DEVELOPMENTS FOR CORNELL'S X-RAY ERL*

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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 which is currently used for the Cornell High Energy Synchrotron Source. Here we describe some of the recent developments for this ERL, including linear and nonlinear optics incorporating the existing CESR lattice elements and a dual turnaround, undulator developments, optimization of X-ray beams, progress in calculations of coherent synchrotron radiation, and the technical design of ERL cavities and cryomodules.

INTRODUCTION

The potential for excellent quality of X-ray beams from low-emittance electron beam produced by a 5-GeV superconducting energy-recovery linac (ERL) is motivating an intensive development study at the Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE). Table 1 compares the ERL design parameters to those of existing light sources. We report on design progress achieved since EPAC08 [1].

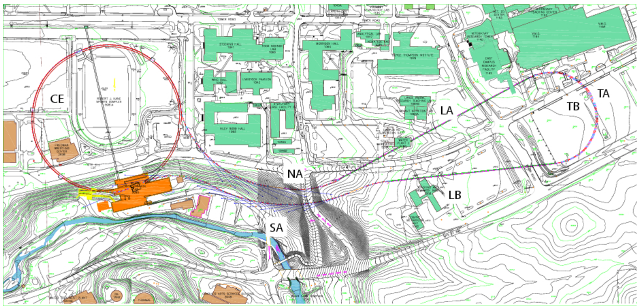

Figure 1: Proposed layout of the 5-GeV superconducting X-ray energy recovery linac design on the Cornell campus.

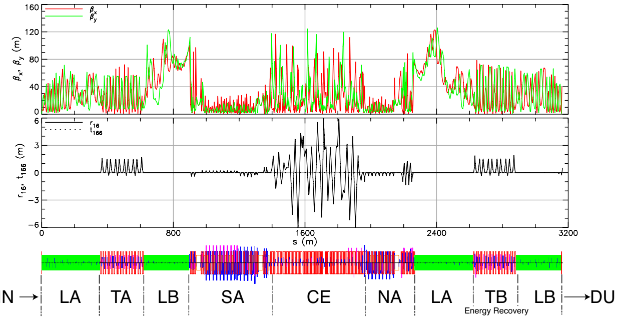

Figure 2: Dual-pass beta functions and dispersion.

Table 1: Operating parameters for the proposed Cornell ERL compared to existing light source facilities.

Name	Energy (GeV)	Current (mA)	Emittance (pm-rad)	σ_z/c (ps)
ESRF	6	200	4000	20
APS	7	100	2500	20
SPring 8	8	100	3000	13
ERL mode A	5	100	30	2
mode B	5	25	8	2
mode C	5	1	500	0.1

OPTICS

The present status of the ERL layout and X-ray beamlines is shown in Fig. 1. A detailed description of the optics design principles, methods, and results can be found in Ref. [2]. Optics design constraints include preservation of the small beam size and emittance and controlling the first and second-order dispersion and time-of-flight terms throughout the undulator arcs providing the X-ray beamlines. The dual-pass sections of the ERL require simultaneous optics optimization at two beam energies. These purposes are served by the TAO accelerator simulation package which remains under active development at Cornell [3]. Optimization procedures are highly modular, allowing quick, convenient re-optimization of the linac, turnaround, arc and CESR sections or subsections thereof. The complete beta functions and dispersion, including the energy recovery pass, are shown in Fig. 2. The capability of this software utility has been recently upgraded with features useful for the design of ERL-based light sources: 1) multi-pass beamline elements, 2) calculations of beam-breakup stability thresholds, 3) tracking through wakefields, 4) modeling of coherent synchrotron radiation, 5) modeling of intra-beam and Touschek scattering, 6) simultaneous optics optimizations for multiple beams in a single linac, 7) spurs for extracted beams, and 8) X-ray beamline design.

