GALORE

hiGh-efficient beAm defLector fOR accElerators

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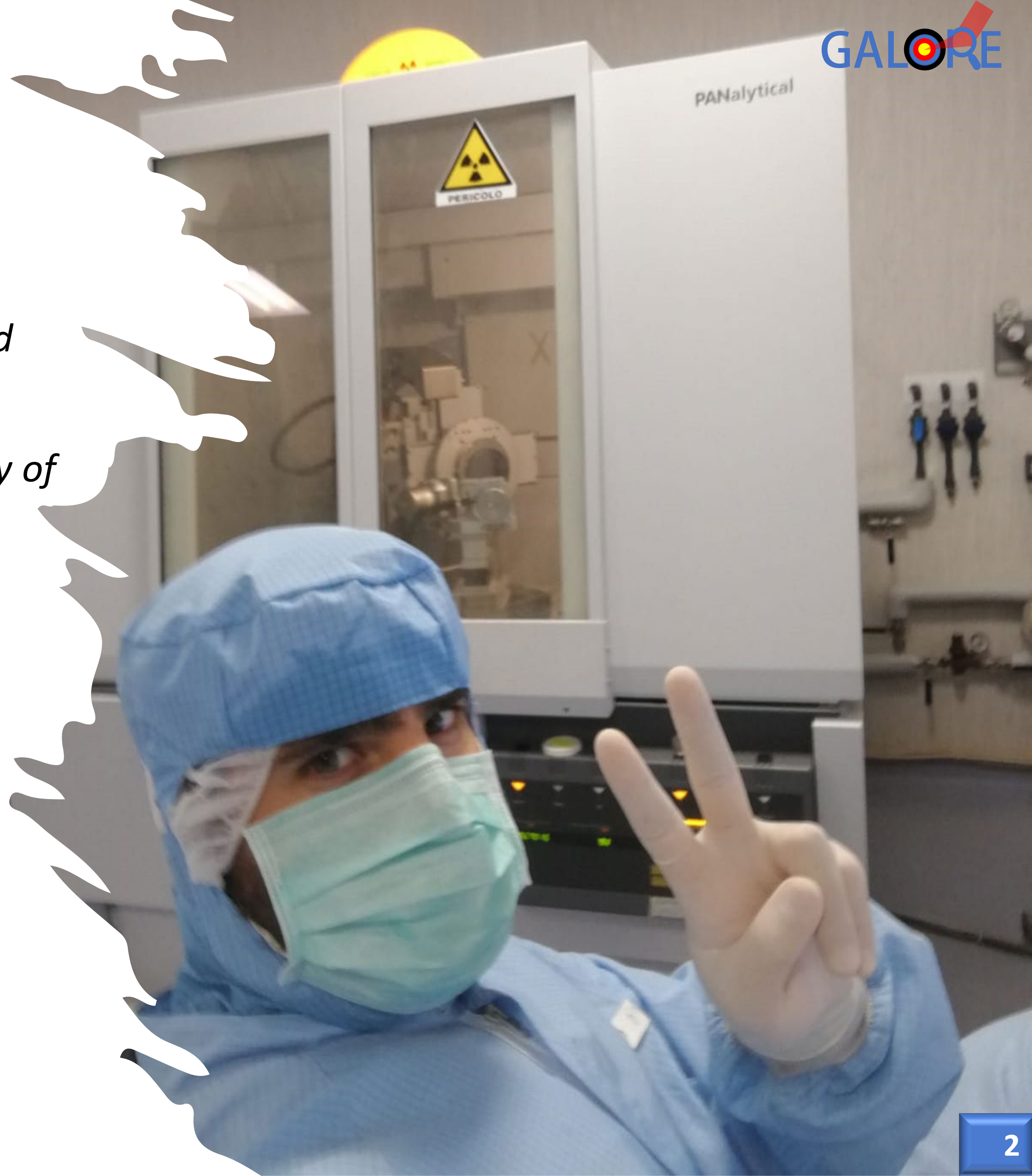
Sezioni Partecipanti: Ferrara, Legnaro

Discussione Bando Giovani Ricercatori CSN5, Frascati, 01/12/2021

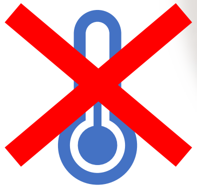
PI (ME)

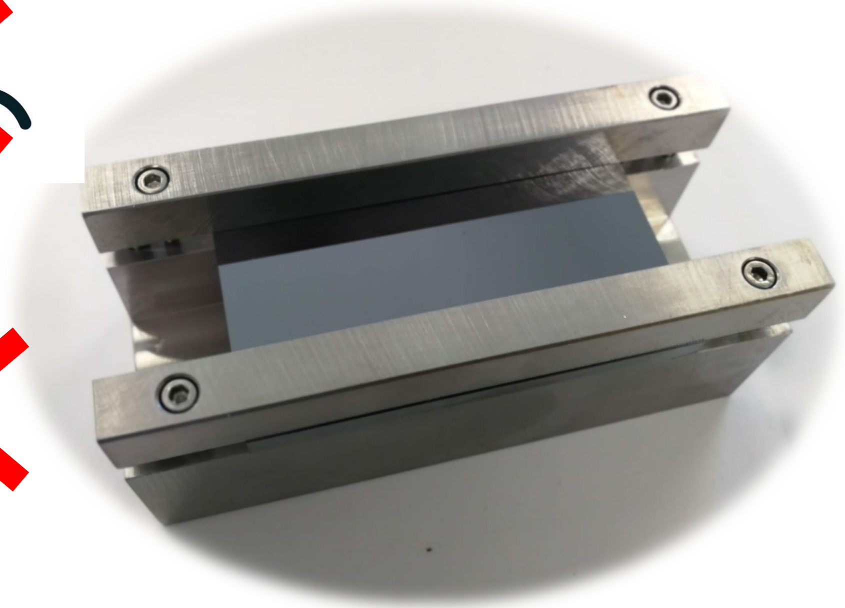
- Education:
    - Bachelor degree thesis: *"Molding of silicon plates with controlled curvatures"*
    - Master degree thesis: *"New schemes for crystal-assisted halo collimation and extraction in the Large Hadron Collider"*
    - PhD degree Thesis: *"Fabrication of bent crystal for study of orientational effects in high energy physics"*
- Production of bent crystal for channeling to:
    - Axial, Chanel (INFN Projects)
    - UA9, HL-LHC upgrade (CERN)
    - PEARL, N-Light (H2020 MSCA RISE Projects)
    - Crysbeam, SELDOM (ERC projects)
- Silicon machining and/or crystal characterization for:
    - LOGOS, OSCAR, ELIOT, STORM, Sherpa, BULLKID (INFN Projects)
    - NU-CLEUS (ERC Project)
- 23 papers published using results from crystal samples I directly contributed to design, produce and characterize on beam



Why bent crystals in particle accelerators?

In bent crystal:
steering equivalent to
1334 T dipole @2TeV

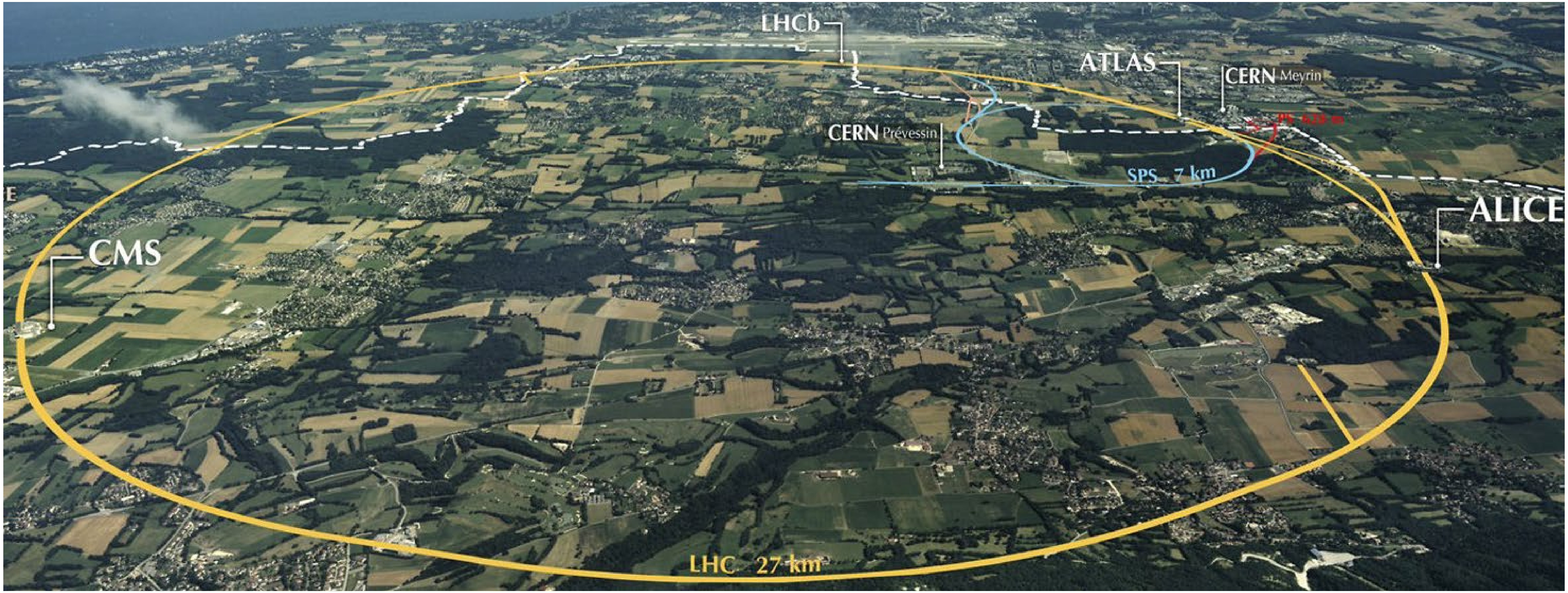




Intrinsic limit: maximum efficiency
limited to ≈80%

In lab: 1200 Tesla for 100µs=**EXPLOSION**

https://doi.org/10.1063/1.5044557



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

COULD FIT INTO

Advanced Photon Source (USA):
- circumference 1.1 km
- crystal equivalent dipole 216 T

GALORE: overcome the limit!

