

June, 21, 2004

LCLS Science Advisory Committee
SSRL, SLAC
Menlo Park, CA 94025

3DX Letter of Intent

This is a short document, in response to a Call of Letters of Intent, indicating our interest in developing instrumentation for use at the LCLS. This is a category C LOI. We would welcome the opportunity to join with other instrumentation or science-orientated teams to design and manufacture a complete large-area, high-frame rate, x-ray camera as well as other beamline devices.

Background

To maximize the scientific productivity enabled by the unique capabilities of the LCLS will require the development of matching instrumentation. The LCLS will require special detectors to make use of the extremely high intensity and pulsed nature of its x-ray beams. Many experiments will want to completely readout their detector after every pulse (i.e. every 8.4 msec). For example, crystallographers will want to take a full image after every pulse because one pulse of the intense beam will severely radiation damage the crystal. This is critical to the imaging of single particles, viruses, nanocrystals, and some time-resolved measurements. Many small angle scattering and dispersive XAFS experiments will have similar requirements. Pixelated silicon detectors are a good choice for a general detector of LCLS experiments since they can have good efficiency, high dynamic range, large area, high readout speed and very low radiation damage. Since they are based on semiconductor technology, they can be made at reasonable cost.

We are developing silicon based pixel detectors that have good efficiency up to 20 keV. Our current prototype detector is made of modules that are 9.6 mm x 9.6mm with a pixel size of 150 um x 150 um (64 x 64 pixels). These modules can be shingled so that a very large area (300 mm x 300mm) can be covered with a dead area of less than 0.5 %. The entire module is readout every 64 usec. At Stanford we have developed the technology to fabricate these pixelated silicon detectors with a thickness of 200 or 400 um and to then bump-bond the detector to custom electronic chips that have the same pixel spacing as the detector. The electronics are based on those used in high energy physics experiments at LBNL.

Our team includes specialists in large-scale systems engineering, radiation sensors, VLSI pixel electronics, synchrotron-beamline instrumentation, as well protein crystallography.

We propose to develop a special detector for LCLS that would have special electronics under each pixel that would give higher dynamic range and have a readout time of less

than 8.4 msec. Depending on the experimental requirements we could also produce pixilated detectors with smaller pixel sizes or thicker elements.

This team already exists. It is local to the site of the LCLS. Many of the parts and much of the work required to build an LCLS-specialized, x-ray camera has been completed as part of the protein crystallography project. It makes sense to leverage this previous investment by having us contribute to the LCLS instrumentation.

Sensor

A key element of the proposed x-ray camera is the silicon sensor where direct conversion of photons occurs. This is based on the widely used and well-understood reversed-biased, p-i-n diode, where ionization from the incident photon is drifts under applied electric fields to collection electrodes. We have developed some unique, new types of silicon sensors using micro-machining techniques.

One advance in sensors is the use of active edge fabrication technology. The sensor edges are defined by precision plasma etching, and then made into electrodes, rather than being sawed. Active edge sensors have efficient collection to within about one micron of the physical edges of the chip, rather than the standard hundreds of microns or more. In Figure 1 a planar strip sensor has been scanned with an x-ray beam at the Advanced Light Source yielding evidence that the sensor is indeed sensitive to within a few microns of the edge. This enables seamless tiling or shingling of sensors to cover an area devoid of insensitive regions.