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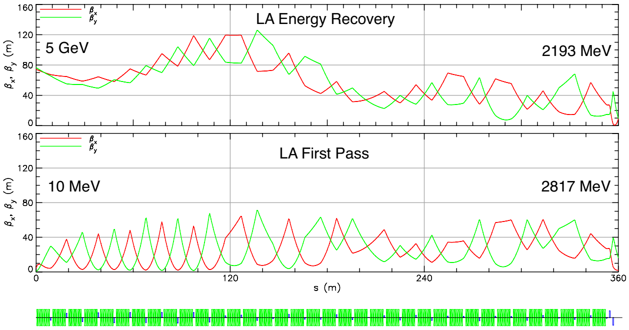

Figure 3: Beta functions for the first pass (accelerating) beam and energy-recovery (decelerating) beam in LA.

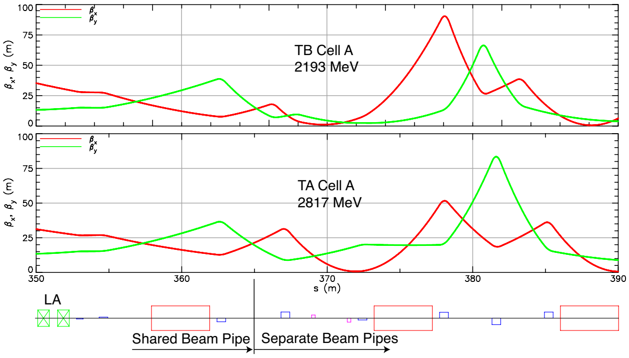

Figure 4: Beta functions for the high- and low-energy turnaround entrance cells.

North and South Linacs and Dual Turnaround

The linac sections comprised of superconducting RF (SRF) cavities, quadrupoles, and steering correctors, have been redesigned such that the first- and second-pass beams pass through the new dual turnaround with differing energies. The high-energy North Linac (LA) now accelerates/decelerates the beam by 2.8 GeV in 36 cryomodules, while the South Linac (SA) is comprised of 28 such cryomodules. This configuration will permit wake field compensation as described in Ref. [4]. Figure 3 shows the resulting beta functions for LA. The optimization criteria keep the beta functions small and match the low-energy beam to the Twiss parameters from the injector. The beta functions of the entrance sections of the two turnarounds (high-energy TA and low-energy TB) are shown in Fig. 4. The two passes in these sections are optimized simultaneously to match into their respective distinct arcs.

CESR and the South and North Arcs

The layout of the North (NA) and South (SA) Arcs and the X-ray beamlines in the proposed new laboratory building is shown in Fig. 5. The first of the nine undulators in the South Arc and the last of the eight undulators in the NA are 25 m long. The rest are 5 m long. The optical design of the SA cells containing 5-m undulators begins with the undulator followed by a two-bend achromat. The bends provide an angle between the beginning and end of the cell so that the beamlines emitted from the undulators of consecutive cells have sufficient clearance from the shielding wall after 30 m to equip the X-ray beamlines. The Twiss parameters at the beginning and the end of the cell are fixed by the requirements of prior and succeeding undulators, where the vertical and horizontal beta functions are chosen to be equal to half the length of the undulator at its center. Seven quadrupole magnets, arranged symmetrically about the center of the achromat, are used to match these requirements, with the center three additionally used to focus the dispersion and its slope to zero at the end of the second bend. As with the previous sections, emittance growth is reduced as much as possible while maintaining the Twiss parameter and dispersion requirements. Two sextupole magnets placed symmetrically about the center of the achromat are used to make the cells achromatic to second order through the two bends. The result of the optics optimization for such an undulator cell in the SA is shown in Fig. 6.

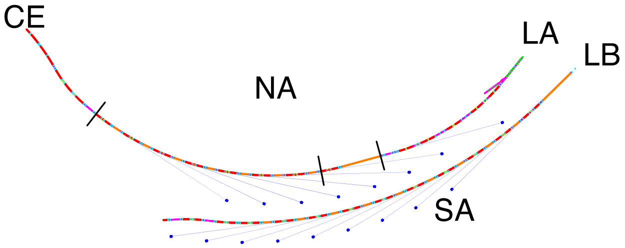

Figure 5: Layout of the North and South Arcs.

