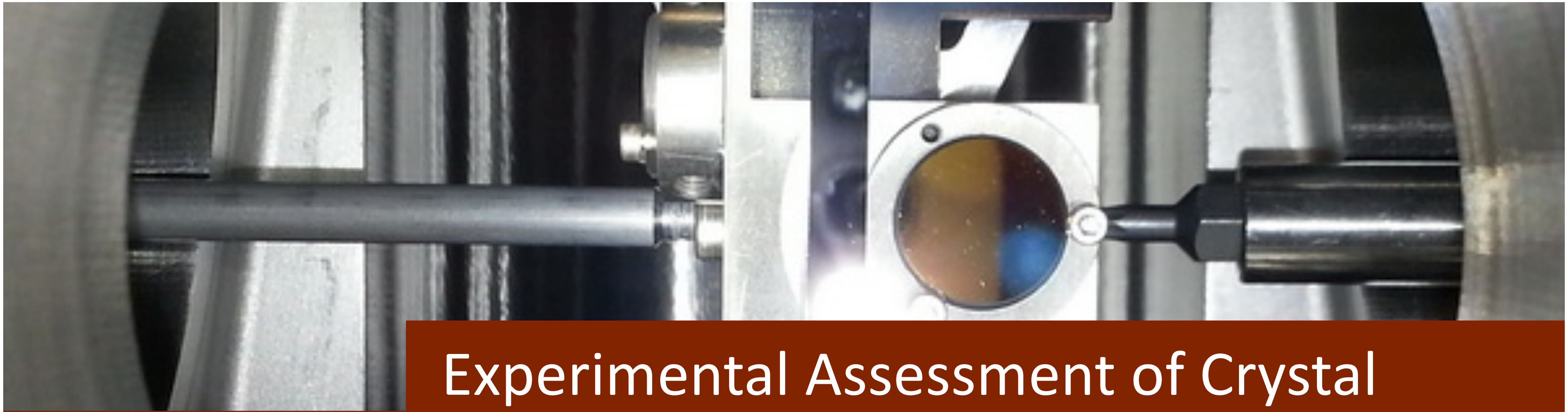


Experimental Assessment of Crystal Collimation at the Large Hadron Collider

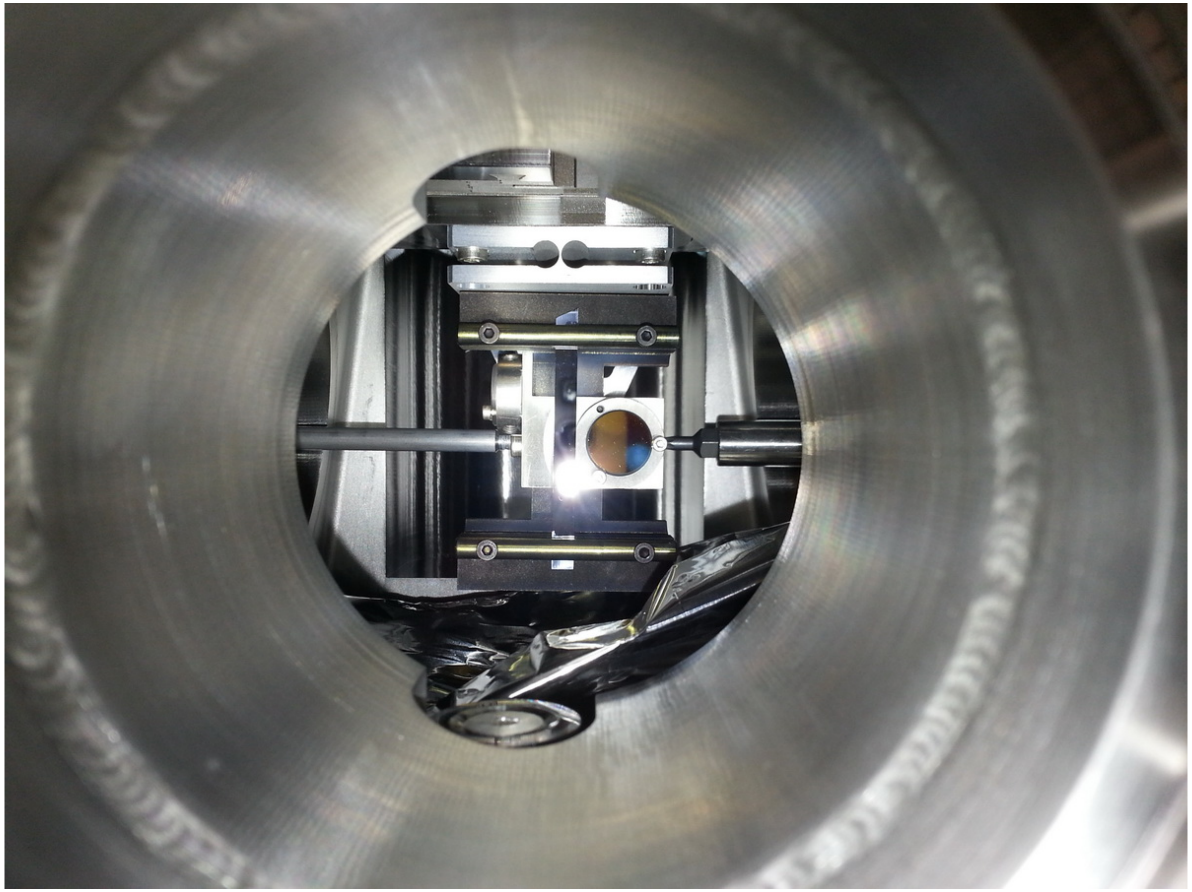
26/01/2018 – PhD Final Exam

Roberto Rossi

Home institusion supervisor: Gianluca Cavoto
CERN supervisors: Stefano Redaelli, Walter Scandale

Outline

- Motivations
- Hadron beam collimation
- Crystal Collimation
- Devices & Layout
- Results
  - Channeling Assessment
  - Cleaning Performance
  - Channeling in Dynamic Phases
- Conclusions



Strip silicon crystal. Installed on the horizontal goniometer in LHC.

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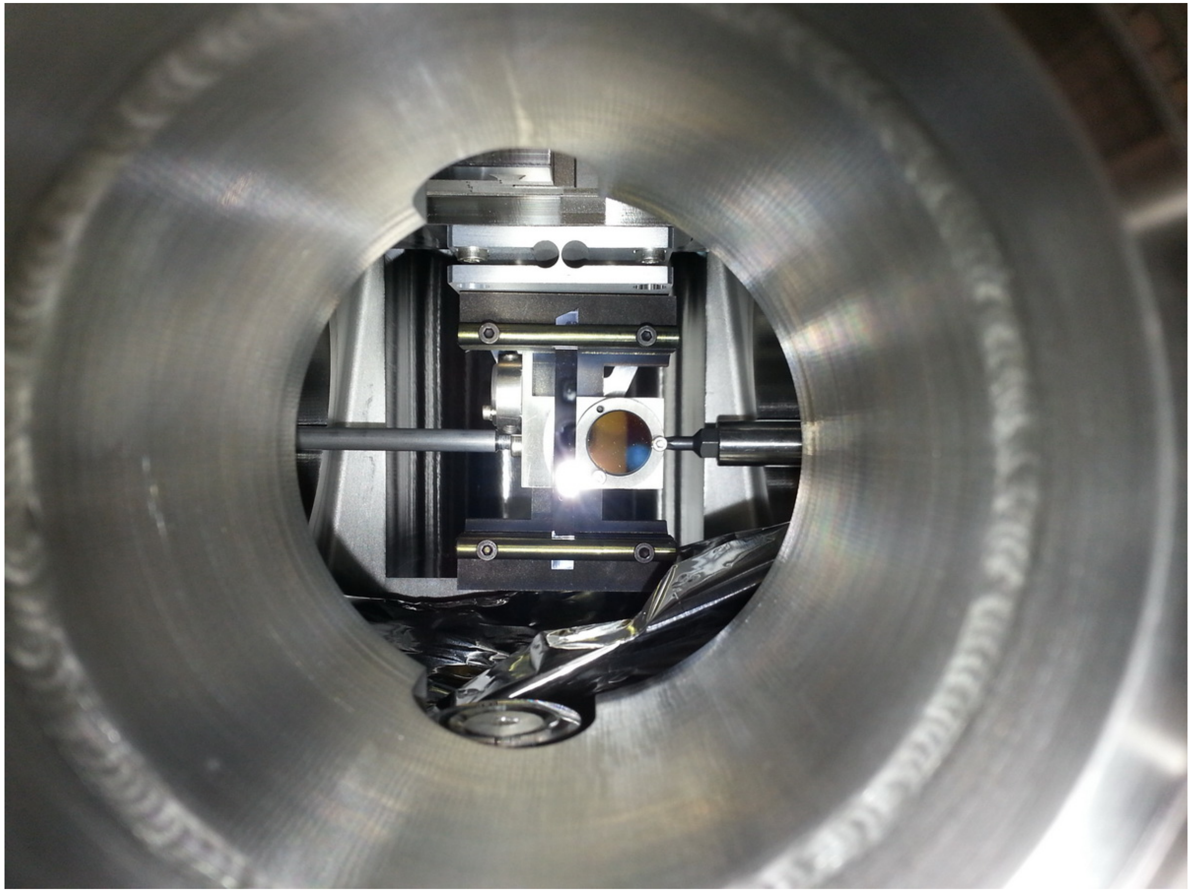
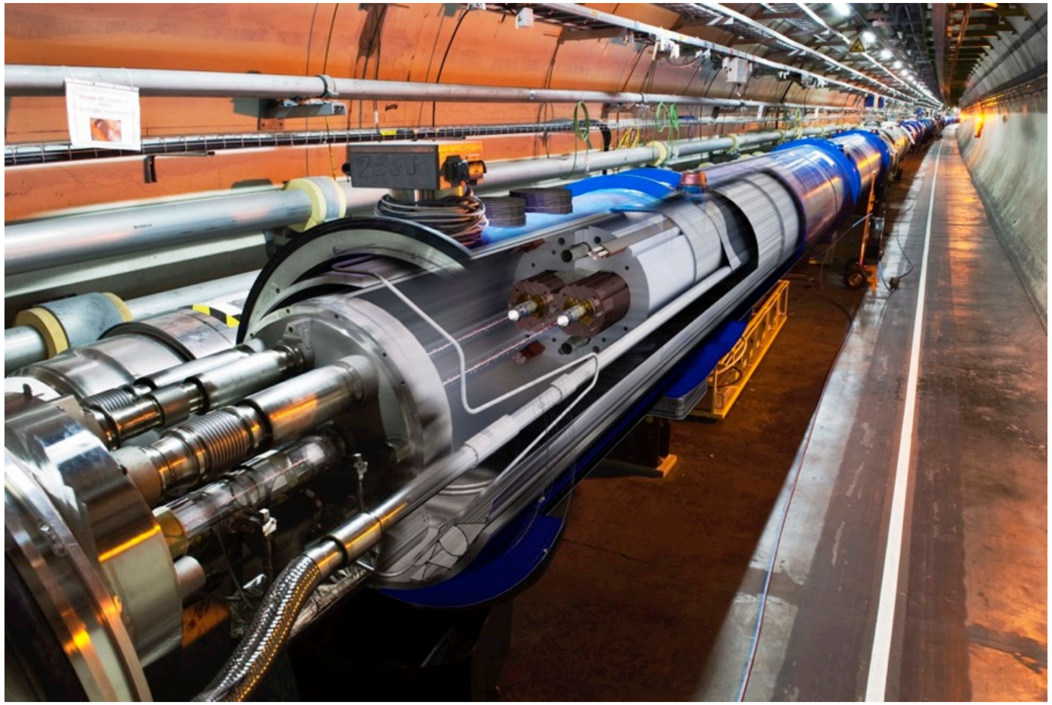


Strip silicon crystal. Installed on the horizontal goniometer in LHC.

Motivations

Superconducting magnets:
- T = 1.9 K
- quench limit ~ **15-50mJ/cm^3**
- 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)

