

## LUX - A RECIRCULATING LINAC-BASED FACILITY FOR ULTRAFAST X-RAY SCIENCE\*

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### Abstract

We present recent developments in design concepts for LUX - a source of ultra-short synchrotron radiation pulses based on a recirculating superconducting linac. The source produces high-flux x-ray pulses with duration of 100 fs or less at a 10 kHz repetition rate, optimized for the study of ultra-fast dynamics across many fields of science [1]. Cascaded harmonic generation in free-electron lasers (FEL's) produces coherent radiation in the VUV-soft x-ray regime, and a specialized technique is used to compress spontaneous emission for ultra-short-pulse photon production in the 1-10 keV range. High-brightness electron bunches of 2-3 mm-mrad emittance at 1 nC charge in 30 ps duration are produced in an rf photocathode gun and compressed to 3 ps duration following an injector linac, and recirculated three times through a 1 GeV main linac. In each return path, independently tunable harmonic cascades are inserted to produce seeded FEL radiation in selected photon energy ranges from approximately 20 eV with a single stage of harmonic generation, to 1 keV with a four-stage cascade. The lattice is designed to minimize emittance growth from effects such as coherent synchrotron radiation (CSR), and resistive wall wakefields. Timing jitter between pump lasers and x-ray pulses is minimized by use of a stable optical master oscillator, distributing timing signals over actively stabilized fiber-optic, phase-locking all lasers to the master oscillator, and generating all rf signals from the master oscillator. We describe technical developments including techniques for minimizing power dissipation in a high repetition rate rf photocathode gun, beam dynamics in two injector configurations, independently tunable beamlines for VUV and soft x-ray production by cascaded harmonic generation, a fast kicker design, timing systems for providing synchronization between experimental pump lasers and the x-ray pulse, and beamline design for maintaining nm-scale density modulation.

### ACCELERATOR SYSTEMS

The LUX recirculating linac configuration is shown in Figure 1. The major systems are rf-photocathode electron sources, an injector linac, a main superconducting linac, arcs to transport the beams of different energies into and out of the main linac, photon production in a variety of insertion devices, and x-ray beamlines. The number of passes through the recirculating linac has been reduced from previous design studies, in order to accommodate

additional x-ray beamlines in each of the return paths. The cost of the recirculating configuration has a broad minimum around three to four passes.

Electron pulses are produced at a rate of 10 kHz in two rf photocathode guns. Two interleaved sources are used - one with a conventional uncoupled beam optimized for x-ray production in FEL's, the other with a strongly asymmetric x/y emittance beam for hard x-ray production by spontaneous emission [2, 3]. We have produced a conceptual design for an rf photocathode gun optimized for operation at high gradient and high repetition rate. The high-power rf photocathode gun has been designed to minimize the beam emittance, particularly against deleterious effects of space-charge at low energies, while using conventional water cooled copper cavities and optimization of the rf parameters to minimize energy deposition in the cavity. In addition to shaping of the cavity interior surfaces to optimize accelerating field while minimizing dissipated power, the cavity coupling factor and manipulations of the phase of the rf drive may be used to further reduce power deposition in the cavity [4]. Selection of the coupling factor  $\beta$  determines the loaded Q-value of the system, and thus the filling time of the cavity. We design the photocathode rf system for a 5% duty factor, and when taking into account the rise and fall times  $\beta > 1$  is advantageous in reducing dissipated power in the cavities (at the expense of additional klystron power). By inverting the phase of the rf drive to the cavity after the electron bunch has exited the rf gun, the stored energy in the cavity may be quickly extracted, and deposited in an external load. The cavity design accommodates the full power deposition from a critically coupled cavity with no phase inversion, thus allowing considerable flexibility in operating conditions [4].

