

WORLDWIDE ERL R&D OVERVIEW INCLUDING JLAMP, BNL, AND CORNELL ERLS*

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Abstract

Energy Recovering Linacs have become an important approach to providing high brightness electron beams for photon production, nuclear physics research, and cooling ions. The technology takes advantage of the ability of superconducting rf cavities to accelerate high average current beams with low losses. After the desired interaction the electrons can be decelerated to low energy so as to minimize the required rf power and electrical draw. When this approach is coupled with advanced continuous wave injectors, very high power, ultra-short electron pulse trains of high brightness can be achieved. This paper briefly reviews the status of worldwide programs including the on-going BNL and Cornell efforts, the Novosibirsk Multipass ERL, ALICE at Daresbury, the KEK/JAEA ERL, and the Peking ERL among others. We will touch on the prospects for proposed machines such as the JLAMP advanced ERL FEL efforts at Jefferson Lab designed to produce ultra-high brightness beams of photons in the 10-100 nanometer soft X-ray region. We will discuss the research efforts underway and the technology hurdles to be overcome to achieve success in this area.

INTRODUCTION

Energy Recovering Linacs have been identified as a promising route for high average current electron beam production for a number of applications. The basic concept was suggested by Tiger [1] but only brought into full demonstration in 1996 at a significant current by Jefferson Lab in conjunction with operation of a high average power Free Electron Laser [2]. A high average current electron beam is accelerated to relativistic energies in typically a superconducting RF CW linear accelerator. The beam is then used for its intended purpose, providing a gain medium for a free electron laser, synchrotron light production, a cooling source for ion beams or a beam for colliding against ions. This process may significantly increase the energy spread or emittance of the electron beam but the major part of the beam power remains. The beam is then sent back through the accelerator again roughly 180 degrees off the accelerating rf phase to decelerate through the linac to a beam dump at around the injection energy. Three benefits accrue from this manipulation: the required rf power is significantly reduced to that required to establish the cavity field and make up minor losses, the beam power

dissipated in the dump is reduced by a large factor, and often the electron beam dump energy can be reduced below the photo-neutron threshold so that activation of the dump region can be eliminated. The costs associated with incorporation of energy recovery must be balanced against the need to provide a beam transport system to re-inject the beam to the linac for recovery. The specifics depend on the machine parameters but JLab experience suggests that 1 mA average current is around the cost breakeven point for incorporation of energy recovery. Figure 1 illustrates the Jefferson Lab IR/UV Upgrade FEL ERL which runs at over 9 mA CW [3,4].

There are additional benefits which accrue from the geometry and physics of such a machine which may drive a decision to incorporate it despite cost disadvantage. First of import to light sources is the ability to supply substantially lower emittances (of approximately equal value in both planes) than can be supplied in storage rings. This is due to the long electron confinement time of rings and therefore equilibration of stochastic beam heating. The emittance achievable in ERLs should allow x rays to reach the diffraction limit in both transverse dimensions. This photon brightness can be further enhanced by the straight beamlines in ERLs permitting accommodation of longer undulators than can be incorporated in rings. ERLs would not be able to substantially benefit from such long undulators without the small energy spreads which are also achievable in ultra-bright injectors. With good energy spread and emittance it is important to optimize the physical match in the undulator. Again the ERL has the advantage of being able to optimize beta functions without exceeding the dynamic aperture limitations that rings present.

Finally, the ability of the ERL to operate at low charges with small longitudinal emittances gives designers the ability to produce very short electron pulses at extremely high repetition rates enabling a number of time-dependent studies in the ERL which would be impossible in a ring-based light source. Much of the limit on the beam emittance comes from space charge forces in the injector. Lower charge per pulse provides benefits in a non-linear way so that operation at the highest pulse repetition rate feasible is desired. This makes very ERLs appropriate for low peak but high average brightness x ray applications. High peak brightness FEL systems may also be incorporated but with much more complexity in the energy recovery system due to the large electron beam energy spread induced during lasing and the necessity of complicated design restrictions in the R56 transport elements.

