Medical applications of Laue lenses and crystal optics for X-ray manipulation

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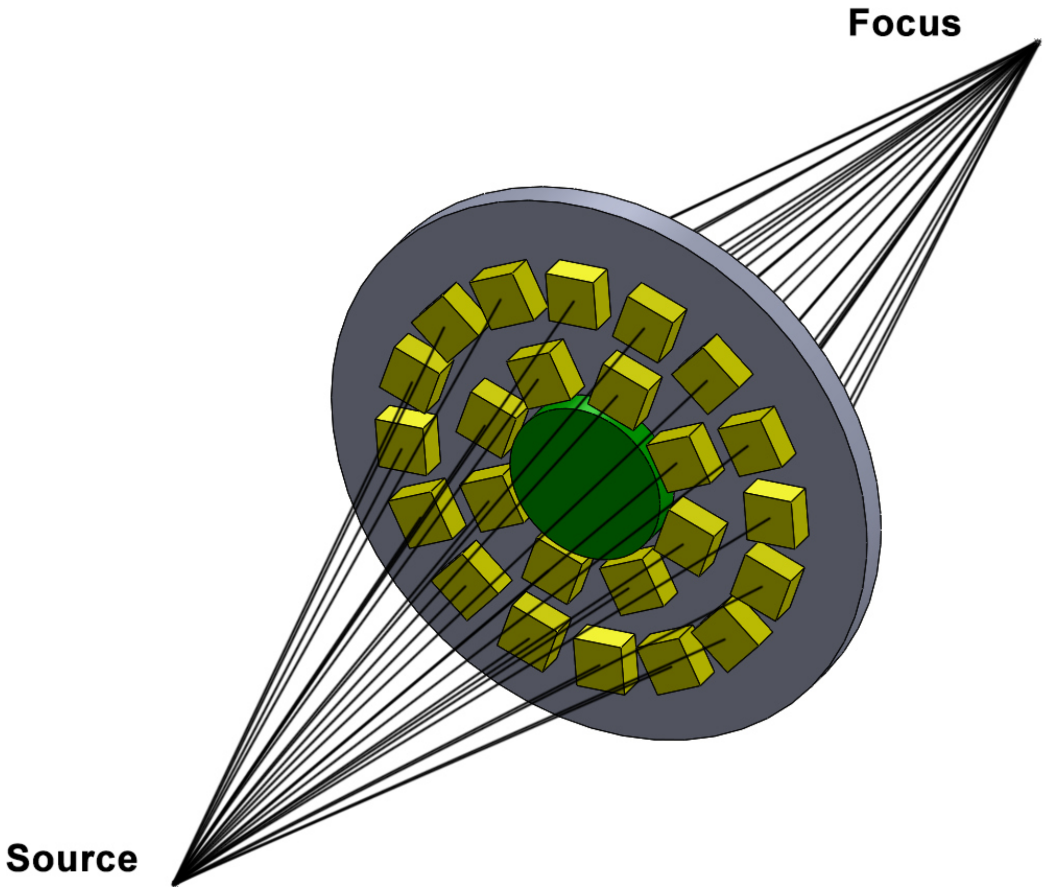
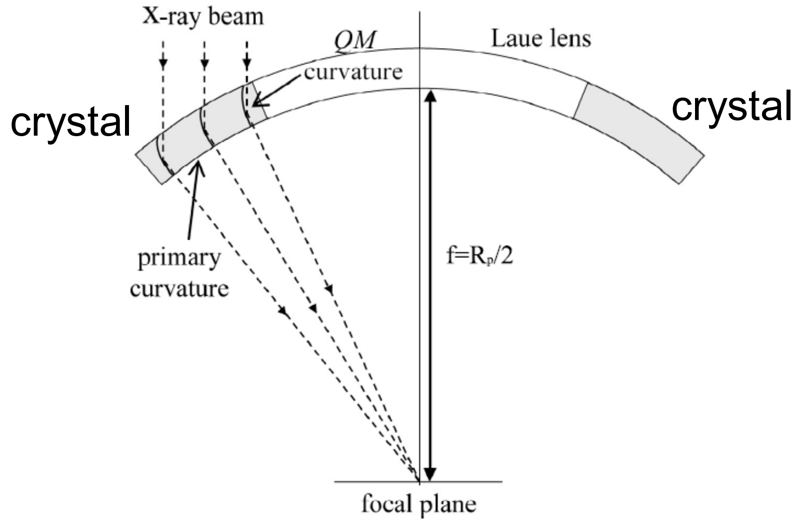
LAUE LENS



A Laue Lens is composed of a **set of crystals**, disposed as **concentric rings**. It exploits **Bragg diffraction** (in Laue or transmission geometry) to **concentrate a photon beam to a small focus**. Using different configurations, it is possible to manage both **divergent** (e.g. medical sources) or **parallel beams** (astrophysical sources).

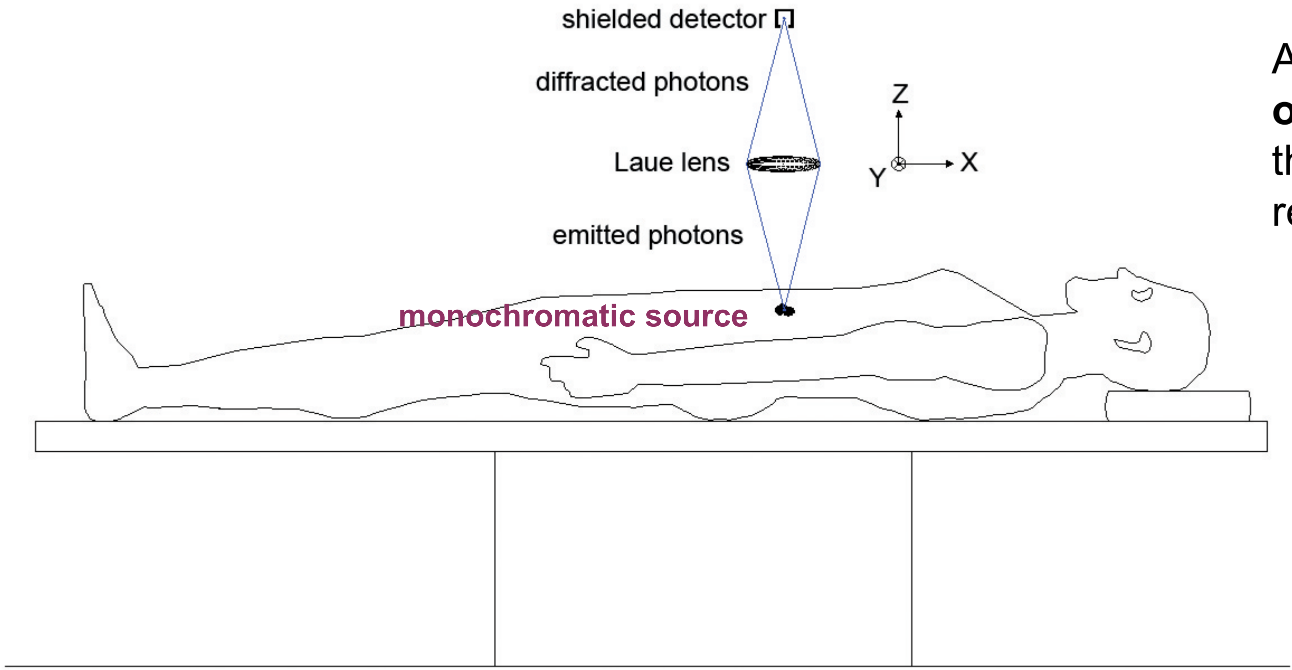


USAGE OF LAUE LENSES IN MEDICAL PHYSICS

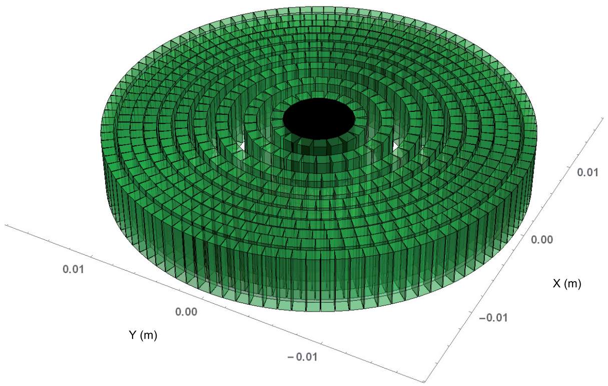
Laue Lenses have been proposed for applications in:

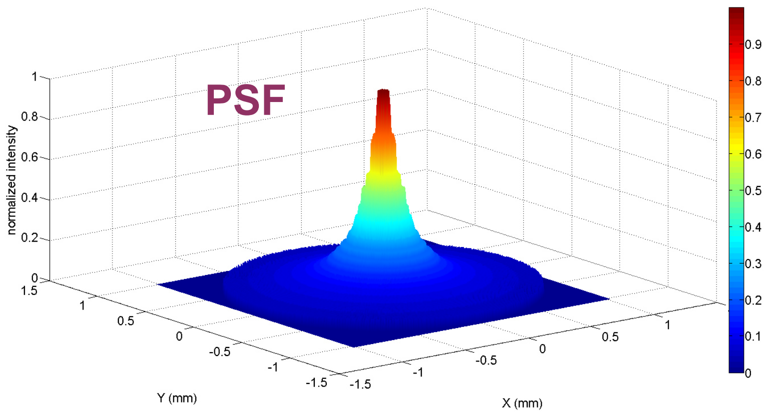
- diagnostic nuclear medicine
- radiotherapy

USAGE OF LAUE LENSES IN NUCLEAR MEDICINE



A Laue lens would permit to obtain a **map of the radioactivity distribution** (due to the injected radiopharmaceutical) inside a restricted region of the patient’s body





Strengths:

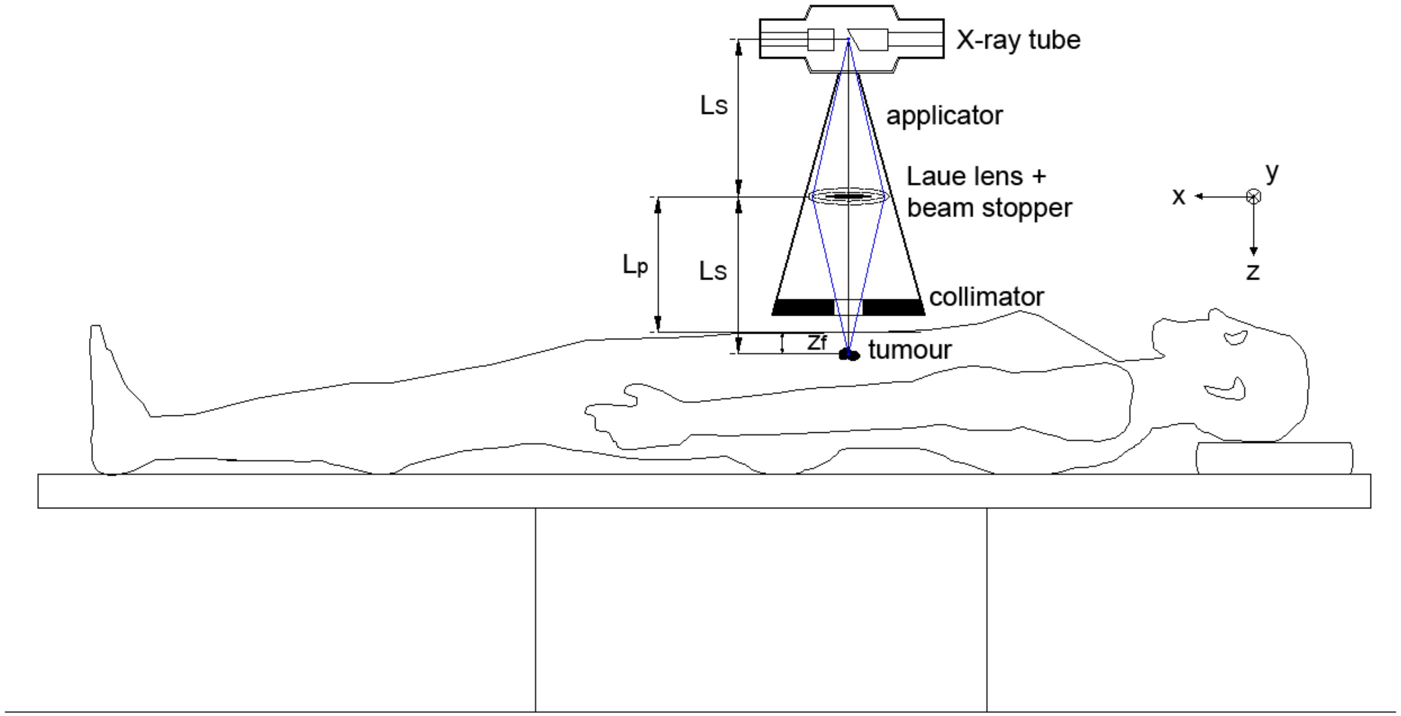
- **High-resolution functional imaging** (one of magnitude better than a pin-hole camera (200 μm) with the same sensitivity).

