

# Bent crystals for beam extraction from the LHC

## Bent crystals for beam extraction from the LHC



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European Research Council  
Established by the European Commission

# OUTLINE AND MOTIVATIONS

- **Motivations**
  - Fixed target experiments @LHC
  - hadron physics
- **Crystal specifications**
- **Crystals manufacturing**
- **Crystals bending**
  - Anticlastic deformation
  - Self standing bent crystals
- **Conclusions**



“Physics opportunities of a fixed-target experiment using LHC beams”  
S. J. Brodsky, et al., Phys. Rep. 522 (2013) 239-255.

# CRYSTAL SPECIFICATIONS

$L \rightarrow$  Crystal thickness along the beam

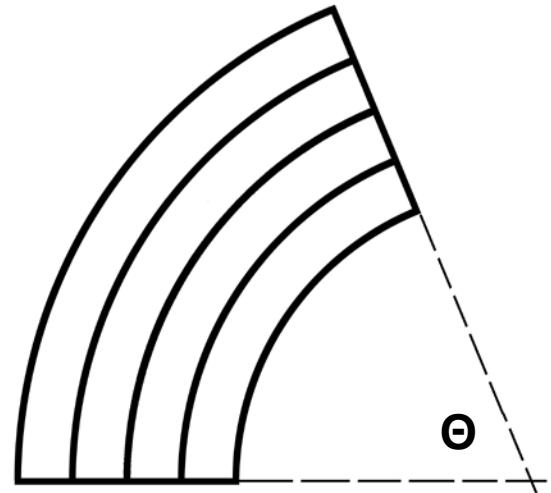
$\Theta \rightarrow$  Deflection angle

$R \rightarrow$  Bending radius

$$L = R * \Theta$$

Required deflection angle:  $\sim 1$  mrad

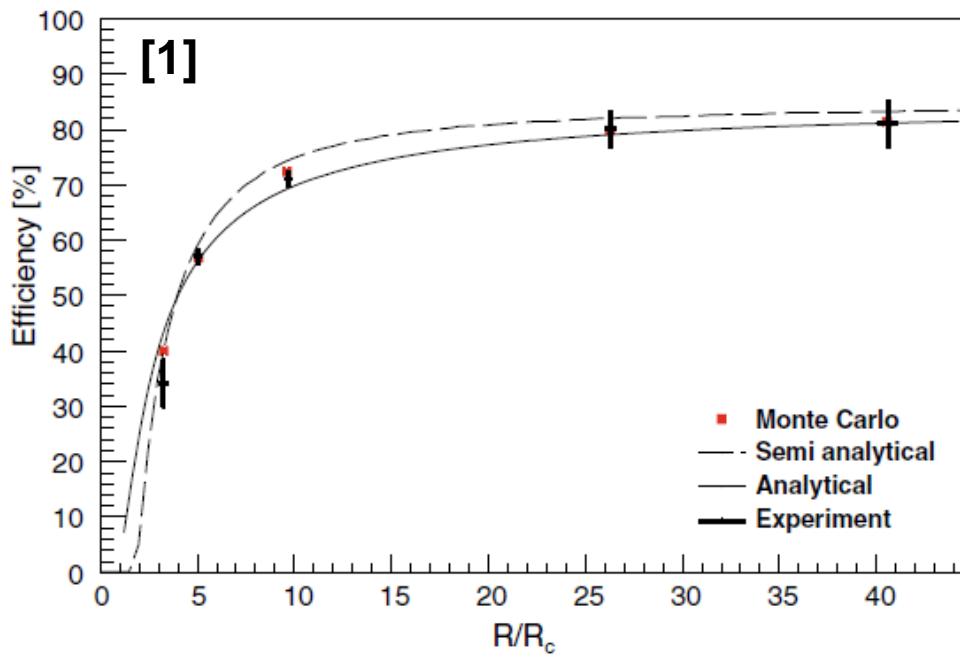
$\Theta = L/R \rightarrow$  Required optimization of both L and R.



$L \rightarrow$  Limited by dechanneling lenght (negligile factor)

$R \rightarrow$  Limited by its influence on the interplanar potential well

# CRYSTAL SPECIFICATIONS



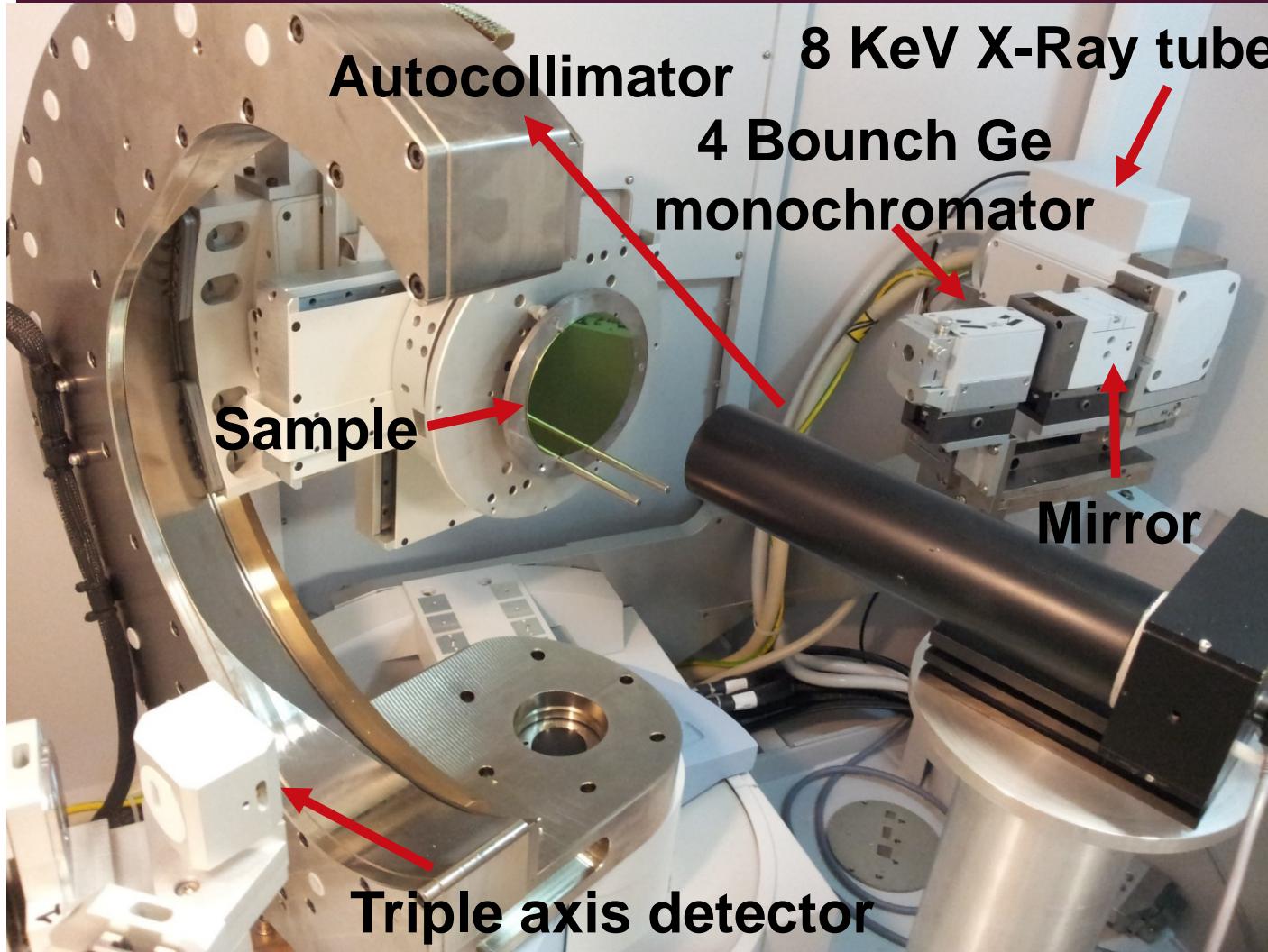
- Reasonable channeling efficiency  
→  $R > \sim 7 R_c$
- At 7 TeV  $R_c \sim 14$  m  
 $R > \sim 100$  m;  $\Theta \sim 1$  mrad  
→  $L > 100$  mm ( $L=R^*\Theta$ )

