

# **Radiation Safety at LCLS: The Photon Beam's Maximum Capability and Material Damage Potential**

J.M. Bauer<sup>1</sup>, J.C. Liu<sup>1</sup>, A.A. Prinz<sup>2</sup>, and S.H. Rokni<sup>1</sup>

<sup>1</sup>*Radiation Protection Department, SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, U.S.A.*

<sup>2</sup>*Linac Coherent Light Source, SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, U.S.A.*

## **Abstract**

The Linac Coherent Light Source (LCLS) at the SLAC National Accelerator Laboratory is pushing with its high-brilliance X-ray beam the boundaries also for Radiation Protection.

One of the factors to be considered during the design of shielding and other safety systems is the strength of the beam that the facility might be capable of. Recent estimates of these capabilities for this new and still evolving facility are being discussed in this report.

Especially close to the Undulator and after focusing elements, the X-ray beam is challenging to contain, since materials like steel and even strong materials like boron carbide (B4C) can be damaged by the beam. Dedicated experiments to understand the damage threshold of B4C have been performed.

Self-seeded beam and expansion to lower energies (down to below the carbon edge at 280 eV) create further challenges that had not been mitigated during the original design. Examples of recent analyses and mitigations are being described.

## **1. Introduction to LCLS**

The Linac Coherent Light Source (LCLS) is a Hard X-ray Free Electron Laser at the SLAC National Accelerator Center, operational since October 2009 [1]. It uses the last 1/3 of SLAC's 2-mile long Linac for acceleration of electrons to up to 16 GeV at 120 Hz repetition rate. These electrons pass through 112 m of active Undulator sections before being dumped. In the Undulator, the electrons create pulses of coherent X-rays, the Free Electron Laser (FEL) beam, on a background of incoherent radiation that is called Spontaneous Radiation (SR). The energy of the FEL is tunable from close to 12 keV down to now less than 280 eV (with this lower limit being significantly lower than considered in the original design). The pulse duration ranges from about 500 fs to less than 10 fs. The photon beam width is of the order of 1 mm when unfocused, but may go down to about 1  $\mu\text{m}$  when focused with mirrors or Beryllium lenses.

## **2. Photon Beam Containment Challenges**

Photon beam is being delivered to one of six hutches: Two of them take soft X-rays with energies up to 2 keV, while the other four hutches take X-rays from 2 keV on up. In general, beam terminates inside a hutch only if the hutch is in no access, *i.e.*, with no one allowed inside the hutch. This is true for all hard X-ray hutches, while at one of the soft X-ray hutches beam may also terminate on a stopper that is located inside an accessible hutch. In addition, photon beam is also transported through some hutches in steel vacuum pipes while the hutches can be accessed.

It is therefore important to understand the limitations of and challenges to the photon beam containment:

- (1) Unfocused beam itself is able to burn through steel, the material of the vacuum chambers. Focused beam can burn through any solid.
- (2) Mirrors and any similar good-quality surface will steer the beam when hit at glancing incidence.
- (3) And good-quality crystals might diffract the beam and redirect a large portion of the beam into any direction.

To meet Challenges (1) and (2), ray trace analyses verify that no beam terminates on steel, only on specially designed collimators or stoppers. Since boron carbide (B4C) has been shown to greatly withstand FEL beam, stoppers and collimators use this material to stop unfocused beam. Focused beam will be stopped by a few centimeters of water, and for these cases a water dump may be used, equipped with sensors to ensure enough water is in the dump. If beam would indeed drill a hole into the water dump enclosure and would drain the water, the sensors will initiate beam shutdown. For low-energy beams (<2 keV), 30 cm of plain air is already enough to stop the beam, and air gaps are therefore enforced either by setting up exclusion zones (disallowing persons to put their hands into these zones), or by closing off access to the whole experimental hutch. The ray trace analyses also take into account the angles of reflections, the drop in reflectivity with higher angles, and, if necessary, hardstops on mirrors.

