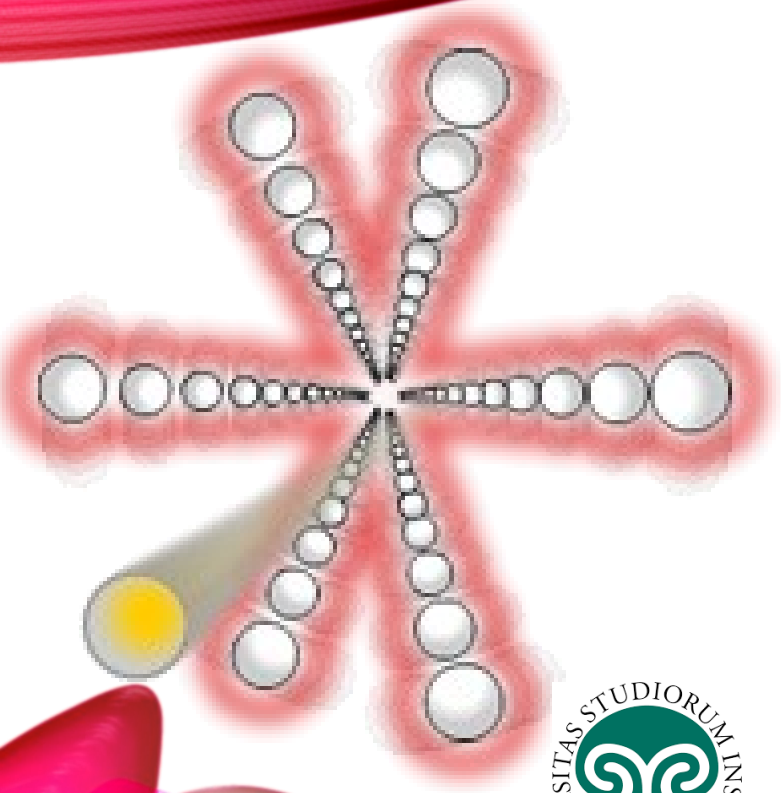
10th International Conference Charged & Neutral Particles Channeling Phenomena, 11th Sept, Riccione, Italy



ENHANCING PLANAR CHANNELING EFFICIENCY: FINAL RESULTS FROM THE GALORE PROJECT

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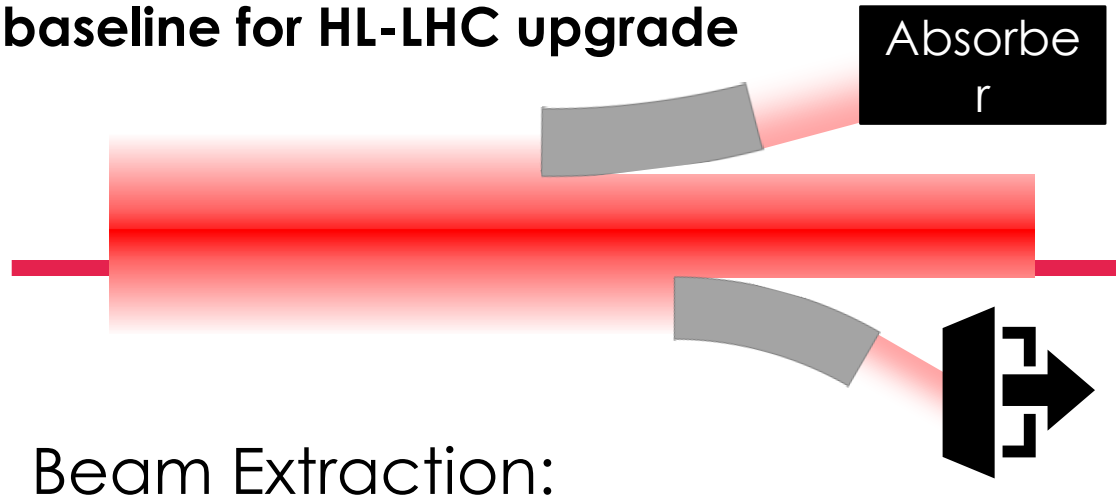
OVERVIEW

- Introduction to the GALORE project
- 2022 activities
- 2023 activities
- Testbeam and final results
- Conclusion

PLANAR CHANNELING APPLICATIONS WITH BENT CRYSTALS

Beam Collimation:

With crystal high control of beam halo separation from primary beam, **now baseline for HL-LHC upgrade**

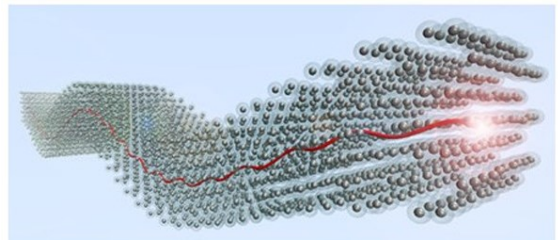


Beam Extraction:

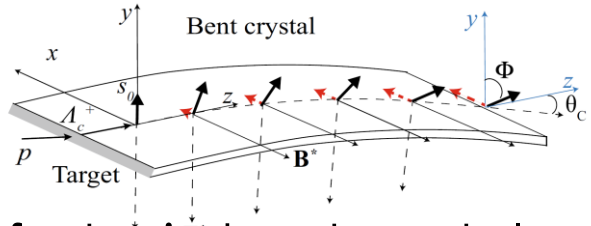
Surgical redirection of a beam portion, towards a precise location in the machine or in an external facility

Novel radiation sources:

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



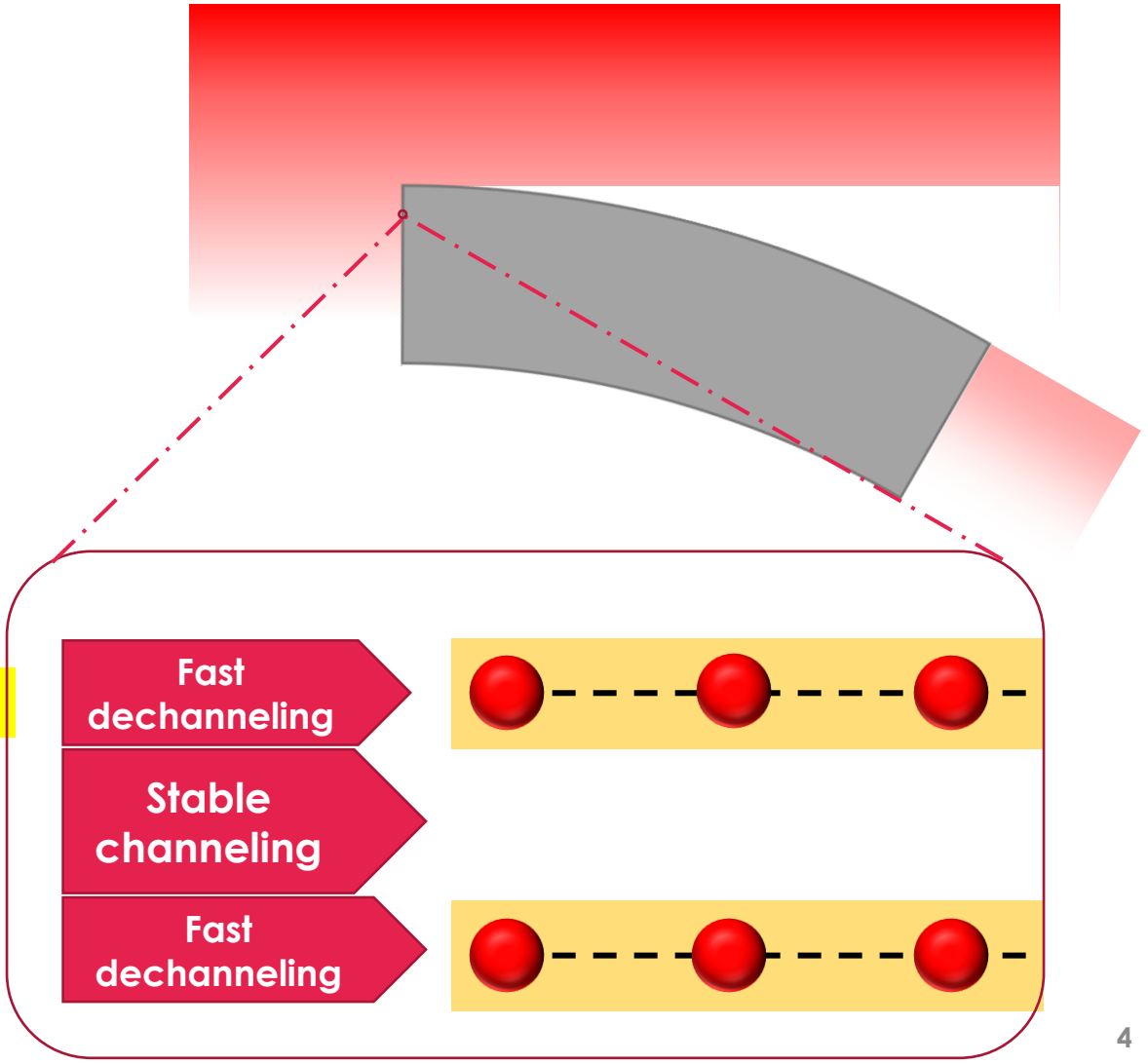
Spin precession:



