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Beam Dynamics Newsletter

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Contents

1: Forewords

1.1 From the Chairman of the ICFA Beam Dynamics Panel

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This newsletter is the first to be edited under the responsibility of Dr. Swapan Chattopadhyay, the newest member of the rotating editorial team. He and his colleagues have compiled a particularly interesting issue with a special section on Recirculated Linac Light Sources. This section provides a very readable introduction to this rapidly developing field that will be very useful and informative for people working in all branches of beam physics. It is a splendid example of what we try to achieve in this newsletter.

I would like to call readers' attention to the other activity reports and to the sections dealing with past and future Beam Dynamics Workshops. As usual, the complete list of workshops, including those announced in previous newsletters, can be found on the ICFA Beam Dynamics Panel home page

http://wwwslap.cern.ch/icfa/

This issue also happens to be the first one edited in Word format. It is now clear that this suits most of our contributors better than our old system using LaTeX although I suspect there may still be some LaTeX issues to come, depending on who is doing the editing. Fortunately, the typesetting requirements of typical newsletter material are straightforward (few formulas) so conversion is generally not very difficult. Still, it would certainly help the editors if contributors would keep this in mind.

1.1.1 Changes to the ICFA Beam Dynamics Panel

Prof. Luigi Palumbo, of the University of Rome and the INFN Laboratori Nazionale di Frascati (Italy), has expressed his wish to retire from the ICFA Beam Dynamics Panel. On behalf of the Panel, I would like to thank Luigi for his many contributions to our activities. Besides providing his expertise in collective effects, electromagnetic theory and other beam dynamics topics, he has been a key member of the Programme and Organizing Committees of several of our most fruitful ICFA Advanced Beam Dynamics Workshops. He deserves special appreciation for the considerable work he has put into ensuring these successes.

Prof. Dr. Ingo Hofmann, of the Gesellschaft für Schwerionenforschung mbH (GSI), Darmstadt (Germany), has also expressed his wish to retire from the Panel. On behalf of the Panel, I also thank Ingo for his many contributions to our activities. Within the Panel, he has contributed his special expertise on heavy-ion and high-intensity beams, maintaining contacts and cross-fertilisation across subject areas. He too has made numerous contributions to our workshops and newsletters.

Both Prof. Palumbo and Prof. Hofmann have been instrumental in what is arguably the most important activity within the Panel's mandate: bringing talented new researchers into our field. I am sure that their association with the activities of the Panel will continue to be very strong.

New Panel Members to replace them will be announced in due course following approval by ICFA. In keeping with our need, discussed in the last newsletter, to ensure that the Panel membership is as representative as possible of the world Beam Dynamics community, I invite anyone with suggestions that may help towards this goal to contact me directly. As far as is feasible with a panel of 17 members, we would like to ensure coverage of the main topics in beam dynamics (especially those relevant to future generations of particle accelerators) but also achieve a rough balance in terms of geography, institutions, sex, age, etc.

1.2 From the Editor

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It is my special privilege to present to you the current ICFA Beam Dynamics Newsletter upon invitation from John Jowett of CERN. This issue focuses on the special topic of Recirculated Energy Recovered Linacs as being investigated at various laboratories such as Cornell, Berkeley, Jefferson Lab, Brookhaven, etc. In addition, a few other laboratories have contributed on general synchrotron radiation and other topics. I must give a special note of thanks to Dr. Geoffrey Krafft and Dr. Yuhong Zhang of Jefferson Lab who have, working in concert with me, jointly solicited, collected and put together this outstanding issue for your benefit. As we continue the newsletter in the future, it is my sincere hope that we can continue this tradition of presenting topical material in such depth as this one. This issue is going to press as the calendar year 2001 draws to a close and so I must wish you all pleasant holidays, season's greetings and a very happy new year.

2: Advances on Recirculated Linac Light Sources

2.1 Introduction

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In this issue of the ICFA Beam Dynamics Newsletter, summaries of recent work in the field of recirculated linac light sources will be presented. This Newletter includes contributions from several of the laboratories engaged in studies on recirculated linacs as light sources, including some of those engaged in research on high average current energy recovered linacs. We begin with a quick note on terminology. The words "synchrotron light source" have come to describe any ring-shaped accelerator that produces electromagnetic radiation as a result of its operation, particularly when that radiation is in the x-ray region of the spectrum. The word "synchrotron", acting as an adjective, was the name of the type of accelerator where this radiation was first observed. The most recent generation of storage ring based light sources have photon emission characteristics that are largely determined by beam dynamical effects associated with the equilibrium between the radiation damping processes that naturally occur in a ring accelerator and the excitation of transverse betatron oscillations by quantized emission of individual photons. The beam size and emittances achieve their equilibrium values after a few radiation damping times for the ring.

The new light sources and proposals are grounded on the idea of basing an electromagnetic radiation source on a recirculated linac, a linear accelerator arranged so that the electron beam travels through the accelerating structures of the linac more than once, without the beam orbit closing on itself. The radiation can originate from insertion devices by mechanisms that are familiar at conventional synchrotron light sources. Because the drive beam comes from a recirculated linac, such sources of electromagnetic radiation will be called, in analogy to "synchrotron light source", "recirculated linac light sources". The terminology is broad enough to include many current and proposed light sources, and is narrow enough that it covers many sources that share many fundamental attributes in common.

For example, because the transit time through the recirculated linacs is much shorter than the equivalent emittance build-up time, and because there is no equilibrium as in storage rings at all, the beam properties at point of beam delivery are largely dictated by the beam properties at injection to the recirculated linac when the accelerator is properly designed. Because of recent work on photocathode sources, it is expected that the emittances in recirculated linacs can be made smaller than in storage rings at the same energy. Likewise, because the orbit does not close, one has much greater flexibility in manipulating the longitudinal phase space of the beam in a recirculated linac, in contrast to the case in electron storage rings, and much as in a standard electron linac. Therefore, it is possible to manipulate the bunch length to very small values at delivery, smaller than 100 fsec rms for light source applications. To illustrate this possibility we note that the first occurrence of sub-100 fsec bunches at beam energy greater than one GeV was in a recirculated linac, the CEBAF accelerator.

As will be seen below, by marrying a high average current source ($I_{ave}\geq 100$ mA), continuous wave superconducting accelerating cavities, and the notion of energy recovery, it may be possible to devise recirculated linac light sources with average brilliances and fluxes several orders of magnitude beyond what is presently possible with conventional storage ring sources. The increases are partly due to the smaller emittances in principle possible in a recirculated linac, and partly due to the fact that long undulators of length of order 25 m positioned on the return beamline now become a natural addition to the accelerator. Of course, short x-ray pulses will originate from the short electron pulses present from the recirculated linac.

The words “fourth generation light source” have recently come to mean a light source, driven by an electron linac, which achieves very high peak brilliance photon beams by utilizing the SASE mechanism and propagating the beam through an undulator longer than many FEL gain lengths. Many anticipated light source applications of recirculated linacs are not conventional fourth generation light sources at all, although there may be benefits in trying to recirculate a “spent” fourth generation light source beam in the future.

This special contribution of the newsletter is structured as follows. Sections 2.2-2.5 will present progress reports regarding some of the existing and proposed recirculated linac light sources. Contributions from Jefferson Lab, the Cornell/Jefferson Lab ERL collaboration, the Brookhaven PERL project, and the Berkeley short-pulse x-ray project are presented. Sections 2.6-2.9 will review some of the anticipated technology developments necessary for these projects. Charles Sinclair will discuss high average current DC photocathode electron sources, Xijie Wang will discuss plans for high average current RF photocathode electron sources, Hasan Padamsee will review the development work in the SRF cavities needed in order to support carrying the high average currents in such accelerators, and David Douglas will present some Jefferson Lab work on generic linac optics for recirculated linacs. The rest of the newsletter will consist of more standard reports from various laboratories around the world.

2.2 Jefferson Lab Work on Recirculated Linac Light Sources

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Since at least 1986, the time when the design of the CEBAF accelerator changed to a superconducting recirculated linac [1], it has been known that a primary benefit of a recirculated linac arrangement is the exceptional beam quality possible from such an accelerator at high energy. It was known internally at Jefferson Lab, and was pointed out separately by a large number of reviewers of the CEBAF project, that superior beam quality was a primary prerequisite for building free electron lasers. At a low level of effort, superconducting linac driven free electron lasers were investigated starting by comparison to the Berkeley storage ring bypass SASE XUV source that had recently been published [2]. In this proposal a storage ring bunch was directed through a SASE undulator once in a ring damping time, the ring radiation damping being used to restore the beam quality after each passage through the FEL undulator. Because the repetition rate is limited by the ring damping time, only a relatively low average power was possible. The conclusions of the initial studies were published in the 1989 PAC [3], where the energy spread growth and emittance growth from cumulative beam-breakup down the CEBAF linac was computed for 2.7 nC bunches and a variety of bunch lengths, comparable to those in the Berkeley proposal (i.e., at the 10 psec bunch length scale). Because the bunch repetition rate is not limited in the same way from the accelerator, and because the CEBAF accelerating structures had been optimized to accelerate 800 μA of beam current, it was pointed out that 3 MHz bunch repetition rate in the linac would give roughly three orders of magnitude more average power from the SASE source, up to 300 W, and acceptable beam quality. The benefits of energy recovery and the fact that energy spread requirements were the most important limiters of the bunch charge in this parameter regime were discussed. However, the electron source, a difficult part of the problem, was not discussed in any detail.

Efforts on FEL oscillator configurations at Jefferson Lab started a year or so later, and it was rapidly realized that kW level IR devices were possible. Initial ideas focused on integrating the FEL system with the existing CEBAF accelerator, which is not energy recovered [4,5]. On the other hand, even the first internal notes considering stand-alone devices incorporated energy recovery [6]. Gradually effort focused exclusively on stand-alone devices, and a whole series of proposals, submitted to different funding agencies, were prepared [7]. Energy recovery became a standard part of these proposals because the overall system efficiency was higher, because the need to develop new, higher-power RF systems was avoided, and because the beam dumping problem was considerably reduced. In 1997, the IR DEMO FEL was funded, leading to the recent achievement of greater than 2 kW CW infrared radiation from an FEL oscillator [8]. Experience with this FEL's driver accelerator, which has energy recovered the highest average current to date, has motivated much of the recent interest in high average current energy recovered linacs (ERLs).

In a recirculated linac, there is a feedback system formed between the beam and the rf cavities, which is closed, and instabilities can arise at sufficiently high currents. Instabilities can result from: a) the interaction of the beam with the fundamental accelerating mode (beam-loading instabilities) [9], b) the interaction of the beam with transverse Higher Order Modes (HOMs) (transverse Beam Breakup (BBU)) [10,11] and c) the interaction of the beam with longitudinal HOMs (longitudinal BBU) [12]. From the three types of multibunch instabilities, transverse BBU appears to be the limiting instability in recirculated, energy recovering linacs [13].

The theory and simulations of these instabilities are quite mature. However, no experimental verification of the theoretical models exists despite previous attempts [14] that took place in the injector of the CEBAF accelerator. The Jefferson Lab IR FEL has provided a unique test bed to experimentally verify a number of these effects.

The experiments that were carried out in the Jefferson Lab IR FEL included an attempt to induce the BBU instability, and measurements of the beam transfer functions in the recirculation mode. The first experiment consisted of both changing the optics of the recirculator so that larger beta functions at the cavity locations were obtained, and lowering the injection energy into the linac to 5 MeV and the final energy to 20 MeV. Under these conditions the predicted threshold was just under 5 mA. However, during the execution of the experiment, the magnified beta functions caused unacceptable beam loss that prohibited beam operations at current above 3.5 mA, and the instability was not observed.

The second experiment consisted of beam transfer function measurements in the recirculating mode. Although these measurements were performed at beam currents below the threshold current of the transverse BBU instability, they led to clear estimates of the instability threshold. Data were recorded by exciting different HOMs at several cavities, with different associated *r/Q* and *Q* values, at two energies, and several optics settings. The threshold current for each configuration was derived from nonlinear least-square fits to the data [15]. For the nominal FEL configuration the threshold was determined to be between 16 mA and 21 mA. This is to be compared with the theoretical prediction of 27 mA, obtained from the simulation code TDBBU [11] and the matrix analysis code MATBBU [16], resulting in agreement at better than 40% level.

Another potential limitation of the average current in a superconducting linac can originate in the excitation of HOMs by the high current, short bunch length beams in superconducting cavities. In addition to beam stability consequences, these HOMs could result in increased cryogenic load due to power dissipation in the cavity walls. At high currents, the amount of dissipated power can be significant. For example, for average current equal to 100 mA, bunch charge of 0.5 nC and $k_{||}$ =10 V/pC, the HOM power dissipation is approximately equal to 1 kW per cavity, in the energy recovery mode. In contrast, the maximum HOM power dissipated to date in the JLab IR FEL is approximately 6 W per cavity. The fraction of the power dissipated on the cavity walls depends on the bunch length and can potentially limit the peak and average current due to finite cryogenic capacity. According to BCS theory, the surface resistance of Nb increases $\propto f^2$; therefore the power dissipated in the cavity walls increases as the frequency of the electromagnetic radiation increases. According to an analytical model that assumes $k_{||} \propto 1/\sqrt{\sigma_z}$, ~70% of the total HOM power is in frequencies above 10 GHz for σ_z =1 psec [17]. In the TESLA project, in addition to HOM filters used to extract the HOM power in frequencies up to ~20 GHz to loads at room temperature, special absorbers are foreseen operating at 70 K and placed between cryomodules [18]. These cooled absorbers are expected to extract power in the range from a few GHz up to hundreds of GHz. The HOM power anticipated in the Cornell/JLab ERL [19] is already ~100 times higher than that of TESLA in the collider mode, and cooled absorbers are foreseen between cavities. The effect of losses in the frequency range beyond the threshold for Cooper pair breakup (about 750 GHz) in superconducting niobium has been investigated [20]. It was concluded that in a string of 9-cell cavities the temperature rise of the inner cavity surface and the resulting Q_0 drop are negligible.

Experimental measurements of the HOM power dissipation under varying beam parameters were obtained at the JLab IR FEL. The amount of HOM power transferred to the loads was measured and compared with calculations. Temperature diodes were placed on the two HOM loads of a linac cavity and temperature data were recorded for a range of values of charge per bunch at three values of the bunch repetition frequency, 18.7

MHz, 37.4 MHz and 74.85 MHz. Figure 2.2.1 displays the measured HOM power vs. charge in one of the two HOM loads per cavity, as well as least-square fits to the data constrained to a single value of the loss factor. The data are consistent with the calculated fraction of the HOM power absorbed by the loads, approximately 30% of the total power. At present no statement can be made about the amount of power dissipated in the cryogenic environment because no instrumentation was in place to measure it. Further experiments are planned to be executed in the Jefferson Lab 10 kW FEL Upgrade, designed to energy recover 10 mA average current, and in the Cornell ERL Prototype, designed to energy recover 100 mA of average current.

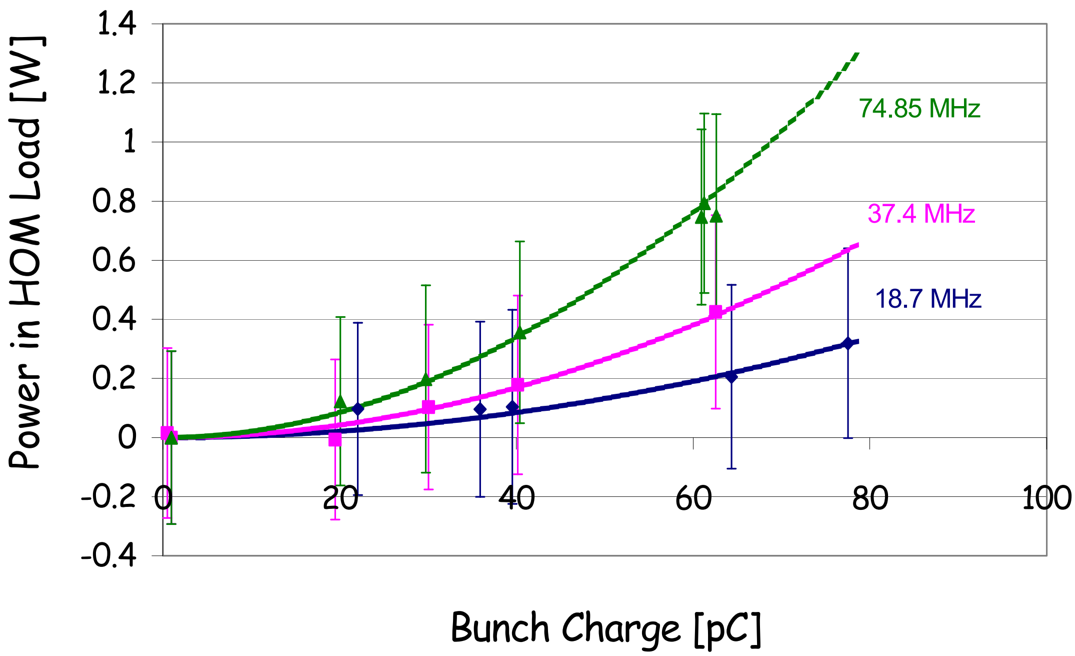

Figure 2.2.1 HOM Power Dissipated vs. Bunch Charge

Based on the present experimental and theoretical understanding of recirculating and energy recovering linacs, energy recovery of a few 100's mA appears feasible in 1300 – 1500 MHz rf cavities. This could open up new opportunities for ERL-based light sources and linac-ring designs of electron-ion colliders (EIC) that are interesting for nuclear and particle physics [21, 22]. Progress on EIC collider designs will be reported in a future issue.

Other investigations at Jefferson Lab have dealt with the question of efficiency of energy recovery. To quantify the efficiency of energy recovering linacs we have introduced the concept of "rf to beam multiplication factor" κ, defined as $\kappa \equiv P_{beam}/P_{RF}$, the ratio of the beam power at its highest energy E_f to the rf power required to accelerate the beam to E_f. For an electron beam of average current I_b, injected into the ERL at injection energy E_{inj}, and in the limit of perfect energy recovery (exact cancellation of the accelerating and decelerating beam vectors), the multiplication factor is equal to

$$\kappa \equiv \frac{P_{beam}}{P_{RF}} = \frac{JE_f}{(J-1)E_{inj} + E_f}$$

where the normalized current J is given by,

$$J = \frac{4I_b(r/Q)Q_L}{G_a},$$

Q_L is the loaded quality factor, G_a is the accelerating gradient and (r/Q) the shunt impedance per unit length of the linac rf cavities. For parameters close to the Cornell ERL [19] design: $Q_L = 2\text{x}10^7$, G_a=20 MV/m, (r/Q)=1000 Ω/m, E_{inj} = 10 MeV and E_f = 7 GeV, the multiplication factor κ is ~500 for beam currents of ~200 mA, approaching efficiencies typical of storage rings, while maintaining beam quality characteristics of linacs, namely emittance and energy spread determined by the source and the ability to have sub-picosecond short bunches.

The multiplication factor κ increases as a function of the loaded quality factor Q_L of the superconducting cavities in the ERL. The higher the Q_L, the higher the overall ERL efficiency. An important question that arises is how high can Q_L be. A high Q_L implies a narrow resonance of the superconducting cavity; therefore microphonic vibrations can cause large phase and amplitude fluctuations that need to be corrected if a certain value of the energy spread is to be maintained at the exit of the linac. Furthermore, for high gradient, high Q_L cavities, the radiation pressure during gradient turn-on can shift the resonant frequency of the cavity by several bandwidths of the cavity, resulting in operational difficulty and, under certain conditions, unstable behavior [23]. To date, no experience exists with regulation of high gradient cavities with $Q_L \sim 10^7$. Several rf control system concepts have been proposed, including the self-excited loop, the generator driven system and a hybrid of the two. Ideas for active suppression of microphonic noise and Lorentz force detuning using piezo elements are also being explored [24]. The multiplication factor also increases with the average beam current, and asymptotically approaches a value that is equal to the ratio of highest to injected beam energy, $E_f/E_{inj.}$

Other work on recirculated linac light sources at Jefferson Lab started from the desire to utilize short-pulse x-rays present in the existing CEBAF accelerator as an alternative to SASE short-pulse sources [25], and separately from the desire to utilize CEBAF as a driver for a SASE fourth generation light source [26]. Much of the work demonstrating short electron pulses had already been developed in support of the CEBAF nuclear physics program, motivated by the desire to produce low energy spread beams in that accelerator [27]. Effort was expended in designing, commissioning, and diagnosing the bunch length of the CEBAF beam. In particular, by measuring the THz (λ=500 micron) synchrotron emission from electron bunches in the CEBAF injector, electron bunches as short as 85 fsec [28,29], and routine operation at 150-200 fsec, have been obtained [27].

Because of this prior work, and because of favorable experience in transporting 5 mA beam in the Jefferson Lab FEL, a split linac arrangement was considered as a short-pulse x-ray facility. It would have a 3 GeV half ring and a 6 GeV half ring patterned on an upgraded CEBAF, with one energy recovery loop and 10 mA average current. One obtains average spectral brilliances far in excess of alternative sources, and the advantage, compared to femto-slicing methods of achieving short x-ray pulses [30], of having the whole beam radiating. In order to maximize x-ray flux and brilliance, it is clearly beneficial to increase the average current to values approaching those in storage rings, if possible.

Finally, as mentioned above, CEBAF or an energy recovered extension of CEBAF provides an ideal accelerator as a SASE driver. By comparison to normal conducting linac drivers, superconducting linacs have the twin advantages of lower transverse impedance and higher average power operation. In principle, higher single bunch instability threshold charges, and higher starting currents against multibunch BBU-type instabilities should exist. These advantages must be set off against the relatively low accelerating gradient possible in superconducting cavities. For a wide variety of applications at beam energies from 1-10 GeV beam energy, a physical plant roughly the size of the CEBAF accelerator is all that is necessary given the performance of superconducting cavities at present.

References

1. Leemann, C. W., D. R. Douglas, and G. A. Krafft, “The Continuous Electron Beam Accelerator Facility: CEBAF at the Jefferson Laboratory”, Annual Rev. of Nucl. and Part. Science, (2001) (in press)

2. J. J. Bisognano, et al., “Feasibility Study of a Storage Ring for a High-power XUV Free-electron Laser, Particle Accelerators, **18,** 223 (1986)

3. Krafft, G. A., and J. J. Bisognano, Proc. of the 1989 Part. Acc. Conf., 1256, (1989)

4. Krafft, G. A. and B. Yunn, “Parameter Lists for an FEL at CEBAF”, CEBAF TN-90-263, (1990)

5. Neil, G. R., J. J. Bisognano, D. Douglas, H. F. Dylla, G. A. Krafft, C. W. Leemann, P. Liger, D. V. Neuffer, C. K. Sinclair, B. Yunn, Nucl. Inst. and Meth., A318, 212 (1992)

6. Douglas, D. R., J. J. Bisognano, G. A. Krafft, D. V. Neuffer, and B. C. Yunn, “A Dedicated FEL Driver Design”, CEBAF TN-91-071 (1991)

7. “Free Electron Lasers For Industry, UV Demo Conceptual Design”, Laser Processing Consortium (1998)

8. Neil, G. R., C. L. Bohn, S. V. Benson, G. Biallas, D. Douglas, H. F. Dylla, R. Evans, J. Fugitt, A. Grippo, J, Gubeli, R. Hill, K. Jordan, G. A. Krafft, R. Li, L. Merminga, P. Piot, J. Preble, M. Shinn, T. Siggins, R. Walker, and B. Yunn, *Phys. Rev. Lett.*, **84**, 662 (2000)

9. L. Merminga, P. Alexeev, S. Benson, A. Bolshakov, L. Doolittle and G. Neil, “Analysis of the FEL-RF Interaction in Recirculating, Energy-Recovering Linacs with an FEL,” Nuclear Instruments and Methods A 429 58-64 (1999)

10. J. J. Bisognano and R. L. Gluckstern, “Multipass Beam Breakup in Recirculating Linacs,” Proceedings of Particle Accelerator Conference, pp. 1078-1080 (1987)

11. G. A. Krafft and J. J. Bisognano, “Two Dimensional Simulations of Multipass Beam Breakup”, Proceedings of Particle Accelerator Conference, pp. 1356-1358 (1987)

12. J. J. Bisognano and M. L. Fripp, “Requirements for Longitudinal HOM Damping in Superconducting Recirculating Linacs,” Proc. of Linac Conference, pp. 388-390 (1988)

13. L. Merminga, “RF Stability in Energy Recovering Free Electron Lasers: Theory and Experiment,” Proc. of FEL Conference 2001 to be published in NIM-A (2001)

14. N. Sereno, “Experimental Studies of Multipass Beam Breakup and Energy Recovery Using the CEBAF Injector Linac,” Ph.D. Thesis, University of Illinois (1994)

15. L. Merminga, I. Campisi, D. Douglas, G. Krafft, J. Preble and B. Yunn, “High Average Current Effects in Energy Recovering Linacs,” Proceedings of PAC Conference (2001)

16. B. C. Yunn and L. Merminga, work in progress

17. L. Merminga, G. Krafft, C. W. Leemann, R. M. Sundelin, B. C. Yunn and J. J. Bisognano, “Specifying HOM-power Extraction Efficiency in a High Average Current, Short Bunch Length SRF environment,” Proc. of XX International Linac Conference (2000)

18. A. Joestingmeier, M. Dohlus, M. Wendt and C. Cramer, “Theoretical and Practical Investigations Concerning the Design of a HOM Broadband Absorber for TESLA,” DESY TESLA-00-11 (2000)

19. I. Bazarov, S. Belomestnykh, D. Bilderback, K. Finkelstein, E. Fontes, S. Gray, S. M. Gruner, G. A. Krafft, L. Merminga, H. Padamsee, R. Helmke, Q. Shen, J. Rogers, C. Sinclair, R. Talman, and M. Tigner, "Study for a Proposed Phase I Energy Recovery Linac (ERL) Synchrotron Light Source at Cornell University", CHESS Technical Memo 01-003 and JLAB-ACT-01-04 (2001)

20. R. Brinkmann et al., “THz Wakefields and their Effect on the Superconducting Cavities in TESLA,” Proc. of 7th EPAC, Vienna (2000)

21. I. Ben-Zvi, J. Kewisch, S. Peggs and J. Murphy, “Accelerator Physics Issues in eRHIC,” NIM A 463, 94 (2001)

22. L. Merminga, G. A. Krafft and V. Lebedev, “An Energy Recovery Electron Linac on Proton Ring Collider,” Proc. of 18th HEACC Conference, Japan (2001)

23. J. R. Delayen, “Phase and Amplitude Stabilization of Superconducting Resonators,” California Institute of Technology Ph.D. Thesis (1978)

24. M. Liepe, W.D. Moeller, S.N. Simrock, “Dynamic Lorentz Force Compensation with a Fast Piezoelectric Tuner,” Proceedings of PAC Conference (2001)

25. Krafft, G. A., “Short Pulse Synchrotron Light from Jefferson Lab’s Nuclear Physics Accelerator”, Proc. of the 1999 Part. Acc. Conf., 2448 (1999)

26. Douglas, D. R., “Incoherent Thoughts about Coherent Light Sources”, JLAB-TN-98-040, 13 October 1998

27. Krafft, G. A., J.-C. Denard, R. W. Dickson, R. Kazimi, V. A. Lebedev, and M. G. Tiefenback, Proc. of the 2000 Int. LINAC Conf., 721 (2000)

28. Wang, D. X., G. A. Krafft, E. Price, P. A. Wood, D. W. Porterfield, and T. W. Crowe, *Appl. Phys. Lett.*, **70**, 529 (1997)

29. Wang, D. X., G. A. Krafft, and C. K. Sinclair, *Phys. Rev. E*, **57**, 2283 (1998)

30. Schoenlein, R. W., S. Chattopadhyay, H. H. W. Chong, T. E. Glover, P. A. Heimann, C. V. Shank, A. A. Zholents, M. S. Zolotorev, *Science*, 287, 2237 (2000)

2.3 Cornell/Jefferson Lab ERL Project

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Hasan Padamsee, Ray Helmke, Qun Shen, Joe Rogers,
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In reference [1] it is proposed that a recirculating linac light source based on closed-loop energy recovery with superconducting linacs offers significant advantages over storage ring sources, both in terms of the possible x-ray beams and, once the technology is developed, cost-effectiveness [2,3]. The basic idea behind an Energy Recovery Linac (ERL) was suggested long ago [4] and the feasibility of operating an ERL has recently been demonstrated with the highly successful infra-red free electron laser (IRFEL) at JLab [5,6]. Our long-term goal is to build a high energy (~5 - 7 GeV) recirculating linac light source at Cornell, both as a development laboratory for ERL technology and as a unique user resource. A high current, high brilliance machine can push ERL technology to new limits.

