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Sustained Kilowatt Lasing in a Free-Electron Laser with Same Cell Energy Recovery[†]

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TJNAF recently commissioned its high-average-power infrared free-electron laser (FEL). It incorporates a superconducting accelerator that recovers about 75% of the electron-beam power and converts it to radio-frequency power. In achieving first lasing, the accelerator operated "straight-ahead" to deliver 38 MeV, 1.1 mA cw average current through the wiggler for lasing at wavelengths near 5 μm. The waste beam was then sent directly to a dump. Stable operation at up to 311 W cw was achieved in this mode. Using a transport loop to send the waste electron beam back to the linac for energy recovery, the machine recently lased cw at up to 1720 W average power at 3.1 μm, for which the electron-beam energy and average current were 48 MeV and 4.4 mA, respectively.

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Despite the fact that high-average-power operation of free-electron lasers (FELs) has been pursued for nearly two decades[1,2], such operation has been stymied by severe technical problems. Thomas Jefferson National Accelerator Facility built and commissioned an FEL (called the IR Demo) that was specially designed to produce high-average-power coherent infrared (IR) light by combining the continuous-wave (cw) operation of superconducting radiofrequency (SRF) accelerator cavities with an approach to recover the "waste" energy of the electron beam after it has been used for lasing. On 15 July 1999 the IR Demo lased stably at average powers up to 1.72 kW at 3.1 μm wavelength. Its demonstrated average-power capability is noteworthy, being a full two orders of magnitude higher than the previous average-power record for FELs (11 W at Vanderbilt University in 1990 [3]). However, the foremost achievement is a convincing demonstration of the underlying, enabling technology, namely same-cell energy recovery (SCER). The IR Demo incorporates SCER in a manner that is scalable to considerably higher average power. The motivation of this paper is to report on the machine design and key highlights of its commissioning, as well as to discuss quantitatively the efficacy of its SCER.

The design of the machine is discussed in more detail elsewhere [4], and the layout of the IR Demo is shown in Figure 1. The electron-beam parameters and measured performance are listed in Table 1. Microbunches with an rms bunch length of 20 psec are produced in a DC photocathode gun [5] and accelerated to 320 keV. The bunches are then shortened by a copper buncher cavity operating at the fundamental accelerating frequency of 1.497 GHz. They then pass through a pair of high-performance SRF cavities operating at a mean gradient of 10 MV/m. The output beam is injected into an eight-cavity SRF cryomodule, where it is accelerated up to ~48 MeV. The beam then passes through the wiggler, having detoured around each cavity mirror by way of a chicane. Afterward it either gets deposited straight ahead in a cooled copper dump, or it is recirculated -- through two isochronous, achromatic bends separated by a quadrupole transport line – back through the cryomodule in the decelerating rf phase and dumped at the injection energy of ~10 MeV. In the latter case, the reduction of electron-beam energy shows up as rf power used to accelerate the injected beam, and SCER is thereby established.

During first lasing, construction of the recirculation loop was incomplete and the machine ran straight-ahead. Subsequently it ran with pulsed electron beam and with no lasing, during which SCER was established. Lasing was then initiated, and a systematic procedure was employed to improve the beam transport, push up the average current, and ultimately establish kW-level lasing.

The eight klystrons powering the eight cryomodule cavities can each deliver not more than 8 kW, thereby limiting the cw average current to a maximum of 1.1 mA in the straight-ahead mode. However, once SCER is established, the decelerated beam powers the accelerated beam, and the recirculation mode thereby provides for currents up to 5 mA, at which point the gun power supply becomes the limit.

SCER was incorporated as a key feature in the design to demonstrate the efficient and cost-effective scalability of the system to yet higher average powers [6]. In view of the modest electron-beam energy increment (~40 MeV) associated with the use of only one cryomodule, SCER improves the wall-plug efficiency of the IR Demo only modestly (~2x). Nonetheless, it reduces the required rf drive power for the cryomodule by 5x, it reduces the dissipated power in the beam dumps by 4x, and it virtually eliminates induced radioactivity in the dump region by dropping the terminal energy below the photo-neutron production threshold. However, several issues needed to be resolved to validate the approach: stability of the electron beam against beam breakup (BBU), stability of SCER against electron-beam loss in the presence of lasing, and preservation of electron-beam quality in the presence of coherent synchrotron radiation (CSR). Each issue is discussed in turn below.

