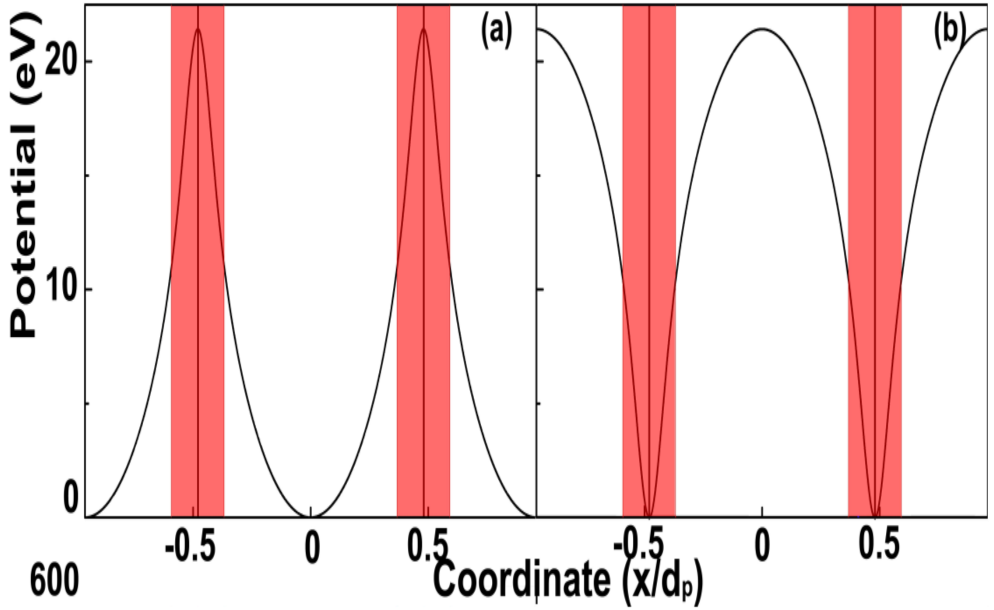
Channeling at accelerators high-energy frontier and future developments from GALORE

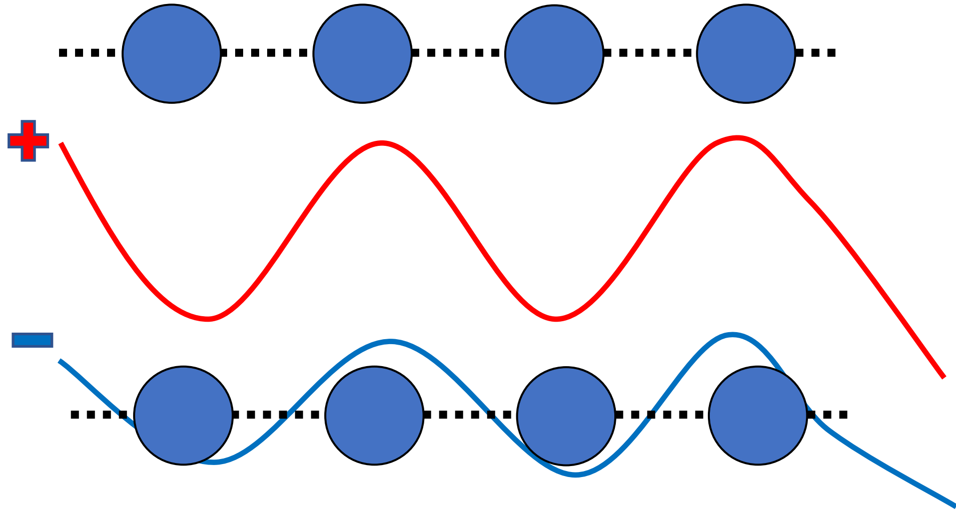
Speaker: M. Romagnoni

INFN

Channelling phenomenon

- Particles aligned with atomic planes perceive a continuous potential with wells and barriers
- Particles within a critic angle $\sqrt{(2U_0)/(pv)}$ can be bound to potential:
  - ⊕ Between adjacent planes if positively charged
  - ⊖ Into plane if negatively charged
- Scattering is strongly different in two cases:
  - ⊕ Reduction of inelastic collision with nuclei
  - ⊖ Increased inelastic collision with nuclei