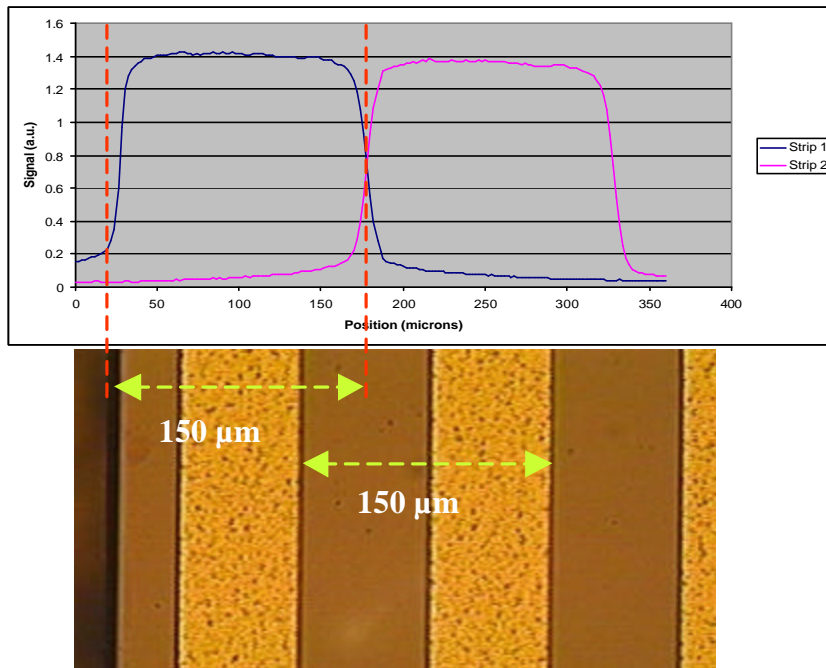


Fig. 1 Active-edge, planar silicon signal from x-ray scan.

Another architecture involves etching electrodes completely through a silicon wafer. This decouples the sensor thickness from depletion distance and allows high radiation hardness, fast sensors, and low operating voltages. Important for x-ray imaging is that 3D sensors have almost no charge sharing between pixels. This creates a flatter image response with reduced under counting or over counting near pixel boundaries.

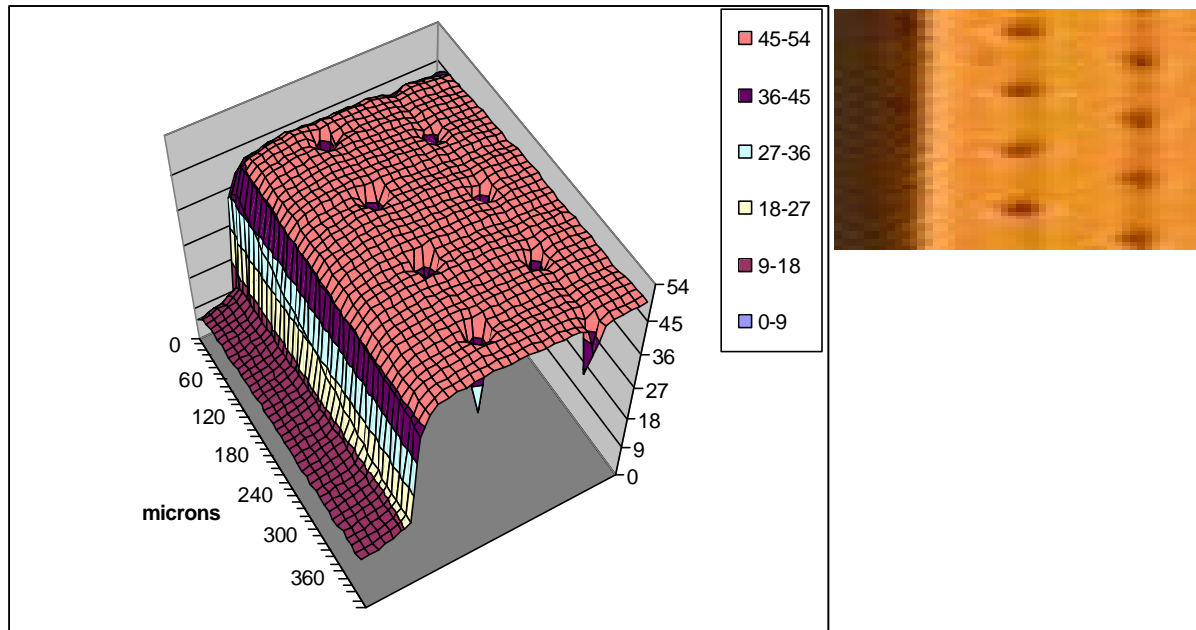


Fig. 1. 3D sensor scanned with x-ray micro-beam at the ALS. Slight dead areas within the electrodes are visible as is the active edge.

Depending on the exact needs of the LCLS end users, the type of sensor architecture with the most benefits for a specific application can be bonded to the ASIC. Both these types of sensors have been tested in synchrotron beamlines (ALS, APS, ESRF) and at CERN.