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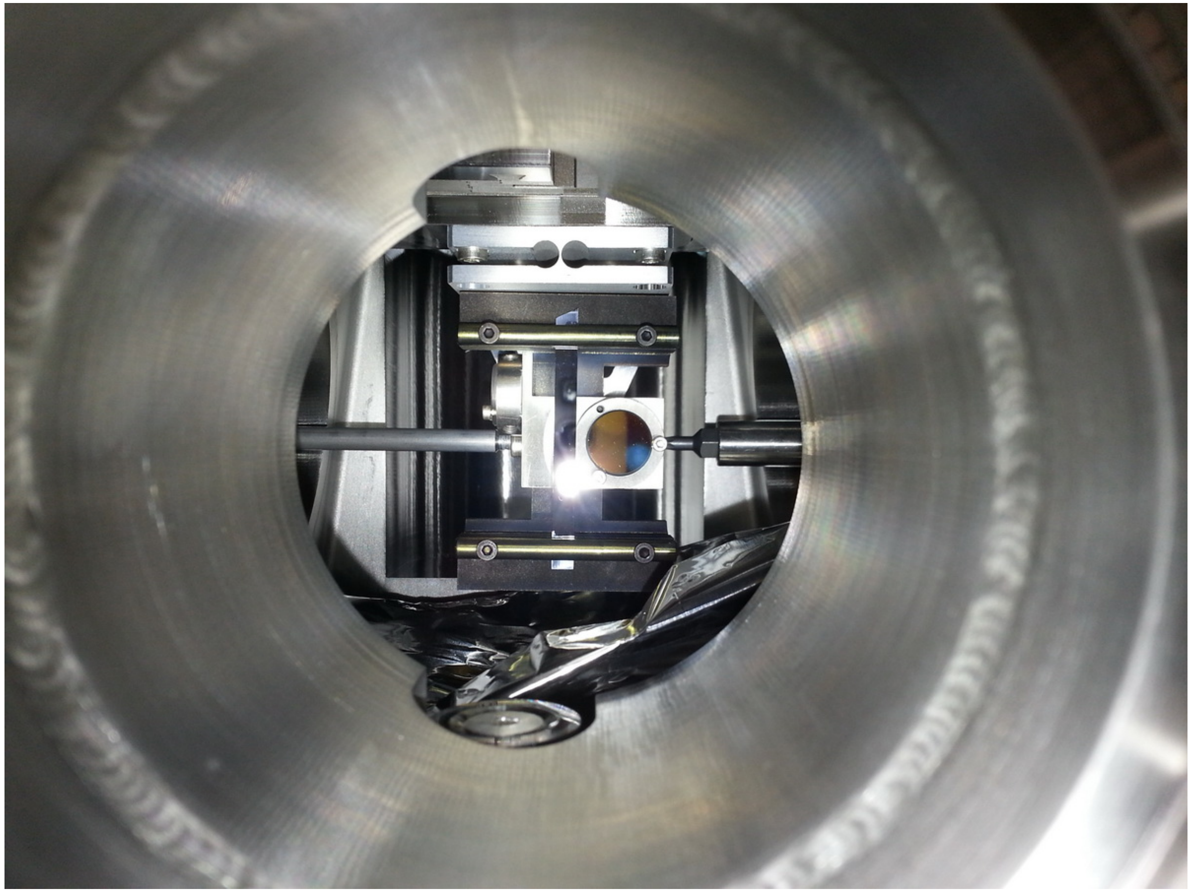
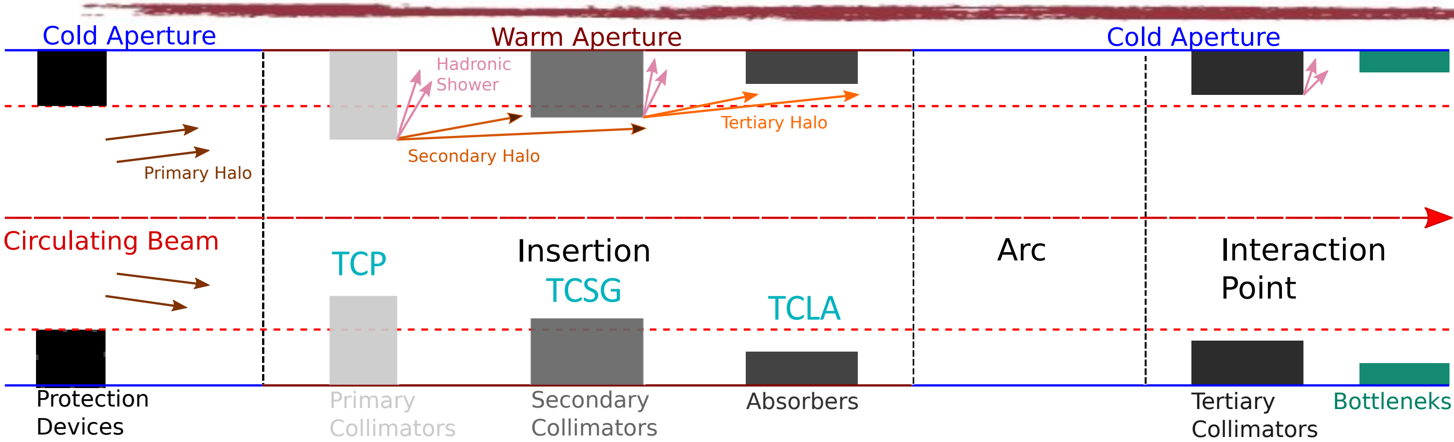
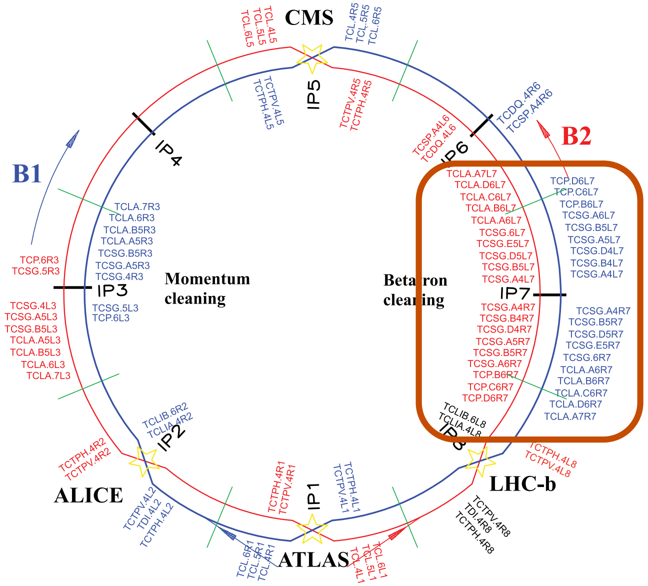


Strip silicon crystal. Installed on the horizontal goniometer in LHC.

Collimation System @ LHC

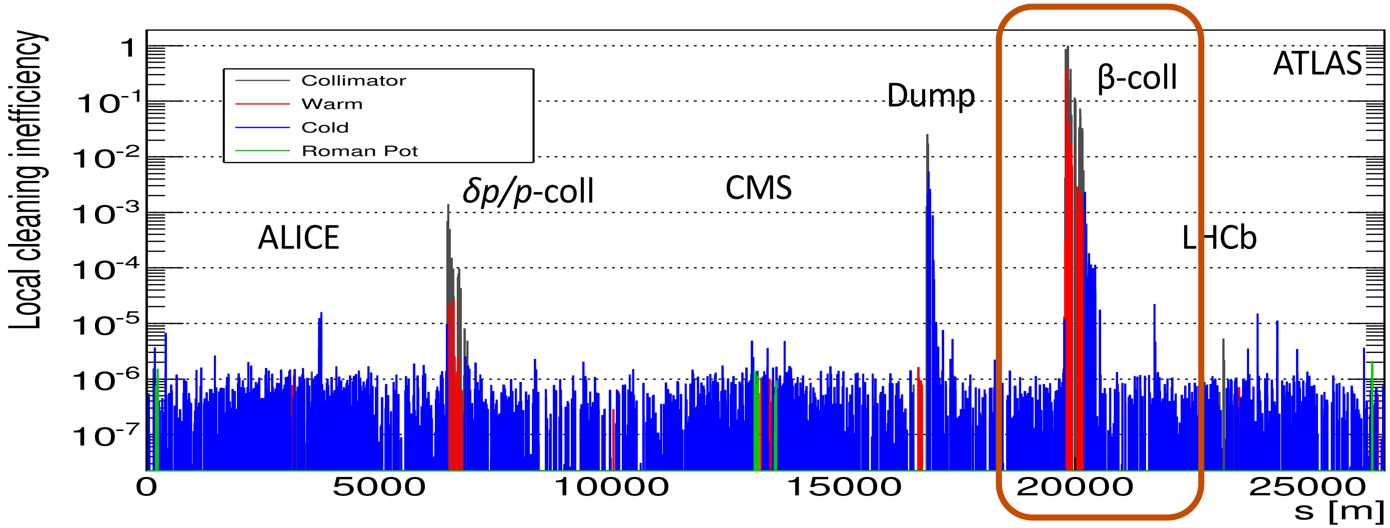


- **Halo cleaning**: reduce the risk of magnet quenches
- **Concentration of losses/activation** in controlled areas
  Avoid many hot locations around the 27km-long tunnel



Multistage system of 50 collimators per beam.

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



Collimation System @ LHC

Main limitations

Proton beams

- Single diffractive interactions

  small deflection & non-negligible δp/p ➔ escape from insertion and are lost in the IR7-DS if δp/p > 10^{-2}

The cleaning inefficiency in the LHC is up to 10^{-4}

Lead ion beams

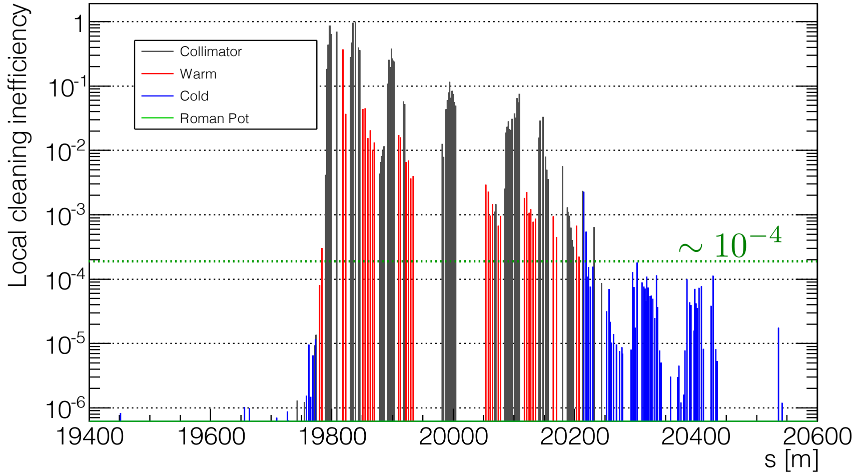
- Fragmentation and dissociation events

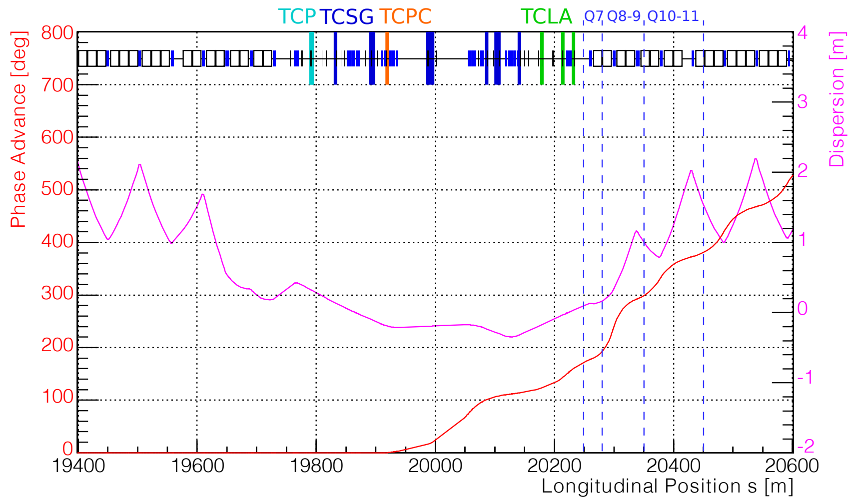
  particles with different magnetic rigidity (q/m) ➔ lost in the IR7-DS reducing of two order of magnitude the collimation system performance wrt to proton collimation

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

Impedance

- Big number of collimators at small gap ➔ 90% contribution to whole machine impedance





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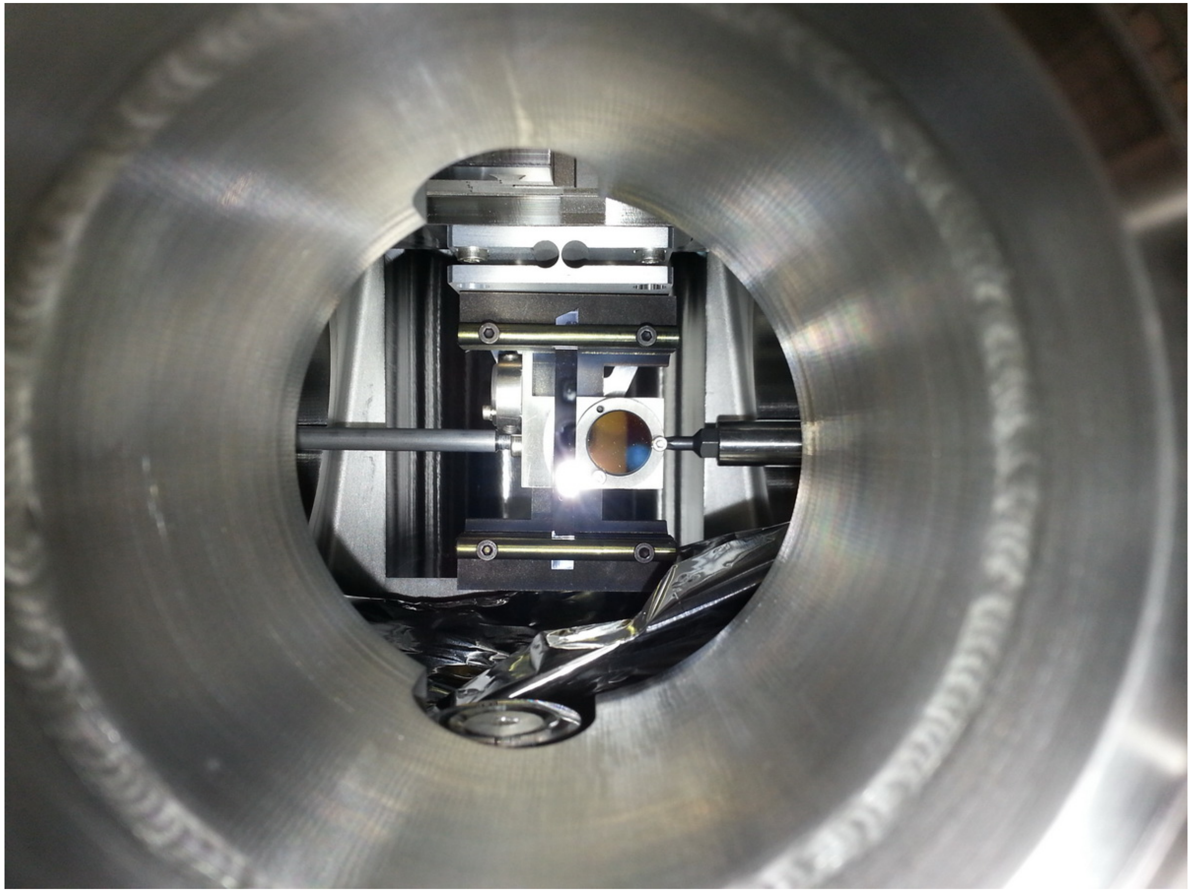
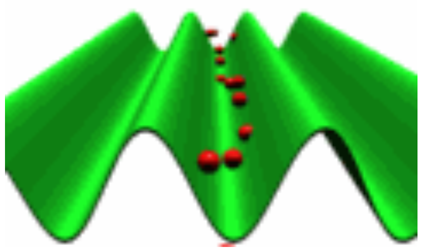


Strip silicon crystal. Installed on the horizontal goniometer in LHC.