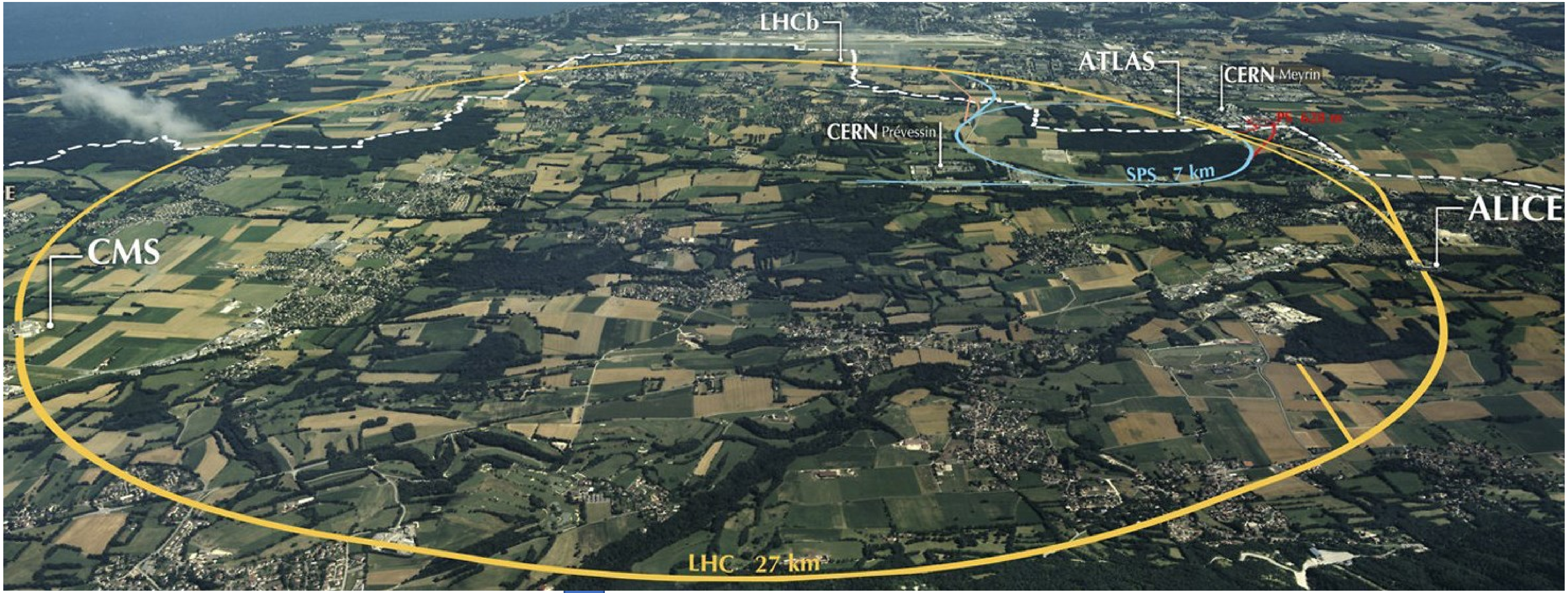


Channeling in bent crystals

- Channeled particle follows the curvature of the lattice plane
- A bent crystal can act as a sort of waveguide for channeled particle, steering them at angle depending on its geometry
- Large steering power can be obtained in few millimeters of crystal, equivalent to that of hundreds of Tesla magnetic dipole

Energy (GeV)	**Deflection**	**Size (mm)**	**Equivalent dipole**
6500	50	4	276 T
0.855	1500	0.015	285 T
20.53	400	0.06	456 T
2000	14000	70	1134 T

To visualize the difference…

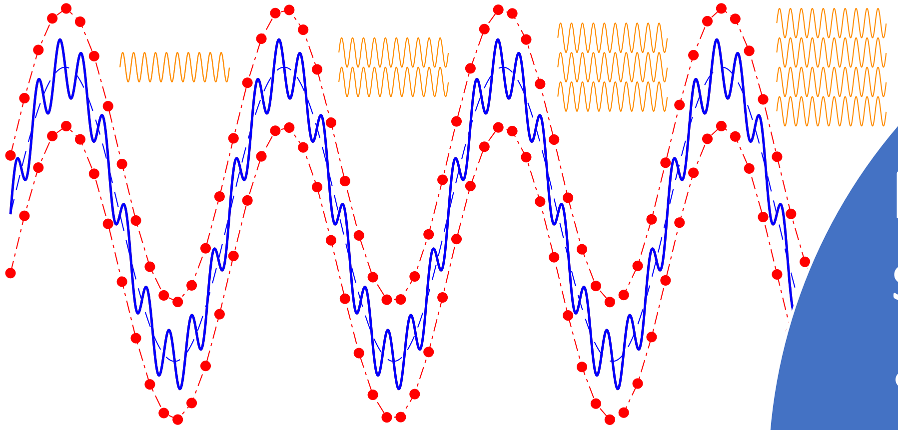


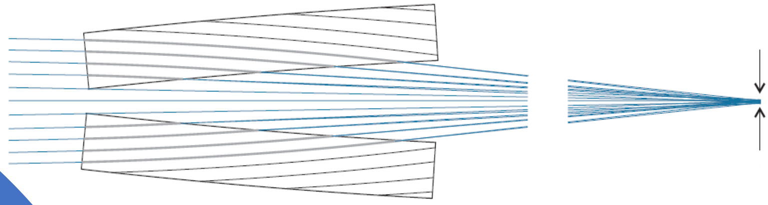
Large Hadron Collider (Fr/Sw):
- circumference 27km
- Dipole max field 8.3 T

WOULD FIT INTO

Advanced Photon Source (USA):
- circumference 1.1 km
- With magnets strong as crystals