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

PLANAR CHANNELING LIMIT

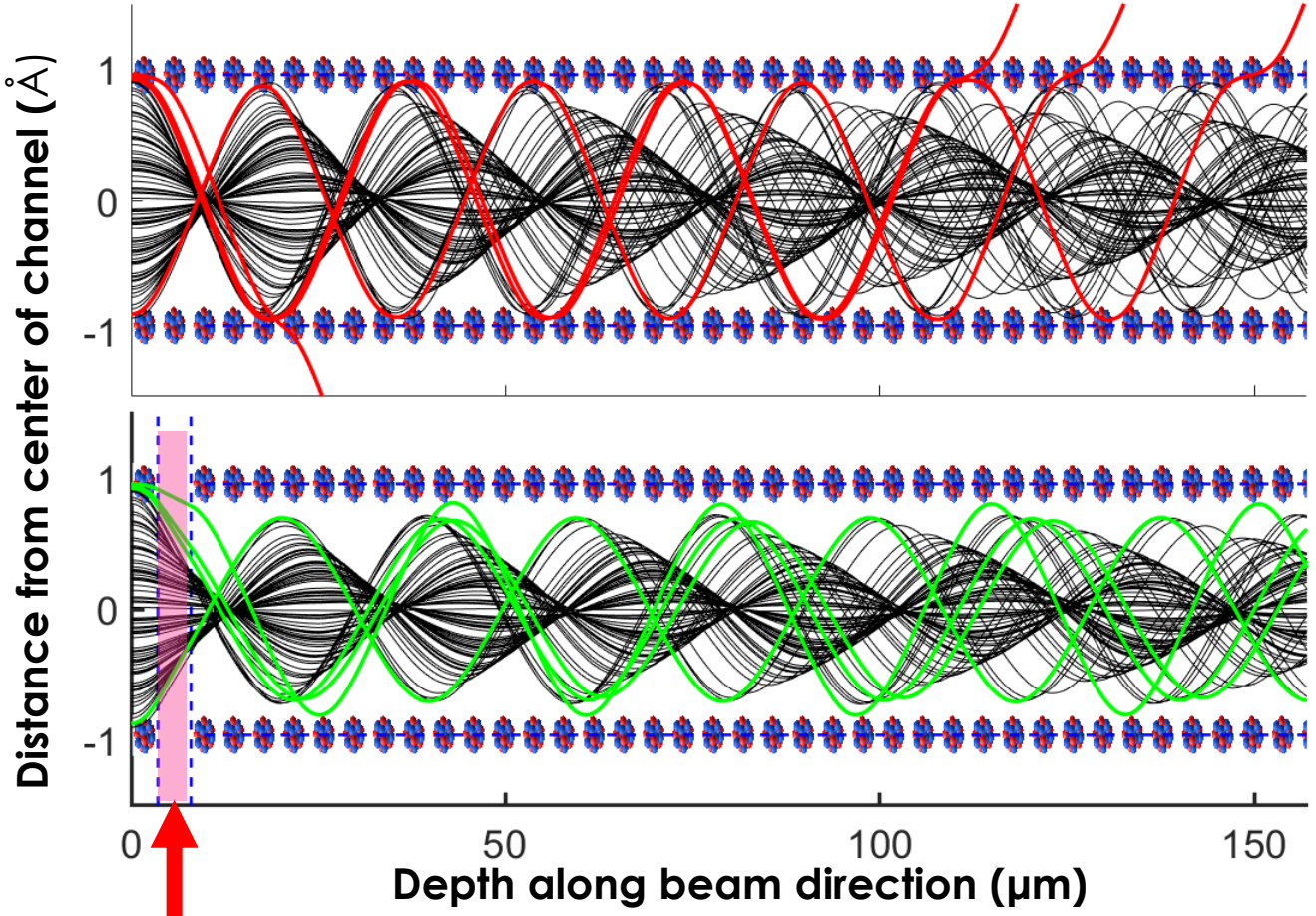
- Scattering with nuclei **quickly remove** particles from channeling
- Rate of nuclear dechanneling is strongly dependent on **impact parameter** on the interplanar channel
- The fraction of the beam impacting close to atomic planes is **not deflected**: hard-limit for channeling efficiency set at ≈80%



THE GALORE PROJECT

CSN5 Ricerca Tecnologica

- **Before** nuclear dechanneling can occur, the crystal is **interrupted**
- The channeled particles continue to travel in straight line, are «**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: **possible deflection efficiency >99%**



Interruption of crystal: empty region here!

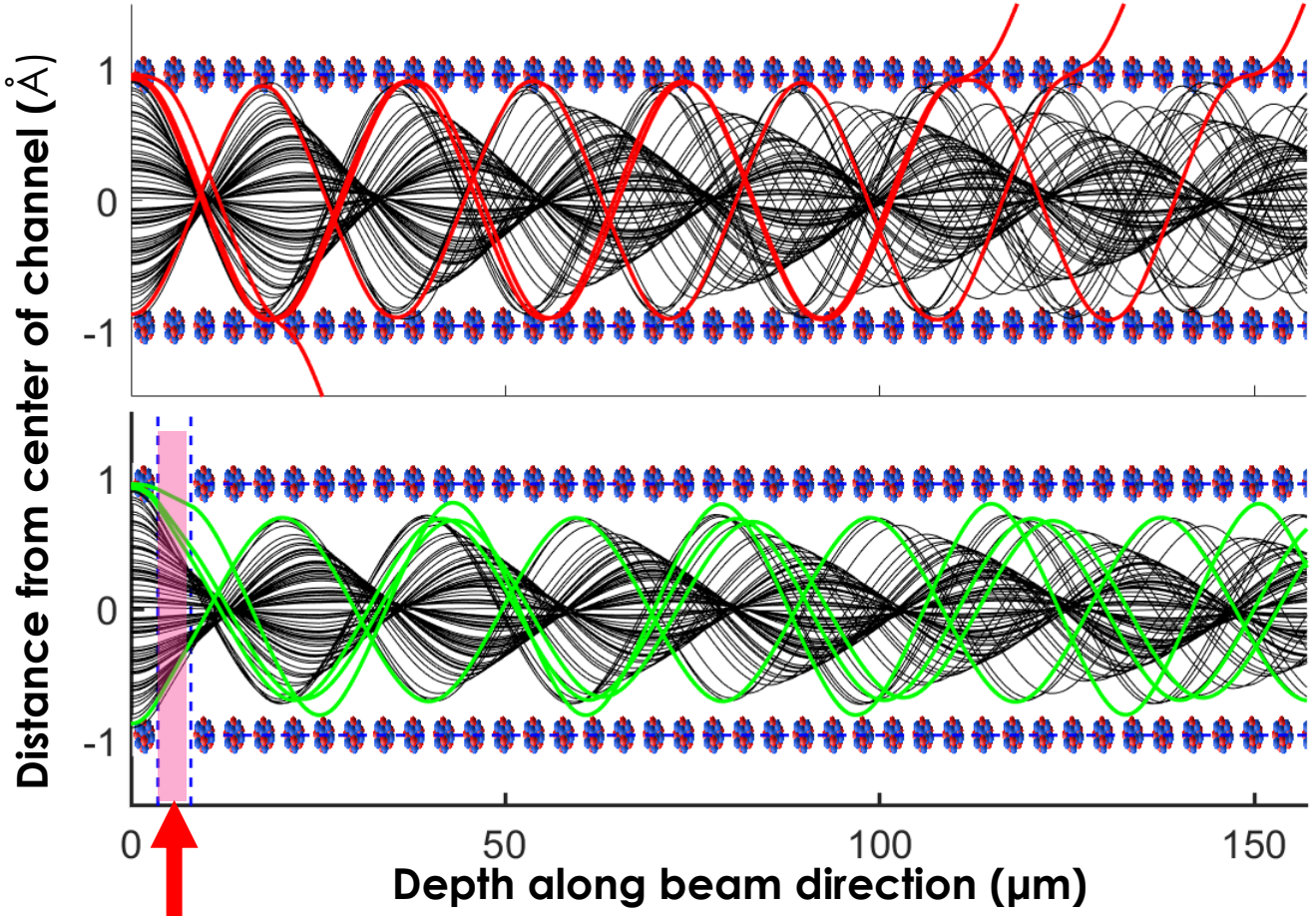
THE GALORE PROJECT

The phenomena was **first conceived and fully explained theoretically by V.V. Tikhomirov**

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

BUT

Since publication in 2007 **no prototype produced nor** experimental test has been performed :
technological challenge!

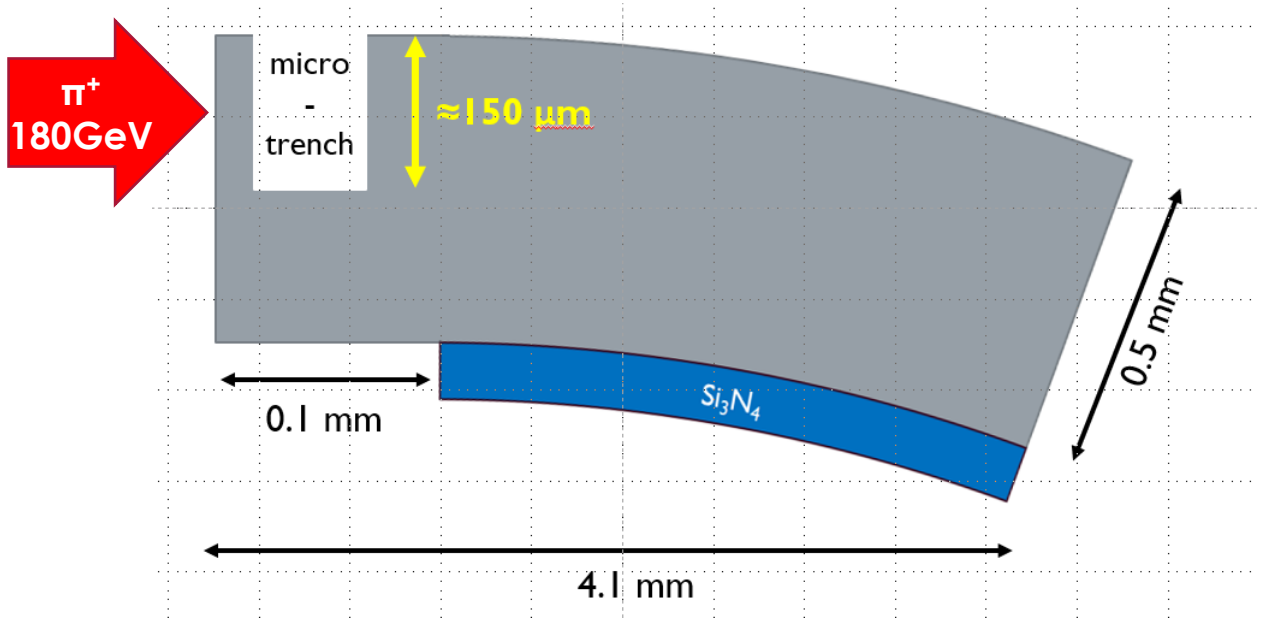


Interruption of crystal: empty region here!