Needed manufacturing, bending and characterization of a crystal with

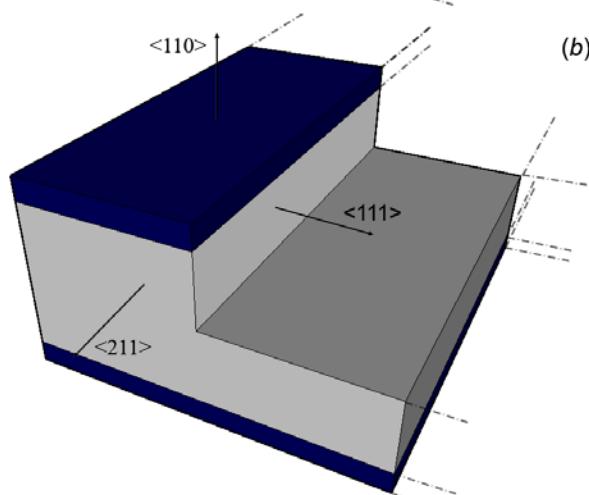
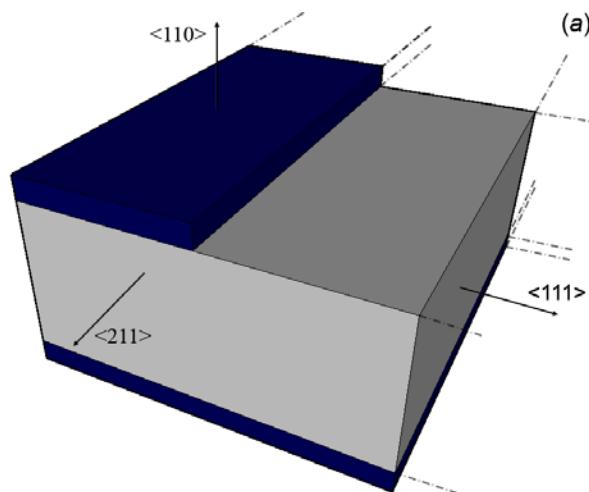
- (110) or (111) channeling planes
- $L \sim 100$  mm
- $R \sim 12$  m
- Uniform bending radius
- < 1 dislocations/cm<sup>2</sup> [2]

# Crystal manufacturing

-Bulk crystalline quality characterization (Ag x-ray)



# CRYSTAL MANUFACTURING -ANISOTROPIC ETCHING-



Anisotropic etching is a feasible way to realize sub-surface damage free crystals entirely by wet chemical methods. **Only for (110) oriented crystals.**

Etch rate on different silicon planes  
for KOH 20% at 40 °C

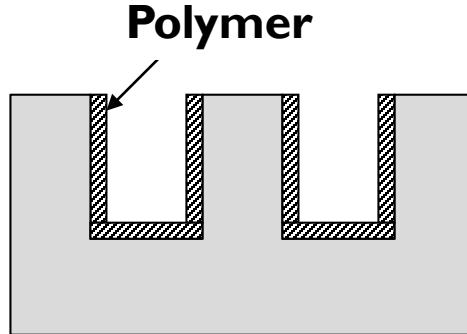
(100)	(110)	(111)
7.1 μm/h	10.7 μm/h	Negligible

# CRYSTAL MANUFACTURING

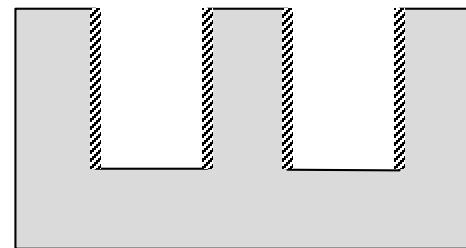
## -DRIE ETCHING-

**For crystals of any orientation (also for (111) oriented)**  
**Tests on (111) crystals already performed.**

**Uses high density plasma to alternatively etch silicon and deposit a etch-resistant polymer on side walls**



**Polymer deposition**



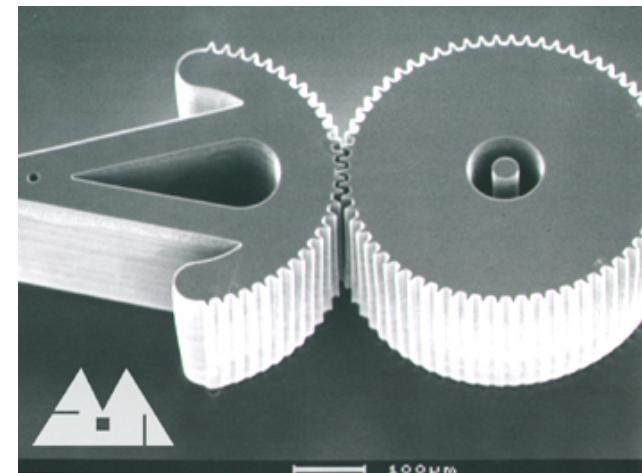
**Silicon etch using  
 $SF_6$  chemistry**



