Bendable crystals in Bragg geometry

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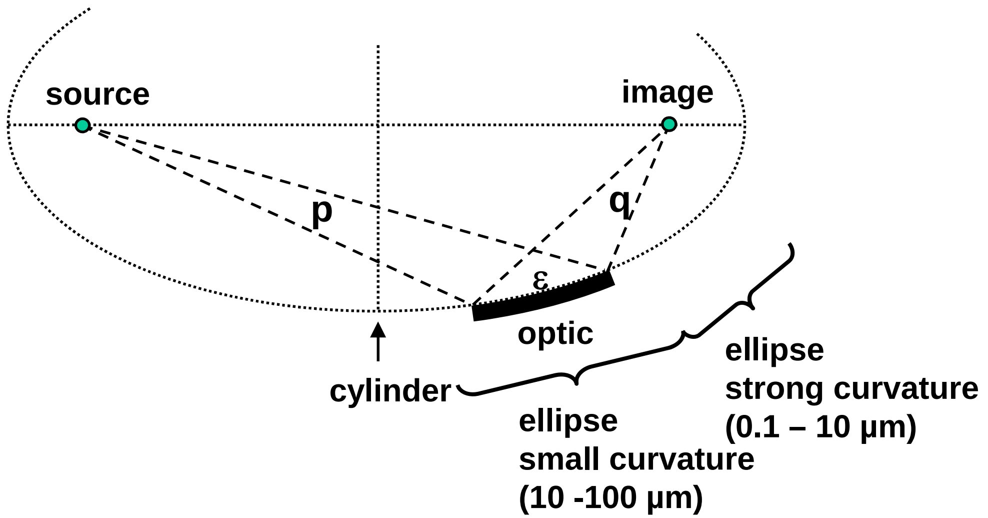
Outline

- Overview of focusing
- Hooke's law + parameters
- ODE beamline description
- Data analysis
- Conclusion

Overview of focusing

- **Image size → two factors : source size and mirror defects**

$$\sigma_{\text{IMAGE}} = (\sigma_{\text{SOURCE}} \frac{q}{p}) \otimes (2q\varepsilon)$$



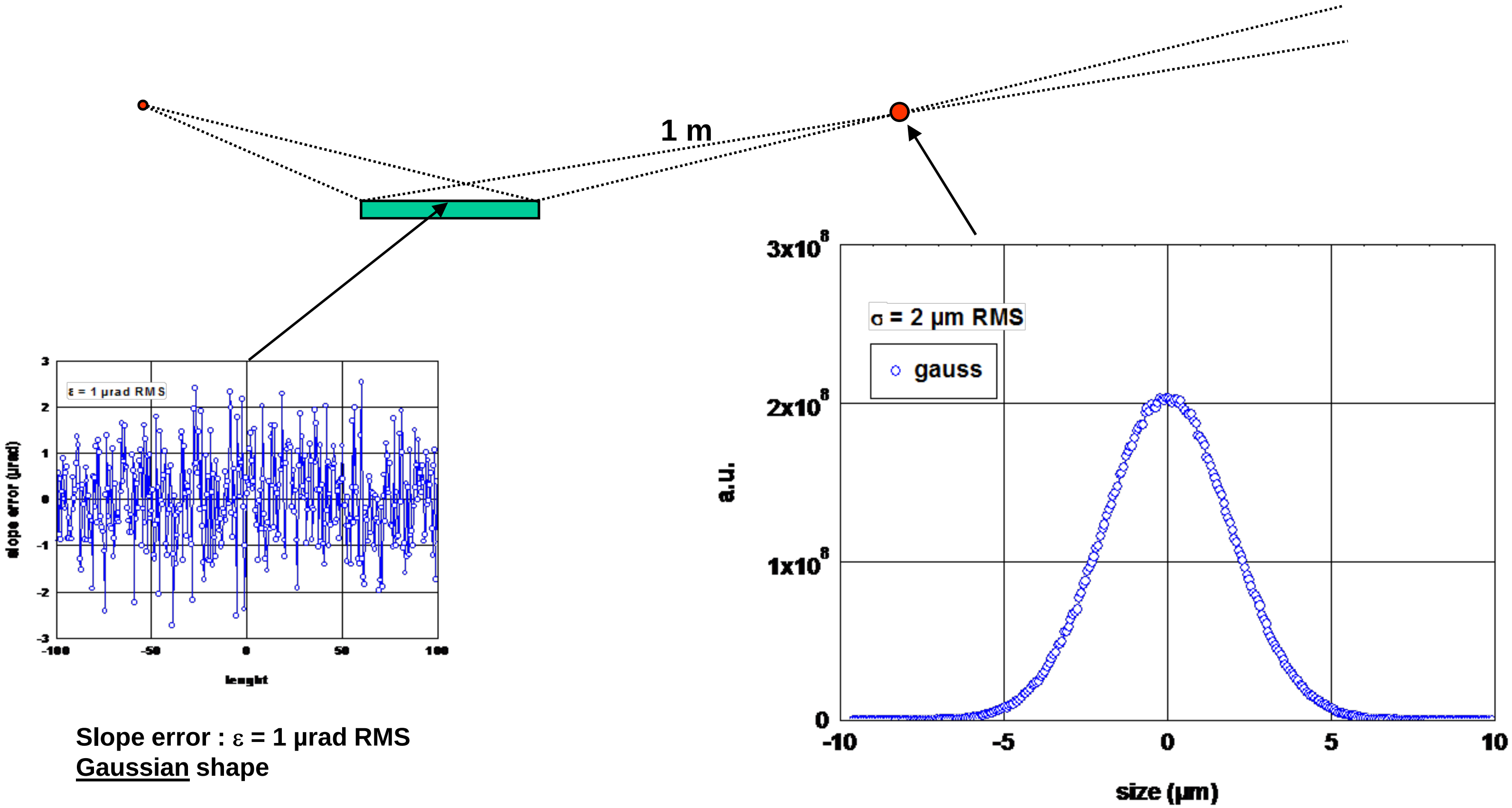
- **Radius of curvature**

$$R \approx \frac{2 \times q}{\sin(\theta)}$$

Long mirrors : 50 µm, 5000 – 1000 m , 60 mm
KB mirrors : 2 µm, 150 – 50 m, 8 mm
<u>Si111 crystal</u> at 7 keV : 10 – 8 m, 1.5 mm

