

## LETTER OF INTENT FOR LCLS (CATEGORY A) ULTRAFAST X-RAY STUDIES OF STRUCTURAL DYNAMICS IN BIOLOGY, CHEMISTRY, AND PHYSICS

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Atomic and molecular dynamics occur on distance and time scales governed by interatomic distances and vibrational periods. These interatomic distances and forces make X-ray science, with Ångström spatial resolution, and ultrafast laser science, with femtosecond temporal resolution, the optimal experimental tools for studying structural dynamics in all states of matter. While standard X-ray diffraction, scattering, and spectroscopy determine the atomic structure of molecules and femtosecond optical spectroscopy observes the temporal evolution of excited molecules, their successful union has been limited by the inherently long pulse durations of synchrotrons and the low X-ray flux of existing ultrafast laser sources. Linear electron accelerators (linacs) provide an alternative approach to ultrafast hard X-ray generation that circumvents both of these limitations via the self amplification of hard X-ray radiation emitted from a femtosecond electron bunch.

The Linac Coherent Light Source (LCLS) will be the first hard X-ray free electron laser and provide transversely coherent hard X-rays with unprecedented flux and time resolution. These attributes of LCLS have the potential to revolutionize the experimental investigation of structural dynamics with X-ray techniques, by directly following the time evolution of the electron density during the course of a biological, chemical, or physical transformation. This *Letter of Intent* (LOI) will outline a series of experiments with the unifying goal of measuring structural dynamics as a function of length scale in a variety of materials that cover a broad range of scientific disciplines. The many common experimental needs and technical challenges that face these experiments further unite this experimental program. The development such a program is a specific aim of the team of investigators assembled in this program.

### I. Experimental requirements

**Laser system:** For many of the proposed experiments at LCLS, an external laser will be utilized to create a transient state of matter, while an LCLS generated hard X-ray pulse will monitor the time dependent transformation of the prepared state. The controlled, reproducible generation of transient samples is as critical to the success of these experiments, as the generation of ultrafast X-ray pulses. The ability to conduct state of the art optical manipulation of matter while monitoring the outcome of these manipulations with atomic resolution provides the opportunity to understand, and potentially control, the outcome of complex structural transformations with unprecedented detail.

Experiments that couple optical lasers with synchrotron and linac light sources require the laser and the X-ray source to be phase locked to one another. This has been achieved at a variety of time resolved beam lines at third generation light sources developed by many participants in this LOI, as well as the sub-picosecond pulse source (SPPS), an LCLS precursor that uses the SLAC linac to generate femtosecond hard X-ray pulses. Experiments at SPPS have demonstrated that a Ti:sapphire oscillator can be phase locked to the radio frequency signal that accelerates the electron bunches down the SLAC linac with  $\sim 300$  fs rms timing jitter between the laser and the X-ray pulses. Measurements of energy fluctuations in the linac indicate that most of this jitter results from jitter between the RF and the electron bunch, with improvements in the linac for LCLS expected to improve this jitter by at least a factor of two. These experiments at SPPS have also brought to light the presence of slow, thermal drift in the RF signal used to phase lock the laser, and additional drift in the linac-derived triggers used for electro-optical switching of pulses into and out of the Ti:sapphire amplifiers. These effects will need to be minimized with better thermal insulation and cable compensation for optimal laser performance.

For experiments at LCLS to generate an improved understanding of structural dynamics in complex materials, we will need the ability to manipulate a wide variety of materials with ultrafast laser pulses. This requires a flexible ultrafast laser for sample excitation. The ability to cover a large range of the electromagnetic spectrum will be critical. For the purposes of chemistry, biology, and materials science, the laser will need to cover from the near UV into the mid-IR. While the ability to generate vacuum UV radiation and higher frequencies will be of value for the LCLS, the scientific objectives and experimental requirements for generating attosecond soft X-ray radiation differ enough from those of a structural dynamics program that they warrant a separate laser source, if not a separate X-ray end station.

The need for flexibility in the laser frequency requires amplified laser pulses. Commercially available Ti:sapphire mode and phase locked oscillators and chirped pulse regenerative amplifier systems similar to those already employed at SPPS will be sufficient to drive harmonic generation and optical parametric amplification. The tens of  $\mu\text{J}$  per pulse of laser light that can be generated throughout the near UV, visible, and mid-IR with such a system provides sufficient energy to reversibly excite systems in a controllable fashion. Much higher energies, when focused to the expected size of the LCLS X-ray beam, lead to multiphoton absorptions in most systems and therefore cannot be used. Standard laser diagnostics will be needed to monitor the pulse energy, spatial mode profile, pulse duration, and spectrum.

