ICFA Beam Dynamics Newsletter, No. 19

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1: From the chairman

Kohji Hirata `kohji.hirata@kek.jp` The Chairman of ICFA Beam Dynamics Panel

When I restarted the publication of this newsletter with S.Y. Lee and F. Willeke more than 4 years ago, I was very worried about collecting contributions. At that time, S. Peggs worked hard and could send me a long report of BNL activity, without which the first issue (No.6) were too thin. I kept the contribution from R. Baartman for the next issue, because I was not sure if I could collect enough for the next issue, too. I recalled these because of another long and detailed activity report from BNL in this issue.

There can be many different styles for contribution. CERN prefers to give short reports in every issue, for example. Some reports appear to be formal as laboratory report and some quite friendly and informal. All these reports are interesting and useful for all of us to see (and feel) what is going on in our society. We encourage everybody in our society to report their activity in any style.

The newsletter has been growing steadily and is now supported strongly by the beam dynamics and accelerator physics society. I want to thank all the contributers to the newsletter and people who had helped it including past and present editors and beam dynamics panel members and also want to ask continuous support of the newsletter. As you can realize on the front cover page, the editorial system has changed a little from this issue. J.M. Jowett and I will work as chief editors who supervise the editorial processes. The six editors will edit each issue alternatively. The August issue will be edited by W. Chou. The schedule will be posted on our WWW page but you can send your contribution to anyone in the editorial board.

The recent sudden death of Prof. Bjørn Wiik has struck me. He was the chairman of ICFA since 1997 and was an ICFA member since 1993. In ICFA, he continuously supported our panel strongly. Also he has worked a lot to innovate the HEACC conference series. I was going to ask him to write something in this newsletter to ecourage our activity. I wish to thank him for all of his help and encouragement to our activity. I believe we will succeed his will for the future of the accelerator society. We deeply express our regret.

S.Y. Lee has left the panel. The panel wants to thank him for his numerous contributions to the panel activity. J. Wei (BNL) and D.H. Whittum (SLAC) have become panel members on January 1999.

2: Letters to the Editors

2.1 From A.Chao and M.Tigner

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For many years, beam dynamicists have been pleased to use the famous "Selection of Formulae and Data for the Design of A.G. Synchrotrons" by C. Bovet et al. More recently there have been Jim Murphy's handbook for synchrotron light sources, the wallet card version of Matt Sands electron storage ring bible, as well as many other useful formula collections put out by our colleagues. Our business has now matured to the point where it seemed that there is need for another attempt to build on the earlier work with a handbook more inclusive of the current knowledge and practice.

In an attempt to meet that need, more than two hundred of our colleagues have joined a 3-year community project to summarize their expertise for the use of their fellow professionals. The work has been organized by Alex Chao and Maury Tigner who serve as editors. The handbook contains 650 pages of text, much of its content shown in the form of equations, illustrations, and tables. World Scientific Publishing Co. has agreed to publish this "Handbook of Accelerator Physics and Engineering" to appear in the spring of 1999. An attempt has been made to make the handbook concise and portable so that it can be carried in travel. Further information can be found at

`http://www.wspc.com.sg/books/physics/3818.html`

It is to be noted that the fees that would normally be paid to authors and editors are being used for scholarships to the two accelerator schools, CAS and USPAS.

We hope to keep it up-dated through WWW as the common property of our community. Any comments or remarks of errors or inconsistencies will be welcome. Please send them to

(achao@slac.stanford.edu)

and we will post them appropriately on the WWW.

3: Workshop and Conference Reports

3.1 RIKEN Workshop on Space Charge Dominated Beam Physics for Heavy Ion Fusion

(Saitama, Japan, 10-12 December 1998)

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Realization of heavy ion fusion program requires delivering of enormously large powerful beam (10 GeV, total current 50 kA) at a small target (several mm) during a period of approximately 10 nanoseconds by a heavy ion particle accelerator. Achievement of fusion parameters is one of the most challenging task for accelerator physics. Beam space charge effects remain the key problem for designers of high intensity accelerators for heavy ion fusion. Subject of RIKEN Workshop was to review the present understanding of space charge phenomena in high intensity accelerators for HIF and to discuss possible solution of unresolved problems.

Workshop was organized and supported by RIKEN Radioactive Isotope Beam Factory Project Office. Symposium attracted 50 scientists who discussed many novel ideas in the field during 3 days of Workshop.

3.1.1 Heavy ion projects

In opening address Yasushige Yano (RIKEN) made a historical overview of heavy ion facilities in Japan and outlined main topics of new RIKEN RI Beam Factory Project.

Ingo Hofmann (GSI) presented experimental and theoretical investigation of space charge dominated beams at GSI. Experimental study of coherent (transverse) quadrupole oscillations depending on beam distribution function and study of nonlinear effects on longitudinal stability were given. Other subjects included multiturn injection optimization, interplay between dispersion and space charge and preparation of halo experiment study.

Boris Sharkov (ITEP) introduced new TWAC project and the use of the laser ion source for production of intense heavy ion beams. The project will use an existing heavy ion accelerator complex, including 13 Tm booster ring, 34 Tm heavy ion synchrotron and 2MV/3MHz two-gap heavy ion injector. After pre-acceleration the He-like ions of medium-A (i.e. from ^{12}C to ^{59}Co) will be injected in the booster ring and accelerated up to 0.7 GeV/u, and then stacked in the storage ring using non-Liouvillian technique. Big number of cycles of the 1 Hz rep-rate ion source and repetition of the whole acceleration-accumulation process could provide final increase of the number of accumulated particles by factor $\sim$ 1000. Accumulation of coasting beam will be done until the Laslett space-charge limit (ΔQ = 0.16) is reached in the synchrotron ring with 1.2 $\times 10^{13}$ ions, corresponding to about 100 kJ stored energy in the beam. A rapid switch on the RF in the synchrotron ring causes ballistic compression (bunch rotation in phase space) of accumulated bunch from a length of 1000 ns down to 100 ns with final power of the beam at the target of 1 TW. However, ion storage during so large number of injection turns will require suppression of beam loss due to intra-beam scattering and interaction with the target.

Yoshiharu Mori (KEK) offered new concept of very fast cycling hadron accelerator. The concept is based on FFAG focusing providing Multi- Orbit Synchrotron (MOS). Design example with beam power of 10 MW was discussed. Key element of the project is a new type of accelerating RF cavity with magnetic allow cores, developed at KEK. A large accelerating gradient of more than 100 kV/m has been demonstrated.

Giovanni Parisi (Frankfurt University) presented results on particle dynamics in Drift Tube Linac for high intensity heavy ion beam in the framework of a European study group on Heavy Ion Driven Inertial Fusion (HIDIF). Ultimate goals of linac design are high transmission efficiency and low emittance growth of 400 mA Bi $^+$ up to the energy of 10 GeV in presence of statistical errors and on-axis mismatch. The required beam quality is defined by the demand for loss-free injection in accumulator ring of the beam with emittance less than 4 π mm mrad and maximum momentum spread of 2 x 10^{-4}.

Gennady Dolbilov and Anatoly Fateev (JINR) outlined experience of development of high current induction linac at JINR and perspective of their application for acceleration of ions. Electron linear induction accelerators at JINR (current 0.3 - 8 kA, energy 0.25 - 2.5 MeV, pulse length 15-250 ns) have been developed in the framework of program of collective methods of acceleration. They are used now for variety applications like free electron lasers, relativistic klystron and two-beam acceleration. New scheme for ions based on RF acceleration of ions via excitation of cavity by prebunched driving electron beam is considered.

3.1.2 Beam-beam effect

Andrey Sery (FNAL) presented an approach to compensate beam-beam effects for antiprotons with the use of electron beam with a corresponding charge density. Due to nonlinear focusing in the interaction point the betatron frequencies in a beam are different for particles with different betatron amplitudes. Compensation of beam-beam induced betatron tune spread within the bunch is expected to be done by an electron beam with equivalent (Gaussian or close to that) charge distribution. Experimental set-up as well as theoretical considerations were given.

3.1.3 Mechanisms of beam emittance growth and halo formation

Robert Jameson (LANL) presented an approach to fundamental study of beam loss minimization. Role of equipartitioning on rms equilibrium condition in linac design was discussed in detail. An approach to systematic study using RFQ accelerator as a simulation testbed was presented. The role of new methods in nonlinear dynamics, complexity and chaos is outlined.

Masanori Ikegami (JAERI) discussed results on particle-core analysis for halo formation in anisotropic beams. The effect of simultaneous excitation of two normal modes on beam halo formation have been studied. Both isotropic and anisotropic coasting beams were treated.

Shinji Machida (KEK) presented results on coherent oscillations and halo formation in a ring. It was outlined that coherent modes are mostly responsible for beam stability and intensity limit in high current rings.

John Barnard (LLNL) considered results on emittance growth in recirculator rings from space charge and dispersion. Moment equations including dispersion in bends and space charge are reviewed. Change of emittance resulting from a sharp transition from a straight section to a bend section was calculated. Comparison with numerical simulation using the WARP code was done.

Irving Haber (NRL) reviewed warm plasma oscillations in a space-charge-dominated beam. Discussion started with collective modes of KV beam oscillation followed by non-KV (semi-Gaussian) beam. Sources of free energy for beam emittance growth as well as temperature anisotropy were discussed.

Yuri Batygin (RIKEN) presented an universal approach to find stationary self-consistent beam distribution in arbitrary continuous focusing and RF field. It was found that incorporation of octupole component in quadrupole structure is not sufficient to suppress beam emittance growth, while utilizing of duodecapole component results in suppression of halo formation. Self-consistent bunch shape in RF field was found which is different from the widely used approximation of bunch by ellipsoid. Equipartitioning in RF field as a direct result of stationarity of collisionless beam distribution function was discussed.

3.1.4 Beam cooling and stacking

Evgeni Syresin (JINR) discussed optimal injection and storage schemes for heavy ion beams. Comparison was done between multi-turn injection with RF stacking and a single turn injection. Multi-turn injection has an advantage in the number of turns. However, it requires cooling of beam with large emittance, which affects cooling time seriously. Single turn scheme has a significant gain in ion storage rate, if the initial emittance of the injected beam is small. Realization of this scheme is mainly determined by performance of intense pulsed source of highly charged ions.

Igor Meshkov (JINR) offered electron cooling with circulating electron beam. The thermodynamics of cooling method was considered and scheme of cooler ring with longitudinal magnetic field was discussed. Proposed method is suitable for electron cooling of ion in GeV energy range. The modified betatron is one of the most appropriate scheme of the storage ring in cooling electron beam.

3.1.5 Electron-ion instability in a ring

Ronald Davidson (PPPL) presented Vlasov-Maxwell description of electron-ion instability in high intensity linacs and storage rings. Analysis is based on kinetic description of ion beam propagating through background population of electrons in electrostatic approximation. System of eigenvalue equations has been derived for small-amplitude perturbations about general equilibrium distributions. Attained coupled eigenvalue equations were used to determine the complex oscillation frequency and detailed stability properties for a wide range of system parameters and choices of distribution functions.

Pavel Zenkevich (ITEP) used new concept of ”two-stream transverse impedance” to study transverse electron-ion instability in ion storage rings with high current. A formula connected this impedance with space charge impedance of the ion beam and neutralization degree was derived. It was shown that in ion ring there is a ”natural” neutralization degree which is defined by an equilibrium between the ionization rate and electron losses due to heating by elastic electron-ion Coulomb scattering. Developed analysis was applied to determination of ”natural” neutralization degree and the threshold momentum spread of the electron-ion instability for TWAC project at ITEP.

3.1.6 Beam transport and target

Takashi Kikuchi and Shigeo Kawata (Nagaoka Univ. of Technology) revealed results of numerical study of intense-heavy-ion-beam transport through an insulator beam guide. Earlier this idea was proposed as a new system for electron and proton beam transport. In presentation it was discussed for transport of single charged beam of Cs^+ and Pb^+. An intense heavy ion beam creates a local electric field on the insulator inner surface and generates a plasma on the surface of insulator guide. Electrons are extracted from the plasma and the beam space charge is neutralized by electrons providing efficient transport.

Kazuhiro Fujita and Shigeo Kawata (Nagaoka Univ. of Technology) discussed numerical study of inhomogeneity smoothing using density valley formed by ion-beam deposition in Inertial Confinement Fusion fuel pellet. Simulation results show that radiation energy is confined in the density valley and the beam non-uniformity can be smoothed out by the radiation transport along the density valley. Formation of density valley is controlled by changing a beam incident angle.

3.1.7 Beam simulation codes

Edil Mustafin (ITEP) offered new numerical code for Monte-Carlo simulation of evolution of ion beam distribution function during storage process. The code allows estimation of growth rate of emittance and momentum spread due to intrabeam scattering and interaction with stripping target of the beam with non-Gaussian distribution function. Code also permits estimation of beam losses. Application to TWAC project at ITEP have been presented and discussed.

Grigori Shirkov (JINR) presented program library for numerical simulation of multi-component ion beams in transportation lines. The library is aimed for simulation of high current, low energy multi-component ion beam through beamline and is realized under the Windows user interface for IBM PC. It is used for simulation and optimization of beam dynamics. Code is based on successive and consistent application of momentum method for beam distribution function (rms technique) and particle-in-cell method. The library has been used for simulation and optimization of tantalum ion beam transport from the laser ion source through Low Energy Beam Transport Line into RFQ linac at CERN.

3.1.8 Discussion

In the final discussion (Chairman Ingo Hofmann) the following items were identified as key issues for future detail study:
- Tolerable beam loss of heavy ions in the 50 MeV/nucleon energy range
- Possibility of electron cooling of 10^{12} -10^{13} heavy ion beams
- Long term ion accumulation schemes with emphasis on ion life time in presence of cooling and intrabeam scattering
- Maximum incoherent betatron tune shift due to space charge forces as a function of beam loss at the injection of high phase space density beam into the ring
- Trade off between large number of ions and required small momentum spread
- Crossing of resonances in presence of space charge
- Integrated Research Experiment Concept
- Possible combination of RF linac and induction linac in HIF accelerator and related problems
- Possibility to use RF linac for acceleration of beams with current of 1 Ampere utilizing IH structure
- Interplay between high current, low emittance and filling large fraction of physical aperture
- Laser ion sources in 40-50 Hz repetition range to reduce storage time and to avoid necessity of cooling
- Possible suppression of electron - ion instability in rings by spread in betatron frequencies and by clearing electrodes
- Links between space charge phenomena in low energy and high energy parts of accelerator
- Prediction capabilities of space charge phenomena by existing tools and computer codes
- Spin off to other projects: halo formation in linacs and rings, high intensity cyclotrons.

Materials of the Workshop will be published as a volume of AIP Conference Proceedings Series. It will hopefully be useful for beam physicists and accelerator designers of intense high brightness accelerators for heavy ion fusion and related projects.

3.2 16th Workshop on Particle Accelerators in Russia

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A regular (sixteenth) workshop on particle accelerators was convened in the Russian proton accelerator center Protvino on October 20-22, 1998. The national workshop, organized by the Institute for High Energy Physics (IHEP) and the Joint Institute for Nuclear Reserch (JINR), was supported by the Ministry for Atomic Energy of Russian Federation, the Russian Ministry for Science and Technology, and the Russian Academy of Sciences.

The first Conference on Particle Accelerators in the Soviet Union was held in 1968 in Moscow, thirty years ago. In his Workshop98 address, Chairman Atlant A.Vasiliev reviewed the history of the biennial Russian Workshops and their impact on Particle Accelerators.

The 16th workshop was attended by 250 physicists from Moscow, St.Petersburg, Novosibirsk, Tomsk, Saratov, Kharkov, Dubna, Troitsk, Obninsk, and Protvino. The major accelerator centers worldwide were also represented: CERN (Switzerland), DESY (Germany), Fermilab and BNL (USA), TRIUMF (Canada), KEK (Japan).

The submitted reports were presented at the plenary and panel sessions. Over 130 reports were delivered on the status of existing accelerators and development of new machines, as well as on using particle accelerators in diverse areas of science and technology. The oral and poster talks were presented at the following panel sessions:

- Current trends in accelerators technology. Projects for new large accelerators. (Chairman - A.A. Vasiliev).
- Superconducting accelerators and cryogenic systems. (Chairman - K.P.Myznikov, IHEP).
- Colliders. (Chairman - V.E.Balakin, BINP).
- Accelerating structures and high-power radio-frequency equipment. (Chairman - S.K.Esin, INR RAS).
- Radiation problems at accelerators. (Chairman - V.N.Lebedev, IHEP).
- Systems for control and diagnostics. (Chairman - A.F.Dunaitsev, IHEP).
- Magnetic and vacuum systems of accelerators, power supplies. (Chairman - M.F.Vorogushin, RIEE).
- Heavy ions accelerators. (Chairman - I.N.Meshkov, JINR).
- Particle dynamics in accelerators and storage rings, new methods of acceleration. (Chairman - E.F.Troyanov, IHEP).
- Linear and circular accelerators of high intensity. (Chairman - V.A.Teplyakov, IHEP)
- Accelerators for medicine, industry and applied research. (Chairman - V.A.Glukhikh, RIEE).
- Upgrade and development of the existing accelerators. (Chairman - Yu.M.Ado, IHEP).

An overview of high energy physics was given by S.S.Gershtein of IHEP, in the invited paper ”Main Problems of High Energy Physics”. The physical motivation for future particle accelerators and capabilities of B factories and the LHC were reviewed. Possible further accelerators such as photon and muon colliders, and Very Large Hadron Collider (VLHC) were also discussed.

Igor N.Meshkov (JINR) gave an overview of various schemes for colliders and the status of the development of key components and various test facilities in his report ”Current Trends in Accelerator Technology”. This review summarized the reports on the current status of accelerator science reported at the 17th International Conference on High Energy Accelerators (September 7-12, 1998, Dubna).

Alexander D.Kovalenko described the status of Dubna superconducting heavy ion accelerator - Nuclotron. The accelerator of relativistic ions with strong focusing, commissioned at the Laboratory of High Energies JINR in March 1993, became the third hadron machine (after Tevatron and HERA) equipped with superconducting magnets. At this superconducting synchrotron, protons and nuclei of heavy elements (including uranium) are accelerated up to energies of 12 GeV and 6 GeV per nucleon, respectively. The use of superconducting magnets resulted in a relatively low size of the ring (252 m in perimeter) as a whole (80 ton).

Nuclotron is based on a miniature iron-shaped field superconducting magnets. Nuclotron-type technology was proposed for the new VLHC project ($E_{c.m.}$=2 x 100 TeV) as well as for intermediate energy synchrotrons and storage rings (100-500 MeV/u) of different applications. The plans for development of a novel superferric design at 2 T and estimated parameters of a 2x100 TeV proton (nuclei) synchrotron/collider based on the Nuclotron-type cryomagnetic system were presented.

A short review was also given including the Nuclotron physics research program as well as development of accelerator systems such as the slow extraction one. The designed and achieved parameters of the Nuclotron systems used during 12 runs of the accelerator operation were presented.

Anatoly D.Nikulin from the Bochvar All-Russia Scientific Research Institute of Inorganic Materials (BARSIIM, Moscow) described the history and progress of High-Temperature Superconducting (HTS) materials. Early hopes of HTS to operate at liquid-nitrogen temperature were soon dashed by the difficulties of making wire out of the brittle oxide materials and achieving high current-carrying capicity.

Nevertheless ten years of work on the HTS materials have led to recent successes, including laboratory demonstration of 250-metre long silver (Ag) sheathed Bi-2223 multifilaments wire tape conductors by the BARSIIM. Significant progress in the development of HTS base conductor manufactured by the ”powder in tube” method reached during the recent years makes these conductors promising in high current applications at liquid nitrogen temperatures.

The basis of this optimistic forecast is high values of the critical current density up to 3x10^4 A/cm^2 at 77 K in the self-magnetic field of ”2223” (Bi) samples and intensive evolution of the process used to manufacture long multifilamentary wires. The cost of HTS wire would decrease down to \$0.8 per ampere$\times$metre for power applications, and researchers hope that it will be a stepping stone to the large-scale commercialization of the high-temperature superconductors.

With low thermal conductivity and excellent critical transport property, HTS current lead has promising prospects for application in electical power engineering, and now much effort is spent at BARSIIM and IHEP on constructing Bi(2223) Current Lead of 1 kA.

Quadrupoles with a high gradient field are needed at collider for high luminosity due to the requirements on emittance in the low-beta insertion cites. In the frame of the collaboration between IHEP, BARSIIM and FNAL, a design of a Nb_3Sn quadrupole with a high gradient field (220 T/m) is being developed at IHEP.

Experimental investigations of the physics of electron-positron collisions are in progress at the Budker Institute of Nuclear Physics (BINP, Novosibirsk). The status report on VEPP-2M and VEPP-4M was presented by S.I. Mishnev. At present, the physical experimental program has started at new detector KEDR installed at the modified storage ring VEPP-4M. The possibilities to measure the total cross-section of e^+e^- annihilation in the energy range from 0.7 GeV to 1.8 GeV were also discussed. The luminosity of the VEPP-2M boosted by superconducting wiggler magnet in the energy range from 2x200 MeV to 2x700 MeV.

The Protvino branch of BINP in collaboration with the KEK Laboratories (Japan) presented the experimental test results of the klystron with a PPM focusing system The high-power klystron developed by BINP successfully generated the 77 MW peak power with the pulse width of 0.1 microsec at the frequency 11.424 GHz. The output power in RF loads was 68 MW with RF pulse duration equal to 300 ns, and the gun voltage equal to 533 kV. It is possible to avoid the beam interception by increasing the magnetic field magnitude in the output section of PPM. These results are a part of the R&D programs at KEK for the future electron-positron linear collider in the ambitious X-band region.

The Protvino branch of BINP reported about development a new type of Beam Position Monitor (BPM) with submicron resolution. In first tests at the BNL (USA) was demonstrated 0.15 micron resolution on beam position.

Much effort is spent worldwide on constructing a safe nuclear plant for generating electricity and development of advanced nuclear power technologies for nuclear waste transmutation. Much interest is focused on a scheme with a linear proton accelerator that is used to produce an intense neutron flux. Efforts to implement this conceptual designes were discussed at IHEP, ITEP and the Moscow Engineering Physics Institute.

The Institute of Theoretical and Experimental Physics (ITEP, Moscow) is planning to upgrade its ion facility to reach the output of 1 TW at beam energy of up to 3 GeV per nucleon. Boris Yu. Sharkov (ITEP, Moscow) described the international program of the upgraded ion facility which will include research in relativistic nuclear physics.

The current trends for hadron therapy were illuminated by V.S.Khoroshkov (ITEP). Plans for a center of proton-ion therapy in Moscow, based on a medical machine (H^- accelerator), were discussed by the specialists from ITEP, Moscow Institute of Radio Engineering, Moscow hospitals and by the physicists from IHEP.

Host-physicists from the IHEP laboratories presented many interesting talks. Alexander V. Vasilevski and his colleagues (Institutes of Protvino and Obninsk) proposed a project of precision beams for hadron therapy, where patients are treated with a linear proton accelerator I-100 (since 1985 out of operation as injector of the U-70). Alvarez-type linac with the total length of 80 m has operated as long as 4700 h. Physicists presented a new facility using carbon ions at this linac.

Alexander G.Afonin reported the record value of extraction efficiency to be over than 40%. This was achieved by using a short Si-crystal 5 mm long, that is bent at a small angle of 1.5 mrad to extract 70 GeV protons. Sergei V.Ivanov reviewed a set of longitudinal feedback systems foreseen around RF 200 MHz in the IHEP 600 GeV UNK PS project. Performance data on these circuits which would govern acceleration of intense beam were estimated. The feedback systems are needed at accelerator for high energy due strong requirements on emittance.

The participants of the workshop were informed of advances in constructing the 600-GeV proton accelerator UNK in Protvino, and had an opportunity of inspecting the tunnel section with installed equipment for injecting the proton beam transported from the existing 70-GeV machine (the strong-focusing synchrotron U-70).

UNK is a large complex for accelerating and storage 6x10^{14} protons for fixed target experiments. The accelerating-storage complex is situated in an underground circular tunnel with circumference of 20.77 km. Up to now the long tunnel with a 5.1 m diameter has been excavated and prepared for installing the equipment. Above 1500 conventional magnets (dipole 5.8 m long) have been manufactured at the Research Institute of Electrophysical Equipment (RIEE, St.Petersburg), but further fabrication of magnets has stopped because of suspended funding, and thus production order has not yet been completed.

The first stage of UNK is the 600 GeV proton accelerator (U-600), and it include a proton injection channel (commissioned in 1994), ring accelerator in the underground tunnel, buildings of conventional engineering systems. About $760 US million have been used for the accelerator purposes out and the necessary financing for the operational launch of U-600 makes near $170 US million. Tunneling has been fully completed and now the ring tunnel (circumference 20.77 km) has the second long in the world (after LEP), but tunnel diameter is 5.2 m.

In 1998 the "Proton" electric substation (rated up 400 MW) commissioned and U-70 electric equipment connected to Kursk Atomic Station. The research program at U-600 is unique due to high intensity of the proton beam (5x10^{14} ppp) and the wide spectrum of the secondary particle beams. The U-70 proton accelerator will be employed in a novel capacity as the UNK injector.

3.3 The School on the Physics of Beam in India

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The Third School on the Physics of Beams was held at the Centre for Advanced Technology (CAT), Indore, India, from 28 December 1998 to 8 January 1999. This was the third in a series of schools funded by the Department of Science and Technology, with the aim of disseminating more widely in India, knowledge of, and interest in, beam physics.

The format of the School included core topics, that were covered in 4-5 lecture hours, and advanced topics that were in the form of 1-2 hour seminars. The School commenced with an overview of accelerators by G. Singh (CAT). Core topics covered included: (i) introduction to accelerators and storage rings (by G. Wuestefeld, BESSY, Germany); (ii) introduction to cyclotrons (V. S. Pandit, VECC, Calcutta); (iii) linear accelerators (R. G. Pillay, TIFR, Mumbai); (iv) nonlinear dynamics (A. Khare, IoP, Bhubaneshwar, and S. Krishnagopal, CAT); (v) free-electron lasers (N. A. Vinokurov, BINP, Russia). Advanced topics covered included: (i) superconducting linacs (A. Roy, NSC, New Delhi); (ii) RFQs (R. C. Sethi, BARC, Mumbai); (iii) Synchrotron radiation sources (D. Einfeld, ANKA, Germany, and G. Singh, CAT); (iv) applications of synchrotron radiation (R. V. Nandedkar, CAT).

