencement of acceptance of abstract submission
Early February, 2006: Commencement of the registration

March 17, 2006: Deadline of the submission of abstracts for contributed papers
April 28, 2006: Deadline of the early registration
May 29 - June 2, 2006: HB2006 Workshop in Tsukuba
June 2, 2006: Deadline of the submission of papers

6.2.9 Committees

The International Advisory Committee:

Caterina Biscari (INFN)
Swapan Chattopadhyay (Jefferson Lab)
Yanglai Cho (ANL)
Weiren Chou (Fermi Lab)
Jie Gao (IHEP)
David Gurd (ORNL)
Ingo Hofmann (GSI)
Stephen Holmes (FNAL)
Roderich Keller (LANL)
In Soo Ko (PAL)
Hitoshi Kobayashi (KEK)
Alessandra Lombardi (CERN)
Yoshiharu Mori (Kyoto U.)
Stephen Myers (CERN)
Chris Prior (RAL)
Robert Ryne (LBL)
Yuri Shatunov (BINP)
Rainer Wanzenberg (DESY)
Jie Wei (BNL)
Yoshishige Yamazaki (JAEA)

The Program Committee:

Rick Baatman (TRIUMF)
John Barnard (LLNL)
Oliver Boine-Frankenheim (GSI)
Romuald Duperrier (CEA)
Alexei Fedotov (BNL)
William Foster (FNAL)
John Galambos (ORNL)
Roland Garoby (CERN)
Stuart Henderson (ORNL)
Norbert Holtkamp (ORNL)
Hideaki Hotchi (JAEA)
Susumu Igarashi (KEK)
Ioanis Kourbanis (FNAL)
Jean-Michel Lagniel (CEA)
Trevor Linnecar (CERN)
Robert Macek (LANL)
John Maidment (DESY)
Nikolai Mokhov (FNAL)
Akira Noda (Kyoto U.)
Peter Ostroumov (ANL)
Deepak Raparia (BNL)
Thomas Roser (BNL)
Francesco Ruggiero (CERN)
Ken Takayama (KEK)
Masahito Tomizawa (KEK)
Bill Weng (BNL)
Frank Zimmermann (CERN)

The Local Organizing Committee:

Yong Ho Chin (yongho.chin@kek.jp): Co-chair
Hiroshi Yoshikawa (hiroshi.yoshikawa@j-parc.jp): Co-chair
Masanori Ikegami (masanori.ikegami@kek.jp): Vice-chair
Kazuo Hasegawa (hasegawa.kazuo@jaea.go.jp)
Hiroyuki Sako (sako.hiroyuki@jaea.go.jp): Electronic publication of proceedings
Rumiko Enjoji (rumiko.enjoji@kek.jp): Secretary

6.3 RuPAC 2006 Announcement

Dear Colleagues,

The XX Russian Accelerator Conference (RuPAC2006) will take place in Novosibirsk, Russia, September 10 - 14, 2006.

The conference will be organized by

- Budker Institute of Nuclear Physics
- Russian Academy of Science
- Federal Agency of Atomic Energy of the Russian Federation
- Federal Agency of Science and Innovations of the Russian Federation

The format of the conference will be as usual: invited plenary talks, short oral contribution and poster section.

The Conference provides a forum for exchange of new information and discussion in the area of acceleration science and engineering, new accelerator design, accelerator use for scientific and applied purposes.

Tentative Conference Topics

1. Modern trends of accelerator development, large accelerator designs. Colliding beams.
2. Heavy ions accelerators.
3. Accelerating structures and power radio engineering.
4. Control and diagnostic systems.
5. High intensity cyclic and linear accelerators.
6. Superconducting accelerators and technology of cryogenics.
7. Magnetic systems, power supply and vacuum systems for accelerators.
8. Beam dynamics in accelerators and storage rings, new methods of acceleration,
9. Radiation problem in accelerators.
10. Accelerators for medical and industrial purposes.

Russian Particle Accelerator Conference is including now in JACoW (Joint Accelerator Conference Website) system. The information about JACoW one can see at http://accelconf.web.cern.ch/accelconf/.

Please take a few minutes to check out your profile (http://www.jacow.org/jacow/repository.html) and if necessary complete your profile and affiliation data.

The working languages of RuPAC 2006 are Russian and English. The Conference proceedings will be published and presented at JACoW in English only.

The Organizing Teams of RuPAC’06 look forward to welcoming you to the conference.

7 Announcements of the Beam Dynamics Panel

7.1 ICFA Beam Dynamics Newsletter

7.1.1 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 a substitute for journal articles and conference proceedings that 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.

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

7.1.2 Categories of Articles

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 on workshops, meetings and other events related to beam dynamics.
4. Announcements of future beam dynamics-related international workshops and meetings.
5. Those who want to use newsletter to announce their workshops are welcome to do so. Articles should typically fit within half a page and include descriptions of the subject, date, place, Web site and other contact information.
6. Review of beam dynamics problems: This is a place to bring attention to unsolved problems and should not be used to report completed work. Clear and short highlights on the problem are encouraged.
7. Letters to the editor: a forum open to everyone. Anybody can express his/her opinion on the beam dynamics and related activities, by sending it to one of the editors. The editors reserve the right to reject contributions they judge to be inappropriate, although they have rarely had cause to do so.
8. Editorial.

The editors may request an article following a recommendation by panel members. However anyone who wishes to submit an article is strongly encouraged to contact any Beam Dynamics Panel member before starting to write.

