PERFORMANCE OF THE ACCELERATOR DRIVER OF JEFFERSON LABORATORY'S FREE-ELECTRON LASER*

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Abstract

The driver for Jefferson Lab's kW-level infrared free-electron laser (FEL) is a superconducting, recirculating accelerator that recovers about 75% of the electron-beam power and converts it to radiofrequency power. In achieving first lasing, the accelerator operated "straight-ahead" to deliver 38 MeV, 1.1 mA cw current through the wiggler for lasing at wavelengths in the vicinity of5 µm. Just prior to first lasing, measured rms beam properties at the wiggler were 7.5 ±1.5 mm-mr normalized transverse emittance, 26±7 keV-deg longitudinal emittance, and 0.4±0.1 ps bunch length which yielded a peak current of 60±15 A. The waste beam was then sent directly to a dump, bypassing the recirculation loop. Stable operation at up to 311 W cw was achieved in this mode. Commissioning the recirculation loop then proceeded. As of this Conference, the machine has recirculated cw average current up to 4 mA, and has lased cw with energy recovery up to 710 W.

1 INTRODUCTION

The Thomas Jefferson National Accelerator Facility (Jefferson Lab) built and is commissioning a cw, kW-level, 3-6µm free-electron laser (hereafter called the IR Demo). The design of the machine is presented elsewhere [1]. It incorporates a superconducting accelerator comprising a 10 MeV injector and a 32 MeV linac to produce a nominally 42 MeV electron beam for kW-level cw lasing. The accelerator is designed to achieve the top-level electron-beam requirements listed in Table 1 of Ref. [1] while transforming 75% of the beam power back into rf power. Beam parameters originally thought to be required for first light differ from those needed for kW power, however, and they are listed in Table 1 below.

First lasing involved running the machine in the "straight-ahead" mode, in which the beam is deposited in a "42 MeV dump" [1,2]. Doing so enabled achieving the first-lasing milestone before construction of the recirculation loop had been fully completed. Subsequently the machine was run in the "recirculation" mode [1] with pulsed beam and with energy recovery from the pulses, first without lasing, then with lasing. In this mode, the beam lands ina "10 MeV dump" after decelerating through the cryomodule.

The eight klystrons powering the eight cryomodule cavities can each deliver up to 8 kW. In turn, the available power limits the cw average current to a maximum of 1.1 mA in the straight-ahead mode. However, once recirculation with energy recovery is established, the decelerated beam powers the accelerated beam, and the recirculation mode thereby provides for currents above 1.1 mA. The injector then sets the limit on average current, which by design is 5 mA. To date the IR Demo has recirculated up to 4 mA cw. It has lased cw at up to 311 W straight-ahead and 710 W with recirculation and energy recovery, in both cases at ~5 µm wavelength.

Table 1: Beam Requirements at Wiggler for First Lasing.

Parameter	**Required**	**Measured**
Kinetic Energy	38 MeV	38.0±0.2 MeV
Average current	1.1 mA	1.10±0.05 mA
Bunch charge	60 pC	60±2 pC
Bunch length (rms)	<1 ps	0.4±0.1 ps
Peak current	22 A	60±15 A
Trans. Emittance (rms)	<8.7 mm-mr	7.5±1.5 mm-mr
Long. Emittance (rms)	33 keV-deg	26±7 keV-deg
Pulse repetition rate	18.7 MHz	18.7 MHz

2 OVERVIEW OF COMMISSIONING

The performance of the accelerator driver is a key product of the commissioning process. The end result is a machine that stably recirculates several mA average current for many hours while lasing cw at several hundred watts. For example, during a recent "longevity" run, the machine lased nearly uninterrupted for six hours with 400 W cw output power and with 2.5 mA recirculated current. The run ended by choice, not by machine degradation. Recently it has been delivering as much as 12 hours of uninterrupted ~100 W light with ~1 mA cw current in support of the first user experiments. Presently its Achilles heel is poor (~30%) availability of the electron gun. Otherwise it is robust and its performance has generally been easy to restore by loading a "golden file" of saved settings. What follows is an overview of the commissioning process that led to the present capability.

