DESIGN ALTERNATIVES FOR A FREE ELECTRON LASER FACILITY

J. Bisognano, R. Bosch, D. Eisert, M. Fisher, M. Green, K. Jacobs,
R. Keil, K. Kleman, J. Kulpin, J. Lawler, G. Rogers, R. Wehlitz,
D. Yavuz, University of Wisconsin-Madison, Stoughton, WI 53589, USA
R. C. York, Michigan State University, East Lansing, MI 48824, USA
R. Legg, Jefferson Laboratory, Newport News, VA 23606, USA
T.-C. Chiang, T. Miller, University of Illinois, Urbana, IL 61801, USA

Abstract

We report on continuing design efforts for a next generation FEL facility, building on the Wisconsin Free Electron Laser (WiFEL) study [1]. The principal goal is to optimize value by minimizing cost while maximizing scientific reach. The most attractive solution is a very high repetition rate cw FEL complex, implemented in phases. The first phase, for substantially less than one billion dollars, supports a strong initial science program and allows application of the experience gained and well-tested innovations to later phases. The additional phases provide an increasingly diverse scientific research program with photon energies extending to hard X-rays.

SCIENCE PROGRAM

An FEL complex operating at high repetition rates (~100s of MHz) and delivering intense, ultra-short, fully-coherent, variably-polarized beams to multiple experiments enables transformational research in diverse science disciplines including materials science, chemical physics, atomic, molecular, and optical physics, life and medical sciences, environmental science, and geology. The facility provides important tools to probe phenomena at the nanoscale and at characteristic electronic and atomic time scales (ps to fs and below). Such an FEL complex, implemented in phases with increased linac energies and enhanced experimental capabilities, provides a strong initial science program at substantially less than $1B while making no compromise in the final scientific reach. Fig. 1 illustrates this phased approach.

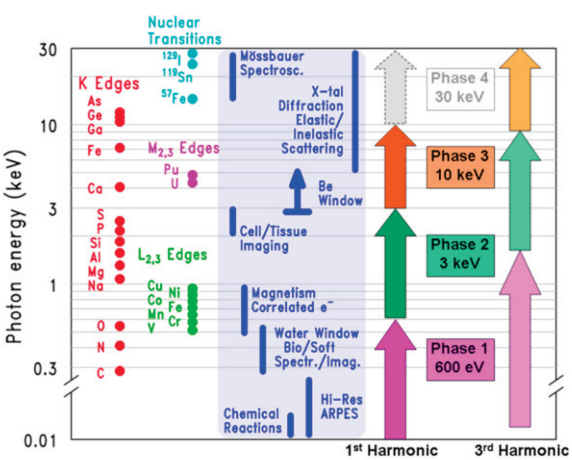

Figure 1: The blue area highlights techniques and science enabled at different energies; the right-hand side depicts the photon energies that can be reached with each construction phase. Further phases are possible.

In Phase 1, the linac energy is chosen to provide output photons of ≤600 eV in the 1st harmonic to support high-resolution angle-resolved photoemission, to enable real time studies of chemical reactions in gases and on surfaces, and to cover the water window that is crucial for spectroscopic imaging of biological materials. The 3rd harmonic output (≤1.8 keV) covers the L edges of the 3d transition metals important for resonance X-ray scattering and absorption studies of correlation effects, electronic complexity, and magnetic and spin effects.

In Phase 2, the 1st harmonic energy is extended to 3 keV. Variations in X-ray absorption and phase contrast make the energy range 2-3 keV well suited for X-ray imaging and coherent scattering analysis of soft matter and biological materials. The 3rd harmonic (≤9 keV) is of great interest to monitor real time changes to atomic structure by X-ray diffraction. Resonance scattering and inelastic scattering studies can be carried out to unravel single-particle and collective excitations.

In Phase 3, the 1st harmonic is extended to 10 keV, which is high enough to use a Be window to separate the beam line vacuum from the sample chamber, allowing convenient study of wet samples. The 3rd harmonic output (30 keV) extends diffraction and inelastic scattering to large momentum transfers and provides much greater penetration depth. The range also covers additional K edges of interest to electronics, as well as several Mössbauer lines.

A short pulse length of ≤5 fs is important to many experiments as this is approximately the time for electronic excitations in photo-chemical reactions. It is also short enough to record diffraction patterns of single molecules *before* they undergo a Coulomb explosion ("diffract & destroy") [2, 3]. This technique is a major step forward because X-ray crystallography of biomolecules is not applicable to the ~40% of molecules that cannot be crystallized. The ≤5 fs pulse is also useful for tracking the migration of inner-shell holes in clusters and molecules.

VALUE OPTIMIZATION

Accelerator Technology

The technology decision for the linac accelerating structures has cost and performance consequences.