Read Out ASIC

An area x-ray camera for the LCLS will entail the design of a custom integrated circuit. The main requirements for this chip are:

- 1) Dynamic range from 1 to 1,000 8 KeV photons
- 2) Low noise to ensure efficient sensitivity for a single 8 KeV photon
- 3) Large area of about 15 cm by 15 cm
- 4) Minimum dead areas
- 5) Frame rate of at least 120 per second
- 6) High yield
- 7) Radiation hard

Our 3DX ASIC is capable of meeting or exceeding all of these except for first: the dynamic range of one thousand photons with a resolution of a single photon. The chips dynamic range at present is around a dozen 8-KeV photons per read-out frame.

The chip with a sensor attached has been read out at frame rates of 5,000 per second. This rate is currently limited by the printed circuit board not the ASIC. We expect to be able to achieve frame rates of over 15,000. We are confident of attaining the required 120 Hz rate with an LCLS-specific circuit, which fulfills all the LCLS parameters.

By using a 144-micron, cell size for the ASIC and a 150-micron, cell size for the sensor, the sensors can be tiled or shingled with no insensitive boundaries.

The 3DX circuit has been fabricated with very high yield using a 0.25-micron, commercial CMOS process. All circuit chips studied so far have been free of dead pixels. A radiation hard, surround gate transistor layout was used. Combined with the thin gate oxide used, we expect these chips to function after a fluence of at least 50 megarads.

To achieve the thousand-photon dynamic range, while maintaining single photon resolution will necessitate using a different analog architecture within each pixel cell. The technique, which seems most promising, is a time-over-threshold (ToT) scheme. This is the type of analog cell used for the ATLAS pixel detector. Dr. Mandelli is part of the team, which designed this ASIC. For details see: E. Mandelli, et al., IEEE, Trans. Nucl. Sci., vol. 49, No. 4, August, 2002, pp. 1774-1777. and L. Blanquart, et al., IEEE Trans. Nucl., Sci., vol. 49, No. 4, August, 2002, pp. 1778-1782. Figures 4 through 7 are from these papers.

The basic idea is that signal charge is amplified and then stored on a capacitor. The charge on this capacitor is then bled off using a constant current source. The length of time the voltage on the capacitor remains over a threshold value is linearly proportional to the amount of signal charge. A diagram in Figure 4 illustrates this concept.

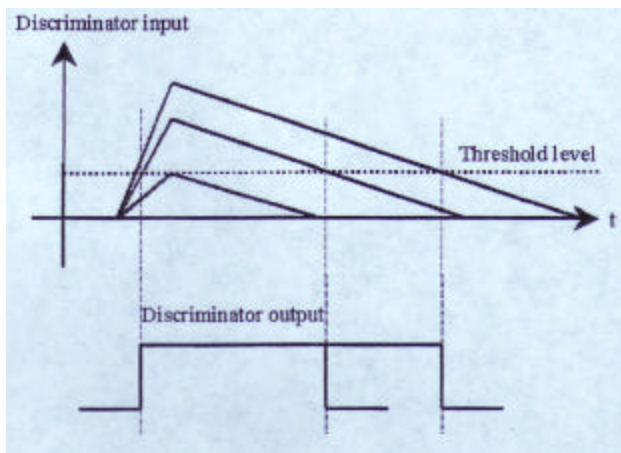


Fig. 4. Time-over-Threshold concept.

In the ATLAS ASIC the pixel size had an area slightly larger than the target of a 150 micron by 150 micron cell for the LCLS x-ray camera. Although the dynamic range must be improved from the ATLAS to the LCLS design, most other parameters are less constrained. For example the 120 Hz beam rate of the LCLS is several orders of magnitude slower than the read out cycle required for the Large Hadron Collider. Since the detector must only be active during a short well-defined time interval, it will be possible to reduce the total power used, while increasing the analog power during the read out cycle.