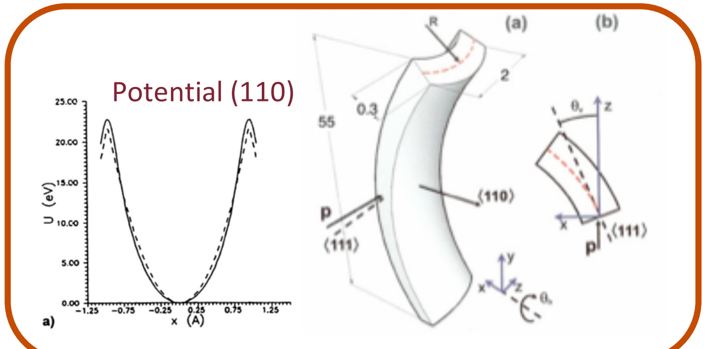
Crystal Channeling

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



Channeling : Tansverse momenta < potential well

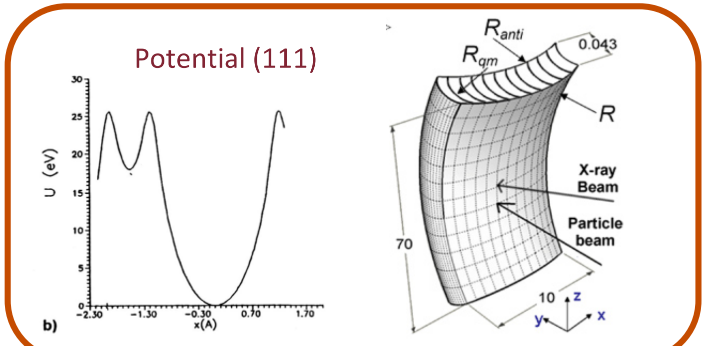
The channeling condition can be defined as $\frac{p^2c^2}{2E}\theta^2 + U(x) \leq U_{max}$



Critical angle

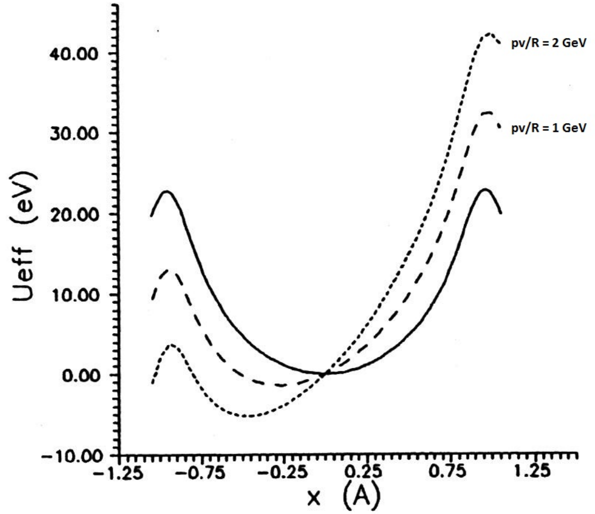
$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}$$

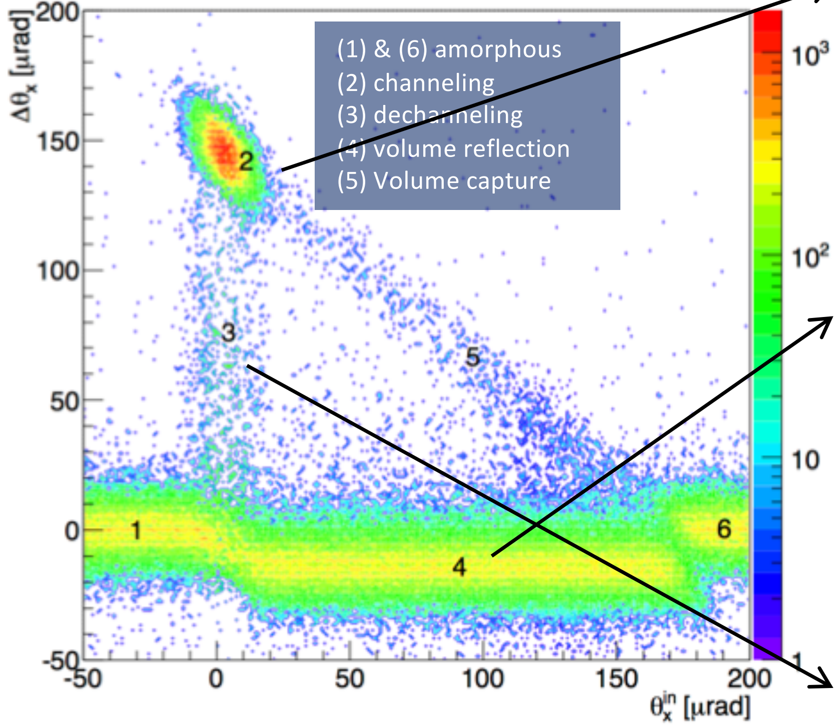
Case	Energy [GeV]	θ_c [μrad]
SPS coast	120	18.3
SPS coast	270	12.2
H8	400	10.0
LHC inj.	450	9.4
LHC top	6500	2.5
LHC top	7000	2.4



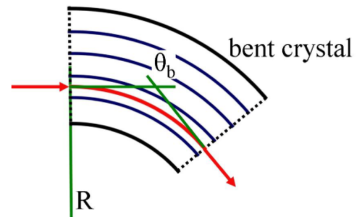
Coherent effect in bent crystals

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

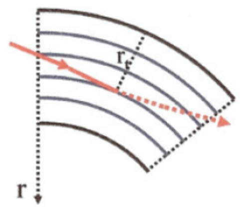




Planar channeling (CH)

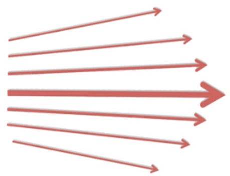


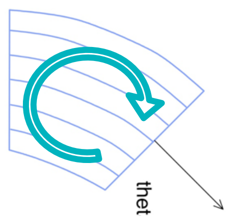
Volume Reflection (VR)



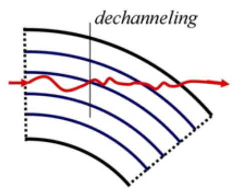
Dechanneling (DC)

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

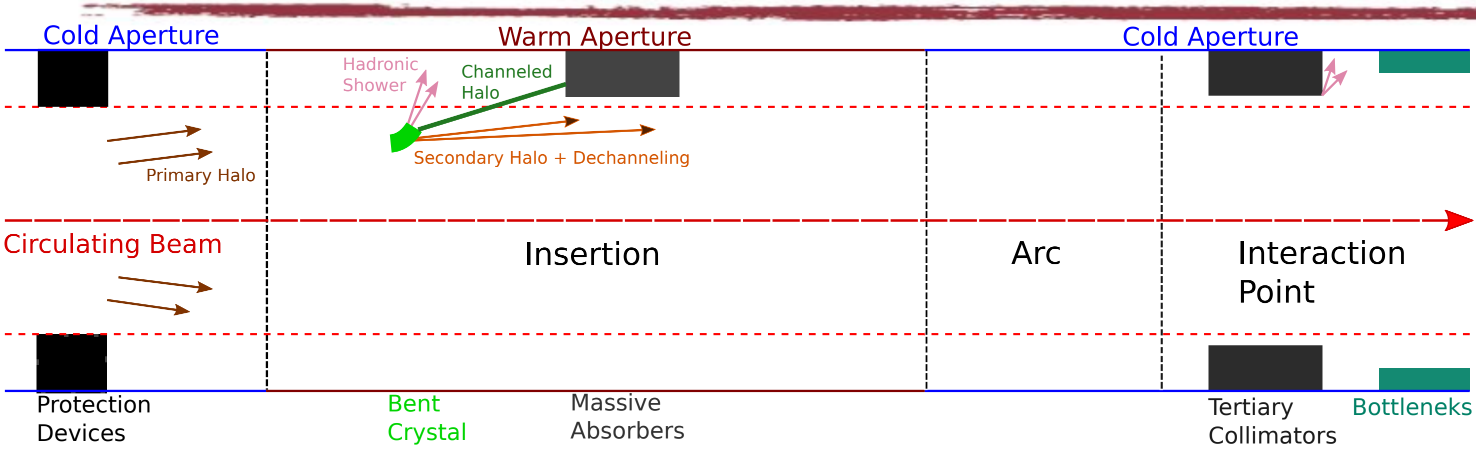




Single pass measurements with 400 GeV protons.
Strip crystal (110) with a bending of 144 µrad.



Crystal Collimation



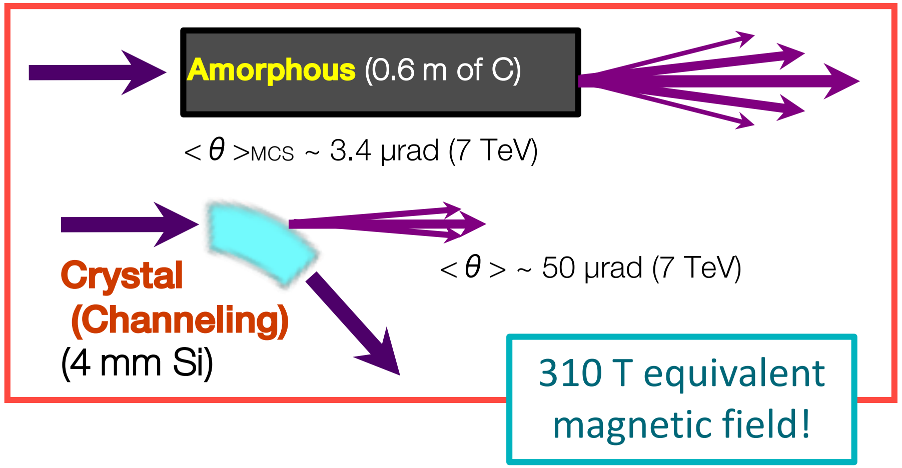
<u>Advantages</u> of crystal collimation at the LHC:

- Improve **collimation cleaning** (by a factor 10);

  Reducing off-momentum losses in DS

- Lower **impedance**;

  Less collimators at larger gaps



Can we use crystal collimation to improve the LHC collimation performance?

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

Different challenges to be addressed

- 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

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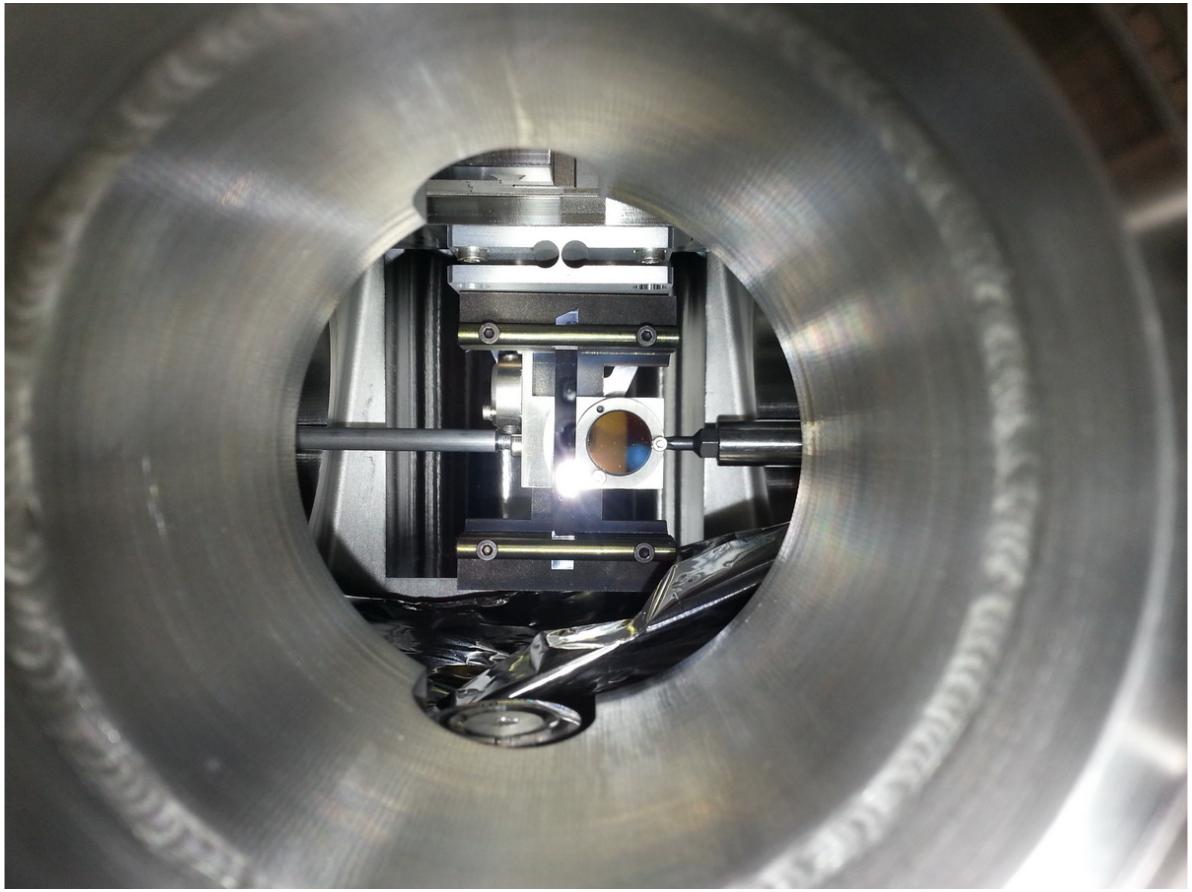
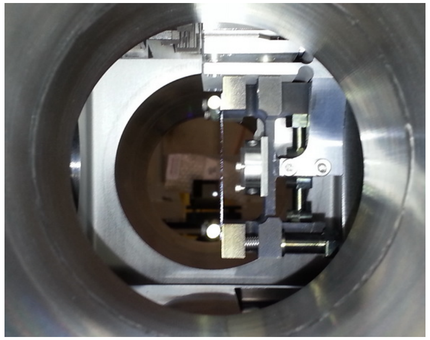


Strip silicon crystal. Installed on the horizontal goniometer in LHC.

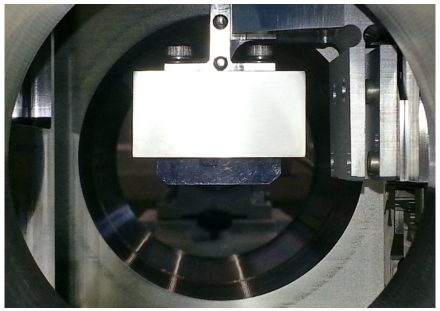
LHC Crystal Device

Prototype system has been integrated in the LHC collimation layout

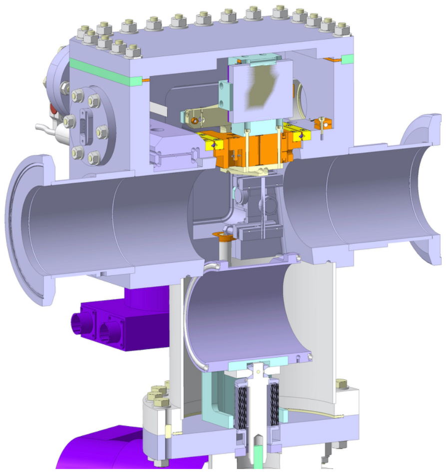
ST



QM



Two goniometers (one horizontal and one vertical) were installed in 2014 in positions where a secondary collimator could be used as absorber. Each is equipped with one crystal.



The goniometers are based on piezo-electric technology, and are able to achieve 0.1 µrad of accuracy

Two new devices have been installed on B2.

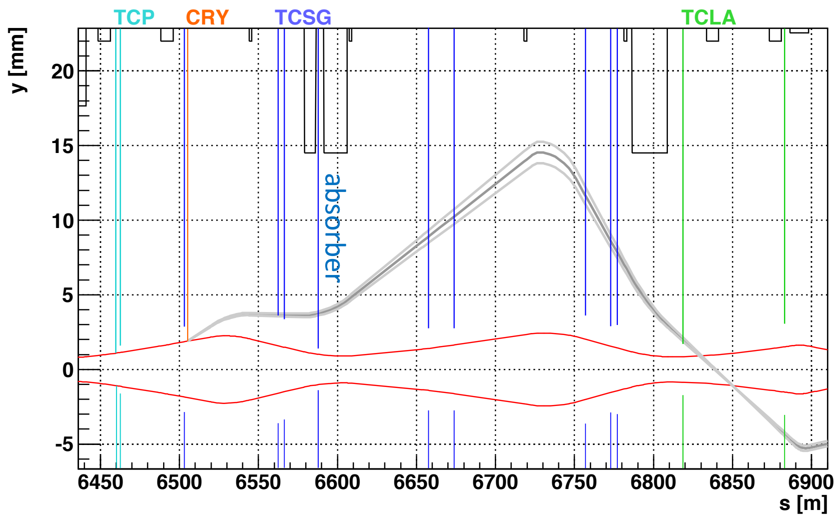
Crystal installation on Beam 2

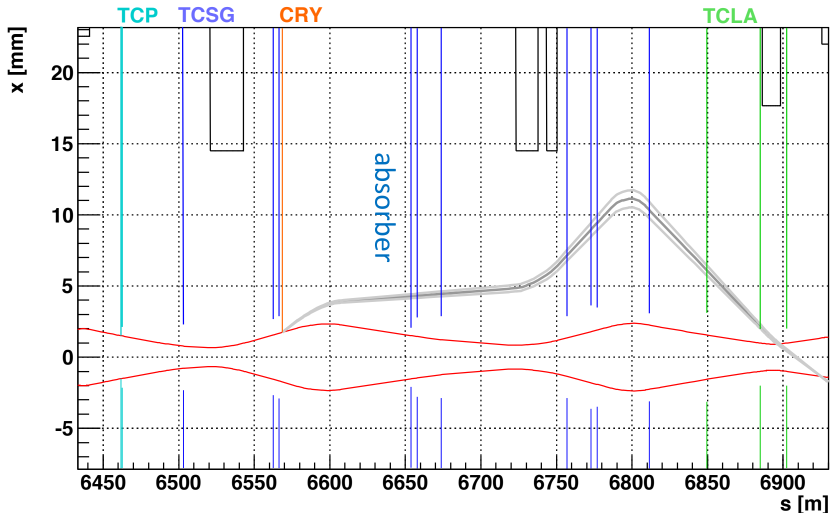
Semi-analytical studies has been provided to find the best location to install the crystal on beam 2 line.