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Although next generation FELs might ideally be based on niobium superconducting radio frequency (SRF) cavities, room temperature copper S-, C-, or X-band accelerating structures may offer comparative cost benefits and several projects have chosen this approach [4]. However, the low duty factor operation of the copper structures impose substantial limitations on the Science Program even if the macropulse length is extended to thousands of bunches or the macropulse repetition rate is increased into the kHz range. Photons per pulse constraints due to target limitations can be only modestly compensated, pulse-to-pulse variations are relatively large, and research efficiency is dramatically reduced given that only a few simultaneous users can be supported effectively.

The technology for an L-band SRF linac is mature and provides the 100% duty factor (cw) operation that best supports the Science Program. CW operation allows a microbunch (photon) structure that when combined with a photo-cathode electron gun and an rf separation scheme similar to that employed at CEBAF [5] can simultaneously provide bunch trains to multiple FELs. Each FEL receives bunch attributes optimized to best meet the research requirements, such as providing high frequency (~100 MHz), modest flux/pulse, and very short pulses. As a consequence, even given the higher cost of an SRF-based system, the facility productivity and cost/user is dramatically improved given the multiple simultaneous users and the breadth of cutting-edge research supported.

The linac portion of the FEL system can be configured as a single-pass device like SLAC or a multi-pass device such as CEBAF**.** Preliminary evaluations have not identified significant cost savings from multi-pass recirculation geometries, nor has the impact of performance degradations been fully evaluated. Energy recovery is not considered because of operational complexities required by multiple FELs at different electron beam energies and the energy spread degradation generated by the FEL process in saturation. The microbunch distribution scheme based on rf separators [6] offers substantial advantages over slower pulsed distribution techniques. This fast system can utilize a microbunch structure of several hundred MHz, allowing many simultaneous users, accommodation of experimentally preferred photons/pulse, high average current with low bunch charge, and a pathway to increase the facility research scope by implementation of research systems to produce and utilize photons of increasing energy. Each of the three research phases described in the Science Program can be accommodated by facility additions as described in the Example Implementation section. In that example, each of the three phases would have four FEL lines feeding four experimental areas using an rf separator distribution. Further expansion is possible. Differential adjustment of the microbunch structure in frequency and intensity would provide pulse trains tailored to best meet individual experimental requirements.

Undulators and Beam Energy

Electron beam energy is a principal cost driver. Given the fundamental resonance relation between undulator period and beam energy, $\lambda = \frac{\lambda_u}{2i\gamma^2}\left(1 + \frac{K^2}{2}\right)$, where λ= radiation wavelength, λ_u= radiator pitch, i = harmonic number, γ= electron energy, K= 0.0934 × B [T] × λ_u [mm], B =radiator peak field, there are advantages to operation at higher harmonics and a lower undulator period. For higher harmonic operation, a cross field configuration [7] is necessary to provide variable/circular polarization, with saturated power in the 3rd harmonic expected to be about 1 % of that in first harmonic [8]. The K value determines both tunability (K=2.6 provides a 3:1 variability) and gain (K~1 provides reasonable gain lengths) of the FEL process.

For conventional undulators the magnetic field (B) varies in the same sense as λ_u / g_{mag} so that decreasing λ_u decreases g_{mag} while maintaining K. The vacuum gap (g_{vac}) is a lower limit of g_{mag} and is set by beam dynamics. Fig. 2 illustrates the advantages of a small g_{vac} for several design approaches. Current work [9] indicates that a SC device can achieve a λ_u= 15 mm with g_{vac} = 5 mm. Using an rf undulator concept, a regime with λ_u roughly < 10 mm may be achievable [10].

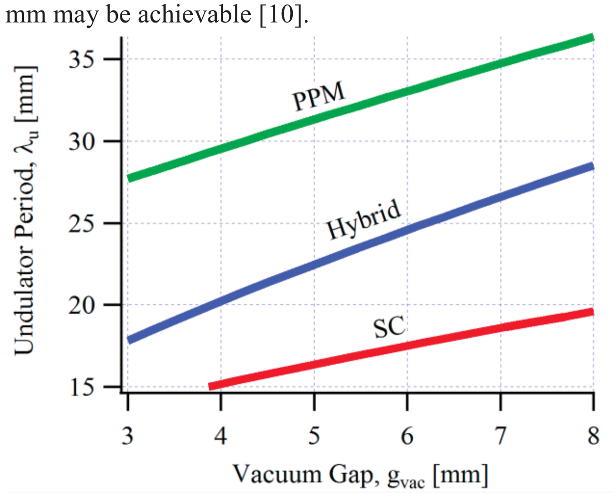

Figure 2: Qualitative examples of magnetostatic devices assuming K_{max} = 2.6. PPM refers to no-iron Pure Permanent Magnet; Hybrid to PPM + Fe poles; and SC to superconducting [11].

