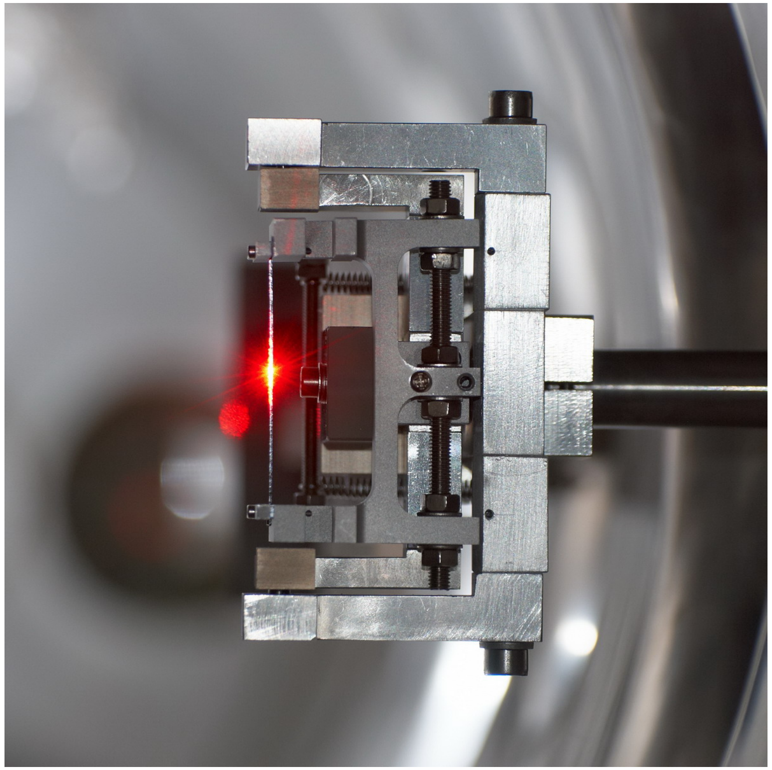
Bent Crystal Assisted Beam Manipulation

Status of UA9

W. Scandale CERN

- Role of UA9
- Highlight of the past results
- Test in LHC
- What next (at least in 2017/18)



MoU 2009-2014

The UA9 Experiment, was approved in April 2008 in view of investigating:

- the feasibility and the parameters of crystal assisted collimation in the SPS,
- the crystal-particle interactions in the North Area of the SPS,
- the crystal assisted collimation in LHC.

Memorandum of Understanding of the UA9 Collaboration signed in 2009

UA9-CERN agreement 2010

Investigation of crystal-assisted collimation as a way to eventually improve the halo cleaning performance in LHC.

Sharing of the duties:

- The **UA9 Collaboration** was in charge of
  - assessing the scientific aspects of the new concept
  - pursuing the technical developments for the various hardware and software components
  - evaluating performance of crystal collimation through experimental tests in the North Area and in the SPS
- The **UA9 Collaboration and the LHC Collimation Project** had the shared responsibility of
  - proposing the layout and the protocol for the implementation of crystal collimation in LHC
  - supporting reference simulation tools to assess the crystal collimation performance
  - performing the tests in LHC
- The **LHC Collimation Project** was responsible for
  - assessing the compatibility of the crystal collimation performance with the LHC machine protection requirements.

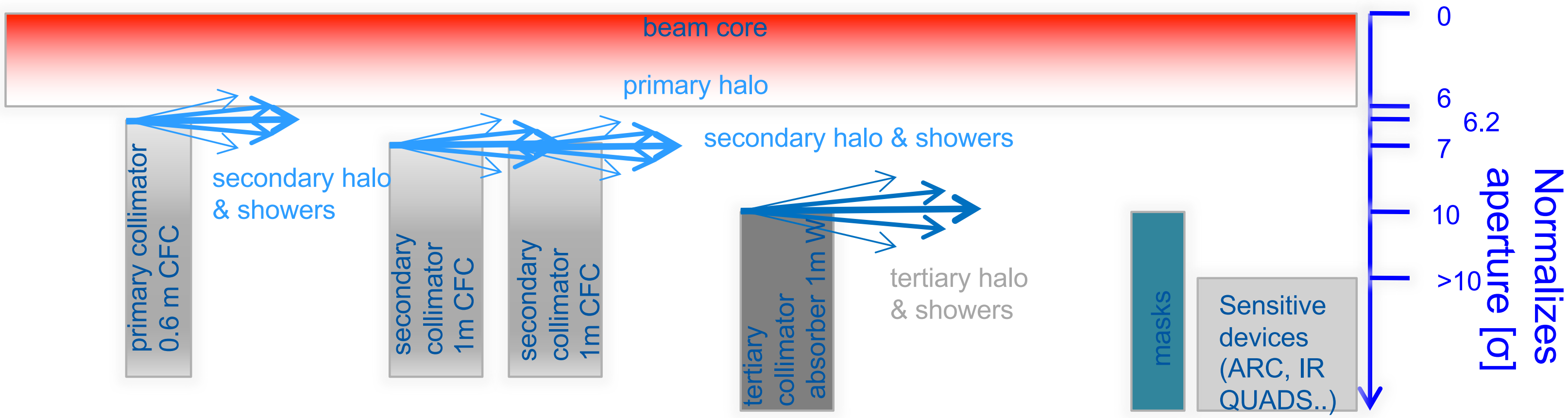
UA9 MoU extension 2015-2019

The UA9 Experiment, was extended in view of

- consolidating the assessment of the crystal assisted collimation performance,
- **providing expertise for investigating crystal assisted halo extraction and crystal assisted resonant and non-resonant slow extraction in CERN SPS**
- investigating crystal-particle interactions in hadronic or leptonic microbeams extracted from CERN SPS accelerator into the CERN North Area.
- consolidating the implementation of crystal-assisted collimation in LHC.

Multi stage collimation as in LHC

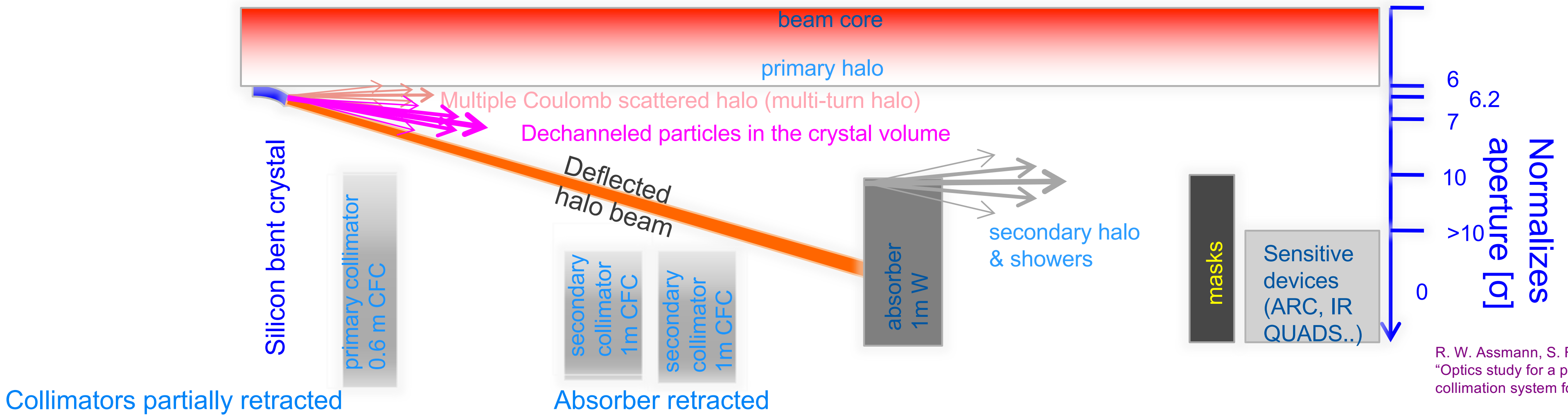
- The halo particles are removed by a cascade of amorphous targets:
  1. Primary and secondary collimators intercept the diffusive primary halo.
  2. Particles are repeatedly deflected by Multiple Coulomb Scattering also producing hadronic showers that is the secondary halo
  3. Particles are finally stopped in the absorber
  4. Masks protect the sensitive devices from tertiary halo



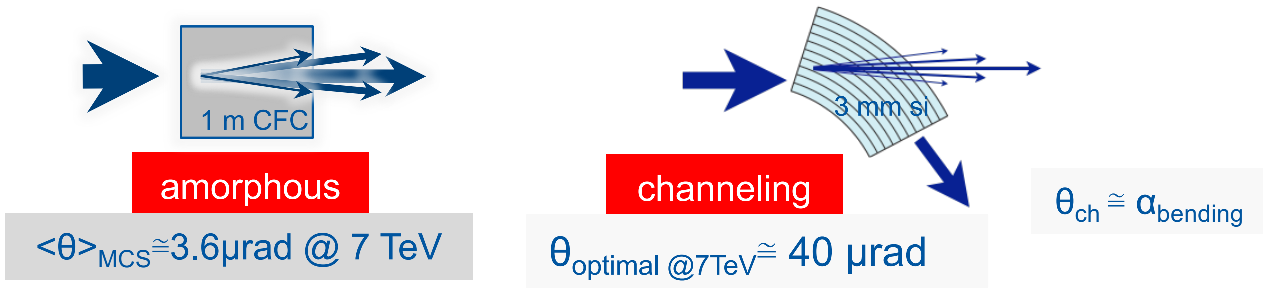
- Collimation efficiency in LHC ≅ 99.98% @ 6.5 TeV
  - ✓ Probably not enough in view of a luminosity upgrade
  - ✓ Basic limitation of the amorphous collimation system
    - ✧ p: single diffractive scattering
    - ✧ ions: fragmentation and EM dissociation

Crystal assisted collimation in LHC

- Bent crystals work as a “smart deflectors” on primary halo particles
- Coherent particle-crystal interactions impart large deflection angle that minimize the escaping particle rate and improve the collimation efficiency



R. W. Assmann, S. Redaelli, W. Scandale, “Optics study for a possible crystal-based collimation system for the LHC”, EPAC 06



CERN | UA9 | LHC Collimation Project CERN | High Luminosity LHC

Potential improvements for LHC

1. Larger impact parameter: crystals deflect the halo particles coherently to a larger angle than the amorphous primary collimator,
   - ✓ better localization of the halo losses → evidence from UA9 data in the SPS
   - ✓ reduced collimation inefficiency → $\times 10^{-1}$ expected from simulations
   - ✓ higher beam intensities (if limited by halo density)
2. Less impedance: Optimal crystals are much shorter than the amorphous primary collimators and produce much less impedance
   - ✓ 20% reduction of the overall impedance (by replacing the primary with a crystal) → from simulations
3. Less nuclear events: inelastic nuclear interactions with bent crystals strongly suppressed in channeling orientation → lower probability of producing proton diffractive events or lead ions fragmentation and dissociation
   - ✓ × 20 less nuclear events in 120÷270 GeV channeled protons ℗ UA9 data in the SPS ring
   - ✓ × 7 less nuclear events in 120÷270 GeV/u channeled lead ions ℗ UA9 data in the SPS ring

W. Scandale et al, Physics Letters B 714 (2012) 231–236

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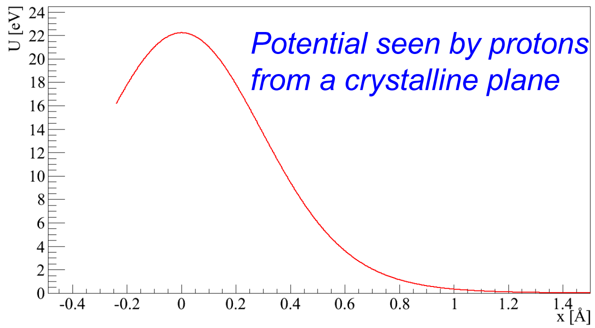
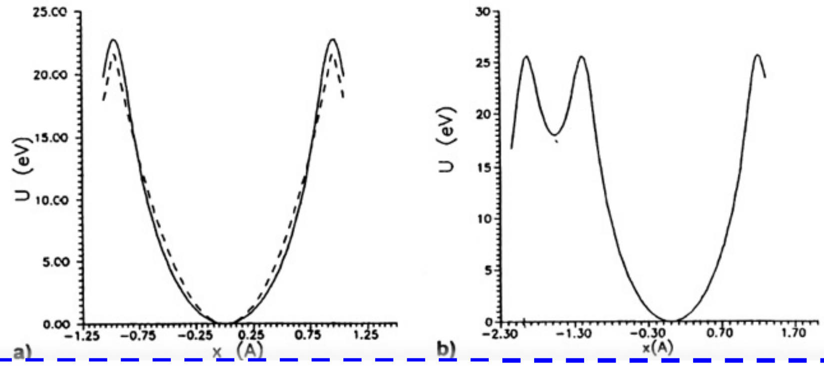
Crystals

Potential between a **particle** and an **atom** described by the **Thomas-Fermi model:**

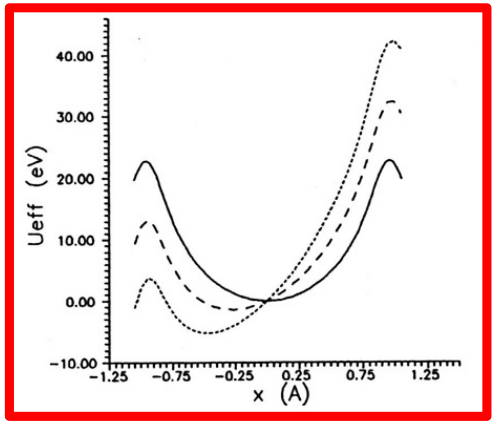


Continuous approximation:

$$U_p(x) = Nd \iint_{-\infty}^{+\infty} V(x,y,z)dydz$$



Effect of a bending angle

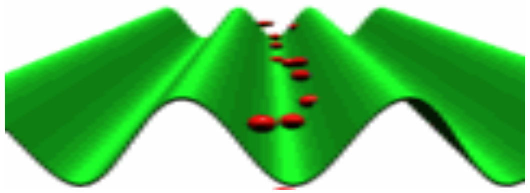


*If the protons **have p_T < U_{max}***

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

Forced to oscillate in a relatively empty space

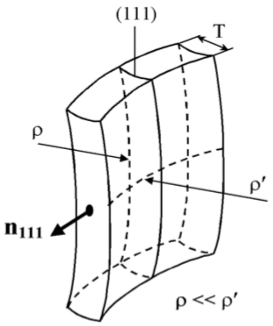
$$x(z) = \frac{d_p}{2}\sqrt{\frac{E_t}{U_{max}}}\sin(\frac{2\pi z}{\lambda} + \phi)$$



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

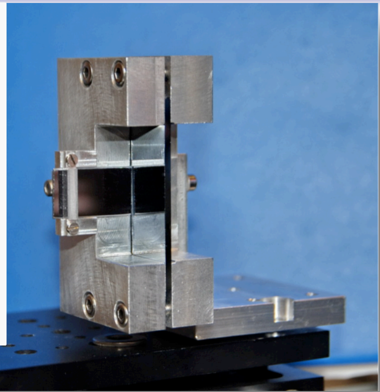
Case	Energy [GeV]	θ_c $[\mu rad]$	λ $[\mu m]$
SPS coast	120	18.3	33.0
SPS coast	270	12.2	49.6
H8	400	10.0	60.3
LHC inj.	450	9.4	64.0
LHC top	6500	2.5	243.2
LHC top	7000	2.4	252.3