Crystal request defined before 2014 restart:

- Bending angle : 50 μrad
- Length : 4 mm

Two new locations have been found and installation was done in the 2017 winter shutdown





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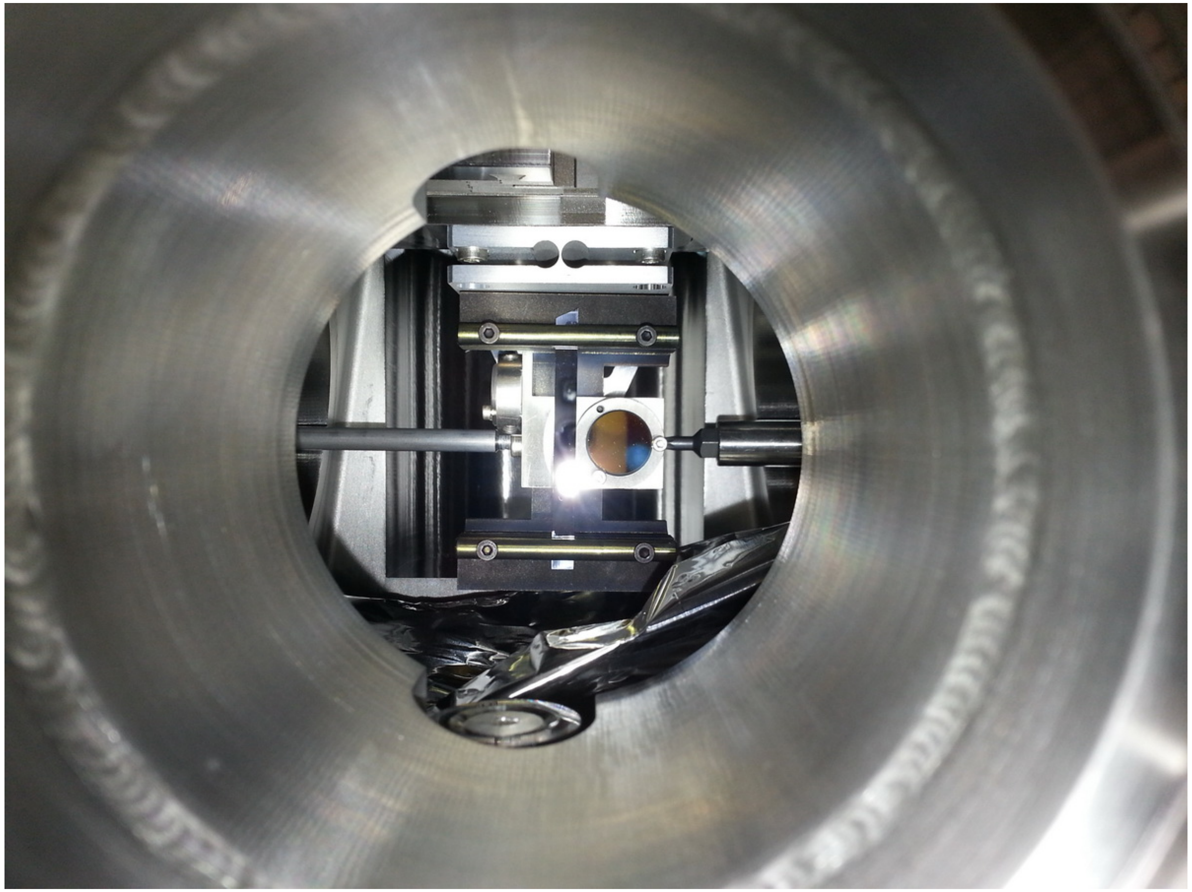
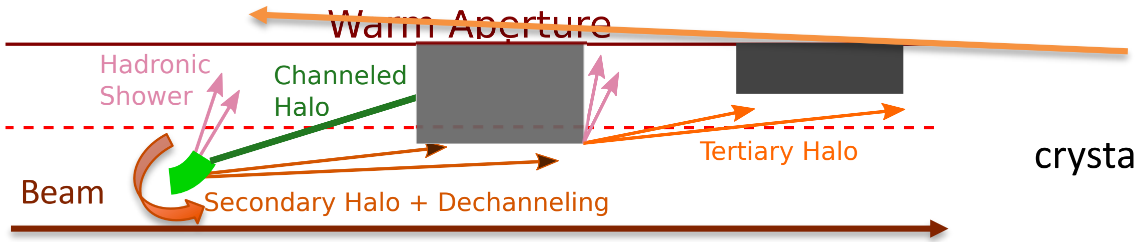


Strip silicon crystal. Installed on the horizontal goniometer in LHC.

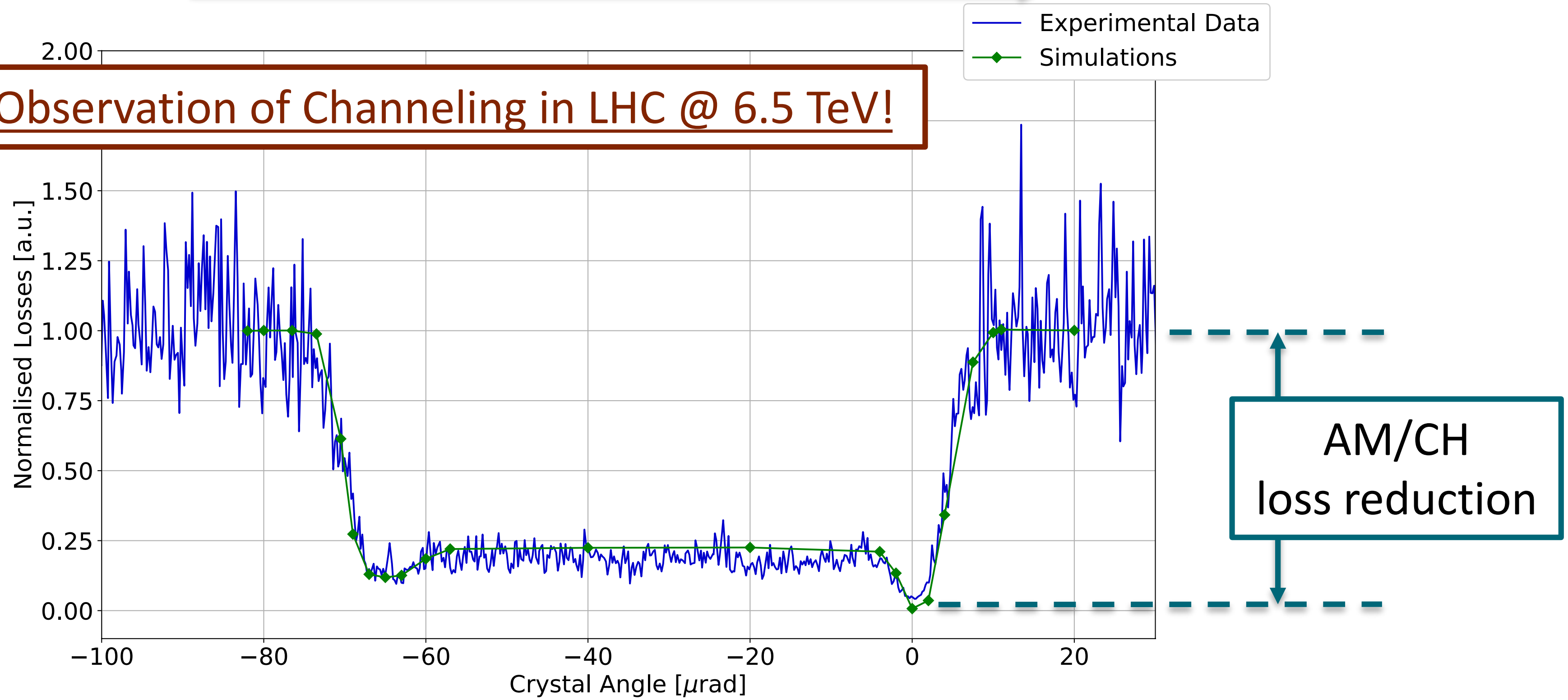
Channeling Observation

1. Angular Scan



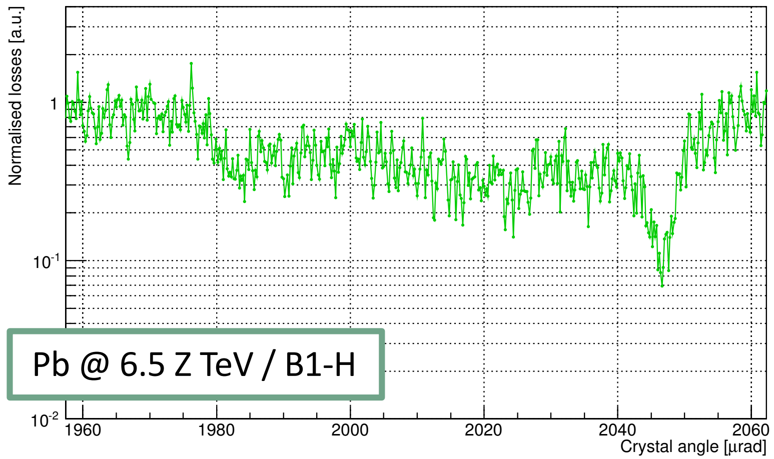
local losses
vs
crystal angular orientation

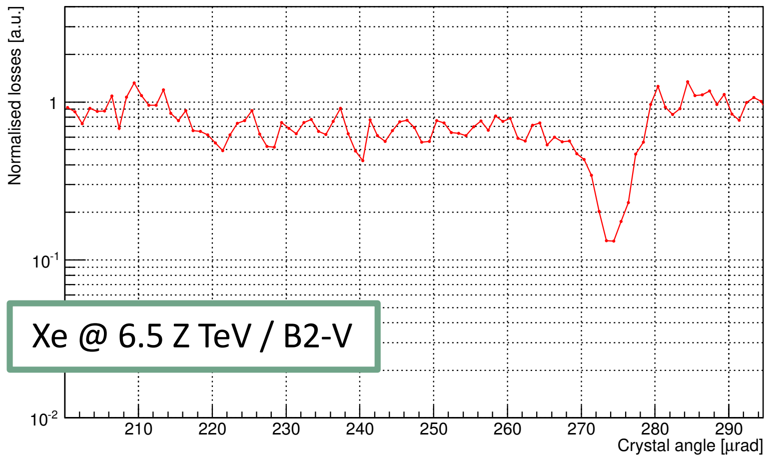
First Observation of Channeling in LHC @ 6.5 TeV!

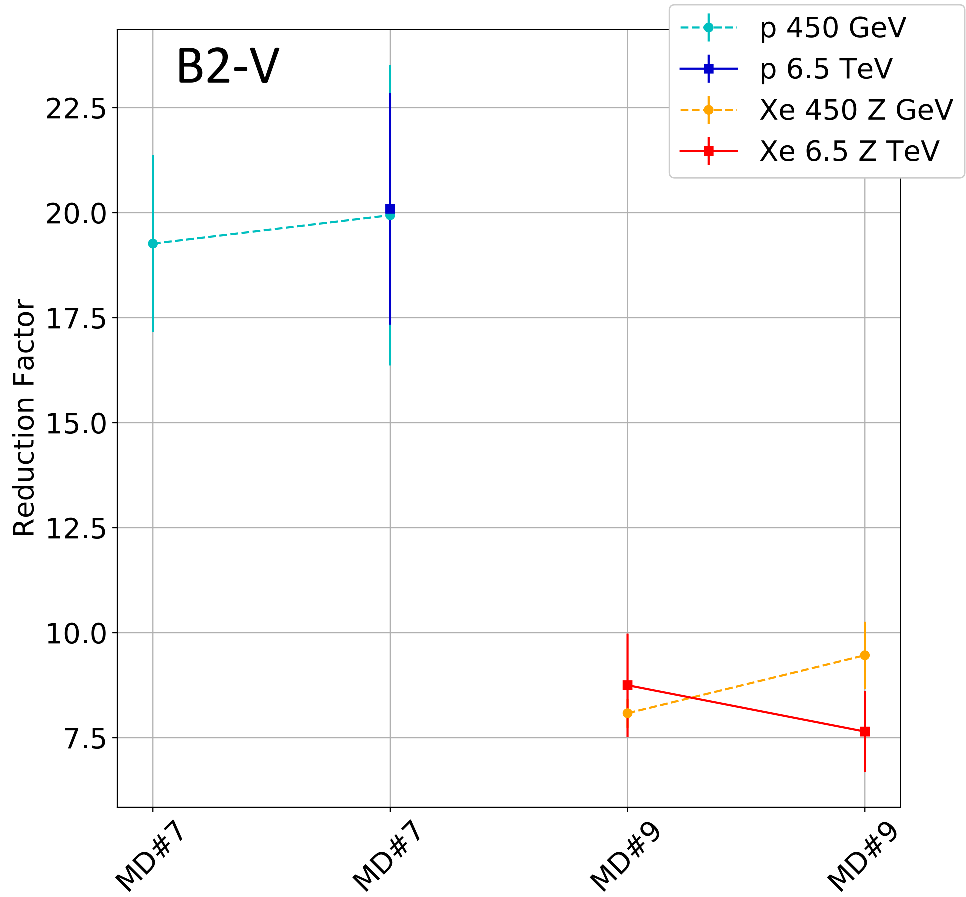


Angular Scans

First observation of channeling with lead and xenon ions at 6.5 Z TeV.

