Fermi National Accelerator Laboratory

FERMILAB-TM-1979

Report of the Transition Crossing Mini-Workshop May 20-23, 1996, Fermilab, Batavia, Illinois, USA

Philip Martin and Weiren Chou

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

July 1996

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Report of The Transition Crossing Mini-Workshop

May 20-23, 1996, Fermilab, Batavia, Illinois, USA

Philip Martin and Weiren Chou

The Mini-Workshop on Transition Crossing was held from May 20 to 23, 1996, at Fermilab. This was the first in a series of mini-workshops on high intensity, high brightness hadron beams. Twenty five people from CERN, KEK, BNL, Fermilab and University of Houston attended the workshop.

The first day was a plenary session with nine presentations. On the second day, three working groups (WG) were formed: WG-I was on theory, simulation and measurements, led by J.-P. Riunaud (CERN) and P. L. Colestock (Fermilab); WG-II was on γ_t-jump systems, led by T. Roser (BNL) and W. Chou (Fermilab); WG-III was on new schemes, led by Y. Mori (KEK) and J. Griffin (Fermilab). Because of the mini size of the workshop, the agenda was flexible so that these groups could work either together or separately, and participants could switch between groups at will. The group leaders worked hard for coordinating the activities and leading the discussions. Each group gave a presentation at the final plenary session. The summaries from the three working groups are included in this report. During the workshop, P. Martin gave a guided tour to the Main Injector tunnel, which is under construction at Fermilab.

There will be no formal proceedings. A list of presentations at the workshop is included. Copies of the presentations are available upon request.

The next three mini-workshops in this series have been tentatively scheduled.

- Second Mini-Workshop: From November 29 to December 1, 1996, at KEK. The topic is "*Beam Loss Mechanism in Intense Hadron Synchrotrons.*"
- Third Mini-Workshop: From May 19 to 22, 1997, at BNL. The topics are:
  - RF cavities (higher order modes, narrowband passive and active mode dampers, wideband passive dampers, beam loading, barrier buckets, *etc.*).
  - Coalescing/Debunching-Rebunching (efficiency, emittance dilution and instability problems, slip stacking, *etc.*).
- Fourth Mini-Workshop: Late 1997 at CERN. The topics are:
  - Longitudinal and transverse emittance budget (emittances growth and preservation, controllable longitudinal emittance blow-up schemes, *etc.*).
  - Diagnostics (BPM and orbit measurement, emittance measurement, *etc.*).

Summary of Working Group I — Theory, Simulation and Measurements
(J.-P. Riunaud, P. L. Colestock)

1. Theory and Simulation:
   Presentations were made regarding aspects of longitudinal stability at transition, particularly with regard to microwave modes. At issue was the ability to predict high

frequency modes, as well as the associated emittance growth, with current simulation tools.

An analytical treatment of the linear stability problem was carried out by P. Colestock and J. Holt, which showed an unstable band just above transition. A numerical criterion, similar to the Keil-Schnell criterion was investigated, which showed significant reduction of the stable operating region in this frequency band above transition.

Bill Ng made a presentation regarding issues encountered in the simulation of microwave stability. In particular, the choice of binning in the simulations was discussed. He has found that there is a direct relationship between the bin width and the characteristics of the resulting unstable spectrum in the simulations. Reference was made to the work of Hardt at CERN who has shown analytically that the unstable microwave spectrum should contain frequencies which are not accessible in most simulations due to the constraints on bin width.

Chandra Bhat presented simulations of longitudinal stability in crossing transition in the Fermilab Main Ring. These simulations showed the development of unstable oscillations which were attributed to microwave modes. Discussion ensued which questioned the origin of these effects. A large increase in the beam emittance was shown, however, the concept of emittance was brought into question in situations where a large coherent motion was involved. This was consistent with the fact that the final emittances well away from transition were smaller than those at transition.

Discussion followed regarding the available simulation codes. Almost all work has been based on ESME, which has not universally included the effects of space charge, and is restricted to longitudinal dynamics. However, a fully six-dimensional code, SIMPSON, has been developed by Shinji Machida and could be effectively used to study transition crossing, and the effect on emittance growth. The consensus of the participants was that it would be beneficial to use this more general code to study transition crossing. It was cautioned that such a general code may have to be adapted slightly to be suitable for studying transition crossing.

2. Measurements:
   J.-P. Riunaud expressed the concern that we need to understand the effect of transition crossing on the blowup of the transverse emittance, a subject that has received rather scant attention to date. T. Roser indicated that at the AGS, operators had found that it was necessary to precisely tune the skew-quadrupoles at transition to prevent transverse emittance blowup later in the cycle. This interesting finding was discussed, but no direct reason for this dependence was found.

   Measurements from the PS at KEK were presented which showed vertical emittance blowup at transition at high intensities. Discussion followed with regard to the possible effect of chromaticity changes at high $\dot{\gamma}_t = 1000\ \mathrm{s}^{-1}$. Such a chromaticity change could lead to a head-tail instability.

