Crystal-assisted collimation at the LHC

18/10/2016 – PhD Seminars

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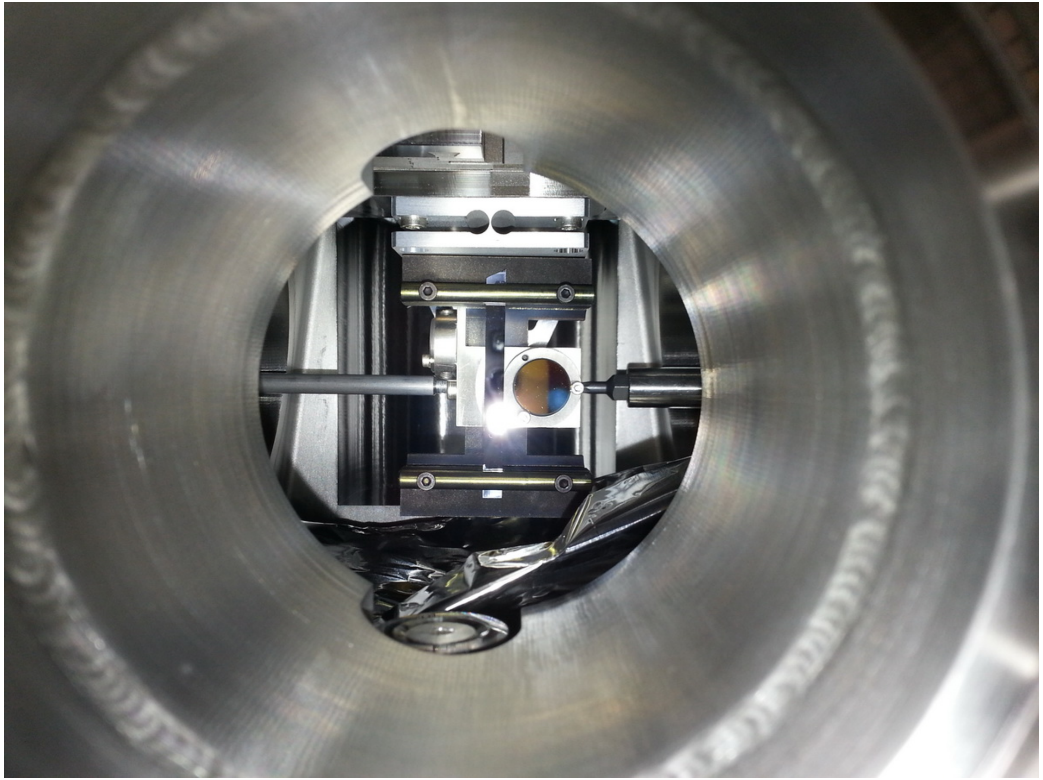
Outline

- Introduction
- Hadron beam collimation
  - collimation system
  - crystal-assisted collimation
- Scope of my PhD
- Experimental results LHC
  - Protons tests
  - Ions tests
- Simulations and semi-analytical studies
  - B2 installation
  - Energy ramp functions
  - LHC & SPS simulation
- Conclusion