Novel design for bent crystal based on silicon micromachining

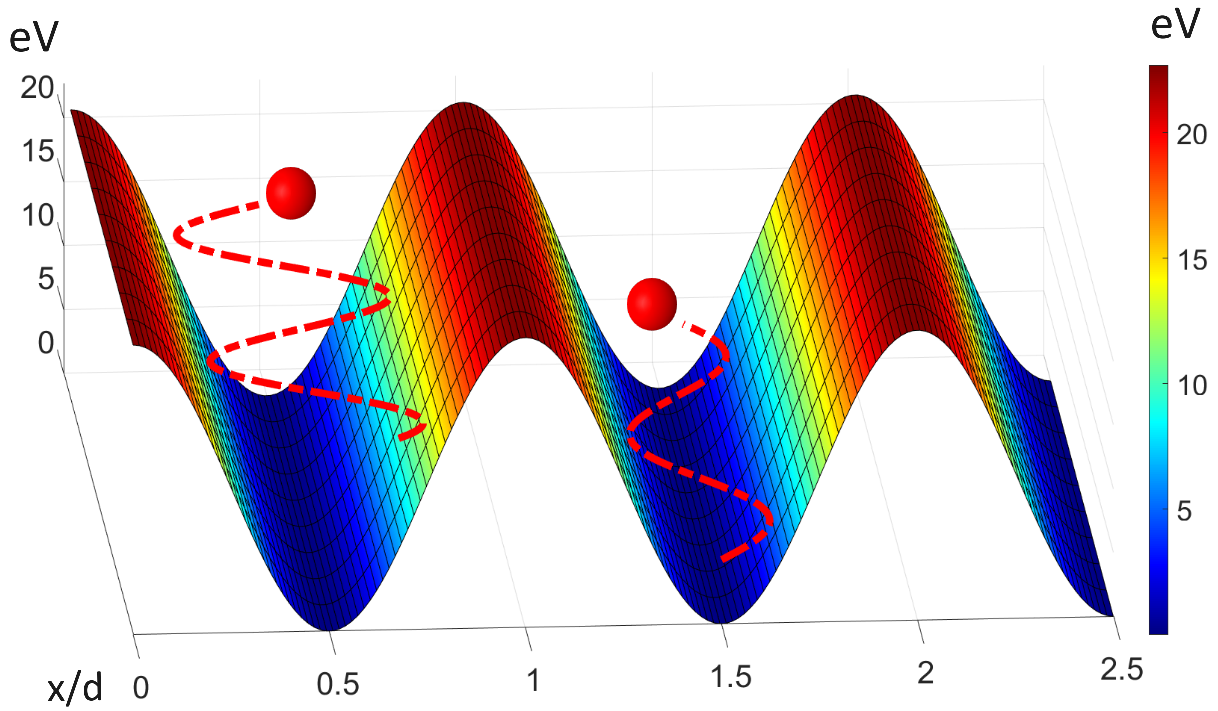
Remove upper efficiency limit: close to **100% efficiency possible**

How does it work? Amophous vs crystals

Amorphous materials: random scattering with single atoms

Crystals: Ordered structure from specific points of view: particles interacts with structures of atoms such as planes and/or axis

How does it work? Planar channeling



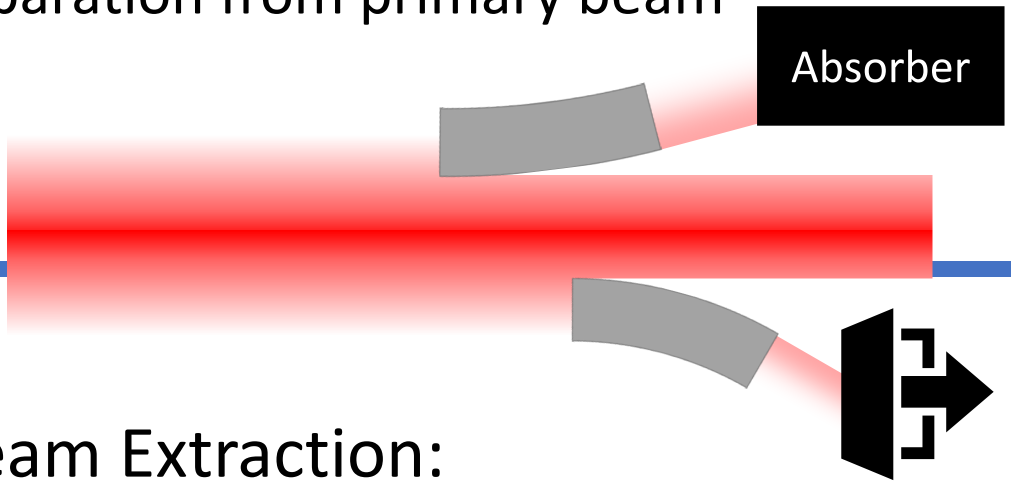
Strong static potential (≈**GeV/cm**) can trap (*channel*) positive particles between two adjacent atomic planes angle

Channeled particles are forced to follow crystal curvature, with steering power ≈ **10^2T** magnetic dipole

Bent crystal channeling applications

Beam Collimation:

With crystal high control of beam halo separation from primary beam

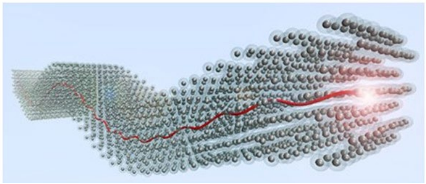


Beam Extraction:

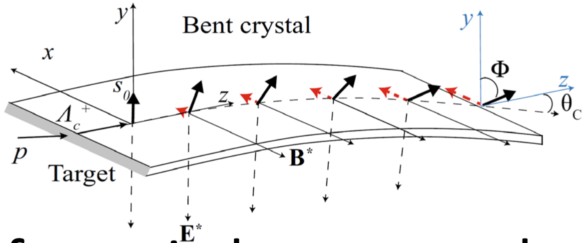
Surgical redirection of a beam portion, towards a precise location in the machine or in an external facility

Novel radiation sources:

For channeled light particles (e+/e-) enhanced photon emission



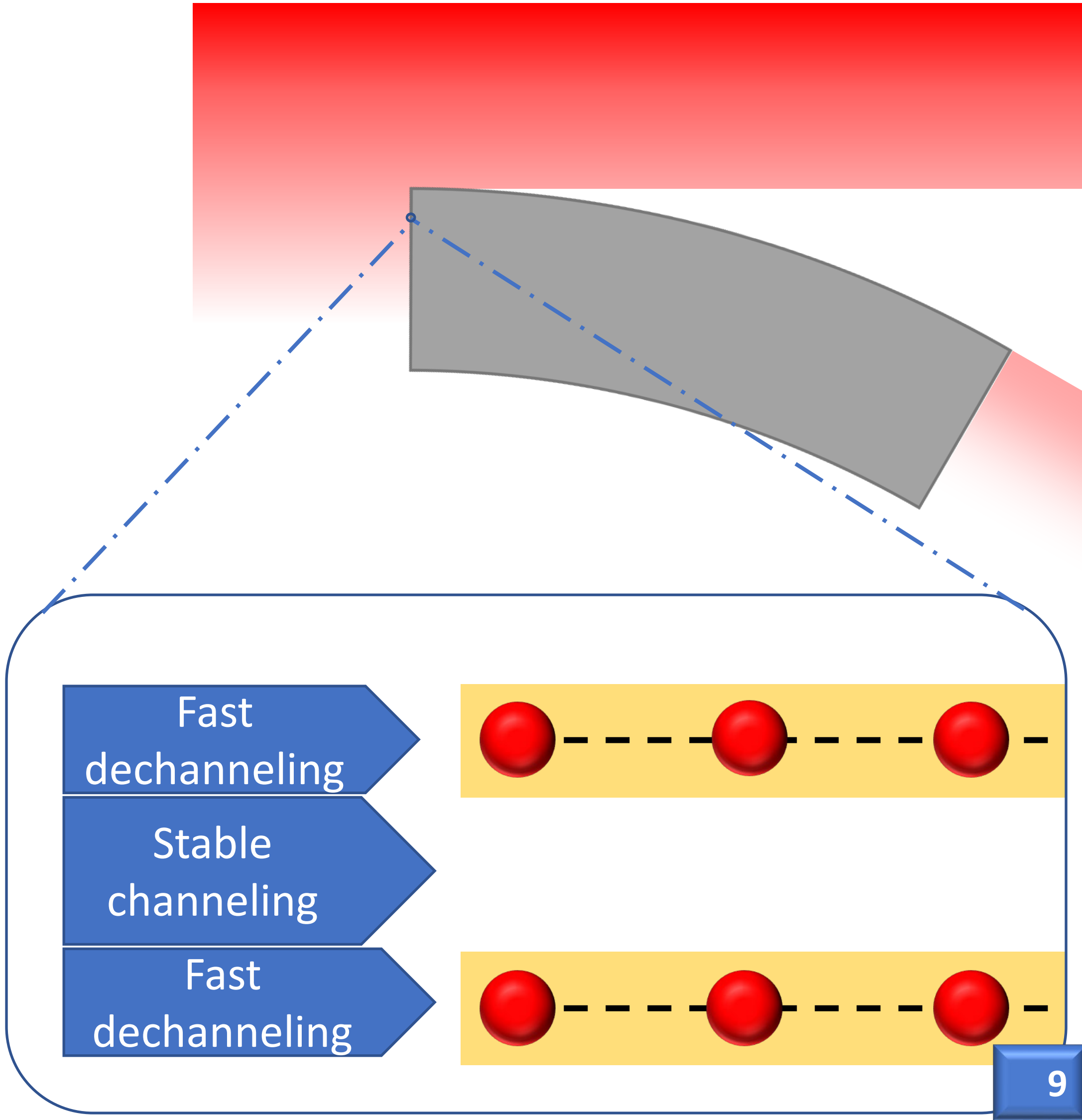
Spin precession:



Spin precession much faster in bent crystal wrt existing dipoles→EDM & MDM study of fast decaying particles

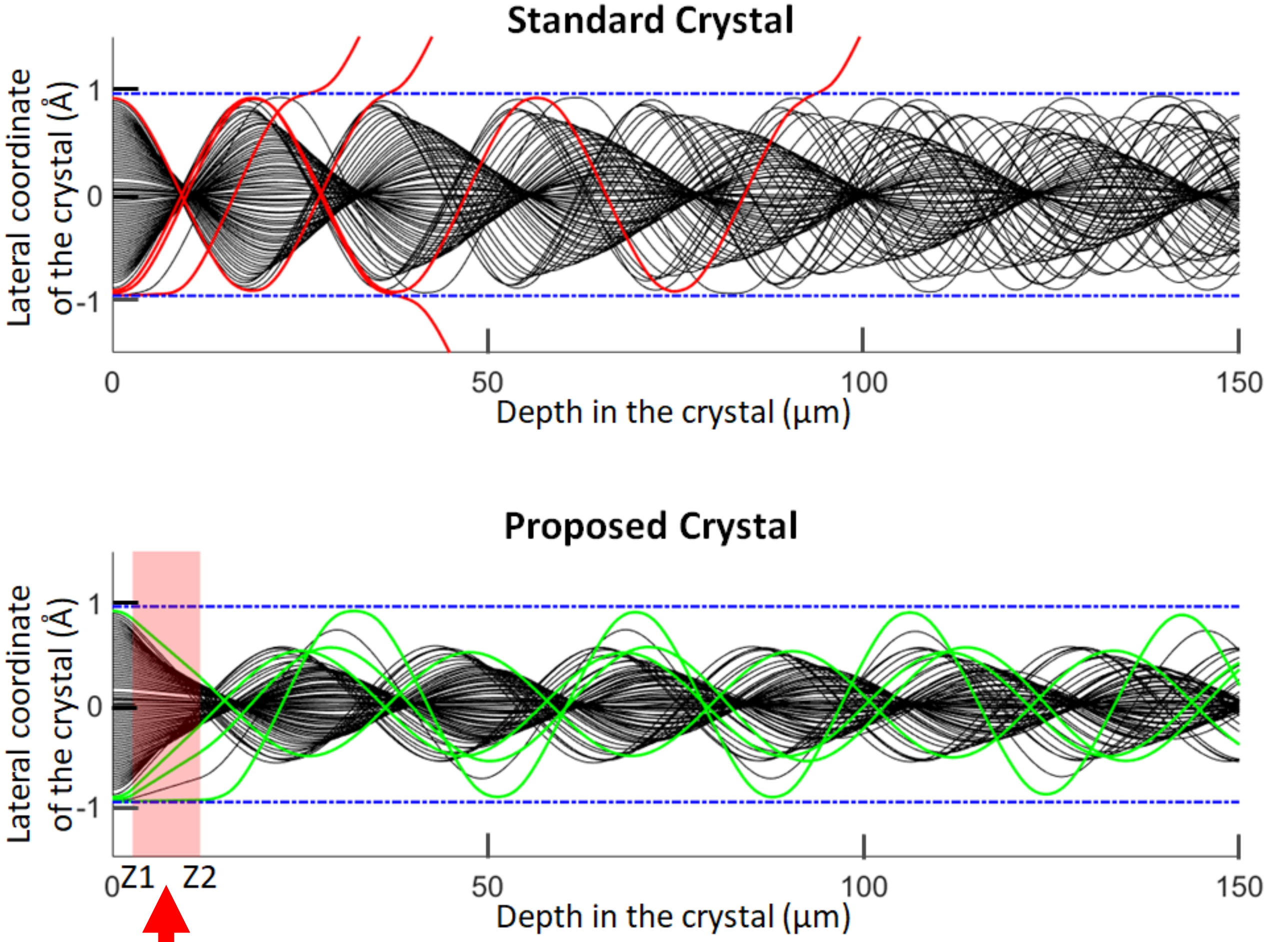
Channeling limit

- 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!

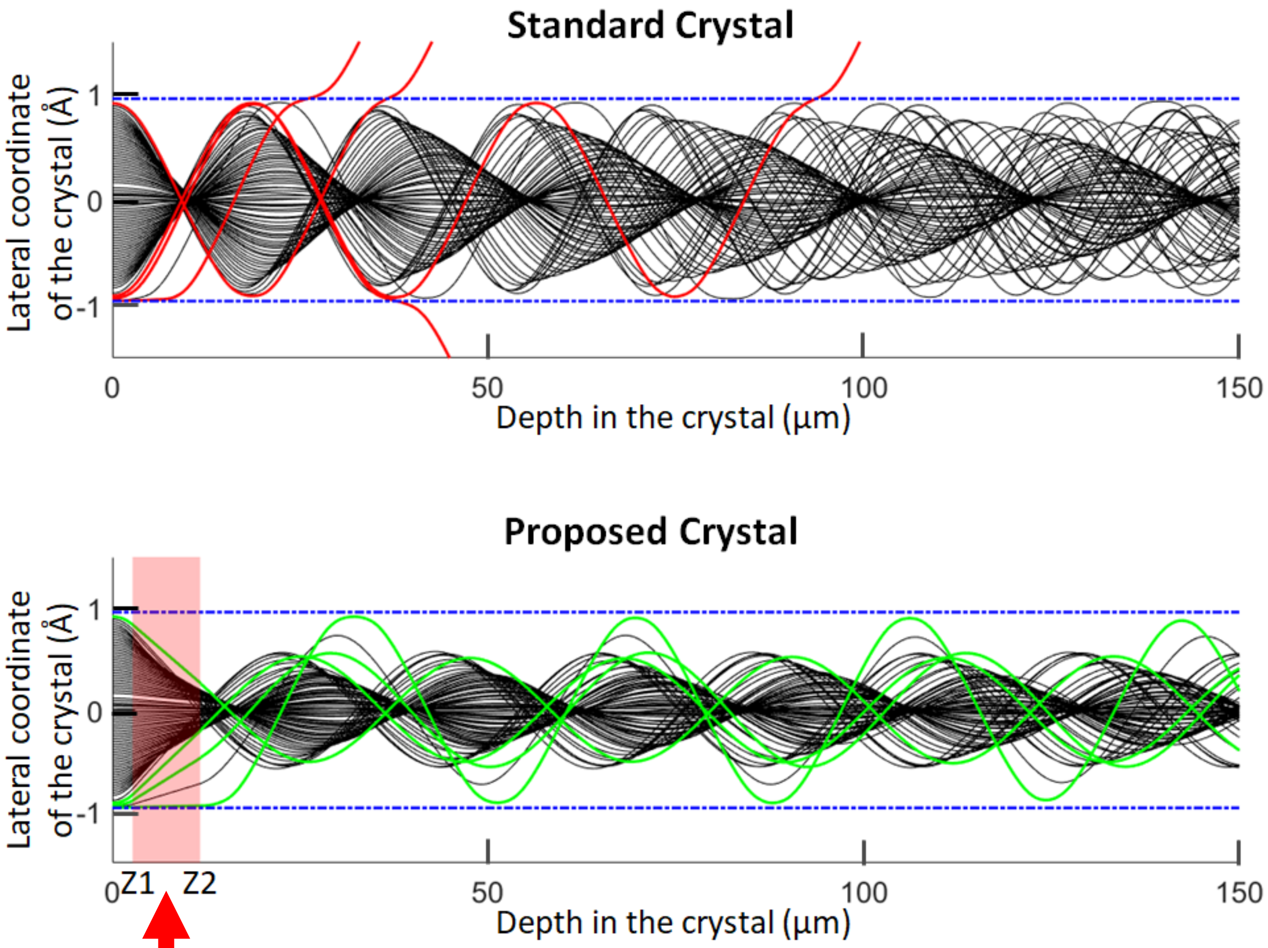
GALORE challenge: lens-assisted crystal

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

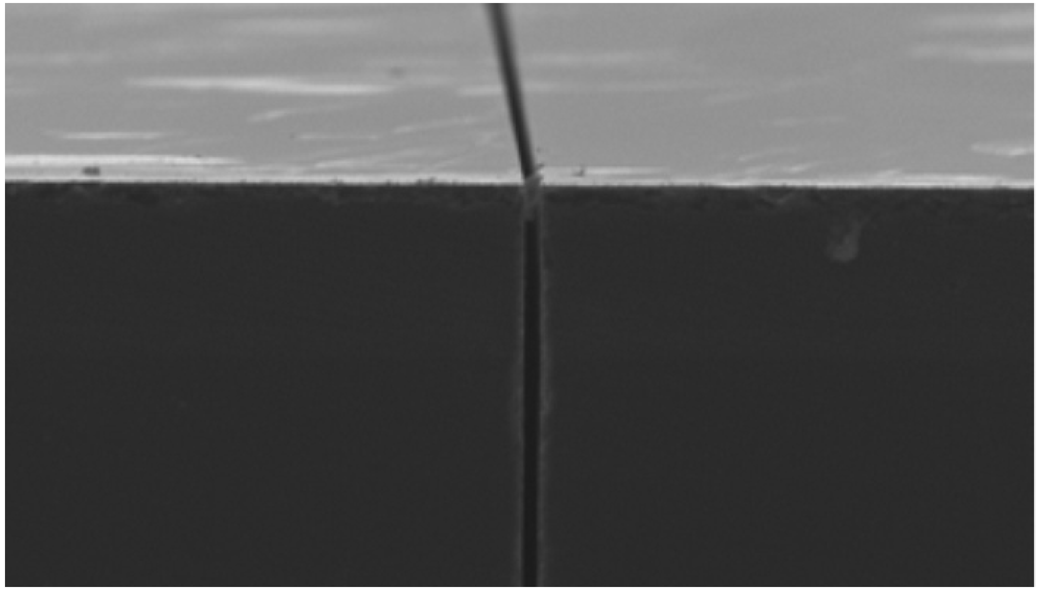


Interruption of crystal: empty region here!

