The Jefferson Lab Sub-picosecond X-ray Program[†]

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Abstract. The kW-class infrared (IR) Free Electron Laser (FEL) at Jefferson Lab had the capability of producing intra-cavity Thomson scattering of the IR off the electron beam thus producing high average flux, sub-picosecond x-rays. We have measured these x-rays and demonstrated the energy tuneability range from 3.5 keV to 18 keV. The corresponding flux and brightness has been estimated and will be discussed. This year, 2002, the FEL was disassembled and has been reconfigured to produce 10 kW average power IR. We present the estimated x-ray capabilities for the new FEL and discuss potential applications.

INTRODUCTION

In recent years, interest has developed in building fourth generation light sources [1,2] capable of producing x-rays needed to explore ultrafast phenomena such as atomic motion within a single atomic vibration – on the order of 100 fs. High brightness x-ray sources are needed to explore this regime. Recently, several groups [3-7] have explored the use of Thomson scattering of short pulses of photons off electron bunches to produce sub-picosecond x-ray bunches. Though these experiments generate short enough x-ray pulses, more work is needed to improve the resulting x-ray fluxes for routine use in femtosecond science. Krafft predicted in 1997 [8] high flux x-rays from intra-cavity Thomson scattering of 10 kW high average power infrared off of the electron beam in the of the Jefferson Lab free electron laser (FEL). We report important measurements confirming predictions. We estimate the peak brightness of our x-ray source to be ~ 10^{10} s.u. (photons/sec/mm^2/mrad^2/0.1%Bandwidth). With the Upgrade FEL now in commissioning we anticipate a 10-fold increase in brightness values.

THOMSON SCATTERING IN THE JLAB INFRARED FEL

Jefferson Lab's infrared free electron laser (IRFEL), uses superconducting RF technology to accelerate electron bunches to multi-MeV energies, guides them through a wiggler where the free-electron lasing action produces infrared light pulses of less than 1 ps amplified to saturation by bouncing between two mirrors forming an 8-meter optical cavity. The design of the machine is discussed in more detail elsewhere [9], and the layout of the IRFEL is shown in Figure 1. The IRFEL produces high-average-power coherent infrared (IR) light by combining continuous wave (cw) operation - a bunch repetition rate of 34.7 MHz or 75 MHz - of superconducting radiofrequency (srf) accelerator cavities with a technique that recovers the "waste" energy of the electron beam after it has been used for lasing [10]. The IRFEL has lased at *average* powers up to 2.1 kW extracted [11] from the optical cavity at 3.1 μm wavelength, a full two orders of

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magnitude higher extracted power than the previous average-power record for FELs [12] set in 1990.

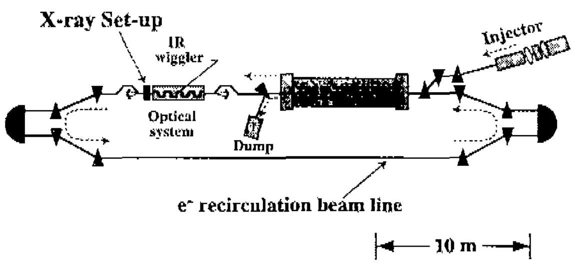

FIGURE 1. Layout of the Jefferson Lab Infrared Free Electron Laser (IRFEL). A photocathode-based injector, generates sub-picosecond duration, 10 MeV energy, electron bunches for the superconducting rf (srf) linear accelerator (linac) that increases electron energies up to final energy – tunable - between 25 MeV and 48 MeV. Passing through the optical (cavity) system, the electrons produce infrared (IR) radiation as they undulate in the wiggler region's alternating magnetic fields. The IR is captured and stored between high reflectivity mirrors, shown on either side of the wiggler, of the optical (cavity) system, while the electrons are transported back around to the linac for re-insertion into the linac at 180-degrees out of phase with the accelerating rf, de-accelerated back to 10 MeV, and finally, deflected into a beam dump. This efficient design recovers rf energy and the residual radiation produced in the dump is minimized. The x-ray detection set-up is in the optical system downstream from the wiggler.

