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FEL Research & Development at the SLAC ***S***ub-***P***icosecond ***P***hoton ***S***ource, *SPPS*[†]

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Abstract

An upgrade project to the SLAC linac allows ultra-short electron bunches to be interleaved with the routine high-energy physics program operation, for use with an undulator to produce short-pulse, high-brightness x-rays. The linac upgrade comprises of the installation in the summer of 2002 of a bunch compressor chicane of similar design to the Linac Coherent Light Source (LCLS) project. A final compression stage in the high-energy Final Focus Test Beam (FFTB) line compresses the 28 GeV, 3.4 nC electron bunch to 80 femtoseconds fwhm, where a 5 m section of undulator (K=4.45) will produce 1.5 Å x-rays with $3*10^7$ photons per pulse and a peak brightness of $4*10^{24}$ photons mm^{-2} mrad^{-2} s^{-1} (0.1% BW). The facility will allow us to test the dynamics and associated technology of bunch compression and gain valuable experience for the LCLS using the SLAC linac. New ultra-short electron bunch diagnostic techniques will be developed hand in hand with the same ultra-fast laser technology to be used for LCLS. Issues of high peak power (27 GW) x-ray transport and optics can be addressed at this facility as well as pump-probe and ultra-fast laser timing and stability issues.

PACS codes: [Click here and type the PACS codes]

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1. Introduction

The Short Pulse Photon Source (SPPS) project at SLAC provides a new and exciting opportunity to do femtosecond science with spontaneous x-ray radiation at 1.5 Å wavelengths[1]. This is a new innovation for high-energy linear accelerators and many of the techniques for tuning and diagnosing the beam will be tried for the first time. The SPPS comes at an opportune time since it will allow us to test and develop these new techniques in preparation for the construction of the Linac Coherent Light Source (LCLS) at SLAC.

2. Bunch Compression

The SPPS electron bunch is compressed in 3 stages, shown in figure 1. The bunch extracted from the damping ring is compressed in an existing compressor in the ring-to-linac (RTL) beamline. This reduces the bunch from its equilibrium length in the damping ring of 6mm down to 1.2 mm using an RF induced energy chirp and the non-isochronous beamline. The bunch is actually over-compressed in the RTL, as shown in figure 2, so that it has a steeper charge distribution at the head of the bunch so that the wakefields generate a more linear chirp in the subsequent section of the linac.

In the next 1/3rd of the linac the bunch is given a second energy chirp by accelerating the bunch off-crest by 20.3°. The exact settings of the linac phase and RTL compression are determined in conjunction with the wakefield contribution and hence the beam charge, as described in more detail in reference [2]. The goal of the tuning procedure for the RTL and linac is to reproduce as closely as possible the near linear energy chirp shown in figure 2, row 4, at the entrance to the linac bunch compressor chicane (LBCC).

The 14.3 m long LBCC is located at the 9 GeV, 1/3rd point of the linac and includes four 1.8 m long 1.6 T dipole. The chicane bends generate an R56 component of -75 mm which compresses the bunch to 50 μm rms, as shown in figure 2, row 5.

The large horizontal beam size in the chicane (up to 7 mm rms) and the small transverse emittances from the damping rings require very good dipole field quality, especially at the inner two bend magnets. The field component tolerances, to control the emittance growth to < 2%, are:

$|\Delta b_0/b_0| < 0.1\%$; $|b_1/b_0| < 0.02\%$; $|b_2/b_0| < 0.2\%$;
$|b_3/b_0| < 1.0\%$; $|b_4/b_0| < 2.0\%$,

where $|b_i/b_0|$ is the $2(i+1)$-pole tolerance over $x = \pm 10$ cm (e.g., $i = 2$ is sextupole). Several features were used in the magnet design and construction to achieve the good field region over the 26 cm pole face width. Six steel slabs, blanchard ground to the final tolerance specification were bolted together to form the low-cost, but high field quality magnet cores.

Wakefields also cause undesirable emittance growth in the small vertical aperture of the final chicane bend where the bunch is shortest. The stainless steel vacuum chamber is therefore polished and copper coated to minimize this.