Following the rf gun a superconducting injector linac accelerates the beam to 200 MeV. A skew-quadrupole channel transforms the magnetized beam into a beam with large x/y emittance ratio [2]. Long bunches, of approximately 30 ps, are produced at the cathode to minimize space charge effects and produce low-emittance beams. The correlated energy spread introduced along the 30 ps bunch by the injector linac is linearized in a 3<sup>rd</sup> harmonic cavity, which prepares the beam for compression in a following arc. Beam dynamics for both guns has been studied from the cathode to the end of the injector line, and design parameters of normalized emittances at 1 nC of 2 mm-mrad (uncoupled),

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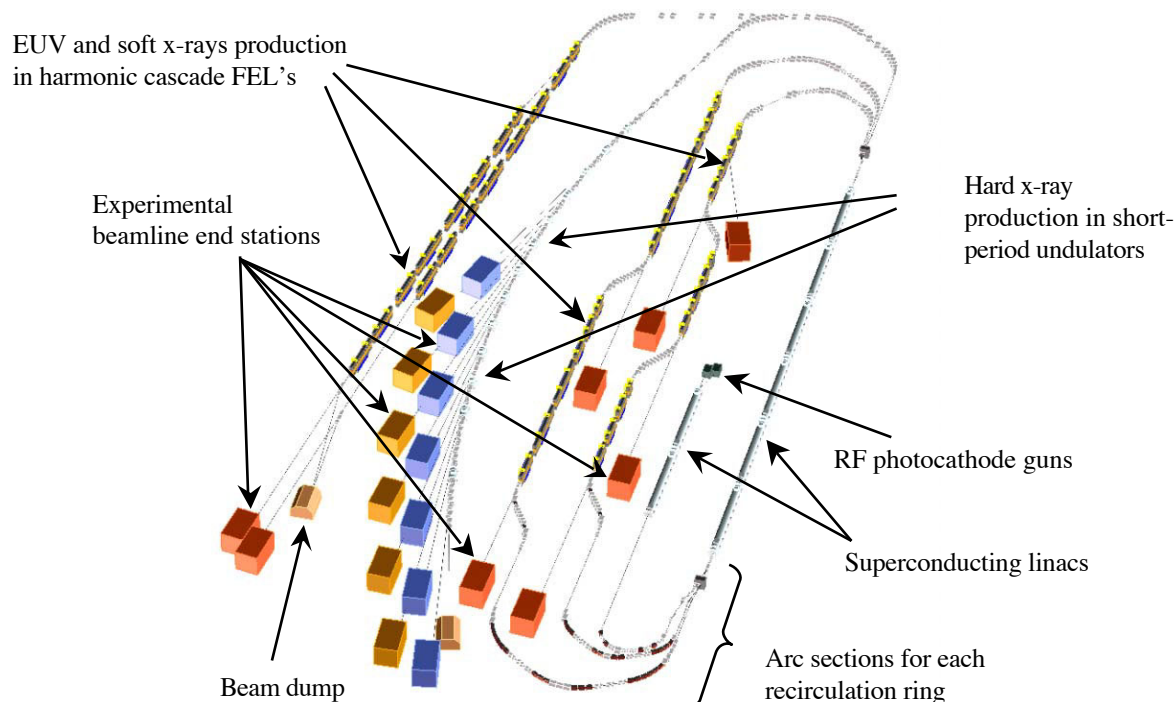


Figure 1. LUX machine layout. The machine footprint is approximately 150x50m. A capacity of approximately 20 beamlines is available, using a combination of harmonic cascade FELs and spontaneous emission in insertion devices.

and 0.4/20 mm-mrad (asymmetric) are readily achieved in simulations [3]. In the arc leading to the main linac, the 30 ps bunches are compressed to 2-3 ps duration.

In the 1 GeV main linac the maximum energy of 3 GeV is achieved after recirculating in three passes through the superconducting rf structures. The linac design is based on the TESLA superconducting rf cavities [5, 6]. Operating in cw mode at a gradient of up to 20 MV/m requires development of cryogenic systems to accommodate the thermal load, engineering models are under development.

The beam transport following each pass through the main linac includes one or more harmonic cascade FEL, in a development to provide independently tunable x-rays at each beamline endstation [7]. By using from one to four stages of laser-seeded harmonic generation in a linear configuration, each endstation may select its operating wavelength independently. Transport of the electron beam in the harmonic cascades while maintaining nm-scale modulations has been studied, and lattices allowing bends of up to 5° have been designed [8]. We now incorporate linear cascades, which eliminates the need to transport the modulated beam through a bend angle, thus simplifying the design and allowing flexibility in operations.

The uncoupled beam with nearly equal x,y emittances is used in the cascaded harmonic generation scheme, where the FEL process is initiated by a coincident seed laser pulse. One, two, three, and four-stage harmonic cascade

FELs are shown in Fig. 1. After the final pass through the main linac, the beam is switched between the four-stage cascade and the hard x-ray production at 3 GeV. We propose to alternate electron bunch trains between these beamlines using relatively slowly switched magnets, although a scheme for a fast kicker has also been investigated [9]. Our technique for hard x-ray production has been described elsewhere [1].