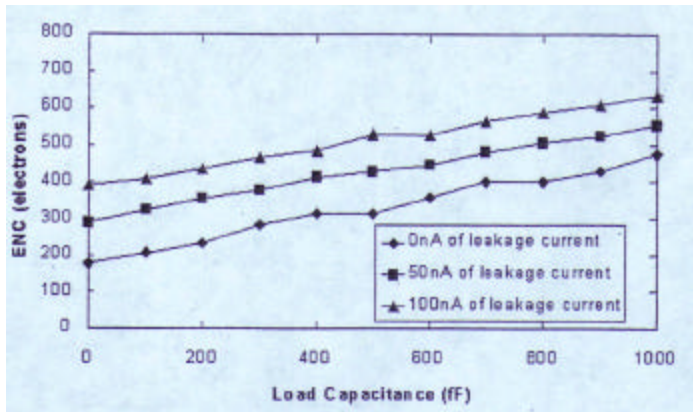


Fig. 5. Noise versus input capacitance for ATLAS chip.

The noise versus input capacitance of the ATLAS chip is shown in Fig. 5. Whether a 3D or planar silicon sensor is used, the input load should be around 500 femtoFarads and the leakage current less than one nanoAmpere. Thus we expect a noise of about 300 electrons. This should allow sensitivity to photons down to 3 KeV.

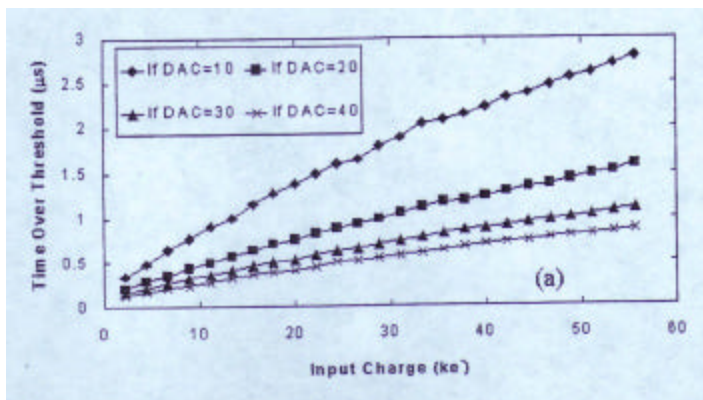


Fig. 6. Time over threshold versus signal for ATLAS chip.

Time over threshold versus input signal is plotted in Figure 6 for the ATLAS design. This shows that the circuit response is linear from 2,500 electrons up to 56,000 electrons, corresponding to a single 8-KeV photon up to over twenty 8-KeV photons.

Although detailed simulations are needed, we believe a ToT architecture can meet all of the requirements for an x-ray camera for the LCLS.

Hybridization

Our group as part of the 3DX protein crystallography project has developed the ability to perform flip-chip hybridization of the ASIC and sensor with high yield at Stanford. Using the Stanford Nanofabrication Facility we can combine photolithography, sputtering of the under-bump metal stack, and evaporation of indium to form bump arrays on silicon wafers. An image of a set of indium bumps is shown in Figure 7. Since Stanford has a class 100 cleanroom, high yields result as shown by the 512-bump array in Figure 8 and the full-size test chip with 4,096 perfect bumps in Figure 9.

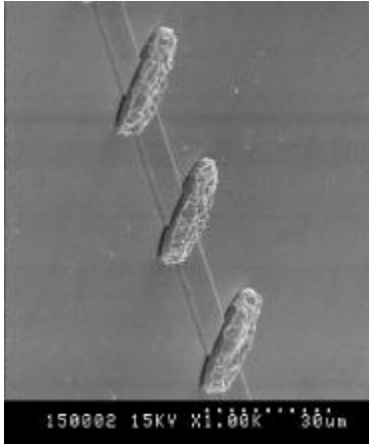


Figure 7.

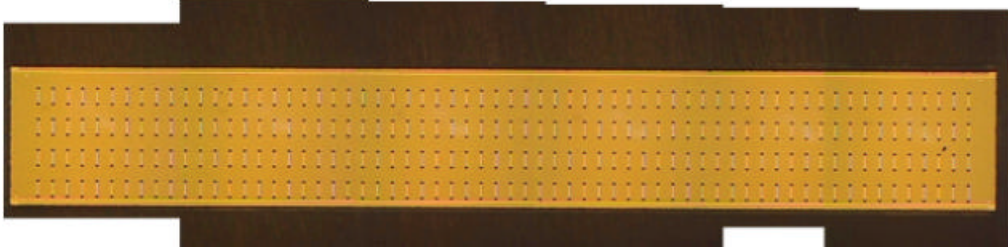


Figure 8. 512 indium bumps on a 8 by 64 array.

