OPERATIONAL ASPECTS OF HIGH POWER ENERGY RECOVERY LINACS

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Abstract

We have been operating a high-power energy-recovery linac (ERL) at Jefferson Lab for several years. In the process we have learned quite a bit about both technical and physics limitations in high power ERLs. Several groups are now considering new ERLs that greatly increase either the energy, the current or both. We will present some of our findings on what to consider when designing, building, and operating a high power ERL. Our remarks for this paper are limited to lattice design and setup, magnets, vacuum chamber design, diagnostics, and beam stability.

INTRODUCTION

Energy recovery linacs (ERLs) were first proposed for use in high energy physics in the early 1960s [1], but only a few were built. Once reliable SRF structures with good higher order mode (HOM) damping and photocathode sources were available, an ERL with a high-average-current beam that could be efficiently energy-recovered was realized at Jefferson Lab [2].

The IR Demo ERL at Jefferson Lab was constructed in 1997 and operated with up to 5 mA of 48 MeV average current and a 74.85 MHz pulse repetition rate. It could produce 400 fsec rms bunch lengths and enabled the operation of an FEL with over 2 kW of power [3]. The design took advantage of the symmetry of the ERL lattice to cancel out higher order transport effects. This allowed very clean transport to the dump. The success of this machine was the inspiration for several other ERL designs, many at higher current and some at much higher energy. One was the IR Upgrade [4] ERL at Jefferson Lab, which is the focus of this paper.

EXTENSIONS FROM THE IR DEMO

The IR Demo can be scaled in energy, charge, and/or current. Increasing the charge requires more attention to halo, wake fields, HOM power, resistive wall heating, and CSR effects. All of these effects are sensitive to both the charge and current and therefore get worse non-linearly as the charge increases at fixed repetition rate. Pushing to higher current requires attention to all of the above plus BBU thresholds, RF stability, and ion trapping. Pushing to higher energy means that the machine is more sensitive to accumulation of magnetic field errors and is more sensitive to growth in energy spread at full energy.

THE IR UPGRADE

The IR Upgrade FEL accelerator was designed to increase the charge by 2X over the IR Demo. The design added two cryomodules in order to triple the accelerator energy. The FEL is now in the backleg and is much more sensitive to emittance and phase jitter. We will discuss several lessons learned from this design.

Lattice Design and Setup

The IR Upgrade design uses an achromatic, non-isochronous 180° bend design from Bates Accelerator Lab at MIT at either end [5]. This bend allows us to cancel out RF curvature effects using sextupoles in the Bates bends. Four trim quadrupoles at each end can be used to set the momentum compaction and linear dispersion. The four sextupoles are also used to set second order dispersion and reduce chromatic aberration. In the second Bates bend, octupoles are used to correct the longitudinal phase space to third order. The FEL wiggler was designed for a minimum efficiency of 1%. We have observed efficiency as high as 2.3% with minimal losses. The acceptance of the second arc is >15%. To cancel chromatic aberrations we balance the two telescopes before and after the 2nd Bates bend. We have discovered however that steering errors can couple angle and position errors to energy offsets through the higher order matrix elements such as T_{116}, T_{126}, …, T_{336}, T_{346}, etc. Machine setup is therefore an iterative process where steering, focusing, and longitudinal matching must be balanced to provide the best transport to the dump. The middle cryomodule in the linac has poor higher order mode damping, resulting in a low beam breakup (BBU) threshold. The threshold can be as low as 1 mA for some lattices. We have now demonstrated that the threshold depends on the state of the FEL. The threshold could be raised from 1.5 to 2.5 mA when lasing was initiated. The threshold can be raised to more than the maximum injector current using a transverse phase space rotator [6]. We use skew quadrupoles to rotate the transverse phase space 90 degrees from the exit of the middle cryomodule back to its entrance. This can raise the BBU threshold to tens of mA [7].

Magnet Quality

Canceling BBU using a rotator relies on having skew focusing only in the rotator. Some of our dipoles use Purcell gaps [8] to flatten the field. We have found that, after years of use, the epoxy in the Purcell gap degrades, leading to delamination of the pole, and thus a skew quadrupole moment in the dipole. This can frustrate the BBU suppression scheme. The quality of the magnet in an ERL not only must be very high to start with, they must be rugged enough to maintain the quality.