We have developed a technique for production of attosecond duration x-ray pulses using an optical laser to selectively excite a controlled short section of the electron beam into resonance in the harmonic cascade FEL [10, 11]. Accessing the sub-femtosecond time domain opens new possibilities in experimentally determining dynamics on the timescales of electronic transitions in atoms [12].

X-ray pulses are synchronized to pump lasers for pump-probe experiments by a timing system based on a mode-locked laser distributing optical pulses over stabilized fiber optic lines [13]. Generating microwave signals from the optical pulse train allows for locking of the beamline endstation lasers to a common master oscillator. Each laser then has flexibility in amplitude, wavelength, and delay, while timing jitter with respect to the master oscillator is reduced to  $\sim 10$ 's femtoseconds. Accelerator rf signals are also derived from the laser master oscillator, and feedback around the rf systems maintains their lock to the master oscillator.

## HARMONIC CASCADES

The harmonic-generation scheme has been developed and demonstrated at the Brookhaven DUV FEL facility [14, 15]. In the proposed cascaded harmonic generation scheme, a laser-seeded harmonic-cascade FEL produces high-flux, spatially and temporally coherent, nearly transform-limited, short-pulse photons over an energy range of tens of eV to  $\sim 1$  keV [7]. In this process the uncoupled (nearly equal x,y emittance of 2 mm-mrad) high-brightness electron beam of 500 A peak current,  $\pm 200$  keV uniform energy spread, is passed through an undulator where a co-propagating seed laser modulates the charge distribution over a short length of the bunch, typically 10-100 fs duration. The imposed modulation results in enhanced microbunching and eventual coherent radiation at both the fundamental and harmonics of the seed modulation wavelength. In a following FEL the beam radiates at a selected shorter wavelength, in an undulator tuned to a harmonic of the seed laser. The electron bunch is then delayed in a short chicane, and the process repeated by modulating a fresh portion of the beam this time with the harmonic radiation produced in the previous undulator. Using an optical parametric amplifier as the seed with wavelength 200-250 nm, and variable undulators in each harmonic cascade FEL, allows significant tunability in up to four stages of harmonic generation. Output power levels in the VUV to soft x-ray wavelengths are in the range 10-100's MW from a 100 MW seed laser and undulator lengths typically a few to several meters. With the LUX parameters, coherent x-rays with wavelength as short as 1 nm are achievable at 3 GeV. Wavelength tuning and pulse duration are determined by laser parameters and undulator K-values. We note that development of suitable VUV-soft x-ray lasers by high-harmonic generation (HHG) in gases would allow seeding at shorter wavelengths, potentially reducing the number of harmonic cascade stages required. Circular polarization of the x-ray beam may be attainable by use of elliptical undulators, and flux stability of 0.1% or better is obtained in seconds from random pulse-pulse flux variations of 10-20% at 10 kHz repetition-rate.

## X-RAY BEAMLINES

There are several qualitative differences between LUX and electron storage ring requirements for x-ray optics and beamlines.

Firstly, the hard x-ray beamline must accommodate the position or angle correlation of the electron bunch - in the wigglers, electrons will have a vertical *position*-time correlation, in the undulators, a vertical *angle*-time correlation [1, 6, 16]. In these beamlines, the average current is low, 10  $\mu$ A, and consequently, the total power radiated by the undulators and wigglers is also low, typically 0.4 W. None of the high power optical engineering typical of the third generation synchrotron radiation sources is required, and silicon or fused silica optics can be used without water-cooling. The design of the photon stops in the front ends is also simplified.

Beamline optics for the coherent VUV and soft x-ray beams produced in the FEL's must accommodate a high peak intensity  $\sim 0.06$  J/cm<sup>2</sup>, and average powers similar to those of existing 3<sup>rd</sup> generation light sources. The position of the first mirrors should be 10 m from the center of the radiator insertion device. A beamline configuration aperture - horizontal mirror - vertical mirror - endstation provides the full  $10^{-4}$  bandwidth of the FEL (no grating). An aperture - vertical mirror - grating - slit - grating - vertical mirror - horizontal mirror - endstation beamline configuration provides a bandwidth of 90 meV at 280 eV (C K edge), in a length of 13.3m.

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