“Beam steering performance of bent silicon crystal irradiated with high-intensity and high-energy protons”

International HiRadMat Workshop

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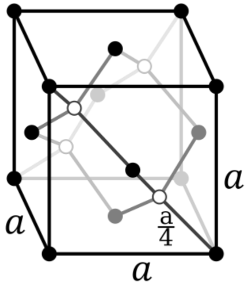
UA9 Collaboration

Outline

- Crystal beam steering
- Crystal applications
- Reasons to irradiate crystals
- Crystal HRMT test
- Crystal hi-dose irradiation with neutron
- LoI: HRMT test on hi-dose irradiated crystals
- Conclusions

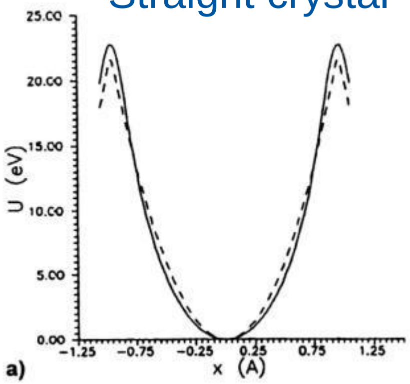
Crystal physics[1]



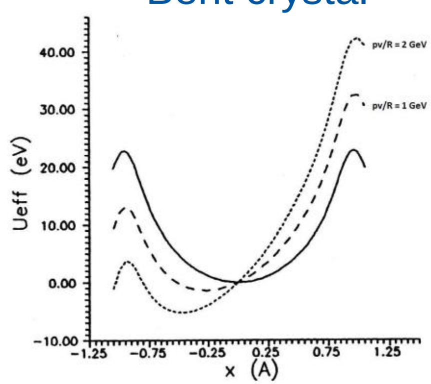
Silicon diamond lattice

Potential well between two planes:

Straight crystal



Bent crystal



Channeling

Channeling only if the protons have

$p_T < U_{max}$

$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}$$

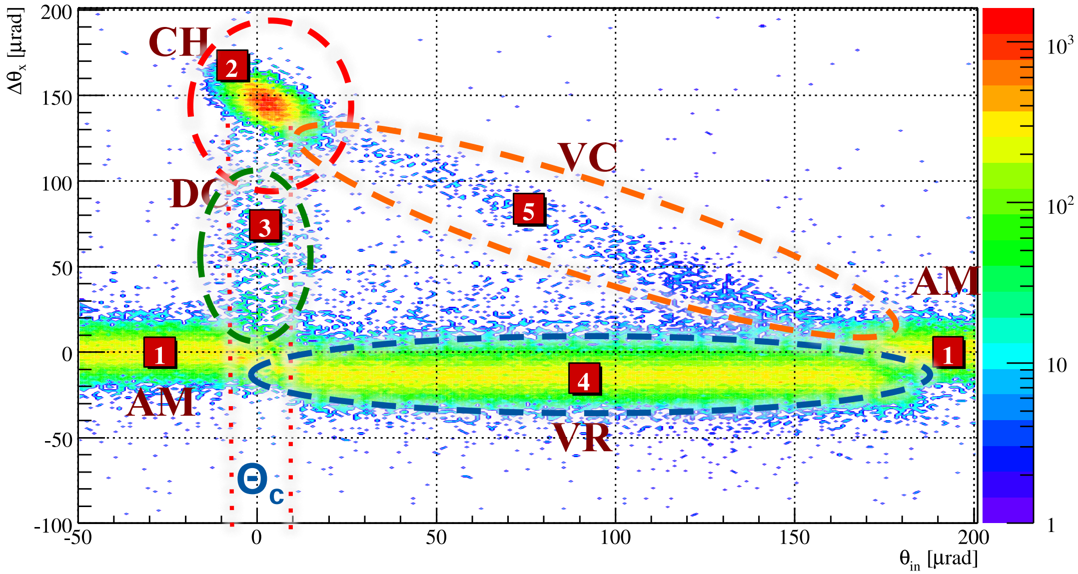
***Typical values** at energies of our interest:*

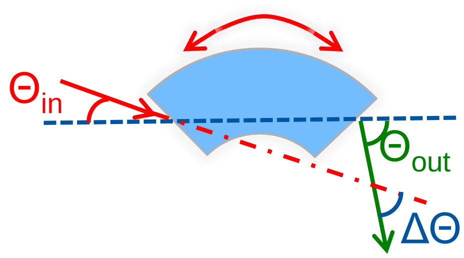
Case	Energy [GeV]	θ_c [μrad]	λ [μm]
SPS coast	120	18.3	33.0
SPS coast	270	12.2	49.6
H8	400	10.0	60.3
LHC inj.	450	9.4	64.0
LHC top	6500	2.5	243.2
LHC top	7000	2.4	252.3

[1]

