UA9: achievements and role for HL-LHC implementation

W. Scandale for the UA9 Collaboration

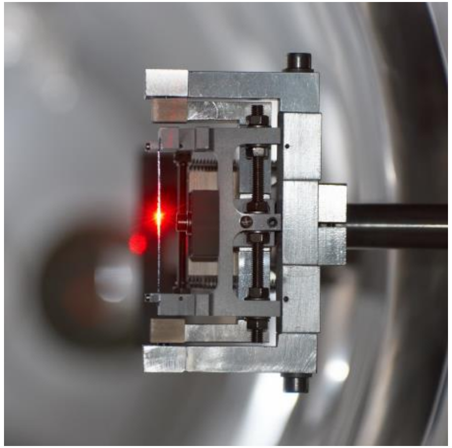
UA9 is a CERN experiment approved by the Research Board in 2008

Main goals

- investigate beam-crystal interactions
- propose and evaluate crystal assisted halo collimation in hadron colliders
- investigate beam manipulations with bent crystals: extraction, steering, focusing,…

TOPICS

- Key achievements in H8
  - The experimental apparatus
  - Identifying particle interactions with bent crystals
  - Channeling efficiency as a function of the bending radius
  - Channeling versus volume reflection
- Key achievements in SPS
  - The experimental apparatus
  - Crystal collimation performance in the SPS
  - Role of the absorber
  - Test of the LHC-type goniometer
  - Crystal miscut and amorphous layer
  - Deflecting particles along planes (110) or (111)
- Simulation codes
- Conclusive remarks



UA9 detector in the North Area

M. Pesaresi et al JINST_P04006
F.Iacoangeli et al.,2015 IEEE
Nuclear sceince symposium

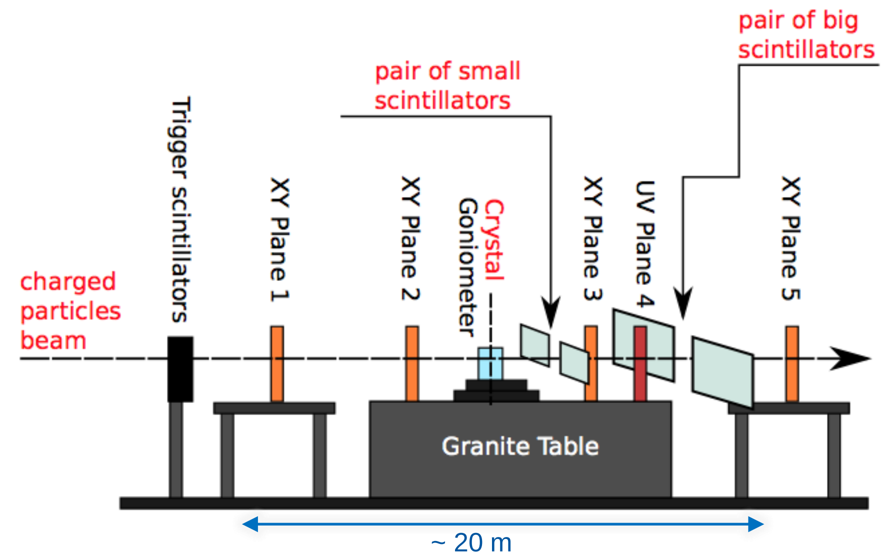
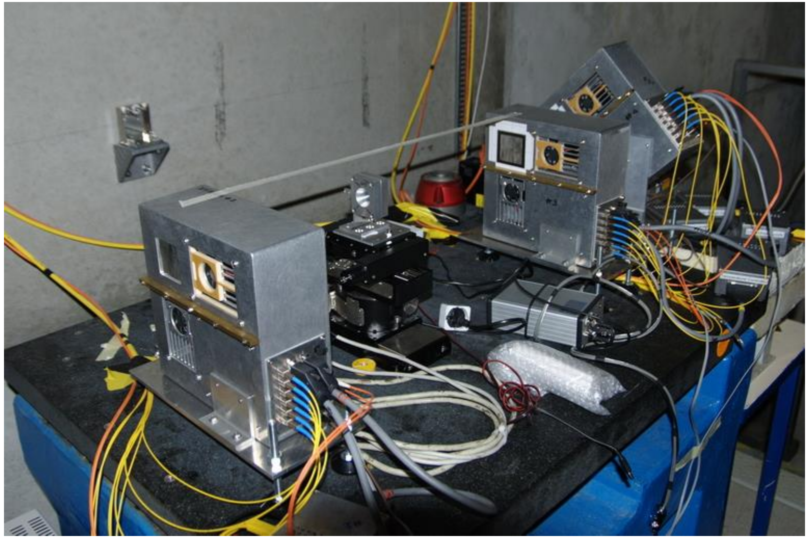


FIG. 1: Experimental layout in the H8 beam line.



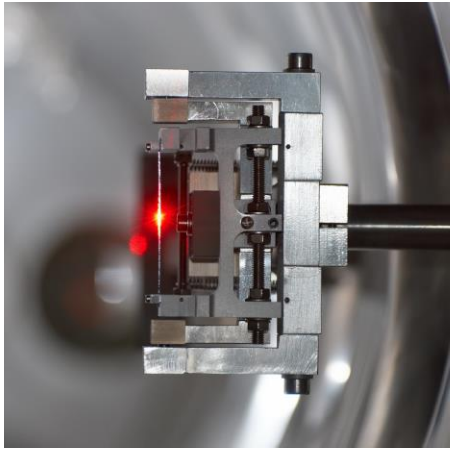
- Use a low-divergence incoming beam
- Choose the crystal orientation by acting on the goniometer
- Excellent angular resolution of each trajectory (~5 μrad)

Observables:

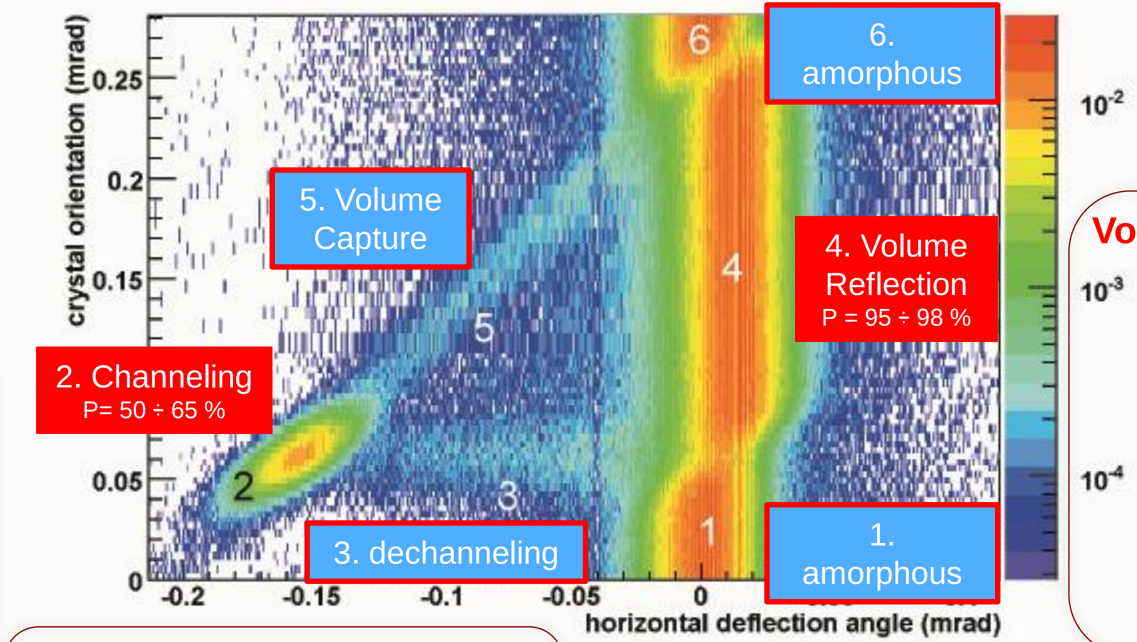
- the incoming trajectory of each particle
- the outgoing trajectory of each particle
- the inelastic interaction events

Interactions in bent crystals

W. Scandale et al,
- PRL 98, 154801 (2007)
- NIM B 268 (2010) 2655-26
- NIM B 355 (2015) 369–373



- ❑ Two coherent effects could be exploited for beam manipulation.