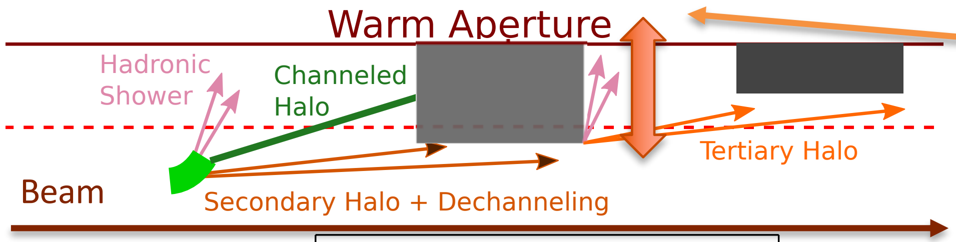




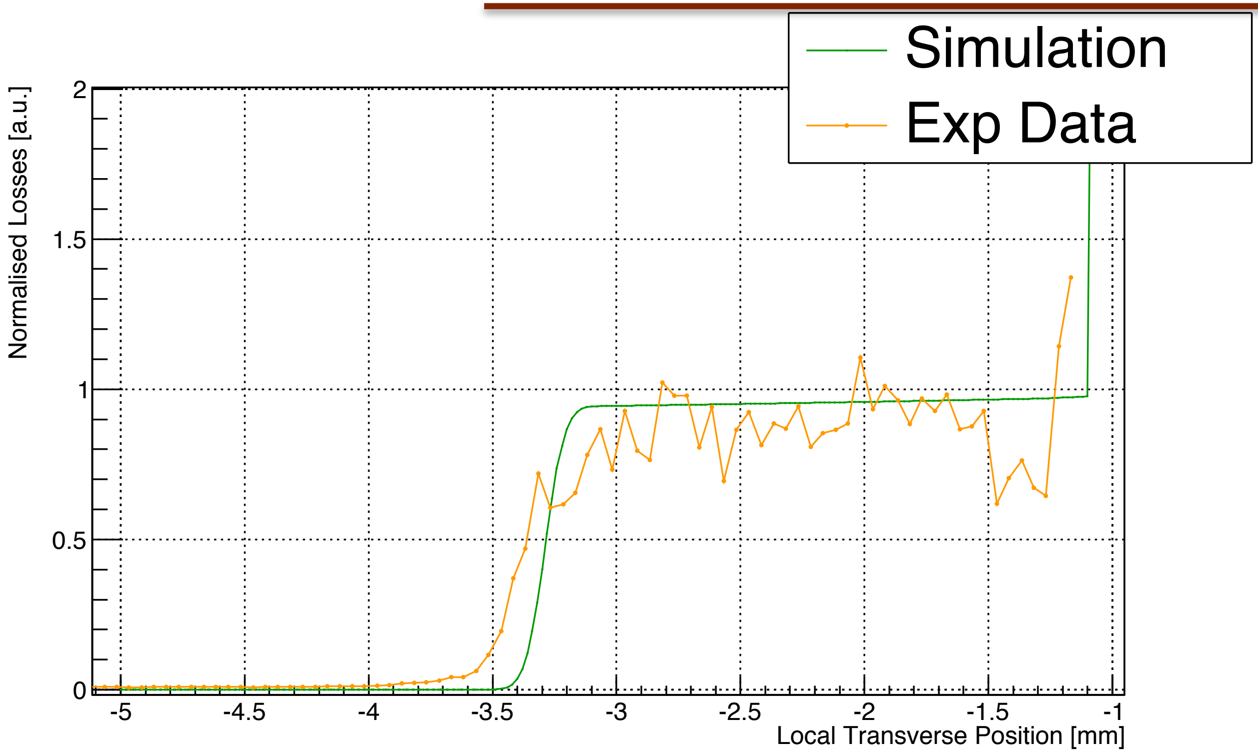


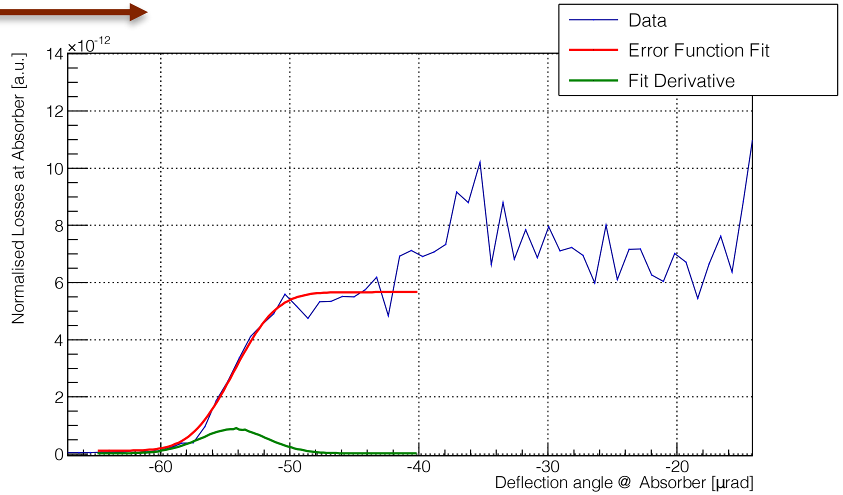
Channeling Observation

2. Absorber Scan



local losses
vs
collimator transverse position





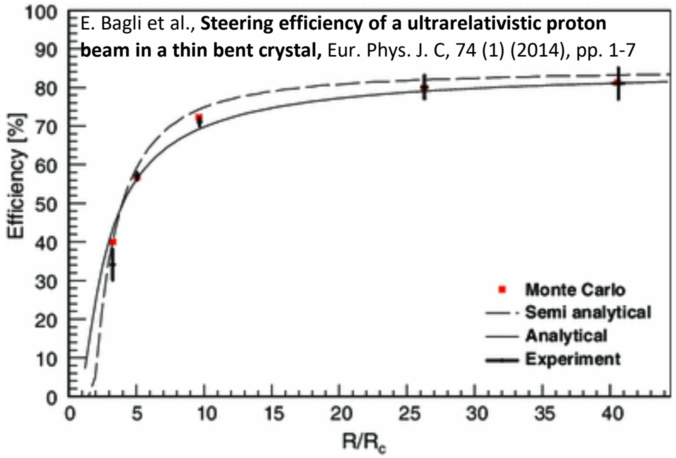
With Transport Matrix can be evaluated the deflection angle at collimator position!

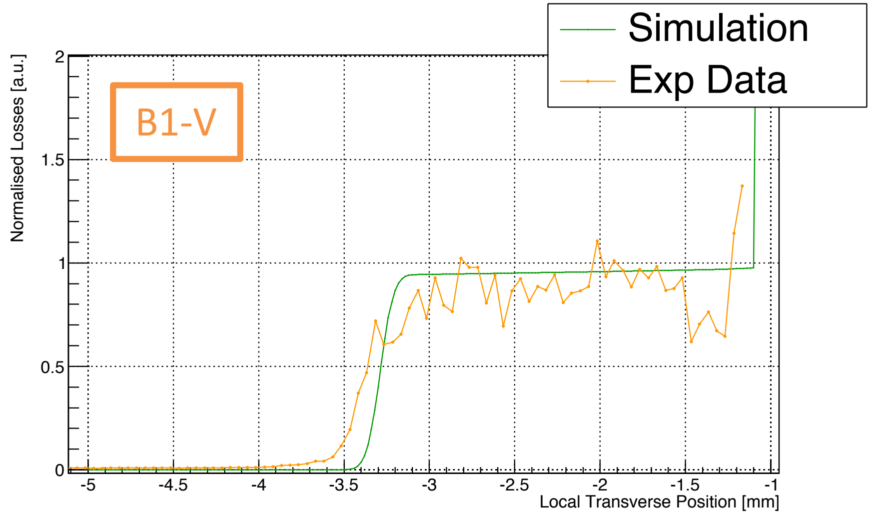
Linear Scans

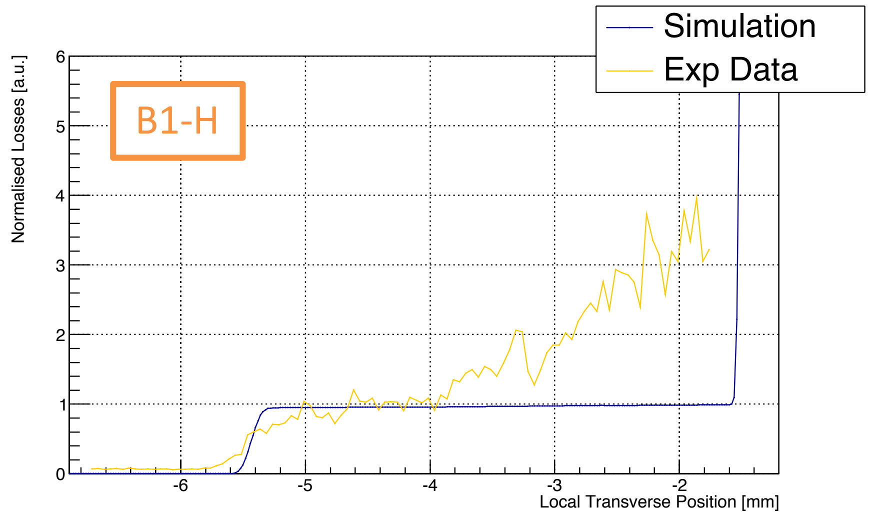
In collimator scan simulations, it is evident that the dechanneled population at lower deflection angles is higher in B1-H.
The main difference we can found between the two condition is the bending angle of the two crystals.

- B1-V: θ_b = 40 μrad, R = 100 m
- B1-H: θ_b = 63 μrad, R = 63 m*

* ~4 critical radius (~15.6 m @6.5 TeV): in this regime nuclear dechanneling is enhanced and there is no analytical description (simulation discrepancies)







Overview

Crystal	Reduction Factor						Bending Angle [μrad]
	p		Pb		Xe		
	Injection	Flat Top	Injection	Flat Top	Injection	Flat Top	
B1-H	17.5 ± 2.9	26.9 ± 5.5	6.1 ± 0.5	8.3 ± 1.2	8.4 ± 0.6	6.4 ± 1.1	63.2 ± 1.7
B1-V	17.8 ± 3.6	17.7 ± 3.9	5.6 ± 0.8	6.2 ± 2.3	5.8 ± 0.7	3.9 ± 0.5	39.8 ± 2.3
B2-H	10.6 ± 2.5	–	–	–	–	–	52.1 ± 1.6
B2-V	19.6 ± 0.5	20.1 ± 0.3	–	–	8.8 ± 1.0	8.2 ± 0.8	56.5 ± 1.5

Crystal on B1 out of specs

For each crystal has been evaluated

- AM/CH reduction factor for different conditions;
- the deflection angle is averaged over all the measurements.

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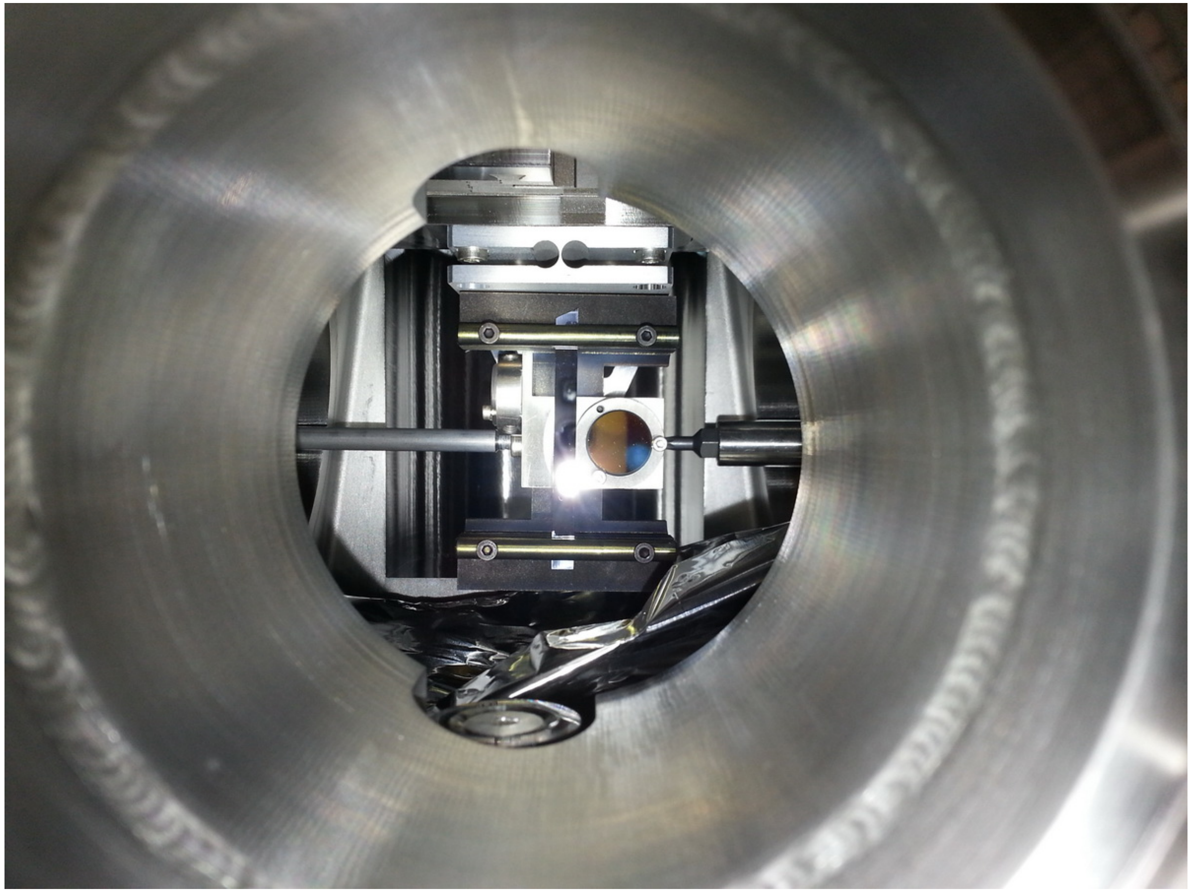
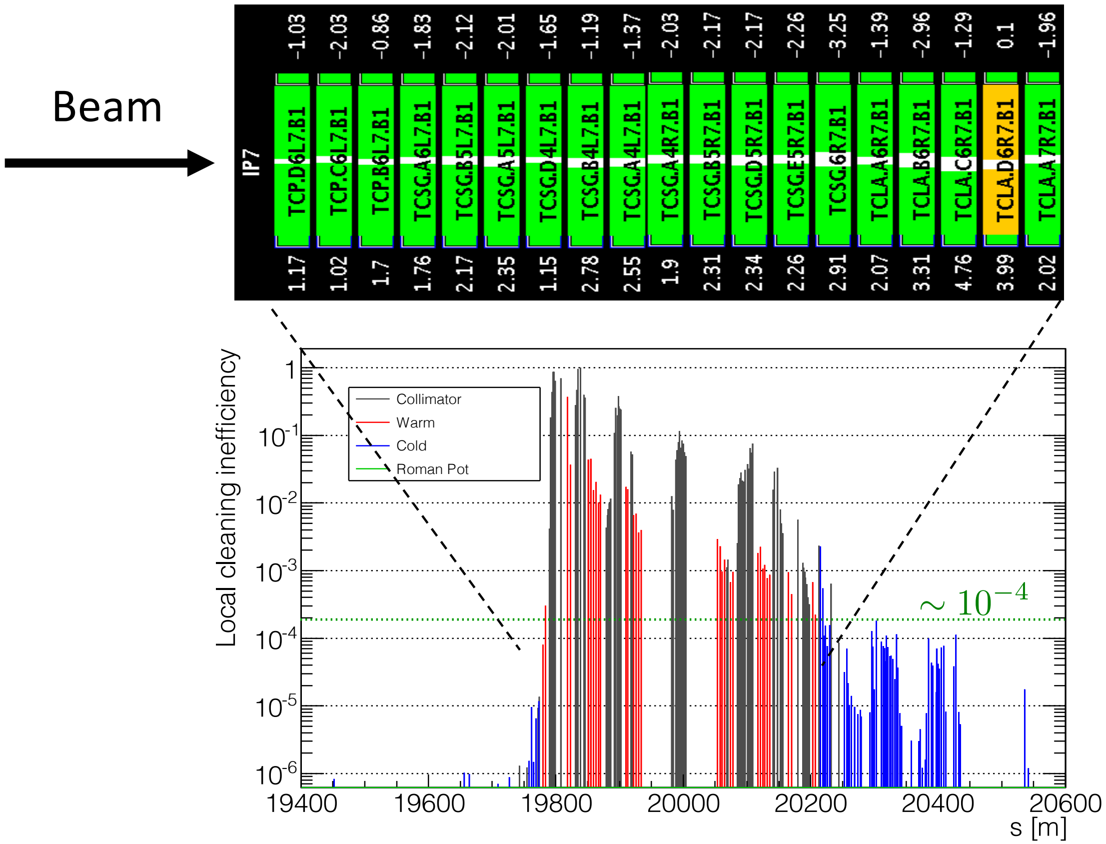


