The Toroidal Mirror for Single-Pulse Experiments on ID09B

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Abstract

ID09 is a dual-purpose beamline dedicated to time-resolved and high-pressure experiments. The time-resolved experiments use a high-speed chopper to isolate single pulses of x-rays. The chopper is installed near the sample (focal spot) and the shortest usable opening time depends on the sharpness of the vertical focusing. In the 16-bunch mode, the opening window of the chopper has to be reduced to 0.300 μs to select single pulses of x-rays. This can only be achieved by lowering the height in the chopper tunnel to 0.143 mm. To ensure a reasonable transmission though the tunnel, we have built a very precise toroidal mirror that focuses the beam 22.4 m downstream in M= 0.677 geometry. The 1.0-m long silicon mirror is curved by gravity into a near perfect toroid with a meridional radius of 9.9 km. The curvature is fine-tuned by a push stepper motor that works from below. The figure error from the gravity sag and the correcting force is less than 0.3 μrad and the polishing error is 0.7 μrad (rms) over the central 450-mm part of the mirror. The measured size of the polychromatic focus is 0.100 x 0.070 mmh x mmv in agreement with the prediction from the long-trace-profiler at the ESRF. The small focus, which integrates the entire central cone of the U17 undulator, is the result of superb optical quality, fine-control of curvature, a strain-free mount, a vibration free cooling system and careful alignment.

Keywords: toroidal mirror, gravity, slope error and bender

1. Introduction

Beamline ID09B at the European Synchrotron Radiation Facility is dedicated to time-resolved pump and probe experiments on photosensitive molecules. A comprehensive set-up is available for studies of chemical or bio-chemical reactions triggered by femtosecond and nanosecond laser pulses. The structural changes are probed by delayed x-ray pulses from single bunches of electrons in the storage ring. In experiments triggered by the femtosecond laser, the time-resolution reaches the 50-200 ps bunch limit (fwhm), the ultimate time-resolution of a synchrotron. Our experimental program includes Laue diffraction on macromolecules, small-molecule diffraction and diffuse scattering from liquids. The success of a pump and probe experiment depends on the quality of the laser excitation and the quality of the-ray beam. Concerning the latter, the key parameter is the number of photons that can be focused on the sample in a single pulse. The second key parameter is the frequency at which the excitation can run. Heatload from the laser (crystals), finite injection speed of the sample (liquids), and of course, the time scale of the phenomenon itself, typically lower the excitation frequency to 1-1000 Hz. This is far below the frequency of the synchrotron that runs between 0.354 to 352 MHz. This dramatic mismatch makes these experiments demanding and only optimized undulator beamlines can undertake such studies. The most important development in the last few years has been the introduction of single-harmonic undulators with a narrow bandwidth which can deliver some 1000 times more photons on the sample as compared to a conventional monochromatic beam. In this paper we describe a second-generation toroidal mirror. Its prime function is to focus and remove higher harmonics from the monochromatic or pink beam.

2. The Optical Layout

In the second-generation layout, the first optical element is a cryogenic channel cut monochromator based on a monolithic silicon (111) crystal. The energy can be varied between 4-50 keV and the (orthogonal) distance between the two crystals is 4.0 mm. The monochromator is cooled from the sides and rocking curve tests have shown that the performance is near perfect up to 450 Watt (reference to Lin Zhang). The monochromator vessel is mounted on a lateral translation stage, which in the near future will allow us to insert a cryogenically cooled multilayer system. The second optical element is a platinum coated toroidal mirror. It is placed 33.1 m from the source and it works at a fixed incidence angle of 2.772 mrad. The mirror focuses the radiation 22.4 m downstream (M=0.677).

Note that an heatload shutter upstream the monochromator is used to protect the toroidal mirror for continuous heatload from the close gap undulator. It is designed to produce 20 ms shots at a frequency up to 5 Hz and it synchronized with the ms-shutter and chopper which are placed just before the sample. As a state of the art Laue experiment is repeated at 3 Hz, this shutter reduces the average heatload on the mirror to 6%. That improves the stability the focus substantially and ensures that the focused beam is always centered in the tunnel of the chopper.