Weakness:

- **Small Field Of View** (few mm) -> need for a **time consuming scan** even for a small region to image.
- Need for a large number of close packed crystals with **tight alignment tolerance**.

G. Paternò et al., J. Appl. Cryst., (2015) 48:125–137

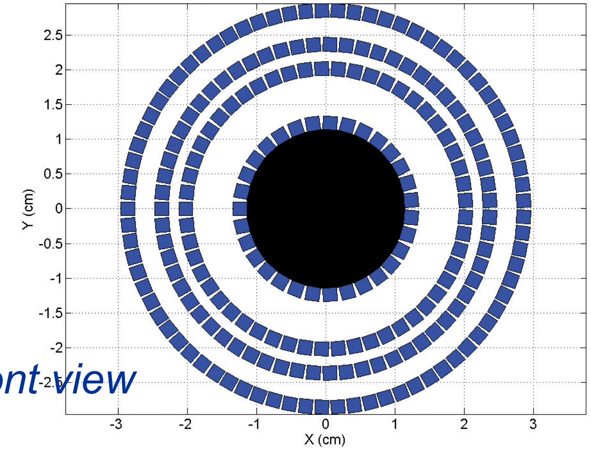
USAGE OF LAUE LENSES IN RADIOTHERAPY



X-rays emitted by a conventional X-ray tube are focused by the lens towards a target tumour inside the patient's body.

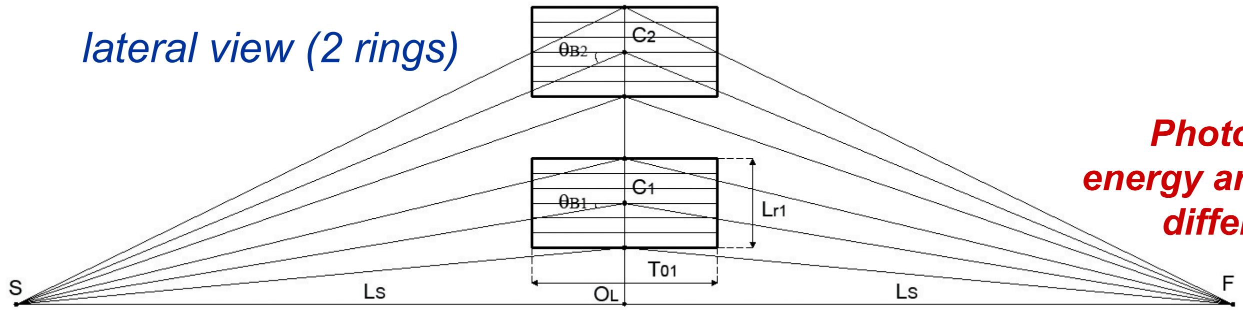
X-ray radiation therapy within 50-150 keV photon energy, in contrast to MeV photons of conventional radiotherapy.
No need for a LINAC.

USAGE OF LAUE LENSES IN RADIOTHERAPY



front view

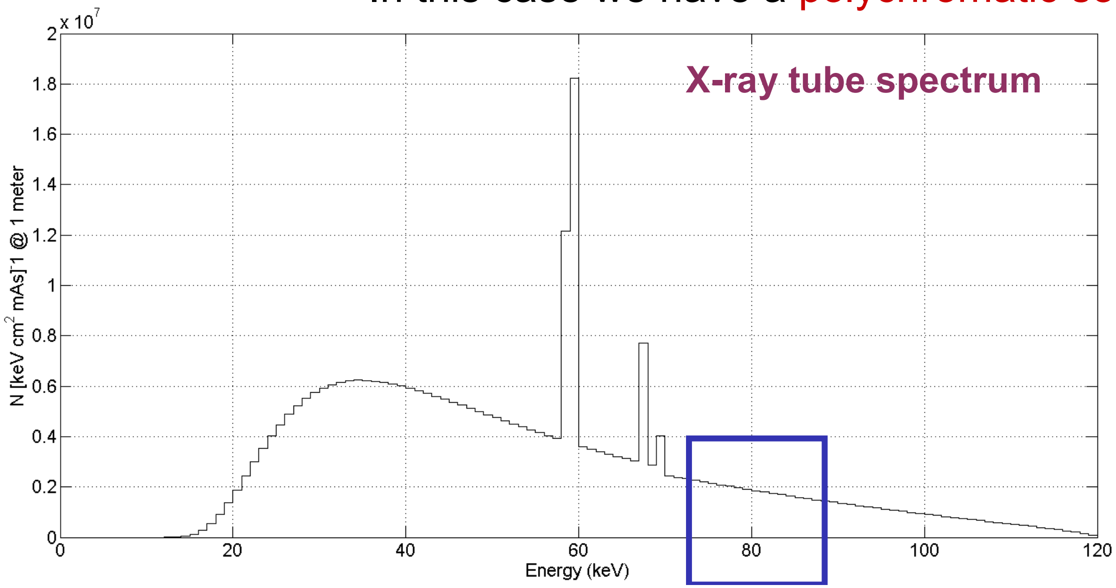
lateral view (2 rings)

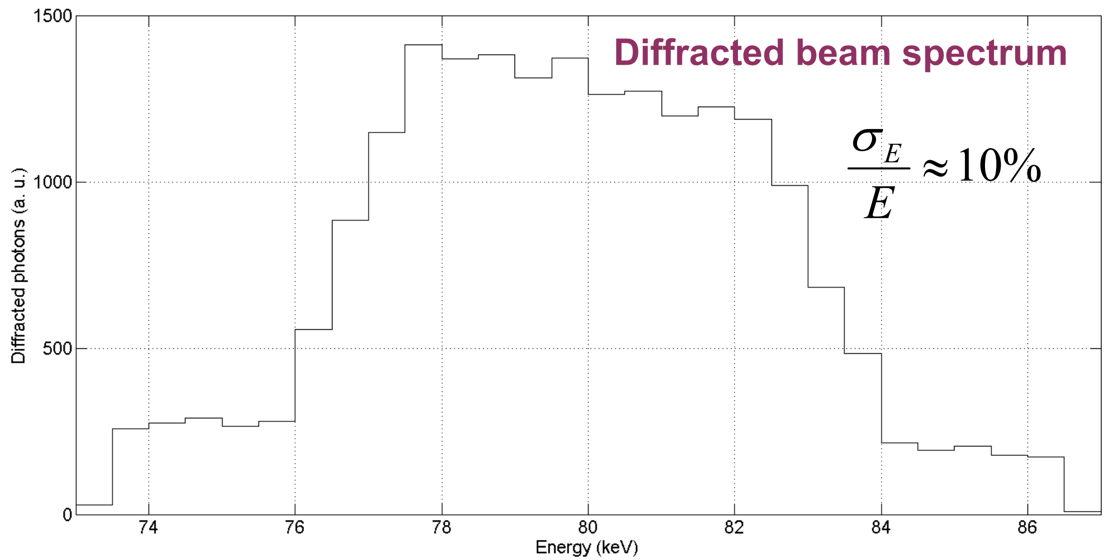


linearized Bragg's law $\theta_B = \frac{h_p c}{2d_{hkl}} \frac{1}{E}$

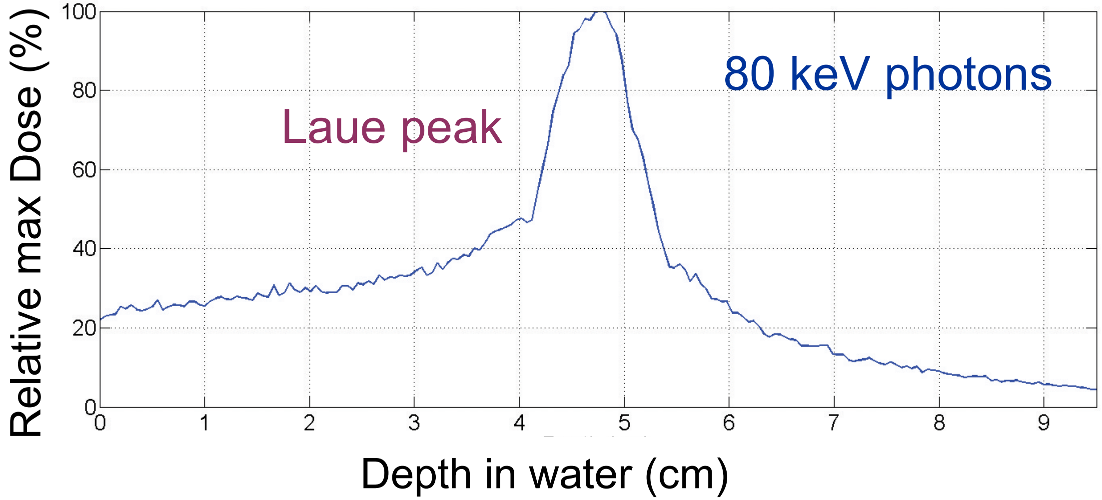
Photons of different energy are diffracted by different part of the crystals

In this case we have a polychromatic source and the **lens focuses and filters the X-rays**

