A letter of intent to

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entitled:

"Enhanced SASE techniques for scientific application at the LCLS"

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Motivation for application of the Enhanced SASE (ESASE) technique at the LCLS

This is a proposal to demonstrate and implement the ESASE technique at the LCLS for important experiments in both scientific applications and the SASE process itself. Many scientific experiments at the LCLS will require refined synchronization of the x-ray output pulse with pulses used to produce excitations in samples. The recently described ESASE technique offers several key advantages over the normal SASE process: synchronization of the x-ray pulse with an optical laser, increased peak x-ray power, control of the x-ray pulse temporal structure, and reduced saturation length of the radiating undulator [1]. The proposed scheme involves enhancing electron bunch peak current in a laser-driven inverse FEL process by interacting the electron bunch with the high field of a laser in a few period wiggler magnet, resulting in micro-bunching of the electrons with a period equal to that of the modulating laser. With conventional laser and accelerator components, the duration of each micro-bunch may be of order 100 attoseconds, and the peak current enhancement a factor of several. These ultrashort micro-bunches radiate via the SASE process in the undulator, resulting in hard x-ray micro-pulses of duration ~100 attosecond. The enhanced peak current results in both greater peak x-ray output, and gain saturation in a shorter length of undulator. Since the micro-bunching is imprinted by an optical laser, the temporal structure of the x-ray pulse is locked to the optical laser, allowing synchronization of the x-ray pulses with the optical laser system. The number and spacing of the micro-pulses is determined by the modulating laser parameters, and a train of such micro-pulses is formed, dependent on the laser pulse duration. Peak powers of 10^{11} W per micro-pulse may be achieved with an optimized system. The duty cycle within the macro-pulse, dependent on modulating laser parameters, is approximately 30-60.

Application of the ESASE scheme at the LCLS may enable critical experiments employing several experimental techniques, including:

- Synchronized pump-probe experiments with ~10 fs resolution using a macro-pulse of duration 10-100 fs
- Synchronized pump-probe experiments with sub-femtosecond resolution using the micro-structure of the pulse that contains a train of x-ray pulses ~100 attosecond duration and separated by the modulating laser period
- Single-shot x-ray diffraction experiments on molecules with controlled and synchronized x-ray pulses of ~100 attosecond duration

In addition, the ESASE technique offers capabilities for exploration of the physics of the FEL process, and provides the potential for different operating conditions, by manipulation of the electron beam parameters. For example, use of the ESASE technique could allow a reduction in electron beam peak current from the photocathode source, easing operational considerations and improving the emittance of the electron beam.

For a proof-of-principle experiment, modifications to the LCLS would be minimal. A modulating laser system would be required, and an appropriately configured wiggler magnet installed in a low-energy section of the accelerator, at 3 GeV beam energy. Together these components introduce an energy modulation in the LCLS electron bunch. The laser could be a Ti:sapphire system delivering approximately 3 GW peak power (150 μJ in 50 fs) at 10-120 Hz, and the wiggler a 16 cm period device with K-value 26 (peak magnetic field 1.7 T). The wiggler design is standard, with suitable devices already operational in storage rings such as the ALS at LBNL. Following acceleration to 14 GeV, and upstream of the x-ray undulator, control of the time-of-flight parameter, R_{56} in the electron beam transport transforms the induced energy modulation into spatial modulation. The x-ray undulator is unchanged in this scenario. We note a significant benefit may be afforded by the concomitant relaxation of the electron beam emittance requirement – even with the x-ray undulator parameters unchanged, the electron beam emittance may be increased by a factor of approximately two and still reach saturation in the normal LCLS undulator length.

Initial implementation of the ESASE technique at the LCLS

Here we describe the proposed technique, which we call Enhanced SASE or ESASE. There are many possibilities for future developments allowing optimization of parameters, and requiring additional equipment and modifications to the LCLS. We postpone development of these concepts, briefly revisiting them in a following section.

A detailed treatment of the ESASE scheme is given in [1], here an overview of the proposed initial implementation at LCLS is given. Figure 1 shows a schematic of the ESASE scheme. To the left of the figure the electron beam is accelerated to 3 GeV in the SLAC linac, and then it enters a wiggler magnet. At the same time a short ~ 50 fs optical laser pulse enters the wiggler and co-propagates through the wiggler with the electron bunch, at a small angle. Alternatively, it is possible to position the wiggler off-line in the middle of a magnetic chicane and propagate the laser co-linearly with the electron bunch. The wiggler period and wiggler parameter are chosen such that there is a resonant interaction between the electrons and the laser pulse propagating through the wiggler.