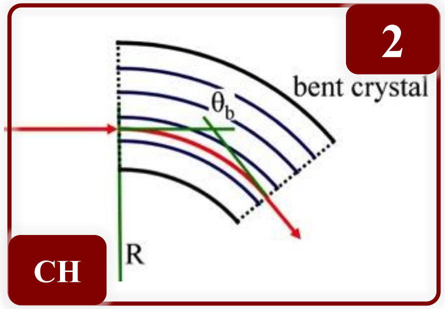
Coherent processes in bent crystals[1]

***From test beam** on the CERN-SPS extraction line H8:*
(in the framework of the UA9 experiment)

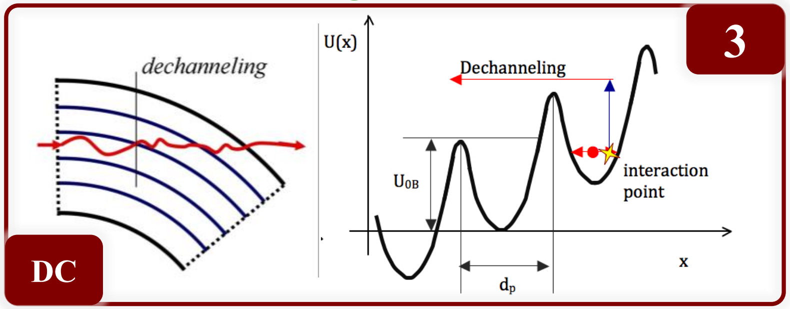




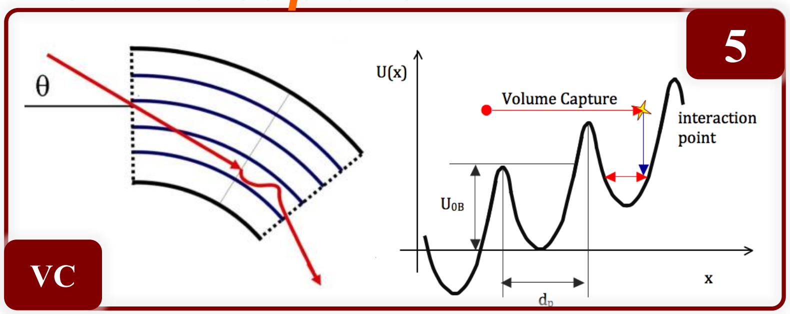
Channeling



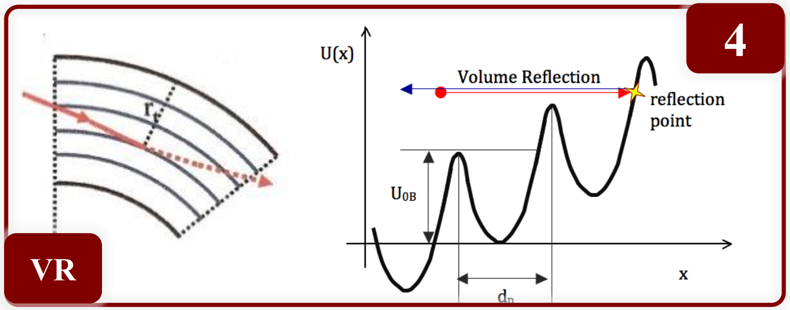
Dechanneling



Volume capture

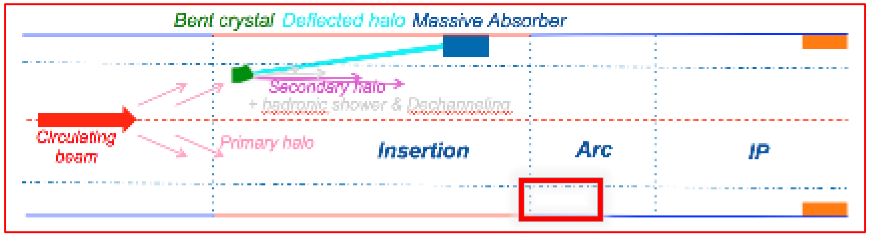


Volume reflection

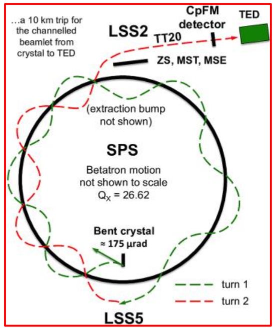


Crystal applications

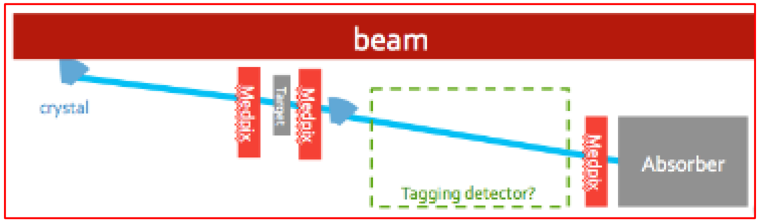
- **LHC Crystal Collimation for Hi-Lumi [2]:** use of a bent crystal to deflect beam halo particles instead of 3 stages of standard collimators (successfully proved in the LHC)
  - Reduced off-momentum losses in DS
  - Impedance reduction
  - Simpler and cheaper solution



