HIGH AVERAGE POWER ERL FELS

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Abstract

Encouraged by the successful operation of the JLab Demo in 1998, many high current Energy Recovered Light Sources (ERLs) are now being designed with not only short pulse synchrotron beamlines but also FELs. High power FELs have continued to make significant progress in the last few years. Power advances are taking advantage of the energy recovering linac technology on both superconducting and room temperature machines. In general, the limiting technology has been the injector current capability but there are a number of other technical factors which must be considered to successfully develop a high average power Free Electron Laser. With a number of groups poised to develop 100 mA ERLs, many with FELs, the importance of resolving limiting issues is becoming more critical. The Recuperator at Novosibirsk has the record current of 22 mA and has produced over 400 W of FEL power and work is underway to extend the power and performance of this pioneering machine. Meanwhile, at Jefferson Lab, the Upgrade FEL achieved 14.3 kW of output while recirculating 8 mA. This talk will review the status of several high average power FELs around the world with an emphasis on the srf technology.

BACKGROUND

Given the rising interest in ERLs incorporating FELs [1], it is helpful to review what specifications of the light source may need revision in order to accommodate the strict demands of the FEL. We have previous discussed many of the physics parameters which are crucial to transporting high current beams in a CW manner as required for high average power FEL operation[2]. These include

1) impact of longitudinal phase space manipulation on rf phase and amplitude control and srf cavity specifications
2) magnetic field quality, higher order term management for transverse and longitudinal acceptance
3) wakefields and resistive wall effects

LONGITUDINAL PHASE SPACE

We briefly reprise our work on tolerances for rf control and longitudinal transport.

Phase Settings

It is generally desirable to let the bunch length remain long during initial acceleration to minimize longitudinal emittance growth. By operating off crest, a correlated energy spread in imposed on the beam that can be used to compress the beam to high peak current at the wiggler. The FEL then imposes an energy spread during lasing with a full width on the order of 6 times the extraction efficiency. This large energy spread must be transported to the dump during energy recovery. In addition the centroid of the distribution loses energy according to the FEL efficiency. If an appropriate M_{56} and path delay in the transport is applied before deceleration the energy spread of the beam can be compressed as the beam decelerates so that the ultimate energy spread as a fraction of the energy is not much larger than the FEL-imposed spread. The offset deceleration angle must be chosen to be sufficient to handle the full energy spread of the beam or successful transport to the beam dump will not be possible (Figure 1). Given the large energy spread of the decelerating beam it is also necessary to match the higher order terms of the magnetics. The Upgrade FEL utilizes sextupoles to help match the rf curvature and minimize dE/E at the dump [3-5].

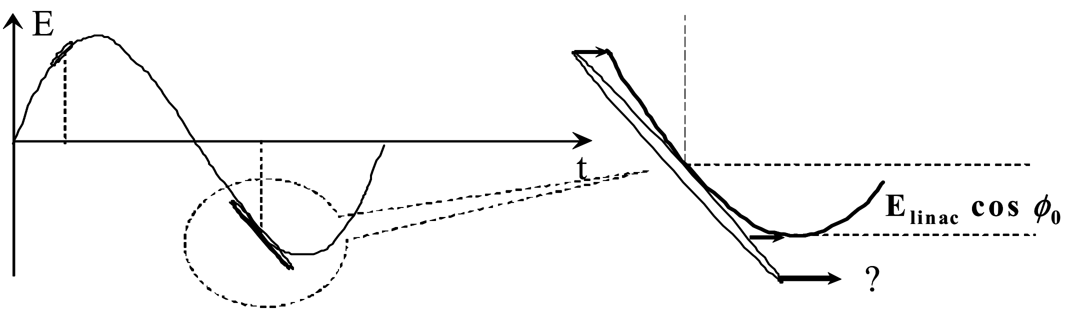

Figure 1. Electron distribution on the acceleration and deceleration rf phase. If the energy spread of the beam exceeds $(\Delta E/E)_{FEL}/2 < E_{linac} \cos \phi_0$ then there is not sufficient rf gradient to decelerate those electrons with the highest energy. This leads to unacceptable energy spread at the dump.

