HIGH POWER LASING IN THE IR UPGRADE FEL AT JEFFERSON LAB

S. Benson*, D. Douglas, M. Shinn, K. Beard, C. Behre, G. Biallas, J. Boyce, H. F. Dylla, R. Evans, A. Grippo, J. Gubeli, D. Hardy, C. Hernandez-Garcia, K. Jordan, L. Merminga, G. R. Neil, J. Preble, T. Siggins, R. Walker, G. P. Williams, B. Yunn, S. Zhang, H. Toyokawa†
TJNAF, Newport News, VA 23606, USA
† Photonics Research Institute AIST-Tsukuba Japan

Abstract

We report on progress in commissioning the IR Upgrade facility at Jefferson Lab. Operation at high power has been demonstrated at 5.7 microns with over 8.5 kW of continuous power output, 10 kW for 1 second long pulses, and CW recirculated electron beam power of over 1.1 MW. We report on the features and limitations of the present design and report on the path to getting even higher powers.

INTRODUCTION

At last years' FEL conference we reported on first lasing of the IR Upgrade FEL in the infrared region [1]. Turn-on and commissioning of that device went quite smoothly and CW power of 300 W at 10 µm and 3 mA of CW electron beam current at 80 MeV were demonstrated. Two problems were noted—the FEL gain and power were lower than expected, and the mirror losses at 10 µm were higher than expected. This paper will discuss how these problems were overcome and how we intend to extend the power even higher that we have to date. The paper will describe the challenges we faced in the accelerator and our understanding of how to set it up to produce an electron beam capable of high power. It will also describe the challenge of running with over 100 kW of CW circulating power in a free-electron laser.

ACCELERATOR CHALLENGES

The accelerator layout is shown in figure 1. By the FEL 2003 conference almost the entire machine had been installed and commissioned. The first arc still used a dipole from the IR Demo machine [2], limiting the beam energy to 80 MeV. We also used pairs of reworked IR Demo sextupoles that limited operation to around 90 MeV and were only in one of the two locations necessary for dispersion suppression. There were no octupoles installed in the second arc. Finally, only two of the three cryomodules had been installed, limiting the energy to less than 90 MeV. In the fall of 2003 we took advantage of a hurricane-induced downtime to install the final dipole in the first arc. In early spring we upgraded the sextupoles with bigger coils that allowed operation at up to 160 MeV and installed the octupoles in the second arc. In May of 2004 we installed the middle cryomodule, which has operated with an accelerating voltage of over 80 MV with beam, giving a total available accelerator energy of 170 MeV.

* email address felman@jlab.org

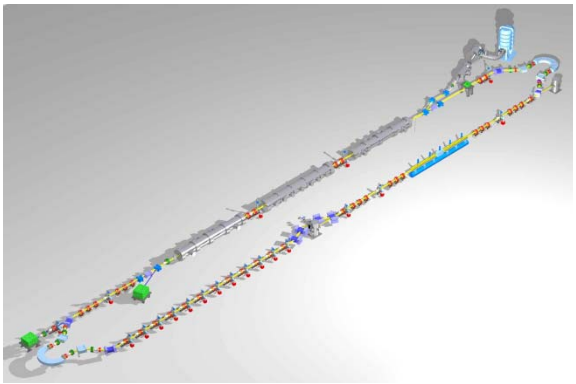

Figure 1. Layout of the IR Upgrade FEL in its final configuration. The beam starts at the injector at the upper right, is merged with the full energy beam in an injection chicane, accelerated up to as much as 160 MeV in three cryomodules, transported to the optical klystron, and from there back to the linac. At the exit of the linac the energy-recovered beam is separated from the accelerated beam and is dumped in a water-cooled copper dump.

The challenge of producing a high quality beam

The main reason for poor lasing performance last year was a large growth in the longitudinal emittance between the injector and the wiggler. To understand the tradeoffs involved with reducing this growth it is useful to describe the longitudinal matching around the accelerator.

The injector is designed to produce an upright longitudinal distribution at the entrance of the first accelerating module of the linac [3]. For our initial design the injected bunch length was 1.5 psec *rms* and the energy spread was 12 kV *rms*. The accelerator is designed to take that distribution and rotate it by 90 degrees in phase space. The bunch length and relative energy spread at the wiggler are then given by:

$$\sigma_{t,W} = \frac{\sigma_{E,I}}{E_L \omega \tan\phi} \text{ and } \frac{\sigma_{E,W}}{E_W} = \frac{\omega \tan\phi}{1 + E_I / E_L} \sigma_{t,I} \qquad (1)$$

where $\sigma_{E/t,W/I}$ are the rms bunch lengths and energy spreads at the injector and the wiggler, ω is the accelerator frequency, ϕ is the off-crest phase, E_L is the energy gain in the linac, and E_I and E_W are the beam energies at the injector exit and at the wiggler entrance. This equation assumes that the quadrupoles and sextupoles in the first arc are set to values that match the M_{56} and T_{566} of the arc to the slope and curvature imposed on the beam by the accelerator and thus perform a 90° rotation [4].

