# First lasing of the Jefferson Lab IR Demo FEL

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**Abstract**

As reported previously [1], Jefferson Lab is building a free-electron laser capable of generating a continuous wave kilowatt laser beam. The driver-accelerator consists of a superconducting, energy-recovery accelerator. The initial stage of the program was to produce over 100 W of average power with no recirculation. In order to provide maximum gain the initial wavelength was chosen to be 5 μm and the initial beam energy was chosen to be 38.5 MeV.

On June 17, 1998, the laser produced 155 Watts cw power at the laser output with a 98% reflective output coupler. On July 28th, 311 Watts cw power was obtained using a 90% reflective output coupler. A summary of the commissioning activities to date as well as some novel lasing results will be summarized in this paper.

Present work is concentrated on optimizing lasing at 5 μm, obtaining lasing at 3 μm, and commissioning the recirculation transport in preparation for kilowatt lasing this fall.

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## Introduction

At the 18th International FEL in Rome we introduced the design of a free-electron laser (FEL) driven by a recirculating, energy-recovered continuous electron beam accelerator to demonstrate scalability to higher powers for industrial applications [1]. The design of this accelerator is such that the full current of 5 mA can only be produced with energy recovery. Without energy recovery only 1.1 mA of current can be produced due to limits on available rf power. Since the repetition rate of the accelerator can be reduced by a factor of two, and since the electron beam quality improves as the charge is lowered, the gain is not very much lower than that at full beam current when the laser is operated with 1.1 mA. This makes it possible to lase in "first light" mode without energy recovery and optimize the laser before energy recovery is attempted. Simulations of the beam using PARMELA indicated that we should be able to achieve an emittance of 5 mm-mrad with an energy spread of 50 keV and a bunch length of 370 fsec (all quantities rms). Using these numbers the predicted gain is well over 100% indicating a good margin for lasing. This paper is a description of the first lasing process and some of the interesting results we have gained since achieving first light.

## Driver Accelerator

The driver accelerator is shown in figure 1. The design and measured performance are shown in Table 1. Microbunches with an rms bunch length of 20 psec are produced in a DC photocathode gun and accelerated to 350 keV [2]. The bunches are compressed by a copper buncher cavity operating at the fundamental accelerating frequency of 1.497 GHz. They are then injected into a high performance superconducting rf (SRF) cavity pair operating at a mean gradient of 10 MV/m. The output beam from this is transported through an achromat, injected into an eight cavity SRF cryomodule, and accelerated up to ~38 MeV. The electron beam is then bent around the two optical cavity mirrors passing through the wiggler along the way and captured in a water cooled copper dump.

The program schedule was very aggressive with first-light hardware installed 15 months after first funding. Commissioning of the injector was started with the wiggler removed so that the radiation dose to the NdFeB permanent magnets could be minimized. The design current of 1.1 mA cw was achieved 21 months after first funding. The beam quality at 60 pC (as shown in Table 1) was found to be more than sufficient for lasing. In fact, the bunch length and vertical emittance are very close to the values predicted by PARMELA. The horizontal emittance is larger than PARMELA either due to wakefield effects or CSR induced emittance growth. Sensitivity to the phase of the cryomodule cavities has prevented good measurements of energy spread when the laser is optimized.

Once first light was achieved the emphasis in the accelerator development shifted to commissioning the recirculation system [3]. To date both pulsed and cw beam have been transported with essentially no loss to the energy recovery dump. The aperture of the system is sufficient that the exhaust beam of the laser can also be propagated with no losses through the recirculation loop back to the accelerating module. There are losses in the final transport to the energy recovery dump at 9.5 MeV, however, leading to a limit on average power. This loss is being investigated so that higher laser power can be achieved with energy recovery.

## Laser Commissioning

Once it was determined that the beam quality was sufficient for lasing [4], the wiggler and optical cavity mirrors were installed [5]. For first light we chose to use a high reflector and a 97.6% reflective output coupler. Using macropulses 200 μsec in duration the electron beam was aligned with the wiggler viewers and the cavity length was scanned. The laser power output immediately rose to saturation. Lasing at 4.9 microns was achieved over a 10 micron range of cavity length with no optimization. The laser was then operated cw. Using a power meter at the exit of the laser, 155 W of average power was outcoupled and over 110 W of power delivered to the optical diagnostic room.

After changing to a 90% output coupler, 311 W of cw laser power was measured on a power meter at the laser exit. Lasing weakly with energy recovery was possible but, as noted above, limited due to beam loss at 9.5 MeV. Once the recovered beam is better matched into the accelerating structure we expect to lase at high power with energy recovery.

