PROGRESS TOWARD THE WISCONSIN FREE ELECTRON LASER *

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Abstract

The University of Wisconsin-Madison/Synchrotron Radiation Center is advancing its design for a seeded VUV/soft X-ray Free Electron Laser facility called WiFEL. To support this vision of an ultimate light source, we are pursuing a program of strategic R&D addressing several crucial elements. This includes development of a high repetition rate, VHF superconducting RF electron gun, R&D on photocathode materials by ARPES studies, and evaluation of FEL facility architectures (e.g., recirculation, compressor scenarios, CSR dechirping, undulator technologies) with the specific goal of cost containment. Studies of high harmonic generation for laser seeding are also planned.

SCIENCE WITH FELS

The frontier of light-source-enabled science in the 21st century is where physical, chemical, and biological systems can be viewed on their characteristic temporal, spatial, and energy scales—femtoseconds, nanometers, and millivolts. This science includes, for example, delineating the elementary steps of catalysis and chemical transformations, understanding how correlations of electrons and spins create high-T_c superconductors, and elucidation of the remarkable functionality of complex biological systems. In addition, high average photon flux density is often required, whether to perform, for example, photon-in/photon-out experiments on condensed matter systems or to study multi-photon atomic physics. Free electron lasers are uniquely suited to achieving these goals, far exceeding the capabilities of other electron-beam technologies because of the inherent coherence of the FEL process. These powerful laser beams will make the kind of contribution to our understanding of dynamic responses that the current generation of storage rings has made to our understanding of static atomic and electronic structures.

TECHNICAL CONTEXT AND APPROACH

Design concepts of soft X-ray facilities such as WiFEL[1] (See Figure 1), NLS[2], and NGLS[3] are representative of the configurations and potential performance specifications for a large scale VUV/soft X-ray FEL user facility. Using high harmonic generation laser seeding or echo-enhanced harmonic generation, the linac-driven FEL source could produce fully coherent, very short (femtoseconds to attoseconds) photon pulses covering the VUV and soft X-ray range. The driver would be a superconducting RF linac, which would be operated in a CW mode and would allow pulse repetition formats up to 5 MHz or higher. Although system optimizations remain to be done, the main requirements for the CW superconducting linac are well within reach of the current state of the art of superconducting RF technology. This approach enables a large number of beamlines, each with flexible pulse format and superb spectral characteristics. The seeded FEL lasing would be optimized for repeatability, spectral purity, and tunability. Further discussion of concepts for such facilities and critical path R&D can be found in reference [4] and references therein.

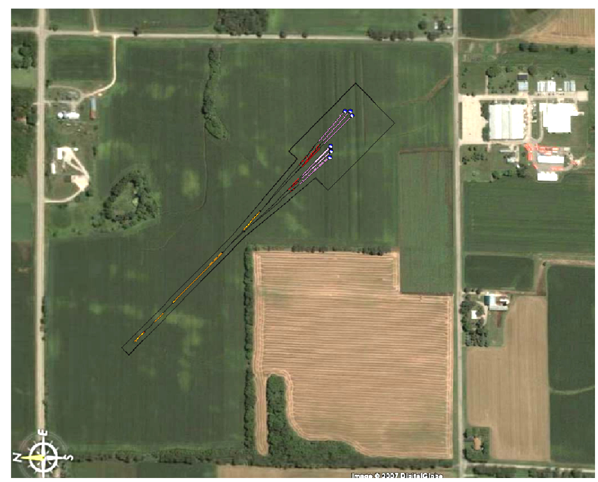

Figure 1: WiFEL on SRC site.

Basic performance goals are:

- Transform-limited fully coherent output—longitudinal and transverse
- Pulse energy up to 0.1 millijoule
- Many beamlines operating independently and simultaneously
- Complete spectral coverage from ~10 eV to ~1 keV in first harmonic, plus higher harmonics
- A wide energy tuning range and polarization control at each beamline
- Peak power and brilliance much larger than the current electron beam VUV/soft X-ray sources
- Average flux and brilliance much larger than the best storage rings and energy recovery linacs

Alternate approaches to a coherent light source include storage rings, energy recovery linacs (ERLs), and high harmonic generation (HHG) based on conventional lasers. For storage rings and ERLs, VUV and soft X-ray radiation is produced in an incoherent process where each electron independently radiates. With sufficiently low electron beam emittance the radiation can have substantial transverse coherence, but is not longitudinally coherent. Emittance requirements are, in fact, more severe than in