   M. Brennan presented measurements of α_1 made at the AGS. These were based on precise measurements of transition crossing with a small $\Delta p/p$ and a flat γ_t. Accuracy in these measurements was rather good, with about 25% agreement with MAD calculations.

P. Colestock presented a scheme to measure diffusive effects at transition using an echo technique, similar to the echoes that have been studied in unbunched beams. Although a bunched-beam echo model has not been formulated, ESME simulations carried out at the SSC have shown a workable scenario, and measurements have been successfully carried out in the Tevatron. The benefit of transition is to provide a natural phase reversal which can lead to an echo formation with a single longitudinal kick. Discussion followed which indicated issues of nonlinearity in echo formation, however, the echo shape itself may carry information on α_1. Efforts should be made to produce a viable model, as well as tests of the concept near transition.

Summary of Working Group II — γ_t-Jump Systems
(T. Roser)

Transition energy jump systems have been around for quite a while and are being used successfully at the CERN PS, BNL AGS, Fermilab Booster and KEK PS. The technique of rapidly changing the transition energy using pulsed quadrupoles is well developed. The working group therefore focussed on a number of topics that are of particular interest for new machines and possible upgrades of existing machines.

1. Limitations of Transition Jump Systems and Possible Upgrades:
   All transition jump systems currently in operation use a global distortion of the dispersion to change the transition energy. The number of quadrupoles and their required strength is quite modest. However, the main drawback is a maximum dispersion that is up to five times larger than the regular value either just before transition for unipolar jumps or both before and after transition for bipolar jumps. The large dispersion distortion has mainly two consequences that can limit machine performance: First the large dispersion limits the momentum aperture and therefore the bunch area. This is a beam intensity limitation at the BNL AGS. Second, the large dispersion distortion also gives rise to a large value for α_1, the momentum dependence of the transition energy. This leads to a chromatic mismatch of the bucket shape during the jump causing emittance growth and possibly beam loss. Note that neither of these effects are intrinsically intensity dependent. In fact, there seem to be no obvious space charge effects observed in the operating transition jump systems except for signs of microwave instablities which, however, don't lead to any beam loss and only minor emittance blow-up.

   If locations with zero dispersion are available a jump in transition energy can be accomplished more easily since it is then possible to change the dispersion only locally and compensate the resulting betatron tune shift at the zero dispersion location. This scheme works well in new lattices and is planned for RHIC and the Fermilab Main Injector. The same scheme could also be used in the AGS if a zero dispersion location is created prior to transition crossing with a one-wave-length dispersion distortion.

   The local dispersion distortion would probably also result in a reduced value for α_1. Even if that is not the case and for global distortion systems α_1 can be reduced and maybe even tuned to its ideal value of -1.5 by using sextupoles. Ideally these sextupoles would have to be pulsed together with the pulsed quadrupoles to account for the changing dispersion function.

This means that it seems possible that a transition jump system could be developed that would allow transition crossing without beam loss or emittance growth even at the highest intensities or bunch brightness. The justification for special lattices with very high transition energy or imaginary transition energy should therefore be based primarily on the higher likelihood of encountering instablities above transition rather than on beam loss or emittance growth from crossing transition.

2. Improvements in the Pulsed Quadrupole Hardware:
There was significant discussion on the plans for the pulsed quadrupole system for the Fermilab Main Injector. The vacuum chamber would be made of Inconel 718 which can be made thinner than stainless steel and also has a higher resistivity. The design of the quadrupoles must have a high Q value to allow for a bipolar operation using a ringing circuit.

For future designs of power supplies for pulsed quadrupoles, it would be interesting to provide for the possibility to independently adjust the jump size and the crossing speed. In all current systems these two parameters can only be changed together.

3. Summary of Proton Synchrotron Performances:
Table 1 is a summary of the performance of proton synchrotrons that need to cross transition. Also included are the performance numbers of planned or upgraded synchrotrons that will need to cross transition or would need to cross it if they used a FODO lattice. The longitudinal brightness defined as the bunch intensity divided by the bunch area is a good measure of the difficulties encountered at transition crossing.

Table 1. Proton Synchrotrons Performance

Machine	$E_{\rm max}$ (GeV)	$N_{\rm tot}$ (10^{12})	$N_{\rm b}$ (10^{12})	$A_{\rm b}$ (eV-s)	$N_{\rm b}/A_{\rm b}$ (10^{12}/eV-s)	$\epsilon_{rms}^{\rm H}$ (μm)	$\epsilon_{rms}^{\rm V}$ (μm)	$N_{\rm b}/\epsilon_{rms}$ ($10^{12}/\mu$m)
Existing:								
BNL AGS	24	63	8	4	2	10	10	0.8
CERN PS	14	25	1.25	0.7	1.8	12.5	10	0.13
KEK PS	12	3.6	0.4	2	0.2	5	15	0.08
FNAL Booster	8	4	0.05	0.1	0.5	3	3	0.02
FNAL MR	150	20	0.03	0.2	0.15	2	2	0.02
Planned:								
AGS for RHIC	25	0.4	0.4	0.3	1.3	1.5	1.5	0.3
PS for LHC	26	14	0.9	1.0	0.9	2.8	2.8	0.3
FNAL Main Inj	150	60	0.12	0.1	1.2	2	2	0.06
KEK JHP	50	200	12.5	5	2.5	55	55	0.2
$\mu\mu$ Proton Dr	30	100	25	4	6.3	50	50	0.5

Summary of Working Group III — New Schemes
(Y. Mori)

The following two topics have been mainly discussed by the working group III.