Another operational problem is magnet accuracy. We found that our quadrupole magnets were not meeting their reproducibility specification. This was due to irreproducibility in the hysteresis cycle. This could be addressed using a so-called "bang-bang" algorithm, which changes the setpoint according to a square wave temporal profile. The performance with this procedure was quite reproducible from day to day. Unfortunately the actual magnet strength was dependent on the intricacies of the power supply and cables supplying the magnet. Any change in the supply or cabling would change the magnet strength. This has been addressed using beam-based measurements to directly measure the fields. In any new machine it is extremely important that the magnets be measured and accurately known to an accuracy of better than 0.1% of the level at which they will be driven. For a high-energy machine this will be essential in enabling the commissioning of the device.

Beam Diagnostics

Setting up an ERL requires excellent diagnostics. All the usual electron beam diagnostics such as beam position monitors, optical transition radiation (OTR) viewers, synchrotron light viewers, and beam loss monitors must be provided. In addition, viewers must have the resolution to view the small spot sizes in the bright beam and a dynamic range of order 10^6:1 to keep from saturating with full beam while still being able to see very weak tails in the beam. The transverse distribution in an ERL is not even close to a Gaussian beam. We have found that a better description of the transverse phase space is a two-beam distribution. Most of the beam is in a "core" distribution that contributes most to lasing. The rest of the beam is in a "halo" distribution that might contain up to 20% of the beam but has different Twiss parameters. If one matches the core beam one might find that the halo beam is badly mismatched in the transport lattice and is lost at choke points such as the entrance to wigglers or undulators. Since these insertion devices are usually sensitive to radiation damage, any loss at their entrance can be very damaging. It is necessary to keep the halo distribution under control while trying to get the core beam optimally matched to the wiggler. This can only be done if both distributions can be imaged. We use insertable neutral density (ND) filters in front of most of our viewers. These allow use to see both the diffuse tails and the unsaturated core beam. We have also installed a very sensitive "halo monitor" after the second Bates bend. This allows us to see extremely faint tails on the beam before it gets rematched to the linac for deceleration. Synchrotron light monitors are used wherever possible. These also have insertable ND filters.

It is also necessary to set up the longitudinal match. This can be done using a modulation system that modulates the phase of RF cavities and looks at the phase response at various points in the transport. Figure 1 shows some samples of how the trim quadrupoles and sextupoles can be set up in the first Bates bend. At high charge the final adjustment must be done using a coherent OTR device since space charge effects can lead to changes in the slope and curvature of the bunch during acceleration. A scan from such a device is show in figure 2. We now routinely produce bunches with an *rms* bunch length of 150 fsec or less providing a peak current for the FEL of more than 300 A.

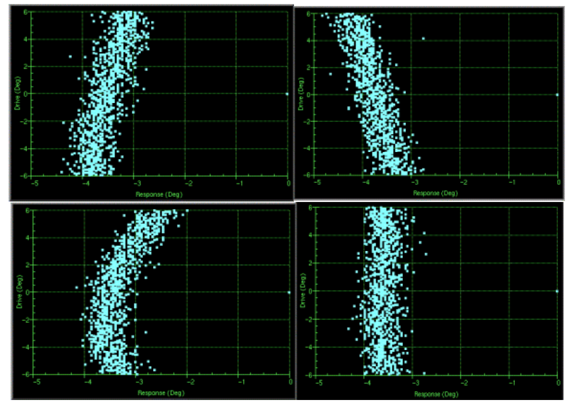


Figure 1. Input phase to linac vs. phase at the wiggler for the IR upgrade. The upper left image is with trim quadrupoles too strong. Upper right is with trim quads too weak. Lower left is with mispowered sextupoles, and lower right is properly set to produce maximum compression.

Vacuum Chamber Design

As current is raised to levels seen in storage rings it seems obvious that the vacuum chamber design must be carefully designed to minimize wake fields and heating of beamline elements. The chambers must also have energy absorbers installed around bending magnets. Storage rings already worry about this but in the presence of very short bunches, there is an added load due to coherent synchrotron radiation emitted in the bends. In the IR Upgrade we have shielded viewer insertions and pump drops and have used tapered transitions when going from a round to a rectangular vacuum chamber. Where the overall chamber cross-section reduces in size we have used so-called "cookie cutters" to absorb the self-fields of the electron beam. In a high current ERL the loads for these cookie cutters must be water-cooled. When the cross section increases it may be better to use a long tapered section to reduce the wakefield effects.

