PERFORMANCE ACHIEVEMENTS AND CHALLENGES FOR FELS BASED ON ENERGY RECOVERED LINACS*

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Abstract

During the past decade several groups have assembled free electron lasers (FELs) based on energy recovered linacs (ERLs). Such devices have been built to obtain high average power electron and photon beams, by using high repetition rate beam pulses driving FEL oscillators. In this paper the performance of many existing and several proposed facilities from around the world are reviewed. Going forward, many questions must be addressed to achieve still better performance including: higher average current injectors, better optimized accelerating cavities, higher energy acceptance and lower loss beam recirculation systems, and better optical cavity designs for dealing with the optical beam power circulating in the ERL FELs. This paper presents some of the current thinking on each of these issues.

INTRODUCTION

The basic idea in same cell beam energy recovery is fairly straightforward to understand and has been discussed in great detail in recent reviews [1,2]. In a front-to-back recirculated linac the recirculation path length is chosen to be approximately an integer plus ½ RF wavelengths, and if the beam current does not change much in the time it takes for a complete circuit of the recirculation loop to be made, then energy can be transferred directly from the decelerating higher-energy beam to the accelerating first-pass beam, without the need for power to be provided by the RF systems attached to the cavities. This opportunity allows one to construct recirculated linacs, particularly those consisting of superconducting cavities, with energy transfer efficiencies approaching those in storage rings. This fact, in turn, allows one to build linacs that can transport and accelerate beam average currents approaching those in storage rings.

The energy transfer efficiency is nicely quantified by the power multiplication factor

$$k = P_{b,ave} / P_{RF} \qquad (1)$$

where $P_{b,ave}$ is the average beam power and P_{RF} is the RF power needed to accelerate the beam. For normal conducting recirculators k is much less than 1, for present day ERL FELs k is of order 10, for advanced ERL light sources k is of order 100, and for typical storage rings k is of order 1000. It is straightforward to show that in the limit the optical cavity losses are small compared to the outcoupled radiation power, the transfer efficiency from RF power to photons is equal to ζk, where ζ is the fraction of beam energy converted to photons per pass in an optical cavity oscillator FEL.

The first superconducting linac to demonstrate same cell energy recovery was the Stanford University Superconducting Accelerator as reported at this conference twenty years ago [3]. In an experiment, the recirculation path length was set to allow energy recovery to proceed. Nearly all of the beam energy was recovered as indicated by the absence of RF power being needed to drive the beam load in the superconducting cavities of the accelerator. However, in this early experiment there was no optical cavity inside the recirculation loop.

PRESENT STATUS

Presently, there are three ERL-based free electron lasers in existence and a fourth being rapidly assembled as a prototype project for an advanced fourth generation light source suite. Two of the existing FELs, at Jefferson Lab and the Japan Atomic Energy Agency (JAEA), are based on superconducting RF (SRF) cavities, and the third, at the Budker Institute for Nuclear Physics (BINP), is based on CW normal conducting RF cavities. In all the devices, an optical cavity FEL is placed inside the beam recirculation loop.

Jefferson Lab Free Electron Laser

A group at Jefferson Laboratory has spent the last decade building and improving many increasingly capable free electron lasers based on energy recovery, including the first ERL to have an FEL inside the energy recovery loop [4]. This demonstration device has been upgraded in order to achieve higher average electron beam and optical beam powers. Some recent electron beam parameters are summarized in Table 1. Beam starts from a DC photocathode source, is accelerated to 10 MeV using two standard CEBAF superconducting cavities, injected onto a beamline containing an energy recovered linac that can achieve up to 150 MeV. The beam is recirculated with two Bates bend beam recirculation systems specially designed to contain and transport the large energy spread generated by the FEL in the electron beam.

Recent work at Jefferson Lab has concentrated on extending high power CW operations at the 10 kW level from 6 microns down in wavelength. Over the last year the average power has increased from about 4 kW to 6.7 kW at 2.8 microns, from 1 kW to 5.4 kW at 1.6 microns, and from 1 kW to 2.2 kW at 1 micron. The short wavelength performance of the FEL has improved as low absorption dielectric coatings have been developed for the high power optical systems. The group expects a considerable improvement of the high power performance

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of the FEL when cryogenically cooled optical cavity mirrors are deployed to help deal with mirror distortion in the optical cavities at high power.

