Crystal-assisted collimation tests at the CERN SPS UA9 experiment report

R. Rossi on behalf of UA9

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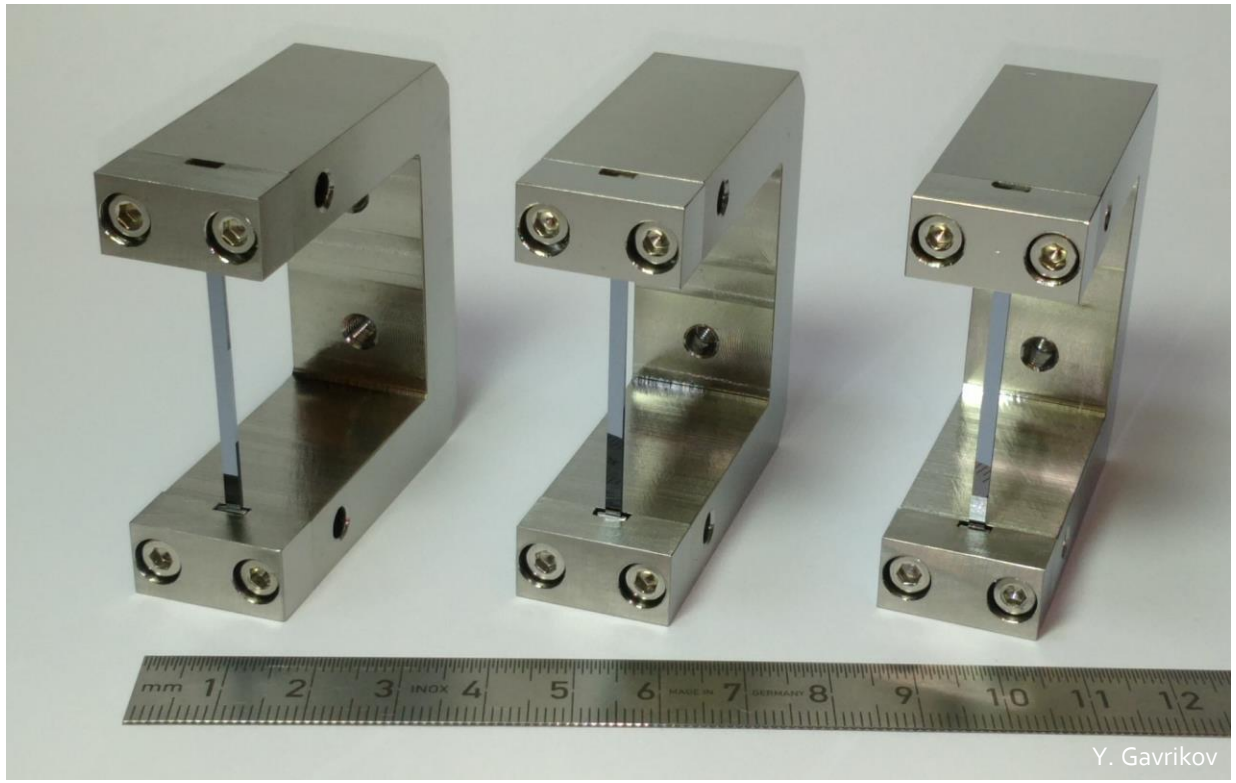
Outline

- Basic introduction to Crystal Channeling
- Bent Crystal applications and selected results
  - Hadron beam collimation
    - Upstream Collimator
    - Absorber Performances
  - Beam Extraction
    - Resonant and non-resonant
  - Double Channeling
- Conclusions



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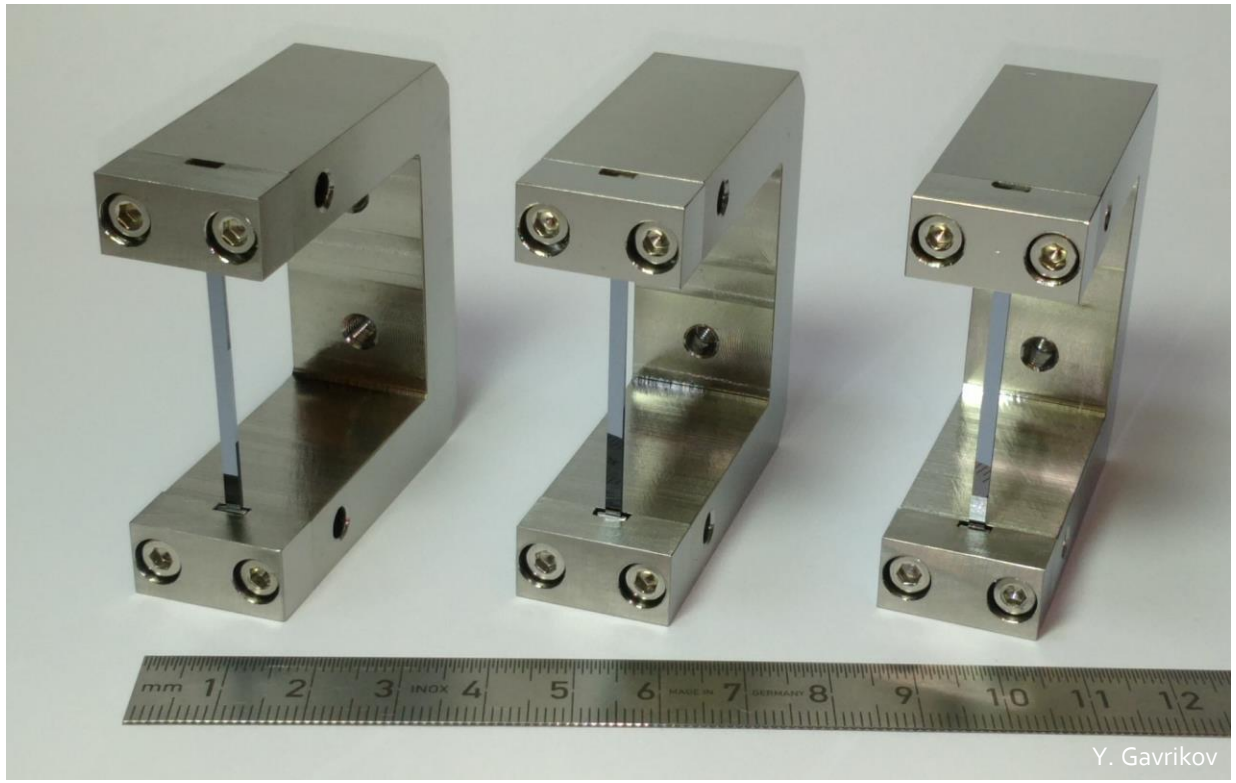
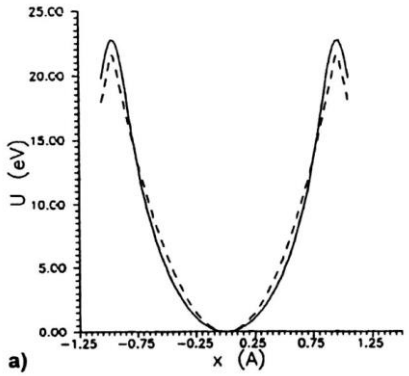
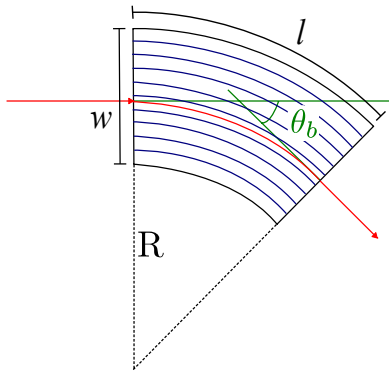


Coherent effects in bent crystals

Channeling : Transverse energy < potential well

$$\frac{p^2c^2}{2E}\theta^2 + U(x) \leq U_{max}$$





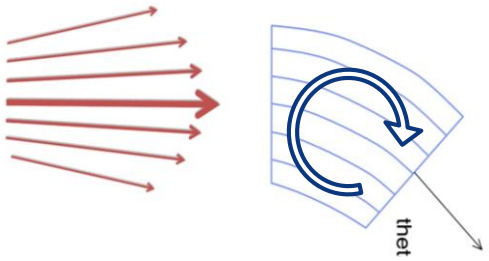
Critical angle

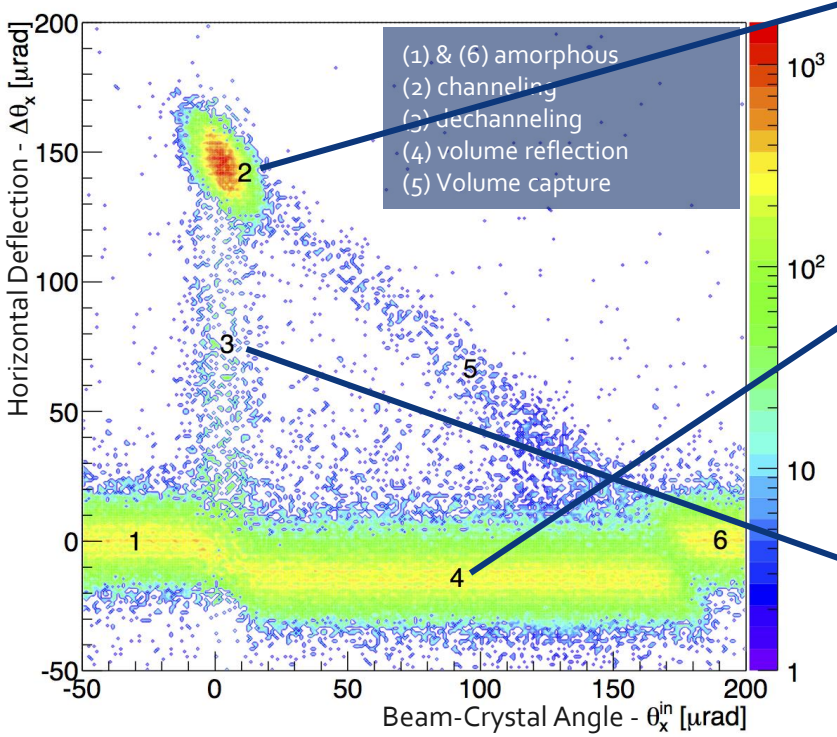
$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}$$

Case	Energy [GeV]	θ_c $[\mu rad]$
SPS coast	120	18.3
SPS coast	270	12.2
H8	400	10.0
LHC inj.	450	9.4
LHC top	6500	2.5
LHC top	7000	2.4

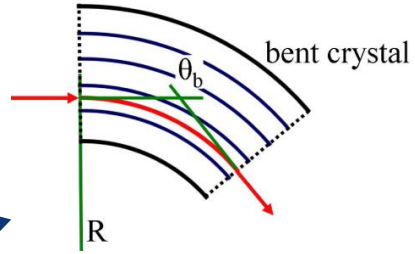
The particles are trapped in the channel, hence if a curvature is given to the lattice the particles direction will be modified by $\theta_b = l/R$

Single pass measurements with 400 GeV protons. Strip crystal (110) with a bending of 144 µrad.

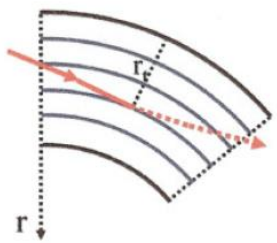




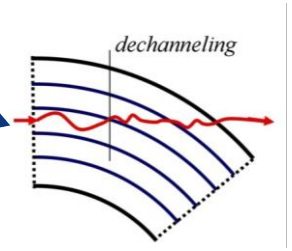
Planar channeling (CH)



Volume Reflection (VR)



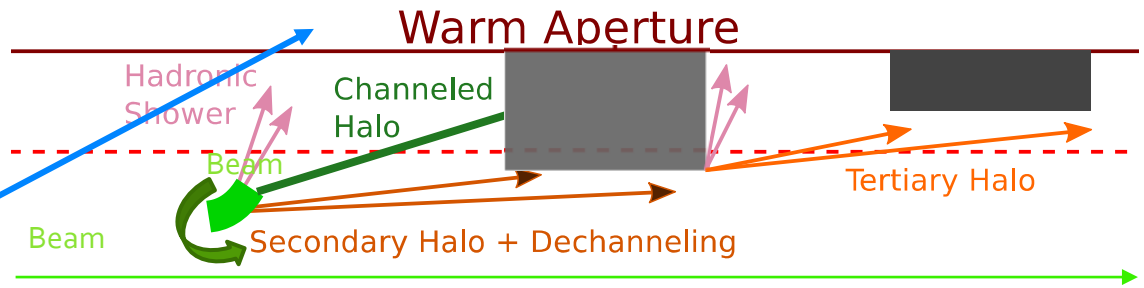
Dechanneling (DC)

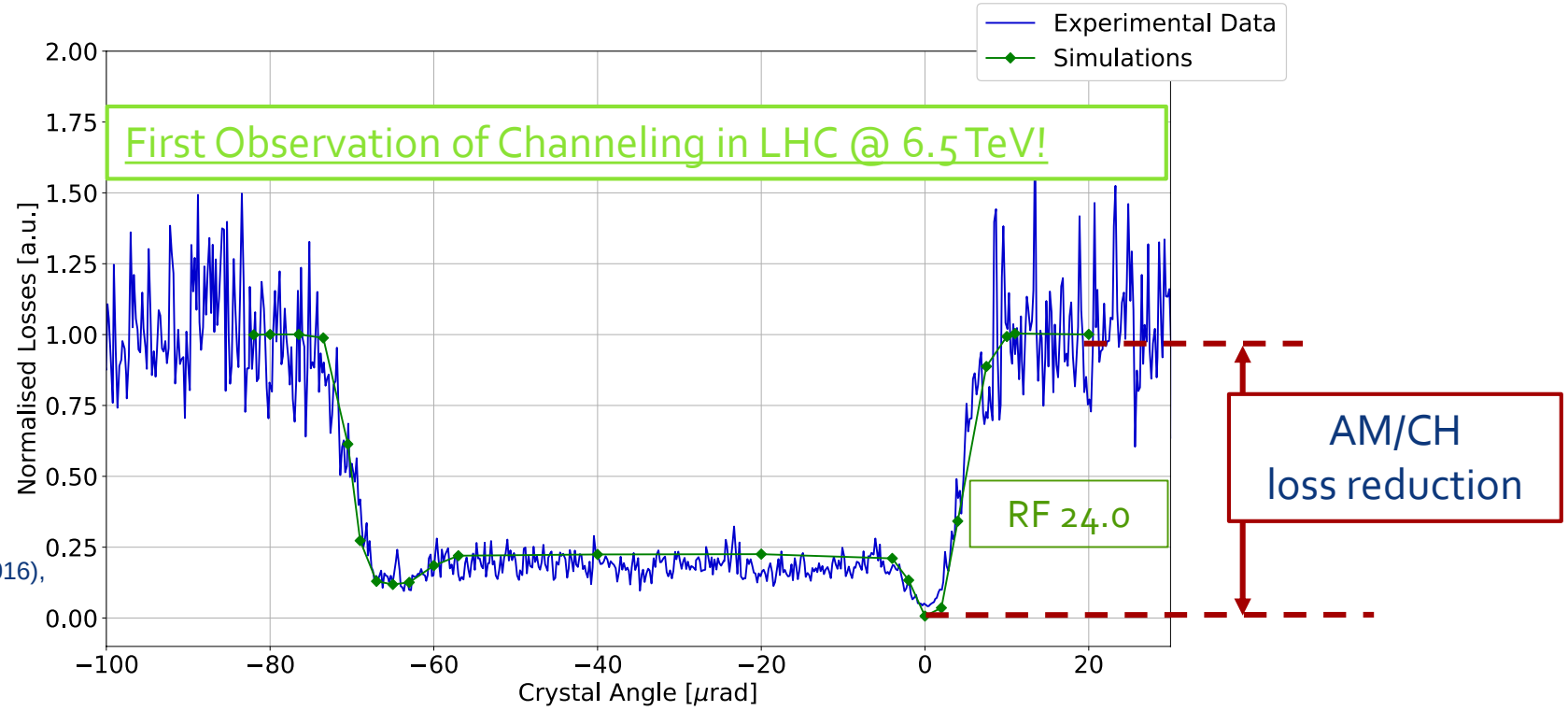


Channeling Assessment in Circular Machines

1. Angular Scan

local losses
vs
crystal rotational
orientation





[1] W. Scandale et al., PhysicsLetters B758 (2016), pp. 129–133. doi:10.1016/j.physletb.2016.05.004.

