Wavefront preserving channel-cut optics for coherent x-ray scattering experiments at the P10 beamline at PETRAIII

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Abstract. We report on the performance of cryogenically cooled monolithic Si(111) channel-cut monochromator optics installed at the coherence beamline P10 of the PETRA III synchrotron source. Our results show that a high quality channel-cut monochromator crystal preserves the beam wavefront and provides excellent beam stability, which offers considerable benefits for coherent x-ray scattering experiments.

1. Introduction

High heat load monochromators are key components of many hard x-ray undulator beamlines. Monochromator optics at third-generation synchrotron sources usually need to fulfill the following tasks: i) provide high monochromaticity, ii) separate the monochromatic beam from the white beam and Bremsstrahlung radiation and iii) protect downstream components from high heat load (total power up to 600 W) of the polychromatic undulator beam. To achieve these needs double crystal monochromator (DCM) optics are commonly used, where a pair of separate silicon crystals are aligned for the same Bragg reflection in parallel configuration. In the DCM design the second crystal can be translated parallel and perpendicular to its surface enabling a wide range of photon energies to be covered, and additionally keeping the exit beam offset constant. Another advantage is that separate crystal plates can be polished to a high degree of surface quality. The primary disadvantage of DCM design relates to the requirement for active cryogenic cooling of both monochromator crystals, in order to avoid thermal distortions caused by exposure to the high heat load of undulator radiation. Inevitably cryocooling induces independent angular vibrations of both crystals, which cause unwanted angular motions of the x-ray beam and thereby increasing the effective source size.

One solution to reduce such directional vibrations of the monochromatic x-ray beam is to employ a channel-cut crystal as the high heat load monochromator. Channel-cut optics are fabricated from a monolithic slab of silicon crystal by cutting a groove which separates two diffracting crystal surfaces [1-8]. This rigid design naturally aligns both diffracting crystal surfaces and prevents their independent angular motions, thus providing a directionally stable beam. Essentially, channel-cut optics transfer spatial vibrations into small variations in energy space. The major drawback of a channel-cut monochromator design is that the exit beam offset is a function of the Bragg angle for the selected photon energy of monochromatic x-ray beam. Another restriction is caused by the fixed length of the second crystal which imposes the upper limit to the accessible range of photon energies.
The homogeneity or smoothness of the beam wavefront is another characteristic which is influenced by the quality of x-ray optics. The wavefront homogeneity is of special importance for coherent x-ray scattering experiments using X-ray Photon Correlation Spectroscopy (XPCS) [9-11] and Coherent X-ray Diffraction Imaging (CXDI) [12-14] techniques. In XPCS and CXDI experiments wavefront distortions can lead to a deterioration of speckle contrast thus hindering data interpretation. The quality of the wavefront is directly coupled to the surface roughness of the crystal optics. In the case of a channel-cut crystal geometry the surfaces are not easily accessible, and the required quality of surface treatment is very difficult to achieve.

In this work we report on the performance of a high quality polished channel-cut monochromator installed at the coherence beamline P10 of the PETRA III synchrotron facility at DESY, Hamburg [15].

2. Experiment
The coherence beamline P10 is located at Sector 7 of the new low-emittance storage ring PETRA III having 2.3 km circumference [16]. The source is a 5 m length U29 undulator with 168 poles and 29 mm period, which delivers maximum power of 7.5 kW at 100 mA ring current. The insertion device is located in a low-beta section of the storage ring and provides an x-ray source with a vertical size of 14 µm and a horizontal size of 85 µm (full-width at half maximum values). The undulator beam subsequently passes through a high heat load Si(111) monochromator (vertically reflecting double crystal or channel-cut optics) located at 38.5 m distance from the source. Using double crystal monochromator enables the photon energy range between 4 and 25 keV. For rejecting the higher-order harmonics, a pair of horizontally reflecting flat silicon mirrors with curvature radius R>100 km is installed after the monochromator at the optics hutch of the P10 beamline.

An important design feature of PETRA III monochromators is the cryogenically cooled copper block with two slots for installing crystal optics. The cryogenic cooling is performed by a closed loop liquid nitrogen cooler, which supplies liquid nitrogen at a controlled and stable pressure to the monochromator crystal optics. Figure 1 shows a photograph of the copper block carrying the first crystal of DCM (lower slot) and the channel-cut crystal (upper slot). The crystal support block is mounted inside the ultra-high vacuum (UHV) chamber on the rotation axis of the monochromator.

