Letter of Intent for provision of ultrafast streak camera-based detectors for LCLS experiments

1) Summary

This Letter of Intent (LoI) sets out a proposal to provide ultra-fast streak camera-based x-ray detectors for the LCLS. The first goal will be to provide a robust platform for achieving 100 fsec temporal resolution with high efficiency. It should be emphasized that although temporal resolutions of <600 fsec with UV (Liu et al. 2004) and 800 fsec with x-rays (Belzile et al. 2002) has been achieved, extension to 100 fsec represents a significant technical challenge. This capability will be needed for a range of LCLS experiments where the x-ray beam is used for sample pumping and the temporal and spectral characteristics of a resulting plasma need to be measured. High Energy Density (HED) science is one area that will rely on such advanced tools. The second goal of this proposal is to put in place the necessary R&D for extending the temporal resolution into the sub-100 fsec domain. The state of the art in ultrafast x-ray detection has only advanced slowly in recent years due to the severe technical difficulties involved. At ALS, the needs of the experimental program have demanded a vigorous development program in this area and significant advances are now being made. These are described below, together with their relevance to the LCLS program. The infrastructure for further advances is in place and an increase in the scope and pace of the work specifically for the LCLS program can be made in a cost effective and timely manner.

2) LCLS needs

The issues considered for this proposal so far have been for the High Energy Density science program (Lee 2004) although similar needs may be common to many of the planned LCLS experiments. The general requirements for this type of plasma spectroscopy have been described in detail in work on heating of thin Al foil targets by relativistic laser beams (Audebert et al. 2002) and references therein. In summary, one of the primary diagnostic tools used in this type of work is wavelength dispersed ultra-fast time-resolved x-ray spectroscopy. A crystal spectrometer is used to disperse radiation in wavelength along the narrow entrance slit of a streak camera, and temporal dispersion in the orthogonal direction is achieved by applying a time varying voltage to deflector plates, in the presence of a 2d electron imaging system. The heating mechanism in the case of the LCLS should occur impusively over relatively thick samples, in the timescale of the LCLS pulse; for the detector, we therefore need to have a temporal resolution significantly better than this to resolve the evolution of all spectroscopic signatures in time; for the baseline LCLS, this means that a camera with 100 fsec temporal resolution is required. It seems clear that LCLS will soon move beyond the baseline temporal resolution specification to a pulse-length regime of a few fsec. For HED experiments, the relatively large volume and long absorption length in the x-ray domain set limits on the best temporal resolution that is needed, but it is clear that a resolution of significantly less than 100 fsec would be desirable. High efficiency is also required so that in some cases, single shot data can be taken, or for multishot experiments, a wider range of experimental conditions can be examined. In these cases, the camera needs to be synchronized to the x-ray beam to provide an absolute temporal origin so that frames can be added without decreasing temporal resolution, and so that the creation of the plasma emission is linked in time to the excitation process. Finally, the camera will need to be integrated into the HED endstation together with other equipment, and potentially with other experiments, and so needs to be designed flexibly enough to fit a variety of environments. The streak camera can also be used as a timing diagnostic for the LCLS as demonstrated recently at the SPPS (MacPhee, Weinstein, Falcone et al).

3) Existing program at LBNL in ultrafast detectors

Ultra-fast streak camera technology is being developed at the Advanced Light Source, LBNL, Experimental Systems Group (ESG) in collaboration with the Falcone group in UCB, for use in a variety of applications from the study of magnetization dynamics to use as a fast gated detector for pulsed x-ray experiments using the energy modulation – dispersion technique of electron beam slicing. The work on magnetization dynamics is funded under a Laboratory Directed Research and Development (LDRD) grant that gives support for a postdoc for magnetization dynamics, a postdoc for development of streak cameras, and assorted equipment costs. The position for the streak camera development position will start in October 2004. In addition, the ESG has set up a fsec laser lab for development work on streak cameras and on other ultra-fast instrumentation, including an amplified laser system comprising a K-M labs oscillator and Positive Light Legend amplifier (0.6 mJ/pulse, 5 KHz, 30 fsec, 800 nm) and associated streak camera equipment. We also have in-house support staff who maintain and develop the laser and streak camera, as well as two graduate students working in this area.

