Photon Source Capabilities of the Jefferson Lab FEL

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Abstract. Jefferson Lab operates a superconducting energy recovered linac which is operated with CW RF and which powers oscillator-based IR and UV Free-Electron Lasers (FELs) with diffraction limited sub-picosecond pulses with >10^{13} photons per pulse (1.0%BW) at pulse repetition frequencies up to 75 MHz. Useful harmonics extend into the vacuum ultraviolet (VUV). Based on FEL model calculations validated using this facility, we have designed both an oscillator-based VUV-FEL that would produce 6 \times 10^{12} coherent (0.5% BW) 100 eV photons per pulse at multi-MHz repetition rates in the fundamental, and a dual FEL configuration that would allow simultaneous lasing at THz and UV wavelengths. The VUV-FEL would utilize a novel high gain, low Q cavity, while the THz source would be an FEL oscillator with a short wiggler providing diffraction limited pulses with pulse energy exceeding 50 microJoules. The THz source would use the exhaust beam from a UV FEL. Such multiphoton capabilities would provide unique opportunities for out of equilibrium dynamical studies at time-scales down to 50 fs. The fully coherent nature of all these sources results in peak and average brightness values that are many orders of magnitude higher than storage rings.

1. Introduction
Jefferson Lab’s FEL facility is based on an energy recovered linac [1] and currently houses two oscillator-based FELs, one in the IR and one in the UV [2], as well as a broadband THz facility [3]. The system uses a DC photo-cathode gun feeding a superconducting linac, and is capable of providing sub-picosecond electron bunches of up to 135 pC to energies to 135 MeV continuously at frequencies up to 75 MHz. Noting that 4.7 MHz is the round-trip time in a 32 meter cavity, it is evident that this type of facility is ideal for the development of oscillator-based FELs. And in this arena, the facility has strong upgrade potential both in photon energy range, in brightness and in multiphoton operation. In this paper we will describe the present capability and some of the upgrades that are possible with the existing machine.

2. Description of existing facility
A layout of the Jefferson Lab FEL is shown in Fig. 1. Photons from this accelerator are fed into one of 4 optical beamlines, THz, IR, UV and VUV, which transport the light to one of 7 user laboratories located on an upper floor. The FEL beams are all treated as class 4 lasers, and each of the user laboratories can be swept and operated in either exclusionary, hutch, alignment or local laser modes.
The average brightness of the 4 existing beams is shown in Fig. 2, where they are compared with 2nd and 3rd generation sources. Note that Fig. 2 also shows potential upgrade paths which will be discussed in later sections of this paper.

3. Upgrades to higher brightness and higher photon energies

Due to improvements in the technology of making, accelerating and transporting higher brightness electron beams, dramatic improvements are possible with the present facility, four of which are outlined here.

Advances in superconducting radio-frequency technology now allow gradients and hence electron beam energies that are 4-5 times higher than were possible 13 years ago when the FEL was first operated. Technological improvements in injectors also make it possible to design the lower emittance injector required for lasing at higher photon energies, while additional improvements in electron beam transport codes allow designs of transport systems for lower emittance beams.

3.1.1. UV and VUV FEL cryo-cooling of mirrors. At present the fundamental power is limited by mirror heating and concomitant distortion, while the wavelength range is limited by the available electron beam energy. Liquid nitrogen cooling of the 2 cavity mirrors would allow an increase in brightness of an order of magnitude for a very modest cost.