![Figure 1. Channel-cut crystal and first crystal of standard double crystal monochromator mounted on the common cryogenically cooled copper block.](image-url)
rotation axis is equipped with a closed loop servomotor and enables high precision angular positioning with an accuracy of 2×10⁻⁵ degrees.

The channel-cut crystal was prepared and fabricated for symmetric Si(111) Bragg reflection. The DESY-FS crystal optics laboratory provided an aligned blank Si crystal, the cutting and polishing has been done by Holm Silicium-Bearbeitung GmbH. The channel-cut crystal has a gap between diffracting surfaces of 11.4 mm which results in 22.2 mm vertical offset between polychromatic and monochromatic beams at 8 keV photon energy. The length of the second surface of the channel-cut is 100 mm which sets an upper limit of 16 keV for the photon energy range of the monochromatic beam (lower limit of 5 keV is constrained by the beamstop collimator design). The presented P10 monochromator design allows to either use the standard DCM or channel-cut optics. The changeover from the DCM to the channel-cut optics is performed by 40 mm horizontal translation of the monochromator UHV chamber.

3. Results and discussion

2.1. Beam profile measurement
Before installing the channel-cut optics at the P10 monochromator UHV chamber, the profiles of the x-ray beam after the DCM were measured without and with the channel-cut optics in the beam. The DCM was selecting the photon energy of 7.9 keV. The channel-cut crystal was positioned in the first experimental hutch of P10 beamline at a distance of 71.5 m from the undulator source (33 m downstream from the DCM). The channel-cut crystal was aligned to diffract the beam in vertical direction in dispersive configuration relative to the DCM optics. The size of incident monochromatic beam at the channel-cut position was 2×0.63 mm² (horizontal×vertical) as defined by frontend slits. The beam profiles were registered using x-ray CCD camera coupled to a scintillator screen. The x-ray camera provided a resolution of about 8 micron and was placed at the detector table at a distance of 93.5 m from the source. The beam profile images obtained for the DCM and the combination of DCM followed by channel-cut crystal are shown in Fig. 2. They are practically identical and reveal smooth intensity distribution defined by the source shape. Slight asymmetry is due to frontend power slits geometry. The beam profile image obtained with the channel-cut crystal reproduces the profile of DCM beam and reveals only several vertical lines originating from surface treatment. Single dot artifacts visible in Fig. 2 originate from sparse dust particles adsorbed to intensity monitor foils.

![Figure 2](image-url)

**Figure 2.** Beam profile images measured using DCM at 7.9 keV photon energy (a) without channel-cut crystal and (b) with channel-cut optics.

2.2. X-ray diffraction surface mapping
The bulk quality of the channel-cut crystal was evaluated by x-ray diffraction rocking curve measurements using standard Si(111) double crystal monochromator at two photon energies of 7.9 keV and 15 keV. The channel-cut crystal was positioned as described in previous paragraph and the diffracted intensity was registered by a silicon photodiode inserted in the beam path behind the channel-cut. Fig. 3 shows the rocking curves measured at room temperature for the symmetric Si(111) reflection of the channel-cut crystal in vertical diffraction plane. Experimental curves are in a good agreement with the curves calculated using dynamical diffraction theory for the given reflections in double crystal monochromator and channel-cut crystal. The energy dispersion was taken into account by integrating of reflection profiles over the source bandwidth. From measurements of rocking curves at 7.9 keV and 15 keV photon energies we obtained full width at half maximum (FWHM) values of 7.2 and 4.87 arcsec. These FWHMs are very close to the theoretical Darwin widths of 7.07 and 3.6 arcsec. for Si(111) Bragg reflection at the considered x-ray photon energies [17]. Experimental rocking curves were normalized to the incident intensities and yielded reflectivity values of 73% and 70% at 7.9 keV and 15 keV photon energies, respectively.

![Figure 3](image-url)

**Figure 3.** Rocking curves of Si(111) reflection from the channel-cut crystal measured using Si(111) DCM at two photon energies, (a) 7.9 keV and (b) 15 keV. Experimental points are shown by dots and calculated curves are plotted by solid lines.