6. amorphous

5. Volume Capture

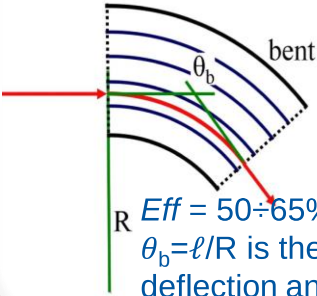
4. Volume Reflection
P = 95 ÷ 98 %

2. Channeling
P= 50 ÷ 65 %

3. dechanneling

1. amorphous

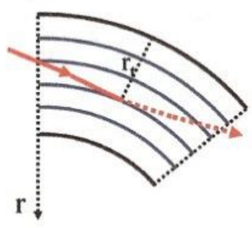
Channeling



Eff = 50÷65%

$\theta_b = \ell/R$ is the desired deflection angle

Volume Reflection



Eff = 95÷97%

$\theta_{VR} \approx 1.6\ \theta_c$

Critical angle

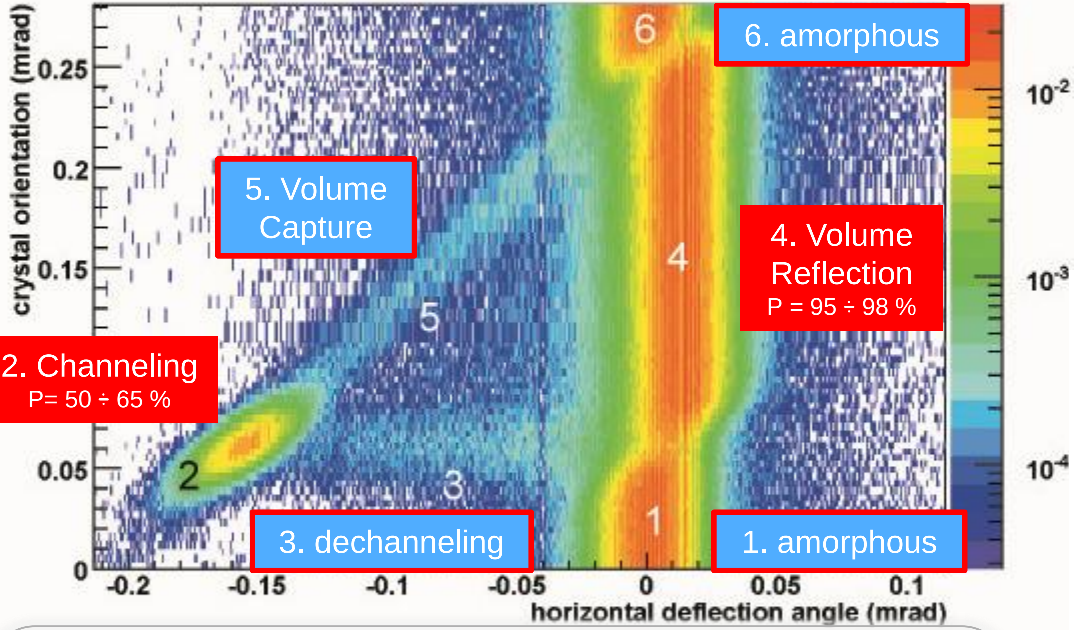
$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}$$

θ_c= 9.4 μrad @ 450 Gev
= 2.4 μrad @ 7 TeV

Characterization of a bent crystal

W.Scandale et al,
Phys. Rev. ST – AB **11**, 063501 (2008)

More details in the presentation of M. Garattini



6. amorphous

5. Volume Capture

4. Volume Reflection
P = 95 ÷ 98 %

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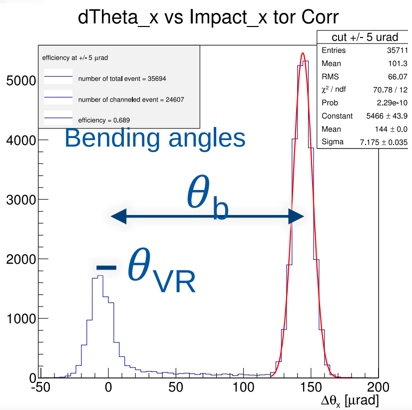
3. dechanneling

1. amorphous

Observables:

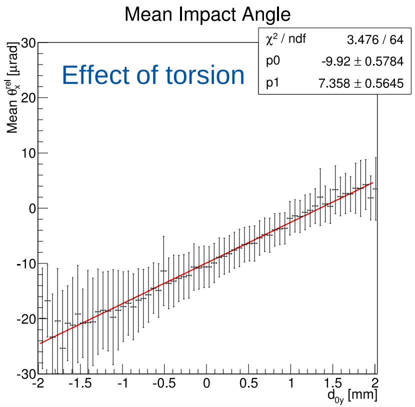
- ☐ Bending angles (for channeling and VR)
- ☐ Channeling efficiency
- ☐ Crystal torsion
- ☐ Nuclear interaction probability



Bending angles

θ_b

$-\theta_{VR}$

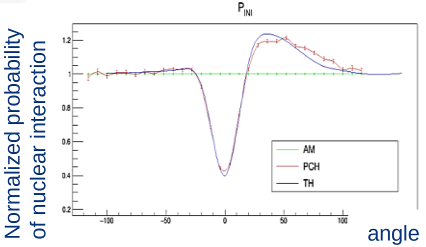


Effect of torsion

Probability of inelastic events

Eur. Phys. J. C (2018) 78:505;
Nucl. Inst. and Methods 268 (2010) 2655–2659

Crystal STF107
--- data (pions 180GeV)
-- simulation
-- reference for amorphous Si



Channeling efficiency

$$\eta_{\mathrm{ch}}^{\theta_x^{\mathrm{cut}}} = \frac{N_{\mathrm{ch}}^{-\theta_x^{\mathrm{cut}}<\theta_x^{\mathrm{in}}<\theta_x^{\mathrm{cut}}}}{N^{-\theta_x^{\mathrm{cut}}<\theta_x^{\mathrm{in}}<\theta_x^{\mathrm{cut}}}}$$

Masking the torsion effect

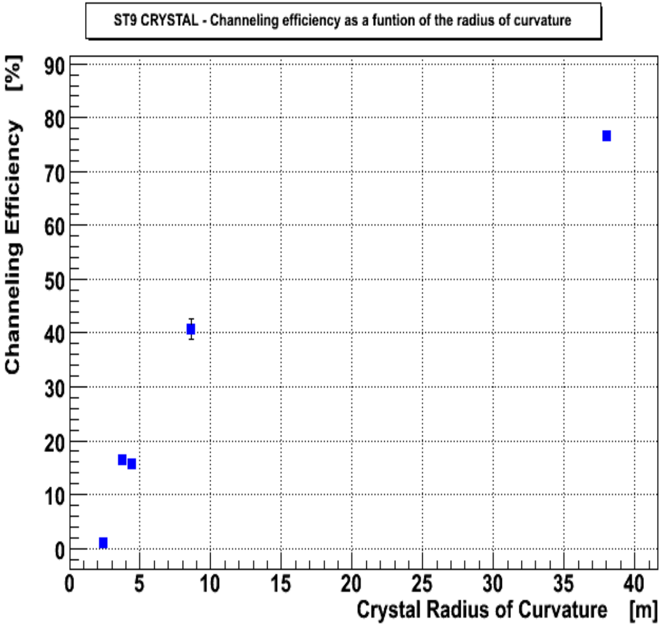
$$\theta_x^{corr} = \theta_x^{in} - (t(y) \cdot d_{0y} + \Theta_x^{off})$$

