Proceedings of the 2003 Particle Accelerator Conference, 12-16 May, 2003. IEEE Press, NY. Vol. 1, pp 192-194

Proceedings of the 2003 Particle Accelerator Conference

THE CORNELL ERL PROTOTYPE PROJECT *

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Abstract

Synchrotron light sources based on Energy Recovery Linacs (ERLs) show promise to deliver X-ray beams with both brilliance and X-ray pulse duration far superior to the values that can be achieved with storage ring technology. Cornell University, in collaboration with Jefferson Laboratory, has proposed the construction of a prototype ERL. This 100MeV, 100mA CW superconducting electron accelerator will be used to study and resolve the many accelerator physics and technology issues of this type of machine. These studies are essential before ERLs can be confidently proposed for large-scale applications such as synchrotron light sources. Key issues include the generation of high average current, high brightness electron beams; acceleration and transport of these beams while preserving their brightness; adequate damping of higher order modes (HOMs) to assure beam stability; removal of large amounts of HOM power from the cryogenic environment; stable RF control of cavities operating at very high external Q; reduction of beam losses to very low levels; and the development of precision non-intercepting diagnostics to allow beam setup, control and characterization. Our prototype design allows us to address these and other issues over a broad range of parameter space. This design, along with recent progress on understanding these issues, will be presented.

INTRODUCTION

To profit from the smaller transverse and longitudinal emittances that a linac can offer, compared to a circular high energy physics collider or synchrotron light source, it is necessary to be able to accelerate beams to the energies (several GeV) and with the currents (several 100mA) that are typical in these storage rings. This would require that the linac delivers a power of order 1GW to beam. Without somehow recovering this energy after the beam has been used, such a linac would be practically unfeasible.

Energy recovery can be achieved by decelerating high energy electrons to generate cavity fields which in turn accelerate new electrons to high energy. With this, large beam powers that are not accessible in a conventional linac can be produced. ERLs were proposed over 30 years ago. However, to continuously transfer field energy from electrons to the RF cavities and back to new electrons, it is essential that the cavities are continuously filled with field energy. This means that they have to be operated in continuous wave (CW) mode. Since CW normal conducting cavities with high accelerating fields require an unrealistic amount of cooling, and since SC cavities have only recently achieved sufficiently high fields, ERLs have not been technically feasabe for many years.

At TJNAF and at JAERI, SC cavities were used to demonstrate energy recovery for low energy (50 and 17MeV) and low current (5mA) beams. These laboratories made significant achievements and showed they could save most of the energy required for beam acceleration. While for the FEL at TJNAF, the beam power in energy recovery mode is about 4 times higher than that without the recovery, these ERLs never produced beam powers that could not have been produced with a conventional linac. However, since the TESLA collaboration has demonstrated the reliable operation of SC cavities with accelerating field well above 20MV/m, several laboratories have proposed high power ERLs for different purposes. Designs for light production with different parameter sets and various applications are being worked on by Cornell University, BNL, Daresbury, TJNAF, and JAERI (see PAC2003), the University of Erlangen, Novosibirsk (see EPAC2002) and KEK. TJNAF has incorporated an ERL in its design of an electron–ion collider (EIC) for medium energy physics while BNL is working on an ERL–based electron cooler for the ions in the relativistic ion collider (RHIC).

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Since neither an electron source, nor an injector system, nor an ERL, has ever been built for the required large beam powers and small transverse and longitudinal emittances, it is essential to build a prototype facility [1] that can verify the functionality of all essential devices and physical processes before endeavoring onto a large user facility. The Wilson laboratory at Cornell University has proposed to the NSF to build such a prototype and to perform the required proof of principle. This proposal has been favorably reviewed by the NSF and is strongly supported by Cornell University. A decision by the NSF is expected soon.

While Cornell plans an ERL light source [2], knowledge obtained in the ERL prototype facility would profit a scientific community that is much larger than the already very large and diverse group of synchrotron radiation users, and includes medium and high energy physicists working on an EIC and at RHIC.

The Cornell CHESS laboratory currently uses the Cornell Electron Storage Ring (CESR) as a second generation synchrotron light source at 5GeV. As a future light source for this laboratory, an ERL seems ideal. It can enlarge the wide range of applications of third generation light sources by producing beams similar to the CW beams from these modern facilities, albeit with higher brilliance due to the

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* Work supported by Cornell University and US DOE under contract DE-AC05-85ER40150

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much smaller horizontal emittance and possibly smaller energy spread. At the same time, it can serve more specialized experiments that require ultra small emittances for high spacial resolution or ultra short bunches for high temporal resolution [2].

Since CESR is planning to phase down its high energy physics program in about 5 years, we have studied whether CESR components, its tunnel, and its infrastructure could be used to house an ERL facility [3].

A detailed set of parameters has not yet been fixed and can still be influenced by findings from the ERL prototype. The currently planned parameters together with those of the prototype are listed in Table 1.