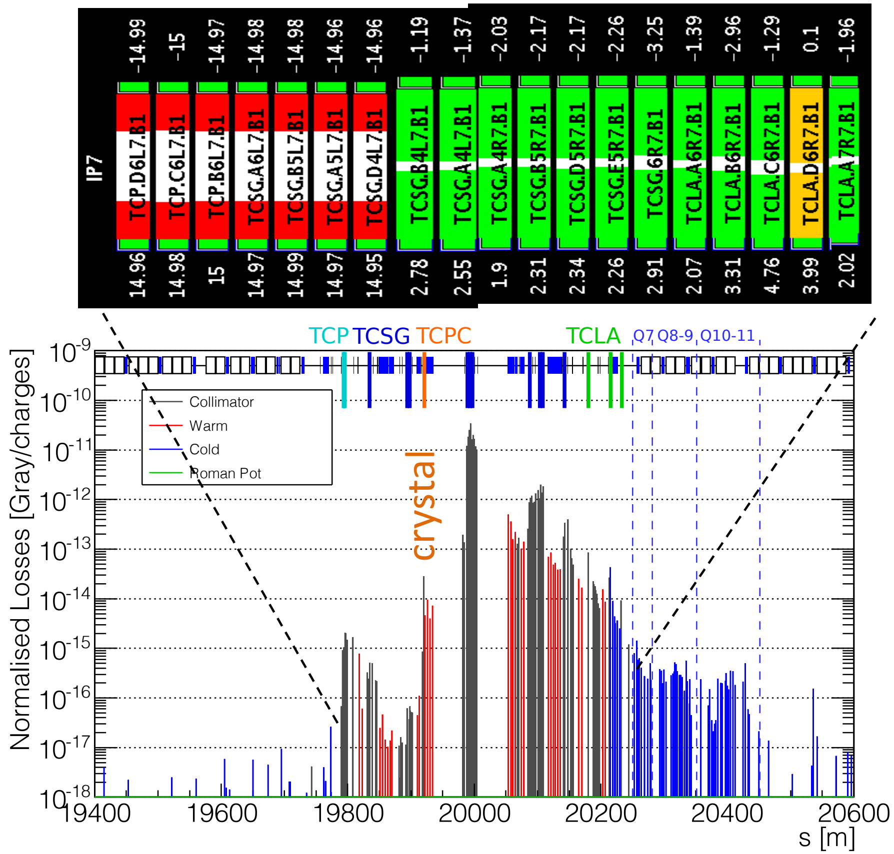
Strip silicon crystal. Installed on the horizontal goniometer in LHC.

Collimation Loss Maps

Present IR7 — tight settings



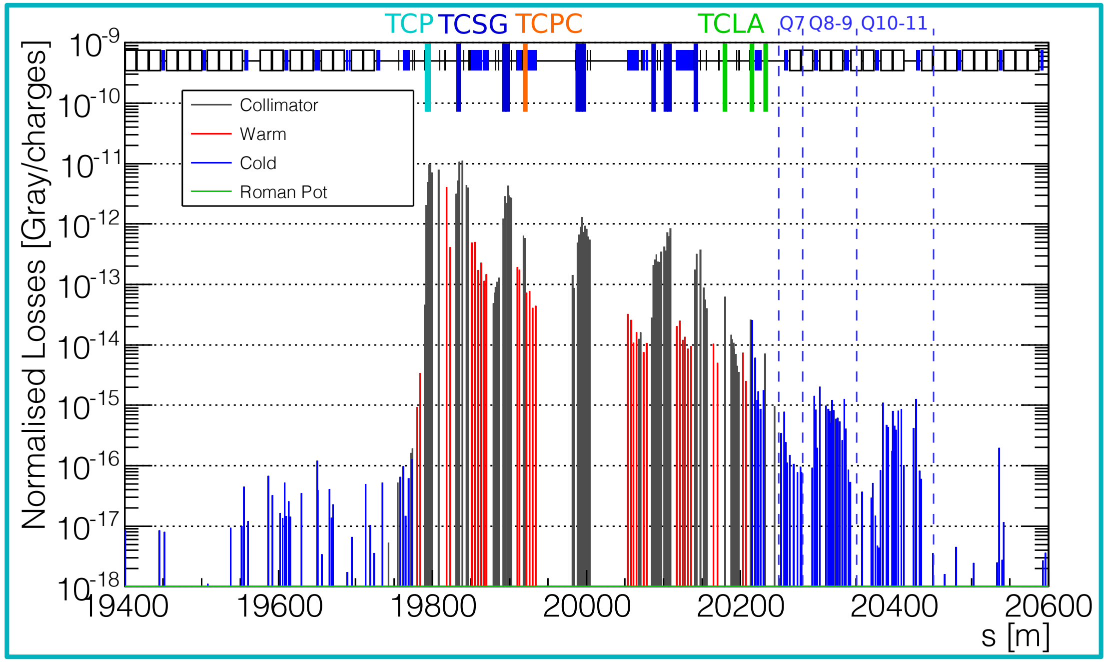
1 crystal, TCSG + TCLA

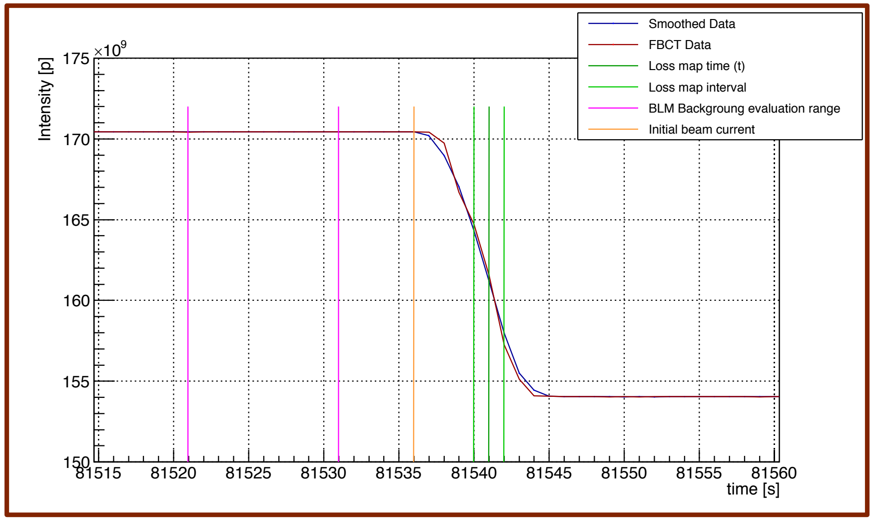


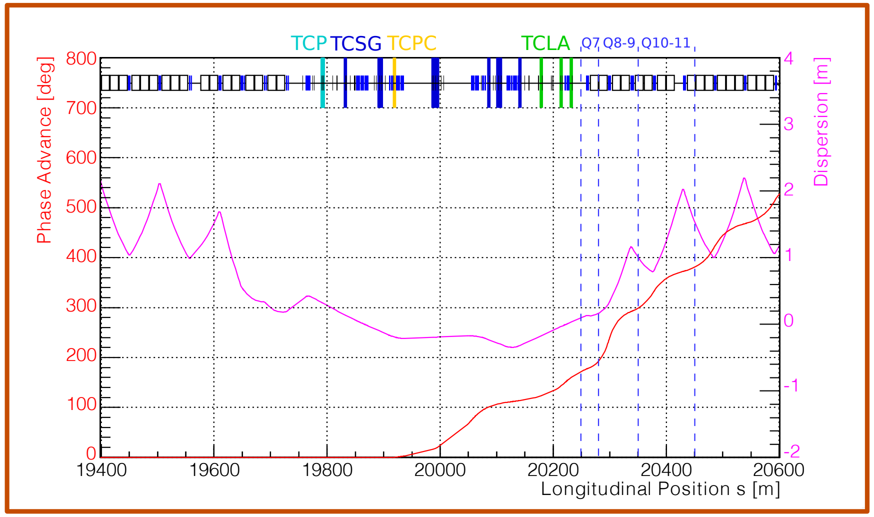
Crystal in CH reduce losses at primary collimation stage: new normalisation needed

Collimation Cleaning - Methods

Normalisation to beam flux ⍰ Particles lost in collimation system

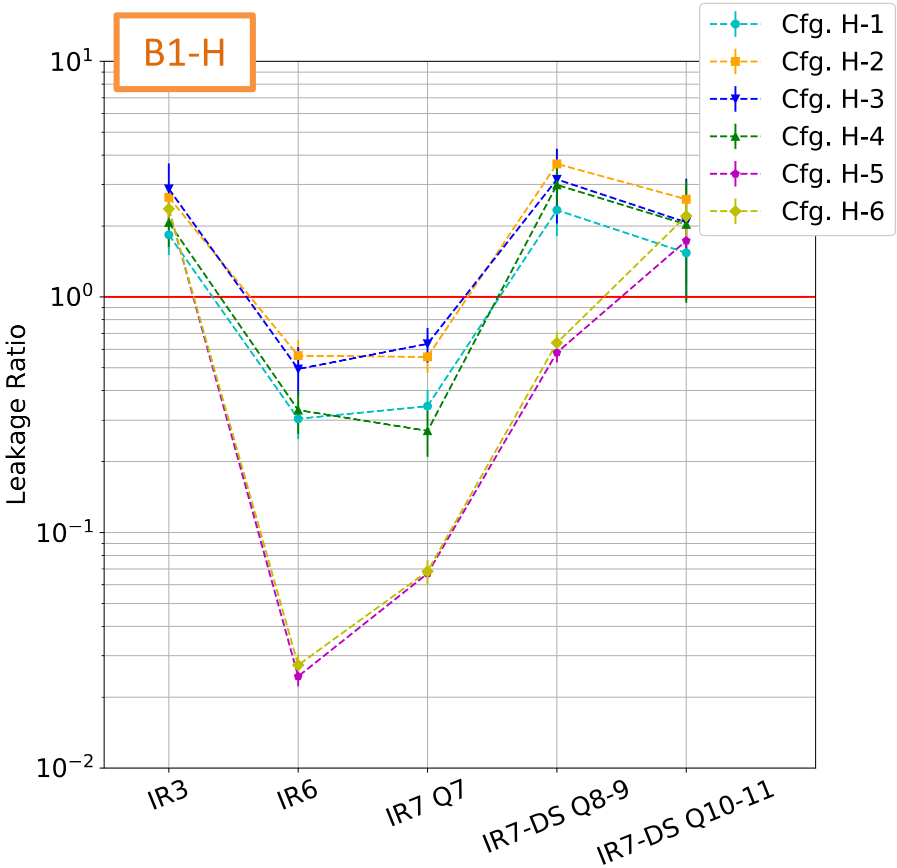




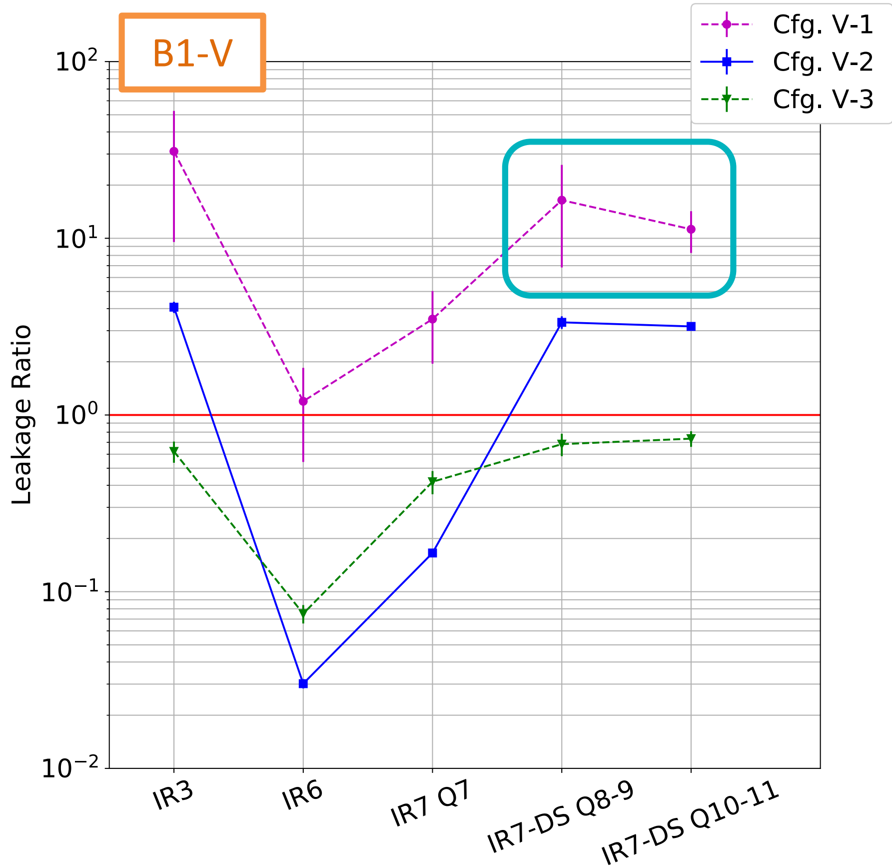


To compare the crystal collimation to the standard collimation the leakage of particles in specific region near to the IR7-DS is evaluated by normalizing losses to the beam flux.