- **SPS extraction [3,4]:** use of a crystal to extract (or support the extraction) from the SPS to the North area (successfully proved in the SPS)
  - Reduction of losses at the extraction septum
  - Simpler and cheaper solution



- **Beam splitting for LHC:** use of two crystal in a raw to split the halo beam and send it on a fixed target (preliminary proved in SPS)
  - At now the only way to split the LHC beam inside the LHC itself



Reasons to irradiate crystals

No systematic study of irradiated crystals has ever been carried out until now

- High-intensity and energy particles could produce thermo mechanical stresses on the crystal system: deformations, evaporations, vetrification, craks, etc…

- HiRadMat test at CERN to study consequences of unwanted fast irradiations during injection or dump procedures

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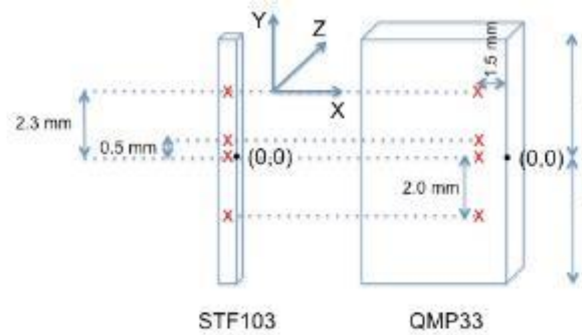
- High fluxes particles produce crystal lattice damages that affects the channeling performance (the channeling efficiency)

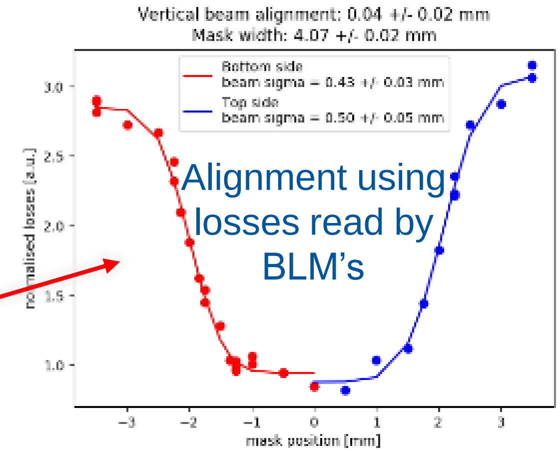
- Efficiency test before and after irradiation to test their robustness

HiRadMat irradiation (2017)

A special thanks to the STI and SMM groups!!!

- E = 440 GeV
- 3 shots with 216 bunches (~2.5e13 ppp)
- 1 shot with 288 bunches (~ 3.2e13 ppp)
- ~ 0.3 x 0.3 mm size at 1σ