The bunch length calculated using equation (1) for the design injector and the accelerator operated at 80 MeV, 15 degrees off-crest, should have had an rms bunch length at the wiggler of 67 fsec and energy spread of 0.33%. In fact the energy spread was close to 0.3%, but the bunch length, measured using both a Martin-Puplett style interferometer looking at coherent OTR and a scanning Michelson interferometer looking at the coherent synchrotron radiation, was over 300 fsec rms and was sensitive to the transverse match in the machine. In addition, the first arc magnet strengths that produced the shortest measured bunch were not those noted above that rotated the phase space by 90 degrees. Finally, the rms energy spread at the end of the wiggler should not depend on the sign of the phase with respect to the peak of the linac's accelerating phase (see equation (1)). In fact, however, the energy spread was 50% larger on one side of crest than on the other side. All these discrepancies between the expected behavior and the accelerator performance are due to longitudinal space charge (LSC) in the linac and transport [5]. The LSC leads to longitudinal emittance growth and a tilt of the energy distribution that alters the longitudinal match to the wiggler. We reduced the effects of LSC by modifying the injector setup to increase the injected micropulse length to 2.5–3.0 psec. This reduced the longitudinal emittance growth, improved the FEL efficiency, and altered the longitudinal match so that the design magnet strengths were nearly optimal for the first arc. One cannot increase the injected bunch length by an arbitrary amount. Due to the energy acceptance of the FEL it is necessary to decrease the off-crest phase angle to offset the increase in bunch length. This leads to problems with energy recovery that will be discussed in the next section.

Using one family of sextupoles per arc it is possible to properly set the T_{566} for the longitudinal match and to cancel the dispersion to first order. It is not possible to correct the second order dispersion, which leads to a reduction in the efficiency of the FEL and to loss of halo at several points in the transport. This halo is produced in the gun at different launch phases than that of the accelerated bunches. The buncher cavity is set to bunch high charge bunches and strongly overbunches the halo. The halo then has a large energy spread at the end of the linac and, when the dispersion is corrected to only first order, grows dramatically in horizontal beam size at the wiggler entrance. With two families of sextupoles we were able to transport beam cleanly through the wiggler. The efficiency also more closely matched predictions.

Once the third cryomodule was installed we had a new challenge. The damping of the higher order modes (HOMs) in this cryomodule is not sufficient to raise the beam breakup (BBU) threshold above 10 mA. In fact one HOM was found to have a threshold of only 3 mA. We found that, since there was only one mode with a low threshold, we could alter the betatron phase advance to increase the threshold up to over 5 mA. As an experiment we also installed skew quads that changed a vertical kick into a horizontal motion at the offending cavity [7]. With these magnets set correctly we could run at least 8 mA at 145 MeV (1.16 MW of beam) with no evidence of beam breakup. In the future we will further characterize the BBU threshold dependence and study other ways to raise the threshold.

Challenges in energy recovery

The magnets after the FEL must transport a beam with very large energy spread to the dump with extremely low losses. To do this, the energy vs. time distribution must be properly matched to the decelerating gradient in the linac. When this is done correctly the longitudinal phase space is rotated 90 degrees by the time the electron beam reaches the beam dump. The matching is done to third order in the energy offset using quadrupoles, sextupoles, and octupoles. This system can, in principal, accept up to 15% energy spread [4]. Operating the accelerator close to crest leads to a problem with this scheme. The highest energy electrons in the distribution must be close to trough in order to decelerate all the electrons to the same final energy. If this is done, the mean phase ϕ_{dec} must be $\phi_{dec} = \sqrt{\Delta E / V_{linac}}$ or more where ΔE is the full energy spread and V_{linac} is the total linac voltage. If we have a distribution with 15% energy spread we must have a mean phase of at least 22.5 degrees. One would like to decelerate the beam 180° out of phase with the accelerating beam since no extra RF power is required as the current is increased. If one accelerates 10 degrees off crest this will not be possible due to the loss of the higher energy electrons at the dump. We have discovered that it is still possible to recover the electron beam with very low loss by decelerating less than 180° from the accelerated beam at the mean phase derived above. A minor drawback of this setup is that some RF is required to accelerate the beam since it ends up at a higher energy than at injection. The FEL power must come from somewhere. In the IR Demo it came from the injector. In the IR Upgrade it comes from the linac. When longer injector micropulses were used, the off crest phase was limited to 10° to keep the energy spread below the wiggler acceptance. We found that it was necessary to run about 4 degrees further from trough to energy recover during high power lasing. This configuration was stable and the electron losses were minimal.