Recirculating electron machines are, in principle, subject to BBU. For example, if the injected beam were transversely offset at the first cryomodule cavity, it would excite higher-order transverse electromagnetic fields in that cavity. Dipole modes would deflect the beam and cause increased mode excitation, thereby leading to instability and disruption of the beam. The effect is enhanced in the second, recirculation pass. A multipass BBU code, TDBBU [7], served as the principal analytic tool, though it had never been benchmarked. Based on a set of assumed mode strengths in the SRF cavities, the threshold current for BBU instability in the IR Demo was calculated to be 76 mA. Once the cryomodule was constructed, the measured mode strengths led to a lower calculated threshold, 27 mA,. Regardless, the threshold current was established to be substantially above the 5 mA design current. Recent BBU experiments on the IR Demo are underway to validate TDBBU[8].

The presence of lasing induces an order-of-magnitude increase in the energy spread of the electron beam. In turn, one must guard against beam loss in the recirculation path. Since SCER uses the waste beam to power the injected beam, beam loss could, in principle, lead to an energy droop in the beam. The reduced energy may then weaken lasing, with concomitant reduction of the energy spread and eventual elimination of the beam loss. Conditions are therefore ripe for a relaxation oscillation. An analysis of this scenario showed that sufficient gain and bandwidth on the RF control loop stabilized the system against such problems [9].

Nevertheless, the challenge remained to design an electron-transport system with sufficient energy acceptance to keep beam loss within acceptable levels. For cw beams, local intercepted currents in excess of only ~5 μA (10^{-3} of the 5 mA design current) are sufficient to burn through the vacuum pipe. The IR Demo comprises a transport similar to that of the MIT Bates recirculator which will transport in excess of 6% energy spread without significant loss [10].

The two arcs in the recirculation loop are achromatic and isochronous insofar as linear optics applies. However, the bunches are of ps length near the arc centers and therefore are sources of CSR. Production of CSR leads to a nonlinear tail-to-head interaction that can change the energies of the constituent electrons and induce growth in both energy spread and emittance [11]. For the same reason, CSR was also a concern in the chicanes that bypass the optical-cavity mirrors. At the inception of the IR Demo, CSR was little understood, and simplified analytic calculations of emittance growth pointed to a serious danger. Consequently we took the added precaution of installing the wiggler before the first recirculation arc [12], and we also took care to design the optical chicane before the wiggler to minimize the effect by accommodating longer bunch lengths. Comprehensive modeling of the IR Demo arcs and recent measurements show that CSR is not a major limitation in the IR Demo transport system, an important conclusion respective to future upgrades.

Lasing is very sensitive to the electron-beam parameters. Measurements of the beam parameters at the wiggler were completed on 12 Jun 98 and have been systematically monitored since. The results, listed in Table 1, motivated installation of the wiggler on 13 Jun 98. All agree with simulations 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. Design parameters for the FEL systems appear in Table 2.

The IR Demo achieved first light on 15 Jun 98 at 4.9 μm wavelength, within six hours from turn-on of the electron beam after wiggler installation [13]. 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 into the straight-ahead dump without energy recovery.

Given the measured values of the electron-beam parameters, a small-signal gain of 90% is expected. The IR Demo lases at reduced pulse-repetition frequencies (PRFs), implying very high gain. Specifically, we sent electron bunches into the optical cavity at double and quadruple the optical cavity period. The total cavity loss was 11% per round trip so the threshold gain was 12.4% for 18.7 MHz PRF, 26.3% for 9.4 MHz PRF, and 59.4% for 4.7 MHz PRF. Strong lasing at 4.7 MHz with an effective (7 μm mirror movement times 4 passes per gain pass) detuning width of 28 μm indicates that the gain is well in excess of 60%. The electron beam in this case was pulsed with a 1.2% duty cycle with 250 microsecond macropulses, so mirror heating should not have been significant. Generally, the performance of the laser itself is in agreement with predictions. One exception is the detuning width which at around 30 μm is narrower than expected for the high gain achieved. A possible explanation is optical guiding effects.