THE GALORE PROJECT

CSN5 Ricerca Tecnologica

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



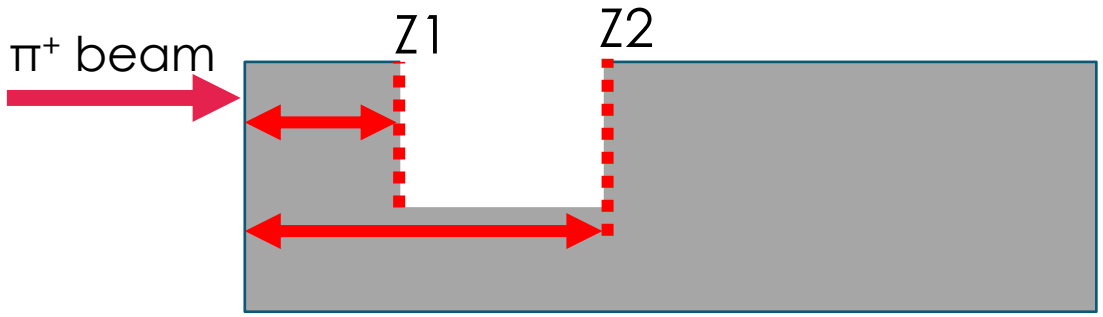
Obtain a new technology for beam manipulation in accelerators compact and powerful like state-of-the-art bent crystals and close to 100% deflection efficiency

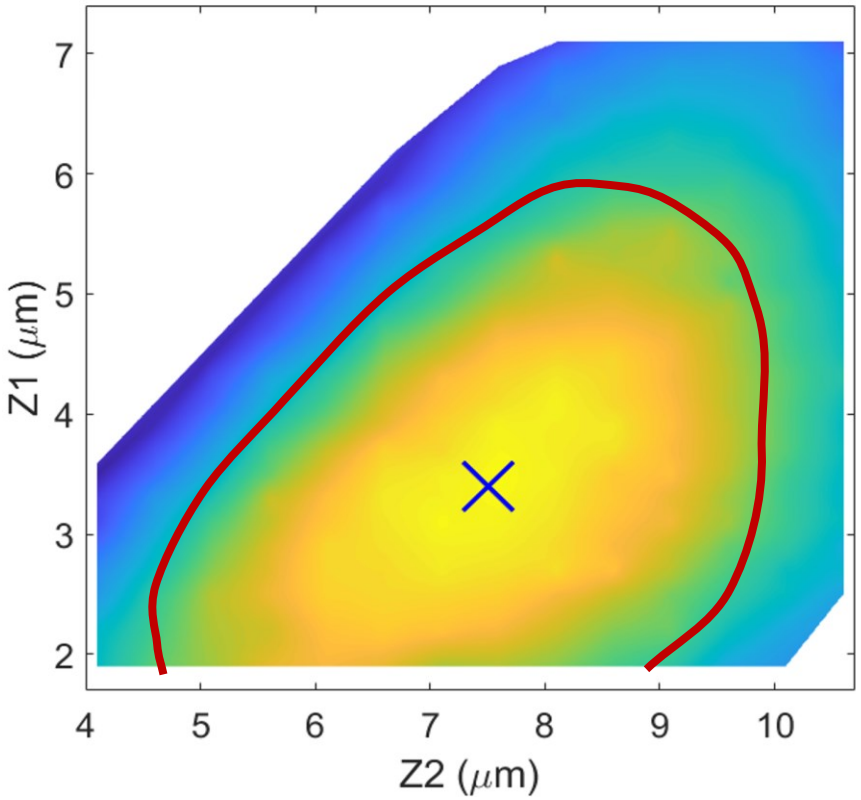
FIRST YEAR OF PROJECT

1. Design of optimal geometry via MC simulations
2. Verify prime material suitable for high-energy channeling experiment
3. Realize the bent crystal via an innovative bending method based on tensile film deposition
4. Realization of the micro-trench (“crystal cut”) using Deep Reactive Ion Etching

SIMULATION FOR

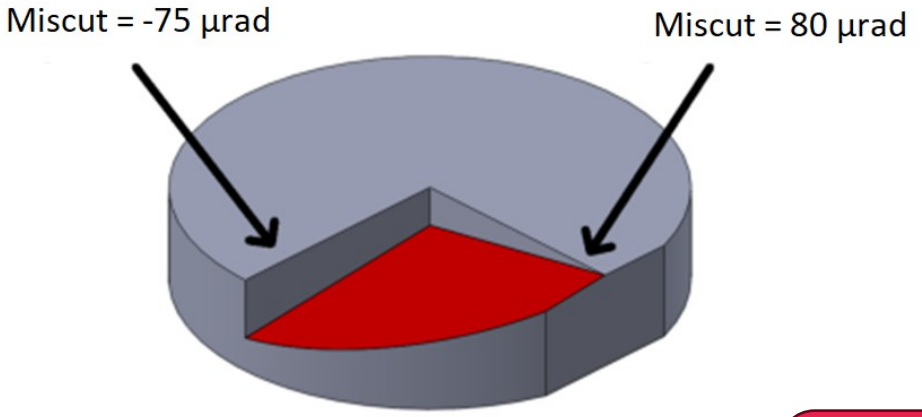
- Collaboration with Marie Curie IF TRILLION project (A. Sytov)
- Simulation of 180 GeV pions for several start and end positions (Z1,Z2) of micro-trench
- Best position for deflection efficiency enhancement z1=3.4μm, z2=7.5μm



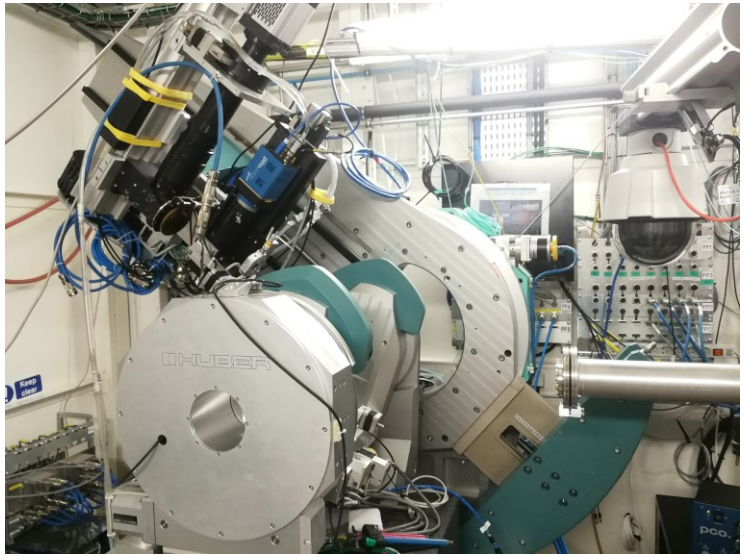


PRIME MATERIAL QUALITY

- Measure of wafer orientation with microradian precision have been verified with XRD
- BM05 topography have been carried out at ESRF



ESRF



High quality confirmed

TECHNIQUES

Silicon Nitride (Si_3N_4) film

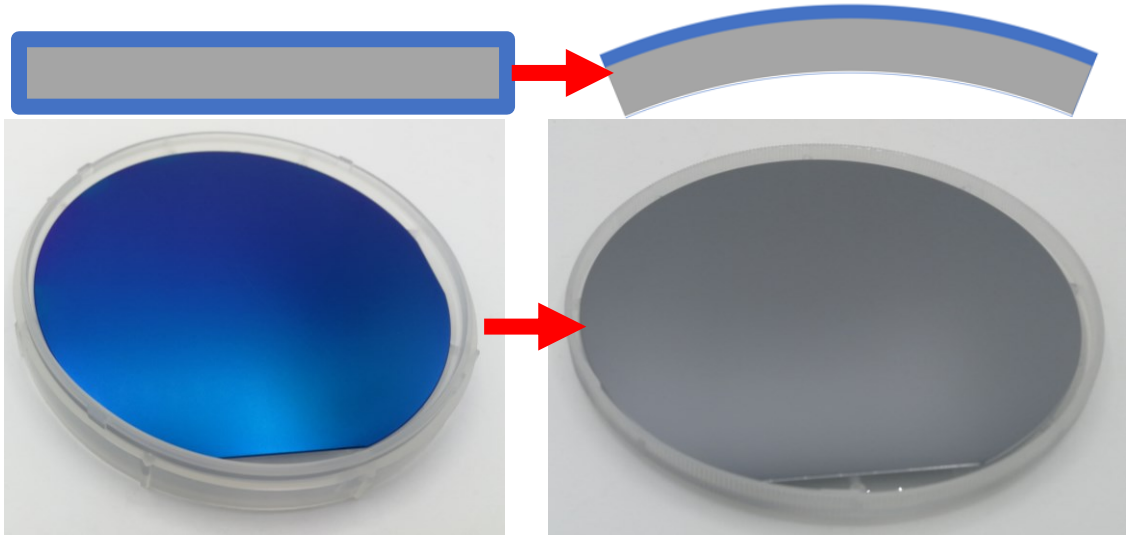
- High adhesion to silicon
- Nanometric precision of film thickness
- Highly patternable with sub-micrometric precision

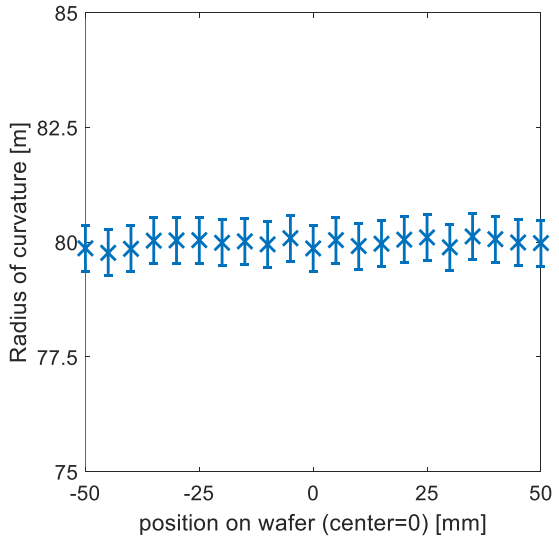
Deep Reactive Ion Etching (DRIE)