Importance of the bending radius

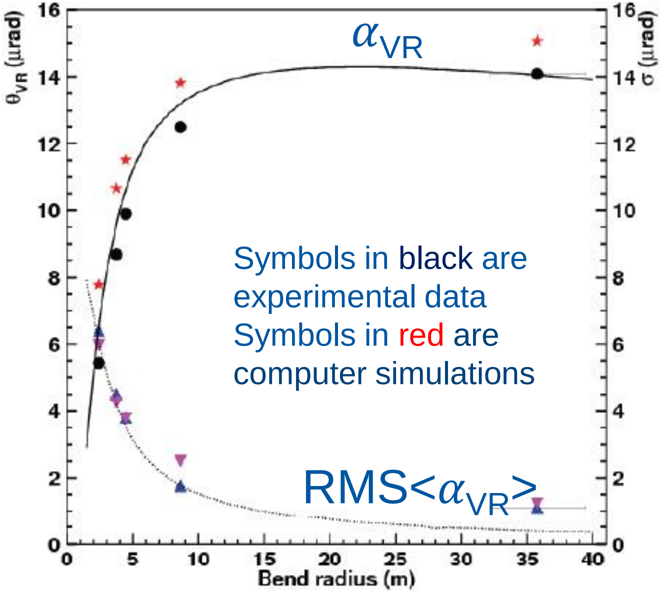
W. Scandale et al.
PRL 101, 234801 (2008)

measurements performed in 2009 using the crystal ST9 build in INFN-FE

Channeling:
Efficiency versus Radius



Volume Reflection:
Deflection Angle versus Radius



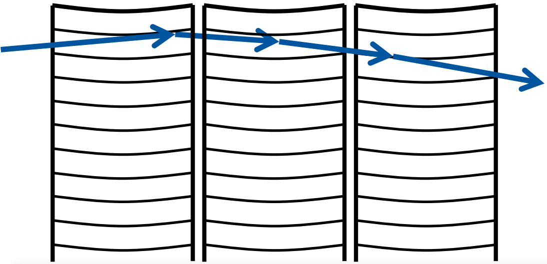
Symbols in black are experimental data
Symbols in red are computer simulations

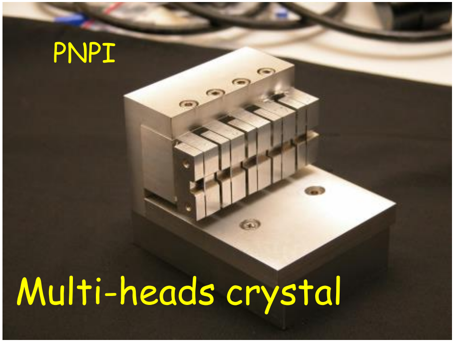
for the effects in LHC see the talks of M. D’Andrea and R. Rossi

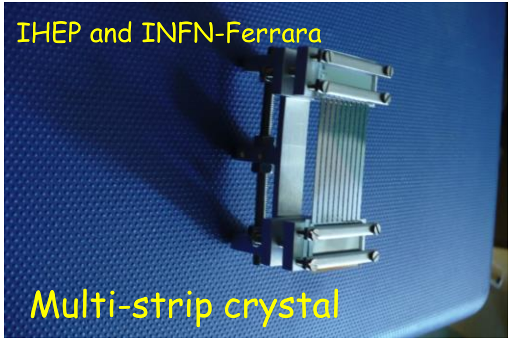
Multi-volume reflection

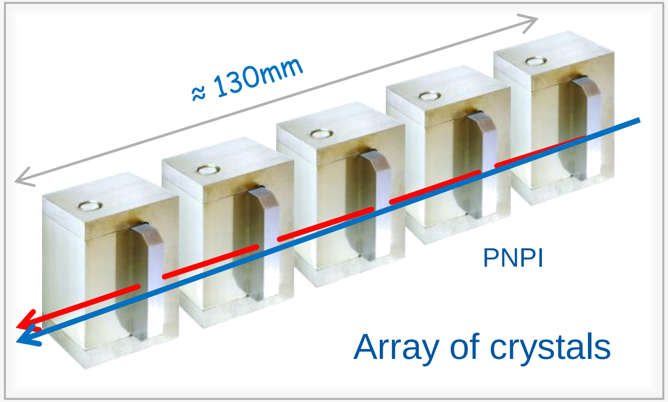
W. Scandale et al.
- Nucl. Inst. and Methods B 338 (2014) 108–111
- Physics Letters B 692 (2010) 78–82

The concept









Array of crystals

Four assemblies conceived for multi-VR deflection:

- Deflection angle $n \times \theta_{VR}$ ***n** is the No. of strips or of crystals in the assembly*
- Single-pass efficiency ≥ 90 %

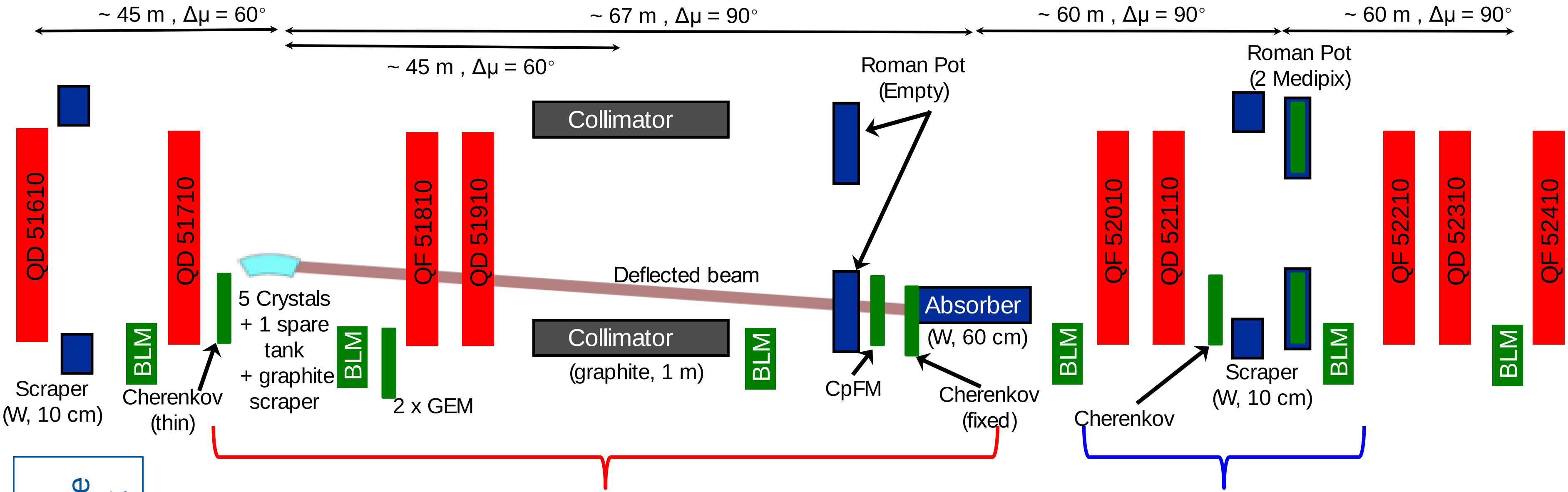
Drawbacks:

- Deflection angle $n \times \theta_{VR} = 1.6\, n \times \theta_c$ energy dependent
- @ 7 TeV n ≥ 10 (required in optical layout of the LHC collimation IR)
- Crystal technologies rather complex
- Crystal optimization with stringent tolerance for strip alignment