There were three lecturers from Europe; unfortunately, because of the sanctions imposed on India by the United States, we could not get anyone from the US to come down and teach at the School. We hope this situation will change in the future.

There were 36 students at the School, representing 16 universities and 4 national laboratories from around the country. All lectures were held at the CAT guest-house, which is also where all the students and lecturers were housed. Having everyone under one roof, all the time, made for excellent interaction amongst the students, and between the students and the lecturers. This helped enormously in getting questions answered outside the class-room, and even in discussions on physics other than beam physics!

There was a one-hour tutorial session scheduled every day, but more useful were the many-hour tutorial sessions that ran most of the nights, often up to midnight. A new feature in this School was the introduction of laboratory experiments. Three experiments were organised: (a) characterization and assembly of NdFeB magnets for an FEL undulator; (b) study of modes in RF structures using SUPERFISH; (c) study of vacuum techniques. The students were divided into four groups, and, along with a visit to the INDUS synchrotron source, the students were rotated amongst the four activities over four afternoons.

Besides work, there was a lot of play at the School. There was a New Year's party (with students and lecturers both participating), with a Sanskrit prayer, short speeches in Tamil, Bengali and Malayalam, and a long song session that went on till 3 AM! Besides the inaugural dinner, there were also two dinners outside the guest-house, including one at Nakhrali Dhani, a Rajasthani theme park, which was enjoyed tremendously. In addition, on Sunday the entire School went on an excursion to the nearby medieval city of Mandu, with which is associated the legend of the queen Rani Roopmati.

The feedback received from the students at the end of the School was very positive. All felt that the School had been a good experience: they had enjoyed themselves and had learnt a bit about beam physics. Particularly appreciated were the laboratory sessions, where they got a real 'feel' for beam physics, and the night tutorials, where they could discuss their doubts in a more informal atmosphere. About half the students expressed interest in doing a summer project in beam physics, and possibly taking up a career in beam physics.

We plan to continue this series of Schools in the years to come. In order to provide a route for students to further their new-found interest in beam physics, the Centre for Advanced Technology, India's premier accelerator laboratory, will, from the summer of 1999, run a Summer Research Programme. Students will be invited to CAT for 6 weeks to work on a research topic. Exceptional students may be offered scholarships to pursue research leading to a Ph. D. at the Centre.

4: Activity Reports

4.1 Beam Dynamics Activities at CERN

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Other activities at CERN have been covered in recent newsletters.

4.1.1 SPS

Beam dynamics activities in the SPS at the moment are mainly defined by the preparation of the SPS for its future role as an injector for the LHC. Parameters of the LHC beam (which was not yet available in the SPS) are different from that reached before. One of the critical issues for this beam is control of the emittances, both transverse and longitudinal.

Single bunch intensity is limited by the microwave instability. Measurements of unstable single bunch spectra allowed the dominant impedances responsible for this instability to be identified. A program to shield guilty elements started last machine shutdown. We hope to follow the change of machine impedance with beam measurements over the next few years.

A longitudinal emittance blow-up of a factor 10 was measured during the acceleration cycle with the present multi-bunch mode of operation. Hunting for the sources of these coupled bunch instabilities has started in parallel with the development of cures. One of the cures is increasing Landau damping by using a higher harmonic RF system which surprisingly worked well only in bunch shortening (BS) regime and not in bunch lengthening (BL). This is explained by the fact that contrary to the BS mode of operation, in BL mode a large increase in synchrotron frequency spread can be obtained only for a very narrow range of phase shifts between the two RF systems, difficult to achieve in operation.

New results with LHC type beams are expected this year.

4.2 Reports on Beam Dynamics Activities at Brookhaven National Laboratory

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4.2.1 Spallation Neutron Source (SNS) Ring design

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`http://server.ags.bnl.gov/bnlags/bnlsns/sns.html`

The Spallation Neutron Source (SNS) is a \$1.3 billion US dollar project collaborated by five US laboratories (Argonne ANL, Brookhaven BNL, Lawrence-Berkeley LBNL, Los Alamos LANL, Oak Ridge ORNL), and coordinated by ORNL. BNL is responsible for the design and construction[1] of the accumulator ring and transfer lines. The project is in the first year of a seven-year construction cycle. The accumulator ring has a circumference of 220 m, and it compresses 1225 turns of proton beam from LINAC into a 1 μs pulse containing 10^{14} particles at repetition rate of 60 Hz. The beam power is from 1 to 2 MW and upgradable to 4 MW. At this design stage, key study issues are flexibility and reliability of the machine.

4.2.1.1 *Lattice optimization and alternative injection schemes*

The nominal lattice for the accumulator ring has a four-fold symmetry consisting of FODO arcs and FODO straight sections.[2] The four straight sections house injection, collimation, rf cavities, and extraction systems, respectively. Chopped H^- beams are injected through charge exchange painting process to the ring, accumulated for 1225 turns, and then extracted with fast kickers.

In recent months, we have been studying the potential benefit of arc sextupoles in minimizing off-momentum optics mismatch and improving dynamic acceptance. Using 16 sextupoles of moderate strength grouped in 4 families, the amplitude of off-momentum beta wave can be reduced from $\pm 12\%$ to less than $\pm 3\%$. Consequently, the off-momentum dynamic aperture can be increased by as much as 30% (Fig. 4.1).[3, 4, 7, 8] The momentum aperture is also increased by about 30% (Table 4.1). The chromatic tune variation can be adjusted as desired across the entire range of beam momentum. Without enhancing the nonlinear chromaticity, the linear chromaticity can be either reduced or enhanced for tune spread optimization and possible instability damping.

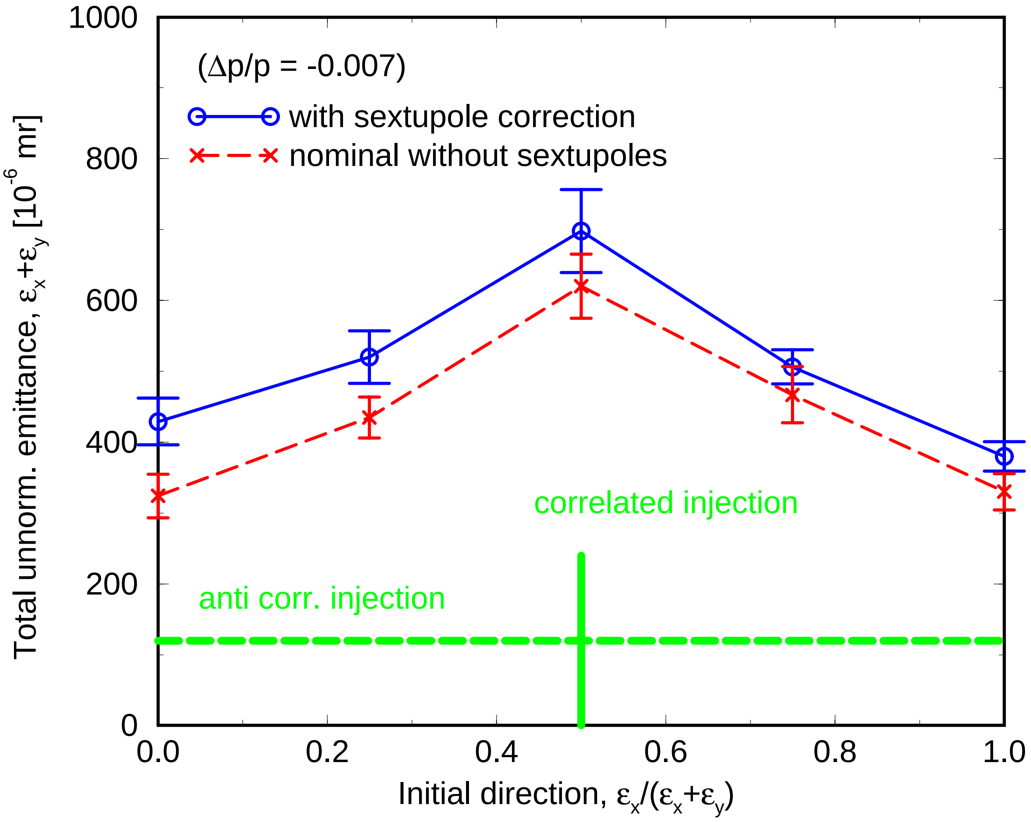

Figure 4.1: Improvement in dynamic acceptance due to off-momentum optics optimization using arc sextupoles. The 6 dimensional tracking is done with TEAPOT incorporating expected magnetic errors, misalignments, and physical aperture of the machine with 10 random seeds at 5 transverse initial direction. The machine file is later transferred for SIMPSONS simulation including space charge effects.

One of the key issues of the ring design is its flexibility and easiness for future upgrade. We have been studying the benefit of an alternative lattice, the so-called hybrid lattice consisting of

FODO structure in the arcs but doublets in the straight sections.[4] The longer uninterrupted straight section is flexible to accommodate e.g. alternative injection schemes like laser-undulator stripping (Fig. 4.2).[5, 6] The FODO structure in the arc is flexible for working-point adjustment, tune split-

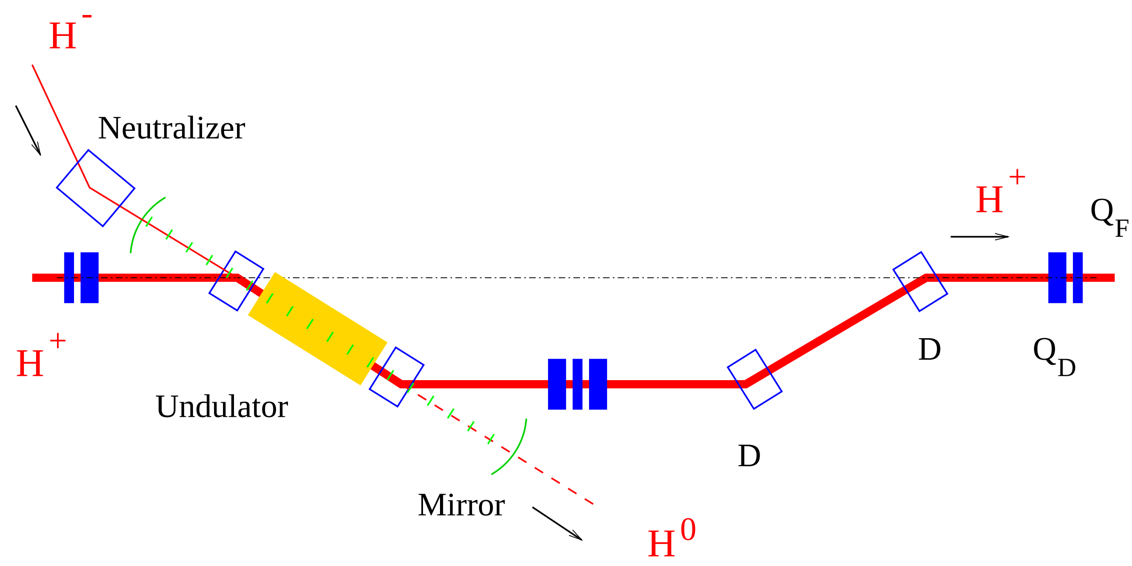

Figure 4.2: Schematic layout of an alternative SNS Ring lattice with doublet straight sections accommodating future laser-undulator charge exchange injection.

ting and tuning. During study, an important figure-of-merit that we have been trying to reduce is the beam envelope variation, i.e. β_{max}/β_{min} ratio.[4]

4.2.1.2 Beam loss and collimation

Due to high beam intensity and beam power, a critical issue for the SNS ring is to minimize the uncontrolled beam loss. Four levels of beam loss is considered: to guarantee hands-on maintenance (average 1 W/m), the total uncontrolled beam loss in the ring needs to be limited well below 10^{-3}; the collimators are designed to collect beam halo at a level from 10^{-3} to 10^{-2}; hardware and shielding are designed to withstand 10^{-2} for engineering reliability; and the machine can withstand a couple of full beam pulses for emergency handling and commissioning.

Presently, concern of beam loss is incorporated into the design at three stages: linear machine design (lattice, aperture, injection and extraction, magnet field errors and misalignment, etc.), beam core consideration (space charge, instabilities, rf requirements, etc.), and beam halo consideration (collimation, beam envelope variation, e-p issues, etc.). Significant efforts have been made to maximize the acceptance-to-emittance ratio (Fig. 4.1), and to optimize beam cleaning and collimation schemes.[9] Loss budget is compiled based on itemized loss mechanisms (LINAC halo, LINAC gap residual, injection stripping efficiency, foil scattering, ionization, kicker misfire, etc.).

In order to eliminate the beam residual between the subsequent micro pulses (beam gap), we are considering a method to simultaneously monitor and clean the gap[10, 12] — kicking the gap beam into a collimator, where it will be observed with a fast gated loss monitor. The hardware is similar to that of the RHIC Damper/Tune Monitor System[13], which uses commercially available MOSFET banks[14] to supply 5 kilovolt, 120 ampere, 10 ns rise and fall time pulses to a transmission line kicker. Burst mode frequency is greater than 1 MHz, permitting turn-by-turn kicking. Given 5 meters of kicker length, it is estimated that kicking at the vertical betatron tune the core of the gap beam can be brought to the collimator in about 25 turns. As shown in Fig. 4.3, the kickers are located

Table 4.1: Momentum aperture and sextupole improvement.

Item	Value
beam momentum spread (99%)	$\pm$ 0.007
rf acceptance at 40 kV	$\pm$ 0.010
ring acceptance at nominal emittance	$\pm$ 0.015
ring acceptance with sextupole correction	$\pm$ 0.020

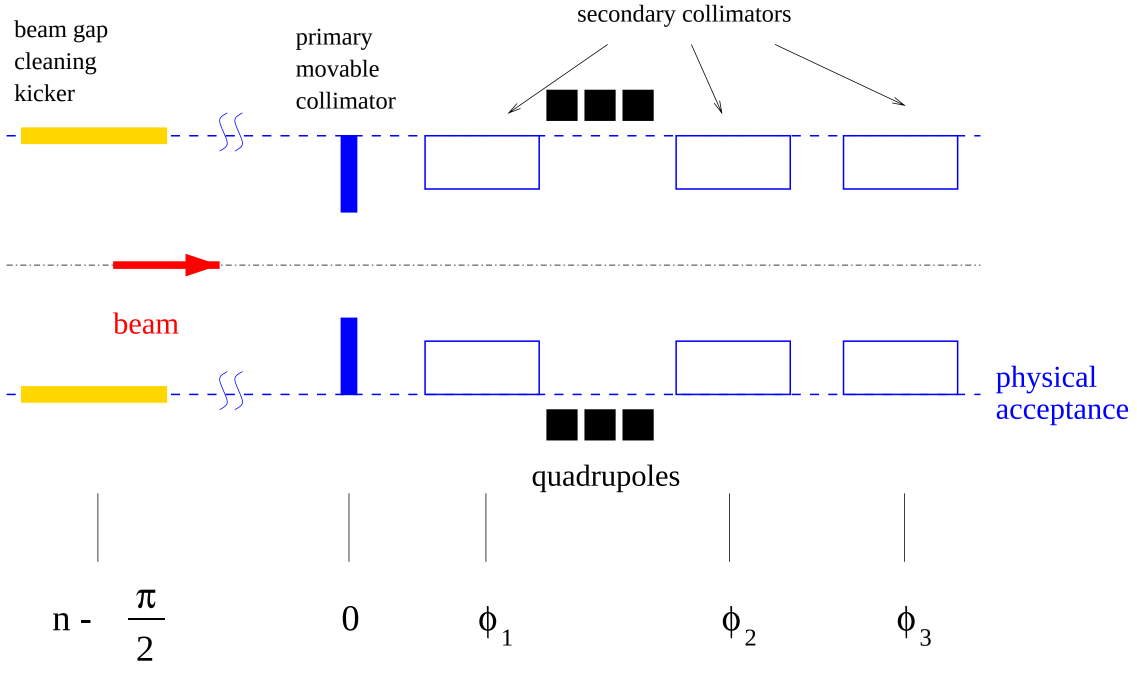

Figure 4.3: Schematic layout of SNS Ring beam gap cleaning and collimation devices. The collimators are housed and shielded in a single straight section.

at an integer plus 90 degree betatron phase ahead of the primary collimator. Downstream of the primary collimator are three secondary collimators located at proper phase to catch the scattered particles from the primary collimator. Each of these collimators consists of layers of steel, borated water, etc to contain secondary charged and uncharged particles.[11]

4.2.1.3 Space charge simulation and benchmarking

A. Luccio and J. Beebe-Wang of BNL are collaborating with J. Galambos and J. Holmes of ORNL to develop a space-charge simulation program named SAMBA. In parallel, S. Machida of KEK has also helped to install simulation program SIMPSONS at BNL. The SIMPSONS program combines 2D and 3D space charge model with thin-lens lattice model using TEAPOT incorporating magnetic field errors, misalignments, and corrections. Fig. 4.4 shows the space charge tune shift evaluated

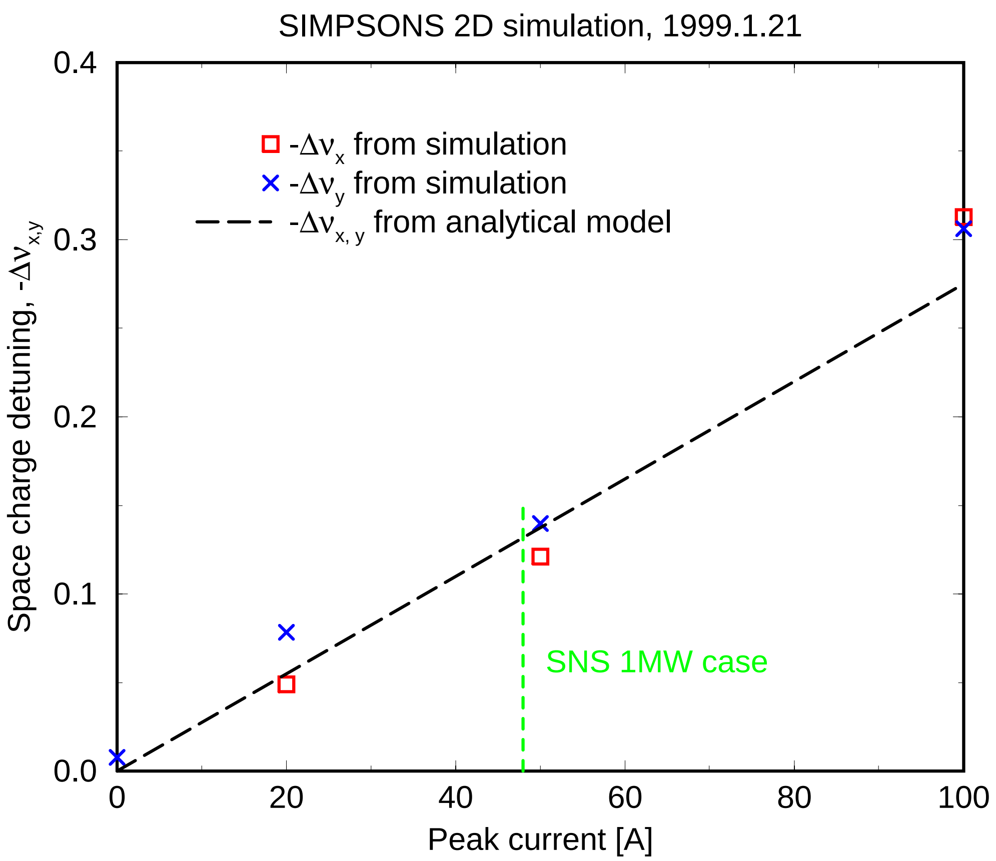

Figure 4.4: Benchmarking of space charge simulation using SIMPSONS. The SNS ring is designed with a space charge tune shift of about 0.1 at 1 MW.

from matched β function obtained from simulation in comparison with the analytically calculated values based on similar Gaussian distribution. In the case of SNS ring analysis, we first analyze the impact of magnetic field errors and misalignments based on expected values using TEAPOT; the machine file is then used as input for SIMPSONS to analyze the combined effects with space charge.[9] Dynamic acceptance, emittance growth and beam tail/halo are used as reference for optimizing the design. Table 4.2 compares features of simulation codes used for SNS ring design. We

Table 4.2: A comparison of accelerator programs used in SNS ring design.

	UAL	FTPOT	MAD8	DIMAD	ACCSIM	SAMBA	SIMPSONS
Interface	Perl	FTPOT	MAD	DIMAD	ACCSIM	SuperCode	SIMPSONS
MAD elem.	Yes	Yes	Yes	Yes	via nodes	via nodes	Yes
Errors	Yes	Yes	Yes	Yes	No	TBC	Yes
Dyn. Proc.	Yes	No	No	No	Injection	Yes	$B\rho$, RF
Tracking	Thin lenses	Thin lenses	Lie Algebra	Simplectic TRANSPORT	Matrices +node-lenses	Matrices +node-lenses	Thin lenses
Mapping	Any order	2nd order	3rd order	2nd order	Linear order	Linear order	No
Space charge	TBC	No	No		3D	3D	2D, 3D
Analysis (Twiss,...)	Yes	Yes	Yes	Yes	No	TBC	No
Lattice optim.	TBC	No	Yes	Yes	No	TBC	No
Correction (Orbit,...)	Yes	Yes	Yes	Yes	No	TBC	No
Lattice integration	Yes	No	No	No	No	No	No
Support of extensions	Yes	No	No	No	No	Yes	No
Integ. w/ controls	TBC	No	No	No	No	TBC	No
Painting	Yes	No	No	No	Yes	Yes	No
Inj. Foil	March	No	No	No	Yes	Yes	No
Collimator	March	No	No	No	Yes	No	No

UAL: N. Malitsky and R.Talman, AIP 391, Williamsburg, 1996.
TEAPOT (FTPOT): L. Schachinger, R. Talman, Part. Accel. **22**, 35 (1987).
MAD8: H. Grote, F.C. Iselin, CERN/SL/90-13 (1990).
DIMAD: R.V.Servranckx, et al. SLAC Report 285 UC-28, May 1985.
ACCSIM: F. Jones, TRIUMF Design Note TRI-DN-90-17, 1990.
SIMPSONS: S. Machida, Nucl. Instr. Meth. A309 (1991) 43
(TBC: to be completed)

are in the process of building a Unified Accelerator Library[15] (UAL) platform to accommodate and integrate various codes for a comprehensive modeling.

4.2.1.4 Injection painting and extraction

Painting[16] is used during H^- charge exchange injection[2] to achieve desired beam distribution at the target and to maintain the space charge tune shift at a moderate level (0.1$\sim$0.2). The beam is injected at a location of zero dispersion to avoid complications caused by transverse-longitudinal coupling. In the longitudinal direction, the frequency of the pre-injection transfer line rf system is modulated to broaden the beam momentum spread without enhancing the momentum tail. In the transverse direction, both correlated and anti-correlated painting schemes[9] (Fig. 4.5) can be

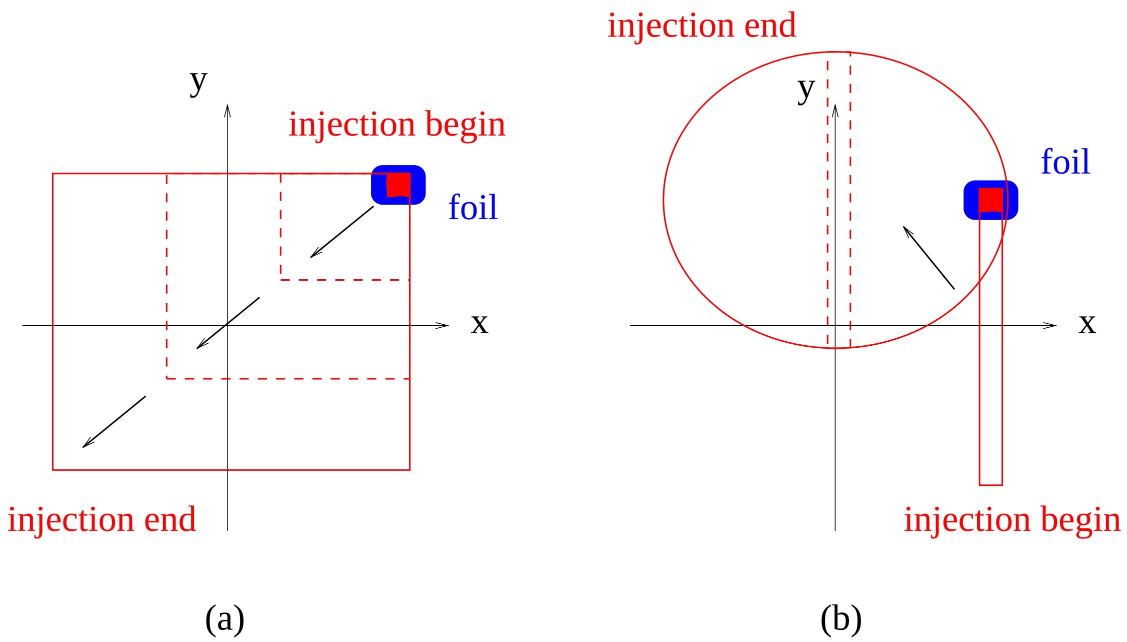

Figure 4.5: Correlated and anti-correlated transverse painting for minimizing space charge effects and for achieving desired beam distribution at the target.

used to optimize operation. Anti-correlated painting is preferred to minimize the possible impact of transverse coupling produced by misalignment and space charge forces.

4.2.1.5 Secondary emission experiment

(P. Thieberger, A.H. Hanson, H. Ludewig, D.B. Steski, V. Zajic, S.Y. Zhang)

Possible e-p instabilities may result in a high-intensity machine like SNS if excessive numbers of electrons are generated through grazing collisions of halo particles with the collimator surfaces. Since relevant experimental data are scarce it was decided to perform measurements at lower energies and with different ions at the BNL Tandem to gain a better understanding of the phenomenon and then be hopefully better able to estimate the electron yield at SNS energies. Furthermore, the gold data are directly relevant to injection issues at the AGS Booster inflector. Table 4.3 shows a few small-angle preliminary data points taken from a comprehensive set of measurements, which are still ongoing. Beams collimated to $\pm$ 0.1 degree impinge on stainless steel surfaces and the number of electrons is calculated from currents measured on an opposing, biased electrode or on the target itself. By displacing this electrode assembly through three different vertical positions for

Table 4.3: Preliminary e/p ratios for grazing incidence on stainless steel.