Bent crystals for UA9



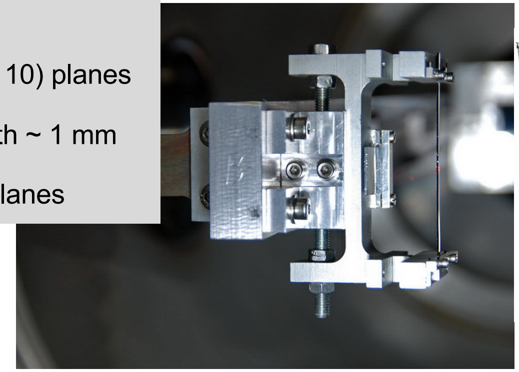
Quasimosaic crystal

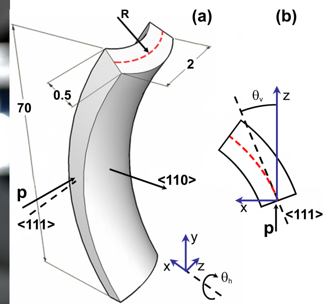
- Bent along (111) planes
- Minimal length a few tenths of mm
- Non-equidistant planes d1/d2 = 3



Strip crystal

- Bent along (110) planes
- Minimal length ~ 1 mm
- Equidistant planes



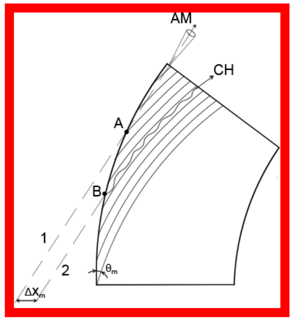


Crystals

- Dislocation-free silicon crystals plates or strips
- For optimal channeling efficiency
  - ✓ short length (few mm)
  - ✓ moderate bending radius 45 ÷ 70 m

> - SPS at 120÷270 GeV) 1÷2 mm length, 150÷170 μrad angle
> - LHC 3÷5 mm length, 40÷60 μrad angle

- Mechanical holders with large C-shape frame imparting the main crystal curvature
  - ✓ Strip crystal: (110) planes are bent by anticlastic forces
  - ✓ Quasimosaic crystal: (111) planes are bent by 3-D anticlastic forces through the elasticity tensor
- Expected crystal defects:
  - ✓ Miscut: can be ≤ 40 μrad, but negligible effect if good orientation is applied
  - ✓ Torsion: can be reduced down to 1 μrad/mm → UA9 data in the SPS North Area
  - ✓ Imperfection of the crystal surface: amorphous layer size ≤ 1 μm



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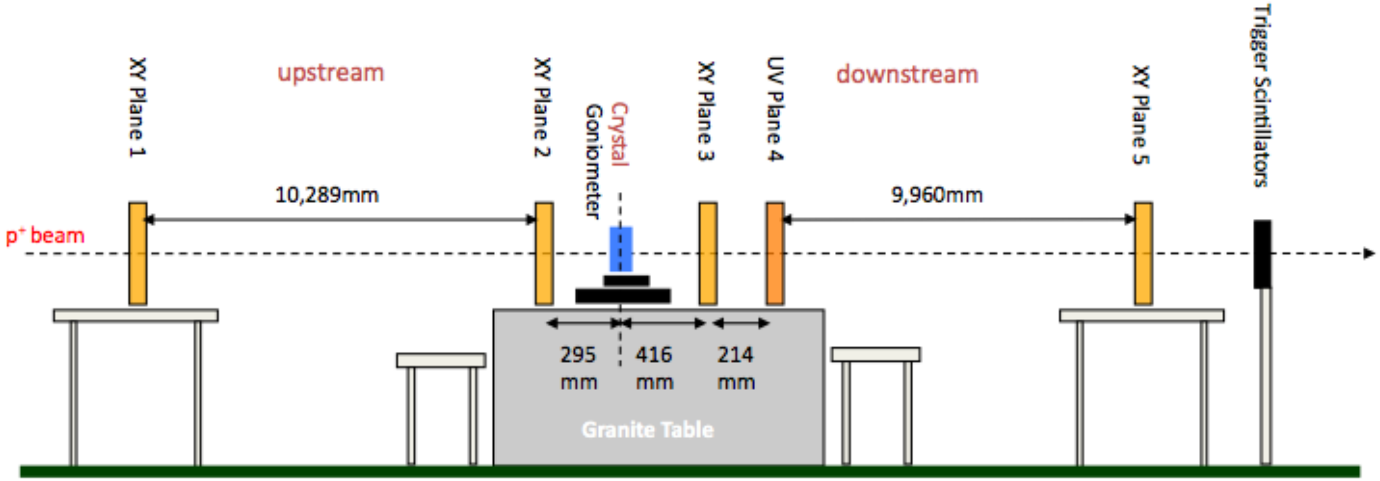
Detectors for UA9 in the North Area

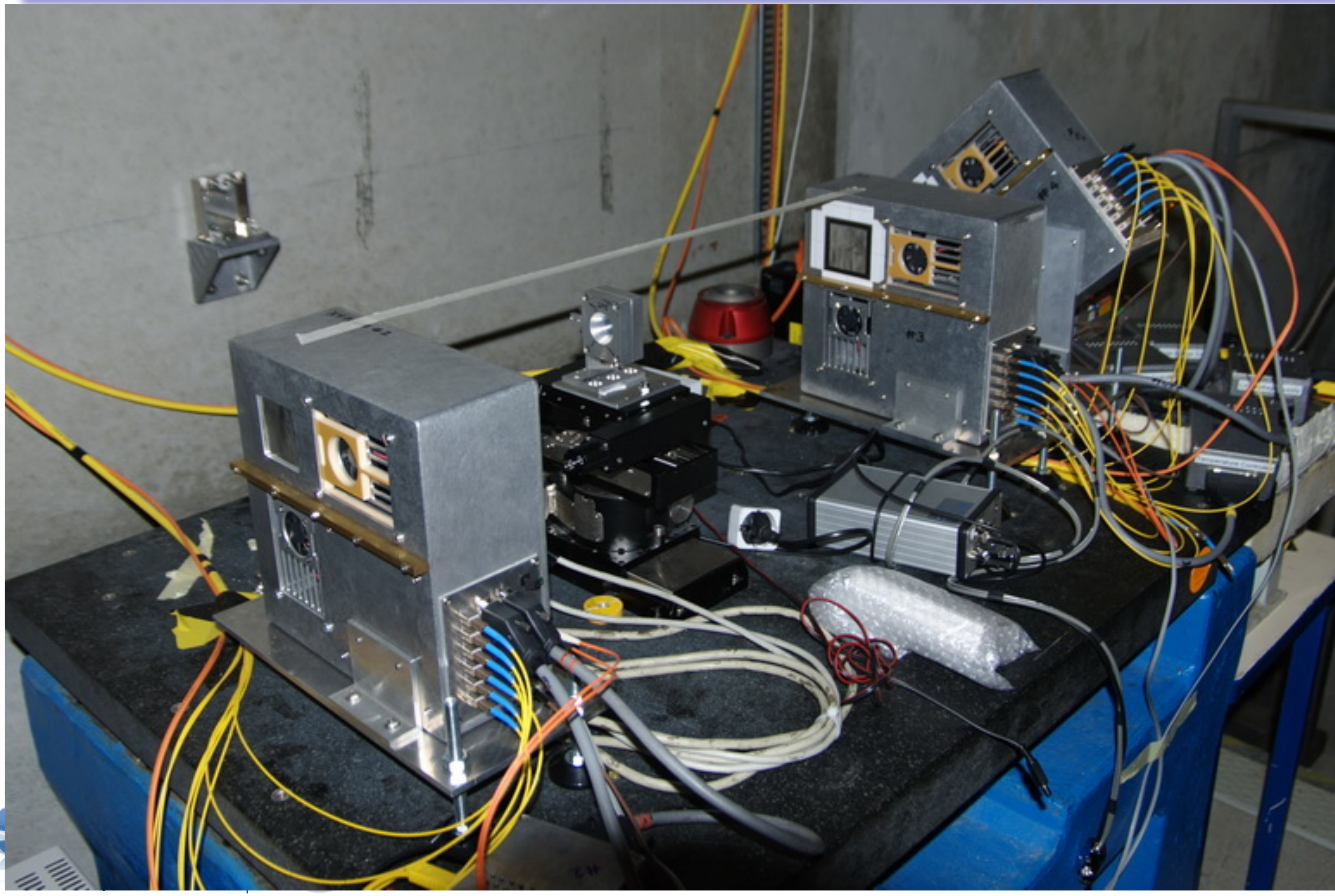
Two measurement arms – 10m length in each



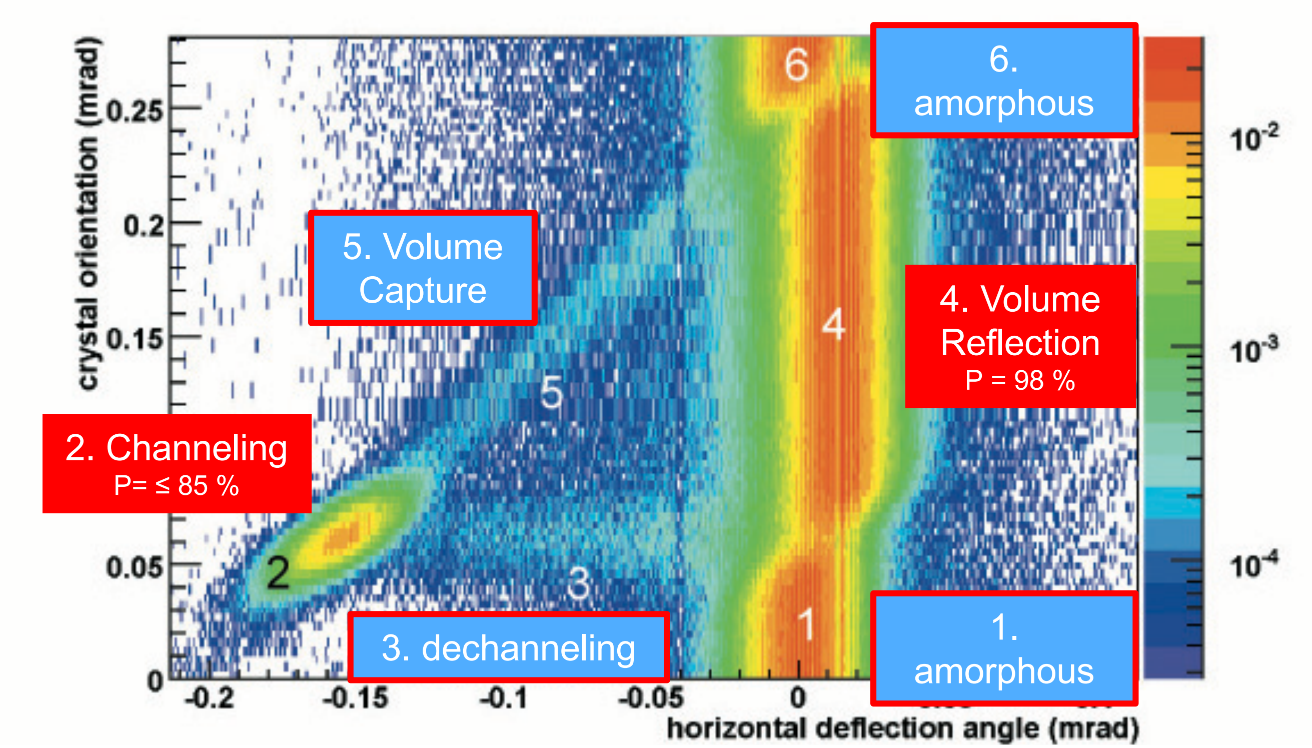
M Pesaresi et al 2011 JINST 6 P04006

- Use a low-divergence incoming beam
- Choose the crystal orientation by acting on the goniometer
- Detect the incoming direction of each particle
- Detect the outgoing direction after the interaction with the crystal
- Detect inelastic events

Detectors for UA9 in the North Area



Coherent interactions in bent crystals



- ❑ Two coherent effects could be used for crystal collimation:
  - ✓ Channeling → larger deflection with reduced efficiency
  - ✓ Volume Reflection (VR) → smaller deflection with larger efficiency

W. Scandale et al, PRL 98, 154801 (2007)

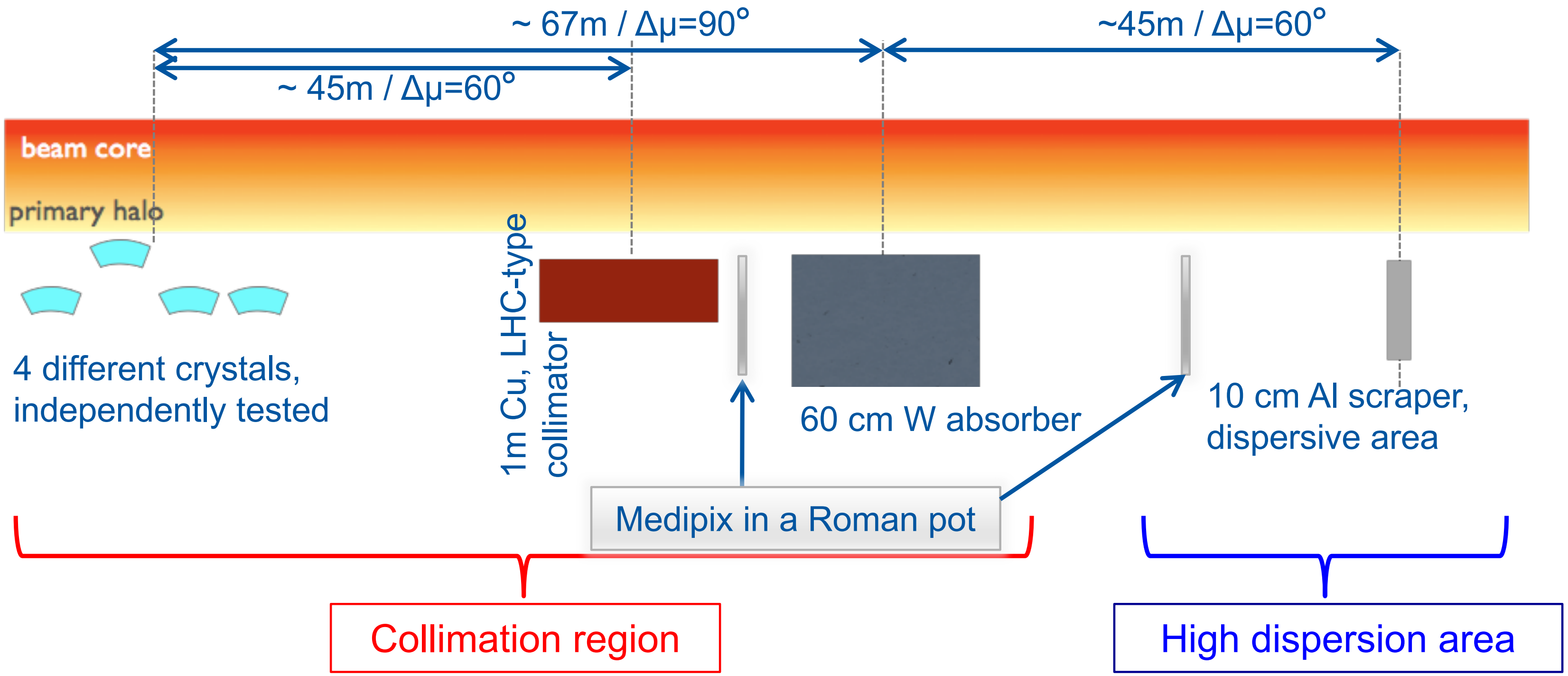
- ❑ SHORT CRYSTALS in channeling mode are preferred

  ×5 less inelastic interaction than in VR or in amorphous orientation (single hit of 400 GeV protons)

W. Scandale et al., Nucl. Inst. and Methods B 268 (2010) 2655-2659.

UA9 basic layout in the SPS (2008-now)

W. Scandale, M. Prest, SPSC-P-335 (2008).
W. Scandale et al, "The UA9 experimental layout", submitted to JINST, Geneva (2011).