Multi-VR abandoned in LHC

UA9 setup in the SPS ring (2008 - 2017)

W Scandale et al
2011 JINST 6 T10002



~ 45 m , Δμ = 60°
~ 67 m , Δμ = 90°
~ 60 m , Δμ = 90°
~ 60 m , Δμ = 90°
~ 45 m , Δμ = 60°

QD 51610
QD 51710
QF 51810
QD 51910
QF 52010
QD 52110
QF 52210
QD 52310
QF 52410

Scraper
(W, 10 cm)

BLM

Cherenkov
(thin)

5 Crystals
+ 1 spare
tank
+ graphite
scraper

2 x GEM

Collimator

Collimator
(graphite, 1 m)

Deflected beam

Roman Pot
(Empty)

CpFM

Absorber
(W, 60 cm)

Cherenkov
(fixed)

Roman Pot
(2 Medipix)

Cherenkov

Scraper
(W, 10 cm)

Collimation region

High dispersion area

Scraper to
suppress/enable
multi-turn effect

Observables in the collimation area:

❑ Intensity, profile and angle of the deflected beam
❑ Local rate of inelastic interactions
❑ Channeling efficiency (with multi-turn effect)

Observables in the high-D area:

❑ Off-momentum halo population escaping from collimation (with multi-turn effect)
❑ Off-momentum beam tails

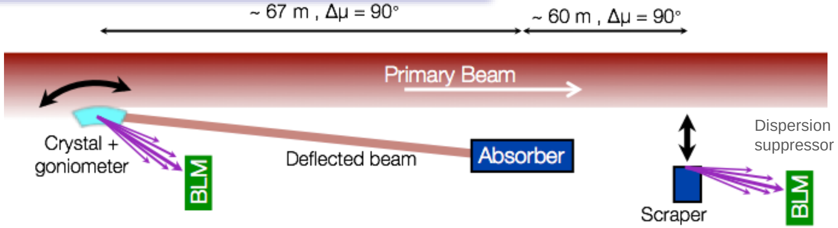
Crystal collimation in the SPS

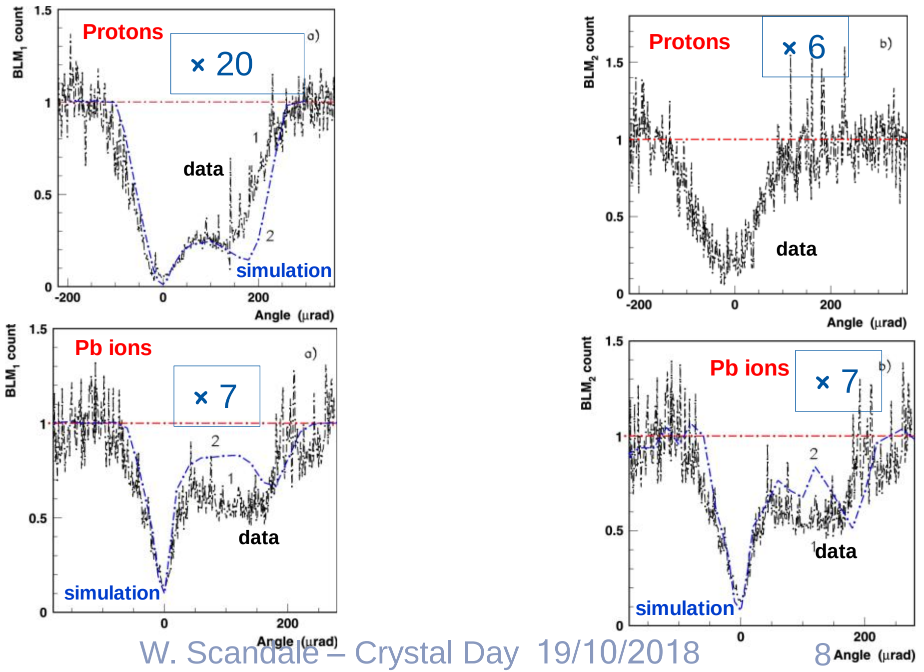
W. Scandale et al.

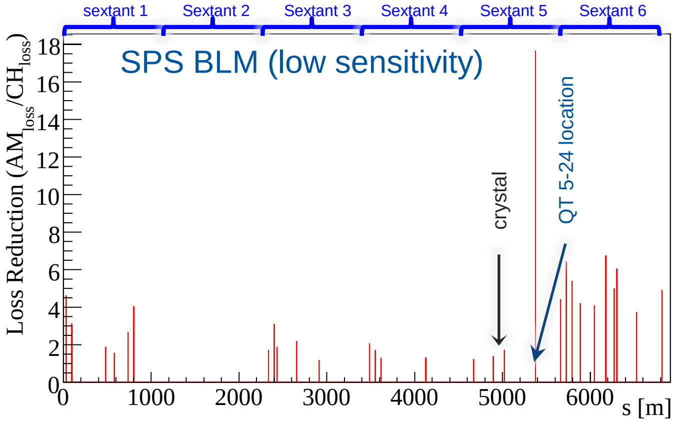
- Physics Letters B 726 (2013) 182–186
- Physics Letters B 714 (2012) 231–236
- Physics Letters B 703 (2011) 547–551
- Physics Letters B 692 (2010) 78–82

Main findings

- ✓ Crystal alignment fast and reproducible
- ✓ Loss rate is reduced everywhere in the SPS ring by well reproducible amounts as compared to a standard collimation scheme







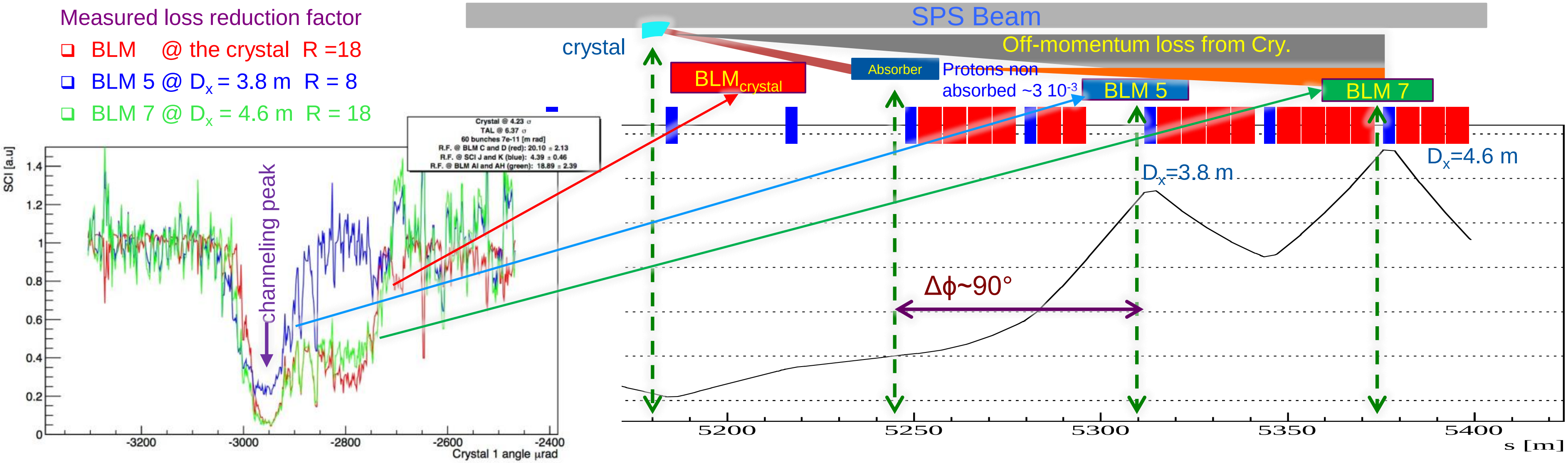
Losses in the dispersion suppressor (proton beam)

