

Femtosecond Width X-ray Generation with the SLAC Linac and the FFTB Beamline*

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We describe a new Sub-Picosecond Photon Source (SPPS) based on proposal to generate 30 GeV bunches as short as 30 fs rms with the SLAC linac. The bunch is compressed in three stages, starting with the existing ring-to-linac compressor. A second stage of compression will be added in the form of a simple magnetic chicane installed at the 9-GeV location in the linac. The short bunch then generates a strong wakefield in the linac which follows the chicane. This wake provides a large correlated energy spread which allows a third stage of compression in the bends of the existing Final Focus Test Beam (FFTB) beamline. A proposed 10 m long undulator in the FFTB can deliver $\sim 10^8$ 1.5 Å photons per pulse in a 0.1% bandwidth with a peak brightness of $\sim 10^{25}$ photons/sec/mm²/mrad²/0.1% BW, in a pulse width of ~ 80 fs FWHM. The short electron bunches with peak currents as high as 30 kA are also ideal for plasma and wakefield studies as well as providing abundant R&D possibilities for verifying short bunch behavior in the future Linac Coherent Light Source (LCLS).

Introduction

The SLAC linac provides a unique opportunity to provide exceptionally high peak current electron bunches that are ideal for the generation of hard X-ray radiation using an undulator. Ultra-short electron bunches are of equal interest to high-energy physics and advanced accelerator research. The proposal described here uses test pulses in the linac in a pulse-sharing mode while the linac continues to function as an electron-positron injector for the PEP II storage rings. The proposed Sub-Picosecond Photon Source (SPPS) differs considerably from conventional storage ring light sources since it is a single-pass source with a relatively low repetition rate of around 10 Hz. This interleaving of pulses with the routine operation of the linac provides a fast, inexpensive way to begin experiments with a new generation of sub-picosecond, hard X-ray sources. The electron beam is generated at a dc photocathode gun after which it passes through a damping ring, which determines its final emittance. This emittance is not small enough for the self-amplified spontaneous emission (SASE) process, so only spontaneous radiation is generated by the undulator. Without the SASE process the brightness and coherence properties fall well short of the proposed Linac Coherent Light Source (LCLS) project¹. However, the peak brightness of the proposed SPPS represents a formidable step in going from

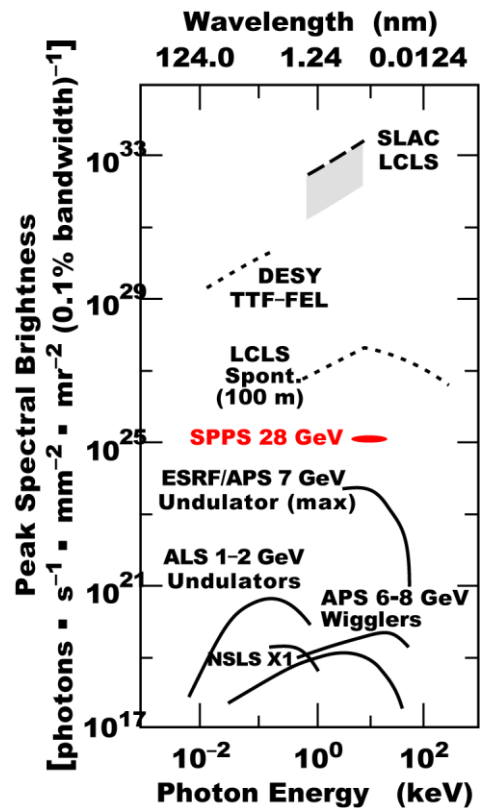


Figure 1. Peak brightness of the SPPS compared to other facilities

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conventional sources towards the LCLS, as shown in Figure 1.

Since the SPPS electron beam does not have to satisfy the low emittance requirements for SASE operation it becomes possible to compress the bunch harder in longitudinal phase space without excessively diluting the initially larger transverse phase space of the beam. Collective effects in the electron beam are also less of a limitation so that higher bunch charges can be used for non-SASE operation. With 2.2×10^{10} electrons the peak current in the compressed bunch approaches 30 kAmp. The electron bunch compression will be done in three stages, starting with the existing Ring To Linac (RTL) compressor² at the exit of the damping rings. A second stage of compression requires the addition of a new magnetic chicane to the linac at the 9 GeV location, as shown in Figure 2. The third stage of compression occurs in the chicane bend of the FFTB beamline.