3. The Chopper

The function of the chopper is to select single pulses of x-rays from the single-bunch, 16-bunch and hybrid mode of operation. It rotates at 896.6 Hz, the 396th sub-harmonic of the ring frequency, and selects one pulse every 1.11 ms. Likewise, the femtosecond laser is running at 896.6 Hz and their relative timing is set by delaying or advancing the laser. The chopper wheel consists of a flat triangular rotor that rotates about a horizontal axis perpendicular to the x-ray beam. The 165-mm long tunnel is located on the edge of the sides of the triangle. The tunnel is 4.0 mm wide and its height varies from 0.9 mm at one end to 0.050 mm at the other end, i.e. it has a trapezoidal cross section. By displacing the chopper laterally, the opening time can be varies from 0.105 μs to 1.892 μs. In the 16-bunch mode, the pulses are 0.176 μs apart and the opening window should be smaller that twice 2 × 0.176 μs = 0.352 μs. As the chopper rotates with a 10 ns(rms) jitter, we are forced to reduce the opening time to about 0.300 μs in order to avoid (partial) double pulses. That corresponds to a tunnel height of 0.143 mm. The vertical focal size should be well below that to ensure a reasonable transmission in 16-bunch mode. Neglecting spherical aberrations, the vertical focal size can be approximated by:

$$F_z = \left\{ (M\,Sz)^2 + (2\,q\,\alpha)^2 \right\}^{1/2}$$

Here S_z is the electron source size, M the demagnifying factor, α the slope error and q the distance between the mirror and the focus. The vertical focus is shown in Figure 1 together with its acceptance though a 0.143-mm aperture (y-scale on the right). Note that a 1.0 μrad error leads to a 0.105-mm vertical focus with 93% transmission though the 16-bunch channel.

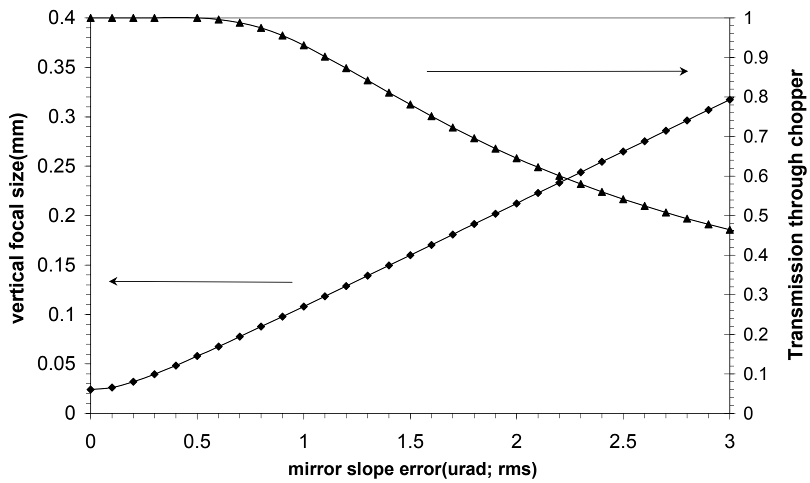

Fig. 1: Vertical focus as a function of mirror slope error.

4. The Toroidal Mirror [1,2]

In the initial layout of the beamline, the toroidal mirror was the first optical element. It was continuously illuminated by the white beam and the varying heatload lead to drifts of the focus. This problem is now solved by the use of a heatload shutter (white beam mode) and placing the cryogenically cooled monochromator first in the beamline (monochromatic mode). The platinum-coated mirror receives the beam at 2.722 mrad, and reflects between 0-30 keV. The mirror is 33.1 m from the source and focuses 22.4 m downstream (M=0.679). The sagittal and meridional radii are 71.6 mm and 9.95 km, respectively.