## Lasing Results

In general the IR Demo laser has been very predictable and easy to run. When the electron beam and optical cavity are set up carefully the laser lases very strongly before any optimization. If the laser power is subsequently optimized, the resulting electron beam configuration is not much different from the original setup. Using measured values for the beam parameters, one ideally expects a small signal gain of approximately 90%. When setting up the system the gain should not be reduced by more than a factor of 3 due to electron beam and optical misalignments. This still allows sufficient gain to lase to saturation. Variation of the electron bunch parameters indicates that the highest power occurs for the shortest electron bunch length and the smallest longitudinal emittance as expected. Sensitivities to variation in steering, focussing, cavity phases, and average current are qualitatively similar to expectations. Note that the mirror sensitivity in table 1 is for pulsed or low power operation with large cavity losses. When the mirrors heat up or when the output coupling is small, we have found that the sensitivity to mirror tilt is much smaller.

In figure 2a we show the power as a function of cavity length as the micropulse repetition rate is varied [6]. To our knowledge this is the first time this has been reported for a FEL. The total cavity loss is 11% per round trip so the threshold gain (defined as $G_{th} = (1-\Gamma)^{-N} - 1$ where $\Gamma$ is the round trip cavity loss) is 12.4% for 18.8 MHz repetition rate, 26.3% for 9.4 MHz, and 59.4% for 4.7 MHz. We see from the detuning width in figure 2a that the gain must be well in excess of 59.4%. The electron beam in this case was pulsed with a 1.2% duty cycle. The electron gun was run at 327 kV for this data so the emittance is not as small as in Table 1. The other parameters are similar. Mirror heating effects should have been negligible. In figure 2b we have scaled both the power and the cavity length detuning by the reduction in the frequency to give an indication of the extraction efficiency as a function of the optical delay from synchronism. Note that the optical delay scales linearly with the number of round trips per gain pass. The curves in figure 2b are remarkably similar to each other. Note, however, that the scaled cavity length detuning curve is actually shorter for a smaller threshold gain (9.4 MHz case compared to 18.8 MHz). This is a very puzzling feature which may be due to optical guiding effects[7].

In figure 3a we show the power vs. cavity length as a function of bunch charge. In figure 3b the power is scaled to the bunch charge. As expected the laser power is approximately proportional to the bunch charge. The length of the cavity detuning curve is a very non-linear function of the charge, however. This is not entirely unexpected since the emittance and energy spread are smaller when the charge is smaller. It is a bit surprising, though, since the bunch length and transverse match are not optimized for the low charge operation. If we assume that the bunch length is unchanged, the predicted gain for 13 pC is around 25% and the length of the detuning curve according to supermode theory [8] is 13 μm, very close to what is observed.

Note how the shape of the curves also changes from convex to concave as the charge is reduced. Also note that the predicted detuning curve length for even 60% gain (and the gain must be at least this large as shown in figure 2) is 31 μm. As noted above, the gain caclulated from measured parameters is approximately 90% which leads to an expectation of a 46 μm long cavity length detuning curve. The length of the curve seems to be shorter than possible assuming a one-dimensional supermode theory.

Spectral measurements have also confirmed that we have quite high gain. When lasing near the synchronous detuning a strong sideband is observed. This should not be the case unless the gain to loss ratio is greater than around 4 which implies at least 50% small signal gain. As expected the spectra become much narrower as the cavity length is shortened. The spectral brigthness varies little over the central part of the detuning curve.

With pulsed operation at 60 Hz and a duty cycle of 1.2% , 4.1 W of laser power was detected in the optical diagnostic lab. The losses in the transport are at least 10% so this means that the laser power was at least 380 W during the macropulse and may have been as much as 480 W. During cw operation with a similar electron beam setup, the power did not exceed 311 W despite repeated optimization. This indicates that mirror heating reduced the laser output by 18 to 35%. Calculations of mirror distortion [5] indicated that the mirror absorption had to be less than 0.1% to achieve over 300 W of laser power. Measurements of the mirrors at the Naval Advanced Warfare Center in China Lake CA put an upper limit of 0.1% on the absorption.

**Conclusions**

In general this laser behaves according to expectations. One exception to this observation is the cavity length detuning curve. There seems to be some phenomenon which is keeping the detuning curves short when the gain is high. One possibility is guiding. Simulations have hinted that guiding effects can shorten a cavity length detuning curve even though the gain is increased. This might explain the very slow change in the cavity length detuning curve length with pulse charge.

