ON THE DESIGN IMPLICATIONS OF INCORPORATING AN FEL IN AN ERL

G. R. Neil, S. V. Benson, D. Douglas, P. Evtushenko, and T. Powers
Thomas Jefferson National Accelerator Facility, Newport News VA 23606 USA.

Abstract

Encouraged by the successful operation of the JLab Demo in 1998, many high current ERLs are now being designed with not only short pulse synchrotron beamlines but also FELs. Such inclusion has major implications on magnet quality, rf feedback requirements, wiggler design, srf cavity Q_L, halo, etc.

Measurements on the JLab ERL FEL have identified new challenges. The JLab Upgrade was designed with a 160 MeV beam of 10 mA in 75 MHz, 300 fs bunches. FEL designers set transverse emittance and longitudinal bunching requirements, but to accommodate an FEL in our ERL also means setting stringent phase stability requirements of ($<6\times10^{-9}/f_m$ *rms*) based on a desired FEL detuning tolerance of 1.2 microns. Recovered beam RF loading on the subsequent accelerated beam complicates satisfying these requirements. Gain in the rf feedback limits the accuracy of energy stability when loaded Qs are $\sim10^7$. Energy recovery to <10 MeV sets magnetic field tolerances at 10^{-4}. We present measurements on the JLab ERL showing how to set system requirements to tolerate such FEL lasing.

BACKGROUND

Given the rising interest in Energy Recovered Light Sources incorporating Free Electron Lasers [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. The discussion below should not be viewed as inclusive but rather is a starting point for further analyses based on experience to date. We give examples of specific criteria based primarily on our experience with the JLab IR Upgrade machine, which has proven to be a great learning tool in the path toward the next generation ERLs. Key areas for discussion 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

For an FEL ERL 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 [2-4].

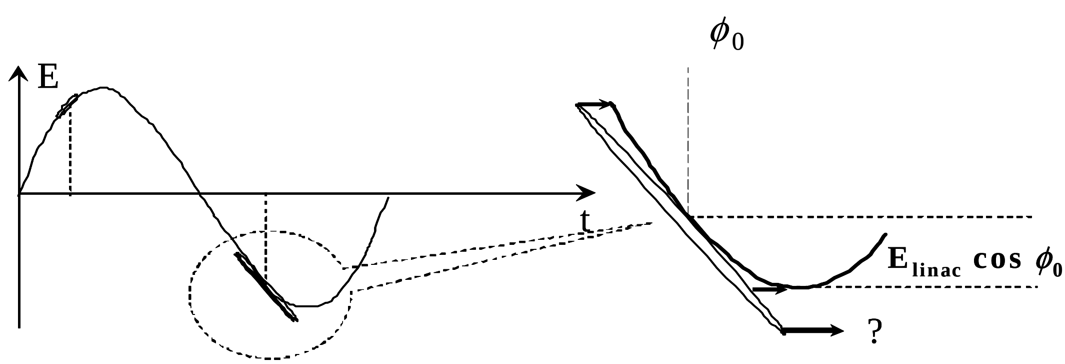

Figure 1. Electron distribution on the acceleration and deceleration rf phase. If the energy spread of the beam exceeds $(\Delta E/E)_{FEL}/2 < E_{linac} \cos \phi_0$ then there is not sufficient rf gradient to decelerate those electrons.