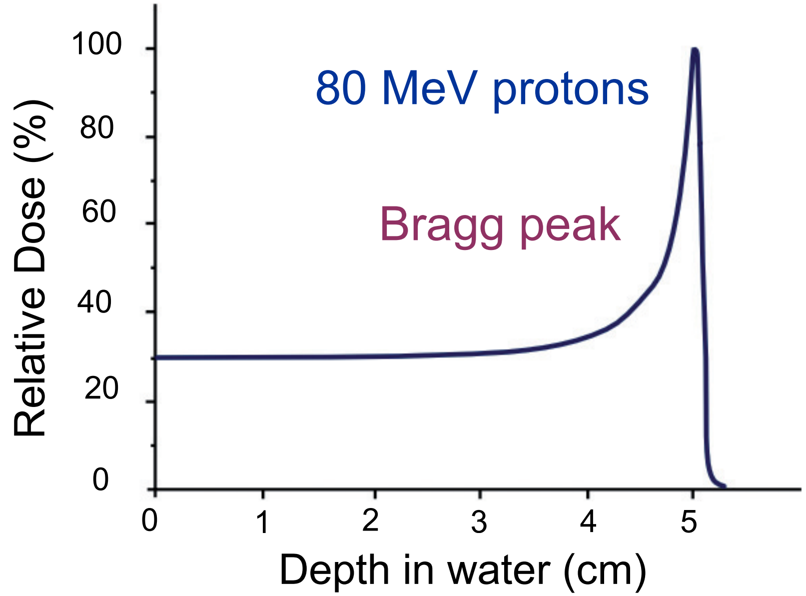


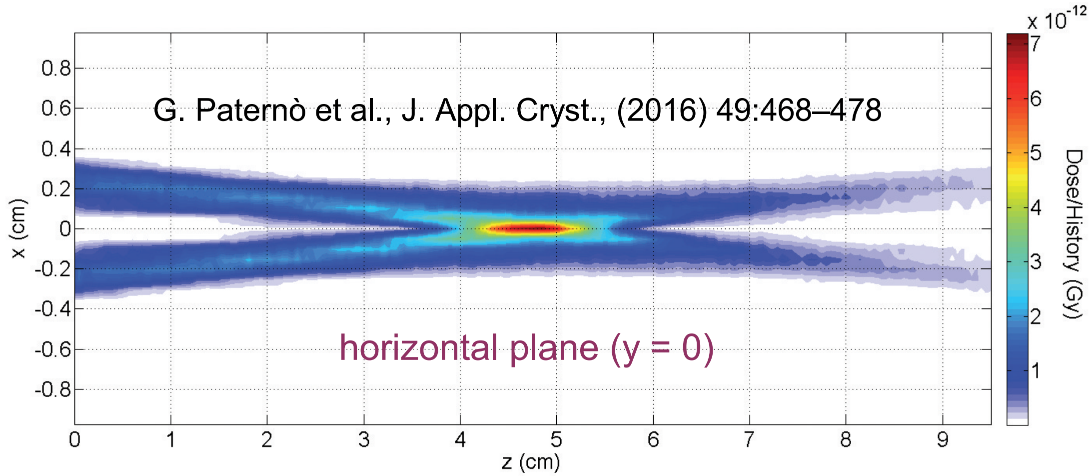


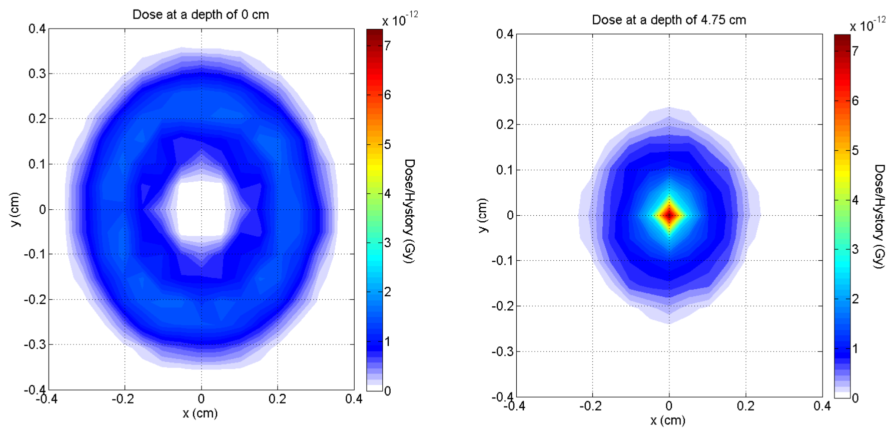
USAGE OF LAUE LENSES IN RADIOTHERAPY



vs



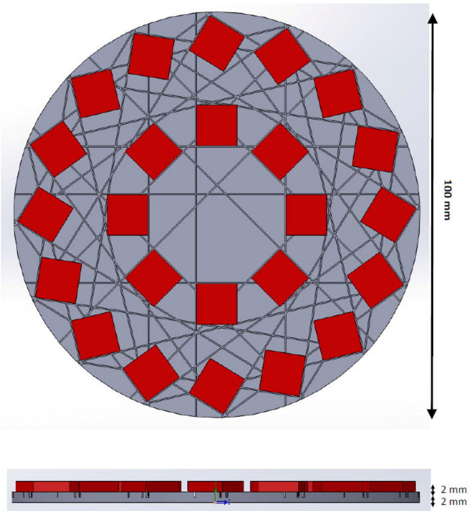


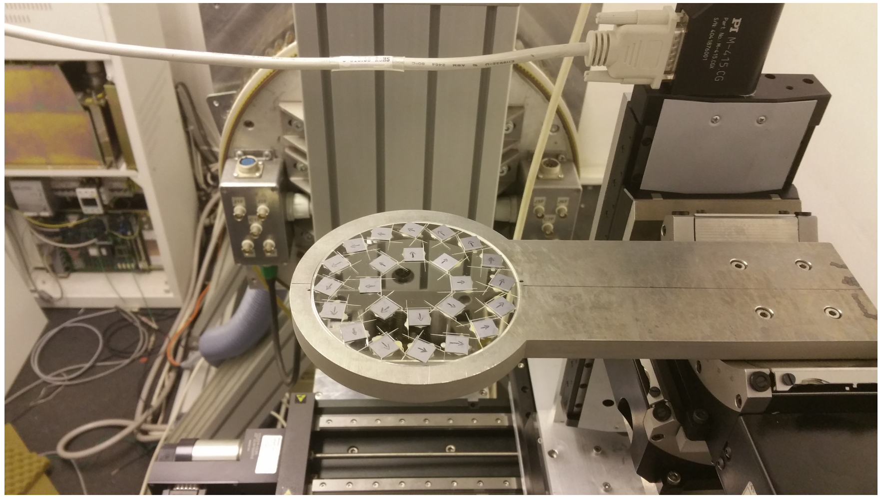


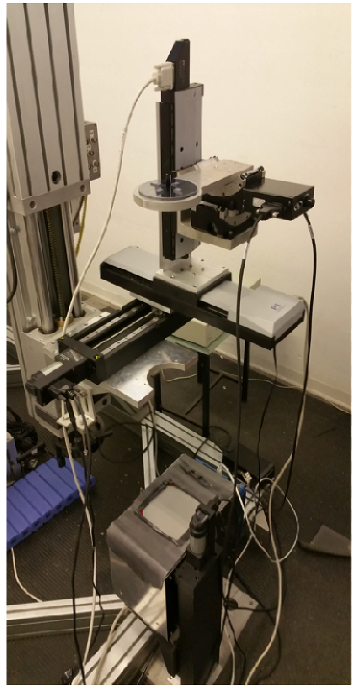
Dose distribution inside a water phantom as it results from the simulation performed with a Monte Carlo code

USAGE OF LAUE LENSES IN RADIOTHERAPY

The **LAUPER** project: Laue lens **proof of principle demonstrator**







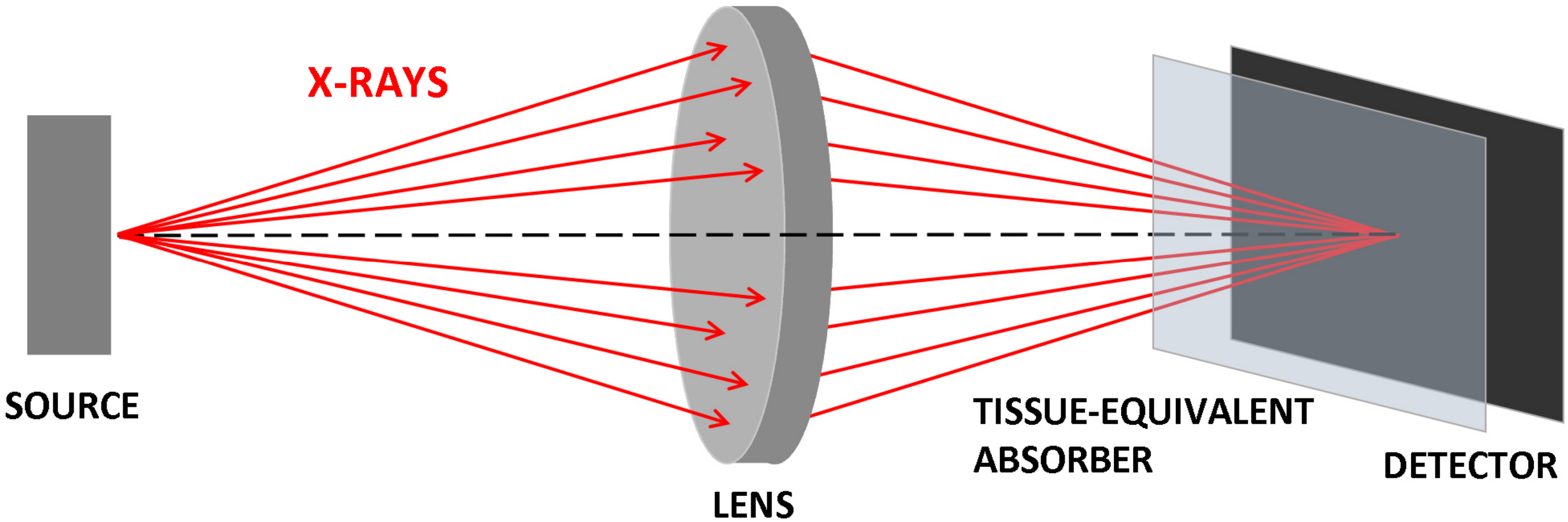
- 2 mm thick glass support

- 8 (111) + 16 $(311)_{skew}$ QM (R_p=80 m) Si sandblasted crystals (10x10x2 mm)

Crystals are bent to increase their angular acceptance

- X-ray tube, linear and rotational axes, lens holder, Pb collimators, PMMA blocks;
- *Alta U9000* CCD camera coupled to a 0.5 mm CsI(Tl) scintillator screen;
- *PM-30* 28 ml thimble Ionization chamber with 0.25 mm air-equivalent plastic walls.

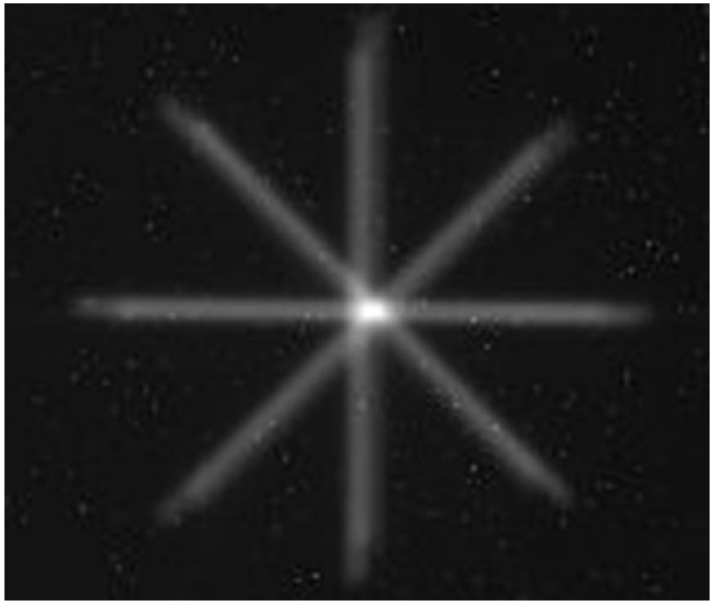
USAGE OF LAUE LENSES IN RADIOTHERAPY

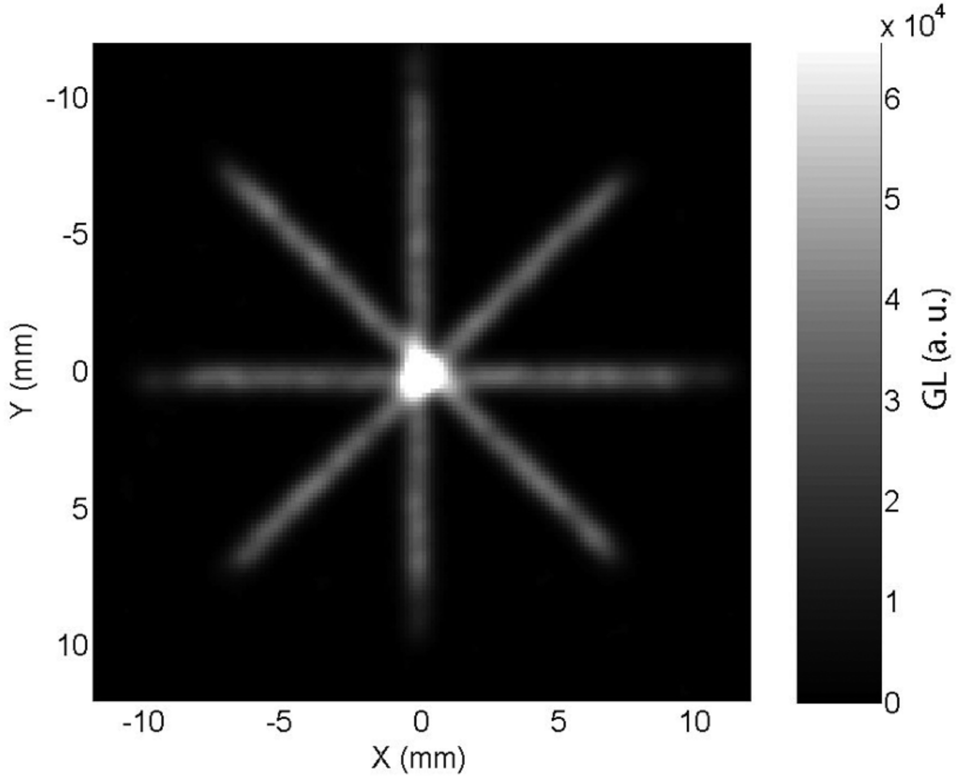


- By analysing the **image on the detector** it was possible to:
  - Check the **alignment** of the crystals (no absorber used, source-to-lens distance = lens-to-detector distance)
  - Measure the **dose distribution** in a phantom (absorber used, lens-to-detector distance varied, GL/dose calibr.)