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

Some UA9 devices in the SPS

CERN

Goniometer

The critical angle governs the acceptance for crystal channeling

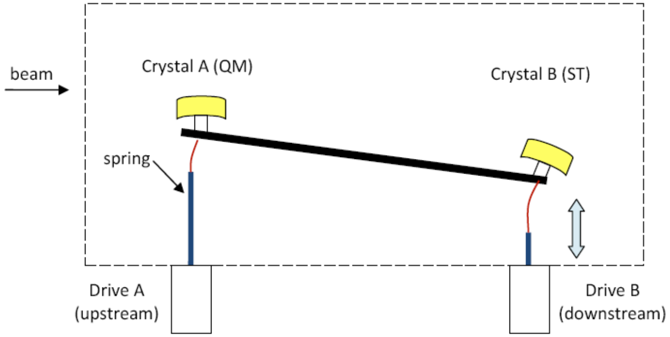
- 120 GeV ⓟ θ_c = 20 μrad
- 450 GeV ⓟ θ_c = 10 μrad
- 7 TeV ⓟ θ_c = 2.5 μrad

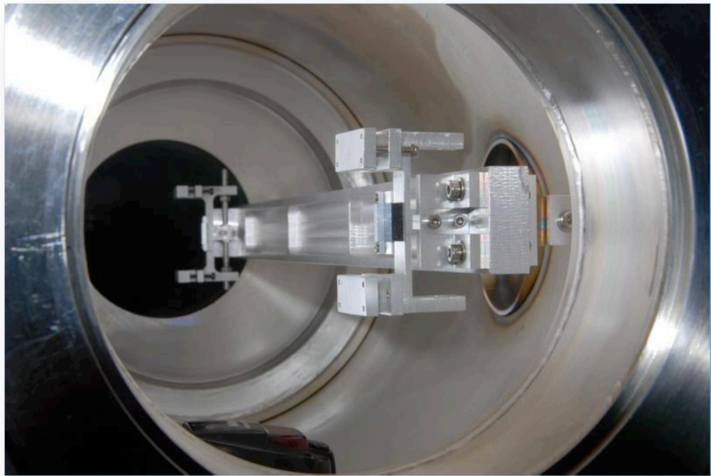
$$\theta_c = \sqrt{\frac{2U_0}{E}}$$

Required goniometer accuracy

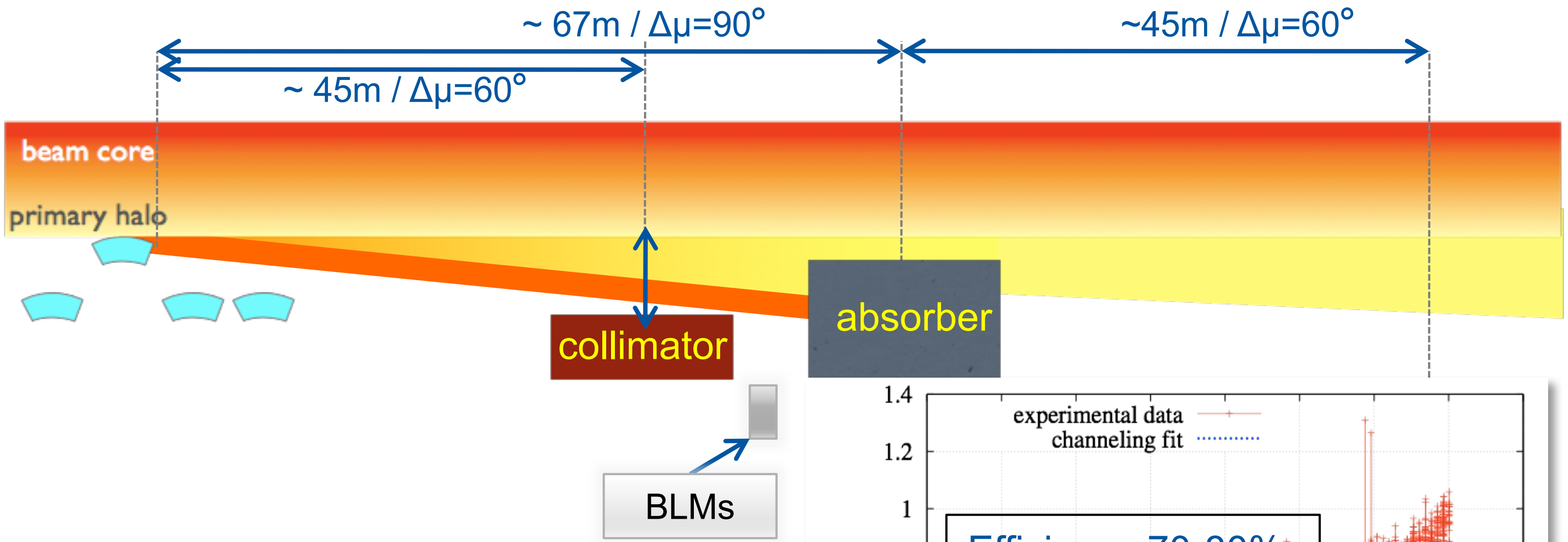
- δθ = 10 μrad for E ≤ 450 GeV
- δθ = < 1 μrad at LHC collision

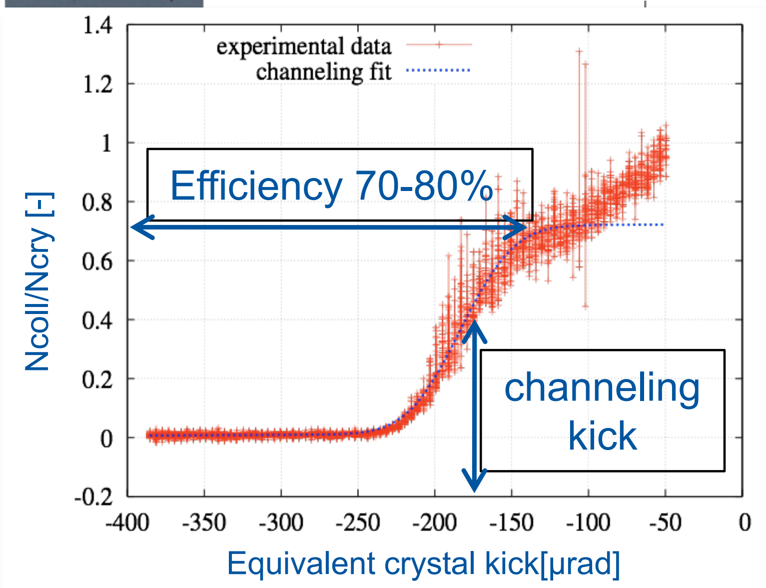
IHEP goniometer providing δθ = 5 μrad





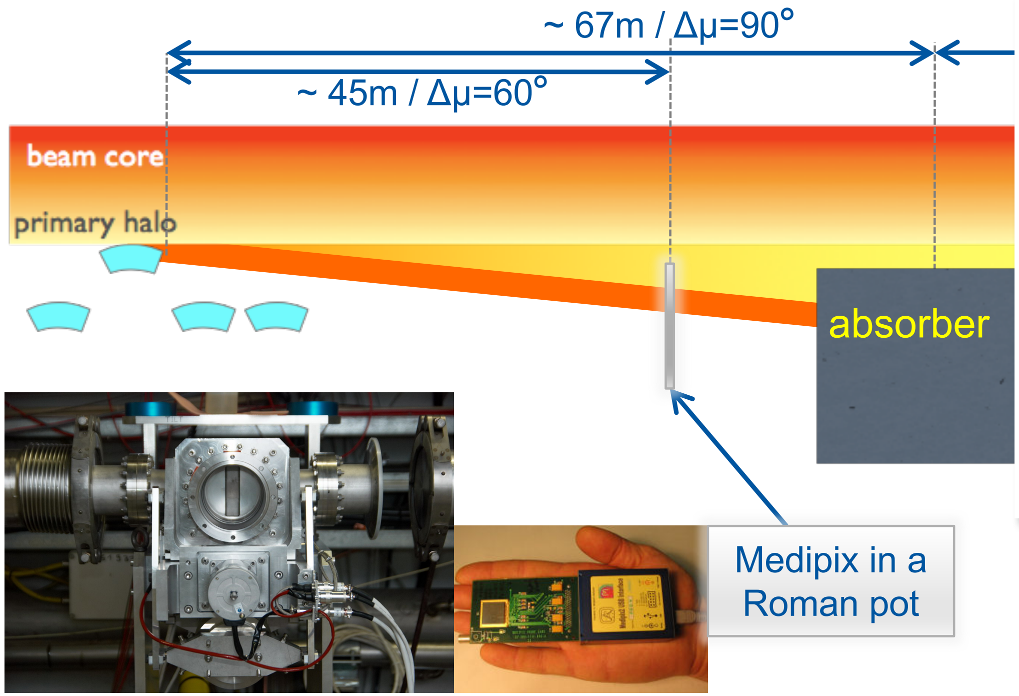
Channeling efficiency by coll. scans

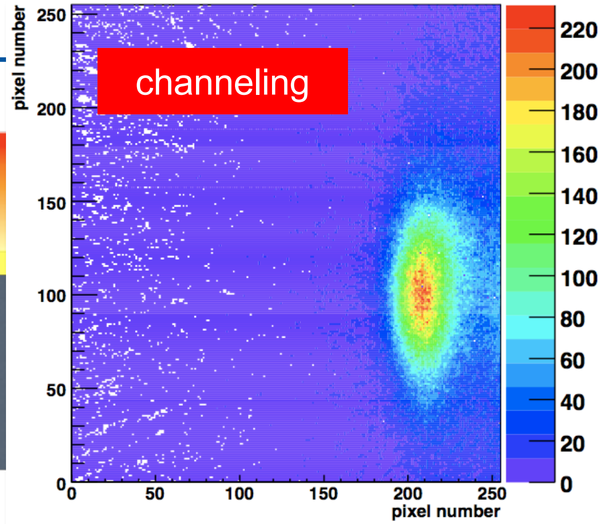


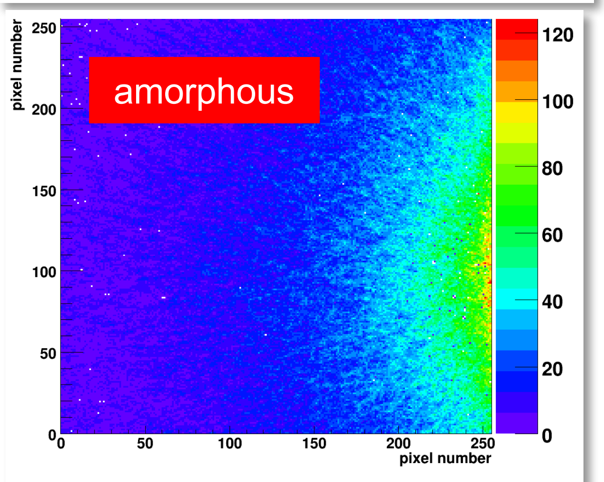


Multi turn channeling efficiency and channeling parameters are measured using a collimator scan, and analyzing the losses detected by downstream BLMs

Direct view of channeled beam







Medipix pixel detector in a Roman pot:

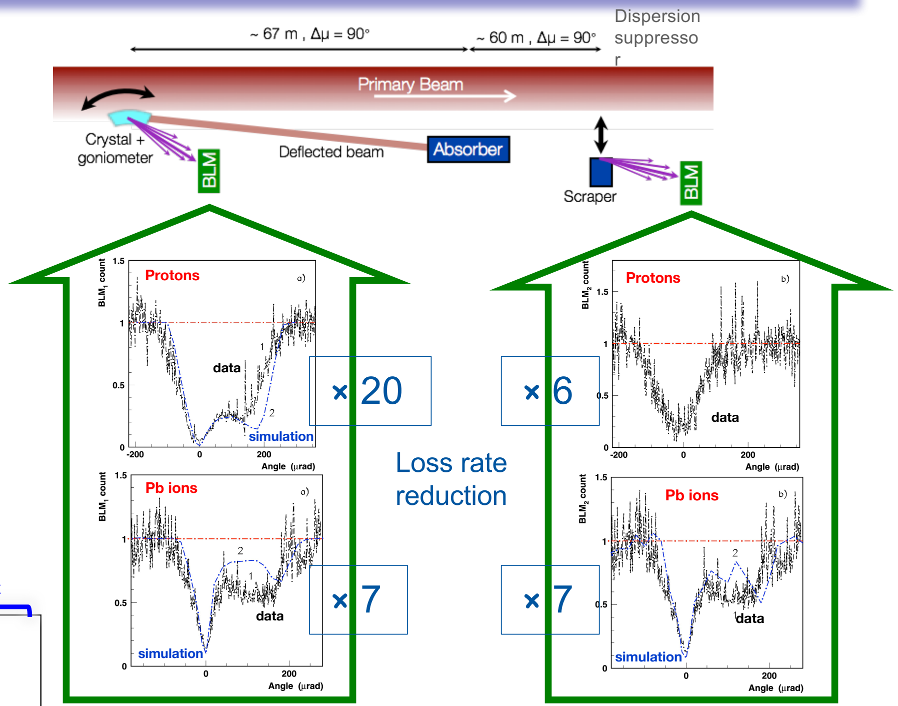
- Intensity, profile and angle of the deflected beam
- Efficiency of channeling (with multi-turn effect) (needs information on circulating beam current)

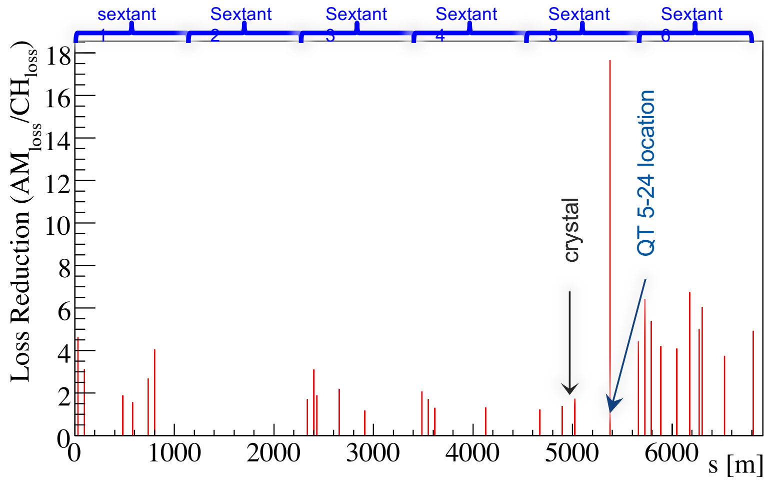
Loss rate reduction

Crystal collimation has been extensively tested in SPS

- ✓ Alignment (linear and angular) of the crystal is fast and well reproducible.
- ✓ Consistent reduction of the losses when comparing the crystal in channeling and in amorphous orientation:

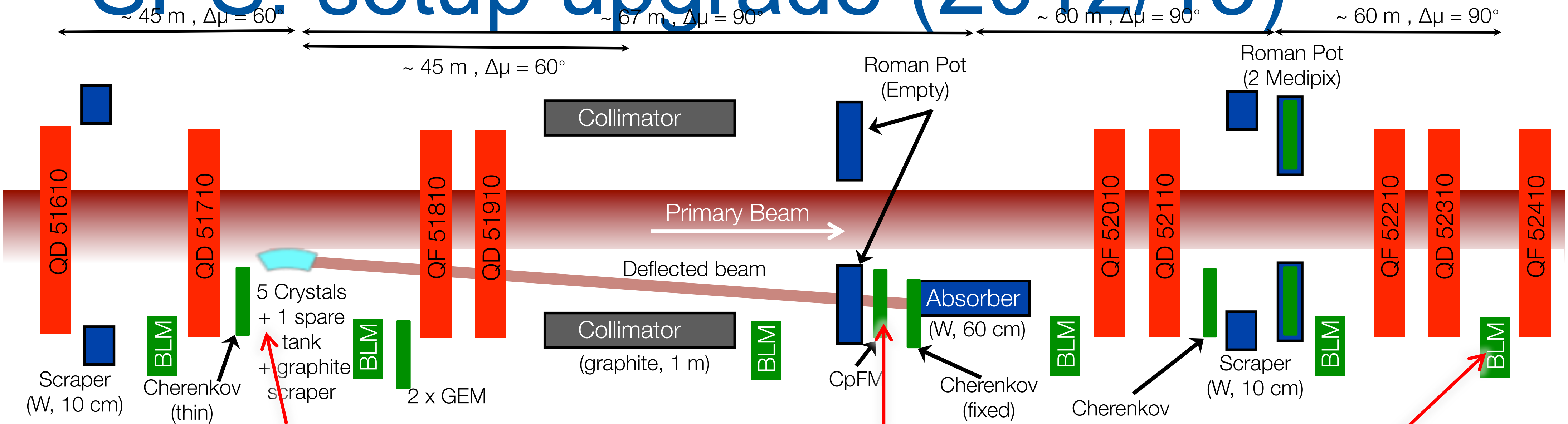
Physics Letters B 726 (2013) 182–186
Physics Letters B 714 (2012) 231–236
Physics Letters B 703 (2011) 547–551