**Unconstrained geometry**  
**90° side walls**  
**High aspect ratio 1:30**  
**Easily masked (PR, SiO<sub>2</sub>)**



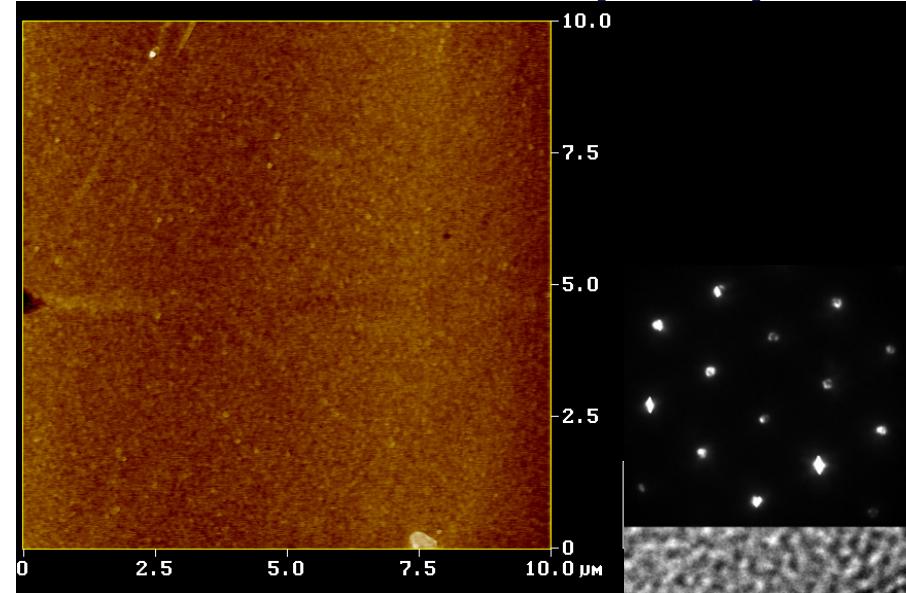
**Process recipe depends on geometry**



# CRYSTAL MANUFACTURING -AFM AND HRTEM-

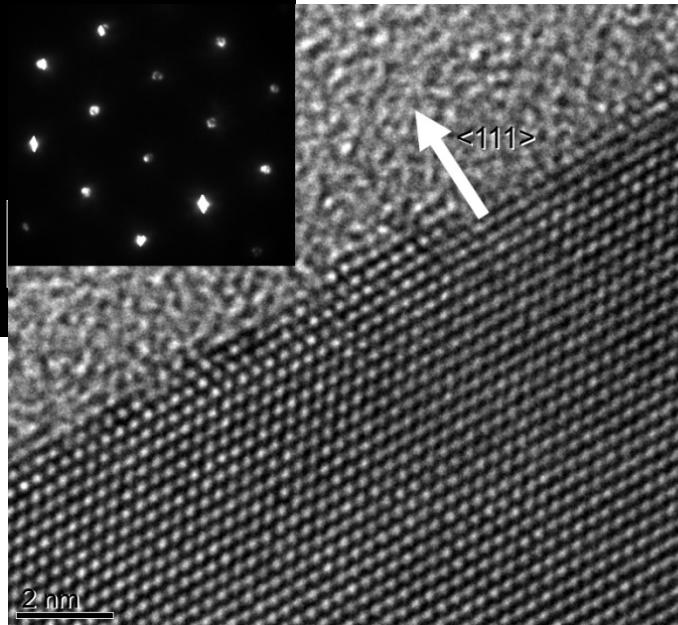
High-quality surfaces achieved via anisotropic chemical etching

Lateral surface (AFM)



Sub-nm roughness  
achieved (0.2 nm)

Entry surface (High Resolution  
transmission electron  
microscopy).  
**Zero nm amorphous layer**



# CRYSTAL MANUFACTURING

## -SUMMARY-

## 2 possible manufacturing approaches

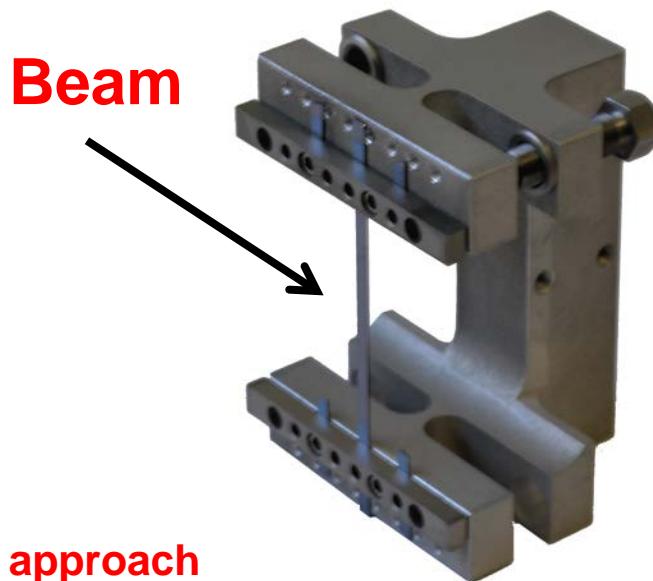
	✓ Anisotropic etching	✓ DRIE etching
<b>Lattice damage free</b>	<b>Yes</b>	<b>Yes</b>
<b>Crystal orientations</b>	<b>(110)</b>	<b>Any</b>
<b>Roughness</b>	<b>Sub-nm</b>	<b>Sub-nm</b>
<b>Possibility to precisely control thickness of crystal along the beam</b>	<b>Yes</b>	<b>Yes</b>
<b>Suitable for crystals bent through anticlastic</b>	<b>Yes</b>	<b>Yes</b>
<b>Suitable for crystals bent through thick or thin films</b>	<b>Yes</b>	<b>Yes</b>

# CRYSTAL BENDING

- Two possible approaches
  - Exploiting anticlastic deformation in «unusual regime»
  - Development of innovative bending schemes (self standing bent crystals)