The advantages of an ERL x-ray source are best understood by first considering storage ring sources. The characteristics of the x-ray beams that may be produced by a storage ring source will always be limited by the qualities of the electron beams used to produce the synchrotron radiation. Specifically, it is desired to have

(1) Low electron beam sixth-dimensional phase space to increase the brilliance and coherence of the resultant synchrotron radiation;
(2) Very short electron bunches to enable fast time-resolved experiments;
(3) Ultra-small round beams;
(4) A radiation output which does not decay over time;
(5) Flexibility of operation to enable easy tailoring of x-ray beams to specific science applications; and
(6) An easy upgrade path as limiting components (e.g., the electron source) improves.

In an ERL machine, the electrons are not stored, constraints of beam equilibrium never become limiting, and the boundaries are different. Photoinjectors can produce bunches with emittances, sizes and lengths which are superior to the equilibrium bunches stored in storage rings. Such bunches are then accelerated to high energy via a superconducting linac (SC linac), which can preserve the salient bunch characteristics. These high energy bunches with superior quality are then passed though undulators to produce SR beams with unprecedented characteristics. For these reasons, ERL sources have recently become the focus of a number of next-generation x-ray source efforts [7-10].

Before committing to specific designs for a large and expensive machine, it is absolutely essential that accelerator and technology issues be explored on a brilliant, high current prototype machine. The reference [1] is a study for construction of the prototype, which is the first step in a two-phase project to build a high-energy ERL light source, and which will provide greater understanding of the process of energy recovery and its limitations. In this contribution we will condense and summarize the findings presented in the study. The discussion will concentrate on beam dynamics and accelerator technology aspects of the project. The full proposal document should be consulted for a more complete discussion of the expected performance of the follow on machine.

2.3.1 Accelerator Physics & Technology Issues

To achieve maximally brilliant x-ray beams, it is important that the ERL be designed so that the photoinjector emittance is as small as possible and that emittance growth during beam acceleration and transport to the undulators is minimized. Another important requirement is that the beam be stable against transverse and longitudinal multibunch instabilities, which are somewhat analogous to the multibunch instabilities that afflict storage rings at high current. It is also required that beam loss be small during beam recirculation, for both cryogenic efficiency and machine protection reasons, and that the RF beam loading from the two beam passes be efficiently compensated to minimize the RF power required. Finally, because the accelerator contains only a few passes, the longitudinal phase space of the accelerated beam can be preserved and manipulated, yielding extra degrees of freedom in design, but also extra degrees of complication. Each of these issues is treated separately and thoroughly in section 3 of [1].

In general, it is necessary to decrease the electron beam emittance as much as possible to maximize the brilliance from the undulators. Because 3rd generation storage ring sources already have very bright beams, the first requirement is to design the machine with an average beam brightness that exceeds that possible in an equivalent energy storage ring. This requirement places a severe limit on the parameter choices possible in the machine. In particular, the requirement tends to drive one to a design with low charge-per-bunch and more frequent bunches, just the opposite of the case with fourth generation sources. One would like the normalized emittance at the undulator to remain as close to the emittance generated at the injector as possible. The emittance from the injector should be minimized by space charge compensation techniques [7,11].

Assume that an injector can be designed with an average brightness better than an equivalent ring. One must then take steps to assure that the beam emittance is not degraded on acceleration and delivery to the undulators. The approach taken in the study involves:

(1) Choosing the single bunch charge low enough that typical single bunch emittance growth mechanisms (e.g. transverse single bunch beam breakup, wakes, non-inertial space charge, and coherent synchrotron radiation), do not result in much emittance growth. This is helped by the fact that superconducting accelerating cavities are being used, thereby permitting large apertures.

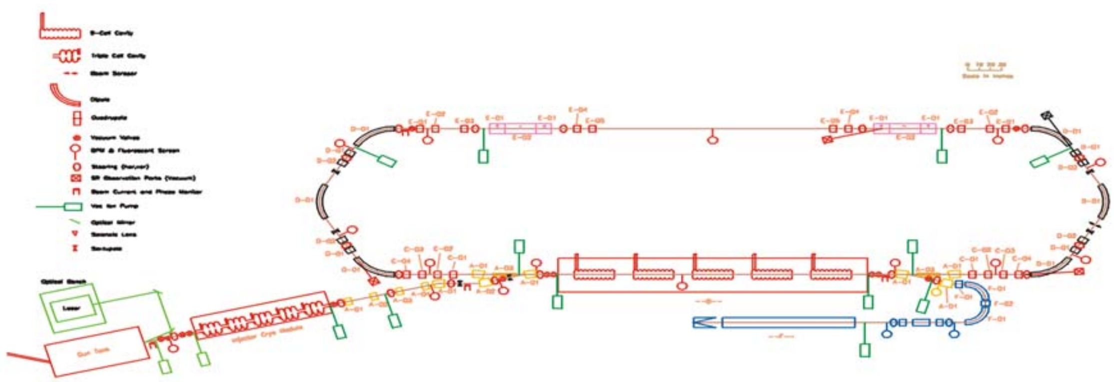
(2) Designing the beam optics such that the single particle sources of emittance growth, in particular that generated by the synchrotron emission in the turn-around arcs, are minimized. The approach is very similar to that taken in storage rings where a minimum emittance lattice design is employed (see section 3.1.5 in the proposal document).

(3) Because the beam average current in the ERL will be high, it is necessary to take care that the beam is stable against multibunch instabilities. The threshold for instability depends strongly on two design parameters, the beam optics of the recirculation loop and the properties of the High Order Modes (HOMs) of the accelerating cavities. Using linac and arc beam optics designs that keep the beta functions small (60 m and smaller) throughout the linac, we have performed simulations that show that a 5 GeV accelerator should be stable at an operating current of 100 mA, assuming the HOMs are damped as well as they have been for the TESLA test facility cavities at DESY [12].

2.3.2 Prototype Design

The prototype, as shown schematically in Fig. 2.3.1, consists of a DC photocathode gun, a superconducting capture section that accelerates the beam to 5 MeV for injection, and a main linac within the recirculation loop that takes the beam to 100 MeV. To achieve the goal of 2 μm or smaller normalized emittance in the undulators, it will be necessary to achieve 1.5 μm or less out of the injector and less than that from the gun. Thus, very good space charge emittance compensation [11] must be achieved and the effects of RF focusing, non-inertial space charge and coherent synchrotron radiation emittance dilution [13-15] must be strictly minimized. Measuring these effects and benchmarking codes will be an essential feature of the accelerator physics program of the prototype. Wake fields in the cavities and beam lines will also present a challenge to emittance preservation and are to be explored in the prototype.

The photoinjector source is at the heart of the facility since it determines the maximum achievable flux and brilliance. Various source technologies are being studied for their potential suitability for an ERL aimed ultimately at x-ray production. Initial surveys and calculations (see section 2.6) convince us that the DC, laser excited photocathode is likely to be successful. Selecting the optimum cathode material and assuring adequate operating life under high current operating conditions present significant challenges that must be surmounted early on.



Beam Energy	100 MeV	Charge per bunch	77 pC
Injection Energy	5 MeV	Emittance, norm.	2* μm
Beam current	100 mA	Shortest bunch length	100* fs

Figure 2.3.1 ERL Prototype Schematic, * values are rms

The superconducting capture section of the photoinjector will require development. The need to minimize emittance-diluting asymmetries while coupling 500 kW to the beam in a flexible way so that RF focusing and RF bunching can be accomplished without destroying space charge compensation is far more demanding than in any existing system. The ERL prototype must demonstrate robust operation of this element of the system.

The main linac posited for the ERL light source will operate at levels beyond existing technology. The economic optimum indicates that 20 MV/m or less is a desirable operating gradient. This gradient has been routinely achieved in pulsed operation with relatively small average beam currents. It must be demonstrated that the required high gradients and Q values can be obtained under the necessary CW, high current operating conditions. Not only must the higher modes be heavily damped for transverse stability but, because of the CW operation and the consequent significant power in these modes, they must be extracted from the low temperature with high efficiency. Careful measurements, using the prototype, will be needed to assure that these criteria can be met and maintained under operating conditions.

To provide sub-picosecond bunches to the undulators while avoiding the severe wake field consequences of such short bunches in the injector and linac, requires that the short bunches be obtained at the highest energy by magnetic compression. The accelerator physics and technology of effecting such compressions without undue damage to the beam properties is beyond today's state-of-the-art and will require exploration on the prototype before one can design the needed system for a full scale facility with confidence.

Measuring the beam properties with the accuracy needed in the face of the enormous circulating beam power will require non-intercepting methods that are robust and easily read out for tuning and feedback control. Optical methods analyzing incoherent and coherent synchrotron radiation originating at various stations around the loop are promising but will need demonstration in this very low normalized emittance context. Likewise, measuring halo in the presence of such high circulating beam power will be difficult. Easily repeated methods for doing so must be developed as tuning and diagnostic tools.

To summarize, we plan to prototype the source and other injector components at full scale. Demonstration of acceptable energy recovery efficiency requires a full ERL configuration. Beyond that, one must be able to probe the instability thresholds for the type of cavities planned for the final facility. This requires sufficient length of cavity that buildup of any instability can be seen. With these considerations in mind the ERL prototype will have high beam power from the injector, 100 mA CW at 5 MeV. A 100 MeV energy for the main linac of the prototype appears adequate for a good evaluation of the beam breakup. Magnetic compression and de-compression sections are a feature of the design. Achievement of 20 MV/m gradient continuously and possible periodic restoration of the gradient capability are essential results to be demonstrated in the prototype.

2.3.3 References

1. Gruner, S. M. and Tigner, M. (Eds) Bazarov, I., Belomestnykh, S., Bilderback, D., Finkelstein, K., Fontes, E., Gray, S., Gruner, S. M., Krafft, G., Merminga, L., Padamsee, H., Helmke, R., Shen, Q., Rogers, J., Sinclair, C., Talman, R., and Tigner, M. "Study for a Proposed Phase I Energy Recovery Linac (ERL) Synchrotron Light Source at Cornell University", CHESS Technical Memo 01-003 and JLAB-ACT-01-04
   http://erl.chess.cornell.edu/papers/ERL_Study.pdf, or
   http://casa.jlab.org/publications/manuscripts/casa01045.pdf

2. Bilderback, D., Bazarov, I., Finkelstein, K., Gruner, S., Krafft, G., Merminga, L., Padamsee, H., Shen, Q., Sinclair. C., Tigner, M., and Talman, R. "New energy recovery linac source of synchrotron x-rays", Synchrotron Radiation News **14**(3): 12-21.

3. Gruner, S., Bilderback, D. and Tigner, M. "Synchrotron radiation sources for the future", Sept. 2000, CHESS, Cornell University, Ithaca, NY,

http://erl.chess.cornell.edu/papers/WhitePaper_v41.pdf.

4. Tigner, M. “A Possible Apparatus for Electron Clashing-Beam Experiments”, Nuovo Cimento **37**: 1228-1231.

5. Benson, S., Biallas, G., Bohn, C., Douglas, D., Dylla, H.F., Evans, R., Fugitt, J., Hill, R., Jordan, K., Krafft, G., Legg, R., Li, R., Merminga, L., Neil, G.R., Oepts, D., Piot, P., Preble, J., Shinn, M., Siggins, T., Walker, R., Yunn, B. “First lasing of the Jefferson Lab IR Demo FEL”, Nuclear Instruments and Methods in Physics Research A, **429**: 27-32

6. Neil, G. R., Bohn, C.L., Benson, S.V., Biallas, G., Douglas, D., Dylla, H.F., Evans, R., Fugitt, J., Grippo, A., Gubeli, J., Hill, R., Jordan, K., Krafft, G. A., Li, R., Merminga, L., Piot, P., Preble, J., Shinn, M., Siggins, T., Walker, R., Yunn, B. “Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery”, Phys. Rev. Lett. **84**(4): 662.

7. Bazarov, I. V., Bilderback, D.H., Gruner, S.M., Padamsee, H.S., Talman, R., Tigner, M., Krafft, G.A., Merminga, L. and Sinclair, C. "The energy recovery linac (ERL) as a driver for x-ray producing insertion devices" 2001 PAC, Argonne Nat. Lab, Argonne, IL: (submitted).

8. Ben-Zvi, I., and Krinsky, S. “Future light sources based upon photo-injected energy recovery linacs”, Synchrotron Radiation News **14**(2): 20-24.

9. CHESS Energy Recovery Linac (ERL) Machine Workshop, Cornell Univ., Ithaca, NY, 11-12 Aug 2000 http://erl.chess.cornell.edu/papers/ERLMachineWorkshopAgenda.htm.

10. Padmore, H. A., Schoenlein, R.W., Zholents, A.A “A recirculating linac for ultrafast x-ray science”, Synchrotron Radiation News **14**(2): 26-31.

11. Carlsten, B. E. “New photoelectric injector design for the Los Alamos National Laboratory XUV FEL accelerator”, Nuc. Instr. Meth. Phys. Res. A **285**: 313-319.

12. Bazarov, I. V., Krafft, G.A., and Merminga, L. "Linac optics for energy recovery linac" 2001 PAC, Argonne Nat. Lab, Argonne, IL: (submitted).

13. Braun, H., F. Chautard, R. Corsini, T. O. Raubenheimer and P. Tenenbaum “Emittance growth during bunch compression in the CTF-II.”, Phys. Rev. Lett. **84**: 658-661.

14. Carlsten, B. E. “Calculation of the noninertial space-charge force and the coherent synchrotron radiation force for short electron bunches in circular motion using the retarded Green's function technique”, Phys. Rev. E. **54**: 838-845.

15. Rosenzweig, J., Serafini, L. "Transverse particle motion in radio-frequency linear accelerators", Phys. Rev. E **49**: 1599-1602.

2.4 Photoinjected Energy Recovery Linac Studies at BNL

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2.4.1 Introduction

BNL has made the decision to aggressively explore the technology of Photoinjected Energy Recovery Linacs (PERL) as the basis for several future projects. The RHIC II initiative, the e-RHIC initiative and the PERL Light-Source initiative are related through a common new technology - high-power, high-brightness electron beams. This technology is a merger of the technologies of high brightness photoinjectors and energy recovery linacs. We have already taken a few steps in this direction, including R&D and a few workshops and we are working on a more extensive examination of the design and scientific case.

2.4.2 Underlying Technologies

The PERL is a combination of two basic, relatively new techniques: The photoinjector (short for laser photocathode RF electron gun) and the superconducting energy recovery linac. The photoinjector is the best source for the production of high-brightness electron beams. A superconducting linac, operating in an energy recovery mode, has the potential to deliver high-current electron beams. Used in unison in a PERL machine these techniques hold the promise of high-brightness, high-average-current, short-pulse electron beams.

2.4.2.1 Photoinjector Technology

In the past decade laser-photocathode RF guns (photoinjector) have increased the brightness of linac beams by several orders of magnitude. It is recognized that electron linacs with photoinjectors can provide GeV energy electron beams with a low emittance [1] and very short pulses [2]. That is why all currently proposed X-ray Free-Electron Laser designs are based on photoinjected linacs.

The photoinjector is capable of generating a very high field on the cathode since there are no insulators to limit the electric field gradient and RF breakdown limits are many 10's of MV/m, sometimes over 120 MV/m. Thus the electron bunch is accelerated rapidly, minimizing the time spent at low velocities where space charge forces lead to emittance growth. In addition, the high field allows for a very high current emission, and the photoemission (with powerful lasers and high quantum efficiency cathodes) allow for a high current density, thus to a high beam brightness.

The PERL requires a CW operation of the photoinjector. The device that came closest to this requirement is the Boeing photoinjector [3]. The 433 MHz Boeing gun has been operated at a 25% duty factor with an average current of 135 mA during the macro pulse, driven by a 13-watt laser on the photocathode. A system at a similar frequency was designed for a high power FEL [4]. The Boeing photoinjector (or one of the other alternative designs) can be improved considerably, leading to the parameters required for the PERL operation of the photoinjector gun. Producing the relatively high currents (~200 mA) anticipated for the PERL represents one of the most challenging development areas of this source. The key issue in this case is the development of a robust photocathode design and environmental structures. Thus additional R&D work must be done on the photoinjector and its laser to achieve the average current and brightness targets for the PERL. In detailed information on various options for a photoinjector for PERL can be found in a recent workshop held at BNL [5].

2.4.2.2 Superconducting Energy Recovery Linac

The Energy Recovering Linac (ERL) was proposed initially for high-energy physics applications in 1965 [6]. In an energy recovering linac, a beam is accelerated to the energy required for the application (say 3 to 6-GeV for the generation of x-rays), and returned to the linac 180 degrees out of phase with respect to the accelerated electrons. In this way the returning high-energy electrons are decelerated, and they recycle their energy to the RF field to provide most of the power necessary to accelerate the entering electrons.

Thomas Jefferson National Accelerator Facility has recently demonstrated the efficacy of the principle, for an infrared FEL application, in producing a 5 mA average current in a 45 MeV linac with an essentially undetectable power loss in the linac [7]. The use of a non-stored-beam linear accelerator for X-ray light source applications, rather than a conventional storage ring, was proposed several years ago by scientists in the Budker Institute of Nuclear Physics in Novosibirsk [8].

The SC linac for the BNL studies is based on the TESLA type structure; a comprehensive summary on the performance of TESLA cavities can be found in reference [9]. The TESLA type cavities are very well known (from work at DESY, Stanford, industry) and they are available commercially from a number of manufacturers. The shunt impedance is R/Q=1036 Ω and the cavity length is 1.038m. We will specify the unloaded quality factor at $Q_0=1.5\text{x}10^{10}$ at a temperature of 2K and at a field of 20MV/m. At this level the refrigeration power is 26 W/cavity, thus for 3 GeV, 150 cavities require a refrigeration power of 4 kW.

2.4.3 Possible Applications of PERL Technology Under Study At BNL

2.4.3.1 Electron Cooling of RHIC

The Relativistic Heavy Ion Collider is an international flagship facility for Nuclear Physics and the major new capability in the BNL Nuclear Physics program. The first improvement cycle for RHIC is called "RHIC II". The goal of the RHIC II Initiative is a 40-fold increase in the luminosity of the machine with necessary improvements of the existing RHIC detectors [10]. Electron cooling of the ion beam currently is under consideration as the means to achieve the luminosity upgrade. A factor of 10 is conservatively achievable with electron beam cooling [11]. We have started work on this project in close collaboration with the Budker Institute of Nuclear Physics in Novosibirsk. The result is a study [12] that has shown the technical feasibility of high-energy electron cooling using a Photoinjected Energy Recovery Linac.

Cooling of the RHIC beams requires many new aspects that have not been done before in electron coolers. The first aspect is the electron energy. RHIC beams, such as 100 GeV/nucleon gold, require an electron cooler energy of about 50 MeV, well above the reach of any electrostatic machine but matching well a PERL machine. This would be the first case for cooling a bunched beam and the first case of cooling a collider beam. Another formidable problem is the cooling solenoid magnet, a 30-meter long ultra-high precision superconducting solenoid.

2.4.3.2 eRHIC

The RHIC Collider lattice is specially designed to hold a very large number of heavy ions in each bunch. Therefore, when multi-GeV electron beams are made to collide with the circulating heavy ion beam, unique experiments probing QCD in the nuclear medium at normal nuclear temperatures can be done with unparalleled luminosity. With international collaboration, BNL presently is exploring the design characteristics of a reference 10 GeV electron beam intersecting in one interaction region with 100 MeV/A gold ions, or 250 GeV polarized protons. It is feasible to achieve luminosities of 5×10^{30} $cm^{-1}s^{-1}$ for e-Au collisions, and 2×10^{32} $cm^{-1}s^{-1}$ for electron-proton. The electrons would be accelerated in a superconducting linear accelerator and intersect directly with the ion bunches. This scheme would involve complete recovery of the linac beam energy. Preliminary results of a feasibility study of an energy recovering electron linac on a proton ring collider were presented in various places [13]. Luminosities up to the 10^{33} level appear attainable and the linac-on-ring scenario presents a significant advantage with respect to spin manipulations, energy variability and synchrotron radiation power loading of the detectors as compared to a ring-ring scenario.

R&D topics that would be required before such a facility is designed and built have been identified and include:

- High current polarized electron source
- High current (~100 mA) demonstration of energy recovery
- Theoretical and, if possible, experimental investigation of the beam-beam induced head-tail instability and feedback
- Electron cooling and its ramifications on the Laslett and beam-beam tune shifts
- Development of multi-pass BBU feedback.

2.4.3.3 PERL Light Source

The National Synchrotron Light Source at BNL is studying the application of PERL technology to a future synchrotron light source with properties that are superior to storage rings based sources [14]. Electron storage rings currently provide the vast majority of the light employed in synchrotron radiation based research. One persistent boundary in these machines is the electron bunch length; no practical means has been found to allow bunches of less than a few tens of picoseconds duration to be stored. The properties of linear accelerator beams are quite different, and it has been demonstrated that using magnetic bunch compressors that electron bunches as short as 100 femtoseconds can be produced.

There are also potential brightness advantages to a PERL light source. For a ring with a Chasman-Green lattice, the horizontal emittance scales as $\varepsilon_x \sim \gamma^2/M^3$, where γ is the electron energy in units of the rest mass and M is the number of superperiods. The scaling is such that it becomes more difficult to obtain very small emittance at higher energies. In a linac, the emittance scales as $\varepsilon \sim \varepsilon_n/\gamma$, where the normalized emittance ε_n is independent of energy, and it is believed to be possible to achieve $\varepsilon_n = 1\ \pi$ mm-mrad. Therefore, linac sources may provide the best approach to achieve emittances of 0.1 nm-rad for 3-6 GeV electron energies. A PERL light source could bring the NSLS users many new insertion device beam lines, brightness greater than 3rd generation light-source's and ultra-short pulse capabilities, not possible with storage ring light sources. These characteristics are key to both current and future applications of synchrotron radiation probing of matter. Finally, one should keep in mind that a high-brightness, multi-GeV linac is a great platform for operating Free-Electron Lasers [15].

To begin to flesh out the accelerator physics issues that must be addressed to make the PERL technology useful to light sources the NSLS staff did a “strawman” design of a 3 GeV PERL light source. The machine consisted of a 3 GeV superconducting linac coupled with a return arc made up of 24 triple bend achromat cells with 5 meter straight section and one 50 m long straight section which could accommodate either an FEL or the a photon compression scheme [16]. The electron beam was assumed to have $\varepsilon_n = 0.5$ mm-mrad and a circulating current of 200 ma with 150 pC per bunch and a rep rate of 1.3 GHz. By manipulating the dispersion in the TBA cell in the returns arc, in conjunction with energy chirps in the SC linac, the electron bunches were compressed in the arcs from 400 fs to 100fs. These parameters were used to examine some of the important beam dynamics effects such as coherent synchrotron radiation and other wakefields [17,18].

The strawman is serving as a basis for an exploration of the scientific opportunities made available with the very bright beams and the sub picosecond pulse lengths.

2.4.4 References

1. M. Babzien, et. al., “Observation of Self-Amplified Spontaneous Emission in the Near-Infrared and Visible”, Phys. Rev E57 No. 5, 6093 (1998).

2. X.J. Wang, et. al. “Experimental Observation of High-Brightness Micro-Bunching in a Photocathode RF Gun”, Phys. Rev. E54 No. 4, R3121, (1996).

3. D.H. Dowell et. al., "First Operation of a Photocathode Radio Frequency Gun Injector at High Duty Factor", Appl. Phys. Lett. 63 (15), 2035 (1993).

4. A. Zholents, R. Rimmer, O. Walter, W. Wan and M. Zolotorev, "FEL Design for Power Beaming", SPIE Conference Proceedings 3614, 72 (1999).

5. Proceedings of the NSLS PERL Photocathode Gun Workshop (January 20-22, 2001), X.J. Wang, Chair, BNL-52624, http://nslsweb.nsls.bnl.gov/nsls/org/PERL/

6. M. Tigner, “A possible apparatus for clashing-beam experiments.” Nuovo Cimento 37, 1228 (1965).

7. G. R. Neil et. al., "Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery", Phys. Rev. Lett., 84 (4), 662-665 (2000).

