THE WISCONSIN FREE ELECTRON LASER INITIATIVE*

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Abstract

The University of Wisconsin-Madison/Synchrotron Radiation Center and MIT have developed a pre-conceptual design for a seeded VUV/soft X-ray Free Electron Laser (FEL) serving multiple simultaneous users. The design uses an L-band CW superconducting 2.2 GeV electron linac to deliver 200 pC bunches to multiple FELs operating at repetition rates from kilohertz to megahertz. The FEL output will be fully coherent both longitudinally and transversely, with tunable pulse energy, cover the 5-900 eV photon range in first harmonic, and have variable polarization. An R&D plan has been advanced that addresses the most critical aspects of the project, including prototyping of a CW superconducting RF photoinjector and development of conventional laser systems for megahertz high harmonic generation (HHG) seeding of the FELs.

DESIGN OVERVIEW

The University of Wisconsin-Madison and the Massachusetts Institute of Technology, together with an extensive emerging user community, have developed a pre-conceptual design for a seeded free electron laser (FEL) facility operating in the VUV to soft X-ray range. This unique facility is expected to enable new science through ultrahigh resolution in the time and frequency domains, as well as coherent imaging and nano-fabrication [1].

The key features of the facility envisioned are shown in Fig. 1. A superconducting injector and 2.2 GeV CW linear accelerator operating with milliampere average current provide high quality electron beams at repetition rates up to many megahertz. Fast electron beam extraction using proven RF separator technology allows steering of these beams to many different beamlines operating independently and simultaneously with different pulse patterns suitable for specific applications.

Fully coherent beams are achieved by laser seeding utilizing high harmonic generation (HHG) operating from 4 to 30 eV and a harmonic cascade scheme. Each of the modulators in a cascade is kept relatively short with little exponential gain until the final stage. The modulation depth in each stage is modest, so that the electron beam energy spread remains reasonable through the cascade, allowing the use of single short, low-charge (200 pC) bunches. The “fresh-bunch” technique requiring long, high charge bunches is not needed. This reduction of charge per bunch has a major impact on the cost and complexity of the facility. It reduces the requirements on power and efficiency for the injector drive laser and photocathode, enables reduced linac RF power or higher bunch repetition rates, reduces higher order mode heating and wakes in the linac, and reduces the effects of incoherent and coherent space charge instabilities. An initial complement of six beam lines provides tunable photon energy and polarization over the range 5-900 eV in first harmonic and timing and synchronization at 10 fs levels. Specifics of beamline performance are found in [2]. Beamline design optimizations are discussed in a companion paper [3].

The microbunching instability, which can disrupt high-current bunch compression, acceleration and distribution, was studied with analytical modeling and tracking simulations. The large microbunching gain of the baseline design, which utilizes two-stage compression and a beam spreader with an R_{56} value of 1 mm, requires that the bunches be heated in a laser-heater prior to compression. In a modified design, which uses single-stage compression and a beam spreader whose R_{56} value is only 40 µm, the microbunching gain is reduced by more than 2 orders of magnitude [4]. Consequently, a laser heater may not be required and bunches with lower energy spread may be provided for the FELs.

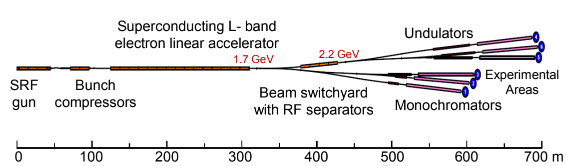

Figure 1: WiFEL Facility Layout.

R&D PLAN

Key R&D issues have been identified, and plans are in place, focused on the most challenging and crucial technologies. The following areas and deliverables have been identified: 1) CW superconducting RF injector, 2) Conventional laser systems for the photoinjector, HHG FEL seeding, and timing, 3) Monochromator design, with particular attention to demonstrating heat load solutions, 4) Prototype advanced, small gap undulators for optimal FEL cost and performance, 5) Refined electron-beam and FEL dynamics simulation and theory, 6) Experimental equipment ideally suited to FEL characteristics and prototype experiments.

In the following, we discuss in detail the two most critical elements—the high repetition rate electron gun and seed lasers.

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ELECTRON GUN

Cavity Design

The injector design is driven by the requirements for the FEL. The gun will be used to drive multiple user beamlines at up to megahertz rates, so CW operation is required. The low compression ratio in the linac [5] mandates a peak current from the injector of 50 A. Simulations of collective effects in the compression process suggest a very smooth longitudinal distribution is necessary to avoid strong density modulations in the final bunch. Self inflating bunches from the gun [6] were chosen to produce an ellipsoidal bunch which has a smooth longitudinal distribution. The technique also 'washes out' many irregularities from the initial bunch distribution during the expansion process; see Fig. 2.

