PHASE I ENERGY RECOVERY LINAC AT CORNELL UNIVERSITY*†

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Abstract

Cornell University, in collaboration with Jefferson Lab, has proposed a novel X-ray source based on the energy recovery linac (ERL) concept [1, 2]. Such a source will exceed the brightness of third generation synchrotron light facilities and will also allow ultra short X-ray pulses and variable pulse formats, to enhance existing, and promote new applications in X-ray science. A multi-GeV ERL synchrotron source requires the extension of present state-of-the-art accelerator technology in several directions, e.g. CW high current photoinjector technology, superconducting RF cavity development, improved HOM damping, etc. To address these challenges, development of a 100 MeV high average current (100 mA) ERL prototype is underway. A description of the facility and the experimental program planned to address outstanding issues in ERL technology is presented. A successful completion of prototype ERL project will be of great use to various ERL projects being contemplated worldwide.

1 INTRODUCTION

While it appears very likely that an ERL-based synchrotron X-ray light source, incorporating state-of-the-art superconducting RF accelerator technology and a high brightness photoemission electron injector will prove practical, there are a large number of accelerator physics and technology issues that must be resolved before one can confidently design and prepare cost estimates for such a machine. A large number of accelerator parameters must be pushed well beyond current levels, making a prototype accelerator where these parameters can be demonstrated and explored an essential step.

To achieve a goal of 2 μm normalized emittance or less in the undulators for x-ray production in a robust manner, it will be necessary to achieve 1.5 μm or less out of the injector and less than that from the gun. Thus, space charge emittance compensation [3] of a high order must be achieved at the low energy end where the beam is most vulnerable. Emittance dilution from effects such as wakefields and coherent synchrotron radiation must be carefully understood and minimized.

The formation of halo on the beam, and beam loss from halo interception, poses problems for RF control, activation of accelerator components, heat losses in the cryogenic system, and energy recovery efficiency. Study of halo formation and its removal will be important in the prototype machine.

The need to minimize emittance diluting asymmetries while coupling hundreds of kW to the beam in the initial superconducting cavities of the injector is far more demanding than in any existing system. The prototype ERL must demonstrate robust operation of this critical element.

The main linac of an ERL light source must work at levels far beyond existing technology. The economic optimum seems to indicate that 20 MV/m or less is a desirable operating gradient. While these gradients have been routinely achieved in pulsed operation with relatively low average beam currents, it must be demonstrated that they can be maintained in CW operation at high average current, with the necessary high Q_o values. To avoid emittance dilution from beam break up driven by higher order modes in the cavities, one will have to achieve heavier higher mode damping than is now the case in superconducting linear accelerator structures, yet this must be done without compromising the achievable Q and gradient. Not only must the higher modes be more heavily damped but, because of the CW operation and the consequent significant power in these modes, they must be extracted from the low temperature environment with high efficiency. This demands not only innovations in the off-beam-line HOM couplers but also development of on-line absorbers to catch the HOM power that propagates down the beam line. Careful measurements in the prototype will be needed to assure these criteria can be met and maintained under full current operation. Operation of the main linac cavities with very high external Q will minimize the cost of the installed RF power system and its operation. The challenge here is the microphonic noise inevitably present in the system. Development of an active feedback tuning system that can operate with the full dynamic range of beam currents and cavity gradients must therefore be a priority for development with the Phase I ERL as well.

It is important that an ERL X-ray source provide sub-picosecond bunches to the undulators. Avoiding the severe consequences of such short bunches in the injector and linac requires that the short bunches be formed at the highest energy by magnetic compression. The accelerator physics and technology of doing this without undue damage to the beam properties is beyond today's state-of-the-art and will require exploration on the Phase I ERL

Measuring the beam properties with the accuracy needed in the face of enormous 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 picked up at various stations around the loop are