8. D.A. Kayran, et. al., "MARS –A Project of the Diffraction Limited Fourth Generation X-ray Source", Proc. 1998 Asian Particle Accelerator Conference.

9. B. Aune et al, "Superconducting TESLA Cavities", Phys. Rev. ST Accel. Beams 3, 092001 (2000).

10. W. MacKay, I. Ben-Zvi, J.M. Brennan, M. Harrison, J. Kewisch, S. Peggs, T. Roser, D. Trbojevic, UPGRADING RHIC FOR HIGHER LUMINOSITY, Proceedings 2001 Particle Accelerator Conference, Chicago, IL. June 18-22, 2001.

11. I. Ben-Zvi, L. Ahrens, M. Brennan, M. Harrison, J. Kewisch, W. MacKay, S. Peggs, T. Roser, T. Satogata, D. Trbojevic, V. Yakimenko, I. Koop, V. Parkhomchuk, V. Reva, Y. Shatunov, A. Skrinsky, ELECTRON COOLING FOR RHIC, Proceedings, 2001 Particle Accelerator Conference, Chicago IL. June 18-22, 2001.

12. V. Parkhomchuk and I. Ben-Zvi, Electron Cooling for RHIC, BNL Collider-Accelerator Department note C-A/AP/47, 2001.

13. L. Merminga, G.A. Krafft, V.A. Lebedev and I. Ben-Zvi, An Energy Recovery Electron Linac-On-Ring Collider, Proceedings of Second Workshop on Physics with a Polarized-Electron Light-ion Collider, September 14 -16, 2000, MIT Cambridge, MA USA. To be published as AIP Conf. Proceedings. BNL 67849.

14. I. Ben-Zvi, et. al., Proceedings 2001 Particle Accelerator Conference, Chicago, IL. June 18-22, 2001.

15. L.H. Yu and J.H. Wu, private communication.

16. V. Yakimenko et al., “Optics for a Photoinjected Energy Recovery Linac at the NSLS”, Proceedings 2001 Particle Accelerator Conference, Chicago, IL. June 18-22, 2001.

17. J.B. Murphy et al., “Beam Dynamics for a Photoinjected Energy Recovery Linac at the NSLS”, Proceedings 2001 Particle Accelerator Conference, Chicago, IL. June 18-22, 2001.

18. J.H. Wu, et al., "Coherent Synchrotron Radiation Analysis for the UVFEL and Photoinjected Energy Recovery Linac Projects at the NSLS", Proceedings 2001 Particle Accelerator Conference, Chicago, IL. June 18-22, 2001

2.5 LBNL Study of an Ultrafast X-Ray Science Facility Based on a Recirculating Linac

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2.5.1 Introduction

The advent of femtosecond lasers has revolutionized many areas of science from solid state physics to biology, and while optical lasers have offered unique insights into ultra-fast dynamics, the key information often needed, the motion of nuclei, is inaccessible. This is a severe limitation in many cases, and a breakthrough in the study of ultra-fast dynamics would be made if we can directly monitor the position of nuclei with < 100 fs time resolution. This goal demands x-ray pulses with ultra-short time duration, and for typical experiments a large flux is more important than high brightness. Our proposed source has the short pulse length necessary (~60 fs FHWM) to study very fast dynamics, high flux to study weakly scattering systems, and tuneability over 1 - 10 keV photon energy. The repetition rate is determined by either the time required for the experimental sample to return to its ground state (often limited by acoustic propagation velocities), the time to translate the sample to a new area after each shot, or the repetition rate of the attendant pump laser systems. Such a facility has differing requirements from other proposed recirculating linac-based light sources [1, 2, 3].

Our proposed facility can be built on a basis of existing technologies, to produce femtosecond x-ray pulses with high flux, and repetition rate matched to the requirements of structural dynamics experiments [4]. The facility uses a recirculating linac for acceleration (and deceleration) of electrons produced by a high-brightness photocathode rf gun, at a bunch repetition rate of approximately 10 kHz. The system design produces a small vertical emittance, which is key to producing the ~60 fs x-ray pulses. After acceleration through a superconducting recirculating accelerator, the electron pulses are compressed in the final arc to ~1 ps duration. A specialized technique is then employed to produce the femtosecond x-ray pulses by first imprinting on the electron bunches a transverse momentum that is correlated to longitudinal position within the bunch [4, 5]. This action results in an emitted x-ray pulse with a time-correlated spatial and angular distribution. The correlated x-ray pulse is then compressed by use of asymmetrical crystal optics to achieve the ultimate photon pulse length. Figure 2.5.1 shows the undulator average photon flux as a function of photon energy for the fundamental and lower-order odd harmonics. Figure 2.5.2 shows the duration of the compressed x-ray pulse as a function of the photon energy.

2.5.2 Accelerator Design

A layout of the present machine concept is shown in Figure 2.5.3. It consists of an rf photo-injector, a linear pre-accelerator, a main linear accelerator, magnetic arcs and straight sections, and a photon beam production section. Electron pulses of ~10 ps duration are produced in a high-brightness rf photocathode gun and accelerated to

10 MeV. Application of a solenoidal magnetic field in the cathode region, followed by a skew-quadrupole channel, allows production of a "flat" beam with x/y emittance ratio > 50 [6,7]. The electrons are further accelerated in a 1.3 GHz superconducting linac pre-accelerator to 120 MeV, and then injected into a recirculating linear accelerator. Passing the arc connecting the pre-accelerator and the recirculating linac the electron bunches are compressed to approximately 5 ps full length. In the recirculating linac the final energy of ~2.5 GeV is achieved after four passes through the 600 MeV superconducting linac. The final arc compresses the bunches to an approximately 1 ps length, and the bunches receive a time-correlated head-tail vertical kick in a dipole-mode rf cavity. The electrons then radiate x-rays in undulators and dipole magnets. There are seven two-meter long straight sections for undulators as well as six 2 T field dipole magnets located between undulators. After passing through the photon production section, the electrons receive a compensating time-correlated head-tail vertical kick, and are stretched back to approximately 5 ps. They are transported back to and decelerated in the recirculating accelerator structure and the 110 MeV pre-accelerator to < 10 MeV and turned into a beam dump. This deceleration reduces the design challenges and radiation hazard of the beam dump. Though the electron beam does return almost all of its energy to the linac rf fields, the circulating beam power is so low that it does not contribute significantly to the overall system efficiency.

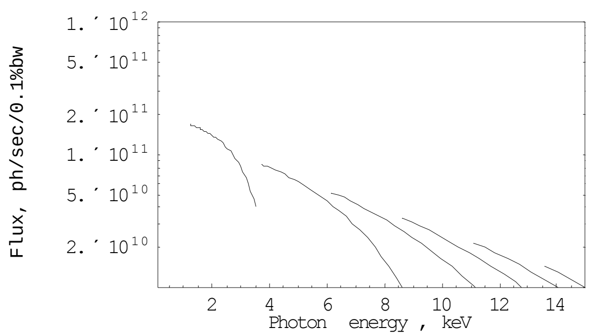

Figure 2.5.1 Undulator photon flux as a function of photon energy for the fundamental and lower-order odd harmonics.

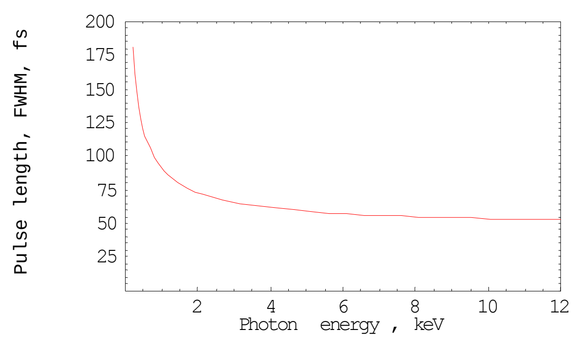

Figure 2.5.2 Duration of the compressed x-ray pulse as a function of the photon energy.

Five arcs transport the electron beam with approximate energies of 120 MeV, 720 MeV, 1.3 GeV, 1.9 GeV, and 2.5 GeV. They are designed as achromats with almost identical lattices. All arcs are comprised of three 120° betatron phase advance cells consisting of a set of bending magnets, three quadrupoles and three sextupoles. This lattice approach provides flexibility in tunability of the betatron phase advance, achromaticity including second order effects, and time-of-flight characteristics. The third cell of each arc leading to the straight section is adjusted to match the optical functions between the arc and its corresponding straight section. At present, we have designed arcs 1 through 3 to be isochronous. They are, however, easily adapted should additional electron bunch length adjustment be required at the various stages of acceleration and deceleration.

A "beam spreader" section separates the beam at various energies into their respective transport paths. Due to the proximity of beamlines of different energies, specialized magnet designs and careful layout of components are employed in this section. Apart from specialized magnets in the beam spreader section, the magnets are of conventional electromagnet design similar to those of existing synchrotron radiation sources.

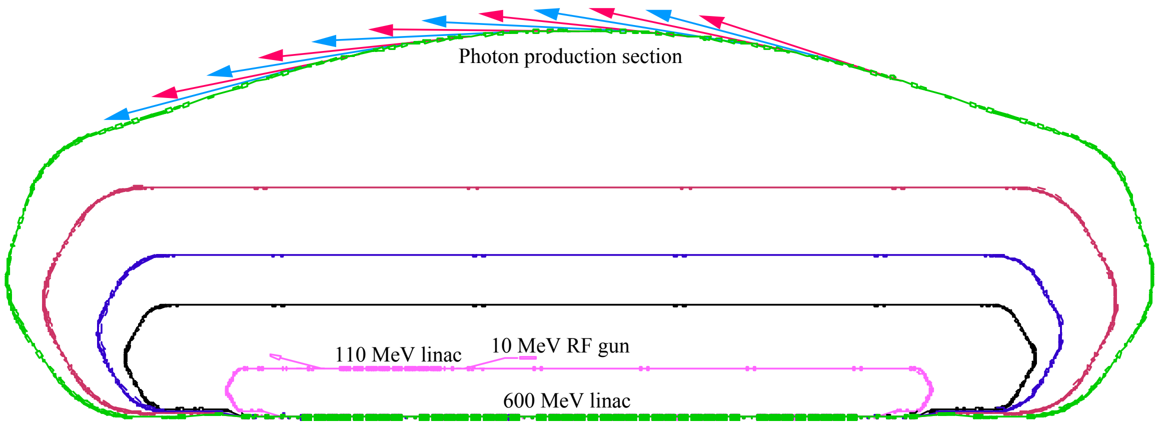

Figure 2.5.3 Recirculating linac for fs x-ray production

At the beginning and end of the photon production section, we use superconducting rf cavities operating in the first dipole mode (TM_{110}) to prepare the electron beam to allow the x-ray compression from ~1 ps to ~60 fs [5]. The first cavity provides a time dependent transverse (vertical) kick to the electron bunches that the second cavity cancels. The rf phase is adjusted so that the kick acts in opposite directions on the head and the tail of the bunches, with no perturbation to the center of the bunch. The electrons perform betatron oscillations after the kick with vertical betatron phase advance of $n\pi$ between the center of the rf cavity and the center of the *n-th* undulator. The vertical betatron phase advance is $n\pi/2$ between the center of the undulator and the center of the adjacent 2T dipole magnets. Therefore within a bending magnet the electrons in a bunch have zero angles and a transverse displacement variation along the bunch. Similarly, we find in the insertion devices that the electrons within a bunch have no transverse displacement and an angular variation along the bunch. Consequently, the photon production bend magnets are x-ray sources with a vertical position-time correlation and the insertion devices are x-ray sources with an angular-time correlation, and these correlations are exploited to compress the x-ray pulses. The design maintains the ability to vary lattice functions over a wide range to control the position and angular correlation. Major parameters of the present machine concept are presented in Table 2.5.1.

Asymmetrically cut crystals may be used as optical elements in the x-ray pulse compression scheme [5,8]. As a result of the different angles of incidence and diffraction, a crystal may be oriented to produce a variable path length across the x-ray beam, and two asymmetrically cut crystals can be used as both monochromator and pulse compressor for the x-rays.

Emittance control and understanding and mitigation of collective effects is critical to a successful machine design, and we are addressing key aspects of accelerator physics involved in beam break-up, coherent synchrotron radiation, the influence of resistive wall wakefields, and other effects. For typical misalignment errors of 0.5 mm for individual cavities and 0.25 mm for cryomodules, simulation results show that by controlling the betatron phase advance between passes through the linac, and the initial offset of the beam, the resulting projected emittance growth from cavity wakefields is only a few percent.

Table 2.5.1 Principal machine parameters

Bunch charge	1 nC
Bunch repetition rate	10 kHz
Beam energy spread at 2.5 GeV	200 keV
Bunch length in photon production section	1 ps
RF deflection cavity frequency	2.6 GHz
RF deflection cavity transverse voltage	9.2 MV
Undulator length	2 m
Field in a bend magnet radiation source	2 T
X-ray pulse length at 8 keV	60 fs FWHM
Undulator photon flux at 8 keV	$3.2\mathrm{x}10^{10}$ ph/sec/0.1%bw
Bend magnet photon flux at 8 keV	$1.1\mathrm{x}10^{9}$ ph/sec/mrad^2/0.1%bw
Bunch length at gun exit	10 ps
Bunch length at first pass through linac	5 ps
X/y normalized emittance at gun	20 / 0.4 10^{-6} m-rad
Beam energy spread at gun	15 keV
X/y emittance in photon production section	4 / 0.08 10^{-9} m-rad
X/y beam size in photon production section	100 / 8.5 μm
X/y beam divergence in photon production section	40 / 8.5 μ-rad
Energy gain per pass	600 MeV
Linac RF frequency	1.3 GHz
RF klystron power	1 MW

The bunch lengths and beampipe apertures under current consideration result in a regime in which the coherent synchrotron radiation impedance may be significant, and studies of such effects are in progress. A smaller beampipe aperture may be beneficial in reducing effects from coherent synchrotron radiation, but the minimum aperture may be limited by transverse wakefields arising from the resistive wall impedance, or surface roughness effects.

The electron bunch length at different stages of acceleration and deceleration is expected to be further refined after more comprehensive simulations. With several linac passes and many arcs we believe we have sufficient flexibility to optimally control the bunch length with consideration to collective effects. In addition, we may gain by manipulation of the longitudinal charge density profile of the electron beam emitted from the rf photocathode.

2.5.3 Technologies

Our approach for producing a short x-ray pulse relies on the availability of an electron beam source with a flat aspect ratio so that one transverse dimension (y, vertical) is small. This principal has been successfully demonstrated at the Fermilab/NICADD Photoinjector Laboratory (FNPL) [9]. An x/y emittance ratio of order 10^2 may be achieved by this procedure, with a normalized emittance of $\gamma(\varepsilon_x \times \varepsilon_y)^{0.5} \approx 10^{-6}$ m-rad/nC at the cathode [6]. The successful demonstration at the FNPL of flat beams with emittance ratio 50:1 is highly encouraging and we have joined the experiment collaboration to help further work in this regard.

Conventionally, photocathode rf guns employ a half-length pillbox cell for the cathode cavity followed by a full cell for rapid acceleration of emitted electrons. For CW or high duty factor operation, thermal limitations may prevent such a design from operating at sufficiently high gradient. We have produced a conceptual design with optimized cavity geometry to allow cooling of the cavity surfaces, and operation at high gradient and high repetition rate [4]. In this design the first cell is modified by the inclusion of a re-entrant nose-cone, on the end face of which the photo-cathode is mounted. This nose-cone serves two purposes: it increases surface area to reduce deposited power density, and it enhances the accelerating electric field at the cathode.

Our linac design is based on superconducting rf technology developed for the TESLA project [10]. The TESLA rf cavity parameters are well suited to our requirements, and many complex issues including higher-order mode damping, suppression of multipacting, cavity materials preparation and fabrication, and input power coupler design, have been studied and solutions developed. Operating at the TESLA gradient of 23 MV/m would allow a final beam energy of ~3 GeV, but a lower gradient provides a design margin and reduced power dissipation in the cryostat. Our design considerations here are for a peak accelerating gradient of 20 MV/m. Identical cryomodules are used for the main linac and the injector linac.

2.5.4 References

1. Bilderback, D., Bazarov, I., Finkelstein, K., Gruner, S., Krafft, G., Merminga, L. Padamsee, H., Shen, Q., Sinclair, C., Tigner, M.; "New Energy Recovery Linac Source of Synchrotron X-rays", Synchrotron Radiation News Vol. 14, No 3 (2001) 12-21.

2. NSLS Photoinjected Energy Recovery Linac Design Study, http://nslsweb.nsls.bnl.gov/nsls/org/PERL/

3. D. A. Kayran, V.N. Korchuganov, G.N. Kulipanov, E.B. Levichev, V.V. Sajaev, A.N. Skrinsky, P.D. Vobly, N.A. Vinokurov, " MARS –A Project of the Diffraction Limited Fourth Generation X- ray Source", Proc. APAC'98, KEK Proceedings 98-10, November 1998.

4. J. N. Corlett, S. DeSantis, N. Hartman, P. Heimann, R. LaFever, D. Li, H. Padmore, R. Rimmer, K. Robinson, R. Schoenlein, J. Tanabe, S. Wang and A. Zholents, "Initial Feasibility Study of a Dedicated Synchrotron Radiation Light Source for Ultrafast X-Ray Science", LBNL-48171, October 2001

5. A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, "Generation of subpicosecond x-ray pulses using RF orbit deflection", NIM A 425 (1999) 385-389.

6. R. Brinkmann, Y. Derbenev, K. Flottmann, "A Flat-Beam Electron Source for Linear Colliders", DESY Report No. TESLA 99-09, 1999.

7. R. Brinkmann, Y. Derbenev, K. Flottmann, "A low emittance, flat-beam electron source for linear colliders", Phys. Rev. STAB, Vol. 4, 053501 (2001).

8. T. Matsushita and H. Hashizume, Handbook of Synchrotron Radiation V.1, ed. E.E. Koch, p.261, North-Holland, Amsterdam (1993).

9. D. Edwards et al, "The Flat Beam Experiment at the FNAL Photoinjector", Proc. XXth International Linac Conference, Monterey, 2000.

10. TESLA Technical Design Report, DESY 2001-011, March 2001.

2.6 DC Electron Guns

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A new generation of synchrotron light sources, employing superconducting RF linear accelerators with energy recovery, and based on passing high brightness electron beams once to possibly several times through light producing insertion devices, is currently receiving considerable interest. The generation of high brightness electron beams for this application is a key issue. As the beam required for injection into these accelerators is CW, it is natural to examine the suitability of DC electron guns, along with RF guns, for this application. Photoemission is recognized as the natural electron generation mechanism for these sources, since it is straightforward to produce an electron beam with RF time structure over a broad frequency range by illuminating a photoemission cathode with suitably modulated laser light.

The first thing to be recognized in developing such an electron source is that a high quantum yield photoemission cathode is essential. Presently, there are only three cathode families that are realistic possibilities for this application. These are the alkali antimonides, the alkali tellurides, and the negative electron affinity (NEA) semiconductor photocathodes. For any linear photoemitter illuminated with light of wavelength λ, one can relate the current delivered to the product of the incident laser power and the cathode quantum efficiency as:

$$I(\text{mA}) = (\lambda(\text{nm})/124)\,(P_{laser}(\text{W}))\,(Q.E.(\%))$$

The above relation is true for both average and peak current, and can be integrated over time to relate the microbunch charge to the energy carried in a single optical micropulse. This expression assumes that every optical photon and every photoemitted electron is useful, and thus represents the absolute minimum product of laser power and cathode quantum yield required to produce the beam current. If, for example, a truncated Gaussian is used for the optical beam to obtain a more uniform transverse profile, then correspondingly more optical power will be required from the laser. The typical operating wavelength, and the minimum optical power times Q.E. product necessary to produce a 100 mA average current beam are given in Table 2.6.1 for a typical cathode from each of the three high quantum yield photocathode families. In general, this table demonstrates that the lasers necessary to provide these high average current beams are quite challenging in their own right, particularly keeping in mind that the laser time structure has to be that required for the application. In general, the difficulty of the laser increases as the wavelength becomes shorter.

Table 2.6.1

Cathode Family	Typical Wavelength (nm)	P x Q.E. (W-%)
Alkali Telluride (KCsTe)	266	46.6
Alkali Antimonide (K_2CsSb)	532	23.3
NEA GaAs	780	15.9

The next important point with the use of photocathodes is that of the beam emittance. We write the normalized r.m.s. emittance from a photoemission cathode illuminated over a uniform circular spot of radius r, in terms of the effective thermal energy of the electrons:

$$\varepsilon_{n,\,r.m.s.}(\text{m-rad}) = (r(\text{m})/2)\sqrt{E_{th}/mc^2}$$

There exist good quality measurements of the emittance, and thus the effective thermal energy, as a function of wavelength, for photoemitted electrons from NEA GaAs [1], as well as very detailed studies of the effective energy at a particular wavelength [4]. Comparable quality measurements for the other photocathode families have not been reported, though there are values given for some specific cases. Although Dunham's measurements [1] were made with a low current DC beam, subsequent measurements at Jefferson Lab have shown that the same emittance result is obtained with a low current beam with 1497 MHz RF structure. Dunham's measurements indicate that for wavelengths of 780 nm and above, the effective thermal energy is smaller than 50 meV – about twice room temperature. As one approaches the bandgap energy, the effective thermal energy becomes quite close to the physical cathode temperature. Orlov [4] has continued these measurements at liquid nitrogen temperature, and finds that there are two components to the beam – one with a very low effective energy corresponding closely to the physical temperature, and a second with an increased effective temperature arising from scattering at the surface of the cathode. The few measurements reported of the effective energy from alkali antimonide and alkali telluride cathodes are typically on the order of 300 meV – a factor of about six larger than from NEA GaAs at room temperature. While all of these cathode systems are able to produce bright beams, to the extent that GaAs offers a lower effective temperature, it allows the use of a larger illuminated area to produce the same normalized emittance. This is an advantage in that the self fields of the larger area beam are lower. Optimal emittance compensation is an important issue for any high brightness electron source, whether based on a DC or an RF gun.

The operational lifetime of the photocathode is a major technical issue. All of the high quantum efficiency photocathodes are very sensitive to their vacuum environment. Ultrahigh vacuum is an essential technology for the use of these cathodes. The photocathodes must either be fabricated in the location in which they will be used, or fabricated outside the gun, and transferred into their operational location under ultrahigh vacuum conditions. Both solutions have been used. Since DC guns offer freedom in the choice of wall materials, chamber size, and the location of ports, compared to the cavities of RF guns, it is much easier to create excellent vacuum conditions in them, and to incorporate load locks and/or cathode manipulation devices.

At Jefferson Lab, we have improved the vacuum conditions in GaAs photoemission guns to the point where the dark lifetime is exceptionally long (years), and the operational lifetime is limited only by ion backbombardment. In this latter case, the cathode lifetime is meaningfully expressed in terms of the total charge delivered per unit illuminated area, rather than the clock hours of operation. The best cathode lifetimes observed in the Jefferson Lab guns are on the order of 2×10^5 C/cm^2 for a 1/e reduction in the quantum efficiency. These very good lifetimes are difficult to measure, and represent a factor of twenty improvements over the initial reported operation of these guns [6]. This improvement is attributed to steadily improved vacuum conditions in the guns.

The highest fields that can be practically employed in a DC gun are limited by field emission. Field emitted electrons may cause charging of the ceramic insulator supporting the gun voltage, leading to breakdown and even vacuum failure of the ceramic. Field emitted electrons striking metallic surfaces release gases and cause local melting, ultimately to the point of initiating a breakdown across the vacuum gap. Recent developments show promise of significantly reducing both the field emission currents and their effect on the necessary ceramic insulator. At LBL, an ion implantation process has been shown to produce a very uniform sheet resistance on the surface of ceramics. It is practical to tailor this sheet resistance to values suitable to drain off the charge delivered by field emission. This technique has been successfully used on the high voltage DC photoemission gun of the Jefferson Lab IRFEL [3,5].

More recently, a method for dramatically reducing the field emission currents from large area electrodes has been demonstrated. In this method, a thin, highly adherent silica coating was applied to the electrodes in a plasma source ion implantation system.

Electrodes with 116 cm^2 area were operated at 125 kV and DC fields up 30 MV/m for many hours, with stable field emission currents below ~ 1.5 pA/cm^2 [7]. Based on these results, it appears possible to consider DC electron gun designs with cathode fields as high as ~ 20 MV/m.

Finally, the problem of developing a laser with adequate output power and the proper RF time structure appears to be close at hand for the case of NEA GaAs photocathodes. A diode pumped Ti:sapphire laser, mode locked by an RF gain-switched diode laser, has been developed at Jefferson Lab [2]. In bench tests, this laser has delivered over 2 W at 780 nm, producing trains of ~ 50 ps optical pulses at either 499 or 1497 MHz. It appears practical to increase the power from a laser of this type to about 10 W. With a typical initial Q.E. for a NEA GaAs photocathode at 780 nm about 10%, a 5 W laser of the above type, and an operational cathode life of 2 x 10^5 C/cm^2, 100 mA CW with a thermal emittance of 0.5 μ could be delivered for 50 hours before any intervention is necessary. Typically, such intervention might involve either moving the illuminated spot on the photocathode, or heating and reactivating the cathode. This latter operation takes only a few hours, and fully restores the Q.E.

The above information indicates that it appears feasible to develop, based on existing technical demonstrations, a DC photoemission source with an NEA GaAs photocathode capable of meeting the demands of an energy-recovered synchrotron light source. Modest improvements in the operating vacuum in these guns, and in laser power, will make even longer continuous operational periods practical.

References

1. Dunham, B.M., Cardman, L.S., and Sinclair, C.K. in Proceedings of the 1995 Particle Accelerator Conference, Dallas, IEEE, New York, p. 1030.

2. Hovater, C. and Poelker, M., NIM **A 418**, 280 (1998).

3. Liu, F, Brown, I., Phillips, L., Biallas, G., and Siggins, T. in Proceedings of the 1997 Particle Accelerator Conference, Vancouver, B.C. Canada, IEEE, New York, p. 3752.