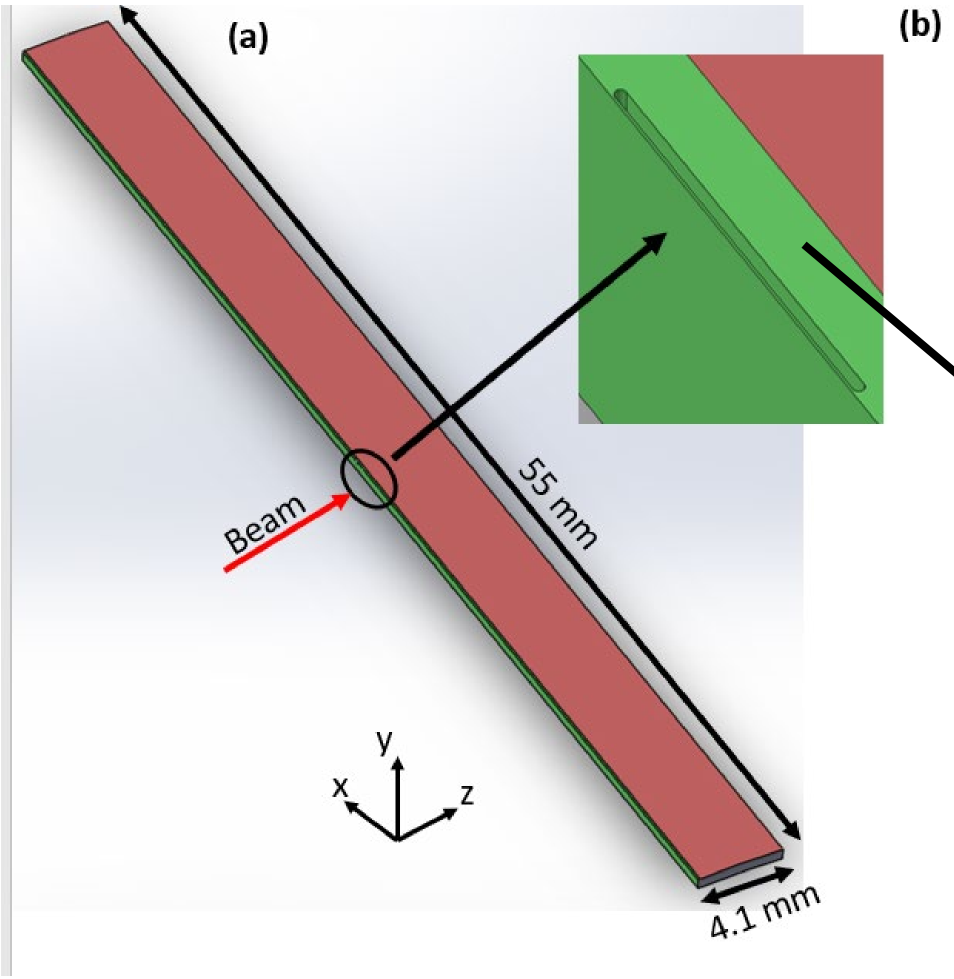
GALORE goals

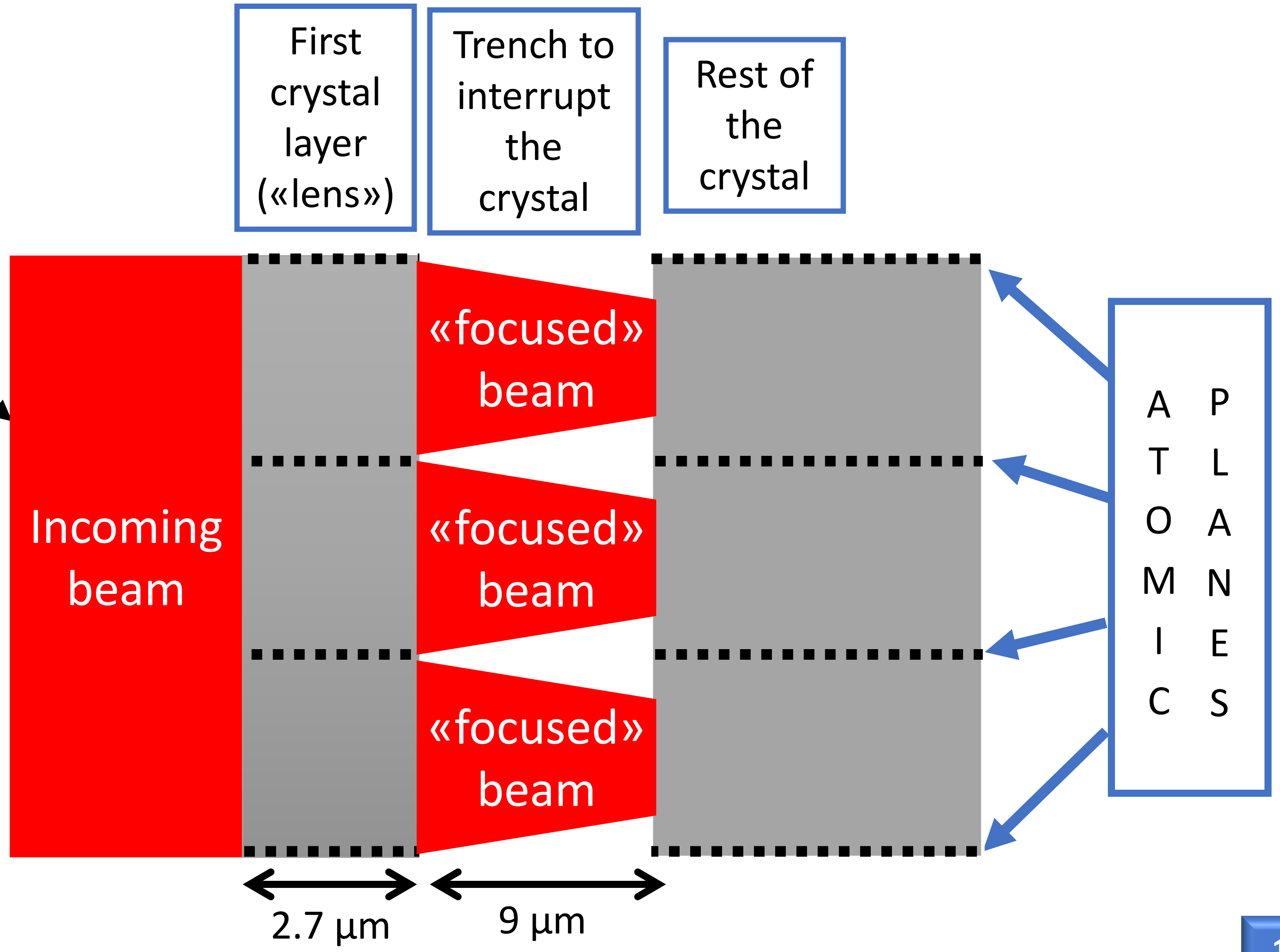
- ✓ To develop a **reliable procedure** to fabricate this type of bent crystals
- ✓ To manufacture and characterize a **first prototype**
- ✓ To **test** a first prototype with 180 GeV/c hadronic beam

Success of GALORE would prove the **feasibility** of this new design and unlock application for **wide energy range**



Schematic of GALORE prototype





State of the art

- Crystal sample maximum level of perfection:
  - Dislocation density >1/cm^2
  - Miscut <2 µrad (≈2 order magnitude reduction wrt standard)
- High standard for crystal quality stability and bending precision and stability **within few microradian** must be met for **operation in LHC**

Nominal «perfection» for crystal manufacturing has been reached!

"INFN KE4350/EN/HL-LHC" between INFN and CERN was signed: 4 *crystals collimators* have been already provided to CERN **by INFN Ferrara**

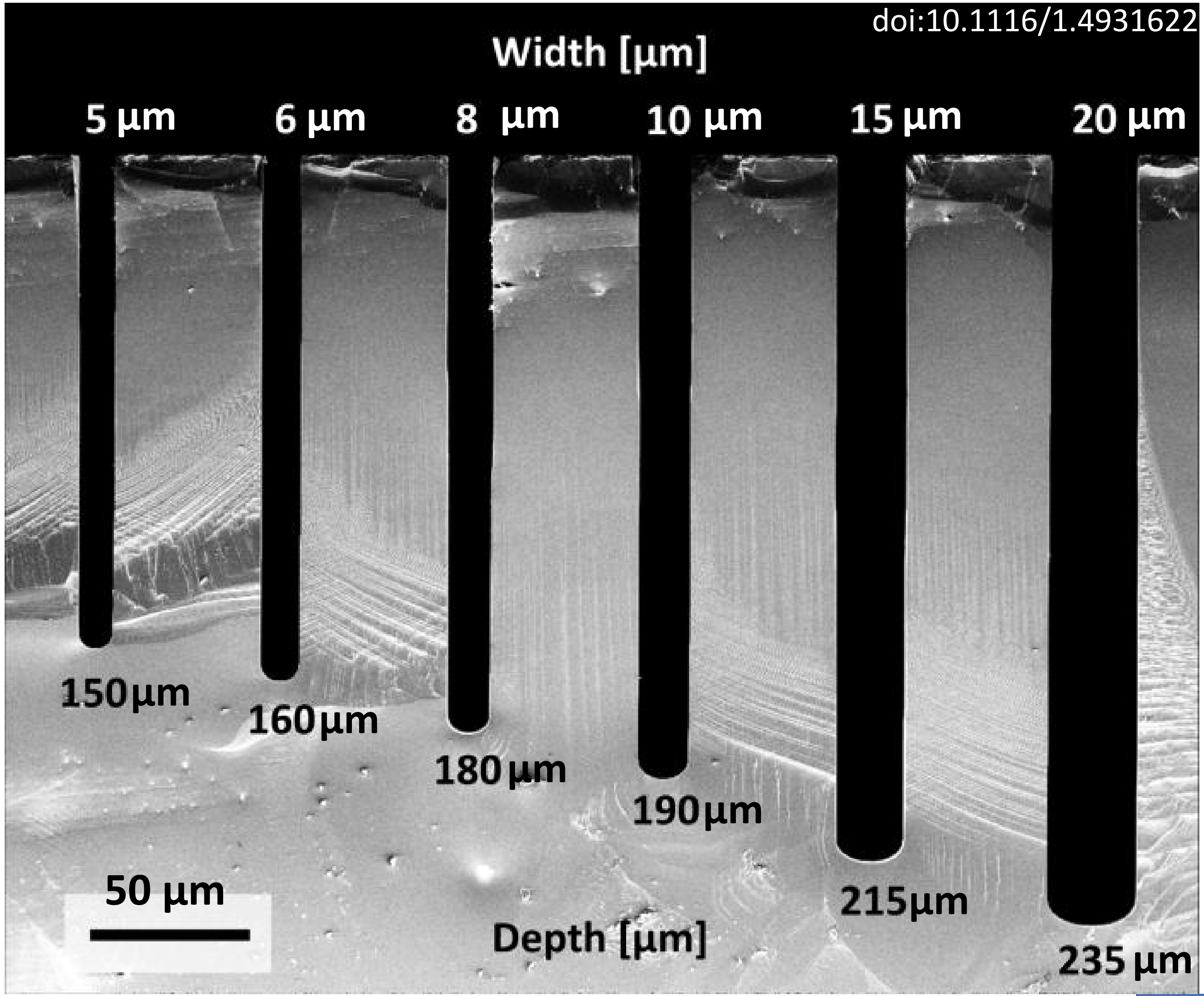
New techniques from semiconductors industry