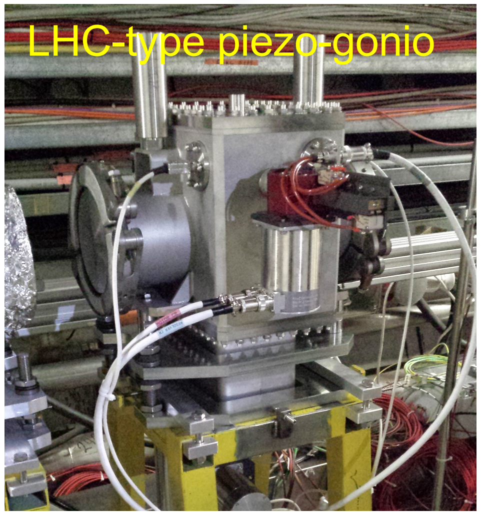


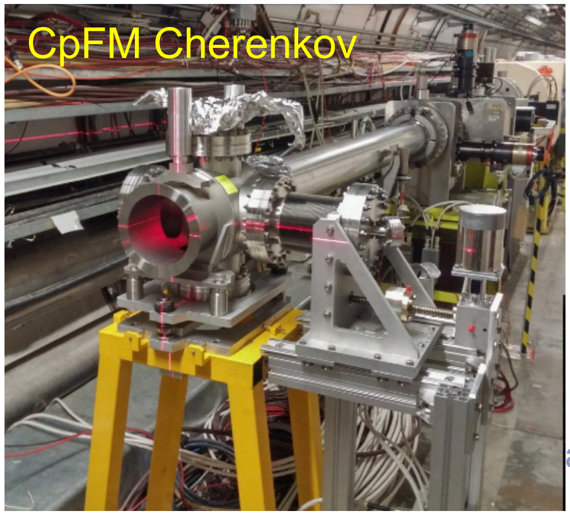


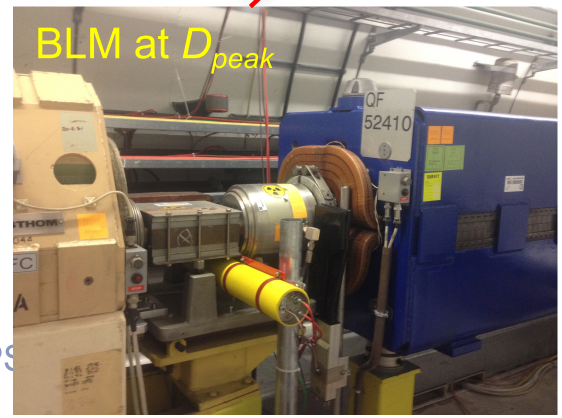
- ❑ Loss rate reduction at the crystal up to 20x for protons, 7x for ions.
- ❑ Loss rate reduction in the dispersion suppressor up to 6x for protons, 7x for ions.
- ❑ Losses all around the accelerator ring consistently reduced.

SPS: setup upgrade (2012/13)









SPS: leakage reduction in the dispersive area

CERN-ACC-2015-0143 ; CERN-THESIS-2015-099

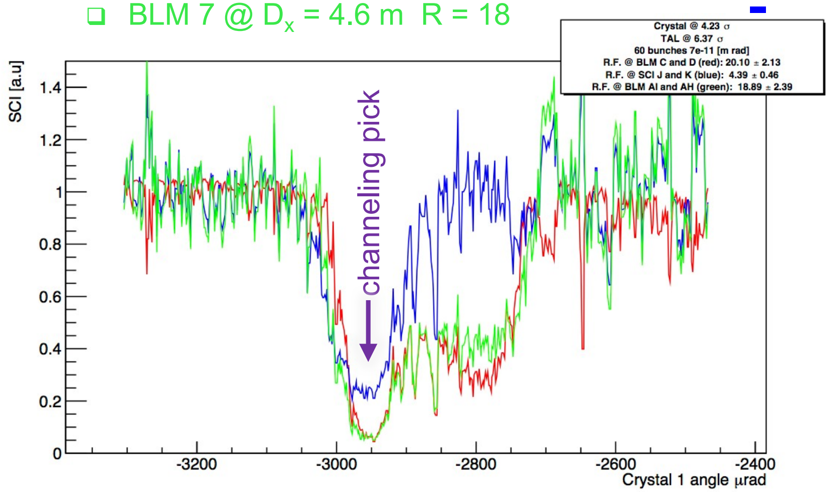
- Beam loss rate at high D_x has two contributions:
  - ✓ diffractive protons coming from the crystal
  - ✓ protons non absorbed in the TAL
- Simulations of SIXTRACK + CRYSCOL (upgraded)
  - ✓ The two fractions are different at the two D_x peaks
  - ✓ Data collected in 2012 with low-sensitivity BLM agree with simulation predictions.

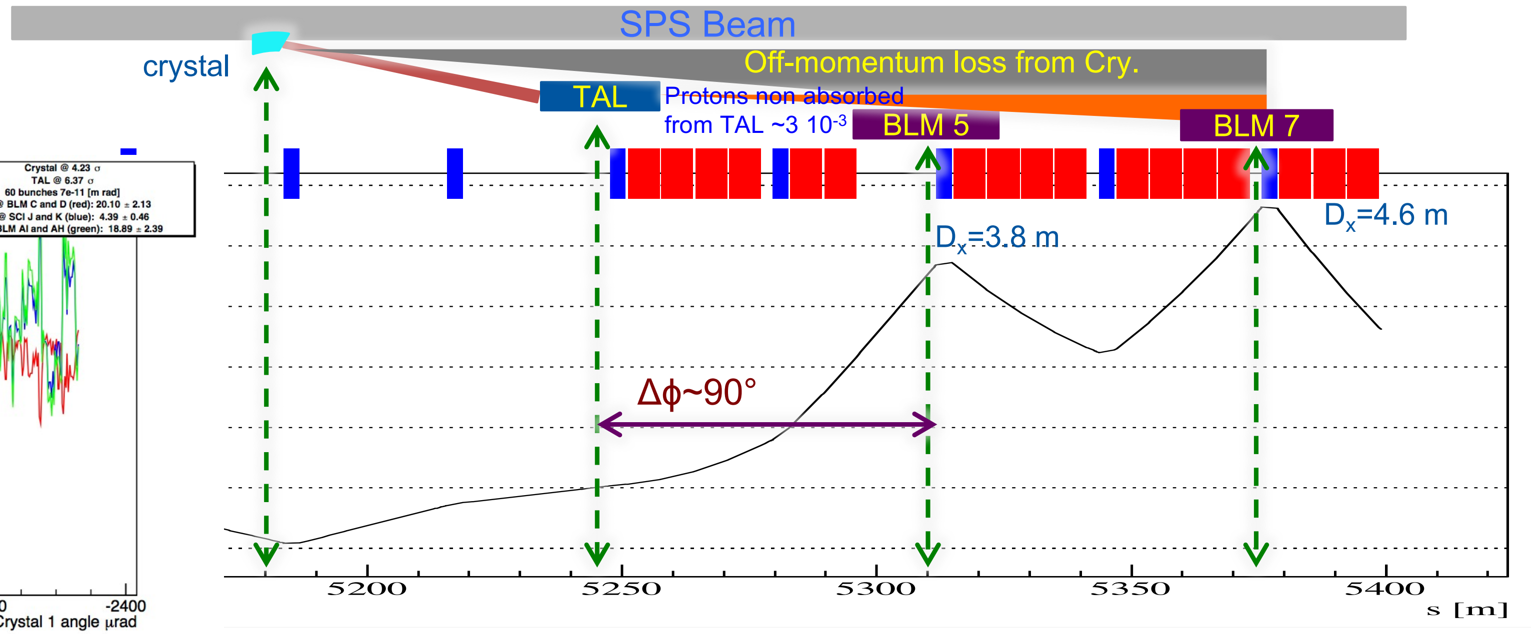
SIXTRACK + CRYSCOL simulation results with BLM7 at QF 5-22

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

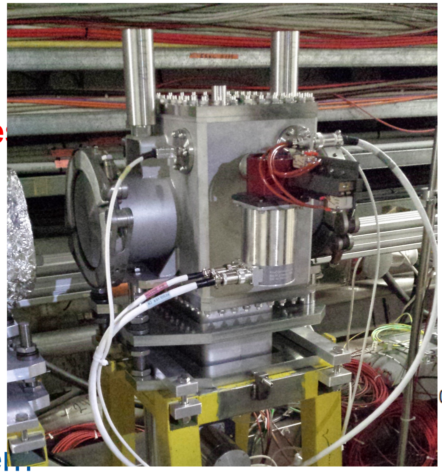
- BLM @ the crystal R =18
- BLM 5 @ D_x R = 8
- BLM 7 @ D_x = 4.6 m R = 18



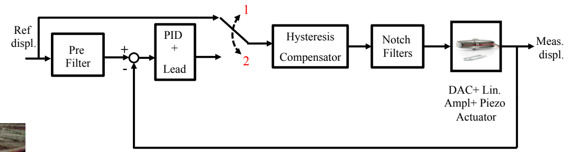


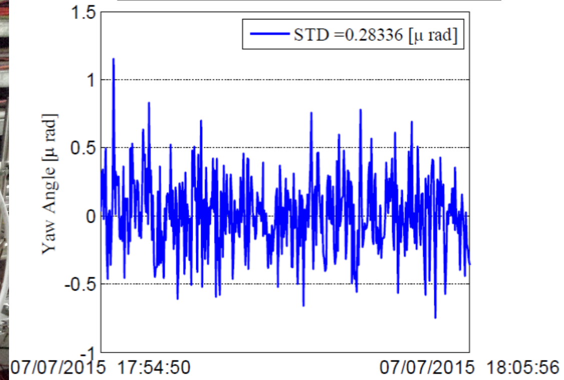
SPS: LHC-type goniometer

- LHC-type goniometers:
  - sophisticated control system developed on the laboratory te bench device
  - the goniometer installed in SPS was used for the first test with the beam in July 2015
- The performance and the reliability of the goniometer is fully verified:
  - 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)
  - successful test of the reproducibility in operation with beam ($\boldsymbol{\delta\theta} << \theta_c$ = 10 μrad)
- The operation of the devices in LHC has been approved after the beam test in SPS!

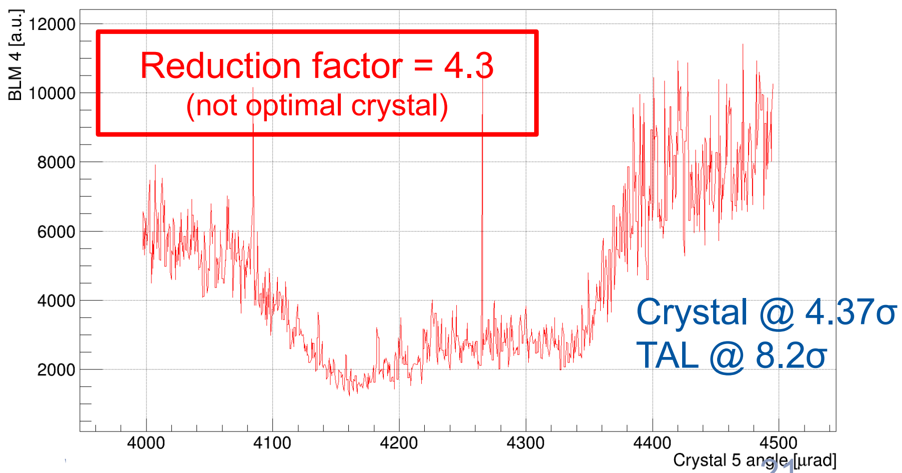


Angular stability with crystal fixed orientation





Angular scan 0.5μrad/s

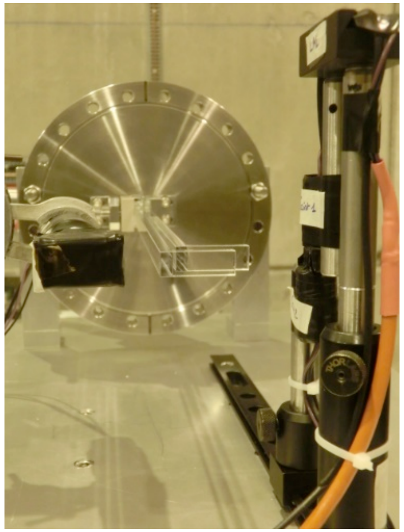


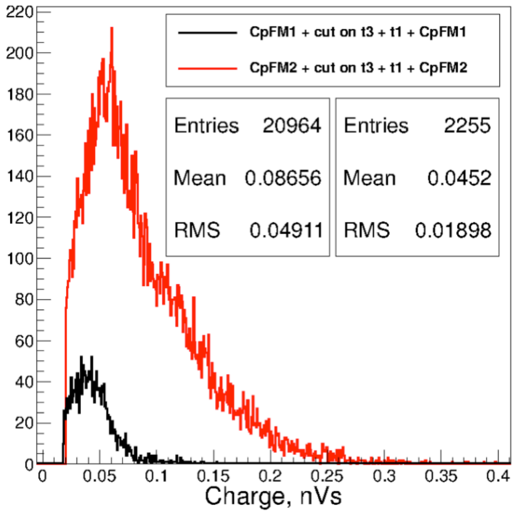
SPS data collected on July 2015

SPS North Area: new detectors tested

New CpFM detector for SPS and LHC

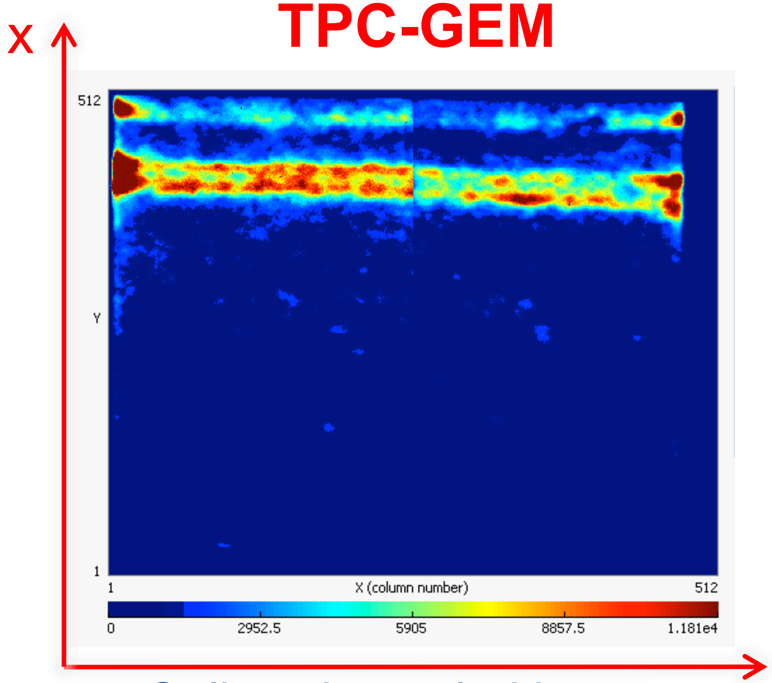
(Cherenkov for proton Flux Measurements)





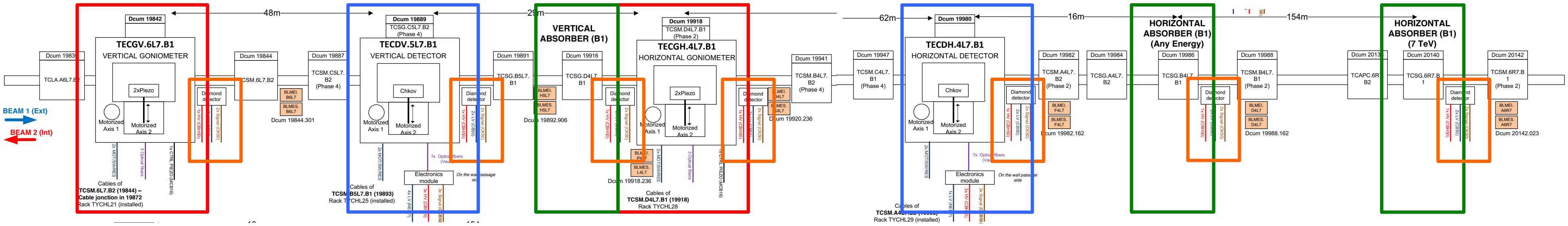
Charge histogram of the two bars of the CpFM

TPC-GEM



Online channeled beam monitoring with TPC-GEM

LHC: experimental runs



Data taking runs:

- November 6^{th} 2015 with protons
  - crystal channeling in the horizontal plane at 6.5 TeV (record energy).
- December 2^{nd} 2015 with lead ions
  - horizontal and vertical crystals deflecting lead ions at injection energy
- July 29^{th} 2016 with protons
  - characterization and measurements of both crystals at LHC top proton energy.
  - Angular and collimator linear scans performed at both injection and top energies.