Table 1: Electron Beam Parameters for ERL FELs

PROJECT	JLAB	JAEA	BINP
Frequency (MHz)	1500	500	180 NC
Energy (MeV)	130	17	13
Current (mA)	10	8	20
Bunch Charge (pC)	130	400	500
Rep. Rate (MHz)	75	83	11.2
Normalized Emittance (mm mrad)	8	20	30

A user program has developed at the FEL. Because of the short bunch length at the FEL, copious amounts of wideband THz radiation are produced in the bend magnets of the chicanes surrounding the wiggler through the coherent synchrotron radiation emission. The THz radiation has been taken up to a user lab and is now routinely used for electron beam diagnostic purposes. Other experiments are performed with the FEL radiation extending from studies in condensed matter physics, to studies of fundamental optical physics using the FEL light to make far off resonance traps, all the way to fundamental particle physics in dark matter candidate searches.

JAEA Free Electron Laser

The JAEA FEL injector consists of a 230 keV thermionic gun, and 83 MHz subharmonic buncher, and two single-cell 500 MHz superconducting cavities that accelerate the beam to about 2.5 MeV. The injected beam is merged onto the axis of a linac that consists of two 5-cell superconducting cavities that boost the beam energy to 17 MeV. Beam is recirculated with three-bend achromats, and the undulator and optical cavity of the FEL are just upstream of the return achromat. As seen in Table 1, the lower cavity frequency allows higher charge per bunch in the beam to be accelerated efficiently.

Recent work has focused on doubling the electron bunch repetition rate by upgrading the gun grid pulser and the RF power for the non energy recovered 2.5 MeV accelerating cavities, increasing the energy acceptance of the achromats by reworking quad magnets and beam pipes in the achromats, and investigating and optimizing the achromat settings for increasing the FEL efficiency. Recently, the FEL extraction efficiency has been measured and the peak efficiency reaches 2.8%, and the group has achieved 0.7 kW output at 22 micron from an 8 mA beam during a 230 microsecond macropulse. A more complete summary of recent work has been given by N. Nishimori at this conference [5].

BINP THz FEL

The Budker Institute THz FEL is based on a normal conducting CW linear accelerator. Beam originates in a thermionic electron gun, is accelerated to 2 MeV through two 180 MHz cavities, injected on the main linac axis and accelerated up to 13 MeV by 16 180 MHz cavities. The beam drives an FEL oscillator which produces radiation in the THz band, and the beam energy is recovered in the second pass through the linac. This device is the highest average power source of narrowband THz radiation. Because of the low frequency and hence large aperture of the accelerating cavities, this device is able to handle much higher average current than the superconducting ERL FELs, achieving 20 mA average current now and planned to achieve 150 mA average current after an injector upgrade. This device has energy recovered the highest average beam current to date, and is unique in that the recirculation loop is oriented vertically.

There are plans to upgrade this device with two higher energy FELs that will produce radiation at 20-100 μm and 3-20 μm, in optical cavity oscillators. The 20-100 μm optical klystron will sit after a second pass of beam recirculated acceleration for a beam energy greater than 20 MeV, and the shorter wavelength optical klystron will sit after four beam passes up to about 40 MeV. The recirculation loops for this device will be oriented horizontally to the existing linac, which does not need to be upgraded substantially. When completed, the BINP FELs will be unique among energy recovered FELs in that a large number of passes will be accommodated, as the other existing ERL FELs are two pass machines. The multipass “energy recuperator” free electron lasers will be assembled throughout 2007 and commissioning is anticipated to begin towards the end of 2007. A more complete summary of recent work has been given by N. Vinokurov at this conference [6].

4GLS

The British 4GLS project is to produce a suite of three superconducting linac based free electron lasers in addition to an energy recovered high average current recirculated linac light source, to be located at Daresbury Laboratory. The IR FEL and the XUV-FEL in this project are not energy recovered, the IR FEL operating at a MHz-scale repetition rate and the XUV-FEL operating at a repetition rate of 1 kHz, ambitious for a SASE or a seeded source. The UV FEL source, based on a regenerative amplifier, is located in the high average current energy recovered recirculation loop. It is anticipated to operate this FEL simultaneously with the high average current ring.

