Thermal bump removal by designing an optimised crystal shape

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French CRG-IF BM32 at ESRF

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Outline

- Motivations
- Modelling
- Results
- Conclusions
Motivations

- **Bending Magnet at ESRF**
  - heat power: 300W
  - acceptance: horiz. >1.5 mrad, vert. 0.1 mrad
- **New Double Crystal Monochromator**
  - Si(111)
  - from 5 to 30 keV
- **keep cheap and simple cooling design**
  - water (avoid LN2)
  - indirect cooling (simple + less vibrations)
**Modelling: FEA - Heat**

- **Heat source:**
  - 2D domain incoming power
  - \( \sim 100-150 \text{ W on 40x50 mm} \)
  - \( \sim 50-130 \text{ mW/mm}^2 \) (on mono)

- **Spatial distribution** (uniform, gaussian-like)
- **current in storage ring**
- **crystal inclination** (working energy)
- **Slits aperture** (hxv), illuminated area

- **Cooling power:**
  - convective transfer: water/Cu
    - \( h = 5000 \text{ W/mm}^2/\text{K} \)
  - heat resistance Si/InGa/Cu

- **XOP**
  - \( E=6.04 \text{ GeV} \)
  - \( R=25 \text{ m} \)
  - \( B=0.8 \text{ T} \)
  - \( H \text{ accept}=2.09 \text{ mrad} \)
  - (mono. 26.9m Slits 23.9m)

- **Cooling power**
  - convective transfer: water/Cu
  - \( h = 5000 \text{ W/mm}^2/\text{K} \)
  - heat resistance Si/InGa/Cu

- 0.1 \text{ W/mm}^2
Modelling: FEA – deformation

Get at (reflective) domain surface:
uz vertical displacement along z => derivative of uz along y (// x-ray beam)
=> \( \mu \) longitudinal slope errors

FEA with COMSOL multiphysics
(ex FEMLAB)

Standard block Si crystal

\( E = 18 \text{keV} \)
\( \Delta \omega = 16 \mu \text{rad} \)
\( I = 200 \text{mA} \)

\( \Delta z_{\text{max}} = 0.4 \mu \text{m} \)
\( \mu_{\text{max}} = 15 \mu \text{rad} \)

\( R_{\text{int}} = 50\% \)
Less than to 25% with \( I = 350 \text{mA} \)
Modelling: design of an optimised shape

- Previous works: side cooling better than bottom cooling
- General idea: decrease $u_z$ gradient by decreasing T gradient...

Reflective area

Water cooling

- First simulations: possibility to reverse the bump curvature!
- For a given heat load: possibility to remove longitudinal $u_z$ gradient (smooth profile)
- Add deformation sources

Constraints to the design:
- several optics configurations
- limited crystal size

Strain and temperature gradient are outside the reflective domain
**Reflectivity Model - surface bump**

**Simple Model:** \( \mu : \) Slope error at \((x,y)\) on 1\(^{st}\) crystal / flat 2\(^{nd}\) crystal
\( \Delta \omega : \) Darwin width

Bragg reflectivity \( \sim \) gate function \( \Delta \omega \) or \( \Delta E \) width

Integrated reflectivity:
\[
R_{\text{int}} = \int_{\text{area}} R(x,y) \, dx \, dy
\]

- Objective function to optimise
- two inputs:
  - local slope error \( \mu(x,y) \) from FEA
  - Darwin width \( \Delta \omega \) (working energy)
Reflectivity Model - thermal lattice expansion

Two origins of lattice planes strain at illuminated surface:
- slope errors (longitudinal z-displacement gradient)
- thermal lattice spacing expansion

\[ \Delta \theta_B = \alpha_{\text{expansion}} \cdot \tan \theta_B \cdot \Delta T = \mu_{\text{th}} \]

- If \( T_1(x,y) \) uniform \( \Rightarrow \) perfect tuning with tilted 2nd Xtal by \( \Delta \theta_B \) with \( \Delta T = T_2 - T_1 \)
- If \( T_1(x,y) \) non uniform \( \Rightarrow \) best tuning with tilted 2nd Xtal by \( \Delta \theta_B \) with \( \Delta T = T_2 - \text{mean}(T_1) \)
equivalent slope error \( \sim \mu = \alpha_{\text{expansion}} \cdot \tan \theta_B \cdot \Delta T_{\text{Max}} / 2 \)

For our heat load range, d-spacing variation can be omitted

\[ \mu_{\text{th}} = (T_2 - T_1(x,y)) \cdot \alpha_{\text{Si}} \cdot \tan \theta_B \]