LHC: collimation in the horizontal plane

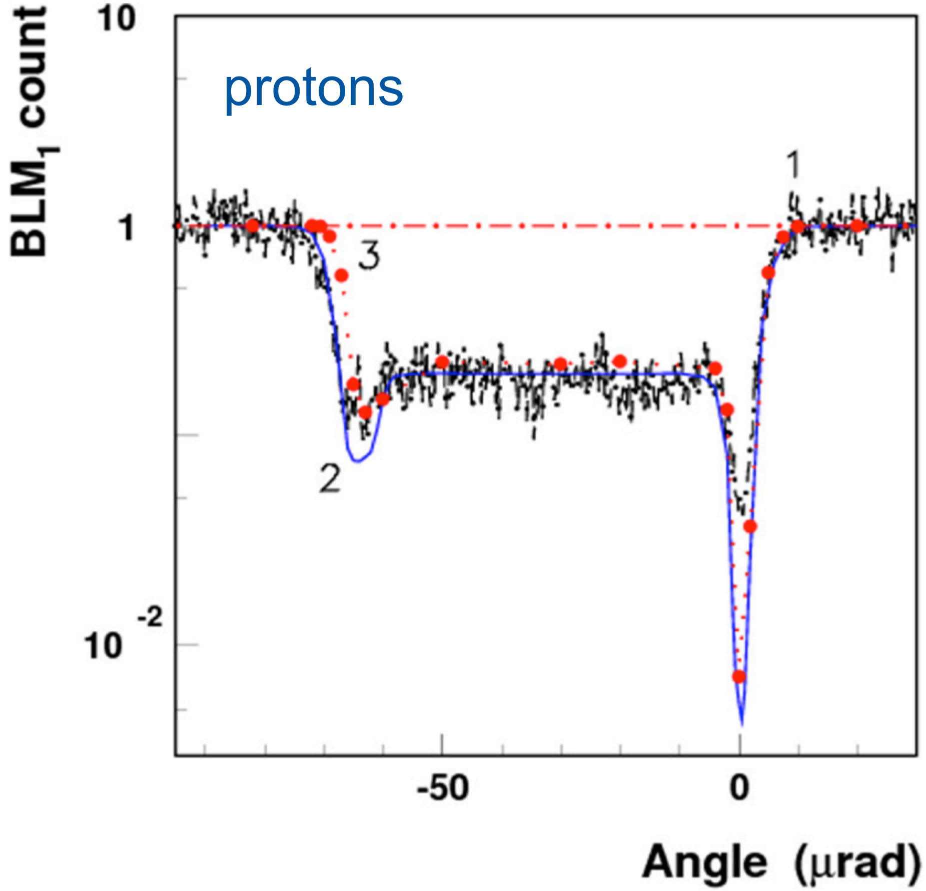
Physics Letters B 758 (2016) 129–133

Angular scan at 6.5 TeV energy. Loss rate as a function of the angle

Curves 2 (solid blue line) and 3 (dotted red line) shows results with two different simulation models.

- Crystal collimation setup:
  - Crystal at ~ 5.6 σ (1 σ = 1.53 mm)
  - Collimators upstream the crystal are retracted
  - TCSGs at 7 σ, TCLAs at 10 σ (nominal position)

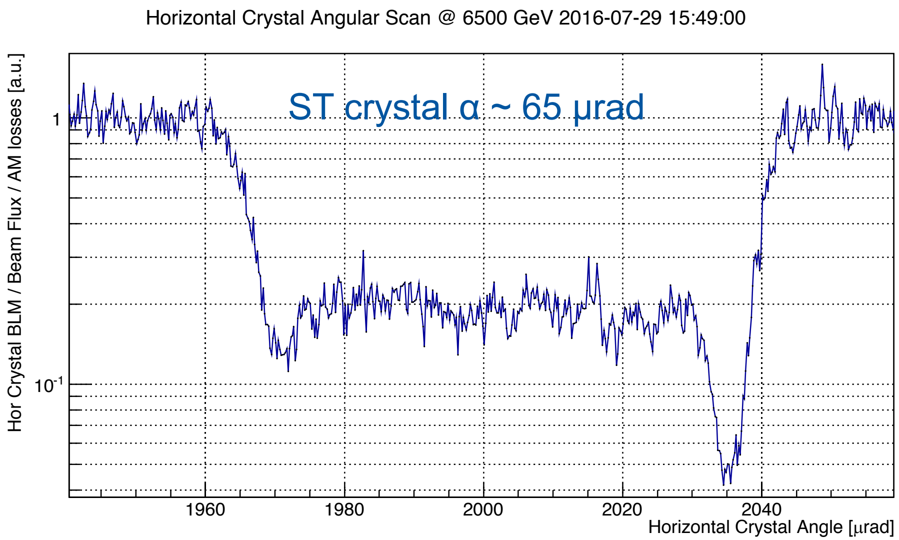
No explanation yet available for the large discrepancy between data and simulation results in channeling orientation



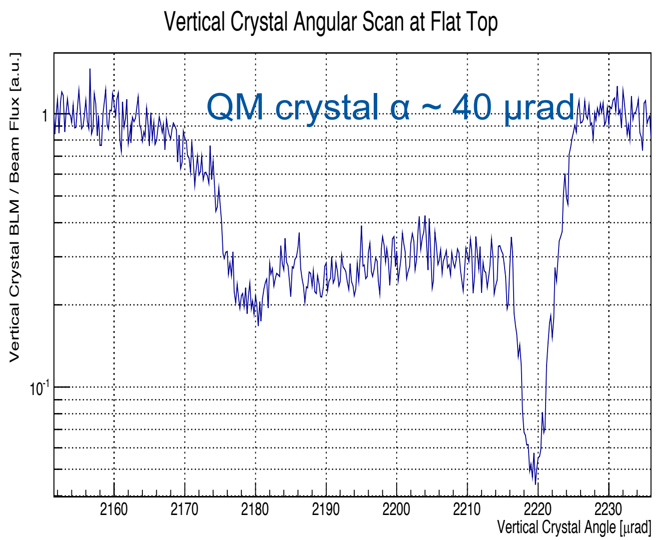
LHC: angular scans at 6.5 TeV

Loss reduction in channeling orientation almost identical

Angular scans of QM and the strip crystals have the same behavior

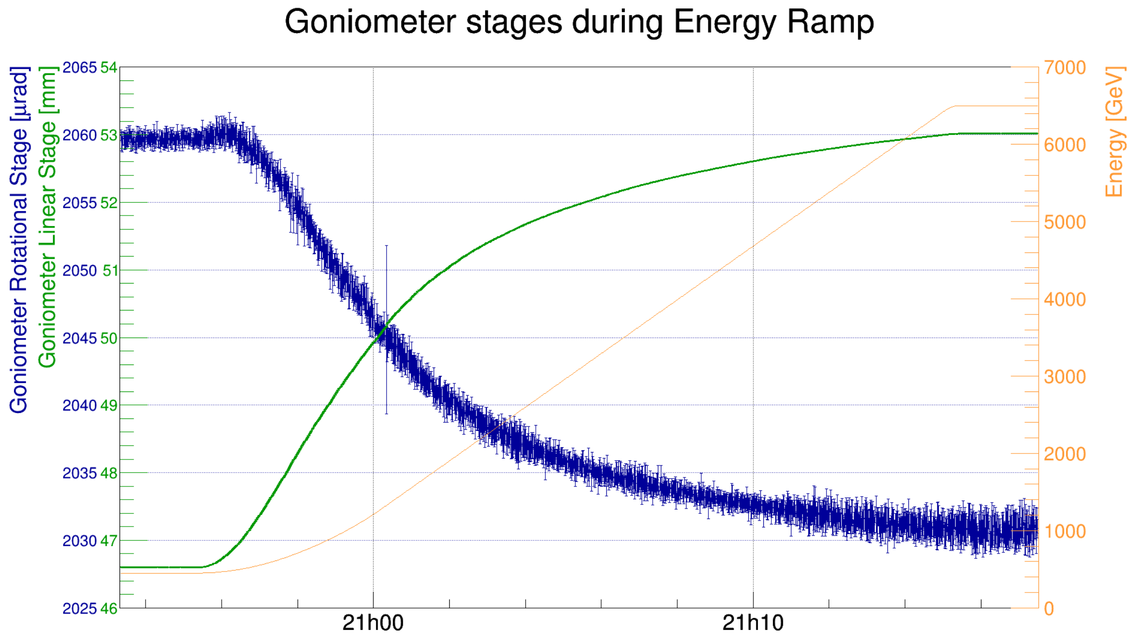


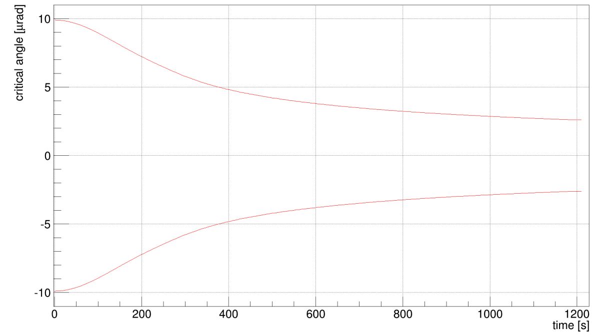
protons

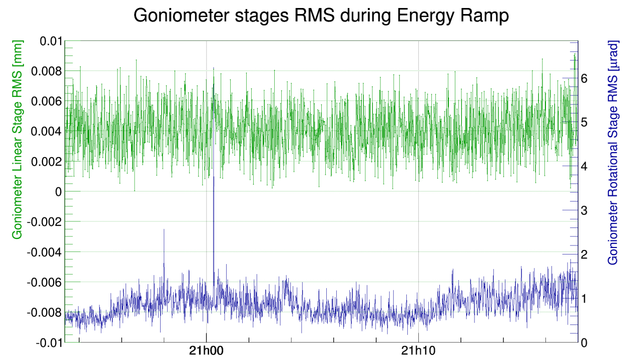


LHC: Channeling during the energy ramp

During the energy ramp function the the position and the orientation of the crystal follow the adiabatic shrinking of the emittance versus time as for the primary collimators



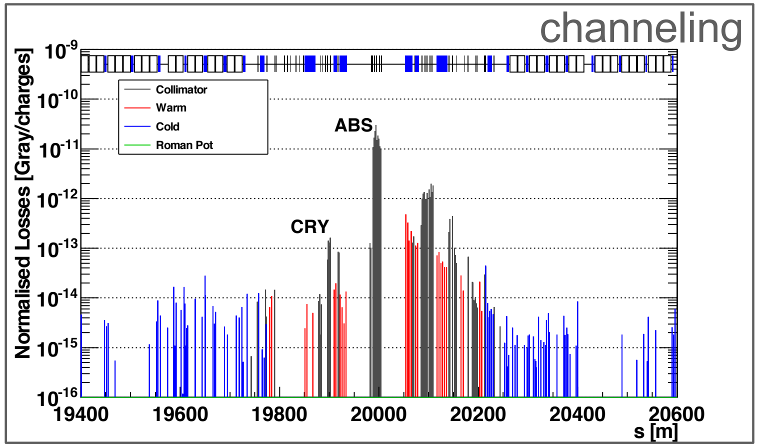


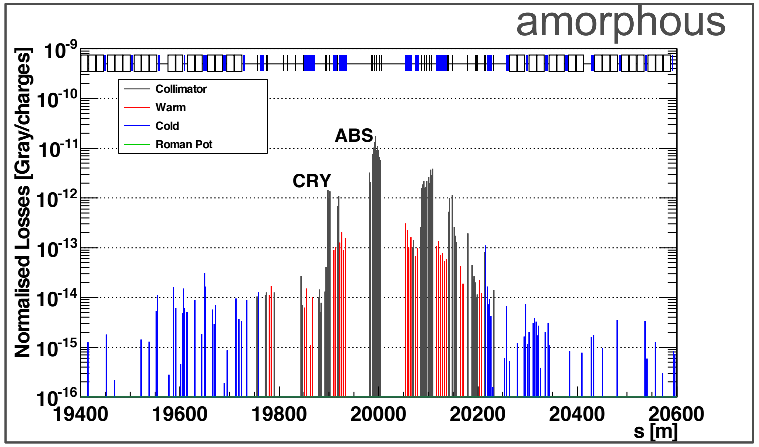


RMS plots show the high stability of linear stage, and a stability within the critical angle for rotational piezo-electric stage

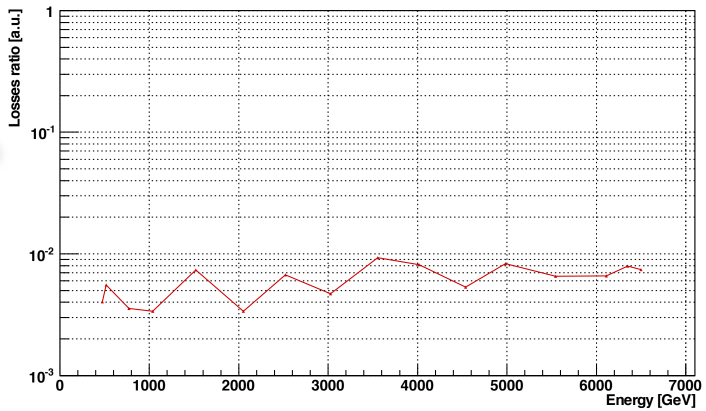
LHC: Channeling during the energy ramp

To evaluate if the crystal was kept in channeling orientation, two monitor at crystal position (CRY) and at the absorber position (ABS) ware used as reference.