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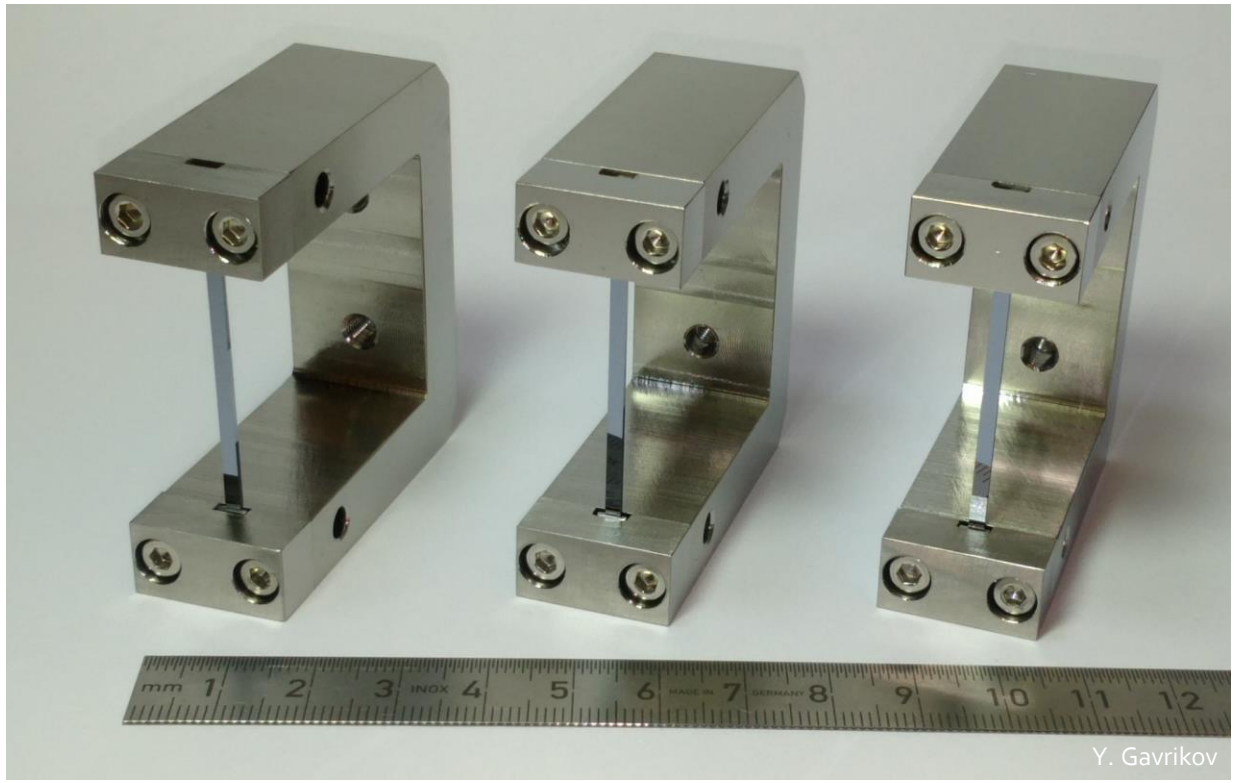
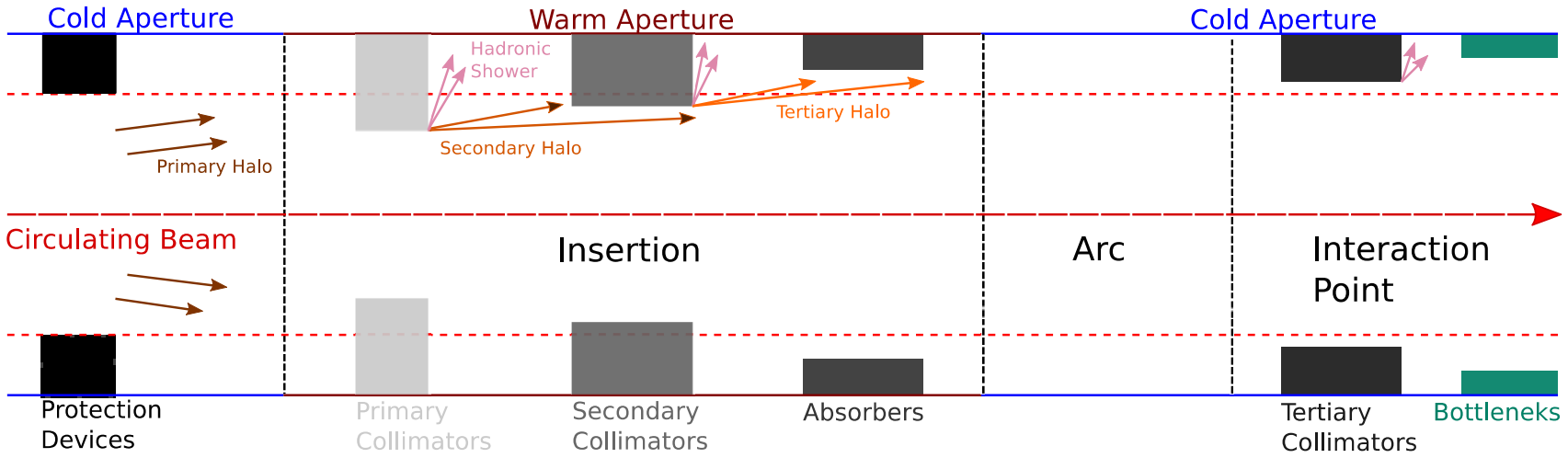


Collimation System in LHC

To protect the superconductive magnets from high energy deposition induced by lost particles

Collimation system is needed!

$\eta = 10^{-4}$ is the actual performance in LHC



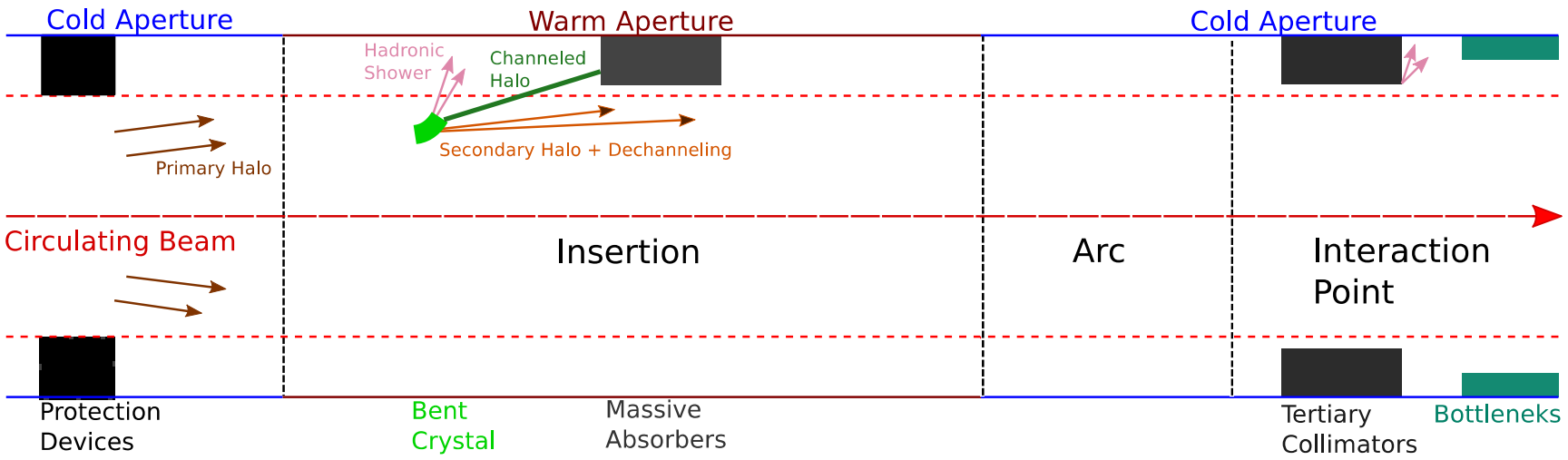
- **Halo cleaning**: reduce the risk of magnet quenches
- **Concentration of losses/activation** in controlled areas
  Avoid many hot locations around the 27km-long tunnel

Multi-stage system of 50 collimators per beam.

LHC: only machine where collimation must be used continuously in operation

The cleaning inefficiency with ions drops to 10^{-2}!

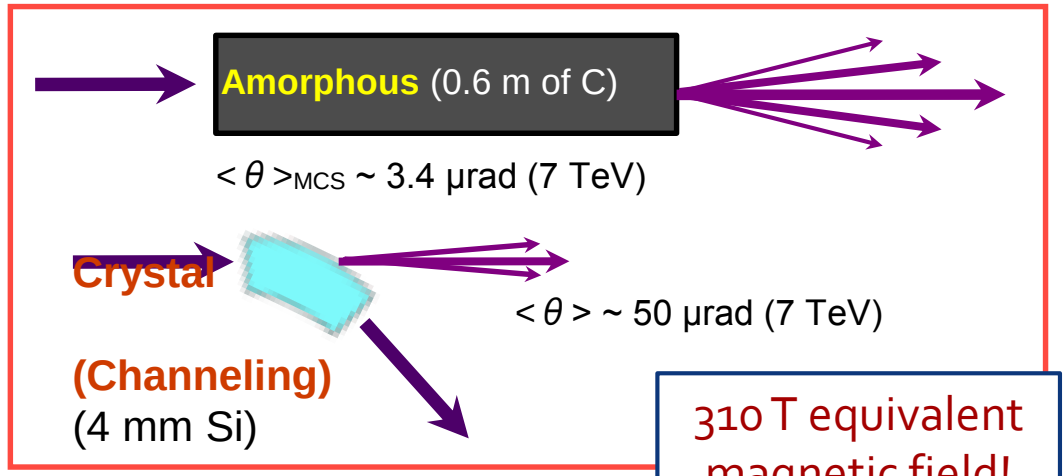
Crystal Collimation



Advantages of crystal collimation at the LHC:

- Improve **collimation cleaning** (by a factor 10);
  Reducing off-momentum losses in DS
- Reduce **impedance**;
  Less collimators at larger gaps

With ion beams the interaction with an amorphous materials generates more ion fragments (>δp/p) than a crystal in channeling orientation



310 T equivalent magnetic field!

SPS Collimation Test-bench

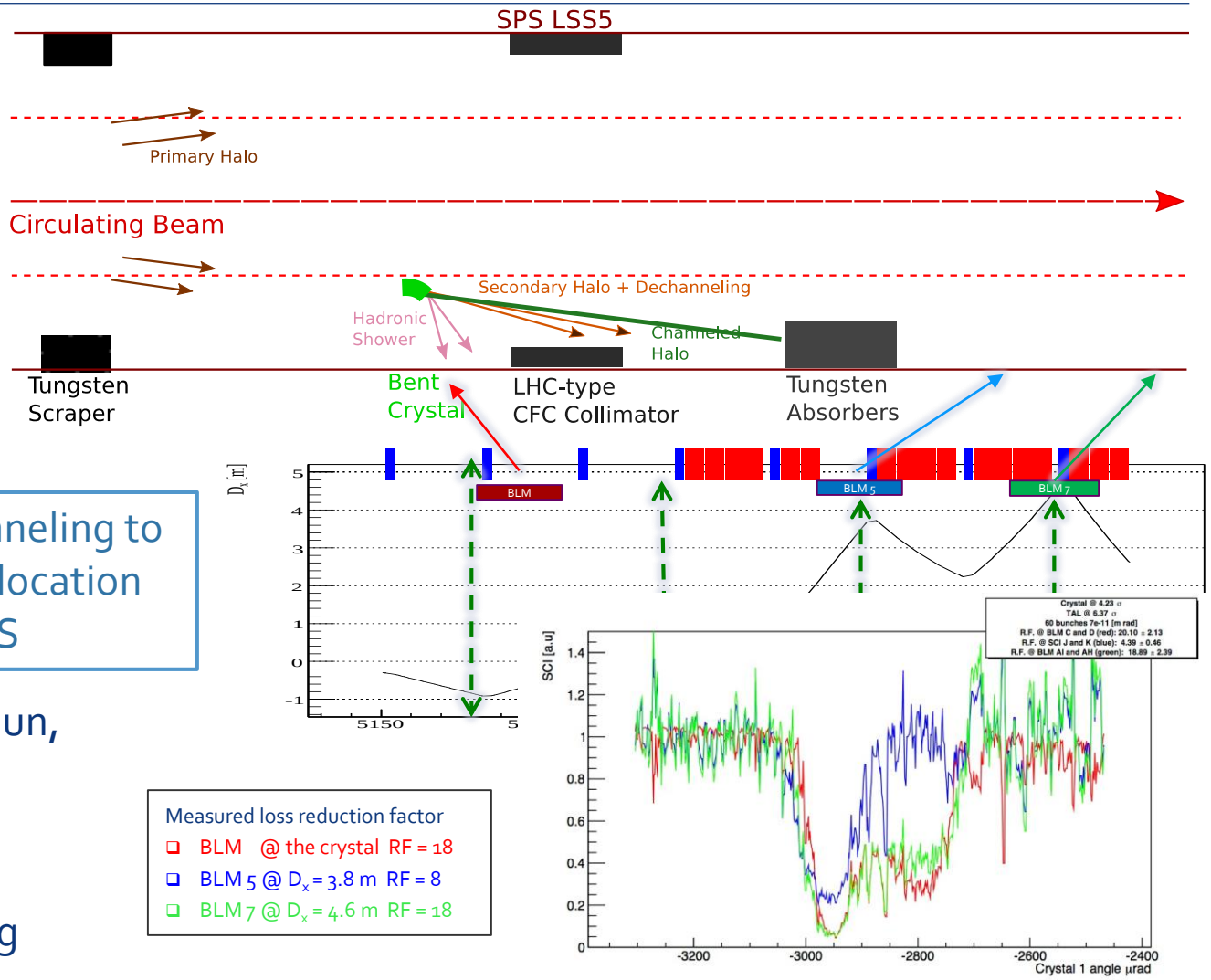
In SPS LSS5 UA9 installed a test-bench for collimation measurements in 2010.

Goniometers with crystals, two different type of absorbers and several detectors (BLMs, Medipixes and a CpFM) were used to prove the basic principle of crystal collimation.

One example is the measurement of Channeling to amorphous losses reduction, at different location in the dispersion suppressor of LSS5 in SPS

In recent years, after feasibility studies in LHC begun, SPS has been used to study in detail the effects observed in LHC:

- Absorber performances
- Upstream collimators effect on Channeling



[2] W. Scandale et al., Physics Letters B750 (2015), p. 666. doi:10.1016/j.physletb.2015.09.001.