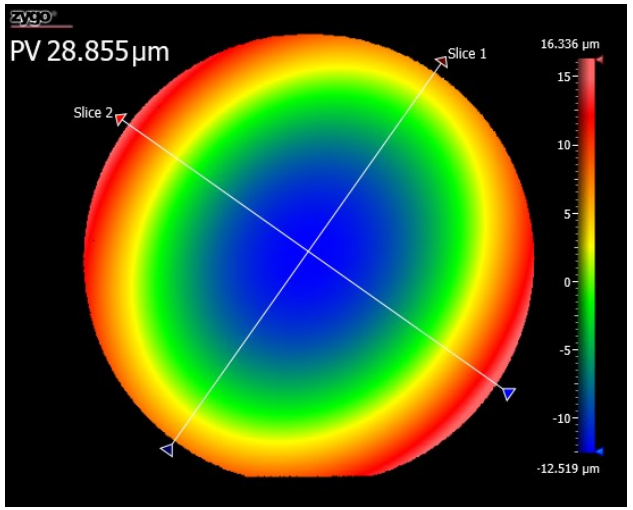
- High spatial precision
- Vertical walls with high aspect ratio
- Chemical removal of material: no damage / stress on crystal

Si_3N_4 BENDING

- Si_3N_4 film is deposited at high temperature on wafer
- Once cooled, different thermal contraction cause stress between film and substrate
- Once film is removed from one side, the stress induce bending of crystal
- Curvature verification:
  - in 2d surface profile with laser interferometer with nanometric precision
  - Direct measure of lattice plane curvature with x-rays diffraction techniques

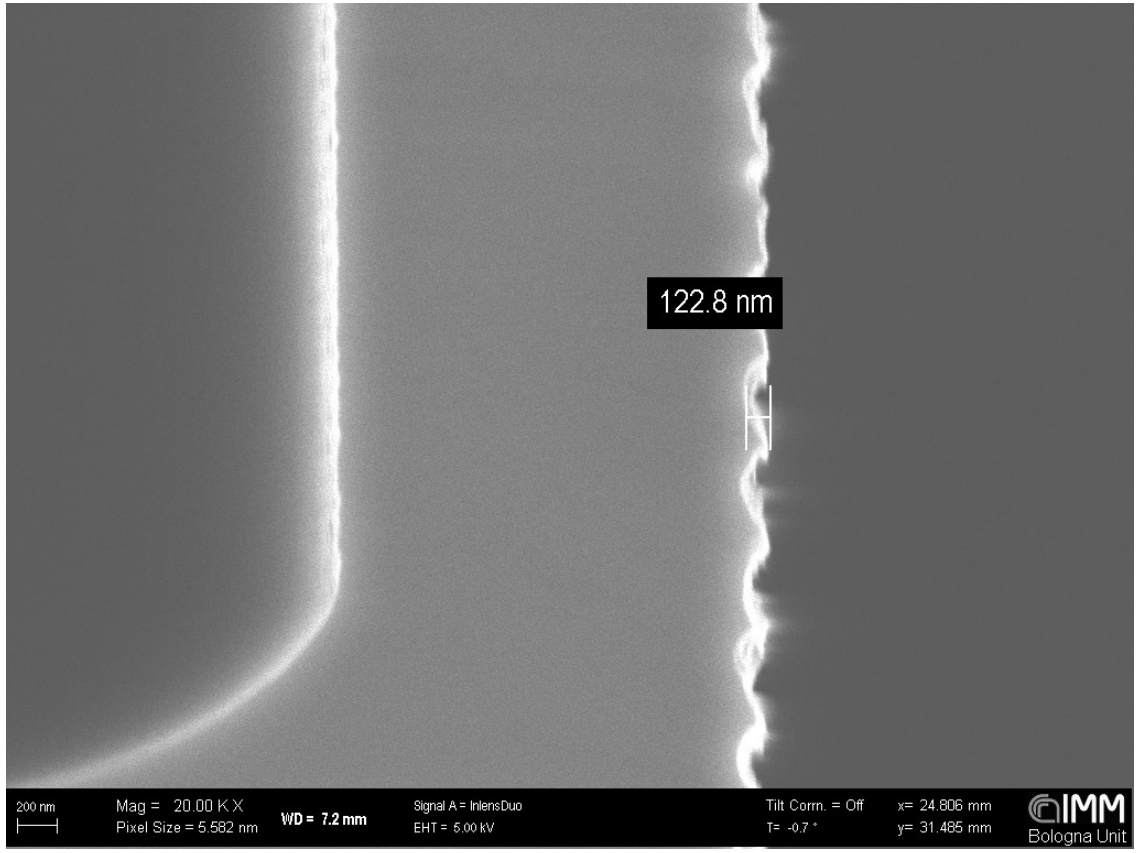




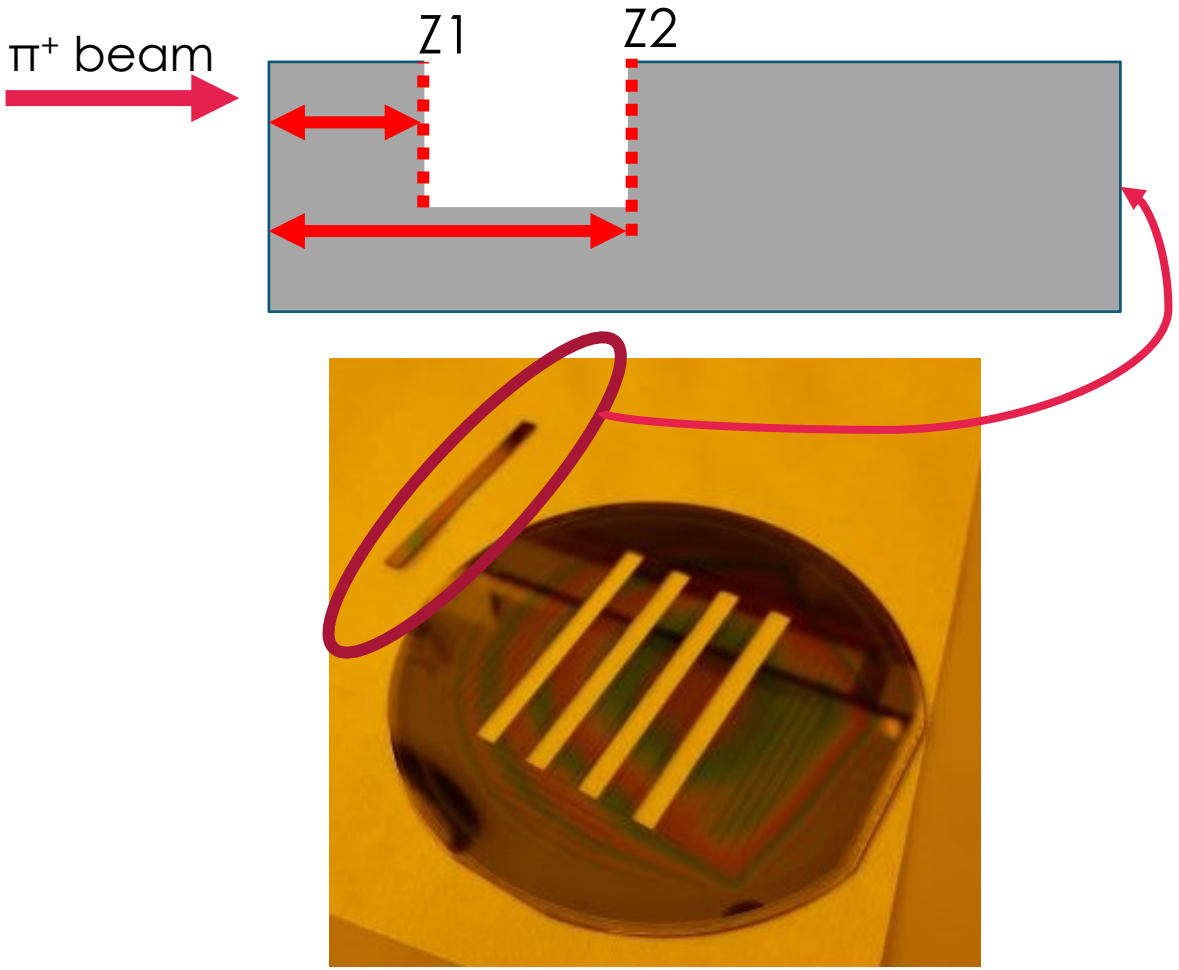


DEEP REACTIVE ION ETCHING (DRIE)

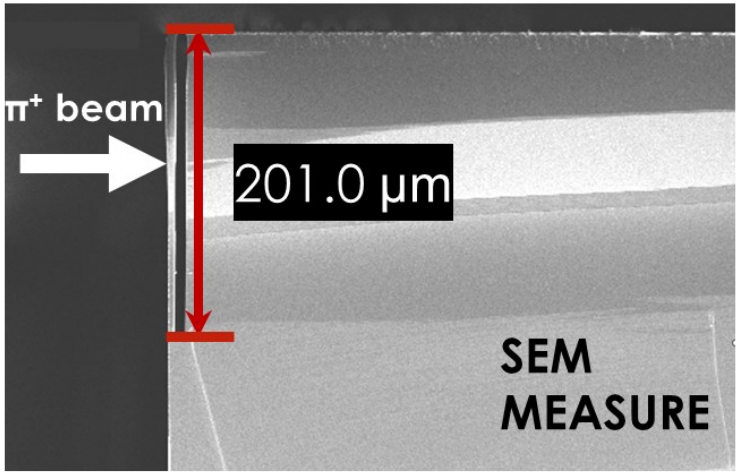
- **Deep reactive ion etching (DRIE)** is a technology which enable to etch into silicon vertical structure with high precision and without damaging the crystal: ideal for micro-trench of GALORE
- CNR Institute for Microelectronics and Microsystems (IMM-CNR) of Bologna has a Deep Reactive Ion Etching machine and years worth of experience
- First tests showed vertical and low roughness along etching