Challenge (3) is more complicated. No general analysis has yet been provided to prove that diffraction of a large portion of the beam is improbable or even impossible. So far, a special analysis is performed for each experimental situation. Complicating the situation is self-seeded beam, already implemented at LCLS for hard X-rays. The properties of self-seeded beam are just like those of regular FEL, but with an energy bandwidth that is smaller than the Silicon bandwidth acceptance. This allows, in principle, full diffraction of the self-seeded beam to any direction.

The sections below expand on the analyses and measurements performed to meet these challenges.

### **3. Maximum Capability of LCLS**

Since a strong photon beam is in the interest of the physics community, no limits are imposed for Radiation Safety reasons on the settings of the Undulator. Any analysis of the damage potential needs to know how strong the LCLS beam can be, in total energy per pulse, energy per area, and divergence as the beam travels downstream. An analysis to determine these limits was performed by Heinz-Dieter Nuhn from SLAC, and his results serve as the basis of the Radiation Protection analysis.

Physics principles are used together with simulations of LCLS and existing operational experience. Due to the novelty of LCLS (being the first of currently two Hard X-ray Free Electron Lasers in operation), new ideas are always being tried out, which could, at some point, lead to actual beam parameters approaching or even exceeding the limits determined with the current simulations.

#### **3.1. SASE Capabilities**

The “normal” FEL consists of the Spontaneous Radiation (SR), which is the typical incoherent Undulator radiation seen in normal synchrotron rings. On top of that is the SASE beam, the beam created by “Self-amplified Stimulated Emission,” in which randomly occurring variations start FEL creation. This SASE beam displays coherence and, due to its small beam size, has the potential to damage material. FEL is generated at exponential rate inside the Undulator up to the so-called saturation point, from which on the increase is only linear. An example of such a rise in FEL power along the length of the Undulator is shown in Figure 1, for both measurement and simulation.

Due to the complexities of the process, running with a large charge in the electron pulse does not necessarily create the strongest FEL pulses. Simulation studies and operational experiences are therefore required to determine the optimal settings. So far, measurements are quite consistent with the simulations.

The energy per pulse is plotted versus photon energy in Figure 2 for both the estimated maximal capabilities (solid line) and measurements from past operation. Note that a safety margin was added to keep the measured values (and the actual operational limit) far enough from the estimated maximum capability that is used for Radiation Protection analyses.

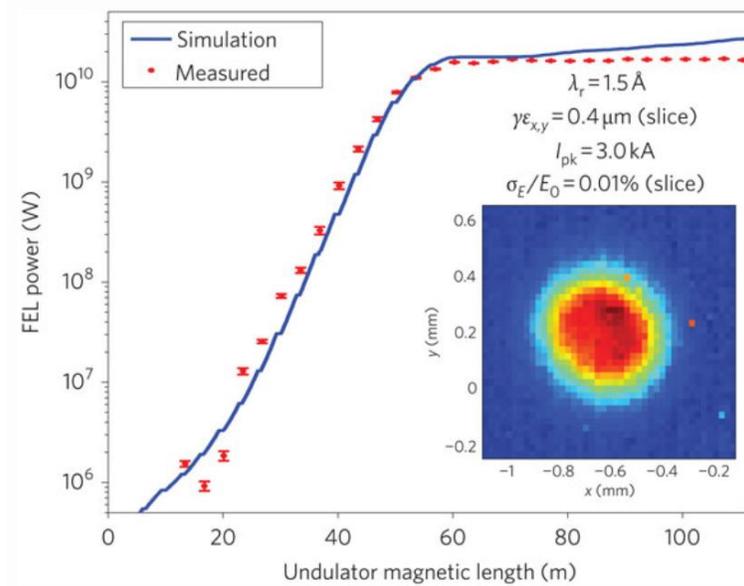


Fig. 1 – Typical FEL gain curve for LCLS Undulator, showing the rise in power in the pulse over the length of the Undulator. In this case, exponential gain is seen until about 60 m into the Undulator, followed by slower rise at approximately linear rate (from [1]).