With high gain and a 40 period wiggler it is not unreasonable to expect that one might extract over 1% of the electron beam power. Since the electron beam power is in excess of 40 kW, this would indicate that over 400 W of laser power is reasonable to achieve. Mirror distortion has limited operation to only 311 W but operation at 3 μm with sapphire mirrors should allow us to increase the power in "first light" mode to over 400 W. Recirculation can raise the electron beam power to 240 kW but may limit the extraction efficiency to no more than 0.75%. This setup should allow much higher power (close to 2 kW) if the quality of the sapphire mirror coatings is similar to those on the $CaF_2$ mirrors now in use.

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Table 1. Measured parameters for the IR Demo driver accelerator and laser

| Property | Design | Achieved | Unit |
|---|---|---|---|
| Pulse length | 1 | 0.4±0.1 | psec rms |
| Charge per bunch | 60 | 60±2 | pC |
| Peak current | 22 | 60±15 | A |
| Average current | 1.1 | 1.2 | mA |
| Transverse emittance | <8.7 | 7.5±1.5 | mm-mrad rms |
| Energy spread | <0.22 | 0.3±0.2 | % rms |
| Kinetic energy | 38. | 48 | MeV |
| Repetition rate | 18.7 | 18.7 | MHz |
| Position stability | 50 | <100 | μm |
| Angular stability | 100 | <200 | μrad |
| Wiggler Wavelength | 2.7 | 2.7 | cm |
| Number of periods | 40 | 40.5 | |
| $K_{rms}$ | 1.0 | 0.98 | |
| Wiggler rms phase error | <5 | 2.6 | ° |
| Trajectory wander | <100 | <100 | μm p-p |
| Optical Cavity Length | 8.0105 | 8.0105 | m |
| Rayleigh range | 40 | 40 | cm |
| Mirror radii | 2.54 | 2.54 | cm |
| Mirror radius of curvature | 4.045 | 4.050 | m |
| Mirror losses | <0.001 | <0.001 | |
| Mirror tilt tolerance† | 5 | ~5 | μrad. |
| Center wavelength | 4.8 | 4.8 | μm |
| Output coupler refl. | 98, 90 | 97.6, 90.5 | % |
| HR reflectivity | >99.5 | 99.85 | % |

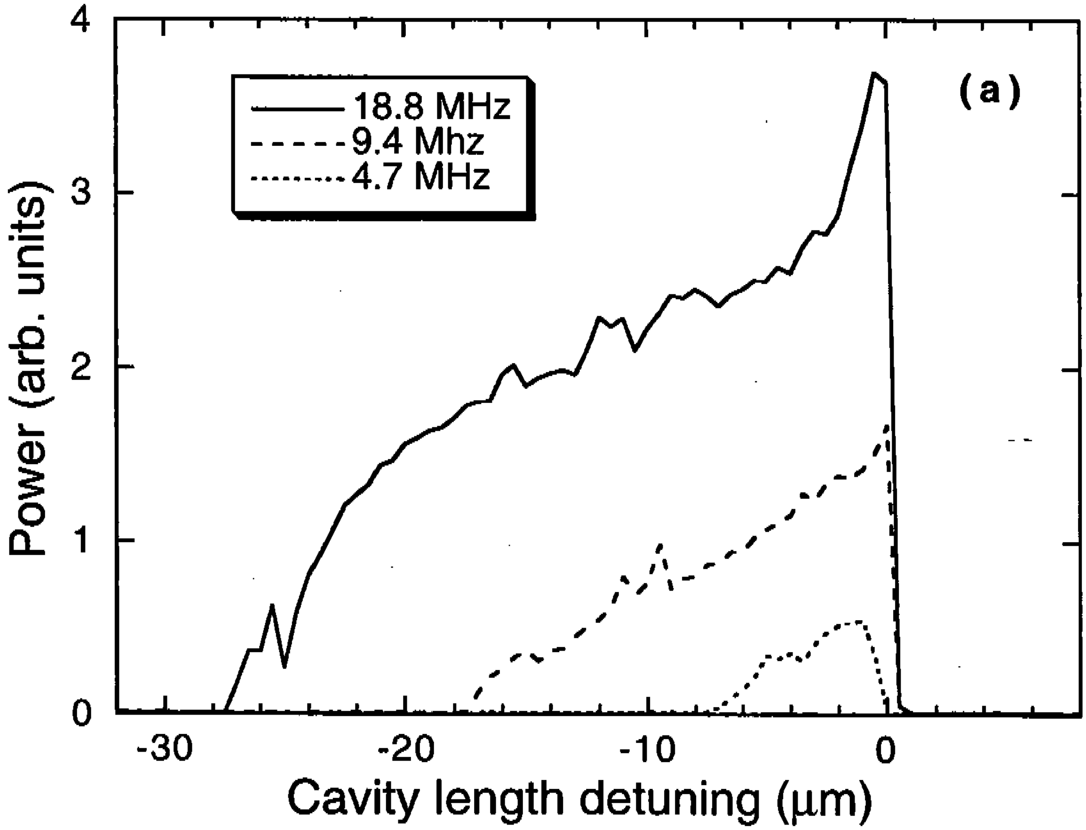
† This is the mirror tilt necessary to rotate the optical mode by 1/3 of the mode divergence. This much tilt has been shown to reduce the power by around 10% when the 90% output coupler is used and the laser is in pulsed mode.