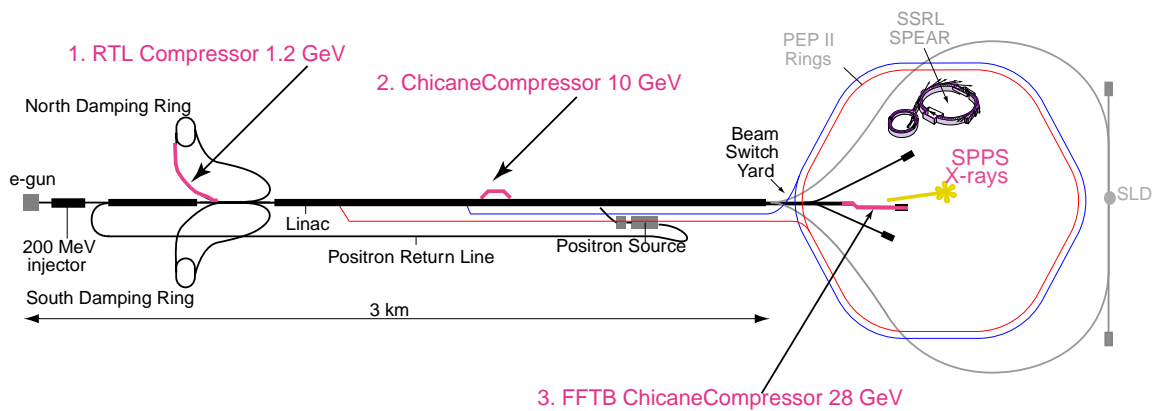


Figure 2. Layout of the SLAC accelerators showing the 3-stage bunch compression for the SPPS.

The undulator will be located in the FFTB tunnel and is limited to about 10 m in length in order to fit within existing beamline components. An X-ray diffracting element will deflect the photon beam out of the FFTB tunnel to an experimental area. The planned experimental area can house a variety of experiments that make use of the extremely short time structure of the X-ray pulse and its high peak brightness. In an alternative mode of operation, based on the introduction of a correlated longitudinal energy chirp in a partially compressed linac bunch, temporal slicing of the emitted pulse with a crystal or multilayer can produce pulses of similar peak brightness and substantially shorter duration.

The short pulse electron beam is also of great interest for plasma wakefield acceleration³ and other advanced accelerator studies⁴. Such experiments can also be performed within the FFTB tunnel, downstream of the undulator.

The present proposal for generating radiation with short bunches draws from several earlier ideas, starting with the idea to use an undulator at the end of the linac with the existing uncompressed beam⁵. After the successful operation of the RTL bunch compressor for the Stanford Linear Collider (SLC) several proposals emerged to add further compression. These included a 10 GeV beamline bypass⁶, a proposal to use the SLC arcs as a compressor⁷, and a proposal for an LCLS style chicane in the linac⁸. Simplified versions of the LCLS in a

minimum startup configuration⁹ have also been considered. A proposal to use the FFTB beamline as a weak compressor¹⁰, when combined with the idea to use an LCLS style chicane in the linac, gave rise to the present concept for generating ultra-short bunches, described here.

Electron Beam Characteristics

The electron beam parameters are largely governed by the boundary conditions of supplying beam to the SPPS parasitically to PEP II operation. The PEP II injection bunches start at the gun and pass through the damping rings and are further accelerated in the high-energy linac. The positron and electron bunches for PEP II are extracted from the linac at the ~ 3 GeV and ~ 9 GeV locations respectively into bypass beamlines. A third electron bunch is accelerated to the ~ 30 GeV location of the linac where it is extracted onto the positron production target. Beyond this extraction point the last one third of the accelerating structures of the linac remain unpowered. A fourth, “test beam” with a 10 Hz repetition rate can be accelerated to the end of the linac, between PEP II injection cycles, into the FFTB beamline with the nominal energy of ~ 30 GeV. The damping rings which operate with a 16.6 ms store time determine the initial transverse emittance, which is typically $\gamma\epsilon_{x,y} \approx 35 \times 5$ microns.

The damping ring bunch length is typically 6 mm at extraction before passing through the Ring-to Linac (RTL) beamline where it can be compressed down to ~ 0.5 mm (or 1.6 ps) rms. The RTL compressor uses a 2.1 m long section of S-band accelerating structure phased at the zero crossing of the RF. An RF amplitude of ~ 34 MV is required to fully compress the beam, given an $R_{56} \approx 0.6$ m generated by the bends in the RTL beamline. The idealized compression process is shown schematically in Figure 3.

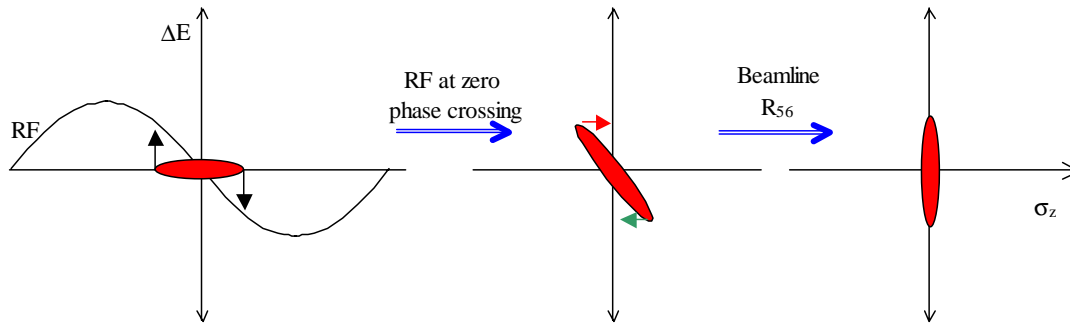


Figure 3. Schematic of ideal bunch compression where the bunch is given a correlated energy spread from head to tail followed by transport through a dispersive section whose path length varies with energy (as in Figure 4).