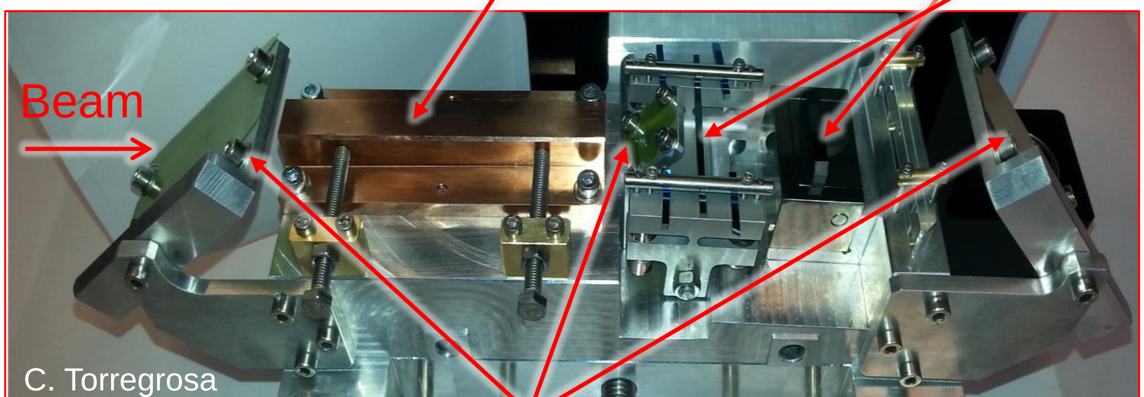


Alignment using losses read by BLM's

The Setup

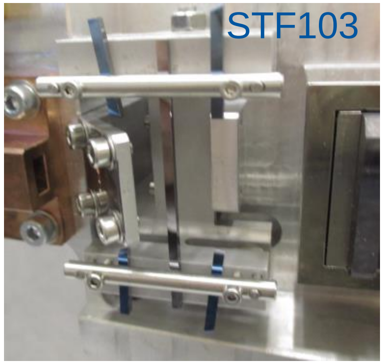
CuCrZr Mask for beam based alignment

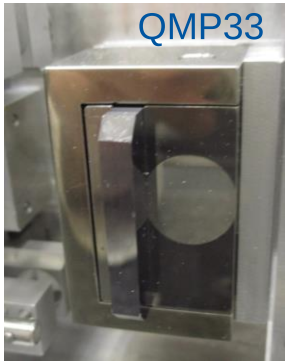
2 different types of LHC crystals



Gafchromic foils for beam impact crosscheck

No macroscopic damages after irradiation





HiRadMat Crystals H8 results

2 LHC crystals irradiated in HiRadMat and tested before and after in H8

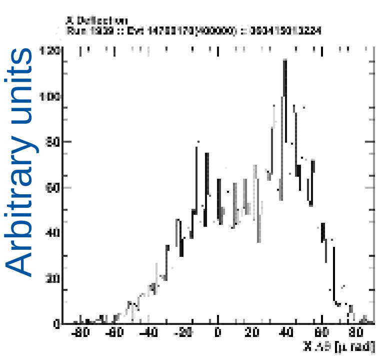
- 1st crystal fully analysed: tested with different beams: 400 GeV *p* & 180 GeV h^+

Crystal	Θ_{CH} (before) (±1 μrad)	Eff. (before) (±2 %)	Θ (after) (±1 μrad)	Eff. (after) (±2 %)
STF103	55 (400 GeV *p*+)	75 (400 GeV *p*+)	54 (180 GeV *π*+)	69 (180 GeV *π*+)

Crystal of the same kind of the STF103, tested with different beams but not irradiated

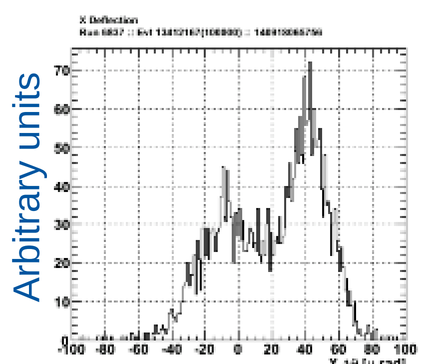
Crystal	Θ_{CH} (400 GeV p^+) (±1 μrad)	Eff. (400 GeV p^+) (±2 %)	Θ_{CH} (180 GeV h^+) (±1 μrad)	Eff. (180 GeV h^+) (±2 %)
STF105	51	74	52	64

- 2nd crystal under analysis: tested both times with 180 GeV h^+



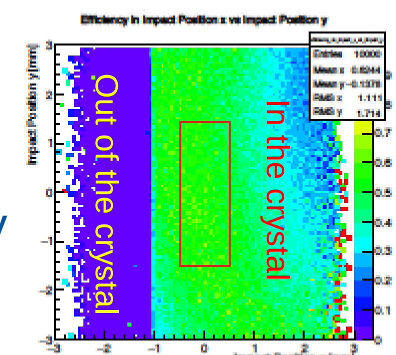
Crystal before HiRadMat

On-line plots



Crystal after HiRadMat

Very promising preliminary results…



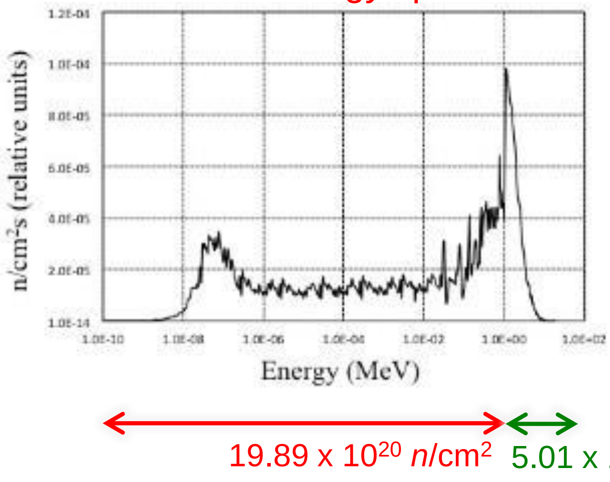
CH efficiency 2D map

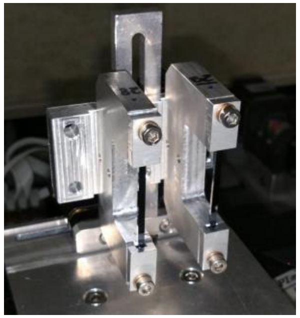
Crystal hi-dose neutron irradiation

A special thanks to the STI group !!!