	Smooth plate			Serrated plate
	0.2 degree	0.5 degree	1.0 degree	max. observed
28 MeV Protons	59	36	16	3
126 MeV Oxygen 8^+	2, 900	2, 100	1, 000	190
182 MeV Gold 31^+	18, 000	17, 000	11, 000	1,000

each angle, the beam alternatively hits a smooth target, a serrated target or an open slot, which allow the beam to be measured in a Faraday cup located downstream. Using serrated surfaces it may be possible to avoid the large electron production cross sections associated with very small angles. The sawtooth pattern of the serrated plate for this test setup consists of 3.2 mm deep triangular teeth with surfaces at $\pm 45°$ to the surface.

4.2.1.6 Debunching instability observation

e-p like instabilities have been observed[17] in many high-intensity machines. Table 4.4 lists conditions when such instability occurs at PSR (LANL), AGS Booster (BNL), KEK PS Booster, and CERN PS. At KEK PS Booster and AGS Booster, the instability occurs only when the beam is debunched. At CERN PS, the instability occurs only when the bunch length is long (about 170 ns), and it damps by itself. However, at PSR, the instability is one of the limiting factor to machine performance. On the other hand, similar instability has not been found at ISIS (RAL) even though maximum beam intensity was attempted. Table 4.4 compares 1D and 3D beam density under corresponding circumstances.

At the AGS Booster, we observed[17] a fast, vertical instability for the coasting beam. Near threshold conditions, the instability does not occur immediately after injection when the beam current is the highest. Instead, the beam suffers approximately a 10% slow loss over about 1 ms and then a 60% fast loss over tens of micro-seconds. The millisecond time scale is much longer than the 3 micro-second debunch time for the linac bunches. The threshold can be changed by a factor of 2 using the vertical betatron tune. The most extreme cases are:

- Q_x=4.70, Q_y=4.48, I_{thresh}=2.7 A, f_{char}= 100 MHz
- Q_x=4.75, Q_y=4.95, I_{thresh}= 5.3 A f_{char}= 80 MHz

where the threshold current refers to the peak current stacked in the ring, and f_{char} is the central frequency of the instability. The intensity was changed by varying the duration of the linac pulse. Since the injection bumps were not changed with the linac pulse length, the 2.7 A beam was approximately a subset of the 5.3 A beam.

4.2.1.7 Impedance issues

We have compiled impedance budget[18] for the SNS ring based on theoretical models. In order to validate these models, we are performing impedance measurements starting with RHIC PUEs. The BPM model has been confirmed in the measurement. It is found that increasing the stripline length from 25 cm to 50 cm have moved the resonance down to 100 MHz, and doubled the peak impedance.

The broadband impedance (Z/n) is in the range of j10 to j30 Ohms, similar to those measured in the AGS, CERN PS, SPS and ISR. In order to minimize resonance effects and complications possibly caused by large variation of vacuum aperture, we are planning to taper all the steps.

Table 4.4: Comparison of machine parameters relevant to e-p like instability. The beam intensity corresponds to instability threshold for PSR, AGS Booster, KEK PS Booster and CERN PS, to the maximum value attempted for ISIS, and to the nominal value for SNS (2MW) and ESS.

Quantity	PSR	AGS Booster	KEK PS Booster	CERN PS	ISIS (inj.)	ISIS (ext.)	SNS	ESS	ESS (RCS)
Circumference (C [m])	90.2	201.7	37.7	628.3	163.4	163.4	220	248	288
Energy (E_k [GeV])	0.799	0.2	0.04	1.0	0.07	0.8	1.0	1.334	3.0
Acceptance [$\pi\mu$m]	140	100	241/49	60/20	500	500	360	480	560
Emittance [$\pi\mu$m] (H/V, $\epsilon_{UN,rms}$)	7/13	8	3$\sim$ 8	7/3	50	17	36	30	14
UNBUNCHED:									
N_0 [10^{13}]	0.8	2$\sim$4	0.35		4	2.5			
1D density [m^{-1}]	0.9	1$\sim$2	0.93		2.5	1.6			
2D density [m^{-2}]	0.13	0.1$\sim$0.2	0.12$\sim$0.33		0.05	0.09			
3D density [m^{-3}]	0.017	0.02$\sim$0.04	0.05$\sim$0.13		0.009	0.016			
Unstable?	yes	yes	yes	yes	no	no			
BUNCHED:									
N_0 [10^{13}]	3.8			0.3			20	23.4	20.8
Bunching factor	0.37			0.048			0.5	0.5	0.35
1D density [m^{-1}]	11.4			1.0			18.2	18.9	20.6
2D density [m^{-2}]	1.63			0.34			0.56	0.63	1.5
3D density [m^{-3}]	0.21			0.02			0.09	0.085	0.16
Unstable?	yes	no	no	yes	no	no			
Growth time [μs]	25$\sim$80	$\sim$20	$>$210	500	–	–	–	–	–
Frequency [MHz] (unbunched/bunched)	$\sim$70/ $\sim$175	80$\sim$100	10$\sim$200	20$\sim$40	–	–	–	–	–
Unstable direction	V	V	H/V	H					
Dependent factors	V_{rf}, ϕ_s $\Delta p/p$, ϵ_{rms} sextupole tunes impedance rf centering	σ_s tunes ...	σ_s vacuum ...	σ_s loss ...					

1D density (N_0/BC) in [10^{11}/m]; 2D density ($N_0/BC\epsilon_{rms}$) in [10^{17}/m^2]; 3D density ($N_0/BC\bar{\beta}\epsilon_{rms}$) in [$10^{17}$/m^3], with B the bunching factor, and N_0 the number of protons

PSR: R. Macek, private communications

AGS Booster (injection): M. Blaskiewicz, private communications

KEK Booster: Y. Irie, et al, KEK Proc. 97-17, (1997) pp. 247 – 255

CERN PS: R. Cappi, G. Metral, `http://www.cern.ch/PSdoc/ppc/md/md980716/epinstab.html`

ISIS, ESS, ESS (RCS, extraction): G. Rees, private communications

The transverse impedance of the window frame extraction kickers is very sensitive to winding terminations and stray parameters. We are considering optimization of the terminations to reduce kicker impedance. The flux leakage through the copper sheet inserted in the kicker magnet modules represents significant inductive longitudinal impedance, which can be used to compensate the space charge impedance. The mechanism is similar to that of the ferrite ring experiments performed at the PSR and KEK. However, the flux leakage through the air gap may introduce nonlinearity in the frequency range below 100 MHz.

The experiences at the AGS and Booster have shown that the conventional formulation used for the resistive wall instability over-estimated the growth rate, presumably due to neglecting various Landau damping mechanism. This formulation now predicts the SNS growth rate of a modest 1 ms at the end of stacking. The growth rate of the m=1 mode is about 1/5 of that of m=0. The choice of stainless steel chamber is adequate.

4.2.2 Relativistic Heavy Ion Collider (RHIC)

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The RHIC project is in the last year of its seven-year construction cycle. The primary motivation for colliding heavy ions at ultra-relativistic energies is the belief that it is possible to create macroscopic volumes of nuclear matter at such extreme conditions of temperature and energy density that a phase transition will occur from hadronic matter to a confined plasma of quarks and gluons. The main goal of the Relativistic Heavy Ion Collider (RHIC)[19] is to provide head-on collisions at energies up to 100 to 250 GeV/u per beam for ion species from gold to protons and polarized protons. The ring circumference is 3833 m, and all of its 1700 magnets are superconducting. During spring 1997, RHIC sextant test has been successfully performed on all accelerator systems with gold beam. Full commissioning of the entire machine will start in June 1999.

Operation of the RHIC Collider at relatively low energies together with the enhanced intrabeam scattering (IBS), which scales as Z^4/A^2, results in beams of large transverse and longitudinal dimensions. This in turn has ramifications for the lattice (short cells, strong focusing) and magnet aperture. The rf system requirements (two systems, 28 MHz and 200 MHz) are also determined by this consideration and the short interaction point (IP) length.

4.2.2.1 Intrabeam scattering

RHIC performance is limited by intrabeam scattering among high charge state particles.[20] Nuclear effects are secondary for nominal ion species (up to Au^{79+}) and energy range. At injection, the IBS growth time of the momentum spread is about 3 minutes. Alternate filling of the two rings, each with 60 bunches, needs to be done within about 1 minute to prevent difficulty in transition crossing and top-energy rf recapture due to increased longitudinal beam size. At storage, emittance growth occurs in both transverse and longitudinal dimension. Transverse emittances grow from the initial 10π mm·mr to more than 40π mm·mr. Longitudinal bunch area exceeds the bucket area of 1.2 eV·s/u in about an hour. Collimation systems are designed to remove particles escaped from the rf buckets. Increasing peak rf voltage only modestly improves the luminosity performance, since transverse growth is significant, and since momentum aperture can be a limitation. The ultimate improvement can be made if cooling methods are adopted. Fig. 4.6 shows the improvement of integrated luminosity over a 10-hour store if transverse and longitudinal stochastic cooling[21] are employed to counter-act intrabeam scattering. However, bunched beam stochastic cooling for colliding beams has so far been unsuccessful due to unexpected instabilities at GHz frequency range.

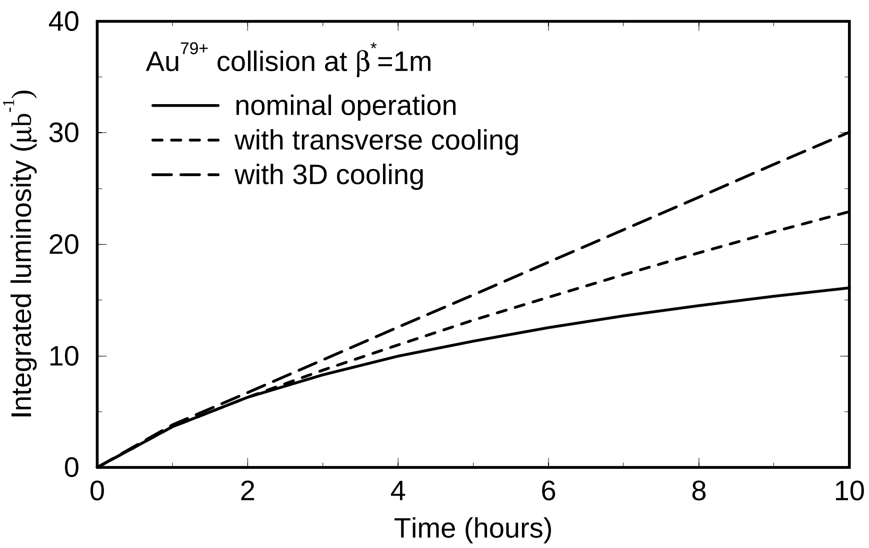

Figure 4.6: Integrated luminosities during a 10-hour store for a) the nominal operation (without cooling), b) with transverse stochastic cooling, and c) with both transverse and longitudinal stochastic cooling. The bandwidth of the cooling system is assumed to be 4–8 GHz.

Preliminary studies on electron cooling has also been performed by several groups.

4.2.2.2 Interaction Region error compensation

In order to maximize the luminosity at two interaction points for STAR and PHENIX experiments, their nearby triplets are designed to enable the collision β^* to be reduced to $\beta^* = 1$ m. Dipoles and triplets of quadrupoles of large bore are placed on both sides of the IP. The peaked β of 1400 m, along with the strong IBS growth, makes the 5σ beam size to increases from 35% to about 70% of the triplet magnet coil radius. In order to optimize the field quality in these elements, some of the most advanced and sophisticated compensation techniques are developed,[22] including individual error correction with tuning shims, amplitude dependent body-ends compensation, low-β^* sorting, and lumped triplet multi-layer corrector packages, as shown in Fig. 4.7. Tuning shims are

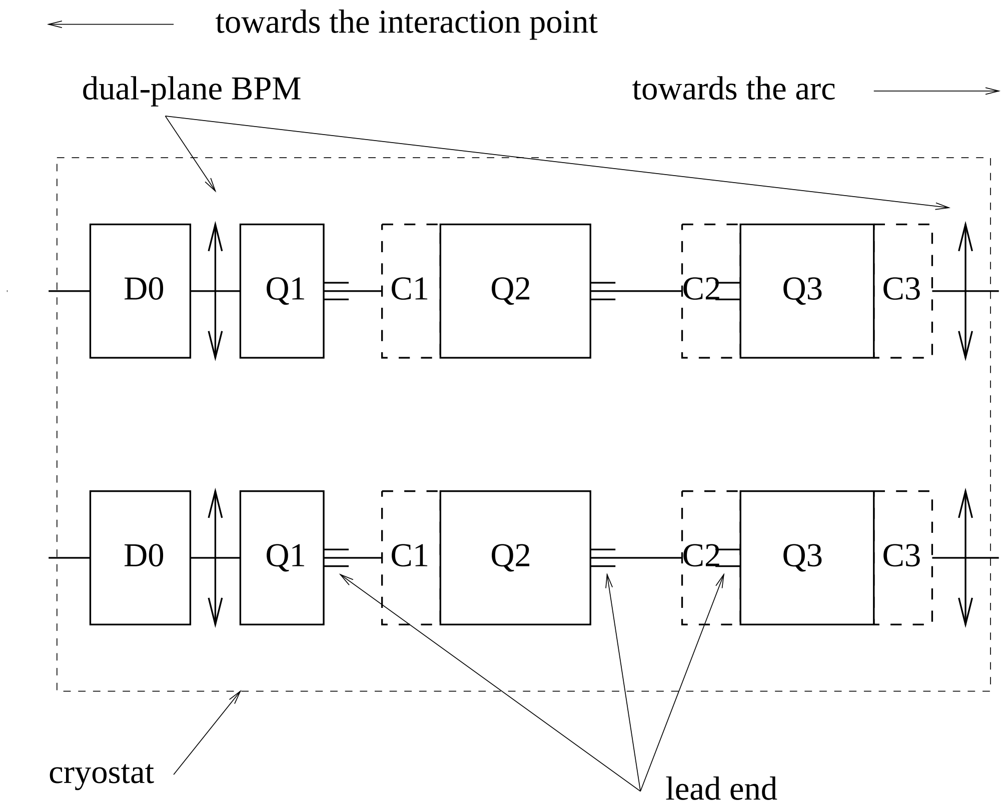

Figure 4.7: Schematic layout of the RHIC triplet cryostat assembly, showing the dipoles (D0), quadrupoles (Q1, Q2, and Q3) and their lead-end orientation, triplet correctors (C1, C2, and C3), and dual-plane BPMs of both rings.

planned to be inserted into the 8 empty slots of the IR quadrupole body to compensate the lower eight harmonics[23] after the magnet is constructed and individually warm measured. Recent experiments indicate that leading multipole errors can be reduced to about 10% rms of the uncorrected value. The expected values for the mean and its uncertainty often become zero, and the standard deviation is associated with a roll up of measurement errors, thermal cycling fluctuations, and quench fluctuations. The non-zero targeted $\langle b_5 \rangle$ and $\langle a_5 \rangle$ are results of amplitude-dependent compensation.

Lumped correctors located in the triplet region are used to correct closed-orbit errors, to perform local decoupling, and to correct higher-order multipole errors both from dipoles (D0) and IR quadrupoles. Because the β-function varies rapidly from body to end in the triplet, higher-order multipole corrections in both horizontal and vertical directions can be best achieved with two correctors in the triplet, which are located at places with significantly different β_x/β_y ratio. The b_4 and b_6 correctors are designed to compensate for the residual errors in the quadrupoles after shimming and for D0 cross coupling. All the skew correctors a_2, a_3, a_4, and a_6 are located at C2, where β_x and β_y are about equal. Except for dipole (b_1/a_1) and skew quadrupole (a_2), all of these correctors are planned to be dead reckoned to correct the measured construction error. The a_2 correctors, totally 12 per ring, are planned to be used along with the dual-plane BPMs for local decoupling.

4.2.2.3 Magnet alignments

An accurate alignment[24] of the arc corrector-quadrupole-sextupole (CQS) assembly is crucial for the polarized proton operation. An accurate alignment of the triplet assembly is crucial for the low-β^* heavy ion operation. The critical issue in the alignment is to accurately locate the magnetic centers and rolls of the cold masses after they are fully assembled. In early CQSs, a colloidal-cell[25] technique was used to locate the transverse quadrupole field center with respect to the external fiducials. In recent CQSs and triplets, a magnetic antenna technique is used to locate the centers of quadrupoles, sextupoles, and multi-layer correctors. The measurement is done at several locations along the longitudinal axis with an estimated error of from 0.05 to 0.1 mm. Choreographed welding is used to balance distortion and to minimize offsets.

4.2.2.4 Transition crossing

RHIC will be the first superconducting accelerator to cross transition energy. Due to the slow ramping rate of the superconducting magnets, both chromatic nonlinear effects and beam self-field effects are strong at crossing.[26] A "matched first order" transition jump scheme is designed[27] to effectively increase the crossing rate by a factor of 8 during the 60 ms time around transition. With such a scheme, the longitudinal emittance growth can be limited to less than 20% at transition with minimum disruption to the transverse particle motion (Fig. 4.8)

4.2.3 Alternating Gradient Synchrotron (AGS)

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`http://www.agsrhichome.bnl.gov/AGS/`

The AGS accelerator complex accelerates high intensity proton beams for the production of secondary kaon and muon beams and high brightness gold and polarized proton beams for future injection into RHIC. In all these three modes of operation the AGS has achieved record performances.

Recently a new record intensity of 7.2×10^{13} protons per AGS pulse was accelerated to 24 GeV. At this intensity the coherent betatron tune shift is typically many times the synchrotron tune and stability criteria had to be reevaluated. To avoid instabilities the bunch area is carefully enlarged using a high frequency cavity. The same cavity was used to smooth out beam "hot spots" during the slow- extraction process. Such "hot spots" appear at high intensity and are stable against decoherence. A new method to shorten bunches was developed. Persistent longitudinal quadrupole oscillations were generated using slow adiabatic excitation.

A new method to accumulate high intensity beam was developed to improve the poor bunching factor that is usually obtained during conventional bunch-to- bucket transfers. By using single sine wave "barrier bucket" cavities the circulating beam can remain essentially debunched with only a

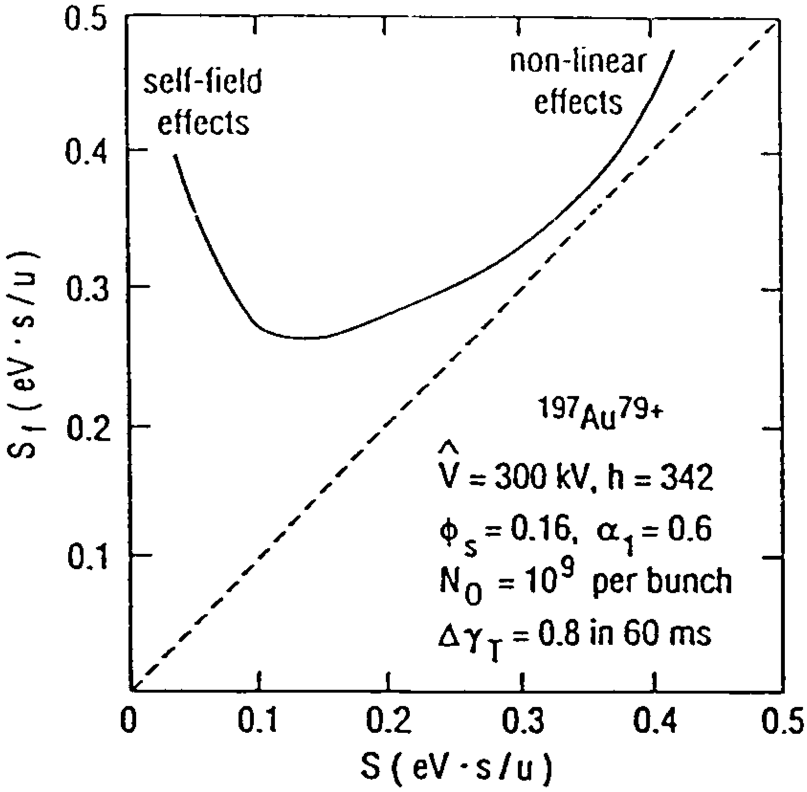

Figure 4.8: Effects of chromatic nonlinearities and self fields at transition.

small gap open for the injection kicker. During high intensity tests beam loading issues were studied and successfully mitigated.

Polarized proton beam has been accelerated in the AGS to a record energy of 25 GeV. More than 40 imperfection depolarizing resonances were overcome with a partial Siberian snake. Depolarization from the strong intrinsic spin resonances driven by the spin precession in the focussing quadrupoles was avoided by driving complete spin flip with nearby artificial spin resonances. The artificial spin resonances were created by adiabatically exciting persistent large coherent vertical betatron motion with a rf dipole magnet. The beam excitation with the rf dipole was very effective in generating large coherent motion without causing emittance growth. It is planned to also use this method to study non-linearities in RHIC.

Studies with gold beam have been mainly focussed on the injection process into the Booster at about 1 MeV/nucleon. The high-quality beam from the Tandem allows for very efficient 4-dimensional phase space painting. However, the intensity is limited to about 2×10^9 gold ions by a strongly intensity dependent loss process. So far studies have focussed on intra-beam scattering and the interaction of the gold beam with secondary electrons. Nevertheless, high brightness gold beams as required for RHIC operation have been produced.

4.2.4 National Synchrotron Light Source (NSLS)

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4.2.4.1 NSLS Storage Rings

At the NSLS there is an active program to upgrade and improve the storage rings. Important goals are increased brightness, improved orbit stability and the development of advanced insertion devices. On the X-Ray ring, we have reduced the vertical emittance from 1 nm-rad down to 0.1 nm-rad by decreasing the horizontal-vertical coupling. More recently, by allowing a small dispersion in the long straights, and increasing the betatron tune, we have reduced the horizontal emittance from 90 nm-rad down to 45 nm-rad. Heat dissipation tests on the copper synchrotron radiation absorbers have been successfully carried out, clearing the way for increasing the operating current from 350 mA to 440 mA at 2.584 GeV. Work has also been done to allow operations at 2.8 GeV, and half of our operation time is presently at this higher energy at a current of 240 mA. We plan eventually to increase the current at 2.8 GeV to 320 mA.

On the VUV ring, we have recently installed six new infrared beamlines. Key to their success is a program of studies aimed at minimizing the noise of the source. Work is underway to evaluate possible noise contributions from mechanical vibrations (59 Hz range), RF noise (kHz range), and orbit or vertical beam size fluctuations. The infrared program is progressing well and is the most rapidly growing area of research on the VUV ring. An interesting observation made on one of the infrared beamlines is coherent emission of radiation with wavelength about 7 mm. The belief is that this results from a density modulation on the electron bunch due to the microwave instability. Other beam dynamics work on the VUV ring involves studies reducing the momentum compaction to a value near zero to shorten the bunch length. There have also been studies running the ring at negative momentum compaction.

Orbit stability is of critical importance on both storage rings. At the NSLS global orbit feedback systems were developed and implemented for the first time. These have provided us with a level of orbit stability unsurpassed even at the newest facilities. Through improvements in orbit monitoring and feedback algorithms, we are working to improve orbit stability even further. Advances in beam position monitoring together with digital feedback technology will provide a significant advance in the state-of-the-art of orbit control. In order to take full advantage of these improvements we must correct for movements of our vacuum chambers and hence beam position monitors due to changes in heat load during a fill. We are engaged in measurements of BPM motion and plan to introduce corrections for it.

One straight section, X13, of the X-ray ring has been devoted to the development of advanced insertion devices. R&D in this straight has led to the successful development of a time-varying polarized wiggler (with APS and BINP Novosibirsk), and of an in-vacuum small gap undulator (IVUN). The polarized wiggler is presently used in normal operations, switching polarization at 2 Hz or 23 Hz. The in-vacuum undulator presently operates with a magnet gap of 3.3 mm and a vertical beam aperture of 3 mm. We are now pursuing plans to reduce the vertical β function at the center of the device, down from 0.33 m to 0.16 m, and thus to make possible operation of an in-vacuum undulator with a magnet gap of only 2 mm. When replacing our old RF cavities by ones of improved design, we plan to leave room between the two cavities in each of the two RF straights for the installation of in-vacuum small gap undulators, thus increasing the contingent of magnetic insertion devices by two.

4.2.4.2 FEL development at BNL

The NSLS has been actively pursuing free electron laser (FEL) sources, and aims to provide its users with access to these powerful new tools. The direction of our FEL development effort has been guided by interactions with potential users through a series of workshops at BNL. Early on, we focused on the vacuum ultraviolet as a promising spectral region; it lies beyond the range of most conventional laser technology, and is near enough to the existing frontier of FEL research that meaningful and challenging experimental contributions can be made. Many of the applications in this wavelength regime require high peak power, short pulses, and good stability in central wavelength, bandwidth, mode and pulse duration. These requirements have greatly influenced our approach to FEL research and development.

Over the last decade we have made important contributions to the theory of FEL devices and are now in the early stages of an exciting experimental program at the forefront of short wavelength FEL development. Key initiatives are our participation in the Accelerator Test Facility (ATF) and our development of the DUV-FEL. The ATF is operated jointly by the NSLS and the BNL Center for Accelerator Physics as a users facility for accelerator and beam physicists. The ATF program in RF photocathode guns is recognized internationally as cutting-edge R&D, as exemplified by its recent measurement of emittance in picosecond time-slices of a 10 ps electron bunch. The photocathode RF gun program at BNL has benefited from collaboration with other institutions such as SLAC and UCLA, and has resulted thus far in a series of guns, BNL.1 - BNL.4, which are utilized in experimental programs throughout the world. The goal of the DUV-FEL is to demonstrate FEL technology in the VUV and to carry out proof-of-principle science experiments. This project was established as an economical approach to pursue the work outlined in the NSLS Deep Ultra-Violet Free Electron Laser (DUV-FEL) conceptual design report. The cost of the DUV-FEL has been minimized by using an existing 210 MeV linac and, initially, the 10 m long NISUS wiggler, originally built by STI Optronics for Boeing Aerospace.

Our approach is based upon developing short pulse, high peak power, single pass FEL amplifiers. Key to our plans are sub-harmonically seeded FELs in which harmonic generation converts a laser seed to much shorter wavelength radiation. Much of the theory of these devices has been developed at the NSLS. A proof-of-principle High-Gain Harmonic Generation (HGHG) FEL experiment is being carried out in collaboration with the APS. To minimize the cost, we are using as the radiator an existing prototype APS undulator-A borrowed from Cornell University, and as the modulator an existing prototype NSLS soft X-ray. This experiment is now installed at the ATF. A CO_2 laser seed at 10.6 microns will be used, and production of the second and third harmonics will be studied. The status is that we have already observed self-amplified-spontaneous-emission (SASE) at 5 microns and the harmonic generation phase of the experiment is scheduled to begin in February 1999.