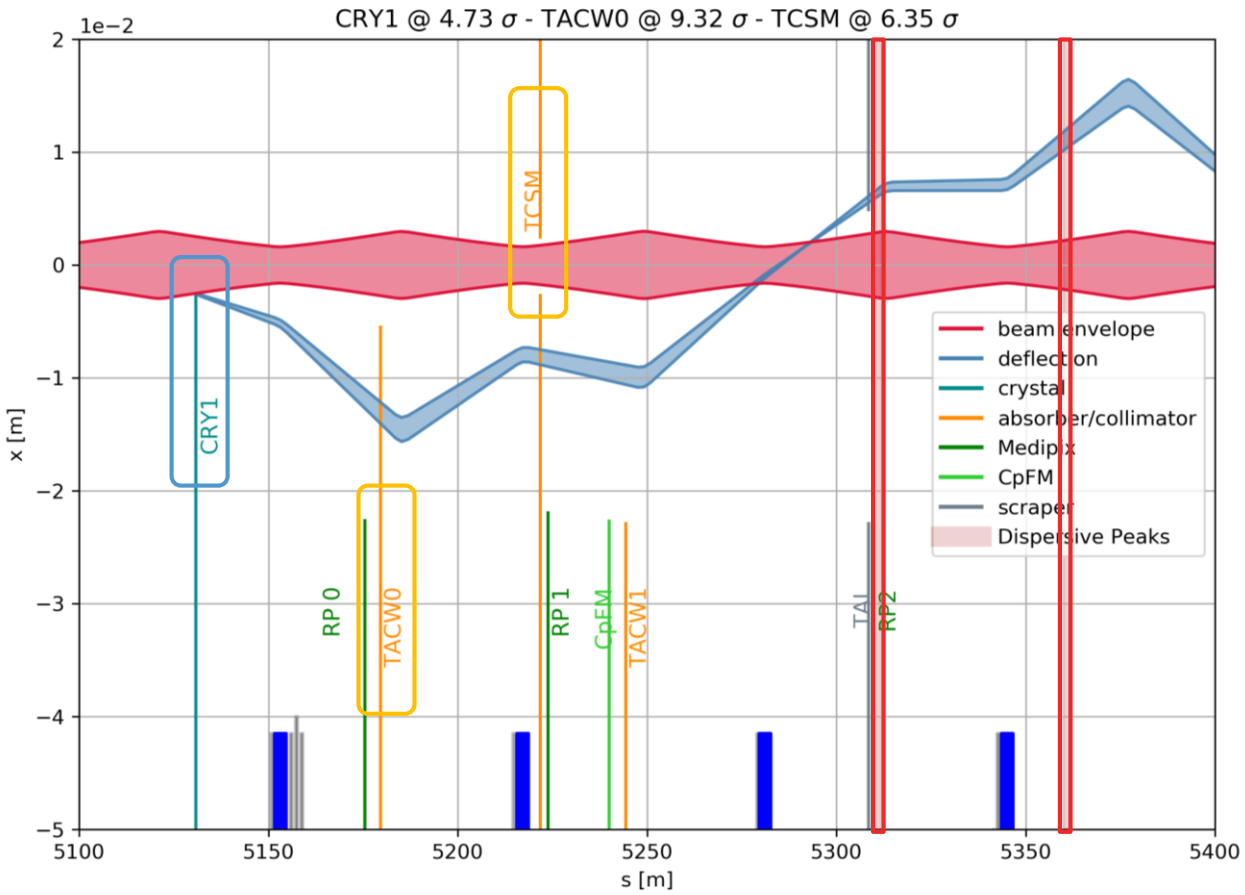
SPS absorbers test

A test in SPS was proposed to study the LHC observation

The idea was to take advantage of the available devices in SPS: the CRY1 channeled halo absorbed by TACW0 (W) or TCSM (C)

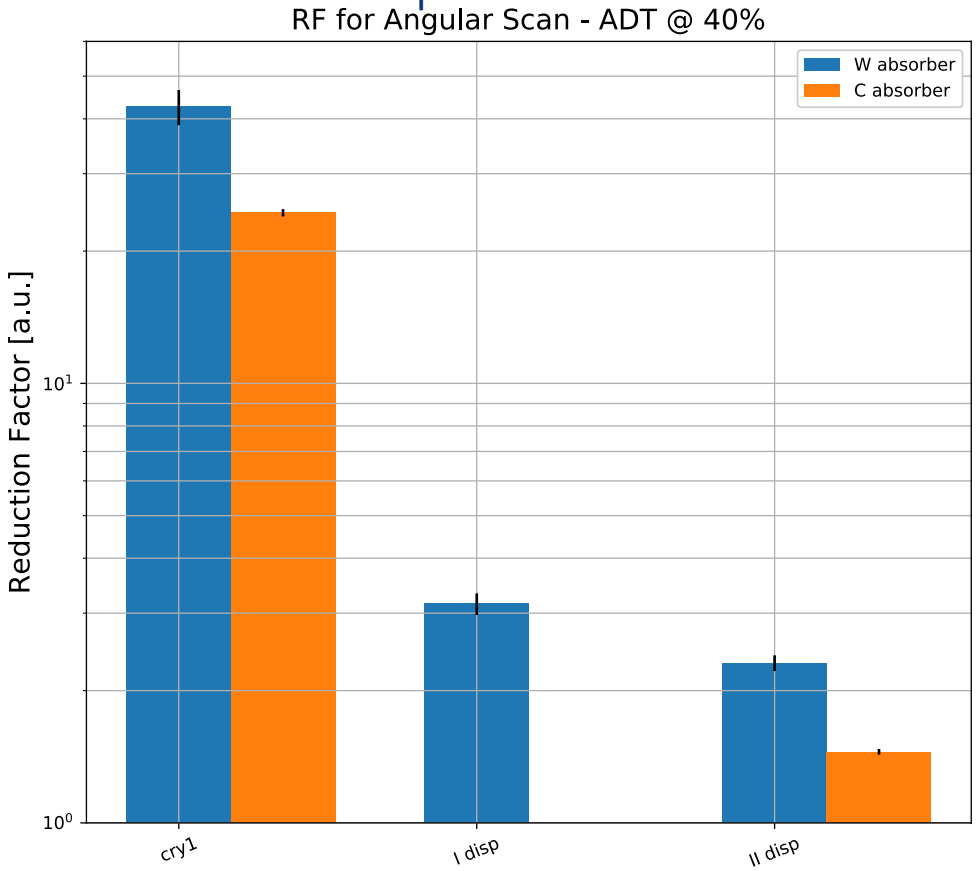
Two measurements:

1. Reduction of channeling to amorphous losses at crystal and at the first two dispersive areas
2. Linear scan of secondary halo (produced by the absorber) with TACW1, and with TAL in the dispersive area

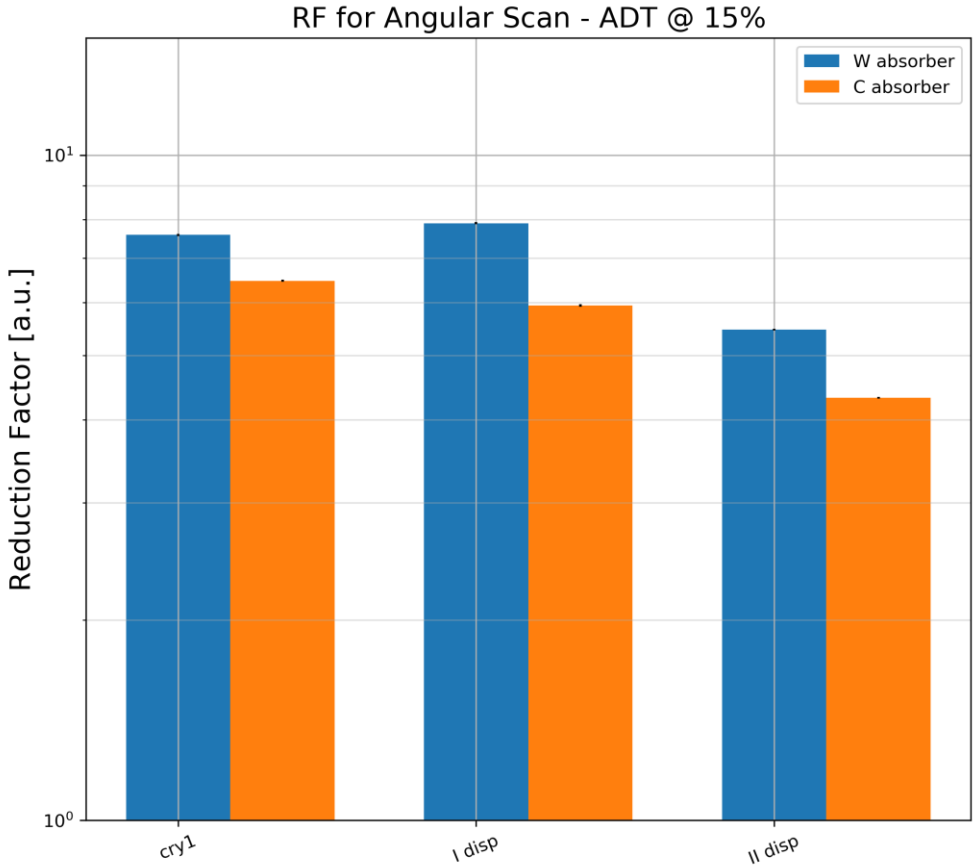


SPS absorbers test – Losses

protons



Lead ions



W absorber gives constantly better results with respect to C collimator, with both p and Pb beams

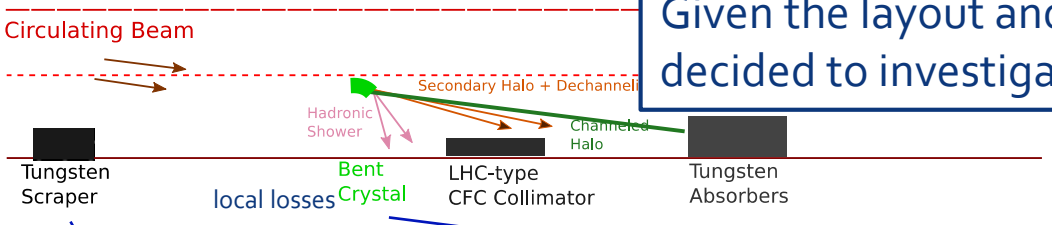
A dedicated absorber would be needed for operational use in LHC. EN-STI-TCD has already started the R&D for this absorber

Upstream Collimator effect

Some strange angular scans shape were observed in LHC when primary collimators were close to the same crystal aperture

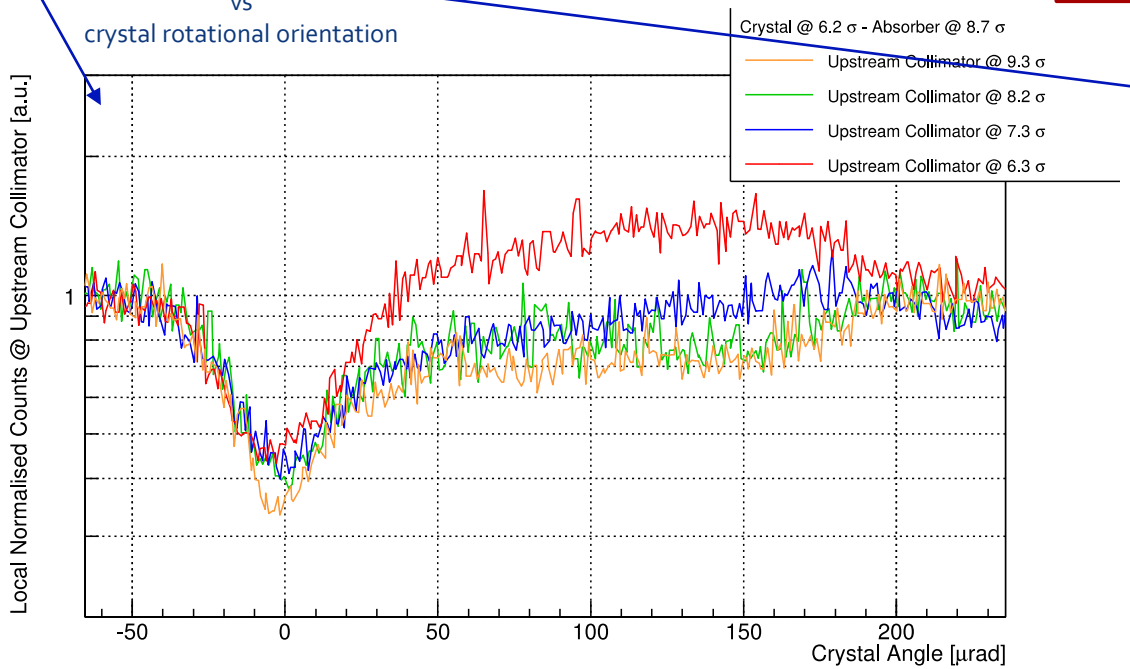
Relative Aperture [$\Delta\sigma$]	Reduction Factor in CH At Crystal	At Upstream Coll.
3.1	3.82 ± 0.10	2.86 ± 0.20
2.1	3.34 ± 0.10	2.48 ± 0.20
1.1	3.22 ± 0.10	2.29 ± 0.20
0.1	2.79 ± 0.10	2.21 ± 0.20

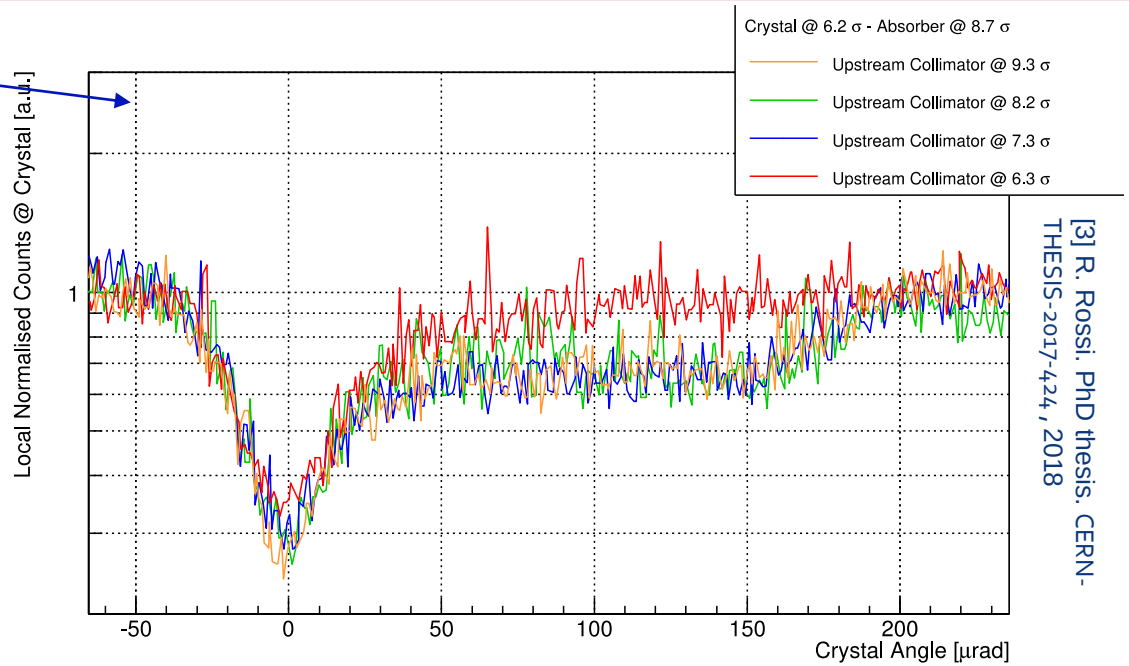
Given the layout and the time available it was decided to investigate the effect in SPS.



local losses vs crystal rotational orientation

Upstream obstacles affects the crystal channeling efficiency





[3] R. Rossi. PhD thesis. CERN-THESIS-2017-424, 2018

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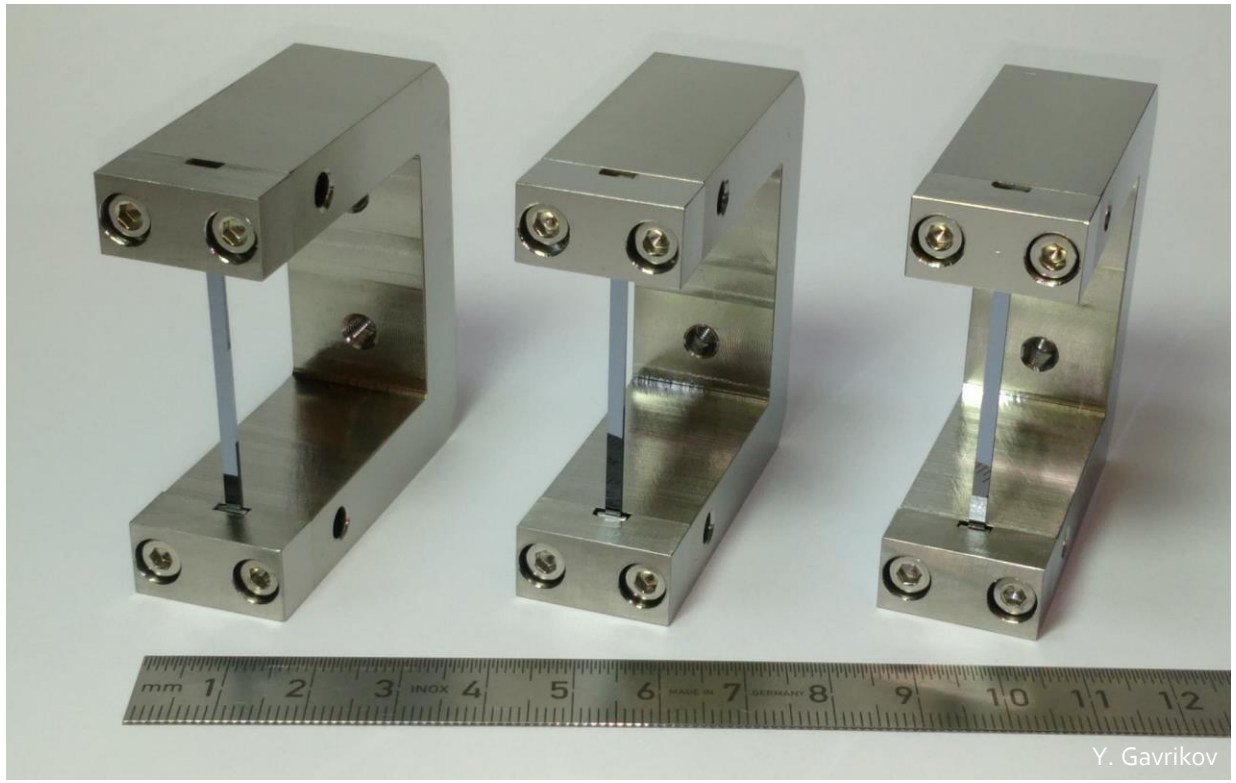


