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A NEW CRYSTAL BENDER FOR THE ID31 LAUE-LAUE MONOCHROMATOR

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Abstract

The ID31 beamline is able to provide X-Ray energies ranging from 20 to 150keV. The energy range 50-150keV is covered by a Laue-Laue monochromator located at 105.2 meters from the source. Two asymmetrically cut Si crystals equipped with benders, based on a new concept, provide an energy resolution ranging from few hundreds of eV down to the Darwin width of few eV.

The bender principle, design, manufacture and first commissioning will be described. The virtual source, produced with a white beam transfocator, can be before or after the monochromator. Therefore the bending mechanism must allow both concave and convex configuration with bending radius from 20m to infinite. Each bender is equipped with two home made piezo-jacks controlled in close loop with capacitive sensors. The system is liquid Nitrogen cooled. The thermal behaviour will be described in detail and thermo-mechanical finite element analysis will be presented.

INTRODUCTION

The X-ray source of ID31 is an in-vacuum cryo-cooled undulator with 14.5mm period and the aim of the optical design of the ID31 beamline is to provide the highest possible X-ray beam intensity over the energy range of 20 to 150 keV. The X-ray techniques available at ID31 are tomography, reflectivity, SAXS and WAXS techniques which are used to study fuel cells, solar cells, rechargeable batteries, catalytic materials and various “dirty” interfaces. The beamline is equipped with three focusing devices used in combination with the ID31 Laue-Laue monochromator which is located at 105.2 meters from the source and covers the energy range from 50 to 150keV.

THE LAUE-LAUE MONOCHROMATOR

The Laue-Laue monochromator consists of two bent Si(111) crystals in non-dispersive geometry with an asymmetric cut of −36°. The crystals can be rotated so that other reflections in the (110) and (001) plane can be used, e.g. the Si(113) reflection with an asymmetric cut of −6.5°. The crystals thickness is 5 mm and they are LN2-cooled. Since the virtual source given by the compound refractive lens can be before or after the monochromator the bending mechanism allows both concave and convex bending. The beam offset can vary between 7 and 25mm. To allow the full energy range with 20 mm offset, the second crystal has a translation along the incident beam from 250 to 750mm relative to the first crystal.

THE BENDER

Various benders for mirrors or crystals have been developed in the past at ESRF [1-2], but none of them fully answer the specifications for the ID31 beam line.

Specification

The beam bandwidth is proportional to the inverse of the bending radius of the crystal determined by the virtual source to crystal distance. Therefore a convex and a concave bending with cylindrical shape is needed from ∞ to 20m. A coarse rotation of the crystals (±40°) is used to select reflections from (110) and (001) plane.The liquid nitrogen cooling is mandatory due to the high heat load generated by X-rays. Furthermore, the cooling scheme has to be optimized for both crystals to minimize thermal bump caused by the incident X-ray beam. Moreover, the absorbed power is tuned with the absorbers located in the first optical hutch. The crystals and bending mechanism has to be high vacuum compatible (10^{-8}mbar). The resolution in energy has to be 1ev. All this constraints led to a new principle for the bender.

Principle and Concept

The main difficulty is to fix the cryo-cooled crystal so that it is not sensitive to the vibrations induced by the cooling or other sources. Furthermore, the crystal should be mounted without torsion. Due to these constraints the concepts based on four-bar-bender or cantilever are not suitable. The new concept consists in finding a clever dimensioning of the bender relatively to the crystal so that the fixing points are placed where no significant aberration of the bender and crystal from the cylinder occurs [e.g, Fig.1a]. The new bender described here is very well adapted to provide at the same time a cylindrical shape of the crystal, a very high stiffness with a very good thermal contact for the cooling [e.g, Fig.1b]. The bender has a rigid middle part which is strongly attached to the support. On each side, one flexure is used as a rotating point to allow the motion controlled by the piezojacks. Two piezo-jacks attached on both side provide the push/pull forces. The piezo jacks are controlled in close loop with capacitive sensors located on both sides.