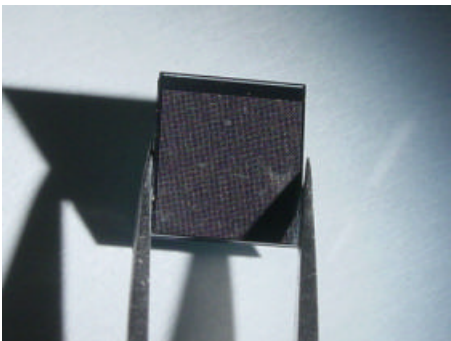


Figure 9. Full size 64 by 64 bump array.

Currently we use a shared flip-chip bonder. As part of our 3DX renewal proposal we are planning on acquiring a dedicated bonding machine.

Beam Profile Monitors

High performance beam profile monitors are necessary to optimize the beam parameters of the LCLS. These are critical for providing feedback for machine operation and hence maximizing the science obtained at the end stations. In some applications such as imaging of biomolecules and nano-scale physics beam sizes of 100 nm are needed. In addition to such small dimensions, the high number of photons in each pulse creates the potential for significant radiation damage in a beam monitor. As many groups have proposed, diamond provides an ideal material given its' high degree of radiation hardness.

The last year has seen the advent of single-crystal, CVD-fabricated synthetic diamond with radically improved charge carrier properties (Isberg, Science, 297, 2002, page 1670). This material overcomes the grain-boundary defect limitations, which have up to now precluded the use of polycrystalline diamond films for sub micron beam position and intensity monitoring. However the closely interrelated subjects of surface preparation and electrical contact technology are still at an early phase of development.

We would like to fabricate diamond beam monitors with element pitches on the order of 100 nanometers. Such a sensor would be able to provide beam position information with an accuracy significantly better than the element pitch by using interpolation. Even a beam with a full-width-at-half-maximum of 50 nanometers would have charge collected by multiple sensor elements due to beam tails, charge diffusion, and capacitive coupling. In particle physics such techniques routinely provide position information with accuracy ten times smaller than the element pitch.

In addition to the beam location the dimensions of the beam could also be reconstructed with a resolution below 100 nanometers.

Diamond's low x-ray cross section will mean that such a beam monitor would have little impact on the beam itself and introduce a limited amount of background. Small angle beam scattering is limited due to the near perfect, single crystal structure. The exceptional thermal conductivity of diamond will allow dissipation of the absorbed beam energy at beam powers that would volatilize even beryllium.

We propose to make diamond sensors with thicknesses between 10 microns and 200 microns with the appropriate thickness to be optimized for the beam energy and intensity. Using the Stanford Nanofabrication Facility, we would pattern metal strips on to the diamond's surfaces. The width of these strips would be between 30 and 50 nanometers with a pitch of 100 nanometers or less.

Due to the fast charge mobility in single crystal diamond, such sensors also offer beam-bunch timing accuracy down to ~100psecs. The charge collection is practically complete, and with appropriate fast electronics the devices can be operated as accurate beam intensity monitors at the 'bunch by bunch' level.

These sensors will be coupled to appropriate, off-the-shelf multi-channel electronics for initial studies. As the diamond sensor itself presents a purely capacitive load, we can exploit the same sophisticated electronics already developed and in use worldwide for synchrotron electron bunch monitoring. At a later stage, new electrode designs possible with the diamond substrate will profit further from ASIC readout. The signals would then be digitized and transferred to a computer. Software could analyze the information on a pulse-by-pulse basis and provide the beam location and dimensions in quasi real time.

Active Beam Stops

Our group is currently developing an active beam stop using the active edge silicon sensor technology. Through the use of active edges, the entire volume of the silicon is sensitive to the beam including the entrance face. This means essentially all of the beam photons are recorded. This is important, given that most of the LCLS beams will be below 8 Kev in energy. Since the sides are also active there is no dead area on the perimeter. This means the beam stop can be made smaller than with a commercial diode.