4. Orlov, D.A., Hoppe, M., Weigel, U., Schwalm, D, Terekov, A.S., and Wolf, A., Appl. Phys. Letts., **78**, 2721 (2001).

5. Sinclair, C.K., NIM **A 318**, 410 (1992).

6. Sinclair, C.K. in Proceedings of the 1999 Particle Accelerator Conference, New York, IEEE, New York, p. 65.

7. Sinclair, C.K., Dylla, H.F., Siggins, T., Manos, D., Venhaus, T., and Wu, L. in Proceedings of the 2001 Particle Accelerator Conference, Chicago, IEEE, New York, to be published.

2.7 High-Average Power Electron Source – CW Photocathode RF Gun R&D

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One of the major challenges in realizing the Photo-injected Energy Recovery Linac (PERL) based light source is the CW high-brightness high-power electron source. The PERL based light source requires about 100 to 200 mA electron beam with not only small transverse emittance (normalized emittance less than 1 mm-mrad), but also small longitudinal emittance capable of producing 100 fs bunches. One of the technologies having the potential to produce such beams is the photocathode RF gun.

The advantage of Photocathode RF guns is that, they produce high field on the photocathode and higher beam energy at the RF gun exit. Time dependent field on photocathode also provide extra flexibility in optimizing the longitudinal electron beam distribution combining with laser pulse shaping. The superior performance of the photocathode RF gun is best illustrated by the saturation of VISA SASE FEL at the BNL ATF with only 4-meter long undulator [1]. The measured normalized emittance is about 1 mm-mrad for charge from 200 pC to 0.5 nC for a S-band photocathode RF gun [2]. A 433 MHz photocathode RF gun at Boeing has demonstrated 25% duty factor with 32 mA average current [3]. CW operation of photocathode RF gun for PERL application requires significant R&D effort in photocathode and heat load handling of RF cavity.

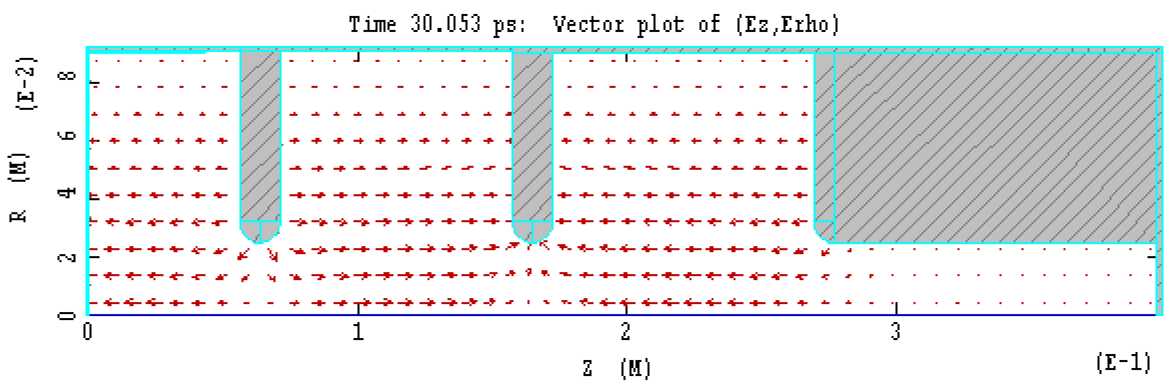

Figure 2.7.1 Two and half cell L-band Photocathode RF gun.

The photocathode plays the critical role in determining the laser system requirement. To keep the laser power on the order of tens Watts, a photocathode with QE about 10 % and work function less than 2.3 eV is needed (corresponding to green and IR laser). Both cesiated GaAs and K_2CsSb satisfy this criterion. GaAs has been used extensively in DC photo-gun, ultra-high vacuum (better than 10^{-11} Torr) required for its good lifetime made it less desirable for photocathode RF gun application. K_2CsSb has been used in photocathode RF gun with lifetime on the order of several hours. Research is needed to investigate sources of QE degradation with goal to extend the lifetime to weeks.

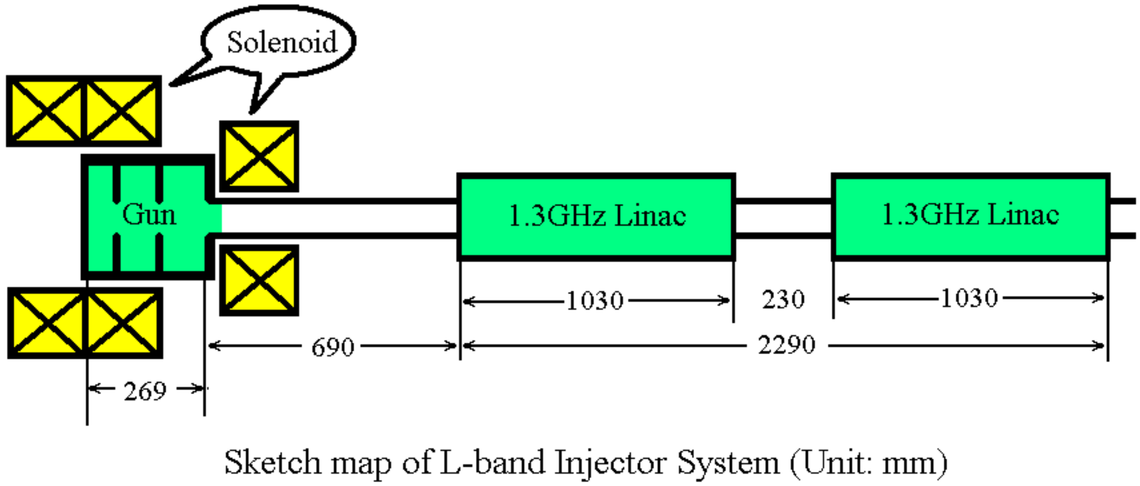

Figure 2.7.2 Schematic layout of L-band injector.

Selecting the operating frequency of Photocathode RF gun must take emittance preservation in PERL linac and transport line into consideration. Generally speaking, high rep rate with less charge for each bunch is preferable for reduction both in heat load on insertion devices and CSR effect [4]. We have carried out simulation study for a L-band photocathode RF gun (200 mA beam current corresponding to 150 pC charge per bunch for the L-band RF gun).

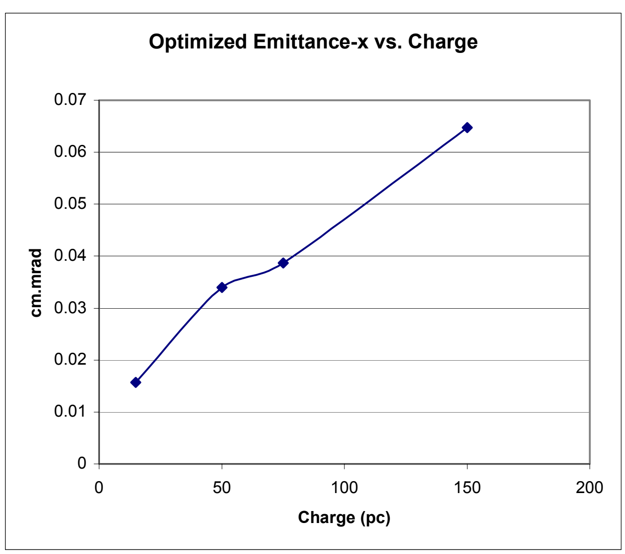

Figure 2.7.3 Transverse emittance as function photoelectron charge

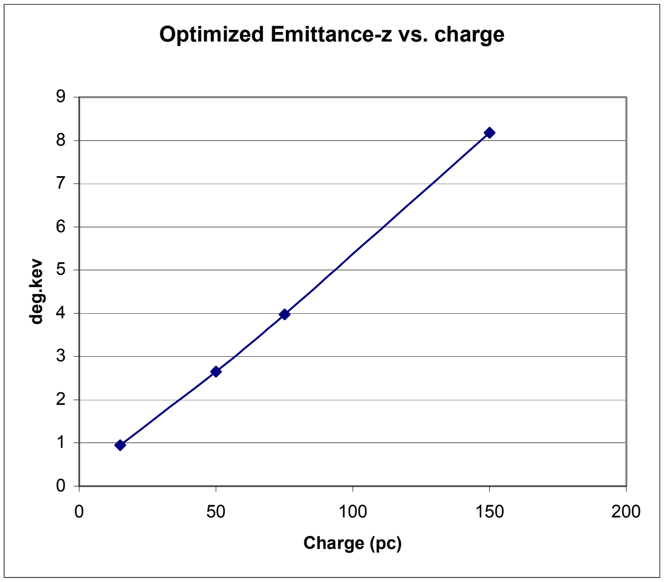

Figure 2.7.4 Longitudinal emittance as function photoelectron charge

To reduce the power density of the L-band photocathode RF gun, we optimized its performance in the following way. First we reduce the peak field from nominal 50 MV/m to about 15 MV/m for a L-band RF gun. To reduce space charge effect, we adopted two-and-half cell photocathode RF gun (Fig. 2.7.1). We are also considering other techniques to further improve the heat load of the RF gun cavity, such as higher order mode cavity.

Fig. 2.7.2 is the schematic layout of L-band injector capable of produce 25 MeV electron beam with emittance less than 1 mm-mrad and b length less than 3 ps (FWHM). Fig. 2.7.3 and 2.7.4 show the transverse and longitudinal emittance as function charge, respectively. For 75 pC charge (100 mA), transverse emittance is less than 0.5 mm-mrad.

References

1. A. Tremaine *et al,* presented at FEL 2001.

2. X.J. Wang *et al.,* PAC 99 Proc., p. 3495 (1999); V. Yakimenko *et al*, presented at the FEL 2001.

3. D.H. Dowell *et al*, Nucl. Instr. And Methods **A** 356 (1995) 167 – 176.

4. J.B. Murphy *et al*, BEAM DYNAMICS FOR A PHOTOINJECTED ENERGY RECOVERY LINAC AT THE NSLS, Proc. of PAC 2001 (2001).

2.8 High Average Current SRF

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The ERL requires optimizations in several arenas of the RF system and accelerating structures. To achieve brilliant x-ray beams it is important that emittance growth be as small as possible. Therefore the beam must be stable against transverse and longitudinal multibunch instabilities. To avoid emittance growth from beam break up driven by cavity higher order modes (HOM), it will be important to ensure strong higher mode damping. Because of CW operation, the beam induced power in HOMs is substantial. HOMs must be extracted from the low temperature with high efficiency demanding not only improvements in off-beam-line HOM couplers used but also development of on-line absorbers to catch HOM power that propagates down the beam-line. Economy of the RF power installation for the main linac demands higher external Q values than customary for superconducting accelerators. The challenge here is the microphonics inevitably present in the system. RF beam loading from the main beam pass and the energy recovery beam pass must be efficiently compensated to minimize the RF power needed. Development of an active feedback tuning system that can operate under the full dynamic range of beam currents and cavity gradients is therefore a priority for development.

Multipass multi bunch beam break up (BBU) is a potential limiting factor in the operation of high current linac based recirculators. If the transverse magnetic field of a dipole higher order mode beam displaces the beam during the first pass, the energy recovery pass will feed energy into this mode, leading to further displacement. If the rate at which the beam feeds energy to the mechanism exceeds the mode's decay rate there will be a transverse instability. Hence transverse HOM's must be well damped, as for example in the same range specified for TESLA 9-cell cavities. A realistic evaluation of instability threshold takes into account the contribution of HOMs from many cavities. A statistical spread in the mode frequency helps because cavities do not act coherently. ERL simulations show that if HOM frequencies have a spread of one MHz, the instability threshold current is higher than 250 mA, more than twice the considered ERL current in a one-recirculation, one-linac scenario.

An ERL linac may also exhibit longitudinal multibunch instability from the interaction of the beam with longitudinal HOMs. An initial excitation of some longitudinal HOM will modulate the energy of bunches exiting the linac. If the recirculating optics is not perfectly isochronous, the energy modulation will translate into a spatial modulation generating a side-band current with the same frequency as the HOM. On the second pass, the side-band current will further excite the HOM setting up a feedback loop to an eventual instability. To avoid this, monopole modes need to be damped strongly. In the most pessimistic case the strongest HOM will need to be damped a factor of two more heavily than for TESLA 9-cell cavities. For a large ensemble of cavities, manufacturing tolerances will lead to a statistical distribution of HOM frequencies, equivalent to a lowering of the Q of the HOM relaxing the damping needs.

High average current and short bunch length beams at ERL will excite HOMs that may result in increased cryogenic load. A 100 mA ERL beam could lose nearly 160 watts to HOMs as it passes through one TESLA 9-cell cavity. This is a factor of 100 higher than the present specifications for TESLA. Better HOM extraction methods are required to deal with the increased HOM power load.

Bench and beam measurements at TTF show that modes below 3 Ghz have Q values between 10^4 and 10^5. A dipole mode at 2585 MHz is potentially troublesome with Q of 10^6. The Q of this mode will need to be reduced. ERL and its prototype will use two HOM couplers at each end of the cavity to ensure adequate damping of dipole modes as well as efficient extraction of monopole modes. Furthermore, one or more of the cells in each 9-cell structure may need to be polarized to get best coupling to dipole modes. This is accomplished by introducing a slight (5%) azimuthal asymmetry in the cell shape.

A large fraction HOM power will be in modes above the cut-off frequency of the beam pipe (3.2 GHz). To intercept this power there will be special beam-pipe HOM absorbers consisting of a pipe of absorbing material integrated into the connection between adjacent cavity units. HOM power dissipated in these beam pipe absorbers will be intercepted by a stream of cold gas at 70 K. Candidate absorber materials are silicon carbide in an aluminum nitride matrix, a ceramic - like macor - or ferrite as used in CESR superconducting cavities.

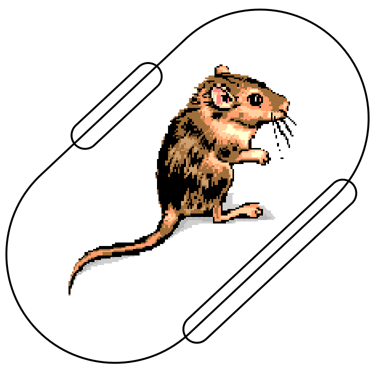
Using one klystron per cavity will provide the greatest simplicity of operation, the best rf stability, and the greatest flexibility for continued operation in the event of a single rf failure. The peak RF power needed for one superconducting linac cavity depends on the gradient, loaded Q, intrinsic Q and the detuning tolerance from microphonics. At the TTF the maximum peak to peak microphonics observed was less than 10 Hz and less than 3 Hz for CEBAF. For a conservative detuning value of 25 Hz, the optimum Qext for ERL will be 2.5 $\times 10^7$ and the corresponding power required is 9.4 kW per cavity. Additional power is needed to overcome imbalances due to beam loss between first and second passes, and path length changes that move the energy recovery beam away from the best phase. If beam loss is less than 0.3% and path length error is less than 0.5 degrees it will be possible to keep the input power below 15 kW per cavity.

The ERL injector calls for a total of 500 kW of CW RF power to be delivered by five separate cavity units, each providing 1- 2 MV acceleration. Design work for these cavities is underway. We anticipate the need to open the beam pipe aperture to achieve stronger coupling (external Q values near 10^5) necessary to deliver 100 kW of beam power per cavity. The large apertures will help minimize transverse beam kicks generated by input couplers and HOM couplers. Further reduction may be necessary by placing symmetrizing ports.

The interaction of the beam with the fundamental accelerating mode can also result in beam loading instabilities. Fluctuations in the cavity fields of the linac can cause beam loss on apertures and phase oscillations. Proper setting of RF feedback characteristics (gain and bandwidth) can bring this effect under control.

To achieve the above goals it will be necessary to prototype the source and other injector components at full scale, given the uncertainties the accelerator physics considerations and technological demands beyond today's state-of-the-art. Demonstration of acceptable energy recovery efficiency demands a full ERL configuration. Beyond that, one must be able to probe the beam break up threshold for the type of cavities planned for the facility and this requires sufficient length of cavity that build up of any instability can be seen. With these considerations in mind we propose a Phase I ERL prototype with full beam power from the injector (100 mA CW at 5 MeV) to avoid excessive space charge dilution during the bunching process. A 100 MeV energy for the main linac of the Phase I ERL appears adequate for a good evaluation of the BBU. Careful measurements, using the prototype, will be needed to assure that these criteria can be met and maintained under operating conditions.

2.9 A Generic Energy-Recovering Bisected Asymmetric Linac (GERBAL)



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Recent interest in Energy Recovering Linacs (ERLs) has led to investigation of issues that can significantly limit the performance of such systems. Results suggest that performance limitations in this class of electron accelerator can be imposed by current-related phenomena such as beam break-up (BBU), halo, coherent synchrotron radiation (CSR), the more typical incoherent synchrotron radiative excitation of the electron beam phase space, and, by virtue of recirculation and energy recovery, issues related to beam transport magnetic field quality.

ERL designs call for SRF linacs operating at currents of 100 mA or higher. This is more than an order of magnitude greater than currents in present energy recovering systems such as the Jefferson Lab IR Demo FEL driver [1]. BBU and other impedance-driven collective phenomena are therefore of concern. Similarly, CSR is a key performance issue [2]. In addition, more mundane mechanisms leading to performance limitations can come into play. Beam halo – present but irrelevant in lower power machines – can lead to significant beam loss. Heuristically, the halo current I_{halo} intercepted during recirculation and energy recovery will scale linearly with total current I_{total} and beam envelope β, and vary inversely with vacuum system aperture A [3]:

$$I_{halo} = C\, I_{total} \frac{\beta}{A}$$

Experience at CEBAF and the JLab IR FEL driver suggests the proportionality constant is of order 10^{-7} to 10^{-6}; thus, a machine with 100 mA current and a transport system with 100 m beam envelopes and a 1 cm aperture would encounter halo losses of 0.1 to 1 mA! This suggests a detailed understanding of halo, careful control of beam envelopes, and adequate aperture will be required for successful ERL operation.

Similarly, radiative excitation of the electron beam phase space can lead to beam quality issues. Synchrotron radiation in CEBAF at 10 GeV, for example, will generate relative momentum spread of order 10^{-4}, or an absolute momentum spread of 1 MeV [4]. Were this to be energy recovered to the 10 MeV dump energy typical of ERL designs, it would represent a 10% relative energy spread – manageable, but not trivially so. Analogous concerns hold for emittance excitation and control.

Magnetic field quality enters as an issue in ERL designs in a unique fashion [5]. Beam line component field quality typically manifests itself as a limitation by driving transverse phase space distortion with attendant emittance dilution. ERLs, however, are fully six-dimensional systems – the transverse and longitudinal dynamics are coupled. A field error will thus couple to RF phase through the associated path length error $\delta l = M_{52}(\Delta Bl/B\rho)$. This translates to a phase error $\delta\phi = 2\pi\delta l/\lambda_{RF}$ during energy recovery, which in turn leads to unanticipated energy spread after energy recovery. Estimates for the JLab 10 kW IR Upgrade driver suggest that uncompensated errors of order 100 g-cm (out of ~4.1×10^{6} g-cm used during energy recovery) can double the final energy spread.

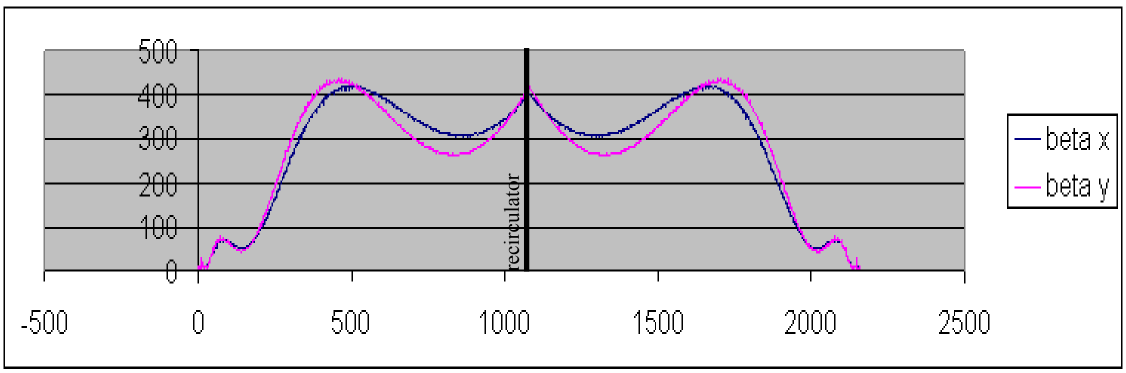

Figure 2.9.1a Beam envelopes (m) in a 10 MeV -> 10 GeV recirculated energy recovering accelerator using constant gradient focusing.

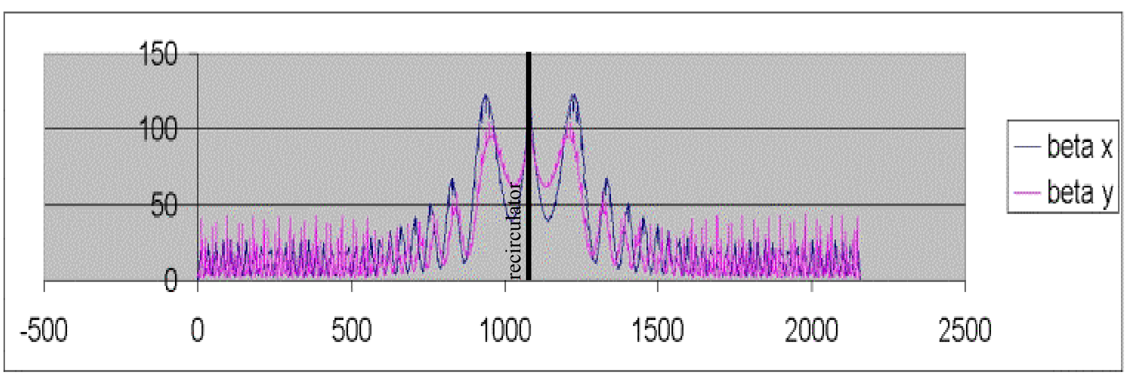

Figure 2.9.1b Beam envelopes (m) in the same system using graded-gradient focusing.

Management of all these phenomena is aided by good beam envelope control. We have found that this is available through observation of a few simple principles [6,7]. The first of these is the use of *graded gradient focusing*. In this scheme, the linac focusing is set to provide constant focal length to the lowest energy beam present at any point of the structure. Conceptually, the focusing then increases in strength for the first half of the linac (to focus the accelerated beam), and decays through the second half (to focus, without over focusing, the energy recovered beam). Figure 2.9.1a presents beam envelopes in a 10 MeV to 10 GeV ERL design using constant gradient focusing and a real-estate accelerating gradient of ~10 MV/m. Figure 2.9.1b presents the same using graded gradient focusing; the improvement is evident. An alternative scheme – constant focal length focusing of either pass – generates such severe mismatch that it is not displayed.

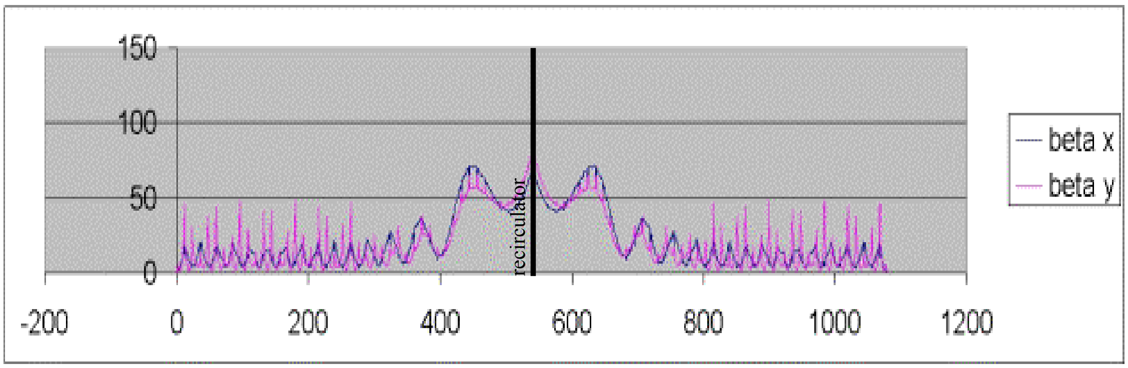

Figure 2.9.2 ERL design operated at doubled accelerating gradient.

A second technique is the *use of high accelerating gradient*. This shortens the linac – reducing betatron mismatch of any higher energy pass(es) – and increases the focusing strength more rapidly after injection and before extraction. Rapid acceleration at the linac front end and rapid energy recovery at the linac back end will in fact dominate the injected-to-final energy ratio that was of concern in earlier, lower gradient SRF-based recirculating linac designs [8]. Figure 2.9.2 presents a 10 MeV to 10 GeV ERL design operated at twice the gradient (~20 MV/m) of the system shown in Figure 2.9.1b. The enhanced focusing reduces the betatron mismatch by a factor of two.

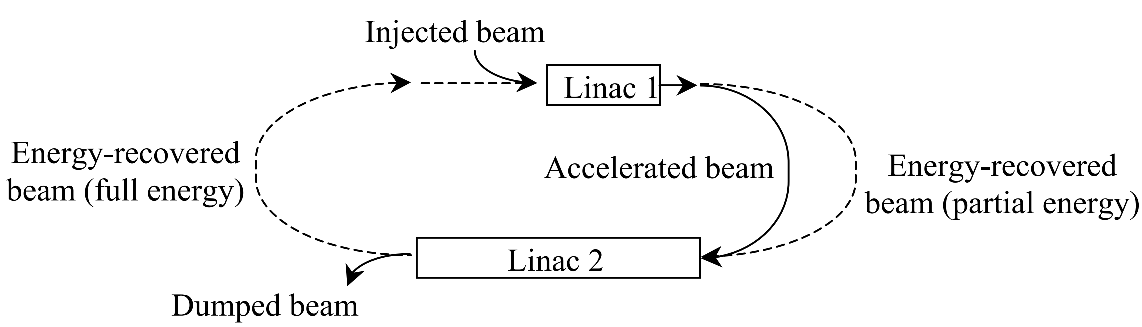

Figure 2.9.3a Asymmetric split linac: “low” energy linac with weak focusing is short, reducing mismatch of higher energy beam.