A new challenge in the IR Upgrade was CSR-induced high-energy tails on the electron beam due to the shorter bunches and higher charge. If the bunches are fully bunched by the transport up to the wiggler, they will produce copious coherent synchrotron radiation. This leads to the growth of a high-energy tail on the beam in the energy recovery section of the beam. We have found that, by setting the transport to the wiggler to slightly underbunch the beam, the CSR can be greatly reduced and the bunch length is only slightly longer than the minimum. The FEL performance is actually better when this is done due to the smaller energy spread.

The final challenge is to correct for chromatic aberration. This can produce large growth in the beam size as the energy spread increases. This was found to be a major cause of beam loss in the linac. We have found that having matched betatron phase advances in the lattices before and after the second arc can suppress the spot size growth due to chromatic aberration and lead to well-contained beams during energy recovery.

The machine is now essentially complete. Except for the average current and the longitudinal emittance the machine matches the design values. A current of 9 mA has been demonstrated at 88 MeV and we do not see any fundamental reason why we will not be able to run at 10 mA, 160 MeV this fall. With two families of sextupoles in the first arc we found that the FEL efficiency closely matched predictions made by pulse propagation codes. We are now working on stability and reproducibility in the lattice and are developing methods to ease setup of the transverse match around the machine.

OPTICAL CHALLENGES

Optical challenges fall into two categories: 1. Getting mirror losses down to acceptable levels, and 2. handling the circulating and outcoupled power. We gradually learned how to accomplish both of these.

Reducing mirror losses

Previous work has shown that there is a limit to how much power the mirrors can absorb before the power saturates [6]. For example a zinc selenide output coupler can absorb 5W/μm*λ of power before the FEL power will saturate. In practice one can slightly exceed this number but it is a good design point. With the first set of 10 μm mirrors we found a large amount of mirror heating for even low power. Mirror losses were found to be 0.74% and 0.3% for the output coupler (OC) and the high reflector (HR) respectively. We replaced the OC with a mirror with 0.4% loss. This allowed us to achieve up to 700 W of CW power but it was clear that 10 kW was out of reach unless the losses could be reduced to under 500 parts per million (PPM). Discussion with mirror vendors indicated that this was highly unlikely.

From our experience on the IR Demo we knew that lower loss coatings were available in the 6 micron range. We remounted our 97.3% reflectivity OC used for the first light operation in a water-cooled mount and found that we could produce up to 2.3 kW from the laser. This exceeded the IR Demo power record and produced a circulating power of 84 kW.

Using an OC with an even lower loss and a reflectivity of 92% we were able to push the power up to 4.1 kW. At this power level the FEL itself becomes a good diagnostic for measuring mirror absorption. This allowed us to tune the wavelength for minimum loss. We found that the loss for the output coupler at 5.75 microns was only 250 parts per million (PPM). The high reflector had a loss of 400 PPM including an estimated 100 PPM of transmission.

One hypothesis for the high losses in the downstream mirror was that THz edge emission from the dipole just upstream of the mirror might dominate the OC heating. Measurements with an electron-beam energy of 80 MeV indicated that this was not the case. At an electron beam energy of 145 MeV the absorbed THz power went up dramatically, ranging from 50–85 W at 5 mA. The maximum allowed power in the output coupler at 6 microns is 30 W. The absorbed THz power would not allow us to run at 10 kW CW, though we could run 10 kW with up to a 30% duty cycle and could run CW with over 6 kW of power output.

In order to avoid THz heating of the output coupler we reversed the optical cavity so that the backplane-cooled high reflector, which can absorb over 200 W of power before limiting laser power, was downstream. The power absorbed in the output coupler was now just the fundamental power. The power absorbed in the high reflector consisted of three sources: the absorbed fundamental power, coherent second harmonic power, and THz edge radiation. This configuration allowed us to run 10 kW with a duty cycle of over 50% and to run CW with up to 8.5 kW of laser output power.