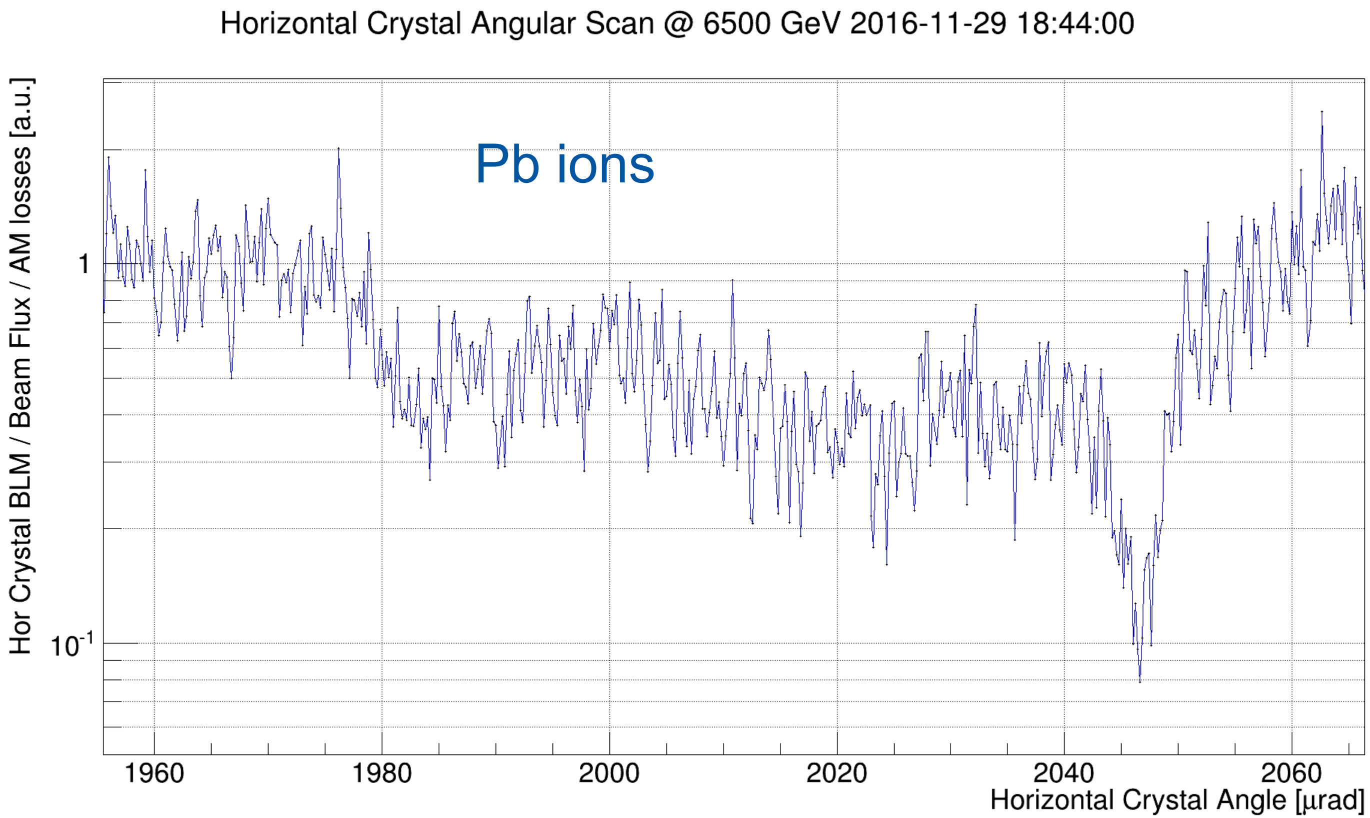


When in channeling the ratio of the losses is well below 10^{-2} , which has been observed constantly during the energy ramp



LHC: angular scans at 6500 z GeV

Crystal @ 5.5 σ
Best CH @ 2046.4 μrad

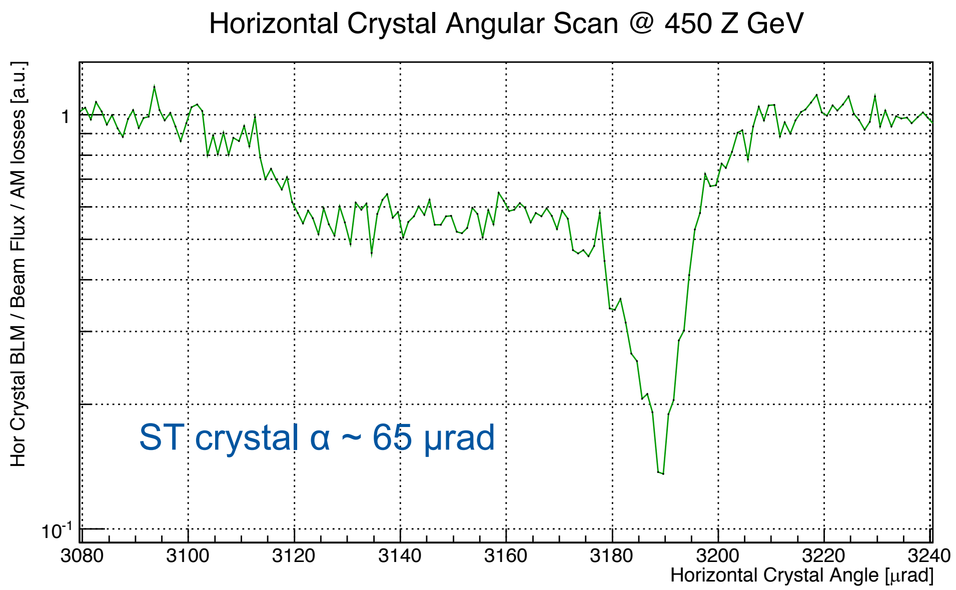


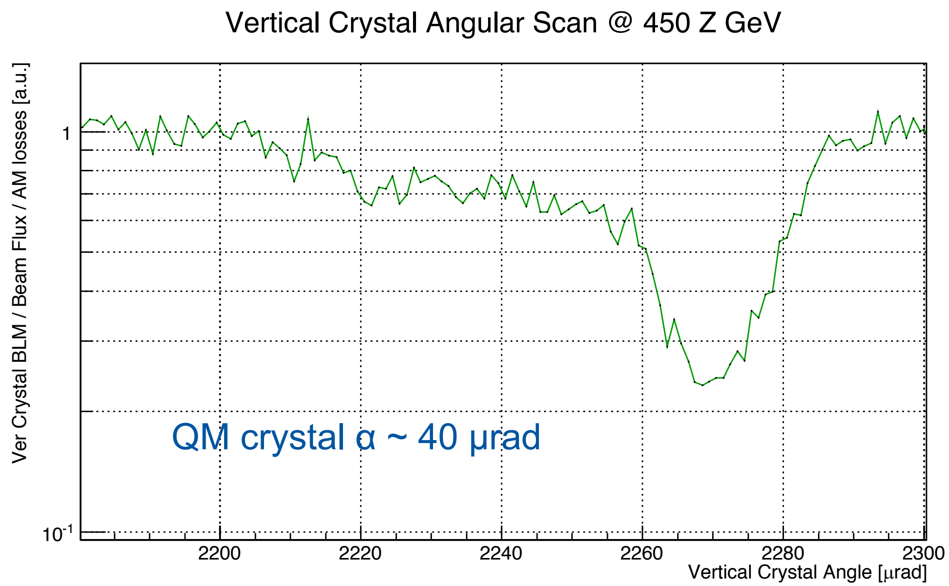
Reduction factor AM/CH
10.33

LHC: angular scans at 450 z GeV

Loss reduction in channeling orientation not the same

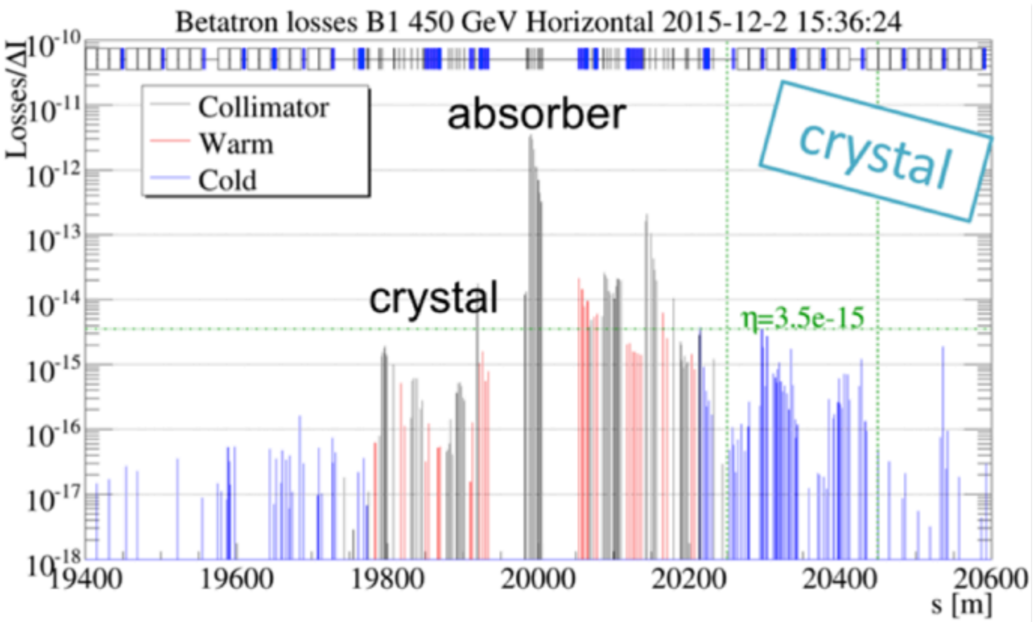
QM has a too small deflecting angle for an efficient absorption of the beam halo

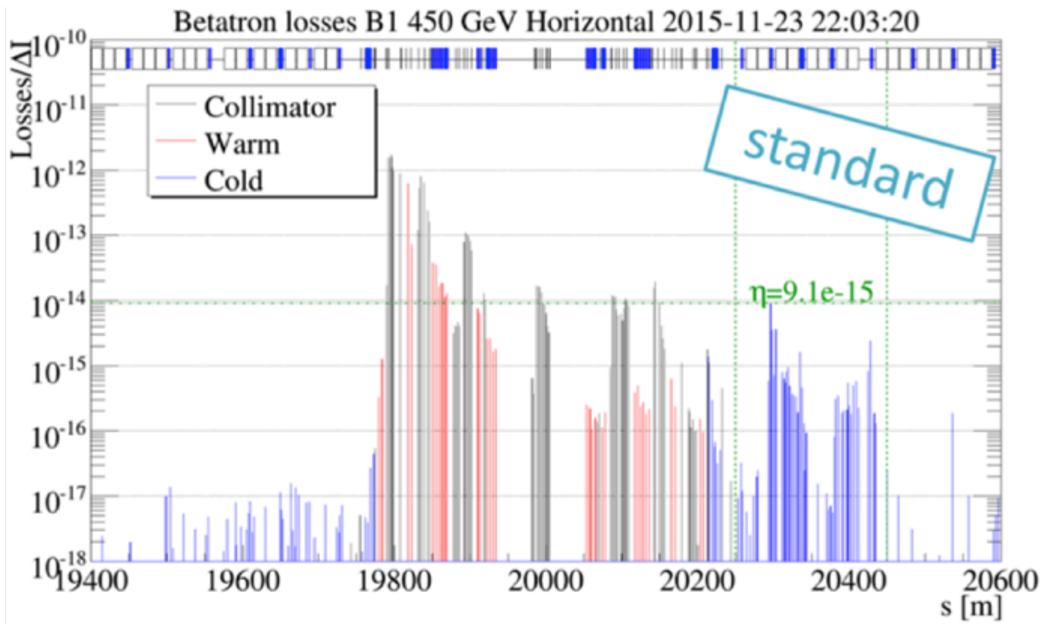




LHC: loss map at 450 GeV with lead ions

Collimation efficiency improved by a factor 2.6 !!



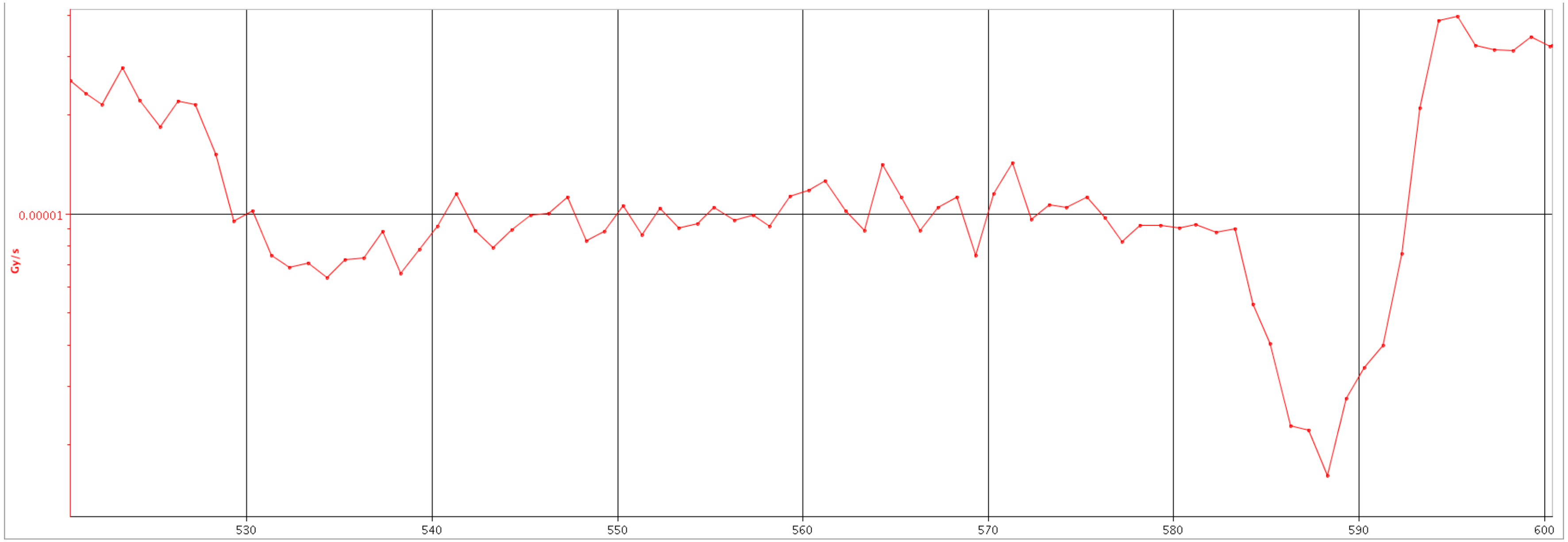


LHC: angular scan at 6500 GeV in Beam 2

Test of the installation on beam 2 (new generation goniometers and new crystals).

Both crystals work very well and the extensive analysis of the data acquired is on going.