- ☐ Beam loss rate at high D_x has two contributions:
  - ✓ diffractive protons coming from the crystal
  - ✓ channeled protons non absorbed (in 60 cm of W)
- ☐ Simulations and measurements show that:
  - ✓ the two fractions sum-up at the first D_x peak location
  - ✓ only the fraction produced at the crystal survives at the second D_x peak location (for optical reasons)

W. Scandale et al, Phys. Lett. B 748 (2015) 451–454
CERN-ACC-2015-0143 ;
CERN-THESIS-2015-099

simulation results

Location	Crystal orientation	Losses from crystal	Losses from TAL	Total losses	Losses reduction
BLM5	AM	$4.7\ 10^{-5}$	$1.2\ 10^{-3}$	$1.2\ 10^{-3}$	~7
BLM5	CH	$7.7\ 10^{-7}$	$1.7\ 10^{-4}$	$1.7\ 10^{-4}$	
BLM7	AM	$1.5\ 10^{-4}$	$4.2\ 10^{-5}$	$1.9\ 10^{-4}$	~21
BLM7	CH	$2.1\ 10^{-6}$	$6.9\ 10^{-6}$	$9.0\ 10^{-6}$	



Measured loss reduction factor
- ☐ BLM @ the crystal R =18
- ☐ BLM 5 @ D_x = 3.8 m R = 8
- ☐ BLM 7 @ D_x = 4.6 m R = 18

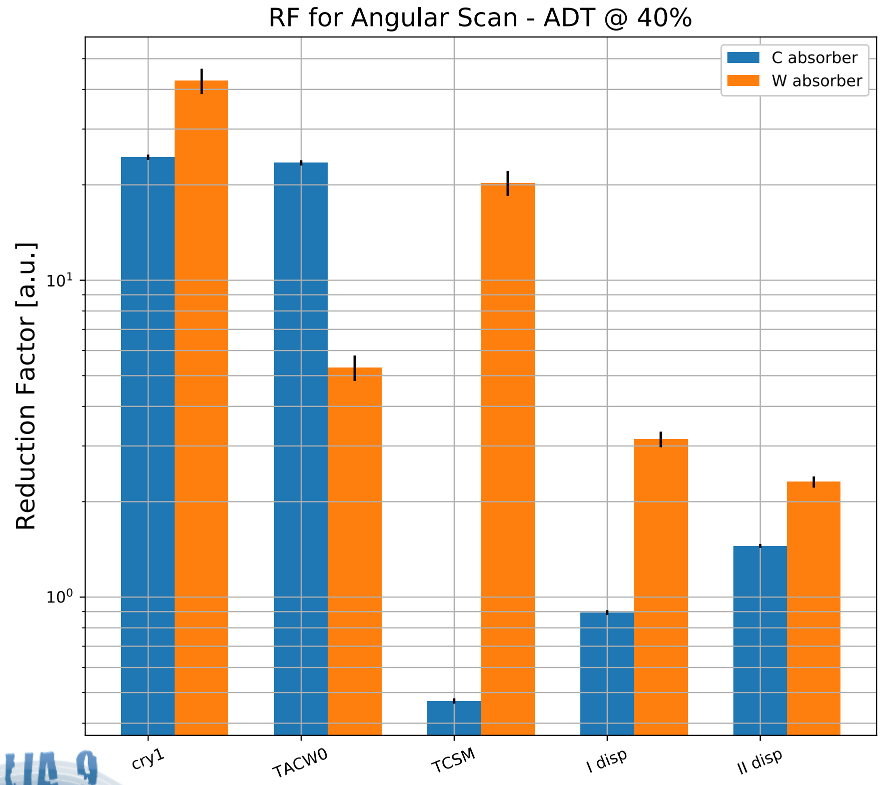
Crystal @ 4.23 σ
TAL @ 6.37 σ
60 bunches 7e-11 [m rad]
R.F. @ BLM C and D (red): 20.10 ± 2.13
R.F. @ SCI J and K (blue): 4.39 ± 0.46
R.F. @ BLM AI and AH (green): 18.89 ± 2.39

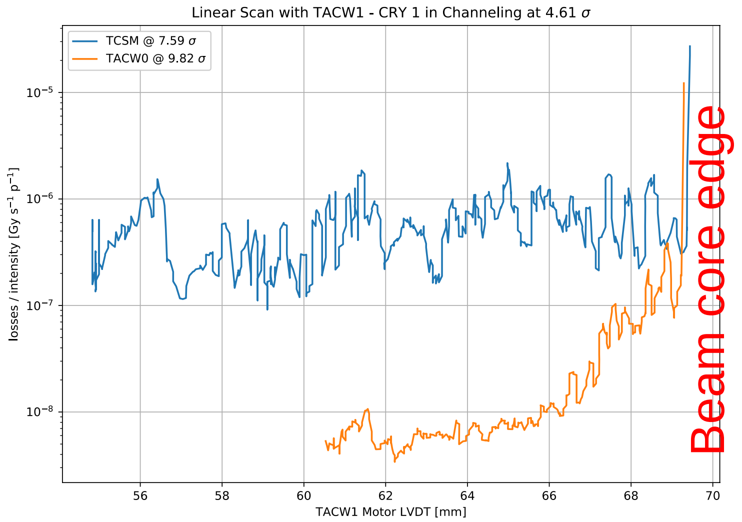
Role of the absorber for proton beam: W versus C

Loss reduction factor recorded during an angular scan

Loss rate recorded during a linear scan

Yet unpublished





Beam core edge

In all the recorded cases:

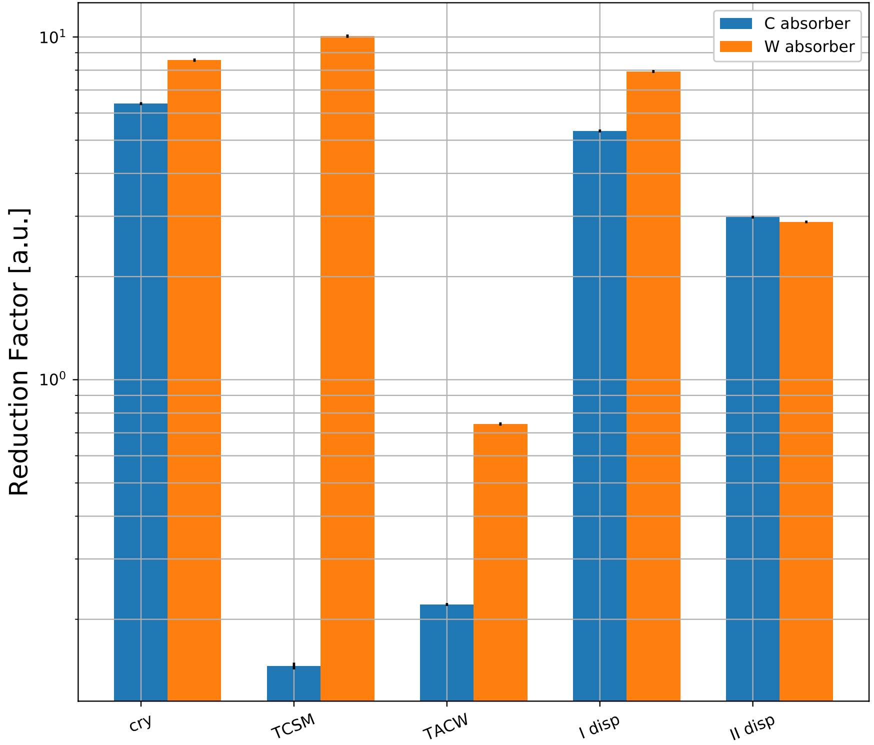
- Much higher leakage for C-collimator 1m long than for a W-collimator 60 cm long