Beam Extraction from SPS

The use of a bent crystal as extraction device has been one of the first application in circular machines

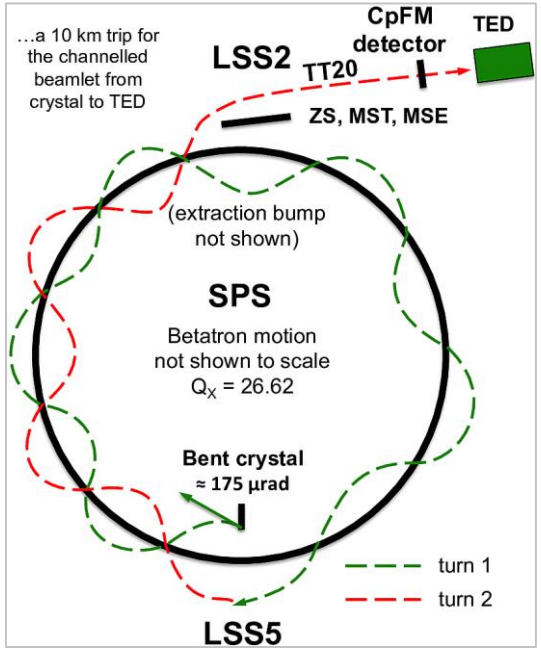
- **Extraction flux ~4 x as today** (up to 4 x 10^{19} PoT/year) required for future Fixed Target programs at CERN SPS (i.e. Beam Dump Facility (BDF) and SHiP)
- At SPS it is expected that about **1-2% of extracted particles hit the Electrostatic Septum** (ES) wires inducing secondary particle showers (measured value is 3.4±0.7%, Fraser, Slow Extraction Workshop 2017)
  - The secondary particle showers strongly activate the area downstream and can also affect the high voltage performance of the ES

- Ongoing studies to reduce the losses at the ES using bent crystals:
  - Non-resonant extraction using bent crystals and a stochastic transverse beam excitation
  - Crystal-assisted shadowing of the ES

Beam Extraction – non resonant

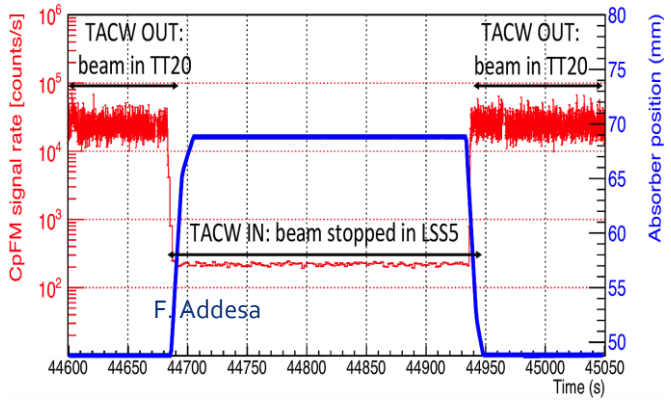
Using crystal as an extraction device in a circular machine was already proven in Russia (currently used at U-70 IHEP!), and was proposed to be tested in SPS

- **Use the original UA9 infrastructure** (goniometers with crystals, absorbers, detectors)
  - → + an on purpose Cherenkov detector (CpFM) down the extraction line TT20
- Non-local → UA9 Goniometers (LSS5) and Fixed Target Extraction Line are opposite in the SPS ring
- Stochastic → particle diffusion from the beam core was enhanced by means of the Transverse Adiabatic Damper (ADT, random transverse kicks)
  - → different ADT excitation = different extraction rate



[4] M. A. Fraser et al., arXiv preprint arXiv:1707.05151(2017). doi:10.18429/JACoW-IPAC2017-MOPIK048.

This test has been performed with success in 2016!



The crystal location, and the crystal characteristics are not optimized for such operations.
Studies to select the best crystal characteristics and a good location are on going

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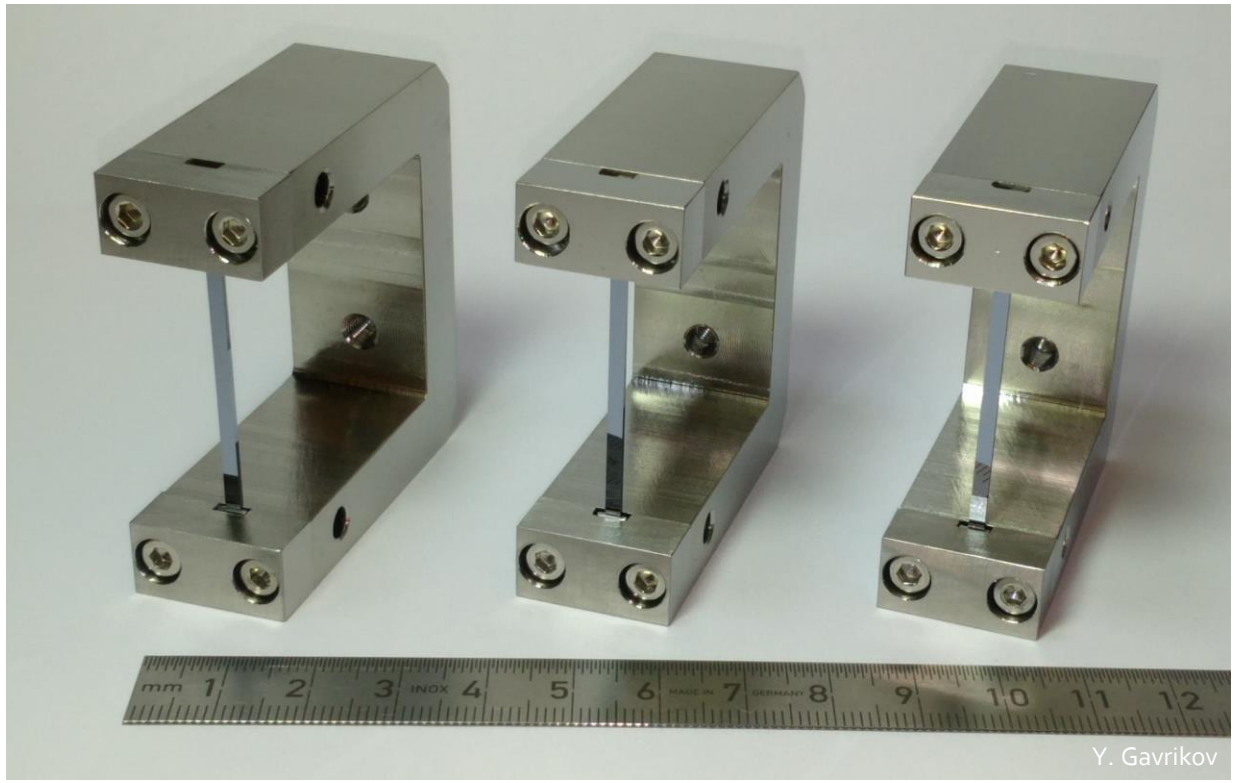
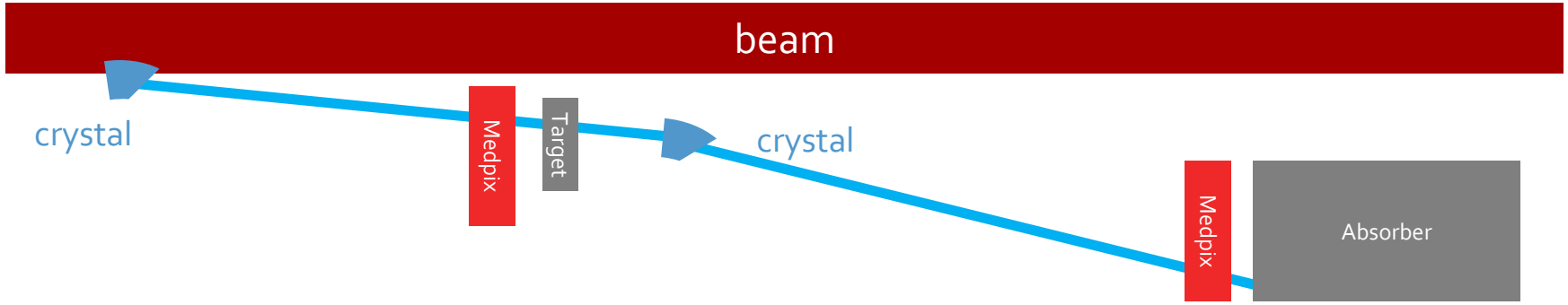


Double Channeling



Magnetic moment of channeled particles should precess in a bent crystal

$$J_{spin} = \frac{g-2}{2} g J_{crystal}$$

See V.G. Baryshevskii, Pis'ma Zh. Tekh. Fiz. 5, 182 (1979) and PLB 757 (2016) 426-9.

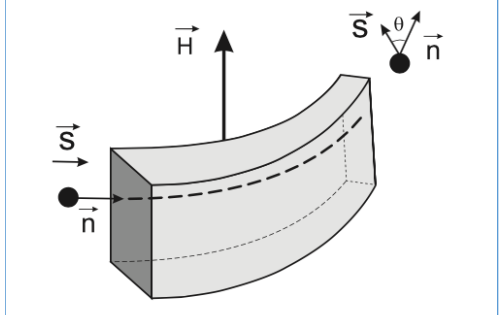


Figure 1. Spin rotation in a bent crystal

In the framework of future fixed target experiment in LHC a double crystal layout has been proposed to measure magnetic moment precession of short living particles, giving the high equivalent magnetic field generated by a bent crystal.

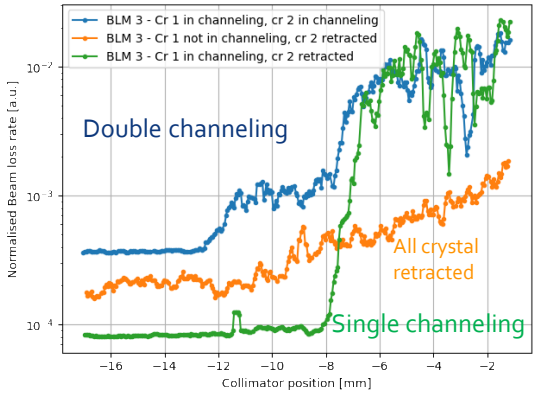
<u>In this scheme:</u>

- One bent crystal is used to separate the halo from the circulating beam, and deflected onto a target
- The second one is used to channel the particles emerging by the target and to let their magnetic moment to precess

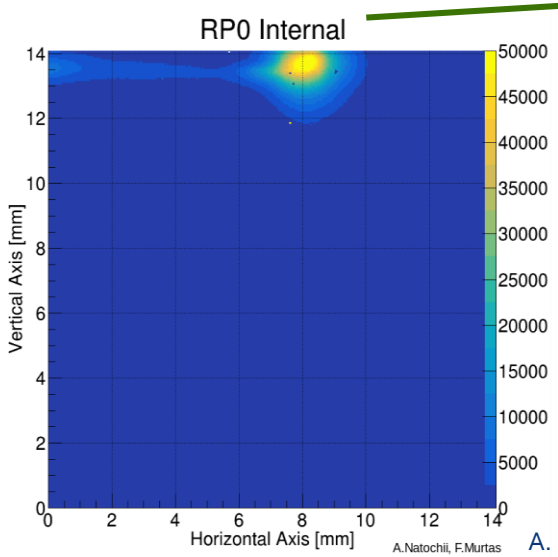
The layout update has been proposed and realized in 2017 to adjust the UA9 equipment to realize the measurement

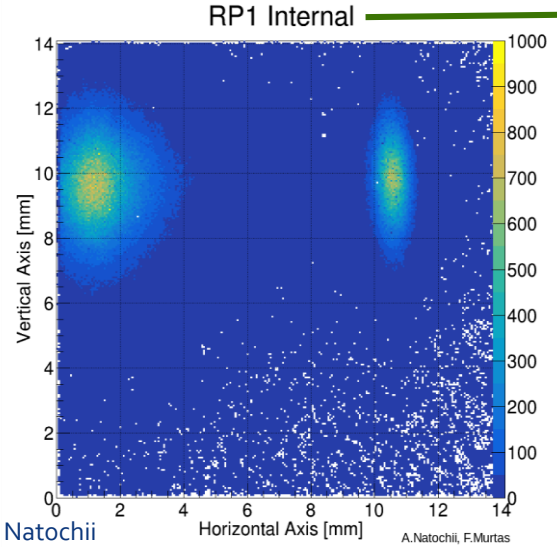
Double Channeling

Double channeling was achieved for the first time in 2017!