While the excitation pulse energy, duration, and carrier frequency represent the most important control parameters, having the ability to control the relative phases of the broadband laser may also prove valuable. While pulse shaping invokes a limited control over photochemical reactions due to the extremely fast phase relaxation of electronic excitations, the potential still exists for improving quantum yield and reducing undesirable reaction channels, such as multiphoton excitation. The ability to optimize the desired product quantum yield with the laser frequency and time duration has already proven to be a valuable tool in time resolved X-ray crystallography. The ability to shape pulses in a more sophisticated manner will only improve our ability to conduct successful experiments.

**X-ray detectors:** Since the majority of the experiments to be proposed in this LOI will use elastic X-ray scattering to investigate structural dynamics, a large area detector will be essential. Given the very high peak brightness of LCLS, it will need to be an integrating detector with a large dynamic range. Most critically, this large area detector will need to be read-out at 120 Hz, the repetition rate of LCLS. For experiments conducted at less than the LCLS repetition rate, an X-ray shutter that can withstand the high LCLS flux will be needed. It is anticipated that a detector meeting the required specifications will be developed by the LCLS project and we anticipate a close coordination with them in this regard.

**X-ray optics:** Experiments that use only X-rays will need X-ray optics for separating the LCLS beam into multiple beams and then recombining them on the sample. This capability will need to be developed for all time resolved X-ray only experiments at the LCLS and is expected to be a part of the core LCLS project.

**X-ray diagnostics:** Since many of the proposed experiments intend to measure amplitude changes in the diffraction pattern to determine the time dependent structure factors, normalization of the signal is absolutely critical. At a minimum, this requires the shot-to-shot measurement of the integrated X-ray flux and the mode profile, the location of the beam, and the X-ray spectrum. Given the stochastic nature of the self-amplified stimulated emission (SASE) process, we cannot assume that any of these properties will be stable from shot-

to-shot. The most challenging diagnostics, however, will be monitoring the X-ray pulse duration and laser/X-ray relative timing jitter.

**Timing diagnostics:** Significant effort has been made at the SPPS to assess the relative timing jitter of the laser with respect to both the X-ray pulses and the electron bunches. This shot-to-shot jitter has been measured with three separate approaches. First, an electron bunch generated rotation of the laser polarization in an electro-optic crystal has been used to cross-correlate the Ti:sapphire oscillator with the electric field of the electron bunch. Second, an X-ray streak camera has been used to monitor the relative timing of the amplified laser and the X-ray pulses. Third, the time of arrival of the X-ray and laser pulses have also been determined by measuring the time dependent decay in X-ray diffraction efficiency that results from a laser induced ultrafast disordering of a semiconductor crystal. As mentioned earlier, these experiments have determined that the relative timing of the X-ray and laser pulses jitters with an rms of ~300 fs. The simultaneous measurement of the laser melting and electro-optic signals, have also demonstrated that electro-optic monitoring of the electron bunch can be used to collect data from many shots with time resolution better than the timing jitter. These measurements have shown that the electro-optic measurement predicts the relative timing in the laser melting experiment with a standard deviation as small as 60 fs, and generally two to three times better than the actual timing jitter.

While this represents a very promising result, an electron bunch monitor, such as the electro-optic sampling technique, does not provide the full range of information desired for experiments at LCLS. These measurements lack two important pieces of information: they do not measure the temporal profile of the X-ray pulse and they do not measure the jitter between the X-ray peak intensity and the electron bunch profile. For an incoherent source like SPPS, the X-ray bunch timing and intensity will faithfully map the electron bunch timing and current. This will not be the case for the LCLS, where simulations show fluctuations between the electron bunch and the X-ray pulse. While X-ray streak cameras directly measure the X-ray profile, without significant improvements in camera design, the poor time resolution of the experiment will make timing jitter measurements of better than 100 fs very difficult and monitoring of the temporal profile of the X-ray pulse impossible. Reinhard Kiensberger's proposal to cross-correlate the laser with the X-ray pulse via a laser induced shift in the kinetic energy of the X-ray photoelectron energy spectra provides an alternative monitor. This, and all other alternative methods, should be strongly supported initially at LCLS, and the potential for early development of the potential methods at the Tesla Test Facility II soft X-ray FEL at DESY, Hamburg should also be considered.