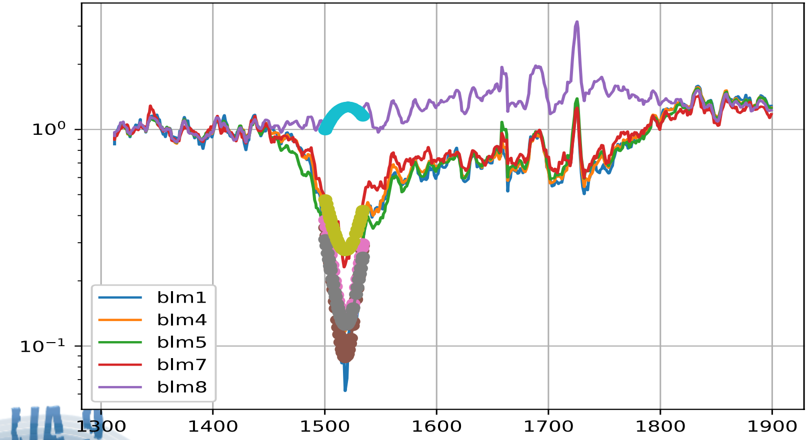
Role of the absorber for Xe beam

Yet unpublished

CH Reduction factor have been measured and compared for crystal collimation with W and C absorber.

In dispersive areas W improves slightly the performance

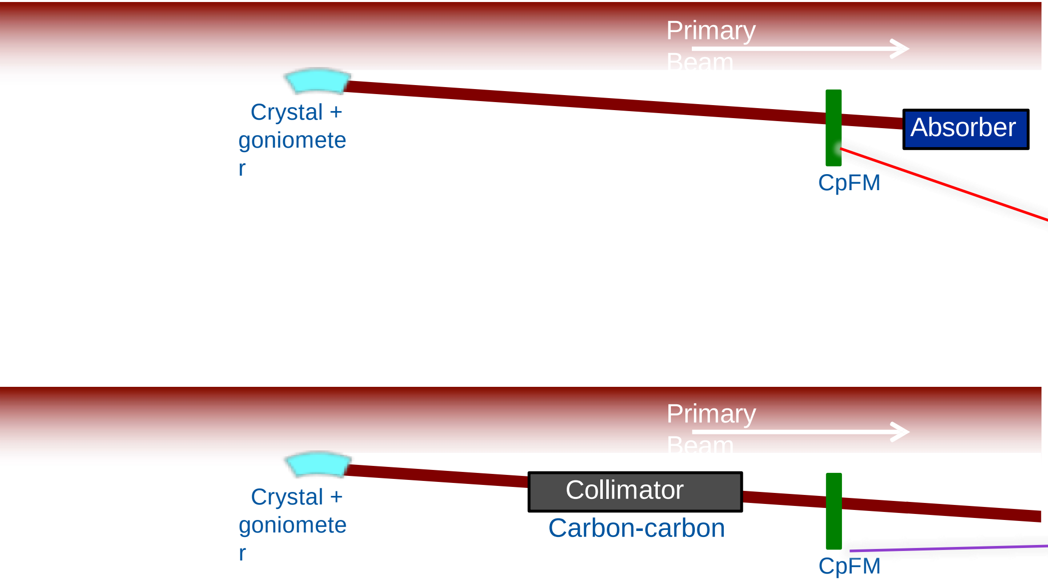




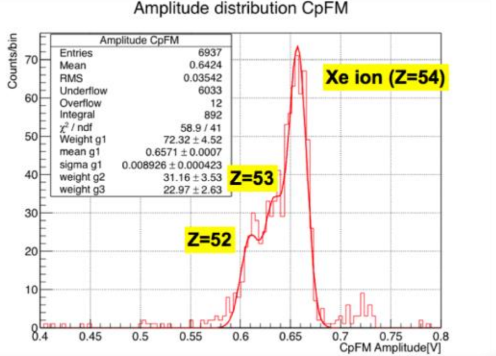
Role of the absorber for Xe beam

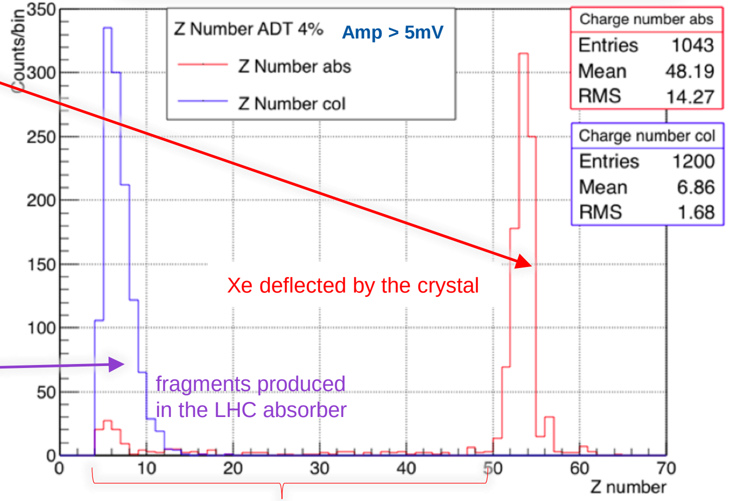
Xe beam

Yet unpublished



data collected with tha Cherenkov detector to disentangle nuclei with different charge





Xe deflected by the crystal

fragments produced in the LHC absorber

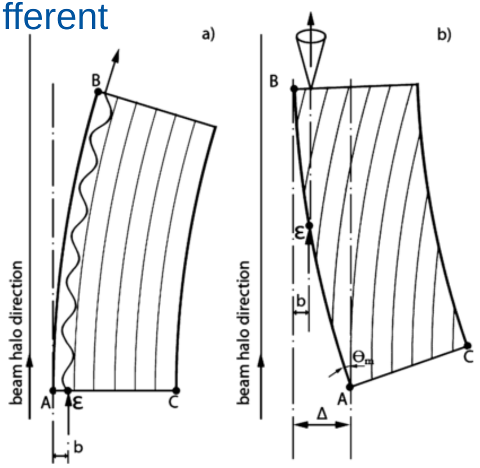
fragments produced by the interaction with the crystal

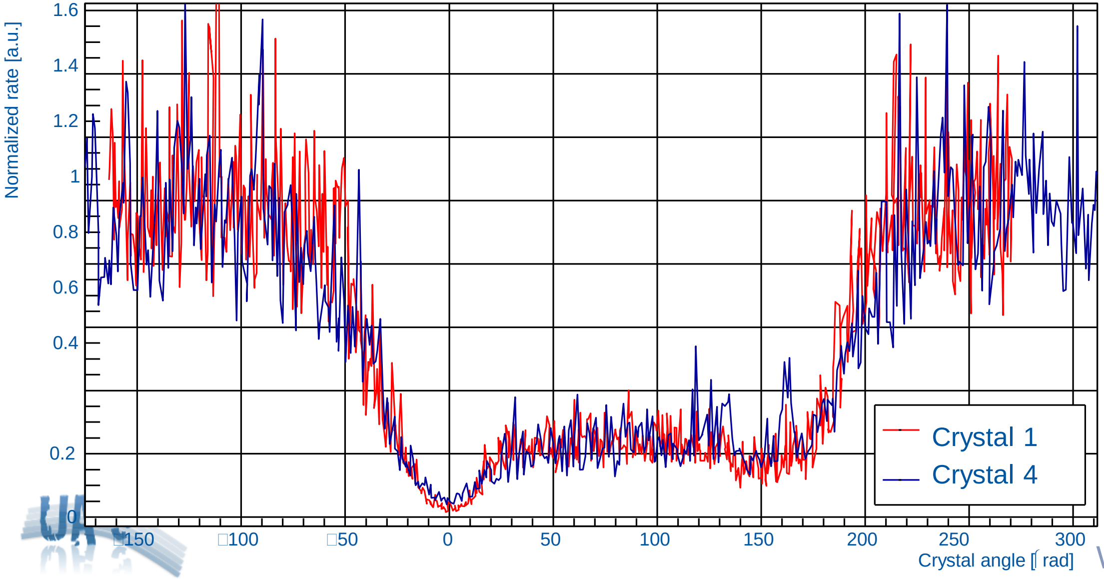
Crystal "miscut"