In order to get to sub-picosecond bunch lengths a second compression stage is required. The limit as to how short a bunch can be achieved is set by the conservation of longitudinal emittance of the beam. The ratio of the product of the initial bunch length, σ_{zDR} , and energy spread, $\sigma_{\delta DR}$, and initial energy, E_{DR} , to the product of the final bunch length, σ_z , and energy spread, σ_δ , and final energy, E_p is constant. The final bunch length will be approximately

$$\sigma_z = \frac{E_{\text{DR}}}{E_f} \frac{\sigma_{\delta_{\text{DR}}} \sigma_{z_{\text{DR}}}}{\sigma_{\delta}} \quad (1)$$

Accordingly, the second bunch compression should be done at the maximum beam energy to achieve minimum bunch length were it not for the deleterious emittance growth effects in the bunch compression process that increase rapidly with energy.

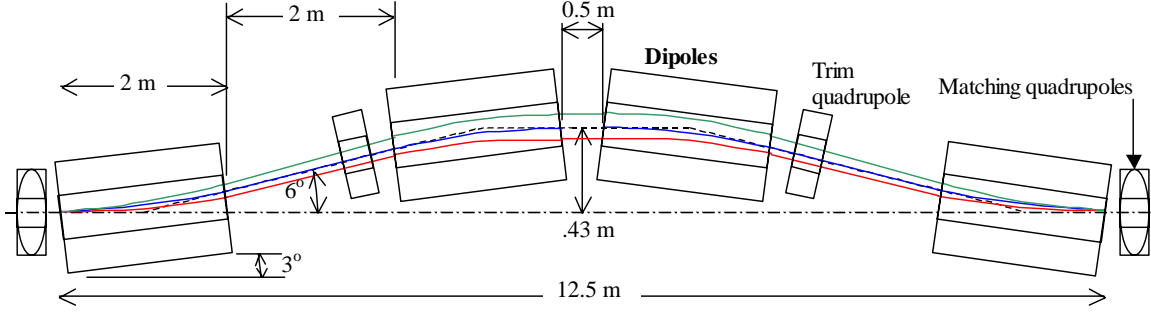


Figure 4. Layout of the magnetic chicane located at the 9 GeV location of the linac.

The second bunch compressor takes the form of a magnetic chicane using a simple arrangement of four dipoles to introduce a dispersive path length difference (R_{56}) in the linac. The compressor, shown in Figure 4, replicates the design used in the LCLS bunch compression scheme¹. The location of the chicane in the linac is a compromise between increasing emittance growth and decreasing bunch length. For practical purposes of maintaining compatibility with PEP II operation the chicane will be located just downstream of the beam extraction locations for the PEP II bypass lines. The beam energy at this location is approximately 9 GeV and the correlated energy spread of 1.6% in the bunch is introduced by accelerating at -20° from crest in the linac sections from the damping ring to the chicane, as shown in Figure 5d. This results in a bunch length of approximately 50 μm , or 165 fs rms, Figure 5e.

The applied RF accelerating voltage is not the only factor effecting the energy distribution along the bunch. At the high peak currents considered here the longitudinal wakefield generated by the bunch in the accelerating structure has a strong influence on the final energy distribution. This is best seen by numerical tracking of individual particles through the accelerator using a calculated wake potential for a point charge ref. The ideal bunch compression described in equation (1) is only valid if the process remains linear, which is not necessarily the case for strong wakefields. Through simulation studies it is found that this can be alleviated by shaping the initial charge distribution in the bunch by over compressing¹¹ the bunch in the first RTL compressor, Figure 5c. Using a realistic distribution for the bunch extracted from the damping ring¹² it is found that a 42 MV RF amplitude giving a 1.2 mm rms bunch length results in the best linear energy distribution along the bunch at the entrance to the chicane compressor at 9 GeV, as shown in Figure 5d.