Deep Reactive Ion Etching (DRIE)

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

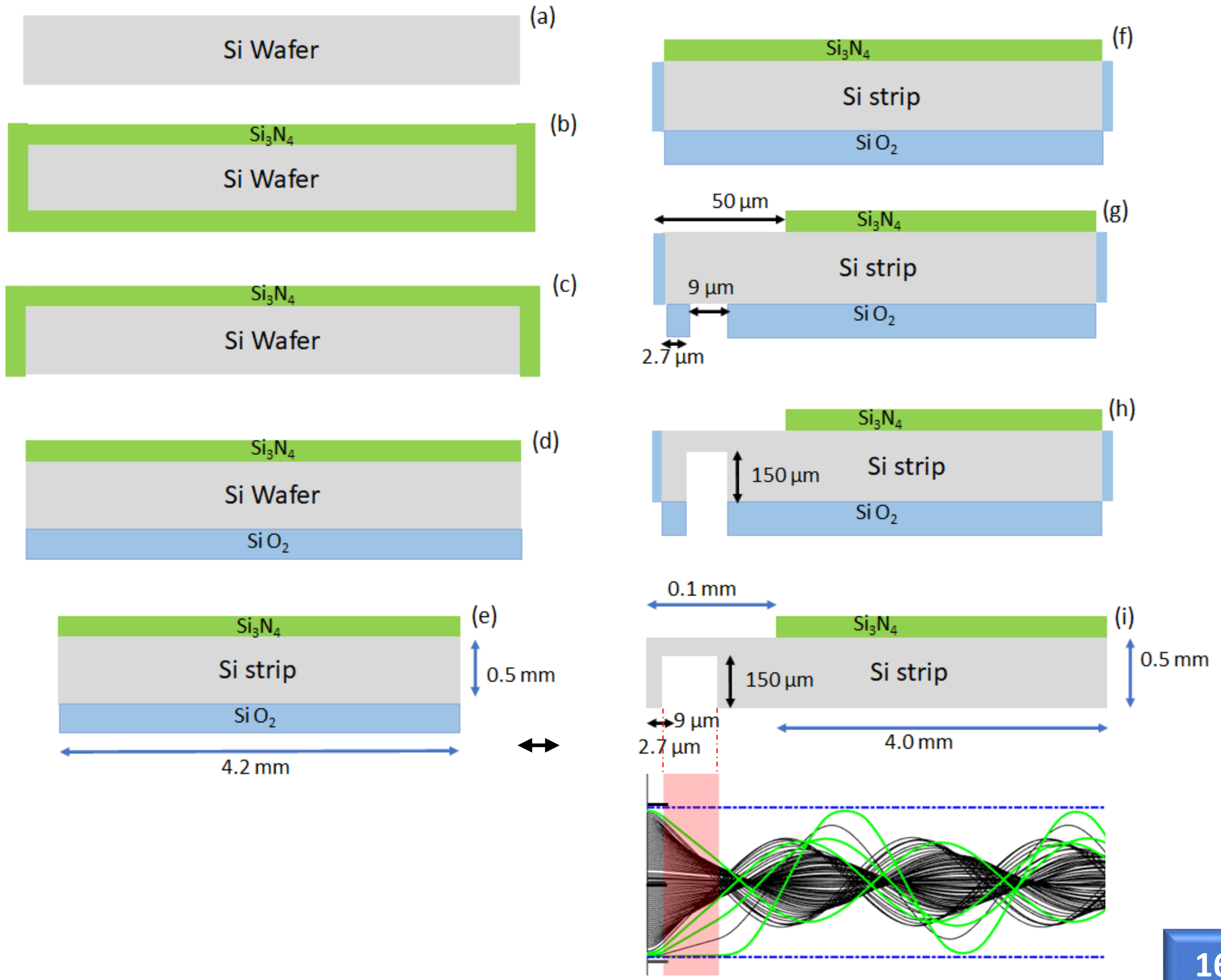
Silicon Nitride (Si_3N_4) film

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



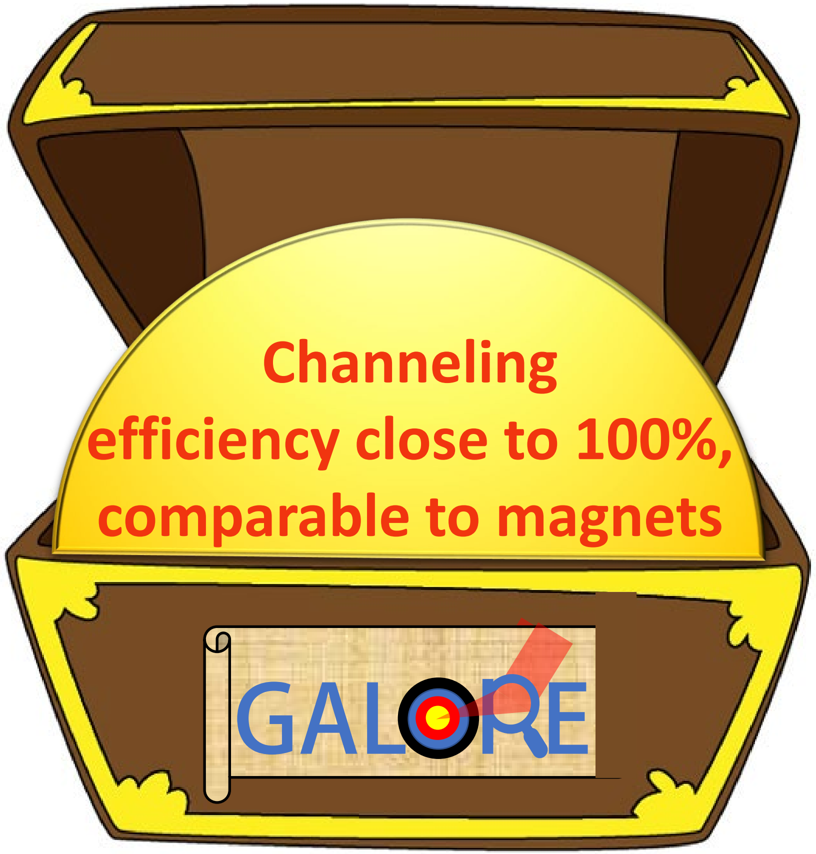
Methodology: GALORE & silicon micromachining

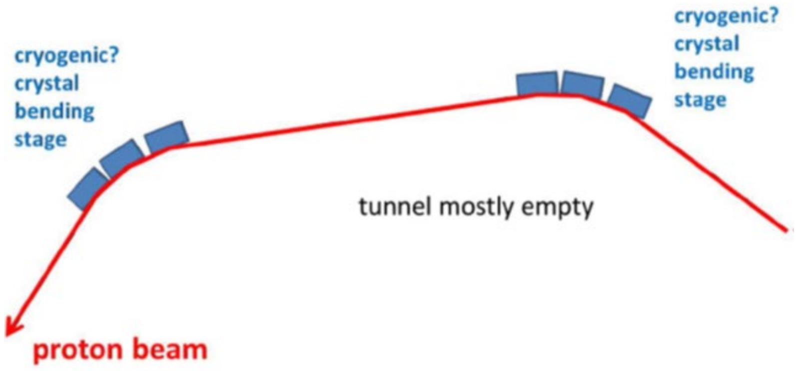
- **Bending** achieved by deposition of Si_3N_4 tensile film
- Si_3N_4 pattern leave flat area for channeling lens to help atomic planes **alignment**
- The channeling lens is obtained with **DRIE** by fabrication of micrometric **trench**



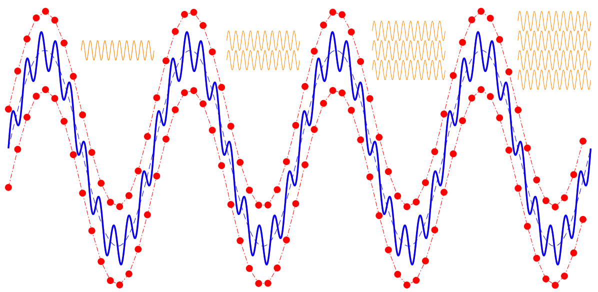
Immediate fruition in current crystal-based schemes (i.e., LHC ion collimation)

High efficient beam manipulation (i.e., extraction) in ALL accelerator's energy range