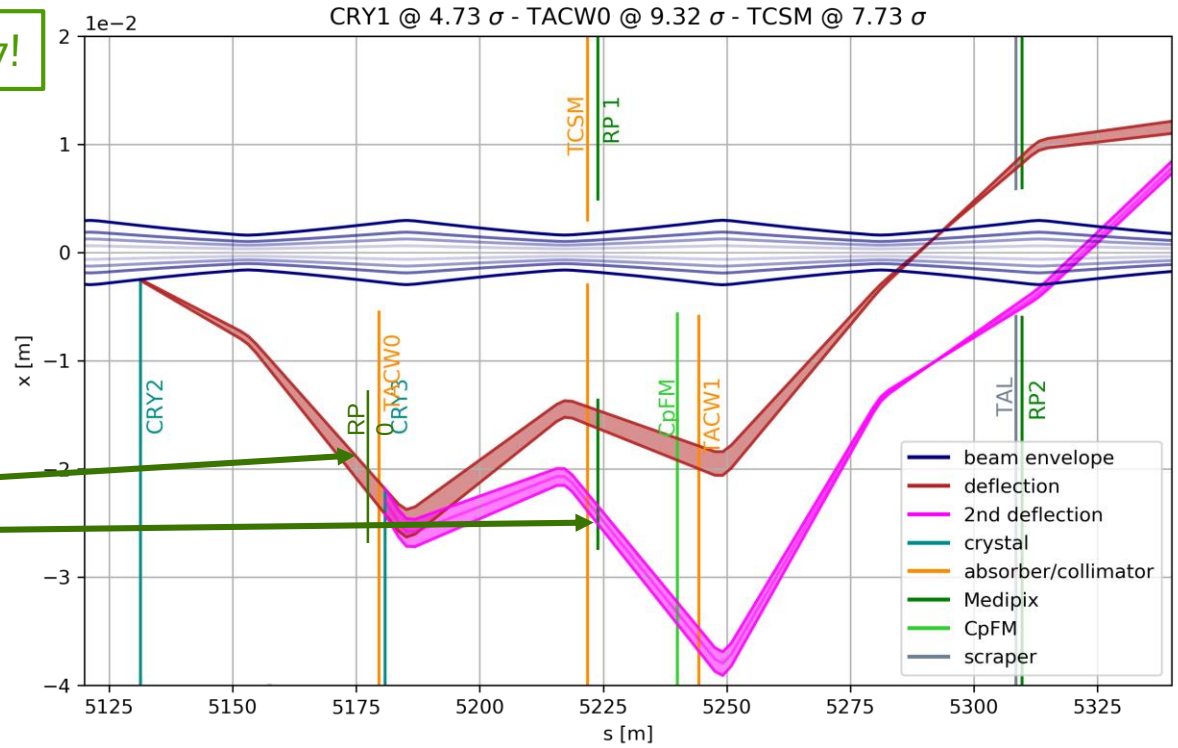


Only BLM measurements were available → very difficult to establish with BLM





A. Natochii

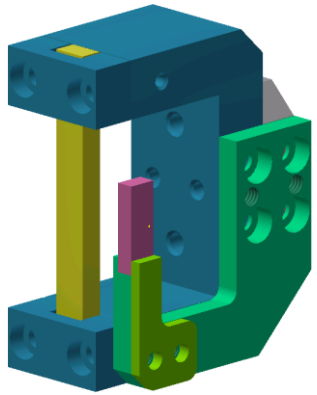


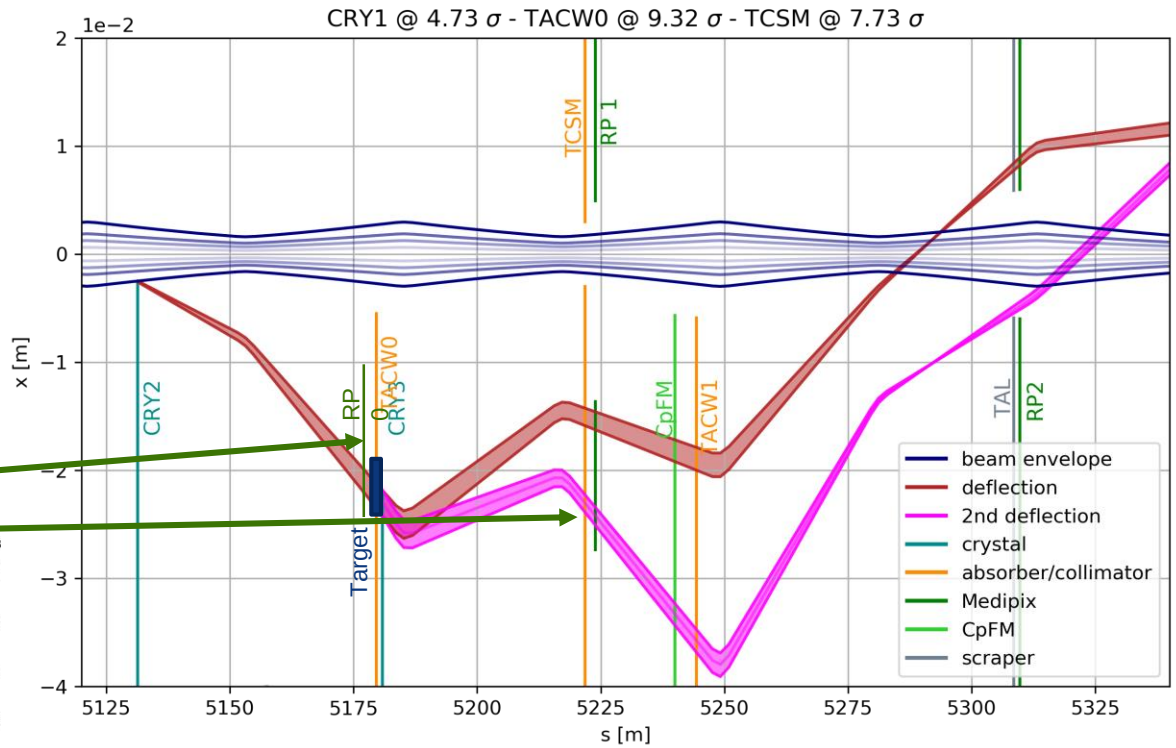
MediPix improved a lot the online measurement conditions, also new crystals with optimized characteristics were installed. Double channeling was easily achievable during all the 2018 data tacking

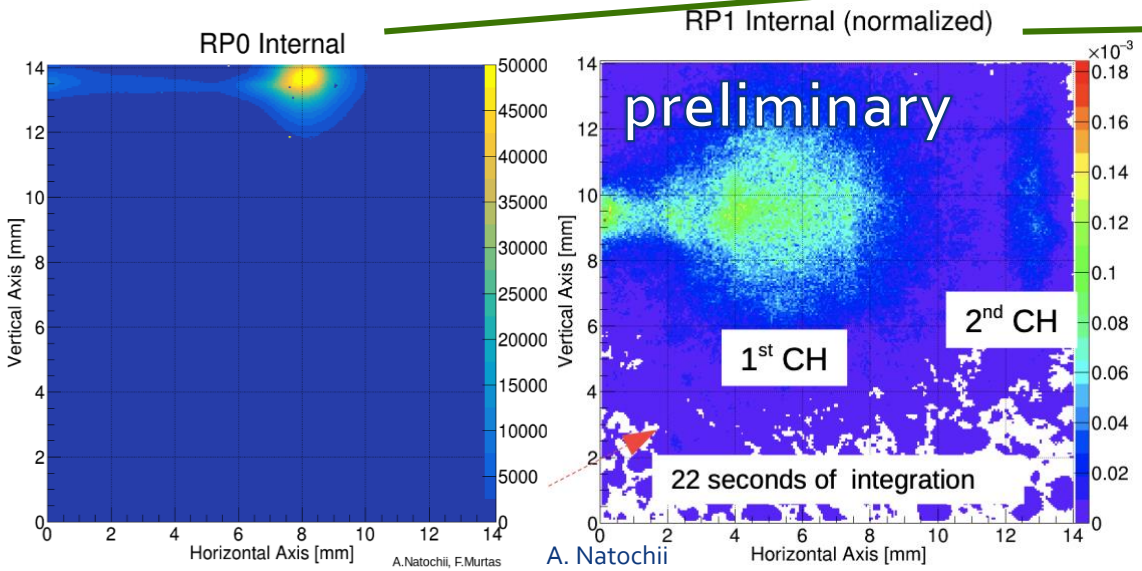
[5] S. Montesano et al., doi: 10.18429/JACoW-IPAC2018-TUPAF043

Double Channeling with Target

In addition, a W target was installed in front of the second crystal was installed in time for a test at the end of Run 2







Double channeling with a target mounted in front of second crystal was as well observed at end of the last year!

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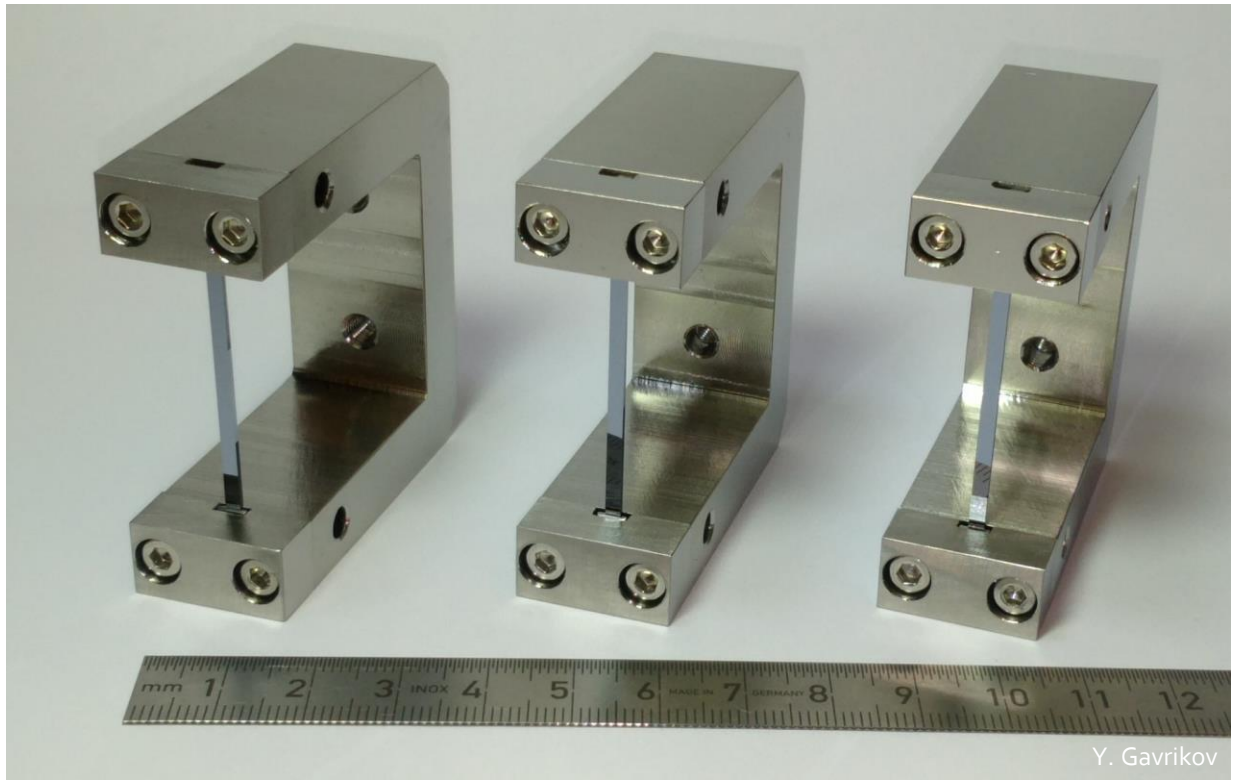

Conclusions

- In recent years, crystals have been increasingly used for different activities in hadron beam manipulation
  - **Bent Crystal Channeling is now considered a reliable technology for various applications**
- In the UA9 framework, crystals are used and tested in H8, SPS and LHC:
  - SPS has been used for crystal collimation feasibility study in Run 1, and as test-bench in Run 2
    - ✓ It was proved that an upstream obstacle close to the crystal transverse aperture affects the channeling efficiency of the crystal itself
    - ✓ It was also proved that a graphite collimator is not suitable to absorb the channeling halo, even in the SPS with reduced energy and beam intensity
      - A dedicated channeled halo absorber is needed for operational use
  - Crystals were also used as support for beam extraction to NA
    - ✓ A crystal was used as deflector of dangerous particles during slow extraction
    - ✓ A crystal was also used to deflect particles into the NA extraction line in a non-resonant mode
  - A feasibility study for a double crystal channeling scheme was carried out successfully
    - ✓ These tests are very important for future fixed target program

Final Remarks

- Has you have seen UA9 works is extremely multidisciplinary
  - Physics
    - Particle Physics
    - Physics of Matter
    - Particle-Matter Interactions
    - Accelerator Physics
  - Instrumentation
    - Detectors
    - Mechanics
  - Experimental Physics
    - Measurements preparation
    - Data Acquisition/Analysis
  - Simulations
- Transversal to several CERN groups: (EN-STI-BMI, EN-STI-TCD, EN-SMM-MRO, BE-ABP-HSS)
  - With support from BI, BE-OP and to TE-ABT etc…
- UA9 is currently planning how to upgrade the equipment installations and proposing new applications

  Several studies have already started…. Update will be ready in the near future

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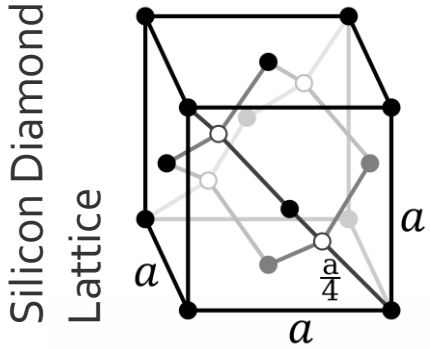
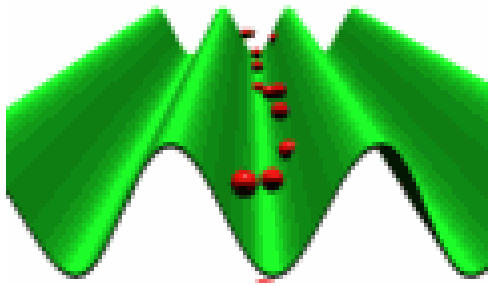
backup

Crystal Channeling





Lindhard: "In the hypothesis of low impact angle, the potential generated by the crystalline plane can be approximated by a continuous potential."

Channeling : Transverse momenta < potential well

The channeling condition can be defined as

$$\frac{p^2c^2}{2E}\theta^2 + U(x) \leq U_{max}$$

Case	Energy [GeV]	θ_c $[\mu rad]$
SPS coast	120	18.3
SPS coast	270	12.2
H8	400	10.0
LHC inj.	450	9.4
LHC top	6500	2.5
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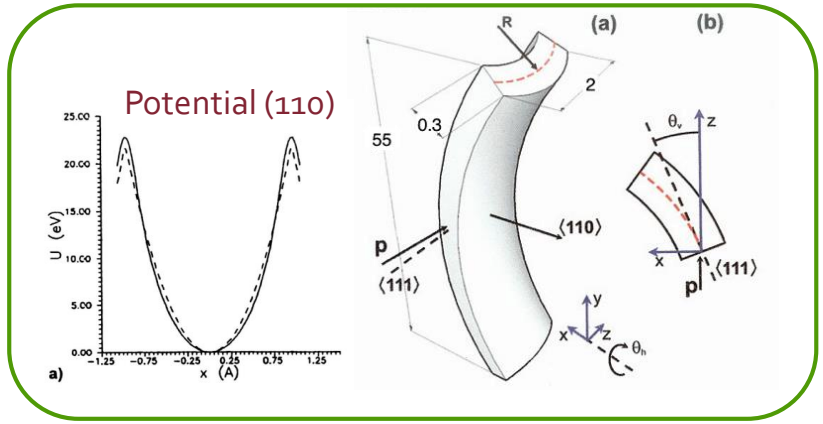
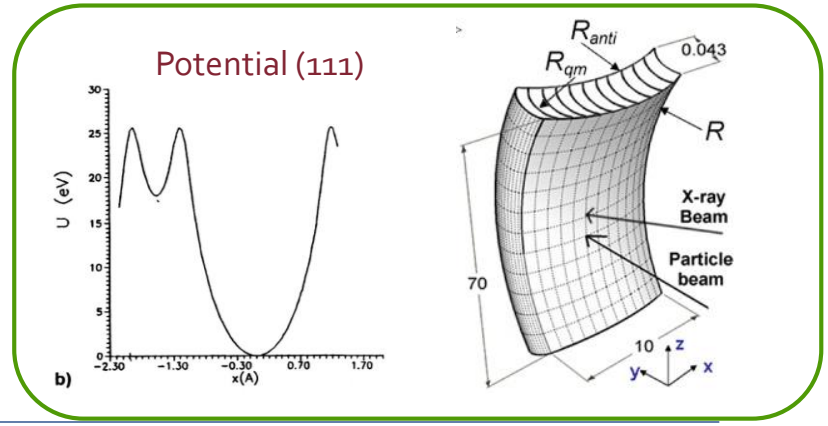
Critical angle

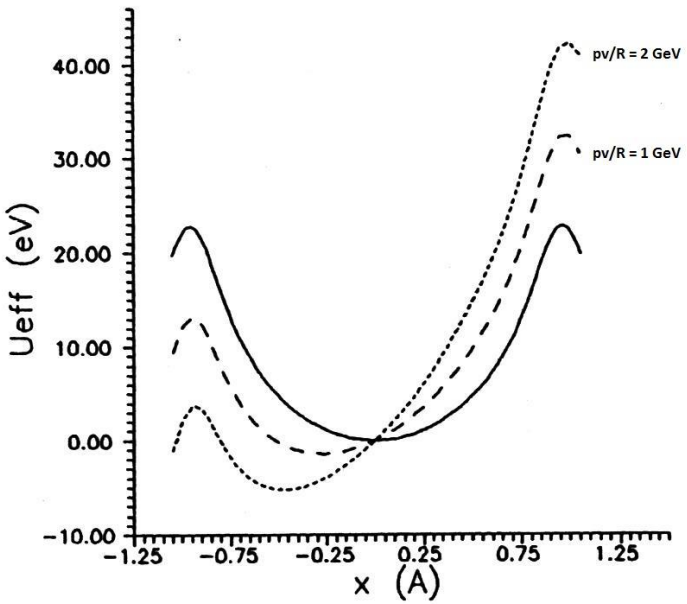
$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}$$