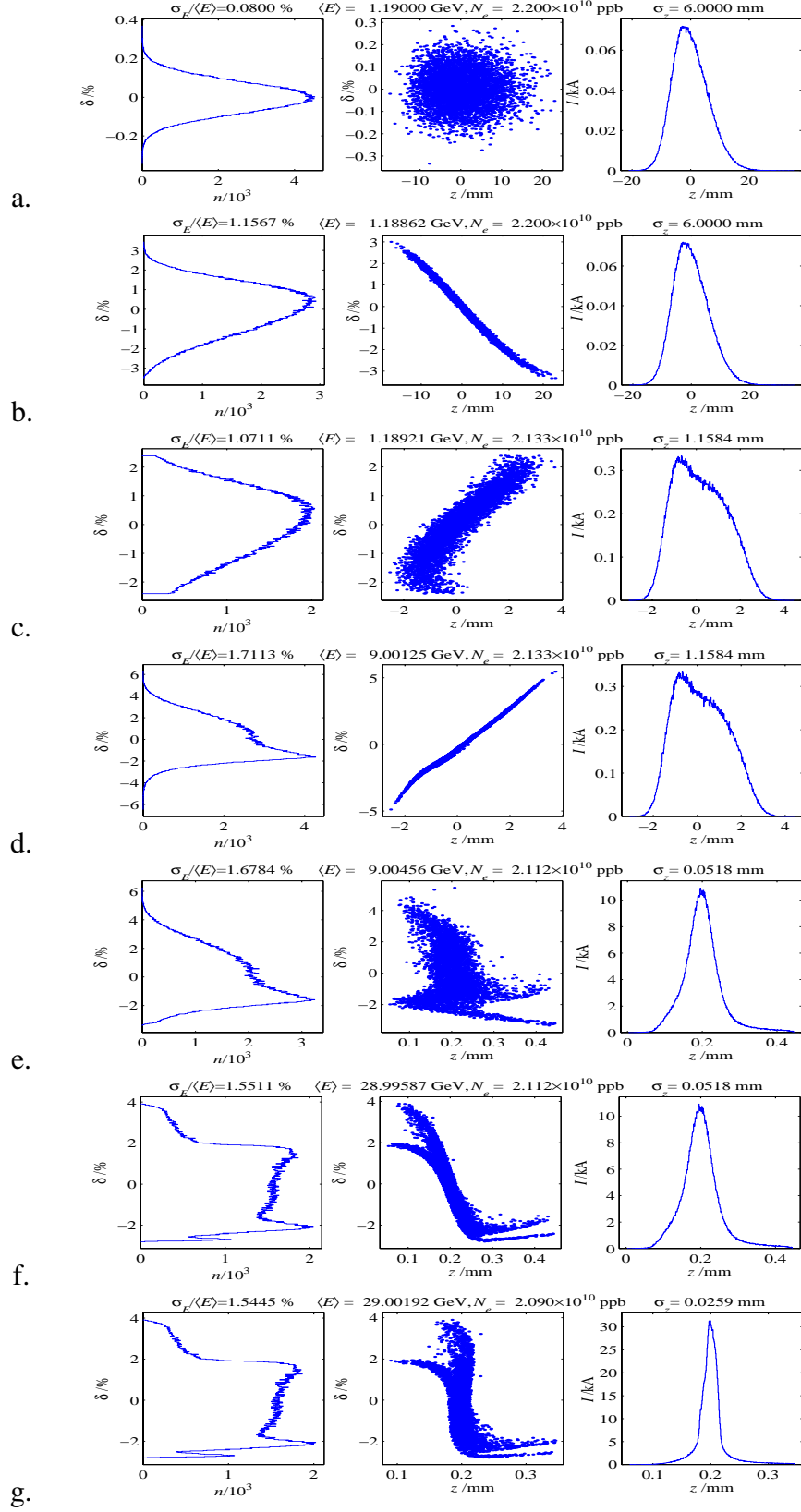


Figure 5 . (Previous page) Compression process at each stage where the energy distribution is shown at left, the center picture is phase space distribution and the longitudinal distribution is shown at right: a. At damping ring extraction, b. after RTL RF, c. after RTL bends, d. at 9 GeV prior to chicane, e. after chicane, f. after linac at FFTB entrance, and g. after FFTB bends. Bunch head toward $z < 0$.

At the exit to the chicane the bunch is compressed to 50 μm rms and generates even stronger wakefields in the remainder of the linac. This wakefield generates in turn a new energy correlation along the bunch, Figure 5f, which makes possible a third compression in the FFTB. On the basis of equation (1) the higher energy of 28 GeV attained at the end of the linac predicts a shorter bunch. A practical limit to the final compression is imposed by the finite energy aperture of the beam line which sets an upper limit of 1.5% FWHM on the allowable energy spread of the beam.

The existing FFTB beamline generates a small R_{56} term in the small, dog-leg bend, which is adequate for the final bunch rotation from 50 μm to 12 μm . The final compressed pulse, shown in Figure 5g, has a FWHM of 80 fs has a peak current of 30 kAmps. The electron beam properties are summarized in Table 1.

Table 1 Summary of electron beam parameters

Parameter	Symbol	Value	Unit
Bunch population	N	2.2	10^{10}
Damping Ring Energy	E_{DR}	1.19	GeV
Damping ring bunch length (rms)	σ_{zDR}	6.0	Mm
Damping ring energy spread (rms)	$\sigma_{\delta DR}$	0.08	%
Final normalized transverse emittance	$\gamma\epsilon_{x,y}$	50 ± 10	μm
Bunch length after stage 1 (rms)	σ_{z1}	1.2	mm
Bunch length after stage 2 (rms)	σ_{z2}	50	μm
Bunch length after stage 3 (rms)	σ_{z3}	12	μm
Final pulse width, FWHM	σ_{zmin}	80	fs
Final relative energy spread (rms)	σ_{δ}	1.5	%
Final energy	E_f	28	GeV
Peak bunch current	I_{pk}	30	kAmp

These parameters have also been verified by 6-D particle tracking using the code *Elegant*⁴³. The processes of incoherent synchrotron radiation (ISR) emittance growth and coherent synchrotron radiation (CSR) emittance growth are taken into account in the chicane bends and found to contribute less than 5% growth. Similarly in the FFTB the bend plane

emittance is expected to grow by ~5% and chromatic emittance growth is expected to add another 2%.