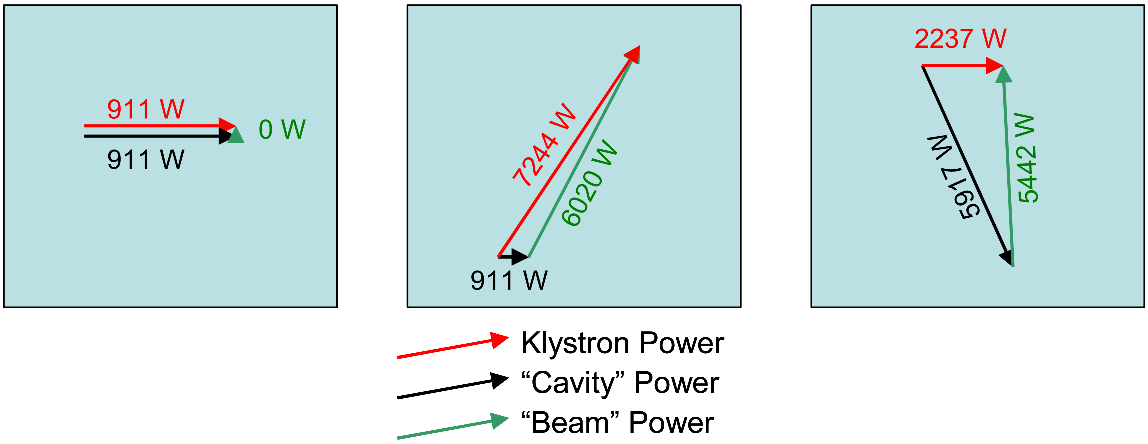

Figure 2. Loading of the rf with a) perfectly matched acceleration and deceleration, b) when the FEL turns on and instantaneously shifts in phase, c) after the srf cavity tunes its resonance to minimize power draw.

RF Power Requirements

A practical rf control system must be able to manage transients associated with the FEL turning on and off. Figure 2 illustrates the beam load phasors in a typical rf cavity with the accelerated and decelerated beam initially perfectly canceling. For the example parameters, when the FEL turns on a phase shift of 7.2 degrees results and initially the rf power draw goes from 911 W at zero degrees to 7244 W at 50 degrees in the rise time of the laser: ~ 10 microseconds. Given time the srf cavity can retune to minimize the power draw (Figure 2c, 3). The resultant is then 2237 W at zero degrees. The energy of the accelerated beam must not change substantially during this transient or a relaxation instability between the FEL and accelerator can be initiated. It is important to note that although an ERL with perfectly opposed accelerating and decelerating beams can operate in principle with a very high loaded Q >> 10^7 such an arrangement makes this turn on and management of the FEL much more difficult. In practice, it may be more practical to trade the high CW power draw for ease of operation by having a lower Q_L [6].

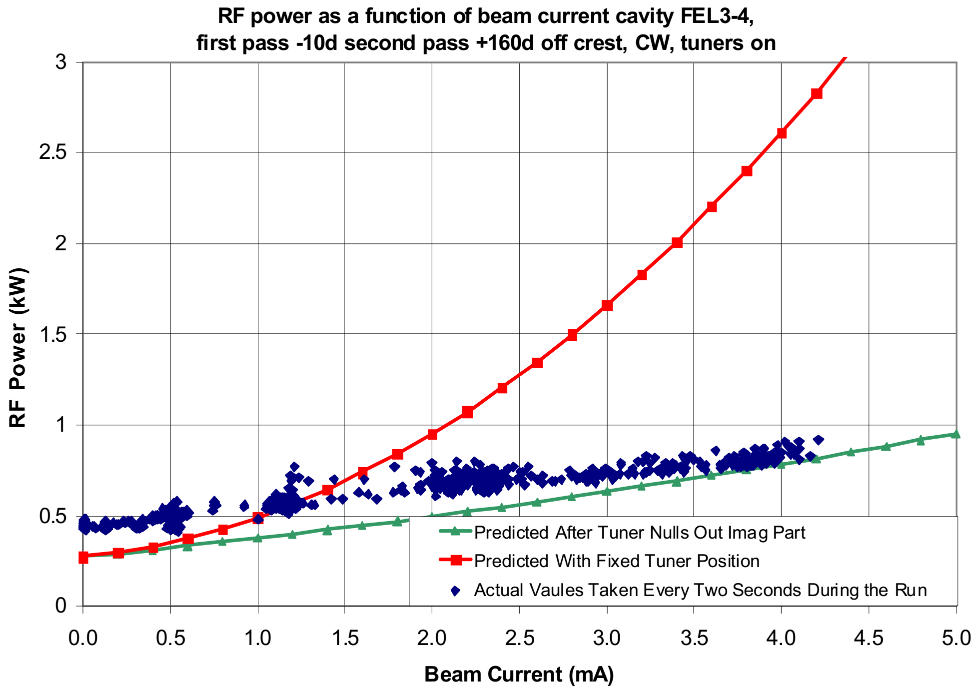

Figure 3. Measured and calculated RF power draw during lasing with cavity tuning for rf power minimum.