4.1 Mechanical Design

As the meridional radius is fixed (9.95 km) and relatively high we have built a very simple mechanical bender, with the idea to minimize degradations of optical slope errors in the central area. The X-ray footprint from U17 undulator, when the incidence angle of the mirror is 2.722 mrad, is distributed only in the 450 mm central zone of the mirror. Due to the recent improvement of mirror polishing, it's now possible to produce optical mirrors with high quality polishing. The slope error of the optical surface of the cylindrical mirror is specified to be less than 0.7 μrad (rms) in the 450-mm central zone. Then it's becoming more and more important to hold, cool and bend the mirror in respect with this high quality polishing. In the absence of vibrations, the vertical focal size should thus be as small as 75 μm (fwhm). Note the vertical size is determined solely by the slope error! We are aiming at a tight vertical focus to optimize the transmission in the chopper in 16-bunch mode, where the tunnel height has to be as small as 145 μm to produce an opening window around 0.3 μs.

The mirror is supported at each end and we use a part of the mirror gravity to bend the mirror. At one end the mirror rests on one point (a ball between two conical mechanical parts in order to have a reference for positioning). This ball is preloaded with mechanical springs (it keeps the ball in the cones and increases the mechanical stiffness for a better vibratory behavior). At the other end, two parts of cylinder, in the width of the mirror are used for the two other points. Then the mirror rests on three points and the mechanical holder allows the mirror to be free for thermal dilatations and bending adjustments. Mechanical stresses are minimized. In order to adjust the curvature, a central stepper motor pushes from below the mirror through a spring and fine tunes the curvature.

4.2 Cooling System

The mirror is loaded with 546 Watt of beam of which 134 Watt is absorbed. The heat is extracted laterally by cooling copper plates that are dipped into indium gallium filled channels (2*50 cm^3). Stress and vibrations from the cooling system are thus eliminated [3]. As the efficiency of the cooling is depending on the good distribution of Indium Gallium, the absorbers can be inserted and extracted from the channels to make the introduction of cooling liquid easier (see Figures 2 and 3).