We established high average recirculated current in the accelerator through a series of adjustments of the higher-order magnetic transport elements. Residual dispersion measured in the back leg is typically less than 5 cm. It was necessary to adjust the total path length around the recirculation leg to within ~1 degree of rf phase corresponding to 2 ps to have the beam correctly decelerated to the desired final energy of 10 MeV. Just as important was proper setting of the linear energy/path length correlation (M_{56}) to the 28±5 cm required to keep energy spread under control during deceleration of the beam. Similar adjustment of the non-linear correlation term T_{566} in the recirculation loop is required to compensate curvature in the rf waveform. During deceleration through the cryomodule, the bunches ride ~11 degrees off the crest of the sinusoidal rf field, which compresses the energy spread by a factor of ~4. Essentially perfect SCER is indicated by the lack of dependence of rf-drive power on average current (Figure 2);

only the power required to establish the initial fields in the cryomodule cavities is required, regardless of the recirculating electron beam power up to 240 kW.

While we were quickly able to establish lasing with recirculated beam, initial attempts to increase power by increasing recirculated currents showed saturation of the power output. The beam was stable while lasing, and no evidence of instabilities in SCER was observed in the beam transport, even during turn-on transients. By replacing one of the CaF_2 mirrors with a silicon mirror, we were eventually able to obtain 710 W of power output at 4.9 μm on 11 March 99.

This limit was ascribed to heating effects in the mirrors and is not surprising given the sensitivity of electron-beam/optical-mode match to mirror parameters and high circulating power in the optical cavity [14]. Measured laser power is in good agreement with model calculations, as evidenced in Figure 3. For these mirrors the implied power loss is on the order of 0.04%.

Despite the several-second thermalization time in the mirrors[15], changes in the local curvature happen quickly, on the order of milliseconds, as was observed for 18.7 MHz operation versus 37.4 MHz. Within 0.01 second the output power becomes identical despite twice the current in the 37.4 MHz case. It should be emphasized that these effects occur despite extraordinary measures taken to edge-cool the mirrors in thermally stabilized, water-cooled copper holders.

On 15 Jul 99, operating at 47.8 MeV and 4.4 mA, we achieved 1720 W of output power at 3.1 microns by replacing multilayer dielectric-coated sapphire mirrors with ones of exceptionally low loss (~0.03%) from another vendor. No significant steering or distortion effects were observed on these mirrors. Higher average currents or operating the FEL closer to zero detuning for higher lasing efficiency resulted in electron-beam interception of greater than 1 μA causing shutoff of the beam by means of automatic protection systems.

The system lased stably for several hours at powers >1 kW; and we terminated the high-power test only out of the desire to proceed directly to our scientific program. Typical detuning curves remain >20 μm wide. It is now straightforward to restore the recirculating machine from a file of saved settings and run it for prolonged periods at kilowatt levels. Lasing has been achieved in three wavelength bands (3.0-3.3 microns, 4.8-5.3 microns and 5.8– 6.4 microns) corresponding to the peak reflectivity of our high-power cavity mirrors. We have also lased at 1 micron in the fifth harmonic[16].

The IR Demo has performed admirably to date, reproducibly recirculating in excess of 4 mA of cw beam and providing up to 1720 W of stable cw laser power. Approximately 70% of this power can be delivered to user labs for application experiments. The electron beam can be quickly and reproducibly set up to run with any of a set of three available high-power mirrors covering the 3-to-6 μm range. Our operational efforts will now focus on providing this light for a range of scientific and industrial applications [17,18] and using the machine to explore accelerator and FEL physics issues, especially those relevant to our planned upgrade to 10 kW output power at 1 μm.