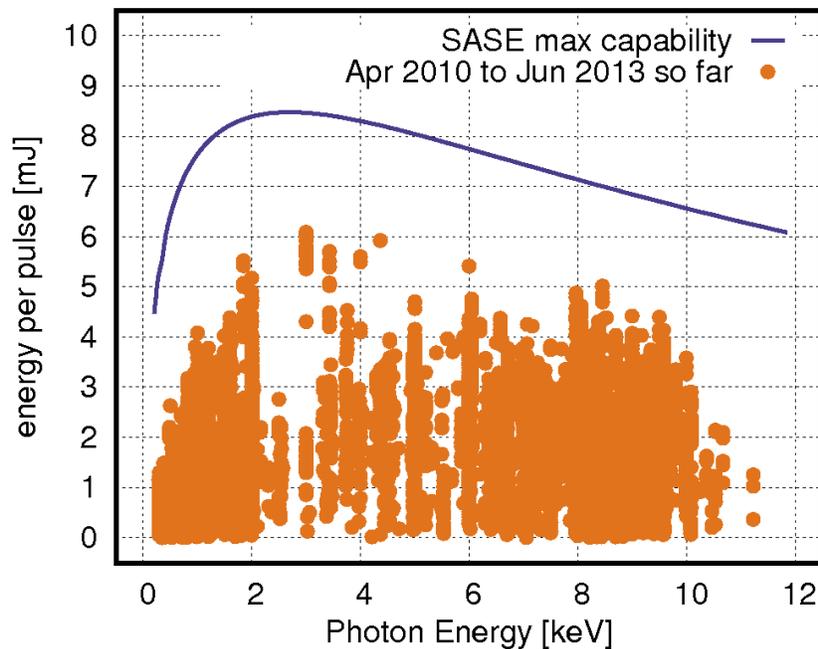


Fig. 2 – Energy per pulse for SASE Beam: Maximum Capability (solid line) and actual measurements of energy per pulse.

### 3.2. Self-seeded Beam Capabilities

Self-seeded beam is created in the following way (described in a very simplified way): After a few sections of the Undulator, a band of energy is picked out of the SASE beam. The remaining beam serves then as a seed for the FEL that is created in the latter sections of the Undulator. Instead of relying on the random fluctuations of SASE to start the lasing process, the seed is able to initiate a higher-quality beam at once. A small amount of energy still goes into FEL creation from spontaneous fluctuation (SASE), just like still some SR will be present.

The energy per pulse is for Hard X-ray Self-seeded Beam 3 to 10 lower than for unseeded SASE beam, but, as mentioned above, the energy bandwidth is much smaller than for unseeded SASE beam.

Soft X-ray Self-seeded Beam is going to be produced from end of 2013 on using a process that is slightly different from the one used for Hard X-ray Self-seeded Beam. Its energy per pulse may be up to 30% higher than for unseeded SASE beam.

Further ideas being pursued are Two-Color Beam and iSASE schemas, where the various sections of the Undulator are tuned in special ways to create FEL with two slightly different frequencies (“colors”) and/or to increase the time that the electrons interact with the photon pulse. Analysis predicts that hazard from such special beam conditions will always be lower than for SASE and self-seeded beam. Once new hardware is installed, further analysis of the maximum capabilities will, of course, be necessary.

#### 4. Extrapolation of Maximum Capabilities to Areas along LCLS

Once the maximum capabilities of the beam are known, the beam’s effect on the various material at various locations in LCLS can be calculated. Details of these calculations were presented by Alyssa Prinz in her talk at RadSynch13 [1]. Here we show only a single plot, Figure 3, with such results, for SASE beam at the SXR beamline with its focusing mirror. The photon energy is displayed along the horizontal axis, the distance from the undulator on the vertical axis, and the colors are indicating the dose to B4C in units of eV/atom. Similar analyses were also performed for other beamlines, for steel, and for self-seeded beam.

