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Design of a Cryo-Cooled Artificial Channel-Cut Crystal Monochromator for the European XFEL

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Abstract. An artificial channel-cut crystal monochromator for the hard X-Ray beamlines of SASE 1&2, cryogenically cooled by the so-called pulse tube cooler (cryorefrigerator), is currently under development at the European XFEL (http://www.xfel.eu/). The fabrication is on-going. We present here the crystal optical consideration and the novel cooling configuration, according to the X-Ray FEL pulses proprieties. The mechanical design improvements are pointed out as well to implement such kind of monochromator based on the previous similar design.

1-DESIGN OVERVIEW

Based on the water cooled, Ultra-High-Vacuum (UHV) compatible artificial channel-cut crystal monochromator design at the APS [1,2], and the replications used on XPP and XCS instruments at the LCLS [3,4] for different experiments, a cryogenically cooled one has been developed for the European XFEL X-ray beamlines, in collaboration with Argonne National Laboratory. In total six individual monochromators are needed at the moment and they will be equipped for FXE, HED and MID instruments.

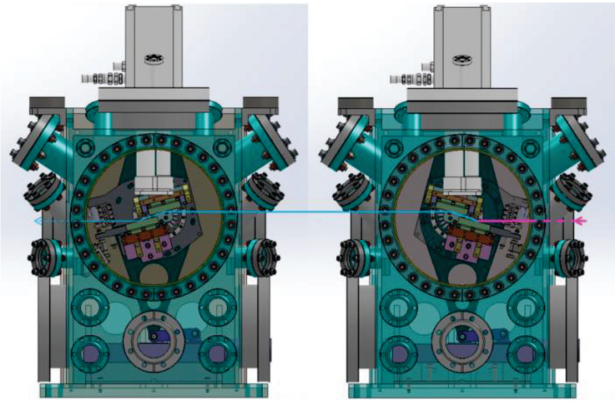

Figure.1 Left-handed version (left) reflecting down-wards, served as the 2nd set of the 4-bounce case; Right-handed version (right) reflecting up-wards

The overview of the monochromator design is shown in Figure.1. Each monochromator chamber can be used individually as a 2-bounce channel-cut monochromator. To compensate for the varied offset of the out-coming beam from the 2-bounce channel-cut monochromator, with two similar monochromator chambers arranged in series, a four-bounce monochromator is designed to achieve a fixed-exit photon beam during energy scan. The two

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monochromator chambers are identically and symmetrically built, as the Artificial Channel-Cut Mechanisms (ACCM, crystal mount holders) [5] are mirrored designs of the left- and right- handed versions.

Compared with a real channel-cut crystal, the most significant benefit of the design is the adaptation of the ACCM, which enables high quality crystal polishing for minimizing wavefront distortions, and minimizes vibrations yet retaining fine tuning of the 2nd crystal according to the 1st one with special weak-link flexure structures of the ACCM. That is very important for the km-long, coherent FEL X-ray beamlines. Energy change and scan are done with the rotation of the ACCM by means of a linear-stage-driven, adapted sine-arm mechanism. Static and dynamic mechanical analysis of the mechanism was considered to ensure the stability of the system.

Crystals operating in a cryogenic temperature is required, due to the European XFEL X-ray design parameters, to increase transmitted pulses. A pulse tube cryo-cooler, based on a water-cooled He-compressor, is chosen because no liquid Nitrogen line is available along the km-long photon beam tunnel and due to its low-vibration performance. The cold head, sitting on the top of the vacuum chamber as shown in the above picture, is separated from the rest of the cooling system. As a result there is no moving part on the cold head to generate any vibration, since it is very important to minimize drift of the photon beam over the km-long beamline.

2-CRYSTAL OPTICAL CONSIDERATION

For the hard X-ray beamlines at the European XFEL, silicon monochromators are required to cover 5-24keV photon energy, and to select the relative bandpass between 1e-4 and 1e-5. Si(111), Si(220) and Si(311), Si(511) are considered for the monochromator design, taking into account the natural bandwidth of the SASE FEL beam. The first two crystals will be implemented for day one operation. Feasibility of extending energy range in both low and high energy ends is expected for the absorption edges of some elements, when needed for the experiments in the future.

