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High-Z Radiation Shields for X-ray Free Electron Laser Detectors

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The Linac Coherent Light Source (LCLS) produces brilliant x-ray in femtosecond pulses of high intensity. Many of the experiments performed at the LCLS use expensive pixel area detectors – the majority of which incorporate custom integrated circuit chips (ASIC). Such circuit chips are susceptible to radiation damage. To protect against this, micro-patterned tungsten foils were designed to cover the section of the circuit chip that extends beyond the sensor near the wire-bond pads. A description of the problem along with the details of how the tungsten foils were fabricated and installed will be given.

I. Introduction

The Linac Coherent Light Source (LCLS) produces coherent x-ray pulses with durations on the femtosecond timescale. This contrasts with the situation in most other ionizing radiation environments where the flux is effectively continuous. Many of the experiments performed at the LCLS use expensive pixel area detectors, the majority of which incorporate custom integrated circuit chips (ASIC). Such circuit chips are susceptible to radiation damage. The Cornell-SLAC Pixel Area Detector (CSPAD), which was jointly developed by Cornell University and SLAC National Accelerator Laboratory, is a 2.3 megapixels camera read out at 120Hz encoded in 14 bits/pixel over a digital data interface. The detector is made of 32 silicon sensors 500µm thick bump-bonded to 64 185x194-pixel ASICs tiled to cover a square approximately 17 cm by 17 cm [1], [2], [3], [4]. The CSPAD camera has experienced radiation damage whose symptoms fall into several categories. In one of these behavioral classes an entire circuit chip ceases functioning in conjunction with a single LCLS pulse. To protect against this, micro-patterned tungsten foils were designed to cover the section of the circuit chip that extends beyond the sensor near the wire-bond pads. Incident x-ray beams undergo significant attenuation when passing through this foil, hence it shields the vulnerable transistors.

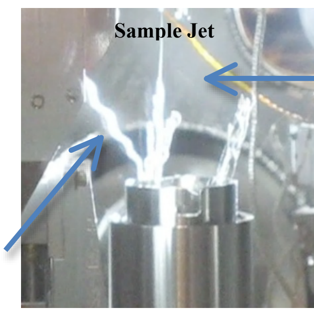

Fig. 1: In the LCLS-CXI (Coherent x-ray Imaging) chamber specimens are delivered to the x-ray beam by a water jet showed in the picture. Notice how the water crystallizes creating ice crystals.

II. Problem

A single, sub-hundred femtoseconds long pulse of the LCLS can contain in excess of $\sim 10^{12}$ x-rays, and this can be focused to a spot on the order of a micron in diameter. This contrasts with a synchrotron, which might deliver a similar fluence over a period of a second. At the core of the ATLAS experiment at the Large Hadron Collider, the innermost tracking layers will experience a comparable fluence, but spread over years. Since the LCLS beam is often focused down to a micron spot and high-quality crystals can diffract a large fraction of the beam, a non-trivial fraction of the primary beam can be scattered into an off-axis area only hundreds of square microns in size (Fig.1). Given these approximate values, the ionizing flux that a circuit element can be exposed to during 100 femtoseconds in the LCLS can be up to 1×10^{13} and 1×10^{15} times greater than in a synchrotron or ATLAS, respectively. On the CSPAD camera such flux can cause an annular locus of point damage, which appears white, and completely unresponsive ASIC (Fig. 2). It is postulated this was the result of a Bragg-spot hitting an

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exposed circuit element near the wire bond pads that controls biasing for the entire chip.

Fig.2: Screen shot of the LCLS-CXI camera showing unresponsive ASIC (black square on the lower right) and white spots in a circular pattern so-called water rings.

Several actions were taken to avoid this type of event or mitigate the resultant damage, such as: avoiding dangerous running conditions, implementation of online monitoring code to trip the beam, shielding the ASICs with high purity tungsten foils.

III. The Solution

At 8,000 eV, which is a typical photon energy used at the LCLS, 50 microns of tungsten will absorb all but one in 10 million of the incident x-rays. This thickness is also easily patterned at the ten-micron level by laser cutting. Since the sensor covers and protects most of the ASIC, pieces of tungsten were designed to overlay the exposed portion of the ASIC.