Overview of focusing

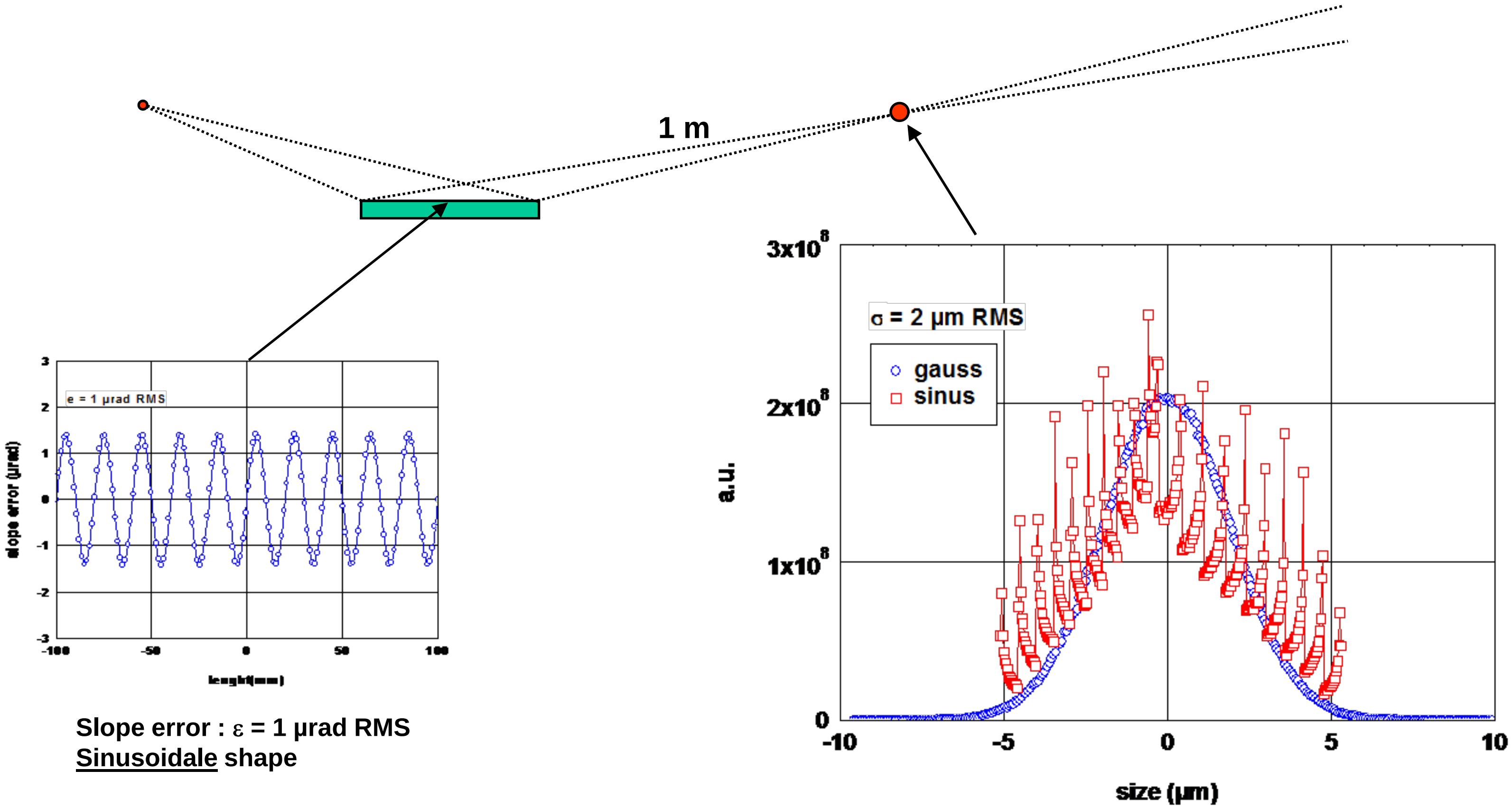
- **slope error effect on the focus**



Slope error : ε = 1 µrad RMS
Gaussian shape

Overview of focusing

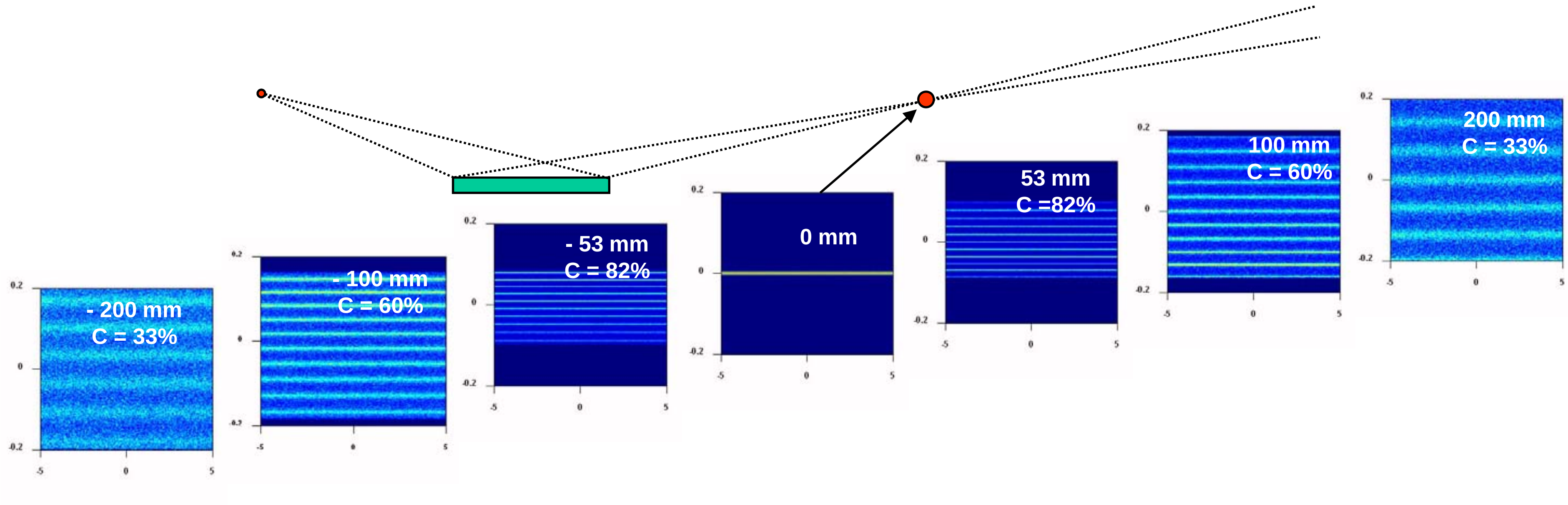
- **slope error effect on focus**

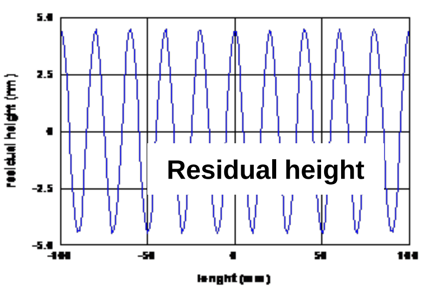


Slope error : ε = 1 µrad RMS
Sinusoidale shape

Overview of focusing

- **slope error shape out of focus**





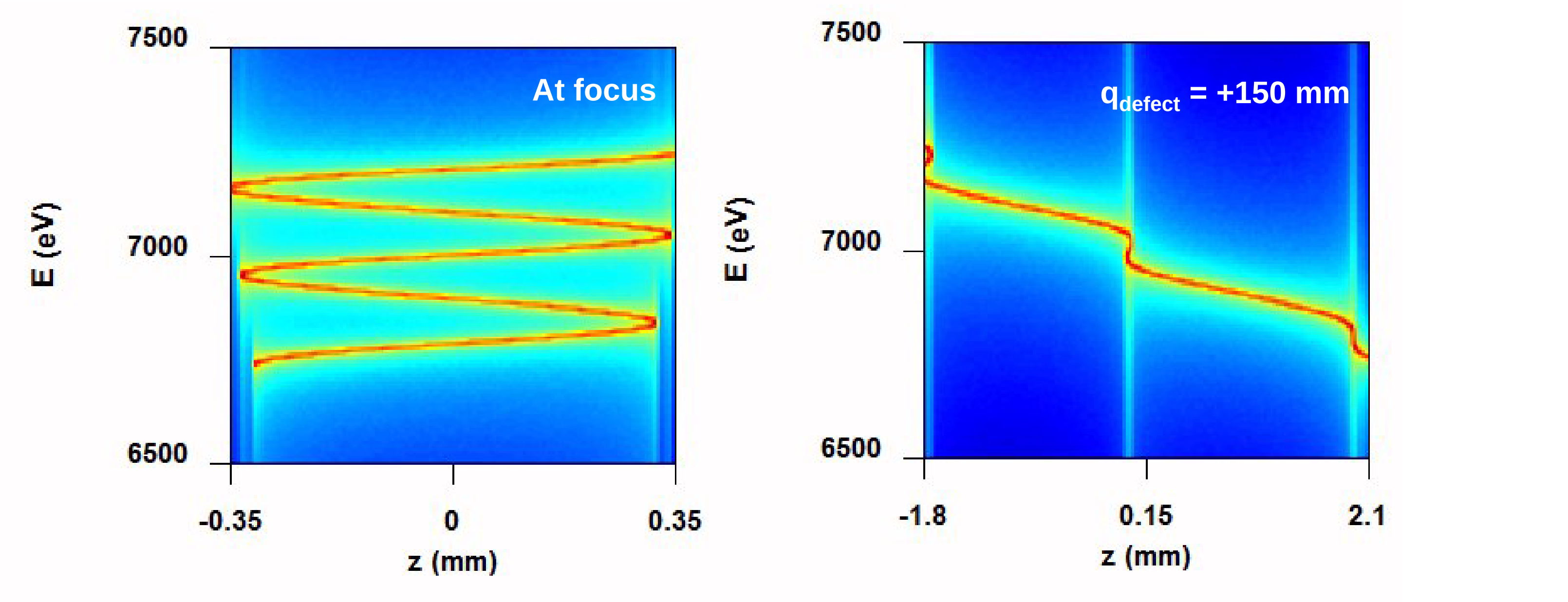
sinusoidale defects resulting of
- polishing defects (mirrors)
- thickness and width defects (crystals)