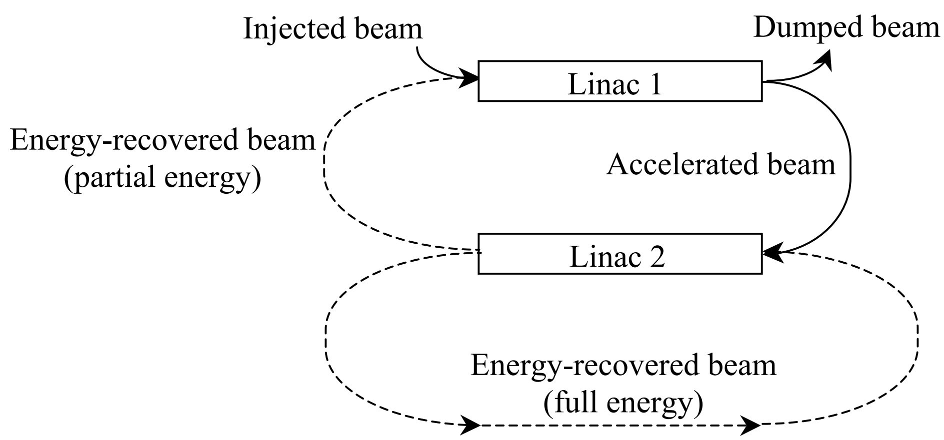

Figure 2.9.3b “Bisected” linac topology. Energy recovery proceeds from high to low energy linac, reducing mismatch of beam energy to focusing excitation.

To the chagrin of beam transport system designers, cost/benefit analyses persistently indicate recirculated linacs are brought to a cost/performance optimum through the use of multipass linac geometries [9]. ERL applications can leverage this circumstance through the invocation of *asymmetric split and bisected linac topologies*. An *asymmetric split linac* (Figure 2.9.3a) has a “short” linac accelerating the injected beam, and a “long” linac applied following a partial recirculation. This reduces the length over which focusing of higher passes is weak, alleviating energy-mismatch induced blowup. A *bisected linac* topology (Figure 2.9.3b) modifies the recirculation order of a split linac from the nominal “low-to-high” (accelerating)-to-“low-to-high” (energy recovering) to an inverted order during energy recovery, in which reinjection occurs from the *high* to the *low* energy linac. This further improves the beam energy to focusing match.

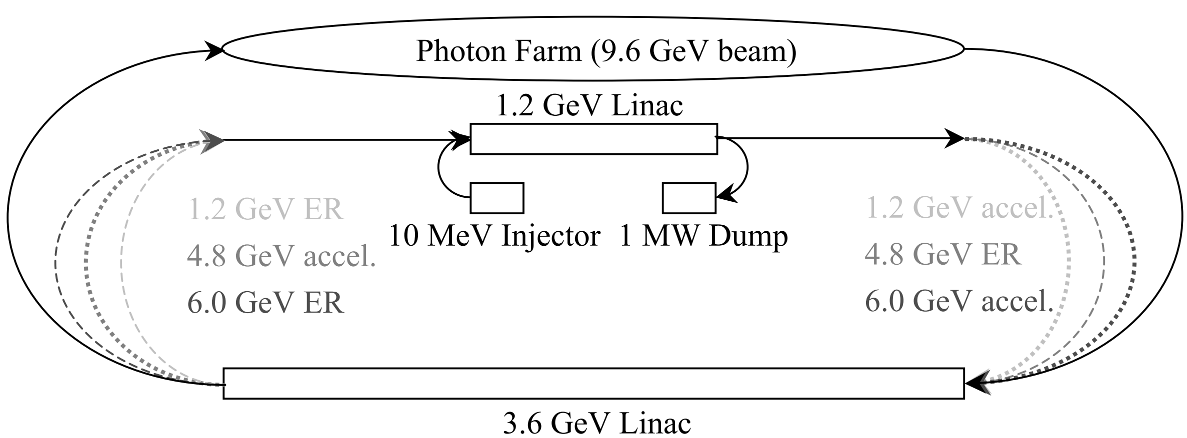

Figure 2.9.4 GERBAL configuration. Asymmetric linacs accelerate 100 mA beam from 10 MeV to ~10 GeV. Full 1 GW beam power is transported to utility region for production of synchrotron radiation; beam power is then recovered using a bisected linac geometry.

These principles can be illustrated by a “Generic Energy Recovering Bisected Asymmetric Linac”, or GERBAL, which is shown in Figure 2.9.4. This machine design, developed as an exercise investigating beam transport issues in ERLs [10], accelerates an injected 10 MeV beam to 10 GeV in two passes, and energy recovers it to 10 MeV in a subsequent two passes, using a bisected linac geometry. A “Photon Farm” allows implementation of various user-defined synchrotron radiation sources. The various design features discussed here provide beam envelope functions as shown in Figure 2.9.5; the maximum value of order 70 m suggests the performance limitations outlined above may be well managed.

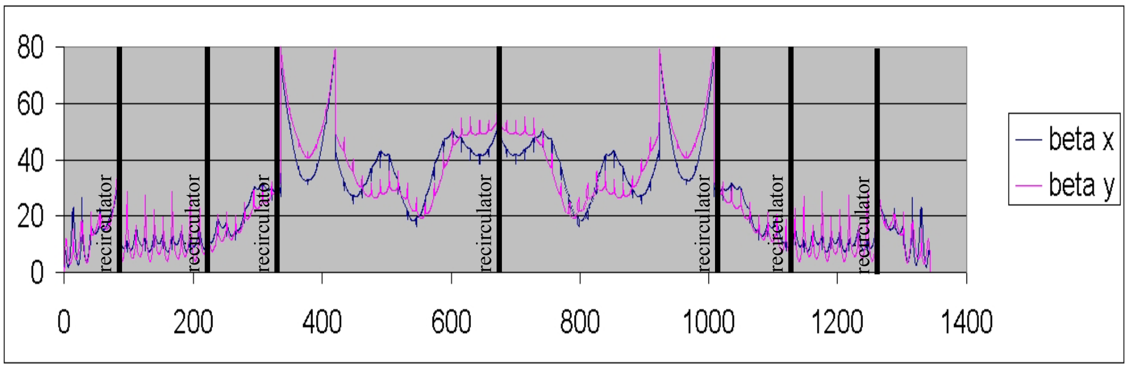

Figure 2.9.5 Beam envelopes in GERBAL configuration. Maxima are limited to ~70 m, despite large dynamic range in energy and use of multiple recirculations.

References

1. L. Merminga, “RF Stability in Energy Recovering Free Electron Lasers: Theory and Experiment”, Proceedings of FEL2001.

2. R. Li, “Analysis and Simulation on the Enhancement of the CSR Effects”, Proceedings of LINAC2000.

3. D. Douglas, “Design Considerations for Recirculating and Energy Recovering Linacs”, JLAB-TN-00-027, 13 November 2000.

4. D. Douglas, “Quantum Excitation Estimates for CEBAF Energy Upgrades”, JLAB-TN-97-038, 15 October 1997.

5. D. Douglas, “The Effect of Field Inhomogeneities In or Near the IR Upgrade Driver Compaction Management Elements”, JLAB-TN-01-053, 12 November 2001.

6. D. Douglas, “Design Considerations for Recirculating and Energy Recovering Linacs”, JLAB-TN-00-027, *op. cit.*

7. I. Bazarov *et al.* "Linac Optics for Energy Recovery Linac", Proc. PAC 2001.

8. D. Douglas, "Lattice Design Principles for a Recirculated, High Energy, SRF Electron Accelerator", Proc. 1993 IEEE PAC.

9. D. Douglas, "Incoherent Thoughts About Coherent Light Sources", JLAB-TN-98-040, 13 October 1998.

10. D. Douglas, "Design Considerations for Recirculating and Energy Recovering Linacs", JLAB-TN-00-027, *op. cit.*

3: Activity Reports

3.1 Beam dynamics activities at the ESRF

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3.1.1 Introduction

The ESRF was the first third generation hard X-ray light source to be commissioned in 1992. It consists of a 200 MeV electron linac, a 6 GeV full energy synchrotron booster synchrotron and a 844 m storage ring providing a 4 nm horizontal emittance with a Double Bend Achromat lattice with distributed dispersion. Since the beginning of operation in 1994, the target brilliance has been increased by 2 orders of magnitude with respect to the original design target value of 10^{18} photons/sec/mm^2/mrad^2/0.1% relative bandwidth by acting on the stored beam current, the refinement of the insertion device technology and beam emittances.

This paper presents an overview of recent beam dynamics activities.

3.1.2 Lattice Studies

The remarkable flexibility of the Double Bend Achromat lattice used on the storage ring has been further illustrated with the implementation of the "Horizontal Focusing Optics". By operating the lattice with a non-zero α_x function in the middle of a given straight section, a virtual focusing of the electron beam is achieved downstream the corresponding beamline. This provides the possibility of reducing the photon beam horizontal spot on the user sample. This in turn leads to a significant increase in spectral flux per unit surface. The challenging issues arise from the breaking of the periodicity of the optics, which should favour the excitation of numerous resonances and lead to a reduction in the dynamic aperture and in the energy acceptance resulting in a lifetime reduction. A configuration with β_x = 55 m, α_x = -1.18 was tested and optimised for all available filling patterns [1]. It is remarkable to note that the lifetime was hardly affected by the breaking of the optics periodicity. The expected gain in performance was confirmed by measuring the characteristics of the radiation on the machine diagnostic beamline. This new optics was successfully operated during normal operation mode and can be set on and off at any time.

3.1.3 Non-linear Optics Studies

Even if the lifetime of the machine is dominated by the Touschek lifetime in all operating modes, the request for a large momentum acceptance is crucial only for the few bunch modes of operation. The energy acceptance of the machine, which stands around ±3 %, is mainly dictated by transverse aperture-related limitations. A good modelling of the non-linear behaviour of the optics is essential to improve the understanding of these limitations. Due to the small momentum compaction and the strong sextupoles required to correct the chromaticity and enlarge the dynamic aperture, the linear description of the optics is inadequate when considering the large excursions in momentum experienced by Touschek scattered particles. Higher order terms are required to provide an accurate description of the change of the orbit path length, the dispersion, the momentum compaction and the chromaticity.

For a long time, experimental investigations of this non-linear behavior and comparisons from tracking codes (BETA, MAD,…) had shown significant discrepancies at large $\Delta p/p$ values. After a careful analysis of the possible sources of divergence (approximation in the description of elements for off-momentum tracking, discarded multipolar components in magnets, thick or thin sextupoles,….), a new sextupole model has been established that produces a good agreement with simulations in all off-momentum conditions [2].

3.1.4 Coupling Reduction

Since achieving small vertical emittance is one of the key features that determine the light source performance, continuous effort has been made to correct the coupling since the early stage of operation. Starting from a 10 % natural coupling, it was possible to reduce the coupling to 0.7 % (i.e. a vertical emittance of 25 pm) by correcting the nearest difference and sum resonances and by minimising the spurious vertical dispersion with 16 skew quadrupoles. A new coupling correction [3] based on the modeling of coupling and minimization of vertical beam sizes measured with two pinhole cameras has recently been developed that uses 16 additional skew correctors, the position of which were determined from the skew error analysis of the measured coupled-orbit response matrix. A record emittance of 10 pm was measured. The beam was delivered to the Users for one week in these conditions. The increased bunch density leads to a Touschek-related lifetime reduction of about 10 hours (from 60 h to 50 h in 2/3 filling mode at 200 mA).

3.1.5 Beam Position Stability

Fast orbit correction systems are used to improve the stability of the X-ray beam. They operate in a 0.01 to 200 Hz bandwidth with a sampling and correction rate of 4.4 kHz. The global vertical feedback [4] uses 16 beam position monitors and 16 correctors to damp the vertical beam motion all around the storage ring. The main 7 Hz frequency peak is damped by a factor of 10 and the global damping factor is 2.5 when averaging all frequencies up to 100 Hz. A few local horizontal feedback systems are implemented on straight sections. The systems use 2 BPMs to measure the electron beam position at both ends of the straight section and four fast steerers to produce a correction bump. The residual amplitude of oscillation is damped from 13 µm down to 1 µm (rms), i.e. 0.25 % of the horizontal beam size.

In addition, the mechanical vibrations of the magnet girder assembly that are transmitted to the electron beam and amplified though the quadrupoles have been significantly reduced by the installation of damping links [5]. These devices consist of a sandwich structure with visco-elastic material that links the 2 extremities of a girder and the floor.

3.1.6 Multibunch Instabilities

The current increase is affected by the resistive wall instability and longitudinal HOM driven coupled bunch instabilities.

The trend towards small gap insertion devices (5 mm for in-vacuum undulators) tends to significantly increase the resistive wall impedance. The classical way of providing damping consists in pushing the spectrum of the unstable modes in the positive frequency region so as to maximize the overlap with the positive resistance. This is performed with increasing the over-compensation of the chromaticity. In the uniform filling mode, the threshold is less than 10 mA at zero chromaticity. Reaching the operating 200 mA current imposes to significantly increase the chromaticity ($\xi_z = \dfrac{\Delta \upsilon_z}{\frac{\Delta p}{p}} \cong 6$). This increase of chromaticity leads to a reduction of dynamic acceptance due to the fact that numerous resonances are on the tune path of Touschek scattered particles. This in turn results in a reduction of dynamic aperture and a lifetime reduction.

As far as HOM driven instabilities are concerned, thresholds have been considerably raised from 60 mA for a homogeneous filling (under the pessimistic assumption that the frequency of the parasitic mode lies exactly on the synchrotron sideband) to well beyond the nominal intensity of 200 mA by adopting a fractional filling with filling one-third of the circumference. The gap in the bunch train induces a modulation of the RF voltage and a subsequent spread in synchrotron frequencies. This results in additional Landau damping [6]. New operation modes (uniform filling, reduced electron beam energy…) could be developed thanks to the use of the temperature regulation of cavities in order to shift the HOM modes and avoid the interaction with the beam spectrum. Very recently, the stored current could be increased to 250 mA. The only limitation came from the radiation that reached the authorized threshold.

3.1.7 Transverse Beam Instabilities

Single bunch and associated time structure modes are limited by strong vertical transverse instabilities. At zero chromaticity, the single bunch current is limited beyond 1 mA by the merging of mode 0 and mode –1. The mechanism of the instability that severely limits the maximum single bunch current unless the chromaticity is set at a large positive value has been investigated both experimentally and theoretically. The discrepancies between the predictions of the classical head-tail theory and the observations led to develop a new approach that considers instabilities faster than the synchrotron motion: the "post head-tail instability" [7]. According to this mechanism, the instability develops when the coherent tune shift exceeds the width of the energy-dependent betatron tune spread in the bunch.

3.1.8 Low Energy Operation

Operation at lower energy than the nominal 6 GeV [8] has been tested with the following motivations: during machine studies running a large machine at low energy allows to probe very small emittances, down to the diffraction limit in both planes. As a second step, the beam was delivered to users for a few shifts during the Users Service Mode at 4 and 5 GeV to provide them with a higher transverse coherence, but to the detriment of the photon flux that is significantly reduced. The other limitations of the low energy operation come from the low thresholds for HOM driven longitudinal coupled bunch instabilities, due to the much lower synchrotron damping times. The main achievements are summarized in the following table.

Table 3.1.1

Energy (GeV)	6	5	4
Horizontal emittance (nm)	3.75	2.5	1.8
Vertical emittance (pm)	28	7	11
Beam current (mA)	200	190	100

3.1.9 Towards the Ultimate Storage Ring Based Light Source

Even if the trend in brilliance increase achieved over the last thirty years is over, a brilliance enhancement by two orders of magnitude can still be envisaged for an X-ray storage ring based light source. A study work has been launched to investigate how a storage ring X-ray source could provide the best achievable performances. The study is deliberately oriented to fulfill the present and future requirements of the majority of the ESRF users. The new facility would have to provide, to at least 40 insertion device beamlines, the maximum constant and stable flux of photons in the 5 – 50 keV range, with an optimum power ratio on the optical components.

The most promising directions to meet these target specifications have already been defined [9]. The key design parameters are presented hereafter.

- The selection of the electron energy around 7 GeV allows covering the required spectrum range with 11 mm gap undulators. Some in-vacuum undulators with gaps as low as 4 mm will cover the need for undulator radiation of higher energy.

- To keep within a realistic budget envelope, the circumference of the ring is constrained not to exceed 2 km.

- Since the undulator radiation has to be collimated by some slits to minimize the heat load on the optical components of the beamlines, the horizontal electron beam emittance is optimized to provide minimum beam sizes of the radiation on the slits. A value in the 0.1 to 0.3 nm range appears as a good compromise to minimize the transmitted power without reducing the flux. Achromats with more bending magnets than operational lattices like the Double Bend Achromat or the Triple Bend Achromat are required to fulfill the emittance / number of cells requirement. The use of damping wigglers as a means of reducing the emittance has been withdrawn since the detrimental effects (unavailable straight sections, power to be handled, ID technology,…) exceed by far the added value (a gain in emittance by a factor of 2).

The key issue for the lattice is the second-order design involving the chromaticity and the realization of a reasonable dynamic aperture for on and off-momentum particles. The stronger focusing required for achieving the small emittance leads to natural chromaticities that are higher than those of the ESRF optics by a factor 3 to 5. The large number of cells and small bending angle leads to a small dispersion requiring stronger sextupoles (2 times larger than for the present ESRF optics) to correct the chromaticity, thus making the chromaticity correction difficult. This results in a very small dynamic aperture that prevents injection. However, preliminary attempts to enlarge the dynamic aperture with adding harmonic sextupoles in the dispersion-free straight sections look promising. The dynamic aperture is comparable to the figure obtained for the ESRF at the early stage of the design and the same optimization work should produce a similar improvement.

- An initial stored current of 0.5 A looks a realistic figure, given the high heat load on absorbers and instability issues. The evolution of the instability related parameters with the lowering of the emittance (smaller momentum compaction, smaller synchrotron tune, shorter bunch length, longer damping times) is expected to have a severe impact on instability thresholds. Preliminary computations show that the use of feedback systems and innovative solutions to reduce the machine impedance will be mandatory for achieving the target current.

3.1.10 References

1. A. Ropert. P. Elleaume, L. Farvacque, J. M. Hasselsweiler, "Horizontal Focusing Optics at the ESRF", EPAC2000, Vienna (2000)

2. A. Ropert, L. Farvacque, "Non-linear optics studies at the ESRF", PAC'01, Chicago (2001)

3. R. Nagaoka, "Work carried out at the ESRF to characterise and correct the coupling", EPAC2000, Vienna (2000)

4. E. Plouviez, J. M. Koch and F. Uberto, " A fast global feedback system to correct the beam position deviation in the ESRF storage ring, ICALEPCS'99, Trieste (1999)

5. L. Zhang, L. Farvacque, J. M. Filhol and E. Plouviez," e-beam stability enhancement by use of damping links for magnet girder assemblies at ESRF", PAC'01, Chicago (2001)

6. O. Naumann, "Landau damping of longitudinal multi-bunch instabilities in electron storage rings", Thesis, Berlin (1999)

7. P. Kernel, "High current single bunch transverse instabilities in storage ring light sources: a new approach highlighting a post head-tail instability", Ph.D thesis, Grenoble (2000)

8. L. Farvacque, "Operation of the ESRF at low energies", Shanghai Symposium on Intermediate Energy Light Sources, Shanghai (2001)

9. A. Ropert, "Ultimate performances of a hard X-ray storage ring based light source". SPIE Annual Meeting, San Diego (2001)

3.2 Beam Dynamics Activities at SLS

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SLS, the national Swiss Light Source has been commissioned in 2001 at Paul Scherrer Institut, Villigen. It consists of a 2.4 GeV low emittance storage ring, a full energy booster synchrotron and a 100 MeV injector linac.

Linac and booster commissioning was done in 2000. Ring commissioning started Dec. 2000; most performance figures were achieved by June 2001. Since August 1, 2001 SLS is operating to 70% for users.

Final commissioning work concerns understanding and suppression of multibunch instabilities, minimization of vertical emittance and commissioning of subsystems as multi-bunch and orbit feedbacks and the dynamic alignment system.

3.2.1 The SLS Storage Ring

The SLS storage ring is built up by a 12 TBA (8^o–14^o–8^o) lattice of 288 m circumference with 6 straights of 4 m length, 3 of 7 m and 3 of 11 m. Four 500 MHz cavities of 600 kV peak voltage occupy two short straights; injection is done in one of the long straights. The lattice is designed to provide an emittance of 5 nm·rad at 2.4 GeV with dispersionfree straight sections. 174 quadrupoles with independent power supplies grouped into 22 soft families allow large flexibility, 120 sextupoles in 9 families are carefully balanced to provide large dynamic apertures.

3.2.2 Machine Status November 2001

The storage ring was successfully set into operation for the three most important operation modes (low emittance with and without dispersion in straights, and relaxed).

Beam currents up to 400 mA have been accumulated after careful tuning of the parasitic cavity modes by means of cavity temperature and HOM dampers.

A vertical multi-bunch instability has been observed; it shows both signatures of ion-trapping and resistive wall impedance. Suppression of the instability requires low gas pressure, a sharp gap of ≈ 200 ns in the filling pattern, a large vertical chromaticity of +6 (non-normalized) or operation of the transverse multi-bunch feedback system.

Injection efficiencies from booster to ring of 100% have been achieved with nominal chromaticities, however increased chromaticity for suppression of the instability lowers the efficiency to <50%. SLS operates routinely in top-up mode keeping the beam current to 10^{-3} constant at a typical level of 200 mA over 20 hours.

The best working point up to now was found at 20.38/8.16. Measurements of tunes as a function of energy deviation for a range of $\Delta E/E$ = -4.7… +3.0% show excellent agreement with the TRACY model.

Measurement and corrections of average beta functions in quadrupoles was straightforward since every quadrupole has its own power supply. Agreements with the model of 5% resp. 2.8% for horizontal, resp. vertical beta functions have been achieved.

Pinhole measurements of beam size confirm the natural emittance of 5 nm and the synchrotron radiation opening angle of 80 μrad, however the values for energy spread and vertical emittance are yet larger than expected: The energy spread seems to be increased by a factor 1.5 … 2.0 depending on the current, which was also observed in the spectrum of the U24 undulator. The vertical emittance measurements indicate an emittance ratio of $\approx$1.5%, considerably larger than the $\approx$0.5% derived from vertical dispersion measurements with contributions from linear coupling negligible.

The orbit correction is running in slow feedback mode with repeated corrections every 8 seconds. The beam stability thus achieved over 20 hour runs is of the order of 0.5 μm and 0.15 μrad rms at the beamline source points. These numbers agree well with XBPM measurement in the beamlines. Up to 250 Hz the beam seems to be rather quiet, with peaks from booster crosstalk (3Hz), seismic noise and girder resonances (10 … 30 Hz) and mains supply (50 Hz and harmonics) at levels of about 1 μm.

3.2.3 Outlook

The dynamic alignment system allowing beam based girder alignments, and the DSP based fast orbit feedback up to 100 Hz are expected to become operational early 2002. In spring a superconducting 3rd harmonic twin cavity for bunch lengthening and damping of coupled bunch instabilities will be installed.

3.3 BESSY

3.3.1 The BESSY SASE-FEL Project *

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3.3.1.1 Introduction to the BESSY SASE-FEL Project

The Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung (BESSY) operates storage ring based synchrotron light source facilities since 1981. The most recent one, BESSY II, started its user operation in January 1999, delivering high brilliance photon beams in the VUV to XUV spectral range [1]. As an addition to the

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existing light-source BESSY proposes the construction of a linac-based single-pass Free-Electron Laser (FEL) user-facility for photon energies from 20 eV to 1 keV (63nm ≥ λ ≥ 1.2 nm). It is expected to achieve a peak-brilliance of 10^{31} photons/sec/mm^2/mrad^2 /0.1%BW, i.e., a peak power up to 10 GW, at pulse-durations of less then 200 fs (RMS) initially and ultimately possibly less then 20 fs. At present a three year design-stage is funded as a collaboration between BESSY, DESY, the Hahn-Meitner-Institute Berlin, and the Max-Born-Institute Berlin.

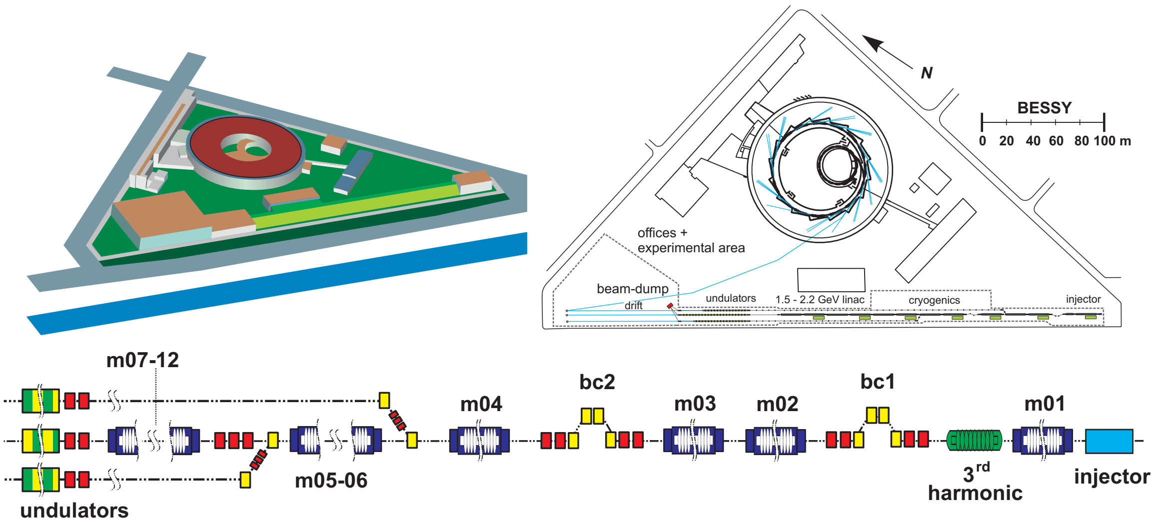

Figure 3.3.1 Schematic overview of the BESSY SASE-FEL.