At the ATF, presently under construction is the visible self-amplified-spontaneous-emission (VISA) experiment, scheduled for installation in March 1999. This experiment is being pursued as a collaboration between BNL, LANL, LLNL, SLAC and UCLA and it is an important part of the R&D for future x-ray FELs. The goal is to reach saturation at 0.8 microns, and observe the time structure and spectra of individual, picosecond output radiation pulses. An innovative 4 m undulator with strong quadrupole focusing is being built for the VISA experiment. An additional 2 m of the undulator is also being constructed, and the plan is to eventually utilize the full 6 m magnet in the DUV-FEL.

The DUV-FEL program will extend the R&D on SASE and HGHG now underway at the ATF in the infrared, down to the VUV region of the spectrum (200 nm - 50 nm). The objective is to achieve 0.3 mJ in 5 ps pulses at 10 Hz repetition rate, with a bandwidth of 10^{-4}. The technology employed in the DUV-FEL is very relevant to the development of x-ray FELs as outlined in the LCLS proposal. A state-of-the-art Titanium Sapphire laser illuminates the photocathode, and magnetic bunch compression is employed to increase the peak electron current. Our plan is to first investigate SASE and then HGHG. An important advantage of HGHG over SASE is that HGHG produces a beam with much higher temporal coherence, which is important for the scientific program. Shaping the temporal profile of the seed laser allows shaping of the temporal profile of the FEL output. Furthermore, we plan to chirp the seed laser and the electron energy to carry out chirped pulse amplification (CPA). The successful operation of an FEL facility in the VUV is an important milestone, and the experience gained in running the DUV-FEL for science will give accelerator and beamline scientists a preview of the system integration issues which will be critical for the success of science programs utilizing short wavelength FELs.

Looking further into the future, we are engaged in a design study of an x-ray FEL based on a 6 GeV superconducting linac, and the refrigeration capabilities of RHIC offer an economical source of liquid helium. Using existing laser technology, we can use HGHG in a straight-forward manner to produce soft x-rays, and hard x-rays with additional complexity. Assuming continued progress in nonlinear optics, we believe there may be available a short wavelength source operating at 20 or 10 Angstroms with sufficient power to serve as a seed for a high gain harmonic generation FEL. Therefore, HGHG may provide an attractive approach for producing coherent radiation at a few Angstroms.

4.2.5 Accelerator Test Facility (ATF) activities

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The Accelerator Test Facility (ATF) is a User's Facility for accelerator and beam physicists, operated by the NSLS and the BNL Center for Accelerator Physics. The ATF is run as a proposal-driven, program committee-reviewed facility dedicated to long range R&D in accelerator and beam physics.

The ATF has a unique combination of a high-brightness electron beam, synchronized-high-power lasers, a well-equipped 3 beam-line experiment hall, and advanced diagnostics and control systems. The ATF's program in RF guns is recognized internationally. With its synchronized lasers and electron beams of unprecedented brightness, the ATF is an ideal site for R&D on advanced accelerator concepts, laser acceleration of electrons [28, 29], FELs and other radiation generation methods [30, 31], femtosecond X-ray sources and similar topics. These tools have been crucial to recent ATF record achievements: the measurement of Self Amplified Spontaneous Emission (SASE) at 1 micron and 0.63 microns, and laser acceleration by the Inverse Cerenkov and Inverse FEL mechanisms.

We are facing now the emergence of a new technology of very high-brightness electron beams. This technology has far reaching implications for future High-Energy accelerators, x-ray sources and other applications. The generation and acceleration of very high brightness electron beams is a key technology for short wavelength FELs as well as other applications, including linear colliders, Compton back-scattering for the production of femtosecond x-rays, laser accelerators and more. A high brightness means that the electron bunch has a high density in 6-D phase space. To achieve high brightness beams, it is necessary to master the production of such beams and their transport and acceleration. This is done using special electron guns and diagnostics.

The production of high-brightness particle beams calls for the development of advanced beam diagnostics. High brightness beams, meaning beams with a high density in phase space, are important for many applications, such as short-wavelength Free-Electron Lasers and advanced accelerator systems. A diagnostic that provides detailed information on the density distribution of the electron bunch in multi-dimensional phase-space is an essential tool for obtaining small emittance at a high charge. This diagnostic system has been developed at the ATF. One component of the system is the measurement of a slice emittance which provides a measurement of transverse beam properties (such as emittance) as a function of the longitudinal position. Changing the laser pulse profile of a photocathode RF gun has been suggested as one way to achieve non-linear emittance compensation and improve the brightness and that can be diagnosed by the slice emittance system. The other element of the diagnostic is the tomographic reconstruction of the transverse phase space density. In our work we give special attention to the accuracy of the phase space reconstruction and present an analysis using a transport line with nine focusing magnets and techniques to control the optical functions and phases. This high precision phase space tomography together with the ability to modify the radial charge distribution of the electron beam presents an opportunity to improve the emittance and apply non-linear radial emittance corrections. Combining the slice emittance and tomography diagnostics leads to an unprecedented visualization of phase space distributions in 5 dimensional phase-space and an opportunity to perform high-order emittance corrections. This should lead to great improvements in the beam brightness.

The next step is to pursue non-linear emittance compensation. Laser photocathode RF guns have provided a major improvement in the brightness, further enhanced by the introduction of (linear) emittance compensation and bunching [32]. The dream of another major improvement by the introduction of non-linear corrections has been brought within reach by the development of the slice-emittance diagnostic and the availability of lasers with longitudinal pulse shaping.

Some representative numbers about the ATF: The ATF users come from 6 national laboratories, 4 industries and 14 universities. Currently there are 14 approved user experiments evenly divided between High Energy Physics and Basic Energy Science subjects. The ATF has 3 current Ph.D. students doing their thesis research at the facility and 13 alumni students. The ATF linac operates at 70 MeV (100 MeV upgrade this year). The ATF provides a 5 GW 150 ps CO_2 laser synchronized to the e-beam to 1 picosecond, with a 3 terawatt, 10 ps laser under commissioning.

One of the experiments that uses the CO_2 laser and the electron beam is the STELLA (Staged Electron Laser Accelerator) experiment. The primary purpose of the experiment is to demonstrate staged laser acceleration of microbunches produced by a laser-energy-modulation process [33]. During staging, optical microbunches, generated with longitudinal density distributions extending over a small fraction of the optical wavelength in duration, are rephased with the light wave for further acceleration. Staging is crucial for scaling laser acceleration devices to higher energies and making them into practical linacs. As such, the results of this program will benefit others in the field investigating alternative laser acceleration schemes.

In the process of demonstrating staging, we are also studying other important phenomena, such as the microbunching process itself, preservation of the microbunch characteristics, trapping, and stability issues. In addition, we will be providing further data to validate our computer models.

It has a fully instrumented experiment hall, three beam lines (and another one in the straight-ahead tunnel), state-of-the-art diagnostics and computer control. Typically 1100 hours beam-time are delivered annually. The Steering Committee approves typically 1-2 experiments annually - essentially a steady-state in the number of experiments.

4.2.6 The $\mu^+ - \mu^-$ Collider: progress and challenges

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4.2.6.1 $\mu^+ - \mu^-$ Collider collaboration activities

The Muon Collider Collaboration consists of more than 100 scientists from 26 different Institutions from the US, Europe, Russia and Japan. The R&D effort has being primarily led by Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (FNAL) and Lawrence Berkeley National Laboratory (LBNL).

Besides continued work on the parameters of a 3-4 and 0.5 TeV center-of-mass (CoM) energy collider, many studies are now concentrating on a machine near 0.1 TeV (CoM) that could be a factory for the s-channel production of Higgs particles. A comprehensive discussion of the research on the various components and beam dynamics issues is reported in a 95 pages preprint [34]. This report is an update of the progress on the R&D since the Feasibility Study of Muon Colliders presented at the Snowmass'96 Workshop [35].

Table 4.5: Baseline parameters for high- and low-energy muon colliders. Higgs/year assumes a cross section $\sigma = 5 \times 10^4$ fb; a Higgs width $\Gamma = 2.7$ MeV; 1 year = 10^7 s.

CoM energy	TeV	3	0.4		0.1	
p energy	GeV	16	16		16	
p's/bunch	10^{13}	2.5	2.5		5	
Bunches/fill		4	4		2	
Rep. rate	Hz	15	15		15	
p power	MW	4	4		4	
μ/bunch	10^{12}	2	2		4	
μ power	MW	28	4		1	
Wall power	MW	204	120		81	
Collider circum.	m	6000	1000		350	
Ave bending field	T	5.2	4.7		3	
Rms $\Delta p/p$	%	0.16	0.14	0.12	0.01	0.003
6-D $\epsilon_{6,N}$	$10^{-10}(\pi\ \mathrm{m})^3$	1.7	1.7	1.7	1.7	1.7
Rms ϵ_n	π mm-mr	50	50	85	195	290
β^*	cm	0.3	2.6	4.1	9.4	14.1
σ_z	cm	0.3	2.6	4.1	9.4	14.1
σ_r spot	μm	3.2	26	86	196	294
σ_θ IP	mrad	1.1	1.0	2.1	2.1	2.1
Tune shift		0.044	0.044	0.051	0.022	0.015
n_{turns} (effective)		785	700	450	450	450
Luminosity	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	7	0.1	0.012	0.0022	0.001
Higgs/year	10^3			1.9	4	3.9

Table 4.5 gives the parameters of the muon colliders under study, which have CoM energies of 0.1 TeV, 0.4 TeV and 3 TeV and Figs. 4.9 and 4.10 show possible outlines of the 0.1 TeV and 3 TeV machines. In the former case, parameters are given in the table for operation with three different beam-energy spreads: $\Delta p/p = 0.12$, 0.01, and 0.003%. In all cases, proton bunches containing 2.5-5×10^{13} particles are accelerated to energies of 16 GeV. The protons interact in a target to produce $\mathcal{O}(10^{13})$ charged pions of each sign. A large fraction of these pions can be captured in a high-field solenoid. Muons are produced by allowing the pions to decay into a lower-field solenoidal channel. To collect as many particles as possible within a useful energy interval, rf cavities are used to accelerate the lower-energy particles and decelerate the higher-energy particles. With two proton bunches every accelerator cycle, the first used to make and collect positive muons and the second to make and collect negative muons, there are about 10^{13} muons of each charge available at the end of the decay channel per accelerator cycle. If the proton accelerator is cycling at 15 Hz, then in an operational year (10^7 s), about 10^{21} positive and negative muons would be produced and collected.

The muons exiting the decay channel populate a very diffuse phase space. The next step in the

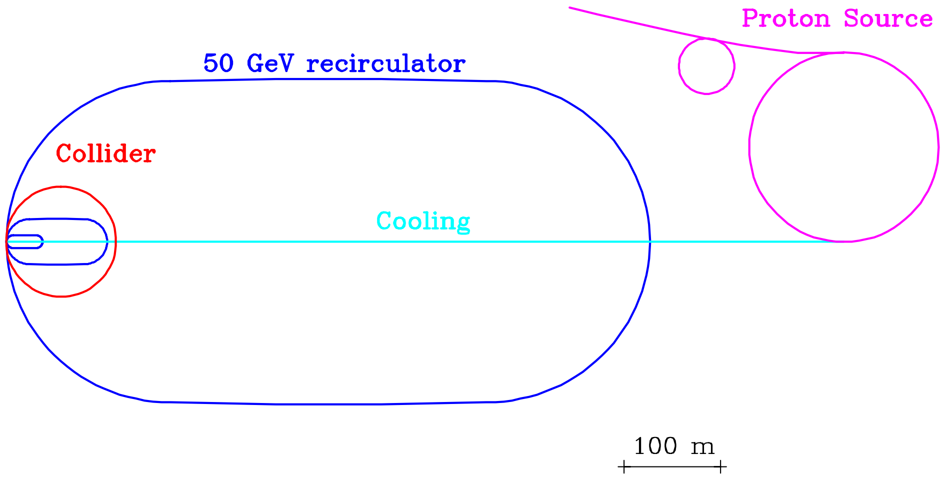

Figure 4.9: Plan of a 0.1 TeV CoM muon collider.

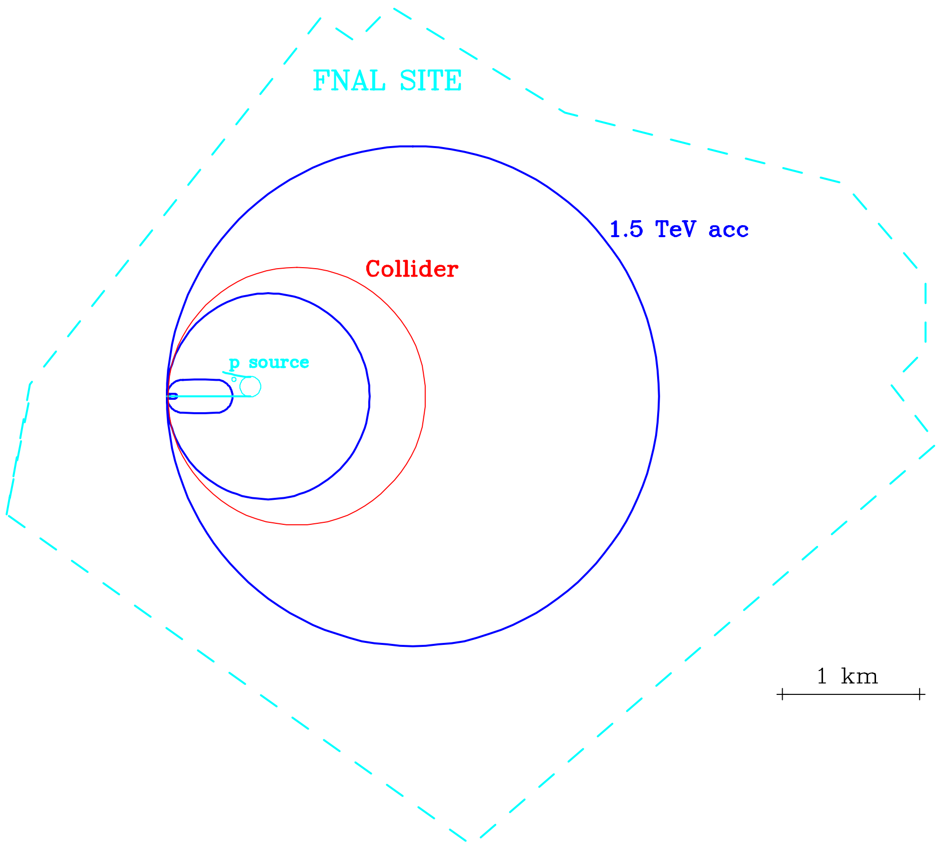

Figure 4.10: Plan of a 3 TeV CoM muon collider shown on the Fermi National Accelerator Laboratory site as an example.

muon-collider complex is to *cool* the muon bunch, *i.e.*, to turn the diffuse muon cloud into a very *bright* bunch with small longitudinal and transverse dimensions, suitable for accelerating and injecting into a collider. The cooling must be done within a time that is short compared to the muon lifetime. Conventional cooling techniques (stochastic cooling and electron cooling) take too long. The technique proposed for cooling muons is called ionization cooling. Briefly, the muons traverse some material in which they lose both longitudinal and transverse momentum by ionization losses (dE/dx). The longitudinal momentum is then replaced using an rf accelerating cavity, and the process is repeated many times until there is a large reduction in the transverse phase space occupied by the muons. The energy spread within the muon beam can also be reduced by using a wedge-shaped absorber in a region of dispersion (where the transverse position is momentum dependent). The wedge is arranged so that the higher-energy particles pass through more material than lower-energy particles. Initial calculations suggest that the 6-D phase space occupied by the initial muon bunches can be reduced by a factor of 10^5-10^6 before multiple Coulomb scattering and energy straggling limit further reduction. We reiterate that ionization cooling is uniquely suited to muons because of the absence of strong nuclear interactions and electromagnetic shower production for these particles at energies around 200 MeV/c.

Rapid acceleration to the collider beam energy is needed to avoid excessive particle loss from decay. It can be achieved, initially in a linear accelerator, and later in recirculating linear accelerators, rapid-cycling synchrotron, or fixed-field-alternating-gradient (FFAG) accelerators. Positive and negative muon bunches are then injected in opposite directions into a collider storage ring and brought into collision at the interaction point. The bunches circulate and collide for many revolutions before decay has depleted the beam intensities to an uninteresting level. Useful luminosity can be delivered for about 800 revolutions for the high-energy collider and 450 revolutions for the low-energy one.

There are many interesting and challenging problems that need to be resolved before the feasibility of building a muon collider can be demonstrated. For example, (i) heating from the very intense proton bunches may require the use of of a liquid-jet target, and (ii) attaining the desired cooling factor in the ionization-cooling channel may require the development of rf cavities with thin beryllium windows operating at liquid-nitrogen temperatures in high solenoidal fields. In addition, the development of long liquid-lithium lenses may be desirable to provide stronger radial focusing for the final cooling stages.

4.2.6.2 Summary of progress and challenges

Unlike protons, muons are point-like but, unlike electrons, they emit relatively little synchrotron radiation and therefore can be accelerated and collided in rings; another advantage resulting from the low synchrotron radiation is the lack of beamstrahlung and the possibility of very small collision energy spreads. A beam energy spread of Δ E/E ≈ 0.003% is considered feasible for a 100 GeV machine. It has been shown that by observing spin precession, the absolute energy could be determined to a small fraction of this width. These features become important in conjunction with the large s-channel Higgs production ($\mu^+\mu^- \to h$, 43000 times larger than for $e^+e^- \to h$), allowing precision measurements of the Higgs mass, width and branching ratios. A higher energy muon collider can also distinguish the nearly degenerate heavy Higgs bosons H^0 and A^0 of the minimal supersymmetric extension of the standard model, since these states can also be produced in the s channel. We have also examined the ability of the muon collider to study techni-resonances, do a high luminosity study of Z boson physics, scan the W and $t\bar{t}$ thresholds to make precision mass measurements as well as SUSY and strongly interacting W boson physics. The high luminosity proton driver and the cold low energy muons permit the study of rare kaon and muon decays. Muon storage rings will permit low-systematics studies of neutrino oscillations for a wide range of mixing angle and δm^2 phase space with hitherto unattainable sensitivity.

An enumeration follows follows:

Proton driver The specification of the proton driver for the three machines is assumed the same: 10^{14} protons/pulse at an energy above 16 GeV and 1-2 ns *rms* bunch lengths. There have been three studies of how to achieve these parameters. The most conservative, at 30 GeV, is a generic design. Upgrades of the FNAL (at 16 GeV) and BNL (at 24 GeV) accelerators have also been studied. Despite the very short bunch requirement, each study has concluded that the specification is attainable. Experiments are planned to confirm some aspects of these designs.

Pion production and capture Pion production has been taken from the best models available, but an experiment (BNL-E910) that has taken data, and is being analyzed, will refine these models. The assumed 20 T capture solenoid will require state-of-the-art technology. Capture, decay and phase rotation have been simulated, and have achieved the specified production of 0.3 muons per initial proton. The most serious remaining issues for this part of the machine are:

- The nature and material of the target: The baseline assumption is that a liquid metal jet will be used, but the effects of shock heating by the beam, and of the eddy currents induced in the liquid as it enters the solenoid, are not yet fully understood.

- The maximum rf field in the phase rotation: For the short pulses used, the current assumptions would be reasonably conservative under normal operating conditions, but the effects of the massive radiation from the nearby target are not known.

Both these questions can be answered in a target experiment planned to start within the next two years at the BNL AGS. See

`http://pubhep1.princeton.edu/ mcdonald/mumu/target/targetprop.ps`

Polarization of the muon beams represents a significant physics advantage and is an important feature of a muon collider. Polarized muon beams are possible. Muons are produced with 100% polarization in the rest frame of the pion, but they travel in all directions. By accepting the forward going muons, it is easy to obtain 25% polarization in either beam easily. The amount of polarization can be increased with an accompanying price in luminosity.

Cooling The required ionization cooling is the most difficult and least understood element in any of the muon colliders studied; achieving the nearly 10^6 reduction required is a challenge. Cooling over a wide range has been simulated using lithium lenses and ideal (linear matrix) matching and acceleration. Examples of limited sections of solenoid lattices with realistic accelerating fields have now been simulated, but the specification and simulation of a complete system has not yet been done. Much theoretical work remains: space charge and wakefields must be included; lattices at the start and end of the cooling sequences must be designed; lattices including liquid lithium lenses must be studied, and the sections must be matched together and simulated as a full sequence. The tools [36] for this work are nearly ready, and this project should be completed within two years.

Technically, one of the most challenging aspects of the cooling system appears to be:

- High gradient rf (e.g. 36 MV/m at 805 MHz) operating in strong (5-10 T) magnetic field, with beryllium foils between the cavities.

An experiment is planned that will test such a cavity, in the required fields, in about two years time. On an approximately six year time scale, a *Cooling Test Facility* is being proposed that could test ten meter lengths of different cooling systems. See http://www.fnal.gov/projects/muoncollider/cool/proposal/proposal.ps.

Acceleration The acceleration system is probably the least controversial, although possibly the most expensive, part of a muon collider. Preliminary parameters have been specified for acceleration sequences for a 100 GeV and a 3 TeV machine, but they need refinement. In the low energy case, a linac is followed by three recirculating or FFAG accelerators. In the high energy accelerator, the recirculating or FFAG accelerators are followed by three fast ramping synchrotrons employing alternating pulsed and superconducting magnets. The parameters do not appear to be extreme, and it does not appear as if serious problems are likely.

Collider The collider lattices are challenging because of the requirement of very low beta functions at the interaction point, high single bunch intensities, and short bunch lengths. However, the fact that all muons will decay after about 800 turns means that slowly developing instabilities are not a problem. Feasibility lattices have been generated for a 4 TeV CoM case, and more detailed designs for 100 GeV machines are been studied. In the latter case, but still without errors, $5\,\sigma$ acceptances in both transverse and longitudinal phase space have been achieved in tracking studies. Beam scraping schemes have been designed for both the low energy (collimators) and high energy (septum extractors) cases.

The short bunch length and longitudinal stability problems are avoided if the rings, as specified, are sufficiently isochronous, but some rf is needed to remove the impedance generated momentum spread. Transverse instabilities (beam breakup) should be controlled by rf BNS damping.

The heating of collider ring superconducting magnets by electrons from muon decay can be controlled by thick tungsten shields, and this technique also shields the space surrounding the magnets from the induced radioactivity on the inside of the shield wall. A conceptual design of magnets for the low energy machine has been defined.

Although much work is yet to be done (inclusion of errors, higher order correction, magnet design, rf design, etc), the collider ring does not appear likely to present a serious problem.

Neutrino radiation and detector background Neutrino radiation, which rises as the cube of the energy, is not serious for machines with center of mass energies below about 1.5 TeV. It is thus not significant for the First Muon Collider; but above 2 TeV CoM, it sets a constraint on the muon current and makes it harder to achieve desired luminosities. However, advances in cooling and correction of tune shifts may still allow a machine at 10 TeV with substantial luminosity ($> \ 10^{35}$ cm^{-2} s^{-1}).

Background in the detector was at first expected to be a very serious problem, but after much work, shielding systems have evolved that limit most charged hadron, electron, gamma and neutron backgrounds to levels that are acceptable. Muon background, in the higher energy machines, is a special problem that can cause serious fluctuations in calorimeter measurements. It has been shown that fast timing and segmentation can help suppress this background, and preliminary studies of its effects on a physics experiment are encouraging. The studies are ongoing.

Detector scenarios We have considered several options for the experimental detector components for various CoM energy colliders. Much work needs to be done to optimize the physics reach at each energy by feeding back the results of detailed simulations of backgrounds and signal to the detector design. Only then will the feasibility of doing physics with a muon collider be fully explored.

4.2.6.3 Muon Collider information resources

The Muon Collider Collaboration maintains a WEB page at:

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

with links to additional WEB sites at FNAL, Princeton, Indiana and CERN. The next scheduled workshops organized and sponsored by the Collaboration are:

- *Collaboration Meeting*, May 20-26, 1999 at St. Croix, USVI
- *Neutrino Factories based on Muon Accumulators*, July 5-9, 1999 at Lyon, France
- *Muon Colliders at the Highest Energies*, Sep. 27-Oct. 1, 1999 at Montauk, NY
- *Physics Potential & Development of $\mu^+\mu^-$ Colliders*, Dec. 15-17, 1999 at San Francisco

Detailed information can be obtained from the respective meeting WEB page. Links to those pages are found in the Collaboration WEB site mentioned above.