Sinusoidale defects in crystals

Si111 crystal at 7 keV (θ = 16.41°)

Sine defect : A = 1.8 µm, D = 80 mm, L = 200 mm

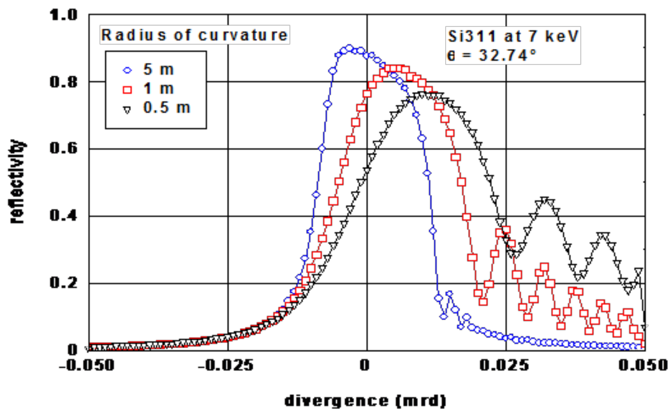
DUMOND Diagrams

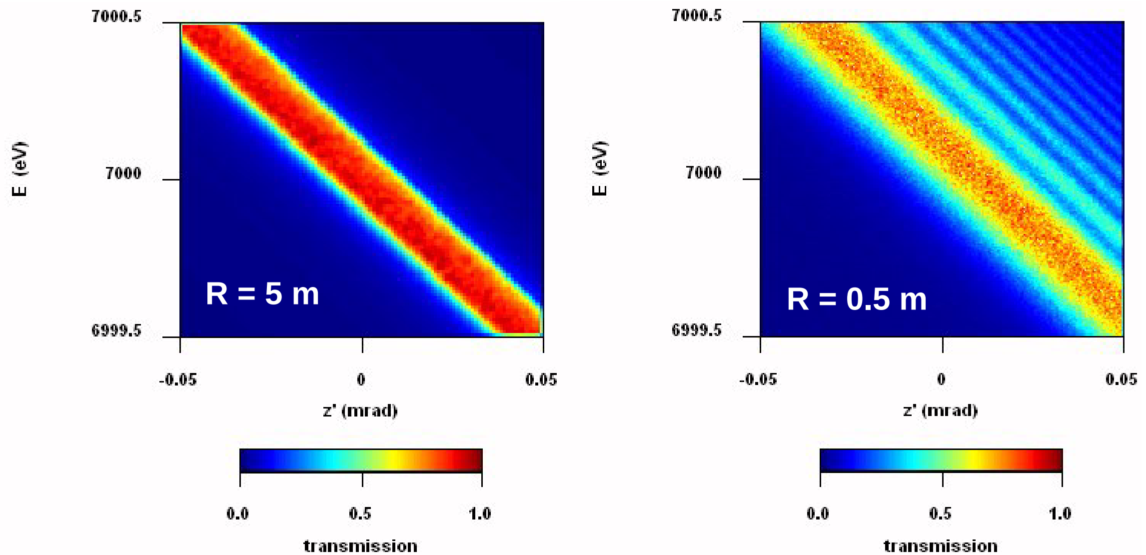


➡ **The DUMOND Diagram changes according to the position of the detector**

Overview of focusing

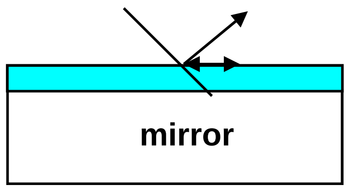
- **Local crystal curvature effect** (Using Takagi-Taupin crystal theory)

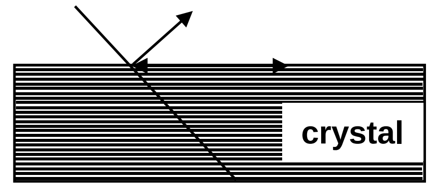


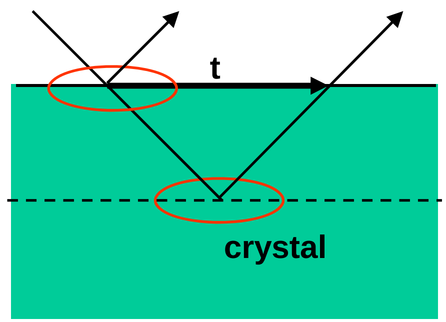


Overview of focusing

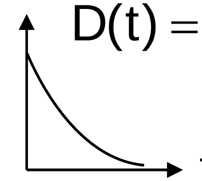
Depth penetration length effect







If only absorption



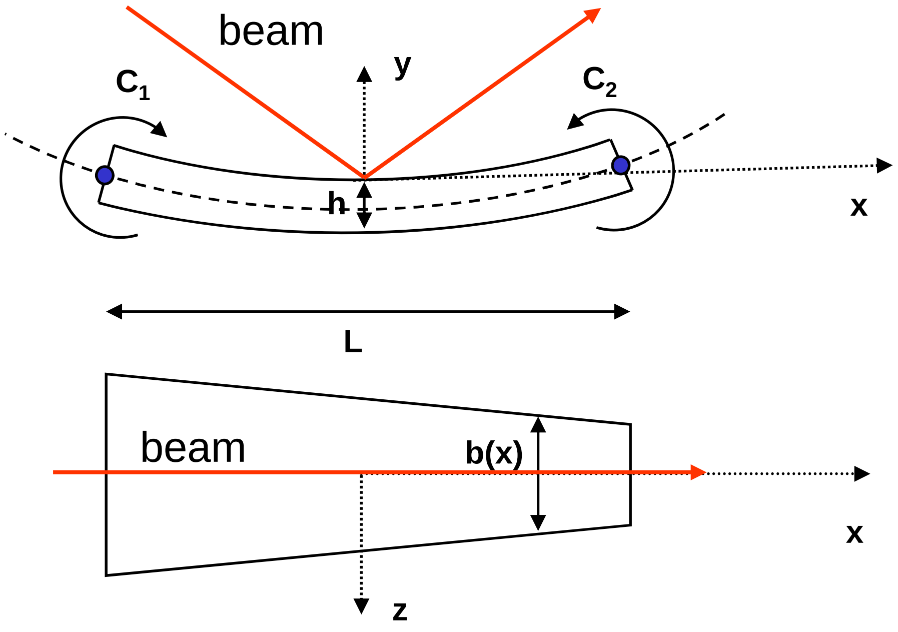
$$D(t) = a \times e^{-a\,t}$$

$$a = \frac{2 \times \mu}{\cos(\theta)}$$

➡ **Focal size limitation for crystals**

Hooke's law definition

$$\frac{1}{R(x)} = \frac{12}{E\,h^3}\,\frac{\frac{(C_1+C_2)}{2} - \frac{(C_1-C_2)}{L}x}{b(x)}$$