Undulator Radiation

The existing FFTB beamline has an approximately 10 m long drift space just beyond the last beamline dipole where an undulator can be installed. The layout of the FFTB is shown in Figure 6. A vertical bend deflects the electrons down to a dump and provides a convenient separation of the electron and photon beam. A crystal or multilayer reflector deflects the X-rays out of the accelerator housing into a separate hutch for user experiments.

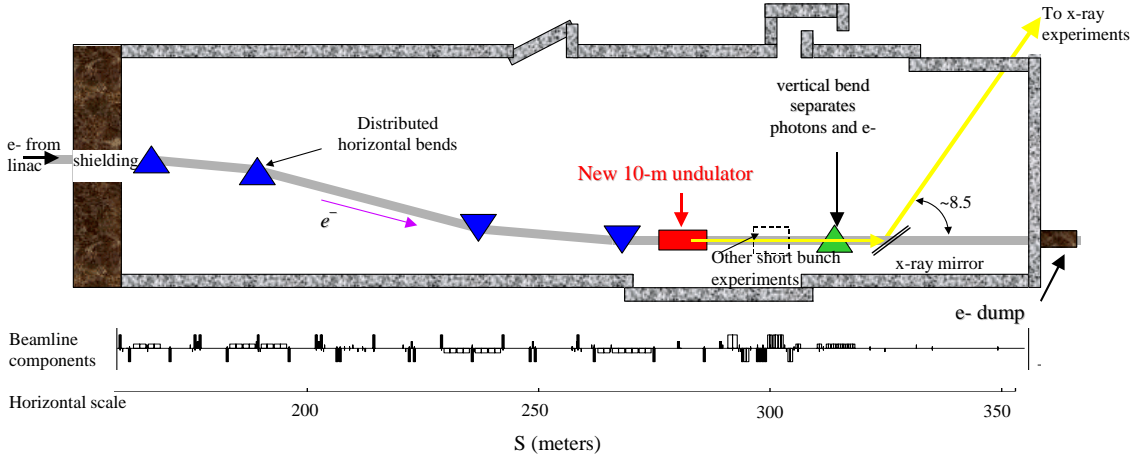


Figure 6 Schematic layout of the FFTB tunnel showing placement of critical components.

Parameter	Value	Units
Undulator period	4.4	cm
Undulator length	10	m
Undulator K	6.25	
Rep rate	10	Hz
Fundamental photon energy	8.3	keV
Peak Brightness	$\sim 1.2 \times 10^{25}$	Ph/s,mm ² ,mr ² ,0.1%BW
Average Brightness	$\sim 1 \times 10^{13}$	Ph/s,mm ² ,mr ² ,0.1%BW
Peak spectral flux	$\sim 3.4 \times 10^{20}$	Ph/s,0.1%BW
Average spectral flux	$\sim 2.7 \times 10^8$	Ph/s,0.1%BW
Output photons/raw pulse	$\sim 2.7 \times 10^7$	Ph/0.1%BW
Coherent output photons/raw pulse	~ 7000	Ph/0.1% BW
Peak Power dens. @200:1 foc., in 1%BW	1.9×10^{14}	W/cm ²

Table 2 Summary of undulator and radiation parameters.

The undulator will be based on a standard asymmetric Halbach hybrid device made of NdFeB magnets and vanadium permendur polepieces, with a gap of 8.5 mm. The intention is to generate radiation close to the 1.5 Å nominal wavelength envisaged for the LCLS. Since

the electron beam energy of the SPPS is almost twice that of the LCLS this implies a rather high undulator parameter of $K=6.25$. As a result, the spectrum from the undulator is rich in higher harmonics, as shown in Figure 7. The parameters for the undulator are summarized in Table 2.

The undulator will be built in 1 m long modules that can be translated into or out of the beamline. The flexibility of the FFTB beamline is thus preserved, and will allow other experiments to be performed using ultra-short electron bunches.