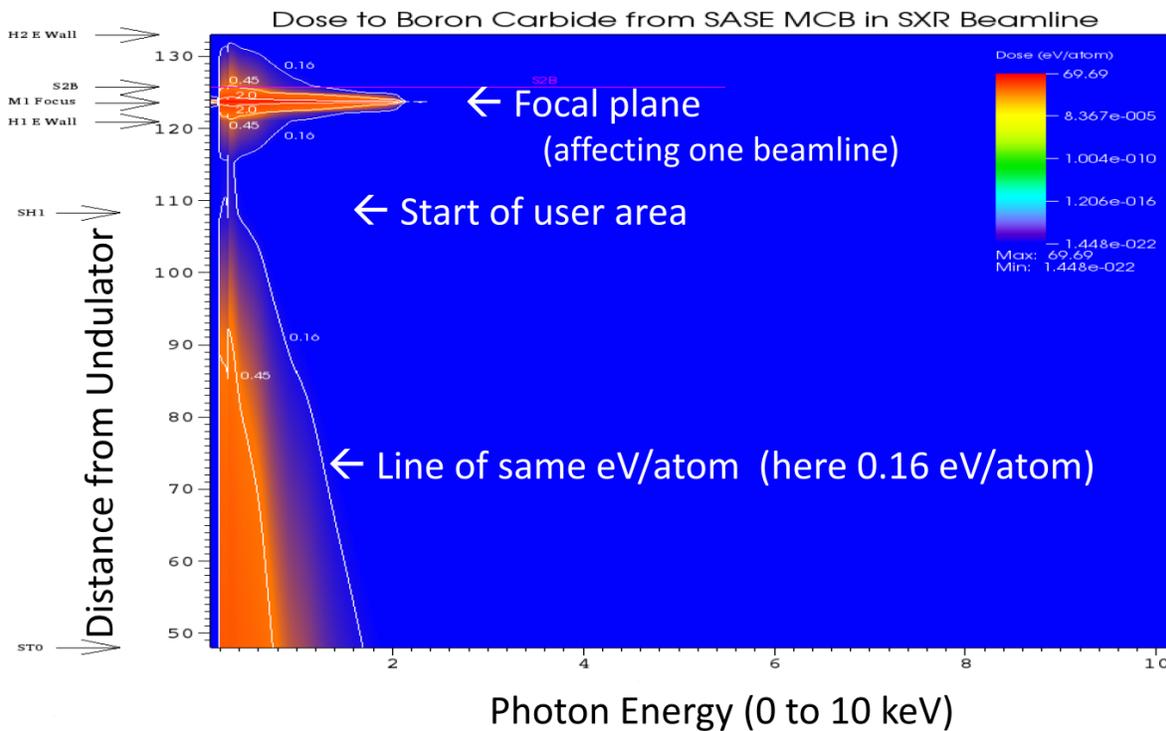


Fig. 3 – Result from application of SASE Maximum Capable Beam parameters to SXR beamline at LCLS. The colors represent the dose to B4C in units of eV/atom.

#### 5. Material Damage Experiments

Another input necessary for proper evaluation of the damage potential by the LCLS beam are measurements of the damage to the various materials used for beam containment. The most important material there is B4C, and recently a series of experiments has been performed by Stefan Moeller and Jacek Krzywinski from LCLS, using focused beam at the SXR instrument at LCLS [3].

They obtained the pulse-by-pulse energy with a gas detector, determined the fraction that is lost in the mirror between that detector and the focal spot, and measured the Lead Tungsten (PbW) single pulse damage threshold with imprints of the beam on PbW. Their result agreed with the known PbW threshold. They then proceeded to use the same process on B4C. They determined the B4C Single Pulse Damage Threshold, *i.e.*, the lowest energy needed to damage B4C in one single shot, to be  $0.49 \pm 0.08$  eV/atom (preliminary result).

Due to concerns of long-term damage, *i.e.*, material fatigue over time, a long run was performed with 650,000 shots at an average per-pulse energy of 0.16 eV/atom, and no damage to the B4C was detected. This value of 0.16 eV/atom is now being used in the LCLS damage analyses as the B4C Safe Limit.