Application in accelerators



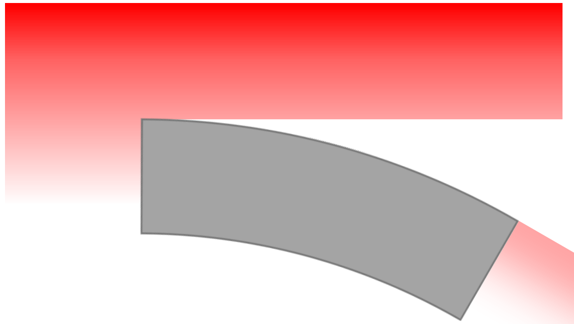


Radiation source

- Channeling radiation
- Crystal undulator

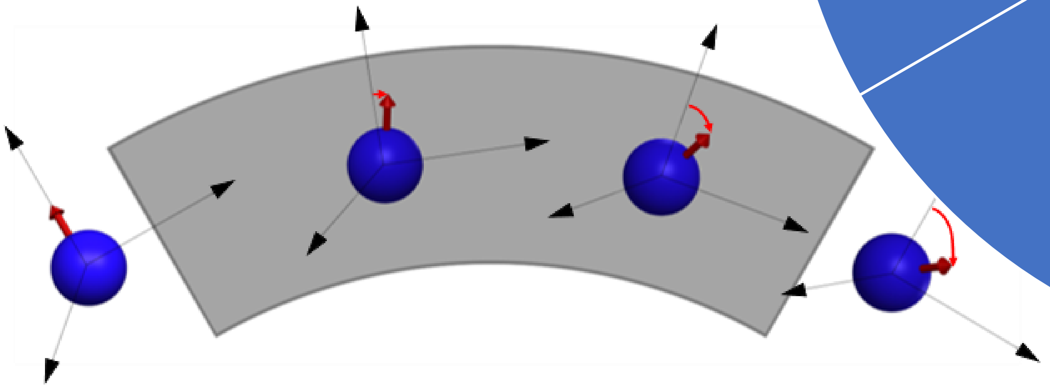
Deflection

- Collimation
- Extraction
- Focusing / De-focusing



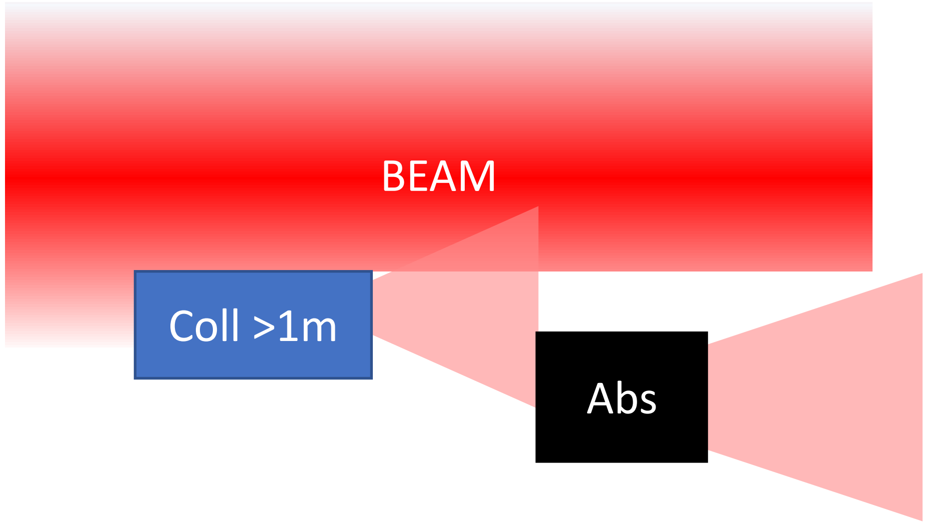
Spin precession

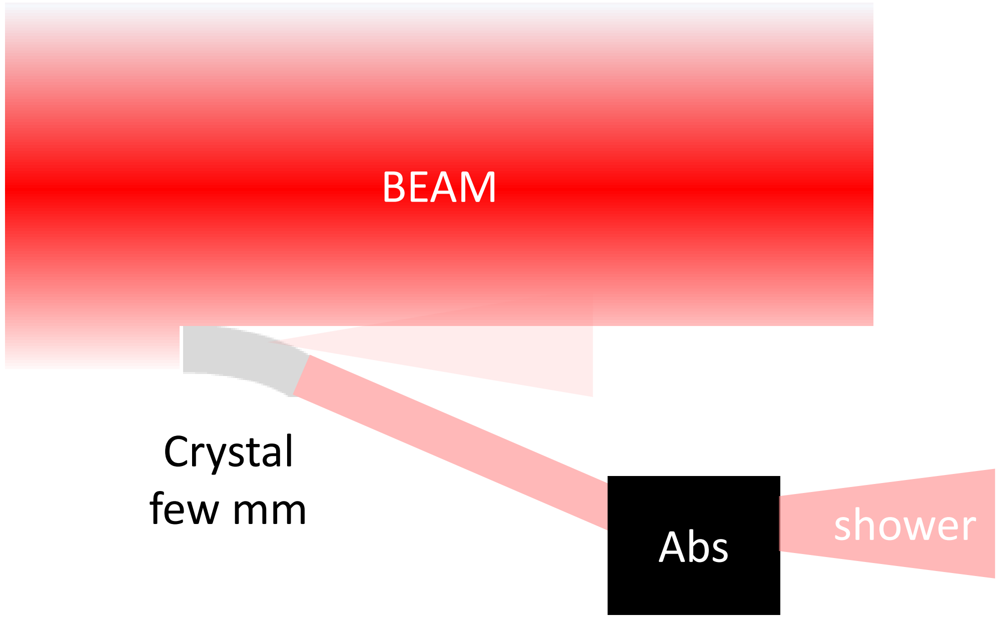
- Study of fast decaying particle EMD and MDM



Crystal Assisted Collimation

- Unavoidably particles diverge from desired trajectory and form **a halo around beam**
- Traditional approach stops the halo with a series of amorphous absorber
- Cons: development of showers in collimators





- Channeled particles in bent crystal while being steered avoid strong scattering: shower development strongly suppressed
- High efficiency in removing halo from beam in controlled manner

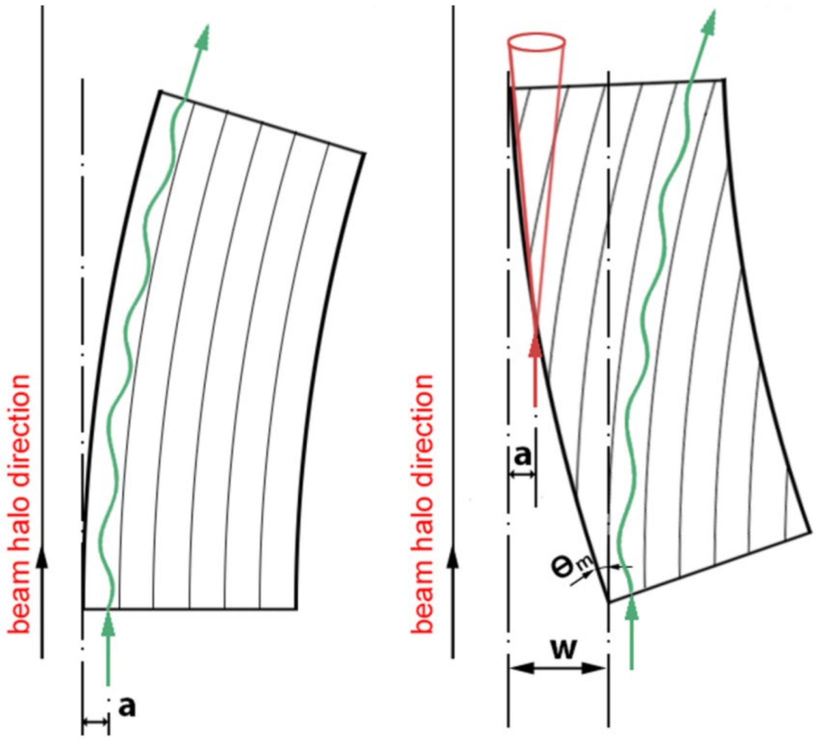
Crystal requirement for LHC

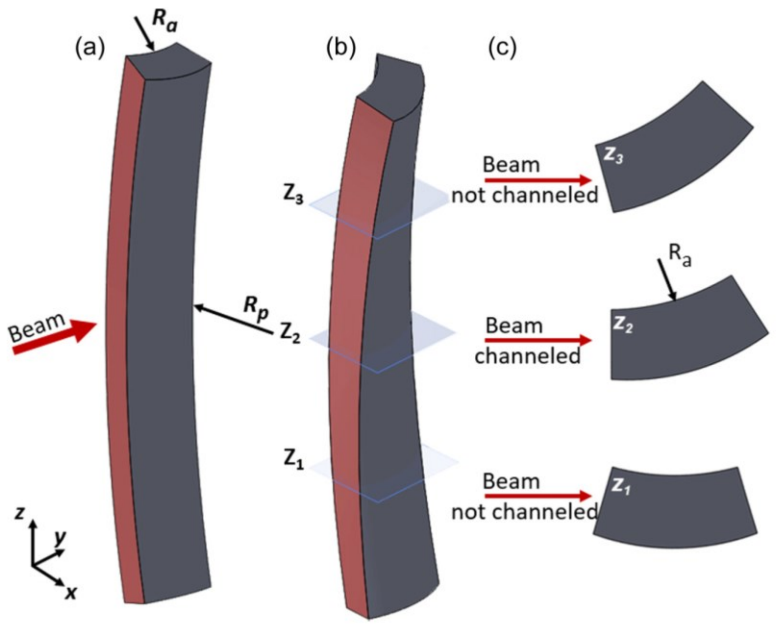
Lattice quality:

- Dislocation density <1/cm^2
- Roughness <100nm
- Miscut angle <10μrad

Curvature:

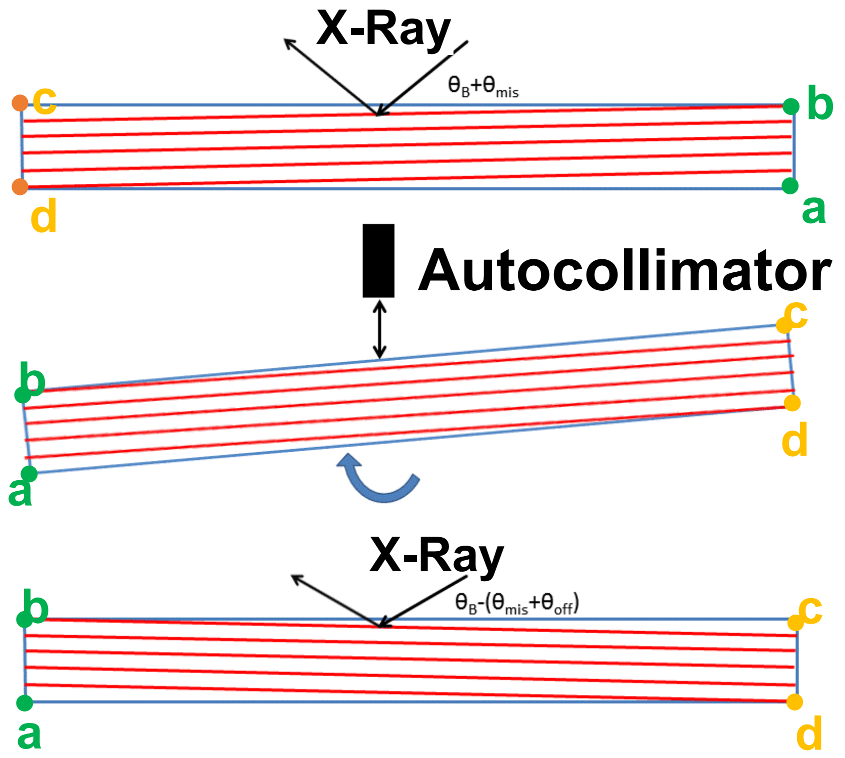
- Thickness across the beam 4mm
- Deflection 50±2.5μrad
- Torsion <1μrad/mm
- Stability after bake-out (@250°C)

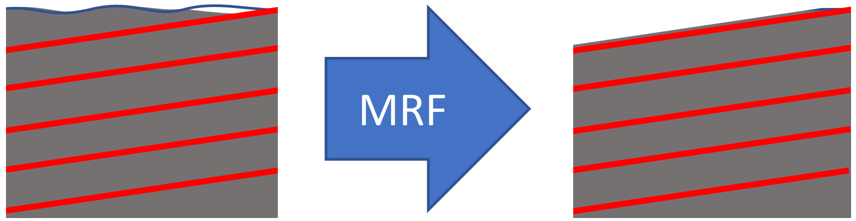




Miscut measure & reduction

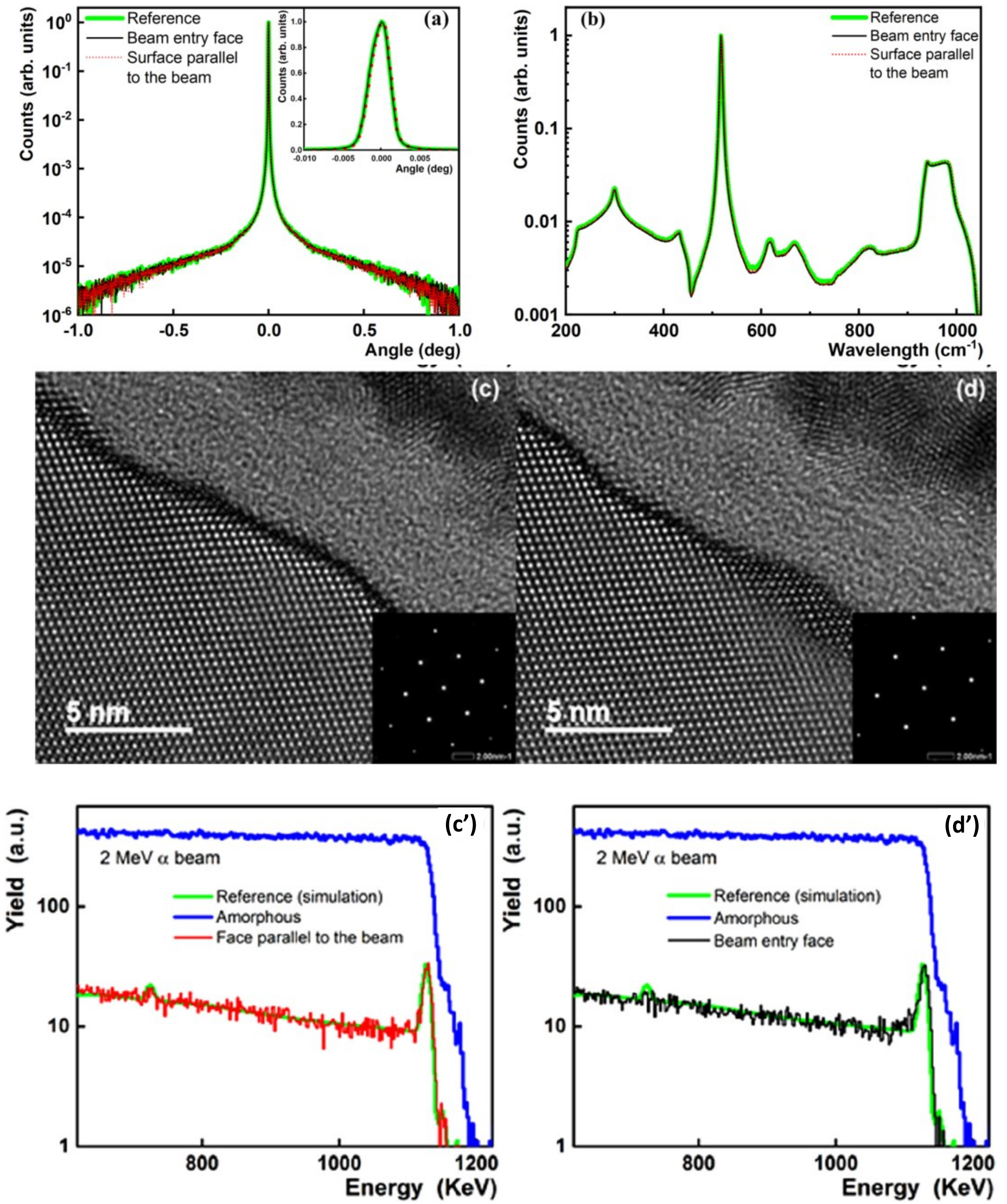
- Miscut measure using X-rays High-Resolution Diffractometer (HRXRD) coupled with laser autocollimator
  - Crystal is aligned to Bragg diffraction & surface angular position is recorded with autocollimator
  - Crystal is rotated 180° over axis nominally perpendicular to surface (misalignment and mechanical imprecisions are measured with autocollimator)
  - Crystal is aligned again to Bragg diffraction: offset between the two measure indicate miscut angle with 1.7μrad resolution
- Miscut reduction:
  - Silicon wafers features generally miscut 200-10000 μrad
  - Magnetorheological Finishing (MRF) remove material with high precision without damaging lattice
    - Planarity: 1λ→1/10λ
    - Miscut 200 μrad → 2 μrad