# CRYSTAL BENDING -ANTICLASTIC DEFORMATION-

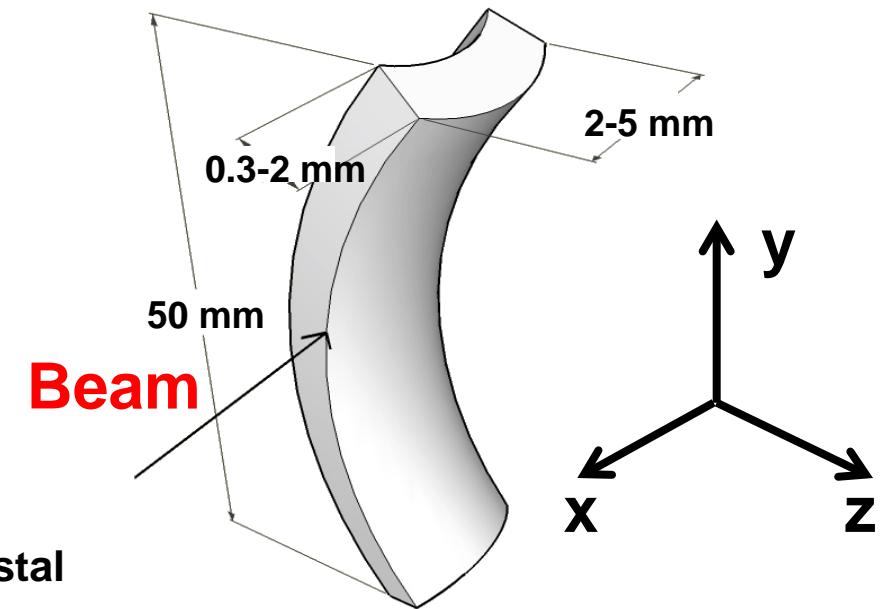


## Analytical approach

- Fast approach for general guidelines on crystal design.
- Does not take into account influence of crystal clamping.

## FEM assisted approach

- More realistic modelling
- Needed for a fine tuning of the crystal and holder geometry



(V.I. Kushriir t, J.P. Quintana and P. Georgopoulos **NIMA 328 (1993) 588-591**)

$$\left( \frac{\partial^4}{\partial x^4} + 2 \frac{\partial^4}{\partial x^2 \partial y^2} + \frac{\partial^4}{\partial y^4} \right) z(x, y) = 0$$

# Crystal bending -anticlastic deformation-

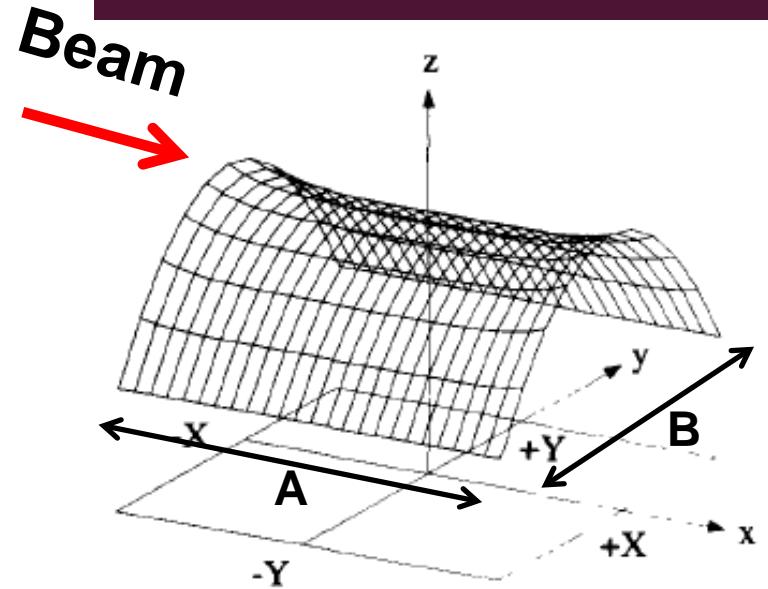
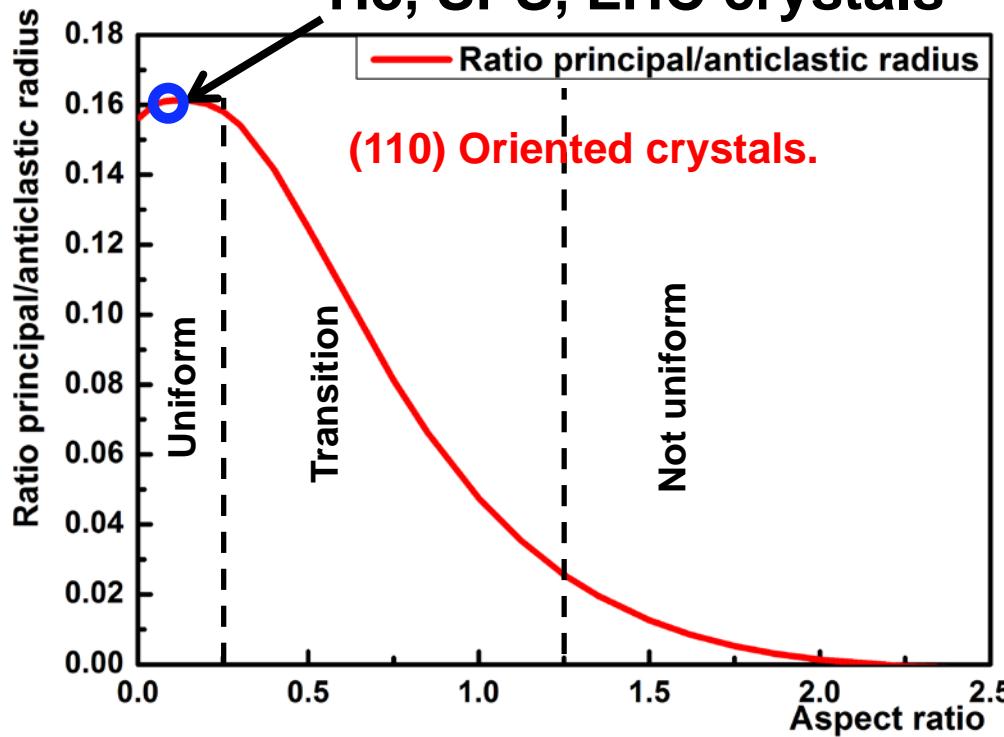