USAGE OF LAUE LENSES IN RADIOTHERAPY

Image at the lens focus (first ring)





Measured:

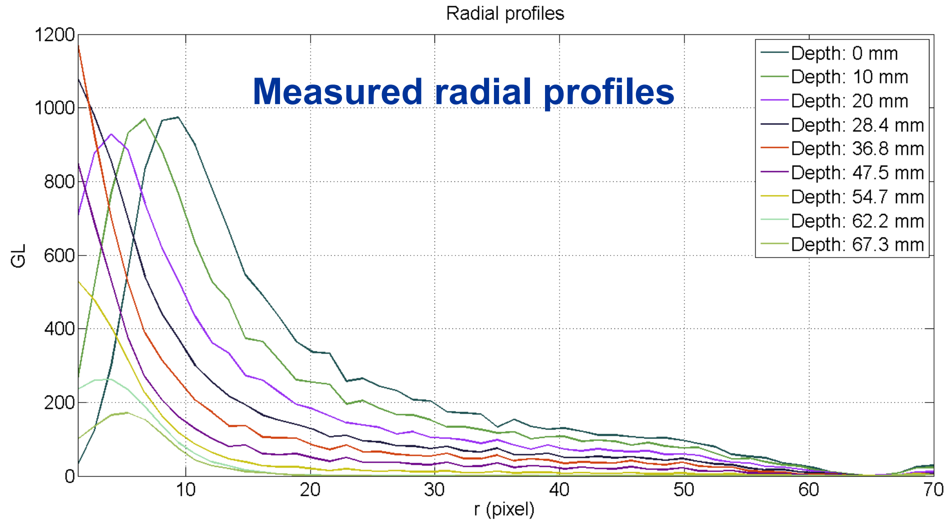
- X-ray tube set to 150 kV and 100 mA,
- acquisition time = 1 s,
- dark and white subtraction.

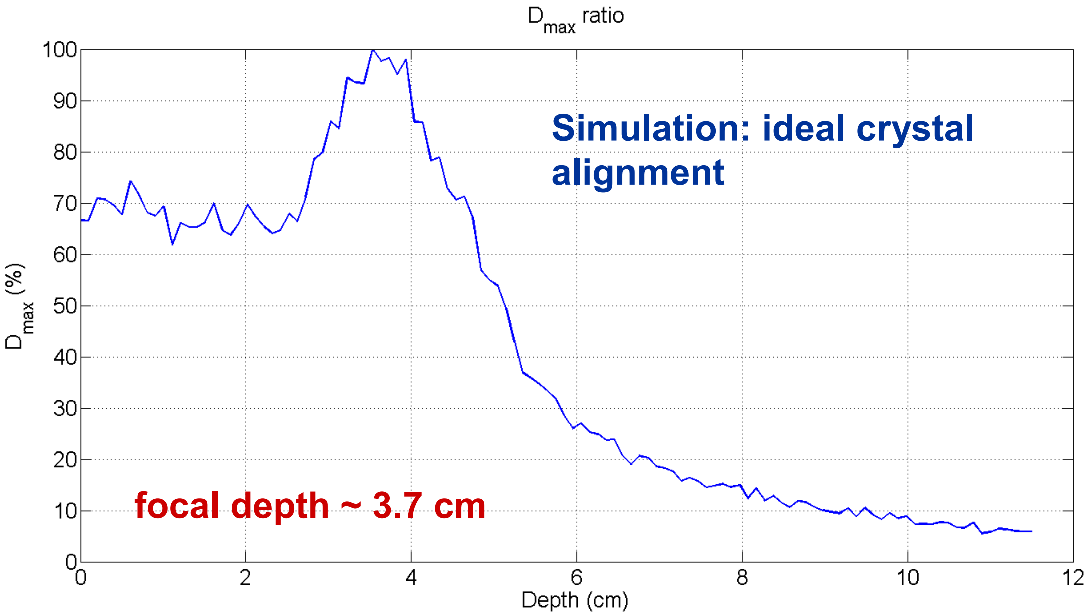
Simulated through the LAUTHER MC code:

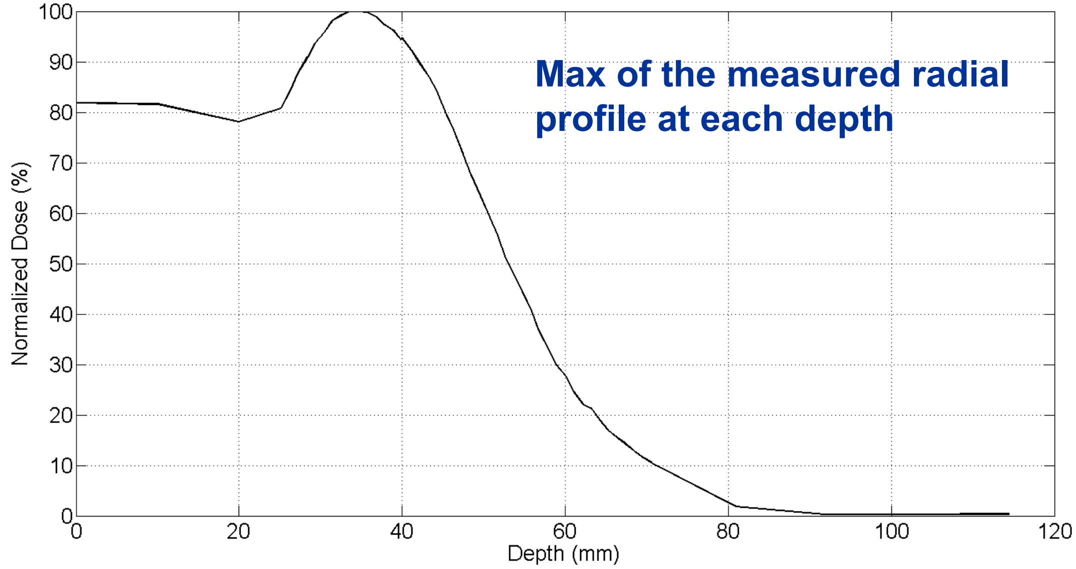
- Ls = 79 cm,
- Band = 55 - 88 keV,
- φ_a = variable, φ_b = 0, Δpos = 0.5 mm.

USAGE OF LAUE LENSES IN RADIOTHERAPY

Analysis of the **measured** dose profiles and comparison with the **simulation** (**first ring**)







USAGE OF LAUE LENSES IN RADIOTHERAPY

Strengths:

- Dose peak well located inside the patient's body.
- Depth of focusing virtually independent from the beam mean energy.
- Cheap equipment (no need for a LINAC).
- Larger and less "dense" lens with respect to the diagnostic case. → **easier to assembly**
- Less stringent requirement on crystalline alignment with respect to the diagnostic case.

Weakness:

- Not uniform spot.
- Efficiency of the order of 10^{-4}.
- Most of the input beam is wasted.

→ **A scan of a few tens of min is required to irradiate uniformly a 1 cm^3 target.**

↓

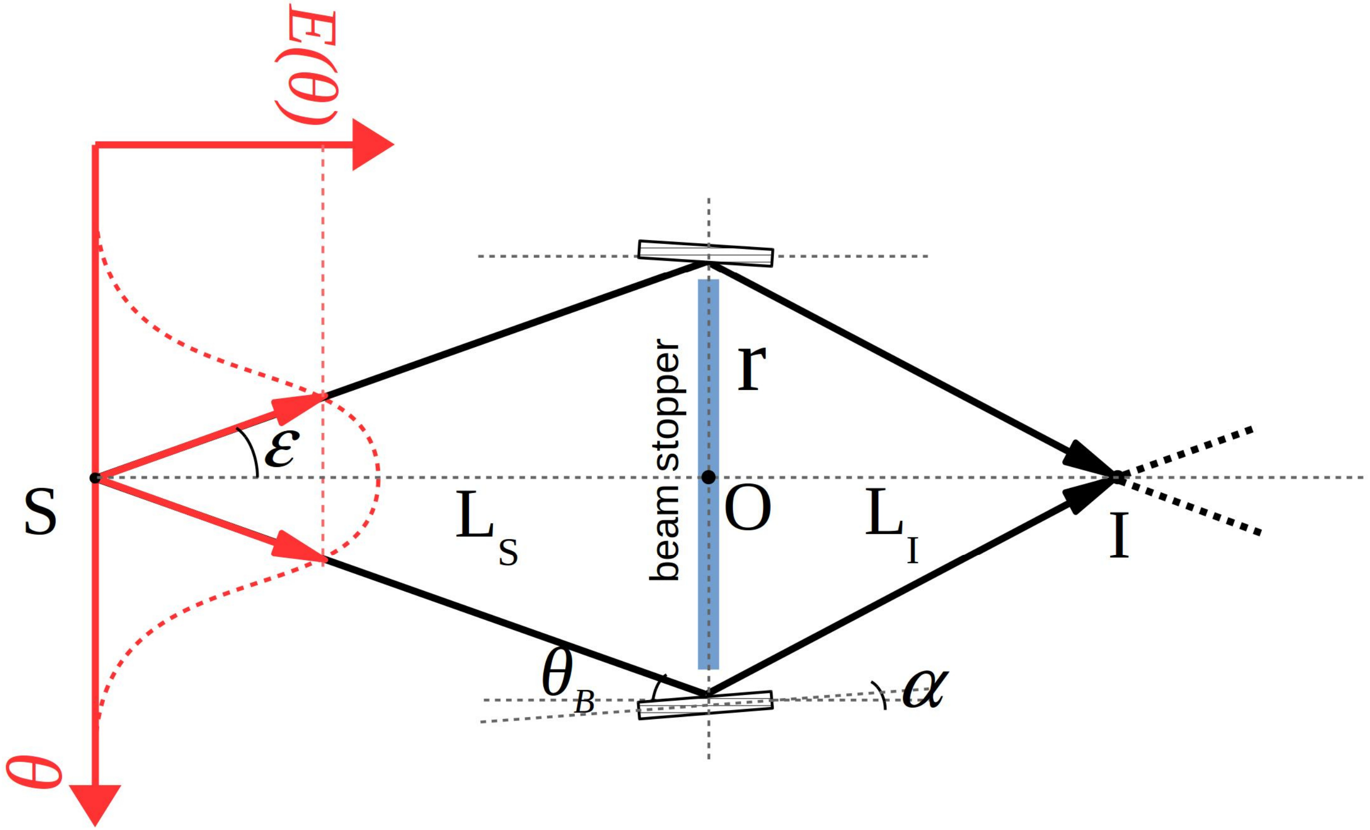
Need for a more suitable and intense photon source

USAGE OF A LAUE LENS WITHIN THE MariX PROJECT

The intense quasi-monochromatic photon beam with energy up to 150 keV from a Thomson back scattering source **is principle suited be used in combination with a Laue lens**. **Radiotherapy applications could be problematic**, due to the low beam divergence, which make difficult designing and assembling the lenses (very long source-to-lens distances are required and crystals have to be (dynamically) tilted). However, **A ring assembly of crystals** or at least **few single crystals** could be successfully used for:

- **Monochromatization** of the X-ray beam coming from the interaction point (without the use of a collimator);
- **Focusing** quasi-monochromatic X-rays on a small target;
- **Steering** and "**Parallelization**" of the beam.