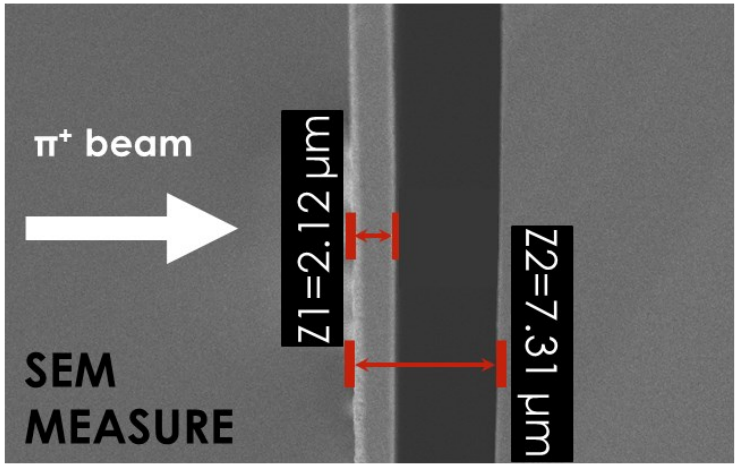


FIRST TESTS



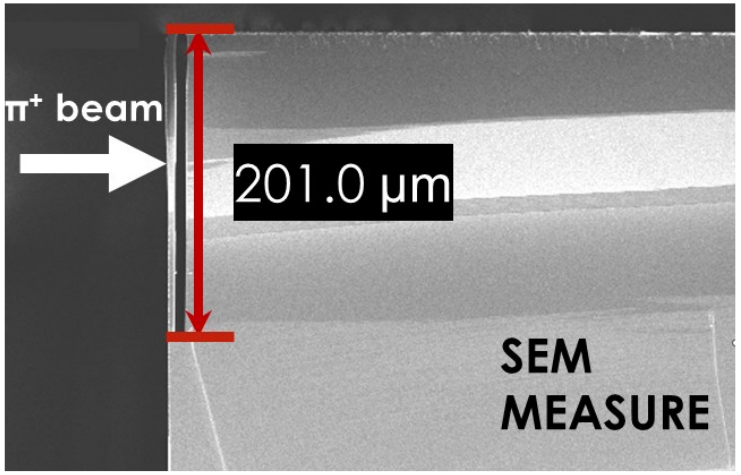
First microtrench set was machined

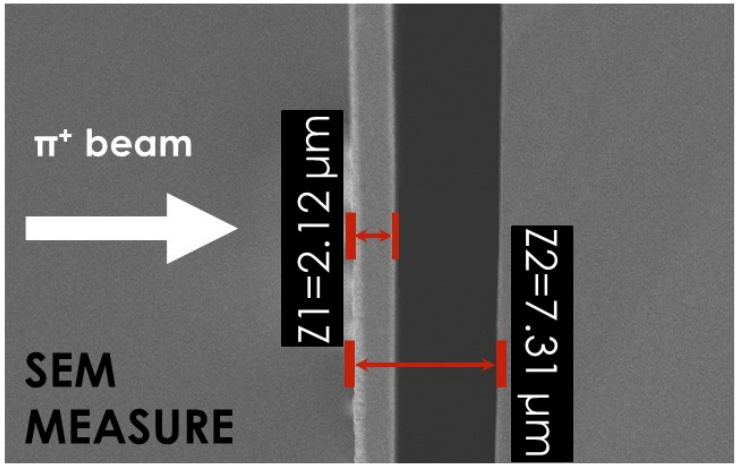


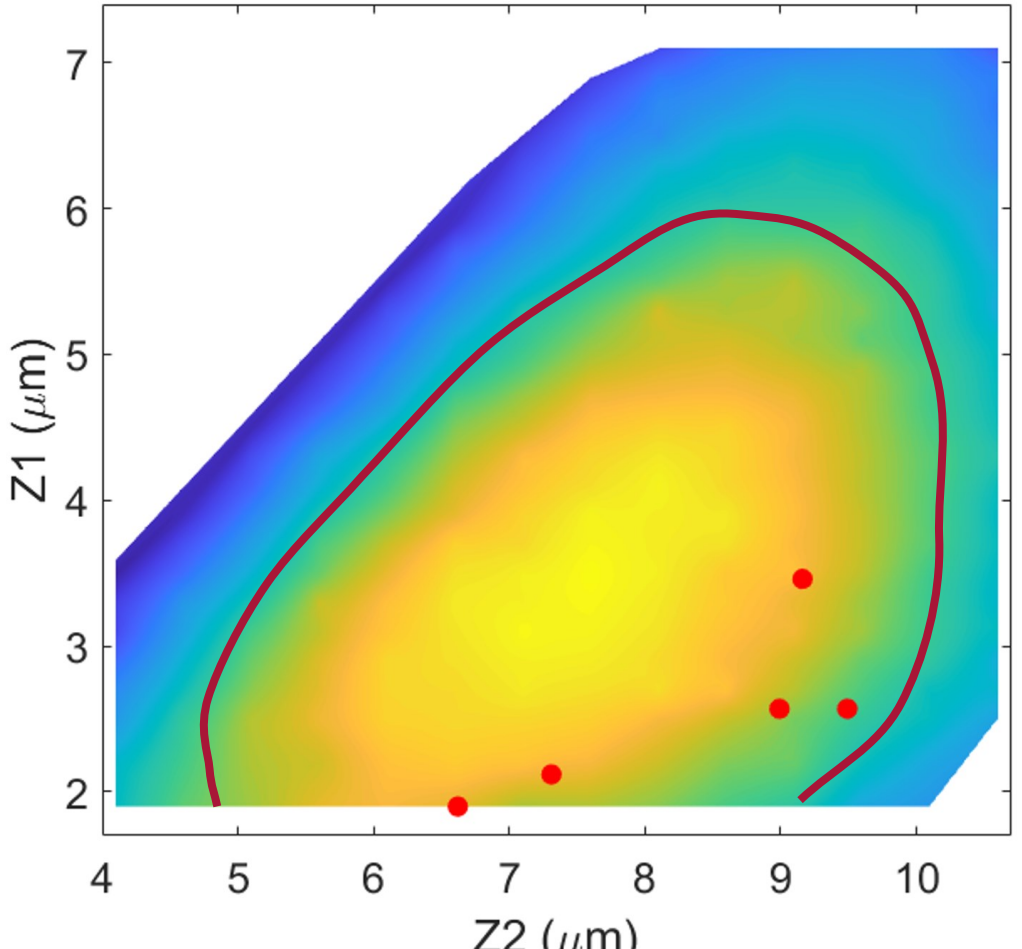


FIRST TESTS

First tests within specs
defined by simulation







SECOND YEAR OF THE PROJECT

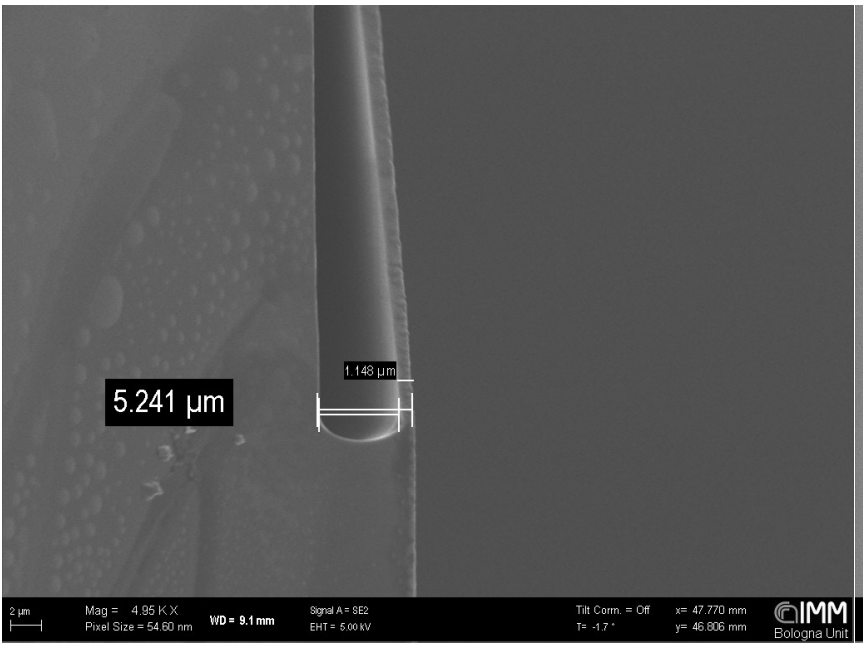
1. Optimization of the sample production process and final prototype ready for beamtest

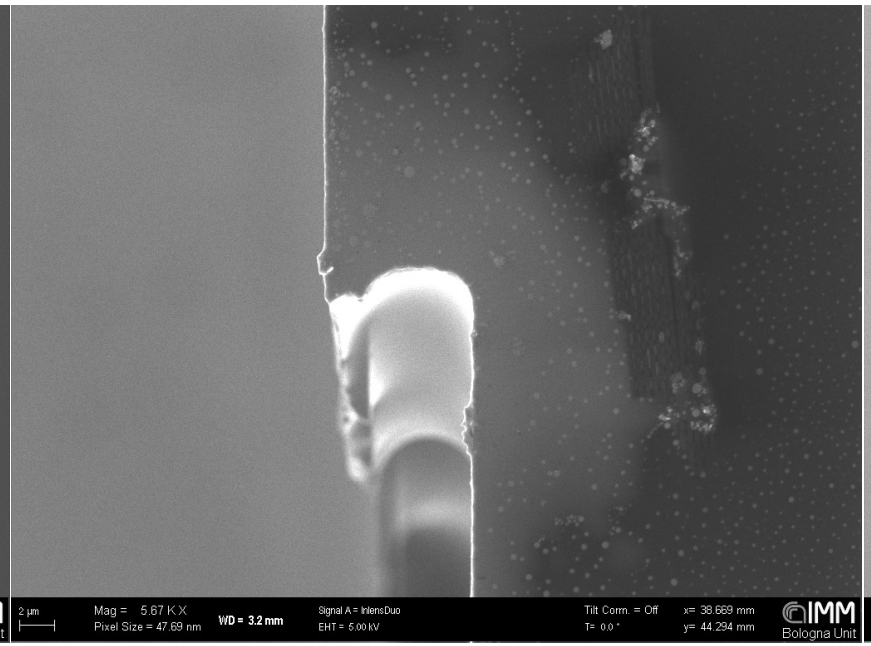
2. Experimental test of deflection efficiency using 180 GeV pion beam