To completely protect the global bias circuits the tungsten shields ended up being over 2 cm in length, 50 microns thick, and 450 microns wide. There are also tabs, as shown in Figure 3, which protruded 50 microns between the wire bonds pads. The extra piece offers more protection and additional real estate for securing the shield to the ASIC.

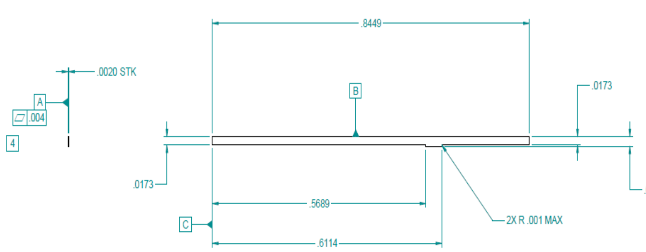

Fig. 3: Detailed drawings of the tungsten shield shape and dimensions. Notice the protruding “tab”.

After the laser cutting most of the foils warped and had to be flattened before being assembled in the detector modules. The foils have a flatness requirement of 4 mils from end to end (Fig 4). To achieve such requirement the foils are placed on a precisely machined piece of stainless steel and a 0.25 inch aluminum dowel is rolled over the length of the foil. The shields are flipped as required and rolled on the opposite side. For extreme cases, a one inch square piece of thin dense foam is sometimes used to roll the foil on so that the foil is allowed to bend. This is a critical requirement in order to successfully glue them in place and allow enough clearance for the wire-bonder wedge to access the adjacent pads (Fig. 5 and 6).

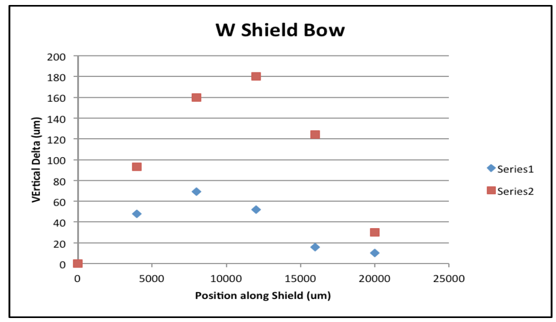

Fig. 4: In this graph is shown an example of a W foil bowing before and after been flatten. The red square series indicates the bowing just after the laser cutting and the blue diamond series inidates the improvments after the flattening process. Note that the delta after the flattening scheme is under 0.5 mils.

Excess current draw across the sensor was observed when the first prototypes were installed. This was likely the result of the tungsten contacting the sensor edge. To avoid this the tungsten shields were conformally coated with a 200 nanometer-thick film of silicon dioxide using plasma-enhanced chemical vapor deposition. Since the silicon dioxide coating is performed for each face, the sidewalls are effectively coated twice resulting in double the thickness ensuring complete insolation from the sensor.

W foils have been delicately installed using minute drops of low outgassing epoxy on more than 50 modules, before wire bonding to the PCB was performed. Also several existing completely wire-bonded modules have been successfully retrofitted.

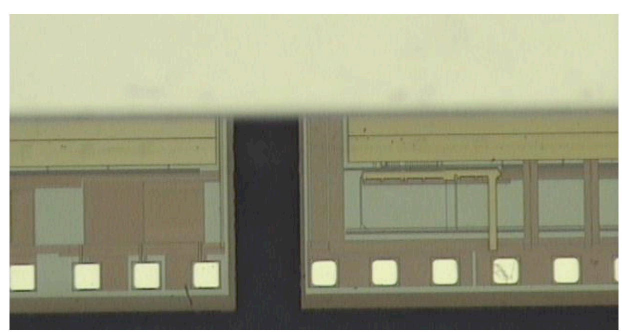

Fig. 5: Example of the exposed ASIC in a module. The sensor is the grey/fuzzy area on top of the picture and below there are the two ends of the ASICs in a 2x1 module.