In order to start the process of building the full 4GLS, which is based on 1.3 GHz superconducting cavities, a 35 MeV energy recovered FEL, ERLP, is being built [7]. Just prior to the conference, beam was extracted from the DC photocathode source of ERLP for the first time. The accelerator consists of two two-cavity cryostats, one inside and one outside the beam recirculation loop. These have now been assembled, as well as the three bend achromat recirculation optics systems. Cold commissioning of the linac, in its planned location is scheduled for the month of October 2006, with the machine completely installed by the end of 2006. Machine studies, including beam energy recovery, are to be completed in the spring of 2007 and there should be a "first lasing" contribution by ERLP at the next FEL conference. A more complete summary has been given by J. Clarke at this conference [8].

High Average Power X-FELs

Perhaps the ultimate light source, i. e., one that could produce both high peak power and high average power X-ray beams, would consist of an energy recovered X-FEL. A superconducting linac as a driver for such an FEL has many inherent advantages: greater potential efficiency and the possibility of high gradient CW operation, the possibility to achieve repetition rates at the MHz or higher level, and the ability to transport cleanly high bunch charges because of the low transverse impedance of the accelerating structures [9]. Such a scheme has been studied in detail as a follow on project for the TTF FEL [10]. A major concern is achieving a high repetition rate injector. As discussed more thoroughly below, this injector would seem to require an SRF gun electron source.

FUTURE DEVELOPMENTS

In order to achieve another order of magnitude in electron and photon beam power many improvements must be made to the existing devices. The present photocathode injectors must be upgraded to produce higher average current. The accelerator design optics must be stable to the higher average recirculated beam current in the more ambitious designs. The optical cavities must be able to handle the increased recirculating beam power. High order mode (HOM) cooling becomes more problematic at higher average currents. Finally, non-invasive electron beam diagnostics should be developed to help monitor the beam during CW operations.

Electron Photocathode Sources

In order to increase the average beam current in the next generation FELs by an order of magnitude, it seems that the easiest method is to increase the bunch repetition rate until every accelerating (and decelerating!) phase in the RF waves are filled. This can be done with little change to the bunch charge presently obtained. This approach has been adopted by Cornell for the first energy recovered recirculated linac light source, which must achieve beam emittances much smaller than is typical for the long wavelength ERL FELs. Because of the higher average current in the non energy recovered portions of such accelerators, it is expected that the injection energy will be reduced and the number of superconducting cavities increased in order to deal with the increased beam power in the non-recovered portions of the accelerator [11]. Also, larger beam dumps may be needed to dissipate the non-recovered beam energy.

In the further future, one anticipates that SRF photocathode sources will be developed to produce electron beams at high energy and high levels of average current. The group at Rossendorf, who have been leaders in developing SRF guns, hope to achieve 1 mA average current from a 10 MV 3.5 cell gun in construction now, and Brookhaven National Laboratory have been developing guns in the 100 mA-1 A class for electon cooling applications [12]. The main benefit of marrying the SRF and photocathode source technology is the possibility to have high CW accelerating gradient on the photocathodes, which may lead to superior emittance in CW high repetition rate applications.

Drive Lasers

In the high average current applications of photocathode electron sources there is a need to develop drive lasers of sufficient power to extract the needed average current. Roughly an order of magnitude in laser power is needed beyond present experience for the DC photocathode sources presently used. In addition to the power requirement, to get the best beam parameters out of photocathode guns laser pulse shaping is needed. Cornell University is developing a fiber based system with 20 W capabilities untilizing transverse shaping and longitudinal pulse stacking in order to obtain a uniform laser pulse longitudinally. Jefferson Lab is also developing a system that should be able to deliver 32 W [13], about 5 times more than the present drive laser for the Jefferson Lab FEL.

Similar high average power lasers with high repetition rate may be quite useful in seeding applications in high repetition rate X-FELs.