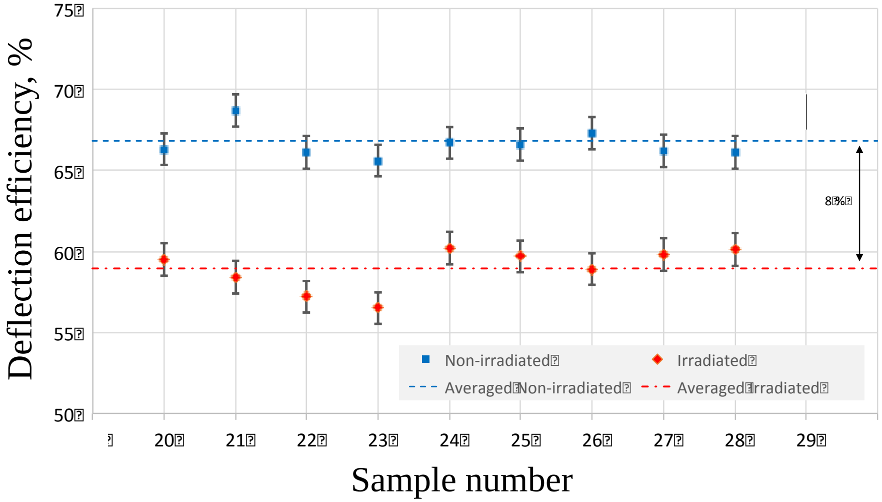
- 9 crystal samples have been irradiated at the SCK-CEN BR2 reactor
- with 2.5 x 10^{21} neutrons/cm^2
- 0 < E < 10 MeV

Neutron energy spectrum





Two crystals samples ready to be measured in H8



- All the 9 crystal samples has been tested in H8 before and after the irradiation in the same conditions

- In particular, their channeling efficiency has been measured

- A mean channeling efficiency reduction of ~ 8 % after the irradiation has been registered

Crystal operational lifetime estimations

- To estimate the real crystal robustness in a hi-energy and intensity particle accelerator, we have to rescale the neutron effect to the proton and heavy ions ones, at different energies
- The parameter used for this rescaling is the number of Displacements Per Atom (DPA) produced during the irradiation
- Using FLUKA it was possible to compute the DPAs produced by the neutron spectrum of the BR2 reactor, by proton and Pb ions at different energies, computing the equivalent doses that produce ~ 8% of channeling efficiency decrease

- LHC collimation:
considering the LHC operational range in 2018, the crystal will lose ~ 8 % in efficiency in a time between ~ 5 and ~27 years

- SPS extraction (shadowing):
considering the machine parameters of the successful test performed in 2018, the crystal will lose ~ 8 % in efficiency in ~ 82 years

These results are a crystal reliability proof in terms of radiation hardiness, also in hi-intensity hadron accelerator applications

LoI: Crystal HiRadMat test on high-fluxes irradiated crystals

New HiRadMat test on high-flux irradiated crystals: to test crystal robustness to fast irradiation during injection or dump procedures at the end of their operational lifetime

The new HiRadMat test will be almost the same of 2017:

- Same beam features
- Same supports, tank, etc…
- Same alignment procedure
- only the crystals will be different: irradiated instead of not irradiated

Quite simple and standard test, but extremely important to verify the reliability of the crystal technology

2019: Letter of Interest from UA9 and STI group


To whom it concerns,

In the framework of the UA9 Collaboration, the robustness validation of Silicon crystals to radiation damage and beam impacts is in progress.

On behalf of the UA9 collaboration

References

The studies about neutron irradiation have produced a paper recently submitted to the *"European Physics Journal C"*

The paper about the HiRadMat test are almost ready and will be submitted soon to the "European Physics Journal C"

References

[1] M. Biryukov, Y. A. Chesnokov, and V. I. Kotov, "Crystal channeling and its application at high-energy accelerators". Springer Science & Business Media, 2013

[2] W. Scandale et al., "Observation of channeling for 6500 GeV/c protons in the crystal assisted collimation setup for LHC", Phys. Lett. B, 2016

[3] Fraser, M. A., *et al*. "Experimental results of crystal-assisted slow extraction at the SPS." *arXiv preprint arXiv:1707.05151* (2017).

[4] F. Addesa *et al.*, "The SE-CpFM Detector for the Crystal-Assisted Extraction at CERN-SPS", 6th Int. Beam Instrumentation Conf.(IBIC'17, Grand Rapids, MI, USA, 20-24 August 2017. JACOW, Geneva, Switzerand, 2018

Conclusions

- The HiRadMat test proves the crystal robustness also in case of a machine accident

- Crystal robustness test with hi-fluxes of neutrons is a proof of the crystal radiation hardiness also in hi-intensity hadron accelerator applications

- The same test will be performed with hi-fluxes of protons

- Future HiRadMat tests on hi-dose irradiated crystals (both with neutron & protons) are fundamental to definitely prove the reliability of the crystal technology

Thank you for your attention !

&

thanks a lot to all the UA9, EN and HRMT colleagues strongly involved !!!