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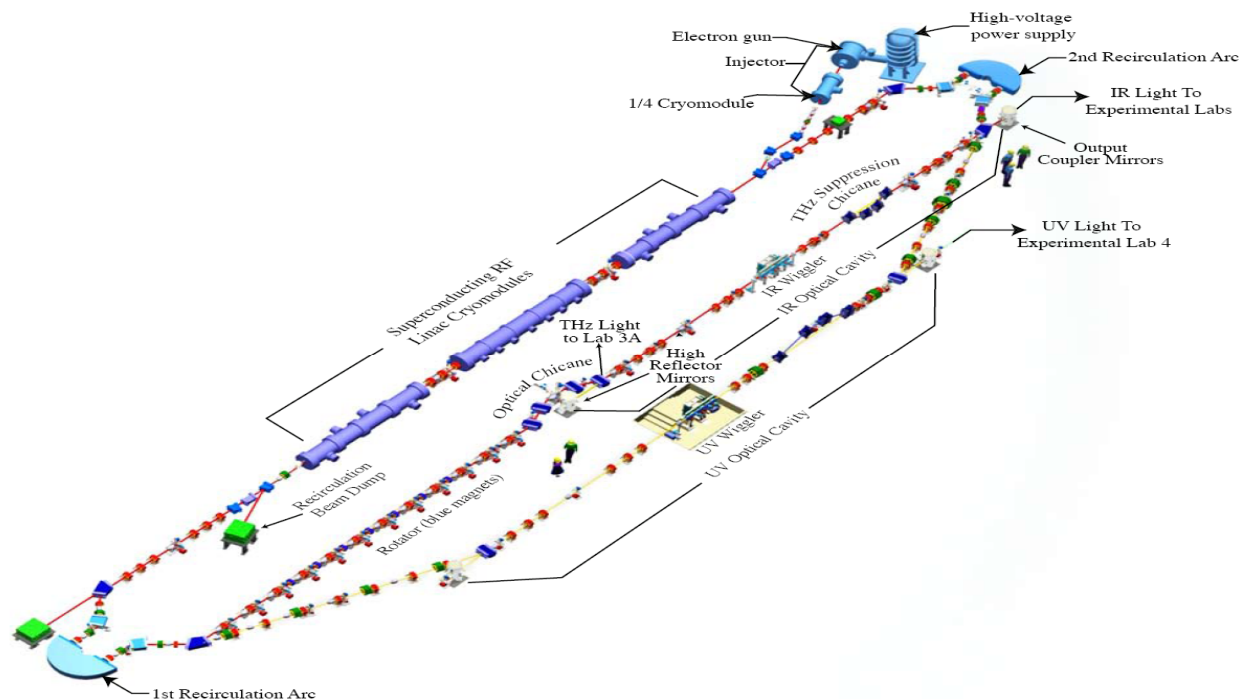


Figure 1: The Jefferson Lab IR/UV Upgrade. The 150 MeV machine provides 135 pC 150 fs pulses of 5 micron emittance at repetition rates of up to 74.85 MHz to either of two FELs. The IR FEL has delivered 14 kW at 1.6 microns and lased from 0.7 to 10 microns. The UV to date has lased at 360 nm and 700 nm with up to 150 watts.

Substantial research efforts are underway around the world to explore the limits of this operation. A list of key issues in ERLs always starts with the injector. At the present time no injector delivers the continuous beam at the high brightness desired for ultimate ERL operation, preferably at thermal limits. Substantial efforts are underway worldwide to address this shortcoming with key results expected at a number of laboratories within three years. Major ERL injector programs include Cornell, Daresbury, JAEA/KEK, BNL, HZB, Peking U., and JLab among others. In addition, CW high brightness injector efforts which may be applicable to ERL efforts are underway at LBNL and the University of Wisconsin.

Other key issues for ERLs include brightness preservation in acceleration and especially in bends (overcoming CSR emittance degradation [5]). Halo in CW machines is a major concern, as are wakefields and resistive wall issues in narrow beam chambers due to the high average current with short pulses. In a closed loop system one must also deal carefully with rf loading and control [6]. Power management of collective THz emission must be dealt with in high average current machines. Dealing with higher order mode damping and eliminating beam breakup has been thoroughly studied and reduced to engineering criteria at this stage. From a practical point of view R&D into srf linac construction cost can have major impact on the cost of facilities and will be the subject of on-going studies for many years. Improving the residual loss factor of srf cavities would have a major impact on cryogenic requirements and electrical operating bills. We will briefly touch on the

major efforts dealing with these issues and their status though progress in this area is rapid and we urge the reader to explore the latest conference papers or facility websites for updates.