Proton Cleaning



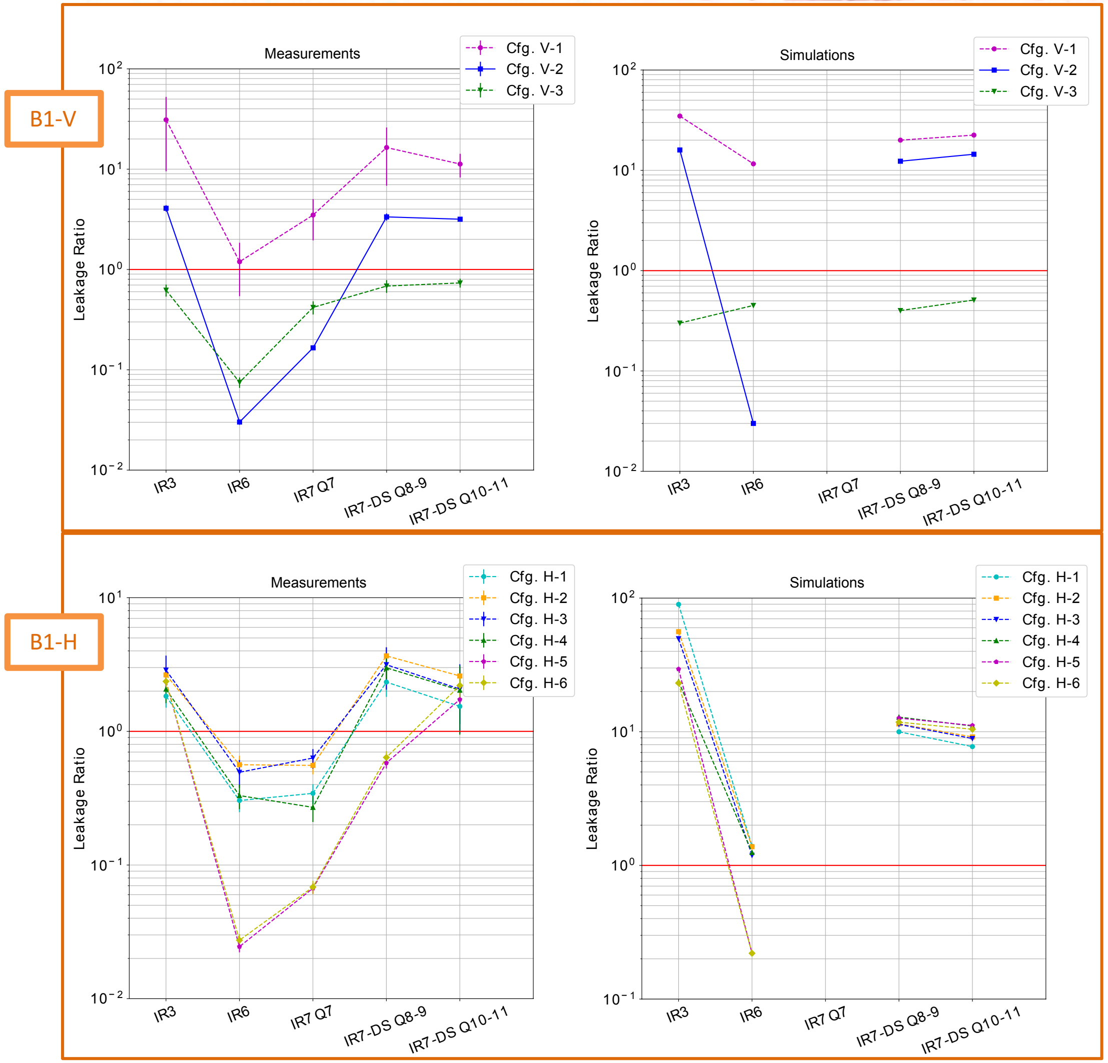
Worse performance with B1-H

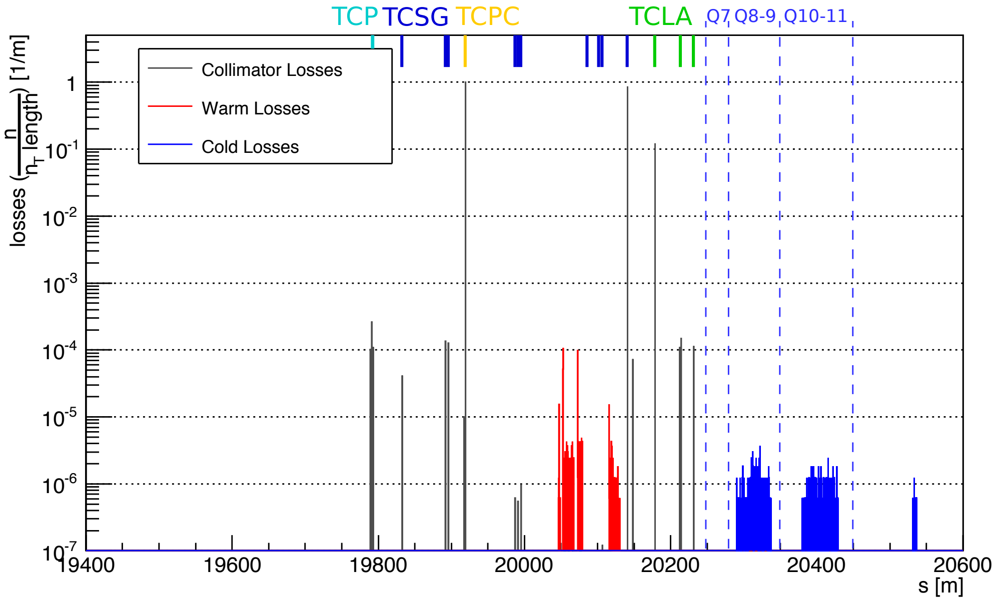


Good results in measurements with B1-V

Factor 10 of improvements in IR7-DS

Simulations Cleaning



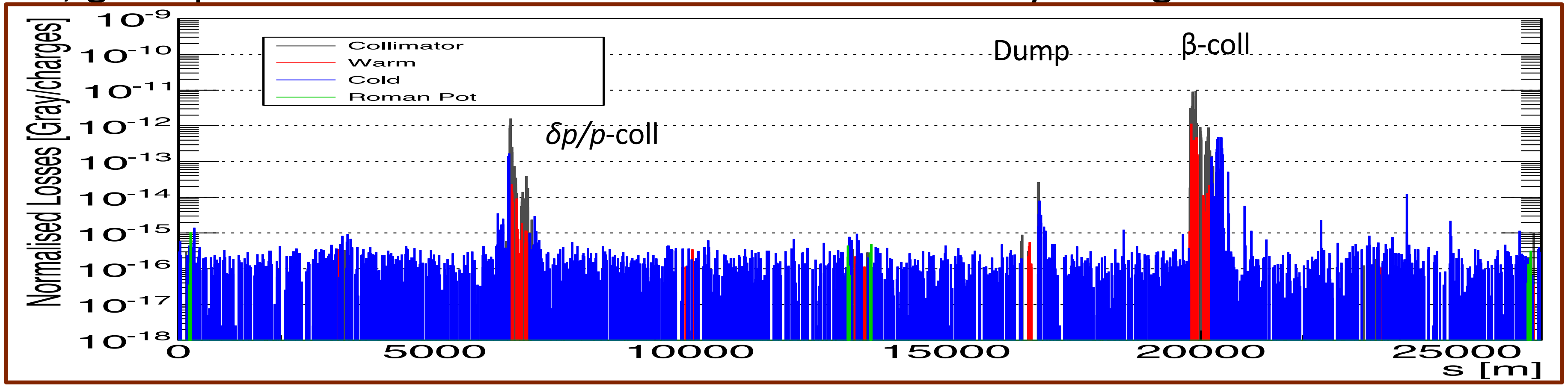


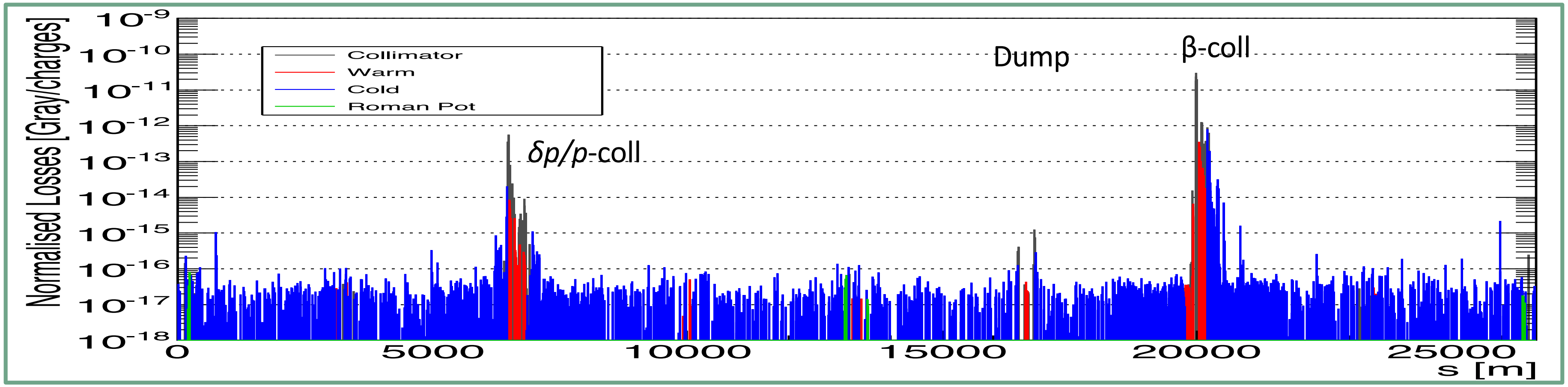
Comparing cleaning simulations to measurements

- good agreement with data is found in vertical plane;
- important difference (factor ~3) is observed in the horizontal plane.

Xenon Cleaning

In general, good performance were observed with almost any configuration



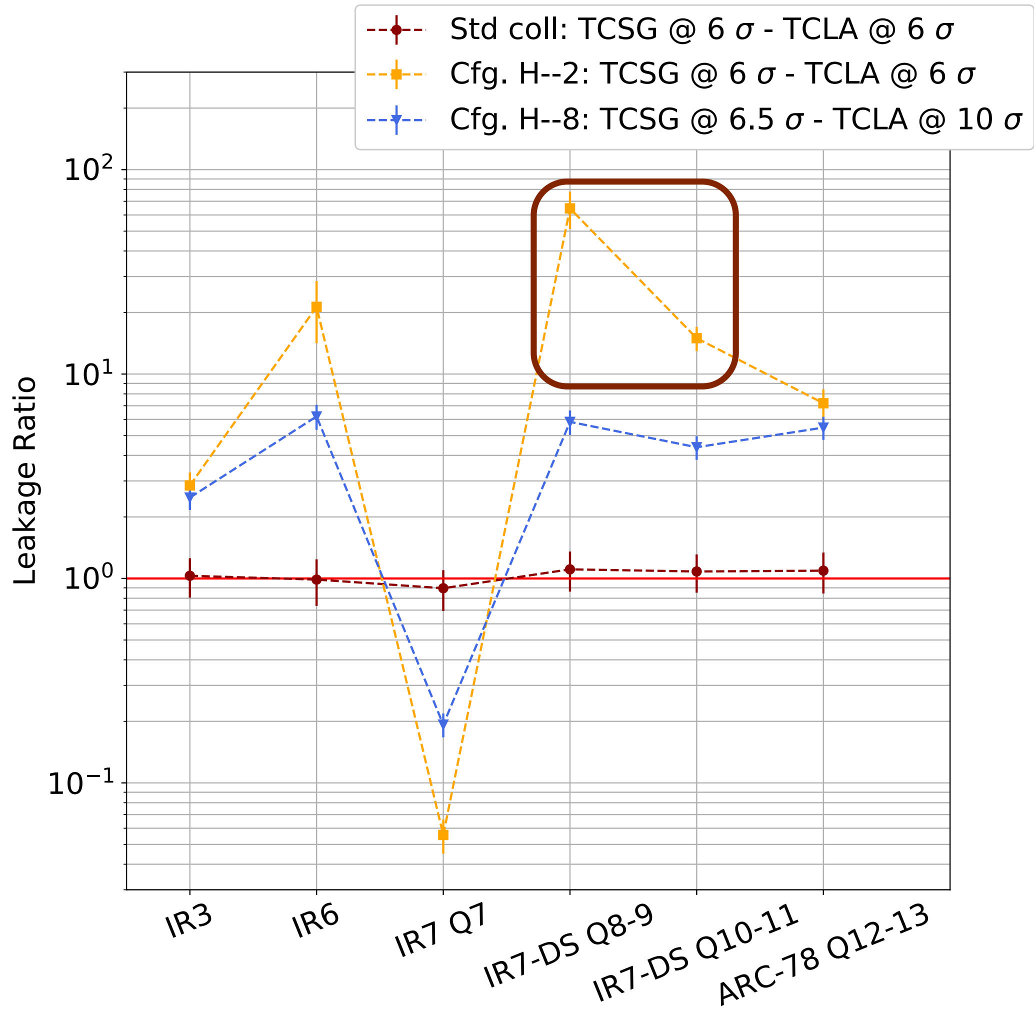


Looking at loss maps along the ring: no dangerous peaks with crystal.

Xenon Cleaning

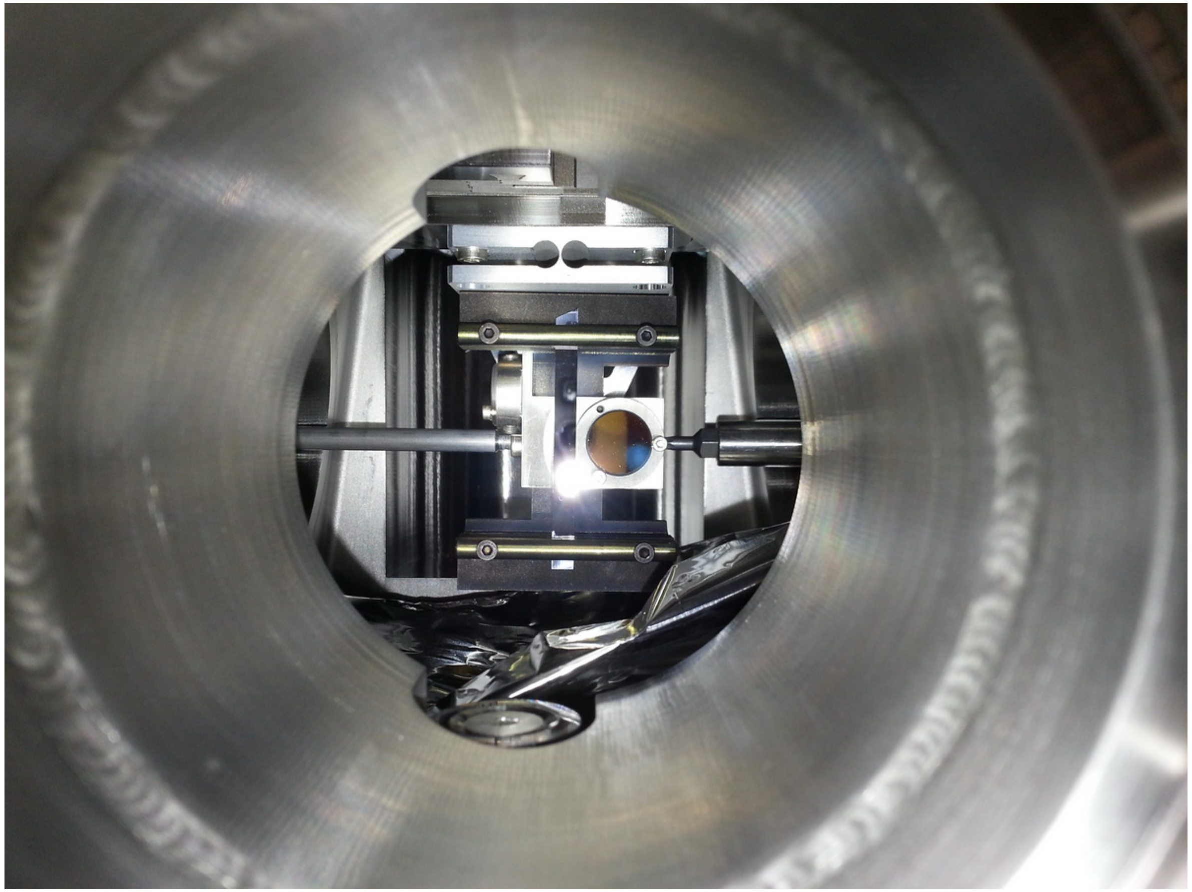
For B1-H the high dechanneling made us close the settings of the downstream collimators

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



Outline

- Motivations
- Hadron beam collimation
- Crystal Collimation
- Devices & Layout
- Results
  - Channeling Assessment
  - Cleaning Performance
  - Channeling in Dynamic Phases
- Conclusions



Strip silicon crystal. Installed on the horizontal goniometer in LHC.