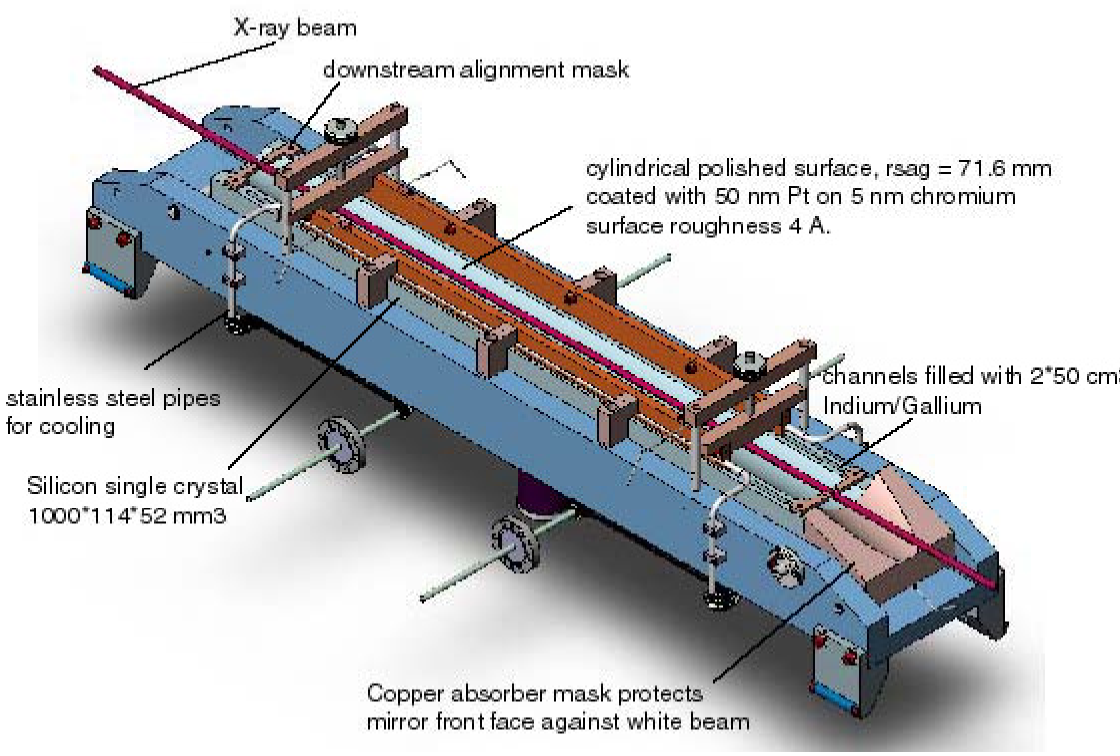

Fig. 2: Mechanical design of the mirror bender.

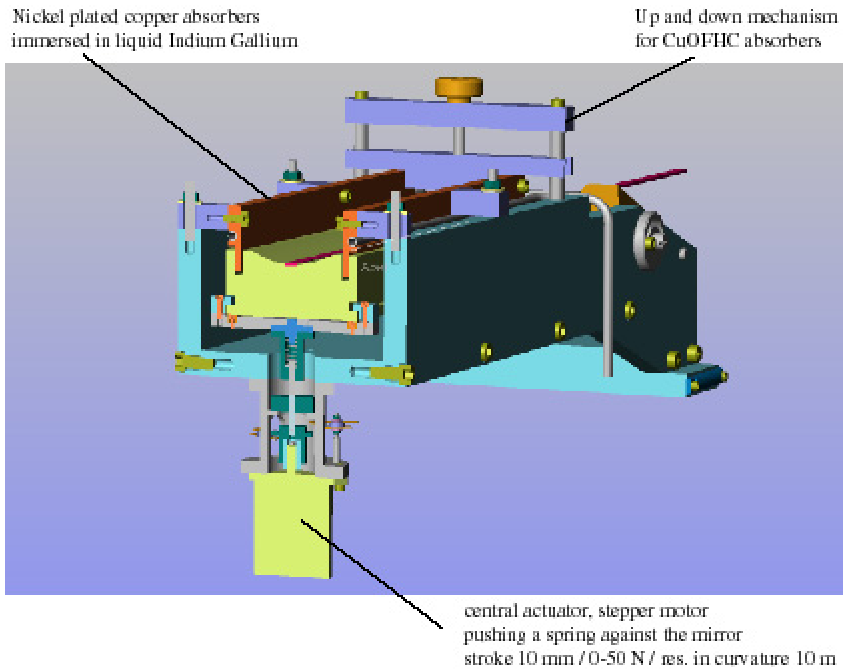

Fig. 3: Central actuator and cooling system.

4.3 FEA Calculations and Results

To take in consideration the real geometry of the mirror (see Table 1) (toroidal shape and cooling channels) and the additional load of indium gallium, slope errors have been calculated with FEA (Finite Element Analysis). It permits to validate the way to adjust the curvature and to determine the optimal dimension of the Si-mirror (in particular the thickness of the mirror which control the inertia) and the characteristics of central actuator (stroke, resolution and stiffness of the spring).

It's important to note that initial shape of the mirror is important to integrated in the calculations. Actually the meridional radius of curvature of the mirror measured without gravity could not be considered to be flat ($R_0=\infty$). It's very difficult and expensive to polish a mirror with a specific meridional radius (9.95 km for example) but it's relatively easy to specify and get a mirror concave with a meridional radius in the range of [∞ to 25 km].