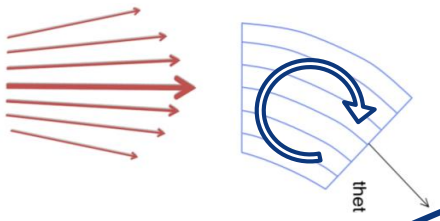
Coherent effects in bent crystals

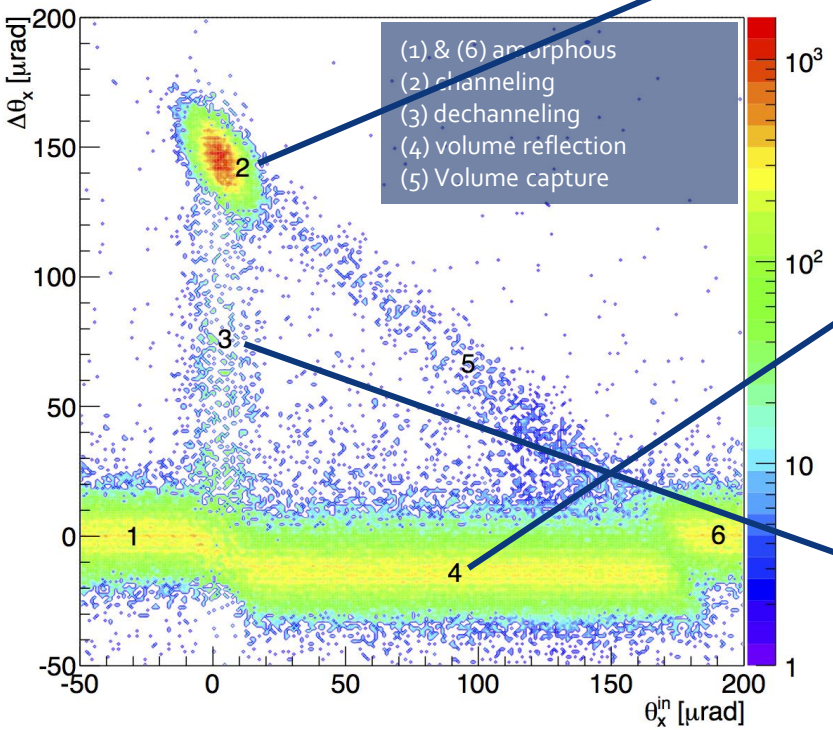
The particles are trapped in the channel, hence if a curvature is given to the lattice the particles direction will be modified by $\theta_b = l/R$



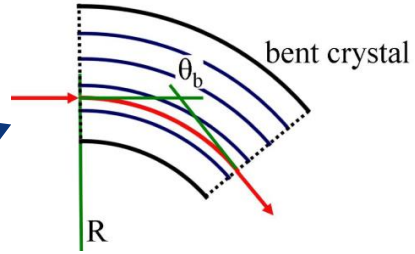
$$R_c = \frac{pvx_{\max}}{2U_{\max}} \Rightarrow \theta_c^b = \theta_c\left(1 - \frac{R_c}{R}\right)$$

Single pass measurements with 400 GeV protons. Strip crystal (110) with a bending of 144 µrad.

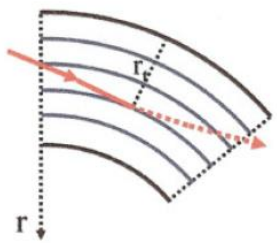




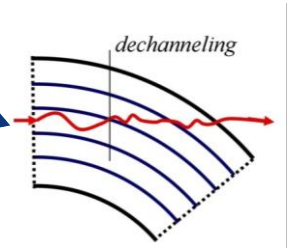
Planar channeling (CH)



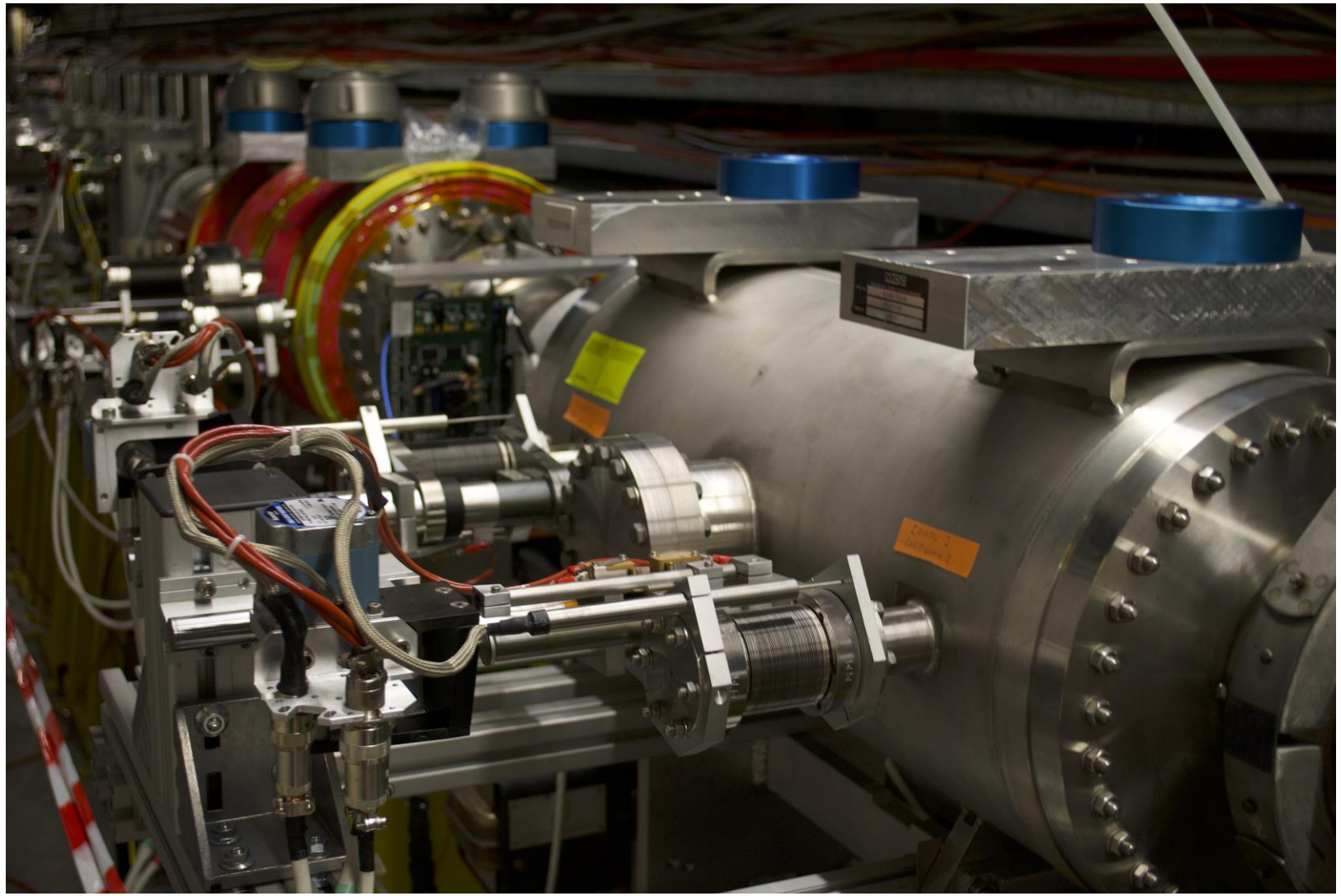
Volume Reflection (VR)



Dechanneling (DC)



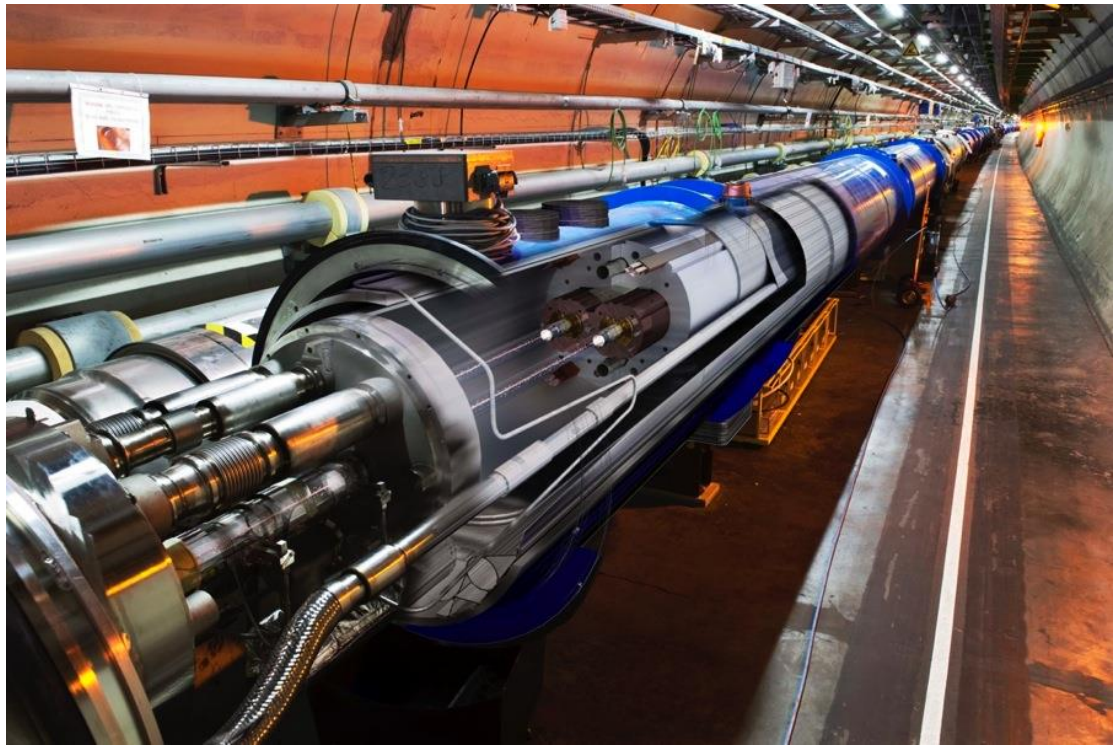
The SPS goniometers



Applications

Superconducting magnets:
- T = 1.9 K
- quench limit ~ **15-50mJ/cm³**
- Aperture: r = 17/22 mm

Stored energy in the machine**:**
- LHC 2016: **280 MJ**
- LHC design: **360 MJ**



Collimation system is needed!

$\eta = 10^{-4}$ is the actual performance

For the HL-LHC is foreseen:
- Increased beam stored energy: 362MJ ⟶ 700MJ at 7 TeV
  Collimation cleaning versus quench limits of superconducting magnets
- Larger bunch intensity (I_b=2.3x10^{11}p) in smaller emittance (2.0 µm)
  Collimation impedance versus beam stability
- Operational efficiency is a must for HL-LHC!
  Collimators: high precision devices that must work in high radiation environment
- Upgraded ion performance (6 x 10^{27}cm^{-2}s^{-1}, i.e. 6 x nominal)

Crystal Collimation for HL-LHC

For the future HL-LHC an upgrade of the actual collimation system is required

- ✓ Good baseline solution for proton beams
- ✗ No solution for lead ion beams

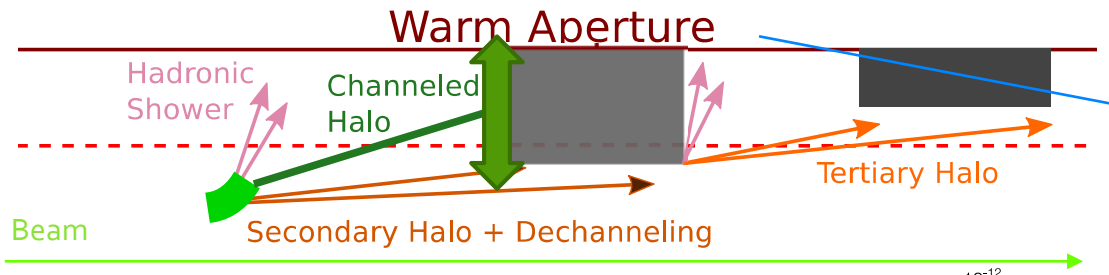
Crystal collimation *could improve the ion cleaning* and is one of the R&D subject

<u>Different challenges to be addressed</u>

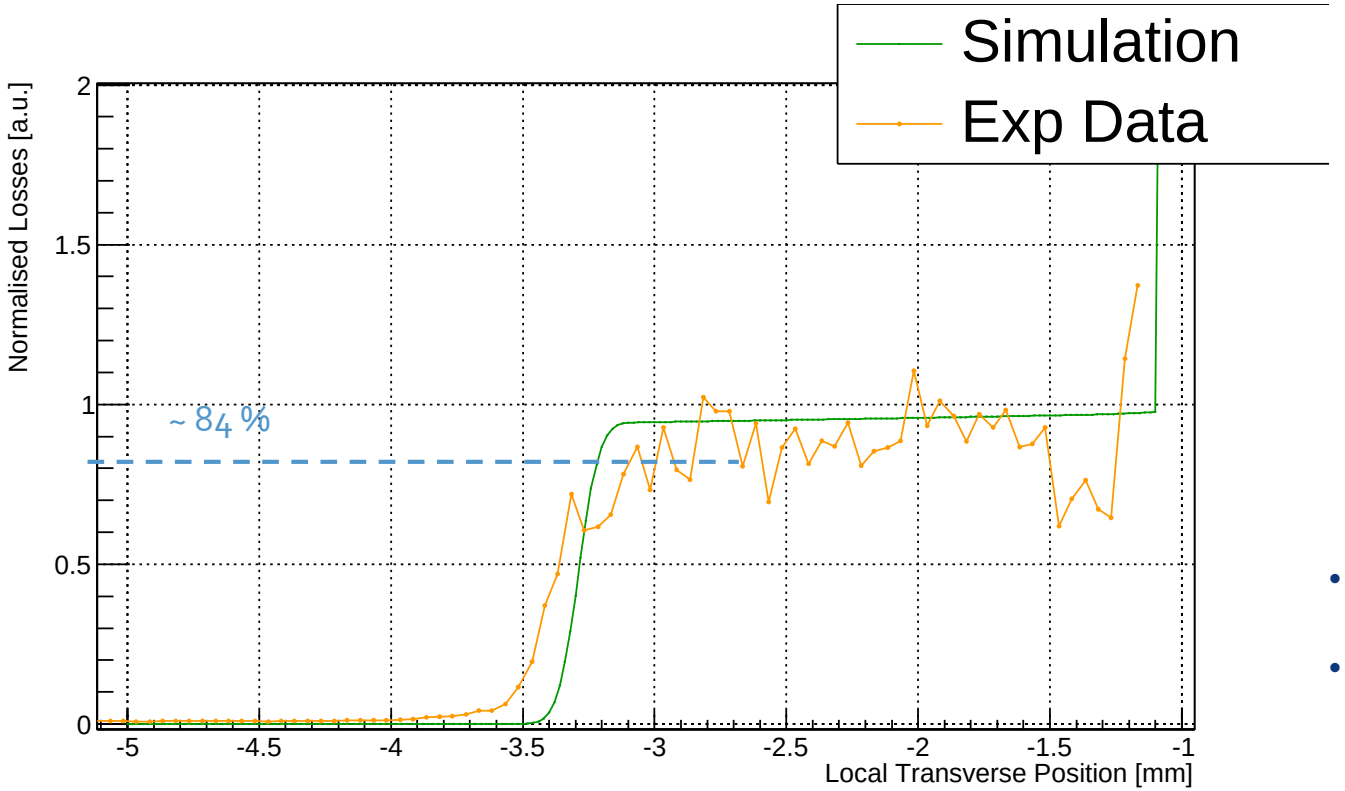
- ☑ Understanding limitations of present Collimation System
- ☑ Channeling assessment at LHC energy range for both proton and ion beams
- ☑ Experimental assessment of crystal collimation performance in the LHC for both proton and ion beams
- ☑ Understanding of experimental results in simulation
- ☐ Study and design of an absorber stage
- ☐ Design of new layouts for a complete crystal system on both beams