2.1 Photocathode Gun

The gun was constructed and tested off-line. In the IR Demo, the space between the gun and the cryounit is too small to

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accommodate beam diagnostics, so reasonable confidence in the gun's performance had to be established prior to its installation. During testing, the gun ultimately delivered bunch charges from 0-120 pC with phase-space parameters that were in reasonable agreement with PARMELA [3,4]. It also delivered up to 2 mA cw average current, but with an e-folding lifetime of only ~2 hours at this relatively high current. The short lifetime was believed to be due to the proximity of the cathode to the beam dump, which was located 2 m straight ahead from the cathode. Once favorable results were achieved off-line, the gun was installed in the FEL injection line.

To date the gun has been operated in the FEL to a maximum bunch charge of 60 pC in view of the first-light requirements in Table 1 as well as the desire to preserve cathode lifetime. The e-folding lifetime of the GaAs cathode has typically been ~10-20 hours at 60 pC, even at average currents in the 3-4 mA range [5]. The cathode wafer used in the most recent run delivered ~700 C total charge. Cathode lifetime is seen to depend sensitively on the quality of the ambient vacuum, which may influence beam operations via ionization of residual gas and back-bombardment of ions onto the cathode. Available data is too sparse to support a more quantitative statement. Of course, in the IR Demo, and unlike in the off-line tests, all beam dumps are located far from the cathode.

Based on findings of the Lab's Polarized Source Group [6], we have tried anodizing the outer regions of the cathode wafer to suppress electron emission from these regions. Although the benefit has been hard to ascertain conclusively, subsequent operation leading to first light proceeded with easily achievable beam transmission to the straight-ahead dump at 1.1 mA cw, something that had been more difficult to achieve prior to anodization. While commissioning the recirculation loop, we have not been anodizing the cathode out of concern that the edge of the anodized region could be a site for field emission that may degrade gun availability. However, without anodization there has been evidence of beam scraping, and in the future we will likely revert to anodized cathodes to see whether scraping is reduced.

The principal reason gun availability remains low is lack of funding to implement planned improvements. We are building an apertured cesiator to reduce cesium deposition on the cathode electrode. We may soon replace the cathode electrode; ion implantation is under study as a possible means for suppressing field emission from the cathode electrode.

2.2 Electron-Beam Diagnostics

Diagnostics for the IR Demo include: arrays of beam-position monitors, optical-transition-radiation viewers, and beam-loss monitors; two interferometric bunch-length monitors, one (BL1) at the entrance to the linac cryomodule and the other (BL2) just after the wiggler; two multislit transverse-emittance monitors, one (MS1) after the injector cryounit and the other (MS2) at the entrance to the linac cryomodule; and four rf cavities to monitor beam current and path length [7].

2.3 Straight-Ahead Mode

Commissioning the straight-ahead machine for first light proceeded well before construction of the recirculation loop was complete. Key diagnostics that ultimately led to the decision to install the wiggler and try for first light were BL2, a multimonitor emittance measurement using five viewers in the wiggler region, and an energy spread measurement using the dipole magnets and viewer in the second optical chicane. Cleanup of the electron beam proceeded systematically and led to gradual improvement in the six-dimensional properties of the beam. Measurements of the beam parameters at the wiggler were completed on 12 Jun 98. The results, listed in Table 1, motivated installation of the wiggler on 13 Jun 98. All agree with PARMELA to within 10% except the energy spread, for which the measured value was a factor of two higher, and correspondingly so was the longitudinal emittance.

The IR Demo achieved first light on 15 Jun 98, within six hours from turn-on of the electron beam after wiggler installation [2]. Two days later it lased stably at up to 155 W cw with 1.1 mA current (60 pC bunches at 18.7 MHz). First light involved a 2% outcoupling mirror that was subsequently replaced with a 10% outcoupling mirror. On 28 Jul 98 the power reached 311 W, again with 1.1 mA current. It is now easy to restore the straight-ahead machine from a file of saved settings and run it uninterrupted for hours at ~300 W.

Because beam quality at the wiggler is good, the injector has never been optimized. For example, it produces a total energy of 9.5±0.1 MeV as inferred from the injection-line dipole strengths, short of the design total energy of 10.5 MeV. Measurements with MS1 gave a normalized rms transverse emittance of 5.5±0.6 mm-mr, about 30% higher than PARMELA [8]. The beam at MS2 is off-nominal enough that good measurements with MS2 or BL1 have yet to be possible, but the bunch compression inferred by measuring the M_{55} transfer function ($=\partial\phi_{in}/\partial\phi_{out}$) using a pickup cavity is close to PARMELA.