S. Petrucci: Master's Degree Thesis 2015 –Roma La Sapienza

- ❑ The angle between the lattice and the surface of the crystal is called miscut
- ❑ Test with two strip crystals (INFN-FE) with almost identical geometry and very different miscut were made to clarify its influence on the crystal collimation performance

Crystal	Bending angle	Length (z)	Width (x)	Mis-cut angle	Torsion
1	165 μrad	1.87 mm	0.5 mm	6 μrad	< 1 μrad/mm
4	176 μrad	2.00 mm	0.5 mm	200 μrad	< 1 μrad/mm





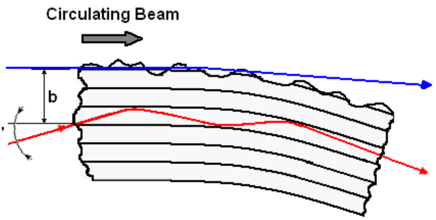
SPS data collected in 2015

- ❑ No significant change of the loss regime during angular scans.
- ❑ Similar results with proton or ion beams

Negligible effects at the SPS energy

Crystal “amorphous layer”

- ❑ In LHC particles in the halo drift outwards at the rate of ~2 nm per turn.
- ❑ Since the tune is not integer, the particles will hit the crystal every ~10-20 turns
- ❑ The first impact parameter of the particles onto the crystal is in the range of ~100 nm
- ❑ Crystal roughness should be lower than 100 nm on the lateral faces of the crystal



Anisotropic etching is the way chosen by INFN-Fe whilst optical polishing is the way chosen by PNPI to realize sub-surface damage free crystals entirely by wet chemical methods

Lateral surface (AFM)

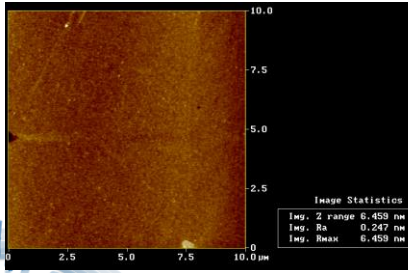
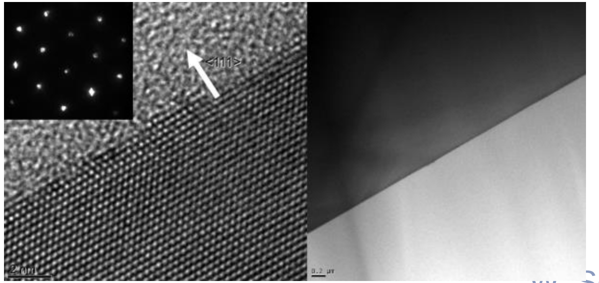


Image Statistics

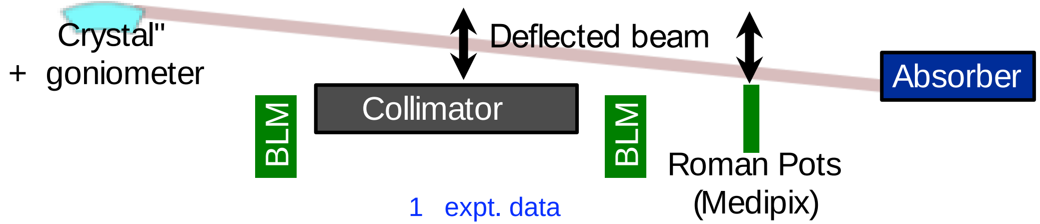
Img. Z range	6.459 nm
Img. Ra	0.247 nm
Img. Rmax	6.459 nm

Entry surface (HRTEM)

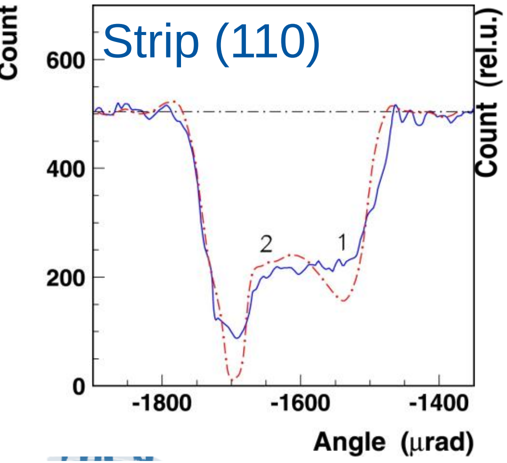


Sub-nm roughness is routinely achieved

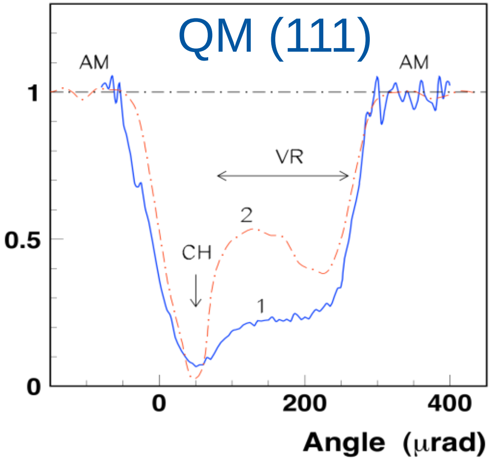
Characterization of crystals: (110) versus (111) planes



1 expt. data
2 simulation

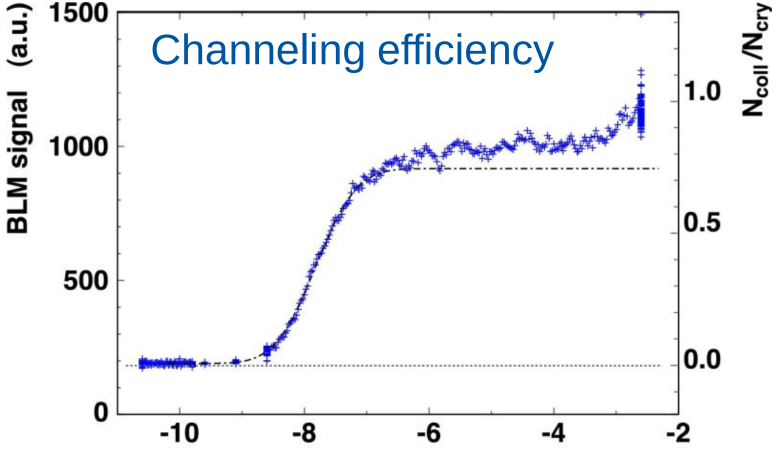

Strip (110)

Channeling efficiency (75±4)%


QM (111)

Channeling efficiency (85±5)%

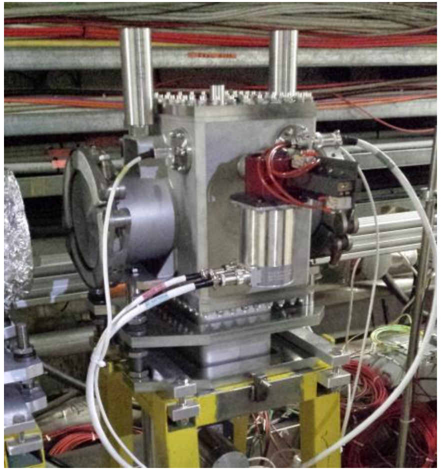
W. Scandale et al. / Physics Letters B 692 (2010) 78–82