4.2.7 US part of Large Hadron Collider (US-LHC)

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The accelerator part of the US-LHC program (a 7-year, 530 million US dollar DOE program) is a collaboration among BNL, FNAL and LBNL contributing to the design and construction of Interaction Region and RF Region superconducting magnets for the Large Hadron Collider currently under construction at CERN. Performance of the Large Hadron Collider (LHC) at collision depends on achieving the highest possible magnet field quality and alignment accuracy in the IR triplet quadrupoles and dipoles (D1) during low-β^* operation when beams cross at a design crossing angle. These superconducting magnets will be mainly built in the USA (BNL and FNAL) and in Japan, and assembled in cryostats in the USA. During the past year, accelerator physics activities at BNL are mainly on evaluating the impact of magnetic field errors of both US and KEK magnets, and on optimizing the performance of these magnets through compensation schemes.[37]

A schematic layout of LHC Insertion region is given in Fig. 4.11. The leading source of errors

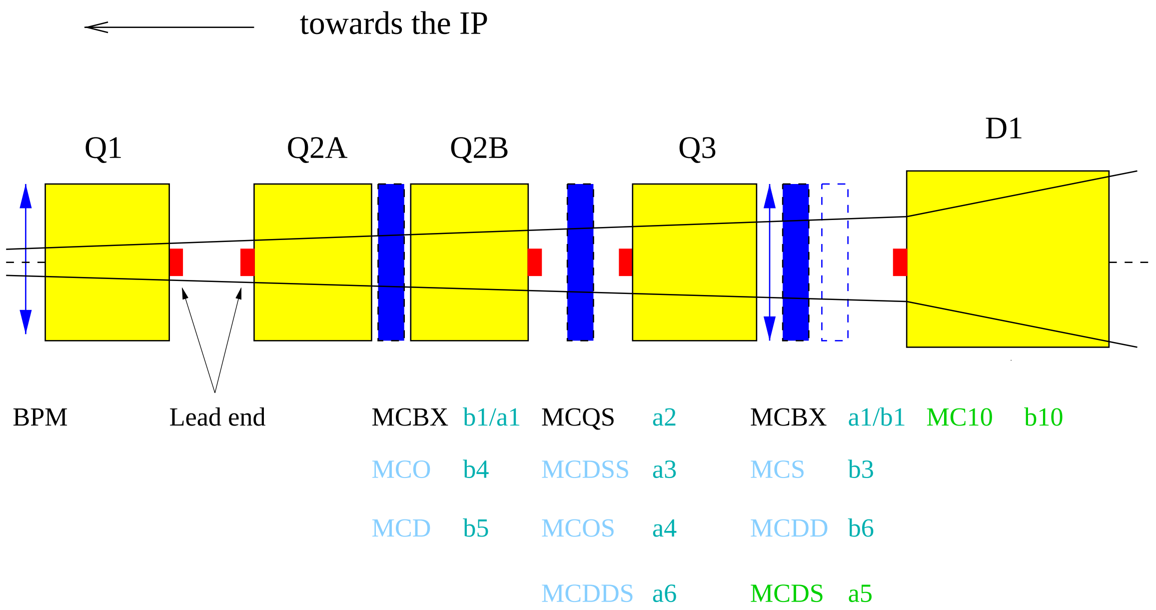

Figure 4.11: Schematic layout of LHC Insertion Region triplet quadrupole, dipole, and correctors.

are from the systematic b_6 from both quad body and lead ends, from the systematic b_{10} of KEK quad body, and from lower order random multipoles. The impact of magnetic errors is assessed by the maximum tune spread among particles with amplitudes of up to 6 times the transverse rms beam size ($6\sigma_{xy}$), and by the DA from 6D tracking of either 10^5 or 10^3 turns of particles of initially up to 2.5 times rms momentum deviation ($2.5\sigma_p$) at 5 horizontal-to-vertical emittance ratios ϵ_x/ϵ_y. End effects are modeled as lumped kicks.[38] Fig. 4.12 shows typical $6\sigma_{xy}$ tune footprints

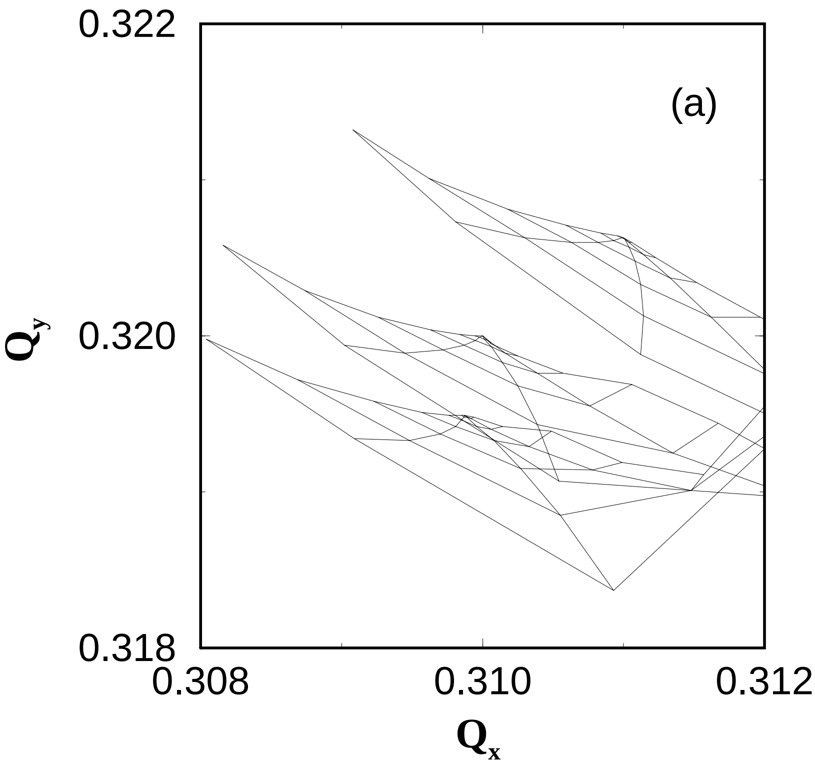

Figure 4.12: Effects of IR magnet errors at collision.

for $\Delta p/p = 0, \pm 2.5\sigma_p$. Without compensation, the impact of MQX magnet errors is exceedingly large. Through iterations of discussions between magnet groups and accelerator physics groups, several design modifications are made to reduce lead end b_6 and body b_{10} errors, and tuning shims are designed to reduce lower order (b_3, b_4, a_3, and a_4) errors. Fig. 4.13 shows improvement through compensation schemes. The average gain in dynamic aperture is about $4\sigma_{xy}$.

Error compensation is based on the minimization of action-angle kicks[22] produced by each multipole error b_n (or a_n) over a pair of inner triplets, i.e. minimizing the quantities

$$\int_L dl\beta_z^{n/2} B_0 b_n + (-)^n \int_R dl\beta_z^{n/2} B_0 b_n, \quad z = x, y \tag{4.1}$$

taking advantage of the negligible betatron phase advance within each triplet and D1, and approximate 180° phase advance between the triplets. The integral is over the entire left-side (L) or right-side (R) MQX triplet and D1. The quantity B_0 is the main field for dipoles and $G_0 R_{ref}$ for quadrupoles. Since two intersecting beams share these magnets, the compensation is designed for both beams in both the x and y directions without considering the closed-orbit deviation caused by the crossing angle.

Magnet Orientation Optimization and Body-End Compensation The typical tune spreads of about 0.002 produced by MQX end b_6 errors can be reduced by more than a factor of 2 by optimizing

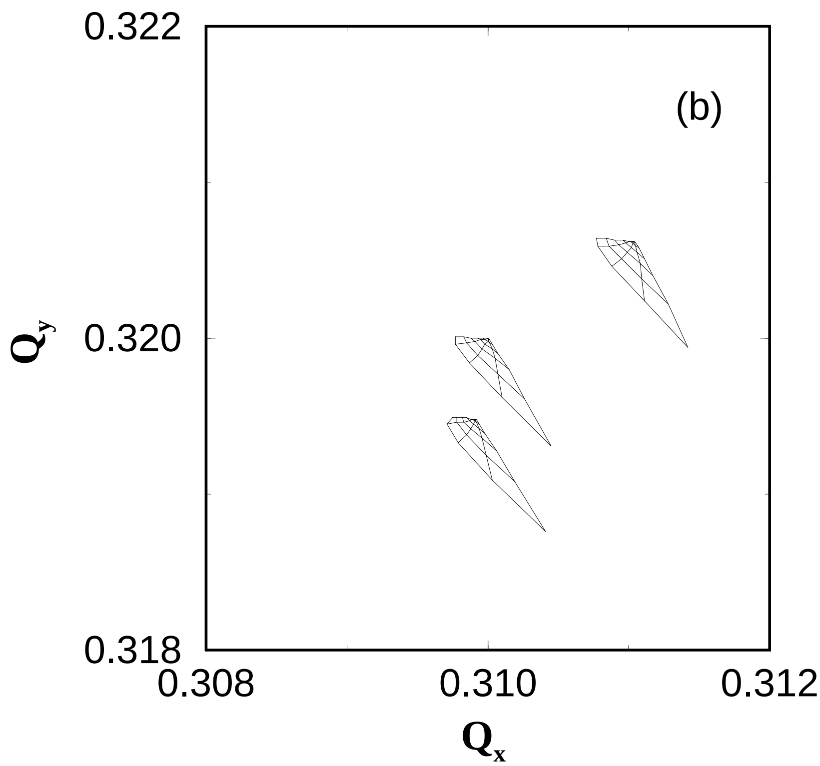

Figure 4.13: Same case as Fig. 4.12 showing the improvement with IR correctors.

the orientation of MQX lead ends (see Fig. 4.11), cancelling b_6 effect between nearby focusing and defocusing quadrupoles. The impact of lead-end b_6 is further reduced by adjusting the design value of body b_6 averaged across each triplet. This choice of body b_6, same for all MQX magnets, is insensitive to lattice optics changes as long as β^* is small.

Magnetic Tuning Shims After the construction and warm measurement of each FNAL-built MQX magnet, 8 tuning shims with adjustable iron thickness will be inserted into 8 slots to individually minimize body b_3/a_3 and b_4/a_4 errors.

IR Correctors Each triplet contains three corrector packages (MCX1, MCX2, MCX3), each consisting of as many as 3 layers of nonlinear correction elements in addition to the linear (dipole or skew quadrupole) layers. For each multipole, two correction elements located symmetrically at opposite sides of the IP can be activated to minimize the kick (Eq. 4.1) in both the x and y directions (hence for both beams due to lattice symmetry).[37] With 3 packages per triplet each consisting of 3 nonlinear layers of multipole elements, we achieve a tune spread of less than 10^{-3} (Fig.4.13), an average DA larger than $12\sigma_{xy}$, and a minimum DA larger than $10\sigma_{xy}$.

Mixed arrangement for KEK and FNAL quads The working assumption during the past years has been that FNAL quads will be installed at IP5 and IP8, while KEK quads will be installed at IP1 and IP2. One way to reduce the impact of excessive b_{10} errors from KEK quads, and to avoid the complication of building b_{10} corrector magnets, is to have KEK to build Q1 and Q3, and FNAL to build Q2A and Q2B for all four IR's. Doing so will also reduce the number of spare magnets, since Q1 and Q3 are of the same length of 5.5 m, while Q2A and Q2B are 6.3 m. On the other hand, combining quadrupoles of different design in the same triplet may cause complications in power supply bus arrangement, power ripple, and snap back.[39]

4.2.8 Very Large Hadron Collider (VLHC) and magnet program

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http://www.rhichome.bnl.gov/FHC/index.html

Early in 1998, a steering committee was set up in the U.S. to look at a proton-proton collider with center of mass energy significantly above that of the LHC. The steering committee was set up in response to one of the recommendations of the 1997-1998 HEPAP Subpanel report on the future of U.S. High Energy Physics. The steering committee chose a temporary name for the machine, very large hadron collider (VLHC), a nominal set of machine parameters (from Snowmass '96) and appointed working groups on accelerator physics, magnets technologies, and accelerator systems. Each working group was asked to hold at least one workshop per year and to make an annual report to the steering committee. This note summarizes the first workshop on magnet technologies, held in Port Jefferson, NY last November. The available talks can be accessed via the BNL magnet group Web site (http://magnets.rhic.bnl.gov/) or via the VLHC Web site (http://vlhc.org). The VLHC Web site also has links to the proceedings of the other two workshops, which were held in February, and information about the annual VLHC meeting (June 28-30 in Monterey, California).

The working group on magnet technologies was asked to focus on innovative concepts that would result in significant cost reductions. Work on new types of magnets, some with new types of superconductors, is underway at BNL, Cornell, Fermilab, LBNL, and Texas A&M. The magnet R&D was discussed in detail at the workshop. Overview talks on the Snowmass '96 parameters, accelerator physics, and superconductors provided a framework for the magnet activity.

The pp colliders studied at the DPF Snowmass '96 workshop had center of mass energy 100 Gev and luminosity 10^{34} cm^{-2}sec^{-1}. Three colliders, characterized by differing magnetic fields, were studied. One collider was based on a dipole magnetic field of 12.5 T. Such a machine would have a circumference of 100 km and a 1.3 hour synchrotron radiation damping time for the beam emittance. Since the familiar NbTi superconductor has a critical field of 10 T, magnets for such a machine would require the use of a new type of superconductor, such as Nb_3Sn or high temperature superconductor (HTS). The second collider was based on the use of NbTi to achieve a dipole field approaching 10 T. None of the work reported at the magnet workshop was based on this type of magnet. The third collider was based on a low field (~ 2 T), iron-dominated magnet. Such a machine would have nominal circumference about 550 km and no synchrotron damping.

Superconductor characteristics place fundamental limits on magnet design, so it is useful to summarize them. NbTi is, of course, the most familiar. Important parameters of NbTi are the current-carrying capacity in the superconductor (J_c), the critical field (H_c), and the critical temperature (T_c). Additional parameters are needed to describe the new materials. Nb_3Sn and HTS are brittle, and their strain sensitivity sets a limit on the minimum winding radius of about 2.5 cm. For HTS, the engineering current density (J_e) must be considered because a significant fraction of the conductor cross section is non-superconducting structural support. HTS materials retain some residual resistance even at low temperatures. This resistance may make the persistent current behavior of these conductors different than that of the low temperature superconductors, NbTi and Nb_3Sn.

Six groups in the U.S. are actively engaged in magnet R&D for a VLHC. Groups at Brookhaven and Berkeley are using a new type of coil configuration called "common coil." Two groups at Fermilab are working on magnets, one on a high field, cosine theta design, the other on a low field, iron-dominated transmission line type of magnet. A group at Texas A&M is working on a high field magnet whose conductor blocks are individually supported.

Common coil magnets are designed for a two-aperture collider. The design uses two "racetrack" coils arranged so that each coil contributes to the field in both apertures (fig. 4.14). There is a two-

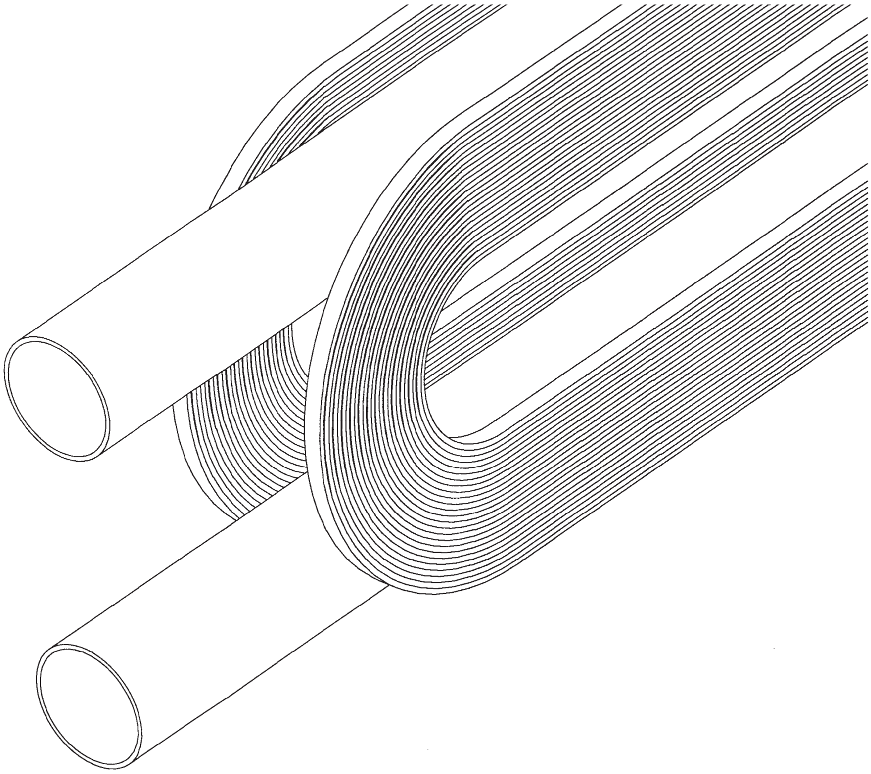

Figure 4.14: Arrangement of two racetrack coils to produce dipole fields in two apertures.

fold advantage to the use of this design with brittle materials. First, the conductor does not have to bend in three dimensions as it does in a saddle coil. Second, the spacing between the two apertures, not the aperture diameter, sets the minimum bend radius of the conductor. The current in one coil is opposite the current in the other coil so that the magnetic fields in the aperture add together. The magnet can reach 12.5 T with a compact iron structure (400 mm o.d.). A cross section of the magnet with trim coils is shown in Fig. 4.15.

The Brookhaven group has built a common coil R&D yoke about 1 m long. NbTi cable from the SSC program was resized at Berkeley so that it could be wound in a racetrack coil configuration. Assembled in the R&D yoke, two of these coils produce a 6 T background field for tests of HTS and Nb_3Sn coils, which produce an additional 1 T. (Nb_3Sn is of interest because it has the same dependence of critical current on strain as HTS.) Thus far, the NbTi and Nb_3Sn coils have been run successfully. Work is underway to improve the assembly and quench performance before construction of the 1 m HTS coils. In parallel, small HTS coils have been made and tested as single windings. A racetrack coil and a quadrupole saddle coil have worked well. The quadrupole coil was a joint purchase with Cornell and Fermilab and made in industry.

The Berkeley group has had quite good success with its first common coil magnet, which was made using Nb_3Sn cable left over from the ITER program. The coils, which were made using a wind and react method, are about 1 m long. The magnet reached a central field of 6 T, the limit of the current-carrying capacity of the superconductor, without training.

An extension of the common coil design to four apertures is now being examined. The yoke shown in Fig. 4.15 is extended vertically at the top and bottom to include apertures above and below

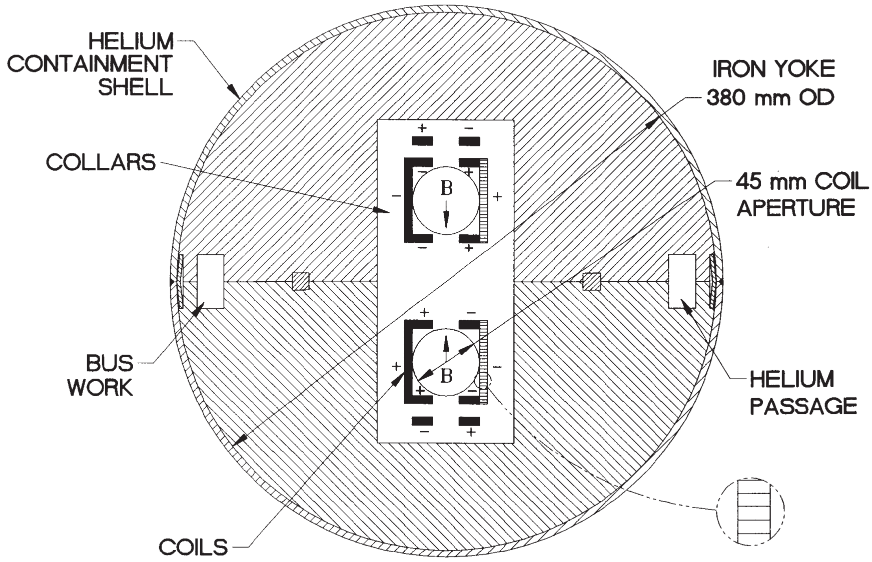

Figure 4.15: Cross section of common coil magnet including racetrack coils, yoke, and correction coils.

the two main apertures. The field in these apertures would be limited to 2 T. As such, it would be produced primarily by the iron ("iron dominated") and require little extra superconductor. With the appropriate ramping, the beam could, in principal, be transferred from the low-field aperture to the high-field ("conductor dominated") aperture. This would extend the dynamic range of the magnet and avoid a class of time-dependent field effects due to the superconductor.

Low-field magnet R&D has been underway at Fermilab for three years. The magnet uses one turn of superconductor, carrying 75 kA, to generate current in two apertures of a warm iron yoke (Fig. 4.16). The vacuum chamber is at room temperature. It is made from an extrusion that may require a large volume outside the magnet aperture to provide sufficient pumping. The current return and helium transport are in a separate cryostat under the magnet. There is R&D on components of the design and a 2 m section of iron has been powered. The group is presently setting up a loop for testing 4 m sections of cable and a 50 m test section of magnet.

High-field magnet R&D at Fermilab increased significantly last year. Plans are centered on a two layer cosine theta cold iron dipole made with Nb_3Sn cable. The nominal superconductor specification would produce a central field of 11.8 T in a 50 mm bore (fig.4.17). Substantial capacity for reacting the Nb_3Sn is being installed at Fermilab and much computational and lab work is underway. The group plans a 1 m magnet for the fall of 2000.

The magnet group at Texas A&M has designed a 16 T dual bore magnet in which the individual blocks of Nb_3Sn superconductor are supported against the Lorentz forces (Fig.4.18). (In contrast, the azimuthal forces in cosine theta magnets accumulate from the pole to the midplane.) Conductor blocks are surrounded by Inconel steel. The Inconel structure transmits the force that accumulates on a group of blocks to a supporting structure outside the coil. Currently, the group has numerous R&D projects underway to develop the individual components needed for the magnet. Model testing will be simplified because the coil blocks needed for one bore in a dual bore magnet can be used to make a single bore magnet, saving time and materials costs.

The three groups that are using Nb_3Sn cable are working with industry to develop a set of specifications that are as much alike as possible. The labs and industry are working to increase critical current and decrease filament size. With ITER no longer making large purchases of superconductor, high energy physics will need to support much of the development formerly carried by the fusion

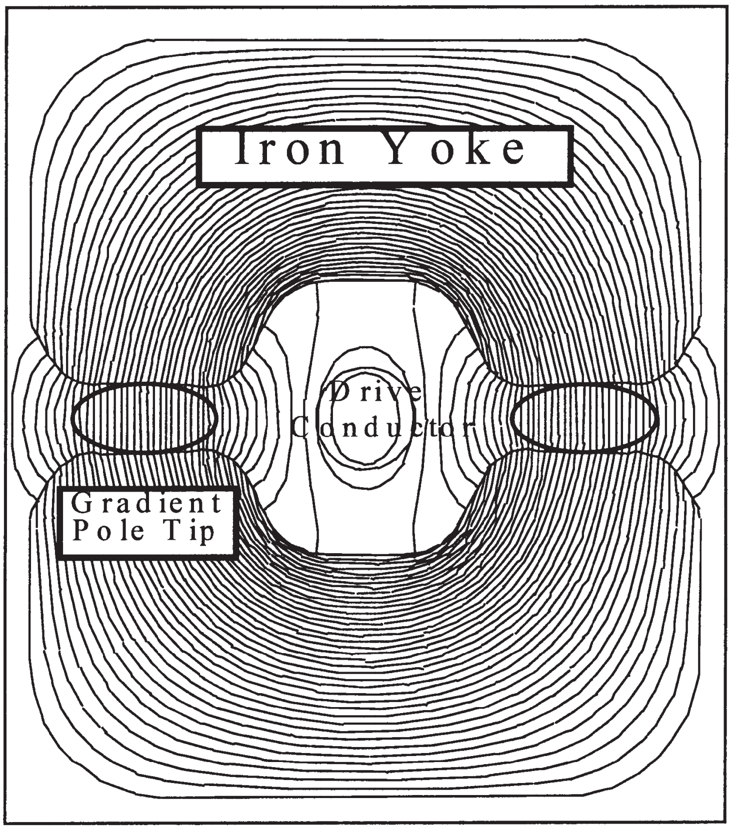

Figure 4.16: Yoke and conductor for transmission line magnet, showing lines of flux.

program.

The VLHC magnet workshop demonstrated that the groups are working with new ideas for both superconductor and magnets, as will be needed for a pp collider beyond the LHC. Both cost and technical performance are receiving attention.

4.2.9 Crystalline beams studies

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Since mid 1980's, there has been experimental[40, 41] and theoretical[42] efforts to achieve crystalline beams. When the beams in storage rings are sufficiently cold in the beam rest frame, the ions may "lock into" a position where the repelling Coulomb force on the average balances the external focusing force (Fig. 4.19). The interest, besides intrinsically on this new state of matter, is primarily on studying the physics of completely space-charge dominated beams, and the possibility of obtaining high luminosity in colliders.[43]

Experimentally, ion crystallization has been observed in radio-frequency (rf) traps[44], static[45] traps, and rf quadrupole rings[46] using laser cooling. Attempts to crystallize ion beams have not been successful due to the lack of effective cooling in directions transverse to the beam motion,[40, 41] and the lack of suitable storage rings with lattices of sufficiently high periodicity.[41] Recently, experimental test has been proposed to realize crystalline beams at low velocity with a table top circular RF quadrupole storage ring[47] for acceleration and cooling of, e.g., $^{24}Mg^{+}$ ions.

Conditions of crystallization There are two necessary conditions[48] to form and maintain a crystalline beam: (i) The ring is alternating-gradient (AG) focusing operating below transition, and (ii)

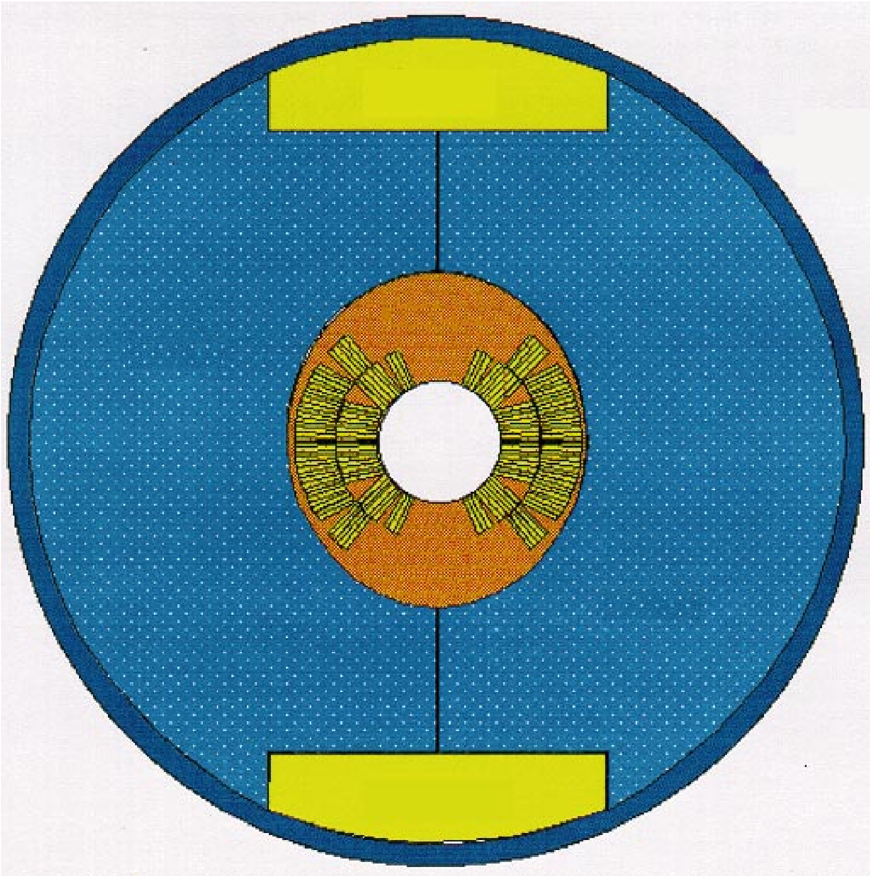

Figure 4.17: Initial design cross section a high-field Nb_3Sn cos-theta dipole.