USAGE OF A LAUE LENS WITHIN THE MariX PROJECT



$$\theta_B = \frac{h_p c}{2 d_{hkl}} \frac{1}{E}$$

$$L_S = \frac{r}{\tan(\theta_B - \alpha)}$$

$$L_I = \frac{r}{\tan(\theta_B + \alpha)}$$

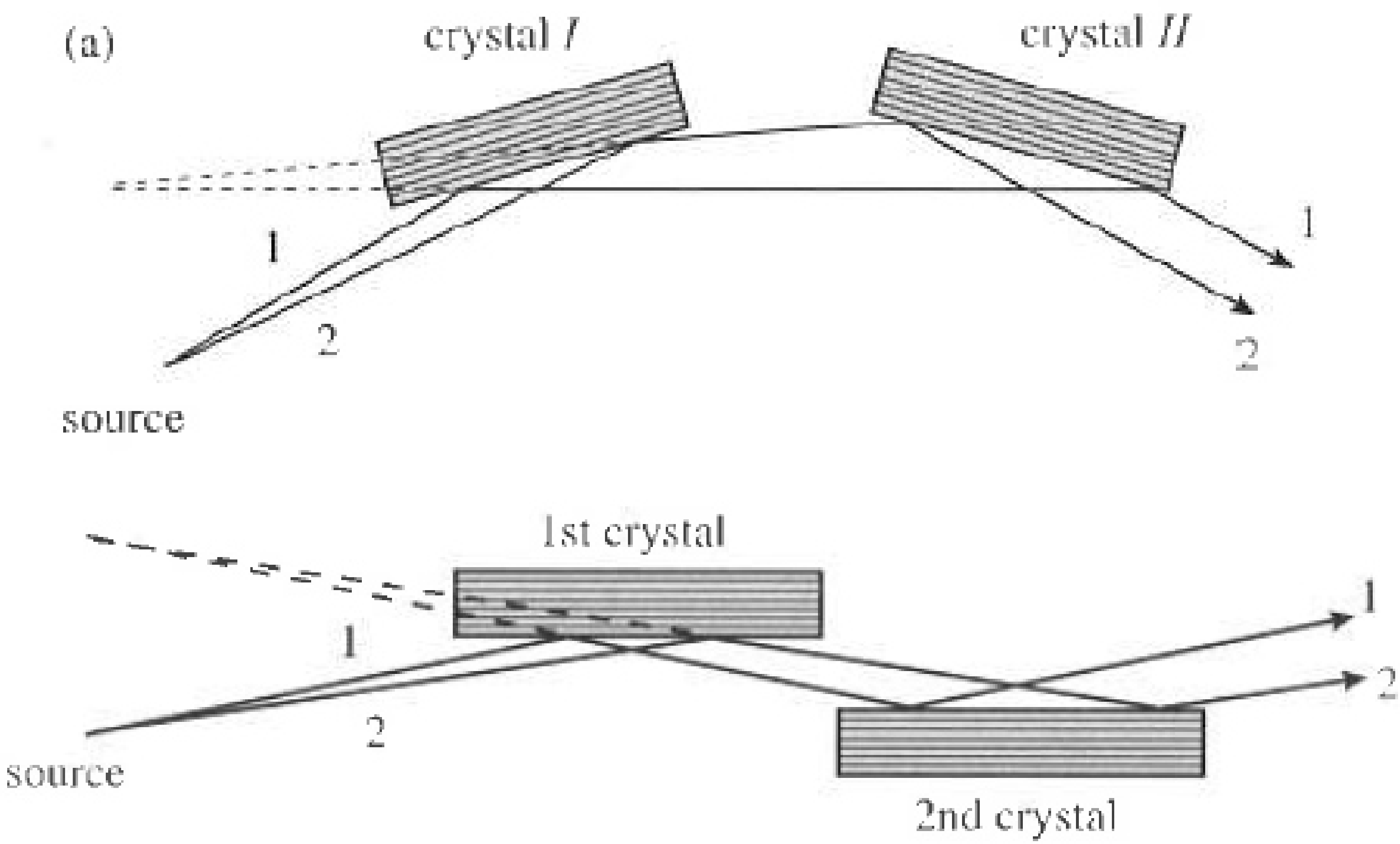
$$\frac{1}{f} = \frac{1}{L_S} + \frac{1}{L_I}$$

$$f = \frac{r}{2\theta_B}$$

Is necessary tilt the crystals because $\theta_B(E)$ > beam divergence ε

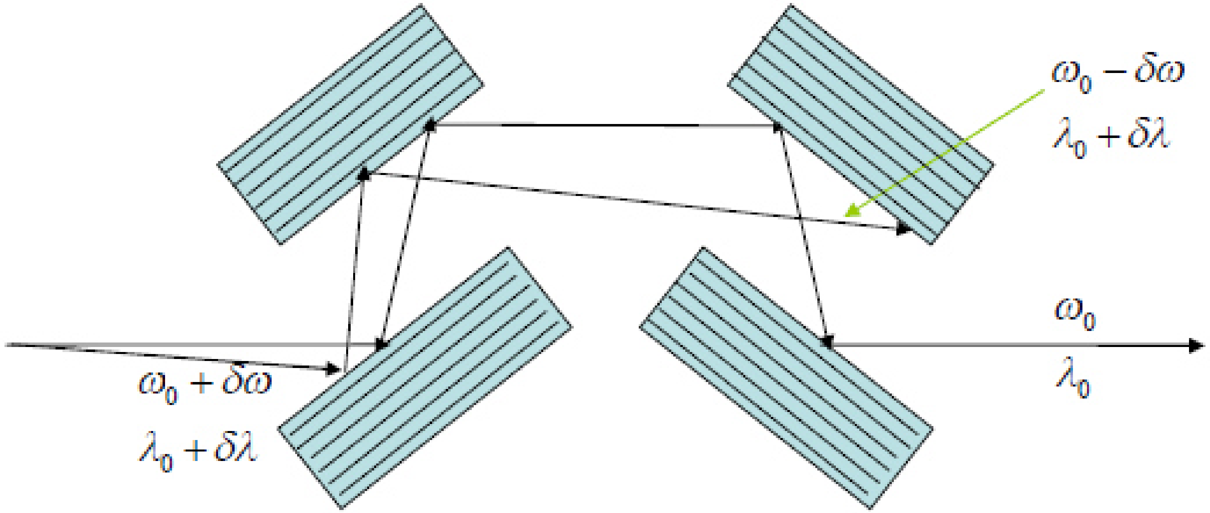
X-RAY BEAM MANIPULATION: monochromators

2 crystals (symmetric) configuration



X-RAY BEAM MANIPULATION: monochromators

4 crystals configuration for high resolution



Bragg conditions are not satisfied, so it won’t be diffracted.

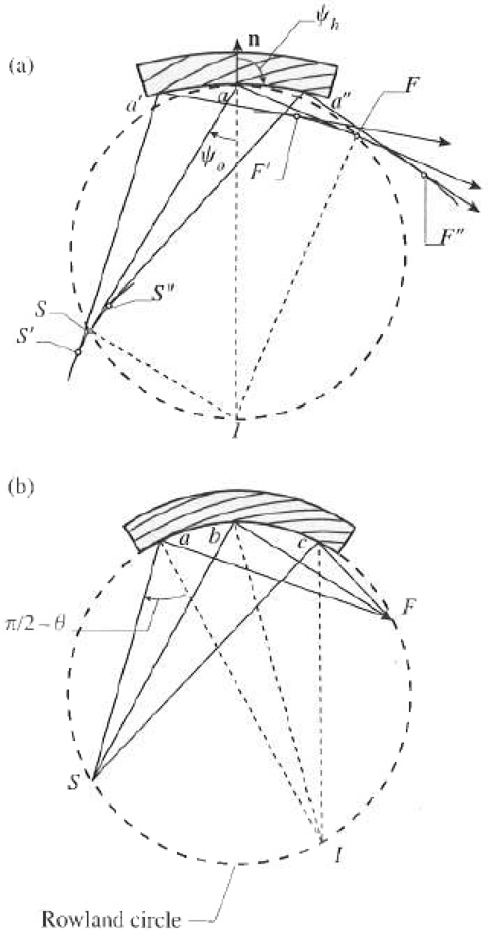
$$\frac{\delta_\lambda}{\lambda} \approx 5 \cdot 10^{-5}$$

X-RAY BEAM MANIPULATION: bent crystals for focusing

Meridional focusing

Bend the crystals to
increase their angular acceptance

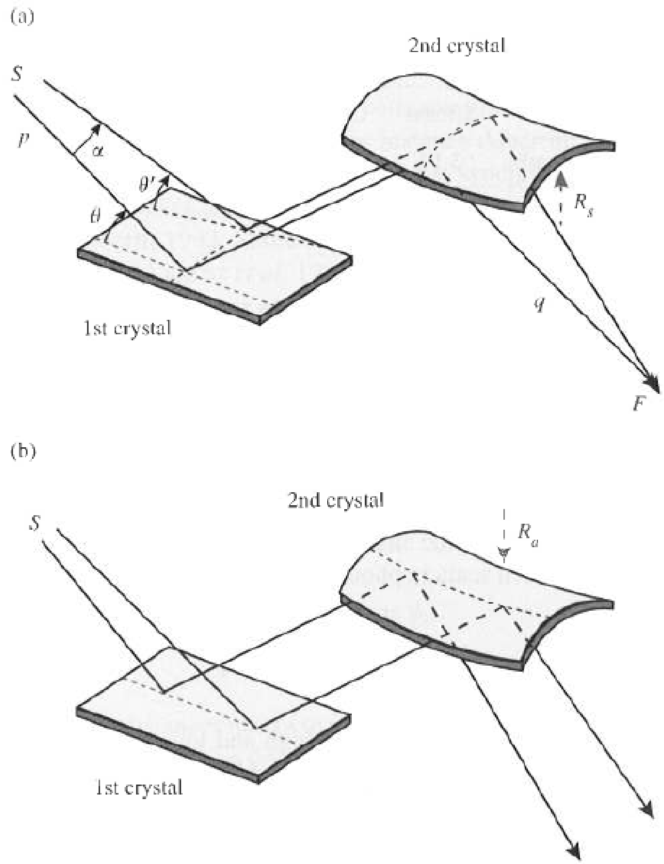
Sagittal focusing



Johann geometry

Johansson geometry

$R_{RW}=R_C/2$



FERRARA EXPERTISE

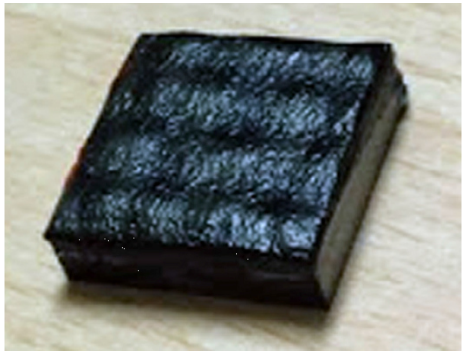
• Production, characterization and simulation of **various types of crystals (perfect, mosaic, bent)** to be used as **X-ray optics element** and for the **manipulation of particle beams through coherent effect (channeling** and related effects).

• A number of techniques (both mechanical and chemical) have been developed to **produce self-standing and non self-standing bent crystals**.

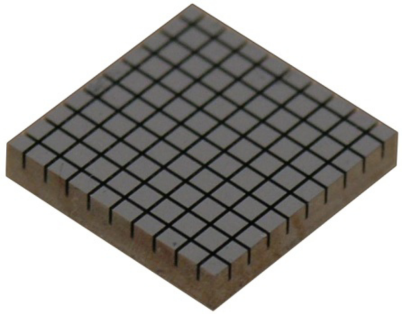
• Various **Monte Carlo codes** have been developed and successfully used to simulate **coherent interactions of X-rays and particle with crystals**.

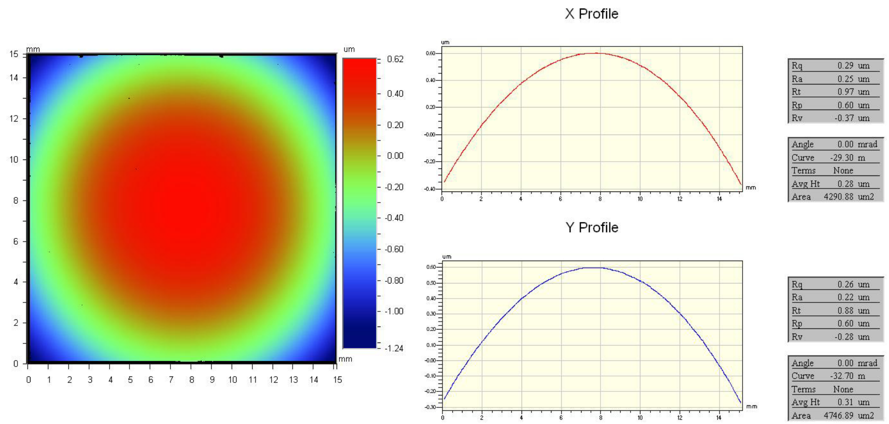
FABRICATION OF BENT CRYSTALS

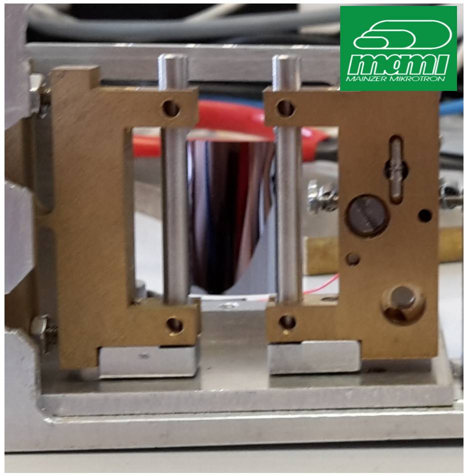
Carbon Fiber deposition



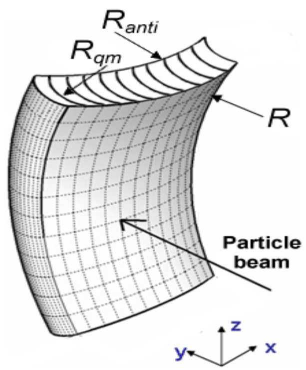
Grooving method







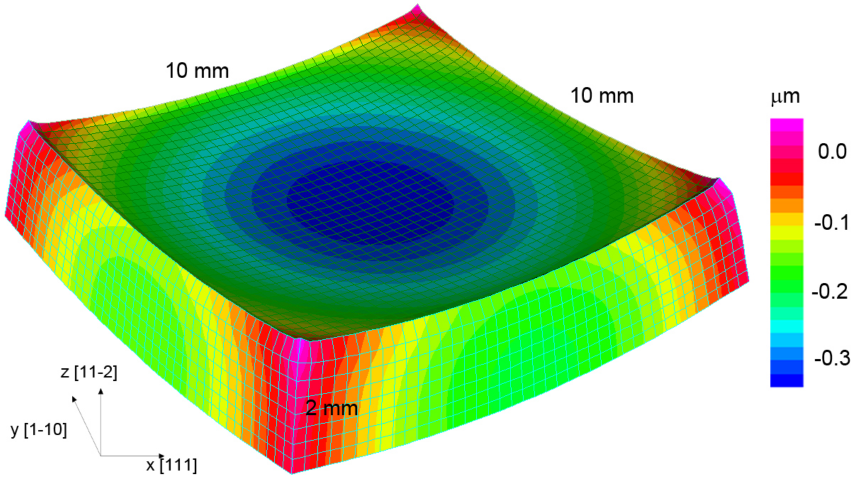
Use of a mechanical older for channeling experiments/applications