## II. Scientific Program

Continuous change, rather than static equilibrium, defines most systems of technical, biological, chemical, and environmental significance. The desire to measure and understand with atomic detail the mechanisms by which biological, chemical, or physical transformations occur unites the scientific program outlined in this LOI.

Given sufficient photo-excitation yields, crystallography provides the most powerful tool for measuring the well ordered structures of excited molecules. This approach has been successfully applied in a variety of time resolved crystallography measurements[1-7] and will certainly be a useful approach for experiments at LCLS. Crystallography does not, however, fully describe the influence of photoexcitation. Photoexcitation results in the random distribution of time-evolving defects throughout the crystal. Given the lower concentration of the excited species and the large range of conformations that excited species can sample during relaxation, the coherent diffraction pattern will only contain a partial picture of the excitation process. The diffuse scattering, however, provides access to local structural information that cannot be observed with crystallography.[8,9] The lack of long range order that leads to diffuse scattering also makes the scattering significantly weaker than coherent Bragg diffraction. This has made time resolved applications of diffuse scattering very challenging at third generation synchrotrons. Given that diffuse scattering experiments will greatly benefit from the increased flux of the LCLS, and disordered systems have a dominant presence in chemistry and biology, developing the experimental and theoretical tools necessary for time resolved diffuse scattering should be a priority at the LCLS. A series of experiments designed to establish a multidisciplinary structural dynamics program at the LCLS will now be discussed.

**Structural dynamics in molecular solids:** In previous applications of time resolved crystallography, the individual species observed have been determined to have time independent diffraction patterns, with only the amplitudes of these patterns being time dependent as a result of time dependent populations. Such a picture emerges when the quasi-equilibration of a species within a local free energy minimum occurs much faster than the activated barrier crossing events that further the reaction mechanism. On the femtosecond to many picosecond time scale, such a picture will not apply. Within the Franck-Condon approximation, electronic excitation preserves the ground state nuclear configuration. Consequently, photoexcitation leads to a non-equilibrium nuclear configuration and structural dynamics dictated by the ground state structure and the excited state potential energy surface. The initial goal of this component of the structural dynamics program will be identifying the best means of accessing these structural dynamics. Since the initially excited ensemble will evolve coherently, these motions should be observable both in the coherent diffraction and the incoherent diffuse scattering. The success of this component of the program will depend critically on the development of a shot-to-shot timing jitter monitor, a fast read X-ray area detector, and standard X-ray and laser monitors, as discussed in the experimental section.

Initial studies will focus on simple molecular crystals and solid state materials, where photoexcitation leads to large bond length or angle changes. A series of bimetallic complexes, primarily investigated by Harry Gray and his collaborators, represents an excellent candidate for these experiments.[10-12] These systems consist of weakly bonding Rh<sub>2</sub>, Pt<sub>2</sub>, or Ir<sub>2</sub> bimetallic cores with long ground state metal-metal bond lengths. In the excited state the bond order between the metal atoms increases, leading to a reduction in bond length that has been proposed to exceed an Å for some of crystalline systems.[11,12] These molecular crystals represent an excellent model system for the observation of the local structural dynamics that result from wavepacket dynamics on an excited state potential. Excited state twisted electron transfer in aromatic molecular crystals also represent a model system for study with time resolved X-ray crystallography.[6,7]

The influence of the ground state structure on reaction mechanisms in solid state chemistry represents another area for investigation with small molecule crystals. Attempts to elucidate the topochemical principle have been initiated with time resolved crystallographic studies of the irreversible dimerisation reaction of *p*-formyl-*trans*-cinnamic acid,[13] but the improved time resolution and X-ray flux of LCLS will greatly enhance our ability to understand this principle in greater detail. For these small-molecule crystals, where the density of Bragg peaks is not too great, powder diffraction represents a viable approach to measuring time dependent structure factors. Powder samples make matching the sample thickness to the laser extinction depth easier, and powder diffraction has the significant benefit of monitoring all of reciprocal space with a single sample orientation.

Photoinduced phase transitions in molecular crystals also represent an important area for investigation. Previous studies in the organic charge transfer crystal tetrathiafulvalene-*p*-chloranil, have shown that the structural phase transition occurs with a 500 ps rise time, but the question remains as to how this structural transition nucleates.[14,15] An increase in the diffuse scattering has been observed during the thermal phase transition, but monitoring the dynamical evolution of the diffuse scattering awaits the high flux and high time resolution achievable at LCLS.[15] Photoinduced phase transitions that occur on the picosecond time scale, such as the metal-to-insulator transition observed in the (EDO)<sub>2</sub>PF<sub>6</sub> charge transfer crystal at room temperature,[16] demonstrates the viability of using organic correlated systems for ultrafast optical signal processing.

