CHALLENGES FOR BEAMS IN AN ERL EXTENSION TO CESR

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Abstract

Cornell University is planning to build an Energy-Recovery Linac (ERL) X-ray facility. In this ERL design, a 5 GeV superconducting linear accelerator extends the CESR ring. Currently CESR is used for the Cornell High Energy Synchrotron Source (CHESS). The very small electron-beam emittances would produce an x-ray source that is significantly better than any existing storage-ring light source. However, providing, preserving, and decelerating a beam with such small emittances has many issues. We describe our considerations for challenges such as optics, space charge, dark current, coupler kick, ion accumulation, electron cloud, intra beam scattering, gas scattering, radiation shielding, wake fields including the CSR wake, and beam stabilization.

INTRODUCTION

Figure 1: Current layout of Cornell's x-ray ERL.

The layout of Cornell's ERL is shown in Fig. 1. Several features have been developed further since the project description at [1]. An injector linac (1) produces 10-15MeV, 100mA beam with 77pC per 2-3ps long bunches for linac A (2). The beam is sent into a 2820GeV Turn Around (3) and is accelerated in linac B (4) to 5GeV for x-ray experiments in the undulator section (5). The beam is then returned through CESR (6) and the North undulator section (7) to linac A for deceleration, followed by a second Turn Around (8) at 2190GeV and by linac B, leading to the 10-15MeV beam dump at (9). This ERL is an extension to the existing CESR storage ring, and it is planned to reuse much of the equipment in CESR.

The spectral brightness of x-ray ERL light sources can be larger than that of ring-based light sources because each bunch experiences radiative emittance growth for one pass, and not for many hundreds of turn as in a storage ring. Furthermore the electron beam's energy spread can be smaller in an ERL, so that undulators with more poles can be used, and the optics can be very flexible, because in a one pass accelerator nonlinear resonances are generally not important.

However, ERLs have some specific beam dynamics problems, most of which are associated with the deceleration of particles. This deceleration is needed to recover the beam energy and to use it for the acceleration of new particles. But any energy deviation produced at high energy, for example by scattering, increases strongly relative the be beam's energy, and transverse oscillation amplitudes are anti-damped by the square root of the deceleration ratio. Here we present the status of Cornell's approach to beam-dynamics issues of x-ray ERLs.

EMITTANCE CONTROL

Space Charge: Simulations have shown that space charge has to be considered to approximately 100MeV to optimize the ERL for emittances as small as 0.3mm mrad [3]. A detailed description of the CSR wakes applicable at the injection energy of the ERL has been derived in [4]. This method has been implemented in `Bmad` [5] and `GPT` [6], which has been used to show that CSR forces should not damage the emittance within the bends of the ERL injector system. In much of the injector, the beam dynamics is space charge dominated. In order to obtain the small emittances for which the ERL is designed, emittance compensation has to be employed and the fields of the injector as well as the charge distribution of the bunches have to be carefully matched. Cornell is currently prototyping an ERL injector to show experimentally that these small emittances can actually be achieved.

The high voltage photo-emission DC gun of this prototype has already been operated. It has transverse shaping with a commercial nonlinear lens, and custom designed longitudinal beam shaping [7]. Several significant results have been achieved with this installation: (a) While most

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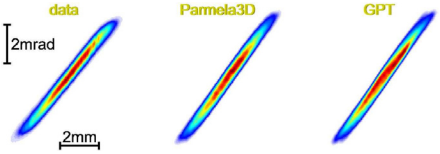

Figure 2: Phase-space measurements after the prototype ERL gun, see [8, 9].

of these tests were performed at only 250keV, they showed that the measured vertical beam distribution can well be described by simulations, as for example in Fig. 2, including inhomogeneous laser beams, misalignments of the laser spot on the cathode and of solenoids. It would be a great success for ultra-small emittance beams if higher gun voltages lead to phase-space distributions that are similarly close to simulations. (b) Furthermore, it has been demonstrated with low bunch charges that Cornell's diagnostics can resolve the desired very small ERL emittances. (c) Up to 20mA have been produced out of the gun already.

Optics and Optics Control: In the high energy beam transport of an ERL, optics considerations are dominated by the need for (a) low radiative emittance growth, (b) isochronicity and (c) dispersion control to 2nd order, and (d) suitable optics functions in undulators.