RF stability

Having excess power available to stabilize fluctuations is crucial. The optical cavity must have its round trip travel time precisely matched to the arrival time of the electron bunches for stable lasing. To keep the peak-to-peak fluctuations smaller than 10% it is necessary to keep the cavity length stable to less than $0.05 G N \lambda$. For example, in the JLab IR Upgrade for G of 0.5, a N of 32, and λ at 1.5 µm one must keep the cavity length constant to <1.2 µm peak to peak. The micropulse arrival time must be kept constant to the same precision:

$$\frac{\delta\omega}{\omega} < \frac{\delta L}{L} < \frac{1.2\times10^{-6}}{32} = 3.8\times10^{-8} \qquad (1)$$

From the frequency modulation constraint you get a timing jitter constraint of $\delta\tau < 6\mathrm{x}10^{-9}/f_m$. Note that the FEL is fairly tolerant of slow timing jitter since the optical cavity can follow this.

FEL SYSTEMS STATUS

Given these stringent requirements and others in magnetic transport it is no wonder that various groups have chosen differing approaches in order to meet the tight demands. Practical experience over the next few years is expected to guide the field to an optimal approach. At the present time there are several groups with operational high power FEL ERLs and several others in various stages of construction and planning.

Budker Recuperator

One machine is a room temperature accelerator operating at very low frequency (180 MHz) to relax longitudinal tolerances discussed above. The machine is called a Recuperator. The full-scale Novosibirsk free electron laser is to be based on a four-orbit, 40 MeV ERL producing 40 mA CW. It is presently being installed and is to generate radiation in the range from 5 micron to 0.2 mm [7,8]. The electron source is a 300 keV DC gun with a gridded cathode producing nanosecond pulses which are subharmonically bunched. The injector can produce 30 mA in a 22 MHz series of pulses. The first (operational) stage of the machine has a full-scale RF system, but has only one orbit bringing the energy to 12 MeV. The 2 MeV electron beam from an injector passes through the accelerating structure, acquiring the 12-MeV energy, and comes to the FEL. After interaction with radiation in the FEL the beam passes once more through the accelerating structure, returning the power, and comes to the beam dump at the injection energy. The FEL has produced over 400 W of CW power (> 1MW peak) at 60 microns. The four loops now being installed are in a plane 90 degrees to the original.

JLab FELs

The JLab FEL program has been discussed in previous papers [5]. In this superconducting machine ohmic losses are reduced to negligible levels with the SRF structures (6 W/cavity at typical gradients) while maintaining high acceleration gradients (5 to 18 MV/m). The IR Demo was completed in September 1998. The injector is the critical technology for operation of systems such as this; it must produce high average currents at high brightness. This original system utilized a DC photocathode operating at 320 kV to produce a 74.85 MHz pulse train of 60 pC. This gun produces the highest average brightness of any injector gun in the world and delivered in excess of 5.3 kilocoulombs from a single GaAs crystal at 1% quantum efficiency operating in the green from a doubled Nd:YLF laser beam. The IR Demo beam was accelerated to between 36 and 48 MeV and produced over 2 kW of CW average power[9]. In addition, the system produced 4 watts of power lasing on the fifth harmonic at 1 micron. Third harmonic operation at 1 micron achieved 300 W CW [10] and, even beyond this, conversion to > 60 W of green and > 10 W of UV at high efficiency in doubling, tripling and quadrupling crystals. Up to 10^9 photons/sec of Thompson scattered X-rays in the 5 to 15 keV range are produced when the FEL pulse scatters off subsequent electron bunches. The system also synchronously produced $>10^4$ more THz power (50 W) in sub-picosecond pulses than any other source [11].

An Upgrade of the system now has produced continuously over 14.3 kW in the IR at 1.6 microns. An additional beamline is being installed to permit operation at over 1 kW in the 250 to 1000 nm range (Figure 4). The system uses energy recovery of the beam