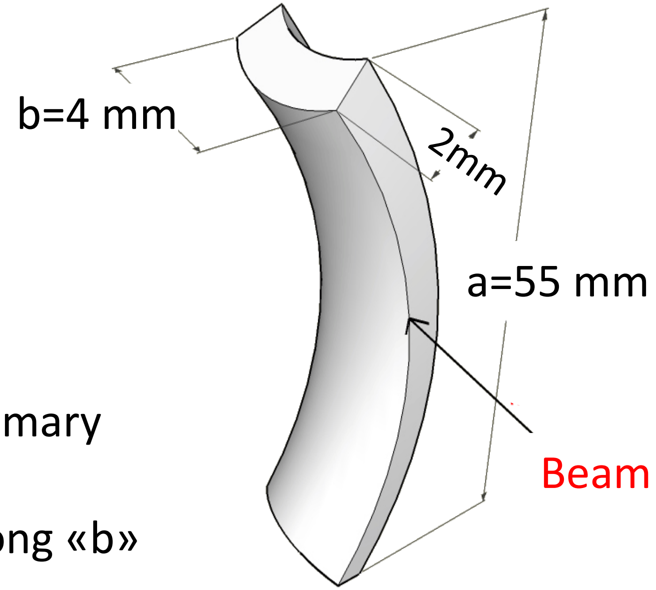
Crystal Shaping & Lattice Quality

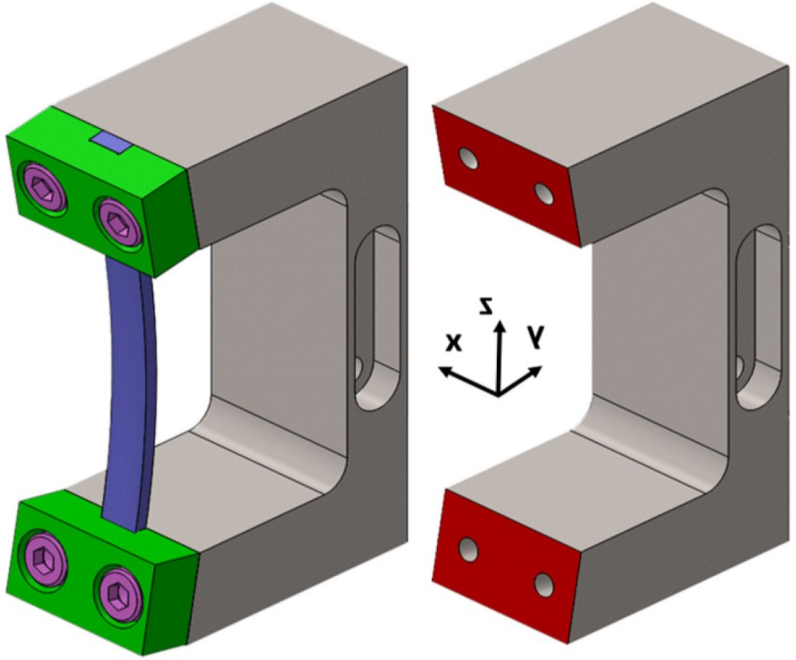
- Crystal shaping:
  - Dicing saw cuts from wafer specimen $2x4.2x55mm^3$
  - Lapping and polish on surface to remove 0.1mm from each side of crystal to discard damaged material
- Lattice Surface Quality verification:
  - (a) X-rays diffraction (depth up to ≈15μm)
  - (b) Micro-Raman spectroscopy (depth ≈1.5μm)
  - (c-d) Rutherford Backscattering (depth ≈1.5μm, nanometric resolution)
  - (c'-d') HR-TEM (direct observation of lattice planes on surface)