**Protein crystallography:** The variability and efficiency of proteins make them powerful molecular foundries. The size, diversity and complexity of proteins also make them enormously challenging to study and understand with atomic detail. X-ray crystallography helped launch the molecular biology revolution and maintains a position of unique prominence in structural biology as the most powerful tool for determining biomolecular atomic structure. While enormously useful, the equilibrium structure cannot capture the full chemical significance of a protein. To understand how a protein functions at a mechanistic level of detail, we need to measure in real time the nuclear motion that accompanies its function. Time resolved protein crystallography represents the most powerful tool for achieving this experimental objective.[1-5] While time resolved crystallographic measurements have been conducted with time resolution as short as 150 ps, these measurements demonstrate that global structural changes have already occurred at the earliest time delay.[4] By extended the time resolution of these measurements into the

femtosecond time domain, the ability to observe how a local distortion can be channeled into a concerted global structural change will be possible for the first time.

While the viability of time resolved protein crystallography has been demonstrated at a variety of third generation synchrotron facilities by many members of our collaborative team, the experimental circumstances at LCLS will be sufficiently different that alternative approaches to time resolved crystallography will need to be addressed. Radiation damage, both by the optical laser and the X-ray beam, greatly limits the allowed flux for experiments. While laser damage limits current time resolved X-ray experiments, X-ray damage represents the primary worry for experiments at the LCLS. Current time resolved crystallography experiments use Laue diffraction techniques to reduce the number of sample angles and data collection time needed to cover a sufficient range of reciprocal space for structural determination. As an example, the 0.13% energy band width of the LCLS will require roughly 20 times as many sample angles as the 3% energy band width used in the ESRF ID-9 Laue experiments. Given the smaller focus, higher flux, and lower energy of the LCLS X-ray source, the total X-ray dose required for measuring a single time point will exceed that used at the ESRF by over two orders of magnitude, and the expected X-ray damage threshold by roughly an order of magnitude. Attenuating the X-ray beam by a factor of 100 would allow for multiple time points to be collected with a single protein crystal, while still increasing the quality of the diffraction data compared to third generation light sources, because the flux per 0.1% bandwidth will still be more than two orders of magnitude higher than the achievable flux at a third generation synchrotron.

Appropriate scaling of the images will also be critical since the measurements require the accurate determination of photoinduced changes in diffraction intensities. As discussed in the experimental section, it will be necessary to measure the shot-to-shot variations in the X-ray spatial mode profile, energy spectrum, and position. Lastly, the quality of the experimental results will depend critically on optimizing the laser excitation. While the large number of changes in the experimental configuration at LCLS will require the initial experiments to focus on well characterized proteins such as CO myoglobin[1,4] and photoactive yellow protein, LCLS should quickly increase not only the time resolution of transient protein crystallography,[2,5] but also the quality of the structures and hopefully the range of systems that can be investigated.

***Diffuse scattering in liquids:*** The vast majority of chemical reactions in biological, environmental, and industrial settings occur in disordered media, with liquid water being the ubiquitous example. As mentioned previously, the development of ultrafast time resolved diffuse scattering will be critical to the success of the structural dynamics program. This effort will be greatly aided by the many team members who have developed the time resolved diffuse scattering capability at the ESRF.[17-19]

Repeating the experiments on the photodissociation of  $I_2$  in solution with femtosecond time resolution will be the initial goal.[17-19] Given the success of these experiments at the ESRF, we should be able to successfully conduct these experiments at LCLS with the time resolution necessary to observe vibrational wavepacket dynamics, solvent caging and geminate recombination, and vibrational cooling, all from the perspective of the  $I_2$  solute. While monitoring the structural dynamics of a solute in solution represents an important experimental goal, much of these dynamics can be indirectly monitored with time resolved electronic spectroscopy. What optical spectroscopy cannot unambiguously determine is the length scale dependent response of the solvent to a chemically evolving solute. This may be achievable in part with diffuse scattering. By measuring the time dependence of the partial structure factors that result from iodine-chlorine correlations in an  $I_2$   $CCl_4$  solution, the solute-solvent interaction could be directly determined. The viability of this approach has been demonstrated for steady-state diffuse scattering and molecular dynamics simulations of  $I_2$  dissolved in  $CCl_4$ . [20] This could also be achieved for photoionization of a simple ionic solute, such as  $I^-$  of  $Cu(I)Cl_2^-$ . [21,22]