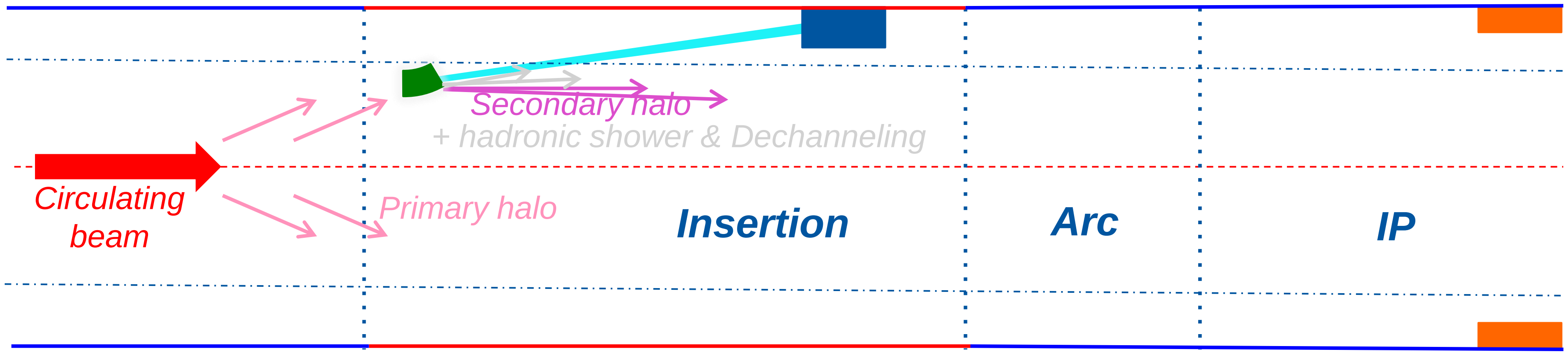
Crystal irradiation history

Facility	IHEP U-70	SPS North Area – NA48	HiRadMat
Reference	Biryukov et al., NIMB 234, 23-30	Biino et al., CERN-SL-96-30-EA	IPAC13 (THPFI059)
Year			2012
Beam	70 GeV protons	450 GeV protons	440 GeV protons
Irradiation	• 50 ms spills of 10^{14} p • one spill every 9.6 s • several min of irradiation	• 2.4 s spills of 5×10^{12} p • one spill every 14.4 s • one year irradiation (2.4×10^{20} p/cm^2 in total)	• 7.8 μs pulses of 3.2×10^{13} p • Several shots
Findings	channelling efficiency unchanged	channelling efficiency reduced by 30%	no visual damage, change in channelling efficiency to be evaluated

Moreover…

- UA9 tested several bent silicon crystals for collimation MDs in SPS and LHC
- Crystals have been irradiated for years during MD operations
- Crystals suffered some accidental beam impacts
- Crystals have shown always the same performances (angle and efficiency)
- Crystals did not show macroscopic damages

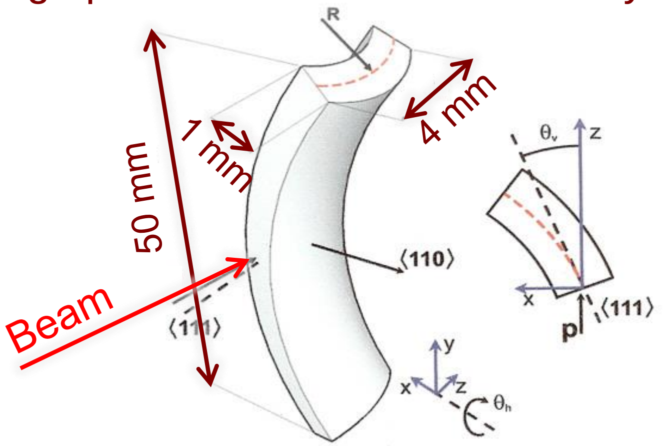
LHC Crystal Collimation[2]



Main gains:

- ✓ Reduction of **inelastic nuclear interactions**
  - ⮡ *Reduced off-momentum losses in DS*
- ✓ **Less collimators** and with larger gaps
  - ⮡ *Impedance reduction*
- ✓ **Similar performance with both p and Pb**
  - ⮡ *Significant improvement of w.r.t. present*

LHC design parameters for Silicon ST Crystals



Bending 50μrad B ≈ 300 T @ 7 TeV!

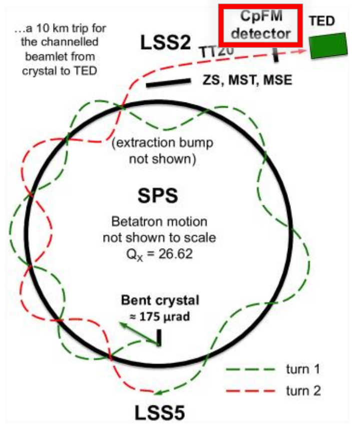
SPS crystal extraction

Joint activity with TE/ABT and EN/STI

2016 - slow non-local extraction of 270 GeV p^+ in channeling mode [6] [7]

beam into the TT20 extraction line towards the North Experimental Area of the SPS was demonstrated using the extraction septa and a bent crystal