Team

Our team is a proposed collaboration between the Molecular Biology Consortium, Lawrence Berkeley National Laboratory, the University of Hawaii, Stanford, and ESRF. This is the same as the 3DX collaboration except for ESRF. At present there is no formal arrangement with ESRF, but Dr. Morse worked with us on the 3DX project during a sabbatical from ESRF and has expressed an interest in working with us on diamond beam monitors. Each of the member institutions brings unique capabilities and knowledge relating to synchrotron science, custom integrated electronics, x-ray sensors, and large-scale detector systems. Everyone participating in this LOI has worked together before and functions well as a team.

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Dr. Westbrook has an M.D. degree from the University of Chicago and a Ph.D. from the University of Illinois at Chicago. Dr. Westbrook led the team, which first developed CCD-based systems for x-ray cameras at synchrotron sources. He has built a protein

crystallography beamline at the ALS. Dr. Westbrook has over 20 publications and 2 patents.

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Dr. Mandelli received his Ph.D. in electrical engineering in 1999 from the University of Pavia with Prof. P.F. Manfredi as his advisor. He has been designing pixel chip ASICs for more than 4 years, as part of the FEH and FEI team for the pixel detector readout for the Atlas experiment at CERN, which is the only working production pixel chip available today. He also has more than 10 years experience in the design and testing of high energy physics experiments, including efforts in the SVT strip readout ASIC for BaBar (SLAC) and the SVX4 ASIC for CDF and D0 (Fermilab). He is currently designing the 0.13um front end for the Atlas Pixel upgrade. Dr. Mandelli was the lead designer on the 3DX ASIC for protein crystallography, which has been successfully bump bonded to a silicon sensor and read out x rays.

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The experimental x-ray tests of the prototype devices will be lead by Al Thompson. He has built several x-ray beamlines at the ALS (11.3.1 and 10.3.1) and pioneered the development of Kirkpatrick-Baez x-ray focusing optics with Jim Underwood. In addition, in October 2000 he organized a Workshop on Detectors for Synchrotron Radiation in Washington, DC.

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Dr. Parker from the University of Hawaii has over four decades of experience in the science of particle physics and radiation sensors. Dr. Parker co-designed the Multiplex integrated circuit, which was the first ASIC for the read out of silicon strip sensors. The Multiplex chip was critical to the first use of silicon strips at the Mark II experiment at the Stanford Linear Collider. The development of multiplexed, ASICs, which are optimized for radiation sensors, has led to the use of silicon strip detectors in almost every major collider or fixed target experiment since the mid 1980s.

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Dr. Kenney has a Ph.D. in particle physics and has participated experiments and tests at accelerators at Brookhaven National Lab, Los Alamos National Lab, Fermilab, SLAC, CERN, ESRF, and the Advanced Light Source. He has over 30 publications and 2 patents. Dr. Kenney has fabricated a variety of devices at the Stanford Nanofabrication Facility over the last decade. Mostly specializing in radiation sensors, but also in micro-mirror arrays, micro optics, and micro-fluidics. Dr. Kenney has been president of a micro-machining based company and is a registered patent agent. Dr. Kenney was part of the MARK II, silicon vertexer team at the Stanford Linear Collider, and has worked on several pixel sensor projects.

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Dr. Morse has over a decade of experience working at synchrotrons in Europe and the U.S, developing beam-line detectors and instrumentation. A particular interest of Dr. Morse is the development of beam monitors for high intensity x-ray beams. Dr. Morse has been investigating single crystal, CVD grown diamond over the last year in association with groups from other European institutes and commercial suppliers.

We are excited about contributing to the science potential of the LCLS and are eager to collaborate with other groups. In particular end-user groups, which are focused on the imaging of single or small volumes of biomolecules, viruses, or cells would offer extensive synergies. Also with the machine specialists where a diamond beam profile monitor might be of use.

Sincerely,

Edwin Westbrook, Al Thompson, Emanuele Mandelli, John Morse, Sherwood Parker,
and Chris Kenney