**Figure captions**

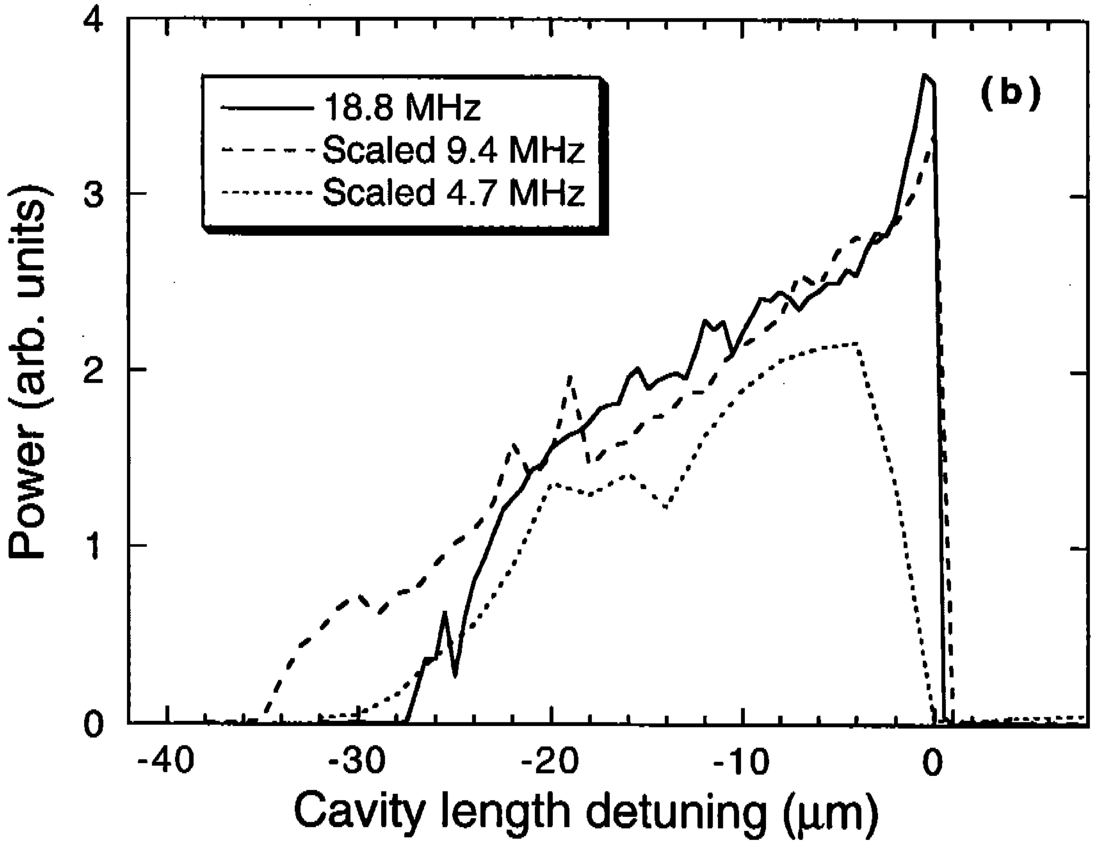
1.) IR demo layout. See text for explanation of operation.

2.) Laser power vs. cavity length for three different micropulse repetition rate. The round trip frequency is 18.813 MHz so the three curves correspond to one, two and four round trips per gain pass. In figure 2a we show the raw data. In figure 2b we have scaled the data by a factor of two and four in both axes to study the variation of the extraction efficiency with the repetition rate.