- elastic deformations
- mechanical beam theory

$$\frac{1}{100} < \frac{h}{L} < \frac{1}{5}$$

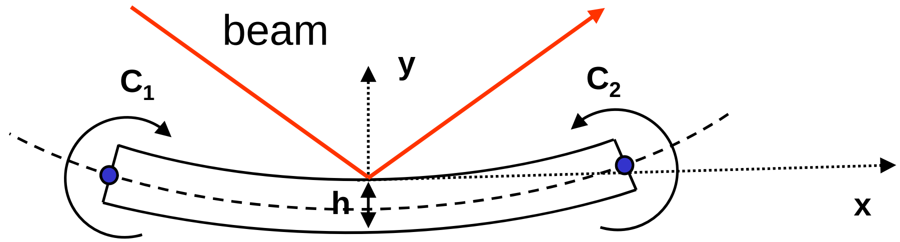
Long mirrors, KB : $\frac{1}{20}$

Bent crystals : $\frac{1}{100}$ $\approx$ **Plate theory** $\rightarrow$ **(FEA verification)**

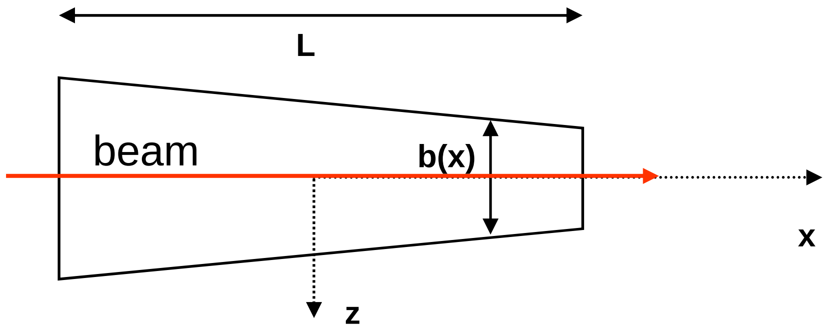
Hooke's law

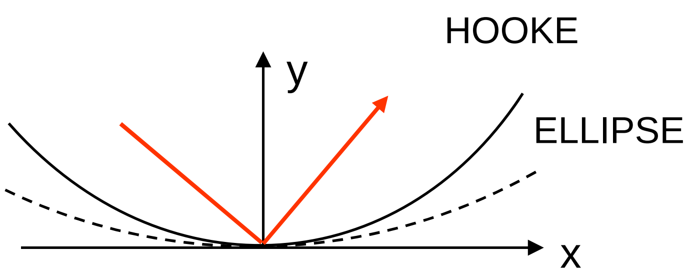
- **Curvature**

$$\frac{1}{R(x)} = \frac{12}{E\,h^3}\,\frac{\frac{(C_1+C_2)}{2} - \frac{(C_1-C_2)}{L}x}{b(x)}$$



$$\frac{1}{R(x)} = \frac{y''(x)}{\sqrt[3]{1+y'(x)^2}} \approx y''(x)$$





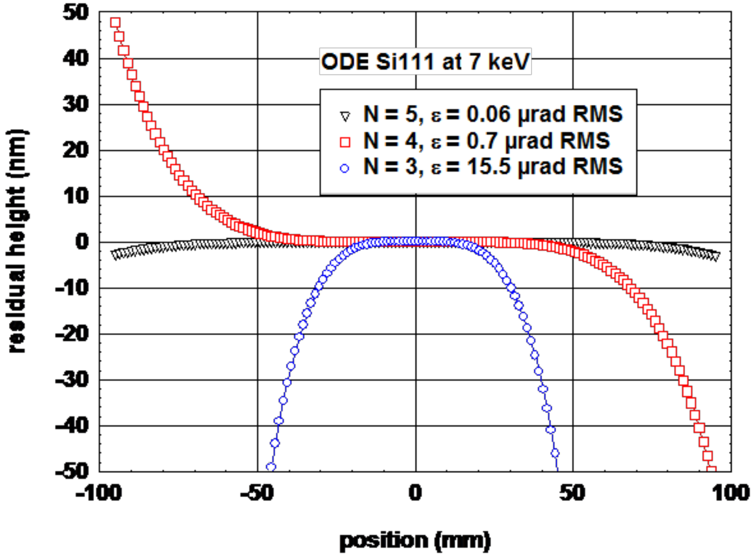
evaluation

$$\varepsilon = y'_{HOOKE} - y'_{ELL}$$

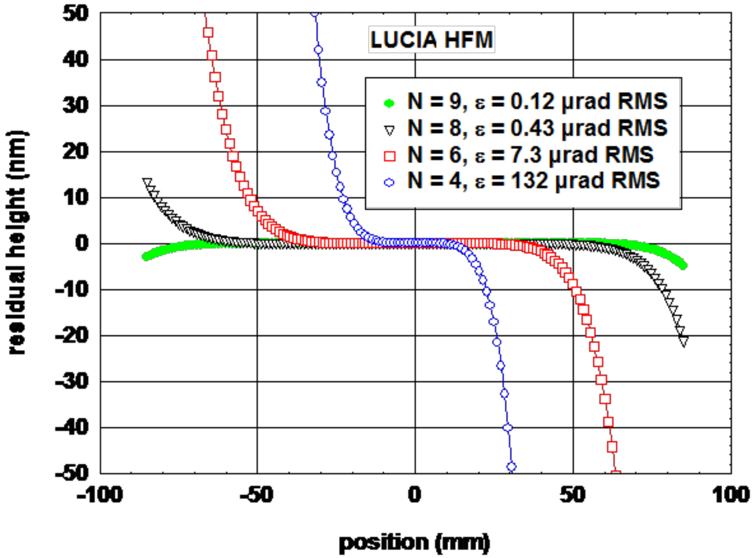
$$\rightarrow \sigma = 2 \times \varepsilon \times q$$

- **Ellipse representation**
  - Polynomial $y_{ELL} = \sum a_n x^n$
    with $a_n = f(p, q, \theta)$
  - Numerical $(x_1, y_1)....(x_N, y_N)$

Polynomial representation :
Si111 ODE crystal
p = 17.2 m, q = 1.2 m, θ = 16.41° (7 keV)
spot of 10 µm FWHM



LUCIA HFM
p = 13.3 m, q = 0.3 m, θ = 0.4°
spot of 2 µm FWHM

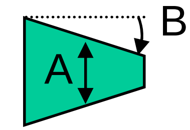


Width side

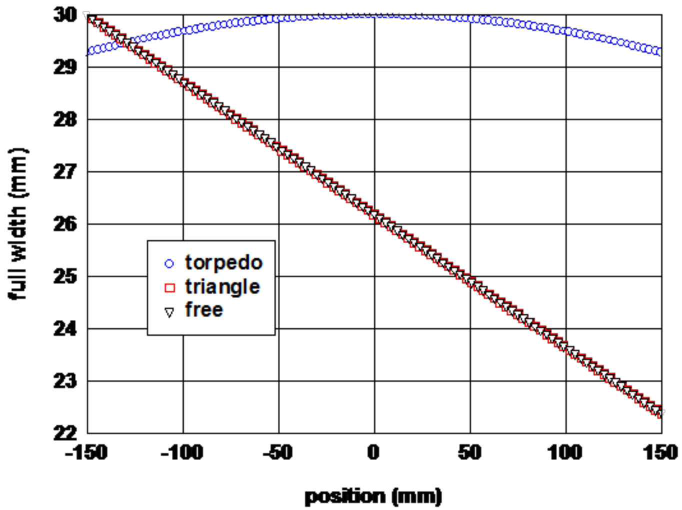
$$\frac{1}{R(x)} = \frac{12}{E\,h^3}\,\frac{\frac{(C_1+C_2)}{2} - \frac{(C_1-C_2)}{L}x}{b(x)}$$

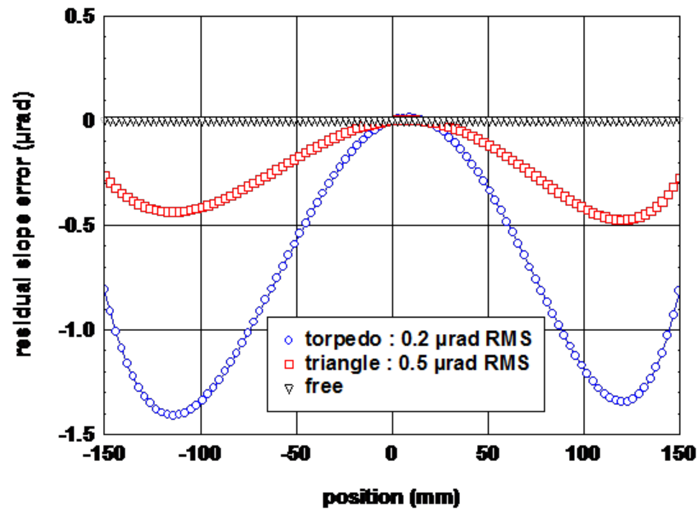
shapes

free : numerical	$(x_1,b_1)\ldots.(x_N,b_N)$	
trapezoidal	$b(x) = A(1-B\,x)$	→
torpedo	$b(x) = A(1-B\,x^2)$	