Extraction in 2 turns



UA9 CpFM

("Cherenkov for proton Flux Measurements") detector for SPS and LHC has seen the extracted beam

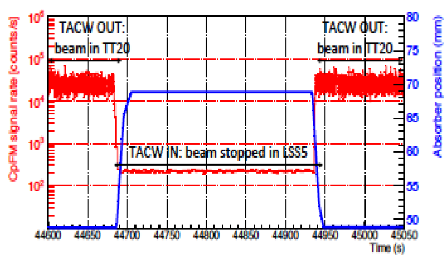
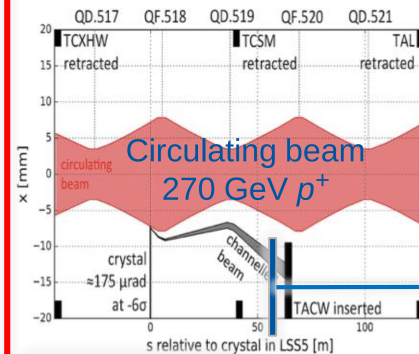
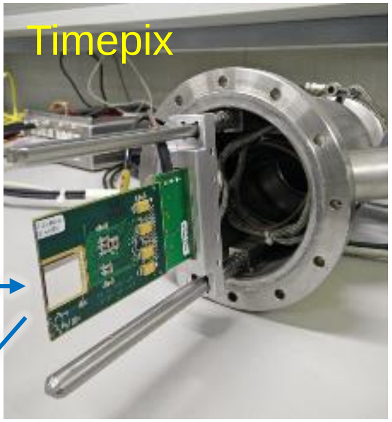


Figure 4: TT20 CpFM signal rate (red) vs. TACW position (blue) [19].

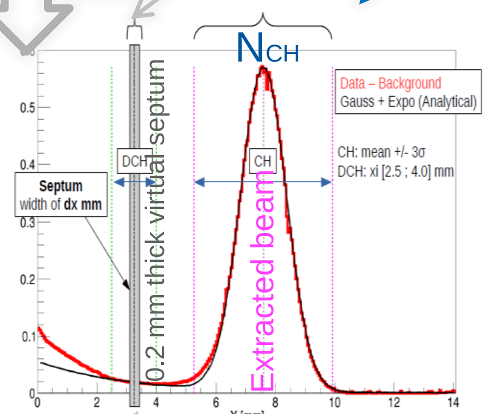
2018 - "Virtual" non-resonant local beam extraction of 270 GeV p^+ in channeling mode





Edge of the circulating beam core

$N_{DCH}(xi)/dx$



Halo density in channeling mode along the horizontal axis

(self-normalized to the total No of impinging particles)

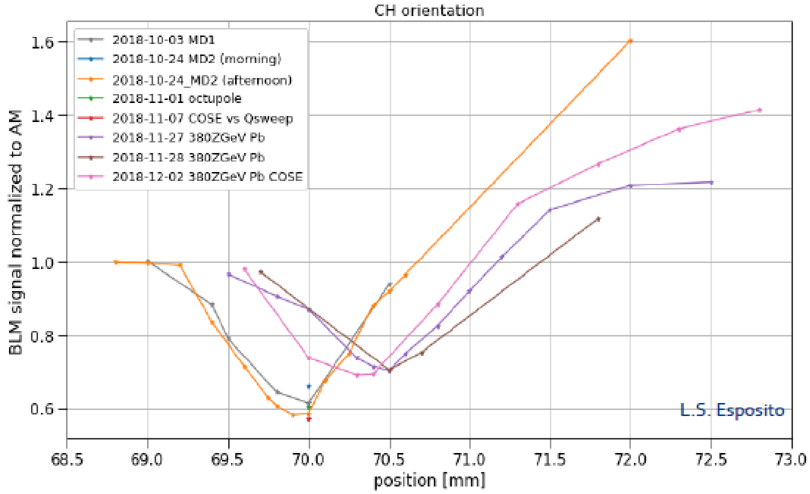
loss ratio R ≈ N_{DCH} / N_{CH}= ~6 ‰

SPS slow extraction with crystal shadowing

- This technique is developed to reduce the number of particles on the SPS extraction septum (ZS wires) and consequently the extraction losses

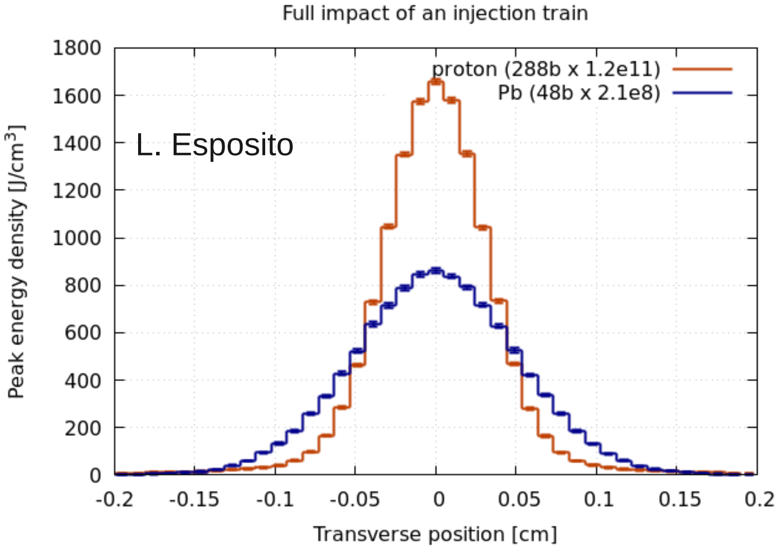
- A crystal is used upstream to shadow the ZS wires deflecting the particles that would hit him