***Four-wave mixing studies of structural dynamics in complex materials:*** While optically excited systems will represent a cornerstone of research at the LCLS, the exploration of techniques that utilize only X-rays must also be pursued. The following section on four-wave mixing briefly addresses some of the possibilities. Four-wave mixing techniques are a cornerstone of ultrafast nonlinear spectroscopy. Formally speaking, four-wave mixing includes most of the time resolved techniques used to investigate isotropic materials, ranging from the common place pump-probe spectroscopy to a variety of more exotic techniques.

We intend to focus initially on transient grating measurements, one of the most versatile and powerful four-wave mixing techniques.[23,24]

The transient grating technique generates a time evolving fringe spacing in an absorptive material by crossing two laser pulses in a material, and monitors the evolution of this grating by diffracting a third laser pulse off of the grating into the phase matched direction. Among the strongest incentives for X-ray transient grating spectroscopy is the fact that X-rays allow the transient grating fringe spacing to be extended, through variation of the four-wave mixing geometry and X-ray wavelength, from the nanometer range to molecular length scales. This includes the mesoscopic length scales containing essentially all condensed matter correlation lengths, including those associated with phase transitions, intermolecular structure in disordered or partially ordered materials (ordinary or supercooled liquids, polymers, structural or dipolar glasses, incommensurate or rotator crystals, *etc.*). For these disordered and partially disorder materials, visible light only accesses the  $q = 0$  limit, making the length scale sampled by the fringe spacing much larger than the relevant correlation length,  $d$ , in these materials. As a result, four-wave mixing with optical wavelengths can measure the dynamics of a very wide range of materials, events, and time scales, but generally gives no direct information about the length scales associated with the dynamics that are measured. The ability to observe these dynamics as a function nanometer length scale with an X-ray transient grating has the potential to transform our understanding of the glass transition and dynamics in complex fluids. Efforts are under way currently to conduct four-wave mixing measurements with soft X-ray pulses that are produced through high harmonic generation. These should provide useful experience and some of the information that is sought, but the low pulse energies and the soft X-ray or extreme UV wavelengths pose substantial limitations that will be fully overcome with the LCLS source. This problem can also be addressed with X-ray correlation spectroscopy, further supporting the importance of generating this capability as well at the LCLS.

The experimental tools needed for the experiments discussed here will also be relevant to a variety of other experiments. By tuning the energy of the LCLS beam to an absorption edge, the transient grating experimental set-up can be used for studying electron dynamics in a variety of materials with a variety of nonlinear spectroscopies.

#### References:

- [1] V. Srajer *et al.*, *Science* **274** (5293), 1726 (1996).
- [2] B. Perman *et al.*, *Science* **279** (5358), 1946 (1998).
- [3] K. Moffat, *Chem. Rev.* **101** (6), 1569 (2001).
- [4] F. Schotte *et al.*, *Science* **300** (5627), 1944 (2003).
- [5] M. Schmidt *et al.*, *Proc. Natl. Acad. Sci. U. S. A.* **101**, 4799 (2004).
- [6] S. Techert and K. A. Zachariasse, *J. Am. Chem. Soc.* **126**, 5593 (2004).
- [7] S. Techert, F. Schotte, and M. Wulff, *Phys. Rev. Lett.* **86** (10), 2030 (2001).
- [8] A. Szöke, *Chem. Phys. Lett.* **313**, 777 (1999).
- [9] P. Sondhauss and J. S. Wark, *Acta Cryst. A* **59**, 7 (2003).
- [10] D. M. Roundhill, H. B. Gray, and C. M. Che, *Acc. Chem. Res.* **22** (2), 55 (1989).
- [11] V. M. Miskowski *et al.*, *Inorg. Chem.* **33** (13), 2799 (1994).
- [12] C. Exstrom *et al.*, *Inorg. Chem.* **35** (3), 549 (1996).
- [13] G. Busse *et al.*, *Faraday Discuss.* **122**, 105 (2003).
- [14] E. Collet *et al.*, *Science* **300** (5619), 612 (2003).
- [15] L. Guerin *et al.*, *Chem. Phys.* **299**, 163 (2004).
- [16] N. Uchida *et al.*, *J. Phys. IV* **114**, 143 (2004).
- [17] R. Neutze *et al.*, *Phys. Rev. Lett.* **87**19 (19), art. no. (2001).
- [18] M. Wulff *et al.*, *Faraday Discuss.* **122**, 13 (2003).
- [19] A. Plech *et al.*, *Phys. Rev. Lett.* **92**, 125505 (2004).
- [20] A. Plech *et al.*, *J. Phys.: Cond. Matt.* **15**, S137 (2003).
- [21] J. A. Kloepper *et al.*, *Chem. Phys. Lett.* **298**, 120 (1998).
- [22] D. D. Davis, K. L. Stevenson, and C. R. Davis, *J. Am. Chem. Soc.* **100** (17), 5344 (1978).
- [23] M. D. Fayer, *Annu. Rev. Phys. Chem.* **33**, 63 (1982).
- [24] J. A. Rogers *et al.*, *Annual Review of Materials Science* **30**, 117 (2000).