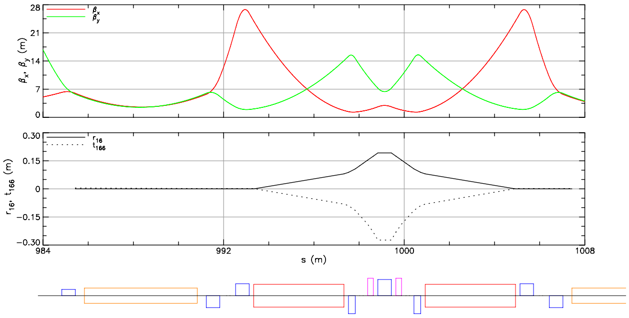

Figure 6: Beta functions and first- and second-order dispersion in the 5-m undulator sections in SA.

These NA and SA sections have been matched to the elements in the existing CESR layout. About 70% of the CESR ring is used. The first- and second-order CESR optics have been redesigned to meet Twiss, time-of-flight and second-order dispersion criteria. The resulting emittance growth, shown in Fig. 7, is very small in the SA and only significant in the CE section. However, the existing CESR element layout is not sufficient to permit operation in the bunch compression mode C, which will be available in an extension to the SA, or following a custom upgrade of the magnet layout in the CESR ring.

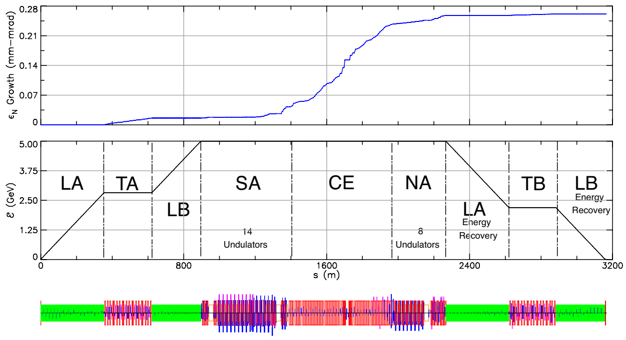

Figure 7: Radiative emittance growth ϵ_N (mm-mrad) and total energy $\mathcal{E}$ (GeV) including the energy recovery pass.

Coherent Synchrotron Radiation

The minimum bunch length which can be achieved in the ERL is limited by the sum of the wake fields. A primary consideration for the 100-fs bunch length planned for the bunch-compression mode C is the contribution of wake fields from coherent synchrotron radiation. Significant progress has been made in developing calculational methods for quantifying this contribution, enabling the investigation of various shielding effects [5, 6].

RF CAVITY AND CRYOMODULE DESIGN

The cw duty factor and low emittance drive the choice to use SRF technology. The cryomodule for the ERL will be based on TTF technology, but must have several unique features dictated by the ERL beam parameters. The main deviations from TTF are that the HOM loads must be on the beamline for sufficient damping, that the average power through the RF couplers can be as low as 2 kW, and that cw beam operation introduces higher cryogenic heat loads. Much has been learned from the design, construction and commissioning of the cryomodule for the prototype ERL injector now in operation [7, 8]

The SRF cavities must have low RF losses to minimize refrigeration and strong HOM damping to preserve low emittance and prevent beam breakup [9]. A design to meet these requirements has been developed [10].

UNDULATOR DEVELOPMENT

A novel design for a compact, round bore undulator with full X-ray polarization control has been developed for use at the Cornell ERL and a 30-cm-long, 5-mm-diameter bore model has been built [11]. The newly developed technique for soldering NdFeB permanent magnet blocks allows a 40% (100%) stronger magnetic field in linear (circular) polarization mode as compared to existing undulators with similar gap. The magnetic field strength is controlled by relative longitudinal adjustment of the two magnet arrays, as is the X-ray polarization control.

X-RAY BEAMLINES

Space has been allotted for four beamlines in Wilson Lab, including preserving the existing G-line and introducing a new 25-m undulator. The ERL can thus accommodate three 25-m undulators and nineteen 5-m undulators.

