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MECHANICAL DESIGN OF A DIAMOND CRYSTAL HARD X-RAY SELF-SEEDING MONOCHROMATOR FOR PAL-XFEL*

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Abstract

As a part of the Argonne Strategic Partnership Project (SPP) 85H21, a collaboration between Advanced Photon Source (APS), Argonne National Laboratory (ANL) and Pohang Accelerator Laboratory (PAL), we have designed, constructed, and tested a thin-diamond-crystal monochromator for the PAL X-ray Free-Electron-Laser (PAL-XFEL) hard x-ray self-seeding project [1]. The mechanical design of the PAL-XFEL diamond crystal hard x-ray self-seeding monochromator is based on the APS design of a thin-diamond-crystal monochromator for the LCLS hard x-ray self-seeding project [2,3] with enhanced diamond crystal holder for two thin-diamond crystals with thicknesses of 30 microns and 100 microns [4]. The customized high quality thin-diamond-crystals and special graphite holder were provided by the Technological Institute for Superhard and Novel Carbon Materials of Russia (TISNCM) [5], and tested at the APS [4]. An in-vacuum multi-axis precision positioning mechanism is designed to manipulate the duo-thin- diamond-crystals holder with resolutions and stabilities required by the hard x-ray self-seeding physics. Mechanical specifications, designs, and preliminary test results of the diamond monochromator are presented in this paper.

INTRODUCTION

This short To longitudinally improve the coherent quality of the x-ray radiation produced by the hard X-ray Free-Electron-Laser (XFEL), and to reduce the level of the spikiness in their spectrum and temporal structures, in 2001 Saldin and et al. proposed the initial idea of self-seeding based on the utilization of Bragg diffraction (BD) from a four-bounce diamond crystal monochromator as a band-pass filter [6]. About ten years later, Geloni and et al. proposed a transmission self-seeding using forward Bragg deflection (FBD) from a single diamond crystal with simple alignment requirements [7].

The first hard X-ray self-seeding with forward Bragg deflection (FBD) from a single diamond crystal was demonstrated at the Linac Coherent Light Source (LCLS) in 2012 [2]. Based on the experiences gained from the first LCLS hard x-ray self-seeding (HXRSS) monochromator design [3], a thin-diamond-crystal monochromator for the PAL-XFEL hard x-ray self-seeding project has been designed, constructed, and commissioned as a part of the Argonne Strategic Partnership Project (SPP) 85H21, a collaboration between APS, ANL and PAL.

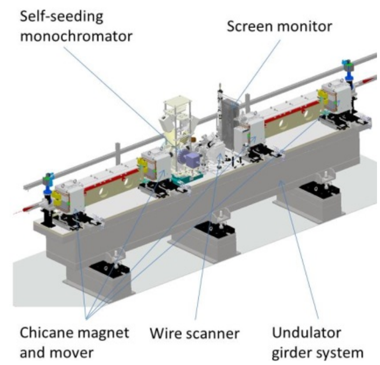

Figure 1: 3D model of the PAL-XFEL self-seeding monochromator integrated on the undulator girder system.

The monochromator was manufactured by a Korean company (VACTRON [8]) based on the ANL/PAL collaborated engineering design, and was installed at the PAL-XFEL in February, 2018. Manufactured by the TISNCM and tested at the APS, the enhanced monochromator diamond crystal holder accommodates two customized high quality thin-diamond-crystals with thickness of 30 µm and 100 µm in the [10] and [11] orientations to satisfy various optimization conditions [4, 9]. The PAL-XFEL self-seeding monochromator has been successfully commissioned without any design flaws soon after its installation [1].

Mechanical specifications, designs, and preliminary test results of the diamond crystal monochromator for the PAL-XFEL are presented in this paper.

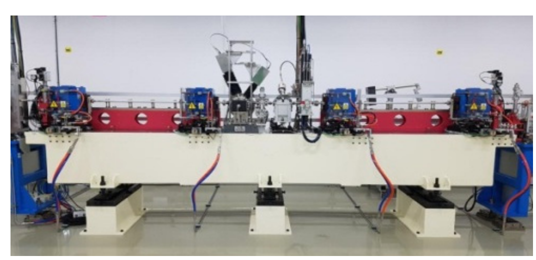

Figure 2: Photograph of the PAL-XFEL self-seeding monochromator integrated on undulator girder system.

COMPACT UHV ENCLOSURE

A compact vacuum enclosure was designed for the PAL-XFEL hard x-ray self-seeding monochromator with ultra-high-vacuum (UHV) compatibility as required by PAL-XFEL vacuum system. As shown in Fig. 1, the hard x-ray self-seeding monochromator is integrated on one of the

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PAL-XFEL undulator girder system with four dipole chicane magnets and various diagnostic tools including: stripline beam position monitor, wire scanner, in-line screen monitor, surveillance camera and et al. The self-seeding monochromator system fits into one original undulator girder as a modular design so that it can be replaced with any undulator and relocated in the future. Figure 2 shows a photograph of the PAL-XFEL self-seeding monochromator integrated on the undulator girder system.