The following are areas of current activity and are listed to give an idea of the scope and depth of the current work. The work is aimed at giving robust multi-shot operation at better than 0.5 psec resolution (at 5 KHz) with an aim of driving this towards 100 fsec over time.

a) *photocathode efficiency*: photocathodes typically have efficiencies for keV photons of a few percent or less. Increasing this has been a major aim of recent work, and we have shown that by matching the penetration of the photon beam from the surface in a grazing incidence geometry to the secondary mean free path, it is possible to obtain a quantum efficiency of 1, ie. on average, 1 or more electrons exit the photocathode for 1 photon in. This is accompanied by a distribution in the number of electrons / photon emitted, and this variance slightly reduces the DQE of the system from the QE of 1. Nevertheless, very high efficiency can be obtained . Further work needs to be done to optimize the efficiency, determine the best materials and surface preparation, and determine the details of how the pulse height spectrum can be tailored to an application to optimize DQE. Finally, the integration of a grazing incidence geometry into a streak camera geometry is non-trivial and is being attempted for the 1st time in our ongoing work.

b) *photocathode temporal resolution:* At present, the primary issues with streak camera resolution relate to time of flight dispersion and jitter. If these can be solved, then the intrinsic remaining issue is the fundamental limit set by the scattering of electrons in the photocathode after excitation. After photoexcitation, a primary electron and auger electron will travel in the solid, losing energy by core excitation and various inelastic processes and undergoing a random walk before emerging as a low energy secondary electron. The difference in the paths and process events for different electrons leads to a temporal dispersion. We have been using methodology developed for simulating the quantum yield of phtocathodes (Boutboul et al. 1999), and have adapted it so that we can determine temporal smearing. We are also adapting the method to include the effect of the accelerating field on the random walk trajectory. The details of the dielectric function are taken into account in a semi-empirical way; we are therefore also investigating other models that take proper account of the bandstructure of the material and LO and acoustic phonon interactions. The aim is to understand the limits that electron scattering plays in determining resolution, and to design photocathodes for specific applications.

c) *space charge simulation and measurement*: Space charge represents a fundamental limit to the temporal resolution of streak cameras when operated at high electron density. We are using both mean field models (Siwick et al. 2002)and N particle tracking codes to simulate the effects of space charge and understand the limits that it imposes. It is also a helpful tool in optimizing designs to avoid high spatial electron density (such as crossovers)

d) photoswitch development: For standard laser pumped experiments, it is convenient to synchronize the detector to the pump using a GaAs photoconductive switch. We are developing low jitter photoconductive switches, as well as high power avalanche switches that require substantially less laser drive power (Loubriel et al. 1997). These are all fabricated in the LBNL Materials Science Division (MSD) semiconductor materials laboratory, and developed in collaboration with Prof Eugene Haller (UCB Materials, MSD) and Jeff Beeman (MSD). One thrust of our current work is to increase the performance of such switches by reducing current crowding at the contacts, using doped contact areas. We are also investigating fundamental semiconductor issues involved in the transition from photoconductive to avalanche mode.