THE CORNELL PROTOTYPE

Table 1: The Cornell ERL Prototype and light source

Parameter		Prototype	Light source
Energy	(GeV)	0.1	5
Current	(mA)	100	100
Inj. energy	(MeV)	5–15	5–15
Rep. Rate	(GHz)	1.3	1.3
Acc. gradient	(MV/m)	20	20
Q of cavities	(10^{10})	1	1
external Q	(10^7)	2.6	2.6
Charge/Bunch	(pC)	77	77
nominal σ_E	(10^{-3})	0.2	0.2
nominal σ_τ	(ps)	2	2
nominal ϵ_N	(μm)	2	2
short pulse σ_τ	(ps)	< 0.1	< 0.1
microbeam ϵ_N	(μm)	0.2	0.2
Main Linac Cavities		5	≈ 250
Refrigerator@2K	(kW)	0.2	≈ 17

The prototype ERL at Cornell, shown in Fig. 1, is planned to have very similar parameters to the light source facility. The differences are essentially that (a) the prototype injector is only capable of producing 5MeV beam at 100mA and the light source might require a higher energy and thus more injector cavities, (b) the main linac in the prototype has only one cryomodule with only 5 cavities while the full facility has 8 cavities per module and more than 30 cryomodules, and (c) the cost and power consumption of the prototype is significantly smaller. After completion, many parts of the prototype, especially the entire gun and injector, can be used for the ERL light source.

Issues that should be investigated by the ERL prototype before a full-scale ERL user facility is built include:

Gun: Achieving the small normalized emittance of 2μm in the undulators requires around 1μm at the high voltage DC gun, which has to deliver 100mA from its negative electron affinity GaAs photo cathode. Design parameters are 500 to 750kV in a pressurized SF_6 atmosphere, a Ti:sapphire laser operating at 780nm with several Watts at 1.3GHz repetition rate [4]. Such a gun relies heavily on space charge compensation [5] and has never been operated at the required high currents. Furthermore, microbeams with ultra-small emittances of 0.2μm in the undulators are envisioned for high resolution X-ray imaging. Such beams could only be produced with reduced currents.

Injector: The injector is designed to send bunches with 77pC and with emittances of less than 1.5μm into the linac. The injector allows the acceleration of 100mA beam current to 5MeV, with every bucket filled, and of 50 or 33mA beam current to 10MeV or 15MeV when every second or third bucket is filled. Testing will show which injector energy should be chosen for the Cornell ERL light source. Each of the 5 two-cell SC injector cavities couples about 100kW to the beam. The cavities are designed to be dipole-mode-free and are equipped with a symmetric input coupler to avoid a transverse kick. [6, 7, 8].

Halo formation: Space charge forces are most nonlinear for particles at the outside of the beam and can create a dilute halo. Collimating the beam, however, can cause activation and heat load in the cryogenic environment. Collimating at high energy additionally reduces the efficiency by wasting power for electrons that do not participate in the energy recovery. Study of halo formation and its removal will therefore be important.

CSR: Coherent synchrotron radiation (CSR) can significantly increase the transverse and longitudinal emittances, especially for short-bunch operation. CSR is such a complex process that it is essential to verify the accuracy of current CSR simulations.

Cavities and cryomodules: While much will be adopted from the successful TESLA cavities and cryomodules, some modifications are needed for CW operation. These modifications are mainly related to the large HOM power that has to be extracted and to the large heat load of about 40W that has to be cooled at 2K per cavity. For frequencies up to about 3GHz, 4 output HOM couplers of the TTF type are used per cavity. Between the cavities there will additionally be a ferrite beam pipe absorber of the CESR type for frequencies larger than about 3GHz [9].

Cavity control: Due to the high external Q, the width of the cavity resonance is very narrow (50Hz for $Q_{ext} = 2.6 \cdot 10^7$). Controlling the cavity under the presence of microphonic noise thus becomes a challenge [10]. Tests in the prototype will show what maximal Q_{ext} can be achieved.

Beam breakup: While the power required for acceleration limits the beam current in conventional linacs, the required power in an ERL is virtually independent of the beam current. However, the total current is limited by the beam breakup (BBU) instability, which arises when cavity modes that deflect the beam transversely are coherently excited by the recirculating beam and grow faster than they can be damped. The particle optics in the linac and in the return arc has been designed to raise the BBU limit to 100–200mA. However, the BBU limit depends on the detailed HOM damping and HOM spectrum, which cannot be simulated very well.