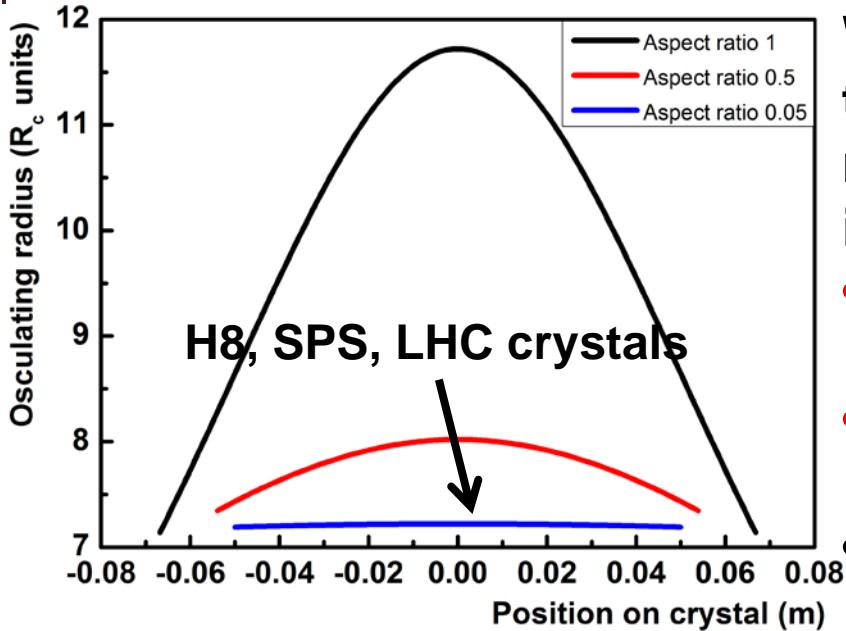
Plate of lateral sizes  $A \times B$   
B is kept constant.  
A is varied.  
Principal curvature along B  
Anticlastic curvature along A

- Ratio between principal and anticlastic curvature in the middle of the crystal
- For aspect ratio  $(B/A) > 0.25$  anticlastic deformation start to be suppressed
  - Not uniform deformation at large aspect ratio

H8, SPS, LHC crystals



# CRYSTAL BENDING -ANTICLASTIC DEFORMATION-



We consider a crystal with thickness along the beam of ~100 mm. Bending angle 1 mrad We increase aspect ratio->

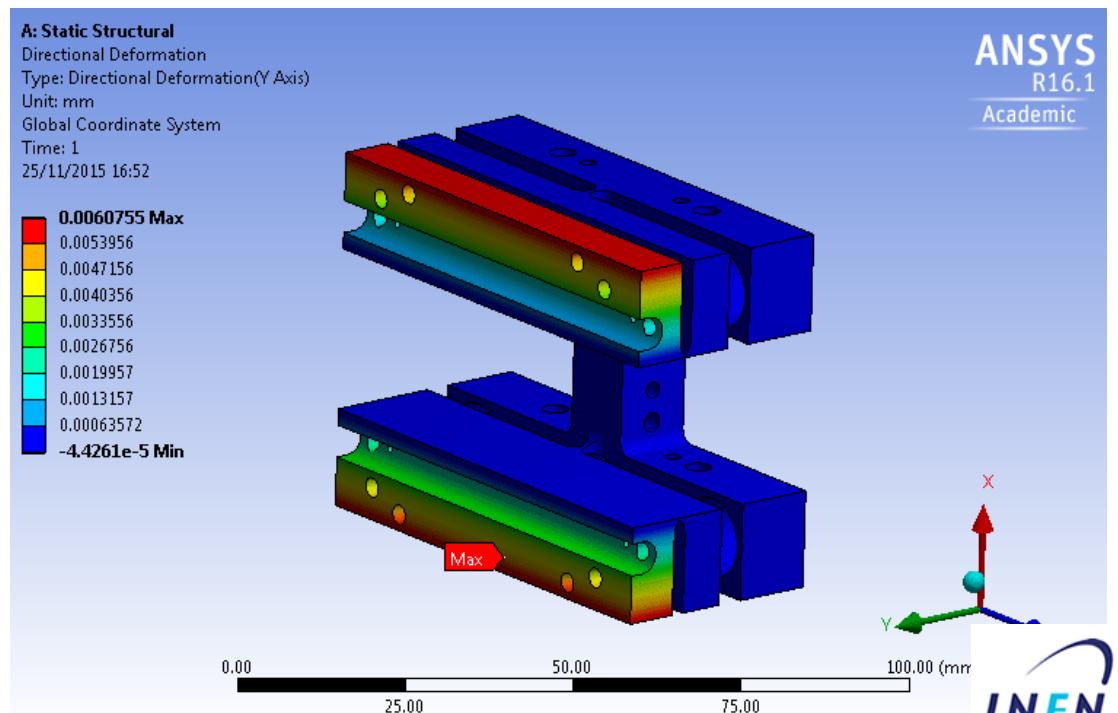
- Compact crystal along the vertical direction
- Decrease of deformation uniformity
- Stronger bending

Thickness along the beam (m)	Crystal height (m)	Aspect ratio	Bending angle (urad)	Principal radius (m)
0.137	0.137	1	1000	7.79
0.11	0.22	0.5	1000	14.01
0.102	2.04	0.05	1000	17.68

# CRYSTAL BENDING -ANTICLASTIC DEFORMATION-

FEM assisted design  
applied to

- design and manufacturing of crystals bending devices
- Crystals dimensions and orientation optimization