The laser pulse overlaps only a short longitudinal section of the electron beam in the wiggler. For convenience we will call this section the *working section* (WS). Electrons in the WS interact with the laser field in the wiggler and emerge from the wiggler with an energy modulation. The peak power of the laser field is chosen such that the amplitude of energy modulation significantly exceeds the uncorellated rms energy spread of the electrons. In the next step, electrons re-enter the linear accelerator and gain energy to reach a final average energy of 14 GeV. Because of the ultra-relativistic electron energies**, t**his acceleration does not affect the energy modulation introduced in the wiggler and there is not significant relative longitudinal motion of electrons.

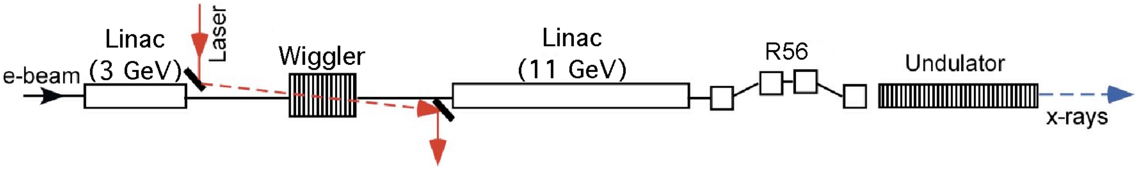

Figure 1. *Schematic of the ESASE x-ray FEL at the LCLS (not to scale).*

After acceleration to the final energy of 14 GeV, the electron beam passes through a beam transport with time-of-flight parameter R_{56}. As previously mentioned, there is negligible relative longitudinal motion of the electrons during acceleration, but we consider this effect in the transport line with time-of-flight parameter R_{56}, where higher energy electrons in the WS travel a shorter path and lower energy electrons in the WS travel a longer path. This produces micro-bunching of the electrons and enhancement of the electron peak current. As an illustration, Figure 2 shows the longitudinal phase space of the electrons following the micro-bunching in a short segment of the WS equal to one laser wavelength. The existing transport line magnets may be adjusted to control the R_{56} parameter to produce the optimal bunching with the most upright longitudinal phase space condition as shown in Figure 2.

Each micro-bunch appears as a "pancake" charge distribution in the laboratory frame, with a very short duration, while the entire WS looks like a sequence of such pancakes separated from each other by the modulating laser wavelength. We calculate with the nominal LCLS electron beam parameters and laser and wiggler described above, the micro-bunch duration would be ~160 attosecond FWHM, and the peak current ~ 20 kA. The increase of the peak current is accompanied by a corresponding increase in the energy spread of electrons. Figure 3 shows the normalized peak current within a micro-bunch, with respect to the unperturbed bunch current I_0 outside the WS.

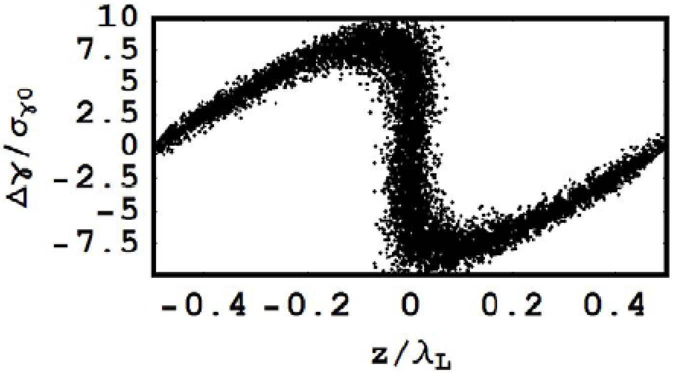

Figure 2. *Longitudinal phase space after microbunching normalized to laser wavelength (one period is shown). Only a part of the WS equivalent to one optical cycle at the laser wavelength is shown.*

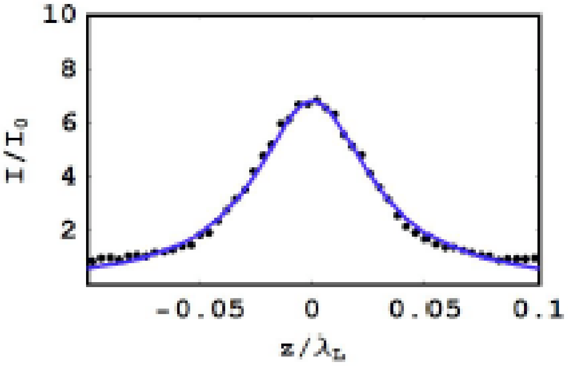

Figure 3. *Normalized peak current versus distance normalized to laser wavelength within the micro-bunch. Dots show computer simulation results while the solid line was obtained with an analytical analysis [1].*