R&D EFFORTS

One of the major efforts in the world is the research underway at Cornell University under support of the US National Science Foundation. R&D on the gun, transport system, accelerator modules, and undulators is on-going as well as an overall system design optimization. This effort is planned to bring into operation an ERL system which would add on to the CHSS Storage Ring a 5 GeV, 100 mA beam produced from a 1300 MHz srf linac [7]. A series of workshops established the science case and since then refinement of the design has been underway. An injector test stand is operational and making progress toward achieving the very high brightnesses projected from the DC gun [8]. The system is designed to run in both a high charge (77 pC at 0.3 mm mrad) and low charge (20 pC at 0.1 mm mrad) mode to optimize output for different classes of users. To achieve the best brightness it is desired to run the DC gun up to 750 kV, a level which has not yet been reliably achieved. The Cornell group has promoted the use of an inverted ceramic design which eliminates field emitted electrons from a cathode stalk which normally impinge on the high voltage standoff ceramic. A JLab version of this inverted approach is shown in Figure 2 [9,10].

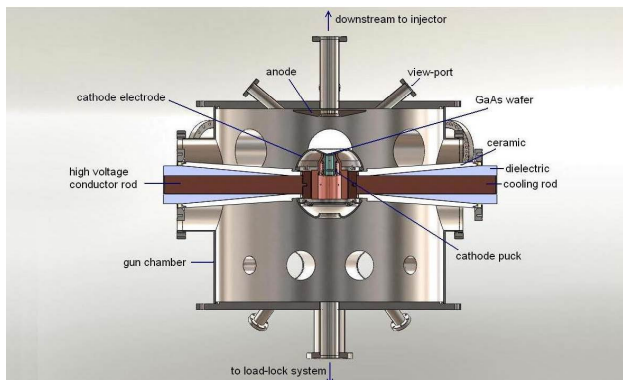


Figure 2: The JLab Advanced DC Photogun. Using an inverted dual ceramic design provides for both high voltage feed and possible cooling of the GaAs cathode wafer as required when operational at 100 mA.

Operation at 500 kV does seem achievable using either the inverted insulator or utilizing the JAEA/KEK approach of a shielded insulator to prevent breakdown due to field emitted electrons. The full configuration has achieved 380 kV as of this writing [11, 12]. The JAEA design appears to be a promising solution to achieve the high voltage necessary to preserve high brightness of the 10 mA electron beam. An illustration of how this approach works is shown in Figure 3.

Once the beam is produced it is necessary to capture and provide initial acceleration to the bunches. A multivariable optimization has been performed by Cornell to establish the layout of their injector and recent measurements seem to confirm the optimization and the strength of this approach [13]. Emittances approaching thermal levels appear achievable at moderate charge. Similarly a set of srf booster cavities has been developed at KEK for the injector and is undergoing cryogenic testing [14].

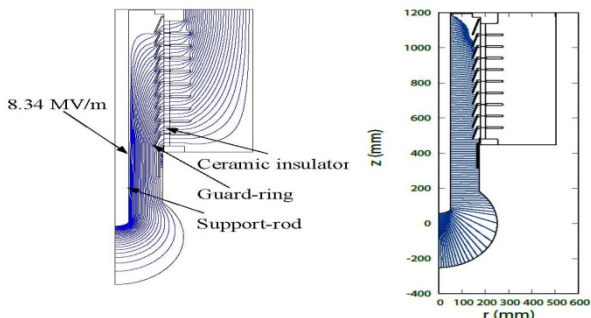


Figure 3: The JAEA/KEK Shielded Ceramic High Voltage DC Gun. On the left is shown the potential contours and on the right electron trajectories illustrating protection of the ceramic from field emitted electrons. Figure courtesy N. Nishimori.

Other guns aimed at very high CW brightness though not specifically directed at high average current are underway at LBNL [15, 16] and the University of Wisconsin [17]. LBNL is pursuing a room temperature

low frequency cavity which will provide gradients of up to 20 MV/m and a total acceleration of 750 keV in a single gap (Fig. 4). The low frequency provides quasi-DC beam transport. Using a copper gun allows for the establishment of ultrahigh vacuum through pumping ports around the outside of the cavity, permits emittance compensation techniques to be applied by adding solenoidal fields and makes insertion of the cathode relatively easy. A srf gun, however, could potentially have much higher gradients (up to 40 MV/m), exit energies of 4 MeV, and excellent vacuum. This is illustrated by the Wisconsin/Niowave gun in Figure 5. The price paid for the high gradient is difficulty in adding emittance compensation solenoids and the tough engineering of a cathode insertion with an rf choke joint.