The technology to fabricate bent crystals was pushed to its extreme limit with the INFN-CHANEL experiment, starting from the ~ mm bent crystals for CERN (120 GeV) to arrive at the 10/15 µm bent crystals used in MAMI (0.855GeV) and SLAC (3 - 20 GeV).

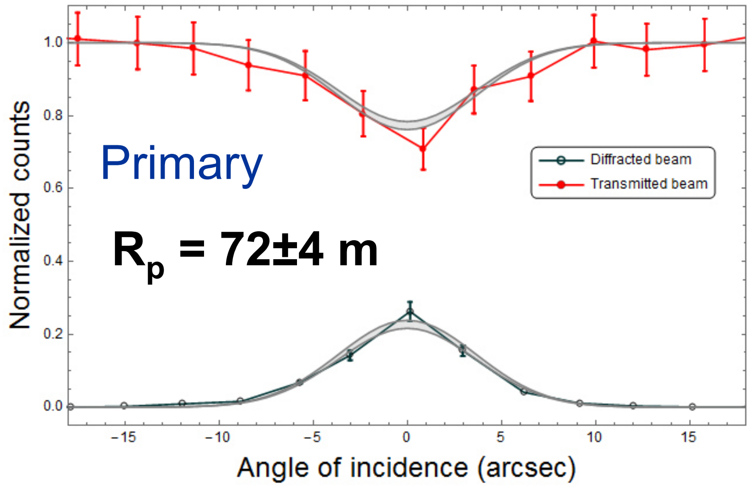
[1] A. Mazzolari et al., Phys. Rev. Lett. 74 (2014) 2740
[2] G. Germogli et al., Nucl. Instr. Meth. B (2015) in press

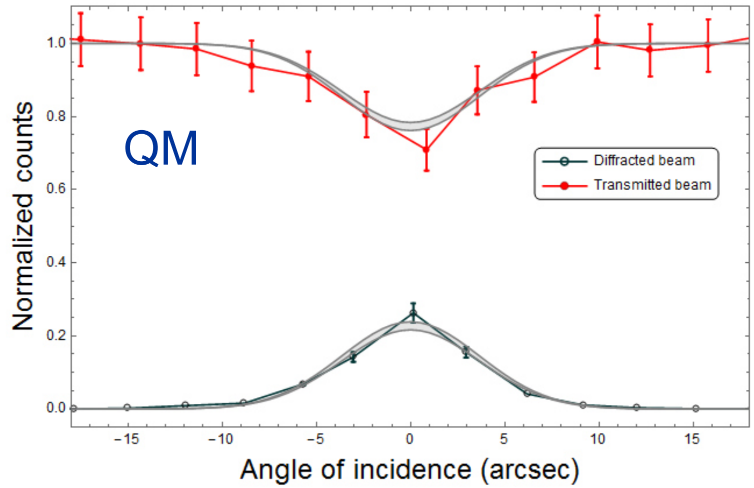
FABRICATION OF BENT CRYSTALS
Bending through sandblasting



Sample size (mm)	10 x 10 x 2
Material	Si
Sandblasting distance	~ 10 cm
Sandblasting time	300 s
Thickness traversed by X-rays (mm)	20 (primary) / 2 (QM)
Diffracting planes	(422) (primary) / (111) (QM)
Beam energy (keV)	181.931
Beam monochromaticity (ΔE/E)	1×10^{-6}
Beam width (mm)	1 x 2
Beam divergence (arcsec)	3.5

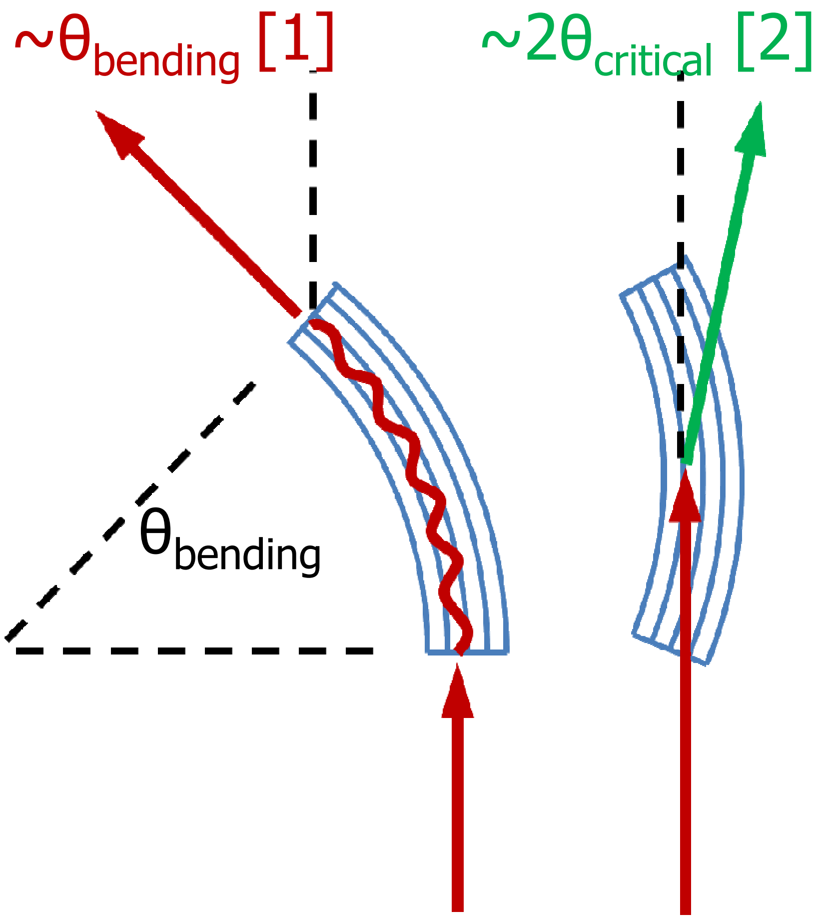
Hard X-ray diffraction at ILL (DIGRA)





R. Camattari et al., J. Appl. Cryst., (2017) 50:145–151

CHANNELING AND VOLUME REFLECTION IN BENT CRYSTALS



[1] Tsyganov (1976)
[2] Taratin and Vorobiov (1988)

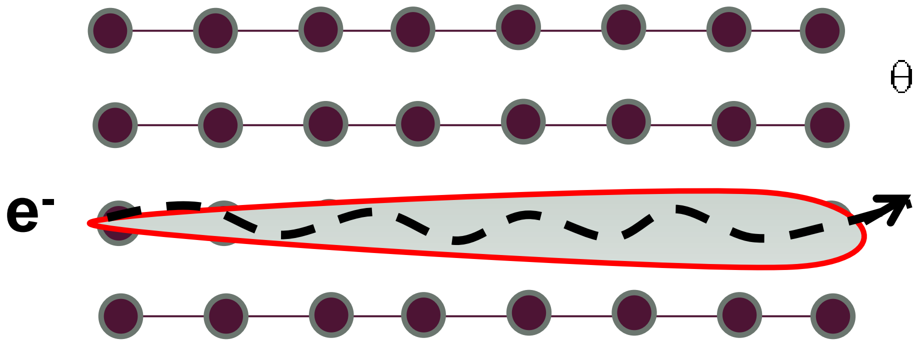
- A channeled particle is deflected by an angle equal to the bending angle of the crystal [1].
- A volume-reflected particle is deflected by the channeling critical angle [2].

- Bent crystals can be used in an accelerator for:
  - extraction of particles from the circulating particle beam;
  - collimation of the beam;
  - steering.

- With short bent crystals (~mm), it is possible to deflect ultra-high-energy particles in CERN (SPS or LHC) with angles (100 μrad – 1mrad) achievable by 1000 Tesla magnets having a similar size.