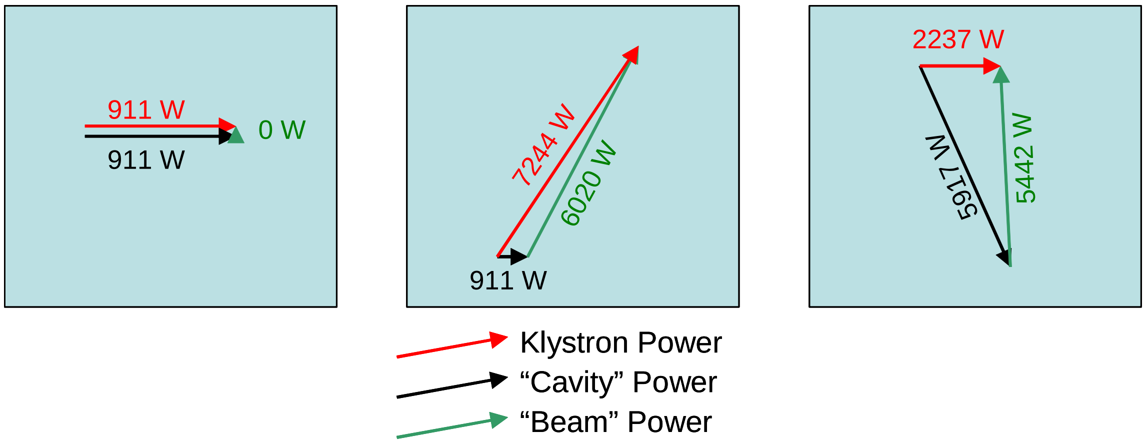

Figure 2. Loading of the rf with a) perfectly matched acceleration and deceleration, b) when the FEL turns on and instantaneously shifts in phase, c) after the srf cavity tunes its resonance to minimize power draw.

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 [5].

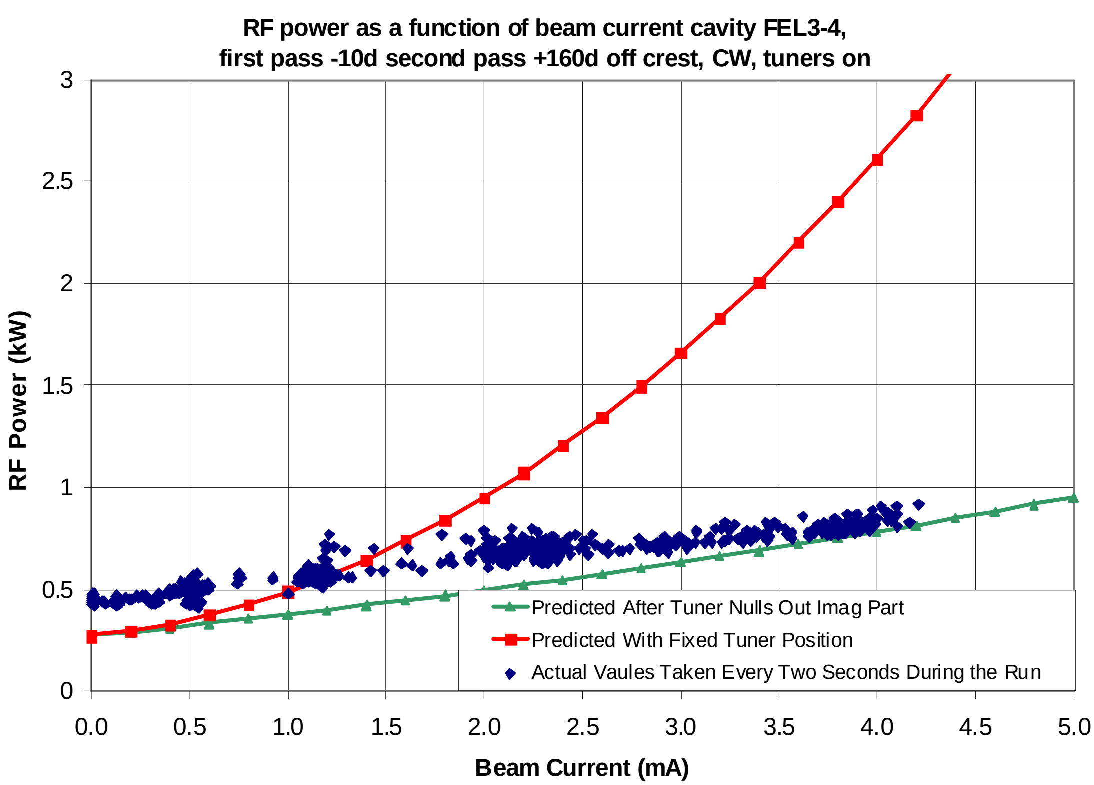

Figure 3. Measured and calculated RF power draw during lasing with cavity tuning for rf power minimum.

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 $0.05GN\lambda$. 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 $\delta\tau < 6\text{x}10^{-9}/f_m$. Note that the FEL is fairly tolerant of slow timing jitter since the optical cavity can follow this.