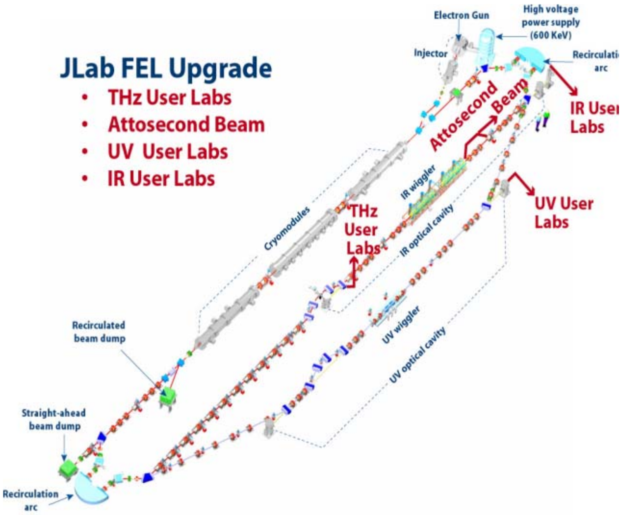

Figure 4: Layout of the IR Upgrade accelerator. The injector is at the upper right. The beam is injected into the three cryomodule linac, accelerated up to 150 MeV, transport through a Bates style bend and a chicane to a wiggler. It then is transport through a second Bates style bend back to the linac to be decelerated and dumped. Output ports provide user light at a number of wavelengths ranging from X-rays down to terahertz.

as demonstrated in the IR Demo to reduce required rf power, virtually eliminate activation of components, and reduce power handling requirements on the dump. Figure 4 illustrates the Upgrade design. It comprises a 10 MeV injector, a linac consisting of three Jefferson Lab cryomodules generating a total of 80 to 160 MeV of energy gain, and a recirculator. The latter provides beam transport to, and phase space conditioning of, the accelerated electron beam for the FEL and then returns and prepares the drive beam for energy recovery in the linac.

The injector is a direct upgrade of the IR Demo injector [9] from 5 mA to 10 mA at 10 MeV. The current is doubled by an increase of the single bunch charge from 67 pC to 135 pC while maintaining the 75 MHz repetition rate. The linac comprises three cryomodules; the first and third incorporate a conventional five-cell CEBAF cavities, and the central module is based on new seven-cell JLAB cavities [12]. That module demonstrated 82 MV of continuous acceleration surpassing all previous such systems before suffering a rf window failure. The resulting contamination now limits the beam energy to 45 MeV due to regenerative electron loading. As shown in Figure 1, the beam is accelerated (energy recovered) off crest (off trough) so as to impose a phase energy correlation on the longitudinal phase space used in subsequent transport to longitudinally match the beam to the required phase space at the wiggler (dump). That is to say, the bunch is kept relatively long during acceleration, compressed to high peak current just before the wiggler, then temporally expanded before reinsertion into the energy recovery phase of the linac.

The energy recovery transport consists of a second Bates-style end loop followed by a six-quad telescope[13]. The beam is matched to the arc by the second telescope of the FEL insertion; the energy recovery telescope matches beam envelopes from the arc to the linac acceptance. Because energy recovery occurs off-trough, the imposed phase-energy correlations are selected to generate energy compression during energy recovery, yielding a long, low momentum spread bunch at the dump. Measurements indicate that the Upgrade will tolerate an induced energy spread from the FEL of 15% – compressing it to a final spread of order ±1% – despite the large ratio of final to initial energy. Calculations and measurements show that the emittance growth due to coherent synchrotron radiation (CSR) is not a problem for this design[14] but may impact operation at higher charge.

The machine delivers beams of high power THz, IR, and soon UV to a set of User Labs for scientific and applied studies. Such studies on the IR Demo were extremely successful in exploring vibrational dynamics of interstitial hydrogen in crystalline silicon, carbon nanotubes, and pulsed laser deposition [15,16]. Future applications will include those as well as microengineered structures, non-linear dynamics in atomic clusters, and metal amorphization. This machine is viewed as the first of a new category of high power, high brightness light sources called Energy Recovering Linacs (ERLs) with the potential to extend beyond the performance of third generation synchrotrons in both brilliance as well as offering the capability of femtosecond light pulses for dynamics studies. [17-19].

JAEA

A similar energy recovery effort for high power generation is underway at the Japan Atomic Energy Agency (JAEA)[20,21]. This uses a superconducting radio frequency (RF) linac FEL driver to produce a high electron beam power in a quasi-continuous wave (long macropulse) mode. It has four 500MHz UHF superconducting RF cavities with four zero-boil off cryostats with a 10K/50K two stage Gifford-McMahon (GM) refrigerator of He gas heat-shield cooling and a 4K Joule-Thomson (JT)-GM 3 stage refrigerator of liquid He re-condensing inside the liquid He containers. The linac utilizes a 250 kV thermionic electron gun, 8 refrigerator compressors, 2 main accelerator modules, and a 7.2 m long optical resonator surrounding a hybrid undulator. They generated strong FEL lasing in long macropulses initially at 0.1kW in the end of 1997 and later 2.34 kW in the end of 1999[22]. They were able to discover a new lasing mode producing a few hundred femtosecond pulse of 3.4 cycles at a high conversion efficiency of 6-9% from the beam power to FEL light, one GW peak power and over 2kW high average power in long macro-pulses[23,24]. These performance parameters were typically obtained with the electron energy of 16.5MeV, bunch charge of 510pC, bunch length of 2.5-5ps, bunch repetition of 10.4125MHz (8 mA), at a wavelength of 22.4 microns.

