ENERGY RECOVERY LINACS FOR LIGHT SOURCE APPLICATIONS*

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Abstract

Energy Recovery Linacs are being considered for applications in present and future light sources. ERLs take advantage of the continuous operation of superconducting rf cavities to accelerate high average current beams with low losses. The electrons can be directed through bends, undulators, and wigglers for high brightness x ray production. They are then decelerated to low energy, recovering power so as to minimize the required rf drive and electrical draw. When this approach is coupled with advanced continuous wave injectors, very high power, ultra-short electron pulse trains of very high brightness can be achieved. This paper reviews the status of worldwide programs and discusses the technology challenges to provide such beams for photon production.

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 Tigner [1], tried at Stanford [2] and LANL [3] but only brought into CW high current demonstration with an FEL in 1996 at a significant current by Jefferson Lab [4] in conjunction with operation of a high average power Free Electron Laser. This was followed by other demonstrations of energy recovery while lasing by JAEA [5] and the Budker Institute [6].

In an ERL, 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 an FEL, 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 only this time roughly 180 degrees off the accelerating rf phase so the beam is decelerated through the linac and then sent to a beam dump at around the injection energy. Three benefits accrue from this manipulation: the required rf power (and its capital cost and required electricity) is significantly reduced to that required to establish the cavity field and make up minor losses, the beam power that must be 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 reduced or eliminated. The cost savings from 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.

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The specifics depend on the machine parameters but JLab experience suggests that 1 mA average current is around the break-even point of considering such a design though the answer is highly dependent on relative costs of tunnel, rf, etc. There are cases where the recirculation line itself is a feature (e.g., a location for undulators and wigglers) and thus the comparative cost is not a factor.

There are additional benefits that accrue from the geometry and physics of such a machine when applied to x ray photon generation. First is the potential ability to supply substantially lower emittances (of approximately equal value in both planes) than can be supplied in storage rings due to the long electron confinement time in rings and equilibration of stochastic beam heating from photon emission. The emittance achievable in ERLs should allow x rays to reach the diffraction limit in both transverse dimensions. This beam brightness can be further enhanced by the straight beamlines in ERLs permitting accommodation of longer undulators than can easily be incorporated in rings. Second, ERLs would not be able to benefit from such long undulators without the small energy spreads which are also achievable. 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 independently 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 ultrashort x ray pulses impossible in a ring-based light source. This has led to significant proposals for high energy photon facilities based on ERLs [7, 8]. To achieve these benefits requires design including answering a number of physics issues.

PHYSICS CONSIDERATIONS

The proper incorporation of energy recovery requires consideration of physics effects on the beam with physical design implications. We briefly consider these below. The reader is referred to [9] for a more thorough coverage than is permitted in this overview. Often the first aspect one hears about in energy recovery machines is the possibility of multipass beam breakup. In this instability an offset of the beam in the initial pass leads to a transverse electric field which is amplified in the recovery pass. If the feedback is greater than the losses the instability quickly grows and kicks the electron beam into the wall. Significant studies of this effect have been performed both at low energy and involving substantial beam deceleration [10,11]. This effect is now considered fully understood and experiments have verified numerical calculations of the BBU current thresholds. Mitigation strategies include transverse mode damping and phase space rotation in the magnetic transport. With proper srf cavities design BBU thresholds exceeding 1A are feasible [12-18].

RF control and turn-on transients are an effect that must be properly dealt with in the machine design. As an illustration consider a machine which runs 100 mA. It may take the initial pulse more than 5 microseconds to return for energy recovery because of the distances involved. Each cavity accelerates the 0.1 A beam by order 20 MV. Thus the cavity is depleted of stored field at the rate of 2J per microsecond. A high frequency cavity may only store 1 J. If the rf power cannot supply this transient power (and quickly respond to the changed demand) then the beam output energy will drop significantly and the beam will be lost.

A similar effect can occur if a free electron laser is part of the return path. The coupling of beam energy loss through the T56 transport term during the lasing turn-on will lead to a phase shift of the return beam. This typically occurs faster than the rf system can respond so large significant rf power transients can result [19].

Other major physics effects such as CSR, longitudinal emittance growth, wakefields, and resistive wall effects play a role [20-22] in the transport design. One factor important for CW ERLs is the issue of halo. Though one tends to think of halo as electrons kicked out from the main distribution due to space charge forces, in fact halo comes from many sources starting with scattered light from the drive laser, to cathode field emission, to field emission in the accelerator cavities, to electrons outside the correct longitudinal phase space. As opposed to storage rings where the envelope is quickly cleaned of marginal beam the ERL continually injects new electrons in bad areas of phase space which must be dealt with to avoid major beam losses in undesirable areas. One must also consider the energy spread of the electron beam and associated chromatics of transport during deceleration or excessive beam loss can develop from this source [23].