Si111 ODE crystal, L = 300 mm, h = 1.6 mm
p = 17.2 m, q = 1.2 m, θ = 16.41° (7 keV)



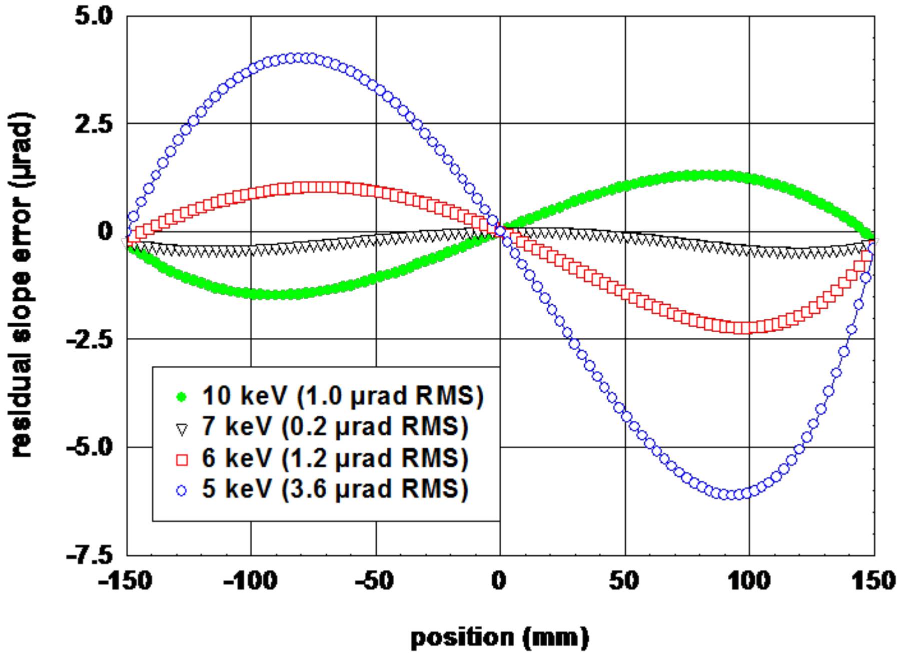


- **Trapezoidal easier to make and to correct**
- **Torpedo well adapted for bending and thermal cooling because symmetric**

Hooke's law

Change of energy

Si111 ODE crystal, L = 300 mm, h = 1.6 mm
p = 17.2 m, q = 1.2 m
Triangular width optimized at 7 keV (θ = 16.41°)



E (keV)	θ (°)	C_1(N.m)	C_2(N.m)
5	23.30	0.2018	0.2077
6	19.24	0.1675	0.1739
7 (opt)	16.41	0.1432	0.1495
10	11.41	0.1000	0.1050

- **The RMS slope error is acceptable for a large spectral domain**
- **The residual slope error shape may structured the Dumond diagram**

Hooke's law

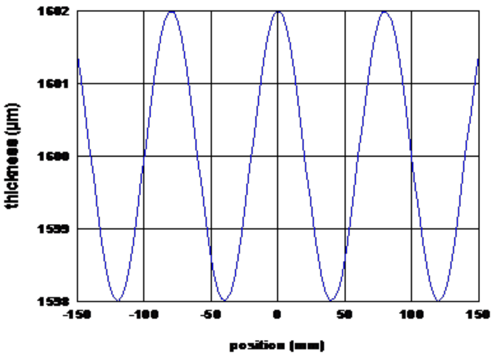
- **thickness** $$\frac{1}{R(x)} = \frac{12}{E\,h^3}\,\frac{\frac{(C_1+C_2)}{2} - \frac{(C_1-C_2)}{L}x}{b(x)}$$

➡ Thickness defects can be corrected with the lateral width

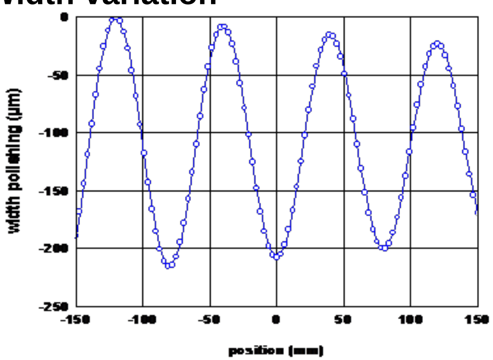
$$(h+\Delta h)^3(b+\Delta b)=cte \;\rightarrow\; \boxed{\Delta b = \frac{3b}{h}\Delta h}$$

(h = 1.6 mm, b = 30 mm → ≈ 60 µm /µm)

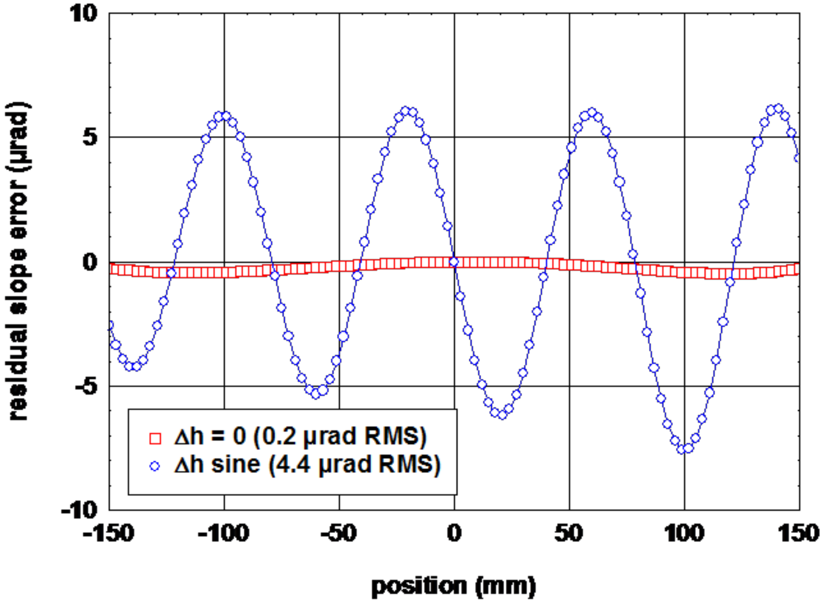
Thickness variation (± 2 µm)