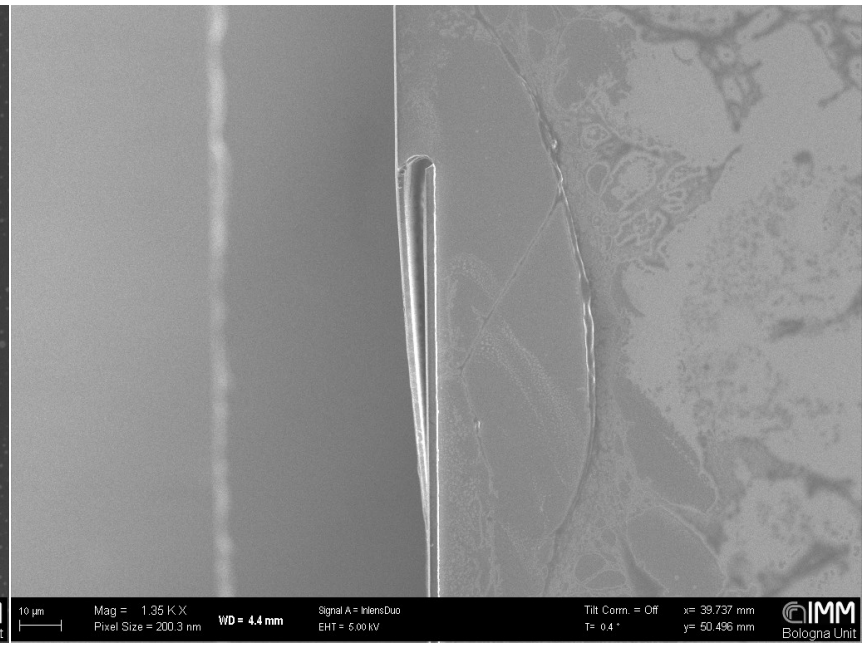
3. Data analysis of beamtest data

PROCESS OPTIMIZATION

The micro-trench fabrication process of 2022 obtained values close to optimal, but in some cases was still subjected to collapse of micro-trench during DRIE and separation of sample from wafer