3.3.1.2 Layout of the BESSY SASE-FEL

Fig. 3.3.1 shows a view of the BESSY site with the existing BESSY II storage ring based synchrotron light source in the central circular building and the proposed FEL at the 480-m long south west side of the triangular cite. Specifications are summarized in Tab. 3.3.1. The bottom figure presents a schematic overview starting on the right-hand side with a laser-driven rf-gun and the first linac module of the TESLA type [2]. Central part is the 260-m long super-conducting linac, accelerating the electrons up to 2.25 GeV energy. Two bunch compressors in combination with a third harmonic cavity ensure sufficient peak-current for the SASE process. In the first phase of the project three undulators will be fed with an electron beam extracted from the linac at 0.7-, 1.1- and full energy of 2.25 GeV. Behind the undulators a distance of 100 m to the experimental stations ensures sufficient space to manipulate the optical beam. To take full advantage of the super-conducting linac it is planned to operate the accelerator in a continuous-wave (CW) mode, i.e., keeping a constant non-pulsed rf-field in the accelerators cavities. This scheme provides the basis for a flexible time-structure as well as a more straightforward stabilization scheme of the electron-beam energy. The main challenge of this scheme is the present non-availability of a photo-injector, capable to generate such a time-structure, and the increased cryogenic load of the linac. Regarding the injector, it is planned to start the operation with a high repetition-rate normal-conducting photo-injector with a time-structure as depicted in fig. 3.3.2a. In a later stage it should be replaced with a superconducting version, capable of handling more flexible time-structures and a higher average current, see fig. 3.3.2b. For both injectors the accelerating gradient of the linac will be limited to 15 MV/m to keep the cryogenic losses contained to an acceptable level.

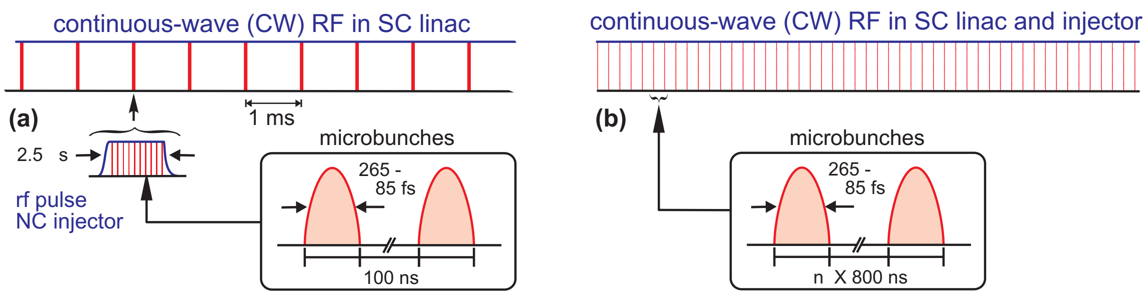

Figure 3.3.2 Timing patterns for the BESSY FEL, n: sub-harmonic of the BESSY II round-trip time

3.3.1.3 Performance of the BESSY SASE-FEL

Figure 3.3.3 and 3.3.4 display the range of brilliance, flux and power anticipated for the BESSY SASE-FEL. For comparison also data from BESSY II, from other, existing and proposed FEL facilities such as the TESLA X-FEL [2], the LCLS [3] and the Tesla Test Facility (TTF)-FEL [4] are included. Peak power-levels from other laser sources as well as higher harmonic generation (HHG) sources are shown for reference. The peak performance presented in fig. 3.3.3 is based on estimates derived from the electron beam parameters presented in Tab. 3.3.1. The time-averaged spectra are based on the initial timing scenario of a normal-conducting injector as depicted in fig. 3.3.2a. The flux is referenced to a relative bandwidth of 10^{-4}, assuming a monochromator transmission of 5%. The top curve in fig. 3.3.4 refers to an enhanced FEL output, where

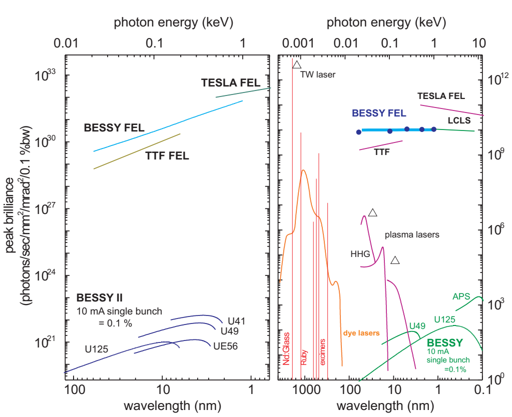

Figure 3.3.3 Spectral peak brilliance and power.

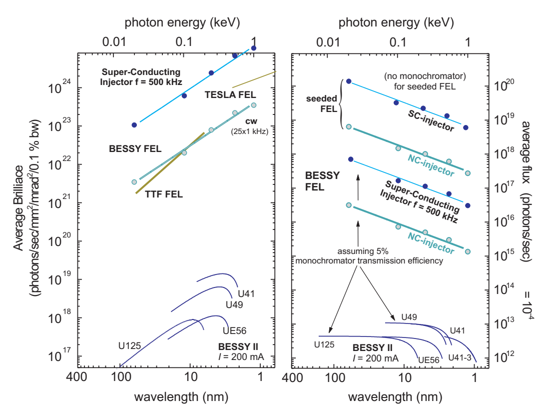

Figure 3.3.4 Spectral time-averaged brilliance and flux

seeding techniques are used to improve the spectral purity of the SASE-FEL radiation. For the 2nd timing scheme, see fig. 3.3.2b, the time averaged performance is expected to improve by a factor of 20 as compared to the values depicted in fig. 3.3.4.

Table 3.3.1 BESSY SASE-FEL: main machine and performance parameters

Electron Beam Parameters:		**Undulator Parameters**	
beam energy	0.7-2.25 GeV	Period length	2.75 cm
bunch charge	1.0 nC	Max. total length	50 m
bunch length	265-85 fs	Tuning range $\Delta\lambda/\lambda$	30%
Peak current	1.5-5.0 kA		
Norm. emittance	1.5 π mm mrad	**Photon Beam Parameters**	
energy spread	0.5-2.0 MeV	Photon energy	0.02-1 keV
Nr. of bunches	$1\text{-}25\cdot10^3/1.25\cdot10^6/n$	nr. of photons/pulse	$1.3\cdot10^{13}$
average current	1-25 μA/1.25/n mA	Min. pulse duration #	35 / 20 fs
Max. acc. Gradient	15 MV/m	Peak brilliance*	$7\cdot10^{31}$
max. av. beam-loading	56 kW / 2.8/n MW	average brilliance	$0.9\cdot10^{23}/45\cdot10^{23}/n$
cryogenic losses @ 2K	3.5 kW	average flux**	$3.2\cdot10^{17}/1.6\cdot10^{18}/n$

* at $\hbar\omega$=1 keV, in photons/sec/mm^2/mrad^2/0.1%BW
** at $\hbar\omega$=1 keV, in photons/sec
\# without/with seeding
n: sub-harmonic of the BESSY II round-trip time (see fig. 3.3.2b)

3.3.1.4 Enhancements and Planning

To further optimize the scientific potential of the user-facility several challenging topics are under investigation. The most important are the shortening of the photon pulse duration down to the 20 fs range, an improvement of the spectral purity, synchronization of the FEL with conventional laser sources, and an increase of the overall output power. The former two issues depend on so-called seeding schemes, where the SASE radiation is modified by properly seeding the FEL with a second light-source. This source could be a conventional laser or radiation from a preceding stage of the FEL. Synchronization with a conventional laser is challenging, however, due to the expected temporal jitter of the SASE-FEL pulses. At present this issue is tackled by a EU financed joint project of the TTF by DESY, MBI, BESSY, the Lund Laser Center, LURE and the university of Dublin. Goal is to synchronize a secondary external laser in the visible with the FEL pulse to an accuracy of 200 fs. A collaboration between BESSY and MBI is on its way to further investigate the feasibility of this scheme as a ending-source of the SASE-FEL. Details will be worked out further in the design-stage of the project which is due to end in 2003. Depending on financial decisions, construction of the facility could thus start as early as 2004, leading to a commissioning phase starting and initial user-runs in 2008.

3.3.1.5 References

1. D. Krämer et al., "BESSY II: Exceeding Design Parameters - The First Year of User Service", Proc. of the European Part. Acc. Conf., Wien, (2000), p. 640.

2. TESLA-Technical Design Report, DESY 2001-011, ECFA 2001-209, CD-ROM, 2001.

3. Linac Coherent Light Source (LCLS) Design Study Report, SLAC-R-521, 1998

4. J. Rossbach, "A VUV Free Electron Laser at the TESLA Test Facility at DESY", Nucl. Instr. Meth. A375 (1996) 269

3.3.2 Steady State Coherent Synchrotron Radiation Detected at BESSY II

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Coherent synchrotron radiation (CSR) is a promising source of high intensity far infrared radiation. The generation of CSR is well established in LINAC based sources, in electron storage rings it is more difficult to achieve. At some few storage rings CSR was observed [1] but always as a bursting, irregular emission process accompanied by longitudinal beam instabilities - a drawback for practical usage of CSR by synchrotron light users.

For the first time stable, steady state CSR was recently detected [2] at the low emittance synchrotron radiation source BESSY II [3], operated in a dedicated 'low alpha' mode, whereas the bursting CSR was detected during the regular single bunch user shift. Time and frequency resolved measurements are crucial to distinguish between bursting and steady state mode. Some few representative measurement results are shown here and the appearance of the far infrared signals of both modes is compared.

Coherent synchrotron radiation can be generated if the emitted electro-magnetic waves superimpose at constant phase. For a given wavelength, λ, the emitted radiative power, P, can be derived from the 'incoherent' power, P_λ, emitted by a single particle

$$P = NP_\lambda + N^2 P_\lambda f_\lambda \qquad (1)$$

where N is the number of electrons in the considered bunch volume and f_λ is a form factor, derived from the Fourier transform of the longitudinal bunch density [4]. In the case of a Gaussian density distribution of *rms* length σ the form factor is simply given $f_\lambda = \exp(-(2\pi\sigma/\lambda)^2)$. This relation states, that short bunches and long wavelengths support CSR emission.

The vacuum chamber can cause long waves to become evanescent if the conducting surface is too close to the beam [4]. For the BESSY II dipole chambers we calculate a cutoff to be 4 mm. This limits possible CSR steady state emission from bunches of our regular machine optics, because the *rms* bunch length of $\sigma_0 = 5$ mm is too long. Applying the Gaussian form factor an *rms* bunch length shorter than 2 mm seems necessary.

A low alpha optics variable within $-3\cdot10^{-4} < \alpha < -1\cdot10^{-6}$ was set up for BESSY II, to manipulate bunch length and shape directly. The zero current bunch length [5] for different α values is calculated at a fixed rf voltage by $\sigma = \sigma_0 f_s / f_{s0} = \sigma_0 \sqrt{\alpha / \alpha_0}$, where α and f_s are momentum compaction factor and synchrotron frequency respectively, and α_0=7.3·10^{-4}, f_{s0}=7.5 kHz are the corresponding values of the BESSY II user optics. Different α values are calculated from measured synchrotron tune frequencies f_s using stripline signals. We did not determine how the bunch length was affected by the different α settings except at the point α = -2·10^{-5} which yields σ = 2 mm [6]. Current dependent bunchlengthening is expected but not further checked. The measurements were mostly performed using moderate values such as α = -1.5·10^{-5} and 15 mA average beam current, resulting in a stable machine and a beam lifetime of some hours. In this mode the beam was stored as a multibunch filling in 100 consecutive bunches.

During the regular user single bunch optics bursting CSR was detected, with a machine optics of $\alpha = \alpha_0$, $f_{s0} = 8$ kHz, and one bucket out of 400 empty buckets of the 500 MHz rf was filled with around 15 mA averaged beam current.

The far infrared radiation (FIR) was detected with an InSb hot electron bolometer [7] of about 5 mm^2 area and of highest responsivity in the wavelength range between 2 mm and 0.5 mm. The detector was placed 12 m away from the source point and the photon beam of 10 mrad^2 divergence was focused onto the detector by a mirror.

The rise and fall time of the detector are 250 ns and 550 ns, respectively, fast enough to resolve FIR signals of the multibunch train of 200 ns length and a free gap of 600 ns. The radiation was not analyzed with respect to its spectral content, we expect broad band radiation at around 1 mm wavelength.

Directly time resolved measurements are shown in figure 3.3.5. Bursting FIR (sine-like) signals from the single bunch optics were accumulated for 500 ms by operating a scope in a persistent mode, as shown in figure 3.3.5a. The FIR signals were superimposed with the same phase as defined by the beam revolution trigger, visible as needle like signals. As seen, there is a variety of different signal amplitudes being mostly of small or even zero amplitude, typical for the bursting mode. The zero amplitude line is located on the top of the figure, including some background noise.

Similar records for the low alpha optics are shown in figure 3.3.5b. These signals are accumulated for 1 s. In contrast to the previous results none of the signals shows zero amplitude. To check the origin of the signal line spread, the FIR radiation was blocked by a 1 cm thick paper book, yielding the same width as before (not shown). The scope signal width was not further broadened by the superimposed FIR signals as anticipated for constant amplitude signals. The measured behavior exemplifies the stable, non-bursting, steady state character of the radiation.

Figure 3.3.6 shows measurements in the frequency domain. Records of bursts with the spectrum analyzer show a broad line of about 10 kHz FWHM, centred at 1.25MHz, as seen in figure 3.3.6a. For comparison, data of the steady state FIR signals are included in figure 3.3.6a, adjusted to the same frequency scale to demonstrate the difference in the line width.

Better resolved records in figure 3.3.6b for the steady state mode show a sharp line of 0.3 kHz FWHM, limited by the electronic setup. Adjacent to this line some satellite lines are seen, the dipole and quadrupole mode of the synchrotron oscillation. To enhance the quadrupole mode further, the bunches were coherently shaken by an externally applied phase modulation of the rf at 2 kHz, shown in the lower part of figure 3.3.6b. The bunches perform coherent density oscillations, leading to the CSR signal intensity modulations observed. Also shape oscillations at higher orders become visible. The detection of the quadrupole mode on the FIR signals and its external manipulation gives a clear indication that the shape of the whole bunch and not of substructures is responsible for the CSR.

For different α-settings the dipole mode of the synchrotron oscillation was tuned from 0.57 kHz to 3.5 kHz. Over the whole range the frequency analyzed FIR and stripline records look very similar, only the higher order mode signals are more enhanced in the FIR data.

Figure 3.3.7 shows examples of time resolved bursts. In figure 3.3.7a a burst with its fast intensity fluctuation from turn to turn (0.8 µs/turn around the storage ring) is seen. Figure 3.3.7b shows an averaged time signal and 3.3.7c a persistent mode record, triggered on larger bursts. Both signals show adjacent to a large burst smaller bursts, preceding and following the larger one by subharmonics of the synchrotron frequency of 8 kHz.

The measured signal intensity of the bursting and the steady state radiation grows in proportion with N^2, as expected from equation (1). Absolute intensity values or enhancement factors with respect to the incoherent power of the radiation are not yet estimated.

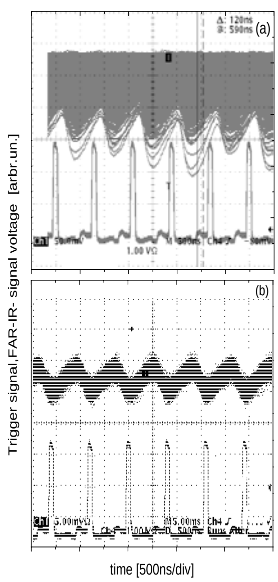

Figure 3.3.5 FIR signals recorded in the persistent scope mode for a) bursting, I=13.6 mA and b) steady state, I=15 mA, α=-1.5·10^{-5} radiation.

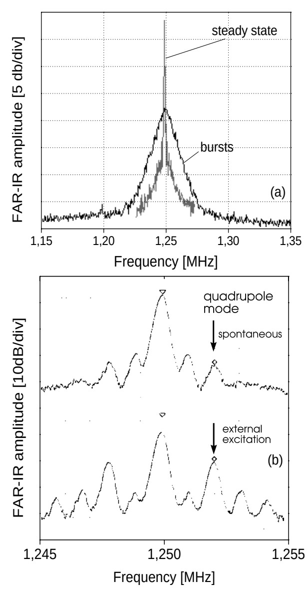

Figure 3.3.6 FIR signals in the frequency domain, a) bursting, I=14.6 mA (for comparison, the sharp line is taken from a steady state mode) and b) steady state mode, I=14.3mA, α= -1.5·10^{-5}.

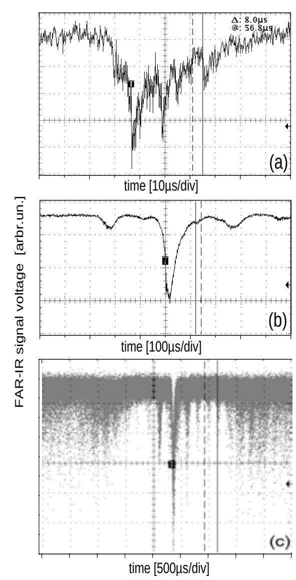

Figure 3.3.7 FIR records of larger bursts in the time domain, a) direct, I=10 mA, b) averaged, I=14 mA and c) persistent mode, I=12.5 mA.

We are very grateful to P. Kuske and D. Ponwitz and our colleagues from BESSY II and DLR for valuable suggestions and technical support.

References

1. 1) at SURF II (NIST, Gaithersburg, MD, USA): A.R. Hight-Walker, U. Arp, G.T. Fraser, T.B. Lucatorto, Proc. SPIE Vol. **3153**, p.42 (1997)
   2) at NSLS (BNL, N.Y., USA): B. Podobedov, G.L. Carr, S.L. Kramer, J.B. Murphy, Proceedings of the 2001 Particle Accelerator Conference, IEEE, Chicago, 2001.
   3) at MAX-I (MAX-Lab, Lund, Sweden): A. Andersson, M.S. Johnson, B. Nelander, Opt. Eng. **39** (12) p. 3099-3105 (Dec. 2000)

2. M. Abo-Bakr, J. Feikes, K. Holldack, H.-W. Hübers and G. Wüstefeld, 'Steady State Coherent Synchrotron Radiation detected at BESSY II', submitted to Phys. Rev. Letters, October 2001.

3. D. Krämer for the BESSY II team, EPAC 2000, Vienna (2000), p. 640.

4. see for example: S. A. Kheifets and B. Zotter in [8], p. 256.

5. see for example: D. Robin, H. Hama, A. Nadjj in [8], p. 150.

6. M. Abo-Bakr et al., Proceedings of the 7th European Particle Conference, Vienna, 2000, p. 720 (ISBN 3-7001-2931-9).

7. H.-W. Hübers, Deutsches Zentrum für Luft- und Raumfahrt Berlin, private communication.

8. E. B. Blum, M. Dienes, J. B. Murphy (Editors) 'Micro Bunches Workshop', AIP conference proceedings **367**, New York, 1995 (ISBN 1-56396-555-0).

3.4 Fermilab

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3.4.1 Tevatron Status

Following a four month commissioning run in 2000, the Tevatron's "Run II" officially began in March 2001 with a best luminosity achieved so far of about 7.6×10^{30}. The luminosity goal of the multi-year physics run is about 20 times higher. One of the major problems so far has been the loss of antiprotons during the various operations leading to collisions. Only about 30% of the antiprotons extracted from the Accumulator have been available at collision energy. Tuning of systems and operational procedures continues.

The proton intensity for collider operation has not been a problem. Currently, proton bunch intensities are roughly a factor of two below the Run II goals (2.5×10^{11}), but have been limited by the poor antiproton efficiencies due to presumed beam-beam effects. The Tevatron is operating with 36 bunches of both protons and antiprotons, up from six bunches during Run I. The long-range beam-beam effects are being more thoroughly investigated for this mode of operation.

Based primarily on luminosity and intensity measurements, the transverse emittances of both proton and antiproton beams are estimated to be close to Run II goals.

3.4.2 Progress in Beam-Beam Interactions Study

Run II is now operating with 36×36 colliding bunches. When design proton intensities are attained, the antiproton beam will experience total beam-beam tune shifts of around 0.025. The head-on interactions are strongly influenced by the fact that the bunch lengths are comparable to beta star. Due to the beneficial aspects of phase averaging, resonance widths and amplitude growth due to these head-on interactions are much smaller than would be the case with short bunches. In addition to the two head-on interactions, there are 70 long-range interactions. The tune footprint with all the beam-beam interactions is largely determined by the head-on collisions with significant contributions from the four long-range collisions with the smallest separations of about 6 sigma. However the head-on collisions are almost irrelevant in determining the stable region. The dynamic aperture without the head-on collisions is the same as with the head-on collisions included. A small tune spread is therefore not a sufficient indicator of a large stable region.

At the nominal working point of the Tevatron, the beam distribution spans the twelfth order sum resonances with the nearest lower order resonances being the fifth and the seventh. These twelfth order resonances are likely not directly responsible for particle loss since a tune scan well within the region bounded the fifth and seventh order resonances shows that the dynamic aperture is not very sensitive to the tune. We find that the long-range forces create a chaotic layer close to the dynamic aperture and the survival times depend very sensitively on the initial conditions in this layer. Synchro-betatron resonances driven by the beam-beam interactions are also a concern. In addition, dispersion at the locations of the long-range collisions creates an amplitude dependent chromaticity. Simulations show that these effects combine to reduce the dynamic aperture for particles with momentum deviations around three standard deviations by about 20%. The effects of long-range collisions and synchro-betatron resonances will be even stronger in the second stage of Run II when the number of bunches is increased to more than a hundred and crossing angles are introduced. It is almost certain that some form of beam-beam compensation will be necessary for Run IIb.

Long-range collisions and coherent phenomena driven by the beam-beam interactions will be important in the next generation of hadron colliders such as the LHC and the VLHC. Coherent phenomena such as the excitation of pi modes, flip-flop effects etc. are already important in the present generation of e^+e^- rings such as PEPII and KEKB. These phenomena and others in the weak-strong and strong-strong regimes were reviewed at a three-day workshop held at Fermilab from June 25th-27th, 2001. The proceedings of this workshop may be found at:

http://www-ap.fnal.gov/~meiqin/beambeam01/beambeam01.html

3.4.3 Compensation of Beam-Beam Effects in the Tevatron Collider

In the Tevatron, the antiproton bunches suffer a tune shift due to their interactions with the more intense proton bunches. In multi-bunch operation, the tune shifts vary from antiproton bunch to antiproton bunch, leading to an effective spread in tune. An electron lens, consisting of a short, low energy, electron beam propagating along the axis of a solenoidal field, can induce a tune shift on the antiproton bunches, which has the opposite sign to that which they experience from the protons. With appropriate choice of parameters two such lenses could provide effective beam-beam tune shift compensation in both vertical and horizontal plane. An R&D program has resulted in the construction and, recently, the successful testing of a single such device. If results continue to be positive the use of such devices could lead to a longer luminosity lifetime in the Tevatron and hence to a large integrated luminosity.

Another potential luminosity improvement may come from compensation of nonlinear beam-beam tune spread. The first Tevatron Electron Lens (TEL) has been designed, built, tested, and installed in the Tevatron collider. Because the horizontal beta function is much larger than the vertical beta function at that location, the first TEL can shift mostly horizontal tune of the Tevatron beams. A second TEL will shift mostly vertical betatron tune, allowing independent control of both tune shifts. In March-October 2001 the TEL operated in a single bunch regime with 47.7 kHz electron pulse repetition rate, with some 3 A peak current in 100-800 ns long pulses of 10 kV electrons. Maximum horizontal tune shift achieved with 980 GeV protons is about +0.0071, while vertical tune shift is about 4 times less - all in a good agreement with theoretical expectations. A reasonable proton beam lifetime exceeding 20 hrs is obtained with maximum electron current. Plans for further beam studies include: a) operation with 980 GeV antiprotons; b) investigations of the proton and antiproton lifetimes and emittances as functions of electron beam steering, current, size and shape, and as functions of solenoid magnetic field, current and position stability. In parallel, hardware improvements will continue.

3.5 Jefferson Lab

3.5.1 CEBAF Upgrade to 12 GeV

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Our fundamental understanding of the structure of nucleons and the nucleus is at an exciting point of development. For many years our models viewed the nucleus as a collection of individual nucleons. With the advent of QCD, those nucleons and their interactions became a much more intricate system. The CEBAF accelerator at Jefferson Lab (a 5-pass recirculating linac delivering beam to three experimental areas simultaneously) was built to provide a cw beam of 4 GeV electrons for exploring the transition from viewing the nucleus as a set of nucleons to viewing it as interacting quarks and gluons. Significant successes have been achieved and this program continues to be rich with potential discoveries, particularly since the beam energy has been increased to nearly 6 GeV. Lattice QCD calculations have shown, however, that doubling the beam energy to 12 GeV would enable further elucidation of the manifestation of quarks in nuclei and, perhaps more importantly, provide a new window into understanding quark confinement (which has been identified as one of the 10 outstanding unanswered questions in physics). The US Nuclear Science Advisory Committee has endorsed the 12 GeV program in its recent Long Range Plan [1]. A proposed cost-effective route for upgrading the existing accelerator to 12 GeV has been developed [2] and is described below.

Doubling the beam energy is typically a costly endeavor for an accelerator. The principal hurdle in the planning has been how to contain the cost. The present plan is to utilize the existing tunnel and virtually all of the hardware and not change the basic layout of the accelerator. As such, the upgrade can be categorized as having three major components; these are: 1) additional acceleration in the linacs, 2) stronger magnets for the recirculation, and 3) transport of the beam to a new experimental area.