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an FEL because the FEL process provides guiding of the radiation. Storage rings cannot effectively produce sub-picosecond pulses, and "pulse slicing" techniques offer very limited photon flux. ERLs, on the other hand, can produce sub-picosecond pulses, but a gigahertz repetition rate is necessary to achieve good transverse coherence with high flux. This high repetition rate is not well matched to, for example, pump-probe experiments in the kilohertz to megahertz range. HHG sources hold some promise to move toward the nanometer wavelength range but likely with very low efficiencies. There is, in fact, a synergy between HHG and seeded FEL sources, where the FEL acts as an amplifier, up-converter, and filter of the HHG radiation. Average flux from a high repetition rate FEL is predicted to be several orders of magnitude higher than from HHG in the nanometer wavelength range.

In broad brush strokes, the critical areas that must be addressed before moving forward with construction of such a user facility include low-emittance, high repetition rate electron injectors; high average power lasers for photocathode electron guns and laser seeding/beam manipulation; cost effective technologies for acceleration systems; synchronization and timing systems; optimized undulator concepts; and theory, modeling, and optimization of beam dynamics and FEL physics. It will be especially critical to keep costs per user reasonable in the context of today's synchrotron light source facilities. Clearly, fully addressing this list requires participation by multiple national programs, and some facets of this work are already under way: room temperature and DC electron guns, next generation modeling, short wavelength high harmonic generation laser systems, timing systems, and seeding schemes [5]. However, even for single items such as the electron gun, various approaches need to be pursued in parallel since the best technological approach has not been identified.

R&D PLAN

To support this vision of an ultimate VUV/soft X-ray light source, we are pursuing a program of strategic R&D addressing several crucial elements. These thrusts work synergistically creating a dynamic center for innovation in coherent light sources. In particular, we are addressing the following:

1) *Development of a high repetition rate, VHF superconducting RF electron gun, including a high repetition rate photocathode drive laser.* This design concept was developed during the past three-year study for the WiFEL project. The U.S. Department of Energy's Office of Basic Energy Sciences is providing funding for the fabrication, installation, and preliminary testing of the electron gun proper. This will be discussed in more detail in the following section.

2) *R&D on photocathode materials, including novel approaches, by Angle Resolved Photo Emission Spectroscopy (ARPES) studies on the Aladdin storage ring at SRC.* Traditional theoretical treatments of beam emittance assume isotropic emission, which leads to a direct link between quantum efficiency and emittance. Progress beyond this limit might be made, however, by considering the actual electronic structure of crystalline cathode materials. Our program aims to reduce the low current emittance of electron guns by understanding how band-structure impacts performance. SRC has been a center for condensed matter research and enabling instrumentation, and can uniquely offer experimental equipment and user expertise in condensed matter physics to address the science involved. Initial studies are currently under way.

3) *Studies of the laser high harmonic generation (HHG) process to establish the necessary noise performance as a seed laser source.* In high gain harmonic generation up-conversion in free electron lasers, the noise-to-signal ratio deteriorates as n^2, where n is the harmonic number of the FEL up-conversion. Thus, low input noise from the HHG seed is critical to achieving the desired performance. There has been only limited theoretical work that analyzes the noise and the coherence properties of the HHG spectrum. We plan to experimentally study the noise and the coherence properties of the generated HHG spectrum under realistic conditions expected in an FEL facility.

4) *Evaluation of FEL facility architectures with the specific goal of cost containment.* We are evaluating, for example, multipass acceleration for cost reduction with consideration of emittance degradation, passive dechirping with coherent synchrotron radiation to reduce the need for off-crest acceleration, and single-stage compression to minimize the microbunching instability. We are also pursuing parametric studies of ultra-low emittance/low charge configurations and optimal RF frequency and technologies. Ultimately, all of these considerations will be put into an overarching context to provide a basis for achieving a cost effective yet high performance and robust configuration for an FEL facility. We expect that such considerations could well reduce capital costs by 50% or more if shown practicable.