In the linac of every ERL, one has to find two optics, one for the accelerating and one for the decelerating beam. For the Cornell ERL we have investigated the possibilities of having three beams within one linac in order to provide a short pulse (100fs), large bunch charge (1nC) beam of below 1mA in addition to the 100mA energy-recovered high spectral-brightness beam. The additional beam would have approximately 3GeV and would be accelerated only by linac B to be available for short pulse experiments for example in a seeded FEL. We showed that the third beam has to be injected with 800MeV into linac B to limit beam functions to approximately 100m for all beams. Simultaneous operation with three beams would, therefore, be very costly.

Coupler Kick: The deviation from rotational symmetry in the cavities' input coupler gives rise to time dependent transverse fields which can increase the emittances. Several options for limiting the effect of coupler kicks have been described in [10]. It has been found that the emittance is sufficiently preserved when a stub on the beam pipe opposite the input coupler symmetrizes the field in that region.

Ion Accumulation and Electron Cloud: An analysis on how ions accumulate in the ERL's beam potential and how this can perturb the electron's motion is described in [11]. A time of flight spectrometer has been constructed to determine the ion species that accumulate in the ERL prototype injector. In a collaboration with Princeton, the two stream instability between electrons and ions is being investigated.

In a collaboration with the University of Southern California the effect of the electron cloud on the ERL's electron beam is being studied.

BEAM STABILIZATION

Orbit Feedback: It has been investigated in [12] how accurately power supplies have to be controlled in order to limit orbit vibrations to 10% of the beam size. The dipoles in achromats are powered jointly so that power supply fluctuations create closed dispersive bumps. However, simultaneous fluctuations of quadrupole strengths let the dispersion leak out of these achromats and induce horizontal orbit fluctuations. Because the beam is much narrower in the horizontal plane than in ring-base light sources, this restriction is particular to an ERL. Limiting it requires stabilizing dipole and quadrupole power supplies to 10^{-4}. The orbit stabilization needed for an x-ray ERL have nearly been achieved in the vertical plane of modern light sources.

Beam-Breakup Instability: Because the re-circulative beam-breakup (BBU) instability can limit the current in ERLs, detailed theoretical studies have investigated how much current the Cornell ERL should be able to transport before the Higher Order Modes excite this instability. Simultaneously, BBU experiments in collaboration with TJNAF have shown satisfactory agreement between theory and experiment.

PARTICLE LOSS RATES

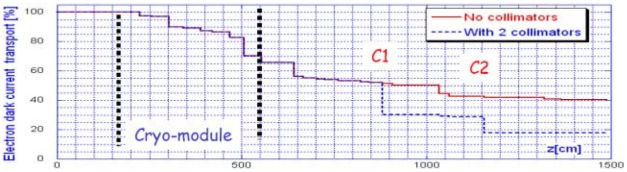

Figure 3: Loss of Halo from inter-bunch current and its collimation at the end of the ERL injector.

Beam Halo: There are many processes that can contribute to the production of beam halo, including stray light from the photo-emission laser, diffusion of electrons in the cathode, field emission at the cathode, spontaneous laser-radiation between pulses, field-emitted electrons in the early part of the linac that get captured and accelerated, *etc*. The halo from electrons that leave the cathode in the bunch gap has been tracked through the ERL injector to establish acceptable limits. Figure 3 shows that most of the halo lost after the cryomodule can be collimated at two shielded places. Because of adiabatic damping, the remaining halo shrinks during acceleration and is transported to high energy, but can be lost during deceleration. The losses establish limit on the inter-bunch current.

Gas Scattering and undulator damage: Scattering on rest gas can produce large enough angles in the vertical to produce particle loss in undulators. In [13] the expected loss rates and lifetimes of undulators is investigated.

Touschek scattering often determines the lifetime in storage rings, and Intra-Beam Scattering contributes to emittance excitation. Because the emittances are exceedingly small in the ERL design, these scattering effects are even more severe and can produce larger loss rates, which are modeled as in [14].

Radiation shielding: The collimators that protect each undulator from electron/gas scattering losses are made of tungsten. To provide sufficient radiation lengths, they are 7cm long with an opening of 5mm by 40mm. The power load is small and cooling is not problematic.

The total Touschek loss current is calculated to 20nA, with most being lost during deceleration at low energies. The North and South undulator sections have to be protected by collimators that have to absorb about 1nA; they then limit the loss current in the user region to a few pA/m, similar to the load in todays storage rings.