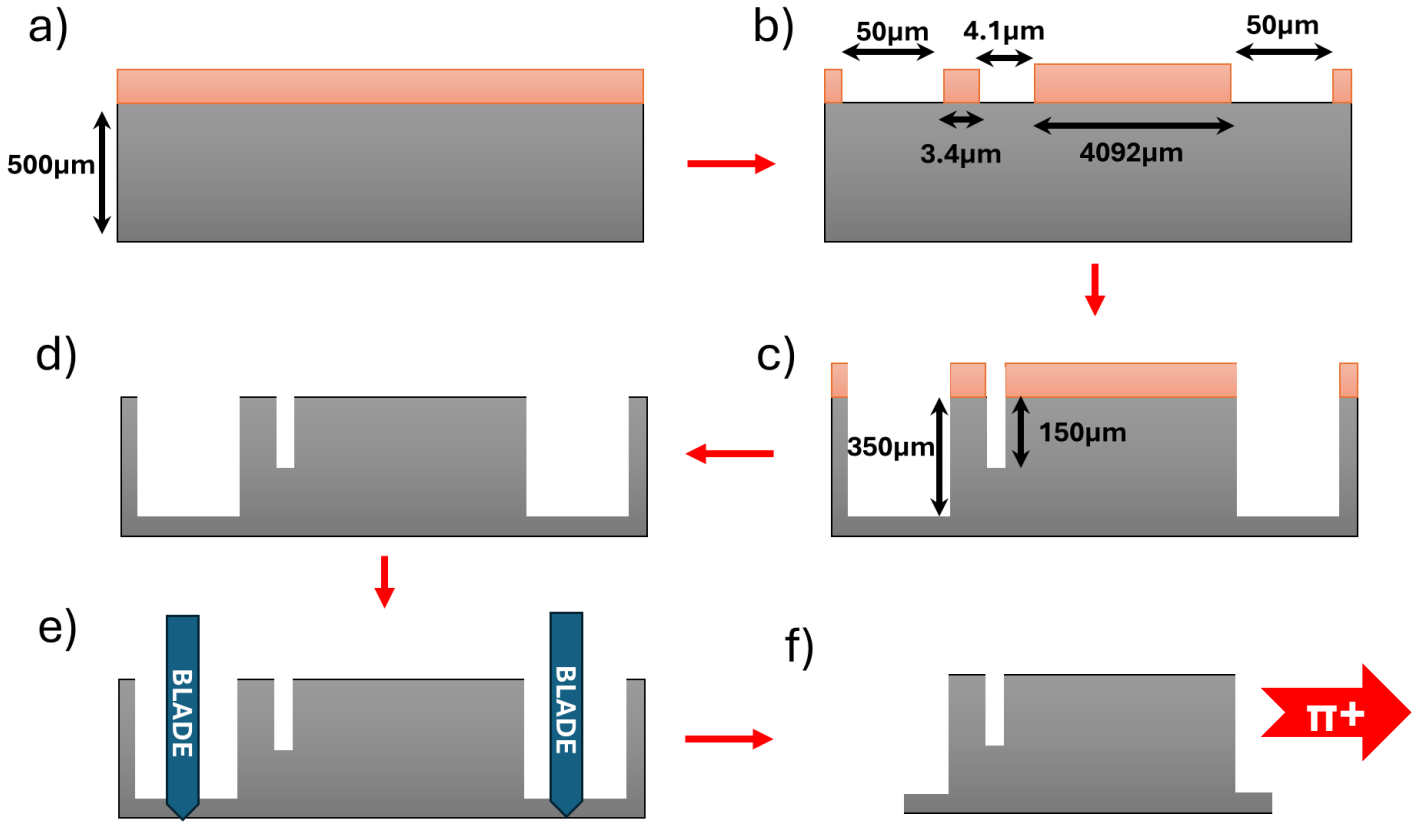






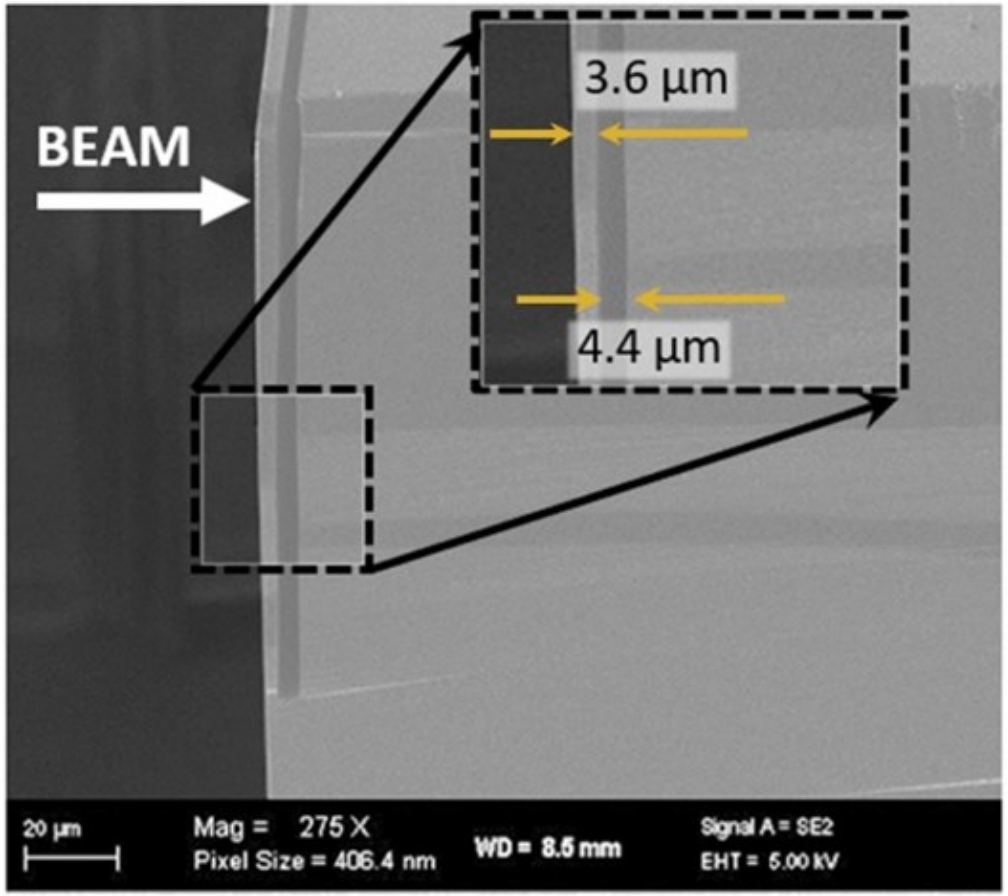
FABRICATION PROCESS OPTIMIZATION

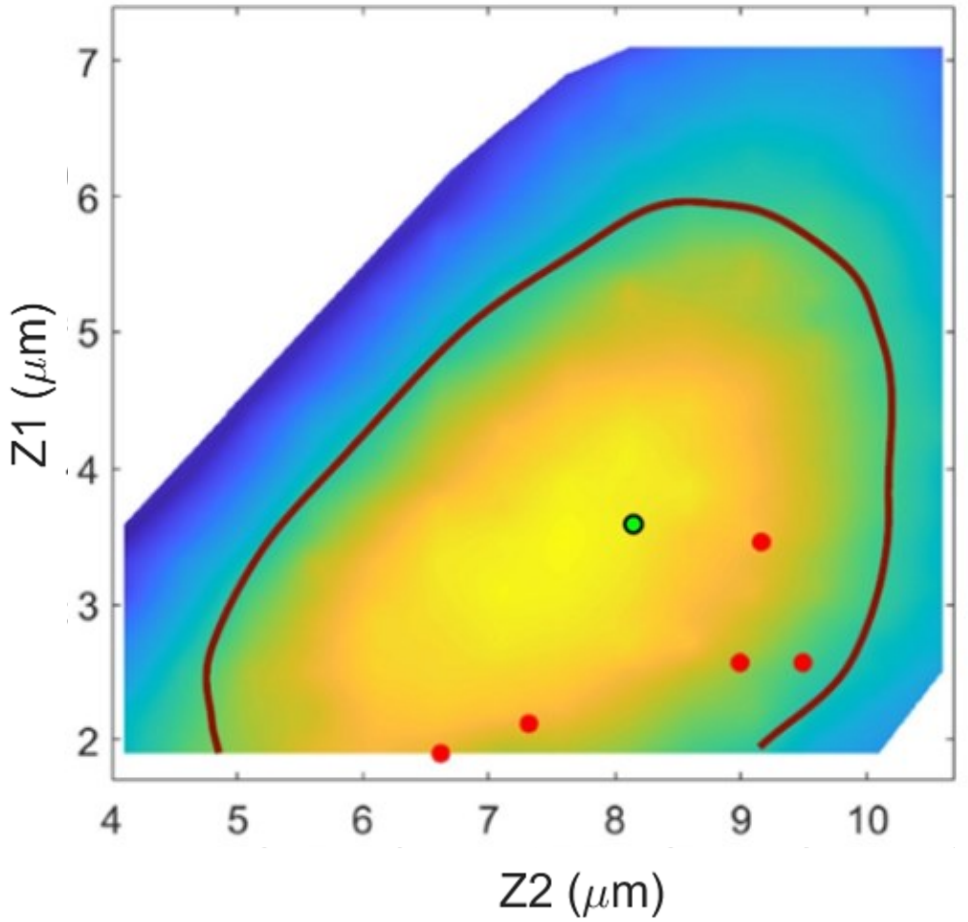
- Optimized masking layer during DRIE
- Optimized separation of final crystal sample (size 0.5x4.1x55 mm^3) from wafer after DRIE, using diamond dicing blade



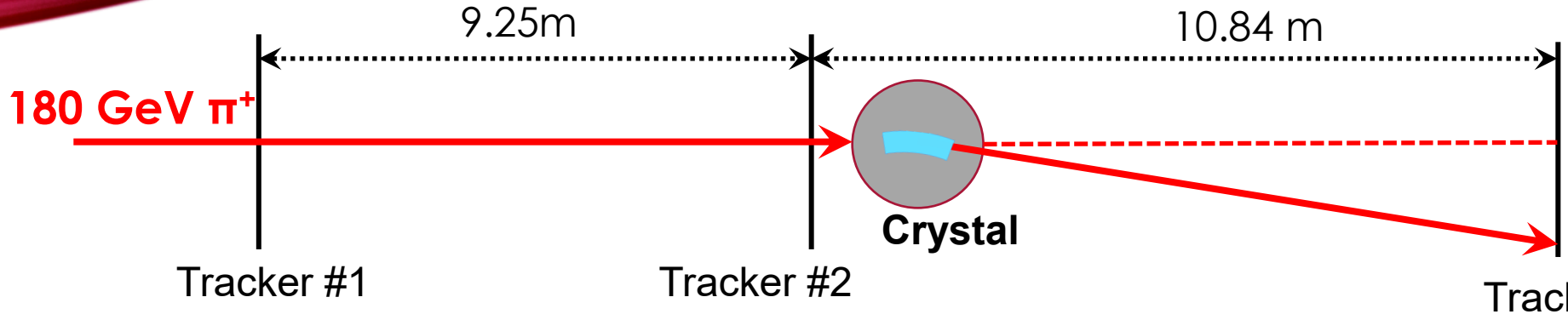
FINAL SAMPLE PRODUCED

- Improved the position and size of micro-trench in final prototype

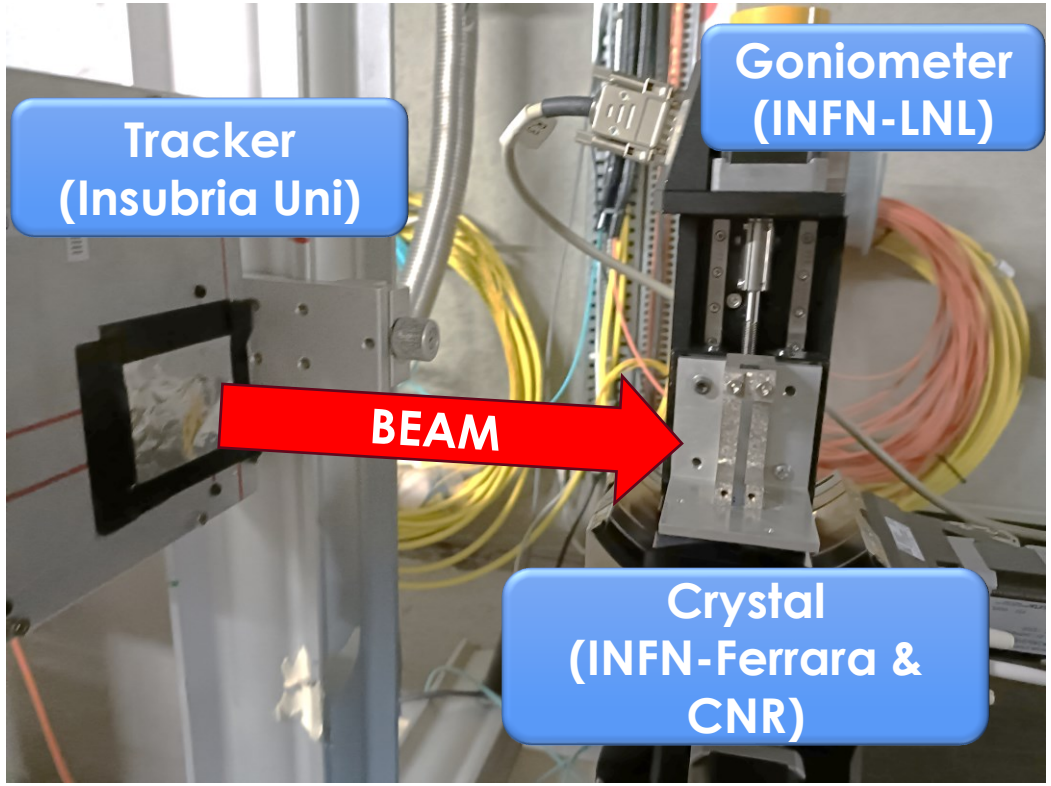




TESTEBEAM AT H8 BEAMLINE

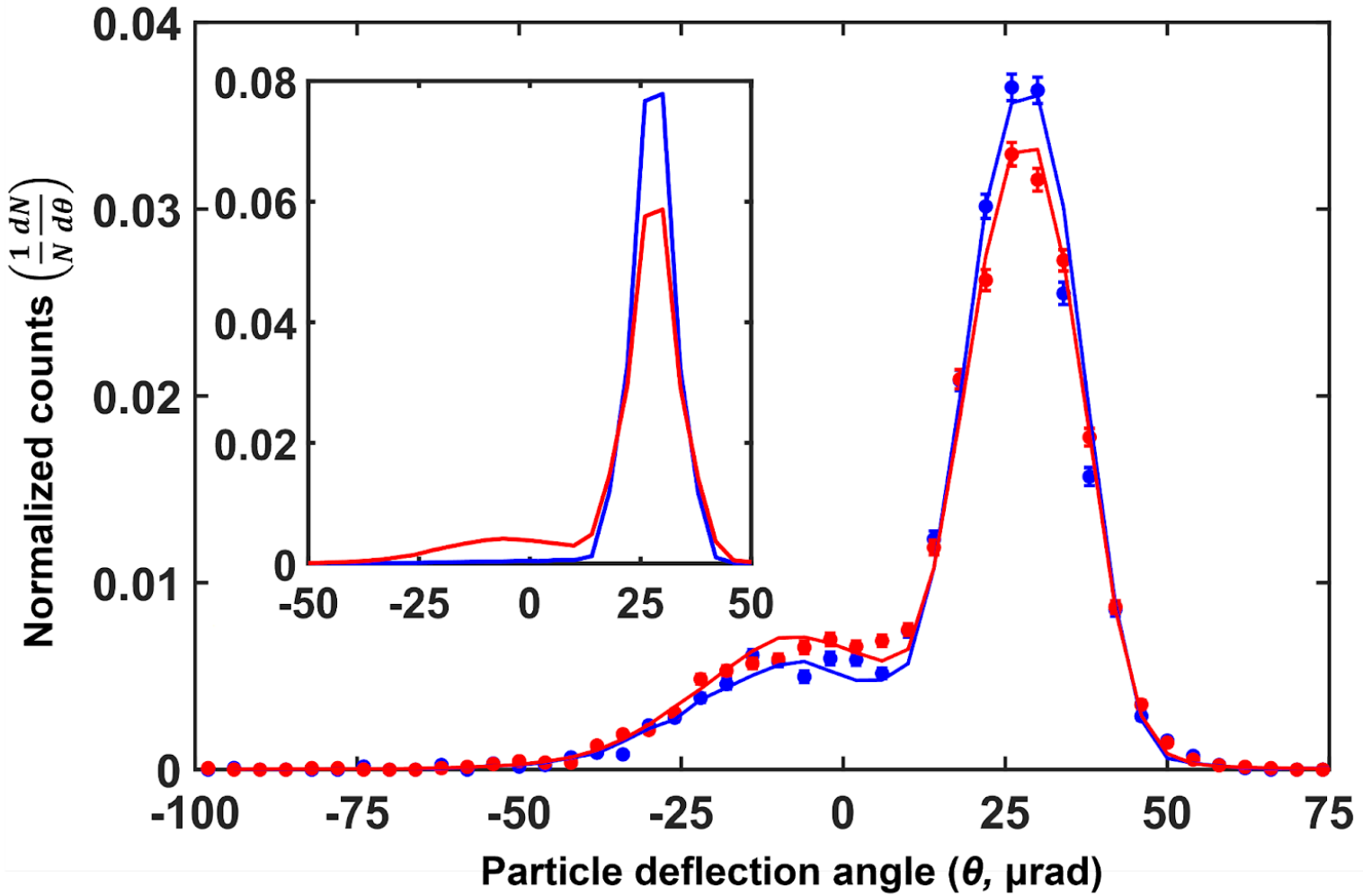


- Setup and crystal were successfully installed and operational at H8 beamline of CERN.
- 180 GeV positive pion beam. Tracking trajectory of each particle of the beam before and after interaction with the crystal.
- High resolution goniometer for alignment of the crystal to the beam
- We were not primary users: beam size, divergence and intensity far from ideal!