Next Generation Devices

The practical demonstration of ERLs has led to a number of proposals for ERL devices around the world. Systems have been proposed at Cornell, Daresbury, at KEK, BNL, KAERI and elsewhere. Some of these incorporate FELs, some just utilize synchrotron emission as a light source and some are designed for other purposes such as cooling of ions. Perhaps the most ambitious and best example to show the range of possibilities of such devices is the 4GLS of Daresbury Lab [25]. It is illustrated in Figure 5. The system has been designed with multiple FELs, two operating as oscillators and one as an XUV amplifier as well as a number of undulators for synchrotron ports. The XUV system does not utilize energy recovery because it operates at high peak but low average current negating the advantage of energy recovery in this case. The group has submitted the full proposal for consideration by the UK Science Council and is commissioning the ERLP, a low energy prototype system with interesting THz, IR, and X-ray characteristics of its own. The real strength of a design such as this is the possibility of having multiple, synchronized, sub-picosecond sources available for pump-probe research.in condensed matter physics. This opens up a wealth of possibilities for srf based ERLs and high power FELs.

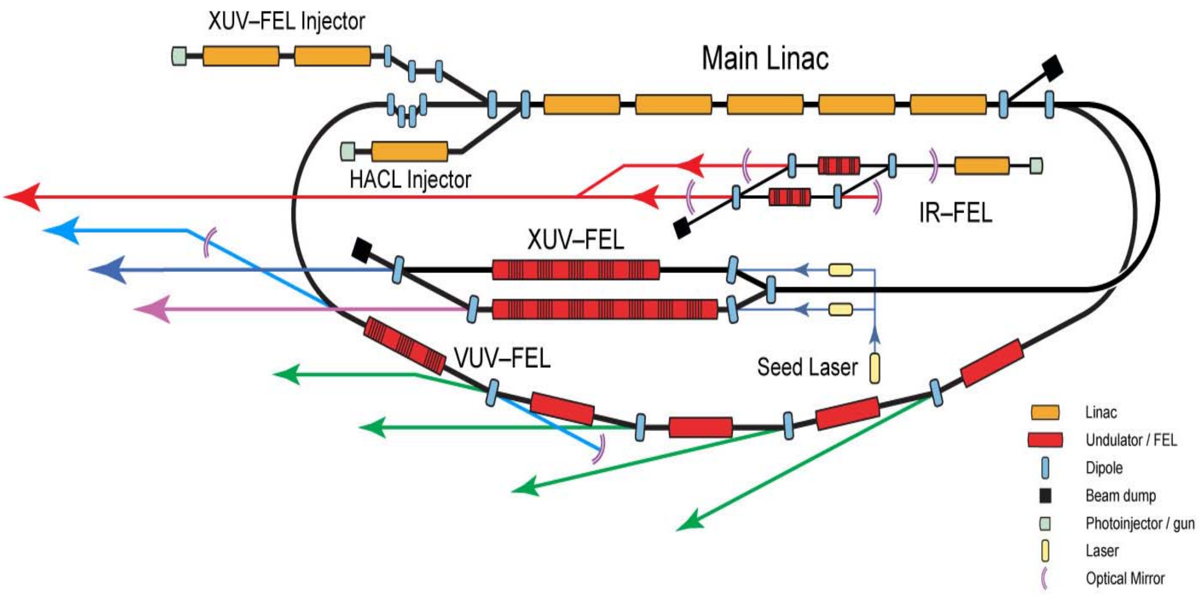

Fig. 5. An illustration of the Daresbury 4GLS. A true 4th generation light source, it utilizes synchrotron ports, collective amplification of light for the XUV region, and VUV and IR FELs and THz to permit a variety of pump probe experiments. The system uses srf cavities at 1300 MHz and multiple injectors; some optimized for high charge to drive XUV FELs and some designed for the lowest emittance for high brightness synchrotron emission and operating at less than 100 pC/bunch. Only the low charge high average current beam is energy recovered.

ACKNOWLEDGEMENTS

We had the support of the entire FEL team in developing this work. Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.

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