Design of a diamond-crystal monochromator for the LCLS hard x-ray self-seeding project

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Abstract. As the result of collaborations between the Advanced Photon Source (APS), Argonne National Laboratory, and the Linac Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory, we have designed and constructed a diamond crystal monochromator for the LCLS hard x-ray self-seeding project. The novel monochromator is ultrahigh-vacuum compatible to meet the LCLS linear accelerator vacuum environmental requirement. A special graphite holder was designed for strain-free mount of the 110-µm thin synthetic diamond crystal plate provided by Technological Institute for Super-hard and Novel Carbon Materials of Russia (TISNCM). An in-vacuum multi-axis precision positioning mechanism is designed to manipulate the thin-film diamond holder with resolutions and stabilities required by the hard x-ray self-seeding physics. Optical encoders, limit switches, and hardware stops are established in the mechanism to ensure system reliability and to meet the accelerator personal and equipment safety interlock requirements. Molybdenum shields are installed in the monochromator to protect the encoders and associated electronics from radiation damage. Mechanical specifications, designs, and preliminary test results of the diamond monochromator are presented in this paper.

1. Introduction
To longitudinally improve the coherent quality of the x-ray radiation produced by the LCLS FEL and reduce the level of the spikiness in their spectrum and temporal structures, a proposal was made at DESY [1] in August 2010 to remove one 3.4-m-long LCLS undulator section near U15 and replace it with a weak electron delay (a small four-dipole chicane) and a diamond crystal in order to monochromatize and self-seed the LCLS hard x-ray radiation when using the 20-pC low-charge operating mode. As the result of collaborations between the APS, Argonne National Laboratory, and the LCLS at SLAC National Accelerator Laboratory, we have designed and constructed a diamond crystal monochromator for the LCLS hard x-ray self-seeding (HXRSS) project. In January 2012, the monochromator was installed in the tunnel of LCLS, and the HXRSS commissioning team started the self-seeding test soon after.

Mechanical specifications, designs, and preliminary test results of the diamond monochromator for the LCLS HXRSS project are presented in this paper.

2. Monochromator UHV enclosure and its space limits
Since the space available for the HXRSS diamond monochromator is considerably limited by its surrounding components and the existing girder system, a compact vacuum enclosure was designed
with ultra-high-vacuum (UHV) compatibility as required by LCLS vacuum system. Figure 1 shows 3-D models of the monochromator UHV enclosure. As shown in figure 1, the monochromator vacuum enclosure hosts a 10” flange for a 4-axis diamond positioning system, a beryllium window for x-ray diagnostics, a 75 l/s ion pump, two 1.33” O.D. viewports, and a pair of all-metal valves connected to the LCLS vacuum system. The distance between the flanges of two valves for bellows is limited to less than 264 mm. The monochromator vacuum enclosure is mounted to the original girder system through a base plate with alignment mechanisms.

Figure 1. 3-D models for the HXRSS diamond monochromator UHV enclosure.

3. Design of the precision motion control in UHV

As shown in figure 2, a 4-axis precision stage system for diamond crystal manipulation is mounted on a 10” base flange. The base flange is equipped with electric feedthroughs for various in-vacuum motors and optical encoders closed-loop controlled from controllers outside vacuum. Precision mounting holes are also prepared on the base flange for diamond-crystal position survey and alignment from outside vacuum. Table 1 summarizes the design specifications for the monochromator 4-axis precision stage system.

Figure 2. 3-D models for the HXRSS diamond monochromator 4-axis precision stage system.