FIELD QUALITY

Since the FEL and energy recovery is sensitive to the phase of the rf it goes without saying that magnetic field quality affects the path that any electron takes and therefore must have tight tolerances. A transverse variation in field ΔB leads to an erroneous angular spread across the beam of magnitude $\delta x' = \Delta Bl/B\rho \sim \Delta Bl/(33.3$ kG-m/GeV * $E_{linac})$. This evolves, via M_{52} a path length spread δl, which differential path length spread in turn translates to a final energy spread ΔE_{dump} which equals $2\pi \sin\phi_0\, M_{52}(\Delta Bl/33.36$ kG-m$)/\lambda_{RF}$ (GeV). From this one can conclude that the allowed error field integral ΔBl is *independent* of linac length/energy gain. In other words the tolerable relative field error falls as energy (required field) goes up. Higher energy ERLs will have increasing difficulty meeting this requirement. For the JLab Upgrade the tolerances are of order $\Delta E_{dump} \sim 3400$ MeV * ($\Delta B/B$) and ~ 0.16 keV/G-cm * (ΔBl); thus a 10^{-4} relative field error budget leads to a remnant momentum spread of 340 keV after energy recovery. This has led to the necessity of careful design, mapping, and hysteresis control of the magnets in the Upgrade. Major dipoles must be spectrometer grade with dB/B of 10^{-4} (see Figure 4 for an example of one of our IR Upgrade magnets).

A substantial amount of effort has gone into making the IR Upgrade FEL transport have the ability to linearize and control higher order transport terms so as to achieve the shortest possible bunch length at the wiggler and successfully transport beam energy spreads of up to 15% all the way to the beam dump with current losses less than 10^{-4}. A full discussion of this system is beyond the scope of this paper. We refer the reader to [3].