Channeling efficiency

- Efficiency = $N_{deflected}$ / $N_{crystal}$
- Assumption:
  the number of particles intercepted by a moving object is proportional to the loss rate downstream the object
- $N_{deflected}$ is proportional to the losses when intercepting the whole deflected beam
- $N_{crystal}$ is proportional to the losses when the collimator is the primary aperture
- efficiency for Pb ions: 50÷70%

Test of the LHC-type Goniometer in SPS

Yet unpublished

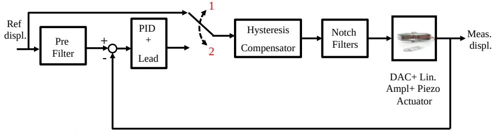


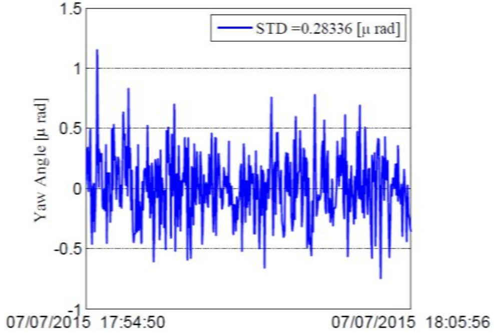
- The performance and the reliability of the LHC-type goniometer fully verified in the SPS:
  - closed-loop control system allows to compensate for mechanical vibrations and noise on the measurement system
  - unprecedented resolution (< 0.5 μrad)
  - good angular stability (STD < 0.3 μrad)
  - reproducibility of the angular positioning << θ_c = 10 μrad

- The operation of the goniometer in LHC was approved after the beam test in SPS

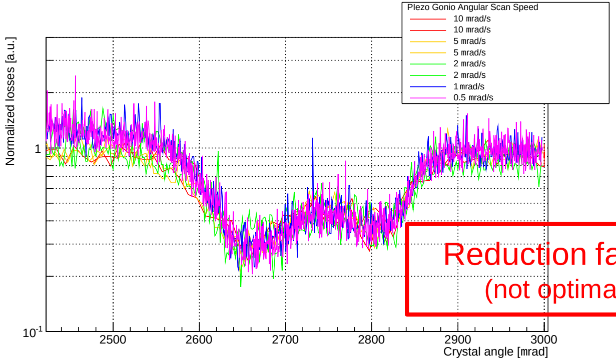
See also the talk of A. Masi

Angular stability with crystal fixed orientation



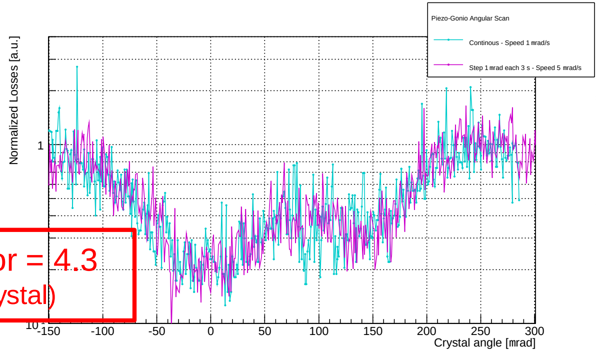


Varying the rotational speed

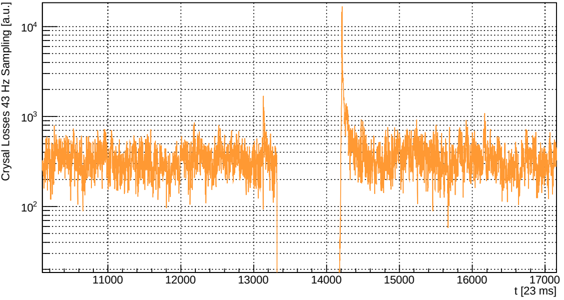


Reduction factor = 4.3
(not optimal crystal)

Varying the rotational step mode



stable loss for a large change of the linear position



Crystal simulations

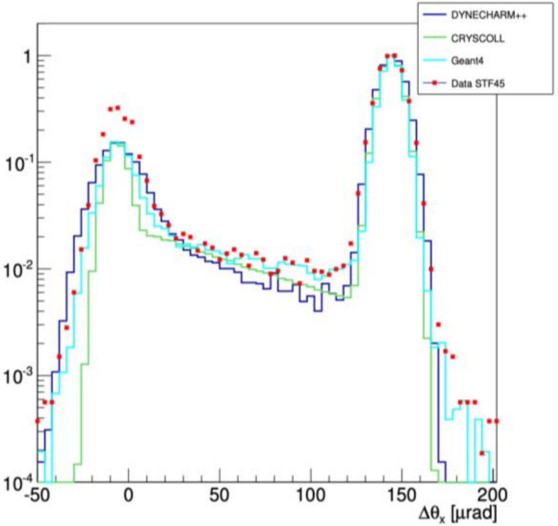
Proceedings of the international conference Channeling 15

Computer codes used in UA9 to simulate crystal-particle interactions:

1) CRYD (A. Taratin) is based on the integration of equations of motion in the crystal, interfaced with a relatively simple transfer matrix tracking code.
2) CrysColl (Y. Yazynin, V. Previtali, D. Mirarchi, W. Scandale) is based on event probability, interfaced to SixTrack by V.Previtali.
3) DYNACHARM++ (E. Bagli) is a Monte Carlo code based on the numerical solution of the equation of motion of particles in crystals whose electron densities and electric fields are computed from x-ray analysis. The code is integrated to GEANT4.
4) Crystal (P. Schoof) modeled in "FLUKA style", although not yet implemented in FLUKA itself. A version of SixTrack exists, already interfaced to FLUKA for the treatment of collimators.

- The four codes reproduce the measured data within 10%, and in particular channeling efficiency within 1% in a range of 1 critical angle.
- Few refinements in the models can still be done, but they would hardly affect the predictive power of the codes for collimation purposes @450 GeV

- The benchmark @ 7TeV is more delicate and is slowly progressing using the data collected during the LHC machine developments.



Conclusive remarks

The feasibility of crystal-collimation in hadron colliders has been fully demonstrated

- The key technologies have been well developed and validated:
  - Reproducible crystal production
  - Reliable bending methods
  - Assessment of crystal performance
  - Alignment methodologies
  - Instrumentation for a fast and reliable operation of crystal-collimation
- An efficient layout has been implemented in the SPS (and later in LHC)
- Experimental methods have been introduced to evaluate the collimation performance

In addition to these achievements, UA9 has investigated with success:

- Development and test of special crystal for other application
- Crystal-extraction in non-resonant mode
- Shadowing of the electrostatic septum to reduce beam-loss during resonant extraction
- New experimental concepts
  - To measure magnetic moment of rare baryons in high-energy hadron colliders, such as LHC
  - To reduce background and enhance the acceptance of an apparatus a la TOTEM investigating low-p physics

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Roberto Losito and later Simone Gilardoni, group-leaders of the CERN-EN-STI group, strongly contributed, together with their collaborators, to the construction, the validation and to the integration of the UA9 setups in the North Area, in the SPS ring and in the LHC.

Simone Montesano secured the technical coherence of the UA9 setups and later Marco Garattini ensured the operation of the H8 facility.
Geoff Hall and collaborator provided the telescope tracker used in the SPS North Area. Earlier versions of the telescope were built by Roberto Battiston and later by Michela Prest and collaborators.
Strip crystals bent due to anticlastic curvature by a special holder were invented in1998 and developed by Yury Chesnokov and collaborators.
“Quasi-mosaic” crystals were developed by Yury Ivanov, Yury Gavrikov and collaborators.
Other crystals were provided by Vincenzo Guidi, Pietro Dal Piaz, and collaborators.
Gianluigi Arduini proposed the initial experimental location of UA9 in the SPS.
Ralph Assman and later Stefano Redaelli and co-worker provided the conceptual support and the financial effort to perform crystal assisted collimation tests in LHC.
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