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

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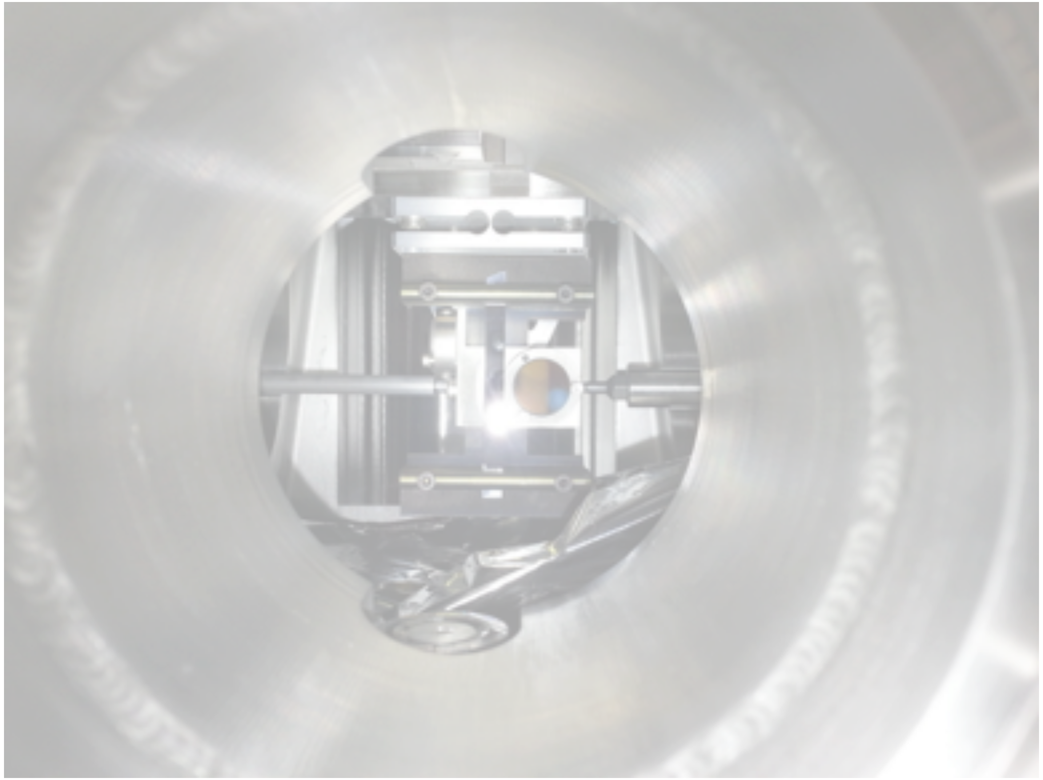


Motivations

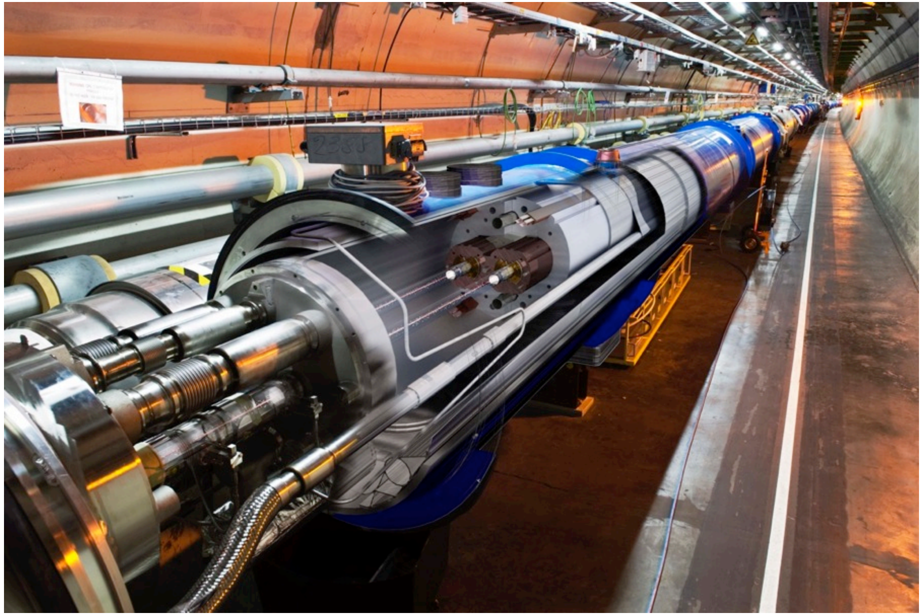
Superconducting magnets:

- 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**

Factor ~ 10^9-10^{10} ➔ *Collimation system is needed!*



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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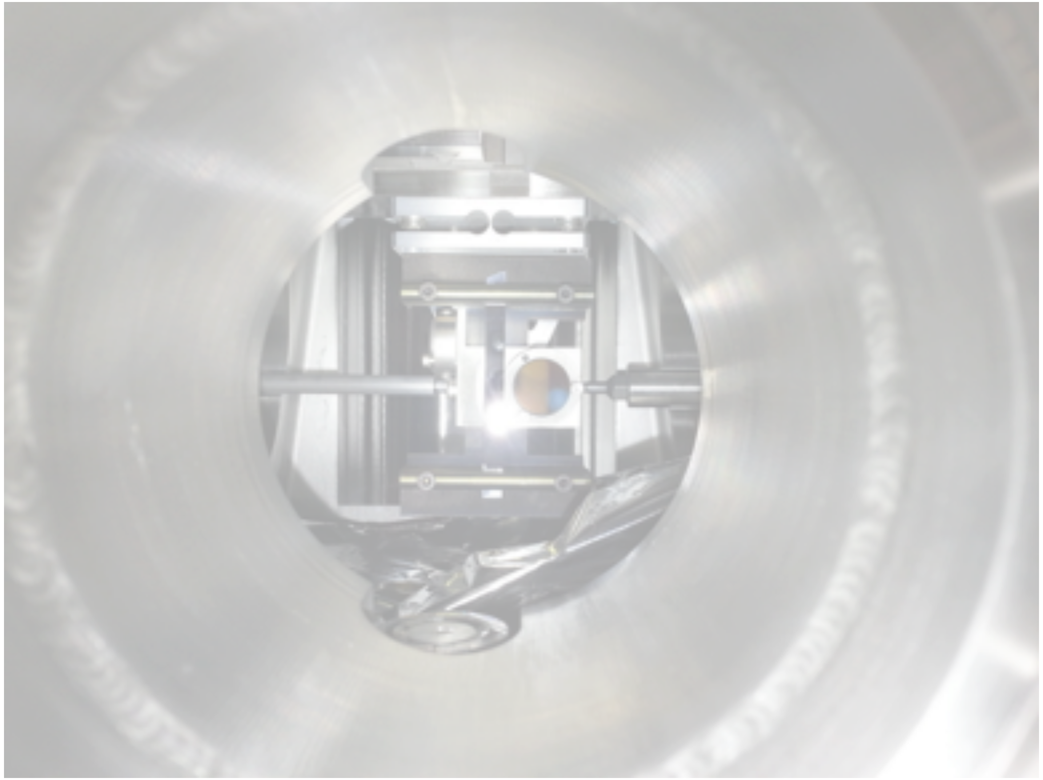
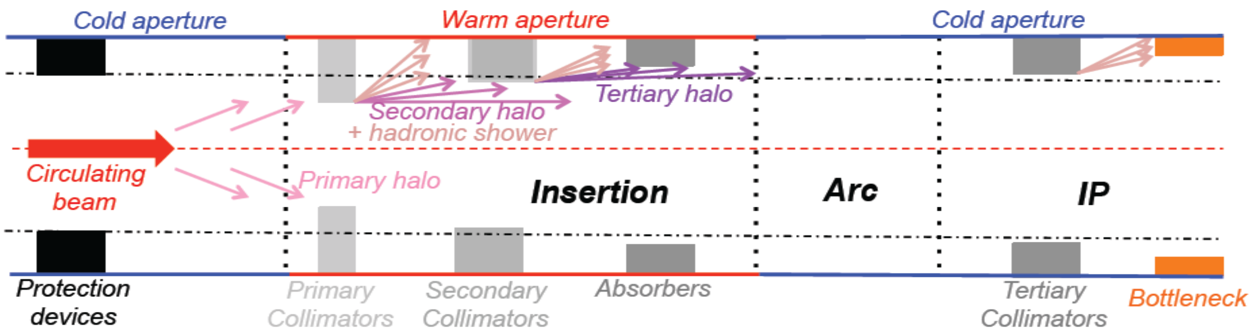
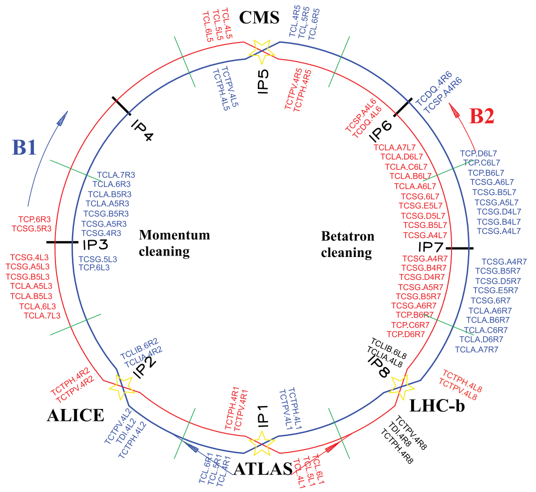
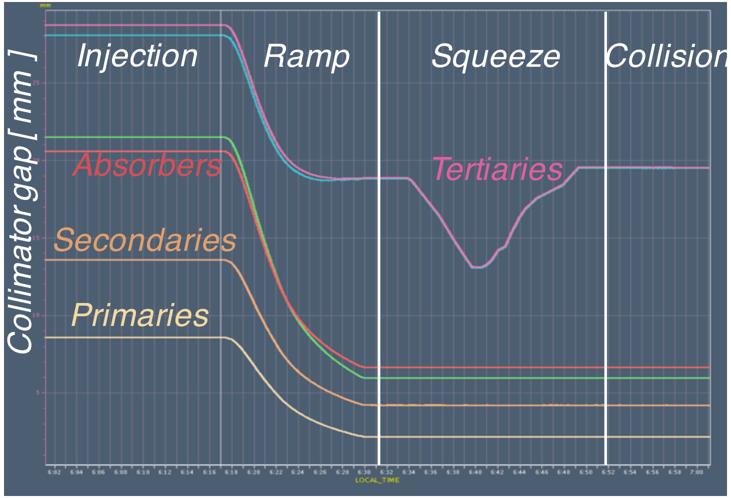