3.1. Pitch rotary stage

The monochromator pitch stage controls the Bragg angle of the diamond crystal. It is a customized Micos™ PRS-110 UHV-compatible stepping-motor-driven rotary stage with a 0.0001-degree resolution optical angular encoder. The pitch stage is specified to have a better than 0.0002-degree unidirectional repeatability with closed-loop control. Molybdenum radiation shielding plates are applied to the rotary stage to protect the optical encoder and electronics components in the stage.
Table 1. Design specifications for the HXRSS diamond monochromator 4-axis precision stage system.

| Parameter                                                      | Value  | Units |
|----------------------------------------------------------------|--------|-------|
| X position control range                                       | -1/+3  | mm    |
| Y_{roll} position control range                                | +1.5/-8.5 | mm |
| X and Y_{roll} position resolution and stability (rms)         | < 0.05 | mm    |
| crystal extraction position (approx)                           | -8.5   | mm    |
| crystal pitch angle hard limit range                           | 42 – 98 | deg   |
| crystal pitch angle limit switch range                         | 45 – 95 | deg   |
| crystal pitch angle operation range                            | 47 – 93 | deg   |
| pitch angle stability (rms)                                    | < 0.005 | mrad |
| crystal roll angle control range                               | ±2.5 – ± 3 | deg |
| crystal roll angle resolution and stability (rms)               | < 0.010 | mrad |
| Vacuum                                                         | UHV    |       |
| F-F distance w/valves                                          | 264    | mm    |

3.2. Tip-tilt and linear stages
The monochromator tip-tilt stage provides a roll adjustment for the diamond crystal alignment as shown in figure 3. The 4-bar flexural bearing structure is modified from an original APS design for a compact multi-dimensional alignment apparatus developed for multilayer Laue lenses (MLLs) with nanometer-scale 2-D focusing [2]. The 4-bar flexural bearing structure is operated by a SmarAct™ PZT-driven linear stage to provide a precise angular positioning around the Y_{roll}-axis, which is rotating with the pitch stage, and agrees with the Y-axis while the pitch angle (equal to the x-ray grazing incidence angle to the diamond crystal) is at the 90-degree position. The X and Y_{roll} linear stages, mounted on top of the 4-bar flexural bearing structure, provide the linear motion required by the HXRSS system. During the self-seeding test, the X and Y_{roll} linear stages align the diamond crystal to the test position. The X and Y_{roll} linear stages can retract the diamond crystal holder to a safe position in the LCLS normal operation condition with safety interlock control.

4. Thin diamond crystal plate handling
The HXRSS monochromator is using a 0.1- to 0.15-mm-thick, very high quality thin diamond-crystal plate with (001) orientation [3]. Since the crystal holder is close to the electron beam in the linear accelerator, it is best that the diamond holder be made of low-Z materials to meet radiation safety requirements. Highly ordered pyrolytic graphite (HOPG) was chosen to form the diamond-crystal holder. The diamond holder was designed to minimize the strain in the diamond crystal induced by the holder structure. The diamond holder consists of two parts as shown in figure 4: a main body and a back plate. A precision slot is machined on the main body with a trapezoid shape, which is matched with the diamond-crystal shape to prevent the crystal sliding out of the holder. With an optimized sliding fit, the diamond crystal is held in the holder with a stable and near strain-free condition. Figure
4 shows two configurations of the diamond holder design. The diamond crystal and its HOPG holder were manufactured by TISNCM [3].

![Diamond Crystal and Graphite Holder](image1.png)

**Figure 4.** 3-D models for the HXRSS diamond monochromator diamond holder. Left: Holder configured with maximized stability. Right: Holder configured with minimized mounting strain.

5. Summary
We presented mechanical specifications and designs of the diamond-crystal monochromator for the LCLS HXRSS project. In January 2012, the HXRSS commissioning team led by Paul Emma found the first seeded FEL signal (at 8.334 keV). The new LCLS results clearly demonstrate self-seeding at Angstrom wavelengths with a factor of 40-50 bandwidth reduction observed with respect to SASE operation [4]. Further testing and development of the HXRSS project towards user operation are forthcoming. Figure 5 is a photograph of the diamond monochromator assembled on the LCLS U16 girder system with surrounding components.

![LCLS U16 Girder System with HXRSS Diamond Monochromator](image2.png)

**Figure 5.** A photograph of the LCLS U16 girder system with HXRSS diamond monochromator and other surrounding components.

6. References
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