Finally, the electron beam with enhanced peak current micro-bunches within the WS goes through the LCLS x-ray undulator where the micro-bunched electrons produce radiation at the x-ray wavelength via standard SASE. The electrons outside of the WS also produce SASE, but with a much longer gain length because of the smaller peak current. The amplitude gain length for a SASE process can be expressed in terms of number of undulator periods and as a function of the electron beam slice emittance, energy spread, peak current, and beta-function in the undulator [2]. Thus, the amplitude gain length varies with position along the micro-bunches, and we find the minimum gain length at the peak of the enhanced current in the micro-bunches.

Figure 4 shows the x-ray pulse at wavelength 1.5 Å from a micro-bunch, with a calculated duration of 65 attosecond FWHM. The peak power within this pulse at saturation is approximately 100 GW, and the average power within the 50 fs WS is reduced by a duty factor ~ 40. We note that this calculation is for nominal LCLS electron beam parameters, and an optimized lattice in the x-ray undulator, with ß-function reduced to ~6 m. For the initial experiments, electron bunch parameters may be adjusted such that there will be minimal modifications required in the x-ray undulator. Detailed accelerator physics studies in collaboration with SLAC will optimize performance of the proof-of-principle experiment for modest cost and low technical risk.

The output radiation from the undulator will appear as a set of ultrafast x-ray micro-pulses separated from each other by the modulating laser period. Each micro-pulse is nearly temporally coherent and approximately Fourier transform limited [3]. Since the x-ray radiation builds up from noise for each micro-pulse, the phase between micro-pulses is random and there is no temporal coherence along the train of micro-pulses.

Radiation coming from electrons outside the WS is much reduced in intensity due to the longer gain length at significantly lower peak current. Thus, there is an absolute synchronization between the chain of the output x-ray micro-pulses and the laser pulse since only electrons from the WS, *i.e.* from the region that experienced interaction with the laser, produce intense x-ray output. This feature can be used in pump-probe

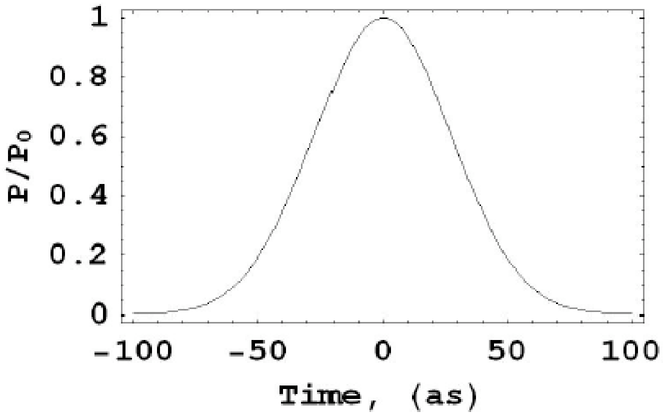

Figure 4. *1.5 Å radiation pulse from a single micro-bunch. In this optimized case, with modifications to the lattice parameters in the x-ray undulator, the peak power is approximately 230 GW in the 65 attosecond FWHM pulse.*

experiments with the x-ray pulse being a probe and the modulating laser pulse or other signal derived from the modulating laser pulse being a pump source. Moreover by changing the duration of the laser pulse and adjusting the number of active wiggler periods one can regulate the length of the WS and therefore the duration of the x-ray output. This feature allows the possibility to generate single intense attosecond x-ray pulses, with potential application to single-shot large molecule diffraction imaging.

To analyze the performance of ESASE in the LCLS we propose both electron beam and x-ray beam measurements. Electron beam-based diagnostics include measurement of coherent synchrotron radiation (CSR) from the modulated beam. CSR occurs at wavelengths comparable to the electron bunch length, and can be measured allowing determination of the micro-pulse duration, peak current, and optimal tuning of the bunching systems. Transition radiation techniques, as well as electro-optic detection techniques, may also offer a diagnostic tool to determine bunching in the beam.

Measurement of x-ray power produced at varying distance along the undulator will allow study of the growth of the SASE x-ray signal from noise, determine the FEL gain characteristics, and slippage effects. Details of the temporal structure may be determined using correlation techniques that have been demonstrated for measuring sub-femtosecond pulses (isolated pulses and pulse trains) in the soft x-ray regime [4,5]. These techniques rely on laser modification of the photoelectron wavevector resulting from a single-photon x-ray ionization process. Since they depend on the laser field, they provide a temporal resolution that is a fraction of a laser optical cycle.