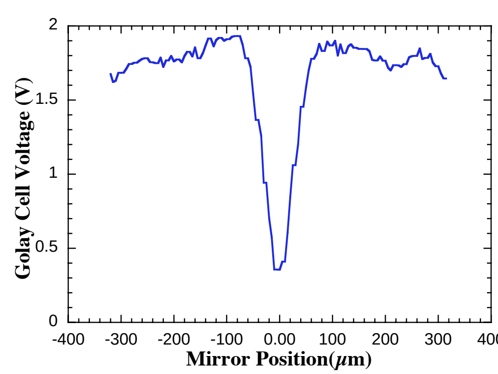
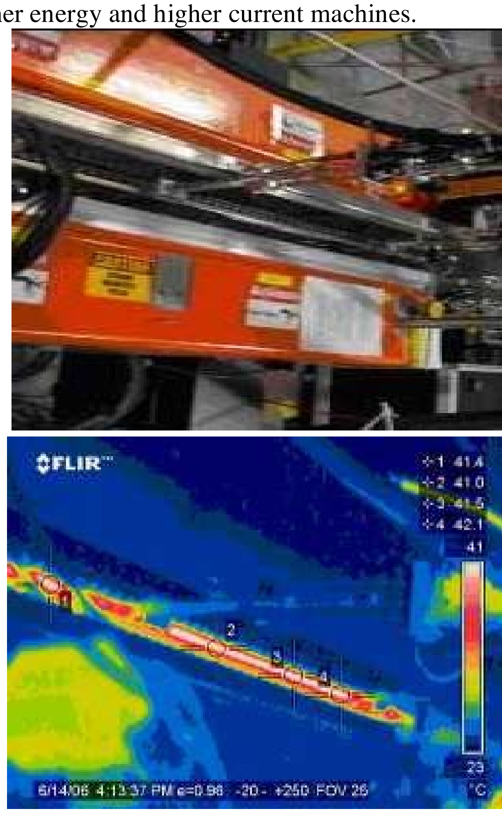


Figure 2. Coherent Optical Transition Radiation interferometer scan for typical operation. This scan indicates an rms bunch length of less than 150 fsec.

Even if the chamber has smooth transitions, the chamber can be heated directly by resistive wall effects. We have observed temperature rises in our stainless steel wiggler chamber (12 mm internal width) of up to 70 °C when operating with 5 mA of beam and 150 fsec *rms* bunch lengths. An example of this is shown in figure 3. Figure 3a is a view of the wiggler chamber in visible light. Figure 3b is the same chamber viewed using a FLIR infrared imaging camera. The edge of the chamber, which is cooler than the face, gets up to 42 °C when exposed to 4.6 mA of electron beam. The calculated loss for this chamber for 130 pC bunches at 37.5 MHz is 35 W/m. Resistive heating must be taken into account for higher energy and higher current machines.



a.

b.

Figure 3. Visible (a) and infrared (b) images of the wiggler vacuum chamber showing strong resistive wall heating. The hottest part of the chamber is on the side hidden by the wiggler.

Electron Beam Stability

Free-electron lasers and synchrotron light sources need excellent stability in order to provide stable light to users. Strong beam jitter can lead to a reduction in efficiency or gain of an FEL device. We have done a careful study of energy and phase jitter at several points in the IR Upgrade. For an FEL it is necessary to keep the cavity length and the arrival time constant to better than 1 micron peak-to-peak. In the case of the IR Upgrade this is for a 32 meter cavity so this is 3 parts in 10^8. The arrival frequency must be maintained to this precision as well. Phase jitter at frequencies less then the characteristic frequency of the optical resonator, equal to the round trip frequency divided by the cavity losses, may lead to frequency jitter larger than this specification. The specification for the IR Upgrade is that the jitter must be less than $6x10^{-9}/f_m$. In an ERL designed to be an FEL driver, the electron beam goes through 90 degrees of longitudinal phase advance between the injector and FEL. This means that phase jitter at the FEL corresponds to energy jitter in the injector. We looked at the energy jitter in the injector and found that the SRF control modules were holding the *rms* energy jitter to less than 0.025%. The conversion from energy jitter to phase jitter is 0.3 psec/%. The *rms* temporal jitter due to injector energy jitter is then less than 8 fsec at all frequencies and is <<1 fsec at the characteristic resonator frequency of 25 kHz.

We also looked at high voltage power supply fluctuations. These produce phase and energy variations at the FEL as well. We found that the specification for the high voltage power supply ripple is that the *rms* voltage ripple must be less than 2.4 kV at 25 kHz. This is much larger than observed voltage ripple.

CONCLUSIONS

Enhancing the IR Demo design with higher charge, higher energy, and brighter beams has highlighted some of the design challenges that must be faced when going to even higher current or energy. We have recounted here a few of the operational and design challenges that must be faced when building the next generation ERLs. Note however that the list here is not exhaustive. There are other effects such as space charge, higher order mode power deposition, and RF stability in the presence of lasing that we have discussed in previous work as well as others we have not had time to discuss here. Great care must be taken in the design stage of the next generation devices so that these issues do not become fatal design flaws.

ACKNOWLEDGEMENTS

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