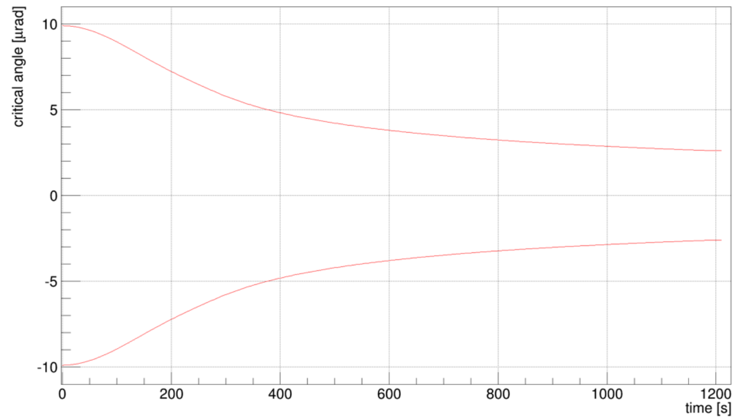
Energy Ramp Up in LHC

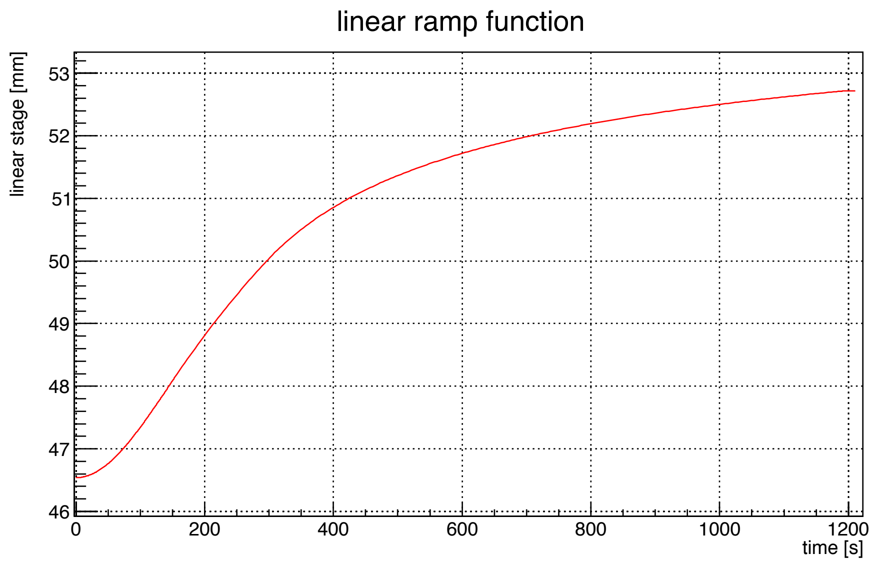
In order to use crystal collimation during operation, it is needed to keep the crystal in the channeling orientation during dynamics phases like the energy ramp.

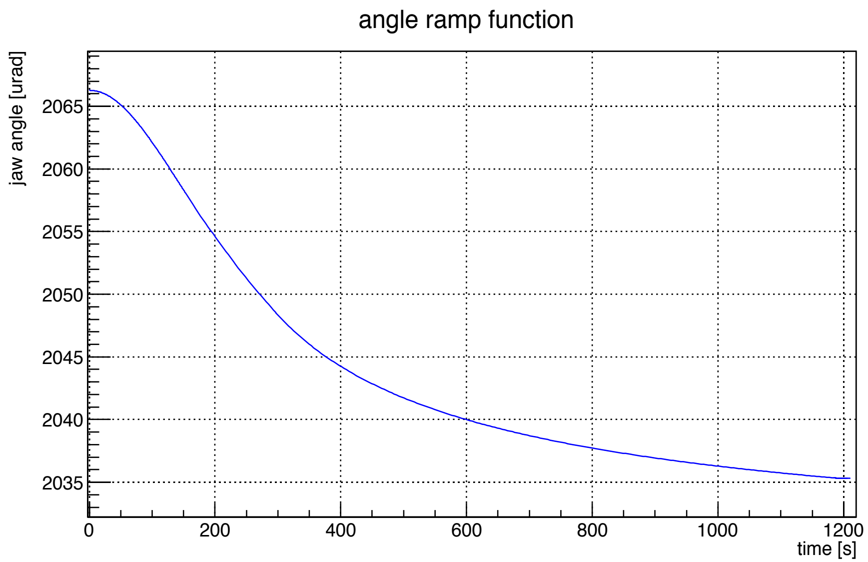
Due to the adiabatic dumping:

- Shrinking of the beam size;
- Changes in the x' distribution as well.

This is challenging because the critical angle θ_c with 6.5 TeV protons for a silicon crystal drops to 2.5 μrad.

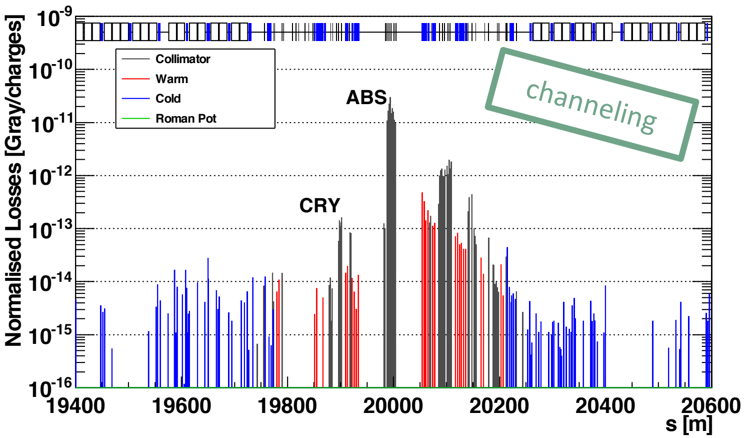


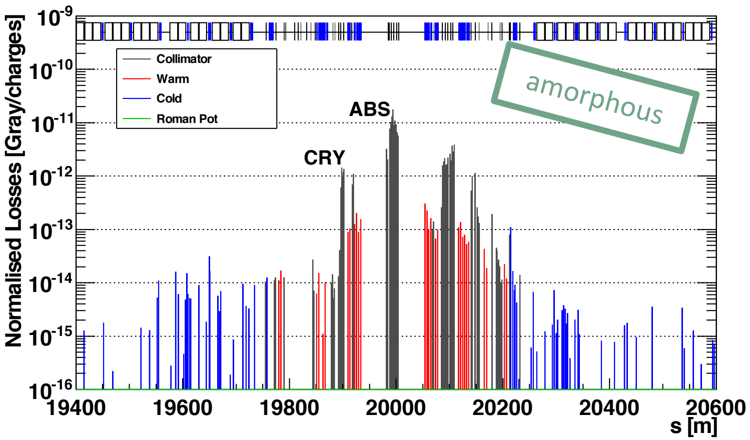


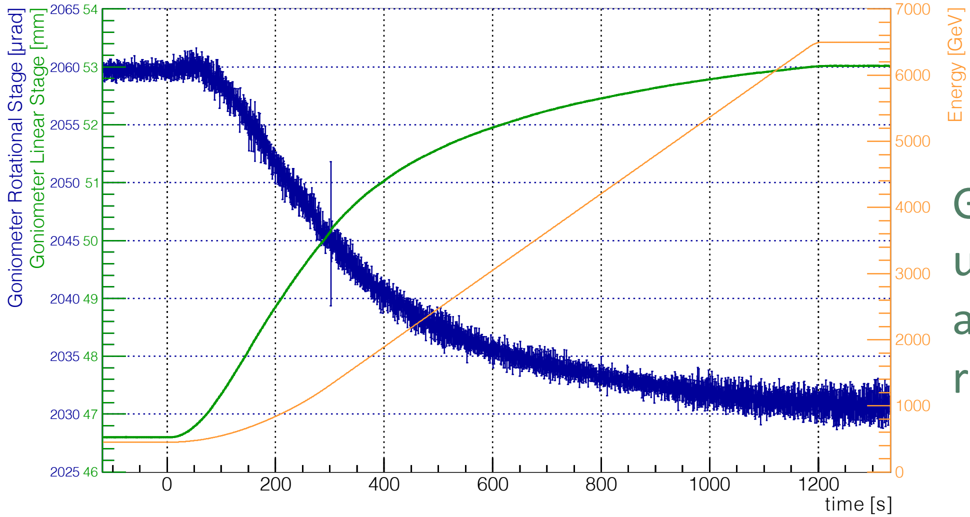


Energy Ramp Up in LHC

Channeling Evidence from Loss Pattern

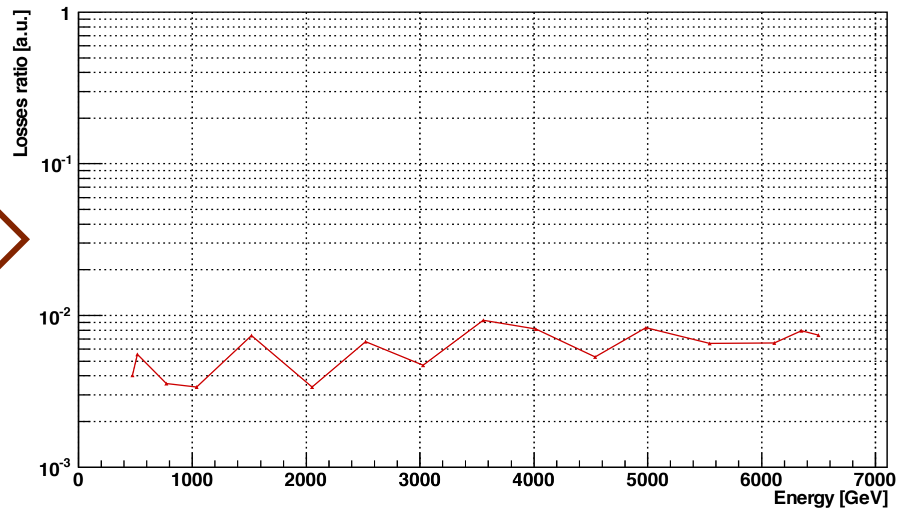






Goniometer stages under control along the energy ramp

Ratio Abs/Cry well under 10^{-2}



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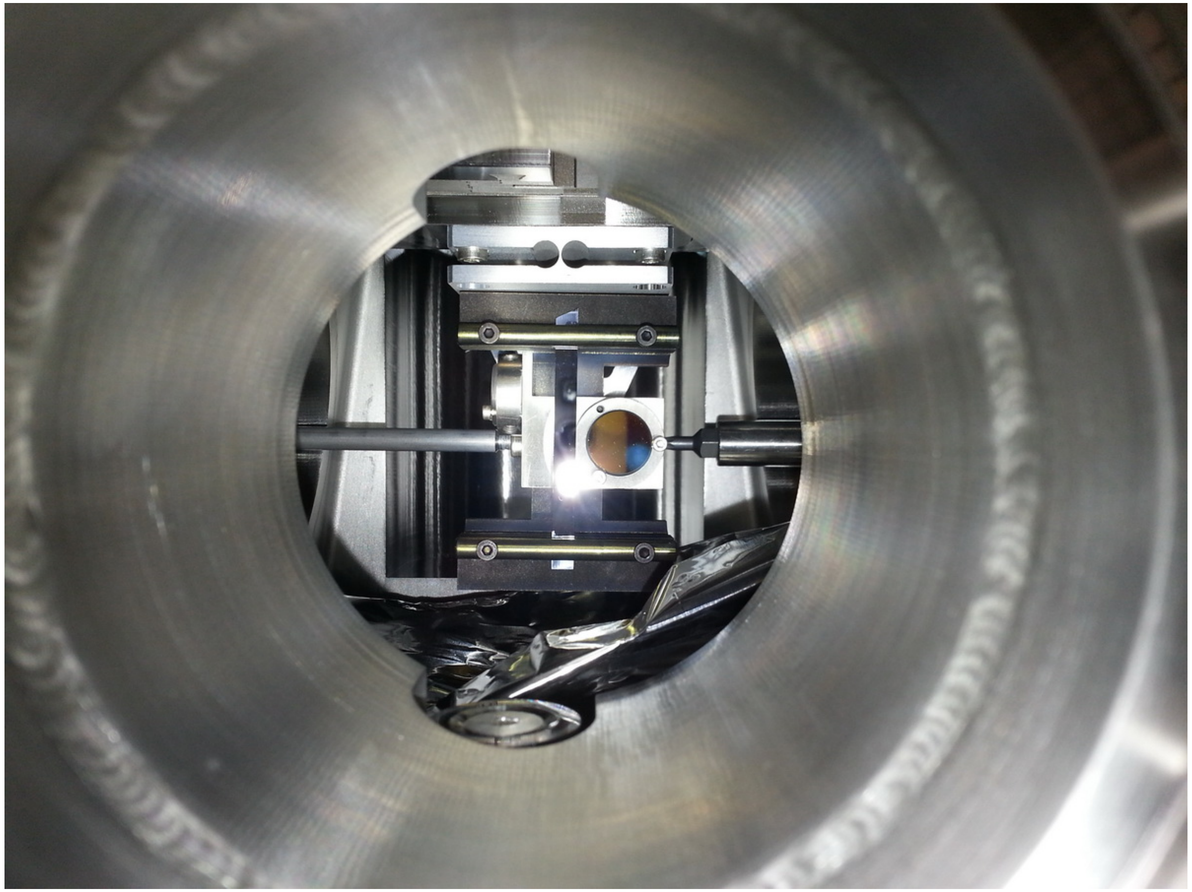

Strip silicon crystal. Installed on the horizontal goniometer in LHC.

Conclusions

Conclusion from this doctoral thesis work:

- ✓ Channeling observed and characterized for the first time at LHC energy
- ✓ Channeling observed with protons at 6.5 TeV and lead and xenon ions at 6.5 Z TeV (world record)
- ✓ An improvement in cleaning performances is obtained in specific conditions
  - With protons an improvement of a factor 10 is observed with B1-V
  - With xenon ions the best results up to a factor higher than 20 were obtained using very tight settings
- ✓ Energy ramp up function generated and tested with old generation goniometers gave excellent results
- ✓ Simulations benchmarked, given the good agreement with experimental data
  - Allowed good understanding of B1-H features,
- ✓ Tool for new crystal collimation layout developed and available

Future goals for the crystal collimation to be deployed for ion beams operations:

- ❑ Confirmation with lead ions of the results obtained with xenon beams
- ❑ Design of a dedicated absorber for a crystal collimation system for the HL-LHC upgrade