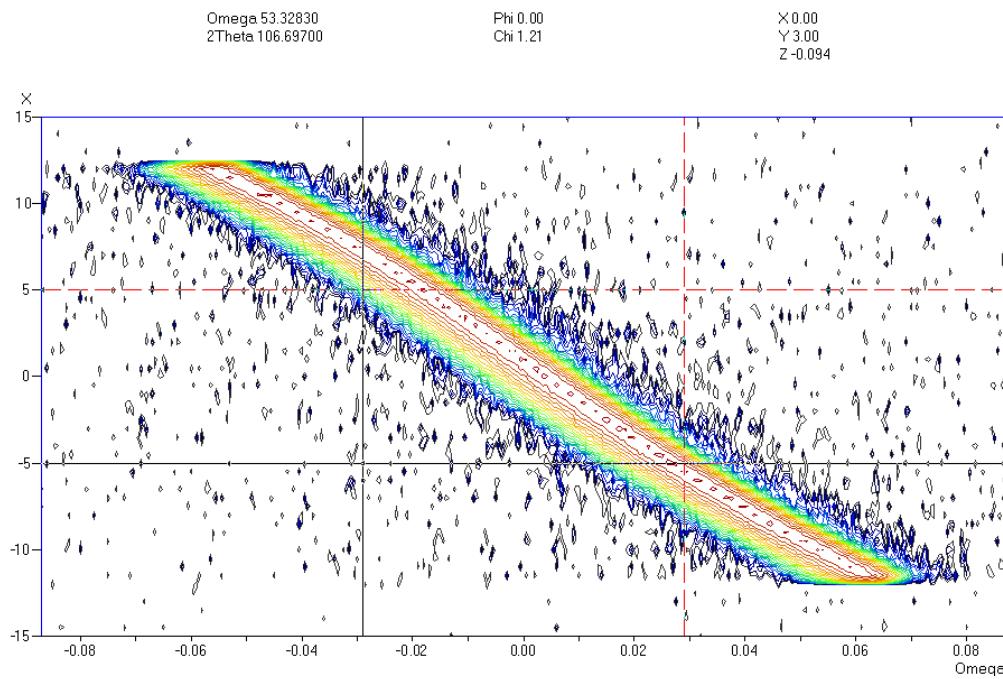


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# CRYSTAL BENDING -ANTICLASTIC DEFORMATION-

440



**Crystal deformational state characterized by HR-XRD**

**Beam size 1x1 mm<sup>2</sup>**

- Crystal bending angle
- Crystal torsion
- Deformation non uniformities.



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# CRYSTAL BENDING

## -SELF STANDING BENT CRYSTALS-

- **Thin/thick films deposited on silicon substrate may induce a deformation of the substrate.**
  - Film deposition performed at high temperature.
  - Film and silicon substrate has different thermal expansion coefficients → deformation while cooling to room temperature
  - Deformation adjustable acting on film thickness and patterning.
- **Deformation occurring thanks to surface plasticization**



# Self standing bent crystals

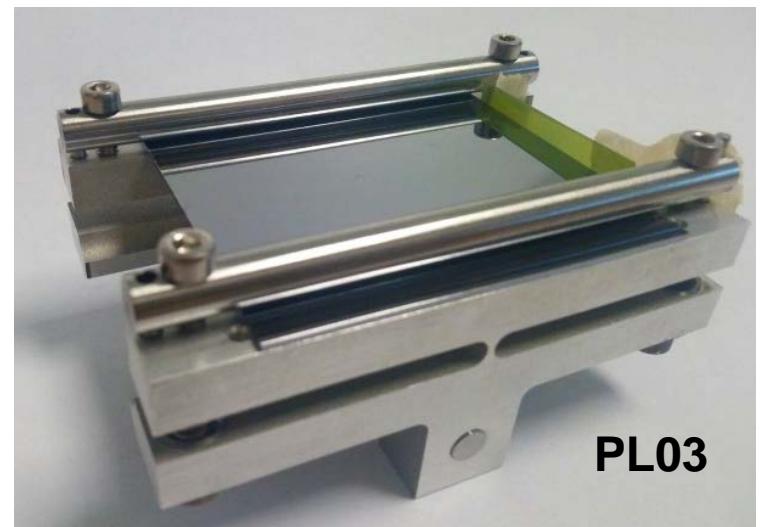
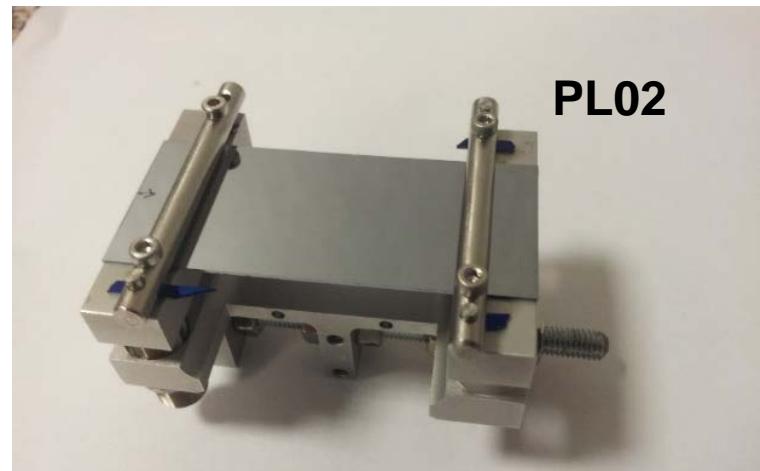
## -Thin/thick film deposition-

- Possibility to deposit a wide class of materials
  - Thin films (**silicon oxide, silicon nitride, mettals, thickness up to ~400 nm**).
  - Thick films (**aluminium based alloys, carbon fiber, thickness from a few micron to a few mm**).
  - **Holder needed for a fine adjustement of crystal deformation**