Width variation



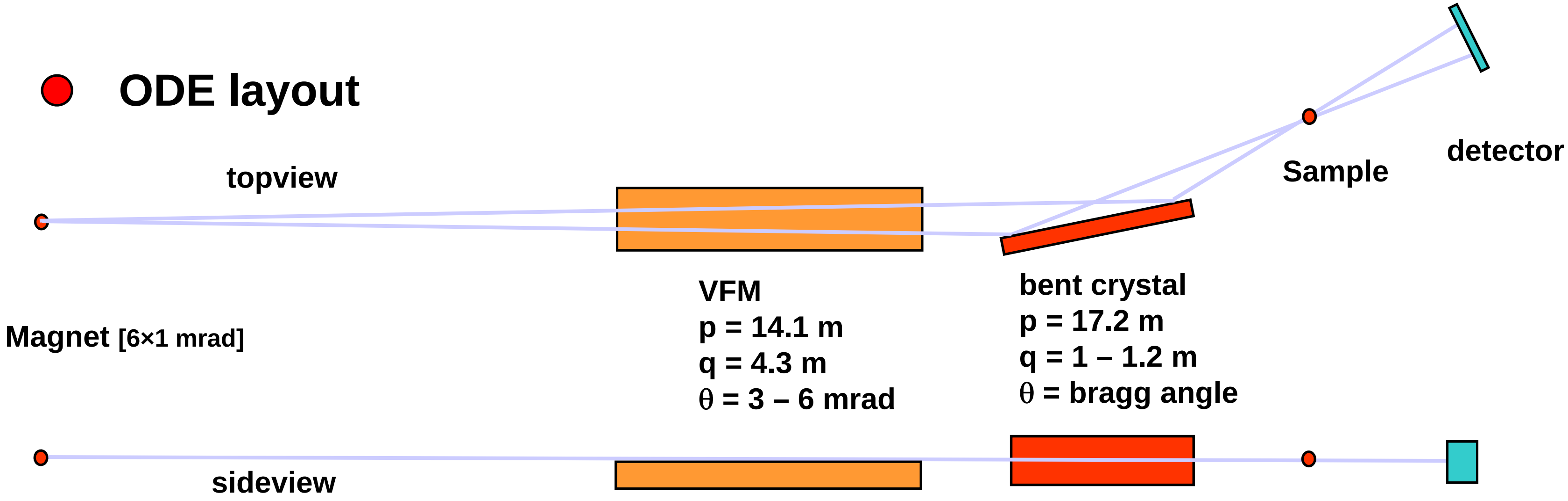
Surface variation



ODE EDXAS beamline

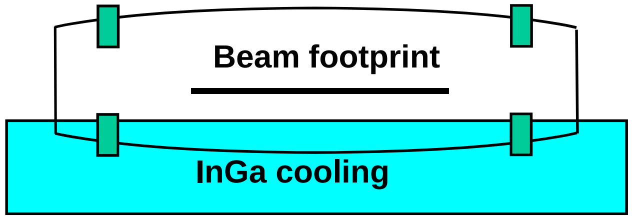
- **ODE beamline : EDXAS**
  - X-ray magnetic Circular Dichroism
  - Materials under extreme conditions
  - Chemistry and time resolved measurements

- **ODE layout**

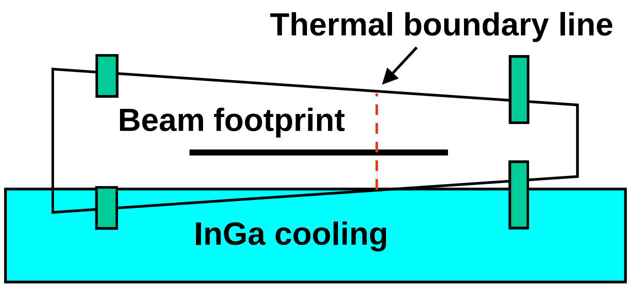


ODE EDXAS beamline

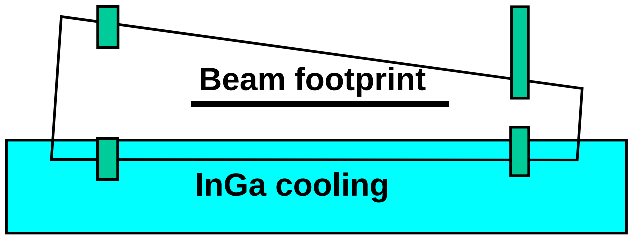
- **Bent crystal**



➡ **Adapted to the bending and cooling**
Difficult to make



➡ **Adapted to the bending**
No adapted to the cooling
Easy to make



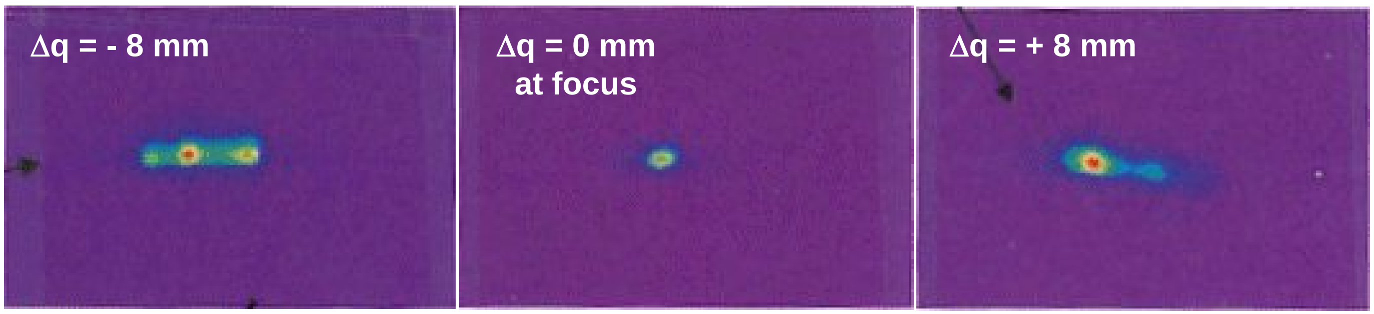
➡ **Adapted to the bending ?**
Adapted to the cooling
Easy to make

➡ **Have to be checked by FEA**

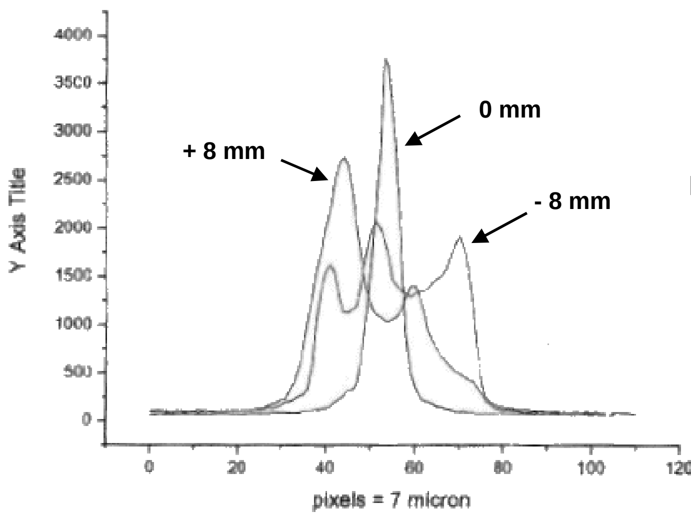
X-ray measurements

Zn edge measurement

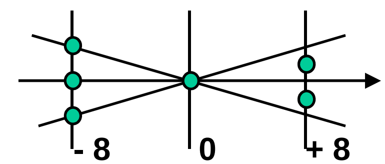
E = 9659 eV, θ_0 = 11.81°, ΔE = 600 eV



CCD : 110×72 pix (7 µm / pix)



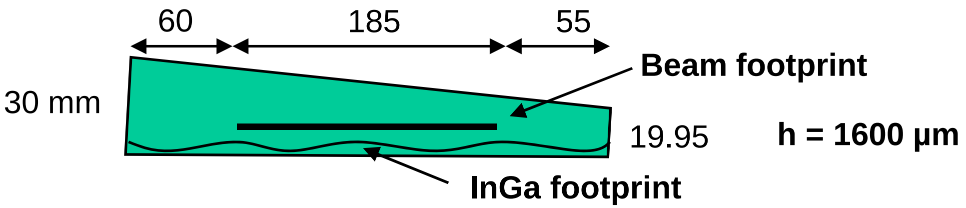
Equivalent sine defect
$q_{striation}$ = 1200 ± 8 mm
δ = 114 µm
→A = 100 nm, D = 80 mm, ε = 5.3 µrad RMS



