## Title

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# A RECIRCULATING LINAC BASED SYNCHROTRON LIGHT SOURCE FOR ULTRAFAST X-RAY SCIENCE[*]

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*Abstract*

LBNL is pursuing a multi-divisional initiative that has this year further developed design studies and the scientific program for a facility dedicated to the production of x-ray pulses with ultra-short time duration. Our proposed x-ray facility [1] has the short x-ray pulse length (~60 fs FWHM) necessary to study very fast dynamics, high flux (approximately $10^{11}$ photons/sec/0.1%BW) to study weakly scattering systems, and tuneability over 1-10 keV photon energy. The photon production section of the machine accomodates seven 2m long undulators and six 2T field dipole magnets. The x-ray pulse repetition rate of 10 kHz is matched to studies of dynamical processes (initiated by ultra-short laser pulses) that typicaly have a long recovery time or are not generally cyclic or reversible and need time to allow relaxation, replacement, or flow of the sample. The technique for producing ultra-short x-ray pulses uses relatively long electron bunches to minimise high-peak-current collective effects, and the ultimate x-ray duration is achieved by a combination of bunch manipulation and optical compression.

## 1 ACCELERATOR DESIGN

The major parts of a machine are an RF photo-injector, a linear pre-accelerator, a main linear accelerator, magnetic arcs and straight sections, deflecting cavities, a photon production section, and a beam dump. The layout is shown in Figure 1.

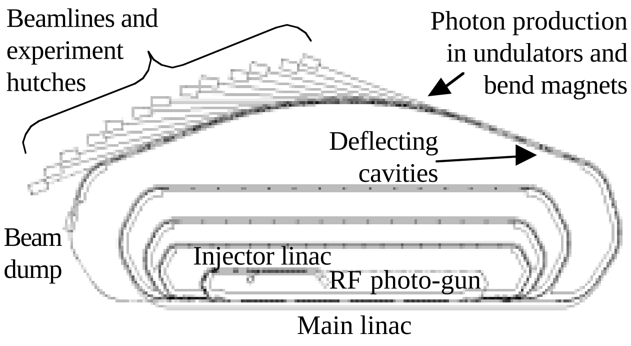

Figure 1. Machine layout. The beam generated at the RF photocathode gun travels through the injector linac, main linac, transport arcs, deflecting cavities, and photon production section, to the beam dump. Machine footprint is approximately 150x50 m.

Electron pulses of ~20 ps duration and ~1 nC charge are produced in a high-brightness RF photocathode gun and accelerated to 10 MeV. As described in [2], application of a solenoidal magnetic field on the cathode, followed by a specially configured skew-quadrupole channel, allows production of a "flat" beam with x/y emittance ratio > 50:1 and vertical normalized emittance less than 1 mm-mrad. This principle has been successfully demonstrated at the Fermilab/NICADD Photoinjector Laboratory (FNPL) [3], and we have joined the experiment collaboration to help further work in this regard.

The electron bunches are then compressed to 10 ps and further accelerated in a superconducting linear pre-accelerator to 120 MeV, and injected into a recirculating linear accelerator. Passing the arc connecting the pre-accelerator and the recirculating linac the electron bunches are compressed to approximately 2 ps full length. In the recirculating linac the final energy of ~2.5 GeV is achieved after four passes through the 600 MeV superconducting linac. At the exit of the final arc the electron bunches receive a time-correlated vertical kick in a dipole-mode RF cavity. This imparts to the electron bunch a transverse momentum that is correlated in amplitude to longitudinal position within the bunch. The electrons then radiate x-rays in the downstream chain of undulators and dipole magnets, imprinting this correlation in the geometrical distribution of the x-ray pulse, see Figure 2. The correlated x-ray pulse is then compressed by use of asymmetrically cut crystal optics to achieve the ultra-short photon pulse length [4].

For a baseline operation at 25 kW beam power, the arc returning the 2.5 GeV beam to the linac will not be built, and the beam will be taken to a shielded dump. The option for energy recovery in the linacs will be maintained for operations with increased beam power.

The machine lattice is described in [5], and our studies demonstrate that the lattice can be made to preserve beam transverse and longitudinal emittance. Emittance control and understanding and mitigation of collective effects is critical to a successful machine design, and we are addressing key aspects of accelerator physics involved in beam break-up [6], coherent synchrotron radiation, the influence of resistive wall wakefields, and other effects. For typical misalignment errors of 0.5 mm for individual cavities and 0.25 mm for cryomodules [7], simulation results show that by controlling the betatron phase advance between passes through the linac, and the initial offset of the beam, the resulting projected emittance growth from cavity wakefields is only a few percent.