Figure 2 illustrates the intra-cavity Thomson scattering process. The FEL optical cavity is symmetrically placed around the center of the wiggler. The optical cavity length was chosen to be the spacing between two electron bunches at 34.7 MHz. Thus, two optical pulses are circulating in the optical cavity at all times. Just before a collision between an electron bunch and an IR bunch, overlapping IR and electron pulses move downstream while an IR pulse moves upstream. Just after the collision, overlapping IR, electron, and x-ray pulses move downstream, and the IR that passed through the electron bunch without scattering continues upstream. Forward scattering at $\theta = 0°$, yielding the maximum x-ray energy, is defined by the direction of electron motion at the point of collision. For the IRFEL this direction is 18 mrad up from the beam centerline due to the undulating trajectory of the electrons in the wiggler. Thus the x-ray distribution in the laboratory frame is angled about 1 degree up from the centerline of the vacuum beam pipe. This allows us to insert – downstream above the electron beam – a diffracting crystal to separate out the x-rays from the IR and electron bunches.

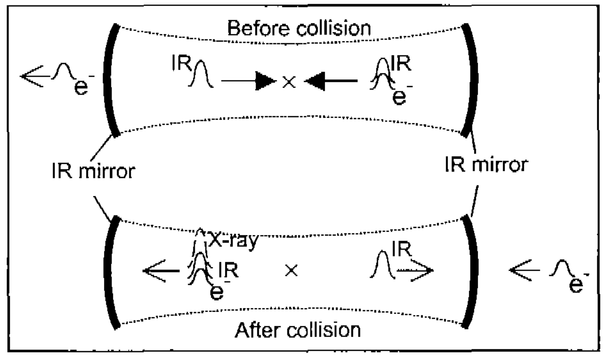

FIGURE 2. Schematic of the basic idea of the Thomson scatter source. The scale of the pulse lengths in the cavity is enhanced considerably for clear presentation. In reality, the pulses are ~ 200 microns long.

In a single collision between IR and electron bunches, the x-ray production can be shown to be: $N_X = \int n_p(x,y) n_e(x,y) \sigma_T dx dy$, where $n_p(x,y)$ and $n_e(x,y)$ are the transverse number distributions of the IR photons and electrons respectively, $\sigma_T = 8\pi r_e^2/3$ is a constant - the total Thomson scattering cross section, and r_e is the classical electron radius. The general solution for overlapping Gaussian distributions of different transverse rms beam sizes is:

$$N_X = \frac{N_p N_e}{2\pi\sqrt{\sigma_{px}^2 + \sigma_{py}^2}\sqrt{\sigma_{ex}^2 + \sigma_{ey}^2}}\sigma_T \qquad (1)$$

where $(\sigma_{px}, \sigma_{py})$ and $(\sigma_{ex}, \sigma_{ey})$ describe the rms sizes of the photon and electron beams, respectively, and where N_p is the number of low energy photons in the IR bunch, and N_e is the number of electrons in the electron bunch. The total X-ray production rate, or flux, is the product of the X-ray production per collision and f, the pulse repetition frequency, i.e., $F_x = f \times N_x$.

The quantity $L = fN_X/\sigma_T$, called "luminosity" in other contexts, may be used to evaluate the effectiveness of the scattering geometry in different Thomson scatter setups. Typical values fall in the 10^{33} $cm^{-2} sec^{-1}$ range. Since N_p tends to be proportional to N_e in an FEL oscillator geometry, luminosity may scale as rapidly as N_e^2.

THOMSON X-RAY MEASUREMENTS

For the first measurements, a LiF crystal - (100) orientation - mounted on a remotely controlled rotatable rod was placed ½ inch above the electron beam centerline (see Figure 3). The FEL optical cavity was configured for 5-micron IR, and the electron beam energy was set at 36.7 MeV. A cooled Si-PIN diode detector was positioned a few inches from the crystal to detect x-rays diffracted by the LiF crystal.