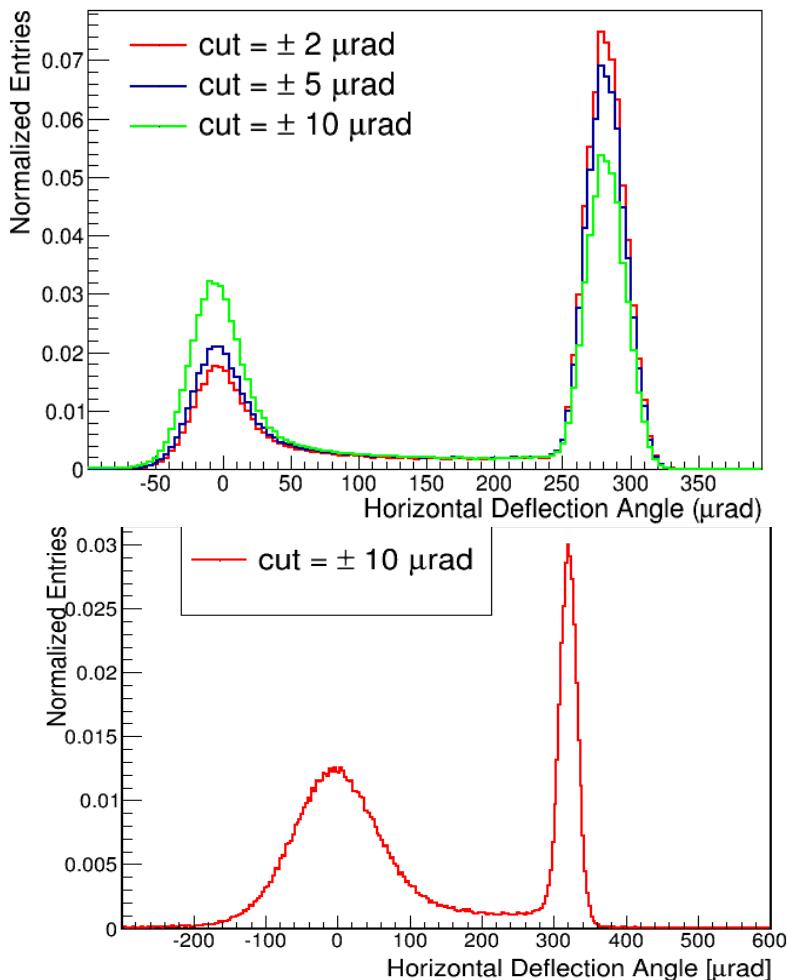


# LONG CRYSTALS – – ANTICLASTIC DEFORMATION –

Feature	PL02	PL03
Crystal thickness along the beam	$23.8 \pm 0.1$ mm	$56.8 \pm 0.1$ mm
Crystal transversal thickness	0.52 mm	1 mm
Channeling plane	(110)	(110)
Channeling axis	<100>	<110>
Bending angle (HRXRD)	280 $\mu$ rad	324 $\mu$ rad



# LONG CRYSTAL «PL02» test with 400 GeV/c protons



## Preliminary data for PL02

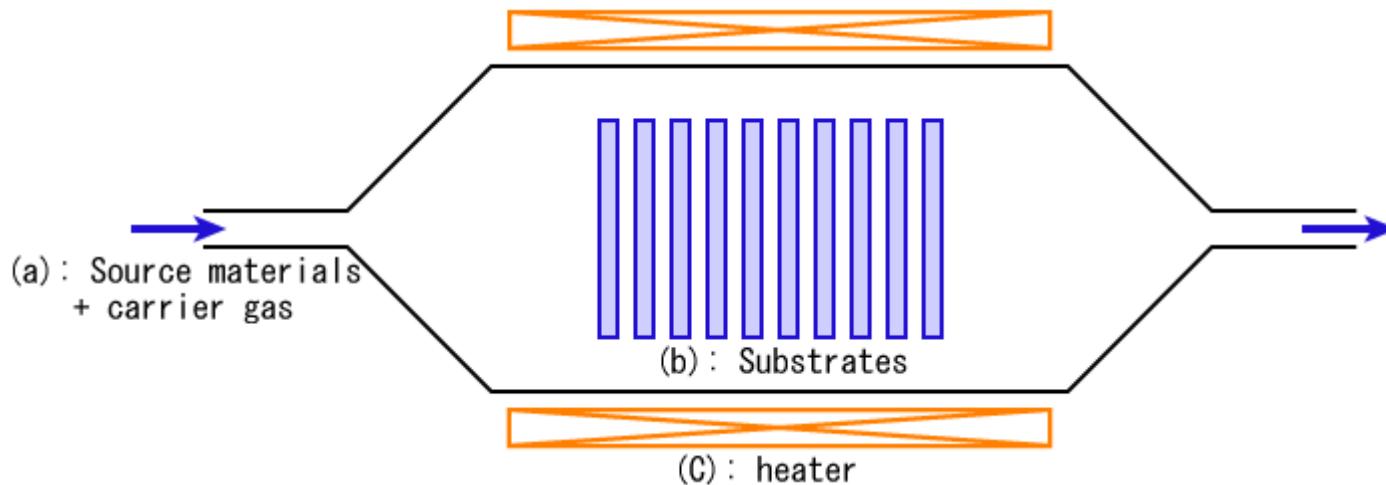
Parameter	Value
Efficiency ( $\pm 2 \mu\text{rad}$ )	$65 \pm 3 \%$
Efficiency ( $\pm 5 \mu\text{rad}$ )	$60 \pm 3 \%$
Efficiency ( $\pm 10 \mu\text{rad}$ )	$47 \pm 3 \%$
Mean Deflection ( $\mu\text{rad}$ )	$280 \pm 10 \mu\text{rad}$
Bending Radius (m)	$\sim 85$

## Preliminary data for PL03

Parameter	Value
Efficiency ( $\pm 10 \mu\text{rad}$ )	$31 \pm 3 \%$
Mean Deflection ( $\mu\text{rad}$ )	$324 \pm 10 \mu\text{rad}$
Bending Radius (m)	$\sim 175 \text{ m}$

# SELF STANDING BENT CRYSTALS -THIN FILMS-

- **LPCVD  $\text{Si}_3\text{N}_4$  or  $\text{SiO}_2$  on silicon**



- $\text{SiCl}_2\text{H}_2 + 2 \text{ N}_2\text{O} \rightarrow \underline{\text{SiO}}_2 + 2 \text{ N}_2 + 2 \text{ HCl}$  ( $T=950 \text{ }^\circ\text{C}$ )
- $3 \text{ SiCl}_2\text{H}_2 + 4 \text{ NH}_3 \rightarrow \underline{\text{Si}_3\text{N}_4} + 6 \text{ HCl} + 6 \text{ H}_2$  ( $T=800 \text{ }^\circ\text{C}$ )