Future possibilities for optimized applications of ESASE at the LCLS

The experiment outlined above presents significant benefits to the LCLS experimental program, with minimal and low-cost additions and modifications to the facility. There are additional benefits to be gained from this technique, and here we indicate some optimizations of the scheme to further improve performance. A more detailed description of these suggestions may be found elsewhere [1].

We note that to produce the optimal gain length, the beta-function in the undulator is 6 m, yielding a minimum gain length of 115 undulator periods. The gain length for the unperturbed electrons outside the micro-bunches is approximately 2.5 times longer. The current beta function is approximately 30 m, and some design changes may be required to realize the lower value. Assuming this case, we estimate that the shot-noise induced bunching at 1.5 Å is $3.5\text{x}10^{-4}$, and it takes 7 – 8 amplitude gain lengths for SASE to reach saturation, thus the total undulator length needed for saturation at the peak of intensity of the micro-bunch is approximately 28 m, Figure 5 shows comparison of 1.5 Å output under nominal conditions and using ESASE. This reduced gain length may be employed in a new configuration of the existing undulator, a new undulator, or to allow margin for operations and accelerator physics studies.

In order to produce a single attosecond x-ray pulse we employ interaction of electrons in the wiggler with a few-cycle laser pulse. Laser pulses with 3.8 fs FWHM intensity and stabilized carrier wave phase have been demonstrated [6]. Such a pulse with ~ 0.2 mJ pulse energy (not yet demonstrated) interacting with electrons in the wiggler magnet with just two periods will produce energy modulation shown in Figure 6. Here the central maximum is approximately 1.5 times higher than the two nearest peaks. The difference in amplitude of modulation between central and two adjacent peaks causes the gain length for the smaller peaks to be approximately 14% longer. After 7.3 gain lengths this small difference results in an output signal where the radiation coming from the central peak dominates the radiation coming from a neighboring peak, as shown in Figure 7. A more detailed discussion of the technique may be found in [7].

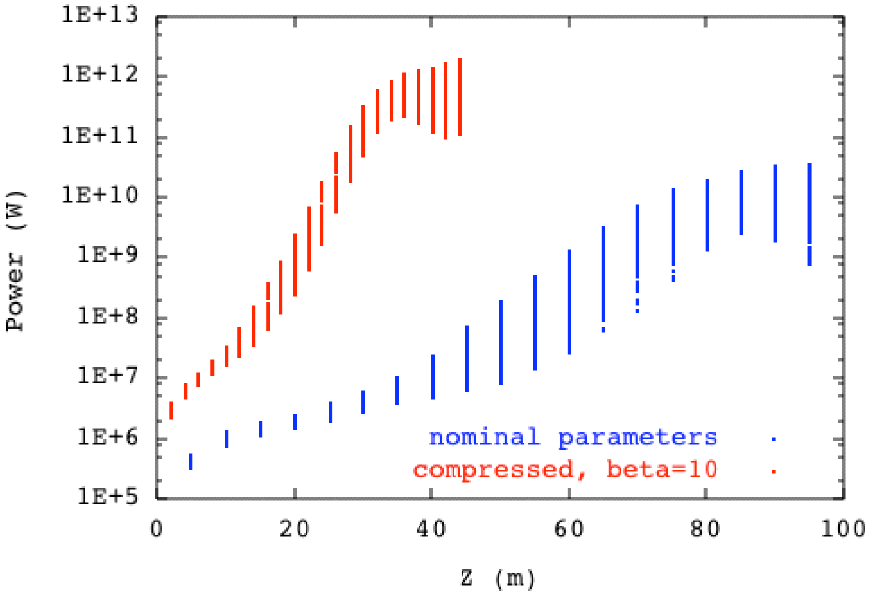

Figure 5. *Peak output power at 1.5Å for nominal LCLS parameters, and using an optimized ESASE technique, plotted as a function of distance along the x-ray undulator. Power from different slices of a bunch is shown, reflected in the spread at each point along the undulator. Calculations using the GENESIS code.*