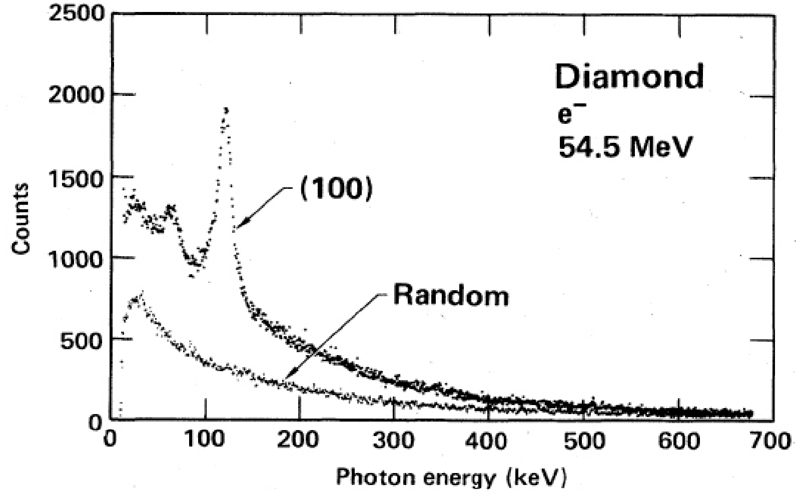
ENHANCEMENT OF BREMSSTRAHLUNG RADIATION IN ALIGNED CRYSTALS

Channeling radiation



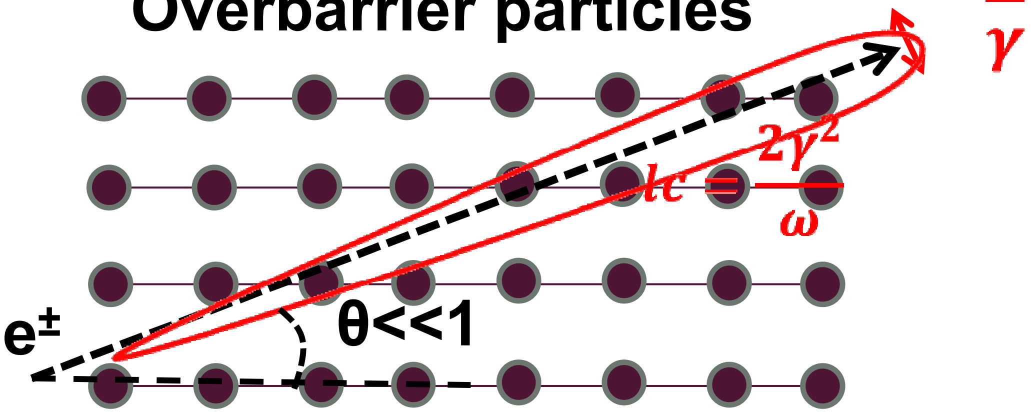
$$\theta_{max} = \sqrt{\frac{2U}{E}}$$

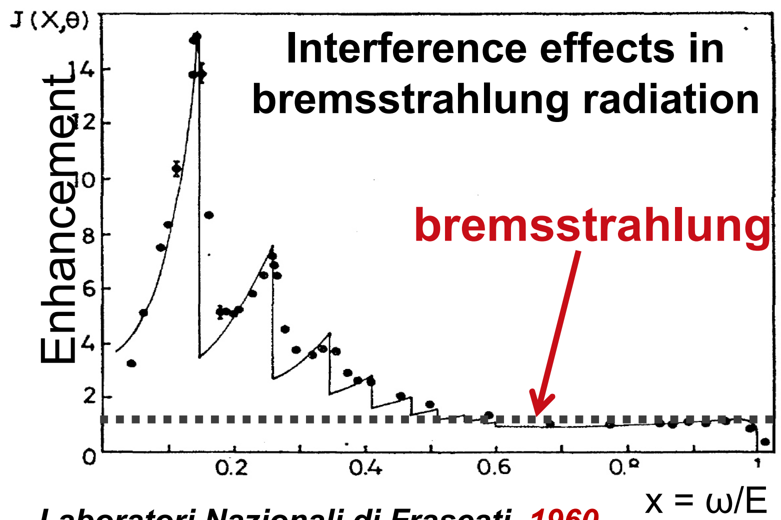
Undulator-like radiation



M. Kumakhov, Physics Letters A 57, 17 (1976).

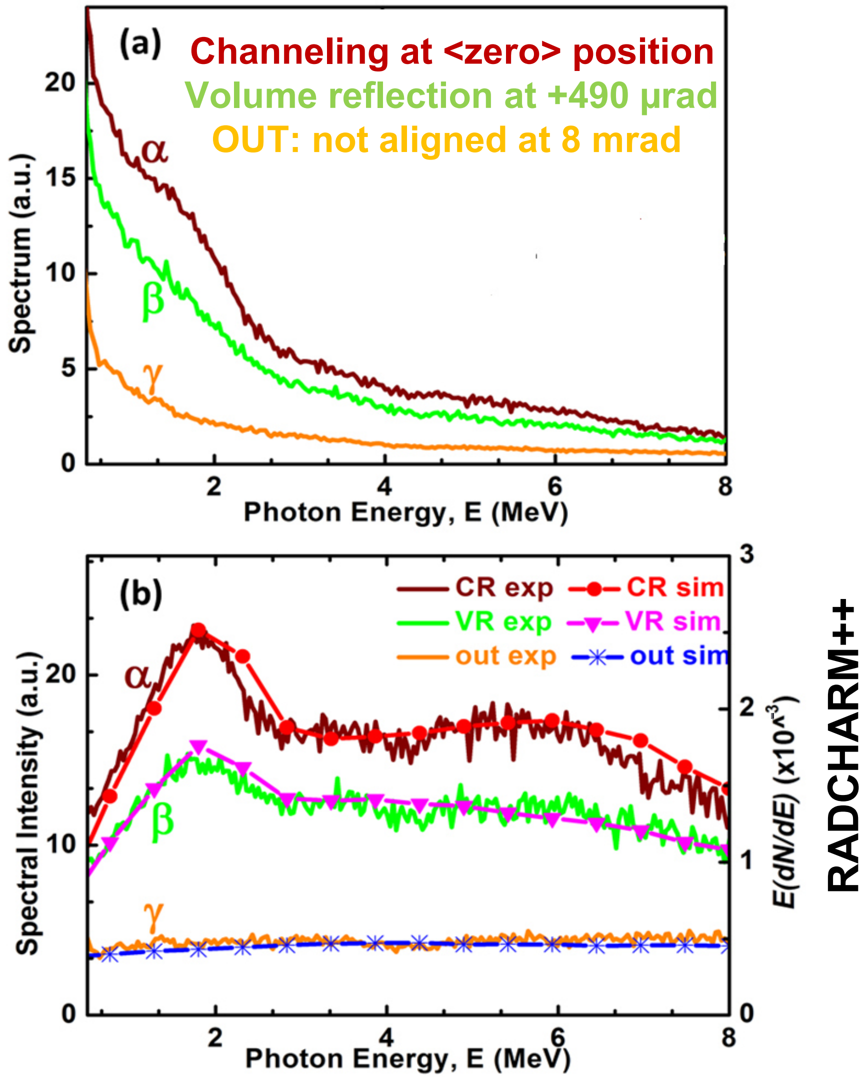
Overbarrier particles

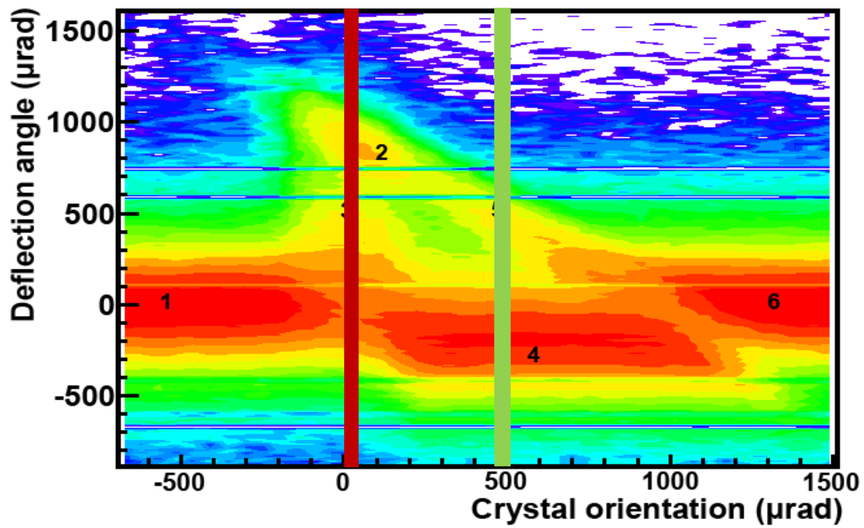




Laboratori Nazionali di Frascati, 1960

EXPERIMENTAL RESULTS ON BEAM STEERING OF SUB-GEV ELECTRON BEAM (MAMI) AND RADIATION EMISSION WITH BENT CRYSTAL





Angular scan for deflected beam distribution: (1) and (6) nonchanneling regime; (2) channeling; (3) dechanneling; (4) volume reflection; and (5) volume capture.

Channeling peak at $E_\gamma \sim 1.8$ MeV for 855 MeV electrons in (111) Si bent planes

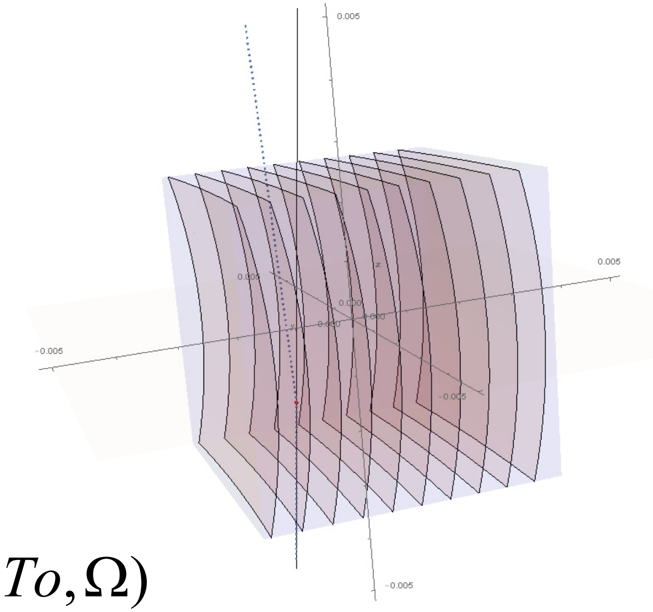
L. Bandiera et al. Phys. Rev. Lett. 115, (2015) 025504.

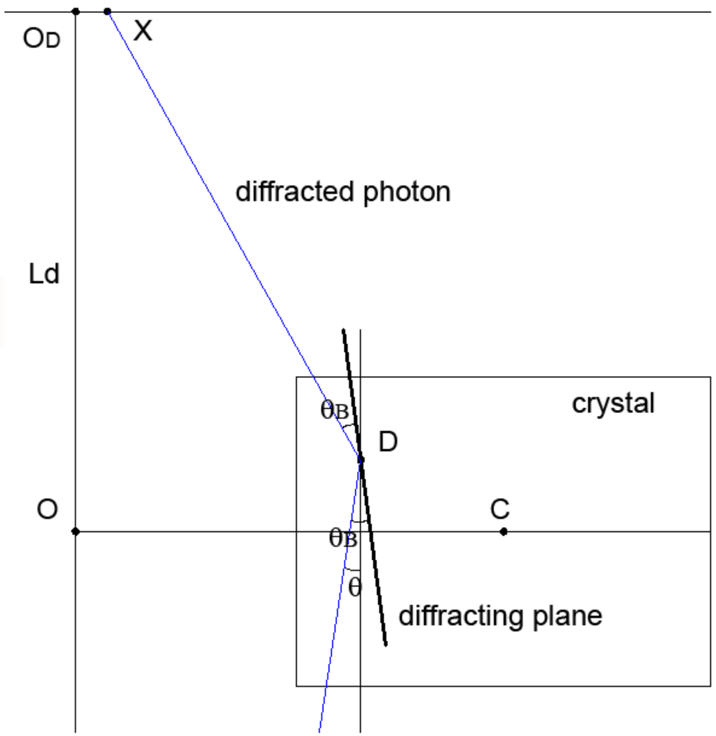
Back-up slides

RAYTRACING CODES FOR X-RAYS

- source description (position, spatial, angular and spectral distribution);
- optical elements/lens description (**crystal features**, position, misalignments);
- tracking of photons from the source to an arbitrary/detector position, managing **crystal-photon interaction**;
- advanced post-processing elaboration.

RAYTRACING CODES FOR X-RAYS
crystal-photon interaction





geometrical conditions

$$\Delta\theta_{OK} = f(\Delta E, Ls, r, To, \Omega, Lr)$$

$$\Delta\varphi_{OK} = f(Ls, r, To, Lt, Lr)$$

point of diffraction

$$(x_D, y_D, z_D) = f(\Delta\theta, \Delta\varphi, \Delta E, Ls, r, To, \Omega)$$

arrival point on the plane at a distance Ld from the lens

$$(x, y) = f(\Delta\theta, \Delta\varphi, \Delta E, Ls, Ld, r, To, \Omega)$$

FABRICATION OF BENT CRYSTALS

Methods for bending a crystal:

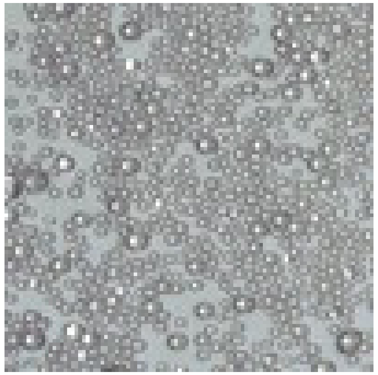
• applying a thermal gradient perpendicular to the desired planes;

• growing a two-component crystal (e.g. $Si_{1-x}Ge_x$) whose composition varies along the crystal growth axis;

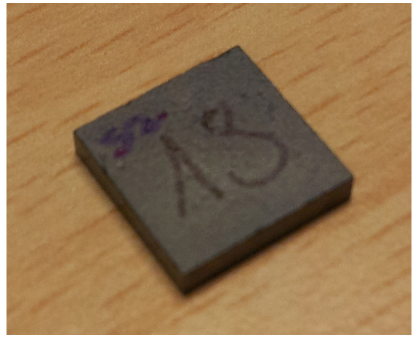
• depositing a coating or by grinding or grooving a face of the crystal;

• Carbon Fibre Deposition, Ion Implantation, and Sandblasting (INFN-LOGOS).