The near-diffraction-limited X-ray photon beam has a divergence proportional to its wavelength, leading to a variation of spot sizes with energy of about a factor of 10. This leads to challenges in optimizing geometry, the gap, and length of the crystal optics. Small gap and short crystal are considered to minimize the offset, and for stability and compactness reasons. The optical scheme is shown in the following Figure.2.

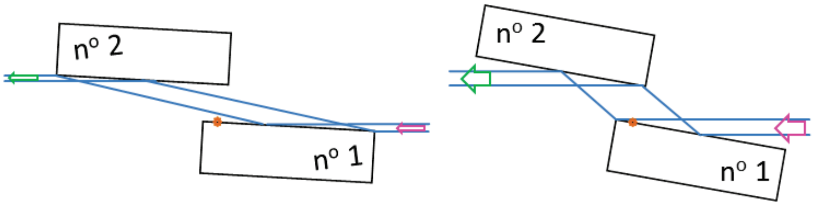

Figure.2 crystal optical scheme: (left) high energy edge, (right) low energy edge, as indicated to define crystals length; and the CoR as shown in yellow, is optimized to get an identical length of both crystals

A crucial point is to define the Center of Rotation (CoR). Locating the CoR on the centre of the 1st crystal leads to longer second crystal and a larger gap. In order to accept 6σ beam for Si(111), a 92.5 mm 2nd crystal is required. We consider this is too long to be compatible with the artificial channel-cut concept without risking mechanical stability. To be located in between the crystals leads to a significantly shorter 2nd crystal. This concept was refined and led to a CoR on the downstream end of the 1st crystal surface.

The scheme as shown in Figure.2 has the following advantages: Both crystals are of equal (minimal) length and their rotation can be better monitored with an autocollimator; A small gap accepting 6σ beam size, limited by the mirror length upstream, of the above energy range, was chosen to minimize the vertical offset of the out-coming beam.

3-CRYSTAL COOLING CONSIDERATION

Thermal load is a critical problem for the Si-monochromator at the European XFEL. The uniquely high repetition rate of X-ray pulses within the 0.6ms of 2700 pulses produces very high peek heat power of about 2000W, and the average heat power is of about 20W during a pulse train of 0.1s.

Crystal performances under such condition were studied to optimize the cooling configuration. The maximum pulse transmitted was evaluated by analytical approximation of thermal transfer, and the peak temperature was calculated with 1D FEA method [6].The crystal temperature gradient and thermal bump effects were performed by 3D FEA simulation with ANSYS® software [7]. The conclusion is that operating at 100K rather than 300K increases the throughput by a factor of two, and >1000 pulses (out of 2700 pulses) per train can be transmitted for bunch charges up to 250pC. During a full pulse train, a P-V displacement of 30nm under 100K was noticed in simulations, but distortion of the crystal diffraction plane over the 50mm crystal length remains below 1/10 of the requested intrinsic silicon crystal's bandwidth.

Feasibility of crystal cooling with copper braid was demonstrated with good results, as shown in Figure. 3, using dummy crystals and a semi-commercial pulse tube cooler (Transmit®PTS 8030). The cooling power capability is shown as a function of temperature, and a power dissipation over 40W at 100 K is sufficient in our case. During the test, the minimum temperature of 36 K was reached in 45 minutes without applying any heat load, and that was remaining fairly stable over 5 days.