B2 Vertical Crystal – angular scan at 6.5 TeV



RAW DATA

Test of HiRadMat crystal test

Main motivations

Experimental verifications:

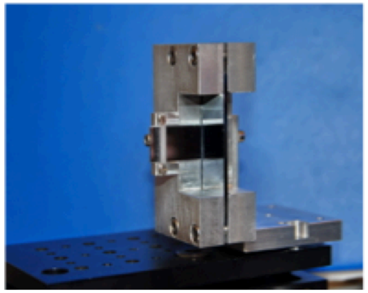
- Crystals robustness (no breakages, no transition to amorphous status)
- Channeling performances under accidental fast irradiation in LHC

Test has been performed with 288 nominal bunch at 440 GeV (May 2017). No damage observed in the irradiated crystals

Crystals irradiated

STF103:
Silicon Strip Crystal
Bending angle: 55 μrad
Width (x): 1.97 mm
Height (y): 55 mm
Length (z): 1.88 mm
Dislocations: < 1 cm^2

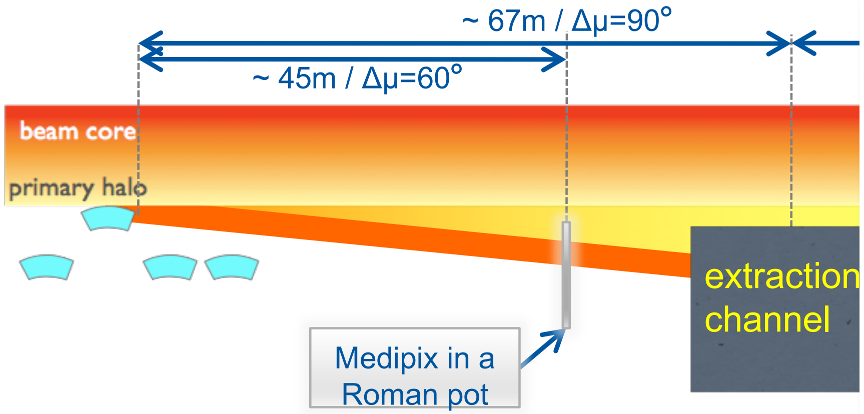
QMP25:
Silicon Quasi Mosaic Crystal
Bending angle: 165 μrad
Width (x): 30.5 mm
Height (y): 57.5 mm
Length (z): 2.1 mm
Dislocations: < 1 cm^2

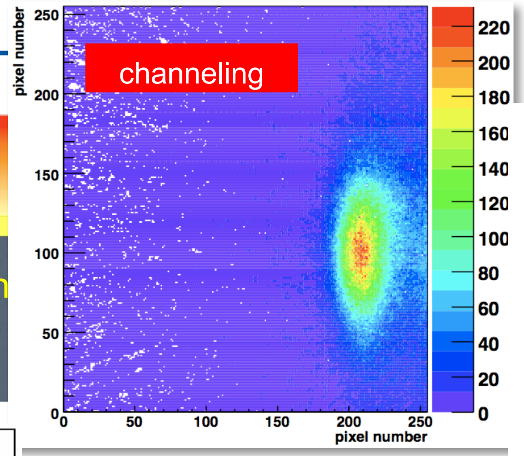


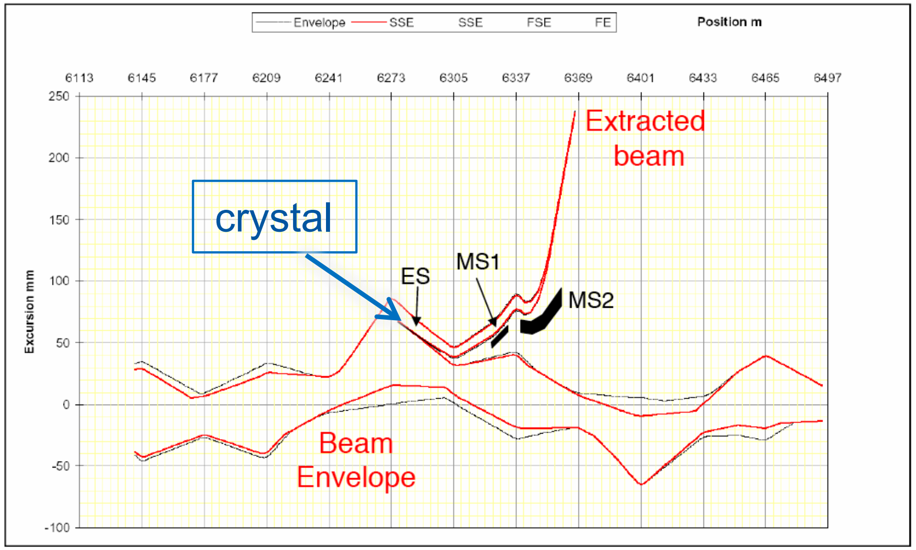
Slow extraction based on bent crystals

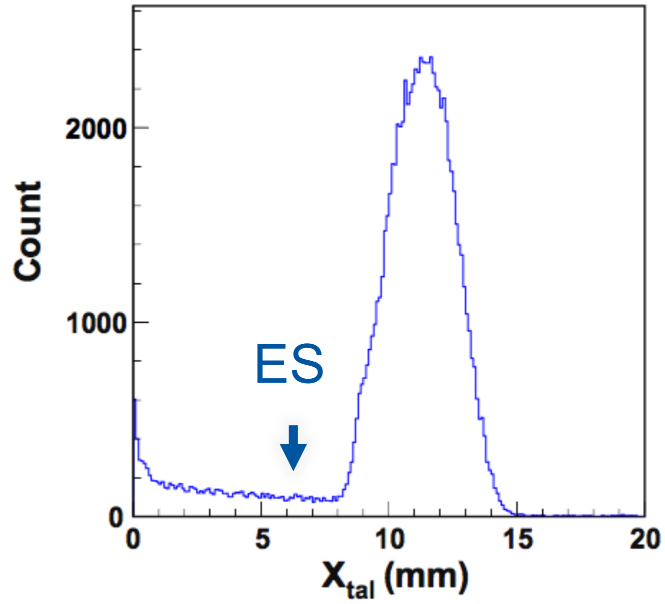
Non-resonant extraction as for RD22 or for UA9

Nuclear Instruments and Methods in Physics Research A 848 (2017) 166–169









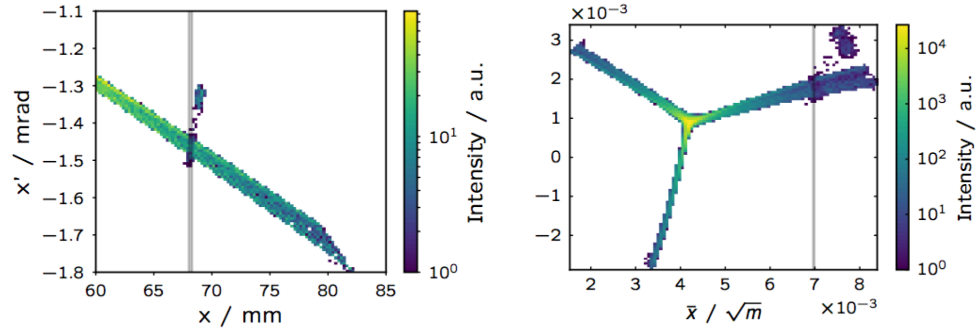
Beam profile at the entrance of the ES

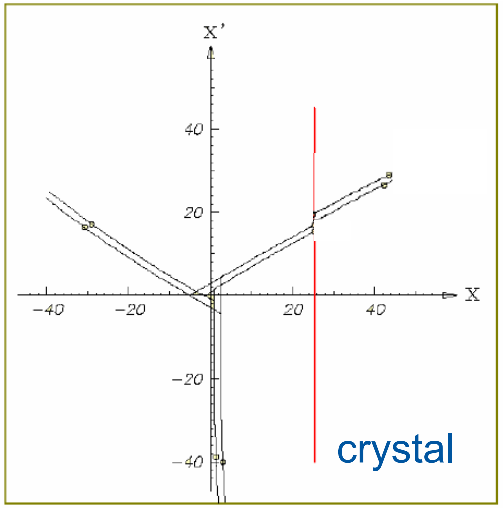
Slow extraction based on bent crystals

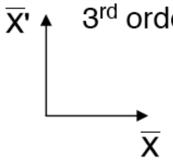
Electrostatic septum wire shadowing

IPAC17 MOPIK050

- Bent crystals could be used to intercept particles in the separatix that otherwise would hit the wires of the ES, deflecting them into the extraction channel, well inside the ES aperture.
- The local beam loss and the debris produced by ES wires will be thus reduced, and shifted in a safer area of the accelerator.







3^{rd} order resonant extraction

Bent crystal replacing of helping the ES septum

- Bent crystals may intercept the totality of the particles to be extracted, deflecting them into the extraction channel by a similar angle as the ES, thus allowing resonant extraction without loss at the ES
  - without ES
  - with a reduced ES deflecting power

Role of the UA9 Collaboration

Edms No. 1509966
7 May 2015

MEMORANDUM

To : Walter Scandale, Chairperson of the UA9 Collaboration

From : Frédérick Bordry, Director for Accelerators and Technology

c.c.: Paul Collier, Head of the Beams Department
José Miguel Jiménez, Head of the Technology Department
Roberto Saban, Head of the Engineering Department
Brennan Goddard, TE-ABT Group Leader

Subject : Slow extraction assisted by bent crystals in the SPS

Following the interest generated by the *Proposal for Investigating Slow Extraction Assisted by Bent Crystals in the SPS,* I would like to ask the support of the UA9 collaboration both for the studies and for the developments of hardware and software which these might entail.

Needless to say, the beam time required for the validation of the concept will be taken from SPS Machine Development time and appropriate funding will be supplied by the EN Department for the developments of hardware and software components.

If you agree, I would like to launch the study with the group composition included in the proposal attached.

sending beam in TT20 (Nov. 2016)

UA9 & TE/ABT

- Single bunch 1.6 10^{10} p stored at 270 GeV;
- UA9 crystal in channeling mode mode
- Q_H = 26.62 to bring the electrostatic septum (ES) in phase with the UA9 absorber

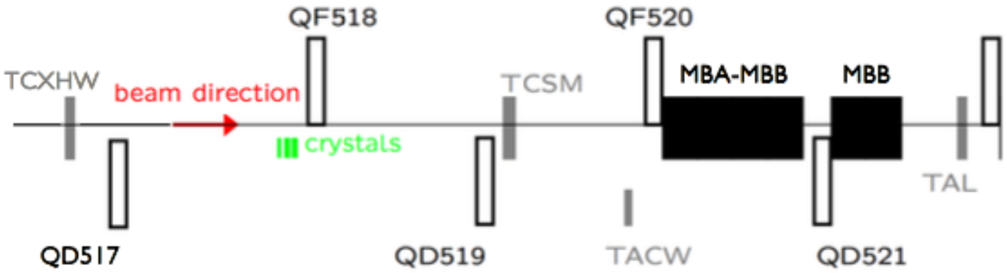
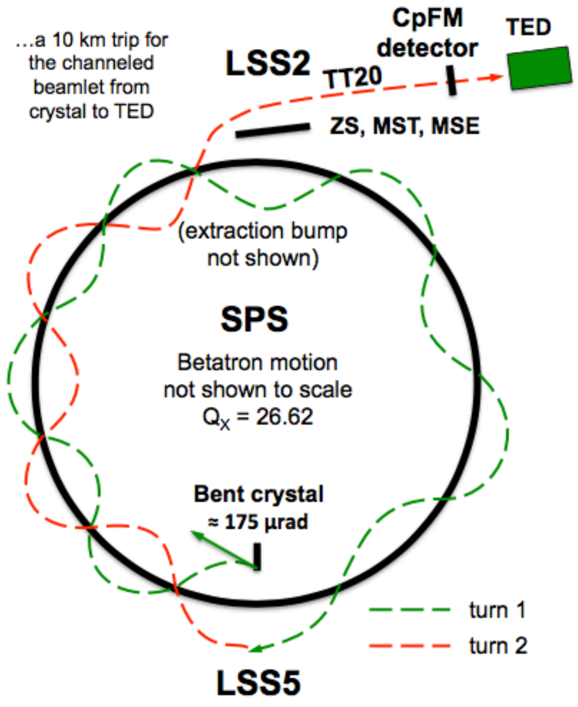


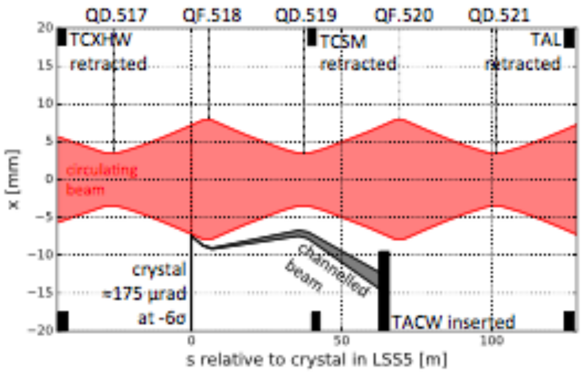
Figure 3: Schematic of the UA9 experiment's installation.



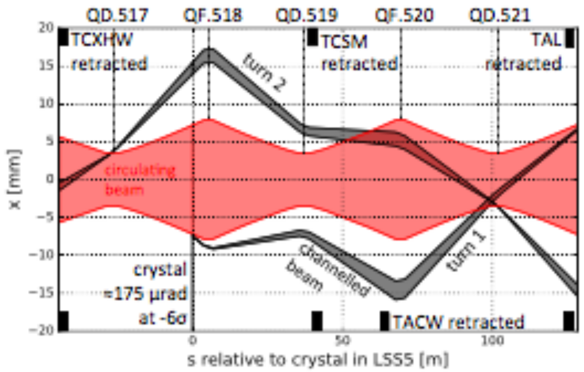
1: Schematic of the crystal-assisted extraction

sending beam in TT20

- By removing the absorber the beam deflected by the crystal was send across the ES
- The TT20 channel was set in extraction mode
- The beam in TT20 was detected by the CpFM (data analysis in progress)



(a) TACW IN.



(b) TACW OUT.

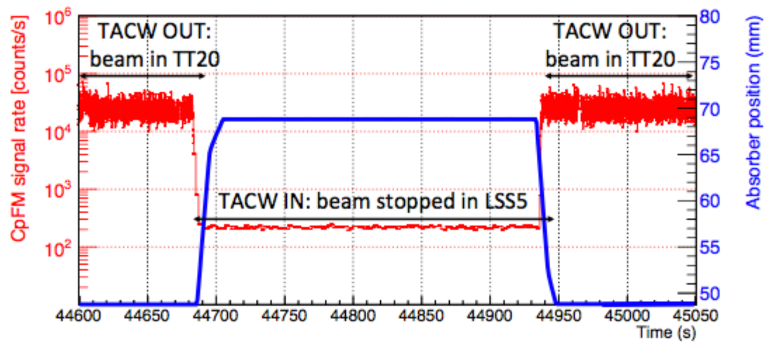


Figure 4: TT20 CpFM signal rate (red) vs. TACW position (blue) [19].

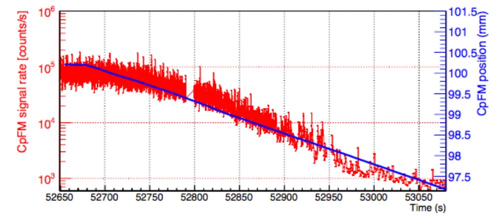
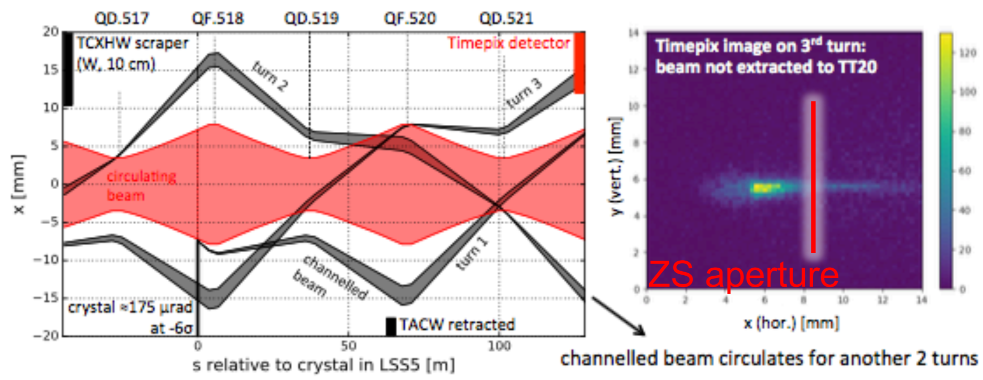


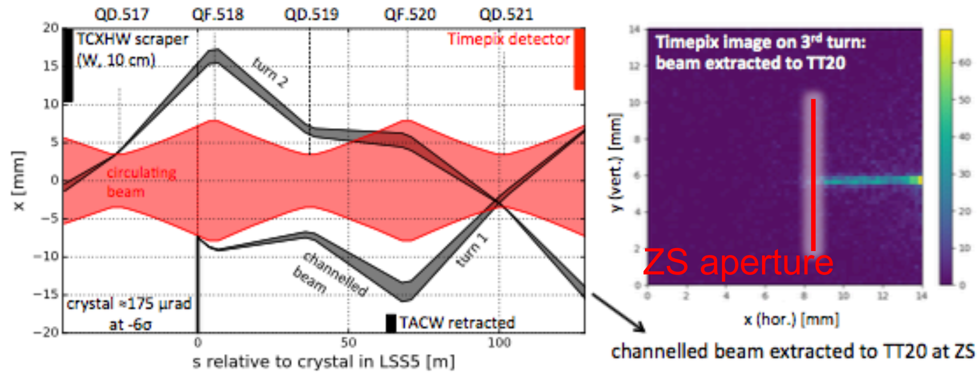
Figure 6: TT20 CpFM signal (red) and position (blue) vs. time as it is moved out of the extracted beam [19].

sending beam in TT20

- Bump OFF:
  - the beam is kept in the SPS
  - at the third turn it crosses the medipix in the Roman Pot
  - just after it is absorbed by the absorber in the SPS dispersion suppressor.
- Bump ON:
  - the beam misses the medipix and
  - it is extracted at the third turn



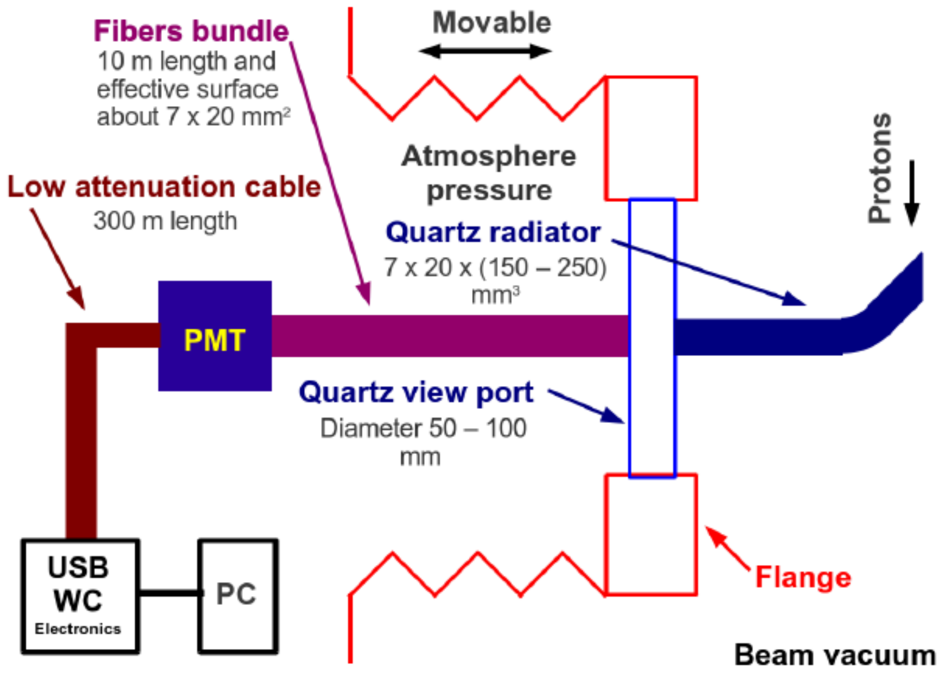
(a) Extraction bump OFF.