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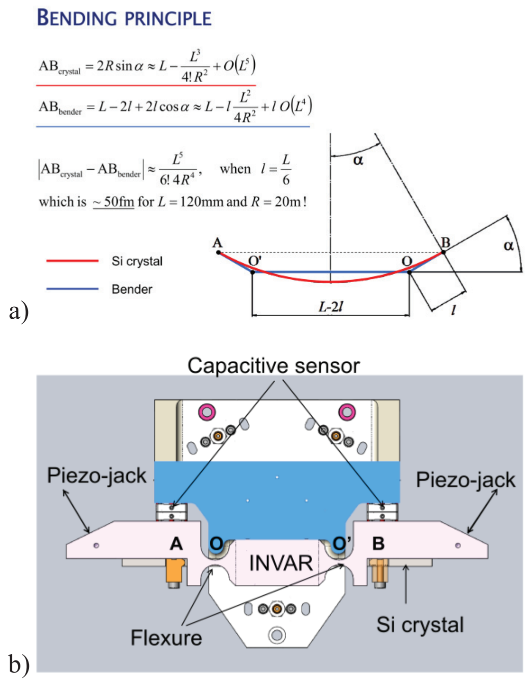

Figure 1: a) The bender is represented in blue line. The crystal is in red. Flexure points are on O and O'. No significant aberration from the cylinder occurs at the fixing point A and B, when the lengths of the lever arms AO' and BO are one sixth of the length of the crystal. b) The concept of the bender. The flexure points O and O' of the bender made from Invar are like in Fig. 1a. The crystal is clamped on the lever arms which are pushed or pulled by the piezo-jacks. The capacitive sensors measure the displacement of the lever arms at the opposite side of the clamps.

Analytical Approach

The deformation of the crystal $u(x)$ is analytically defined starting from the mechanical beam theory approximation [e.g, eq.1].

$$\frac{\partial^2 u}{\partial x^2} = \frac{M(x)}{EI} \quad (1)$$

where E is the Young modulus of Si, I is the inertia of the beam which equals $bh^3/12$, b is the width of the crystal, h is the thickness, and $M(x)$ the local bending moment.

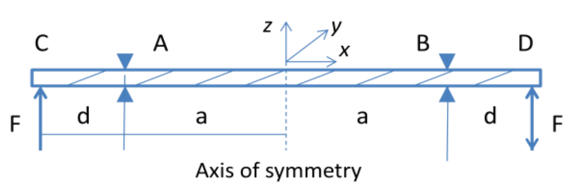

Figure 2: The crystal is attached to the bender on points A and B. F is the pulling/pushing force delivered by the piezo-jacks at C and D. Note the similarity with the four-bar-bender.

The crystal is bent in the horizontal plane and therefore the weight of the crystal can be neglected. The forces applied on both sides on points C and D [e.g, Fig. 2] by the piezo-jacks are equal. The anticlastic effect is neglected and the origin of the referential is taken in the middle of the crystal [e.g, Fig. 2]. The deflection is zero at the origin to simplify the equations. The deflection of the crystal between the fixing point A and B follows a pure cylinder as expressed in the following equation:

$$u_1(x) = \frac{d.F}{EI} * x^2 \quad (2)$$

The deflection of the crystal between the fixing points A and B and the pushing/pulling points C and D, respectively, follows the motion of the bender which can be considered rigid in this region, rotating around the flexures located in O and O'[e.g, eq 3].

$$u_2(x) = \frac{2d.Fa^2}{EI} x - \frac{dFa^2}{EI} \quad (3)$$

A matlab program developed by the authors calculates the deformation along the crystal and determines the displacement of the the piezo jacks for a specified bending radius. Figure 3 shows the deflection curve of the crystal for a requested radius of 20m. As an example the analytical model indicates that a radius of curvature of 20m is obtained with a displacement of 283.7 microns of the jacks. A displacement of zero of the piezo-jacks corresponds to an ∞ radius, i.e. a flat crystal.