e) *improvement of temporal resolution:* One of the fundamental resolution limits in a streak camera is set by chromatic time of flight dispersion. This primarily affects the short accelerating anode – cathode gap, but at high field gradients, the effect of dispersion over the long length of the camera becomes important. Roughly, the accelerating gap dispersion amounts to 100 fsec, for a 250 KV/cm field, and a 1 eV secondary energy distribution (FWHM). Achieving such a high field gradient is a challenge, especially if robust, user operation is needed. In order to achieve a drift region that contributes less than this, the camera has to be short, giving engineering problems with integration of the high field region, sweep plates and focusing in a small space. It appears possible that with significant effort this might be possible and 100 fsec temporal resolution could be achieved, however, whether the solution is robust and practical remains an open issue requiring R&D. A better way in principle to achieve high temporal resolution is to correct the positive time of flight dispersion in the gap and drift regions, with negative time of flight in another part of the optical system. A system for doing this uses a pair of 127 degree (or any focusing angle, paired to make it non-energy dispersive) electrostatic sectors, followed by an inverted pair (Jaanimagi 2003). This parallels work in isochronous electron storage rings, used for storing short bunches of electrons. We have examined this system in detail using electrostatic modeling and electron raytracing. The basic idea works, and shows on paper a resolution of < 50 fsec, however, implementation involves solving some tricky issues with fringe fields that might prove quite difficult. We are currently looking at alternative strategies to achieving negative time of flight compensation. Much of this work is based on the infrastructure developed to build an aberration corrected photoemission microscope at the ALS, PEEM3 (Wan et al. 2004)

f) sweep plates: Achieving high sweep sensitivity means that we have to be careful to match the propagation of the electrical sweep pulse, to the velocity of the electron beam. Typically the beam is traveling at 1/3 – 1/2 light speed, and so this velocity mismatch would mean that the electrical sweep plate impulse would soon outrun the electron beam. This is solved in principle by making the electrical signal meander back and forth across the electron beam direction. However, great care has to be taken in impedance matching the system to the voltage source or else a large drive voltage will be required, defeating the original aim of high sensitivity. This work is being done using existing accelerator RF simulation codes such as MAFIA.

g) *temporal fiducialization:* Jitter in streak cameras is primarily cause by laser intensity fluctuations being translated into carrier concentration changes in the GaAs switch, which consequently change the system impedance and hence its temporal response. Great efforts have been made by several groups to reduce these problems by reducing the laser ASE and pulse intensity fluctuations to an absolute minimum (Belzile et al. 2002; Liu et al. 2003). However, these methods are painful and it is doubtful whether passive measures can lead to a robust solution in a complex experimental environment. We have taken the approach of temporally fiducializing each sweep of the camera. A 3rd harmonic pulse derived from the amplified laser is used to hit the photocathode, displaced in time or position from the signal. The imaging system then reads out the data, and post-processing is used to line up all the temporal fiducials. Work by MacPhee et al on the SPPS has shown that this works to the 100 fsec level using a fairly crude system at 10 Hz. The work we have been doing is to use very fast CCDs to read out a few lines of data at the laser rep rate of 5 KHz, and then process the data in real time using FPGA / DSP technology. The first version of this very fast fiducialization system should be in operation in fall this year.

h) *detectors:* We are putting considerable effort into design of an optimum back end detector. There is no universal solution. For low rep rate applications, we can use directly illuminated CCDs. These have excellent spatial resolution, but poor DQE. Thick fully depleted back illuminated CCDs developed for the LBNL SNAP project should avoid the surface trapping that reduces the DQE of commercial CCDs, and these are being investigated. For applications that require high rate and need gating, then currently we are using channel plate – phosphor CCD combinations. Even here there is considerable work going on to determine the best surface coating on the MCP for electron efficiency, and the optimum gap / phosphor / fiber geometry for high spatial resolution and good MTF.

i) *optical sampling camera*: We are investigating use of an all optical method to produce ultra-high temporal resolution sampling of an x-ray signal. The method uses the photocathode, extraction field, and focusing of a conventional streak camera or photoemission electron microscope, but in order to provide sampling of the electron and hence x-ray beam, the beam is crossed with a focused fsec laser close to the photocathode. The ponderomotive field gradient (Bucksbaum et al. 1987) should be sufficient to deflect the beam well outside the normal beam pencil angle, providing a route to ultra-high temporal resolution optical sampling.