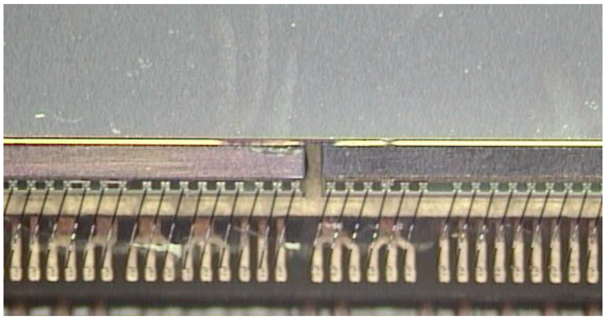

Fig. 6: In this picture the W foils have been applied as well as wire bonding to the PCB. Comparing this figure with Figure 5 is easy to see that the exposed ASIC is now completely protected

IV. Analysis

We investigated a couple of particular events that took place in the LCLS-CXI experiments. The first event we called "the ice hit" (Fig. 1 and 7). A water jet, used to deliver the specimen, crystallized causing the beam to scatter into the camera [5][6]. In this case the module did not have any W foils installed. The detector lost at least three (3) ASICs, a full module 2x1 consisting in two ASIC and one half of a module equal to one ASIC.

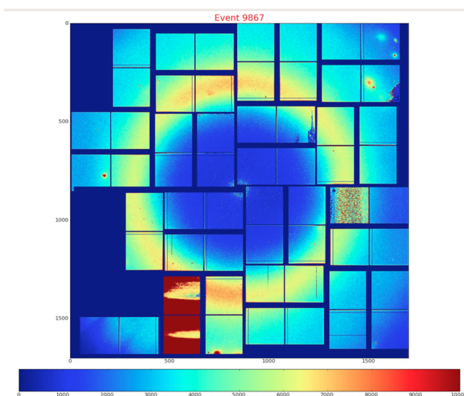

Fig.7: Screen shot of the CSPAD camera just after "the ice hit" event. The yellow ring is what is called water ring and it is composed of damage points. Notice the lower left module in red.

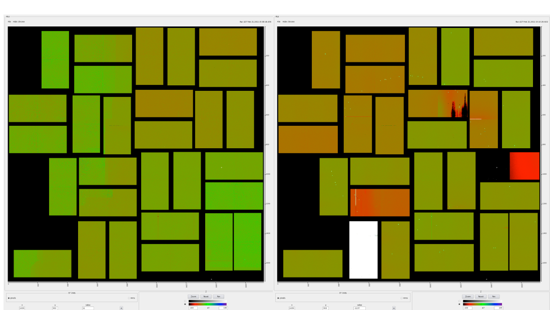

Fig. 8: This is a comparison side by side of the first and the last event of "the ice hit" run. On the picture on the right it is obvious that the lower left module is not responding, resulting in a white rectangle. On the same image another ASIC is not functioning anymore resulting in a black square.

In the second incident, named "the time flight chamber" event (Fig.10), extensive exposure to the right-hand side of the CSPAD camera occurred. This was caused by the scattering of the beam hitting the ceramic support of a repeller-extractor structure forming part of a time flight mass spectrometer.

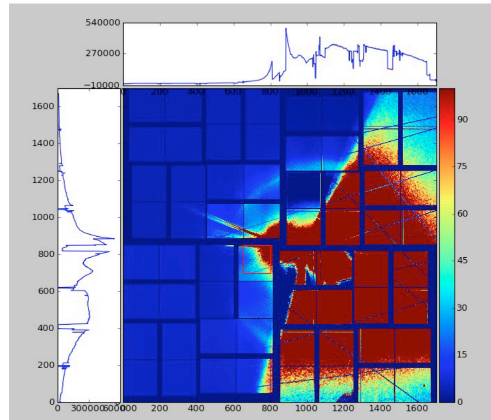

Fig.10: Screen shot of "the time flight chamber" event. In this image it is possible to observe also the shadows of wires used as reference for alignments of the camera.

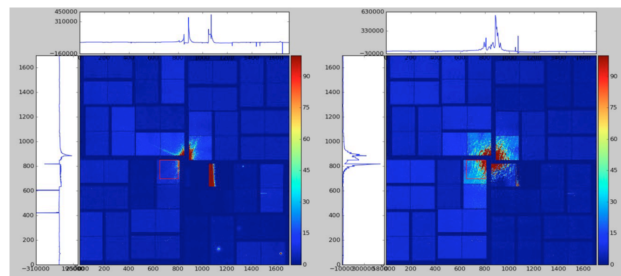

Fig 11: Screen shots of the images after "the time flight chamber" event. On the left, one soon after the hit and on the right, one seven (7) hours after.

This version of the camera had most of the modules protected by tungsten foils (Fig.11). In this incident no ASICs were lost. In subsequent experiments in the LCLS-CXI chamber we did not lose any shielded modules of the camera.