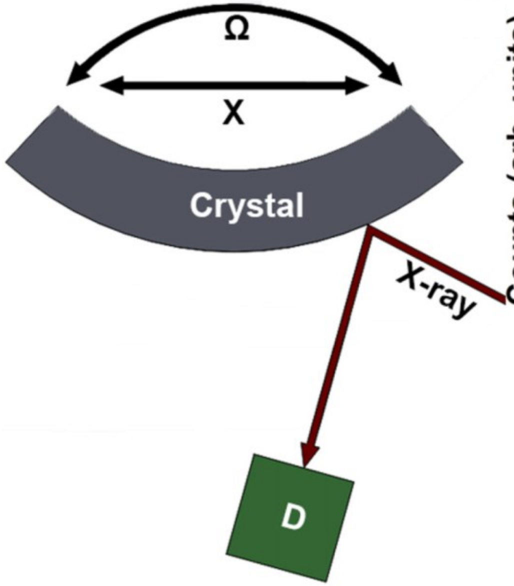


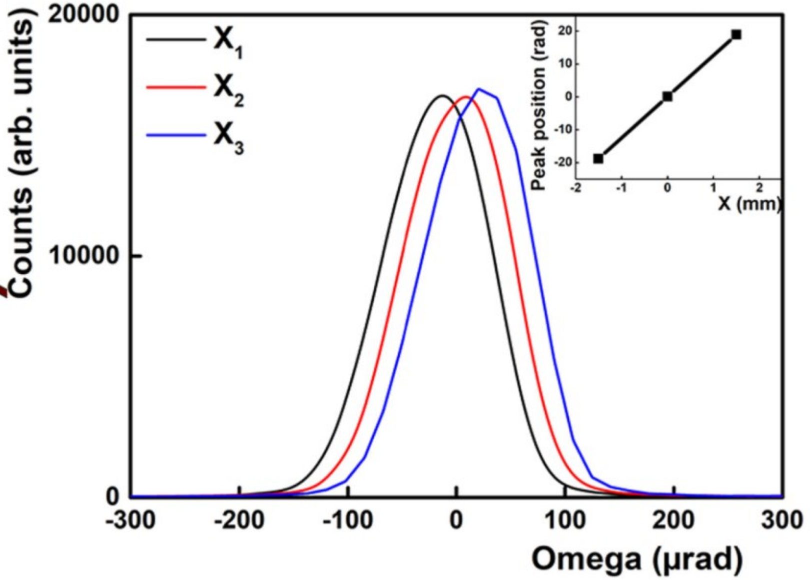
Bending
& Characterizations

- Crystal bending:
  - All holder components made in Ti gr V
  - Red faces cut at precise angle to impose primary bending along «a»
  - In center of crystal, anticlastic curvature along «b» is exploited to deflect the beam
- Bending Characterization:
  - Crystal+Holder installed on HRXRD
  - Bragg diffraction measured in different position along curvature
  - Angular shift between reflection directly linked to curvature
- Thermal stability verified after annealing in vacuum oven (T=250C, P=1nbar)