4) Specific program for the LCLS

The above section emphasizes the scope and depth of the current work on streak cameras at LBNL. For the LCLS there would be 2 separate programs, a) to develop a robust 100 fsec streak camera based on extrapolation of current technologies, and b) to develop more complex electron optics that would compensate for time of flight dispersion and allow access to the time domain less than 100 fsec. For this, we would envisage programs that would concentrate on the following topics;

a) *optimization of the anode-cathode gap:* to operate reliably at 250 KV/cm requires very careful engineering of the photocathode and mesh extraction. We will probably go to a custom slotted anode with micromachined edges to reliably attain this field. This area still requires significant R&D.

b) *photocathode efficiency:* we will continue to pursue grazing incidence designs as well as more conventional normal incidence configurations, in order to optimize efficiency where needed.

c) *photocathode resolution:* we need to continue our studies in electron scattering to determine optimum photocathode materials, fields and geometries.

d) *photoswitch trigger:* in principle, the GaAs switches we have can be directly triggered by the LCLS x-ray beam. If this proves not to be viable, then we could trigger the GaAs switch with a fsec laser synchronized to the LCLS RF (as we do at ALS). Triggering with x-rays needs to be investigated.

e) *fiducialization:* this will be achieved in similar way to now, except that the fiducial will be derived directly or through scattering from the LCLS beam. This will establish time zero for each shot. We would most probably use the fast CCD + FPGA we are currently developing for readout.

f) *meander plates:* the design of meander plates is still something of an art and we need to complete a full study and optimization using modern RF simulation tools such as MAFIA. This is underway for the ALS streak camera work.

g) *space charge:* we need to continue and develop our space charge modeling and apply this to the LCLS case. Space charge is a serious issue for LCLS fluxes and needs to be understood in detail. We are currently using mean field models, and N particle models for this work (Parmella and Impact)

h) *system integration:* all the above pieces have to be integrated in a whole system that is robust, user friendly and can be used by non-experts. This by itself will be a difficult engineering task and needs special attention. We are trying to design the ALS system to be as robust and automatic as possible and this will offer something of a guide in this work. This category also includes all the back end detector, FPGA, computing system necessary to run the system.

The above areas are all required for production of a robust 100 fsec camera. In order to go beyond this we need to correct the most serious problem of high temporal resolution streak cameras, the time of flight dispersion caused by the chromaticity of the lenses in the presence of the chromatic nature of secondary electron emission from the photocathode.

i) *design study of isochronously corrected electron optical streak camera systems*. The system described above needs to be studied in detail, and compared in performance to competitor solutions. If successful, this would spawn its own R&D tasks designed to build such a system and test and evaluate it.

5) The research team

The work described in section 3) has been carried out over the past couple of years in collaboration with the Falcone group in UCB Physics and this is expected to continue for the presently proposed project. In addition to the UCB group, at present the team is made up of;

Howard Padmore	ESG group leader	PI
Jun Feng	ESG staff scientist	electron optics
Phil Heimann	ESG Staff scientist	development / applications
Ernie Glover	ESG staff scientist	laser / applications
Jamie Nasiatka	ESG scientific eng. assoc	instrumentation
Position start Oct 04	postdoc	streak camera development
Kathy Opachich	UCB grad student	switch, sweep plates…
Mike Greaves	UCD grad student	CCD camera, switch....
Weishi Wan	accelerator physics staff sci	electron optics
Greg Morrison	technician	mechanical fabrications
Andrew MacPhee	visitor / LLNL	streak camera development