Previous experiments at LCLS had determined the safe threshold of steel to be 0.28 eV/atom, and of drywall (gypsum board, also called sheetrock) to be 3.0 eV/atom. Note that the material's density and composition and the elements' X-ray absorption characteristics have to be taken into account when comparing the materials. In general, the resilience to photon beam is highest for B4C, followed by drywall, then steel.

## **6. Damage Analyses at LCLS**

The maximum capabilities, the calculated dose on the material, and the experimentally determined safe limits and single pulse damage thresholds were now put together to analyze various situations.

### **6.1. Unfocused Beam**

As can be seen from Figure 3, the dose at SH1 (the location of the safety stoppers in front of the experimental hutches) is at about the safe limit; therefore, B4C at these stoppers will not be damaged. Further upstream, however, at ST1 and ST2 (close to location ST0), the safe limit is significantly exceeded. To avoid any B4C damage with further beam improvements, a properly designed stopper is being installed upstream of ST1 and ST2. If, in the worst case, that stopper's B4C would be breached, a burn-through monitor would be punched through, causing a pressure drop in its vessel that would initiate beam shutdown.

### **6.2. Focused Beam**

A special case exists in the SXR beamline, where Stopper S2B sees focused beam due to a permanently installed focusing mirror. With expansion of LCLS to lower and lower beam energies, the stopper is now able to see beam close to the single pulse damage threshold. The use of this stopper is therefore disabled until a proper solution is found, *e.g.*, by installing a suitable stopper upstream.

### **6.3. Diffracted Beam**

Since no proof has been presented that diffraction of a significant fraction of the photon beam is impossible or improbable, the actual geometry of the experiments are being considered in a series of analyses. Of largest concerns are focused beam experiments. The studies look at the location of all good-quality crystals, like in mirrors, diagnostic equipment, and experimental samples, at the location of vacuum and hutch walls, and at the properties of the focusing optics.

Based on these analyses, experiments using crystals could be performed under certain conditions:

At times, restriction on the focal length of Be lenses have to be imposed. Often it can be shown that for the given optics no simultaneous damage is possible to both the vacuum chamber and wall. This ensures that beam is always stopped by at least one of those two walls. If no vacuum chamber exists or the distance between vacuum chamber and wall is too close, an extra drywall might be required. Once also the argument was used that the crystal in question would melt before drywall would be damaged, hence automatically stopping the diffraction. And for energies below 2 keV, common materials like Silicon, Germanium, or YAG do not diffract.

## 7. Conclusion

To evaluate the hazards from the new type of photon beam provided by the Linac Coherent Light Source at SLAC, the Radiation Protection Department embarked with colleagues of LCLS and the SLAC Accelerator Directorate on a program, in which the maximum capabilities of the facility were estimated, safe thresholds of shielding materials were determined, and the effect of the beam on material at various locations were estimated. Various mitigations were being implemented, with new mitigations for the challenges from future improved beam operation still being installed.

Since the accelerator physicists are working hard to improve the output from this novel machine, the RP Department will keep an eye on the performance of LCLS in case actual operation approaches the current limits.

## Acknowledgements

The authors wish to thank their SLAC colleagues for the many fruitful discussions and contributions to the Radiation Safety analysis. Special thanks for Heinz-Dieter Nuhn (SLAC Accelerator Directorate) for his analysis of the maximum beam capabilities, and to Stefan Moeller and Jacek Krzywinski (both LCLS) for their material damage studies. The work was supported by Department of Energy contract DE-AC02-76SF00515.

## References

- [1] P. Emma *et al.*, *First lasing and operation of an angstrom-wavelength free-electron laser*, Nature Photonics 4, 641-647 (2010).
- [2] A.A. Prinz, *Estimation of the Survivability of Boron Carbide and Steel Struck by the Direct FEL X-Ray Beam of LCLS*, these proceedings.
- [3] SLAC Memorandum, *Results of B4C survivability test at 2.7 GeV (330 eV) in the focused beam of the SXR beamline*, S. Moeller and J. Krzywinski, August 6, 2013.