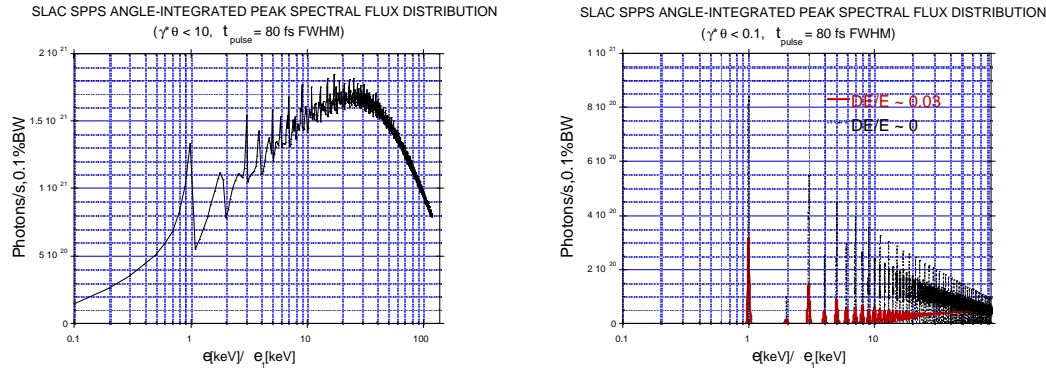


Figure 7 (left) angle-integrated undulator spectrum assuming zero beam energy spread, (right) undulator spectrum integrated over the emittance-defined angular aperture of the fundamental.

Ultrashort Pulse Production by Temporal Slicing

At minimal compression the linac pulses will be ~ 3200 fs FWHM, allowing for a well-defined longitudinal energy chirp of up to $\sim 1.5\%$ to be superimposed by means of rf phase adjustment. This will generate a corresponding energy chirp of $\sim 3\%$ in the X-ray pulse. As shown in Figure 8, diffracting this pulse off a multilayer with a reflectivity bandwidth narrower than the chirp will reflect only that part of the pulse that fulfills the Bragg condition, effectively slicing a proportionately short interval out of the incoming pulse¹⁴.

Based on earlier studies¹⁵, realizable multilayers with bandwidths of $\sim 0.08\%$ and efficiencies of $>50\%$ will be used to generate pulses of down to ~ 80 fs duration. Exploring linac parameter space in concert with the development of even narrower-bandwidth multilayers or crystals to probe the limits of the pulse slicing technique will be one of the basic R&D undertakings of the SPPS.

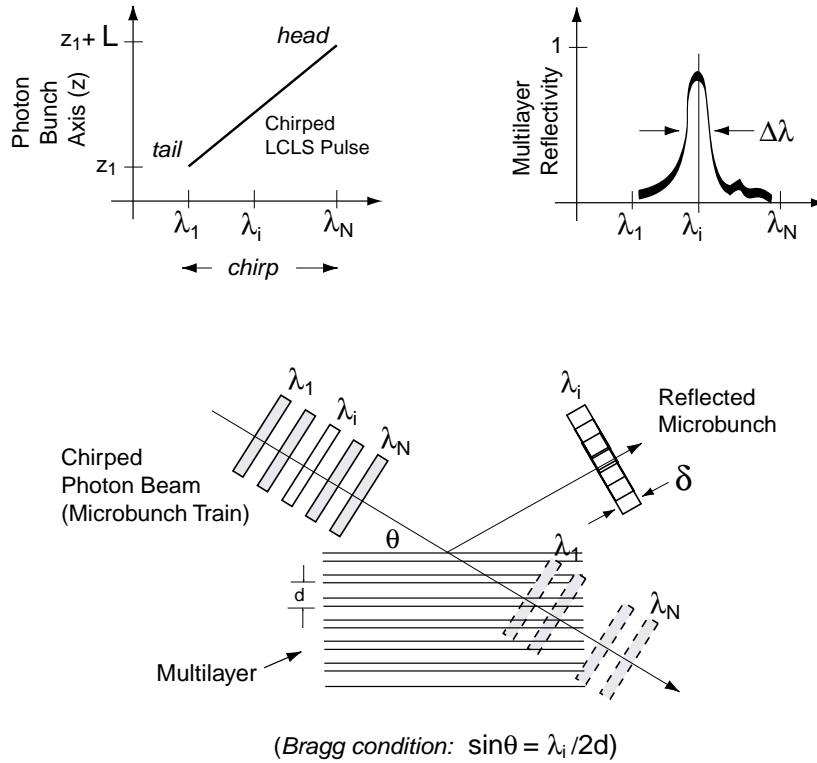


Figure 8 Wavelength dependence of chirped LCLS pulse (top left). Wavelength dependence of multilayer reflectivity (top right). Schematic side view of pulse/multilayer interaction (bottom).

Short Pulse Timing

A notable feature of the SPPS is the sub-picosecond duration of the radiation pulse. This invites the use of SPPS for fast time-resolved experiments. In considering this application, one must consider the expected pulse-to-pulse variations in timing, intensity and pulse width. The bunch compression process in the accelerator is sensitive to RF phase and bunch charge since variations in either of these cause changes in the relative correlated energy spread of the bunch. Random fluctuations in the accelerator RF phase and in the electron gun output will cause a spread in the pulse widths and pulse arrival times as seen by the x-ray experimenter. This spread can be estimated by particle tracking using a large number of randomized initial starting conditions. In Figure 9 the spread is shown resulting from an rms variation of 0.1° S-band in linac phase, a 0.1% rms variation in linac voltage, a 0.5° S-band rms phase variation of the damping ring plus a 2% rms variation in bunch charge. The mean pulse width of 82 fsec has a rms variation of 19 fsec and the pulse arrival time varies by 0.26 ps rms.