Short bunches: The ERL light source will have users that

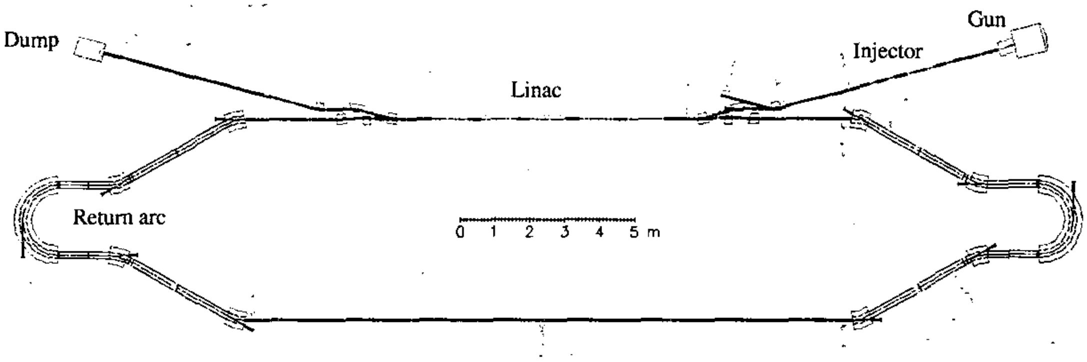

Figure 1: Layout of the Cornell ERL Prototype

require 100fs pulses and users for which a 2ps bunch length is sufficient. While 2ps pulses can be created in the injector by a 20ps laser pulse and subsequent bunching, a 100fs pulse requires additional pulse compression. In order to reduce HOMs, the bunch will be compressed at full energy. A flexible nonlinear bunch compression optics has been designed and will be tested [11].

Phase space: The relative energy spread at high energy of below $0.2 \cdot 10^{-3}$ can increase strongly when the beam is decelerated. If the longitudinal phase space distribution was uncorrelated, the rms energy spread would become at least 20% after deceleration from 5GeV to 5MeV, which may well result in beam loss in the last RF section. The longitudinal phase space therefore has to be manipulated by nonlinear optical elements so that the nonlinear phase space correlation is reduced by the waveform of the decelerating cavities [12].

Dump: To first approximation the energy at the dump is the same as the injector energy. A quadrupole optics will spread the 1MW beam power (that would result from 10MeV operation) over a cooled collector.

Beam diagnostics: In order to allow for the planned detailed beam dynamics studies in the prototype, a very precise knowledge of beam position, the three emittances, and the beam halo will be required along the accelerator. The following tools will be developed: high precision BPMs, beam-ionization profile monitors, transition radiation and synchrotron radiation beam size monitors for reduced and full average current operation, bunch length monitors that use infrared spectrometry of the coherent synchrotron and diffraction radiation, and moving wires for halo measurements. All of these will be very valuable for the ERL light source as well, since reliable diagnostics will be needed for controlling the high power beam and for stabilizing the beam-position to the requirements of the users.

CONCLUSION

There are strong reasons to believe that SC cavity technology is sufficiently advanced to allow for high fields, high average current, CW operation in an ERL. However, many components will have to be optimized and beam dynamics issues have to be investigated in a prototype accelerator. The risks of not building a prototype seems too high, and the financial burden of building one at Cornell seems relatively benign considering the benefit that it would have to all the ongoing ERL projects.

REFERENCES

[1] I.V. Bazarov, et al. *Phase I Energy Recovery Linac at Corell University*, proc. of EPAC02.

[2] S.M. Gruner, M. Tigner (eds.), *Phase I Energy Recovery Linac (ERL) Synchrotron Light Source at Cornell University*, Report CHESS-01-003 at http://erl.chess.cornell.edu/papers/ERL_Study.pdf (2001)

[3] G.H. Hoffstaetter, et al., *A Lattice for a 5GeV ERL in the CESR Tunnel*, proc. of PAC03.

[4] C. Sinclair, *Very High Voltage Photoemission Electron Guns*, proc. of PAC03.

[5] I.V. Bazarov, C.K. Sinclair, *High Brightness, High Current Injector Design for the Cornell ERL Prototype*, proc. of PAC03.

[6] V. Shemelin, et al., *Dipole-mode-free and kick-free 2-Cell Cavity for the SC ERL Injector*, proc. of PAC03.

[7] V. Veshecherevich, et al., *Input Coupler for ERL Injector Cavities*, proc. of PAC03.

[8] H. Padamsee , et al., *Overview of the Cornell ERL Injector Cryomodule*, proc. of PAC03.

[9] M. Liepe, S. Belomestnykh, *First Studies for a Low Temperature Higher-Order-Mode Absorber for the Cornell ERL Prototype*, proc. of PAC03.

[10] M. Liepe, et al., *RF Parameter and Field Stability Requirements for the Cornell ERL Prototype*, proc. of PAC03.

[11] P. Piot, D. Douglas, and G. A. Krafft, *Longitudinal phase space manipulation in energy recovering linac-driven free-electron lasers*, Phys Rev ST-AB, 6, 030702 (2003)

[12] I.V. Bazarov, G.H. Hoffstaetter, *Lattice options for a 5GeV Light Source at Cornell*, proc. of PAC03.