Beam Breakup and Advanced Beam Optics

Recent work at Jefferson Lab has allowed direct quantification of the multipass beam breakup instability, as in some electron beam optical conditions the FEL beam is unstable. A recent review of the subject has been performed [14], including discussions of utilizing special electron beam optics to suppress the instability. The methods studied are likely sufficient for stabilizing the instability in future FELs, but simulation evidence exists indicating that some of the intended solutions may not apply to larger scale accelerators [15]. Significantly, many of the BBU simulation codes have now been properly benchmarked against experimental instability data.

Driven by the desire to operate the ERL FELs at higher energy extraction, advanced beamline designs for beam recirculation with energy spreads of 10% or more have been developed [16]. These designs feature magnet shapes and edges chosen to automatically yield nearly isochronous beam recirculation due to the shape choices. It is anticipated that such designs will become increasingly important as higher average power ERL FELs are built.

High Power Optical Cavities

In designing the next generation of optical cavities the following aspects of the problem must be understood [13]:

- One must minimize the absorptive loss which can quickly lead to mirror distortion and low output.
- Scatter loss should be minimized to control subsequent absorption on components causing pressure rise and drift.
- Mirror coatings and substrates must be chosen to mitigate the effects of any power loading from out-of-band radiation which may be incident on the mirrors.

Optical cavities and beam transport lines must be designed with these effects in mind.

HOM Power

Superconducting RF cavities have been used in storage ring applications for many years at beam average currents of 100 mA and above. Because the power deposited into HOMs can be substantially larger than the heat deposited in the cavity walls when the cavity is operated at gradient, it is particularly important to couple the HOM power out of the cavity volume to be absorbed at locations with higher temperature to reduce cooling requirements on the He refrigerator. Recent storage ring HOM absorbers consist of ferrite absorbers located upstream and downstream of the SRF cavities mounted on the beam pipe wall with a separate cooling loop to deal with the HOM power.

Similar solutions will be needed to absorb the HOM power in 100 mA-scale ERLs, and there is an additional complication. The bunch durations in ERLs can be up to two orders of magnitude smaller than in storage rings and now there is bunch spectrum available to excite HOMs at much higher frequencies than in rings. Thus, the overall power excited increases and the operational range of the HOM absorber must be much broader in frequency to handle the wider range of frequencies excited. This problem afflicts advanced ERL light source designs, and already a group has investigated material which is highly absorbing at frequencies up to 40 GHz at a temperature of 80 K [17]. Also, it is anticipated that advanced HOM absorbers will include several different materials absorbing in different frequency bands [18].

Electron and Photon Beam Diagnostics

Because the average current of next-generation ERLs is approaching that in storage rings, one would expect that the more standard electron beam diagnostics, e.g. beam position monitors, beam profile monitors, and current monitors, would follow the techniques previously developed for storage ring applications. The beam attributes unique to ERLs and ERL FEL sources are the need to diagnose and control short bunches, the need to deal with low average power tune up beam diagnostic modes, and the need to deal with high average beam power. Many longitudinal techniques are being investigated in X-FEL projects. Mainly they are highly disruptive and might not be technically useful in the higher average beam power regimes we are pushing into.

Real time measurements of bunch longitudinal distribution and phase space based on electro-optic methods or based on coherent synchrotron, edge, or undulater radiation, may provide correct approaches for non-invasive monitors. Presently, there seems to be a lack of a universal method yet demonstrated that is unambiguous in the results it reports [19]. Achieving such a universal longitudinal measurement will be at least as important for future ERL development as the development of good profile monitoring was in storage rings.

For photon beams, the key near-term developments need to occur in the shaping, both longitudinally and transversely, of the higher average power drive laser beams for electron production on the photocathodes. The production methods will be need to be diagnosed to some level with techniques suitable for power levels of several tens of W needed in the next generation electron sources. In the further future it will perhaps be required by the users of high average power FELs that the emerging high power optical pulses display customized and controlled characteristics. Very little is known about this subject now.

CONCLUSIONS

- The field of ERL-based FELs continues to grow and the performance of devices continues to improve.
- Upgrade paths for at least an order of magnitude in both electron beam and photon beam power, though not trivial, have been identified.
- Many new ideas are being explored, some in conjunction with recent work on Energy Recovered Linac light sources.
- The field seems to be thriving and there is no shortage of interesting problems to work on.

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