Collimation System @ LHC



- **Halo cleaning**: reduce the risk of magnet quenches
- **Concentration of losses/activation** in controlled areas
  Avoid many hot locations around the 27km-long tunnel
- Optimize **background** in the experiments
  Minimize the impact of halo losses on (no big issue for the LHC)



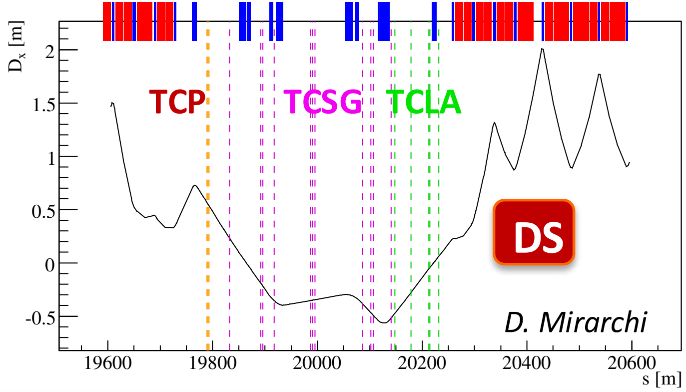


Multistage system of 50 collimators per beam.

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

Collimation System @ LHC

The cleaning efficiency measured in the LHC is with the present system up to 10^{-4}