(b) Extraction bump ON.

Basic detector in TT20

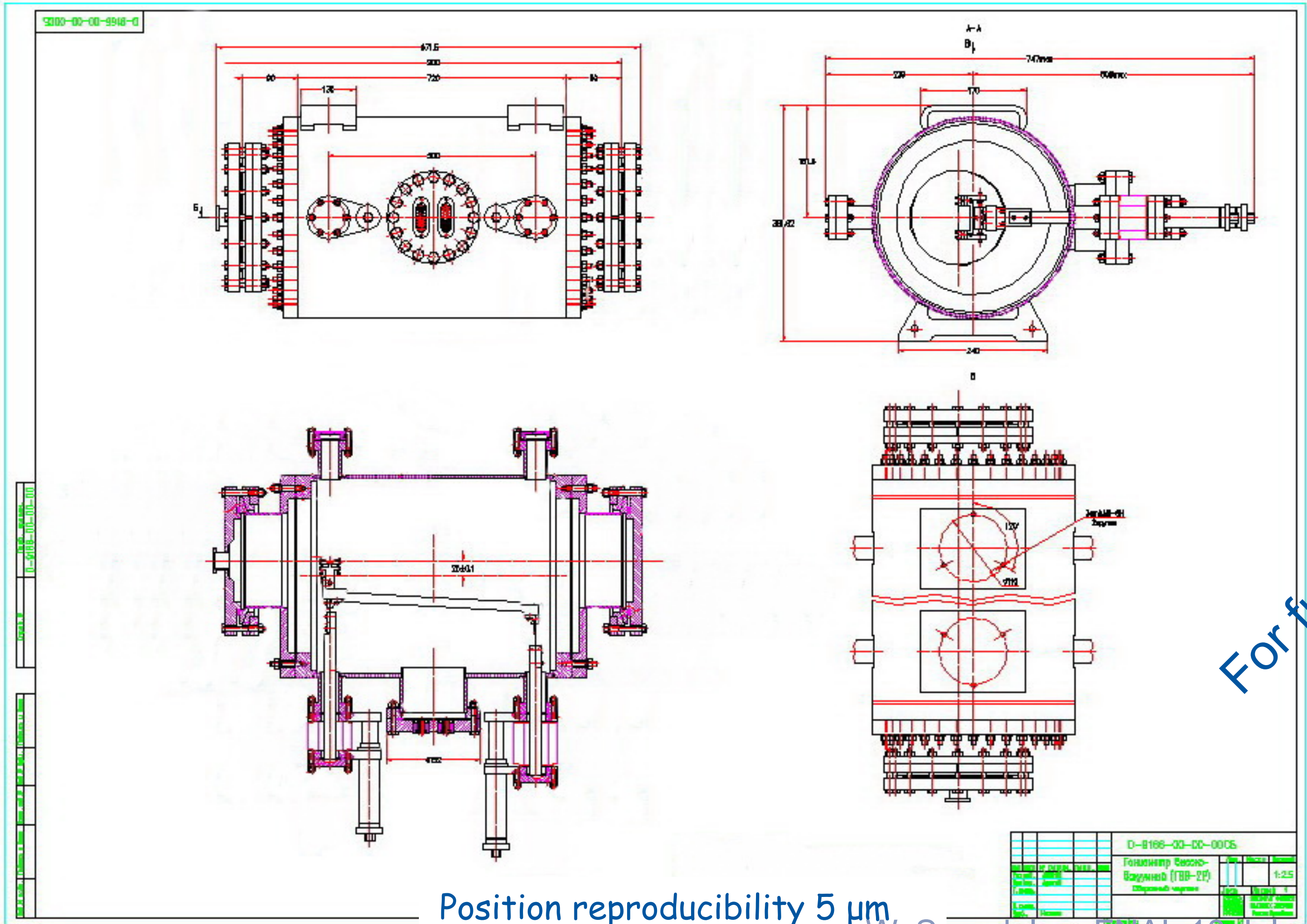
UA9 Cherenkov proton flux counter



5-10% resolution on number of incident protons (100) achieved

A similar Cherenkov detector is installed in the UA9 area and has been tested with stored proton beams

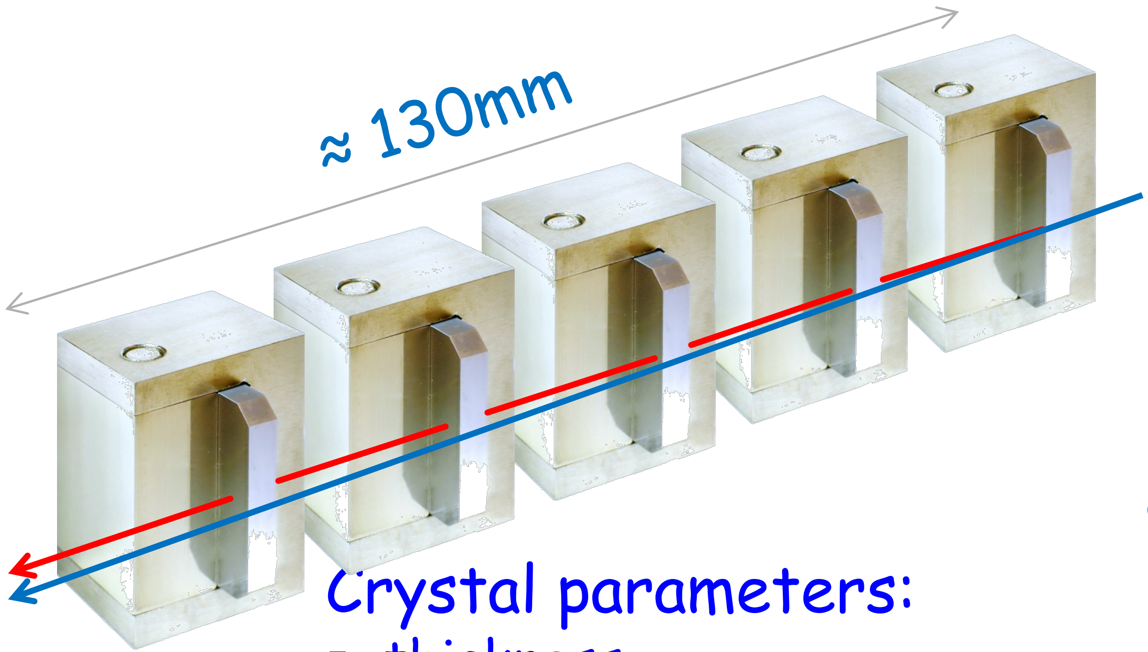
IHEP Goniometer (fits in a SSS)

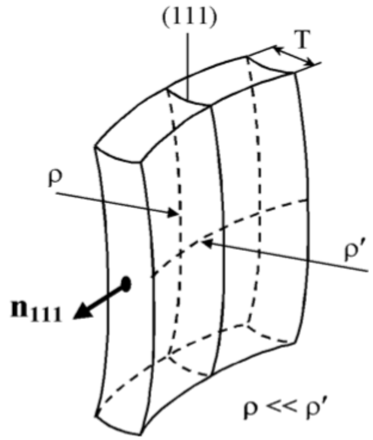


For future applications

Position reproducibility 5 μm
Angular reproducibility 1 μrad

Crystals in an array for VR





Quasimosaic bending

For future applications

Crystal parameters:

- thickness 1-4 mm
- CH deflection angle 60-150 μrad
- MVR deflection angle ≈ 60 μrad
- open area ≤ 5 x 20 mm²

In alternative use a single crystal in channeling mode

Timeline of the UA9 Experiment (1/2)

- Test with extracted beams at the SPS North Area (few weeks per year):
  - ✓ Crystal – beam interactions for different type of crystals and different species of particles (p, π^+, e^+, e^-, pb^{82+},ar^{18+})
  - ✓ Measurement of crystal properties before installation in CERN-SPS and LHC
  - ✓ Test of the crystals and the detectors to be installed in SPS for crystal collimation
- Prototype crystal collimation system in the SPS (~ 4 / 5 days per year):
  - ✓ 2009 ➔ First results on the SPS beam collimation scenario based on bent crystals *(Phys. Lett. B, 692, 78–82)*.
  - ✓ 2010 ➔ Comparative results of crystal collimation in SPS with protons and Pb ions *(Phys. Lett. B, 703, 547–551)*.
  - ✓ 2012 ➔ Strong reduction of the off-momentum halo in crystal assisted collimation of the SPS beam *(Phys. Lett. B, 714, 231–236)*.
  - ✓ 2013 ➔ Optimization of the crystal assisted collimation of the SPS beam *(Phys. Lett. B, 726, 182–186)*
  - ✓ **2014 ➔ Observation of strong leakage reduction in crystal assisted collimation of the SPS beam *(Phys. Lett. B, 748, 451–454)*.**
  - ✓ 2015 ➔ Test and validation with beam of the LHC-type goniometer.
  - ✓ 2016 ➔ effect of the miscut angle and procedure to for high precision evaluation of the crystal bending angle

Timeline of the UA9 Experiment (2/2)

- Prototype crystal collimation system in the LHC:
  - ✓ 2006 ➙ First layout of a crystal-assisted collimation for LHC *(Assmann, Redaelli, Scandale EPAC2006).*
  - ✓ 2011 ➙ Letter of Intent (CERN-LHCC-2011-007 / LHCC-I-019 10/06/2011).
  - ✓ 2012 ➙ First goniometer industrially produced suited for the LHC requirements.
  - ✓ 2014 ➙ Two crystals with their goniometers installed in IR7 Beam 1 of LHC (EDMS 1329235)
  - ✓ **2015 ➙ Test in LHC ring 1 of the crystal-assisted collimation with p and Pb beams at 450 and 6500 GeV (**Physics Letters B 758 (2016) 129–133)**.**
  - ✓ 2016 ➙ Two crystals with their goniometers installed in IR7 Beam 2 of LHC
  - ✓ 2016 ➙ Crystal collimation in IR7 Beam 1 of LHC during the energy ramp (IPAC17 MOPAB007)
  - ✓ 2017 ➙ successful test of crystal collimation in IR7 Beam 2 of LHC

Crystal-collimation validated

- Crystal extraction
  - ✓ 2014 ➙ Proposal for investigating slow extraction assisted by bent crystals in SPS and LHC – UA9-SE
  - ✓ 2015 ➙Investigation on slow extraction accepted only in the frame of the SPS (EDMS1509966)
  - ✓ 2016 ➙ shadowing concept assisted by bent crystals (IPAC17 MOPIK050)
  - ✓ **2016 ➙ Beam at 270 GeV deflected from the SPS ring to TT20 (IPAC17 MOPIK048).**

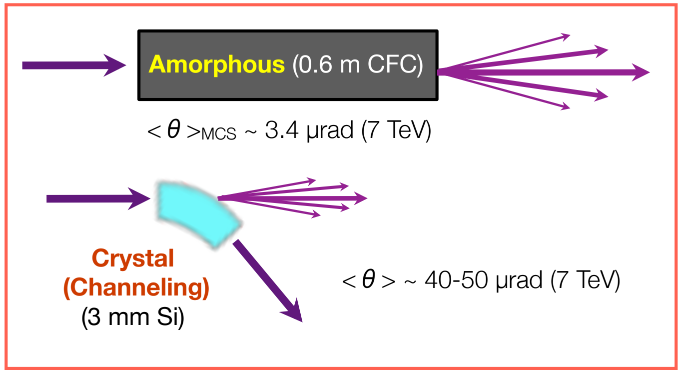
Present/future tasks of UA9

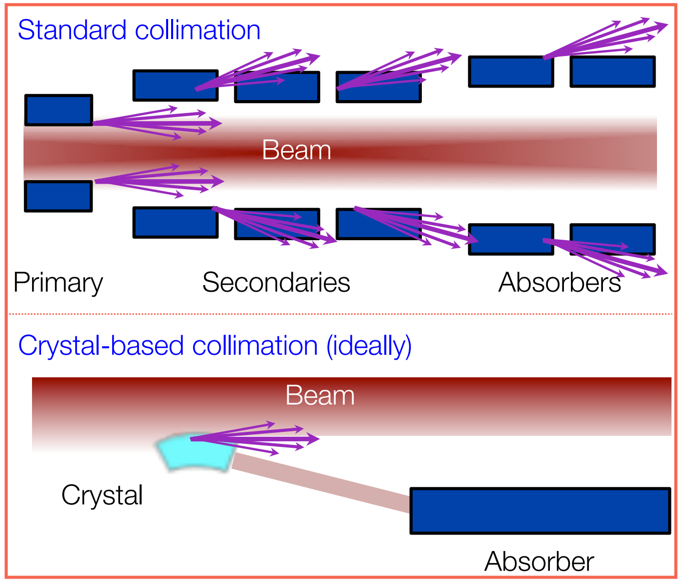
$\theta_{ch} \cong \alpha_{bending}$

$\theta_c \cong \sqrt{2U_0/E}$

$$\theta_c = \begin{cases} 10\,\mu rad\,@\,400\text{ GeV} \\ 2.6\,\mu rad\,@\,7\text{ TeV} \end{cases}$$

- Crystal collimation for LHC
  - Demonstration of feasibility completed
  - Detailed studies undergoing with the LHC Collimation team.
- Extraction in the SPS
  - Studies started but role of UA9 yet undefined
  - Only a small fraction of UA9 involved
  - Team to be strengthened for long term results
- Physics with bent crystals (Baryons)
  - Expression of intent independent of UA9 (see SPSC-EOI-012)
  - Team to be defined
- Physics with bent crystals (Pions/kaons)
  - Goals in preparation (PNPI-IHEP) – production rates and form factors
  - Team to be defined





Support from new Institutions mostly welcome