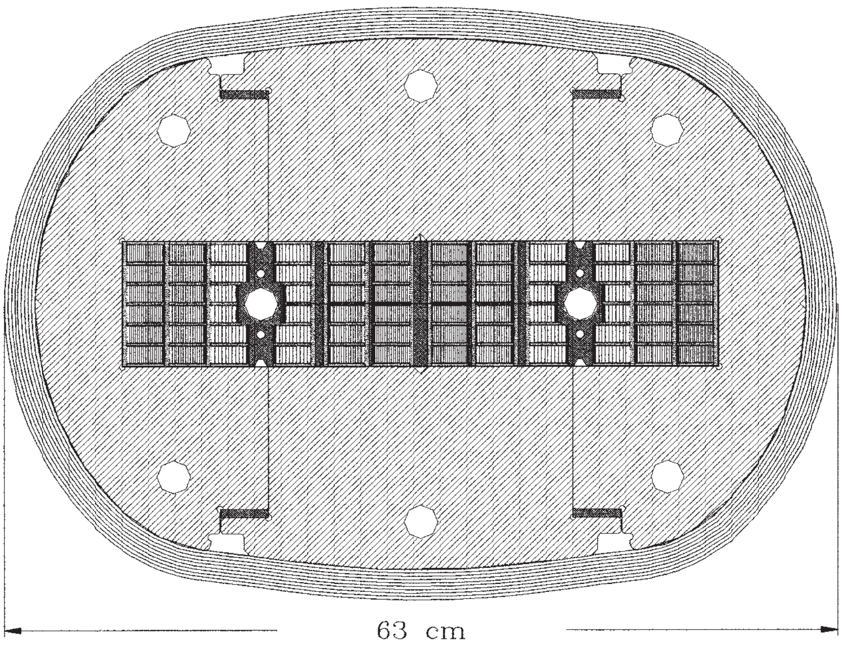

Figure 4.18: Cross section of high-field dual bore block dipole.

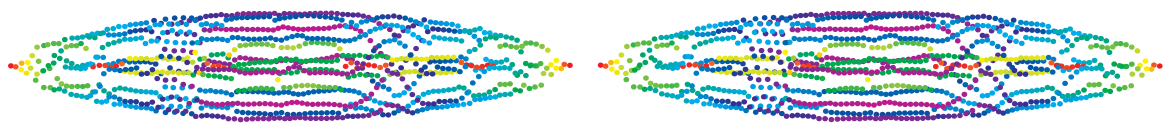

Figure 4.19: A set of stereo-scopic pictures of a crystal ball in TARN II at its ground state (a), obtained by MD calculation with 1000 particles (total $N = 10^6$ in the ring) and displayed at the cooling location. (The stereo-scopic effect can best be seen by holding the paper close to your nose). The color code is associated with the scaled radial distance from the axis. The object is finite in all three dimensions due to the transverse focusing forces of the external magnets and the longitudinal rf force. The physical dimensions in the horizontal, vertical, and longitudinal directions are approximately 0.3, 0.2, and 8.0 mm, respectively. A typical distance between ions is 30 μm ($\xi = 23$ μm).

The ring lattice periodicity is at least $2\sqrt{2}$ as high as the maximum betatron tune. Condition (i) arises from the criterion of stable kinematic motion under Coulomb interaction when particles are subject to bending in a storage ring. Condition (ii) arises from the criterion that there is no linear resonance between the phonon modes of the crystalline structure and the machine lattice periodicity.

Beam rest-frame Hamiltonian [48, 49] Rest-frame Hamiltonian for a circulating beam has been derived using general relativity formulism. In this frame, the Coulomb force takes its simple non-relativistic form, and well-developed condensed-matter methods can be readily adapted. Numerical study of the crystalline state has been performed with the molecular dynamics (MD) method iterating the equations of motion derived from the Hamiltonian. Ewald-type summation is performed in the azimuthal direction to evaluate the long-ranged Coulomb forces among particles and their image charges modeled in periodic "supercells" for computing efficiency.

In a bending region with pure dipole magnetic field, the rest-frame Hamiltonian in dimensionless units is

$$H = \frac{1}{2}\left(P_x^2 + P_y^2 + P_z^2\right) + \frac{1}{2}x^2 - \gamma x P_z + V_C \tag{4.2}$$

where V_C is the Coulomb potential. In a non-bending region with longitudinal electric field and non-dipole magnetic fields,

$$H_i = \frac{1}{2}\left(P_x^2 + P_y^2 + P_z^2\right) - \frac{n_1}{2}(x^2 - y^2) - n_{1s}xy - \frac{n_2\xi}{6}(x^3 - 3xy^2) + V_C \tag{4.3}$$

where the quad, skew quad, and sextupole strengths are represented by $n_1 = -(\rho/B_0)(\partial B_y/\partial x)$, $n_{1s} = -(\rho/B_0)(\partial B_y/\partial y)$, $n_2 = -(\rho/B_0)(\partial^2 B_y/\partial x^2)$, respectively.

Ground-state structure In a crystalline ground state, the motion of the circulating particles is periodic in time [48] with the period of the machine lattice. As shown in Fig.4.20, particle trajectory in the transverse direction conforms to AG focusing (breathing), and in the longitudinal direction conforms to the change in bending radius (shear). In the presence of a longitudinal electric field, momentum P_z also varies periodically conforming to the energy gain at the cavity. [49] The ground state structure is a 1-D chain when the beam line density is low. The structure becomes 2-D lying in the plane of weaker transverse focusing. For even higher density, the particles arrange themselves into 3-D crystals, becoming helices and then helices within helices.

Lattice heating A crystalline beam in its ground state, despite breathing and shear motion, remains in the zero-temperature state. [48] At any non-zero temperature the crystalline beam absorbs en-

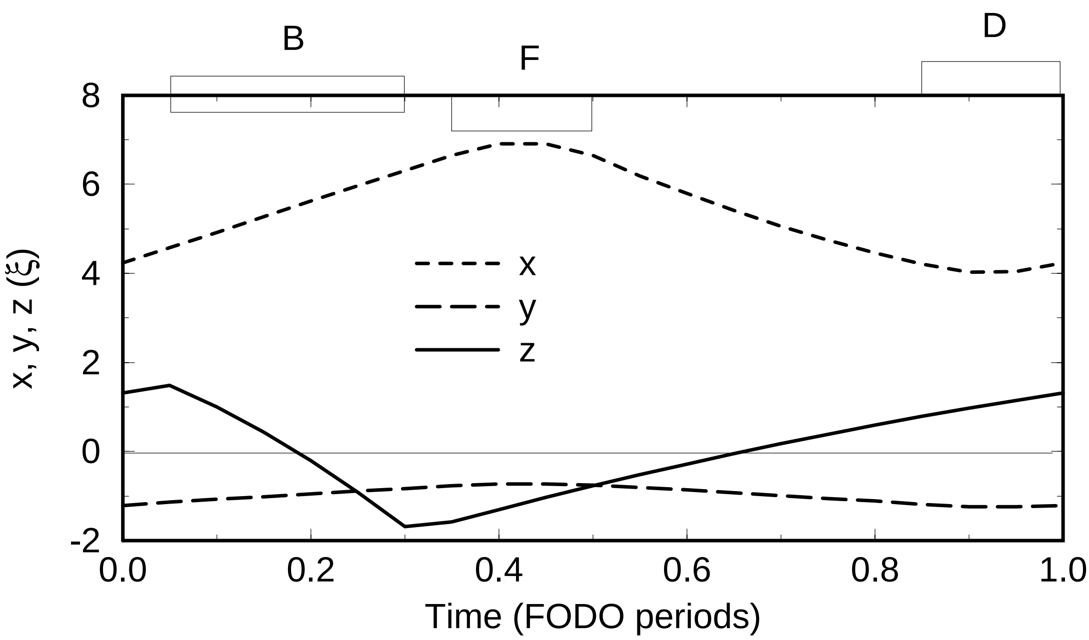

Figure 4.20: Particle trajectory of a bunched crystalline beam. The machine consists of 10 FODO cells with $\nu_x = 2.8$, $\nu_y = 2.1$, and $\gamma = 1.4$. Lattice components in each cell are displayed on the figure: B is a bending section, F and D are focusing and de-focusing quadrupoles.

ergy and heats up under time-dependent external forces caused by variations in lattice focusing and bending. In the high temperature limit, this intra-beam scattering results in a growth rate $\propto \lambda T^{-5/2}$.

Cooling methods In order to attain a crystalline state, the beam must be effectively cooled in 3-D with a sufficient speed to overcome the heating. Both electron and laser cooling provide high cooling efficiency in the longitudinal direction, reaching a beam temperature of less than 1 K, but not in the transverse directions (around 100 K). [41] "Sympathetic cooling" due to intra-beam scattering does produce transverse cooling, [50] but the heat exchange becomes ineffective as the beam approaches an ordered state. Coupling cavities operating on a synchro-betatron resonance or regular rf cavities in a dispersive region can provide effective 3-D cooling, [51] but the coupling mechanism ceases to work due to space-charge de-tuning before an ordering can be reached. Realization of crystalline beams requires cooling that provides the ions with constant angular velocity, rather than constant linear velocity (so called tapered cooling). [49]

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4.3 Beam Dynamics Activities at SLAC

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Recent work at SLAC ranges from B-factory commissioning to linear collider developments and advanced accelerator research, including experimental studies at the Next Linear Collider Test Accelerator, the Final Focus Test Beam Facility and the Two-Mile Accelerator.

4.3.1 PEP-II Colliding Beams

Ina Reichel `reichel@slac.stanford.edu` *for the PEP-II commissioning team*

PEP-II recently finished the last commissioning run without the BaBar detector, now being installed in the ring. The commissioning was very successful so far. The highest current reached in the High Energy Ring (HER) so far was 750 mA of electrons. The positron current in the Low Energy Ring (LER) exceeded 1.16 A. Typical lifetimes are 50 minutes for the LER at currents of 700 mA and several hours for the HER. The lifetime in the LER is still limited by dynamic pressure.

So far 153 Ah of integrated current have been reached. It is assumed that 200 to 400 Ah are needed to get to the design values for the dynamic pressure. The bunch patterns used range from single bunches to design pattern (1658 bunches using every other RF-bucket and leaving a 10% ion clearing gap). Many studies were done using either twice or four times the nominal bunch spacing.

Most of the commissioning was spent on single ring programs. Only a few days so far were devoted to colliding beam studies. Nevertheless the highest luminosity measured so far was 5.22 $\times 10^{32}$ cm^{-2}s^{-1}. Beam sizes at the IP are obtained from beam-beam scans. The smallest Σ_y seen thus far was 8.6 μm with the design being 6.7 μm. Single bunch luminosities of half the design values have been reached which is very positive regarding the total commissioning time so far.

4.3.2 SPEAR 3: Ready for Upgrade

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The Stanford Synchrotron Radiation Laboratory at SLAC is planning an upgrade of the SPEAR light source to reduce beam emittance from 160 nm-rad to 18 nm-rad and increase the beam current $>$ 200 mA. The new lattice is a double-bend achromat (DBA) with 18 straight sections. The vacuum chamber is rated for 500 mA operation as photon beam line upgrades permit. Mode-damped cavities are planned for the RF system.

As shown in Fig. 4.1, the SPEAR 3 lattice has low β-functions throughout the cell to maximize photon flux density, reduce sensitivity to field errors and minimize beam stay-clear. Injection system elements and existing ID's are located in 3-m straights with β-function values of β_x/β_y=10.1/4.8 m and D_x=0.0. Tracking simulations with a full complement of magnet errors show the horizontal dynamic aperture exceeds 20 mm (at the injection point) with minimum reduction for particles beyond 3% momentum deviation. With the new DBA lattice and 200-mA current, ID beam lines will receive an order of magnitude increase in focused flux density while dipole beam lines will receive up to two orders of magnitude increase due to the higher critical energy. The 7-m racetrack straights

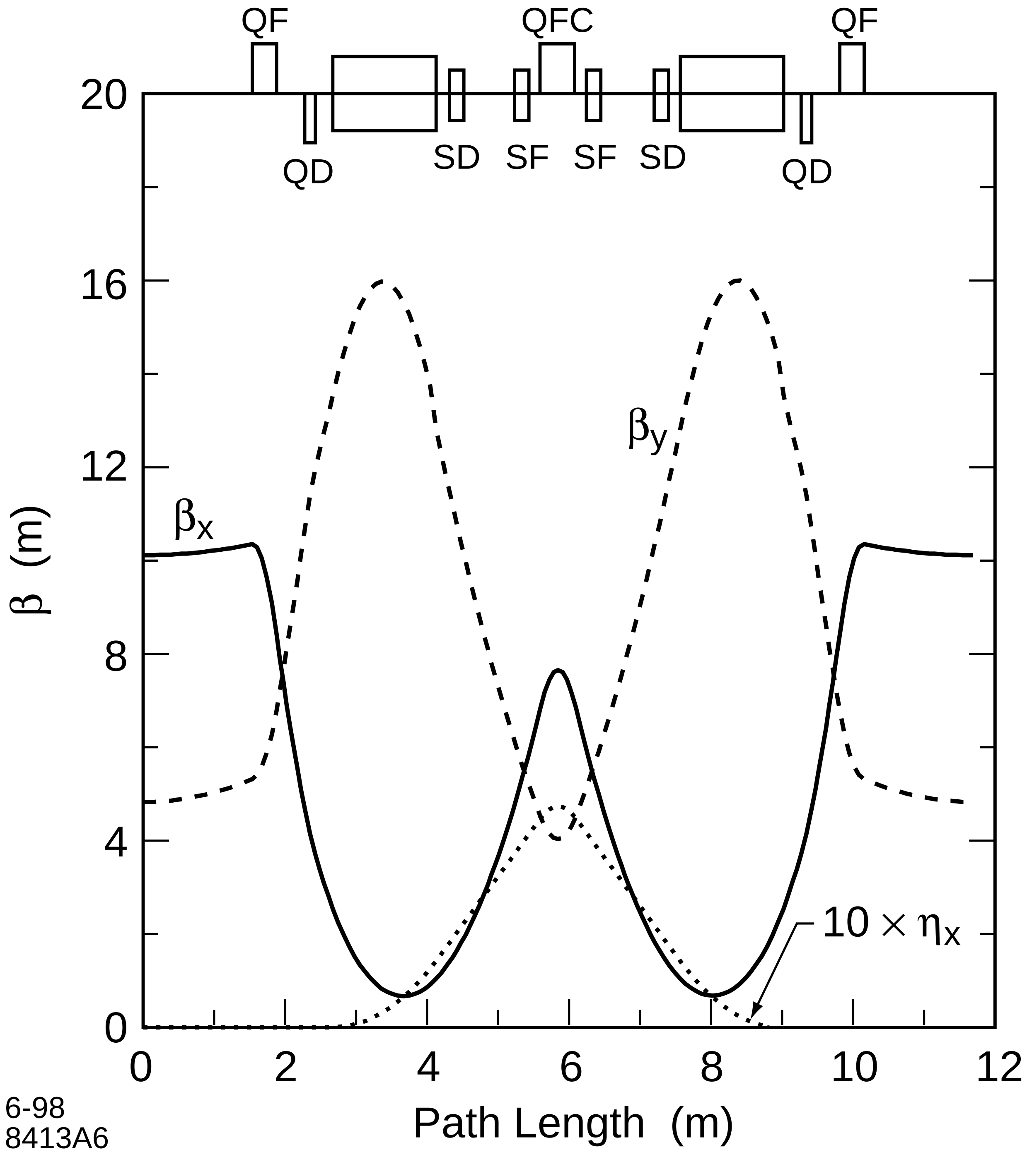

Figure 4.1: SPEAR 3 optical functions.

and the four 4.5-m straight sections adjacent to the matching cells allow for longer ID's in the future. Photon brightness for a future 4-m undulator would exceed 10^{18} photons/s-mr^2-mm^2-0.1$\%$ in the 1-5 keV energy range.

Operational performance of the storage ring will also be improved with on-energy injection (3 GeV), new power supplies, a beam lifetime of $\approx$30 hr at 200 mA and an aggressive beam stability program. All magnets and power supplies are rated for 3.3 GeV operation. Table 4.6 provides a list of important storage ring parameters. The ring conversion is planned to take place in FY 2002 during a 6-month shutdown period to minimize impact on the user community.

Table 4.6: SPEAR Machine Parameters.

	Spear 3	Spear 2
Energy	3 GeV	3 GeV
Circumference	234 m	234 m
Number Cells	18	18
Current	200-500 mA	100 mA
Q_x, Q_y	14.19, 5.23	7.13,5.23
Emittance	18.1 nm-rad	160 nm-rad
σ_x/σ_y at ID's	425/30 μm	2000/50 μm
Energy Spread	0.1$\%$	0.1$\%$
Bunch Length	5.7 mm	22.7 mm
Lifetime	$>$ 30 hr (200 mA)	40 hr (100 mA)

4.3.3 C and X Band Structures Tested with Beam

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X and C-Band structure development continues apace, with studies of beam-induced, beam-witnessed wakefields in the ASSET test facility on the Two-Mile Accelerator. Structures studied in December included the new "DDS3" X-Band structure and the KEK C-Band structure, and associated cavity beam position monitors. With the ASSET facility one can infer the average offset of the drive beam (e^+) in the structure based on the kicks imparted by the short-range wakefield. This kick is quite large insofar as a 1-μm drive-beam offset yields about a 1-μm witness-beam oscillation downstream. At the same time, wakefields may be directly monitored via higher-order mode (HOM) couplers. These RF signals were processed by downmixing to 310 MHz, followed by digitization to extract amplitude and phase. In this way one can use the dipole signals as a guide to center the drive beam and then observe witness-beam deflections to assess the result.

For the DDS3, results indicate that the structure is fairly straight, varying smoothly within a $\pm$ 30 μm band in y and $\pm$ 20 μm band in x, and comparison with coordinate-measuring-machine results is in progress. Attempts to center the beam by minimizing the induced dipole mode signals achieved a better than 20 μm alignment based on the resulting short-range transverse wakefield, although monopole-like components of the wakefield were also observed that need to be understood.

Following studies of DDS3, Shintake's choke-mode C-Band structure was installed. Attached to each end of this 1.8 m long structure are two RF beam-position monitors (BPMs) which sense only the vertical beam offset. Four pickups were located at the *center* of the structure, spaced at 90° in azimuth, to couple out the dipole signals, and produce an analog of vertical position, after subtraction in a hybrid tee. Thus the vertical beam position could be measured at three positions along the structure. A complete set of wakefield and HOM measurements was carried out for the C-band structure, and the three RF BPMs and phase reference cavity worked well, yielding a resolution in the range of 1 to 2 μm using the simplest method of computing the signal amplitude, limited by noise within the processor electronics. From the beam scans, and the beam-centering measurements, the alignment of the assembly was assessed, and is roughly consistent with a known kink in the structure.

In summary, a lot was learned from both the DDS3 and C-band structure measurements that can be used to improve future structure designs and the methods used to study them experimentally. The ASSET team is looking forward to measuring the CERN 15 GHz structure and "RDDS1" later this year. An up-to-date summary of other NLC developments is available in electronic form [1].

4.3.4 Dynamic Beams in the Damping Rings

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The Stanford Linear Collider (SLC) damping rings have gained reknown for the rich variety of single bunch collective effects manifested there at high current, including potential well distortion, synchronous phase shift and synchrotron frequency shift with current. One effect, the microwave instability ("saw-tooth") was baneful enough to require replacement of both DR vacuum chambers. After this revision, in 1993, and contrary to theoretical predictions, the threshold for the instability went *down* from 3×10^{10} to about 2×10^{10} particles per bunch. Fortunately, the instability in the new vacuum chambers was not as severe as in the old one, and this circumstance, and subsequent experimental investigations, have lead to some interesting observations.

The longitudinal dynamics in the new chamber have a limiting behavior, saturating at a level that permits SLC operation at currents 2-2.5 times higher than the instability threshold. One of the easiest ways to observe the instability is by looking at the BPM signal spectrum at high frequencies. Depending on the values of the stored current and the RF voltage the instability causes the appearance of either quadrupole or sextupole side-bands to the revolution harmonics. These side-bands blow up and damp on the time-scale of milliseconds, comparable to the energy damping time. A convenient way of looking at the instability involves demodulating the BPM signal from the side-bands of the high frequency revolution harmonics producing a waveform like that of Fig. 4.2

Extensive bunch-shape studies have been performed on unstable beams employing streak-camera imaged beam profiles, and RF signals as in Fig. 4.2. Correlation of these different measurements has revealed that the instability (when quadrupole) causes roughly 10% modulation in bunch length, and displacement of a few percent of the beam particles. Correlating the instability signal at extraction with the trajectory of extracted beam in the linac has shown that the instability is a significant source of the transverse beam jitter in the SLC. Although the instability does not inhibit SLC operation it does compromise the damping ring performance as an injector. Depending on the instability phase at extraction bunches have different shapes and hence different transport properties.

Theoretical understanding of the instability is not complete; however, numerical simulations with the calculated wake function serve to explain some of the basic features, such as threshold value and frequency dependence on current. These simulations are based on the either the linearized Vlasov equation or direct particle tracking. The most interesting nonlinear features, like the characteristic "breathing" behavior seen in Fig. 4.2 have yet to be explained. Theoretical and simulation studies continue.

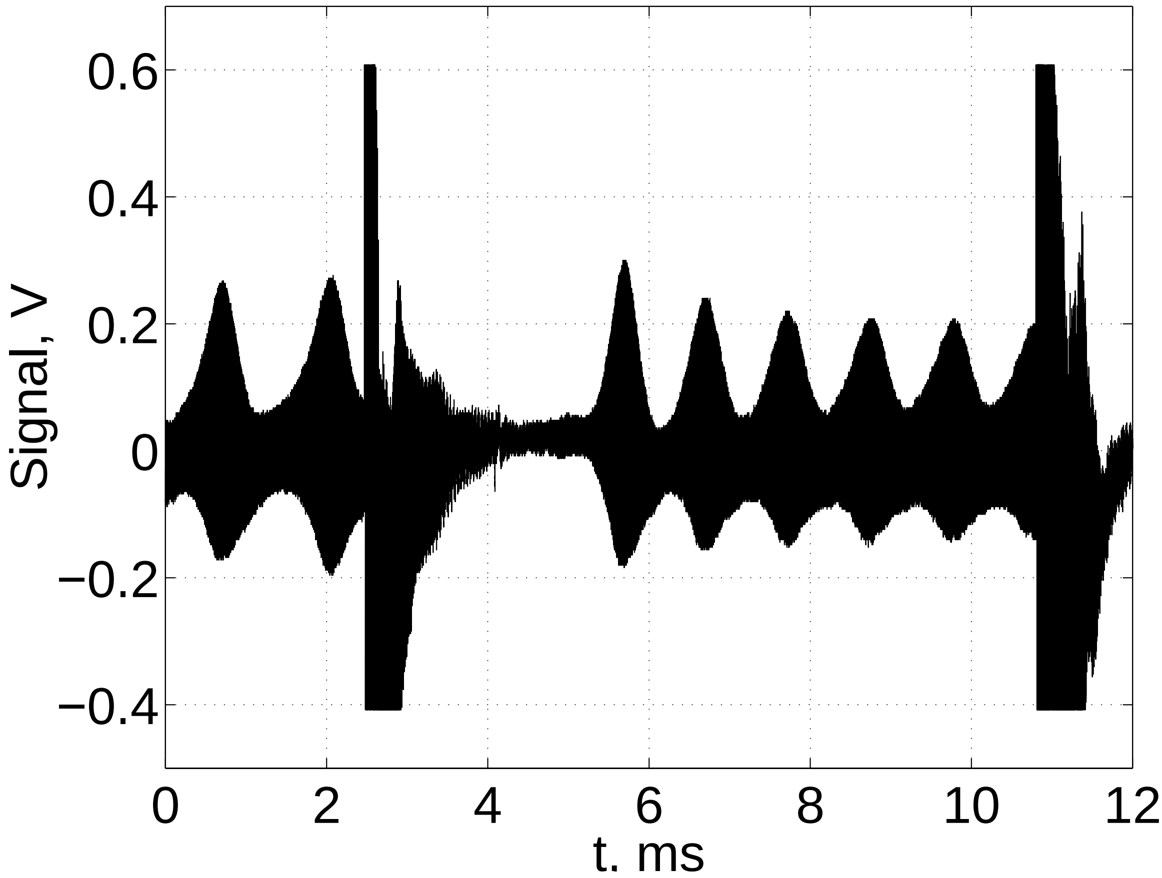

Figure 4.2: Demodulated side-band signal versus time. The SLC injection cycle starts at t=2.5 ms. Initially there are transients associated with injection. By the time t=4 ms the beam has damped to a quasi-equilibrium state, however it does not stay there for long. A quadrupole mode ($f \leq 2f_s$) blows up on the beam and then it saturates and damps down. The process repeats with a period of about 1 ms until the extraction at t=11 ms.

4.3.5 How Long Was That Beam at the IP?

For some years, researchers have been interested to monitor the lengths of SLC bunches in collision, for purposes of luminosity tuning. Theoretical predictions were that luminosity could be enhanced by a factor of *two*, provided the bunch length was sufficiently long to permit the colliding beams to pinch, and not so long as to cause them to suffer from the hourglass effect. For the terawatt peak-power beams of the SLC, a non-destructive technique was required, and this suggested a gap-coupled bunch length monitor (BLM) as employed on the SLC main linac. The linac monitors however do not provide direct information on the bunch lengths in collision, due to bunch length variation in the 1.2-km long collider arcs. Previous attempts to commission a monitor after the arcs, in the final focus complex, were not successful due to the presence of large noise in the detected signals, since attributed to the technique employed, situating a crystal detector and video amplifier in the accelerator housing, where they are subject to ionizing radiation, and pulsed noise coincident with the beam transit. During the last SLD run, bunch-length and beam-timing monitors were commissioned by Frank Zimmermann, Jerry Yocky and colleagues [2].

The primary hardware work involved installation of 150′ of WR90 waveguide from the Compton polarimeter laser housing (“the laser shack”), through a ventilation shaft underground to the south final focus beamline. The broadband microwave signal was filtered into channels, and power levels were monitored from shot-to-shot, for both beams, using crystal detectors, with outputs to a gated ADC. The gap-based BLM employs coherent radiation by a transient current waveform passing through a gap in conducting pipe. A sampling of the radiated power spectrum, normalized by squared beam-charge, correlates with the bunch length. Roughly half of the radiated energy is at wavelengths shorter than $\lambda \approx 4\pi\sigma_z$. At longer wavelengths sensitivity to σ_z is reduced and at shorter wavelengths the signal level is reduced.