The quality of surface treatment of the channel-cut crystal was evaluated by surface x-ray diffraction mapping. For surface mapping measurement we used a high resolution x-ray camera PCO Edge equipped with magnifying optics and scintillation screen, which provided about 1 µm resolution. The PCO Edge camera was positioned at the distance of 93.5 m from the source, thus having 22 m distance downstream from the channel-cut. The x-ray camera was used to collect projection images of the reflected beam while raster scanning of the channel-cut crystal over the incident monochromatic beam. At each position of the raster mesh the channel-cut crystal was realigned to the maximum of a rocking curve. We collected raster meshes with 0.5 mm step in vertical and horizontal directions which resulted in the full accessible crystal surface areas of 9.5×47 mm² (horizontal×vertical) and 9.5×40 mm² at the photon energies of 7.9 keV and 15 keV, respectively. The obtained surface maps are shown in Fig. 4. Every single-view image in these maps was divided by an averaged beam profile and normalized to the total incident intensity. The single-view images were stitched together to produce the full-field surface maps. The resulting maps confirm high quality of both crystal surfaces of the channel-cut monochromator. Large central areas of the crystal surfaces are artifact free which guarantees beam wavefront preservation after passing through the channel-cut optics. One can observe only a few mainly longitudinal striations, apparently due to polishing treatment. After these
measurements the channel-cut crystal was installed in its working position at the UHV chamber of P10 monochromator.

![Figure 4](image)

**Figure 4.** Surface x-ray diffraction maps of the channel-cut crystal measured at two photon energies, (a) 7.9 keV and (b) 15 keV.

2.3. Beam stability measurements

Measurements of beam stability after the channel-cut monochromator were performed using transfocator optics based on compound refractive lenses. The transfocator was installed at the second experimental hutch of the P10 beamline at a distance of 86 m from the source [18]. Using the transfocator the monochromatic beam was focused onto the blades of motorized slit system located at 1.3 m distance downstream from the focusing optics. Vertical and horizontal slit blades were used for knife-edge scanning and cutting the focused beam to 50% level of incident intensity for stability measurements. The transmitted intensity was monitored using a storage oscilloscope. The time dependences of oscilloscope signal overlaid with knife-edge scans measured in vertical and horizontal directions are shown in Fig. 5. Each knife edge measurement was repeated three times and the resulting profiles are displayed in Fig. 5 by red lines. Focused beam size FWHM values of 1.3 µm in vertical and 2.5 µm in horizontal direction were determined from the widths of derivative curves. Intensity signal deviations were scaled to the slope of the knife edge profile to determine the amplitude (r.m.s value) of beam deviations as depicted by blue arrows and horizontal cyan lines in Fig. 5. The time dependence measurements performed for the channel-cut monochromator demonstrate high stability of the monochromatic beam. Spatial deviations of 50 nm (r.m.s. value) were observed in vertical direction and 70 nm in horizontal direction, which is equivalent to angular beam deviations of 45 nrad and 62 nrad, correspondingly. In comparison with the standard Si(111) DCM, the beam stability using Si(111) channel-cut monochromator has improved by more than five times in vertical direction and about 50% in horizontal direction. Measured efficiency of channel-cut monochromator at 7 keV photon energy is about 80% as compared to DCM conditions.

4. Summary

We describe the performance of cryogenically cooled channel-cut monochromator optics implemented at the coherence beamline P10 of the PETRA III synchrotron facility. A new monolithic channel-cut
crystal has been fabricated and subsequently subject to fine surface treatment. From rocking curve measurements at room temperature we have obtained reflectivity values above 70% and the widths of rocking curves which are very close to theoretical values of Bragg reflection in perfect Si crystal. This result confirms high quality of the bulk of channel-cut crystal optics. Beam profile and surface x-ray diffraction mapping measurements performed at 7.9 keV and 15 keV photon energies indicate high surface quality of both diffracting surfaces of the channel-cut crystal. No wavefront deterioration was observed. Rigid design of monolithic channel-cut monochromator crystal results in excellent beam stability of less than 50 nrad measured in vertical plane under high heat load conditions. The performance of channel-cut monochromator optics offers considerable benefits for coherent x-ray scattering experiments at the P10 beamline.

![Figure 5. Time dependences of oscilloscope signal $I/I_{\text{max}}$ (black lines) monitoring the intensity of the beam focused onto slit blades. $I/I_{\text{max}}$ signal is overlaid with knife-edge scans in (a) vertical and (b) horizontal directions (red lines). Amplitude of beam deviations is depicted by blue arrows and cyan horizontal lines.](image)

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