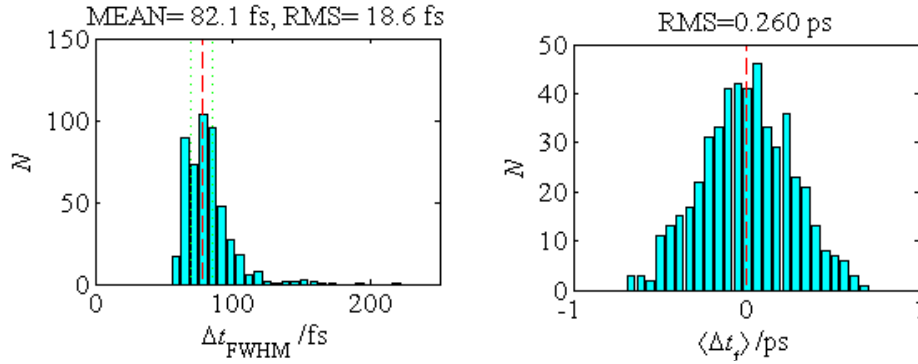


Figure 9 Estimated distribution in pulse width (left) and pulse arrival time (right) arising from phase and intensity variations in the accelerator.

These calculations show that, while the width of the SPPS pulse is well-defined at the 100 fs level, the pulse arrival time fluctuates around the nominal value (defined by a synchronization signal) by a significant fraction of a picosecond. This means that timing experiments requiring synchronization, such as pump-probe experiments in which the SPPS x-ray pulse is the probe and an external laser is the pump, would have their timing resolution limited by the jitter in the pulse arrival time. Any jitter in the firing of the pump laser would of course further limit the experimental resolution.

For pump-probe experiments that can be repeated, there is a way around this limit on the time resolution. The technique involves precisely measuring the actual time interval between pump and probe signal, for every shot. The experimental data can then be reordered *ex post facto*. In this case, the limit on time resolution would be determined by the lengths of the pump and probe pulses, and the precision in measuring the time interval between them.

At the femtosecond level, measuring the time interval between a laser pulse and an x-ray pulse is not an easy task. One possible scheme is shown in Figure 10. This scheme contains two key features: 1) an x-ray/laser coincidence detector with fs resolution, and 2) a geometric trick that translates time intervals into displacements. The x-ray and laser pulses enter the coincidence detector at a large crossing angle. Their transverse dimensions are tailored so that their overlap will occur in a small region of space, whose position depends on the time interval between them. The overlap is detected by a physical process that requires the simultaneous (at the fs level) presence of x-ray and optical radiation. Such a process could be a non-linear interaction with atomic electrons in a gas. Glover, et al.¹⁶, have shown that x-ray photoelectron spectra can be highly modified by the presence of a strong laser beam. Therefore, a position-sensitive detector tuned to the difference in photoelectron spectrum and located at the crossing region of the x-ray and laser pulses, could measure the time interval between them with fs precision.