We considered a pool of pixels that showed substantial change in behavior after "the ion chamber" event. The plot of few random pixels (Fig. 12) from this pool indicates a slow but promising recovery trend.

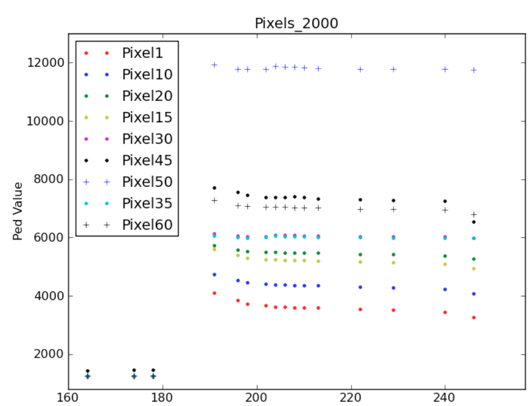

Fig. 12: Plot of the difference between dark runs of pedestal values before and after the event. A cut was applied to select only pixels that show a particular high value. The event happened on run 188.

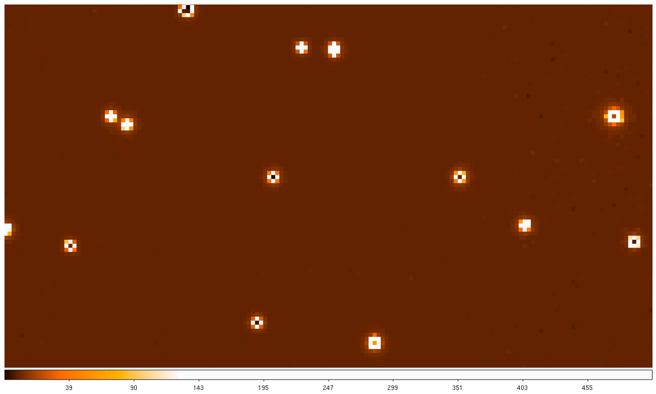

Fig. 13: The plot shows the result of the difference in pedestal for a particular quadrant, q131 of the CSPAD camera, between the pre-heating state and the annealing state after 24 hours at 140^{o}C.

Annealing studies have been also performed on the CSPAD camera. Most of the pixels showed some recovery after annealing. Notice in Figure 13, the cross (+) structures of pixels surrounding many abnormal pixels.

Furthermore, two test sensors, a 100µm pitch pixels array and a 2x3 diode on 500µm thick silicon substrate, were irradiated with a 7008eV beam in a single mode shot, producing a $1x10^{11}$ photons per pulse which is equivalent to 1.75 mille-Joule per pulse. Several attenuation beam settings were applied in exposures to individual pixels. If bulk crystal sensor damage was the dominant effect, the expected variation in the pixels' current after the exposure would have been around 40µA, yet measurements before and after the dose showed only 1µA or 2µA variance, which was within the systematic error.

Another study of radiation damage is shown in Figure 14, contrasting the pedestal for a damaged region with and without the input amplifier in reset. This suggested that some radiation damage is occurring on the sensor surface.

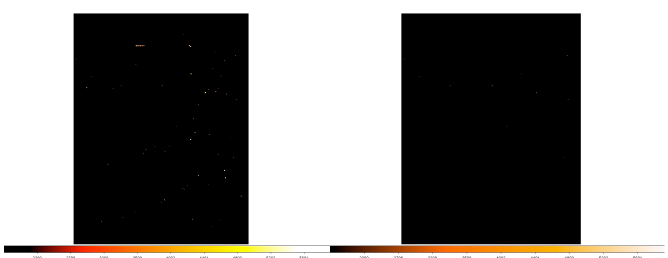

Fig. 14: Side by side comparison of the dark pedestal with input- amplifier not in reset (on the left) and in reset (on the right). Observe that the decoration of spots in the first image mostly disappears in the second image suggesting that this variety of damage is in the sensor surface.

V. Conclusion

The radiation hardness of the CSPAD camera has been dramatically improved by the employment of W shields. An effective design and micromachining of tungsten foils has been implemented giving successful results. Since the foils' application, none of the ASICs have been lost or damaged. Further studies of detector damages are under way. Preliminary results have shown that radiation damage is not likely to occur in the bulk sensor.

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