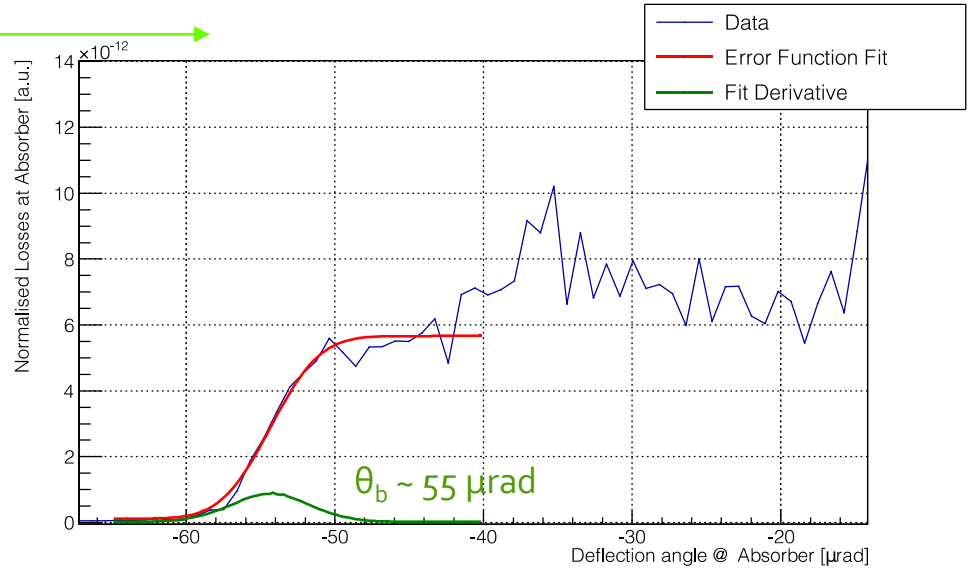
Channeling Assessment in Circular Machines

2. Absorber Scan



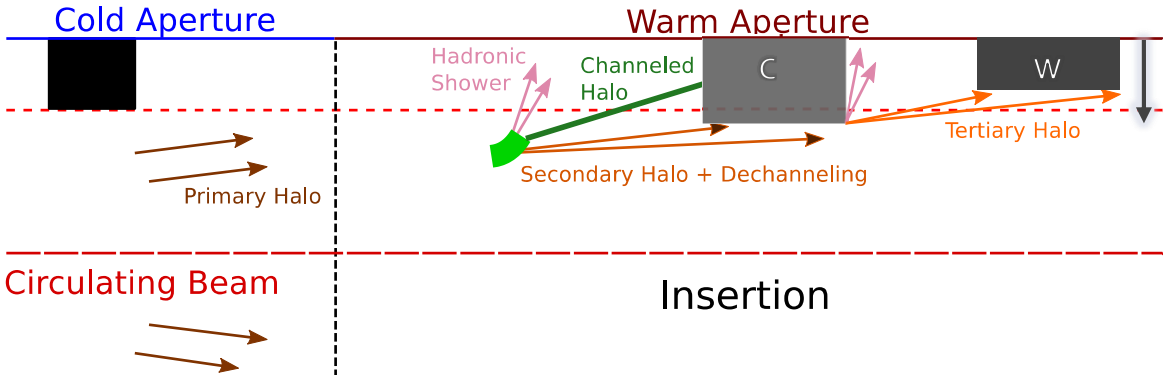
local losses
vs
collimator transverse position

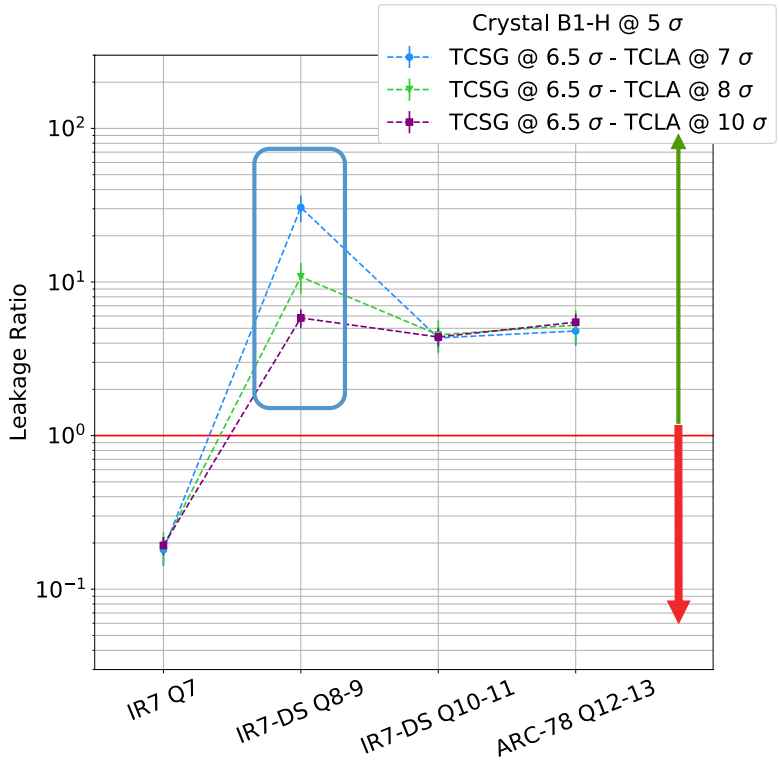




- The deflection angle can be evaluated with the Transport Matrix
- The multi-turn channeling efficiency can be evaluated by the losses at channeling plateau, normalised to the primary beam spike

LHC Observation With Xe ions



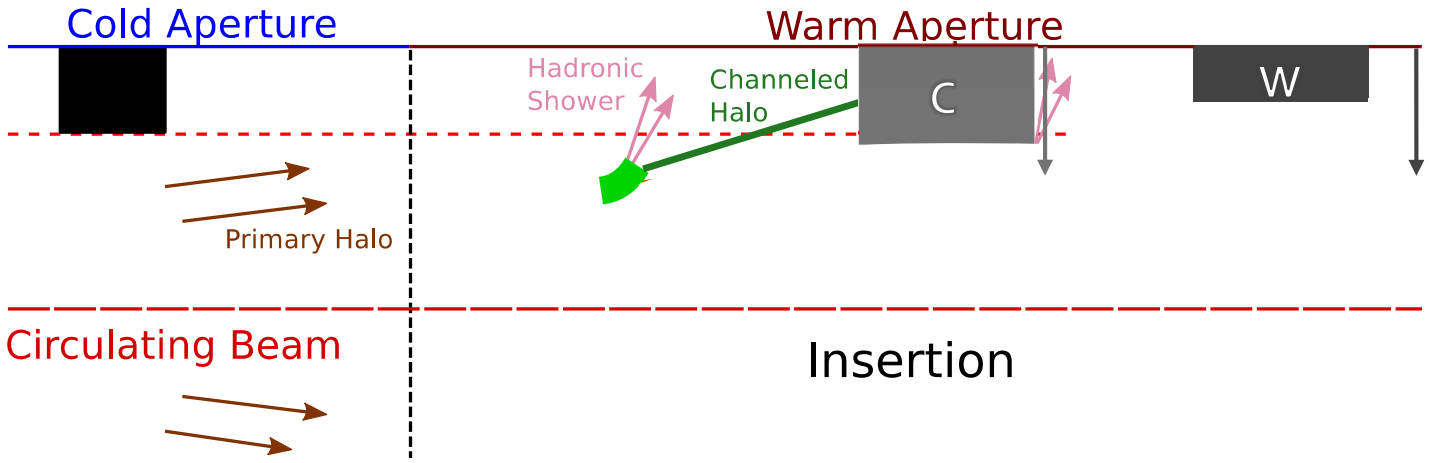


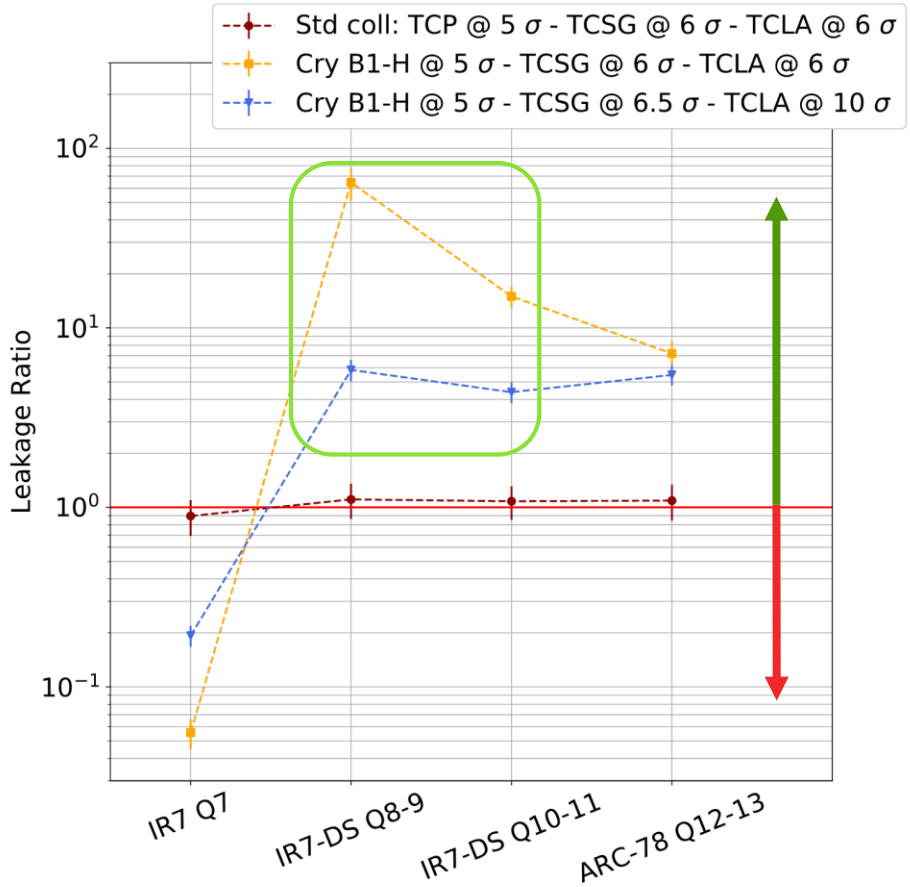
The LHC ion beam collimation was improved closing W collimators to same settings of C collimators.

Off-momentum particles produced by secondary collimators (C) can be stopped using higher Z absorber, e.g. absorber collimators (W)

In SPS both kind of absorbers are available and were used to evaluate the leakage for the different collimator materials

Ions Collimation Cleaning in LHC



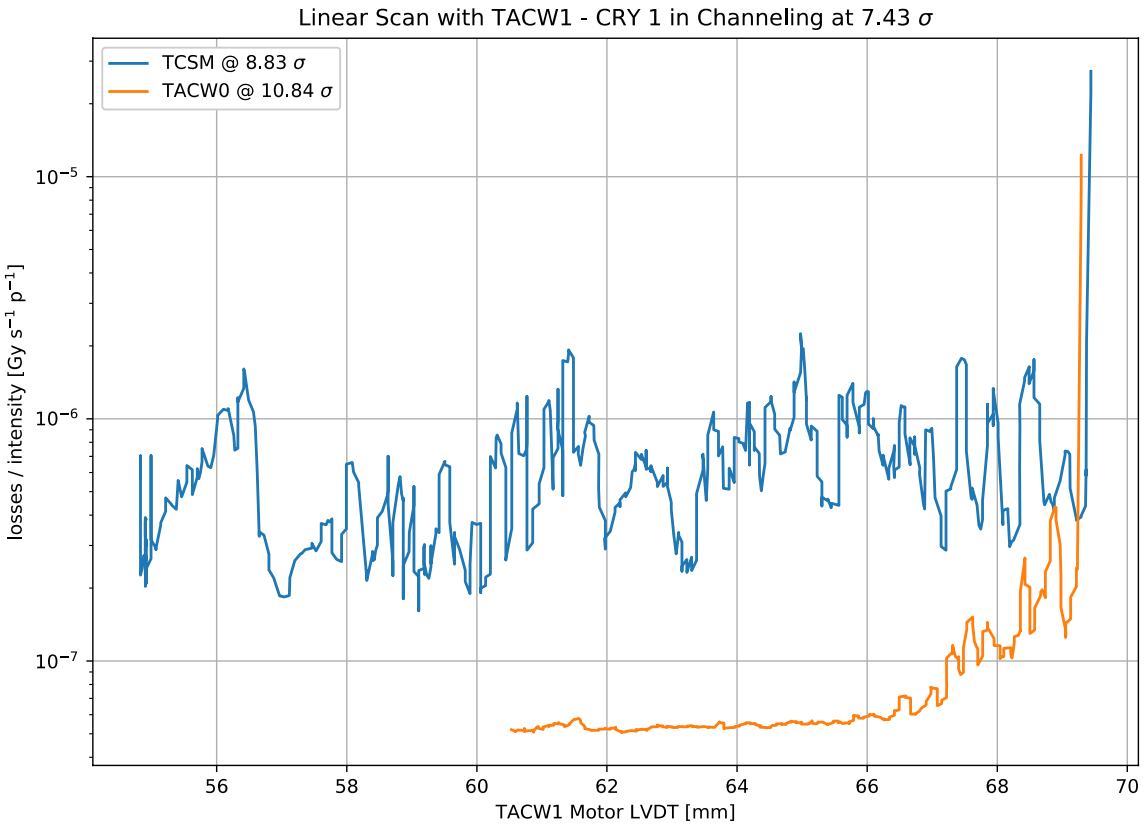


An improvement larger than an order of magnitude is observed in the IR7-DS

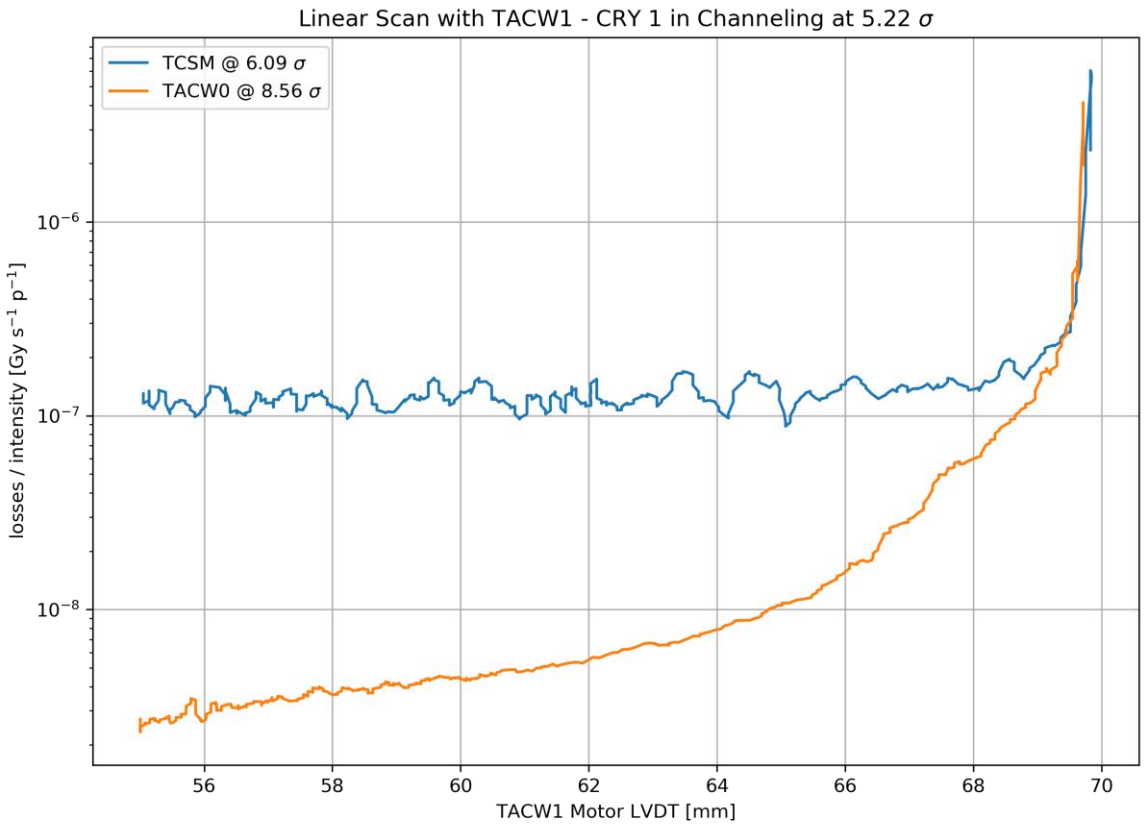
Crystal collimation *improved the ion cleaning* and is one of the R&D subject for HL-LHC upgrade

SPS absorbers test – linear scans

protons



Lead ions



Even more clear is the study of losses at TACW1 during a linear scan. This measurement shows that the population of particles leaking from the C collimator (secondary halo) is almost one order of magnitude higher than the W collimator.