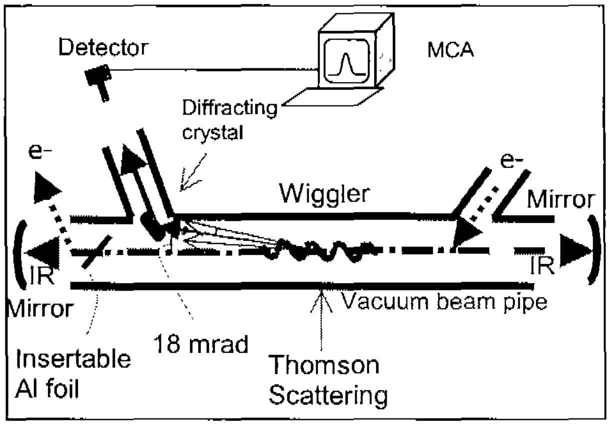

FIGURE 3. Schematic representation of the production and detection geometry for the Thomson x-rays. One of the IR pulses, traveling from left to right, collides with the electron bunch, traveling from right to left, in the center of the wiggler. The x-rays resulting from the collision, travel at an angle of ~1°above the electron beam centerline.

With the FEL lasing at a modest 250 Watts extracted IR power (10% of the intra-cavity power), the LiF crystal was rotated in small increments until a signal appeared in the multi-channel analyzer at the predicted x-ray energy. Energy pulse height spectra were taken with the FEL lasing and not lasing. In Figure 4, a pair of 60 second live-time run spectra clearly demonstrate the copious production of Thomson x-rays. The x-ray detector was calibrated with ^{55}Fe and ^{241}Am sources before and after the run. The signal to noise ratio between the Thomson x-ray flux and the accelerator room background flux was up to 90:1 in the energy region of interest.

Since the x-ray bunches have the same longitudinal time distribution as the electron bunch at the collision point, we used electron bunch distribution as a measure of the x-ray distribution. The electron bunch distribution was determined by an autocorrelation measurement of coherent transition radiation (CTR) [12] emitted as an electron bunch crosses a very thin (1.5 μm) aluminum foil remotely inserted into the beam path (see Figure 3). The CTR is transported to a Michelson-type interferometer (not shown in the figure). Figure 5 shows a typical measured autocorrelation function under accelerator operating conditions identical to the operating conditions for the x-ray measurements.

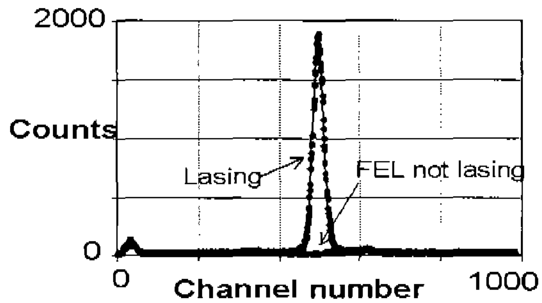

FIGURE 4. Two spectra demonstrating the production of Thomson x-rays. Signals from a cooled Si-PIN diode sent through a multichannel analyzer were accumulated for 60 seconds and plotted in a pulse height distribution where channel number is proportional to energy. The first spectrum was taken with the FEL lasing and the second with a shutter preventing IR lasing. Before and after calibrations with ^{55}Fe and ^{241}Am show this peak at 5.12 keV with a 320 eV FWHM.

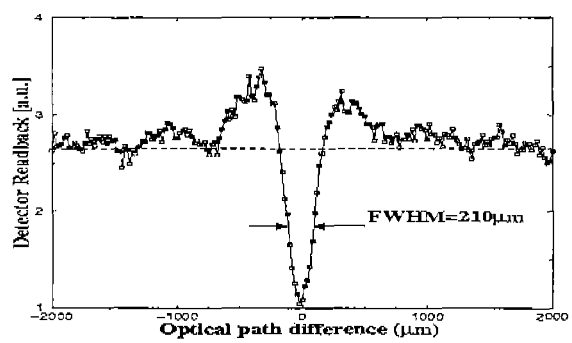

FIGURE 5. A typical measurement of the electron bunch length using coherent transition radiation (CTR) from thin Al foil in Optical Cavity (See Figure 3. The foil is retracted for lasing.) FWHM implies a bunch length rms value of 89.4 μm or 298 fsec for the electron bunches and since x-rays are traveling with (~40 MeV) electrons at c, their bunch rms distribution is also ~300 fsec.