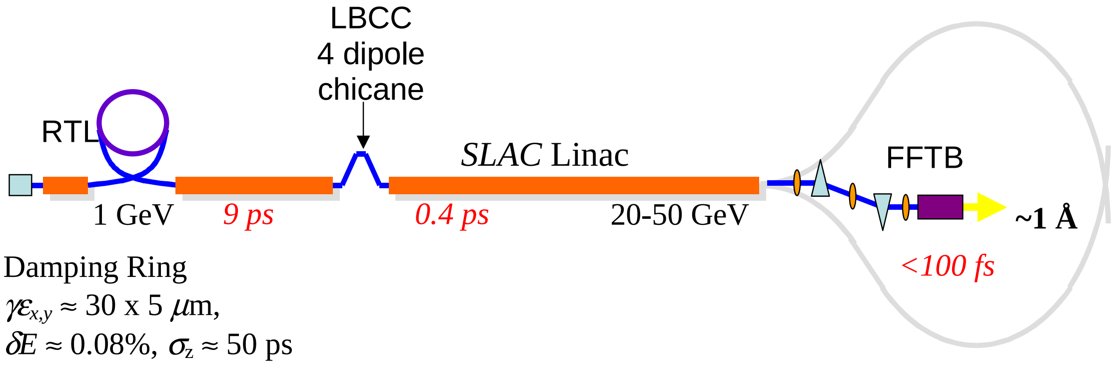

Figure 1: The bunch from the damping ring is compressed in 3 stages, starting with the RTL, followed by the linac bunch compressor chicane (LBCC) and finally in the FFTB beamline.

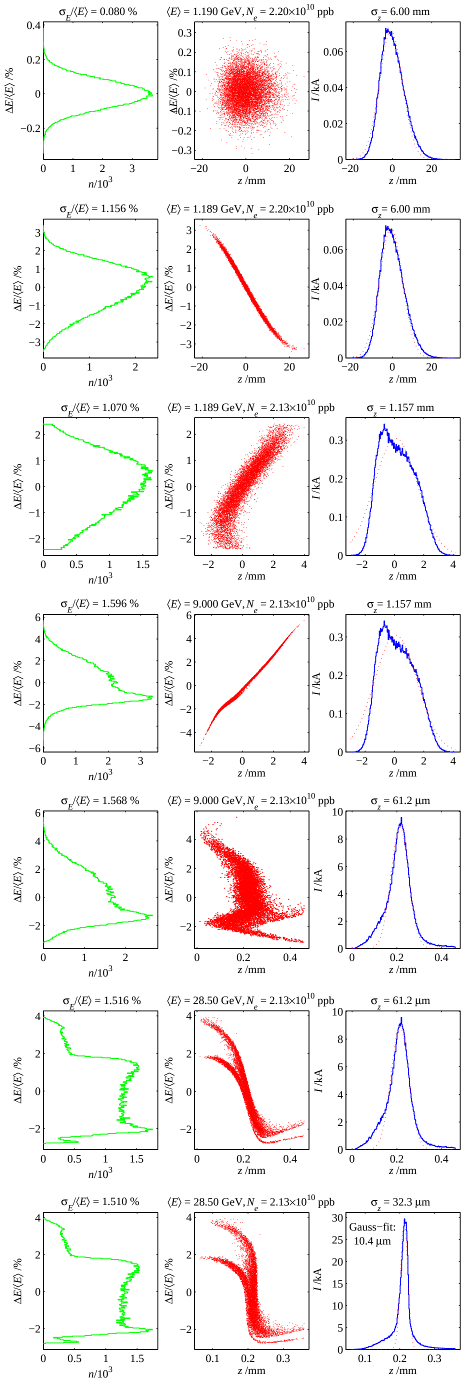

Figure 2: Longitudinal phase space progression through linac (*row*-1: DR exit, *row*-2: after RTL rf, *row*-3: after RTL bends, *row*-4: at chicane entrance, *row*-5: after chicane, *row*-6: at linac end, *row*-7: after FFTB bends).

The short, 50 µm bunch generates strong longitudinal wakefields in the remaining 2 km of the linac which in turn produce a new energy chirp on the bunch, shown in figure 2, row 6. The final non-isochronous "dog-leg" bend into the final focus test beam line (FFTB), where the undulator is housed, results in a 3rd stage of compression down to 12 µm rms bunch length.

The 1.5% final relative energy spread in the beam prevents SASE operation in an undulator. However, the 30 kA peak current, when passed through a short undulator, produces spontaneous radiation with a peak brightness that exceeds that of any existing storage ring x-ray source.