As shown in Fig. 3, the monochromator vacuum enclosure hosts a 12” flange for a 4-axis diamond positioning system, a beryllium window for x-ray diagnostics, a 25 l/s ion pump, two viewports, and a pair of UHV bellows connected to the PAL-XFEL vacuum system. The distance between the flanges for bellows is limited to less than 212 mm. The monochromator vacuum enclosure is mounted to the girder system through a base plate with alignment mechanisms.

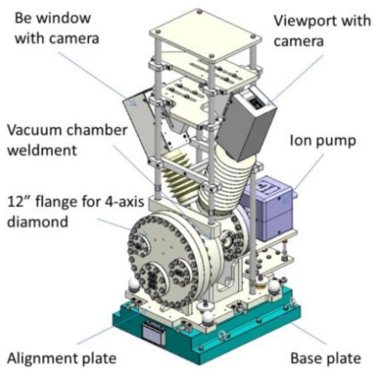

Figure 3: 3D model of the PAL-XFEL self-seeding monochromator UHV enclosure.

PRECISION DIAMOND CRYSTAL MANIPULATION IN UHV

Similar to the LCLS self-seeding monochromator design, a 4-axis precision stage system for diamond crystal manipulation, which includes a precision rotary stage for diamond crystal pitch motion control and a set of tip-tilt and linear stages is mounted on a 12” base flange as shown in Fig. 4. The 12” 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 for diamond-crystal position survey and alignment from outside vacuum.

Pitch Rotary Stage

The self-seeding monochromator pitch stage controls the Bragg angle of the diamond crystal. It is a customized PI^{TM} PRS-110 UHV-compatible stepping-motor-driven rotary stage with a 0.0001-degree resolution optical angular encoder [10]. The customized pitch stage is specified to have a better than 0.0002-degree unidirectional repeatability with closed-loop control. To protect the optical encoder and electronics components in the stage, molybdenum radiation shielding plates are applied to the rotary stage as shown in Figure 4.

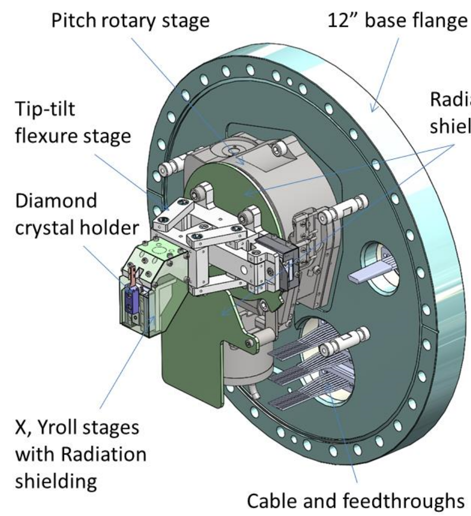

Figure 4: 3D model of the PAL-XFEL self-seeding monochromator 4-axis precision stage system.

Tip-tilt and Linear Stages

As shown in Fig. 4, the PAL-XFEL self-seeding monochromator tip-tilt stage provides a roll adjustment for the diamond crystal alignment. Similar to the LCLS self-seeding monochromator design, 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 flexure tip-tilt stage is operated by a SmarAct^{TM} PZT-driven linear stage [11] to provide a precise angular positioning around the Y_{roll}-axis, which is rotating with the pitch rotary stage, and agrees with the Y-axis while the pitch rotary angle is at the 90-degree position.

Table 1: Design Specifications for The PAL-XFEL HXRSS Monochromator 4-axis Precision Stage System

Stage Design Specifications	
Crystal pitch angle operation range (deg)	32 - 95
Crystal pitch angle limit switch range (deg)	31 - 96
Crystal pitch angle hard limit range (deg)	29 - 97
Pitch angle stability (rms mrad)	<0.005
Crystal roll angle control range (deg)	-5.5 - +4.8
Crystal roll angle stability (rms mrad)	<0.010
X position control range (mm)	-2.8 - +4.8
Yroll position control range (mm)	-12.6 - +2.1
X and Yroll position stability (rms mm)	<0.006
Crystal extraction position (approx. mm)	-11
Vacuum	UHV
F-F distance (mm)	212

The X and Y_{roll} linear stages, mounted on top of the flexure tip-tilt stage, provide the linear motion required by the PAL-XFEL self-seeding monochromator system. During the self-seeding test, the X and Y_{roll} linear stages align the diamond crystal to the test position. With safety interlock

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control, the X and Y_{roll} linear stages can retract the diamond crystal holder to a safe position in the PAL-XFEL normal operation condition. Table 1 summarizes the design specifications for the monochromator pitch rotary stage system. Figure 5 shows a photograph of the PAL-XFEL self-seeding monochromator 4-axis precision stage system.