2.4 Recirculation Loop

The first attempt to take beam around the recirculation loop occurred on 28 Jul 98. In the ten days of operation that followed, the recirculated cw current was pushed to 0.6 mA at 37.4 MHz with energy recovery, and the machine lased cw at low power while recirculating. Lessons learned from this experience motivated several modifications that expedited commissioning for high power. The most important of these were: adding a 74.8 MHz beam mode that would generate 4.4 mA beam with 60 pC bunches, putting a hole in the viewer foil at the cryomodule exit to pass the prelasing beam unperturbed and thereby permit a clean view of the 10 MeV energy-recovered beam, and adding a viewer after the quadrupole telescope in the energy-recovery dump line to help set up the beam at that dump.

There have been ~60 days of operation between making the cited modifications and this Conference. That period brought pronounced improvement in performance, in part by implementing longitudinal matching and energy compression. The laser power eventually plateaued at ~550W and did not increase as the current was raised from ~3mA to 4 mA, the highest current achieved to date. The suspected cause was a thermal limit in the CaF_2 mirrors comprising the optical cavity; they were specified to support first lasing at powers not exceeding ~200 W. Upon replacing the high reflector with a silicon mirror having better thermal properties, and despite the anticipated power limit of the remaining mirror, the IR Demo lased cw up to 710 W, at which the recirculated current was 3.6 mA. It is now straightforward to restore the recirculating machine from a file of saved settings and run it for prolonged periods at nearly 700 W.

3 ACCELERATOR EXPERIMENTS

Coherent synchrotron radiation (CSR) is almost surely present in the IR Demo's magnetic bends and may cause measurable growth in the transverse emittance [9]. With a 60 pC bunch charge, estimates indicate growths of about 10% in each optical chicane surrounding the wiggler, and about 50% in each recirculation bend. Concern about CSR-induced beam degradation was one motivator for placing the wiggler at the exit of the linac rather than following the first recirculation bend. However, the estimates carry considerable uncertainty, and the machine is an ideal platform for CSR experiments. Both self-consistent simulations and experiments in the form of parametric studies of emittance growth in the bunch decompressor following the wiggler and in the first recirculation arc have begun. Initial data suggest the presence of CSR-induced emittance growth, but conclusive, quantitative statements must await further measurements.

A series of beam breakup (BBU) experiments is being formulated. The motivation is to benchmark the code TDBBU that is used to predict thresholds for multipass BBU. Despite previous concerted effort [10], the code remains to be conclusively validated. The calculated BBU-threshold current in the IR Demo is 27 mA, well above the maximum achievable 5 mA. Planned experiments involve attempts to induce BBU in the recirculation mode by kicking the beam and/or powering deflecting modes with an amplifier. Beam-transfer functions would be measured while modulating the current moment $I\Delta x$ at frequencies or subharmonics of higher-order modes in the cryomodule cavities. The single-pass beam-transfer functions would also be measured to obtain the transverse shunt impedances of the strongest deflecting modes, thereby providing the requisite input for code calculations.

4 SUMMARY

The IR Demo has performed admirably to date, reproducibly recirculating nearly 4 mA of cw beam and providing nearly 700 W of stable cw laser power. Efforts continue toward boosting the power to the full design value of 1 kW, as well as toward improving the availability of the electron gun. The accelerator is an ideal platform for experiments concerning beam-quality degradation from coherent synchrotron radiation and beam breakup. The project' s success has led Jefferson Lab recently to propose upgrading the IR Demo to deliver ~10 kW infrared and ~1 kW ultraviolet cw lasing.

Rapid progress continues. During the week before this Conference, the accelerator recirculated 47 MeV beam at up to 3 mA current (all the cathode would produce) with energy recovery. The outcoupling mirror was replaced with a sapphire mirror of marginal quality, after which the IR Demo quickly lased cw at 3.2μm, thereby establishing its broadband capability. During PAC99 week, a new cathode wafer was being installed, and in parallel, plans are to install two high-quality, thermally robust sapphire mirrors to support high-power lasing at ~3 μm. These mirrors and the increased electron-beam power should be key to reaching the full 1 kW.

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