A High-Precision Cryogenically-Cooled Crystal Monochromator for the APS Diagnostics Beamline

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Abstract

A high-precision cryogenically-cooled crystal monochromator has been developed for the APS diagnostics beamline. The design permits simultaneous measurements of the particle beam size and divergence. It provides for a large rotation angle, -15° to 180°, with a resolution of 0.0005°. The roll angle of the crystal can be adjusted by up to ±3° with a resolution of 0.0001°. A vertical translational stage, with a stroke of ±25 mm and resolution of 8 μm, is provided to enable using different parts of the same crystal or to retract the crystal from the beam path. The modular design will allow optimization of cooling schemes to minimize thermal distortions of the crystal under high heat loads.

Keywords: Crystal Monochromator, Cryogenically-Cooled, Diagnostics Beamline.

1. Introduction

Undulator radiation is used in one of the APS diagnostics beamlines for measuring divergence of the particle beam at high resolution [1]. The beam emittance can be deduced from such measurements with the knowledge of beta functions of the lattice [2]. Alternatively, one can use an x-ray pinhole scan or multi-pinhole aperture measurements to obtain beam emittance independent of the lattice functions [3,4].

Simultaneous measurements of particle beam size and divergence have been proposed recently [5]. This approach yields beam emittance that is robust against fluctuations of lattice functions due to partial cancellation of systematic errors present in both measurements. A thin monochromator crystal is used to measure the divergence from Bragg-reflected x-rays. The thin crystal allows high-energy x-ray flux passing through it to be imaged simultaneously by a pinhole camera for the source size. In this paper we present mechanical features of a cryogenically-cooled crystal monochromator designed specifically for this emittance measurement approach.

2. Mechanical Design Requirements

The monochromator is optimized for beam diagnostics with high flux or high photon energy, using the third or fifth harmonics. A single-crystal monochromator is preferred for reducing the measurement error introduced by the mutual alignment of crystals. In this arrangement, a high quality crystal is used to select the wavelength of the reflected x-rays, λ, according to Bragg's Law,

$$\lambda = 2d \sin\theta ,$$

where d is the spacing of the crystal planes, and θ is the angle of incidence of the beam. The reflected x-rays are detected by an instrument located at a 2θ angle from the original beam direction. Since x-rays are reflected by the crystal's lattice planes rather than its physical surface, adjustment of the roll angle in the beam is required. A vertical translation stage is added to allow for the use of a different part of the crystal, or to retract the crystal completely out of the beam. Additionally, a horizontal translation stage is used to align the monochromator transverse to the beam.

The silicon crystal needs to be cooled by liquid nitrogen (LN_2). At 70° K, silicon's thermal conductivity is 17 watts/cm/°K, which is approximately 10 times higher than that at room temperature. Thermal gradients and deformations in the crystal are thus reduced by an order of magnitude at cryogenic temperatures. A direct vacuum-to-coolant interface is avoided as an accepted design practice at the APS.

3. Mechanical Design

The mechanical design of the crystal monochromator is governed by the requirement of providing a clear path for the x-ray flux passing through the crystal. All translational and rotational mechanisms are, consequently, designed outside the vacuum chamber. Figure 1 shows major components of the crystal monochromator: (1) Huber goniometer, (2) detector positioning mechanism, (3) vertical motion stage, (4) roll angle mechanism, (5) horizontal motion stage, and (6) crystal cooling configuration. These are described in more detail below.