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Table 1: Beam Requirements at Wiggler for *kW* Lasing

Parameter	**Required**	**Measured**
Kinetic Energy	48 MeV	48.0 MeV
Average current	5 mA	4.8 mA
Bunch charge	60 pC	Up to 60 pC
Bunch length (rms)	<1 ps	0.4±0.1 ps
Peak current	22 A	Up to 60 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 frequency (PRF)	18.7 MHz, x2	18.7 MHz, x0.25, x0.5, x2, and x4

Table 2: FEL System Parameters

Parameter	**Design**	**Measured**
Wiggler period (cm)	2.7	2.7
Number of periods	40	40.5
K_{rms}	1	0.98
Wiggler phase error (rms)	<5°	2.6°
Trajectory wander (μm p-p)	100	<100
Optical Cavity Length (m)	8.0105	8.0105 stable daily to 2 μm
Rayleigh range (cm)	40	40 +/- 2
Mirror radii (cm)	2.54	2.54
Mirror tilt tolerance (μrad)	5	~5
Output Wavelength (μm)	3-6	3.0-3.2, 4.8-5.3, 5.8-6.2
Output coupler reflectivity (%)	98, 90	97.6, 90.5
HR reflectivity (%)	>99.5	99.85

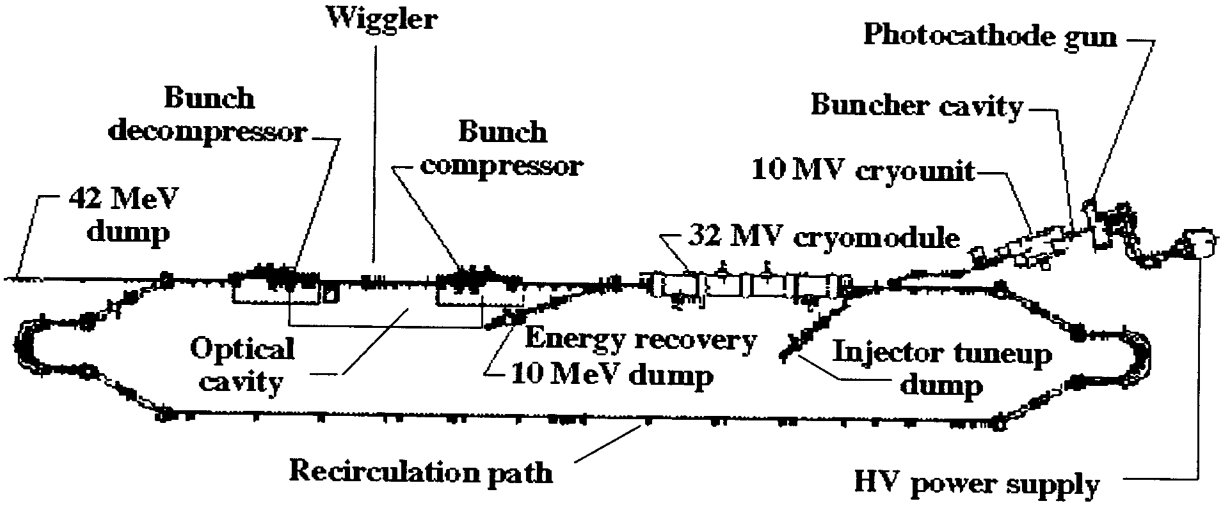

Figure 1. Schematic of IR Demo; dimensions of the recirculation loop are roughly 49m x 6m.