In the above team, several members such as the staff scientist have other responsibilities and so are not available full time, but make significant contributions to the program; for example Jun Feng is responsible for PEEM3 electron optics, Ernie Glover for BL 5.3.1 etc. However, the above gives an outline of the staff currently working on the project. We also have active collaborations with other LBNL groups, for example in the ALS accelerator physics group, the Center for Beam Physics, and the ALS mechanical and electrical engineering groups. We also strongly collaborate with the group of Bob Schoenlein. We also have joint projects with our colleagues in high energy physics and engineering on back end detector design and signal processing, as well as with colleagues in the Materials Science Division (Jeff Beeman, Eugene Haller) on photoswitches and GaAs. We are now well set up with a full fsec laser lab (0.6 mJ, 30 fsec, 5 KHz), streak cameras, and all the ancillary equipment for ultrafast measurements. The whole of this activity is coordinated within the ALS Experimental Systems Group (ESG). One of this groups prime responsibilities is to build the complex instrumentation of beamlines and end stations for the ALS and so has access to a wide range of tools and skill sets for taking on difficult scientific instrumentation projects. Having built ~25 beamlines at ALS and numerous endstations, we also have a proven record in delivering successful projects on time and on budget through the use of project management tools and methods.

6) Estimate of costs and schedule

Without a much more detailed evaluation and discussion with LCLS it is difficult to gauge the scope of the projects that need to be undertaken. However, they fall into the following broad classes

A) R&D and fabrication of a 100 fsec streak camera

This involves items in section 4, a) – h). It will take the concepts and implementation that we have today and push this technology as far as it can go. The result will be a fully instrumented streak camera system for LCLS that will be integrated into the HED physics experiment.

Year 1

a) experimental and theoretical evaluation of limits of current system set by intrinsic issues such as extraction field gradient, photocathode electron scattering, space charge etc. The experimental aspects will be evaluated on one of our current cameras modified to suite the required conditions.
b) evaluation of the experimental conditions and requirements of HED and other LCLS experiments
c) design of the prototype LCLS streak camera
d) design of the back end imaging and data treatment systems

It should be noted that the streak camera will require a very fast 2d CCD detector system for detection of temporal information in one direction and spectral information in the orthogonal direction. This in itself is a very challenging project (at 120 Hz) but the R&D is largely covered in a separate proposal (Letter of Interest) for provision of fast CCDs for LCLS.

e) construction of prototype LCLS streak camera

Cost: personnel 0.6 M$, hardware 0.4 M$

Year 2

a) construction of the fast back end imaging system for the streak camera
b) evaluation of the temporal resolution of the prototype LCLS streak camera

This work requires a very short pulse x-ray source and would be initially done using VUV harmonic generation at relatively low energy (sufficient to generate the wide secondary electron distribution responsible for time of flight dispersion).

c) R&D and optimization of the prototype
d) design of a streak camera system specifically optimized for HED experiments

Cost: personnel 0.5 M$, hardware 0.4 M$

Year 3

a) construction of HED streak camera and detector backend processing / acquisition system
b) evaluation of performance of the HED streak camera system (as in b) above)
c) optimization and installation and testing at LCLS

Cost: personnel 0. 5 M$, hardware 0.3 M$

TOTAL: personnel and equipment, including LBNL overhead **2.7 M$**

B) R&D towards a sub-100 fsec streak camera

This sub-project involves development of an isochronously corrected streak camera, ie. one in which time of flight is independent of initial electron energy at the photocathode. It will also involve significant work on optimizing sweep plates and methods of getting higher sweep rates than presently used. Finally, it will involve improvement of the back end detector towards smaller pixels, and possibly direct illumination of either a CCD, or an active pixel sensor. It should be noted that an LBNL LDRD starting FY05 will fund initial development of both the fast CCD detector needed for section A) above, and work on an active pixel sensor (APS) for electron microscopy. The latter would be the ideal next generation back end electron detector for a streak camera.

We have not included a breakdown of funds here for this R&D activity as it will be highly dependent on the needs of the various experimental groups. If we assume that this activity starts in year 2 of the above project (A), then it would roughly be of the same magnitude of project as the 100 fsec streak camera project, ie. 2 – 3 M$ over 2 – 3 years.

7. Contact Information

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