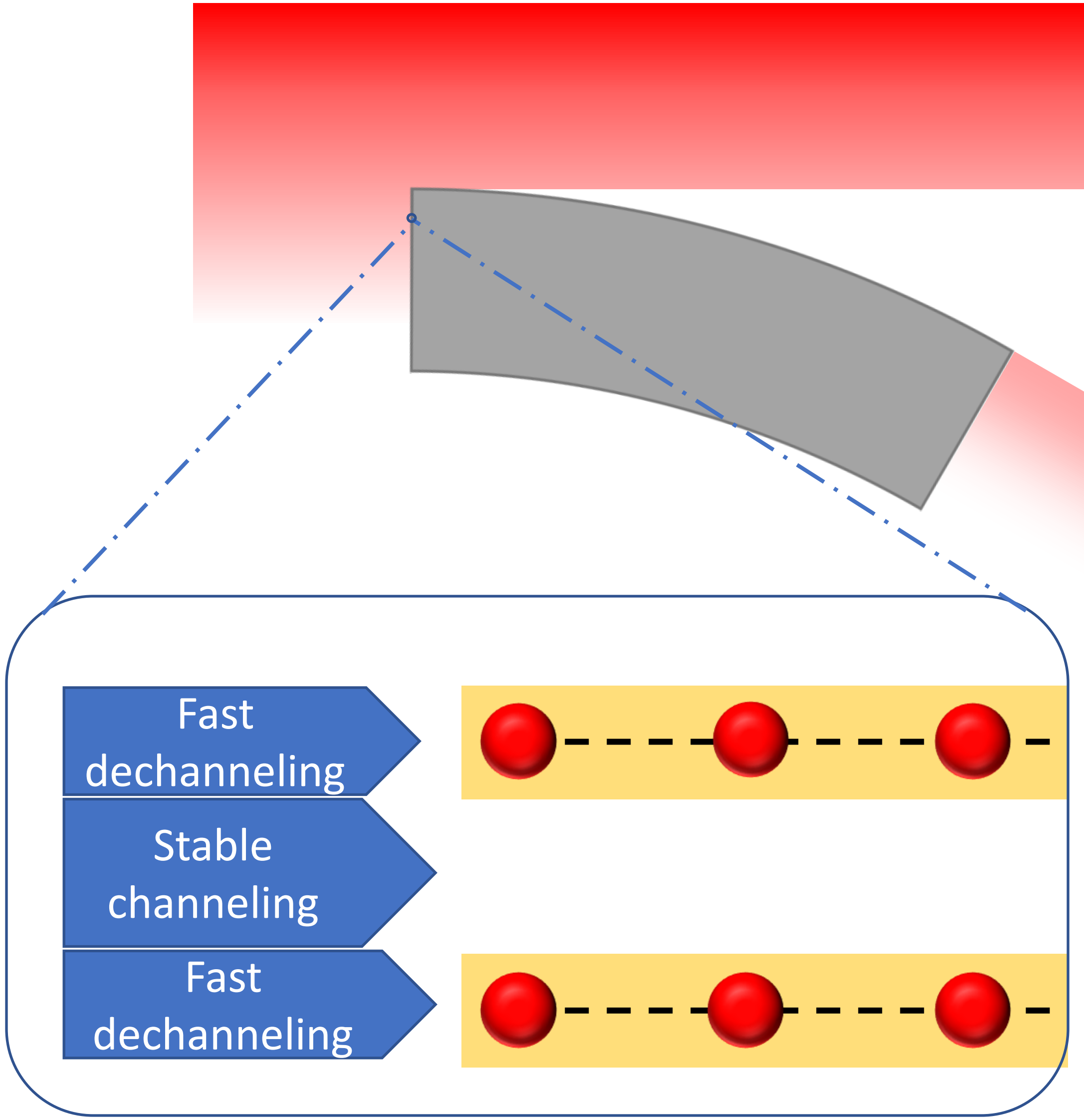






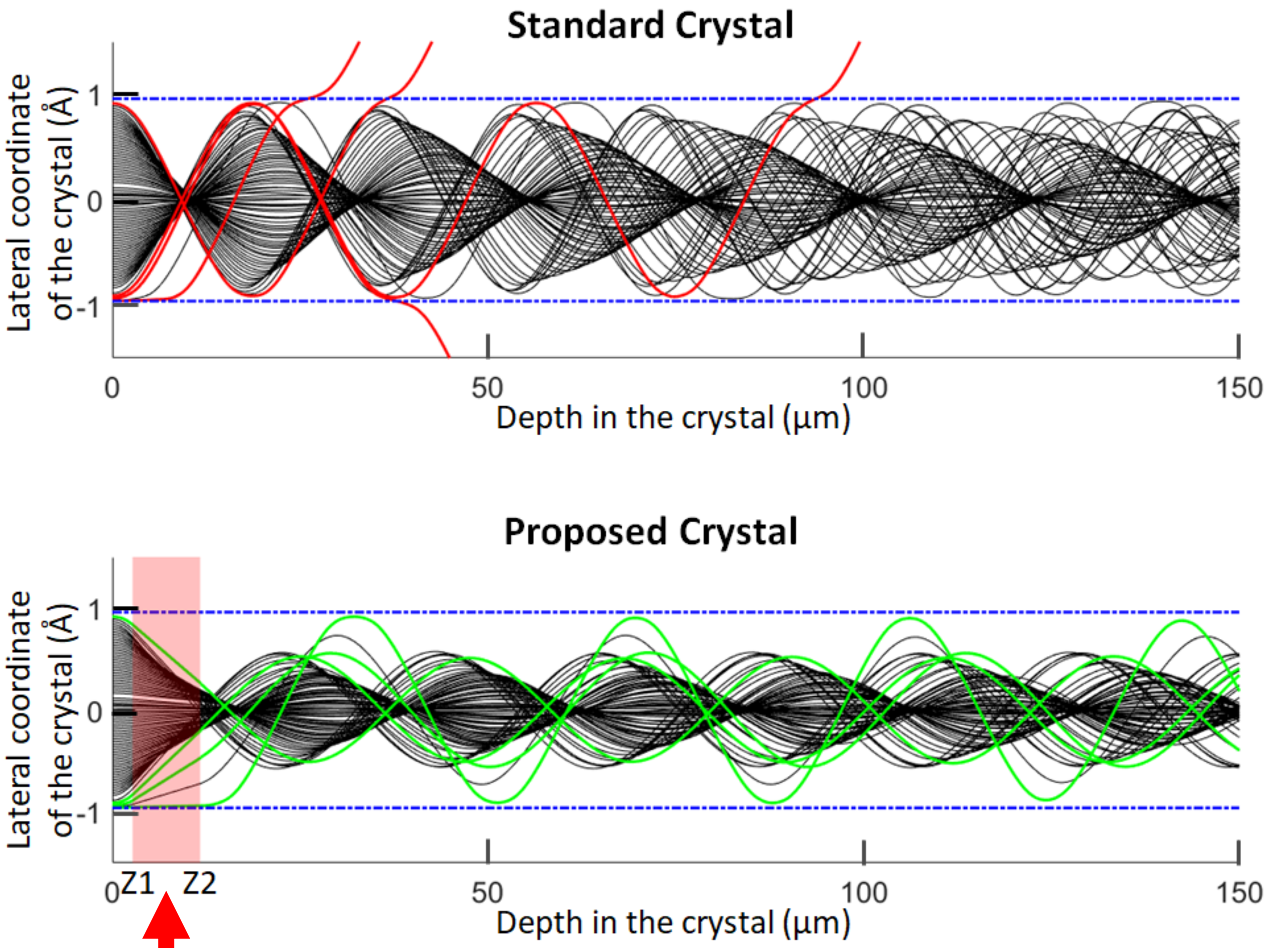
Channeling limit

- Scattering with nuclei **quickly remove** particles from channeling
- Rate of nuclear dechanneling is strongly dependent on **impact parameter** on the interplanar channel
- The fraction of the beam impacting close to atomic planes is **not deflected**: hard-limit for channeling efficiency set at ≈80%



GALORE challenge: lens-assisted crystal

- At the very **beginning** of channeling, most particles trajectories point towards the **center** of the interplanar channel
- **Before** nuclear dechanneling can occur, the crystal is **interrupted**
- The particles continue to travel in straight line, being «**focused**» **at the center** of the channel
- Once the crystal interruption ends, particles re-enter the crystal **far from nuclei** in zone of **stable** channeling



Interruption of crystal: empty region here!