Since the longitudinal length of the electron bunch does not change inside the optical cavity, and since a Thomson x-ray bunch can be no longer than the electron bunch, we conclude the Thomson x-rays are generated in a cw train of bunches, each 300 fsec long.

Over the two year operating period of the JLab FEL other x-ray measurements cover the energy range 3.5 keV to 18 keV by various combinations of electron beam energy, FEL wavelength, or wiggler parameters. In addition, simultaneous spectra were taken of sub-picosecond pulses at three wavelengths of photons: IR, x-rays, and THz radiation, offering the possibility of fsec pump-probe experiments spanning 10^7 in photon wavelengths.

UPGRADE FEL POSSIBILITIES

The year 2002 marked a new phase in the Jefferson Lab FEL program: disassembly of the first FEL and construction of an Upgrade FEL designed to produce (extracted) 10 kW extracted IR light and 1 kW UV. Figure 6 shows calculations of expected peak brightness.

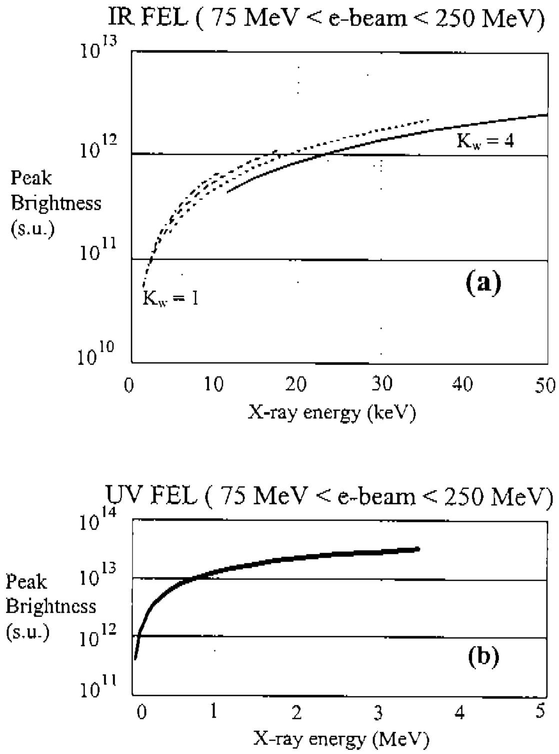

FIGURE 6. (a) Calculated peak Brightness of x-rays for the IR Upgrade FEL. The Upgrade wiggler is electromagnetic and the wiggler parameter K_w can be varied from 1 to 4, hence the four curves. **(b)** Similar calculations for the 1 UV FEL. Note the change from keV to MeV in photon energy.

CONCLUSIONS

We have presented our initial experimental results on an intra-cavity Thomson x-ray source at the Jefferson Lab FEL. This source produces IR and x-ray radiation with unique characteristics. The IR and x-rays are highly time-correlated and both of sub-picosecond time duration. We measured the electron bunch length, and thus the x-ray rms bunch length, to be ~ 300 fsec in duration. We have verified that the overall x-ray production rate is consistent with predictions based on beam current, on the IR and electron beam spot sizes, and on the re-circulating power in the FEL. The x-rays are produced in a 37.5 MHz or 75 MHz streams, and signal to noise ratio is high, even in our first experiments. We believe that this type of source complements synchrotron-based fsec x-ray sources (due to simultaneity with IR) and to fourth generation light sources (due to the high repetition rate). Such a source may well have important applications in the burgeoning field of "femtosecond science". Commissioning of the FEL upgrade is anticipated to be completed in 2003.

ACKNOWLEDGMENTS

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11. Note: intra-cavity IR power = 10 x extracted IR power.
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13. Transition radiation is emitted whenever a charged particle crosses a boundary between two media of different electric permittivity.