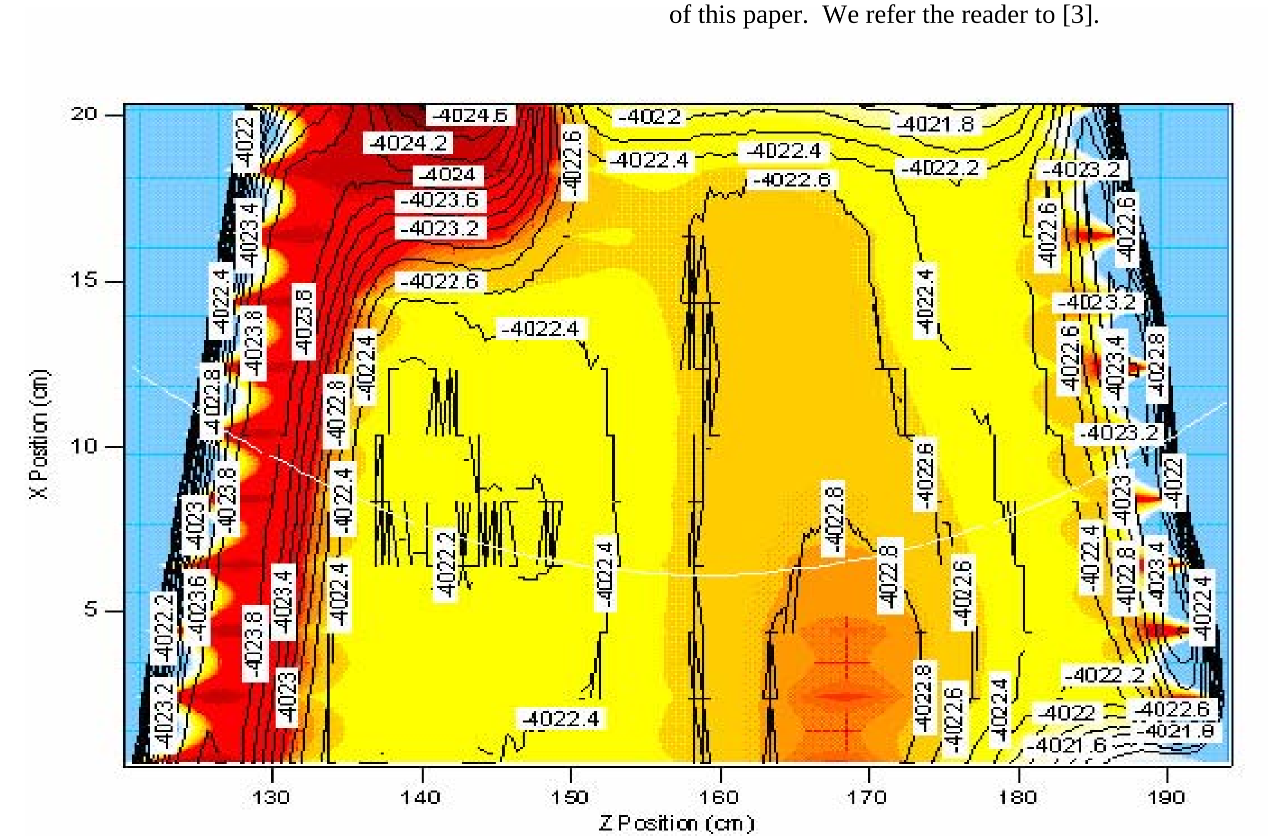

Figure 4. Measured field contours of a GX dipole at 0.4 G resolution. Precision measurements such as these must be made at all desired operating points (or ranges) and B• dl calculated for high order transport.

WAKEFIELDS

The wakefield produced by relativistic particles is an issue often dealt with in storage rings so techniques to address this are well known in the community. The issues with an ERL can be more severe than with such storage rings because of the short bunch lengths required at the FEL itself. This causes the high frequency collective emission cutoff to move to much higher frequencies, a benefit if one is looking for THz emission but a detriment in terms of resistive wall heating and excitation of unintended cavities along the beam pipe. Transitions between different size and shape chambers must be engineered to minimize wakefield problems or significant heating of the electron beam can result.

In addition, the narrow chamber required for wigglers exacerbates the problem since the longitudinal wake goes inversely with the square of the pipe diameter. Such effects can have dramatic consequences even at the modest currents (5 to 10 mA) of our first generation ERLs (Figure 5).

SUMMARY

We have illustrated a number of ways in which the demands of high longitudinal brightness at the input of the FEL, and large energy spread at the output of the FEL can drive tight specifications for the magnetic transport system and its apertures. In addition the need for output stability and the impact of laser transients sets additional strict requirements on the RF control system, and phase and timing stability of the beam. While existing engineered solutions meet the need of first generation machines, improvements will be needed to extend the performance to systems presently in the planning stage.

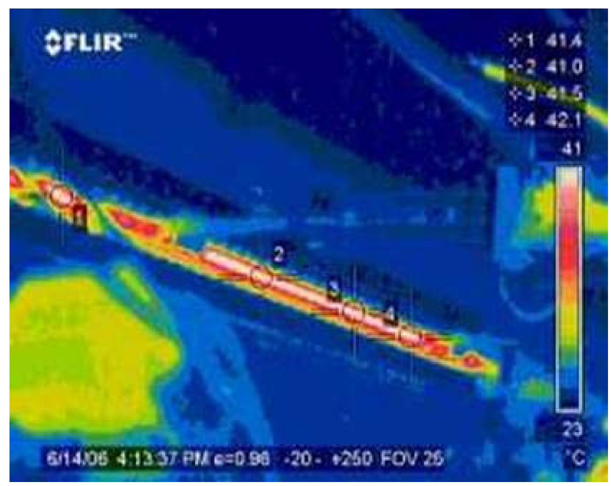

Figure 5. An image of the IR Upgrade wiggler chamber in the visible and infrared during 4.6 mA of beam. Heating is estimated at 35 W/m with the chamber reaching 42°C on top and 100°C at midplane.

ACKNOWLEDGEMENTS

We had the support of the entire FEL team in developing this work. We especially appreciate the help of Rui Li and Eduard Pozdeyev of CASA in analyzing the wakefield effects. This work was supported by U.S. DOE Contract No. DE-AC05-84-ER40150, the Office of Naval Research, the Air Force Research Laboratory, the Army Night Vision Laboratory, the Commonwealth of Virginia and the Laser Processing Consortium.

REFERENCES

[1] G.R. Neil, et al., *Nucl. Inst. And Meth. In Phys. Res.* **A557**, 9-15(2006).

[2] D. R. Douglas, et al., Proc. Linac 2000, Monterey, August 21-25, 2000.

[3] D. R. Douglas, JLab Technical Note JLABTN02002, (2002).

[4] S. Benson, *Nucl. Inst. And Meth. In Phys. Res.*, **A507,** 40-43 (2003).

[5] A.M. Vetter, *Nucl. Inst. And Meth. In Phys. Res* **A429,** 52-57(1999).