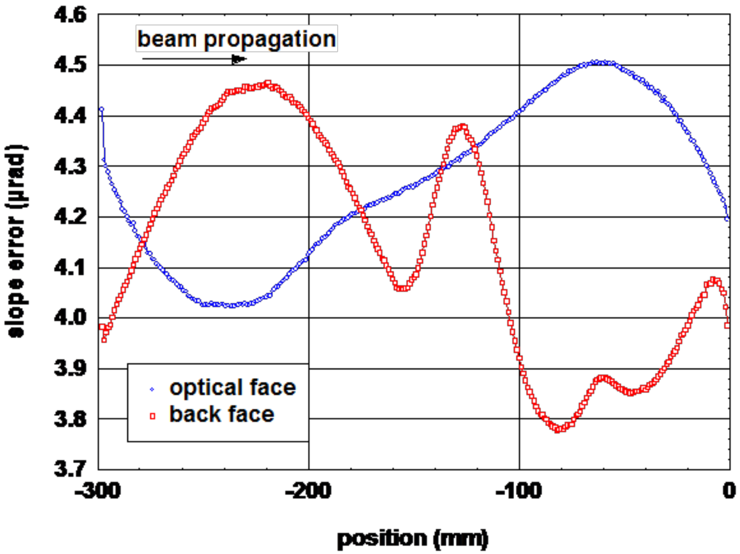
Δx_{the} = 30 µm FWHM
Δx_{mes} = 45 µm FWHM (factor 1.5)

Thickness crystal measurement

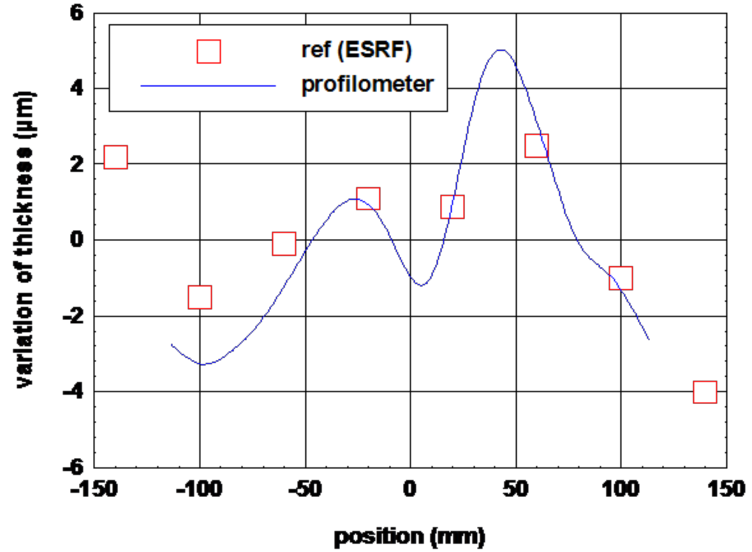
- Use of a profilometer : the support of the crystal is <u>critical</u>



Slope errors measurements (without curvature)

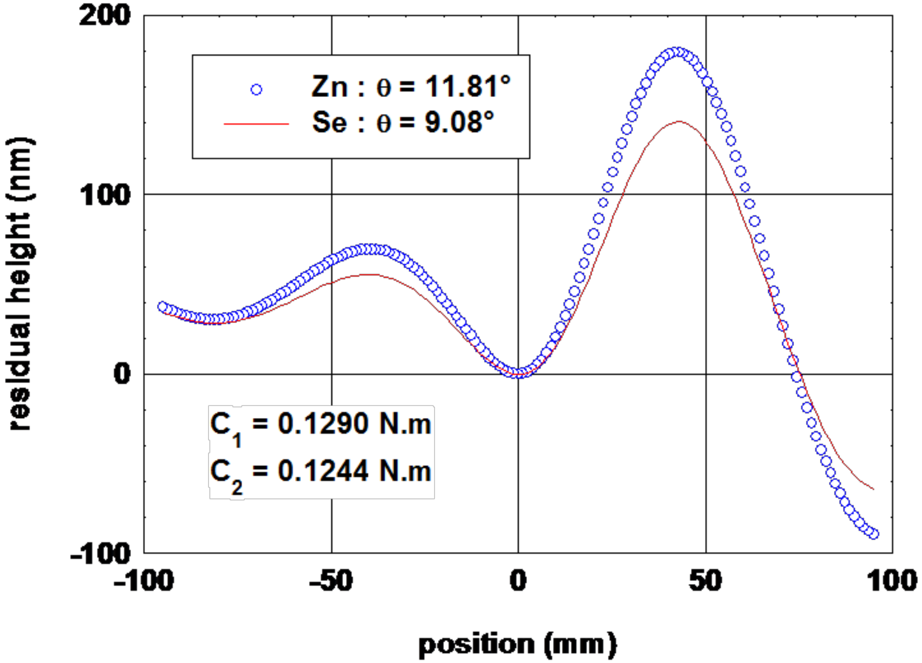


Thickness reconstruction



- **Next step : to use a fixed crystal curvature for the profilometer measurement**

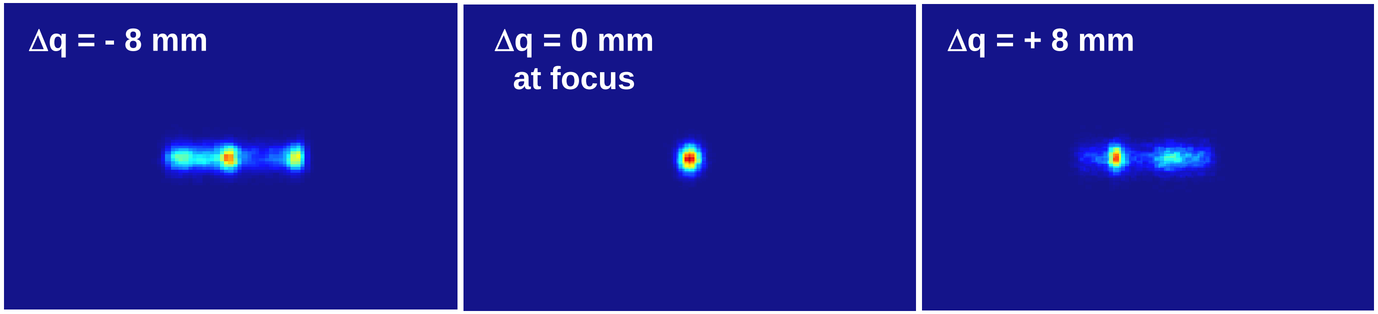
Shape of the surface

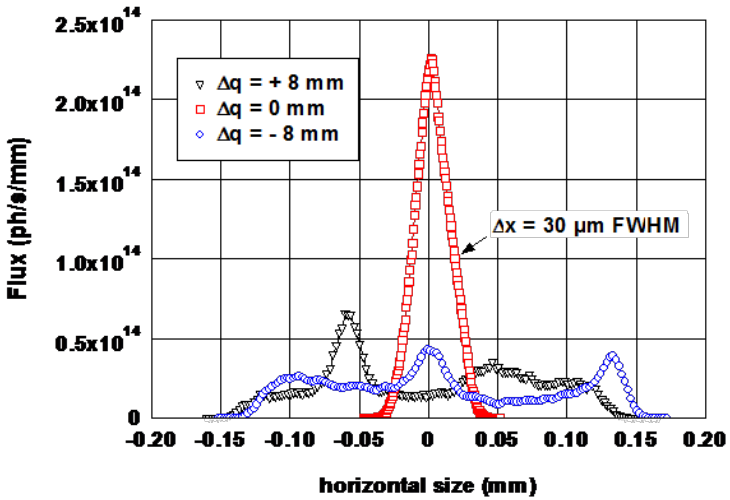


- The optical shape varies with the Bragg angle
- The optical shape is very sensitive with C_1 and C_2
- Period = 80 mm