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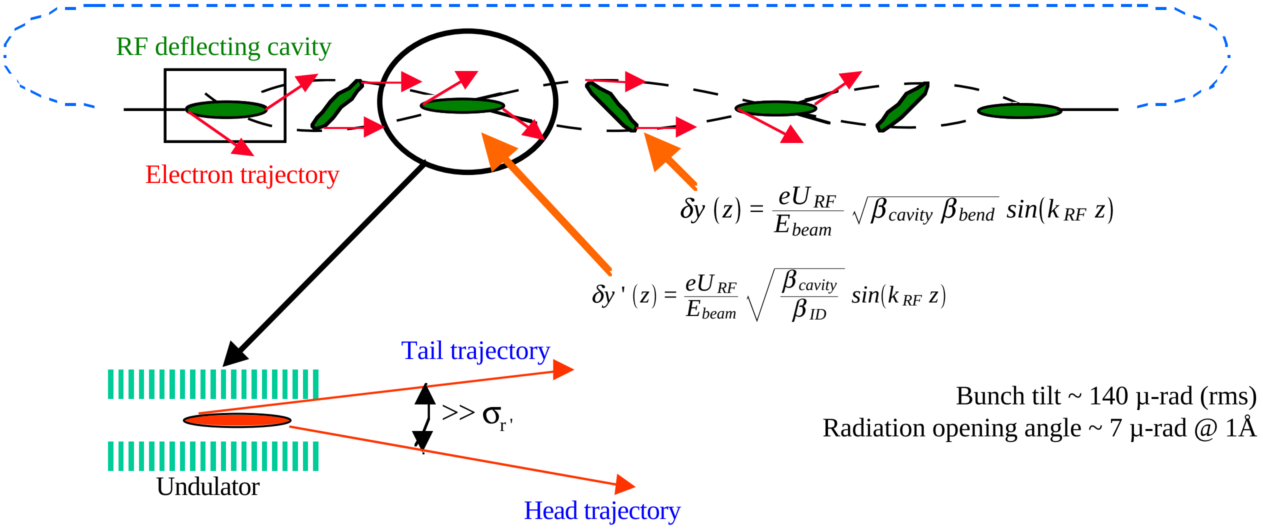

Figure 2. Time/position/angle correlation of the electron bunches. By providing divergence larger than the radiation opening angle, or beamsize greater than the diffraction limited size, optical elements can be used to compress the radiation from a bunch [4,8]. The resultant x-ray pulse length may then be limited by the electron bunch emittance.

Longitudinal dynamics have been modelled from the RF gun through the injector linac and all passes of the main linac, and emittance dilution due to non-linearities in the RF waveform have been assessed. In the injector, harmonic cavities may be used to linearize the longitudinal phase-space. An energy spread of ±200 keV in the final arc requires a bunch of a less than few piscoseconds length. The bunch lengths and beampipe apertures under current consideration result in a regime in which the coherent synchrotron radiation impedance may be significant in the lowest energy arcs of the machine, and studies of such effects are in progress. A smaller beampipe aperture may be beneficial in reducing effects from coherent synchrotron radiation, but the minimum aperture appears to be limited by transverse wakefields arising from the resistive wall impedance. We find that for a typical aperture of 3 cm the vertical emittance growth from resistive wall is about 1% after all four passes. For the low energy beam, the emittance growth from resistive wall is approximately 1.5% for a 25m length of arc with aperture 1 cm connecting the injector to the main linac.

Several narrow-gap in-vacuo superconducting undulator designs have been characterized as high-flux sources and are summarized in Table 1. The machine design accommodates an energy upgrade to 3.1 GeV, and in that case the flux of 10 keV photons from 1 nC bunches at 10 kHz may be increased to $5.6\mathrm{x}10^{10}$ photons/sec/0.1%BW. The deflecting cavity voltage then would be 8.5 MV.

Table 1. Average flux for three in-vacuo undulator designs, 1 nC bunches at 10 kHz rate

| Period | Gap | Peak magnetic field | Kmax | Flux at 2 keV 2.5/3.1 GeV | Flux at 10 keV 2.5/3.1 GeV |
|---|---|---|---|---|---|
| mm | mm | T | | 1e10 photons/sec/0.1%BW | |
| 20 | 5 | 1.5 | 2.8 | 8 / 11.4 | 1.1 / 2.7 |
| 14 | 5 | 1.5 | 2.0 | 15.6 / 17.8 | 2.3 / 4.5 |
| 14 | 3 | 2.0 | 2.6 | 15.6 / 17.8 | 3.4 / 5.6 |

In addition to an energy upgrade facilitated by addition of another RF cryomodule in the main linac, we also design for higher currents achieved through higher repetition rate, and increased charge per bunch. Figure 3 shows x-ray pulse duration as a function of photon energy, for a vertical normalized emittance of 0.4 mm-mrad at 1 nC and 2 mm-mrad at 3 nC. As described in [8], the pulse duration at long wavelengths is dominated by the radiation diffraction limit, and at short wavelengths is limited by the electron beam emittance.