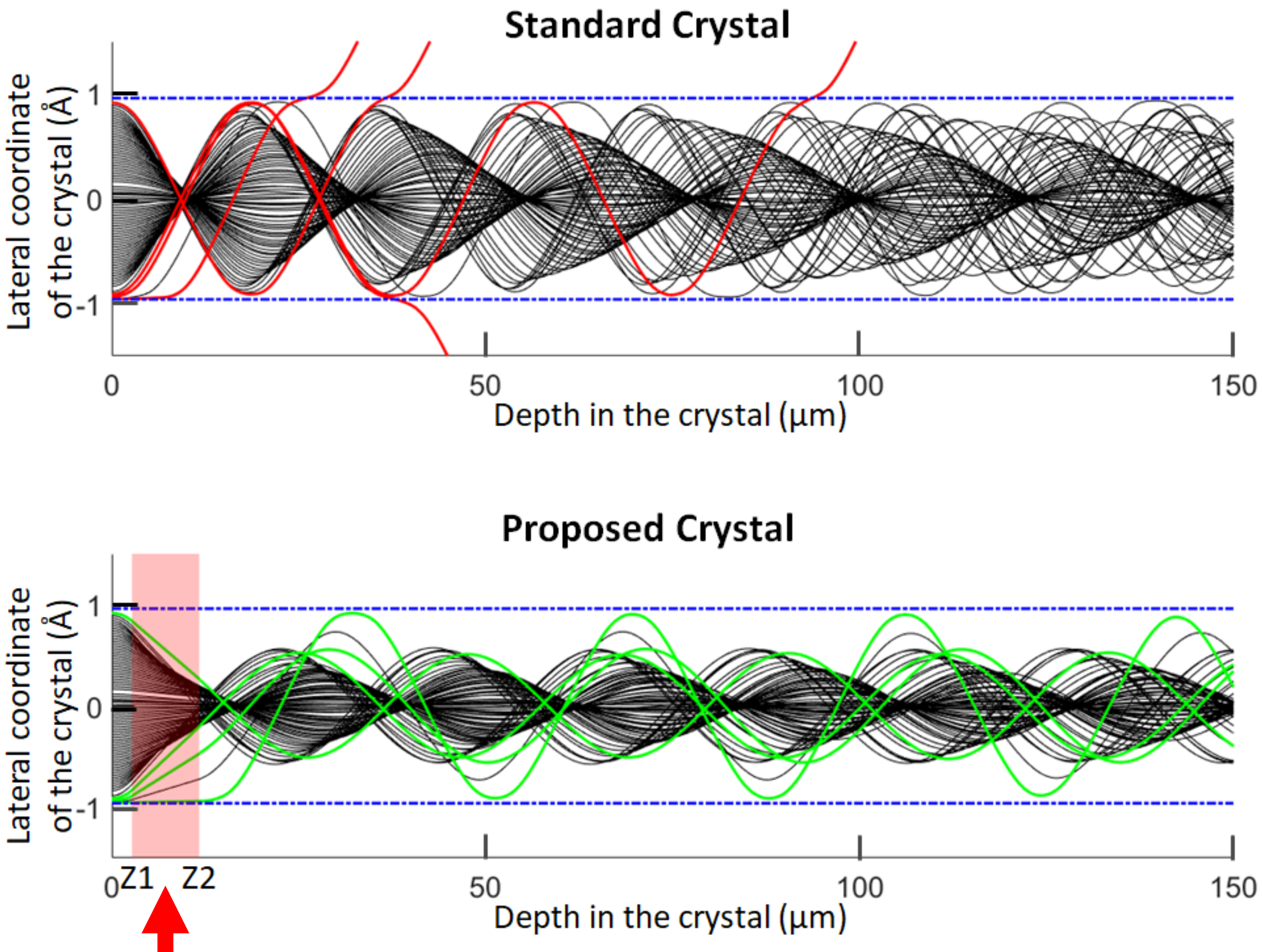
GALORE challenge: lens-assisted crystal

The phenomena is **fully understood theoretically**

(https://doi.org/10.1088/1748-0221/2/08/P08006)

BUT

Still **no prototype** has been produced and no experimental test has been performed



Interruption of crystal: empty region here!

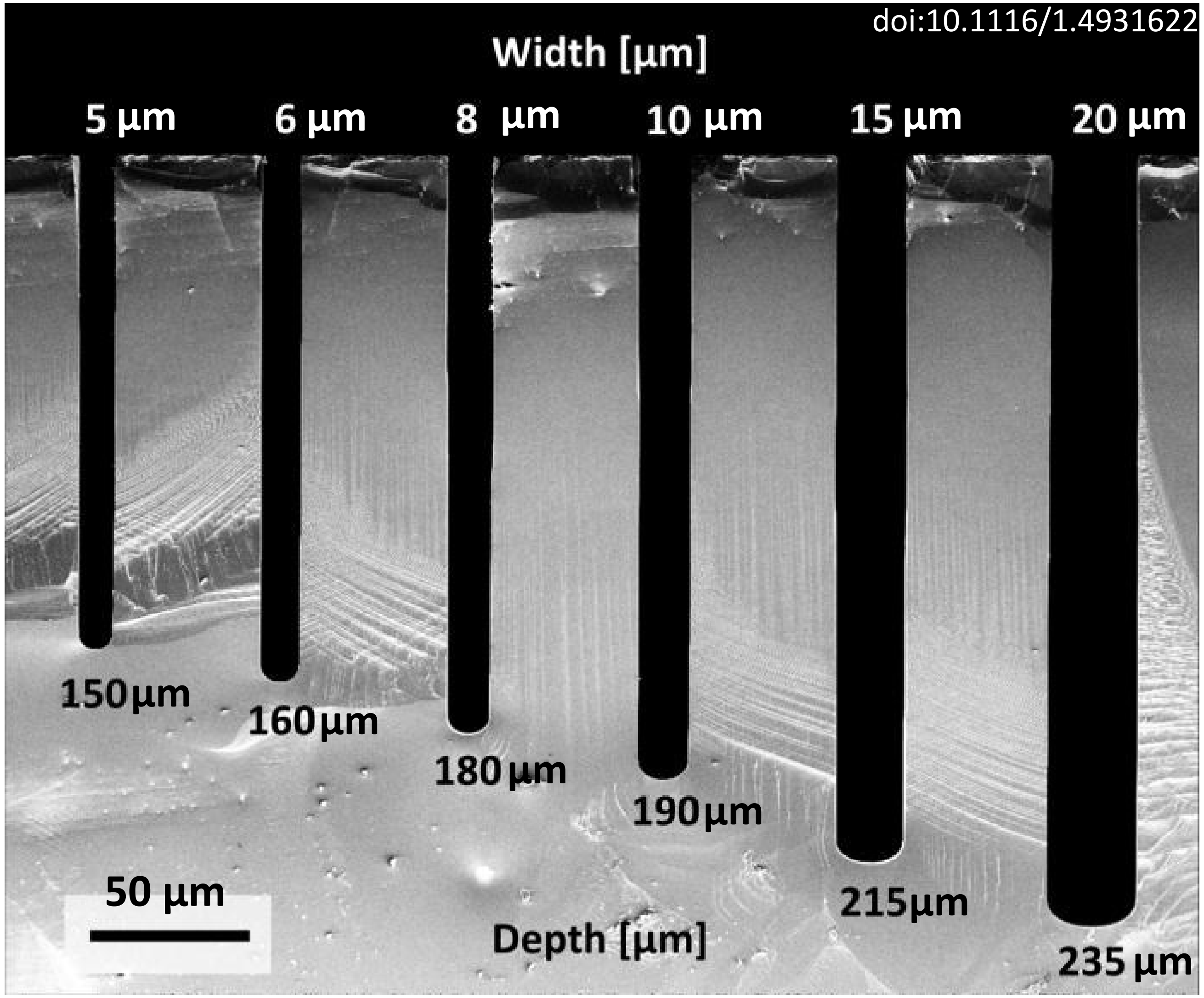
New techniques from semiconductors industry

Deep Reactive Ion Etching (DRIE)

- High spatial precision
- Vertical walls with high aspect ratio
- No damage / stress on crystal

Silicon Nitride (Si_3N_4) film

- High adhesion to silicon
- Nanometric precision of film thickness
- Highly patternable with sub-micrometric precision



Future

- LHC test of crystal assisted collimation for ion beam
- Fabrication of first prototype of crystal with cut
- First observation of channeling enhancement w 180 GeV π^+ @ NA CERN as proof of concept: **new** possibility for crystal usage

Thank you for your attention!