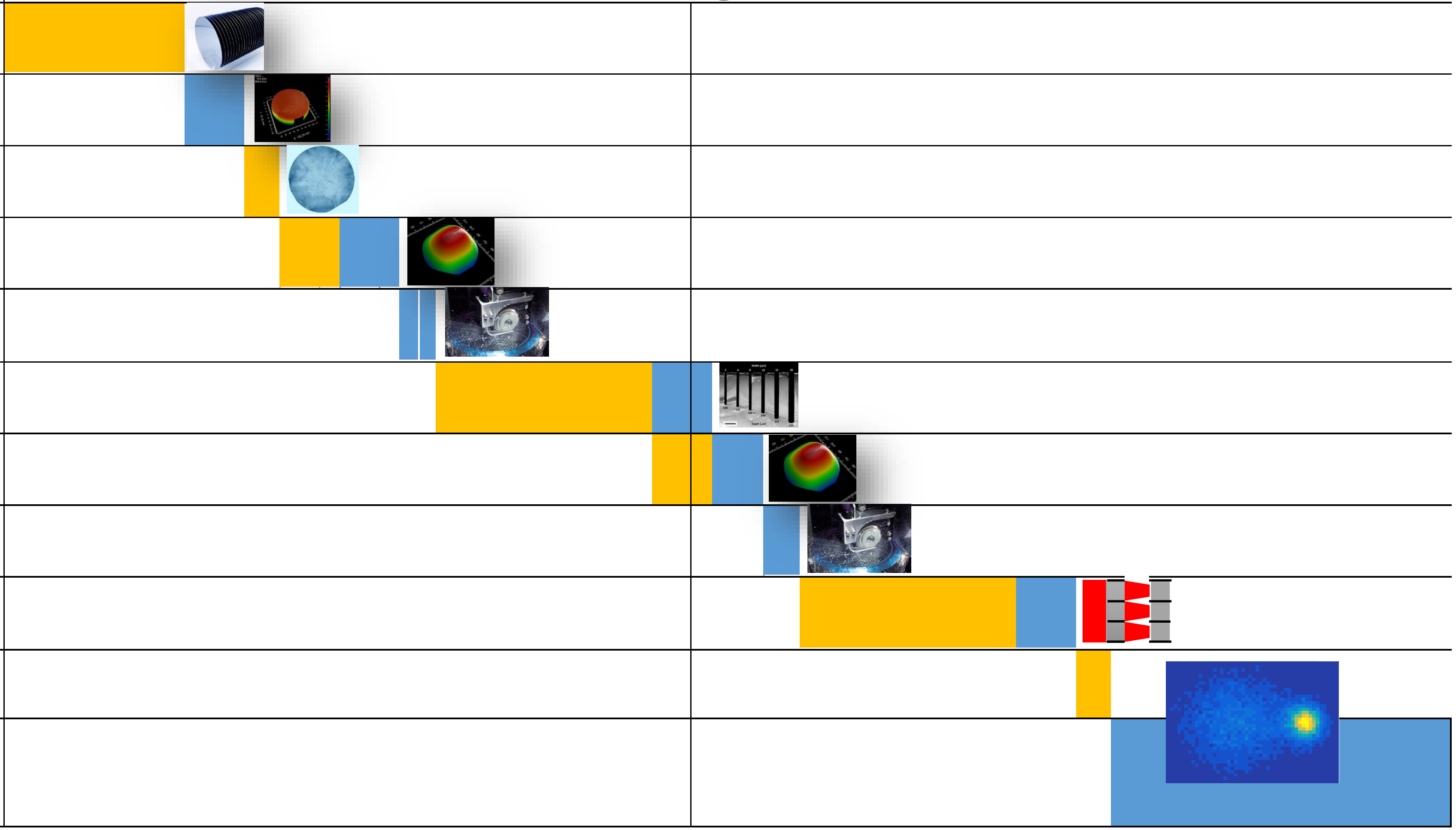
Enhanced features for crystal-based radiation sources (i.e., crystalline undulator)



Design of new crystal-based accelerators

Timeline

Task	Days	Progress
Supply of prime material	90	
Wafer characterization at INFN-Ferrara	30	
Wafer characterization at ESRF	15	
Coating with tensile films & stress characterization	60	
Shaping of the crystals to final sizes	15	
R&D DRIE setup and characterization	135	
Coating with tensile films & stress characterization	60	
Shaping of the crystals to final sizes	15	
Micro-lens fabrication and characterization	135	
Beam Test at CERN	15	
Writing of papers and dissemination of the results	150	



External facilities

INFN Laboratories

BUDGET

	Year 1	Year 2
Crystal Material + validation	9 k€	4 k€
Laboratory consumable	11 k€	11 k€
Film desposition	3 k€	3 k€
Sample dicing and lapping	7.5 k€	5.5 k€
Micrometric trench fabrication	20 k€	12 k€
Machine Upgrades	21 k€	23 k€
Beam Test	--	10 k€
Total	**71.5 k€**	**68.5 k€**

Research Team

Name	Unit	FTE	Expertise
Marco Romagnoni (PI)	INFN Ferrara	1	Bent crystal production & characterization
Andrea Mazzolari	INFN Ferrara	0.2	Bent crystal production & characterization
Laura Bandiera	INFN Ferrara	0.2	Channeling and data analysis expert
Vincenzo Guidi	INFN Ferrara	0.1	Crystal design
Mattia Soldani	INFN Ferrara	0.2	Testbeam & data analysis expert
Melissa Tamisari	INFN Ferrara	0.2	Bent crystal production & characterization
Francesco Sgarbossa (LR)	INFN Legnaro	0.4	RBS characterization
Davide De Salvador	INFN Legnaro	0.1	Crystal design and RBS characterization
Chiara Carraro	INFN Legnaro	0.1	RBS characterization

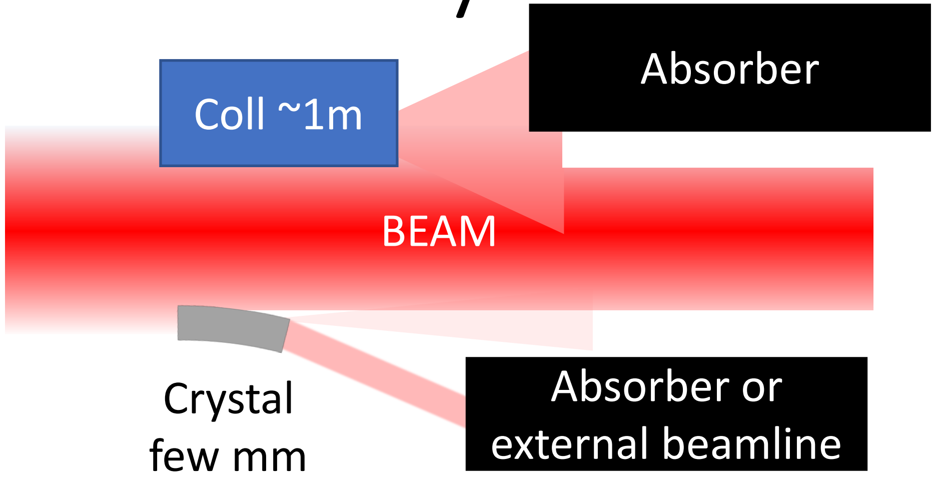
Team previous experiences with bent crystals

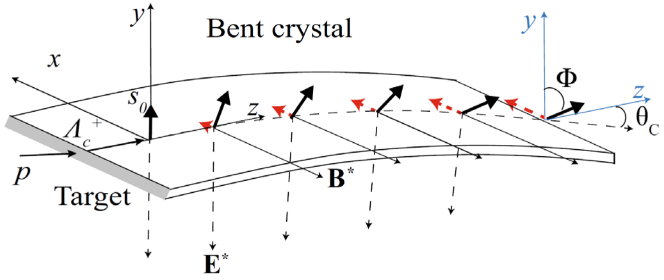
:Beam collimation

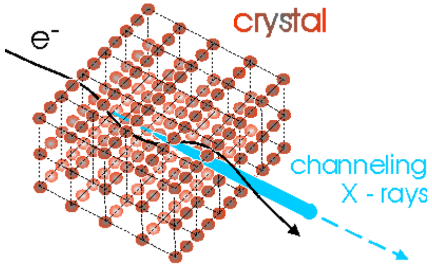
:Beam halo extraction

:Charmed baryons spin precession

:Novel radiation sources



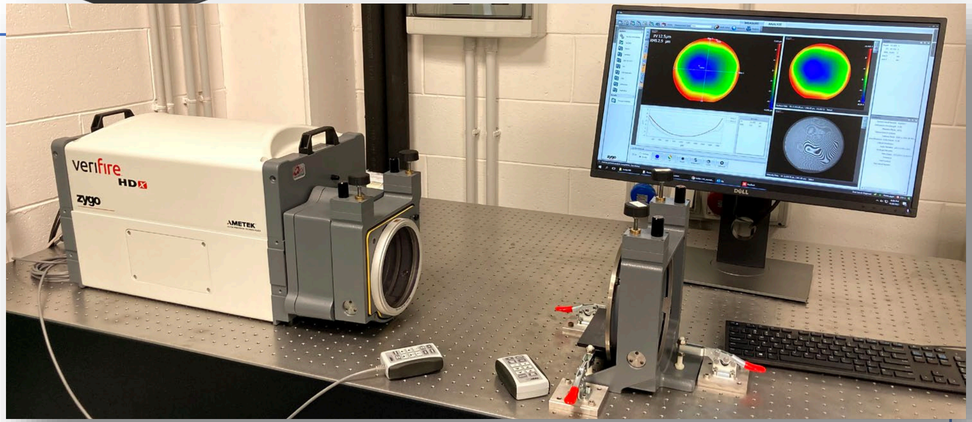




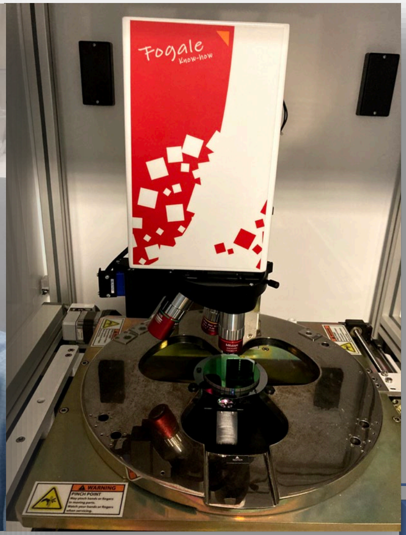
(300 MeV/c → 855 MeV/c MAMI) (6 GeV/c DESY.) (9 GeV/c → 20.5 GeV/c SLAC) (30 GeV/c → 6500 GeV/c CERN)

