SUB-PICOSECOND, HIGH FLUX, THOMSON X-RAY SOURCES AT JEFFERSON LAB'S HIGH POWER FEL*

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Abstract

With the advent of high average power FELs, the idea of using such a device to produce x-rays via the Thomson scattering process is appealing, if sufficient flux and/or brightness can be generated. Such x-rays are produced simultaneously with FEL light, offering unprecedented opportunities for pump-probe studies. We discuss non-invasive modifications to the Jefferson Lab's FEL that would meet the criteria of high flux, sub-picosecond, x-ray source. One allows proof-of-principle experiments, is relatively inexpensive, but is not conducive as a "User-facility." Another is a User facility configuration but requires FEL facility modifications. For all sources, we present Thomson scattering flux calculations and potential applications.

INTRODUCTION

Atomic vibrations in crystals occur on femtosecond time scales. In order to image motion in that temporal regime, one needs a stroboscopic source of x-rays capable of generating crystallographic images in the same time frame. This requires pulses of x-rays of high brightness and shorter than a few hundred femtoseconds. Electron beam technology in the form of synchrotrons provides x-rays of high enough brightness for "snapshots" of frozen protein crystal structures - for example - but because the x-rays are nanoseconds in length, these sources cannot make the "molecular movies" required for understanding the molecular dynamics of such crystals. Progress in electron beam generation and control systems over the past 15 years has yielded several possible means of shortening x-ray pulses by three or four orders of magnitude, but these sources have yet to be bright enough. [1-4] Simultaneously generating both high brightness AND short pulses is a technological challenge.

The advent of high power Laser technology, has led to exploring the feasibility of using Thomson scattering off of very short, high energy, electron bunches to produce the desired x-ray sources. [5] Significant 300 femtosecond Thomson x-ray fluxes from the 2 kilo-Watt IR FEL at Jefferson Lab, predicted by Krafft [6] and measured by Boyce [7], demonstrate the feasibility of such approaches to generating pulses of x-rays with both high flux and femtosecond pulse length.

The Jefferson Lab FEL is currently being upgraded to a 10 kW IR and 1 kW UV capabilities. In this paper we present concepts and supporting calculations for expected Thomson scattering x-ray beams resulting from such increase in lasing power with the upgrade FEL configuration.

JLAB FEL FACILITY

Jefferson Lab's high average power (10 kW) FEL facility, described elsewhere [8], is in commissioning. When complete, it will have the capability of producing 10 kW of IR light and 1 kW of UV. It is based on the first Jefferson Lab's FEL which used superconducting rf (srf) and energy recovery technology to produced 2 kW of IR.

Figure 1 shows the layout of the upgrade FEL facility with a proposed additional electron beam transport loop. There are three locations in the electron beam line where significant Thomson x-rays can be generated: inside the optical cavity – specifically inside the wiggler – and in the last leg of the chicane prior to the wiggler. A third location, C, requires additional electron beamline.

In the wiggler, the IR in the optical cavity is automatically focused onto the electron beam, producing Thomson x-rays. The Rayleigh range of the cavity, however, limits the IR beam spot size to a value that is about twice the size of the electron beam spot size. Thus only a fraction of the available IR beam actually intercepts the electrons.

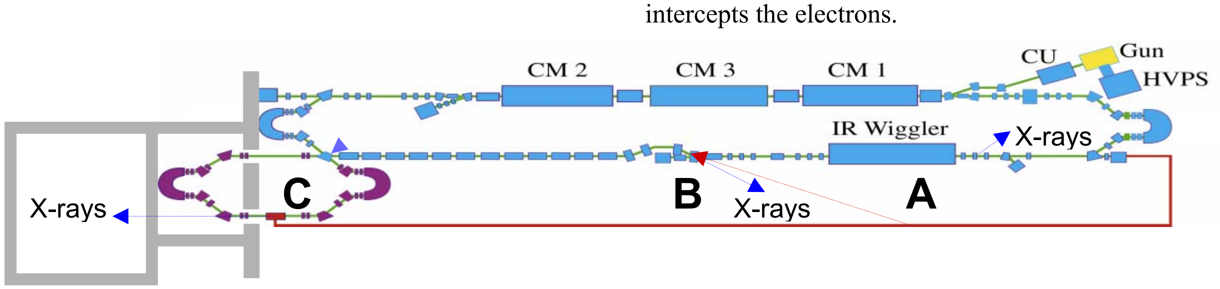

Figure 1: The Jefferson Lab Upgrade FEL layout (modified) with three site locations for Thomson x-ray sources. A) is intra-cavity production by the IR in the cavity automatically focused onto the electron beam. B) requires extracted IR brought to focus onto the electron beam in the chicane. C) has extracted IR brought to the loop and allows both beams to be focused to the smallest rms size.