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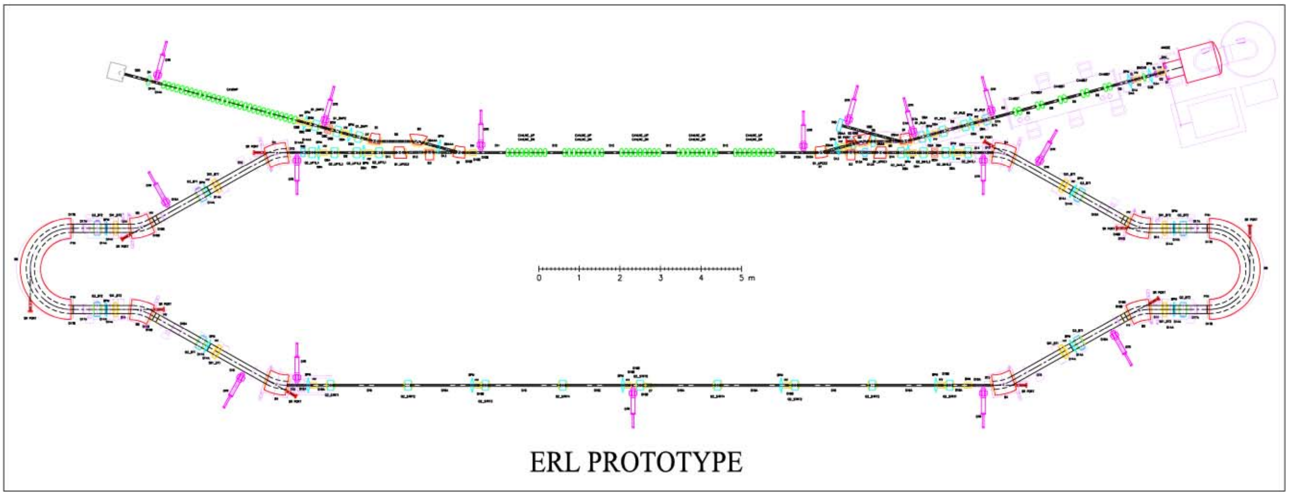

Figure 1: ERL Phase I layout.

promising but will need demonstration in this very low normalized emittance regime. Likewise, measuring halo in the presence of such high power flow will be difficult. Easily repeated methods for doing so must be developed as tuning and diagnostic tools.

Table 1: ERL Phase I Parameter List

Parameter [Units]	**Value**
Energy [MeV]	100
Normalized Emittance, rms [mm-mrad]	2 @ 77 pC
Fractional Energy Spread, rms [%]	0.02 – 0.6
Average Current [mA]	100
Charge / Bunch [pC]	1 – 400
Bunch Length, rms [ps]	0.1 – 2
Max Rep Rate [GHz]	1.3

2 ERL PROTOTYPE DESCRIPTION

We have developed a design for a nominal 100 MeV, 100 mA CW prototype accelerator which will allow us to address the critical accelerator physics and technology issues identified above. The high level parameters of this machine are given in Table 1, and a plan view of the machine is shown in Fig. 1. Various key elements of this machine are described in the paragraphs below.

2.1 Electron Source

We will us a high voltage DC electron gun incorporating a negative electron affinity GaAs photoemission cathode. The gun will operate at 500 to 750 kV in a pressurized SF_6 atmosphere. The GaAs photocathode will be illuminated by a mode-locked Ti:sapphire laser operating at 780 nm and delivering a several Watt optical pulse train at 1300 MHz [4]. Special pulse patterns will be made by electro-optic switching.

2.2 Injector Accelerator

Five two-cell cavities will accelerator the beam from the DC gun and buncher to a nominal 5 MeV, requiring each cavity to deliver ~ 100 kW to the beam. Operation to ~ 15 MeV will be possible at reduced average current, limited by the total RF power available.

2.3 Main Linac

The main linac will use five 9-cell cavities of the TESLA type. Two HOM loop couplers will be added to each end of the cavity, and a beam line HOM absorber will be located on axis before and after each cavity. A variable coupler will allow a relatively low Q_{ext} for high-peak-power processing and a fairly high Q_{ext} for operation. The design Q_{ext} is 2.6 x 10^7. Calculations indicate that five cavities are sufficient to reasonably explore beam breakup. TDBBU calculations indicate BBU thresholds between 100 and over 200 mA depending on the recirculation optics.