The electron bunch length at the undulator of 200 fs was selected to ensure temporal overlap between the seed laser pulse, τ_p=30 fs, and the electron bunch while accounting for the electron temporal jitter driven by the chicanes and RF systems. To use self inflating or 'blow-out' mode bunches of 200 pC charge, 50 A peak current and an emission spot radius with a thermal emittance less than 1 mm-mrad, the minimum peak field on the cathode is about 40 MV/m, with greater peak field producing bunches with less distortion of the final ellipsoidal shape and higher bunch charge densities. The most direct method of producing CW, electric fields of ~40 MV/m is to use a superconducting RF (SRF) electron gun.

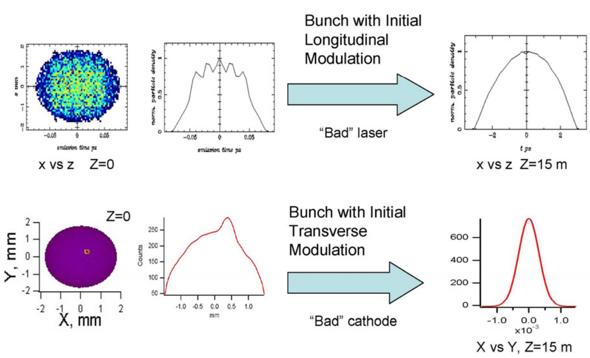

Figure 2: Initial longitudinal (upper) and transverse (lower) bunch distributions are shown on the left. Distributions at the end of the injector, Z=15 m, p=100 MeV/c, are shown on right.

For this application, a low frequency, 200 MHz quarter wave structure has been selected [7]. It has a cathode to anode gap which is much shorter than the wavelength. This provides a slowly varying field profile during the electron transit time with almost no phase slip so the cavity can be operated with the maximum electric field on the cathode. A back-to-back pair of low frequency quarter wave resonators (QWR) design was originally selected [8] because it allowed a very high field on the cathode, a large exit momentum and only half the B_{pk} per unit E_{pk} of an elliptical cavity. A design using only a single QWR cavity has since been selected to accommodate real world issues in the fabrication and cleaning of superconducting cavities. This design has a larger anode hole to accommodate a cleaning wand, smaller toroidal ends and a one degree tapered anode plate to allow cleaning fluid to drain; see Fig. 3. The cavity filter was also redesigned to increase the clearances around the cathode support rod, reduce the radial fields at the cathode surface and minimize heating in the cathode support rod from RF currents. Extensive modeling was done in SUPERFISH to minimize the defocusing radial electric fields at the cathode as this is a significant issue in the beam dynamics simulations.

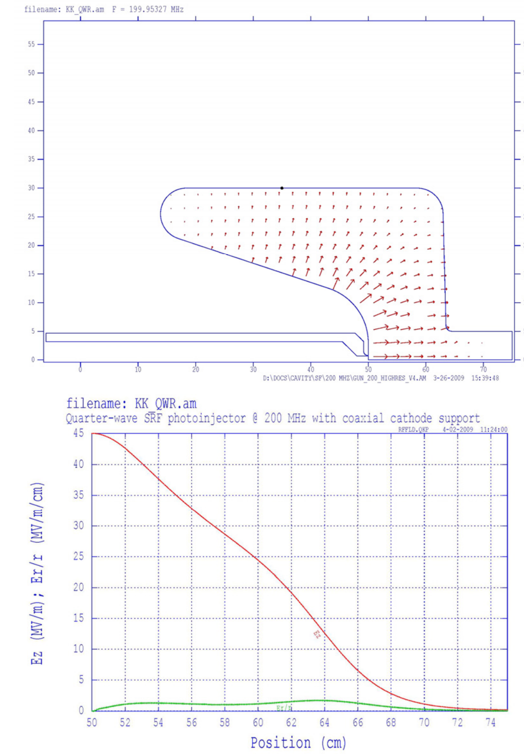

Figure 3: Quarter wave cavity design with choke filter; E_z and E_r/r shown for accelerating gap.

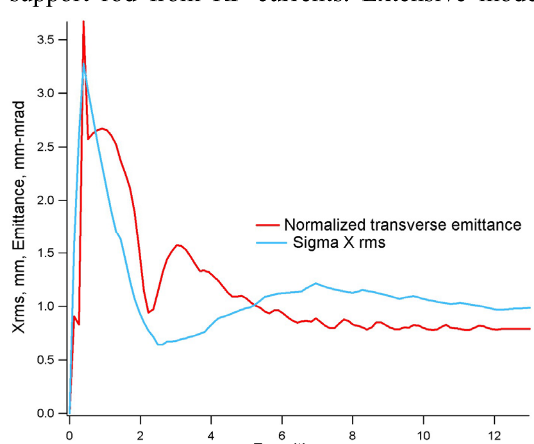

Figure 4: Transverse emittance and sigma X tracked through injector.