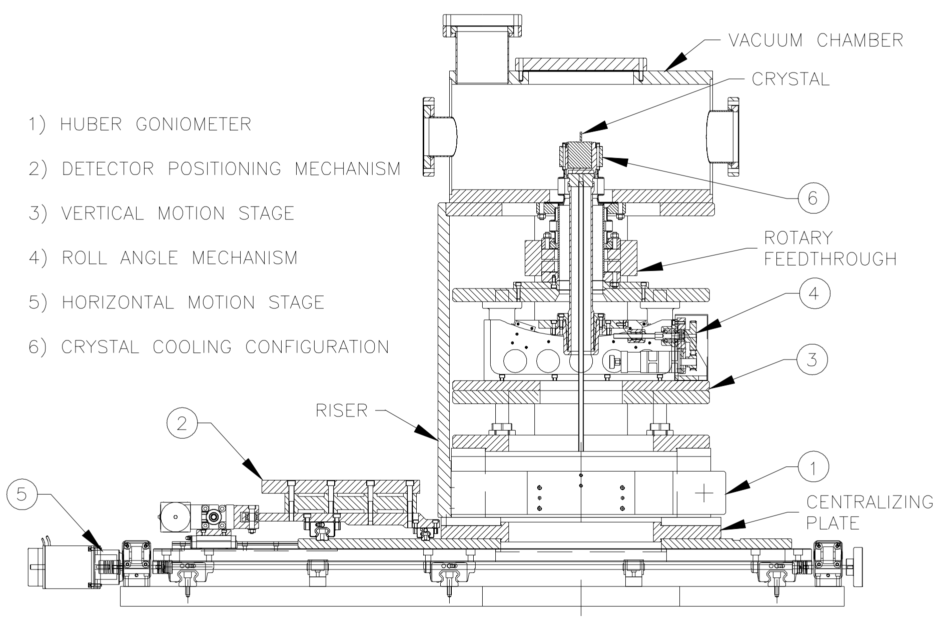

Fig. 1: Mechanical components of the diagnostics crystal monochromator.

3.1 Huber Goniometer

For the θ-rotation of the crystal, a Huber goniometer, Model 440 is used. With the 10:1 gear reducer available with this model, a resolution of 0.0005° is achieved for a full step of the stepping motor. The range of rotation is –15° to 180°. Negative rotations of the crystal can be used for the measurement of absolute Bragg angles using spectral features of the undulator radiation. The comparatively large range of rotation will allow Laue diffraction experiments in the future.

The goniometer is seated on top of a centralizing plate (Fig. 1) that is pre-aligned with the center of rotation of the detector mechanism. Three risers attached to the goniometer (the middle one is depicted in the figure) support the vacuum chamber enclosure for the silicon crystal. A rotary feedthrough with differential pumping allows the crystal assembly to rotate relative to the vacuum chamber.

3.2 Detector Positioning Mechanism

The detector components are assembled on top of the detector mounting plate (see plan view in Fig. 2). The mounting plate is fastened to three carriers riding on two radial tracks of 300 mm and 500 mm radius. One of the carriers is linked to a rod-less screw-driven linear actuator. The actuator, with its stepper motor and reducer assembly, travels on linear tracks as it drives the attached carrier on circular tracks. This mechanism provides a minimum angular resolution of 0.0002°. The resolution, which depends on the motor torque requirement for the mechanism, is better than the required resolution by a factor of 10.

