KILOWATT LASING IN A FREE-ELECTRON LASER

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Abstract

A Free Electron Laser (FEL) called the IR Demo is operational as a user facility at Thomas Jefferson National Accelerator Facility in Newport News, Virginia, USA. It utilizes a 48 MeV superconducting accelerator that not only accelerates the beam but also recovers about 80% of the electron-beam power that remains after the FEL interaction. Utilizing this recirculation loop the machine has recovered cw average currents up to 5 mA, and has lased cw with up to 1720 W output at 3.1 microns. It is capable of output wavelengths in the 2 to 6 micron range and can produce ~0.7 ps pulses in a continuous train at ~75 MHz. This pulse length has been shown to be nearly optimal for deposition of energy in materials at the surface. Upgrades in the near future will extend operation beyond 10 kW average power in the near IR and kilowatt levels of power at wavelengths from 0.3 to 30 microns. This paper will cover the performance measurements of this groundbreaking laser and present an overview of the applications tests underway.

1 INTRODUCTION

One of the newest 4th generation light-source user facilities to come on line is the IR Free Electron Laser at the United States Department of Energy funded Thomas Jefferson National Accelerator Facility in Newport News, Virginia. Called the IR Demo, this FEL was specially designed to produce high-average-power coherent infrared light by combining the continuous-wave 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 FEL 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 [1]). However, the foremost achievement is a convincing demonstration of the underlying, enabling technology, namely same-cell energy recovery (SCER). Previous work demonstrated SCER without lasing [2] or lasing with energy recovery in a second linac [3]. The IR Demo incorporates SCER in a manner that is scalable to considerably higher average power.

2 MACHINE DETAILS

The layout of the machine is shown in Figure 1. Microbunches with an rms bunch length of 20 psec are produced in a DC photocathode gun [4] and accelerated to 320 keV. The bunches are 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

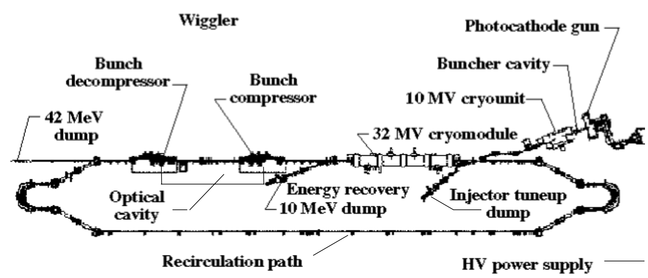

Figure 1: Layout of IR Demo

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.

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 [5]. 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, 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. Each of these issues is a major topic in itself and further details are contained in [6,7].

3 FEL PERFORMANCE

The IR Demo lases not only at the cavity round trip time but also 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. Given the measured values of the electron-beam parameters, a small-signal gain of 90% is expected. 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 even at 4.7 MHz with an effective (5 µm mirror movement times 4 passes per gain pass) detuning width of 20 µm indicates that the gain was still 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 20 microns at 3 µm, is narrower than expected for the high gain achieved. Possible causes for this are still under study.

On 15 July 99, operating at 47.8 MeV and 4.4 mA, we achieved 1720 W of output power at 3.1 microns by using multilayer dielectric-coated sapphire mirrors of exceptionally low loss (~0.03%). The system lased stably (fluctuations < 10% p-p; subsequently we measured the noise to be +/- 3% at the stable operating point) for several hours at powers >1 kW; and we have produced nearly 200 hours of equivalent full power running in the period of 7/99 through 4/00 at various wavelength bands (see Figure 2). Typical detuning curves remain triangular and >20 µm wide (see [7] for detailed curves and spectra showing bandwidths ranging from transform limited around 0.1% FWHM at 3 microns far from zero detuning to 5% FWHM at near zero detuning). At the end of our optical transport system employing 14 mirror reflections the beam quality has been verified as better than 2x diffraction limited. 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 [8].

An additional feature of the FEL is the fact that 500 femtosecond X-ray pulses are produced within the cavity by the Thomson scattering of the laser light with the electron beam. This has recently been measured [9] and confirms theoretical predictions of the intensity. X-ray energies are ~ 5 keV with average photon fluxes of ~ 10^8 photons/sec.

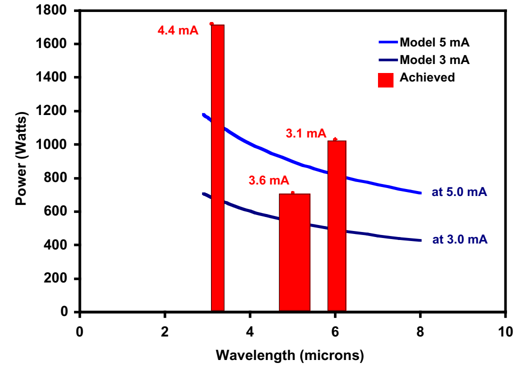

Figure 2: Experimental power produced in three wavelength bands compared with predictions based on some assumed mirror losses.

4 CURRENT STATUS

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 [10] 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.

The IR Demo is a unique source of tunable mid-IR light, producing the highest average power of any ultrafast laser source. With its high beam quality and modest energy/pulse, the brightness is of order 1 x 10^{20} Phot/sec.mrad^{2}mm^{2}0.1%bandw, and by using a moderately short focal length lens, we routinely achieve intensities on the order of 10^{12} W/cm^2. Such an intensity can initiate nonlinear effects in materials, and coupled with the high PRF enables detection of weakly absorbing species. The properties of the laser also enable material processing opportunities that heretofore were rendered uneconomical by the relatively slow (Hz to kHz) PRFs of other laser sources. As the FEL program has always been user-oriented, the facility was designed with approximately 600 m^2 for user labs. Each lab is equipped with utilities such as low conductivity water, temperature-regulated chilled water, dry nitrogen, and compressed air. Each lab also has purge lines leading outside the building (*e.g.*, for vacuum pump exhaust) and it's own cable tray so that users have a convenient way for routing signal cabling to data acquisition equipment.

All labs are connected to the lab network, which provides another way for remote instrument control. About half the labs have chemical hoods.

Our first user experimental period occurred in July/August of 1999, and as of this writing we are providing beam time to users for one month per quarter, with four of the six experimental areas operational.

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