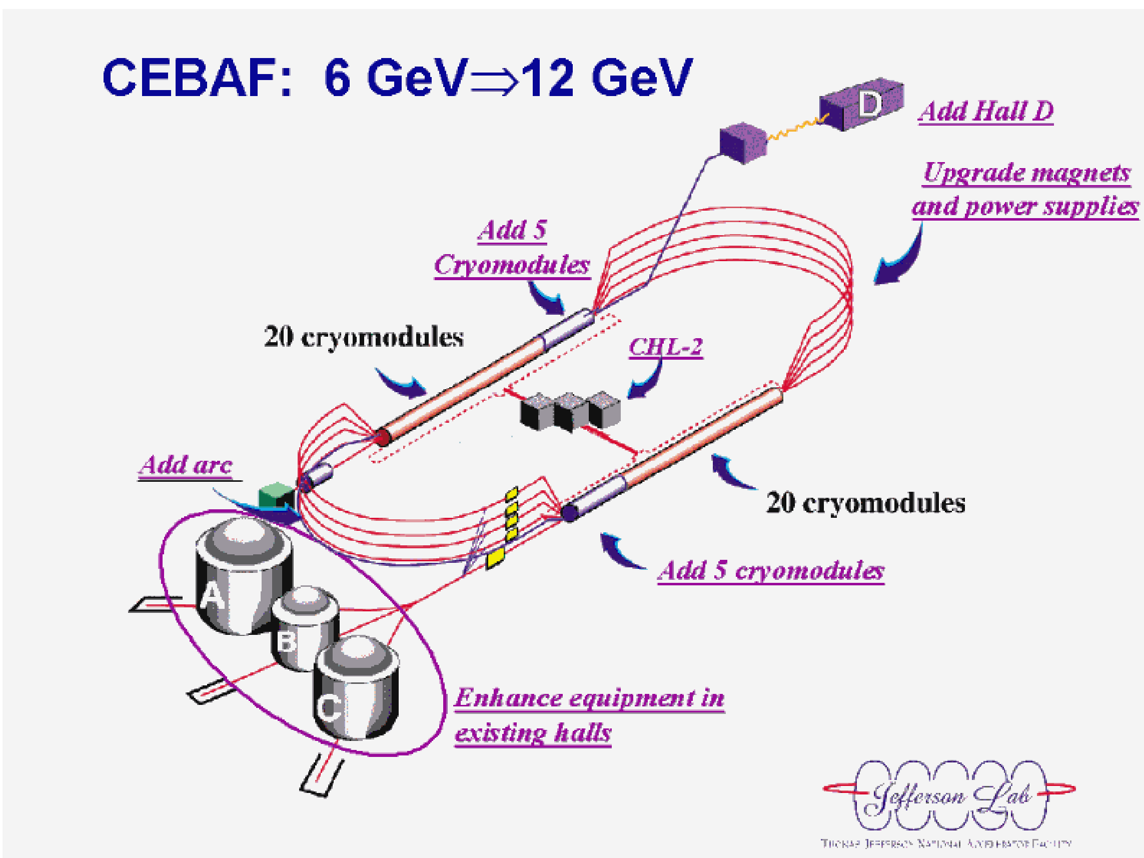

Figure 3.5.1

3.5.1.1 Acceleration

Beam will reach the new experimental area (the only one requiring the full 12 GeV) after transiting a linac one more time than is possible for any of the other halls. 12 GeV beam to this area is thus achieved if each linac provides 1080 MV (vs. the present 540 MV). The additional voltage will gained by installing a total of 10 new cryomodules (5 per linac), plus the associated rf systems, in the presently unoccupied spaces at the ends of the linacs. Recent developments in SRF technology indicate that we can plan to achieve 98 MV with each new cryomodule, which greatly exceeds the 28 MV performance of the existing cryomodules. Equally important, surface treatments of the cavitities with electropolishing will make $Q_0=8x10^9$ at 19 MV/m achievable [3]. The additional cryogenic load from these cryomodules will be handled by doubling the refrigerator capability. The 4K portion of the plant will be based on the MFTF-B refrigerator (trasferred from LLNL) and will be coupled with our existing standby 2K coldbox with the net result of achieving the desired doubling of the 2K capacity.

Multi-bunch beam breakup (BBU) was a critical concern during the conceptual development of the existing CEBAF accelerator. Higher-order mode (HOM) Q's were specified to be greater than $2x10^6$. It has been re-evaluated [4] for the upgraded modules. For the new crymodules, the HOM's need only be damped to $Q=1x10^5$.

The 19 MV/m fields that will be used greatly increase the Lorentz detuning of the cavities. Minimizing the required rf power pushes the external Q to higher values. The net result is a multi-valued detuning curve, with could be problematic for recovery should a cavity trip off. Several avenues are being investigated to deal with this problem. They include: 1) use of a self-excited loop instead of a generator-driven system, 2) piezo-electric actuators, and 3) addition of a variable reactance in the power coupler. The self-excited loop received endorsement at an international workshop on low-level rf control held in April, 2001 [5].

3.5.1.2 Beam Transport

Unlike the existing machine, synchrotron radiation has a significant effect on the emittance of the full energy beam. At 6 GeV the emittance is 1 nm-rad; at 12 GeV it increases to 7 nm-rad in the horizontal plane and 2 nm-rad in the vertical plane. Similarly, the energy spread increases from 0.01% to 0.02%. Explorations were done to identify lattice changes that would reduce the emittance increase. The cost for reducing the emittance growth by 50% was ~$5M; this was not considered cost effective

The beam transport for the recirculation requires relatively little change. In essence, the fields in the magnets in the primary bending arcs need to be increased. Although the magnets were not designed for operation at those levels, simple work-arounds have been identified for almost all of the magnets. The dipoles' fields will, in general, be doubled by installing power supplies with twice the currents and voltages as at present and doubling the return iron (needed in order to prevent power-wasting saturation) by turning the present "C" magnets into "H" magnets through the addition of a simple bolt-on piece. The addition of the iron will not require removal of the magnets from the tunnel. Roughly 3% of the 700 quadrupoles will be replaced and another 6% will receive larger power supplies. An additional recirculation arc must be installed in order to bring the beam into the last pass through a linac. The new magnets for this are simply longer versions of the original designs.

Perhaps the most complex changes to the beam transport systems occur in the spreaders and recombiners (the beams are co-linear in the linacs and must be separated at the end of the linacs and then put back together before entering the next linac). The topologies in these portions of the machine are sufficiently congested that adding the requisite iron for higher fields was not possible. Re-conceptualization of these sections has been done, resulting in slight adjustments in several magnets' positions and replacement of some magnets with longer magnets. Separating off the additional beam that will be present in the spreader at the end of the north linac, i.e. the beam going to Hall D, has also been accommodated in the new layout.

There will be three interleaved bunch streams each with variable current. Any one of these can be extracted on each pass around the accelerator and delivered to any experimental area. The new experimental area will receive full energy only.

3.5.1.3 Cost and Schedule

The full project (accelerator and experimental equipment) will cost around $150M (FY01$). Jefferson Lab is working with the Department of Energy toward a start of construction in the middle of this decade.

3.5.1.4 References

1. NSAC 2001 Long Range Plan;
   http://www.sc.doe.gov/production/henp/np/nsac/lrp.html

2. JLab White Paper on the 12 GeV Upgrade:
   http://www.jlab.org/dnp_tm/jlab-town-final.pdf

3 C. Reece, 2001 International Workshop on SRF Technology (Tskuba, Japan; Sept., 2001)

4. Byung C. Yunn, "Dipole HOM damping requirement of new 7-cell cavity for the 12 GeV CEBAF upgrade", JLab Tech Note, JLab-TN-01-028 (2001)

5. International Workshop on Low-level RF Control (Newport News, Virginia, USA; April, 2001).

3.5.2 Tuning the Beam Circulation Time in the CEBAF Recirculating Linac

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At Jefferson Laboratory, some experiments have required the relative beam energy variation to be less than $1{\cdot}10^{-4}$. We had already provided feedback energy stabilization to the beam being delivered to one selected experiment, regulating the energy on whichever acceleration pass that experiment required [1]. However, we must provide equivalent beam energy stability and energy spread to all users (who may be using beam from any of five acceleration passes). Long-term drifts in the recirculation time (or equivalently, “path length”), as well as residual path length errors after tuning the machine, interact with RF phase reference drifts of 1-2 degrees across the accelerator site to change the relative energy of the different passes by more than the $1 \cdot 10^{-4}$ limit. As a result, gradient-based feedback stabilization for any one acceleration pass will not stabilize the beam energy for all passes.

We have devised means to measure and procedures for correcting drifts in the RF phase references and in the machine path length without interrupting beam delivery [2,3]. In the process, we have found that the accelerator changes in length on a fine time scale, even showing measurable diurnal variations.

3.5.2.1 Introduction

In RF particle accelerators, careful relative timing of the beam and the RF phase is required to achieve peak performance with respect to such parameters as the beam energy stability and beam energy spread on various time scales. In recirculating machines, the phase stability principle is often useful to synchronize the circulation time of the beam and the RF frequency. In the CEBAF 5-pass recirculating linac, however, on-crest acceleration was chosen to provide a small energy spread for the delivered beam, providing at the same time the maximum beam energy from a given complement of accelerating cavities.

The choice of a very short electron bunch and on-crest acceleration eliminates the already small linear variation of beam energy along the particle bunch. Handling the beam transport and acceleration this way also requires that the linear variation of particle revolution time with beam energy (which we will denote by M_{56}) be nearly zero. This acceleration scheme works for a machine with a limited number of beam recirculations because the stretching of the bunch due to errors in M_{56} tuning does not have time to generate significant energy spread.

3.5.2.2 Method and Performance

The beam itself would ideally be the primary time (and RF) reference for the accelerator. In practice, we have an RF distribution system from which the beam is generated and all the cavities are referenced. Relative timing errors between the beam and the linac RF are detected by imposing a 0.1 degree (peak-to-peak) phase modulation in each of the two linacs, each at its own frequency. The energy gain of the beam in each linac is modulated synchronously with the phase, the fundamental Fourier component of the energy modulation being proportional to the amplitude of the phase modulation and to the phase error of the beam with respect to the RF.

The variation in beam energy is measured through its effect on the beam position in a dispersive region. The first pass beam is monitored by a dedicated BPM detector installed in “spreader” (the region where the multi-pass beams are separated vertically prior to being transported to the next linac; see Fig. 3.5.2). The first-pass dispersion in this region is 1.4 m. With a 0.05 degree offset of the beam with respect to the RF, the beam phase would vary from 0.0 to 0.1 degree, resulting in a relative energy modulation of $1.5 \cdot 10^{-6}$. The product of this with the 0.4 m dispersion gives an expected beam position modulation of 2 microns, which can readily be detected by feeding the analog BPM signal into a lock-in amplifier. Simultaneous measurement for each linac is possible by using a unique frequency for each linac. The resulting phase error signal is used for feedback correction of the global phase for each linac [2]. We are able to maintain the RF phase with respect to the beam at a level of ± 0.1 degree. While maintaining the relative phases of the beam and the RF, we are able to stabilize residual gradient variations in the linacs by detecting the beam energy in the transport lines leading to the experimental halls through feedback control of the accelerating gradient in selected linac cavities [1].

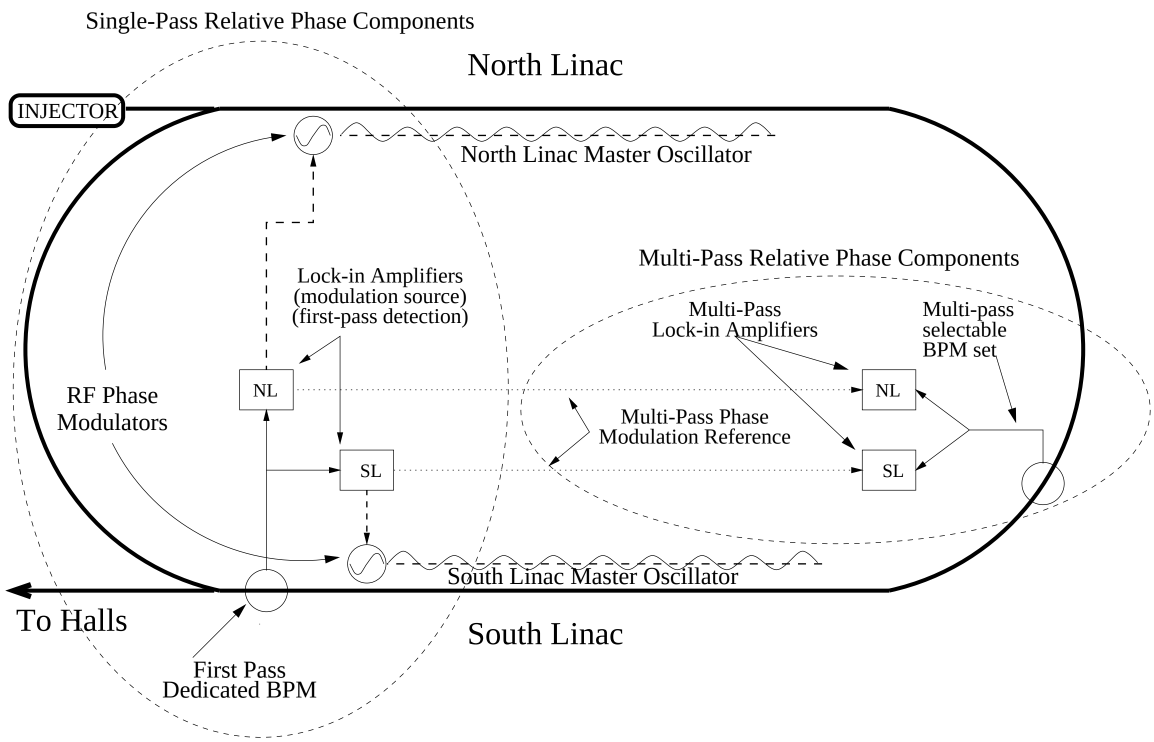

Figure 3.5.2 Schematic representation of the layout and connections of the phase modulation and beam diagnostic hardware around the CEBAF accelerator. The pickups consist of a BPM dedicated to the first pass beam at the end of the South Linac, and a set of five BPMs, selectable one at a time, for the various passes available in the East Arc between the two linacs.

Because the beam continues to experience the RF phase modulation on subsequent acceleration passes, a detection system in the higher-pass beam regions monitors the cumulative phase difference between the beam and the RF. The residual RF phase drift (outside the correction resolution of the RF feedback) is common between the first and higher acceleration passes, so by differencing the first- and higher-pass phase errors, one can monitor changes in the circulation time of the beam around the machine.

The differences between the measured relative beam-RF phases are shown in Fig. 3.5.3, with an apparent resolution of less than 0.1 degree even after the subtraction.

The multipass phase differences in Fig. 3.5.3 show long term drifts of the average phase of the higher-pass beams with respect to the first pass beam. A 1 degree shift for fifth pass beam, for example, would be caused by a ``path length" change equivalent to 0.5 RF degrees (approximately 0.3 mm) in the circumference of the machine. The time delays are cumulative, with the first pass as the reference, so the second pass is delayed by 0.5 degrees, the third by 1.0 degrees, the fourth by 1.5 degrees, and the fifth by 2.0 degrees. The average phase delay over five acceleration passes is 1.0 degrees. This is far larger than will be tolerated after the path length correction process is automated and feedback control is enabled. The machine was allowed to drift this far before correction only because the users requiring tight energy stability at the time were on the pass being used as the energy feedback reference.

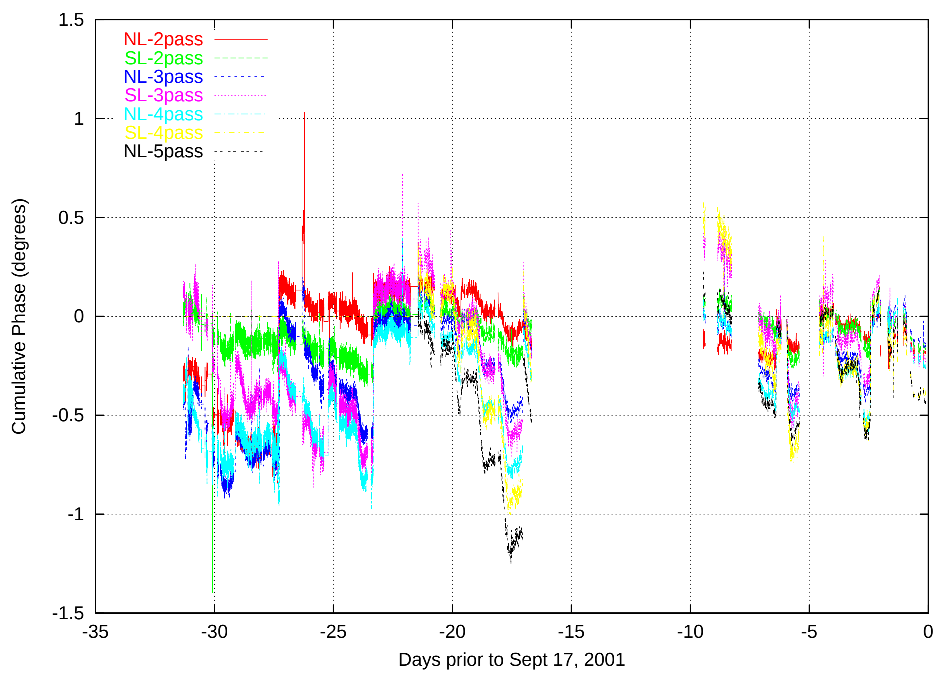

Figure 3.5.3 Measured variation of the accelerator “path length" for approximately 30 days prior to Sept. 17, 2001. “NL” and “SL” denote the North Linac and South Linac. The measured phases are averaged over the indicated numbers of acceleration passes, as discussed in the text. The gaps in the data curves occur for periods when either the accelerator or the data logging was down. The shutdown time following the Sept. 11 World Trade Center destruction is clearly visible across the -5 day mark. The abrupt changes at approximately -27 days, -25 days, -17 days, and -2.5 days, as examples, are the result of manual path length tuning. One can see, especially during the -22 to -17 day time frame, clear diurnal variation superimposed on a large cumulative shift in the path length around the accelerator.

The path length in the accelerator is adjusted by three-element chicanes at the end of each linac, one for each beam pass. Operational procedures initially called for these chicanes to be adjusted during setup of the accelerator, and only intermittently thereafter. The tuning was infrequent because initial experimental requirements for the beam were looser, and because the setup procedure required low duty-factor pulsed beam, not allowing beam delivery to experiments. The diagnostics described above allow for continuous beam delivery for long periods of time, while measuring and maintaining the path length. The correction procedures are presently manually executed, but the long term goal is to automate the process.

The diurnal variations visible in Fig. 3.5.3 are potentially due to environmental (e.g., temperature) changes affecting the instruments used for this measurement, but appears to indicate a real change in the beam circulation time, caused by changes in the temperature of the cooling water for the beamline elements, for example.

3.5.2.3 Further Applications

Energy Recovered Linacs (ERLs), such as the Jefferson Laboratory Free Electron Laser [4], are being proposed for several large projects, such as the Cornell/JeffersonLab ERL [5] and other proposals. In the examples mentioned above, the recirculation is for the purpose of decelerating the beam to recover the beam energy after the primary beam has served its purpose. The wallplug efficiency of the system is greatly improved by this technique, and beam dump radiological issues are greatly simplified. Large machines of this type will benefit from the RF phase and path length measurement and stabilization techniques described above.

3.5.2.4 References

1. Fast Digital Feedback System for Energy and Beam Position Stabilization, V.A. Lebedev and R. Dickson, Proceedings of the 1999 Part. Acc. Conf., New York, New York, USA

2. High-Precision Beam-Based RF Phase Stabilization at Jefferson Lab, V.A. Lebedev, J. Musson, and M.G. Tiefenback, Proceedings of the 1999 Part. Acc. Conf., New York, New York, USA

3. On-Line Measurement and Tuning of Multi-Pass Recirculation Time in the CEBAF Linacs, Michael Tiefenback, Proceedings of the 2001 Part. Acc. Conf., Chicago, IL, USA

4. G. R. Niel, C. L. Bohn, S. V. Benson, G. Biallas, D. Douglas, H. F. Dylla, R. Evans, J. Fugitt, A. Grippo, J. Gubeli, R. Hill, K. Jordan, G. A. Krafft, R. Li, L. Merminga, P. Piot, J. Preble, M. Shinn, T. Siggins, R. Walker, and B. Yunn, Physical Review Letters, v.84 (2000) 662-665

5. Bazarov, I. V., D.H.Bilderback, S.M.Gruner, H.S. Padamsee, R. Talman, M. Tigner, G.A. Krafft, L. Merminaga, C.K. Sinclair; "The Energy Recovery Linac (ERL) as a Driver for X-ray Producing Insertion Devices", Proceedings of the 2001 Particle Accelerator Conference, Chicago, IL, USA, May 2001

3.6 Beam Dynamics Issues of Muon Acceleration in a Recirculating Linac[♣]

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3.6.1 Introduction

A conceptual design of a muon accelerator based on recirculating superconducting linacs is proposed. In the presented scenario, acceleration starts after ionization cooling at 210 MeV/c and proceeds to 20 GeV, where the beam is injected into a neutrino factory storage ring. The key technical issues are addressed, such as: the choice of acceleration technology (superconducting versus normal conducting) and the choice of RF frequency, and finally, implementation of the overall acceleration scheme: capture, acceleration, transport and preservation of large phase space of fast decaying species. Beam transport issues for large-momentum-spread beams are accommodated by appropriate lattice design choices. The proposed arc optics is further optimized with a sextupole correction to suppress chromatic effects contributing to emittance dilution. The presented proof-of-principle design of the arc optics with horizontal separation of multi-pass beams is extended for all passes.

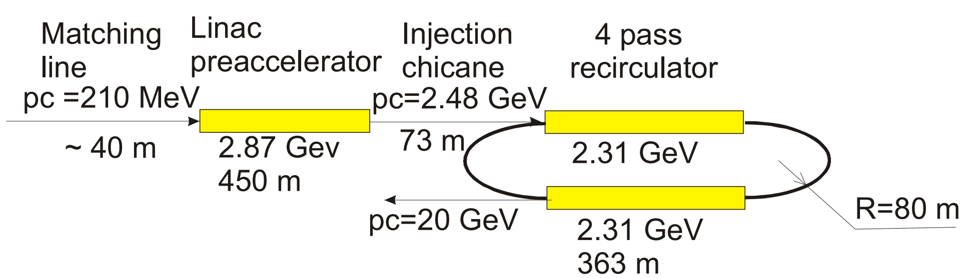

Figure 3.6.1 20 GeV muon accelerator complex based on RLA machine layout.

3.6.2 Muon Acceleration Scheme

A neutrino factory [1] is aimed to produce narrow neutrino beams via decay of muons in long straight sections of a storage ring. As illustrated schematically in Figure 3.6.1, a proposed muon accelerator complex features a 0.2-to-2.8 GeV straight pre-accelerator linac and a 2.8-to-20 GeV four-pass recirculating linear accelerator (RLA).

The pre-accelerator captures a large muon phase space coming from the cooling channel and accelerates them to relativistic energies of about 2.8 GeV. It makes the beam sufficiently relativistic and adiabatically decreases the phase-space volume, so that effec-

[♣] Work supported by the US DOE under contract #DE-AC05-84ER40150

tive acceleration in recirculating linacs is possible. The RLA further compresses and shapes the longitudinal and transverse phase spaces, while increasing the energy.

3.6.3 Accelerating Technology – Design Choices

To ensure adequate survival rates of short-lived muons, acceleration must occur at high average gradient. Our estimate [2] shows that a "real estate average" RF gradient of 15 MV/m will allow survival of about 80% of source muons throughout the RLA. Since muons are generated as a secondary beam they occupy large phase-space volume (even after the most optimistic stages of ionization cooling). The accelerator must provide high average gradient, while maintaining very large transverse and longitudinal accelerator acceptances. The above requirement drives the design to low RF frequency, e.g. 200 MHz. If normal-conducting cavities at that frequency were used, the required high gradients would demand unachievable high peak RF sources. Superconducting RF is a much more attractive solution. The RF power can then be delivered to the cavities over an extended time, and thus RF source peak power can be reduced.

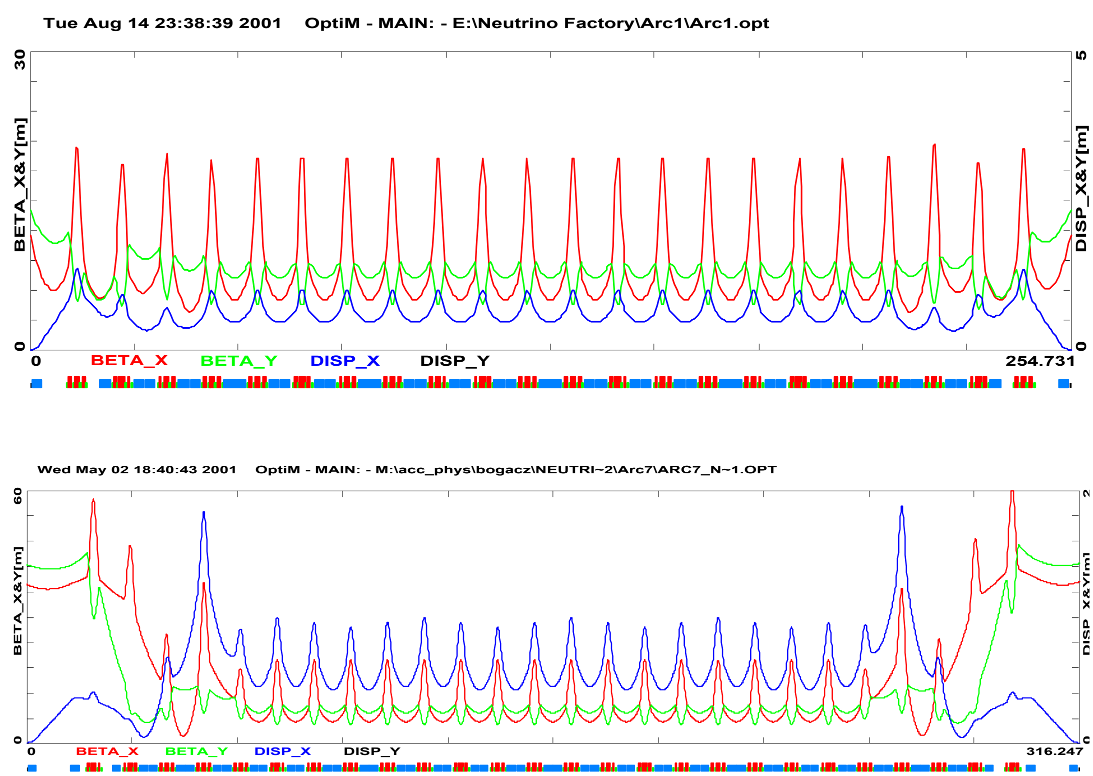

Figure 3.6.2. Optics of Arc1 (top) and Arc7 (bottom) – beta-functions and the horizontal dispersion matched to both adjacent linacs, Much larger difference (compared to Arc 1) between the values of beta functions in the adjacent linacs and Arc7, A quest to maintain 'smooth' transition of beta functions across spreaders and recombiners.