- Focus free transition crossing (FFTC)
- Imaginary γ_t lattice

In addition to the following, a bunch-shortening scheme and a quasi-isochronous bucket related to the transition crossing have been also discussed.

1. FFTC:
   This scheme was proposed by Griffin some years ago, the concept of which was reviewed by him at the workshop. The growth of momentum spread occurs at a transition crossing by non-adiabaticity due to the RF focusing force. If the RF focusing force can be eliminated by flattening the RF voltage near to transition energy, momentum spread and longitudinal emittance growth can be avoided (see Figure 1).

   A proof-of-principle experiment was recently carried out by Bhat *et al.* at the FNAL Main Ring with the 3rd-harmonic RF cavity (f = 159 (53) MHz, V = 0.27 (2.1) MV). No beam loss was observed with the FFTC at a beam intensity of 2.2x10^{10} ppb, while there was beam loss of 5% without FFTC at the transition crossing.

   A transition crossing with the FFTC treats any longitudinal potential or bucket distortion. On the other hand, the ordinary transition γ_t jump scheme with an α_1 correction is based on the beam dynamics. There are many advantages in a transition crossing with the FFTC, such as a small beam size at large dipersion and small longitudinal and transverse emittance distortions, because the momentum spread is small and the bunching factor is large. However, it has also been pointed out that small Landau damping due to a small tune spread might be a problem in suppressing any microwave instability when the beam intensity becomes relatively higher.

2. Imaginary γ_t lattice:
   Three examples of imaginary or high-γ_t lattice designs have been invoked at the workshop.

   (a) FNAL Main Injector:
   Ng showed a ring design with a proposed imaginary γ_t lattice for the FNAL Main Injector (see Figure 2). This design has the following features:

      i. There is no large dispersion, which is unlike Teng's lattice.
      ii. The packing factor is good.
      iii. The cell length is relatively longer.
      iv. The dispersion is zero at the straight sections.
      v. Modulation of beta functions are relatively large.

   (b) JHP 50-GeV PS:
   Machida presented the lattice design of the JHP (Japanese Hadron Project) 50-GeV PS. An imaginary γ_t can be realized in this design by modulating the

curvatures (ρ-modulation), which makes it possible to minimize the modulation of the beta function. This scheme allows sufficient space for RF cavities, which would be beneficial for a high-intensity machine with a large repetition rate. Although the dispersion becomes large at the position of the missing bending section (Figure 3), the value is not very large. Zero dispersion in the long straight section is also possible. The momentum compaction factor can be relatively changeable and the linear optics stability is fairly good.

(c) AGS & Proton Driver for μ^+/μ^- collider:
Roser showed the high-γ_t option of the present AGS lattice, which is realized by modulating the dispersion function by invoking additional Q magnets (see Figure 4). In this modification, the transition energy becomes close to the extraction energy. Roser also showed an example lattice design for the proton driver of a μ^+/μ^- collider (Figure 4). This is the same lattice as that for JHP, except that γ_t is not imaginary.

(d) Discussions:
The fundamental problems concerning an imaginary γ_t lattice have been discussed. In a hadron machine, LEAR at CERN is the only operational machine to have an imaginary γ_t. In order to make γ_t imaginary, it is unavoidable to have some irregularities and a smaller periodicity for the lattice parameters. These might affect the dynamic aperture, especially when the beam intensity becomes high. On the other hand, it was also pointed out that an imaginary γ_t machine might have a better performance against a longitudinal microwave instability. Since LEAR is an anti-proton decelerator, its beam intensity is relatively low. Discussions concerning an imaginary γ_t lattice have mainly concentrated on these issues, although simulations including space-charge effects for the JHP PS lattice seem to show sufficient dynamic aperture. Every member of this working group has agreed that a "dry run" to simulate practical control and operation of an imaginary γ_t machine is essential to understand the problems and difficulties. It was also pointed out a measurement of α_1 is very important, particularly in a commissioning run.

3. Others:
One of the requirements for the proton driver of a μ^+/μ^- collider is to make very short bunches, which gives an RF phase rotation to increase the longitudinal acceptance and provide better muon beam polarization. The required bunch length should be less than 1 ns. In order to make such a short bunch, a scheme with RF manipulation near to transition energy has been proposed. Norem presented this scheme at this working group (see Figure 5). He mentioned that (1) fast bunch rotation should be possible, and (2) bunching and extraction without instabilities seem to be possible.