Gate function Xtal 1 with \( \mu + \mu_{\text{th}} \)
Gate function Xtal 2 with \( 2\mu + \text{offset} \)

@20 keV, \( \alpha_{\text{Si}} = 2.66 \times 10^{-6} \text{ K}^{-1} \)
\( \Delta T = 1^\circ \text{C} \Leftrightarrow \Delta \theta_B = 1/4 \mu\text{rad} \)
\( \Delta T = 60^\circ \text{C} \Leftrightarrow \Delta \theta_B = 60^\circ \text{C} \)

A more accurate computation can be done:

\[ \mu (\mu\text{rad}) \]

y // beam

\( \Rightarrow \) offset for highest \( R_{\text{int}} \)
Results

Optimised shape for 3 Energies x 3 horiz. acceptance

\[ E = 18\text{keV} \]
\[ \Delta \omega = 16 \mu\text{rad} \]
\[ I = 200\text{mA} \]

\[ \Delta z_{\text{max}} = 0.4 \mu\text{m} \]

Gradient is along x!

\[ \mu = -2 \text{ to } 11 \mu\text{rad} \]
\[ \mu_{\text{mean}} = 2 \mu\text{rad} \]

\[ \text{Rint} = 90\% \]
Results: comparison old-new crystal

**Old Xtal**

- 8 keV 40x5 mm
  - $\Delta \omega = 40 \, \mu\text{rad}$
  - Total power: 129.25 W
  - In rectangle $h = 45.02 \, \text{mm}$ and $v = 22.64 \, \text{mm}$ on monochromator
  - Mean power density: 0.127 W/mm$^2$ (mono), 0.5 W/mm$^2$ (HxV)

- 18 keV 50x3 mm
  - $\Delta \omega = 16 \, \mu\text{rad}$
  - Total power: 122.8 W
  - In rectangle $h = 56.28 \, \text{mm}$ and $v = 30.36 \, \text{mm}$ on monochromator
  - Mean power density: 0.072 W/mm$^2$, 0.1 W/mm$^2$ (HxV)

- 27 keV 50x3 mm
  - $\Delta \omega = 10 \, \mu\text{rad}$
  - Total power: 98.24 W
  - In rectangle $h = 45.02 \, \text{mm}$ and $v = 45.55 \, \text{mm}$ on monochromator
  - Mean power density: 0.048 W/mm$^2$ or 0.66 W/mm$^2$ (hXV)

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Results: comparison Exp. - FEA

Old Xtal

8 keV 40x5 mm
\[ \Delta \omega = 40 \mu \text{rad} \]
\[ R_{\text{int}} = 70\% \]
\[ 0.5 \times 10^{11} \text{ ph/s/200mA} \]

18 keV 50x3 mm
\[ \Delta \omega = 16 \mu \text{rad} \]
\[ R_{\text{int}} = 56\% \]
\[ 4.32 \]

27 keV 50x3 mm
\[ \Delta \omega = 10 \mu \text{rad} \]
\[ R_{\text{int}} = 56\% \]
\[ 5.36 \]

New Xtal

8 keV 40x5 mm
\[ \Delta \omega = 40 \mu \text{rad} \]
\[ R_{\text{int}} = 85\% \]
\[ 0.7 \]

18 keV 50x3 mm
\[ \Delta \omega = 16 \mu \text{rad} \]
\[ R_{\text{int}} = 90\% \]
\[ 8.0 \]

27 keV 50x3 mm
\[ \Delta \omega = 10 \mu \text{rad} \]
\[ R_{\text{int}} = 92\% \]
\[ 8.74 \]
Conclusions

• Optimised crystals mounted on BM32 and BM02 at ESRF
• Photons flux at sample is very close to the theoretical flux
• FEA predicts high $R_{\text{int}}$ even for higher storage ring current

Advantages

• Longitudinal bump removed
• Self-tuning crystal
• For one optics configuration => it should exist an optimised shape
• Cheap (indirect cooling + water)
• Simple to design & simple iterative converging methodology
• Standard manufacturing and tailoring
• Easy to mount & not sensitive to mounting defaults

Drawbacks (?)

• Increase of temperature  (but whole setup might be cooled down anyway)
• Weak sagittal bump  (but could be compensated)
Outlook

- Automatic iterative method, use ray-tracing method
- Install on other BM beamline @ ESRF, SOLEIL (DIFFABS,…), etc…
- Apply on Ge/Si (Smart Cut)
- Apply on other reflective surfaces:
  - monochromator with higher power load (wiggler, ondulator)
  - mirror
  - other spectral range (laser)
Thank you for your attention