Main limitations

Proton beam

- Single diffractive events

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

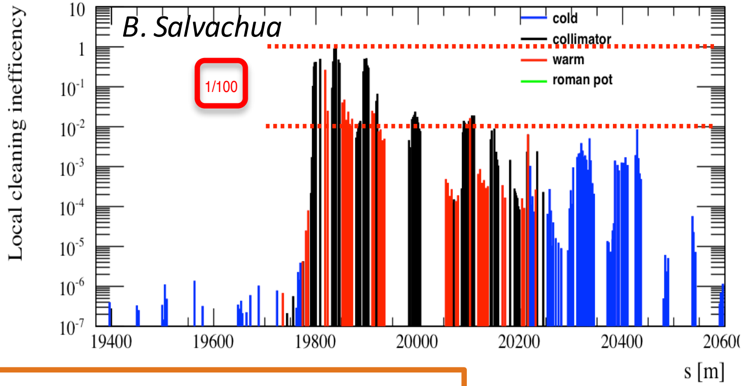
- Impedance

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

Lead beam

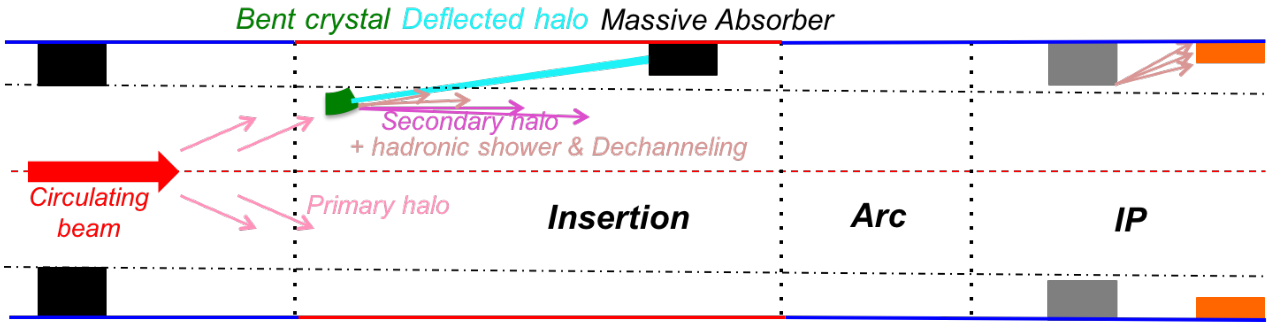
- Fragmentation and dissociation events

  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



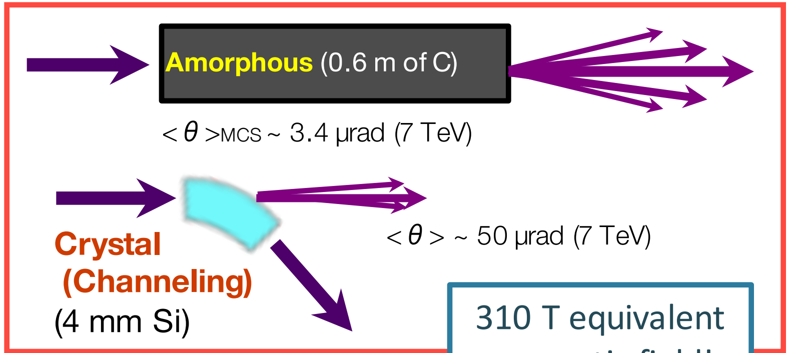
Limitations to be assesed during Run III

Crystal-assisted collimation



<u>Promises</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
- Similar performances with both p and Pb;
  Main outcome for lead ion operation