For ERLs operating at high average currents and short pulses the production of copious amounts of THz radiation from CSR and edge radiation must be considered and means to absorb such radiation without detrimental effects must be developed [24].

It is generally acknowledged that the chief technical hurdle to producing a truly attractive ERL is the development of a high current, ultra-high brightness, CW electron source. Photoguns, which have achieved very high brightness for existing x ray FEL experiments, have generally used pulsed copper cavities operating at gradients in excess of what can be maintained continuously. Extensive development efforts for CW sources are underway at many laboratories [25-31]. Substantial efforts are also required for diagnostics [32].

RESEARCH EFFORTS

With these considerations in mind we will now discuss some of the on-going worldwide development efforts in ERLs for light sources.

JLab

Jefferson Lab operates the world's most powerful FEL as part of its ERL research activity funded by ONR. It utilizes a DC gun operating at 325 kV providing up to 10 mA of current in 135 pC bunches at 74.85 MHz [4]. A pair of 5 cell srf cavities brings the beam energy to 10 MeV before acceleration to 135 MeV in the main linac comprising three 8-cavity srf modules. The beam is bent 180 degrees and sent down one of two paths, to an infrared wiggler which has delivered 14.3 kW of power at 1.6 microns [33], or to a UV wiggler [34] which has provided up to 200 W in the 700 to 350 nm region. Further improvements to the hardware are anticipated to bring the power of the latter up to the kW level. Studies with this machine have elucidated BBU physics and made detailed comparisons with simulations [10]. The system has also served as a testbed for study of many mirror issues associated with high power optical cavities for FELs [35]. Gun studies have explored the limits of GaAs photocathodes and identified QE degradation mechanisms (primarily ion back bombardment for ionized background gas) while showing cathode QE life to > 150 C. An improved design of this gun and injector is under construction which is expected to improve the emittance to significantly better than the 5.5 mm mrad achieved for 135 pC while providing the ability to run up to 100 mA average current [36].

In exploring the technology for future light sources the team has developed a proposal for a soft x ray amplifier/oscillator called JLAMP [37]. In addition to providing unprecedented average brightness the program is designed to investigate physics and technology for next generation hard x ray user facilities. In addition to the overriding issue of injector design, key open issues include the control and management of CSR and longitudinal space charge instabilities in transport and pulse compression as well as halo generation and control. From a practical implementation point of view the cost of srf cryomodules and cryogenics, beamlines, rf, undulators etc., is also a limiting factor in the affordability and hence approval of more light source user facilities.

Novosibirsk

A unique design in Novosibirsk utilizes very low frequency (180 MHz) copper cavities and high average current in an energy-recovering racetrack microtron configuration. Average powers exceeding 400 W have been achieved at 60 microns using this device. It is in the process of being upgraded from two acceleration passes and 12 MeV to five for up to 98 MeV and thereby shorter wavelength 2 micron output. To produce a high average current CW beam, a gridded thermionic gun and low frequency bunching and acceleration were used. Up to 20 mA CW current has been produced though the normalized emittance is somewhat large for x ray production [6,38].

Daresbury

A machine at Daresbury Laboratory called ALICE became the first ERL based FEL in Europe this fall. The system uses a pair of 1.3 GHz 9-cell srf cavities as a booster for the DC gun injector followed by a second 2 cavity accelerator module. The system lases in the 4 to 12 micron region using the 27.5 MeV 40 pC charges at 81.25 MHz repetition rate in a 40 period 2.7 cm wavelength undulator [39,40]. The system also serves as an injector to a non-scaling FFAG accelerator called EMMA [41]. Other uses of the beam include collective THz production and Thompson scattering from the sub-2 ps bunches to the x ray region.

Cornell

The ERL effort at Cornell is one of the most extensive in terms of directed development toward an ERL x ray light source. The ultimate goal is an upgrade of the CESR machine to ERL performance with high average current and ultra-high x ray brightness. Use of the existing ring is anticipated as part of the recirculation path [8]. Substantial funding for R&D efforts has been provided and ongoing work in the cryomodule and injector is providing many insights into the proper design considerations of such a machine [12,20,22]. The machine would be expected to operate in two modes, a high coherence operation at lower charge but higher brightness and a high flux operation at higher bunch charge but ultimately lower photon brightness. Average currents of up to 100 mA are desired. To achieve such operation with brightnesses approaching thermal limits, an optimization of the injector design was performed using a genetic algorithm driving on the order of 100,000 PARMELA runs with only a minimal set of design constraints. The latter was to ensure the system was physically realizable using settings within the technical capabilities of the hardware [28,42]. The resulting design utilizes a DC gun operating at up to 700 kV followed by five 2-cell cavities with independent phasing. In addition to giving the freedom to match the beam for emittance preservation, having 5 independent cavities splits the significant rf power requirements into manageable slices. The gun has been operated up to 400 kV but is presently running at 250 kV while awaiting fabrication of a new insulator similar to one developed by JAEA that has been shown to withstand 500 kV [43,44]. Cathode research is underway with recent excellent results from CsKSn demonstrating delivery of 20 mA for 90 minutes with no QE degradation.