7.1.3 How to Prepare a Manuscript

Before starting to write, authors should download the template in Microsoft Word format from the Beam Dynamics Panel web site:

http://www-bd.fnal.gov/icfabd/news.html

It will be much easier to guarantee acceptance of the article if the template is used and the instructions included in it are respected. The template and instructions are expected to evolve with time so please make sure always to use the latest versions.

The final Microsoft Word file should be sent to one of the editors, preferably the issue editor, by email.

The editors regret that LaTeX files can no longer be accepted: a majority of contributors now prefer Word and we simply do not have the resources to make the conversions that would be needed. Contributions received in LaTeX will now be returned to the authors for re-formatting.

In cases where an article is composed entirely of straightforward prose (no equations, figures, tables, special symbols, etc.) contributions received in the form of plain text files may be accepted at the discretion of the issue editor.

Each article should include the title, authors' names, affiliations and e-mail addresses.

7.1.4 Distribution

A complete archive of issues of this newsletter from 1995 to the latest issue is available at

http://icfa-usa.jlab.org/archive/newsletter.shtml

This is now intended as the primary method of distribution of the newsletter.

Readers are encouraged to sign-up for electronic mailing list to ensure that they will hear immediately when a new issue is published.

The Panel's Web site provides access to the Newsletters, information about future and past workshops, and other information useful to accelerator physicists. There are links to pages of information of local interest for each of the three ICFA areas.

Printed copies of the ICFA Beam Dynamics Newsletters are also distributed (generally some time after the Web edition appears) through the following distributors:

Weiren Chou	chou@fnal.gov	North and South Americas
Rainer Wanzenberg	rainer.wanzenberg@desy.de	Europe* and Africa
Susumu Kamada	Susumu.Kamada@kek.jp	Asia** and Pacific

* Including former Soviet Union.

** For Mainland China, Jiu-Qing Wang (wangjq@mail.ihep.ac.cn) takes care of the distribution with Ms. Su Ping, Secretariat of PASC, P.O. Box 918, Beijing 100039, China.

To keep costs down (remember that the Panel has no budget of its own) readers are encouraged to use the Web as much as possible. In particular, if you receive a paper copy that you no longer require, please inform the appropriate distributor.

7.1.5 Regular Correspondents

The Beam Dynamics Newsletter particularly encourages contributions from smaller institutions and countries where the accelerator physics community is small. Since it is impossible for the editors and panel members to survey all beam dynamics activity worldwide, we have some 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
Sameen Ahmed KHAN	rohelakhan@yahoo.com	MECIT Middle East and Africa

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

7.2 ICFA Beam Dynamics Panel Members

Caterina Biscari	caterina.biscari@lnf.infn.it	LNF-INFN, Via E. Fermi 40, C.P. 13, Frascati, Italy
Yunhai Cai	yunhai@slac.stanford.edu	SLAC, 2575 Sand Hill Road, MS 26 Menlo Park, CA 94025, U.S.A.
Swapan Chattopadhyay	swapan@jlab.org	Jefferson Lab, 12000 Jefferson Avenue, Newport News, VA 23606, U.S.A.
Weiren Chou (Chair)	chou@fnal.gov	Fermilab, MS 220, P.O. Box 500, Batavia, IL 60510, U.S.A.
Yoshihiro Funakoshi	yoshihiro.funakoshi@kek.jp	KEK, 1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305-0801, Japan
Miguel Furman	mafurman@lbl.gov	Center for Beam Physics, LBL, Building 71, R0259, 1 Cyclotron Road, Berkeley, CA 94720-8211, U.S.A.
Jie Gao	gaoj@ihep.ac.cn.	Institute for High Energy Physics, P.O. Box 918, Beijing 100039, China
Ingo Hofmann	i.hofmann@gsi.de	High Current Beam Physics, GSI Darmstadt, Planckstr. 1, 64291 Darmstadt, Germany
Sergei Ivanov	ivanov_s@mx.ihep.su	Institute for High Energy Physics, Protvino, Moscow Region, 142281 Russia
Kwang-Je Kim	kwangje@aps.anl.gov	Argonne Nat'l Lab, Advanced Photon Source, 9700 S. Cass Avenue, Bldg 401/C4265, Argonne, IL 60439, U.S.A.
In Soo Ko	isko@postech.ac.kr	Pohang Accelerator Lab, San 31, Hyoja-Dong, Pohang 790-784, South Korea
Alessandra Lombardi	Alessandra.Lombardi@cern.ch	CERN, CH-1211, Geneva 23, Switzerland
Yoshiharu Mori	mori@kl.rri.kyoto-u.ac.jp	Research Reactor Inst., Kyoto Univ. Kumatori, Osaka, 590-0494, Japan
Chris Prior	c.r.prior@rl.ac.uk	ASTeC Intense Beams Group, Rutherford Appleton Lab, Chilton, Didcot, Oxon OX11 0QX, U.K.
David Rice	dhr1@cornell.edu	Cornell Univ., 271 Wilson Laboratory, Ithaca, NY 14853-8001, U.S.A.
Yuri Shatunov	Yu.M.Shatunov@inp.nsk.su	Acad. Lavrentiev, prospect 11, 630090 Novosibirsk, Russia
Junji Urakawa	junji.urakawa@kek.jp	KEK, 1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305-0801, Japan
Jie Wei	wei1@bnl.gov	BNL, Bldg. 911, Upton, NY 11973- 5000, U.S.A.
Jiu-Qing Wang	wangjq@mail.ihep.ac.cn	Institute for High Energy Physics, P.O. Box 918, 9-1, Beijing 100039, China
Rainer Wanzenberg	Rainer.wanzenberg@desy.de	DESY, Notkestrasse 85, 22603 Hamburg, Germany