## 2 TECHNOLOGIES

Conventionally, photocathode RF guns employ a half-length pillbox cell for the cathode cavity followed by a full cell for rapid acceleration of emitted electrons, and operate in the 10 Hz pulse repetition frequency range. For CW or high duty factor operation, thermal limitations may prevent such a design from operating at sufficiently high gradient. We have produced a conceptual design with optimized cavity geometry to allow cooling of the cavity surfaces, and operation at high gradient and high repetition rate. In this design the first cell is modified by the inclusion of a re-entrant nose-cone, on the end face of which the photo-cathode is mounted. This nose-cone serves two purposes: it increases surface area to reduce deposited power density, and it enhances the accelerating electric field at the cathode. The design is further described in [9].

Our linac design is based on superconducting RF technology developed for the TESLA project [7]. Identical cryomodules are used for the main linac and the injector linac. Our design considerations here are for a peak accelerating gradient of 20 MV/m in the main linac. The

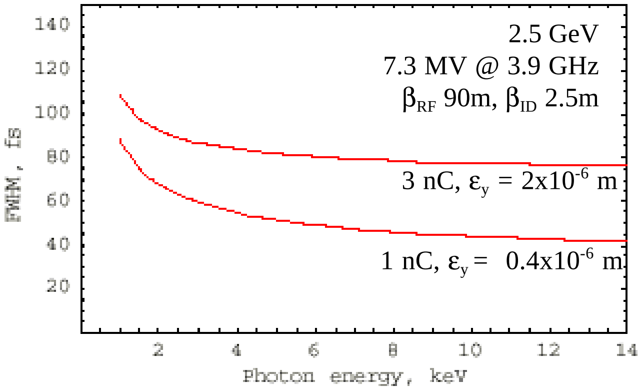

Figure 3. Photon pulse duration as a function of photon energy for bunches of different emittance.

pulse repetition time of 100 μs is less than the superconducting cavity filling time, and we must operate the linacs in CW mode. The RF power requirement for the linacs is dominated by the need to overcouple to provide bandwidth necessary for feedback systems to maintain phase and amplitude control against cavity detuning by microphonics. Approximately 8 kW RF power is required per cavity, assuming a bandwidth of 40 Hz. The total linac RF power requirement is approximately 300 kW. The heat dissipated in the power coupler and the cavity helium bath is then approximately 100 times greater than for TESLA operations, however a preliminary analysis indicates that with additional connections from the supply line to the helium bath for each cavity we may operate at these levels [10, 11].

In addition to the 1.3 GHz linacs, we require 3.9 GHz superconducting cavities to provide the deflecting voltage along the bunch, and third harmonic cavities to linearize the longitudinal phase space in the injector. We have RF designs for 7-cell cavities operating in a hybrid TM/TE mode, and seven such cavities will be required to provide the deflecting voltage of approximately 8.5 MV. Damping of the monopole mode trapped at a lower frequency will be important in reducing energy spread in the electron bunches, further design studies are presented in [12].

The cryogenic system for the accelerator complex must have capacity for over 2.5 kW heat removal at 1.9K, plus significant power, dominated by the RF coupler feedthrough, at intermediate temperatures. We have designed for a cryogenic plant demanding approximately 2.5 MW wall plug power.

Lattice magnets are of conventional water-cooled electromagnet design, with the exception of a few specialized magnets in the beam spreader and combiner regions adjacent to the main linac. In these compact regions we employ special septum magnets, dipoles which act on beams of differing energy, and small quadrupole designs in order to act on separate orbits of beams at different energies. Total magnet power requirement is approximately 2 MW.

Synchronization and timing of the ~ 60 fs x-ray pulse to the experimental laser optical pulse is critical to studies of ultra-fast dynamics. For our scheme of bunch manipulation followed by x-ray pulse compression we find that the phase jitter of the deflecting cavities with respect to the experimental laser pulse dominates timing issues [13]. We propose to derive all accelerator RF signals from phase-locked laser oscillators. The RF gun, linacs, and deflecting cavities are thus phase-locked to the experimental pump lasers, and timing jitter between the optical laser and the x-ray pulse emitted by the beam is minimized. Phase and amplitude feedback of the deflecting cavities is expected to provide x-ray pulse to laser pulse stability of better than 100 fs.

## 3 SUMMARY

We propose a user facility for ultrafast x-ray science based on a novel technique for generating ultra-short x-ray pulses. Advantages of this technique include relative insensitivity to collective effects through the use of long electron bunches, and potential for accurate sycnhronization of the x-ray pulses. Technical challenges have been identified and work is in progress to develop key technologies and perform demonstration experiments.

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