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#### **IV. Scientific Organization and Management**

The diversity and scope of scientists within our collaboration has been chosen to reflect the wide range of skills and knowledge needed to construct a scientific facility on LCLS and conduct excellent science. We anticipate the timeline for the program will begin in FY2005 with development of detailed design and planning of the experimental instrumentation (in parallel with continuing experiments on SPPS). We will be prepared for first LCLS experiments in FY2008 and plan a program which will extend over the first three years of LCLS operations.

Among the members of the team, many have been directly involved in setting up beam lines and carrying out science with them. These people include Michael Wulff, Thomas Tschentsher, and Britt Hedman, with Michael Wulff being the senior scientist on the time resolved beam line at ESRF. Aaron Lindenberg has also been instrumental in setting up the SPPS experimental station.

We have extensive expertise in ultrafast laser science, with team members Kelly Gaffney, Philip Anfinrud, Keith Nelson, and Michael Fayer having many decades of experience with a variety of ultrafast laser tools and techniques.

Team members Harry Gray and Shin-Ya Koshihara provide chemical and materials synthesis expertise and Keith Hodgson, Britt Hedman and Keith Moffat bring extensive experience with X-ray scattering or absorption methodologies.

For the focus areas presented in this LOI, we have team members with an excellent publication record in all areas covered. Simone Techert, Thomas Tschentscher, Eric Collet, Hervé Cailleau, Shin-Ya Koshihara, and Michael Wulff in time resolved small molecule crystallography. Keith Moffat, Phil Anfinrud, and Michael Wulff in time resolved protein crystallography. Richard Neutze, Simone Techert, Phil Anfinrud, Aaron Lindenberg, and Michael Wulff in time resolved diffuse scattering. X-ray four-wave mixing represents the sole exception to this rule, though Michael Fayer and Keith Nelson have an extensive background in four-wave mixing with visible lasers and Shaul Mukamel has greatly advanced the theoretical methods used to describe nonlinear spectroscopy and has begun to study nonlinear X-ray science, as well.

#### **V. Preliminary Budget**

The budgetary requirements can be grouped into six general areas: laser and diagnostics, timing jitter and X-ray temporal profile diagnostics, X-ray detector, X-ray optics, X-ray diffraction and scattering tools, and personnel. The laser, laser transport materials, and laser diagnostics will cost roughly \$1.0M dollars. This does not cover the costs for timing jitter analysis equipment, with the expectation that those funds will go directly to the teams of scientists involved in their development associated with the LCLS program. Clearly funds will need to be invested in X-ray detector development as well, but that is again expected to be done by a core LCLS project. The same is true of X-ray optics, where the development of the hard X-ray analogues of beam splitters and optical delay stages will need to be developed. This experimental setup will require an X-ray diffractometer, as well as other X-ray diagnostics and sample manipulation and cooling devices, instrument/computer control and other associated components. This is estimated to cost \$625K. The total instrumentation cost is \$1.63M. The 13 collaborating institutions will be contributing manpower to the project (integrated, about 10 FTEs per year). We anticipate needing staff support for engineering and design, technical assembly and scientific support (postdoctorals) numbering about 5 FTEs per year. At an average cost of \$170K/FTE, over the 7 year period this would total \$5.95M. Operating expenses (materials, supplies, expendables, etc) of about \$100K/year (or \$700K over 7 years) are anticipated. Funding for the \$8.28M effort would be sought primarily through a grant that would be submitted to DOE-BES (although NSF is another possibility). Third party funding is another possible source of support.