A variety of X-ray beam-line design projects are underway. These include a diffraction-limited scattering line, a short pulse/cw line, an ultra-short pulse, high-repetition-rate line for time-resolved scattering and spectroscopic structural studies, a highly coherent, high-flux line for diffractive imaging and dynamics studies of bulk materials, interfaces and biological samples, as well as a beamline for meV-resolution inelastic X-ray scattering.

CONCLUSION

The conceptual design for a dual-pass energy-recovery-linac-based X-ray source at Cornell is under active development. Complete linear and second-order optics have been designed incorporating the existing CESR ring and optical elements, and a dual-turnaround scheme for wake field compensation has been included. Progress has been made in the design of X-ray beamlines. A novel design for an undulator which controls X-ray polarization is in the prototyping stage. Many ongoing aspects of the design effort exceed the scope of this report, including vacuum design, instrumentation, siting issues, intra-beam scattering estimates, beam breakup computations, as well as work on collimation and shielding. Much is yet to be learned from operation of the injector prototype as progress continues toward a complete conceptual design report.

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[6] D.C. Sagan, G.H. Hoffstaetter, C.E. Mayes, and U. Sae-Ueng, Phys. Rev. ST-AB **12**, 040703 (2009)

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Thank you!

The 23rd Particle Accelerator Conference came to a close at 4:45 pm Friday 8th May with concluding remarks from PAC09 LOC chairman Yuri Bylinsky and a pre-recorded farewell from conference chairman Paul Schmor.

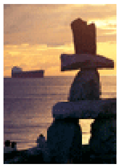
By any measure, this was an outstanding conference as the following statistics demonstrate:

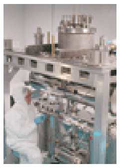
1309 participants, 74 industrial exhibits, 147 students, 197 orals, 1625 posters, 23 satellite meetings. What the statistics cannot capture was the vitality of the meeting: the standing-room-only orals sessions, the enthusiastic and energetic poster sessions, the myriad conversations. Behind the scenes the proceedings office toiled away to produce the permanent conference record formed of papers and speakers slides. By Friday all 1545 of the received contributions had begun processing, and of these 1329 were completed and ready for the final Quality Assurance stage. We owe the proceedings team a vote of thanks. The conference organizers wish also to express their thanks to the speakers, the session chairmen and the delegates for making PAC'09 a resounding success.

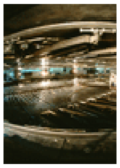
Conference photos are available through this **link**. Conference proceedings will be published at the JACoW Site tentatively by the end of August 2009. Every participant will receive a DVD containing both proceedings and photos in September 2009.

Finally, we wish similar good fortune to the three following conferences: PAC'11 the next in the continuing North American series, to be hosted by Brookhaven National Laboratory in New York City, the IPAC'10 in Kyoto Japan, the first of the 3-year international cycle, and the IPAC'11 in San Sabastien Spain.

Good luck and good bye,さようなら。御幸運をお祈りします。Adiós y buena suerte.







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Book of Abstracts

MO4PB — Parallel Oral LSAFEL

Current Status and Future Perspectives of Energy Recovery Linacs

MO4PBI01

R. Hajima (JAEA/ERL)

Energy Recovery Linacs (ERL) have been successfully operated in three high-power FEL facilities, Jefferson Laboratory (JLAB) IR FEL Upgrade, Japan Atomic Energy Agency (JAEA) FEL and Budker Institute of Nuclear Physics (BINP) THz FEL. The ERLs are now considered a promising candidate for uses as high-power FELs, synchrotron radiation sources, electron cooling devices, electron-ion colliders and Compton X/gamma-ray sources. All these applications are based on the excellent feature of the ERL that is simultaneous attainment of multiple beam parameters: small emittance, short bunch duration and high-average current. In order to overcome technological challenges and realize the above future ERL applications, several R&D efforts have been launched in the world. In this paper, we overview the current status of these R&D programs and envision the future of ERLs.