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Table 1: Parameters

Shape :	**Cylindrical(in gravity -> toroidal)**
Dimensions : L × W × H (mm^3)	1000 × 114 × 52
Material (Silicon)	$E = 130*10^9$ Pa -$\rho_{si} = 2340$ kg/m^3
Sagittal radius (mm)	71.6
Coating	Pt – 50 nm
Surface roughness (Å; rms)	1.3
Incidence angles (mrad)	2.684
Energy range (keV)	4-34
P = source-mirror distance (m)	33.05
Q = mirror-focus distance (m)	22.37
Demagnification M	0.677
Slope-error (µrad; rms) – 450 mm	0.7 µrad
Residual meridional radius (km) (no gravity)	[∞ to 25.0]
Gravity curvature (km)	9.9

4.4 Discussion

The thickness of the mirror (52-mm) and the distance between the supports (900-mm) have been chosen so that the central actuator has only to push (simplicity of the central actuator and better slope error results, because of gravity compensation).

The best results have been obtained for R_0 = 25 km (see Table 2). In effect, the gravity introduces some slope errors (it's why that most of mechanical bender use mechanical pusher springs in order to first compensate the gravity). For R_0 = 25 km, these errors have been almost totally compensate with the actuator (Fc = 27N). Thus the residual slope error is low and acceptable (0.15 μrad), in the central area (-250 / +250 mm). In the case of $R_0 = \infty$, no compensation of gravity is possible, just because Fc ≈ 0 N. The residual slope error is high and not acceptable (0.83 μrad). But according mirrors manufacturers, the probability to have a flat mirror is negligible (polish process), especially if we expected the mirror to be concave with a limit fixed to 25 km. In this extreme case we will stand aside the supports from 900mm to the maximal distance (almost 1000-mm) and the slope error will come to a reasonable value (< 0.3 μrad in the central zone).

Table 2: FEA Results

$R_{desired}$ = 9.95 km		
R_0	∞	25 m
R_{mean} gravity	9.94 km	16.5 km
$F_{actuator}$	0.398 N	27.238 N
R_{mean} gravity + $F_{actuator}$	9.95 km	9.95 km
Slope error $\Delta\theta_{rms}$ (500 central mm)	0.83 μrad	0.15 μrad

Figure 4 shows the slope error for R_0 = 25 km and $R_0 = \infty$. If we weight these slope errors by the intensity distribution from U17 undulator, the slope error becomes very low (less than 0.1 μrad in the central zone). See Fig. 5.

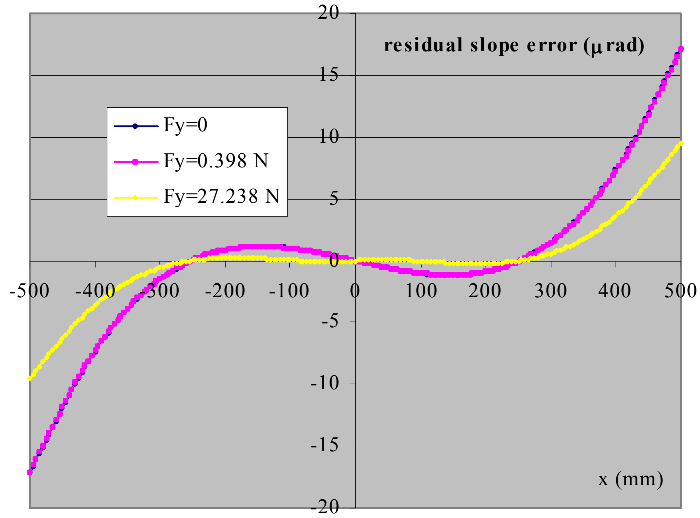

Fig. 4: Slope errors for R_0 = 25 km and $R_0 = \infty$.