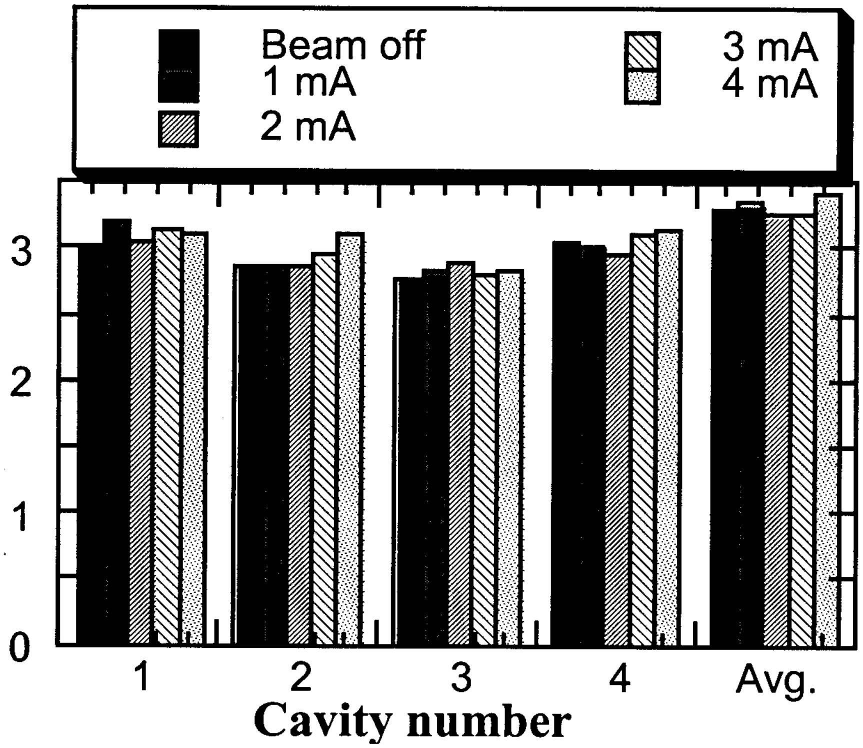

Figure 2. Cryomodule rf power in Watts versus recirculated current while lasing. The first four of eight cavities and the average of all eight cavities are shown. Variations in power are comparable to fluctuations due to microphonics.

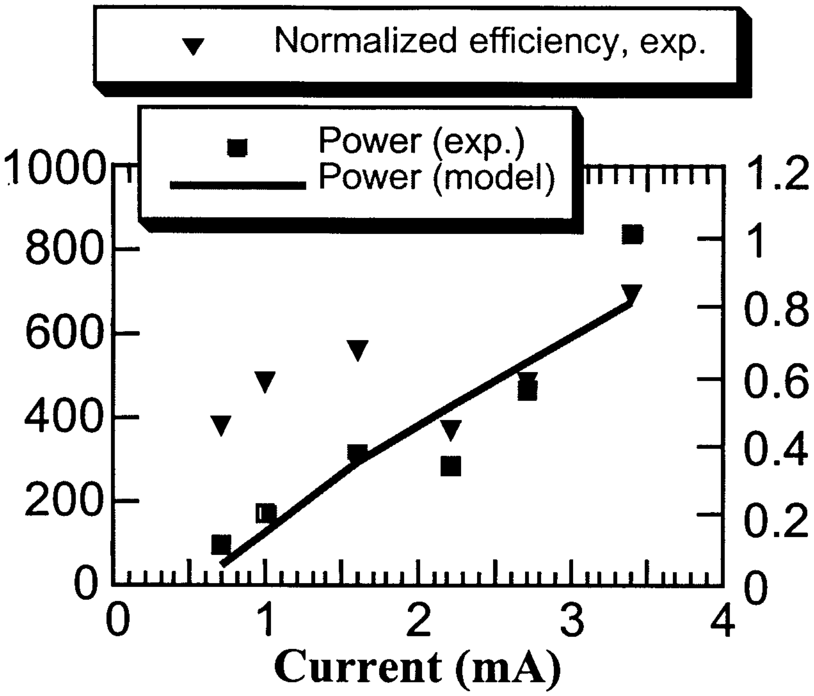

Figure 3. Experimental power at 4.9 μm and product of the efficiency and $4N_W$ compared to theoretical power predictions. The power and efficiency was measured 28% of the way out on the detuning curve.