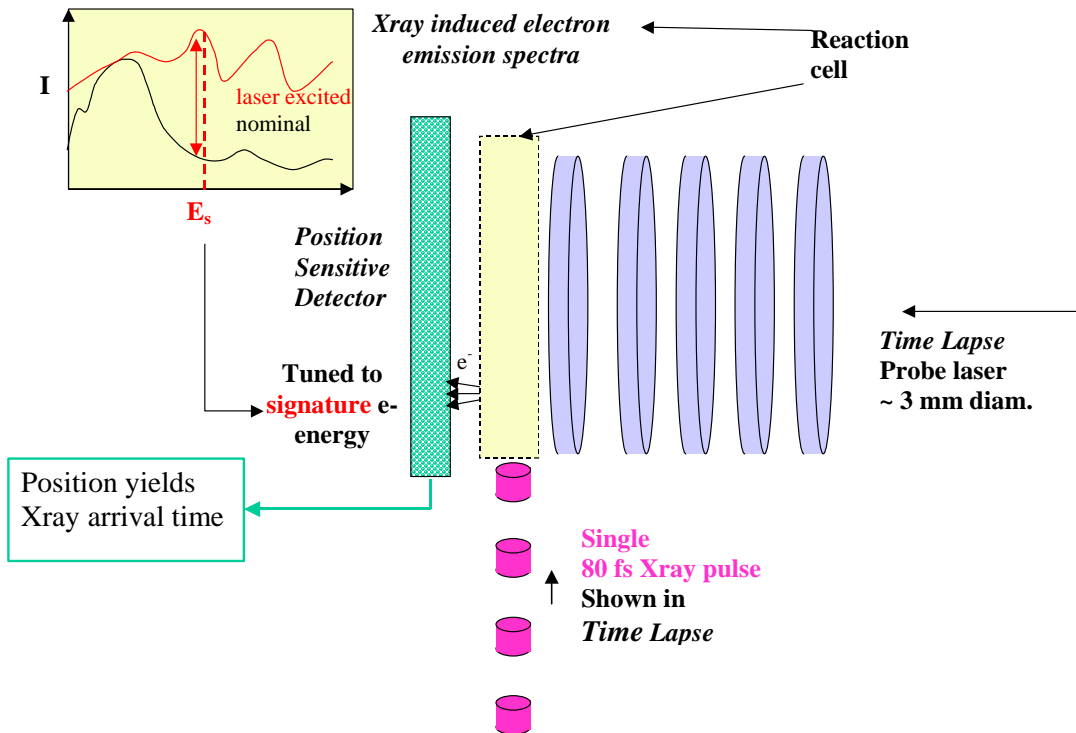


Figure 10 Pump probe principle in which a large diameter short-pulse laser can time the X-ray arrival time through spatial coincidence measurement.

Summary

The opportunity to use the SLAC linac beam with only the relatively simple addition of a new bunch compressor chicane provides a remarkably fast way to embark on a program of femtosecond X-ray science. The SPPS is fully compatible with the operation of PEP II and other SLAC programs, using spare machine cycles in the accelerator. The undulator would be installed in an available space in the FFTB beamline where there is also space for an adjacent X-ray user facility. The brightness and pulse width are significantly better than any existing X-ray sources and would yield exciting new results in many fields. The SPPS proposal represents an intermediate step towards the vast leap in beam parameters for the planned Linac Coherent Light Source. Many of the LCLS techniques for bunch compression, tuning and diagnostics will be tested first hand within the same infrastructure as the future LCLS. As a result we can further expect to strengthen the LCLS design and considerably reduce its commissioning time. The same applies to the experience gained with pump probe experiments and handling of high power X-ray beams.

The ultra-short pulse electron beams are also of considerable interest to the high energy physics program at SLAC. Advanced accelerator research using plasma wakefields expect dramatic effects with shorter bunch lengths. A future laboratory astrophysics experimental program¹⁷ would fully exploit the intense fields associated with the high peak currents of femtosecond pulses.

References

- ¹ *LCLS Design Study Report*, SLAC-R-521 (1998).
- ² K. Bane, "Simulation of Longitudinal Phase Space in the SLC", IEEE Particle Accelerator Conference, San Francisco, 1991, SLAC-PUB-5549.
- ³ P. Muggli et al, "E-157: A Plasma Wake Field Acceleration Experiment", in *LINAC-2000*, 2000.
- ⁴ J. S. T. Ng et al, "Results On Plasma Focusing Of High-Energy Density Electron And Positron Beams" in *LINAC-2000*, 2000.
- ⁵ P. H. Fuoss, Nucl. Inst. and Methods **A264**, p. 497-501 (1988).
- ⁶ J. Seeman, R. Holtzapple, "An 'NLC-Style' Short Bunch Length Compressor in the SLAC Linac", SLAC-PUB-6201 (1993).
- ⁷ P. Emma, J. Frisch, "A Proposal for Femtosecond X-ray Generation in the SLC Collider Arcs", SLAC-PUB-8308 (1999).
- ⁸ P. Krejcik, "Parameters for a 30 GeV Undulator Test Facility in the FFTB/LCLS", SLAC-PUB-8806 (2001).
- ⁹ R. Tatchyn, G. Materlik, A. Freund, J. Arthur, Executive Summary, Proceedings of the SLAC/DESY International Workshop on Interactions of Intense Sub-picosecond X-ray Pulses with Matter, Dec. 1998, SLAC-WP-12.
- ¹⁰ P. Raimondi, SLAC, private communication
- ¹¹ F.-J. Decker, R. Holtzapple, T. Raubenheimer, "Over-Compression, a Method to Shape the Longitudinal Bunch Distribution for a Reduced Energy Spread" in *LINAC94*, August 1994.
- ¹² K. Bane, et. al., "High-Intensity Single Bunch Instability Behavior in the New SLC Damping Ring Vacuum Chamber", in *Partide Accel. Conf.*, May 1995.
- ¹³ M. Borland, "A Simple Method for Simulation of Coherent Synchrotron Radiation in a Tracking Code", in *ICAP-2000*, September, 2000 .
- ¹⁴ R. Tatchyn, "Multilayer-Based Radiation Pulse Slicers for Linac Coherent Light Source (LCLS) Applications," (December 22, 2000); LCLS Technical Note 34) LCLS-TN-00-16 .
- ¹⁵ R. Tatchyn, R. Bionta, "Performance studies of a multilayer-based radiation pulse slicer for Linac Coherent Light Source (LCLS) applications, SPIE Proceedings 4143, 89(2001).
- ¹⁶ Glover et al, Phys. Rev. Lett. **76**, p. 2468 (1996).

¹⁷ P. Chen, “Laboratory Astrophysics using Intense Particle and Photon Beams”, these proceedings.