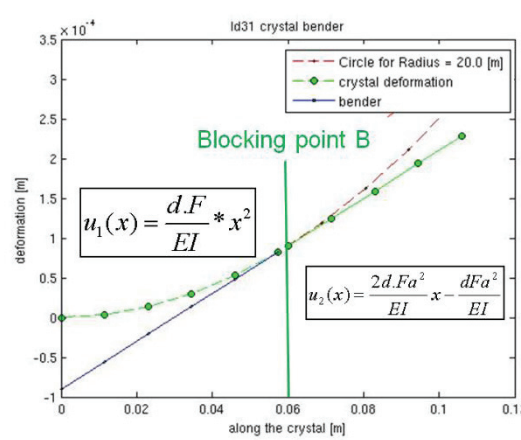

Figure 3: The deformation of the crystal follows the green curve. It is composed of a cylindrical shape between the fixing points AB and a linear slope given by the bender beyond these points.

Finite Element Analysis

The material of the bender has been determined taking into account the behaviour in a cryo environment. The

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relative motions between the bender and crystal must be small enough to reduce the stresses during the cooling down of the assembly from room temperature to 88K. Furthermore, the final stresses should be as low as possible to avoid any torsion of the crystal. Invar was a natural candidate despite of its very low thermal conductivity. Two studies were made with finite element analysis with "Solidworks Simulation". The first model is a mechanical study of the bending of the crystal and the bender [e.g, Fig 4]. As expected, the maximum stress is registered in the flexure.

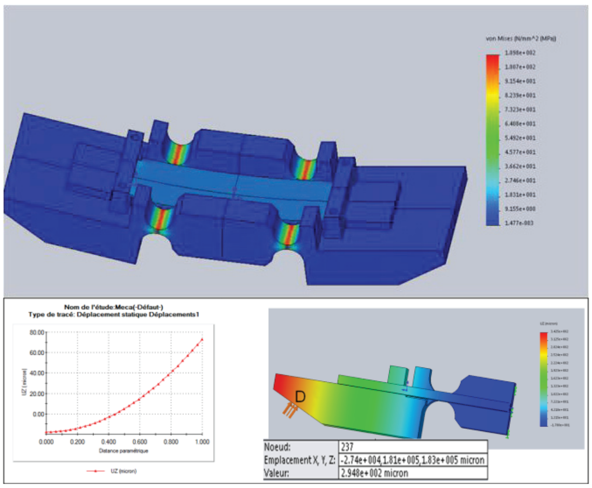

Figure 4: FEA for a radius of curvature of 20m. Top: the maximum stress is 110MPa. It remains much lower than the invar limit of 450MPa. Bottom left: deformation along the crystal . Bottom right: the jack motion is 295microns.

The second model is a non-linear thermo-mechanical model which takes into account the variations of the expansion coefficient and thermal conductivity as a function of the temperature [3-6]. The variation of the Young modulus as a function of the temperature has been estimated as a second order effect in the calculations and has not been taken into account. This model simulates the behaviour of the system during the cooling from room temperature to LN2 cryogenic temperature (88K).The stresses between the crystal and the bender are very close to the limit. This point has been solved by adding a layer of Indium between the crystal and the bender. Furthermore, it serves as well as an excellent thermal contact. The final stresses at 88K temperature due to the different thermal expansion of the Invar and the Si predicts a slight bending of the crystal.

Design and Prototype

Taking into consideration the different results from analytical and FEA analysis, the bender was designed as shown in the Figure 5. The bender with 3mm thick flexures and the clamps are in Invar. The crystals are 5mm thick. Copper cooling parts (not shown in the Fig. 5) are strongly attached on both sides of the bender and are also in contact with the end parts of the crystal with indium foil that insures a good thermal contact and a reduction of stresses. The thermal stability of the assembly is guaranteed by a thermal regulation made with resistive heaters on the interface plate between the bender and the rest of the mechanics below the bender. The crystal is stiffly maintained on to the bender. All the mechanics are high vacuum compatible (10^{-8}mbar). The resolution is insured by the piezo- jack in close loop with the capacitive sensors located at the opposite side of the crystal clamps. The piezo-jacks specially designed for this application have a very high resolution: 20nm.

