AXOC: Advanced X-ray Optics
Components coupled high accuracy mechanics for X-ray nano-focusing
01/12/2009- 31/05/2013

Project coordinator: A. Somogyi, Soleil

Journées Nationales Nanosciences et Nanotechnologies 2012
AXOC: project goals

Development of a state-of-the-art scanning hard X-ray nanoprobe including:

- nano-focusing Kirckpatrick-Baez mirror-system
  - mirror fabrication
  - mechanics
  - a high precision sample stage

Development of optical and at wavelength metrology techniques adapted to the characterization of very high optical quality mirrors

adapted to the Nanoscoptium beamline of Synchrotron Soleil
Nanoscopium: Scanning hard X-ray imaging beamline at Synchrotron Soleil (St Aubin)

155 long nanoprobe beamline, aiming down to 30 nm spatial resolution

Exploitation of beam coherence for focusing and contrast formation

Diffraction limited focusing

Multimodal and multi-technique imaging

Chemical and structural information

Responsible: A. Somogyi
Focusing optics
X-ray fluorescence detector
SXRF elemental imaging
XANES chemical information
Diff. phase contrast imaging
Coherent scattering imaging
Structural information, electron density distribution

Sample stage: Precision XYZ
~5-10 nm resolution (encoder, feedback)

Beam-size and beam quality at the sample

Overall stability

Scanning hard X-ray nano-imaging

Resolution, performance

AXOC-project
Deliverables of the AXOC project

Focusing optics: Kirkpatrick-Baez mirror system

Diffraction-limited focusing and coherence based applications: high optical mirror quality, Mirror conception (Task1, Soleil)

Two alternative principles

- Monolithic, elliptically shaped Si mirrors, deterministic polishing (Task3, SESO)
- Bent Si mirrors, lateral shape optimisation, deterministic polishing (Task3, SESO)

High stability, high precision mirror positioning (Task2, ISP)

Adaptation of the existing bending system (ISP) constructed by FEASO RTRA Project (2007)
Deliverables of the AXOC project

Development of adapted mirror metrology tools (Task 5)

Surface correction of flat SiO$_2$ mirrors by det. deposition: high quality metrology standard for intercomparison (Task 4, LMA)

Vertical translation stage with nanometer precision and mm travel range (Task 2, ISP)
Task 1: Mirror conception

The conception of 3 mirror-pairs has been finished

Total reflection KB mirror systems for Nanoscopium with Elliptical mirror shape: by two alternative principles

- Monolithic, elliptically shaped Si mirrors
- Flat Si mirrors, lateral shape optimisation, elliptical shape by bending

Surface finishing by deterministic polishing (SESO, Task 3)

- Flat SiO₂ mirrors: for high quality metrology standard

Surface correction by deterministic deposition (LMA, Task 4)
Figure errors must be below 0.75 nm-rms to achieve more than 0.8 Strehl ratio over 5-20 keV energy range.

The amplitude of periodic errors, particularly with spatial period above a few mm, must be minimised.

Example: Flat Si mirrors, lateral shape optimisation, elliptical shape by bending

Working strategy:
- High precision bending mechanical system (ISP)
- Two high optical quality flat mirrors with lateral shape optimization for the required working conditions (Thalès-SESO, SOLEIL)

Required characteristics by wave-optical calculations (SOLEIL)

10 mm spatial period
P-V = 1 nm → 10% $I_{\text{max}}$ side-lobes
2 actuators bending mechanical system
Large range of elliptical profiles achievable
Dynamic Range: $R = 800$ m $\rightarrow$ $R = 20$ m
Sag up to 40 µm over 80 mm useful length
Finite Element Analysis Model (IDEAS):

Solid elements: 4 mm mesh
Mirror surface: 1 mm mesh
(allowing to retrieve the local slopes with 1 mm spatial resolution)

Modal analysis shows a first vibration mode at 379 Hz

Mirror width profile optimisation

Elastic Beam Theory approximation

FEA Influence Functions and Interaction Matrix based Optimisation

Lateral profiling and surface finishing in progress (SESO)
Task 2: Construction of positioning systems (mechanics, motion control)
High precision, high stability positioning system for monolithic, elliptically shaped Si mirrors

Technical specifications, tolerances, stability criteria (Soleil): based on wavefront propagation calculations

Demanded mirror motions:

**M1 mirror**
- 3 motorised translation: X1, Y, Z1
- 2 motorised rotations: θ1 and φ1
- 1 rotation manuelle: ψ1

**M2 mirror:**
- 2 translations motorisées: X2, Y2
- 1 rotation motorisée: θ2
- 2 rotations manuelles: φ2 et ψ2

### Critical motions for mirror performance

<table>
<thead>
<tr>
<th></th>
<th>Range</th>
<th>Resolution</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>θ2, θ2 Pitch</td>
<td>-0.1°-0.2°</td>
<td>0.15 µrad</td>
<td>0.5 µrad</td>
</tr>
<tr>
<td>φ1 Roll, perpendicularly</td>
<td>+/- 100µrad</td>
<td>5µrad</td>
<td>10µrad</td>
</tr>
</tbody>
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2 independent, closely embedded mechanics
Prototypes

Validation of the dimensioning of the critical elements

Working strategy:

Finite element calculations and dimensioning, calculation of the first eigen-frequencies (≥40Hz)

Thermo-mechanical analysis of the ensemble

Distortion-free mirror fixation

Finite element calculations and dimensioning, calculation of the first eigen-frequencies (≥40Hz)

Validation of the dimensioning of the critical elements

Mirror support

Pitch: 0.15 µrad resolution 0.5 µrad precision

distortion-free mirror fixation

Fabrication of the components of the validated final design

Assembling tests: 2012 Nov-Dec

Delivery to Soleil 2013 Febr
HJ11  modifier le bandeau à gauche pour différencier des présentation officielle ANR?
HACCON Julien; 25/07/2012
Technical specifications, tolerances, stability criteria (Soleil)

- Travel range: 1-2 mm
- Resolution: 5 nm

Scanning modes:
- Continuous fast (1 mm/s) «fly scan»
- Precision step scan, with ~5 nm resolution

Working principle:
- High precision translation stage (linear motor, flexure based guidance) with load compensation mechanism
- Dedicated electronics for motion control

Challenges:
- Obtaining electronic noise levels compatible with 5 nm resolution & mm travel range
- «Flyscan» mode
Sample positioning

→ Optimization: minimizing the heat transfer to the sample
Take into account and correct for the differential dilatation in the closed loop feedback

Dépôt de brevet (ISP):
→ Actuateur linéaire sans contact à guidage flexible et application à une table de déplacement
modifier le bandeau à gauche pour différencier des présentation officielle ANR?
HACCOUN Julien; 25/07/2012
Sample positioning

→ Validation of the electronic control and the closed loop feedback

→ Stabilization time: 1ms

→ Scanning range: +/- 1mm

~10 nm steps (50 µV)

→ Flyscan at low speed: 10nm/s

→ Resolution <1nm with 24 bits control electronics
modifier le bandeau à gauche pour différencier des présentation officielle ANR?
HACCOUN Julien; 25/07/2012
Task 3: Mirror fabrication by deterministic ion-beam polishing (IBP)
Aim: correction of the artifacts of standard polishing

Local correction of less 1 nm in height can be reliably applied

**IBP Steps**
1. Measure height profile \( P(x) \)
2. Ellipse equation (goal), \( E(x) \)
3. Evaluation of residual height \( R(x) \)  
   \[ \Rightarrow R(L) = R(0) = 0 \]
4. Calculation \( v(x) \)
Mirror fabrication by IBP (SESO)

Results: surface finishing is in progress

Si substrates for monolithic elliptically shaped mirrors

Substrat A

Nano-MRX (before IBP)  Nano-MRX (after IBP)

Si substrates for flat, torpedo shaped mirrors

Before torpedo cutting

CNC Cutting of TORPEDO shapes (in progress) (+/- 30 µm accuracy)
Task 4: Surface finishing by deterministic deposition
Working strategy

Definition of mirror characteristics (SOLEIL)

Polishing of SiO₂ substrates & visible metrology & fiducial markers for comparative metrology and det. deposition (SES0)

Comparative métrologie before det. deposition (SES0, SOLEIL, LMA)

Deterministic deposition (LMA)

Comparative métrologie after det. Deposition (SES0, SOLEIL, LMA)

Validation
Starting SiO$_2$ substrates (polished by SESO)

**Substrat A**

Shape error P to V: 218 nm

**Substrat B**

Shape error P to V: 76 nm
After surface correction (LMA)

Substrat A
Shape error P to V: 3 nm

Substrat B
Shape error P to V: 3.2 nm
Task 5: Mirror metrology developments
Aim: to develop optical metrology adapted to nanofocusing optics

The spatial frequency range from 0.5 to 20 1/mm was missing. The defects must be precisely located on the substrate for evaluating the opportunity of attempting a further deterministic polishing iterations.

Re-polishing process removes the surface errors in a desired spatial frequency bandwidth but induces local side effects increasing the spatial frequency range of defects.

Available instruments, methods in the framework of AXOC
Stitching interferometry, under development at Soleil

**Aim:** to link a process of local surface **modification to surface shape measurements.**

**Needed:** sub-nanometer height accuracy and a lateral resolution below 1 mm.

**Goal:** ±0.1 nm height accuracy; field of view up to 20 mm and, below 100 µm spatial resolution.

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**2nd prototype**

**Results**

Without any filtering, the short term repeatability is <0.8 nm PV.

First stitching topography of a plane mirror stitching 20 individual images on 105 mm length.
Measurement step is 5 mm.
The slope error: 0.9 µrad rms (by LTP).

Polishing streaks are clearly visible
Muriel Thomasset, et al., *A new Phase-shift Microscope Designed for High Accuracy Stitching Interferometry*, Submitted for publication

F. Polack et al., *Determination and compensation of the “reference surface” from redundant sets of surface measurements*, Submitted for publication
Intercomparison metrology SOLEIL-SES0-LMA: for each mirror

Fiducial markers:

Sensibility of mirror positioning: 20µm, repeatability: < 50 µm
Intercomparison metrology SOLEIL-SESO: results

Mirror slope

Residual mirror height

Residual variation of the mirror slope and height after subtraction of the best sphere

SiO$_2$ substrate