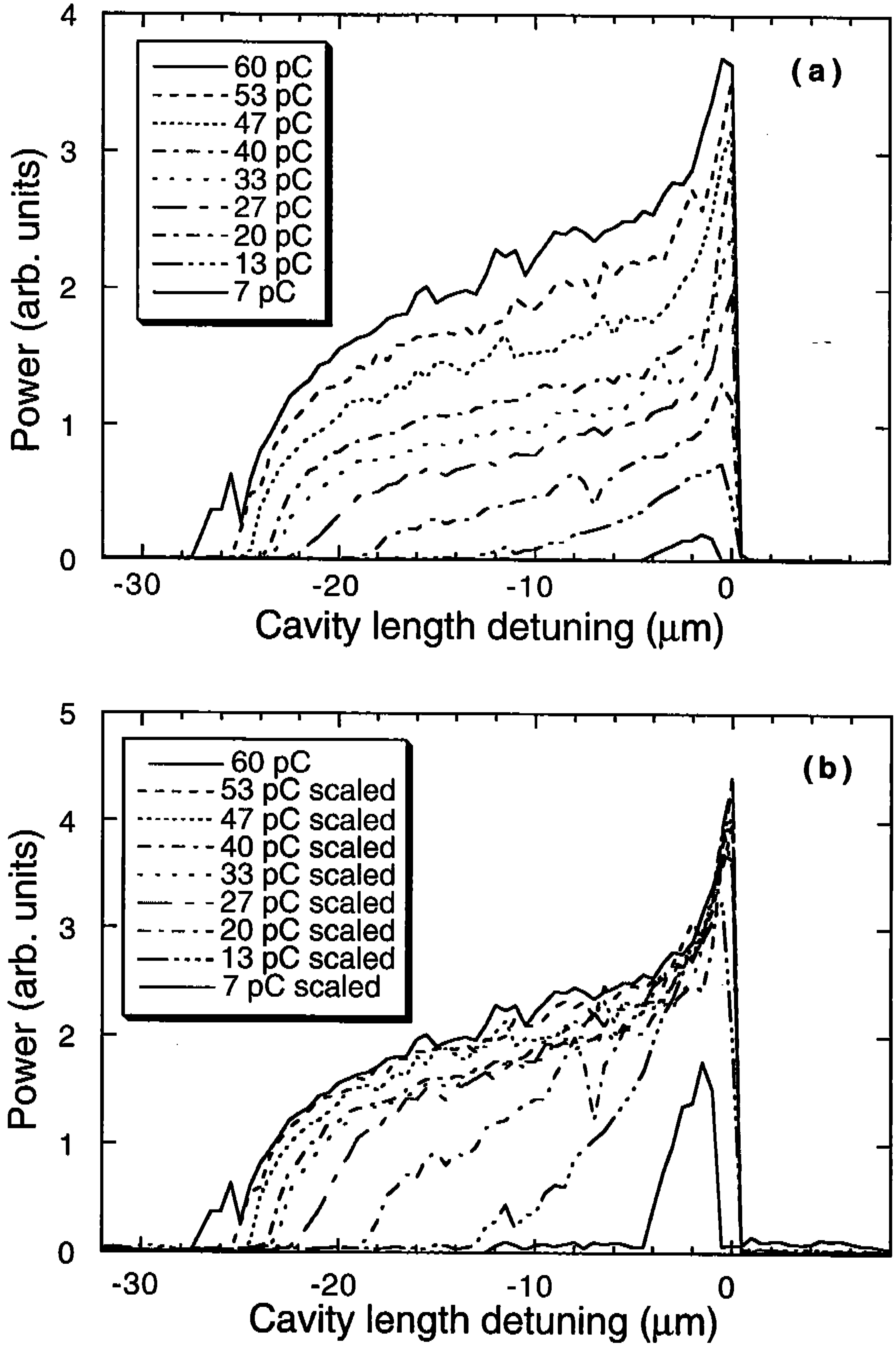
3.) Laser power vs. bunch charge. In (a) is the raw data. In (b) we have scaled the power to the maximum charge so that the extraction vs. charge is evident.



4
3
2
1
0
Power (arb. units)
18.8 MHz
9.4 Mhz
4.7 MHz
(a)
-30
-20
-10
0
Cavity length detuning (μm)

4
3
2
1
0
Power (arb. units)
18.8 MHz
Scaled 9.4 MHz
Scaled 4.7 MHz
(b)
-40
-30
-20
-10
0
Cavity length detuning (μm)



(a)
60 pC
53 pC
47 pC
40 pC
33 pC
27 pC
20 pC
13 pC
7 pC
Power (arb. units)
Cavity length detuning (µm)
(b)
60 pC
53 pC scaled
47 pC scaled
40 pC scaled
33 pC scaled
27 pC scaled
20 pC scaled
13 pC scaled
7 pC scaled
Power (arb. units)
Cavity length detuning (µm)