Beam Dynamics

The injector uses a simple gun-solenoid-drift arrangement, rather than a more complicated gun-solenoid-RF/SRF buncher and capture arrangement. This allows the use of an invariant envelope emittance compensation scheme similar to the one demonstrated at LCLS [9]. The transverse emittance and rms bunch size have been tracked through the injector, Fig. 4.

LASER SYSTEMS

Tunable UV Seed-Laser

High-energy tunable UV pulses can be generated by ultrashort pulse amplification and frequency up-conversion based on nonlinear optical processes. Fig. 5 shows a broadband optical parametric amplification (OPA) system covering the wavelength range 680-1050 nm, followed by the second-harmonic generation (SHG) and sum-frequency generation (SFG) processes that allow the generation of tunable ultrashort pulses in the wavelength range 205-347 nm. The broadband

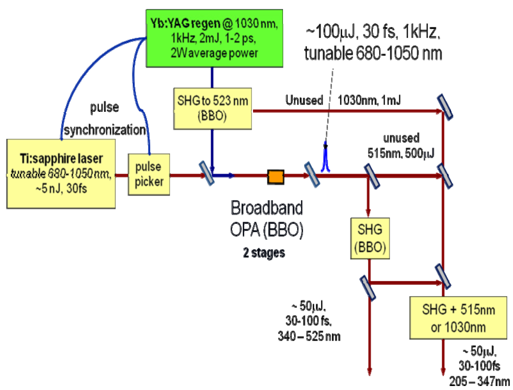

Figure 5: Schematic diagram of a tunable UV seed laser based on OPCPA technology. Note that the stretcher and compressor are not shown here.

Ti:sapphire oscillator provides the seed beam not only for the broadband OPA but also for the pump laser (Yb:YAG regenerative amplifier) with a narrow band at 1030 nm. The two OPA stages using BBO nonlinear crystals, pumped by 1 mJ of energy at 515 nm (SHG of 2-mJ 1030 nm beam), boost the ~nJ seed energy up to ~100 μJ over the entire spectral bandwidth. The SHG process up-converts the near-IR wavelength to 340-525 nm and these up-converted pulses are further sum-frequency mixed with either the 515 nm or 1030 nm beam to cover the wavelength range of 205-347 nm. Pulse durations of <100 fs are available through proper control of dispersion at each stage. Fig. 5 does not show the stretcher and compressor schemes to match the signal pulses to the pump pulses before the OPA states and for the final recompression.

Tunable XUV Seed-Laser

High-order harmonic generation (HHG) driven by high-power femtosecond laser pulses is a reliable method for producing coherent XUV pulses. FEL simulations show that the XUV seed must provide 10 MW peak power at photon energies up to ~30 eV, or approximately 300 nJ in a 30 fs pulse. Considering the demonstrated HHG conversion efficiencies of ~10^{-4} using 30-60 fs, 800 nm pulses in Xe, we need a driving pulse energy of ~3 mJ. A key challenge for the WIFEL facility is to extend this capability to 1 MHz repetition rate, requiring 3 kW of average power. Currently sub-100 fs pulsed lasers at this power level are not available. Yb-doped lasers emitting at 1 μm wavelength may enable such sources. Candidates are Yb:YLF, Yb:Y_2SiO_5 and Yb:$LuScO_3$ laser crystals. Cryogenically cooled lasers based on these materials can potentially deliver sub-100 fs pulses with the required 3 kW of average power while maintaining a diffraction limited beam [10]. Up to 450 W of output power in CW-operation from a cryogenically cooled Yb:YAG laser has been already achieved [11], and recently a 287 W picosecond laser at 80 MHz repetition rate [12] was demonstrated based on this technology. Similar techniques and laser architectures are employed for power scaling of the Yb-doped femtosecond lasers needed as drive lasers for the XUV seed source for WIFEL.

Another key requirement is the spectral tunability of the HHG source. The spectral tunability of the proposed 1 μm driver sources is limited, so the primary tuning mechanism will be pulse shaping of the drive laser [13-14]. It has been demonstrated that this technique can be used to provide continuous tuning of the generated high-order harmonics over twice the base frequency, the separation of the discrete lines in the HHG spectra.

CONCLUSION

A VUV/Soft-X-ray seeded free electron laser facility is technologically achievable and the scientific potential is compelling. There is a clear path of R&D and design that makes a construction start early in the next decade realizable.

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