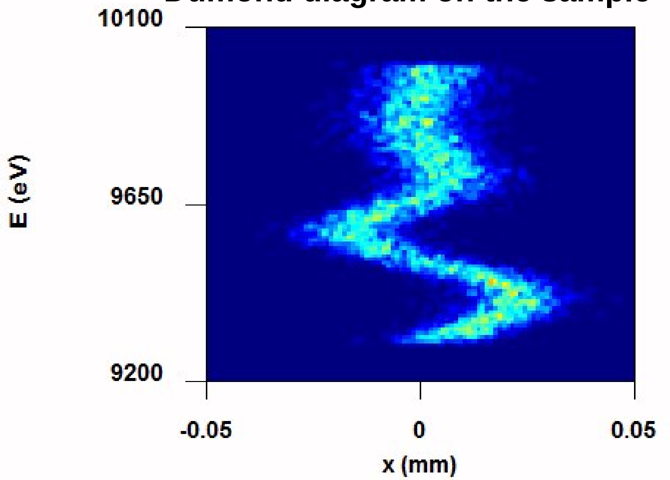
- **Zn edge simulations**

➡ **E = 9659 eV, θ_0 = 11.81°, ΔE = 600 eV**





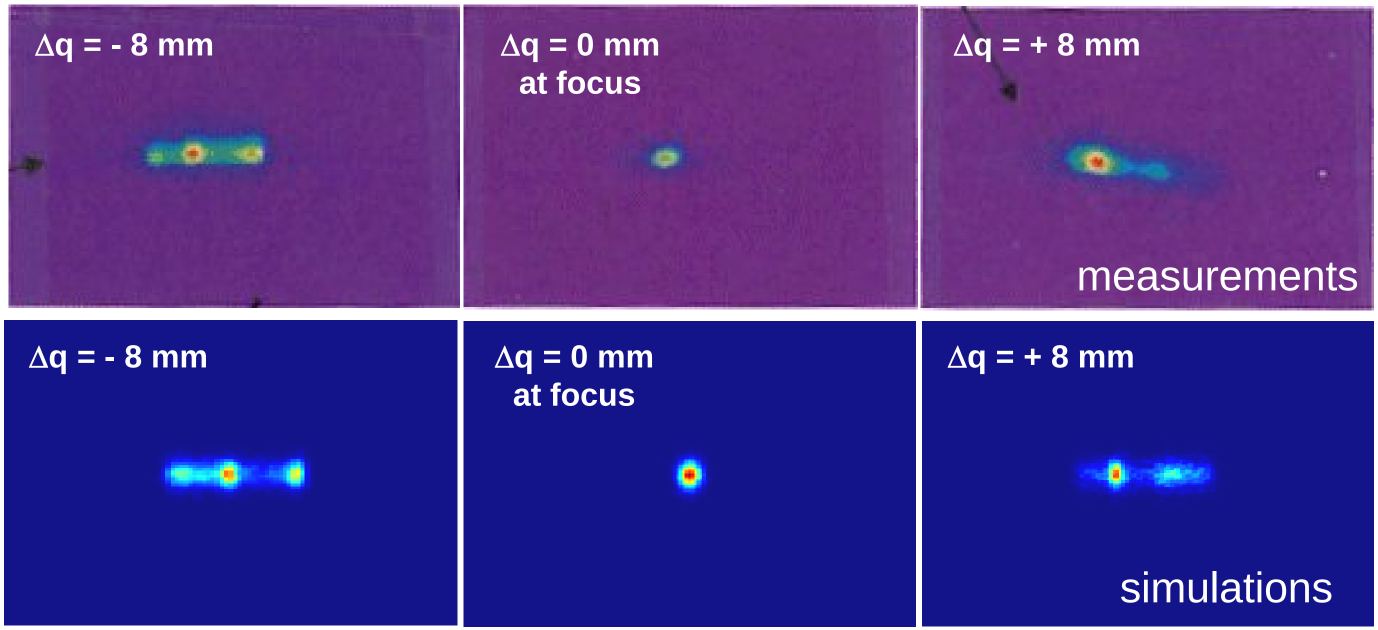
Dumond diagram on the sample



Data analysis

Comparison experience - theory

- E = 9659 eV, θ_0 = 11.81°, ΔE = 600 eV



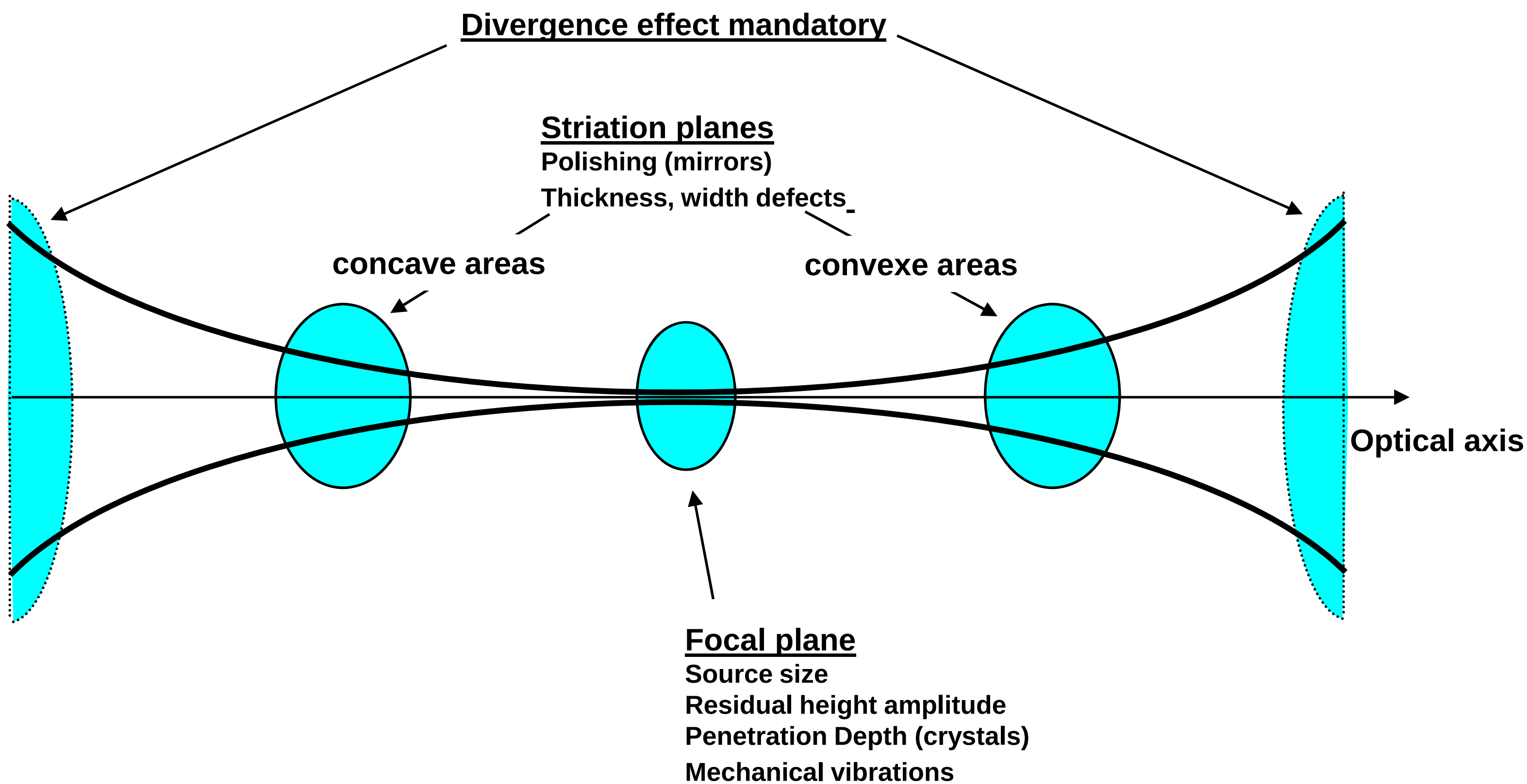
- **Structures out of focus correctly depict through thickness defects**

- **Focal spot size strongly dependent of depth penetration (not yet implemented on the ray tracing)**

Conclusion

- **Intensity modulation scheme**

➡ Intensity modulation = f(source size, period defects, beam divergence)



Acknowledge

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- ODE beamline team and Metrology Laboratory team of SOLEIL

Simulations tools

- **Ray tracing software SPOTX**
  - Based on the MonteCarlo method
  - Dynamical absorption calculation
  - Very fast and well suited for X-ray beamlines simulations

- **Surfaces defects**
  - Function (sinusoidal, ..)
  - Random
  - Data file : profilometer, interferometer