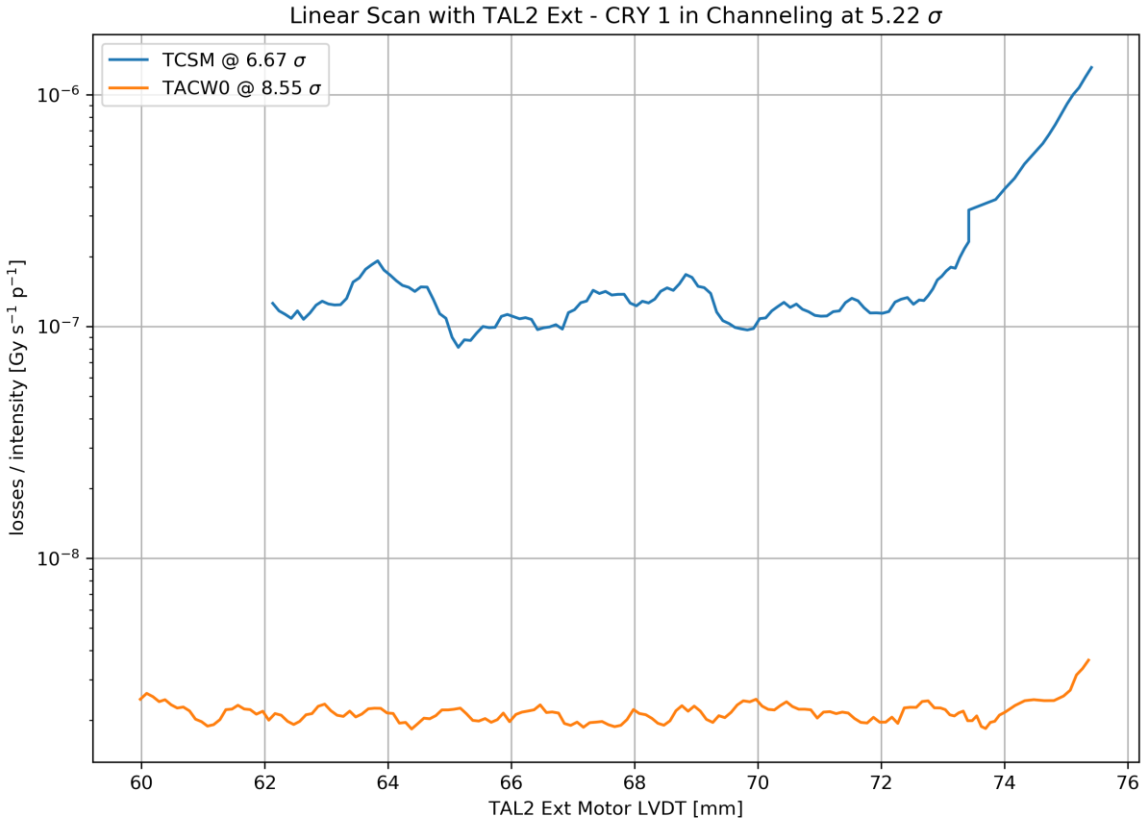
SPS absorbers test – linear scans

At the first dispersive peak, another movable scraper (W, 10 cm), the TAL2, is available.

A linear scan allowed to measure the off-momentum particles generated by the interaction of channeled halo with the absorber.

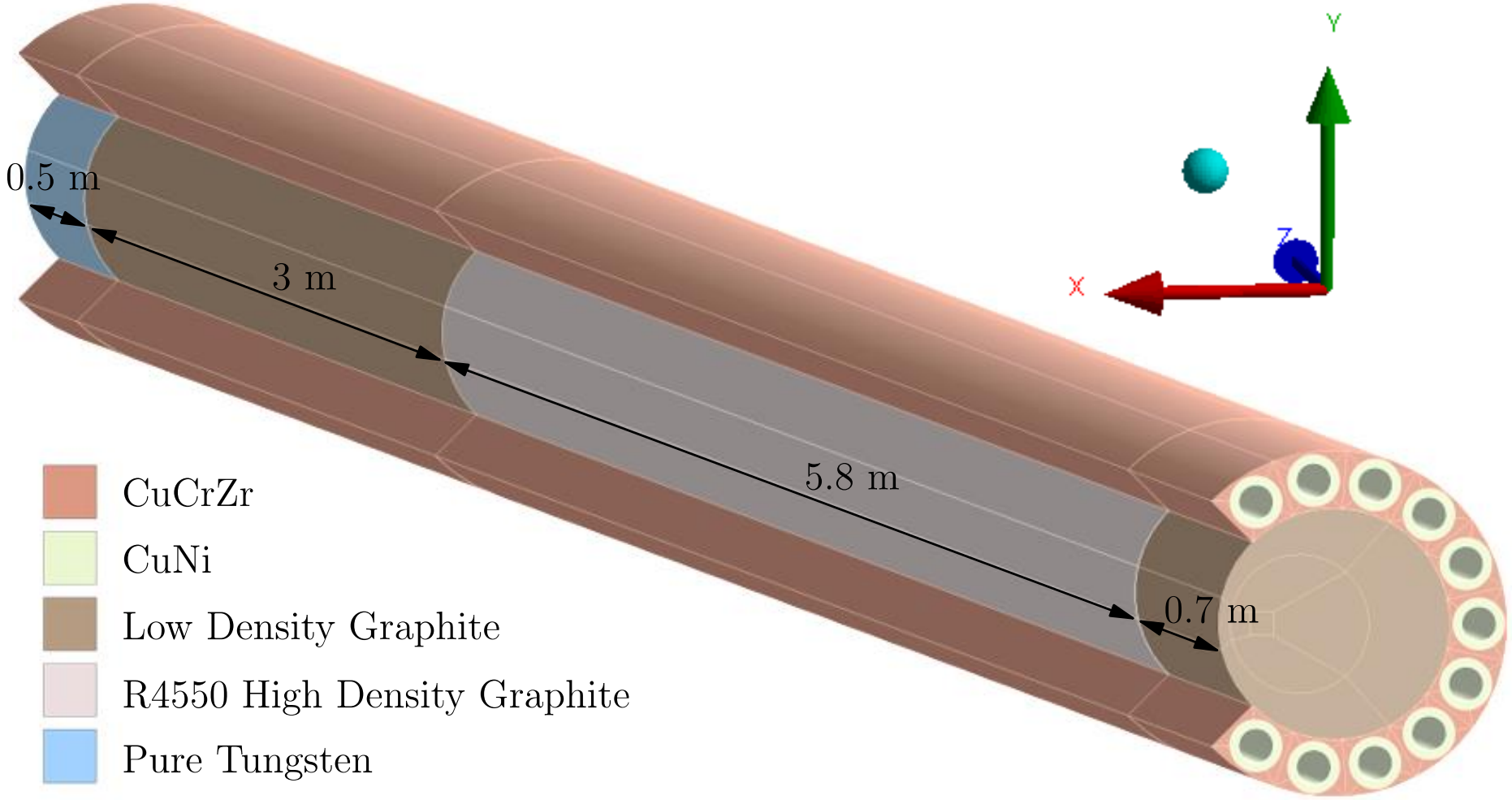
In this case an even larger difference can be observed

Lead ions



Dedicated LHC absorber

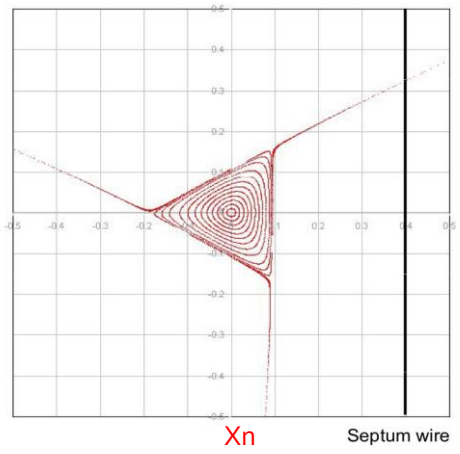
Samuele Gould

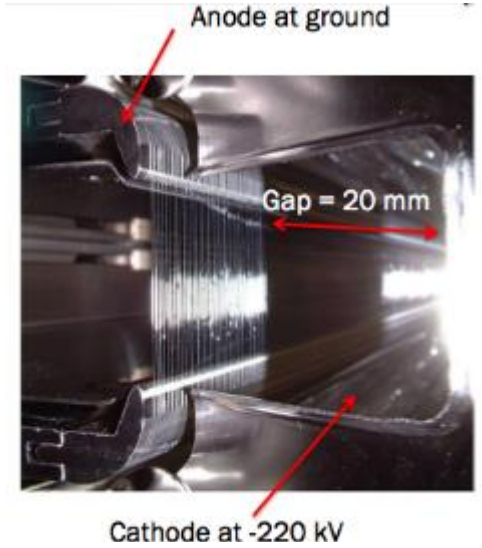


Beam Extraction – resonant

One of the scheme proposed by TE-ABT group was to shadow the septum wires with an obstacle used as passive diffuser.

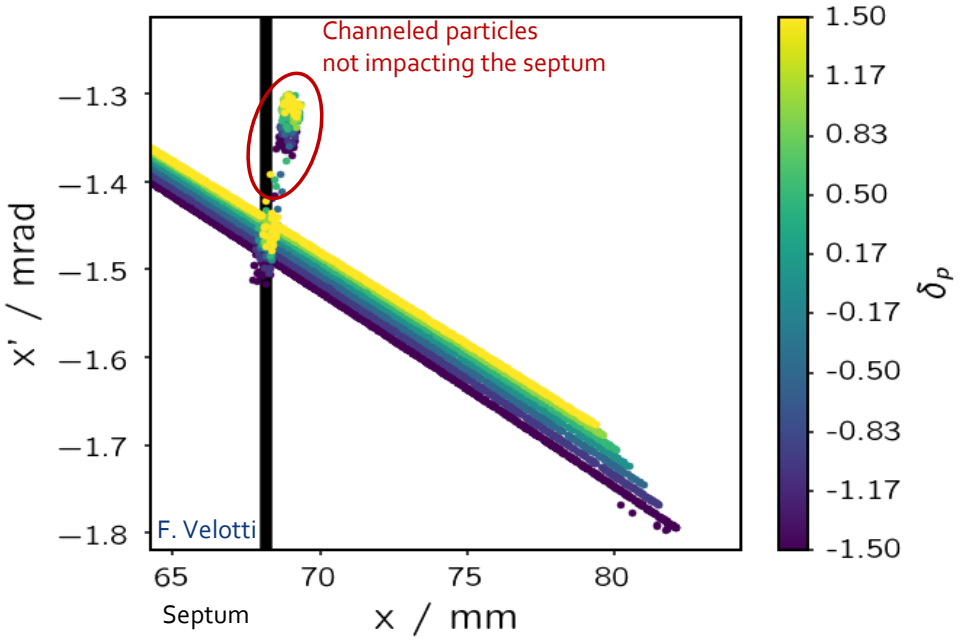
A crystal was proposed instead as an active device, that is able to coherently deflect particles away from septum wires.





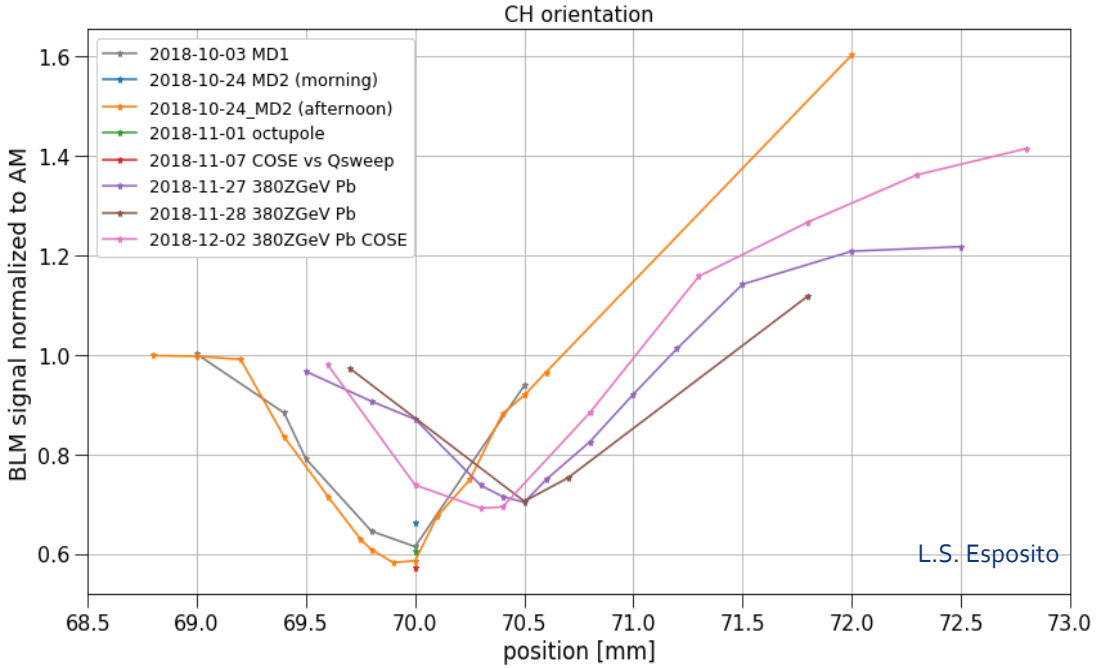
- The crystal was installed in September 2018 in place of the already-tested passive diffuser 5 m upstream of the ZS
- Tested during several MD parasitically to SHiP T6 tests on October 3rd and 24th with a 1-second 400 GeV spill

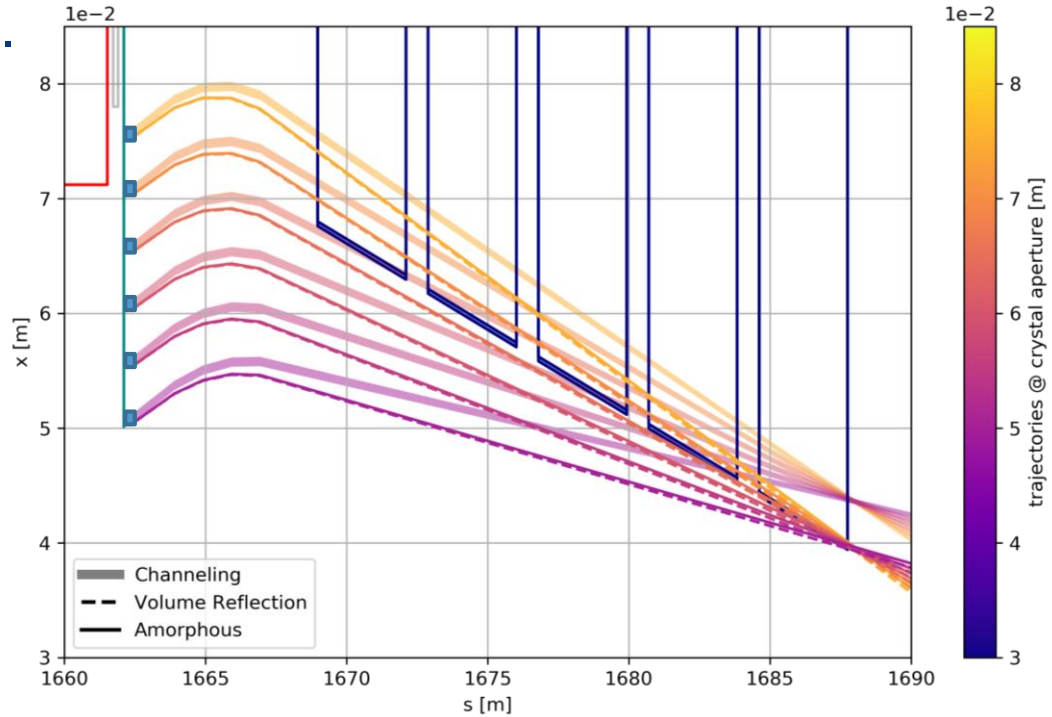
Protons are deflected 5m upstream of the ES, to avoid loss with the anode wires



Slow Extraction with crystal shadowing

Test aimed to reduce number of particles on ZS wires. Changing the crystal transversal aperture and optimizing channeling orientation, allowed to reduce the extraction line losses, when the deflected beam was coherently deflected away form ZS wires.





A reduction of 40% of losses with protons and 30% with lead ions was observed when crystal is in channeling at the best aperture.