- In 2018, a feasibility test has been performed and a reduction of 40 % of losses with protons and 30 % with lead ions was observed



FLUKA simulations

Accidental impact on crystal at injection



	Protons	Pb
Energy [GeV]	450	450 Z
#bunches	288	48
#particles/ bunch	1.2E11	2.1E8
Norm. emit. [µm]	1.3	1.5

- Impact of a full injection train on TCPCV.A6R7.B2 (smaller $\beta_x \cdot \beta_y$)
- Crystal assumed as amorphous
- Same optics for the injection of proton and Pb

Remark on induced energy densities:

- Due to small dimensions of the crystal (4 mm thick) peak energy density dominated by ionising energy loss of impacting protons
- Electronic stopping power of protons in silicon only varies by 10% between 440 GeV and 7 TeV → a test in HiRadMat with 288 bunches at 440 GeV allows also for conclusion valid at higher energies
- For an asynchronous beam dump at top energy few bunches are expected to be lost on the crystal

UA9 Experimental apparatus at the H8 SPS extraction line

High rate and high angular resolution beam telescope based on CMS Tracker HW&SW

M. Pesaresi, T. James, J. Borg

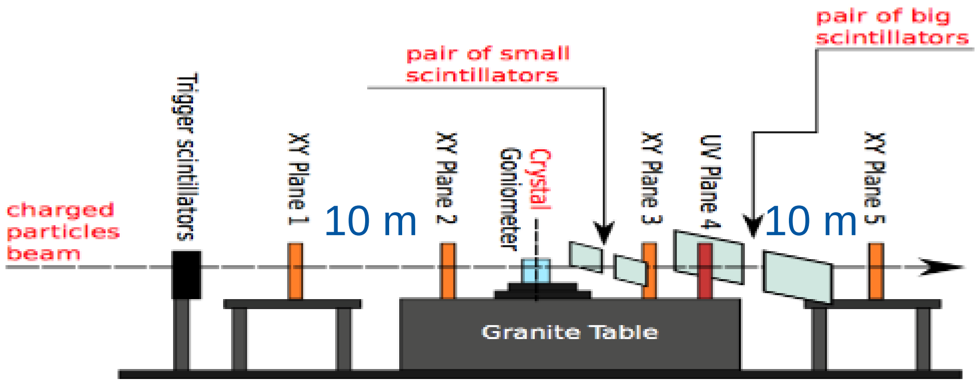


FIG. 1: Experimental layout in the H8 beam line.

Main steps in the characterization of bent crystals:

- Systematic error < 1μrad
- Statistical error negligible

1. **Alignment run:** only the tracking stations are in the beam line
2. **Linear scan:** the crystal is placed on the beam line
3. **Angular scan:** ~10^5 events/step are acquired around the channeling orientation looking for CH
4. **High statistics runs:**
   - the crystal is left in the optimal channeling position for hi-stat. of ~16 M events

Rescaling to different particle and energy

- To estimate the real crystal robustness in a hi-energy and intensity particle accelerator, we have to rescale the neutron effect to the proton and heavy ions ones, at different energies
- The parameter used for this rescaling is the number of Displacements Per Atom (DPA) produced during the irradiation

$$DPA = \frac{1}{\rho}\Sigma_i N_i N_i^F$$

ρ = atomic density
Ni = number of particles per interaction channel
N_i^F = number of Frenkel pairs (dislocations)

- Using FLUKA it was possible to compute the DPAs produced by the neutron spectrum of the BR2 reactor and by proton and Pb ions at different energies

Part.	E [GeV]	DPA [p.p.p.]	ϕ_{eq} $[1/cm^2]$
n	Spectrum	$5.7 \cdot 10^{-20}$	$2.5 \cdot 10^{21}$
p	400	$5.8 \cdot 10^{-20}$	$2.4 \cdot 10^{21}$
p	$6.5 \cdot 10^3$	$6.2 \cdot 10^{-20}$	$2.3 \cdot 10^{21}$
Pb	$400 \cdot Z$	$4.7 \cdot 10^{-17}$	$3.0 \cdot 10^{18}$
Pb	$6.5 \cdot 10^3 \cdot Z$	$4.8 \cdot 10^{-17}$	$2.9 \cdot 10^{18}$