Undulator radiation: While the energy spread from ERL beams can be significantly below that in a storage ring, and while this allows for significantly longer undulators, care has to be taken that the undulator radiation does not scrape at the poles of these long, narrow gap devices. The power load on the vertical undulator walls can otherwise reach a destructive level of kW/m.

Wake Fields, including CSR: The sum of all wake fields limits the shortest bunch length that can be obtained in the ERL. Time of flight terms can be controlled in the many bends along the transport lines of the ERL to suppress the bunch length down to below 100fs for low bunch charges. For the bunch charge of 77pC, however, the energy spread that is created by wake fields can become unbearably large relative to the energy at the dump. In [15] and [16] it is discussed how nonlinear time of flight terms within the linac can be used to reduce the energy spread at the dump when two Turn Around loops are used between linac A and linac B, as shown in Fig. 1 for Cornell's ERL.

OTHER R&D CHALLENGES

There are many other R&D challenges for Cornell's ERL. These include the Cryomodule [17, 18, 19], cavity and RF control [21, 20], optics correction and feedback, the fast ion instability, BPMs for two beams, maintenance of low pressure, development of x-ray beamlines, to mention a few. More has been said about these subjects in [1].

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REFERENCES

[1] G.H. Hoffstaetter et al., Progress toward an ERL Extension to CESR, Proceedings PAC07, Albuquerque/NM (2007)

[2] These proceedings of EPAC08, Genoa/IT (2008)

[3] I.V. Bazarov, T. Miyajima, private communication (2008)

[4] D.C. Sagan, G.H. Hoffstaetter, C.E. Mayes, U. Sae-Ueng, Extended 1D Model of Coherent Synchrotron Radiation including Shielding, submitted to Phys. Rev. ST-AB and arXiv0806.2893v1 (2007)

[5] D.C. Sagan, G.H. Hoffstaetter, C.E. Mayes, U. Sae-Ueng, CSR including Shielding in the Beam Dynamics Code BMAD, in [2]

[6] I.V. Bazarov, T. Miyajima, Calculation of Coherent Synchrotron Radiation in General Particle Tracer, in [2]

[7] I.V. Bazarov et al., Efficient temporal shaping of electron distributions for high brightness photoemission electron guns, Phys. Rev. STAB 11, 040702 (2008)

[8] I.V. Bazarov et al., Benchmarking of 3D space charge codes using direct phase-space measurements from photoemission high voltage DC gun, submitted to Phys. Rev. ST-AB and arXiv 0806.2595v1 (2008)

[9] F.E. Hannon et al., Phase-Space Tomography Using the Cornell ERL DC Gun, in [2]

[10] B. Buckley, G.H. Hoffstaetter, Transverse Emittance Dilution due to Coupler Kicks in Linear Accelerators, Physical Review ST-AB 10, 111002 (2007)

[11] G.H. Hoffstaetter, C. Spethmann, Equilibrium ion distribution in the presence of clearing electrodes and its influence on electron dynamics, Phys. Rev. ST-AB 11, 014001 (2008)

[12] C. Song, G.H. Hoffstaetter, Magnetic Field Error Sensitivity in an Energy Recovery Linac, Report Cornell-ERL-07-03 (2007)

[13] A.B. Temnykh, M.P. Ehrlichman, G.H. Hoffstaetter, Beam Losses Due to Intra-Beam and Residual Gas Scattering for Cornell's Energy Recovery Linac, in [2]

[14] G.H. Hoffstaetter, M.P. Ehrlichman, A.B. Temnykh, Intra-Beam Scattering in Linear Accelerators, Especially ERLs, in [2]

[15] G.H. Hoffstaetter, Yang Hao Lau, Compensation of wake-field-driven energy spread in Energy Recovery Linacs, arXiv:0805.2637v1 (2008)

[16] G.H. Hoffstaetter, M.G. Billing, Yang Hao Lau, Wake-field Compensation in Energy Recovery Linacs, in [2]

[17] E.P. Chojnacki et al., Design and Fabrication of the Cornell ERL Injector Cryomodule, in [2]

[18] P.A. McIntosh et al., An Update of the Daresbury International Cryomodule Collaboration (DICC) Project, in [2]

[19] S.A. Belomestnykh et al., First Test of the Cornell Single-cavity Horizontal Cryomodule, in [2]

[20] M.U. Liepe et al., First Test Results from the Cornell ERL Injector Cryomodule, in [2]

[21] S.A. Belomestnykh et al., Commissioning of the Cornell ERL Injector RF Systems, in [2]

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Caterina Biscari, INFN-LNF
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