FABRICATION OF CDP CRYSTALS
Bending through sandblasting

Sandblasting method, developed within the **INFN-LOGOS** project, allowed obtaining samples as thick as 2 mm **homogeneously bent**. The main advantages of the method are: **simplicity**, **reproducibility**, and above all **absence of any contaminating material.**

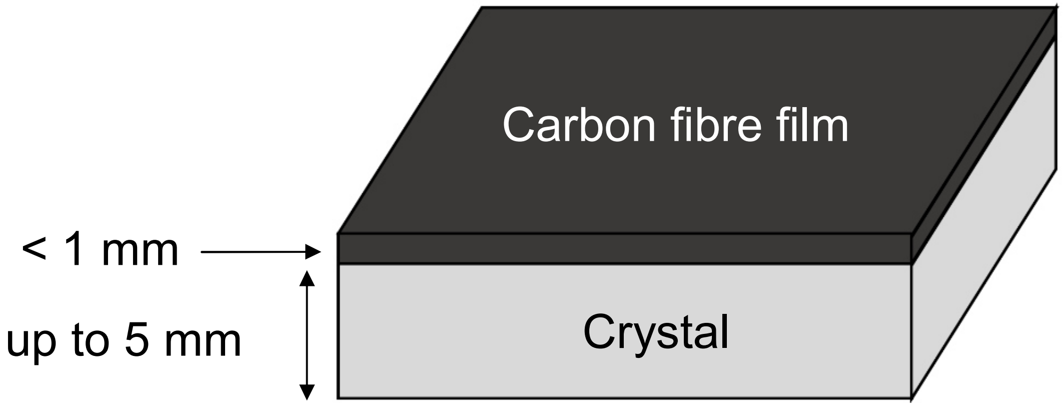


Sandblaster	SAMAC
Compressed air consumption	560 lt/s @ 6 bar
Blasting medium	natron glass
Blasting medium size	1 - 50 μm
Blasting medium density	2.3±0.3 g/cm³
Blasting medium hardness (Mohs)	6

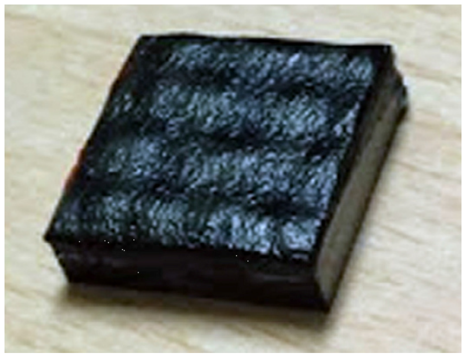
Sandblasting causes a **compressive layer** on the surface of the sample, which results permanently bent accordingly to its elastic properties.

$$R = \frac{1}{(s_{11} + s_{12})} \frac{h_s^2}{6 h_f \sigma_f}$$

FACRIBATION OF CDP CRYSTALS
Bending through carbon fiber deposition

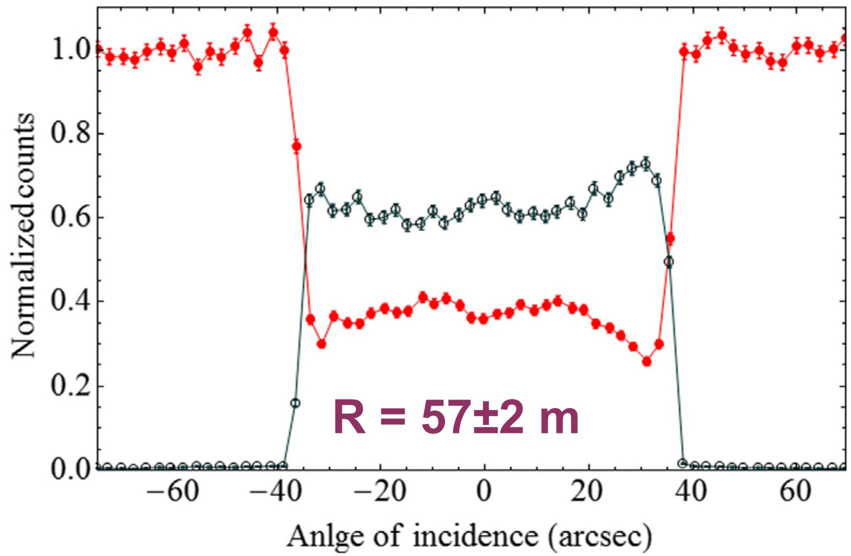


Carbon fibres deposition, developed within the **INFN-LOGOS** project, allowed obtaining samples as thick as 5 mm homogeneously bent.



Sample size (mm)	20 x 20 x 5
Carbon fibre film thickness (µm)	600
Number of carbon fibre layers	4 (alterned)
Young Modulus of the carbon fibre (GPa)	600 (230)
Cure cycle	135°C, 6 bar
Thickness traversed by X-rays (mm)	20
Diffracting planes	(111)
Beam energy (keV)	150
Beam width (µm)	50 x 50
Beam monochromaticity (ΔE/E)	2×10^{-3}

Hard X-ray diffraction at ESRF

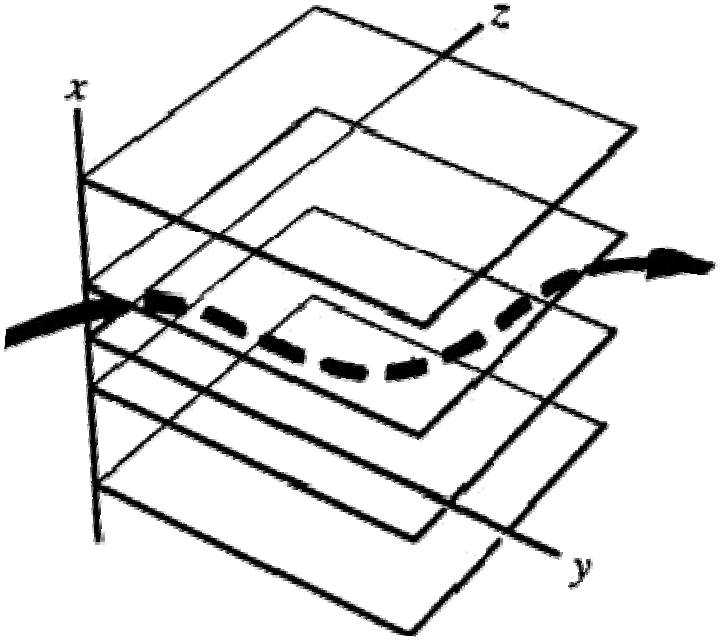


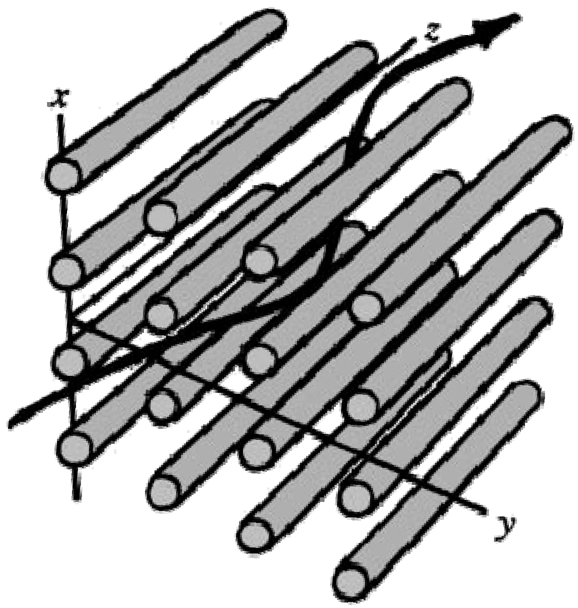
A. Mazzolati et al., NIM B 35, (2015) 297-300

Channeling

Coherent interactions in straight crystals:

Channeling is the confinement of charged particles travelling through a crystal within atomic planes (planar or axial modes)





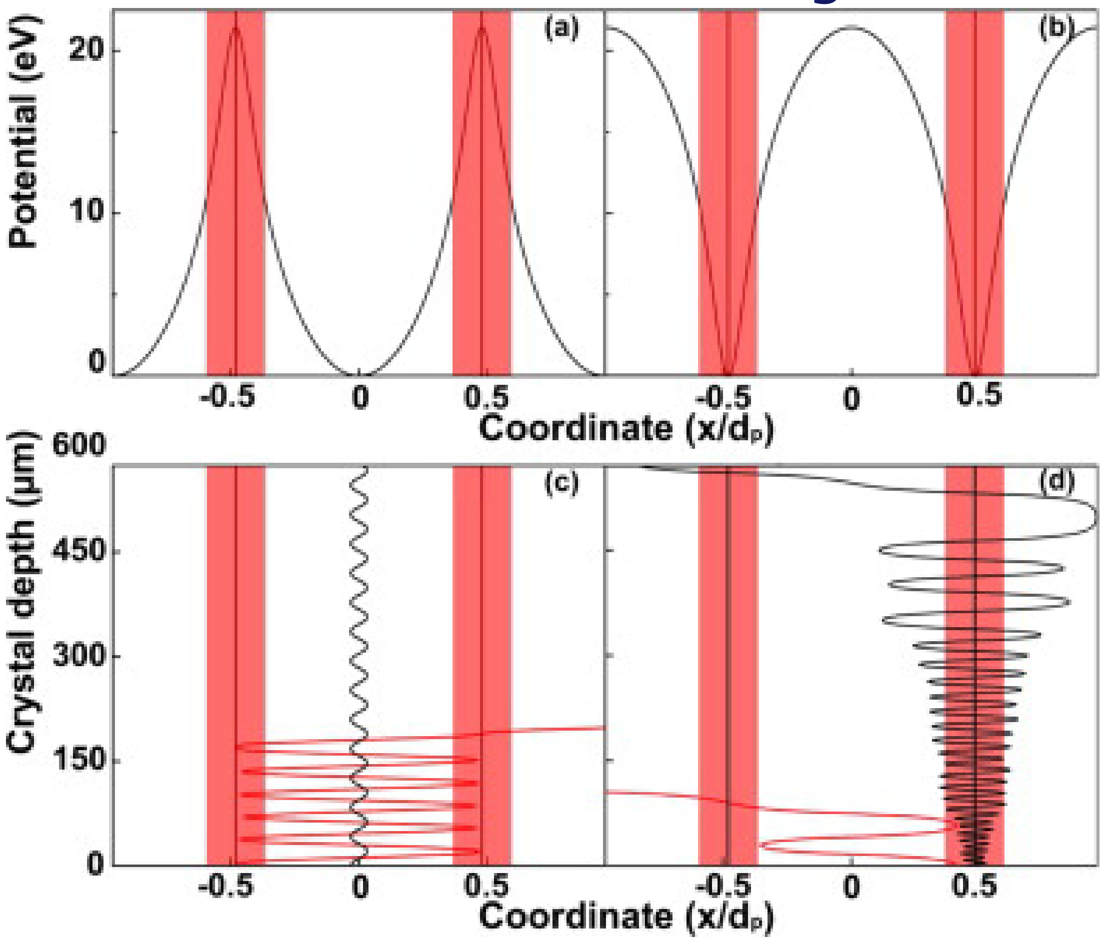
Channeling occurs as the trajectory of particles forms an angle lower than the critical angle [1]

$$\theta_{max} = \sqrt{\frac{2U}{E}}$$

[1] J. Lindhard, K. Dan. Vidensk. Selsk. Mat. Fys. Medd. 34 (1965) 14.

Dechanneling of positive vs negative particles

Positive vs negative



Channeled negative particles are dechanneled faster than positive ones due to higher probability to suffer nucler incoherent scattering;

Ultra thin bent crystals are required for efficient deflection of negative particles

To determine how thin, one has to know the dechanneling length for negative particles!

N.B. L_d decrease with energy, being some tens of microns for 1 GeV electrons in Si [1].

[1] W. Lauth, H. Backe, P. Kunz, A. Rueda, Int. Journal of Modern Physics A, 25, 1 136-143 (2010)

Simulation of channeling and channeling radiation

The algorithm for direct integration of the BK formula has been included in the RADCHARM++ routine [1] , which is an expansion of the DYNECHARM++ code [2]

•The electrical characteristic of the crystal are evaluated by using the atomic form factors from x-ray diffraction data;

•Numerical integration of the classical equation of motion of particle trajectories under the continuum potential approximation;

•At the end of each step the multiple and single scattering by nuclei and electrons is sampled.

DYNECHARM++ has already been implemented in Geant4 [3]. The RADCHARM++ can also be implemented to include the Bremsstrahlung radiation enhancement in crystals.

[1] L. Bandiera, et al., Nucl. Instrum. Methods Phys. Res., Sect. B 355, 44 (2015).
[2] E. Bagli, V. Guidi, Nucl. Instr. and Meth. in Phys. Res. Section B 309 (2013) 124
[3] E. Bagli, M. Asai, D. Brandt, et al. Eur. Phys. J. C (2014) 74: 2996.

Development of the G4Channeling process in Geant4 (E. Bagli)

- **simulation of coherent interactions in crystals for high-energy particles**:
  - Planar channeling
  - Volume reflection
  - Axial channeling
  - Multi-Volume Reflection in one crystal