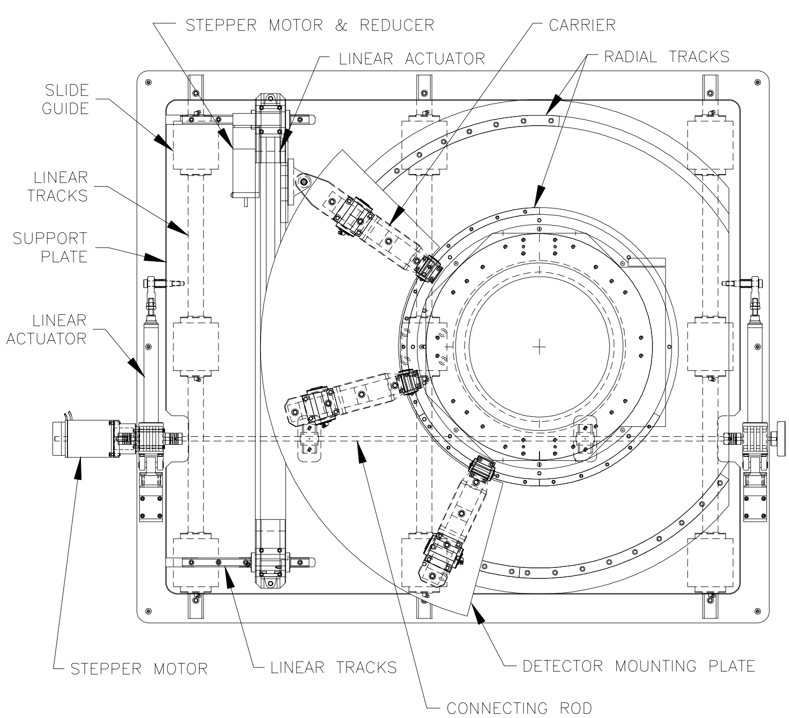

Fig. 2: Detector positioning mechanism shown with horizontal translation stage.

3.3 Vertical Motion Stage

Figure 3 shows the vertical motion stage mounted on top of the Huber goniometer. This stage consists of upper and lower plates separated by four uprights. Each upright houses two linear bearings riding on a vertical slide shaft. Two linear actuators, driven by stepper motors, move the lower plate in the prescribed range of ±25 mm. The lower ends of the actuators' rods are inserted into preloaded spherical bearings to compensate for slight angular misalignment during travel. These bearings are assembled in a plate that is fastened to the top of the goniometer. Motion resolution for a half step of the stepper motors is 8 μm. The stepper motors are synchronized electronically with a motion controller as well as mechanically with a timing belt.

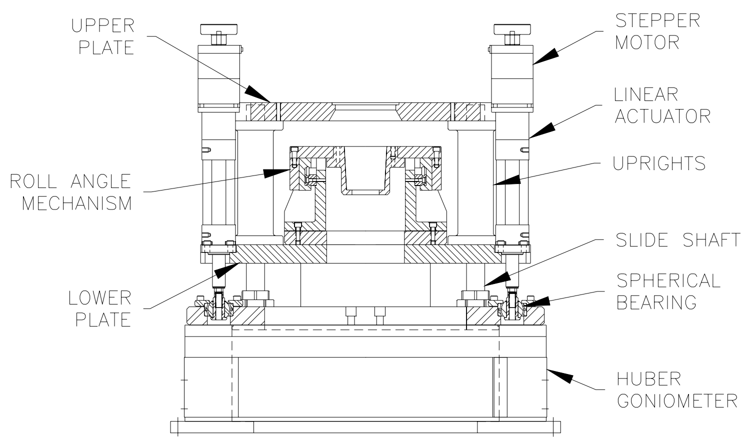

Fig. 3: Vertical motion stage mounted on the Huber goniometer.

3.4 Roll Angle Mechanism

The roll angle ξ is implemented by using two parallel radial tracks in vertical orientation (Fig. 4), each with a radius of 400 mm. The tracks are fastened to a frame that is bolted to a mounting plate attached to the vertical motion stage. Radial centers of the tracks are in line with the center of the beam on the crystal. This eliminates "beam-walking" when the crystal is rotated.

As shown in Fig. 4, a linear actuator and a stepper motor are assembled in a bracket using a belt drive to save space. Double nuts on the actuator are tightened against each other to eliminate backlash. The nut assembly is connected with a bracket to the saddle that rides on the radial tracks. Both the actuator and the nut assembly can pivot inside their respective brackets to account for small changes in angles as the saddle travels on the radial tracks. The saddle has a tapered cavity in the center that captures the base of the crystal holder's shaft by tightening a tapered collar. This mechanism provides an angular resolution of 0.0001° and a range of ±3°.