FINAL RESULTS

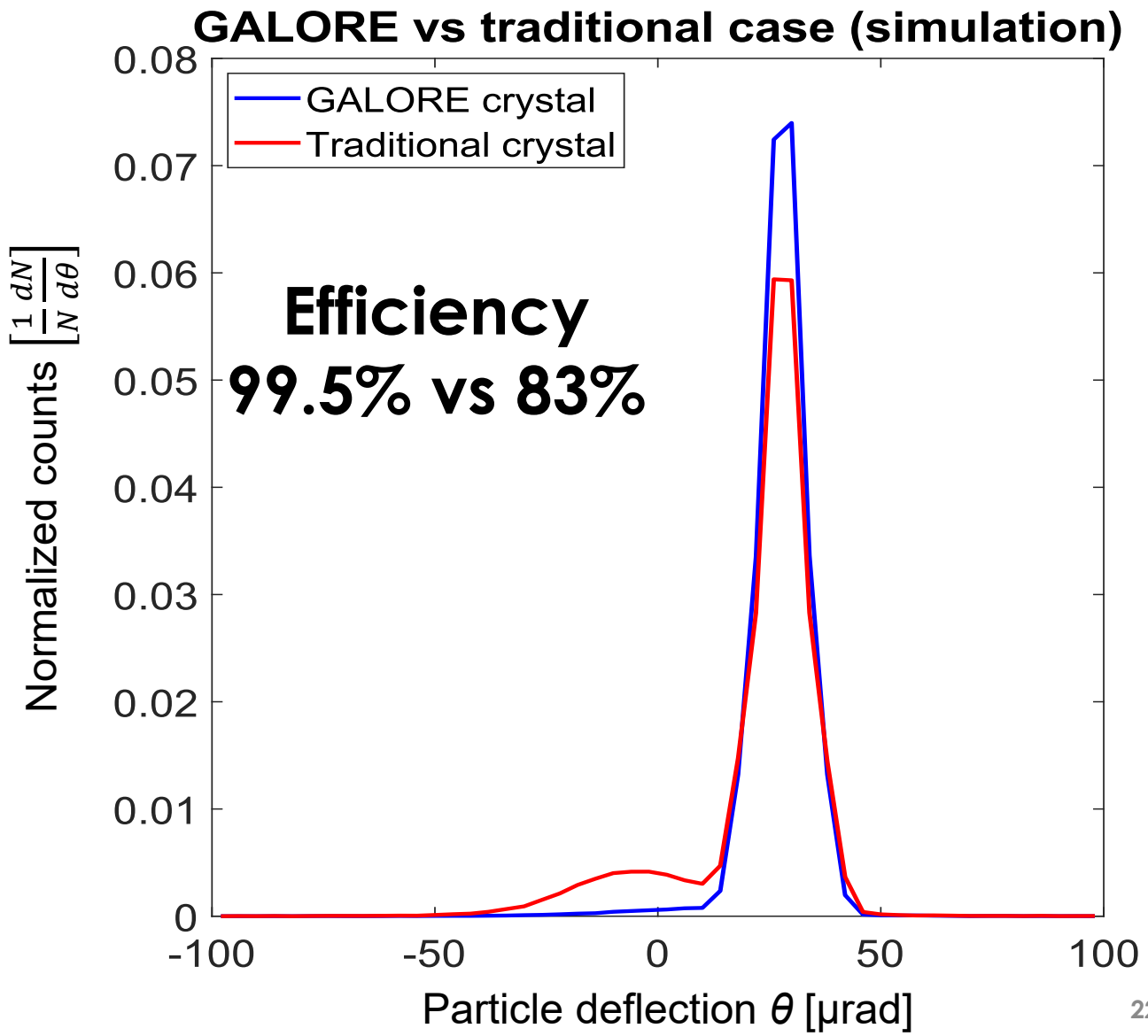
1. Measured increase in efficiency compared to crystal without micro-incision
2. Perfect agreement with simulations taking into account all beam and experimental apparatus characteristics
3. By removing air and tracker from the simulation, larger effect of efficiency increase is observed



FINAL RESULTS

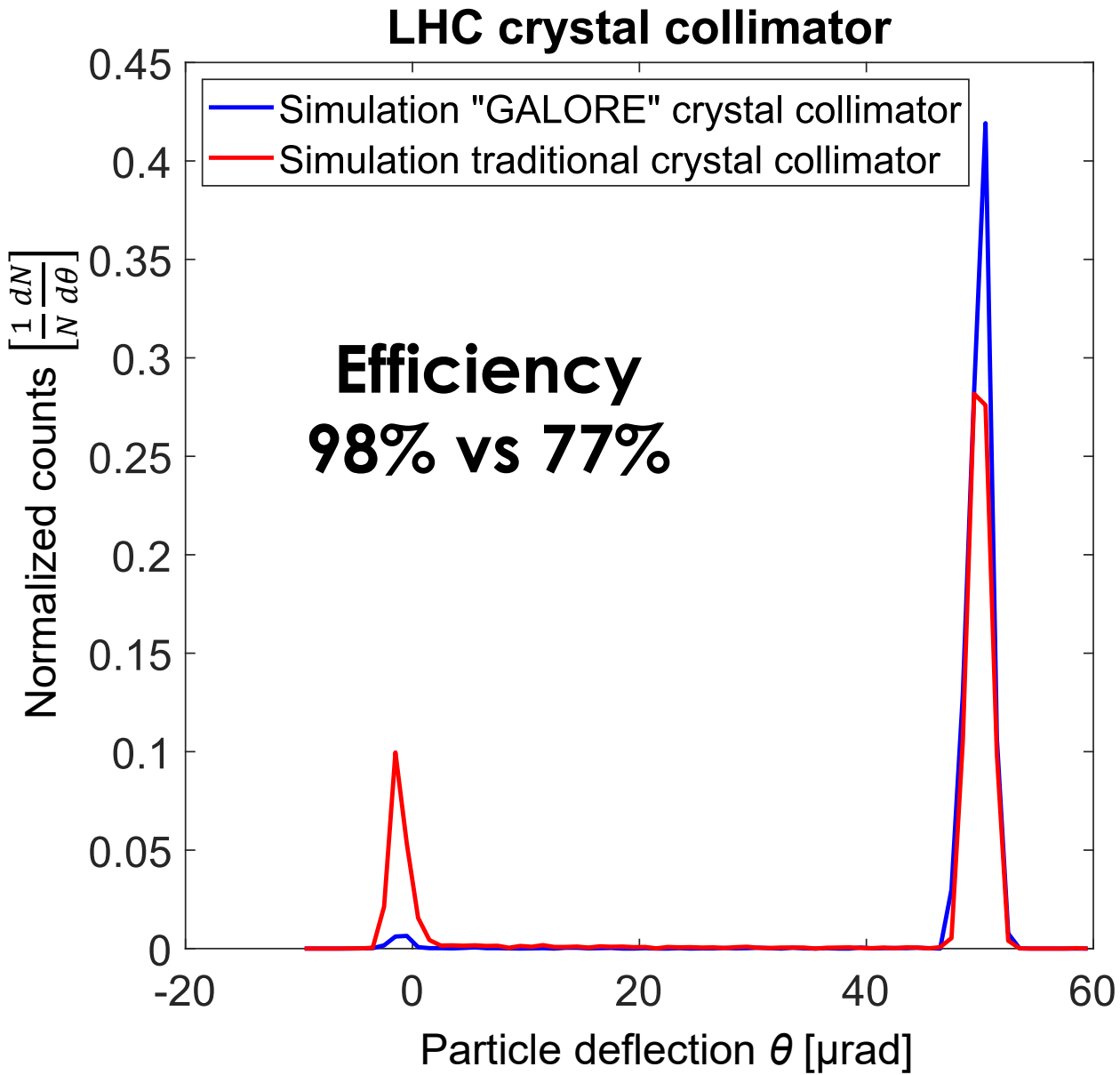
Particle beam of low divergence and crystal in vacuum

standard case for beam extraction/collimation from a particle accelerator ring, one would observe an almost complete suppression of non-deflected particles.



CONCLUSION

- The project GALORE developed a new type of bent crystal, featuring enhanced deflection efficiency
- The experimental results validate the channeling enhancing mechanism theorized in 2007
- This will lead to novel application, especially at energies such as LHC where geometry of microstructure would be **<u>much less</u>** challenging than the 180 GeV case.



FINAL THANKS TO THE GALORE TEAM…

Thanks to the INFN teams of the projects allowed to achieve the results:

- **INFN-Ferrara Team**
- **INFN-LNL Team**
- **INFN-MiB**

Special thanks to the personnel of the **CNR-IMM in Bologna** working in the scientific collaboration with the GALORE project, who produced the microstructure critical for the channeling efficiency enhancement

…AND THANKS FOR THE ATTENTION