Other significant efforts include design, testing, and optimization of the cryomodules and rf control system. It is necessary for the HOMs to be strongly damped if 100 mA beam is to be recirculated. It is also desired to minimize rf control power through use of piezotuners to handle cavity microphonics. Substantial work on the rf control has been performed and use of feedforward has been employed to deal with voltage ripple on the klystrons. The damping of HOM modes is through the use of cylindrical ferrites in the beam pipe exit from the cells. Initial tests with such a system were problematic due to the ferrite magnetization and electrostatic charging. The ferrites facing the beam were removed and those shielded by a metallic substrate retained. On reprocessing the cavities exhibited better Qs [45,46].

KEK

Initial ERL efforts in Japan involved srf linacs and FELs at JAEA [47,48]. Now a second major world effort is underway at KEK with construction and R&D studies well in progress. Plans are to build a two pass 245 MeV recirculator termed cERL as a proof of principle for a 5 GeV ERL[49]. The work is in collaboration with JAEA, University of Tokyo and other srf institutes in Japan. The cavity design uses 9-cell 1.3 GHz cavities with fluted HOM dampers containing ferrite cylinders cooled to 80K on an eccentric beam pipe to manage currents up to 100 mA. The beam pipe is large with a diameter of 120 mm. Coaxial power couplers with double ceramic windows provide 20 kW power handling [17,50]. Work is also underway for the 2-cell srf cavities planned for the booster including couplers designed for up to 170 kW transmission. Double feeds are provided for each of the three cavities in the injector. The prototype cavities have achieved 30 MV/m though operation is designed for the 7.5-15 MV/m range [51]. Four or more HOM couplers are used to damp unwanted modes in each injector cavity.

Major work is underway on the injector design using a 500 kV DC gun. The design uses a segmented ceramic insulator with guard rings on the HV insulator to prevent charge buildup and punch though of the ceramic as seen in JLab and Cornell designs. The gun has already been conditioned to 500 kV and is undergoing commissioning at 380 kV. The maximum surface field is limited to below 11 MV/m. Ultimately an operating voltage above 500 kV is desired to meet the demands of high brightness generation in the presence of non-linear space charge forces. This effort is already enticing adoption of new shielded ceramic designs at Cornell and JLab based on the excellent commissioning results. The gun incorporates a transfer mechanism to install a puck holding a GaAs wafer. Initial tests of cathodes have shown a static life of 270 hours on an initial QE of 7% at 532 nm [43].

HZB

The Helmholtz-Zentrum Berlin fur Materialien und Energie (HZB), in Berlin is developing a plan for a 100 MeV ERL to investigate the critical physics and technology issues which stand in the way of x ray ERLs. Termed B*ERL*inPRO, the facility has specific goals of generating ultralow emittance beams at high average current and maintaining such low emittance through acceleration to high energy through optimized management of CSR and other degrading effects. Bunch lengths will be kept long until short pulses are required at high energy so as to minimize CSR, longitudinal space charge instabilities, and HOM generation from the 50 to 100 pC charges. A booster module is presently being developed based on the Cornell design using 1.3 GHz cavities with dual power couplers of 150 kW capacities each. Assembly and test of the supporting systems including rf and cryogenics is underway [52,53].

PKU, KAERI, FSU

Additional long wavelength efforts in srf ERLs involve the generation of IR to THz light. Peking

University has initiated the construction of a 5 to 8 micron FEL from a 30 MeV srf ERL accelerator. An advanced hybrid DC/srf injector will provide the CW beam. It is an upgrade of designs previously tested at the university to provide 60 A peak current pulses [54]. In the long wavelength regime an ERL FEL system provides 100-1200 micron light output from a 4.5 to 6.7 MeV single cryomodule accelerator operational at the Korean Atomic Energy Research Institute. [55]. The Florida State University has proposed the construction of a 50 MeV ERL system for THz to IR production (2 to 1500 microns) in a user facility associated with the National High Magnetic Field Laboratory in Tallahassee [56].

CONCLUSION

In the above paragraphs I have attempted to give an overview of activities proceeding toward the development of major photon user facilities based on ERL technology and touch on the technical issues involved. I encourage the reader to also review other summary papers in the field for further information [57-59] as well as study the proceedings of the ongoing biannual ERL Conference sponsored by ICFA. Although many efforts are directed at resolving issues for a next generation ultra-bright photon source in the x ray region, other applications are also important, including electron cooling for ion beams [60] and production of beams for electron/ion colliders [61]. Continued progress is eagerly anticipated by the world community.

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