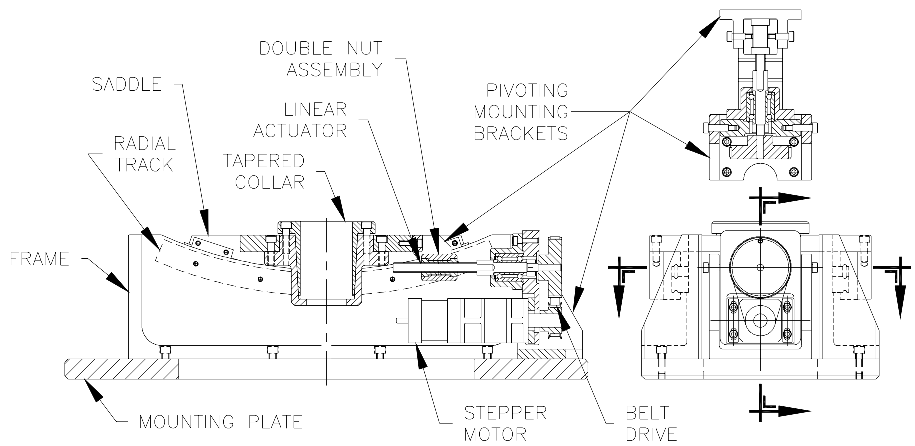

Fig. 4: Roll angle mechanism.

3.5 Horizontal Translation Stage

The detector positioning mechanism and the Huber goniometer share a common support plate (see Figs. 1 and 2). This support plate rides on nine slide guides transverse to the beam when driven by two linear actuators (Fig. 2). A connecting rod, supported by pillow boxes under the table, synchronizes the worm gears of the actuators. The worm gear of one of the actuators is connected to a stepper motor and a torque-limiting clutch. The support table has a total transverse motion range of ±50 mm with resolution of 1 μm.

3.6 Crystal Cooling Configuration

Designs for different LN_2 cooling configurations are being developed. Figure 5 shows the indirect cooling scheme that will be implemented initially. Cooling channels are machined in a copper crystal holder that is brazed to a stainless steel plug and to a ceramic break. Also brazed to the plug are two stainless steel tubes that carry LN_2 to and from the cooling channels. A hollow shaft, enclosing the tubes covered with super insulation, is welded to the plug. The ceramic break prevents bellows to come in direct contact with LN_2-cooled surfaces

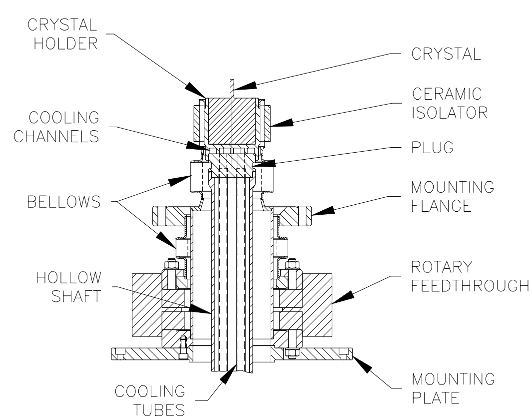

Fig. 5: Crystal cooling configuration.

The silicon crystal exposed to the beam is only 300 μm thick and 19 mm in height. It is a machined part of a large (46 mm in diameter, 50 mm in height) block of silicon. The block provides stability, improved heat conduction, and resistance to deformations under bonding stresses. The base of the block is attached to the crystal holder with a thin interface of indium. The crystal holder is easily accessed by lifting the vacuum chamber after unbolting the upper mounting flange. The entire crystal assembly can be replaced by additional releasing of the lower mounting plate and the tapered collar in the saddle (Fig. 4). This flexibility will be useful in testing and evaluation of the crystal cooling designs.

4. Concluding Remarks

Mechanical design of a cryogenically-cooled crystal monochromator for the APS diagnostics beamline has been presented. The unique design of the monochromator will permit simultaneous measurements of the particle beam divergence and size. Tests are planned to evaluate the performance of the different drive mechanisms currently under fabrication, as well as to compare the performance of different cryogenic cooling configurations.

Acknowledgment

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