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The second location, B, for Thomson scattering is in the last section of the electron beam line chicane around the first optical cavity mirror system. This location requires extracted IR transported back to this location and focused onto the electron bunch. Extracted power is about 10% of the IR power in the optical cavity, but it can be focused to match the electron beam spot size, thus fully utilizing the available IR. The limitation of this location is the minimum spot size of the electron beam, a limitation set by electron beam transport requirements for energy recovery. (Full IR power requires transporting the electron beam back through the cryomodules (CM1, CM2, and CM3) for energy recovery.

The third location, C, requires an additional beam line (achromatic) loop. By turning off the magnet that normally directs the electrons down the straight-a-way, the electrons can enter the loop, travel clockwise around a pi-bend, focused down to a minimum spot size of about 75 microns rms, then back around another pi-bend and into a straight section and into the straight-a-way. Thomson x-rays are produced by transporting extracted IR to this region and focusing it down to the same size as the electrons. The IR can then be transported to user labs for experiments there. Part or all of this IR could be used as the pump of a pump-probe system.

X-RAY PRODUCTION

In order to adequately evaluate and compare the merits of each location, we need to calculate the anticipated x-ray source strengths for each case. The theory of photon scattering off electrons is well known. [See, for example, Refs. 9 and 10]. Careful treatment here also requires inclusion of the Rayleigh range of the IR in the optical cavity and the wiggler characteristics, which, in our case, has adjustable field strengths.

One assumption we have made is that both the electron and IR beams are Gaussian distributions. This simplifies the calculations while maintaining the ability to compare source strengths of each site.

The number of x-rays, N_x, produced by an IR bunch colliding with an electron bunch is:

$$N_x = \frac{N_e N_{IR}}{4\pi\sigma^2}\sigma_T \qquad (1)$$

where Ne and N_{IR}, are the number of electrons and IR photons respectively, σ is the bunch rms size, and σ_T is the Thomson cross section of the electron.

Table 1 is a comparison of the Jefferson Lab FEL Thomson x-ray sources using equation (1). It included values for the IR DEMO – the first FEL.

Table 1: Jefferson Lab FEL Thomson X-ray Sources

FEL →	**IR DEMO**	**IR Upgrade**		
Parameter	Wiggler	A. Wiggler	B. Chicane	C. Loop
E_e: e^- beam energy (MeV)	37	80	80	80
γ (E_e/m_oc^2)	72.41	156.56	156.56	156.56
Charge per bunch (pC)	60	130	130	130
N_e	3.7E+08	8.1E+08	8.1E+08	8.1E+08
frequency (MHz)	75	75	75	75
IR Power (kW)	10	100	10	10
IR wavelength (μm)	5	10	10	10
N_{IR}	3.4E+15	6.7E+16	6.7E+15	6.7E+15
e^- bunch $\sigma_x = \sigma_y$ (μm)	500	250	200	75
IR bunch $\sigma_x = \sigma_y$ (μm)	800	500	200	75
E x-ray max (keV)	5.20	12.15	12.15	12.15
X-rays per bunch	17	2306	721	5125
N_x (x-rays/sec)	1.2E+09	1.7E+11	5.4E+10	3.8E+11

Another feature of these sources is the tunability of the x-rays. Figure 2 emphasizes this point. These curves are calculated for the "A" source location and show the peak brightness for four settings of the wiggler strength parameter K_w.

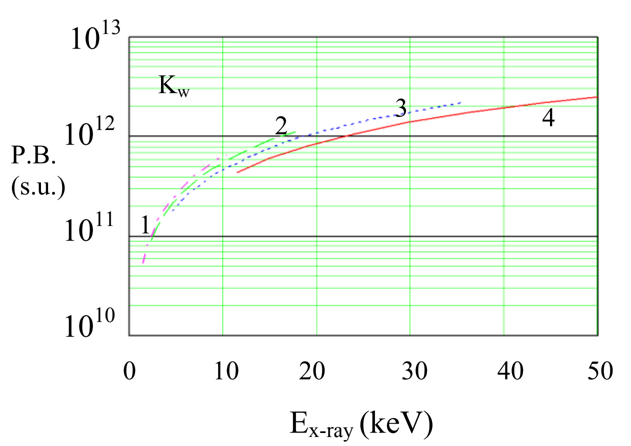

Figure 2: Peak brightness curves for Thomson x-rays generated in the wiggler of the Upgrade FEL, in standard units (s.u.): x-rays/sec/mm2/mrad2/(0.1% bandwidth). Input to these calculations include electron beam energy from 75 MeV to 125 MeV, intra-cavity IR power of 65 kW, and bunch frequency of 75 MHz.

CONCLUSIONS

Jefferson Lab's new 10 kW FEL is shown to be a source of high flux, sub-picosecond, x-rays. Three configurations have been examined and compared. The intra-cavity location requires the least amount of modification to the existing beam line, but the resulting

User Station, located inside the accelerator ring, would be inconvenient for experimenters. The location with the highest flux, and thus brightness, requires a loop addition to the electron beam line, and a modification to the FEL facility. Once built, however, such a facility is ideal for a User Laboratory outside the main accelerator vault.

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