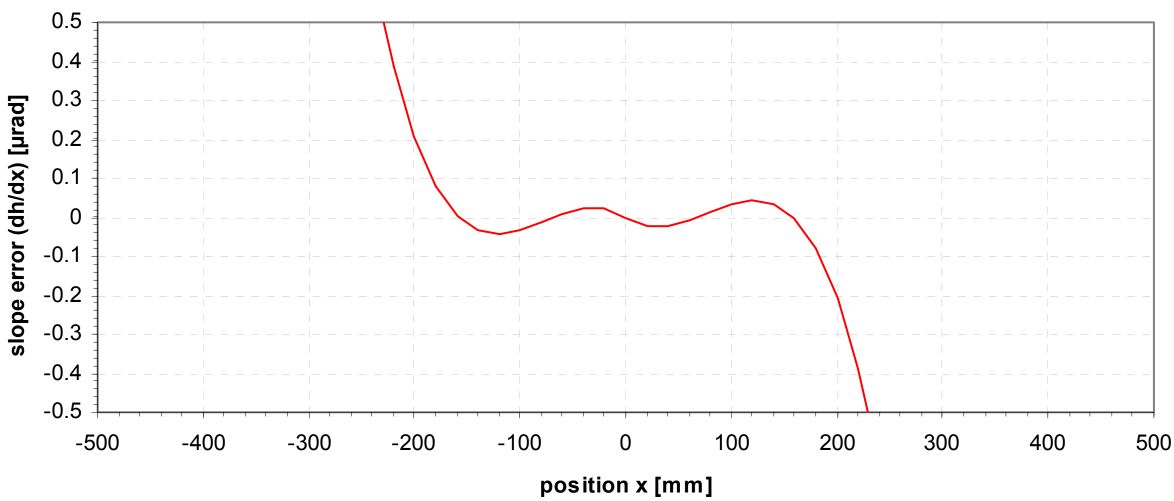

Fig. 5: The slope error weighted by intensity from U17 undulator footprint distribution is less than 0.1 μrad in the zone –250 to + 250 mm.

4.5 LTP Results

Radius of curvature, slope errors, profile and shape errors of the mirror provided by SESO (Société Européenne de systemes optiques) have been measured at ESRF on a Long Trace Profiler (LTP) (see Table 3).

Table 3: LTP Results

	Measured length (mm)	**Gravity removed**	**Actuator displacement (mm)**	**Radius of curvature (km)**	**Slope error RMS (μrad)**
Mirror alone	450	yes	/	28	0.7
Mirror + bender	450	no	0	7.6	1
Mirror + bender	450	no	4	8.9	0.8
Mirror + bender	450	no	5	9.6	0.8
Mirror + bender	450	no	6	10.1	0.8

The measurements obtained with the LTP have confirmed the FEA results:

- The initial mirror shape error is conserved after mounting the mirror in the bender.
- When the actuator pushes the mirror (to adjust the meridional radius), part of slope error due to the gravity is eliminated and slope error is improving.
- Slope error is really good (<1 μrad) in the central 600 mm

The measured size of the polychromatic focus is 0.100*0.070 mmh*mmv in agreement with the prediction from the long-trace-profiler (LTP).

5. Conclusion and Outlook

The optical finish of synchrotron mirrors have recently improved very substantially due to advances in machining and polishing techniques and better metrology for shape and roughness analysis. The first toroidal mirror on ID09 had a slope error of 4.3 μrad (rms) as compared the new one at 0.8 μrad (rms). The gain in flux for time-resolved experiments is roughly the ratio of the two, which gives a six-fold increase in the flux on the sample in the 16-bunch mode. In addition new single harmonic undulators have increased the flux by factors between 5-10. This enormous increase in flux for pump and probe experiments has recently been used in experiments on the formation of the I_2 molecule in the CCl_4 solvent. Note for example that a pink beam from the U17 undulator running at 896.6 Hz has the intensity of a classical undulator beam with a Si(111) monochromator. The increase in flux is not only giving better data for of known phenomena, it will hopefully also enable many new discoveries to be made in the near future. We hope that our technical and scientific developments at the ESRF will lay the practical foundation for future femtosecond experiments with a free electron laser.

6. References

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