After commissioning the system, it was realized that beam-timing in collision could be monitored as well, and the set-up for this is seen in Fig. 4.3. This beam timing monitor is essentially a single-shot microwave interferometer, with resolution at the level of 5° at 11.4 GHz. The X-Band filter employed was an old, disused CLIC accelerator prototype, one more link in the strong collaborative ties between the two labs. Total equipment cost was less than that for a Matlab installation diskette.

4.3.6 MIA: An Acronym Redefined

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Novel data analysis methods have been developed to study beam dynamics in linacs and rings. The methods do not rely on any particular machine model, and therefore are referred to as *Model Independent Analysis* (MIA). There are two major parts in MIA. One is noise reduction and degrees-of-freedom analysis using a singular value decomposition of a BPM-reading matrix. The other is a physical base decomposition of the BPM-reading matrix based on the time structure of pulse-by-pulse beam and/or machine parameters. The combination of these two methods allows one to break the pulse-by-pulse resolution limit set by individual BPMs and observe beam dynamics at more accurate levels. A physical base decomposition is particularly useful for understanding various beam dynamics issues. MIA is a statistical analysis of BPM readings which can be collected non-invasively during normal machine operation, and can lead to better understanding and control of beams [3].

Figure 4.4 shows the results of a test experiment, in which the transverse wakefield effect of a local corrector bump was measured via MIA. The wake signal is no larger than the 10 μm BPM

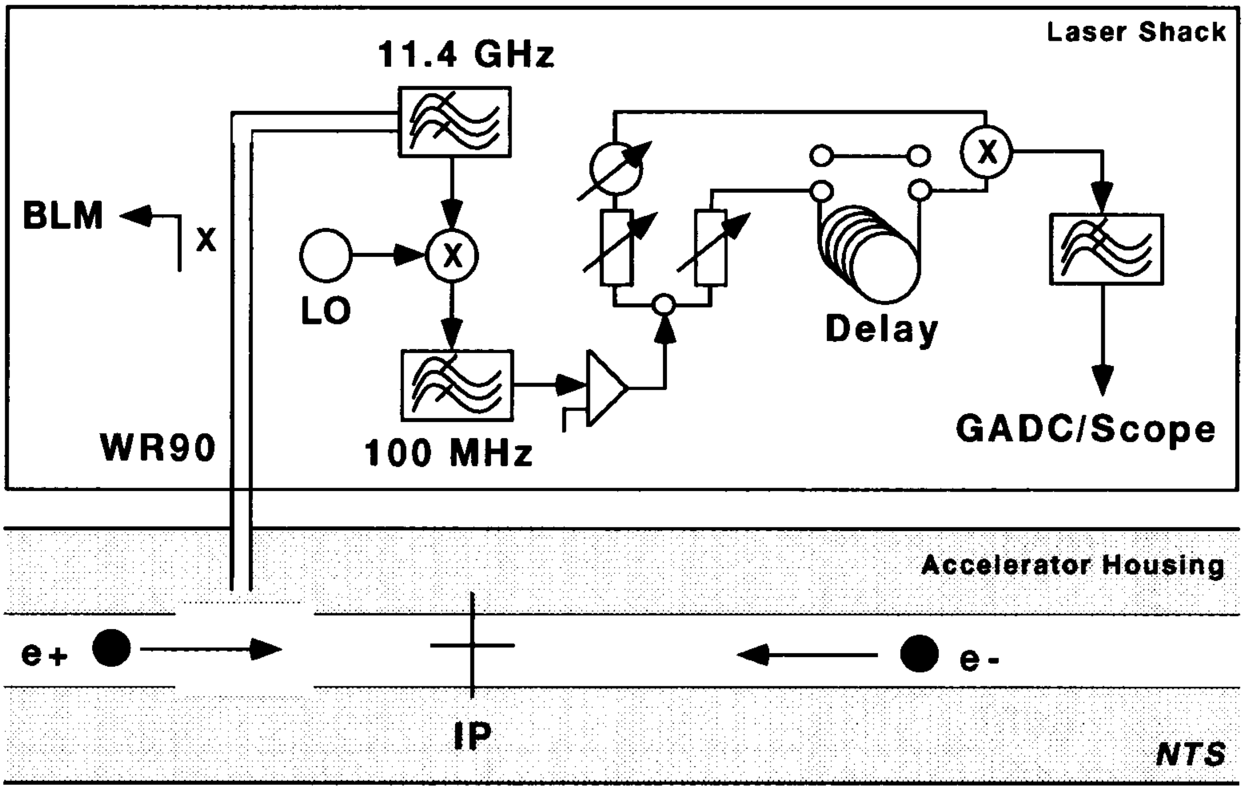

Figure 4.3: Set-up for pulse-to-pulse monitoring of beam timing and bunch-length in collision.

resolution and 2 order of magnitudes weaker than the averaged-orbit change, yet the measurement result compares well with the theoretical prediction.

4.3.7 Beam Delivery In Less Than 20 km?

In recent months, Rainer Pitthan, Frank Zimmermann, and colleagues have initiated investigations of advanced beam-delivery concepts for future colliders [7]. A critical problem for the multi-TeV collider is that the length of the beam delivery section scales quadratically with energy, easily exceeding the length of the linac. This unfavorable scaling is due to the need to correct chromatic aberrations at the IP, and the requirement that collimators survive the impact of a bunch train, as seen in Fig. 4.5.

For collimation, effort concentrates on use of non-linear magnetic elements, and non-linear dynamics to remove halo particles in the linac. The scheme presently being studied makes use of octupoles distributed through a FODO lattice, and is described in the next section. Other concepts include laser or liquid-metal collimation.

To reduce the length required for chromatic correction, several approaches are being pursued. Irwin contemplates use of beam-based focusing, and this, like the plasma lens concept, relies on generating only a small chromaticity at the outset. A different approach is to reduce the correlated energy spread in the linac, either by bunch shaping, or by harmonic acceleration. Pitthan and Zimmermann are presently continuing their quest for collimation and compactified beam delivery at CERN. Following is an overview of the octupole concepts.

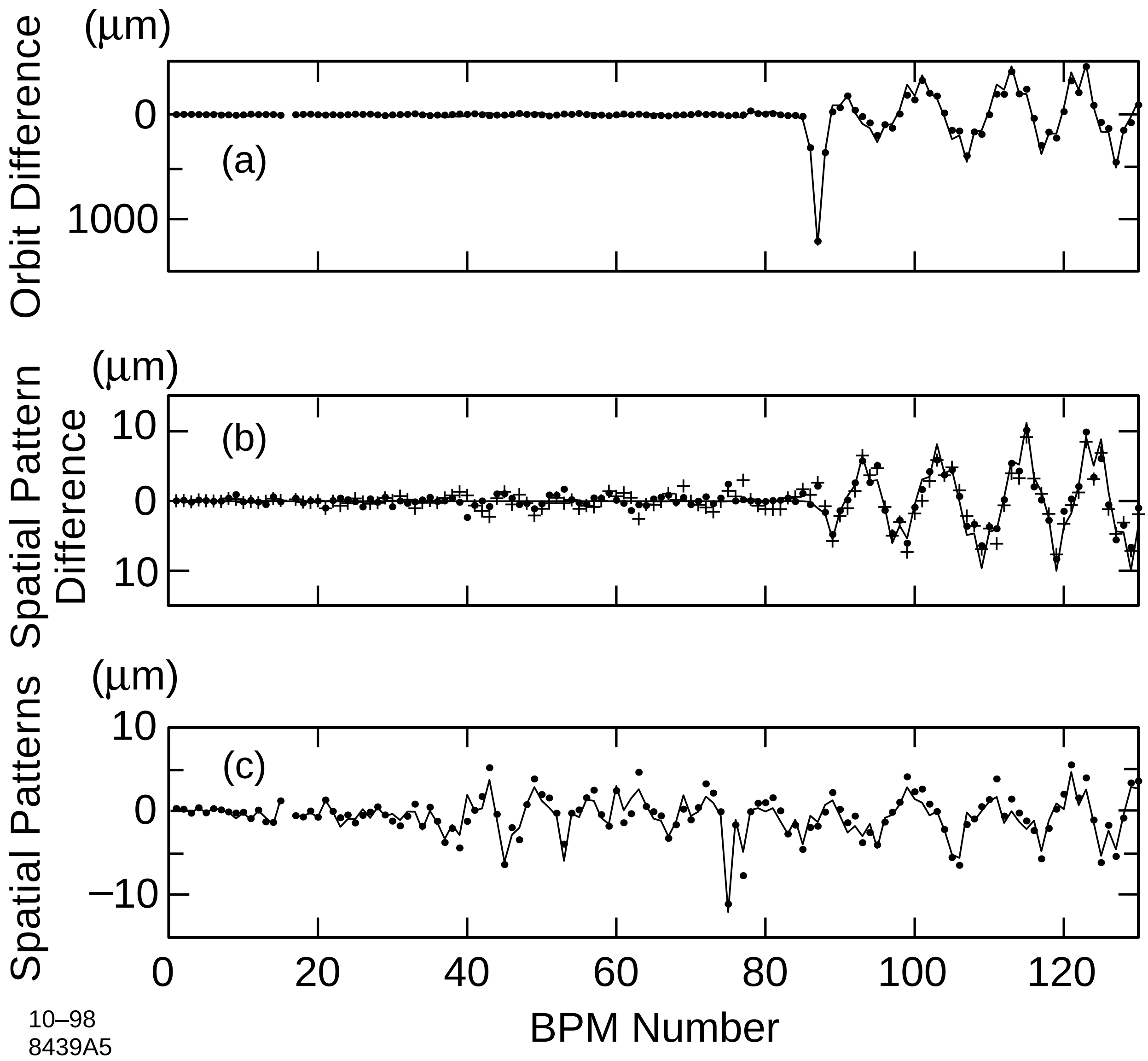

Figure 4.4: Transverse wakefield effect measurement in vertical plane for the SLC. In (a) one sees the average orbit difference with and without a bump introduced on the particle trajectory. Plot (b) reveals the difference between the spatial patterns from current jittering with and without the bump. Plot (c) shows the spatial patterns under nominal conditions.

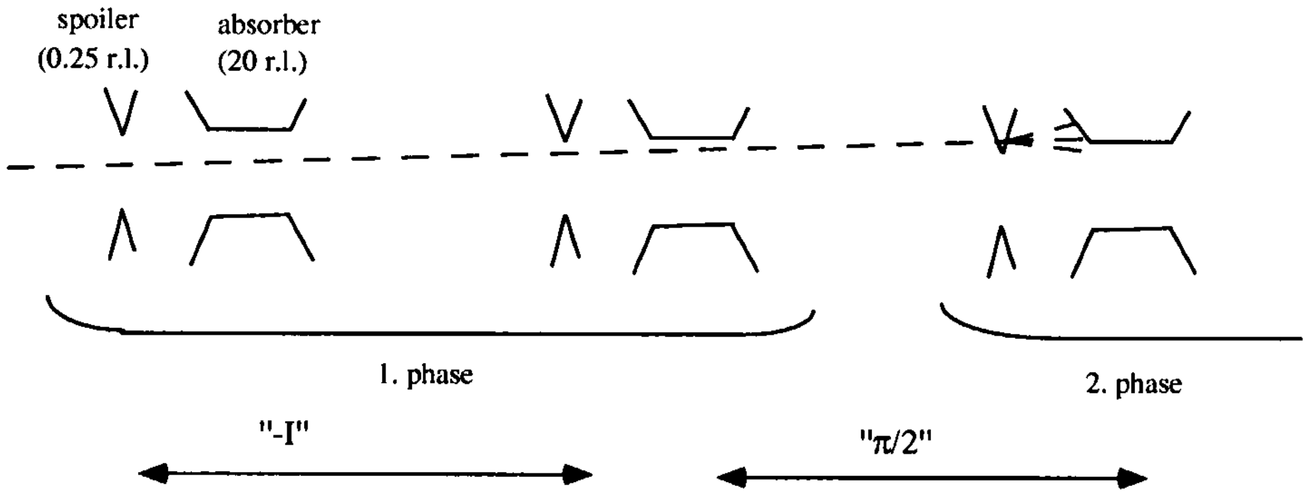

Figure 4.5: (*Pitthan and Zimmermann*) Schematic of a conventional collimation system, consisting of a series of spoilers and absorbers that collimate in two planes and two lattice phase advances. The size of the spoilers and absorbers is approximately 1/4 and 20 radiation lengths (r.l.), respectively. A beam coming from the left hits first a spoiler, where its size is enlarged, before it interacts with an absorber. Cost of this scheme at 5 TeV? 20 km.

4.3.8 Octupoles for Background Control

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Applications of octupoles for background control fall into three different categories: linac collimation, post-linac collimation, and final focus optics.

For linac collimation, the proposed lattice uses one octupole for each quadrupole in the existing standard linac FODO lattices. The octupolar kicks are applied repetitively at the points where the betatron functions in the FODO lattice are at their normal maximum. Beam halo is resonantly “spoiled” This approach makes parasitic use of real estate already needed for acceleration, and does not require enlarging the size of the beam core, nor mechanical collimators very close to the beam. The collimation depth depends mainly on the strength of the octupole fields. Since these fields are close to zero within several σ around the beam axis, perturbation to the beam core is small. The maximum pole tip fields for the systems along the linacs are modest, in the 3-4 kG range, for an octupole similar in dimension to the quadrupoles. This lattice will accomplish the following:

- removal of the bulk of the tail at low energies in the linac front-end
- 100% tail removal outside a tunable removal depth
- have a 1:100 reduction of particles within the collimation depth
- tail removal distributed longitudinally over a great length of the FODO lattice, thereby reducing or eliminating heat load and radiation damage
- permit round copper pipes as collimators, with inner diameter of 6-8 mm —a factor of 5 wider than the baseline design—thereby reducing damage risk and engineering cost, and eliminating wakefield problems
- removes errant beams with betatron oscillations of 5-15 σ amplitude, by means of adiabatic blow-up, without damage to collimators or machine components

This lattice does require a 20% change in the spacing of the FODO lattices of the pre-linac, but much less of change in the main linacs. The new elements have an aperture comparable to the quadrupoles proposed for the linacs, and alignment tolerance of 100's of microns. Because of the high misalignment tolerance, remote adjustment mechanisms (stepper motors) are not needed. From an engineering point of view two basic designs compete: electromagnetic magnets or permanent magnets. The advantage of an electromagnet design is easy tunability of the octupole strength to minimize background. The advantage of the permanent magnet design is cost, in the omission of water and power supply hook-ups.

The post-linac collimation section would follow the same basic concept of a combination of quadrupole FODO lattice with octupoles. But here the real estate is precious and not parasitic, therefore, octupoles should be built to the maximum strength and length possible.

Nonlinear elements would also serve in the final focus to further reduce the number of tail-particles hitting the final focus doublet and masks, and to reduce the synchrotron radiation impact produced by particles in the tails. Nonlinear elements are proposed to fold in those tails. Because of the very stringent chromatic requirements in this part of the machine one might be forced to go to higher order than octupoles to protect the core of the beam from chromatic aberrations.

4.3.9 BPM's No Bar to A_{LR}

The *E-158* collaboration proposes to employ Møller scattering of a polarized electron beam on the atomic electrons of an unpolarized liquid hydrogen target, in SLAC's End Station A, to measure the left-right asymmetry, A_{LR}, at low center-of-mass frame squared transverse momentum, $Q^2 \approx 10^{-2}\ GeV^2$ [4]. The motivation for this is that the cross-sections may be calculated very precisely in the Standard Model, and thus a precision measurement of the asymmetry may be employed to accurately discern deviations from the Standard Model. The left-right asymmetry will be inferred from the difference over many pulses between calorimeter readouts for alternate polarizations.

An essential aspect of the E-158 experiment is monitoring of beam position at the level of 1μm in the presence of beam orbit motion at the level of $\pm 500\mu$m. These figures were sufficiently far from the "real-axis" that it was judged necessary to require a demonstration experiment, before permitting E-158 to proceed. Faced with choices ranging over four existing kinds of S-Band cavity BPM, an infinity of possible *new-fangled* designs, and no demonstrated system adequate to the task, Princeton's Krishna Kumar, Caltech's Yury Kolomensky and colleagues elected to employ the 0.8-in aperture "linac-style", single-output cavity monitors. They settled on a new scheme for RF signal processing employing homodyne detection based on S-Band IQ mixers, with output to 16-bit ADC's. Common-mode rejection was aided by 3-stub tuners, and arduous bench-work by Caltech undergraduate Klejda Bega. One BPM station includes three cavities, an x-cavity, a y-cavity and a phase-cavity. In-situ tuning adjustment at temperature and under vacuum was required, aided by vector network analyzer. Three such triplets were tested in December and January on girder 2A of Sector 2 ("ASSET"), employing a mechanical layout and installation overseen by Caltech undegraduate Jason Turner.

Persevering through December's 28°F temperatures in the klystron gallery, Kolomensky and colleagues demonstrated sub-μm residuals in fits of the three cavity readouts, with dynamic range on the order of 500 μm. Best residuals are rumored to be much lower, but only future publications will tell the whole story. Resolution was aided by Yury's occasional short jogs up and down the aisleway to thaw out the software.

4.3.10 Plasma: Coming Soon to the FFTB

Two experiments involving the propagation of 28.5 GeV electron beam in plasma, *E-150* [5] and *E-157* [6], have completed preliminary check-outs with beam as of February, and are nearing dedicated beam-time on the final focus test beam facility (FFTB). These efforts represent a new and unusual collaboration between the university-based plasma experimentalists, and SLAC accelerator physicists. The experiments are led by post-docs, supported by the Accelerator Research Departments. While in recent years, plasmas have produced 100 GV/m gradients over a mm-scale, and beam demagnification by factors of a few, these experiments are the first to aim for operation with a high-energy beam, with extensible gradients, integrating to 1 GeV, and beam-optical characterization under collider-like conditions. In addition, E-150 may be able to access the current-neutralization regime, proposed long ago for compensation of beamstrahlung.

To appreciate the challenges of these experiments, note that the optical effect of the plasma is transient, varying at the 100% level along the short 0.6-1.0 mm bunch, and that lens strength and voltage gradient are sensitive to charge, bunch length, and other aspects of the beam distribution. Meanwhile, the SLC beam is subject to orbit jitter, head-tail jitter, and longer time scale transients. These are experiments where streak-camera based, pulse-to-pulse diagnosis will be critical in assessing the results. During the most recent parasitic runs, in February, Cherenkov and optical transition radiation signals needed for streak-camera work were checked out by Palma Catravas, Mark Hogan, Patrick Muggli, and colleagues, with Rick Iverson and OPS delivering beam.

4.3.11 Small Accelerators Get Beam-Time Too

Electromagnetic accelerators of mm-scale are of interest for the low peak power required at a prescribed gradient, and the more favorable scaling for pulsed-heating at higher gradients. Whereas an S-Band (2-4 GHz) accelerator requires on the order of 50 MW to produce a 20 MeV/m gradient, at W-Band (75 -110 GHz) the peak power requirement is under 100 kW. As a practical matter one is interested to fabricate structures, and test them at high-power, and the first experimental studies along these lines have been completed as of January. A Harvard graduate student, Marc Hill, performing his thesis work at SLAC, has tested the first mm-wave cavity at power levels of 1 kW, at the Next Linear Collider Test Accelerator (NLCTA). The 11.424 GHz, 0.5 A, 300 MeV NLCTA beam drives the mm-wave structure, resonant at $8\times$ higher frequency, 91.392 GHz into steady-state early in the 100 ns beam-pulse, and provides a flat, phase-stable shunt-impedance limited power output of about 1 kW.

For this work it was essential to develop a a vacuum window in WR10, with VSWR$\leq$1.1. This was accomplished with a 1-λ alumina ceramic window. The small structure aperture of 700 μm, and the nominal normalized emittance 10^{-4} m-rad, required β functions on the order of 0.2 m. This led to the addition of one quad just upstream of the tank, and revision of the downstream lattice to maintain reasonable optics at the spectrometer. The result was reliable current transmission through an exquisitely small beam port, and a working W-Band power source and mm-wave diagnostics system.

By run's end in January, Hill's quest for high-power mm-waves had galvanized a large collaboration of physicists and engineers from the Klystron and Accelerator Research Departments. The cavity was modified from a W-Band klystron output structure fabricated by Randy Fowkes. The window was developed in collaboration with Rich Callin and his expert rf window crew. Rich Atkinson and his precision assembly team undertook the mechanical and installation work required. Peter Tenenbaum explored the optics setup and commissioning was aided by the experienced NLCTA team of Chris Adolphsen, Bill Baumgartner, Ted Lavine, Chris Nantista, Tim Slaton and colleagues.

The result of this prodigious effort is a facility for high-power mm-wave studies, integrated into the X-Band test linac at SLAC. This year one can look forward to tests of more sophisticated demountable mm-wave structures, couplers, loads, and, above all, miniature accelerators. The next component to test is a high-shunt impedance travelling-wave structure, employing recirculation from the output to the input. With recirculation, and a structure 1″ in length, it is theoretically possible to attain MW power levels. For this purpose Hill has developed a squeeze-type phase-shifter in WR10, along the lines of a design proposed by Mike Seidel (now at DESY). Insertion loss below 1 dB, and linear phase-shift have been confirmed using ARB's home-built mm-wave vector network analyzer [8].

In parallel with this effort, Dennis T. Palmer has been developing multi-cell travelling wave structures at W-Band. Eddie Lin has been developing diamond coating for pulsed heat reduction, and planar dielectric structures. Alumina ceramic and diamond prototypes are being assembled for tests with beam. Instrumentation is also essential to the mm-wave concepts, and Harvard undergraduate Jennifer Burney has developed a wire-scanner for integration into the mm-wave accelerator assembly. Development of planar dipole and quadrupole cavities, scaled to X-Band, is being pursued in collaboration with Jin-Soo Kim, Jesse Goldberg, Bill Spence and other colleagues in the private sector.

4.3.12 Have Gun Design, Will Travel

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In related developments, a small but international crew is developing a photocathode rf gun that will operate at 91.392 GHz. In collaboration with Massimo Ferrario and Luca Serafini from INFN Milano, Mark Hogan and yours truly are developing an electron source based on the 1.6 cell rf photoinjector of the BNL/SLAC/UCLA collaboration. This will be an emittance-compensated photoinjector with modifications based on wire-EDM manufacturing techniques. Wire-EDM has been used on the constant impedance W-band traveling wave accelerating structures being developed at SLAC. The rf design is fully dipole symmetric and utilizes a race track full and half cell to minimize the quadrupole rf contributions.

The multi-cell W-band photoinjector does not require a mode-locked laser system. This eliminates the stability requirements at W-band, as the laser pulse is allowed to be many rf periods long. In principle, the photoinjector can then be considered as a thermionic rf gun. But instead of using an alpha magnet to compress the electron bunch, it is proposed to use long pulse laser system and a pair of wigglers to produce a low emittance, high current, ultra-short electron bunch for beam dynamics experiments at W-Band. Avoidance of the alpha-magnet eliminates the detrimental effect of longitudinal phase space mixing on the transverse phase space.

Simulation studies have begun utilizing a new beam dynamics code HOMDYN developed by at INFN Milano. Excellent agreement has been found between HOMDYN and PARMELA when used to simulate the 1.6-cell S-band photoinjector.

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4.4 Beam Dynamics Activities at LAL/Orsay

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Together with the continuing efforts in the domain of future linear colliders as described in the last activity report [1], in the last three years we shared some of our research time to tackle a few of classical but still challenging problems in storage rings and high current proton linacs. In this report we want to give a panoramic view to the critical readers of some subjects we worked on and the results obtained.

4.4.1 Electron storage rings

In an electron storage ring, the phenomena of bunch lengthening, single bunch energy spread increasing, and the threshold current for the fast single bunch transverse instability can be imagined as a locked chain, and the *key* is the relation of the bunch length increasing vs the bunch current. By introducing the concept of *collective random excitation*, we derived the bunch lengthening equation ($\mathbf{R}_z = \sigma_z/\sigma_{z0}$) [2]:

$$\mathbf{R}_z^2 = 1 + \frac{C_{PWD} I_b}{\mathbf{R}_z^{1.5}} + \frac{\mathcal{C}(R_{av} R I_b \mathcal{K}_{||,0}^{\mathrm{tot}})^2}{\gamma^7 \mathbf{R}_z^{2.42}} \tag{4.4}$$

and energy spread increasing equation ($\mathbf{R}_\varepsilon = \sigma_\varepsilon/\sigma_{\varepsilon 0}$):

$$\mathbf{R}_\varepsilon^2 = 1 + \frac{\mathcal{C}(R_{av} R I_b \mathcal{K}_{||,0}^{\mathrm{tot}})^2}{\gamma^7 \mathbf{R}_z^{2.42}} \tag{4.5}$$

where

$$\mathcal{C} = \frac{576\pi^2 \epsilon_0}{55\sqrt{3}\hbar c^3} \tag{4.6}$$

ϵ_0 is the permittivity of vacuum, $\hbar$ is Planck constant, γ is the normalized particle energy, $\mathcal{K}_{||,0}$ is the bunch total longitudinal loss factor at the natural bunch length, $I_b = eN_e c/2\pi R_{av}$, R is the local bending radius, N_e is the particle population inside the bunch, and R_{av} is the average radius of the ring. Recently, an empirical bunch lengthening equation has been proposed [3]:

$$\mathbf{R}_z^2 = 1 + \frac{\sqrt{2\mathcal{C}} R_{av} R I_b \mathcal{K}_{||,0}^{\mathrm{tot}}}{\gamma^{3.5} \mathbf{R}_z^{1.21}} + \frac{\mathcal{C}(R_{av} R I_b \mathcal{K}_{||,0}^{\mathrm{tot}})^2}{\gamma^7 \mathbf{R}_z^{2.42}} \tag{4.7}$$

and it agrees well with experimental results of INFN accumulator ring, ACO, Super-ACO, KEK-Photon Factory, SPEAR, and BEPC. It should be noted that in this equation the longitudinal loss factor, $\mathcal{K}_{||,0}^{\rm tot}$, is the only dominant factor concerning the impedance of the storage ring.