3.1.2. VUV-FEL increase in electron beam energy. The VUV light is currently generated as the third harmonic of the fundamental, and its power and brightness are lower than the fundamental by the factor $10^n$, where $n$ is 3. It follows that a 1000-fold increase in brightness may be obtained in the VUV if the electron beam energy were to be increased and combined with a lower emittance injector and re-designed magnetic arcs.
### Table 1. Performance parameters for the existing Jefferson Lab Free-Electron Laser and the upgrades discussed in the earlier sections. The nominal FWHM for these pulses is 300 fs.

| Wavelength or photon energy | Power/pulse | Rep. rate (MHz) |
|-----------------------------|-------------|-----------------|
| THz existing                | 0.1 microJoules | 0-75 |
| THz potential with additional bunch compression | 1.0 microJoules | 0-75 |
| IR 1-5 microns existing machine | 125 microJoules | 4.7, 9.4, 18.7 |
| UV 370 – 900 nm existing machine | 8 microJoules | 4.7, 9.4 |
| VUV 4 – 10 eV 3rd harm. existing machine | 5 nanoJoules | 4.7 |
| UV 370 – 900 nm cryo-cooled optics (Sec. 3.1.1) | 30 microJoules | 4.7, 9.4, 18.7, 37.4 |
| VUV 4 – 10 eV cryo-cooled optics (Sec. 3.1.1) | 30 nanoJoules | 4.7, 9.4 |
| VUV 4 – 10 eV fundamental (Sec. 3.1.2) | 20 microJoules | 4.7, 9.4 |
| Mid-IR 30 microns (Sec. 3.1.3) | 50 microJoules | 4.7 |
| XUV 10 – 100 eV (Sec. 3.1.4) | 40 microJoules | 4.7 |

3.1.3. **VUV+IR multiphoton.** There is a programmatic desire to excite a system in a precisely controlled manner, then observe the system as a function of time to learn about the relaxation dynamics. An example is the pumping of a high $T_c$ superconductor into the normal state, but with its lattice cold [4], while observing the electronic quantum structure during the return to the superconducting state [5]. This requires well synchronized tunable mid-IR and VUV photons. It turns out that the installation of a canted undulator downstream of the existing UV undulator would allow 2 FEL oscillators to operate using the same electron beam, the mid-IR undulator being in the exhaust of the UV undulator [6].

3.1.4. **VUV/soft X-rays.** We have determined that it is possible to design an oscillator capable of operating at 100 eV in the fundamental [7]. Upgrading to the VUV optical range requires higher energy, a brighter electron beam, and a longer undulator to greatly increase the gain. The latest cryomodule designs offer gradients of around 20 MV/m, compared to 7 MV/m in earlier models, and one can thus achieve 300 MV of acceleration in the linac. Using a two-pass recirculating linac scheme with new beam transport arcs around the ends, it is possible to conceive of a 600 MeV electron beam that could make 100 eV light in the fundamental in the same footprint as the present 150 MeV accelerator. The FEL acts as a high-gain, low-Q oscillator. A small amount of power from the output is fed back to the start to seed the next pulse. The power is outcoupled through a hole in the center of the mirror downstream of the wiggler. This provides an advantage in tunability since for photon energies less than 12.4 eV, the mirrors are relatively broadband and the wavelength is controlled by the beam energy and the wiggler parameters. At higher photon energies, the mirror coatings become narrow-band. The mirror substrates will be cryo-cooled silicon. To allow for lasing at many different wavelengths, different mirrors can be exchanged without breaking vacuum, which makes it possible to change the coating parameters and outcoupler hole size as necessary.
4. Conclusions
We have presented a rather general overview of relatively straightforward upgrades to the Jefferson Lab FEL which could be implemented within the framework of the existing facility, and which would offer considerable performance upgrades for scientific studies in sub-ps time-resolved relaxation dynamics. Details of each of these schemes are contained in the references. At present we are continuing to operate both IR and UV FELs while designing a new injector.

Figure 2. Photon source landscape plot showing performance of the Jefferson Lab FEL (filled ovals) and the performance upgrades (open ovals) discussed in section 3. The purple, red and blue lines are for 2nd, 3rd, and 4th generation sources. These generic plots were made using an electron beam energy of 3 GeV, a bending radius of 5m, and 1nC electron bunches at 100 MHz (100 mA). Source sizes used were 500 – 1000, 10 – 100, and 5 – 5 microns respectively for the 2, 3 and 4th generation sources. 3rd generation sources were elevated by 500 for insertion devices, and 4th generation sources were elevated by a further 100 to account for longitudinal coherence.

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