5) *Studies of laser-beam interactions.* With a superconducting gun and Ti:Saph laser ultimately available, there are several possibilities for studying their combination in, for example, a laser-undulator configuration. Colliding the laser and electron beams head-on could be investigated with a hollow dielectric fiber used to increase the effective interaction time and enhance the gain. Although the available laser pulse power will not be sufficient for FEL lasing, the above idea, along with other concepts, will be explored with the proposed systems to address the key issues of extending the interaction time, beam transport and wakefields, and laser shaping.

SRF GUN UPDATE

The University of Wisconsin FEL team is moving forward with the development a ~200 MHz superconducting RF gun that meets the required specifications for a CW FEL in the soft X-ray region. A three year program is being pursued, with key

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procurements in place and installation of the hardware and commissioning in a year time frame. The principal parameters for the electron gun are shown in Table 1.

Table 1: SRF Electron Gun Parameters

Parameter	Units	Value
Beam kinetic energy	MeV	4.0
Bunch charge	pC	10–200
Norm. trans. emit.	mm-mr	0.2–0.9
Max. average beam	mA	1.0
Peak current (at 100 MeV)	A	50
Photocathode		Cs_2Te, etc.
Driving laser wavelength	nm	266
Pulse duration (FWHM)	ps	0.100
Bunch repetition rate	MHz	5
Electric field at cathode	MV/m	45

An SRF electron gun was chosen because it is well suited to the requirements of an accelerator based lightsource. It uses low charge bunches with a high peak current at the exit of the injector to minimize downstream magnetic compression and reduce collective effects. The electric fields on the cathode in an SRF gun are higher than other CW sources (>20 MV/m) resulting in greater ultimate brightness. Finally, the electron bunch pulse repetition rates for SRF guns are only limited by the RF power couplers and HOM suppression, meaning that many user beamlines can be driven at tens of kHz or higher by a single accelerator. These features make the SRF gun very attractive at moderate currents compared to other devices proposed. The SRF electron gun design is shown in Figure 2. Further details of the design may be found in reference [6]. This approach complements programs in room temperature RF guns at LBNL, DC guns at Cornell, and L-band guns in Europe.

The electromagnetic design itself was optimized to produce maximum electric field at the cathode while minimizing the peak electric field in the cavity. This will reduce the possibility of field emission limiting the cavity gradient. Similarly, the peak surface magnetic field was minimized to reduce the possibility of magnetic quench of the cavity. The cavity was also optimized to produce a large integrated field between the cathode and anode gap in order that the gun should have a large exit energy. The overall design produces very bright bunches that have sufficient momentum to use the demonstrated LCLS emittance compensation scheme (gun / solenoid / linac section) as part of the injector for an FEL. The cathode is warm with respect to the cavity. Another feature of the design is a high T_c superconducting solenoid for emittance compensation.

To meet the stringent requirements on the longitudinal distribution of the bunch to avoid density modulations in the FEL, we plan to use self inflating (blow out mode) bunches for the FEL. Blow out mode is a scheme in which a laser pulse that is significantly shorter than the final bunch length is used to create a charge pancake on the surface of the cathode, which then expands under its own self space charge force to an ellipsoidal bunch with uniform charge density [7].

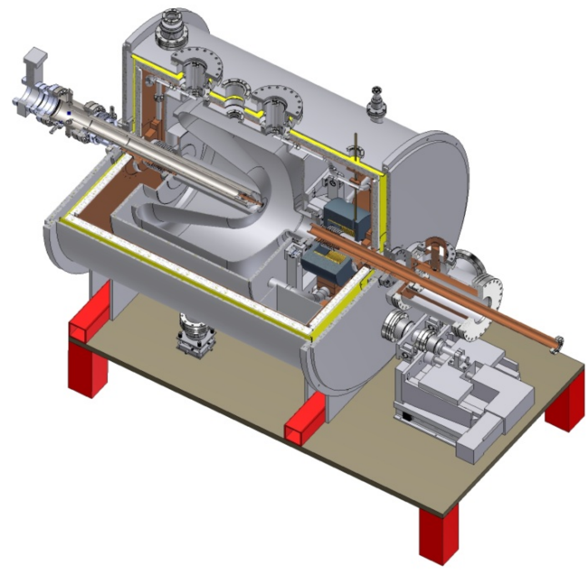

Figure 2: SRF Gun and Cryostat.

SUMMARY

The R&D effort at Wisconsin is moving forward vigorously. We believe that a cost effective design for the next generation soft X-ray facility can be in place to allow a construction start mid-decade.

ACKNOWLEDGMENT

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