INFN Laboratories in Ferrara

- Optical interferometry laboratories for nanometric morphological characterizations

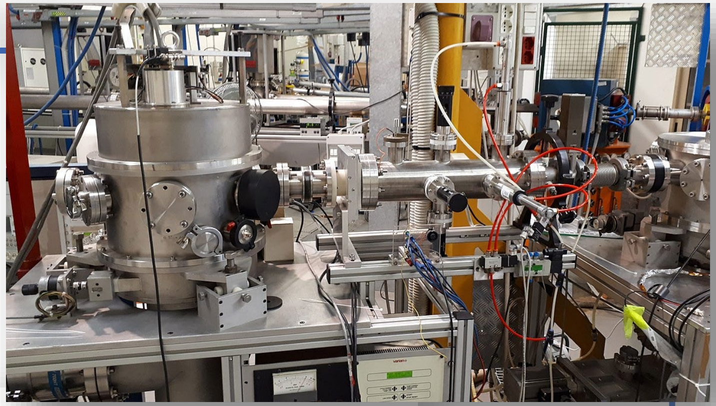


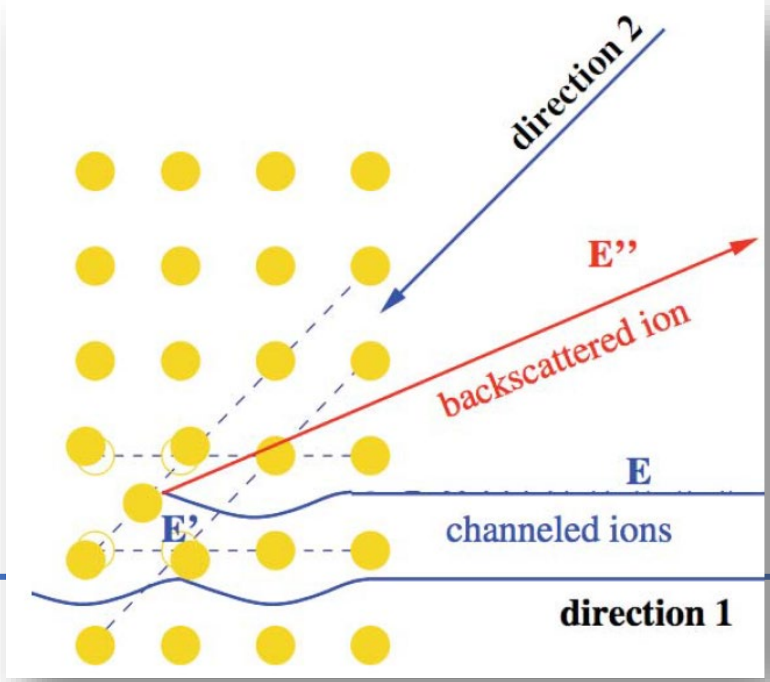
- High-precision automated dicing station
- Clean Rooms
  - Chemical laboratories for cleaning samples
  - High resolution X-rays diffractometry
  - IR interferometry

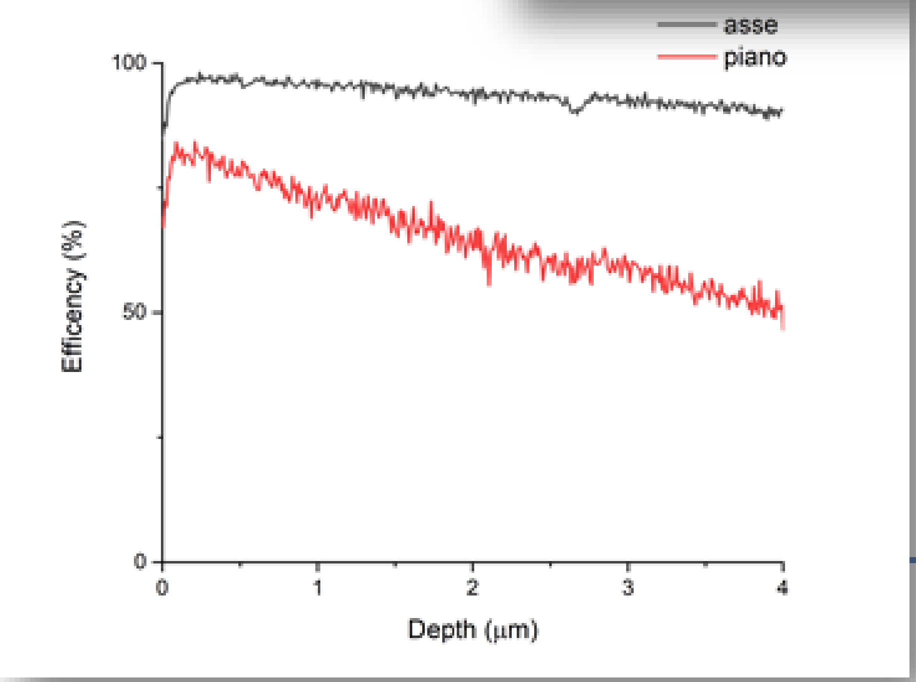


INFN laboratory in Legnaro

AN2000 accelerator for **Rutherforth Backscattering** characterizations:
test of 2 MeV proton channeling after silicon machining processes







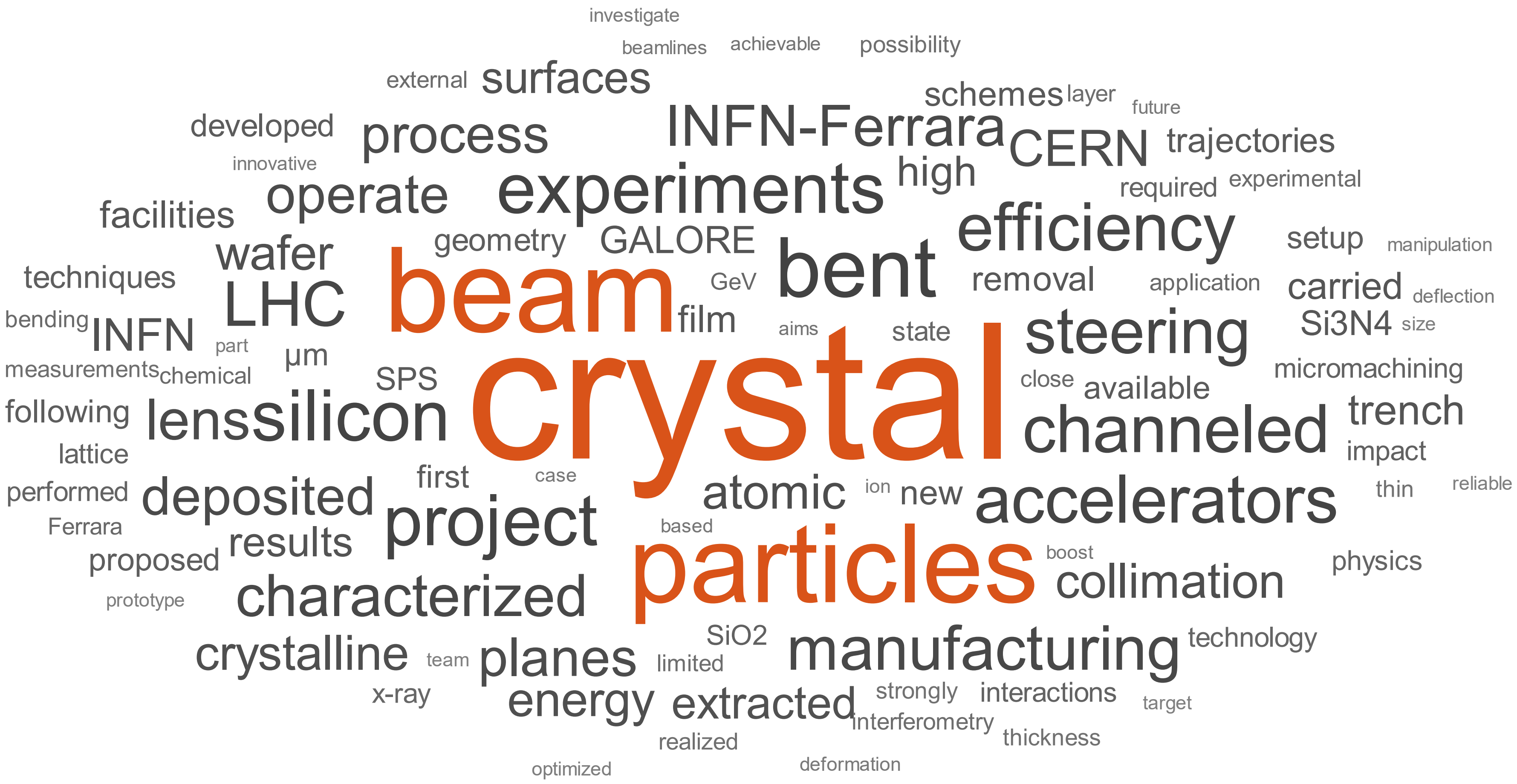
GALORE

External Facilities

Conclusions

- Planar channeling in bent crystal is a powerful tool for numerous applications in a wide energy range of accelerators
- Maximum channeling efficiency is limited by scattering with nuclei at the entrance of the crystal
- GALORE propose to test a new design for bent crystal which suppresses such limitation
- The results of GALORE can impact on any channeling-based application and unlock novel crystal-based technology in particle accelerators