As far as the single bunch fast transverse instability is concerned, it is believed that the loss of Landau damping rather than mode coupling is the physical cause of the effect. The corresponding instability threshold current is found to be [4]:

$$I_b^{th} = \frac{F' f_s E_0}{e < \beta_{y,c} > \mathcal{K}_\perp^{tot}(\sigma_z)} \tag{4.8}$$

with

$$F' = 4\mathbf{R}_\varepsilon |\xi_{c,y}| \frac{\nu_y \sigma_{\varepsilon 0}}{\nu_s E_0} \tag{4.9}$$

where $\xi_{c,y}$ is the chromaticity, ν_y and ν_s, are the vertical and the synchrotron tunes, respectively, f_s is the synchrotron oscillation frequency, E_0 is the particle energy, $< \beta_{y,c} >$ is the average vertical beta function value in the rf cavity region, and $\mathcal{K}_\perp^{tot}(\sigma_z)$ is the transverse loss factor of the bunch over one turn. It should be noted that this threshold current is proportional to the absolute value of chromaticity which is not predicted by the transverse mode coupling theory. To open the locked chain of the three the single bunch instabilities discussed above, one should start with eq. 4.4 or 4.7, then eq. 4.5, and finally eq. 4.8.

One of the mysterious phenomena in storage ring colliders is the maximum beam-beam tune shift. Restricted to e^+e^- storage ring colliders, it is found that there exists a maximum beam-beam tune shift value which is expressed (flat beam case) [5]:

$$\xi_y \leq \xi_{y,max} = \frac{H_0}{2\pi\gamma}\sqrt{\frac{T_0}{\tau_y}} \tag{4.10}$$

where $H_0 = \frac{1}{6} \times 10^6$, γ is the particle normalized energy, T_0 is the revolution time, and τ_y is the vertical synchrotron radiation damping time. For an isomagnetic ring, eq. 4.10 can be simplified as:

$$\xi_y \leq \xi_{y,max} = H_0\sqrt{\frac{\gamma r_e}{6\pi R}} \tag{4.11}$$

where r_e is the electron classical radius, and R is the local bending radius. Obviously, the maximum beam-beam tune shift doesn't depend on the number of the interaction points. The physical ingredients for us to arrive at this theoretical explanation are the stochastic heating and the plasma pinch effects at the interaction points together with the synchrotron radiation damping effect. Taking Beijing Tau-Charm Factory parameter for example [6], one finds $\xi_{y,max} = 0.043$ with $R = 8.58$ m and $\gamma = 3914$ (2GeV).

Some other subjects, such as multibunch transverse instabilities in an electron storage ring, and analytical investigation on the dynamic apertures of circular accelerators, have been discussed in detail in refs. [7] and [8] with some interesting results, in this report, however, we will not discuss them in detail.

4.4.2 Proton storage rings

Quite different from the situation in an electron storage ring, the single bunch energy spread in an proton storage ring is due to the nonlinear longitudinal focusing force induced stochastic motions of some particles near the separatrix, and the threshold current for this stochastic motion to occur is established in ref. [9].

4.4.3 Halo formation in high current proton linacs

One of the major concerns in the design of a high current proton linac is the halo formation and the related particle loss rate along the accelerating tube. Assuming that a matched beam's transverse particle density follows Fermi-Dirac distribution, one can estimate the beam current loss rate at the beam pipe radius R_m due to the beam envelope oscillation [10]:

$$\mathcal{R}(A/m) \approx I_b f \frac{\Delta R_0^3}{\mathcal{L} R_0 R_m^2} \ln \left(\frac{1 + \exp\left(2\Delta x_{max}/\Delta R_0\right)}{\exp\left(2\Delta x_{max}/\Delta R_0\right)} \right) \tag{4.12}$$

with

$$\Delta x_{max} = \left(\frac{16 R_0^8}{9 L^2 K^2 \Delta R_0 \beta(z)^2} \right)^{1/3} \tag{4.13}$$

where L is the envelope oscillation period, $K = 2(I_b/I_0)/(\beta\gamma)^3$, γ and β are the normalized particle's energy and velocity, respectively, I_b is the bunch current, and $I_0 = 4\pi\epsilon_0\pi m_0 c^3/q$ with m_0/q being the mass charge ratio of the particle, R_0 is the matched beam radius, ΔR_0 is the envelope oscillation amplitude, $\beta(z)$ is the beta function of the focusing channel, $\mathcal{L} = L$ when $L \geq \lambda_p/4$, $\mathcal{L} = \lambda_p$ when $L \leq \lambda_p/4$, λ_p is the plasma wavelength, and f is the ratio of the average beam current to the bunch current.

4.4.4 Single bunch emittance growth in linear colliders

According to the general linear collider design principles described in ref. [11], the normalized beam emittance in the vertical plane (the normalized beam emittance in the horizontal plane is larger) at IP can be expressed as:

$$\gamma\epsilon_y = \frac{n_\gamma^4 r_e}{374 \delta_B^* \alpha^4} \tag{4.14}$$

where γ is the normalized beam energy, $r_e = 2.82 \times 10^{-15}$ m is the classical electron radius, $\alpha = 1/137$ is the fine structure constant, δ_B^* is the maximum tolerable beamstrahlung relative energy spread, and n_γ is the mean number of beamstrahlung photons per electron at IP. Taking $\delta_B^* = 0.03$ and $n_\gamma = 1$, one finds $\gamma\epsilon_y = 8.86 \times 10^{-8}$ mrad. To preserve this small transverse emittance one has to take care of the emittance growth in the main linac of the linear collider. As far as single bunch beam dynamics is concerned, one can estimate the transverse normalized emittance growth in analogy to the diffusion process in Brownian motion of a molecule. By solving either Langevin or Fokker-Planck equations one arrives at an analytical expression for the single emittance growth due to accelerating structure misalignment [12]:

$$\epsilon_{n,rms} = \frac{\sigma_y^2 l_s \overline{\beta(s)}}{2\gamma(0) G} \left(\frac{e^2 N_e W_\perp(z_c)}{m_0 c^2} \right)^2 \tag{4.15}$$

where σ_y is the r.m.s. structure misalignment error, l_s is the structure length, $\overline{\beta(s,z)}$ is the average beta function of the main linac, $\gamma(0)$ is the injection normalized energy, $\gamma(s) = \gamma(0)(1 + Gs)$, N_e is the particle population inside the bunch, $W_\perp(z)$ is the short range dipole mode wakefield, and z_c denotes the bunch center. The quadrupole and BPM misalignment errors are also considered in ref. [12].

4.4.5 Wakefields due to surface roughness

Wakefields due to surface roughness of a beam pipe is becoming a subject of concern [13] as the bunch length gets very small (for example: 30 μm for the design of LCLS at SLAC [14]). We consider first a specific type of surface roughness, viz., the beam pipe surface rectangular protrusion is cylindrically symmetric and periodic, the mechanical dimensions are protrusion length h, protrusion height δ, protrusion period D, and the pipe radius R. Based on the analytical approach in the disk-loaded structure described in ref. [15], it is found that the total longitudinal monopole mode loss factor per unit length of a bunch of σ_z can be expressed as [16]:

$$k_{//,total}(V/C/m) = \frac{h\delta^2}{8\epsilon_0\pi^{3/2}DR\sigma_z^3} \tag{4.16}$$

In reality, the pipe surface roughness is not so regular as in our specific model, to apply Eq. 4.16 to the irregular surface roughness case one should replace δ, h, D, and R in Eq. 4.16 by statistical variables, $<\delta>$, $<h>$, $<D>$, and $<R>$.

Eq. 4.16 provides us useful scaling laws. Recalling the scaling laws of the loss factors due to resistive wall and cavity with respect to the bunch length, $k_{//,resistive} \propto \sigma_z^{-3/2}$ and $k_{//,cavity} \propto \sigma_z^{-1/2}$, it appreas that the loss factor due to surface roughness scales with bunch length quite differently, *viz*, proportional to σ_z^{-3}.

4.4.6 Beam dynamics in HCS of CTF2/CLIC

To accelerate the drive beam for CTF2/CLIC, two high charge structures (HCS), working at $\frac{11}{12}\pi$ mode with operating frequencies of 2998 ± 7.8 MHz, have been designed and constructed for CERN [1] [17]. To explain the experimental results of a train of 48 bunches of norminal total charge of 650 nC accelerated by HCS, continuing efforts has been taken to simulate the single bunch and the multibunch emittance growths due to the wakefields inside the two structures [18], and possible comparisons with the experimental results will be done in the near future.

4.4.7 The CANDELA photo-injector beam dynamics studies

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Radiofrequency photo-injectors are among the most brilliant electron sources and achieve the required performances for the most demanding of applications such as e^+/e^- colliders and short wavelength free electron lasers. CANDELA is an S-band, sub-picosecond, laser-triggered photo-injector. It is capable of producing a beam with a peak current of the order of one hundred Amperes and an energy greater than 2 MeV. The original design of the accelerating cavities was aimed at minimising the transverse and longitudinal emittances [19]. Numerical simulations have been carried out in order to evaluate the gun performance for the experimental conditions, using the Orsay version of PARMELA. The main concern was to simulate the tilted photo-electron beam and the saturation of the charge extraction from the photo-cathode.

The phase-lock system between the rf and the laser has been greatly improved in order to achieve stable and reliable photo-injector operation. Typical measured beam parameters are a charge of 1 nC and an average energy of 2.3 MeV. The transverse and longitudinal properties of the beam have been measured as a function of the main parameters, namely the bunch charge and the phase between the laser and the rf. Normalized rms emittances of 10 mm.mrad, rms bunch lengths ranging from 3 to 6 ps have been measured. An entire set of experimental results has been compared with numerical simulations. The comparison exhibits a good agreement for most of the beam properties over a wide range of parameters [20].

4.4.8 Beam dynamics studies on a laser triggered electron source for pulsed radiolysis

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The Physical Chemistry Department of the CNRS at the Université de Paris-Sud and the Laboratoire de l'Accélérateur Linéaire (LAL) will collaborate on a dedicated radiolysis user facility named ELYSE [21]. The irradiation of user's samples will be performed using electron beam energies varying from 4 to 9 MeV, produced from a laser triggered rf gun. The accelerator group at LAL, benefitting from the theoretical studies [22] and the experience gained with the experimental rf gun CANDELA [23], are responsible for the design and construction of the accelerator. The nominal beam requirements for ELYSE are 1 nC pulses of 5 ps FWHM. However, there is a strong scientific interest in obtaining bunch charges of 10 nC. The need to extract such high charges necessitates the use of CsTe photocathodes which are the best up to date choice for high efficiency and long lifetime [24]. A dedicated preparation chamber for CsTe inspired from the new chamber used at CERN/CTF [24] is needed.

An essential user requirement is to keep the dark current emitted during the rf pulse of 3 microseconds below 1% of the charge of the main beam. A reasonable electric field of 65 MV/m in the rf gun, the choice of CsTe photocathodes, a dispersive dipole, and a collimating slit in the transport line are the elements which will enable us to achieve this requirement.

The accelerator beam line design is inspired from the CANDELA experiment design: an injection section with a rf gun, a solenoid and a booster, then a first triplet of quadrupoles followed by two 30 degrees dipoles with a doublet of quadrupoles in between, and a final triplet of quadrupoles. The machine layout has a symetry point in the middle of the doublet, were the collimating slits stands. The simulations of the beam transport made with PARMELA have shown that we could meet the user's requirement, moreover, a bunch length compression is possible with the help of the two dipoles.

At present, the design period of the accelerator is almost over, and the machine installation at the Université de Paris-Sud should begin in march 2000.

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4.5 New Doctral Thesis in Beam Dynmamics

4.5.1 Yoshihiro Shobuda

Author: Yoshihiro Shobuda (`shobuda@post.kek.jp`), KEK, High Energy Accelerator Research Organization and Tohoku University, Sendai 980-8578, Japan.

Institution: Tohoku University.

Title: On the Solutions of the Haissinski Equation with Some Simple Wake Functions.

Date: March 25, 1999.

Supervisor: Prof. Kohji Hirata (`hirata@soken.ac.jp`), Graduate University for Advanced Studies, Shonan Village, Hayama, Miura, Kanagawa 240-0193, Japan and KEK.

Reference Part. Accel. **62**, p.165, 1999.

Abstract: The existence and uniqueness of a solution for the Haissinski equation is not clear. There was not any successful approach to prove its existence and uniqueness. We have proven it for two examples. For a purely capacitive wake function, we have proven the existence and uniqueness rigorously.

A purely inductive wake function was the only known example of the case where a solution did not exist beyond a certain threshold. We have numerically shown that such strange property comes from the ill-defined treatment of the wake function. After introducing a physical regularization of its singularity, there always exists the solution of the Haissinski equation. The existence of a stationary solution and its stability are not the same. We have also shown that the instability exists but the threshold is higher than the previously belieced "threshold" for the existence of the stationary solution.

4.5.2 Dmitry V. Parkhomtchouk

Author: D. V. Parkhomtchouk (PARKHOMD@kekvax.kek.jp), KEK, High Energy Accelerator Research Organization.

Institution: Graduate University for Advanced Studies.

Title: Effects of Parasitic Collision Points.

Date: March 24, 1999.

Supervisor: Prof. Kohji Hirata (hirata@soken.ac.jp)

Abstract: In multibunch circular colliders with small bunch spacing we have to deal with parasitic collision points (PCPs) when the opposite bunches interact not only at the interaction point (IP). The interactions in PCPs may change the stable orbits and influence the luminosity by dynamic effects. Here we will study some of the effects which are introduced by PCPs. The subject is not well studied yet because in the usual designs the effects of PCPs are done small. But in order to increase the luminosity in future designs it may change as the currents become large, bunch spacing smaller and the separation in PCPs decreases. As will be shown here there are unusual effects under that conditions. They are of highly non-linear nature, so the study was done mainly by computer simulations.

4.5.3 Nuria Catalan Lasheras

Author: Nuria Catalan Lasheras (Nuria.Catalan.Lasheras@cern.ch) Brookhaven National Laboratory, Upton, NY 11973, USA

Institution: Department of Theoretical Physics, University of Zaragoza, Spain

Supervisor: nlagos@posta.unizar.es (Prof. Rafael Nunes-Lagos Rogla) University of Zaragoza and Bernard.Jeanneret@cern.ch (Dr. Jean-Bernard Jeanneret) CERN, Geneva, Switzerland

Title: Transverse and longitudinal collimation of the halo of protons in the Large Hadron Collider (LHC).

Date: February 1999.

Abstract: In the Large Hadron Collider (LHC), particles from the beam halo might potentially impinge on the vacuum chamber, effecting harmful transitions of the superconducting magnets ('quenches'). This can be prevented by a collimation system which confines the particle losses to special, non superconducting sections of the machine. Due to the high energy and intensity of the LHC, any removal system must attain an unprecedented efficiency. While the cleaning system can be designed and optimised on the basis of linear optics, the calculation of absolute efficiencies requires to consider true scattering in matter and multiturn tracking.

A collimation system simpler but comparable to that of the LHC was set-up in the CERN SPS ring where a 120 GeV beam of protons was put in coasting mode and made to diffuse transversely. The rates of nuclear interaction were measured in every collimator with scintillation counters and compared to the predictions of the numerical model used to compute the efficiency of the LHC collimation system.

The experiment pointed to areas for further refinement of the design model. It revealed the importance of the mode of diffusion of the halo particles and of the aperture limitations in the machine. It also confirmed the necessity of controlling the closed orbit excursions in the collimation sections as well as the need of online data acquisition of interaction rates in every collimator.

The good agreement between the data and the model at 120 GeV indicate that the high efficiency required for operation of the LHC can be reached.

4.5.4 Mei Bai

Author: (mbai@bnl.gov), 1005-3, RHIC, Brookhaven National Laboratory, Upton, NY 11973, U.S.A

Institution: Indiana University

Title: Overcoming Intrinsic Spin Resonances by Using an RF Dipole

Date: January 12, 1999.

Supervisor: Prof. S. Y. Lee (shylee@indiana.edu), Indiana University Cyclotron Facility, Indiana University, Bloomington, IN 47405, U.S.A

Abstract: Although the 5% partial Siberian snake has been demonstrated to be able to overcome the imperfection spin resonances in the AGS, it is still too weak to correct the intrinsic spin resonances in the AGS as well. To accelerate polarized protons to 25 GeV/c, the injection energy of the Relativistic Heavy Ion Collider, seven intrinsic spin resonances are encountered, i.e. $0+\nu_z$, $12+\nu_z$, $24\pm\nu_z$, $36\pm\nu_z$ and $48-\nu_z$. Four of them are strong ones: $0+\nu_z$, $12+\nu_z$ and $36\pm\nu_z$, and every one of them can partially or even fully destroy the beam polarization.

To overcome these strong intrinsic spin resonances, an RF dipole was employed in the AGS polarized proton acceleration. A strong coherent oscillation was excited by the RF dipole at each of the spin resonances. Particles in the beam core then experienced stronger focusing fields and the average effective spin resonance strength of the beam was greatly enhanced. If the driven coherent oscillation is strong enough, a full spin flip can be induced under the normal AGS acceleration rate. This has been proven in the recent AGS polarized proton acceleration experiments. Unlike other non-adiabatic beam manipulations, the coherent oscillation can be excited in an adiabatic manner by slowly turning on and off the RF dipole and beam emittance can be preserved.

The principle of the adiabatic excitation of a coherent oscillation by an RF dipole is discussed in this thesis. The experimental data of using an RF dipole to overcome intrinsic spin resonances are presented. The results of a new type of second order spin resonance observed in the AGS polarized proton acceleration experiment are also included.

5: Forthcoming Beam Dynamics Events

5.1 Workshop on Instabilities of High Intensity Hadron Beams in Rings

Thomas Roser roser@bnl.gov BNL
S.Y. Zhang syzhang@bnl.gov BNL

Brookhaven National Laboratory, from June 28 to July 1, 1999

Hadron beams with intensities exceeding present performance values are a central feature of many planned and proposed new facilities, such as SNS, ESS, JHF, NSP at JAERI, and the Muon-Collider proton driver, as well as of possible upgrades of existing facilities, such as the AGS as proton driver and CERN-PS as spallation driving facility.

This workshop will be devoted to

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

The workshop will consist of invited talks and three working groups: 1. Impedance. 2. Instability thresholds and damping. 3. Short bunches.

We are planning to publish workshop proceedings.

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

Invited Talks (as the order of presentation): A. Hofmann (Plenary), G. Rees (ISIS), R. Macek (PSR), W.T. Weng (SNS), F. Ruggiero, K.Y. Ng, B. Zotter (Plenary), T. Roser (AGS), R. Cappi (CPS), Y. Mori (JHF), T. Linnecar, S. Peggs (RHIC), C. Ankenbradt (Fermilab), V. Vaccaro*(ESS), R. Gluckstern, I. Hofmann, F. Willeke* (HERA), T. Toyama (KEKPS), R. Palmer (Muon-Collider), K. Koba, J. Norem. *: To be confirmed.

For information please contact Thomas Roser or S.Y. Zhang or visit the workshop web site: `http://www.agsrhichome.bnl.gov/AGS/Workshop99/`.

5.2 Workshop on Beam-Beam Effects in Large Hadron Colliders

Francesco Ruggiero Francesco.Ruggiero@cern.ch CERN

CERN, 12–16 April 1999

The beam-beam interaction can limit the ultimate performance of hadron colliders, since the associated tune footprint has to be accommodated in a small region of the working diagram free from high-order betatron resonances. Both the nearly head-on collisions and the parasitic encounters contribute to the footprint, and both contributions must be kept under control. To minimize the effect of parasitic encounters, the design of future large hadron colliders with many bunches includes collisions with a crossing angle and suitable separation schemes; even a few long-range collisions, however, eventually couple all circulating bunches. The study of beam-beam effects is therefore particularly important for the design and operation of such future machines and special care will be needed to avoid luminosity degradation caused by emittance growth, bunch-by-bunch orbit distortions and possible loss of stability for some coherent beam-beam modes.

This workshop will be devoted to: Review of current knowledge and past experience on the weak-strong and strong-strong beam-beam interaction in hadron colliders. Discussion of ongoing studies and planning of future research work (analytic approaches and beam-beam simulations) with special emphasis on the LHC. Discussion and planning of beam-beam machine experiments at existing and future hadron accelerators (SPS, Tevatron, HERA, RHIC, etc.).

For further information, see

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

5.3 Sixth International Workshop Beam Dynamics & Optimization

V.Stepanchuk `step.ph.sgu@oda.ssu.runnet.ru` Chair Local Organizing Committee, SSU, Saratov, Russia

BDO'99

September 6–10, 1999, Saratov State University, Saratov.

The series of the BDO Workshops is supported by Russian Foundation for Basic Research and Russian Federal Program ”Integration”. Organized by the Saratov State University, Joint Institute of Nuclear Research (Dubna), St.Petersburg State University, D.V. Efremov Institute of Electrophysical Apparatus (St.Petersburg), Peoples' Friendship University of Russia.

Chairman of Organizing Committee – D.I.Trubetskov (Russia), co-chairman - D.A. Ovsyannikov (Russia). First five workshop have been carried out with V.I.Zubov (Russia) as chairman. The objective of the Workshop is to bring together mathematicians, physicists and engineers to present and discuss recent developments in the area of mathematical control methods, modeling and optimization, theory and design of charged particle beams. The subjects to be included at this workshop include:
- nonlinear problems of beam dynamics;
- methods of control theory in the problems for the beam and plasma;
- mathematical modeling of the electro- and magnetic fields;
- computing problems for beam physics, object-oriented modeling dynamics optimization;
- software for the beam dynamics and optimization.

All correspondence should be sent to: bdo99.ph.sgu@oda.ssu.runnet.ru
The complete text First Announcement and other information you can get if your request will be sent at this address. Recently, the BDO'99 home page is being completed will be place in server SSU. Now, for more information of this workshop see home page Accelerators Laboratory SSU:

`http://www.sgu.runnet.ru/english/niimf/page.htm`

5.4 ICFA Workshop on Physic of High Brightness Beams-PRELIMINARY ANNOUNCEMENT

James B. Rosenzweig `rosen@guiness.physics.ucla.edu` UCLA

November 9-12 1999, UCLA Faculty Center

It is envisioned that the program will contain aspects of both high brightness electron, and heavy ion beam physics, in the hope that significant cross-fertilization of ideas will take place between the two communities working in these areas. It should include a wide-ranging set of issues to discuss, such as: - space-charge dominated beam dynamics; emittance compensation,
- longitudinal dynamics; pulse expansion and compression,
- non-inertial space charge and coherent synchrotron radiation,
- long range transport and halo formation,
- extreme beams, ultra high currents, or ultra-low emittances
- high brightness beam design and technology issues,
- high brightness beam diagnostics,
- computational tools.

Please look at the poster design on the preliminary web site,

`http://pbpl.physics.ucla.edu/ICFA_Workshop/`

as it will soon contain registration and other relevant information.

5.5 ν Fact'99, ECFA/ICFA Workshop on Neutrino Factories Based on Muon Accumulators

Lyon (France), 5–9 July 1999

Bruno AUTIN `Bruno.Autin@cern.ch` CERN

For information on this workshop, please see
`http://MuonStorageRings.cern.ch` (then ”Lyon workshop”)

Muon beams provide two flavours of neutrinos (ν_e and ν_μ) when they decay. This unique property combined with the precisely known spectra of the neutrinos when the muons circulate in a storage ring opens a new realm to the experiments of neutrino oscillations. In the workshop, various scenarios of neutrino factories will be discussed. In one configuration, the proton driver is a 20 MW, 352 MHz linac. Other schemes use a rapid cycling synchrotron. The pions and muons produced at the target are collected in as large an angle and momentum spread as possible. The muons are conditioned so that they can be accelerated to 20 GeV in a re-circulator and finally injected into a storage ring. In the last operation, the muon decay e-folding time is much longer than the revolution time and an accumulation process is required to have an efficient production of neutrinos. The technical challenges of the machine concern the proton intensity, the target technology, the capture methods, the fast acceleration and the accumulation into the final ring.

6: *Announcements of the beam Dynamics Panel*

6.1 ICFA Beam Dynamics Mini Workshop

The 7th ICFA Mini-Workshop on
High Intensity High Brightness Hadron Beams
Fermilab, September 13-15, 1999

The topics to be covered include beam halo creation, control and measurements, nonlinear phenomena, beam loss causes; experience at AGS, Fermilab, CERN and KEK machines, studies for ESS, SNS, NSP, APT, JHF, Proton Driver, LHC and RHIC projects; tolerable beam loss rate with respect to machine component activation and lifetime, and impact on the environment (prompt and residual radiation); beam collimation possibilities, constraints, experience, design studies for new projects, and use of bent crystals.

Organizing Committee:

Jose Alonso (ORNL)	Nikolai Mokhov (FNAL - co-chair)
Weiren Chou (FNAL - co-chair)	Yoshiharu Mori (KEK)
Pat Colestock (FNAL)	Thomas Roser (BNL)
Alexandr Drozhdin (FNAL)	Monica Sasse (FNAL - secretariat)
Roland Garoby (CERN)	Cynthia Sazama (FNAL - secretariat)
Yoshiro Irie (KEK)	Tom Wangler (LANL)
Bernard Jeanneret (CERN)	Chris Warsop (RAL)
Hans Ludewig (BNL)	Bill Weng (BNL)
Shinji Machida (KEK)	Hideaki Yokomizo (JAERI)
Phil Martin (FNAL)	

Further information and registration procedures can be obtained via WWW at (`http://www-ap.fnal.gov/m̃okhov/icfa99/`) or by contacting:

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Abstract deadline: 15 August 1999

6.2 ICFA Beam Dynamics Newsletter

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

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6.2.1 Aim of the Newsletter

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

6.2.2 Categories of the Articles

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

The categories of articles in the newsletter are the following:

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

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

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

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

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

   (a) Name, email address and affiliation of the author,
   (b) Name, email address and affiliation of the supervisor,
   (c) Name of the institution awarding the degree,
   (d) The title of the thesis or dissertation.
   (e) Date of award of degree. (For a while, we accept the thesis awarded within one year before the publication of the newsletter.)
   (f) A *short* abstract of the thesis is also very desirable.

8. Editorial

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

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

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

6.2.3 How to Prepare the Manuscript

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

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

where you can find the template also.

Please follow the following:

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

6.2.3.1 Regular Correspondents

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

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

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

6.2.4 Distribution

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

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

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

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

6.3 World-Wide Web

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

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

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

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

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

6.4 ICFA Beam Dynamics Panel Organization

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

Chairman K. Hirata

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

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

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

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

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

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

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

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