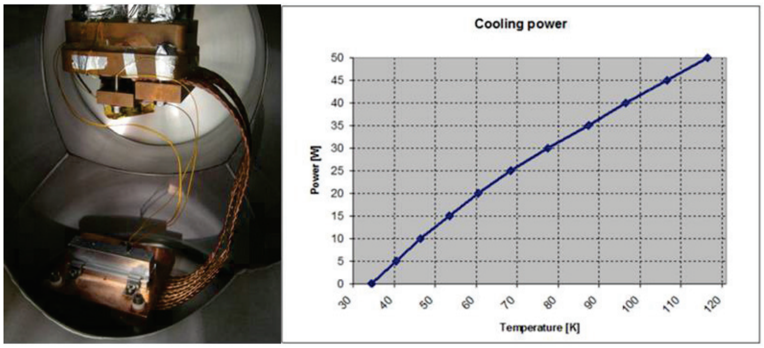

Figure.3 (left) Test set-up with dummy crystals and PTS 8030; (right) Cooling performances

Mock-up of a more flexible copper braids, with smaller copper wires structure, is tested for larger rotation angle range and real design conditions. Furthermore, a fully commercial pulse tube cooler (Cryomech® PT30-RM) is currently under testing for final integration into the monochromator. It will offer higher vacuum compatibility, better insulation and more stable operation.

Both crystals will be connected to the cold finger directly, to avoid Bragg angle variation for operating at diffident temperature. Furthermore, adding heaters and thermocouples on both crystals is also expected, to adjust temperatures during operation and to reduce the time to reach temperature equilibration.

4-MECHANICAL DESIGN DETAILS

We adapted the mechanical design of the existing similar one in the APS [8], but there are modifications and changes for the new design to meet our requirements.

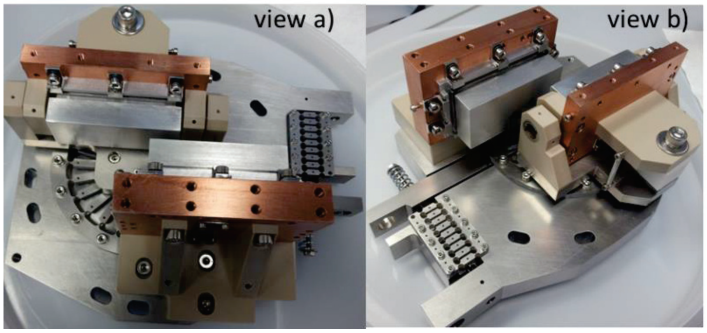

Figure.4 As built ACCM prototype with aluminum dummy crystals (Fabricated by A.J.R. Industrials, Inc., IL USA)

The ACCM prototype, as shown in Figure 4, is optimized for thermal isolation and manufacturing feasibility, and better mechanical stability. PEEK is used as interface between copper plates of crystal holders and the weak-link structures.

The sine-bar mechanism is for the pitch motion of the two crystals. In the previous APS design, the sine-bar arm is coupled to the driving mechanism with a set of anti-backlash springs. The springs provide the restoring force to ensure that the sine bar always stays in contact with a ruby ball when the linear stage is moved. However, it will be difficult to cover a larger angle range of more than 25 deg. with good reproducibility. To reach such a larger angular range, a new design with flexure bearing (C-flex® pivot) joints will be implemented as shown in Figure.1. One concern regarding the new design is that the flexure joints will add low eigenfrequencies to the system. This is evaluated by analytical methods and we got a result of ~200Hz frequency. It's verified by FEA with COMSOL® software as well, using the 3D model of the system, where we got a result of ~300Hz. With the above preliminary calculation, this design should be feasible, provided that the oscillations of the real system are dampened out of the 100ms scale between two pulse trains in our case, although damped motion and driver influence are not taking into account.

The chamber design is slightly modified for in-vacuum alignment and diagnostic purpose especially for the 4-bounce case by adding tilt viewports. Compact design of the chamber itself helps the integration into the underground tunnel to cope with space constraints, and for easy transport and handling for installation as well.

5-SUMMARY

The design of the monochromator is completed, and details as presented above show that it's a suitable device to deliver the XFEL X-Ray pulses. Moreover, a compact support table is being built, with motorized vertical and horizontal movement for remote operation, positioning in the tunnel according to the incoming photon beam, and retracting from the beamline for peak beam mode. The support table has 5-DOF (Degree of Freedom) manual adjustments for pre-alignment of the chamber, and for compensation for floor construction tolerances and mis-alignment along the tunnel. Off-line commissioning of the first set monochromator is expected in spring 2016.

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