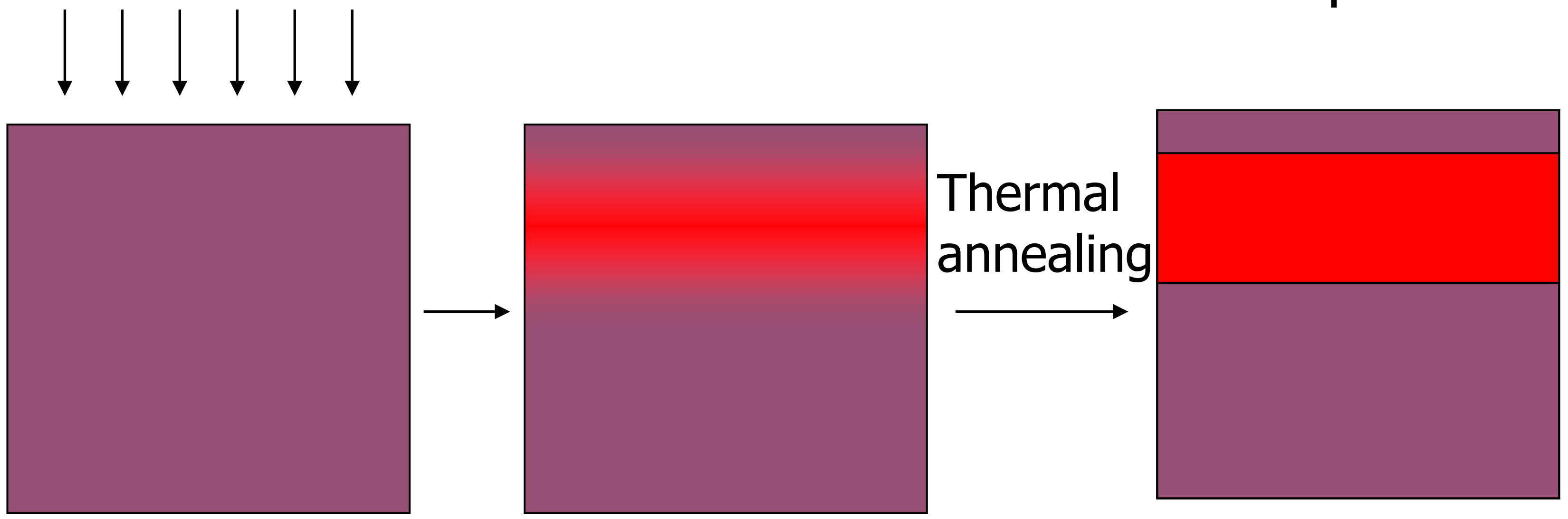
THANK YOU FOR YOUR ATTENTION !



SIMOX structure I

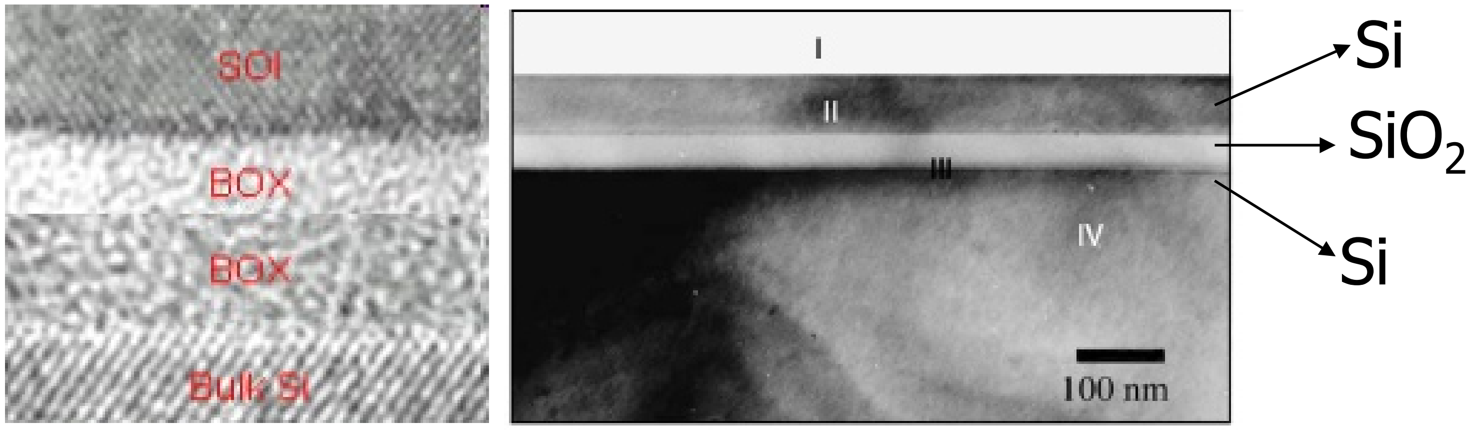
Substrate heated at 650 °C and oxygen ions implantation

Thermal anneling at 1320 °C in O_2/Ar atmosphere



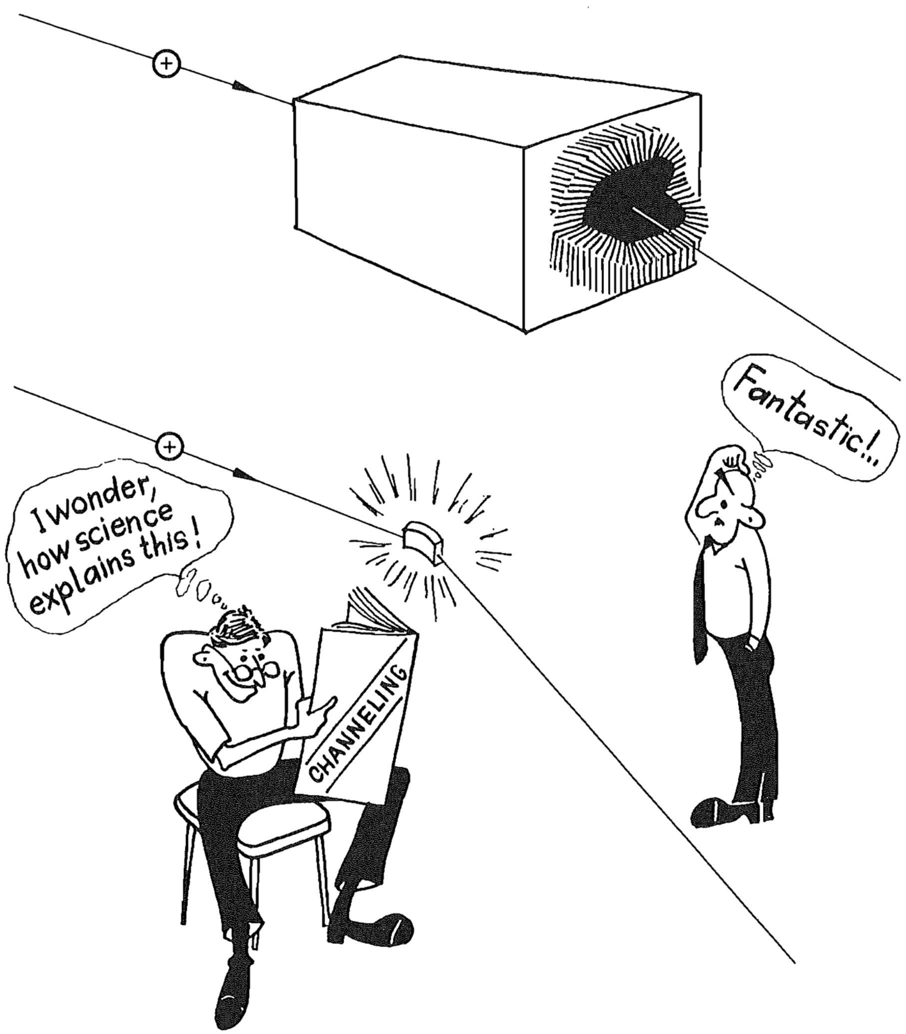
SIMOX structure II

Implementation of the method of the cut through a buried SiO_2 layer.



- Thermal annealing restores silicon cristalline quality and creates a buried SiO_2 layer.
- Interfaces between Si and SiO_2 are well terminated.
- Misalignment between silicon layers in available SIMOX structures: less than 0.7 Å/mm

CHANNELING in bent crystals

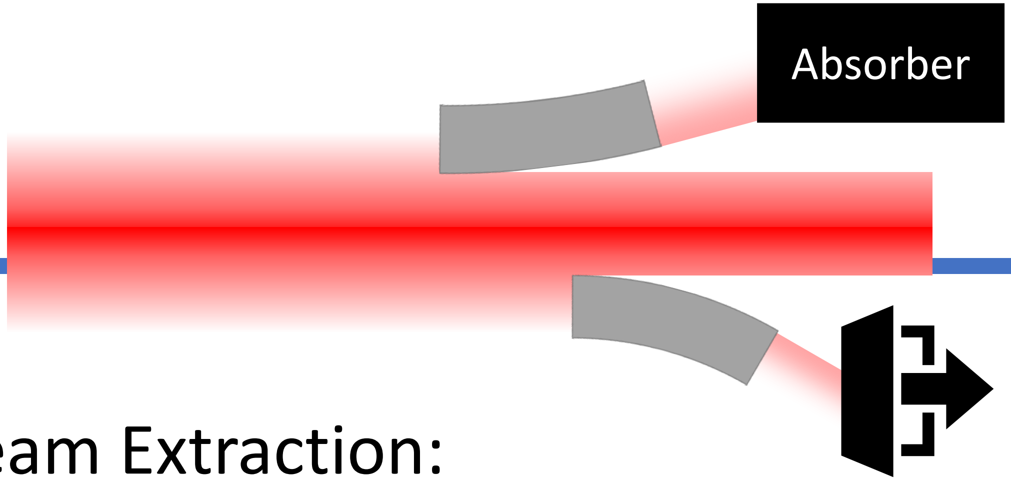


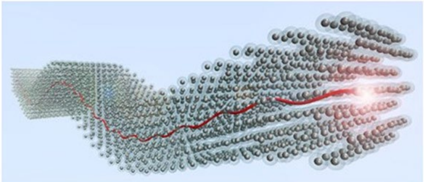
Particle	Energy	Deflection	Thickness	Field of equivalent dipole
Ions / protons	6500 GeV	50 μrad	4 mm	216 T
Electrons	0.855 GeV	1500 μrad	0.015 mm	285 T
Positrons	20.53 GeV	400 μrad	0.060 mm	456 T
Charmed Baryons	2000 GeV	14000 μrad	70 mm	1134 T

Channeling applications…with GALORE

Beam Collimation:
reduced inelastic scattering

Novel radiation sources:
reduced background





Beam Extraction:
higher flux delivery

Spin precession:
increased channeling efficiency