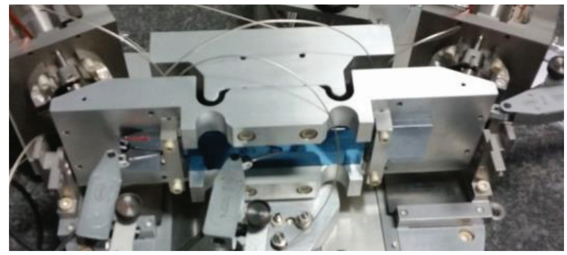

Figure 5: A prototype of the bender with its crystal. Two piezo-jacks behind are pulling/pushing on both sides. The path is free in the middle for the X-ray beam.

Commissioning

Preliminary measurements have been made in optics laboratory with a Fiseau interferometer. The first measurement is made when the crystal is free, i.e. before the mounting. This gives the zero reference radius of the crystal planes. Figure 6 shows the curvature of the surface of the crystal when bent to 20m radius. One can observe the anticlastic effect in the middle of the crystal. When the initial topography of free crystal was subtracted the slope errors from the cylinder are less than 1nm at the middle part of the crystal. At the vicinity of the clamps the errors are close to 100nm due to the clamping which prevents the anticlastic bending.

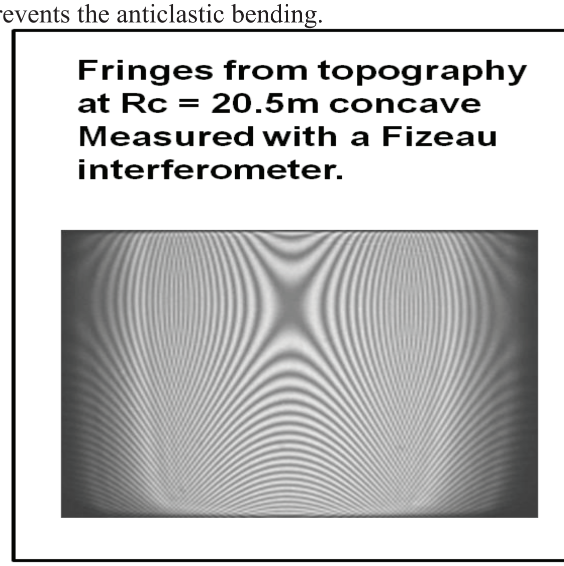

Figure 6: Optical franges showing the deformation of a crystal bend at radius 20.5m from zero lattice plane reference.

The ID31 Laue-Laue is now installed at ID31 with its two crystals and two benders inside. The first X-ray

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measurements were done to determine the initial radius of curvature. Results shown in the Fig. 7 are in good agreement with the FEA analysis.

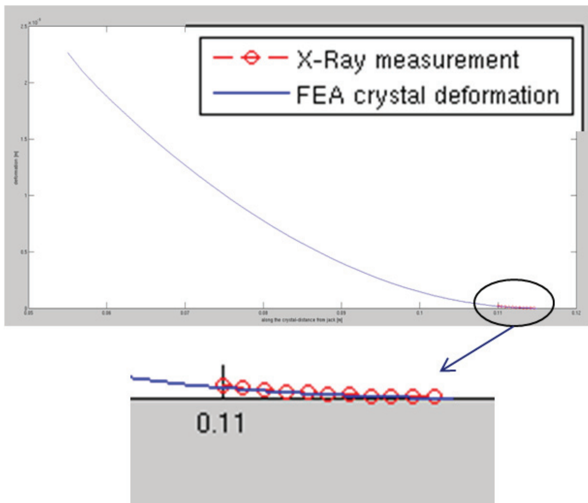

Figure 7: Behavior of the bender and its crystal when cooling down to 88K. The blue curve is the result of the deformation of the crystal as a result of the FEA analysis. The red circles represent the deformation as measured at the beam line with X-rays.

CONCLUSION

As described above the analytical analysis, the FEA analysis, the optical results and the first X-ray commissioning converge to give similar values for the behaviour of the system. As a resume we can say that the strong point of this system is its stiffness which makes the system insensible cryo cooling or other vibration sources. The cylindrical bending is reached in the region of interest and the resolution is given by the piezo-jacks, specifically developed for this application, in close loop with capactive sensors.

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