2.1 *Spontaneous X-ray production*

A pair of 2.5 m long insertion devices, Wiggler "A", on loan from the Argonne Advanced Photon Source, will generate x-rays with a peak brightness of $4.0\text{x}10^{24}$ ph/s/mm$^{2/}$mr$^{2/}$0.1%bw at its fundamental wavelength of 1.5 Å and with an output of $2.9\text{x}10^{7}$ photons/0.1% b.w. (all angles) per pulse.

With a peak radiation power of 26.9 GW and a power density of 4.4×10^{13} W/cm^2 (in a 200:1 focus in 1% b.w.) we can perform radiation damage tests at the SPPS for the LCLS x-ray optics.

3. Ultra-Short Bunch Length Diagnostics

Beam tuning and feedback control require reliable measurements of bunch length. The nature of the pulse-to-pulse jitter dictates that this should be a single shot measurement. Both the electron bunch profile and the temporal profile of the radiation from the undulator need to be measured independently in the LCLS since the SASE process is sensitive to spikes in the electron distribution.

In the SPPS a relative measurement of the rms electron bunch length can be performed on a single shot basis by monitoring the CSR radiation power generated, for example, at the chicane bend. When the bunch length becomes shorter than the wavelength of the synchrotron radiation the emission becomes coherent, as shown in spectrum calculated in figure 3. Although this coherence can cause

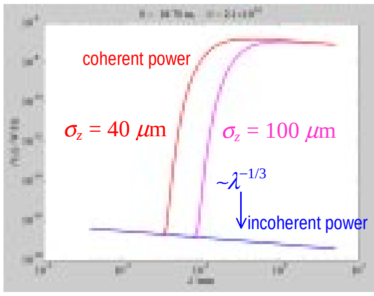

Figure 3: CSR power spectrum for two different bunch lengths in the chicane bend of the SPPS.

troublesome emittance growth and lead to micro-bunching instabilities, the extreme sensitivity to bunch length, seen in figure 3, makes it a powerful diagnostic. A 3 THz bandpass filter, centered at 4.5 THz, corresponding to the nominal bunch length, coupled to a photon detector (or bolometer) will detect a relative change of 10^4 in power for a factor of 3 change in bunch length.

All mechanisms that produce radiation from the bunch also generate coherent THz power when the bunch is shorter than the emission wavelength. Coherent Diffraction Radiation (CDR) and Coherent Transition Radiation (CTR) will be measured upstream of the SPPS undulator to determine how well the bunch length can be monitored

3.1 Bunch profiling

Reconstruction of the intensity profile of the bunch can be made from the coherency of the radiation. Auto-correlation techniques using interferometry, for example, measure the square of the magnitude of the bunch radiation, but do not preserve phase and timing information.

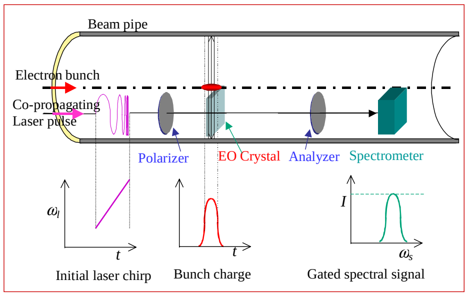

Figure 4: Pump probe measurement of electron bunch length with a chirped laser pulse and an electro-optic crystal.

The most promising technique for full reconstruction of the bunch profile uses an electro-optic (EO) crystal to detect the free-space THz radiation from a bunch[3]. An EO crystal is placed in close proximity to the beam path, where there is no dispersive propagation medium to cause loss of phase information. A chirped laser pulse probes the change in birefringence induced in the crystal by the electric field of the bunch, as shown in figure 4. A Ti:sapphire laser used for x-ray pump probe experiments at SPPS should have ample spare power at 800 nm to allow some of it to be coupled to an EO bunch length measurement in the FFTB.

The SLAC linac has been recently equipped with an RF transverse deflecting structure[4] for high resolution bunch profile measurements. A 50 μm bunch length resolution has been demonstrated with 25 MW of RF deflecting power on 28 GeV test beams in the linac. The measurement is invasive but the device is configured for “pulse stealing” at 1 Hz to minimize impact.

The bunch length measurements also yield bunch timing information with similar precision. This will provide important evaluation of RF phase and amplitude jitter for the LCLS linac.

4. References

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