2.4 Recirculation Bends

We will use 180 degree recirculations bend magnet systems of the Bates design. The magnets for these bends are taken from the Jefferson Lab IRFEL . With the FEL upgrade underway, these magnets are no longer used. While recirculation bends of this type would not be considered for a high energy ERL light source, they are an economic choice for the prototype, and they provide sufficient R_{56} to allow bunch compression to 100 fs or less. CSR in the main 180 degree dipole is substantial, but calculations indicate the CSR emittance degradation is tolerable.

2.5 Spent Beam Dump

The injected beam energy is not recovered. In general, it is difficult to design a beam dump to handle the high spent beam power at low electron energy. We will use a deceleration structure to remove the great majority of this beam power, followed by a spent beam collector similar to a high power klystron collector, to handle the nominal 500 kW, 5 MeV spent beam.

2.6 Refrigerator

A 500 W refrigerator will permit accelerator operation at 2 K for eight continuous hours. This operation period will be followed by a 16 hour period with RF off, during which helium will be reliquified followed by pumpdown to 2 K. This 1/3 duty factor operation reduces the capital cost of the refrigerator, and is adequate to address the accelerator physics program of the prototype.

2.7 Beam Diagnostics and Measurements

Beam diagnostics in the prototype are matched to the accelerator physics questions we will study.

Fast, automated measurement of difference orbits with high precision BPMs will give a good measurement of the optical functions. These, coupled with beam size measurements, allow a determination of the emittance. Beam size will be measured by optical transition radiation with full bunch charge and reduced duty factor. Beam size at full average current will be measured by imaging the synchrotron radiation in the bend magnets.

Far infrared spectrometers will be used for bunch length and bunch profile measurements, using coherent synchrotron radiation and coherent diffraction radiation. Coherent diffraction measurements of beam size will also allow emittance determination outside of the bend magnets.

Moving wires coupled with bremsstrahlung detectors will be used for both beam halo and very low frequency beam motion studies.

Precision RF cavity pickups, coupled with a small modulation of the beam energy allow precision measurement of R_{56}. Similarly, a small transverse modulation of the beam at some moderate frequency can be used with a lock-in amplifier looking at the amplitude signal from an RF cavity can be developed as a very sensitive pickup for small beam losses.

A beam ionization profile monitor is planned for full current beam size measurements in the injector, and it may be practical to develop this technique for use in the return leg as well.

Finally, measurement of the RF power coupled out by the loop couplers, coupled with thermometry on the beam line HOM absorbers and helium mass flow measurements from the cavities will allow a thorough assessment of the HOM power deposition.

Broadband kickers will be provided in the 5 MeV injection beam line to allow driving the beam at HOM frequencies, for exploration of the BBU threshold. The optics of the return leg provide a range of ~ 2π in betatron phase advance which will be useful in BBU studies. Similarly, the Bates bend magnet systems allows varying the total path length by ~ 4 $\lambda_{RF.}$

The optics in the return leg allows us a location with β values well over 100 m, which may be useful for some beam size measurements.

3 PROJECT STATUS

A formal proposal to design, construct, and operate the ERL Prototype accelerator was submitted to the National Science Foundation in July 2001. The proposal has now been favorably reviewed by external reviewers, and by a formal review committee of accelerator and X-ray scientists at a site visit at Cornell. At this point, the project is awaiting a funding decision from the NSF.

Cornell University is strongly supporting this proposal, and has agreed to provide the shielded building housing the prototype. A site for the prototype accelerator has been selected, and a schematic design of the building is complete. Detail building design will follow a favorable funding decision from the NSF. It is estimated that the building would be available about fifteen months from the start of detail design.

The prototype project is envisioned to require five years to complete. Of this time, the first three and a half years will be required for construction, followed by about one and a half years of operation. It is intended to commission and operate the critical injector systems, from the gun itself through to the full 5 MeV injector and the high power beam dump system, prior to the completion of the full accelerator.

4 REFERENCES

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