Commissioning Results with Multi-Pass ERL

MO4PBI02

N. Vinokurov, E. N. Dementyev, B. A. Dovzhenko, N. Gavrilov, B. A. Knyazev, E. I. Kolobanov, V. V. Kubarev, G. N. Kulipanov, A. N. Matveenko, L. E. Medvedev, S. V. Miginsky, L. A. Mironenko, V. K. Ovchar, V. M. Popik, T. V. Salikova, M. A. Scheglov, S. S. Serednyakov, O. A. Shevchenko, A. N. Skrinsky, V. G. Tcheskidov, Y. Tokarev, P. Vobly (BINP SB RAS)

The first stage of Novosibirsk high power free electron laser (FEL) is in operation since 2003. Now the FEL provides average power up to 500 W in the wavelength range 120 - 240 micron. One orbit for 11-MeV energy with terahertz FEL lies in vertical plane. Other four orbits lie in the horizontal plane. The beam is directed to these orbits by switching on of two round magnets. In this case electrons pass four times through accelerating RF cavities, obtaining 40-MeV energy. Then, (at fourth orbit) the beam is used in FEL, and then is decelerated four times. At the second orbit (20 MeV) we have bypass with third FEL. When magnets of bypass are switched on, the beam passes through this FEL. The length of bypass is chosen to provide the delay, which necessary to have deceleration instead of acceleration at the third passage through accelerating cavities. Now two of four horizontal orbits are assembled and commissioned. The electron beam was accelerated twice and then decelerated down to low injection energy. Project average current 9 mA was achieved. First multi-orbit ERL operation was demonstrated successfully.

Developments for Cornell's X-Ray ERL

MO4PBC03

J. A. Crittenden, I. V. Bazarov, S. A. Belomestnykh, M. G. Billing, E. P. Chojnacki, B. M. Dunham, M. P. Ehrlichman, M. J. Forster, G. H. Hoffstaetter, Y. Li, M. Liepe, C. E. Mayes, A. A. Mikhailichenko, H. Padamsee, S. B. Peck, D. Sagan, V. D. Shemelin, A. B. Temnykh, M. Tigner, V. Veshcherevich (CLASSE) D. H. Bilderback, J. D. Brock, S. M. Gruner (CHESS) C. Johnstone (Fermilab)

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 which is currently used for the Cornell High Energy Synchrotron Source (CHESS). Here we describe some of the recent developments for this ERL, including linear and nonlinear optics, tracking studies, vacuum system design, gas and intra beam scattering computations, and collimator and radiation shielding calculations based on this optics, undulator developments, optimization of X-ray beams by electron beam manipulation, technical design of ERL cavities and cryomodules, and preparation of the accelerator site.

MO4PBC04

The Wisconsin Free Electron Laser Initiative

K. Jacobs, J. Bisognano, M. Bissen, R. A. Bosch, M. A. Green, H. Hoechst, K. J. Kleman, R. A. Legg, R. Reininger, R. Wehlitz (UW-Madison/SRC) W. Graves, F. X. Kaertner, D. E. Moncton (MIT)

The University of Wisconsin-Madison/Synchrotron Radiation Center and MIT are developing a design for a seeded VUV/soft X-ray Free Electron Laser serving multiple simultaneous users. The present design uses an L-band CW superconducting 2.2 GeV electron linac to deliver 200 pC bunches to multiple FELs operating at repetition rates from kHz to MHz. The FEL output will be fully coherent both longitudinally and transversely, with tunable pulse energy, cover the 5-900 eV photon range, and have variable polarization. We have proposed a program of R&D to address the most critical aspects of the project. The five components of the R&D program are:

1. Prototyping of a CW superconducting RF photoinjector operating in the self-inflating bunch mode.
2. Development of conventional laser systems for MHz seeding of the FEL, and femtosecond timing and synchronization.
3. Address thermal distortion and surface contamination issues on the photon optics.
4. Investigate advanced undulator concepts to help reduce facility cost and/or extend performance.
5. Perform detailed modeling of all aspects of the FEL, as part of production of a Conceptual Design Report for the FEL facility.