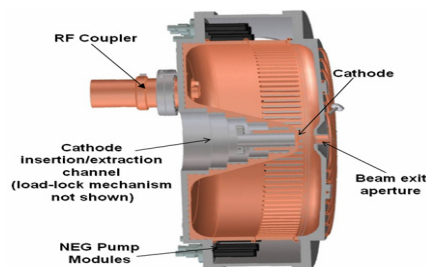


Figure 4: The LBNL VHF RF Photogun. The copper CW photoinjector is presently under assembly. Slots around the perimeter provide good vacuum pumping. Figure courtesy F. Sannibale.

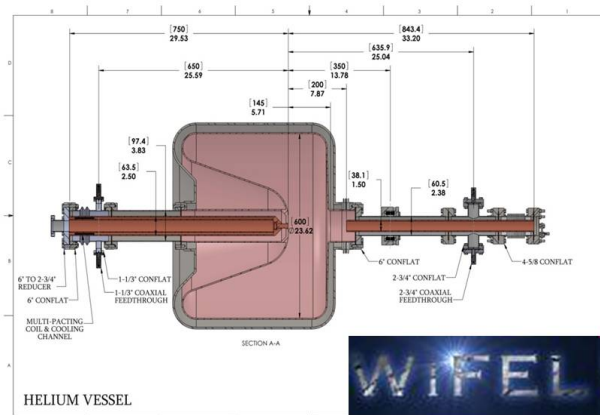


Figure 5: The Wisconsin SRF Photogun. A 200 MHz re-entrant cavity can operate at 4.2K while providing high gradient for high brightness. Figure courtesy J. Bisognano.

Very high currents are the aim of the srf gun development at BNL [18]. The srf gun which has been assembled and put under test is planned to deliver up to 1 amp of average current to meet the needs of electron cooling [19]. The cathode gradient is designed to be 20 MV/m. Not only must the previously mentioned challenges for an srf system be met but also the difficulties of feeding large rf powers into the cavity and having a cathode which can survive the srf environment. The ERL test stand there is being assembled and the

injector is undergoing tests (Fig. 6). It is designed to produce up to 1.4 nC at 700 MHz repetition rate with a normalized emittance of less than 10 microns.

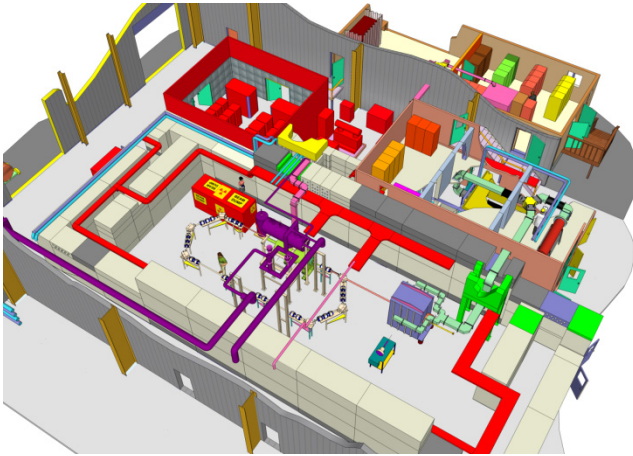


Figure 6: The BNL ERL Layout. A very high average current srf gun provides a 2.7 MeV beam for acceleration in a two cavity srf module before energy recovery. Figure courtesy I. Ben-Zvi.

Recently the ALICE facility at Daresbury Laboratory became the first ERL-driven FEL in Europe [20]. Designed to provide an FEL, a Compton source, and collective THz radiation, the system is also the driver for a non-scaling Fixed-Field Alternating Gradient (FFAG) accelerator setup called EMMA. A layout is shown in Figure 7. The system uses a high voltage DC gun operating at 250 kV to produce 40 pC charge with 10-20 mm mrad emittance. A booster brings the beam to 6.5 MeV before the two-cavity srf linac module accelerates the 81.25 MHz beam to 27.5 MeV for lasing followed by recovery. First lasing was achieved at 8 microns on October 23, 2010 producing 21 mW [21].