Since the time constant for mirror distortion is quite long it proved possible to run for periods of up to 1 second with power exceeding 10 kW. The power during the laser pulse vs. time for a run on July 21, 2004 is shown in figure 2. The power during 1 second pulses was as large as 10.6 kW. When shorter pulses were run the power was as high as 11 kW during 0.25 second pulses. The macropulse power vs. pulse length is shown in figure 3.

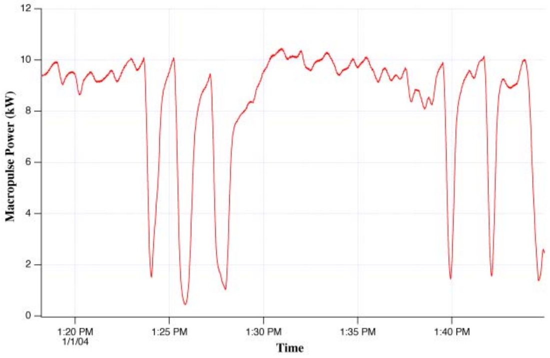

Figure 2. Power during 1 second pulses during time on July 21, 2004. The power could be repeatedly raised to higher than 10 kW. Dropouts are due to accelerator trips or mirror mis-steering.

Handling the power

When the power output of an FEL is several kilowatts in the mid-infrared even measuring the power is a challenge. We found that calcium fluoride windows could not handle transmitted power exceeding 1500 W at 6 microns. We therefore moved to an *in vacuo* power meter designed and built at Jefferson Lab capable of handling up to 50 kW of laser power. The power is absorbed in a black copper coating in a water-cooled cone. The rise in the water temperature of the cooling water and the flow are monitored and used to calculate the absorbed power. It is possible that power is also lost due to backscatter and conduction so the power numbers quoted here are lower limits. Comparison at low power with a commercial power meter indicated that the power reading might be as much as 10% low, though the uncertainty was large in this calibration.

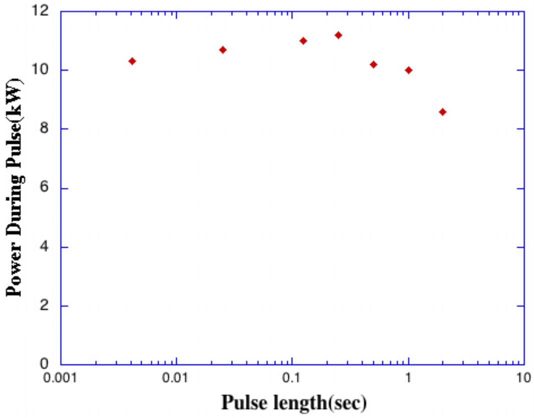

Figure 3. Macropulse averaged power as a function of pulse length. The point at 0.5 seconds was not fully optimized. The power was calculated assuming negligible turn-on time. The rise in power with pulse length is partly due to this and partly due to the fact that the high reflector radius of curvature was optimized for the longer pulses.

When lasing at 5.75 microns and 10 kW the output coupling was 8%. This means that the circulating power exceeded 125 kW. Even scatter of parts per thousand can lead to major problems in the cavity. We found that the rings holding the mirrors tended to heat after a time running at high power. This caused changes in the mirror alignment and cavity length. We had planned to use a helium-neon laser to track the mirror angle. Scattered light absorbed in the windows for this system distorted them sufficiently so that this was not possible. When we tried to shield the windows with metal screens we found that the scattered light melted holes in them. THz light also heated beamline elements and led to vacuum rises and optical distortion. Clearly, high power laser systems have to account for all power losses in the system and must be shielded from spurious light of all wavelengths. Our optical cavities are being modified to account for this reality.

CONCLUSIONS

The IR Upgrade has been a learning experience. Lessons learned from this machine can be used to both upgrade the present machine and better design the next generation machine. For example, in the future we plan to install a small chicane close to the wiggler that debunches the electron beam and reduces the THz edge emission to tolerable levels. We also plan to install a shorter period wiggler with a higher gain-efficiency product. This will allow us to increase the output coupling and reduce circulating power. It will also allow us to access shorter wavelengths where mirror losses are very low. We expect to be able to reach 10 kW CW with this setup. It should also allow operation at over 10 kW in the 6 micron range. Due to the lack of good mirrors we do not expect more than about 5 kW at 10 µm. We plan to explore broadband cavities to see what the average power limit is for a hole or scraper outcoupler system.

All these experiments dumped the laser power in the accelerator vault. We are in the process of installing an optical transport that will allow transport of the high power beam up to users. Note that we can produce over 300 µJ/micropulse with this laser in a subpicosecond pulse. It is not just a high average power laser but also a high peak power laser. This will be of great importance to users of the laser.

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