FEL Seeding

Full 3D coherence is an essential feature of the facility. For the lower energy FELs, some combination of conventional laser seeding (HHG or EEHG) with modest harmonic up-conversion would be the likely choice. The highest repetition rate achievable will be determined by progress in high average power lasers. For the higher photon energies there could be a transition to self seeding. However, since the repetition rate can be ≥ 1 MHz for several beamlines simultaneously, soft X-ray oscillator seeding schemes such as that suggested by Wurtele et al. [12] and XFELO [13] for hard X-rays could be supported.

Electron Gun Performance Requirements

Shown in Fig. 3 is the FEL Saturation Length vs. normalized emittance for a peak current of 1 kA and energy spread of 200 keV. Simulations of 20 pC bunches from the Wisconsin SRF electron gun [14] resulted in a transverse emittance of 0.3 mm-mrad and peak current of 8 A with slice energy spread of 0.6-0.9 keV (13.3 to 8.9 A/keV). Since the ratio of peak current to energy spread exceeds the 5A/keV needed to produce a peak current of 1 kA with an energy spread ≤200 keV, such gun performance should meet requirements for the phased facility with acceptable undulator lengths, possibly up to 30 keV photons. A combination of velocity bunching and a single stage of magnetic compression are envisioned to allow this small energy spread while controlling the microbunching instability.

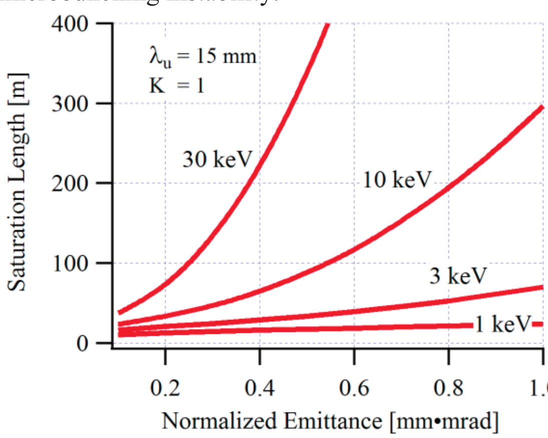

Figure 3: FEL saturation length vs. normalized emittance. The peak current is assumed to be 1 kA with an energy spread of 200 keV.

EXAMPLE IMPLEMENTATION

An example phased implementation of an FEL facility spanning the Science Program of Fig. 1 is shown schematically in Fig. 4. It is based upon incremental additions of SRF linacs and associated lasing and experimental systems. Given an arbitrary unit cost of $X for Phase 1, Phase 2 and 3 are estimated to cost approximately $1X and $1.7X, respectively. The linac layout assumes an accelerating module similar to that utilized for the JLab 12 GeV upgrade [15]. The phased approach has substantial advantages by providing a) initial implementation with a strong science program while limiting costs to substantially less than one billion dollars, b) scientific and technical efficiencies and synergies inherent in localization of all phases of the Science Program and c) for application in later phases, early confirmation of cost-reducing, performance-enhancing technical approaches such as seeding schemes, beam halo management, or very short wavelength undulators. The phases can be implemented in a manner that builds on extant infrastructure, avoiding duplications and their inherent costs, and the configuration allows upgrades that do not impact the operating facility's scientific productivity.

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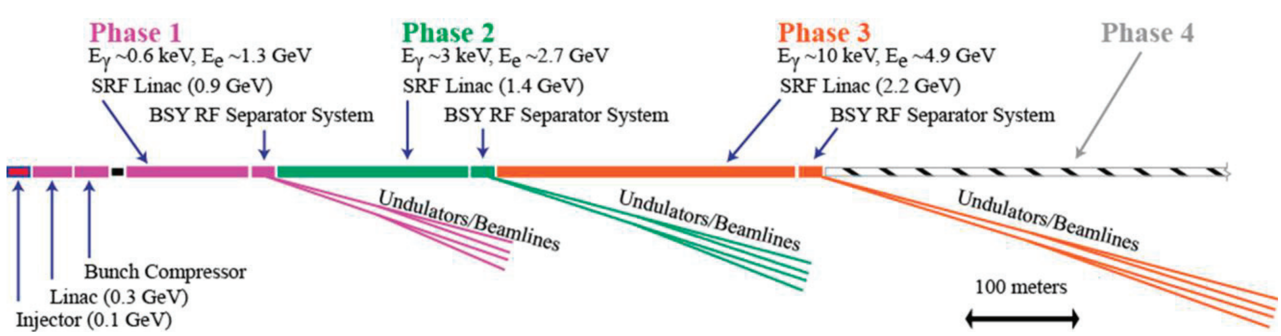

Figure 4: Step-wise implementation of an FEL facility supporting the discussed Science Program as outlined in Fig. 1. Each Phase can be implemented with virtually no impact on research with operational Phases. The phased approach can be extended with, e.g., the addition of a Phase 4 providing E_γ ~ 30 keV and E_e~8.4 GeV by adding an additional 3.5 GeV of acceleration and further undulators/beamlines, if sufficiently low emittance can be realized. A site of roughly 3.2 by 0.5 kilometres (~400 acres) could accommodate four phases.

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