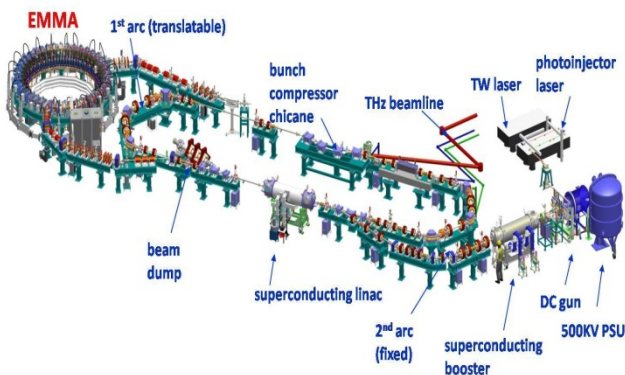


Figure 7: The ALICE ERL. This facility uses two superconducting modules at 1.3 GHz and a DC photogun with a GaAs cathode. Figure courtesy S. Smith.

All of the ERLs mentioned so far have been based on superconducting linacs, however there is one major system that is room temperature. The Multipass ERL in Novosibirsk achieves CW operation in 180 MHz cavities and accelerates very high average currents of 22 mA [22,

23]. The system is design for multiple passes up and down in energy. It has lased on both the first and second pass and produced more than 500 W at 50-240 microns.

Most groups worldwide are planning ERLs based on systems similar to the Cornell [24] or DESY cavity/cryomodule at 1300 MHz utilizing HOM damping in the beam pipe or couplers. ERL systems under design and construction include the cERL two pass system at KEK as a test stand for a much larger system [14] which would deliver an ultra-bright beam to a 5 GeV ERL hard x ray source. Also in construction is the BERLinPro facility in Helmholtz Zentrum, Berlin, utilizing an srf gun with a 1.6 cell, 1 MV exit energy Tesla-style cavity at 1300 MHz [25, 26]. It would provide 100 mA at less than 1 micron emittance. Several proposed systems in China include that at Peking University where they are applying a hybrid DC/srf gun design for injection. The first version of this injector has already been tested and an upgrade is underway. Serious studies are underway in Geneva for an energy recovery system for the Large Hadron Collider (LHeC), a 8.5 km 700 MHz superconducting linac with 18 MV/m gradient [27]. The layout uses both recirculation and energy recovery. In energy recovery mode the beam energy is 60 GeV for the 6.6 mA beam. Since the system uses a multipass linac and high energy, the turn-on transients must be carefully considered since the recovery beam doesn't provide full energy back to the cavities for 170 microseconds, i.e., many cavity rf fill times [28].

Jefferson Lab has proposed a soft x ray upgrade of its existing FEL ERL. Providing 600 MeV beam in two passes before lasing in an FEL amplifier followed by a two-pass energy recovery, the ERL would provide exceptional average brightness in the 10 to 100 eV photon region [29, 30]. The system is design to use 200 pC, 1 mm mrad emittance charge at up to 4.68 MHz pulse repetition rate. An illustration of how the system would fit in the existing facility is shown in Figure 8.

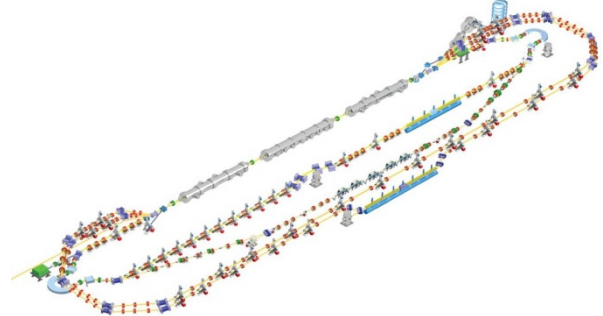


Figure 8: The Proposed JLab Recirculating, Energy Recovering Soft X Ray Light Source. Three advanced srf modules each provide 100 MeV of energy gain per pass. A 10 m undulator can provide lasing at high average brightness for wavelengths as short as 10 nm.

CONCLUSION

A wide body of research is underway around the world to exploit the advantages of energy recovery

linacs. The key issue of producing the ultra-bright beam from the injector is the most challenging but other technical areas also need significant research. A set of key program research directions can be found in [31]. They include both physics-related questions such as control of CSR in bends and economic issues such as reducing the high cryogenic-load-driven electric demand and capital cost of very long accelerators. Continued progress is eagerly anticipated by the world community.

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