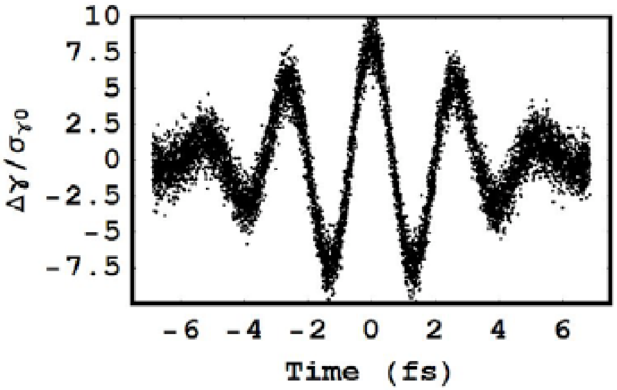

Figure 6. *Energy modulation produced in the interaction with a few-cycle laser pulse.*

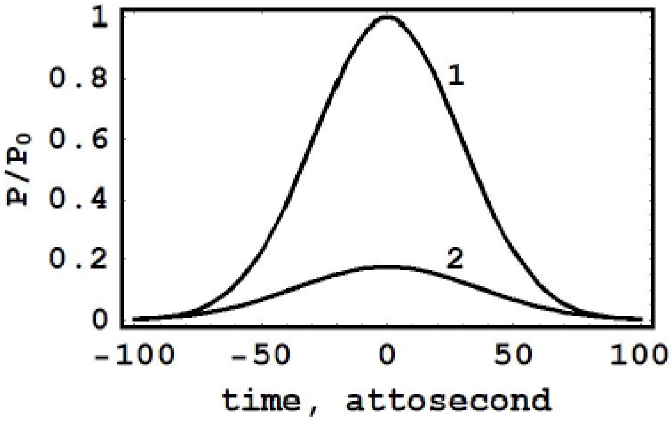

Figure 7. *1.5 Å radiation pulse from a single micro-bunch. Peak power is approximately 230 GW in the 65 attosecond FWHM pulse. 1 is the main pulse from the central peak in modulation shown in Figure 6, and 2 represents the accompanying pulses from the adjacent peaks in Figure 6.*

Accelerator physics applications of enhanced SASE at the LCLS

The ESASE technique offers capabilities to explore the physics of the FEL process, and potential for different operating conditions. By enhancing the electron beam peak current using the ESASE technique, a reduction in electron beam peak current emitted from the photocathode source may be feasible. This reduces a multitude of deleterious collective effects in the electron beam, from space-charge at low energies in the gun and injector, to wakefields in the linac accelerating structures. Reduced charge extracted from the gun generally allows a reduction in beam emittance. Increasing peak current for a given emittance reduces the gain length of the FEL process. Peak current may be adjusted to study and minimize effects of the resistive wall wakefields in the x-ray undulator. Thus, the electron beam properties may be manipulated, improving overall performance, while easing operational demands, and allowing exploration of different electron beam parameters to study the hard x-ray SASE FEL process.

We note that the ESASE technique does not require phase space manipulation and compression of the whole electron bunch in order to achieve controllable, short, synchronized x-ray pulses. Acting on a section of the relatively long bunch alleviates many peak-current dependent problems such as wakefields in the linac accelerating structures. Peak current enhancement does not occur until compression of the modulated WS in the final R_{56} section. The effects of resistive wall wakefields downstream may be studied by varying peak current, beam offset, and macro-pulse duration.

Measurement of x-ray power at varying distance along the undulator will allow study of the growth of the SASE x-ray signal from noise, determine the FEL gain characteristics, and study slippage effects.

References

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Cost estimate

The proposed initial proof-of-principle experiment would be designed to demonstrate significant benefits for the LCLS experimental program, while not providing the most optimal physics conditions and thereby minimize costs. We adjust parameters such that the only major items of additional equipment would be a commercially available Ti:sapphire laser system, and a wiggler magnet of design already produced and in service at existing light sources. For example, there exists a suitable wiggler recently removed from the ALS and possibly available from LBNL for use in this application. There remain details of the scheme to be resolved, such as the impact of installing a wiggler at ~ 3 GeV, these will be addressed in collaboration with SLAC. Much of the effort would involve detailed modelling of the accelerator physics issues. A rough order-of-magnitude estimate is approximately $2M.

50 fs laser system	$500k
Laser opics	$20k
Laser diagnostics	$60k
Laser room infrastructure	$20k
Wiggler	
Transport and installation	$10k
Beamline and vacuum chamber components	$20k
Survey & alignment	$5k
Diagnostics and instrumentation	
Electron beam	$50k
X-ray beam	$50k

Laser engineer	1.0 FTE
Accelerator physicist	3.0 FTE
Diagnostics physicist	1.0 FTE
Mechanical engineer	0.5 FTE
Designer	0.5 FTE

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