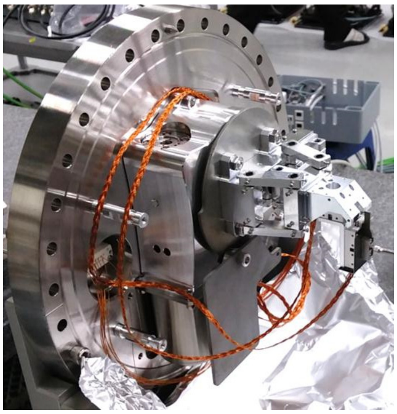

Figure 5: Photograph of the PAL-XFEL self-seeding monochromator 4-axis precision stage system with a dummy of diamond crystals holder for stage test.

THIN DIAMOND CRYSTAL PLATE HANDLING

Since the diamond crystal holder for PAL-XFEL self-seeding monochromator is close to the electron beam in the linear accelerator, it is best that the diamond holder be made of low-Z materials, such as highly ordered pyrolytic graphite (HOPG) to meet radiation safety requirements. The new design of diamond crystal holder for PAL-XFEL self-seeding monochromator kept the same toothbrush-shaped HOPG mechanical design of the LCLS self-seeding monochromator with several important design improvements as shown in Fig. 6:

- The new holder is designed to host two thin-film-diamonds with thickness of 30 μm and 100 μm in the [10] and [11] orientations to satisfy various optimization conditions at the PAL-XFEL.
- The new holder includes a HOPG holder base and a CVD diamond mounting base to ensure a good heat transfer between the diamond crystal and the heat sink.
- CVD diamond post and thin graphite springs are used to hold the thin diamond crystals and provide a gentle clamping force between the thin diamond crystal and CVD diamond mounting base to ensure a good thermal contact with minimized strain added on the thin diamond crystal.

The customized high quality thin-diamond-crystals and the special graphite and CVD diamond holder components were manufactured by the Technological Institute for Super-hard and Novel Carbon Materials of Russia (TISNCM) [4, 12].

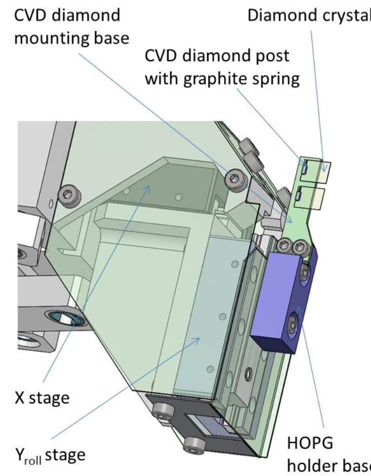

Figure 6: 3D model of the PAL-XFEL self-seeding monochromator thin diamond crystal holder.

SUMMARY

We presented mechanical specifications and designs of the thin-diamond-crystal monochromator for the PAL-XFEL hard x-ray self-seeding project. In April, 2018, the PAL-XFEL commissioning team led by Heung-Sik Kang demonstrated the first seeded FEL signal (at ~8.4keV) as shown in Figure 7. The results showed spectra amplitude of the self-seeding FEL with four times higher than SASE at Angstrom wavelengths. The bandwidth of self-seeding FEL is as small as 0.5 eV. Further testing and development of the PAL-XFEL hard x-ray self-seeding project for user operation are forthcoming.

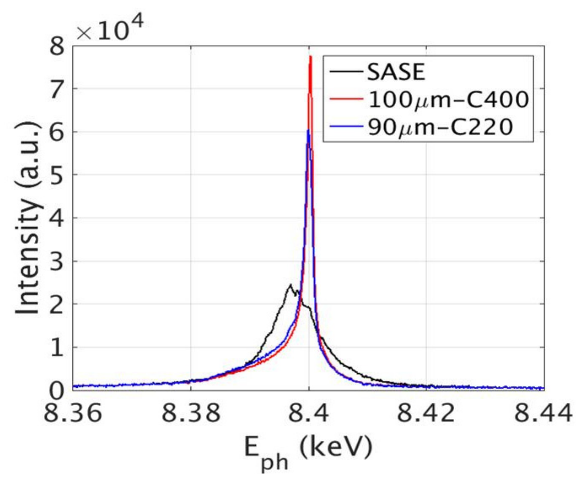

Figure 7: Spectra of the preliminary self-seeding test with PAL-XFEL hard x-ray self-seeding monochromator.

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