3.6.4 Machine Architecture

At low energy, 210 MeV/c, muon beam is not sufficiently relativistic, which would yield a phase slip for beams at higher passes, significantly reducing acceleration efficiency for subsequent passes. Here we choose a linear pre-accelerator to about 2.8 GeV, which makes the beam sufficiently relativistic and adiabatically decreases the phase space volume, so that further acceleration in recirculating linacs is possible.

In a recirculating linear accelerator one needs to separate different energy beams coming out of a linac and to direct them into appropriate arcs for recirculation. Experience at Jefferson Lab suggests that in order to manage initially large emittance and energy spread, a ratio of final to injected energy should be well below 10. In addition, the number of passes in the RLA should be limited to about four. Here a single dipole spreader is chosen as a consequence of small energy difference between injection and extraction energy and because of rather high injection energy into the RLA.

For multiple practical reasons horizontal rather than vertical beam separation was chosen. One of the drawbacks would be an enormous vertical aperture of the vertical spreader/recombiner dipole, if the vertical separation were chosen. Furthermore, rather than suppressing vertical dispersion created by the spreaders and recombiners we chose the horizontal separation with no dispersion suppression; it is smoothly matched to the horizontal dispersion of the arc. Finally, to assure compact arc architecture very short matching sections in spreaders and recombiners are desired (see Figure 3.6.2).

Another crucial beam transport issue is to maintain manageable beam sizes in the arcs. This calls for short cells and for putting stringent limits on dispersion and beta functions (beam envelope). Since spreaders and recombiners were chosen in the horizontal plane, the uniform focusing and lattice regularity was broken in that plane and the horizontal beam envelope requires special attention. On the other hand, the vertical beam size remains small due to maintaining uniform focusing and small beta functions in that plane.

3.6.5 Arc Optics – Proof-of-Principle Lattice Design

Focusing in all arcs is based on a periodic triplet focusing structure, rather than a FODO lattice, which allows use of longer straight sections as in the linacs. This simplifies spreader and recombiner design by maintaining similar betatron periodicity in linacs and arcs. It also reduces vertical beam envelopes and alleviates chromatic effects.

In addition, there is a need for high periodicity and smooth transition between different types of optics, e.g. linac-arc-linac, to alleviate emittance dilution due to chromatic aberrations (second order dispersion). Suppression of chromatic effects via sextupole corrections in spreaders and recombiners was implemented [3] via three families of sextupoles to control the horizontal emittance blow-up. To perform bunch compression in RLA the beam is accelerated off-crest with phase offsets in the range of 5 to 23 deg for different passes The number of periodic cells in the arcs was chosen so that the desired value of momentum compaction factor required for optimum longitudinal phase space compression (M_{56} = 1.4 m in all arcs) is built into the arc optics.

Lattices for two extreme arcs of the RLA (Arc 1 and Arc 7) are illustrated in terms of the beta functions and dispersion in Figure 3.6.2. Short matching sections in spreaders and recombiners (consisting of six quads) allow one to match all TWISS functions and to join 'smoothly' regions of different optics.

3.6.6 Conclusions

Results of this study suggest there are no obvious physical or technical limitations precluding construction of an RLA for acceleration of muons to 20 GeV. The use of 200 MHz accelerating frequency and superconducting RF technology seems well justified.

The resulting optics is well suited for transporting large phase space beams. Proposed chromatic corrections via two families of sextupoles in spreaders/recombiners are proven to be very effective in emittance dilution control.

3.6.7 References

1. R. Raja et al. “The Program in Muon and Neutrino Physics”, Proceedings of Snowmass 2001

2. V.A Lebedev et al. “Muon Accelerator for Neutrino Factory”, Proceedings of NuFACT’00, May 2000

3. S.A. Bogacz and V.A. Lebedev, “Recirculating Linacs for Neutrino Factory – Arc Optics Design and Optimization”, Proceedings of NuFACT’00, May 2000

4: Recent Doctoral Theses

4.1 Spin-Orbit Maps and Electron Spin Dynamics for the Luminosity Upgrade Project at HERA

Author: Mari Berglund (contact: via D. P. Barber, DESY)
Institution: Alfven Laboratory, Division of Accelerator Technology, Royal Institute of Technology, Stockholm and Deutsches Elektronen--Synchrotron (DESY), Hamburg
Title: Spin-Orbit Maps and Electron Spin Dynamics for the Luminosity Upgrade Project at HERA
Date: June 2001.
Supervisors: Dr. S. Rosander, Alfven Laboratory, Division of Accelerator Technology, Royal Institute of Technology, Stockholm (rosander@plasma.kth.se); Dr. D.P. Barber, DESY (mpybar@mail.desy.de).
Reference: DESY--THESIS 2001-044 from the library at http://www.desy.de/
Keywords: polarised electron beams, depolarization, HERA, luminosity upgrade, numerical spin--orbit maps, overlapping fields, Sokolov--Ternov effect, spin diagnostics, spin rotators, storage rings, T--BMT equation, unitary model.
PACS: 29.27.Hj, 29.20.Dh, 41.60.Ap, 02.50.Ey, 03.65.Sq

Abstract:

HERA is the high energy electron(positron)--proton collider at Deutsches Elektronen--Synchrotron (DESY) in Hamburg. Following eight years of successful running, five of which were with a longitudinally spin polarized electron(positron) beam for the HERMES experiment, the rings have now been modified to increase the luminosity by a factor of about five and spin rotators have been installed for the H1 and ZEUS experiments. The modifications involve nonstandard configurations of overlapping magnetic fields and other aspects that have profound implications for the polarization. This thesis addresses the problem of calculating the polarization in the upgraded machine and the measures needed to maintain the polarization. A central topic is the construction of realistic spin--orbit transport maps for the regions of overlapping fields and their implementation in existing software. This is the first time that calculations with such fields have been possible. Using the upgraded software, calculations are presented for the polarization that can be expected in the upgraded machine and an analysis is made of the contributions to depolarization from the various parts of the machine. It is concluded that about 50% polarization should be possible. The key issues for tuning the machine are discussed.

The last chapter deals with a separate topic, namely how to exploit a simple unitary model of spin motion near a synchrotron sideband resonance to estimate the equilibrium electron depolarization. An erroneous treatment given in the literature for another ring is examined and the correct procedure is demonstrated.

5: Announcements of the Beam Dynamics Panel

5.1 ICFA Workshops on Advanced Beam Dynamics

5.1.1 24th Advanced ICFA Beam Dynamics Workshop on Future Light Sources

We wish to announce an upcoming workshop entitled,

24th Advanced ICFA Beam Dynamics Workshop on Future Light Sources
1-4 May 2002, Spring-8, Kouto, Sayo-gun, Hyogo, Japan

This workshop is a sequel to the 17th ICFA workshop held at APS:
http://www.aps.anl.gov/conferences/FLSworkshop/
The main objective of the workshop is to provide a forum for discussions to explore the future of the LINAC-based light sources, particularly FELs and ERLs (Energy Recovery LINACs) in the photon energy region from the vacuum ultraviolet to hard X-ray by sharing experiences and by exchanging ideas on current trends and situation. Participants will discuss issues relating to light source developments including FELs, LINACs, ERLs, optics, insertion devices and other essential technologies. The workshop will also address various kinds of difficulties in developing FELs in order to realize angstrom FELs with their subsequent scientific applications in early stages.

Please visit the workshop web site at http://icfawsx.spring8.or.jp/ for detailed workshop information as well as information regarding pre-registration, etc.

We look forward to seeing you in Japan in May 2002!

The Workshop Organizing Committee
FAX: +81 791 58 2810
e-mail: fls-sp8@spring8.or.jp

5.1.2 Future Light Source Subpanel Miniworkshop "Coherent Synchrotron Radiation (CSR) and Its Impact on the Beam Dynamics of High Brightness Electron Beams"

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The Future Light Source Subpanel (K.-J. Kim, Chair) will hold an ICFA Beam Dynamics Miniworskshop "Coherent Synchrotron Radiation (CSR) and its impact on the beam dynamics of high brightness electron beams" on January 14-18, 2002 at DESY-Zeuthen (Berlin, GERMANY). Recent advances in modeling of coherent synchrotron radiation effects during bunch compression have underscored the importance of this phenomenon in the design of free-electron lasers and other high-brightness light sources. This Mini-Workshop will concentrate on computation and modeling of the effect of coherent synchrotron radiation during magnetic bunch compression. Please refer to the Miniworshop home page, http://www.desy.de/csr/, for detailed information.

5.1.3 Summary of the 25th ICFA Advanced Beam Dynamics Workshop: Future Light Sources

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The 25th ICFA Advanced Beam Dynamics Workshop was held September 24-26 at the Good Hope Hotel in Shanghai, China. With over 100 registered participants representing 29 laboratories from 17 countries, the Shanghai Symposium on Intermediate-Energy Light Sources (SSILS) provided a forum for exchange of ideas between storage ring light source and beam line scientists. The first day was kicked off with a plenary seminar on trends in ~3 GeV intermediate-energy light source (ILS) design and cost projections for the main accelerator components and beam lines. At this time, most machines are leaning toward 10-20 cell double-bend achromat configurations with optional use of gradient dipole magnets to control betafunctions and/or harmonic sextupoles to correct geometric sextupole aberrations. The beta function parameters and length of straight sections vary between machine designs with the most conservative designs producing β_x~10 m x β_y~4 m in 4-5 m insertion device straights. More aggressive designs utilize alternating-beta configurations for small gap insertion devices with straight sections over 10 m for future ID applications. Costs to construct ILS machines were the subject of some debate. Estimates range from $30M US for the main accelerator components in a smaller, more economic machine to well over $200M US for more advanced machines with multiple beam lines and modern detector components.

The next two plenary talks focused on properties of synchrotron radiation (SR) from intermediate-energy storage ring light sources and fourth generation light source machines. The standard figures of merit (flux, brightness) were identified and extended into the more specific notion of mapping phase-space density of the photon beam source onto sample acceptance. The example of protein crystallography science was cited as a classic case where phase-space mapping is the appropriate figure-of-merit. In this case, ILS machines are competitive with higher energy machines in the ~10 keV photon beam range. In terms of flux density and brightness, the high current, intermediate energy storage ring light source is also competitive with high energy machines around 10 keV, but experiments requiring extremely high brightness beams will need to be conducted at the cornerstone SR machines (APS, ESRF, Spring-8). Looming on the near horizon are the electron-recirculating linac (ERL) and SASE FEL. These more specialized machines require high brightness photocathode guns that are the subject of intensive research at laboratories worldwide.

The morning session of Day 1 was concluded with a description of plans for the Shanghai Synchrotron Radiation Facility (SSRF) and commissioning results from the Swiss Light Source (SLS). SSRF has developed prototype components in almost all technical areas (magnet, vacuum, power supply, rf, beam lines) and is poised for construction start at the earliest possible date. The SLS turned on with the accuracy of a Swiss Watch in every respect. Perhaps the most impressive commissioning of a new accelerator, the SLS team delivered 400 mA beam current with top-up injection on a very short time scale. Innovations in girder and alignment techniques combined with an impressive instrumentation and control system produced extremely stable photon beams for the user community.

The afternoon of Day 1 featured parallel sessions on insertion device technology and facility reports from laboratories engaged in the design, construction or operation of storage ring light sources in the ~3 GeV energy range. The insertion device forum covered general ID design concepts, properties of helically polarized sources, operation of elliptic undulators, super-conducting wavelength shifters, in-vacuum undulators and high field normal-conducting devices. Participants were impressed by the wide array of insertion device technology and discussed specific applications of these innovative devices to ILS machines. Status reports from laboratories engaged in ILS machine construction were heard from Armenia, Australia, Canada, China, France, India, the United Kingdom and the United States. Additional status reports on operational facilities in China, Japan, and Korea helped elucidate issues associated with on-line machines.

The morning of Day 2 featured focus sessions on beam line technology, electron beam stability and vacuum technology. Issues in beam line technology include production of faithful photon beam optics and performance of specific beam line components (filters, mirrors, monochrometers, etc). The recent application of refractive lenses in the X-ray regime was compared to more conventional reflective focusing techniques. A review of circular polarized beam line components and plans for beam line build-out at new and existing SR sources were presented. The session on electron beam stability focused on sources and mitigation of electron beam motion from DC to several kHz. Advanced girder design and stabilization techniques, in-situ beam-based magnet alignment and tunnel temperature control can reduce ambient beam motion to the sub-micron level over time scales extending up to several days. Mirror feedback applied on the photon beam lines shows promise to reduce jitter by an additional order of magnitude. Alternative vacuum chamber fabrication techniques based on aluminum, stainless steel and copper were presented. Although any of these materials can be used, factors including local manufacturing experience, vacuum-induced stress handling, power loading and in-situ bake out must be considered before selecting the proper chamber material for the specific application. A trend toward deep-drawn stainless steel fabrication for intermediate-energy light sources is evident, with designs for machine/weld clamshell fabrication in either aluminum or copper also in use.

The afternoon of Day 2 included parallel sessions on photon beam line applications and radio frequency drive systems. Innovative electron beam manipulations and progress in beam line engineering include femtosecond slicing of the electron beam to produce extremely short x-ray pulses and robotic handling of crystallized protein samples for high throughput. An advanced scanning microscope at the ALS and a trace-profiler constructed in-house at SSRF were presented along with XAFS science at Heifei and plans for beam line construction at Indus I and II. The RF forum featured a general plenary talk on systems for synchrotron light sources, developments in the field of HOM-damped cavities (US, Germany, Japan) and an overview of the Cornell-style super conducting RF system under construction at Accel for Taiwan and the Canadian Light Source. Phase modulation for beam dynamics control and application of 3rd harmonic cavities in Japan were presented.

The morning of Day 3 began with parallel sessions on high power beam line components and orbit feedback technology. For high current, intermediate-energy light source applications photon beam lines are subject to intense radiation beams from either normal or super conducting insertion devices. Power loads from different types of insertion devices were discussed and optics required to handle the power loading reviewed. In particular, high stability first mirrors and liquid-nitrogen monochrometers have emerged as critical technologies. Two orbit feedback systems were presented from ESRF and NSLS. The trend in fast orbit feedback is to acquire complete sets of BPM data on a 1-4 kHz clock cycle to produce closed-loop bandwidths approaching 200 Hz. Modern orbit feedback systems have completely digital architecture and utilize fibre optic lines for communication. Even faster systems utilizing high-speed microprocessors and/or DSP technology are utilized for longitudinal and transverse bunch-bunch feedback systems.

The afternoon session of Day 3 was dedicated to future trends in light source development. In particular, operational issues and electron beam lifetime measurements observed with a low energy beam at the ESRF with were presented. Based on projections that the ‘ultimate’ low emittance storage ring light source might have a 1-2 km circumference with an intermediate energy beam, these results give a look at what might be expected in the future. Top-up mode at the APS was then presented. The results indicate that not only is top-up possible, but it might be necessary for future machines now in the planning stages. The extreme case of top-up is the electron-recirculating linac (ERL) as presented by representatives from Novosibirsk. In the ERL, a very low emittance beam emanating from a photocathode gun cycles through a CEBAF-like accelerating structure servicing high field, small gap undulators to produce high brightness photon beams rivaling even FEL sources. In closing, Professor Winick presented a sweeping overview of synchrotron light sources from their original inception through the years of parasitic operation, second and third generation sources and finally projections for build out of the ILS generation of machines and prospects for performance of fourth generation synchrotron light sources.

In summary, it is important to point out that two of the main themes at SSILS were to share innovative design concepts emerging from different laboratories and to provide for exchange of ideas between accelerator and beam line scientists. In this respect, the 25th ICFA Workshop on Beam Dynamics was extremely successful as it brought scientists together from a range of geographical regions and scientific disciplines for discussion on the future of intermediate energy light sources. The local organizers of the Symposium provided wonderful hospitality and excellent opportunities for informal interactions among the participants during the reception, the on-going poster session, the workshop banquet and night tour of the vibrant city of Shanghai. Proceedings of the 25th ICFA workshop are now in press.

5.1.4 Summary of 23rd ICFA Beam Dynamics Workshop on High Luminosity e+e- Colliders

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The 23rd ICFA Beam Dynamics Workshop on High Luminosity e+e- Colliders was held October 15-19, 2001, in Ithaca, NY, hosted by Cornell University's Laboratory of Nuclear Studies, which operates the CESR collider.

Participation was light in the aftermath of the September 11 event, however, the 17 participants from outside of Cornell represented well most of the critical topics facing e+e- circular colliders. After assessing the interests of those present and the contributed papers, the working group chairs agreed to coalesce the 4 working groups into 2 – "Collective Effects, RF & Feedback" and "IR, Optics, Operations, Instrumentation & injection." A suggestion was made and accepted to turn two of the working group sessions into Beam-beam interaction joint sessions since most of the participants expressed interest in this topic.

Reports from several machines on important accelerator physics topics filled the first day's agenda.

Leading off the reports, both asymmetric B factories reported achieving luminosities well in excess of 4 x 10^{33} cm^{-2}-sec^{-1} and beam-beam parameters over 0.05 (though in asymmetric colliders determining each of the 4 beam-beam parameters is non-trivial). In both machines the electron cloud instability in the positron (low energy) ring is a primary factor in determining performance. Adjustment of the compensation of coupling from the experiment solenoid and the effects of high currents are important issues in both machines. Reports were made by Y. Funakoshi and U. Wienands

D. Rubin reported on CESR where compensation of solenoid coupling has also received attention. Measurement of coherent beam response using the BPM system is used to correct local coupling. The multi-bunch / bunch train operation in CESR has led to extensive study of parasitic beam-beam interactions (89 total !) and coherent effects on closed orbits and betatron tunes.

Nonlinearities in wiggler magnets at DAΦNE are a focus of study, described in a report by M. Boscolo. The wigglers provide half of the radiation damping in the machine, but introduce a significant cubic field nonlinearity (b3 multipole term) having an impact on performance. Tunable octupoles will be installed to compensate these effects. Experiment backgrounds (primarily from Touschek losses) have limited beam currents. New scraper configurations are providing some improvement.

Accelerator activities at BINP, Novosibirsk, presented by I. Koop, include operation of VEPP-4M at 1.5 GeV and construction of VEPP-2000, a 2 x 1 GeV machine with round beams and the VEPP-5 pre-injector complex. Work presented on VEPP-4M includes dynamic aperture measurements and determining polarization from variation in Touschek lifetime. VEPP-2000 will use round beams and solenoid focusing to reach a luminosity of 1 x 10^{32} cm^{-2}-sec^{-1} in the 1-2 GeV c.m. energy regime.

R. Talman presented a report on LEP operation prepared by M. Lamont (whose flights were cancelled just before the workshop). With a transverse damping time of only

80 turns at 100 GeV, LEP data provide a unique insight into beam-beam interactions. The dependence of the vertical beam-beam parameter on both bunch charge and energy was measured, implying a dependence on the damping decrement of $\xi_y \propto \delta^{0.4}$. To add the last 3.5 GeV of energy, several resourceful tricks were used, including changing RF frequency and increasing the effective length of bends using steering magnets.

T. Sen discussed the issues of a very large electron-positron collider which could be placed in the proposed VLHC tunnel. Significant preliminary design work has been done, addressing issues such as IR chromaticity compensation, limitations to optics design, cell parameters, intensity limits, etc. A 200 GeV (beam) energy machine might have beam-beam parameters of 0.18 using LEP based scaling and reach 8.8 x 10^{33} cm^{-2}-sec^{-1} with 50 MW/beam of synchrotron radiation.

All at the workshop missed the presence of BEPC representatives who were unable to obtain visas for the workshop.

The Wednesday plenary session covered special topics. J. Seeman outlined parameters for a "generic" 10^{36} (1 pb^{-1}/sec) luminosity machine to meet the needs for the next level of B physics. KEK has presented a conceptual plan for a 10^{35} upgrade to KEKB. Reaching 10^{36} will require a new machine designed for continuous injection, very small β_y*, and 10-30 ampere beam currents. The challenges to accelerator technology of such a machine are clearly substantial.

J. Flanagan summarized presentations in the Two-Stream Instability workshop held earlier in the month in Tsukuba. The workshop covered calculations and measurements for electron cloud, dust, and ion effects from several laboratories.

R. Erickson discussed methods used at PEP-II to maximize the accelerator operating duty cycle. Interesting statistics include: the time to fully recover collider performance after a shutdown is roughly equal to the length of the shutdown; and power supplies are the single largest source of lost time.

M. Neubert gave an excellent overview of the physics potential of a Super-B Factory such as described by J. Seeman. He explored several possible future scenarios in precision CKM physics, rare and forbidden B decays, and τ and Charm physics. He concludes that the long-term future of B physics will be a comprehensive analysis of rare and extremely rare decays, for which lepton colliders will have significant advantages over hadron machines. 10^{36} scale luminosity will be required to take full advantage of B physics.

The working group meetings were active and engendered extensive discussion on a wide range of topics. While the number of contributed papers was reduced by travel problems (and the coincidence with the startup of both KEKB and CESR), the variety of interesting topics presented resulted in some detailed discussion, often continuing beyond the nominal session ends.

In the IR, Optics, & Operations working group papers were presented by M. Boscolo, I. Koop, Y. Nosochkov, D. Sagan, Y, Funakoshi, U. Wienands, and Y. Yan on experiment backgrounds, optics measurement and correction, measurement of energy acceptance and Touschek lifetime, and some observations on limits to β_y*.

While the several machines represented had specific unique features (though the two asymmetric B factories had much in common as would be expected), the working group found several common issues. Achieving the design compensation of coupling from the experimental solenoid has required a determined effort in all machines. Lack of proper compensation was a major impediment to achieving the expected beam-beam space charge parameter ($\xi_{x,y}$) in the early stages of operation. Other effects limiting $\xi_{x,y}$ varied among machines – electron cloud instability, machine non-linearities, multiple parasitic crossings. Both B factories plan to increase luminosity by adding bunches, reducing the minimum bunch-to-bunch spacing. Initial tests at KEKB suggest some beam dynamics effects – possibly interaction between ECI and BBI – will have to be overcome to achieve this. Both machines face potential ECI issues with higher linear charge densities.

Nearly all machines have experienced temporary current limits due to heating of vacuum chamber components, however ECI appears to be the most serious limit. The chosen remedies at this time are further lowering of the secondary emission coefficient and putting positrons in the high energy ring.

In the combined beam-beam interaction and collective effects sessions beam-beam observations were reviewed from CESR, PEP-II, KEKB, VEPP-2M, VEPP-4, and HERA-e by M. Palmer, J. Seeman, Y. Funakoshi, A. Valishev, E. Simonov, R. Talman, J. Seeman, and T. Sen. Presentations on BBI theory, simulation, and instrumentation were made by R. Talman, B. Schmekel, J. Rogers, J. Seeman, T. Sen, V. Shiltsev, Y. Cai, and A. Valishev.

Other collective effects covered included observations (T. Ieiri, J. Flanagan, A. Temnykh, M. Boscolo, J. Seeman), and theory/simulation (S. Heifets, J. Flanagan).

A. Valishev reviewed calculations of the beam-beam head-tail coupling and showed experimental data from VEPP-2M of head-tail modes vs. bunch current which were in excellent agreement with the calculations.

R. Talman described the dependence of $\xi_{y,sat}$ on damping decrement, δ, in terms of dominant x-y resonances in the tune plane. In his model $\xi_{y,sat} \propto \delta^k$ where $1/3<k<1$ depending on the order of relevant resonances at the operating point.

Several people discussed electron cloud effects. The anti-chamber in PEP-II clearly helps control ECI effects, but KEKB has had comparable success with a combination of solenoids and processing. A remaining difference between the machines is that micro-gaps are effective in PEP-II, but appear not to help in KEKB. T. Ieiri presented tune shift vs. bunch position in train data clearly showing growth and decay. S. Temnykh showed tune shift vs. trailing distance between two bunches. Data included observation of “negative space charge” effects for electrons.

Impedance measurement data from KEKB and DAFNE showed general (10-20%) agreement with design values, where available, for Z/n, $Z_\perp$, and k_{HOM}.

Multi-bunch tune shifts resulting from lack of cancellation of horizontal and vertical wake fields in flat beam pipes were measured at KEKB and presented by T. Ieiri.

V. Shiltsev described the electron lens used to individually trim tunes of protons in the Tevatron. Application to electron machines would be straight forward.

The collective effects working group summarized the salient issues for performance improvement as:

Beam-beam interaction – work on beam-beam models until they are really predictive; explore the round beam option (VEPP-2000, CESR-c)

Two- (or three-) stream instabilities – Simulations and models need to predict effect with much better precision and include all important physics (ions? bunch length effects?). Vigorous experimental programs help.

Geometrical impedance – 3-D modelling of all structures is necessary to avoid surprises in impedance or loss factor. Investigate coherent synchrotron radiation effects.

Feedback for BBI – Long range BBI creates need for bunch-by-bunch correction of collision offset, tunes, (beam sizes…?). Hardware development: fast kickers, RFQ's, electron lens….

Papers will be posted on the workshop web pages as they are available. The URL is

www.lns.cornell.edu/icfa/

5.2 ICFA Beam Dynamics Newsletter

5.2.1 Editors

5.2.2 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.

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

5.2.3 Categories of Articles

The categories of articles in the newsletter are the following:

1. Announcements from the panel

2. Reports of Beam Dynamics Activity of a group

3. Reports 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 are 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. Editorial
   All articles except for 6) 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 example below.
   Each article should have the title, author's name(s) and his/her/their e-mail address(es).

5.2.4 How to Prepare the Manuscript

Instructions can be found in WWW at

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

5.2.5 World-Wide Web

Recent issues of this newsletter are available through the World-Wide-Web via the address given below. This is now intended as the *primary method of communication.* The home page of the ICFA Beam Dynamics Panel is at the address

http://wwwslap.cern.ch/icfa/

This Web page provides access to the Newsletters, information about Future and Past Workshops, and other information useful to accelerator physicists. There are links to pages of information of local interest for each area.

5.2.6 Distribution

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

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

* including former Soviet Union.

** For mainland China, Chuang Zhang (zhangc@bepc3.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 wish to receive it regularly can request this from one of the distributors. In order to reduce the distribution cost, however, please use the Web as much as possible. In particular, if you no longer need a paper copy, please inform the appropriate distributor.

5.2.7 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

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

5.3 ICFA Beam Dynamics Panel Members

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The views expressed in this newsletter do not necessarily coincide with those of the editors. The individual authors are responsible for their text.