# SELF STANDING BENT CRYSTALS -THIN FILMS-

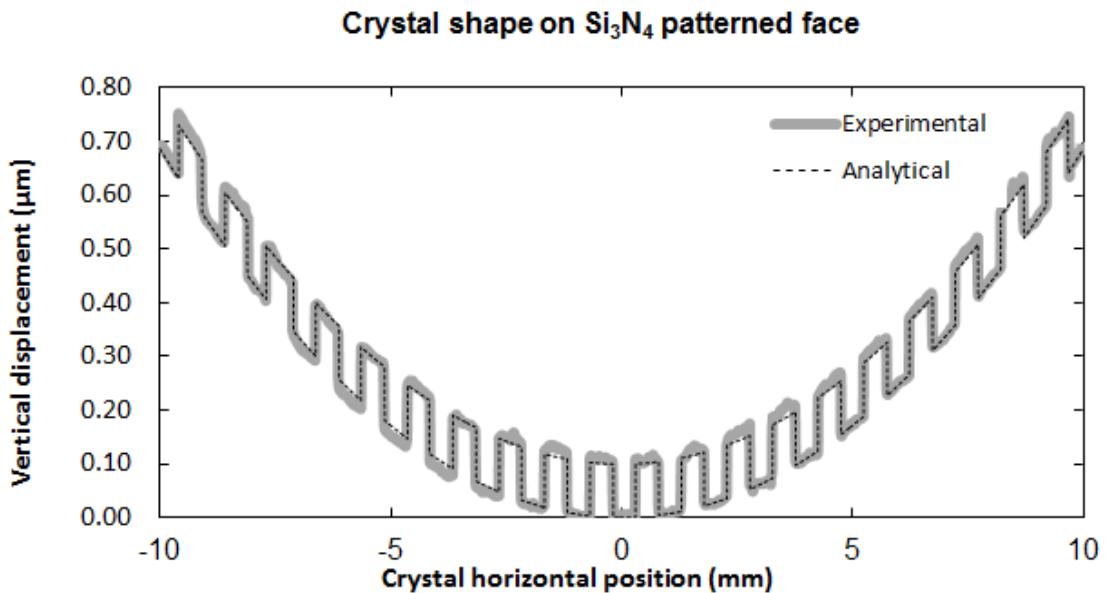
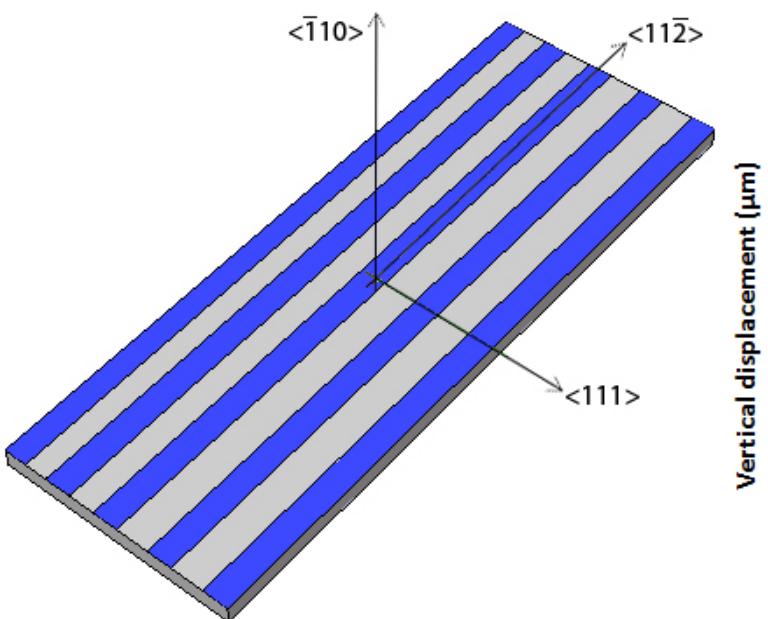


Measured values of  
curvature and stress in 300  
 $\mu\text{m}$  thick Si wafers

$\text{Si}_3\text{N}_4$ thickness	R (m)		$\sigma$ (MPa)	
	Measured	Simulate d	Measured	Simulated
150nm	$14.7 \pm 0.5$	14.4	$1217 \pm 40$	1238
200nm	$10.5 \pm 0.1$	10.8	$1271 \pm 13$	1237
250nm	$9.3 \pm 0.1$	8.6	$1152 \pm 14$	1235

Optical profilometry  
with 1 nm resolution

# SELF STANDING BENT CRYSTALS -THIN FILMS-



Perfect agreement between deformed and predicted crystal shape.

Deposition of 100 nm thin silicon nitride and patterning

- lines 500  $\mu\text{m}$  wide
- spacing 1000  $\mu\text{m}$

# LONG CRYSTALS «PL04» - a self-bent crystal

Feature	Value
Crystal thickness along the beam	$20 \pm 0.1$ mm
Crystal transversal thickness	0.3 mm
Channeling plane	(110)
Channeling axis	<111>
Bending angle (HRXRD)	280 $\mu$ rad

Crystal surface is patterned with a silicon nitride film 100 nm thick



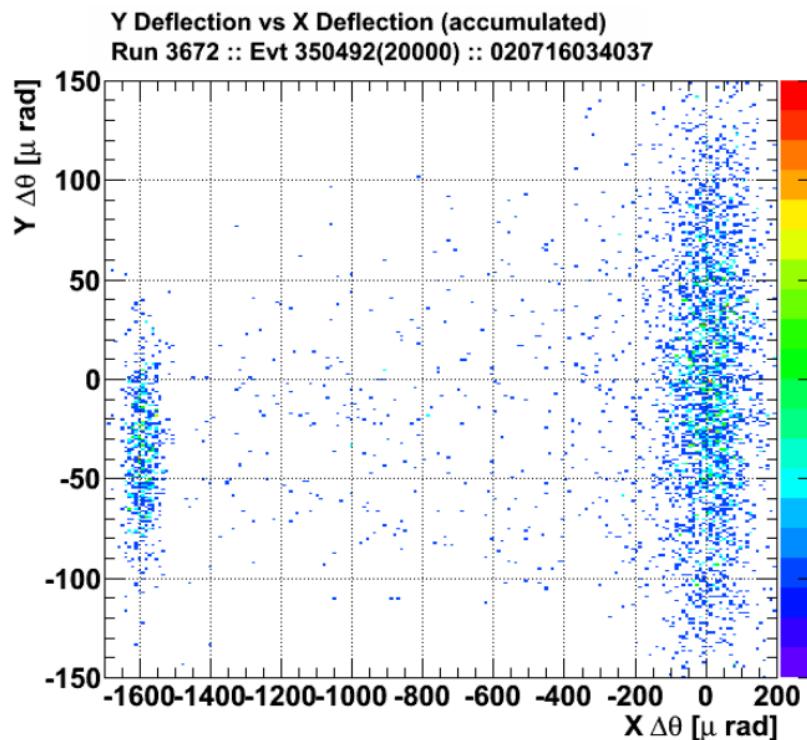
# LONG CRYSTALS «PL05» - a self-bent crystal

Characterization	Value
Crystal thickness along the beam	$55 \pm 0.1$ mm
Crystal transversal thickness	1 mm
Crystal height	55 mm
Channeling plane	(110)
Channeling axis	<111>
Bending angle (HRXRD)	1.6 mrad

- **Self standing crystal**
- Crystal deformation occurs as a consequence of plasticization of one of its main surfaces



# PRELIMINARY DATA FOR «PL05»



Deflection angle  $\sim 1.6$  mrad  
(very preliminary)



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# CONCLUSIONS

- Crystals suitable for LHC extraction are under development
- Bending relies on
  - Anticlastic deformation
  - Self bent crystals
- Characterizations performed with HR-XRD, white light interferometry, 400 GeV proton beam (400 GeV protons, UA9 experiment)