310 T equivalent magnetic field!

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

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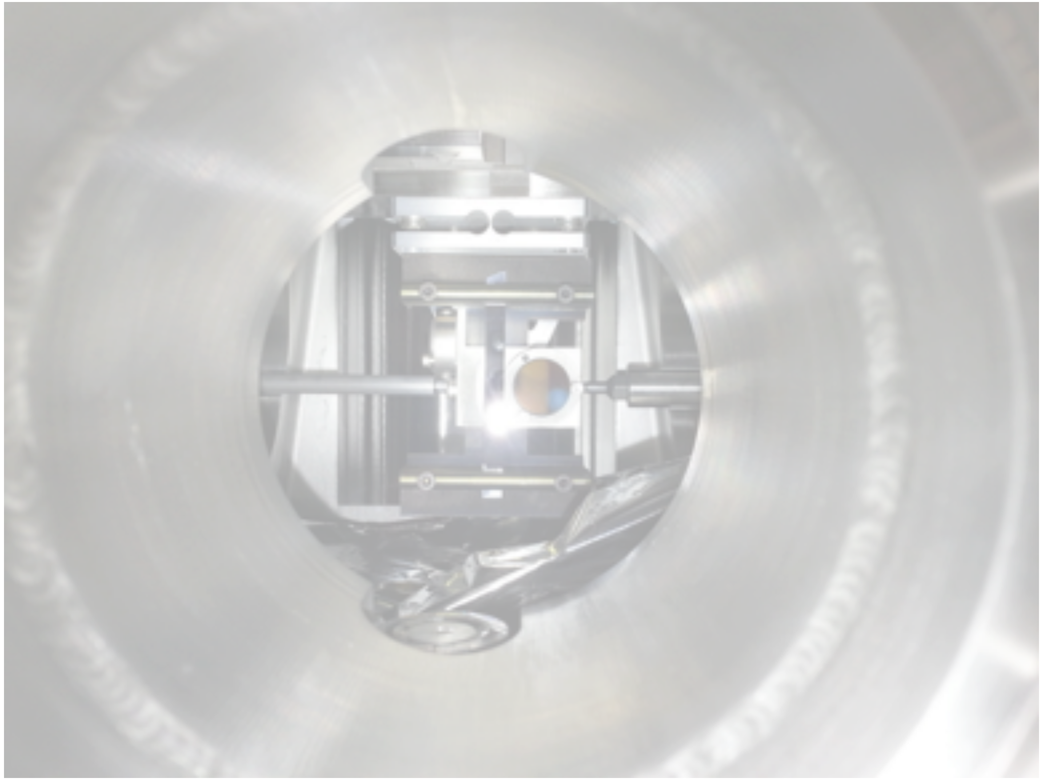

Can crystal be used in LHC?

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

request	baseline solution	drawback
Improve cleaning performances	11 T dipole with embedded collimator	very expensive
Reduce impedance	New materials for collimators	

Crystal collimation *can improve the cleaning and reduce the impedance* and is one of the R&D subject

Still different challenges has to be addressed

- Can we have a sufficient angular accuracy?
  - *The acceptance angle for channeling is 2.5 μrad @ 6.5 TeV* ➔ *goniometers with accuracy of 0.1 urad are required also stable throughout dynamic machine operation*
- Can crystal collimation improve the cleaning achieved with the actual system?
- Are crystal robust enough to maintain the same efficiency during a year of operation?
  - *NA62 and HiRadMat showed no damage for an equivalent 2 year LHC operation exposition*
  - *New tests on HiRadMat foreseen for the next year and will give more detail*
- Can a single collimator absorb all the channeled beam energy?
  - *High energy confined in a small spot* ➔ *a mini-dump is under investigation by collimation team*

Where are we?

In recent years several PhD works have been completed in order to provide feasibility studies (simulations and/or measurements):

V. Previtali:	CERN-THESIS-2010-133 (2010, PhD)	*simulation code for SixTrack*
D. Mirarchi:	CERN-THESIS-2011-136 (2011, master)	*measurements on SPS*
	CERN-ACC-2015-0143 (2015, PhD)	*improvement of simulation tools and benchmark, design of the crystal system prototype installed in the LHC*
R. Rossi:	CERN-THESIS-2014-187 (2014, master);	*measurements on single pass for simulation benchmark*

The setup for the PhD is built on those works, especially for the simulation tool that I'm using every day

Goals of PhD thesis

Now

The current work is aimed to measure the performances of the Crystal Collimation prototype installed in the LHC and results comparison with the simulation routines. The final goal is to provide the layout for a Crystal Collimation system for a future upgrade of the LHC.

The work can be sumerized as

1. Experimental assessment of crystal collimation performance in the LHC
2. Understanding of experimental results in simulation
3. Design of crystal-based systems for the LHC

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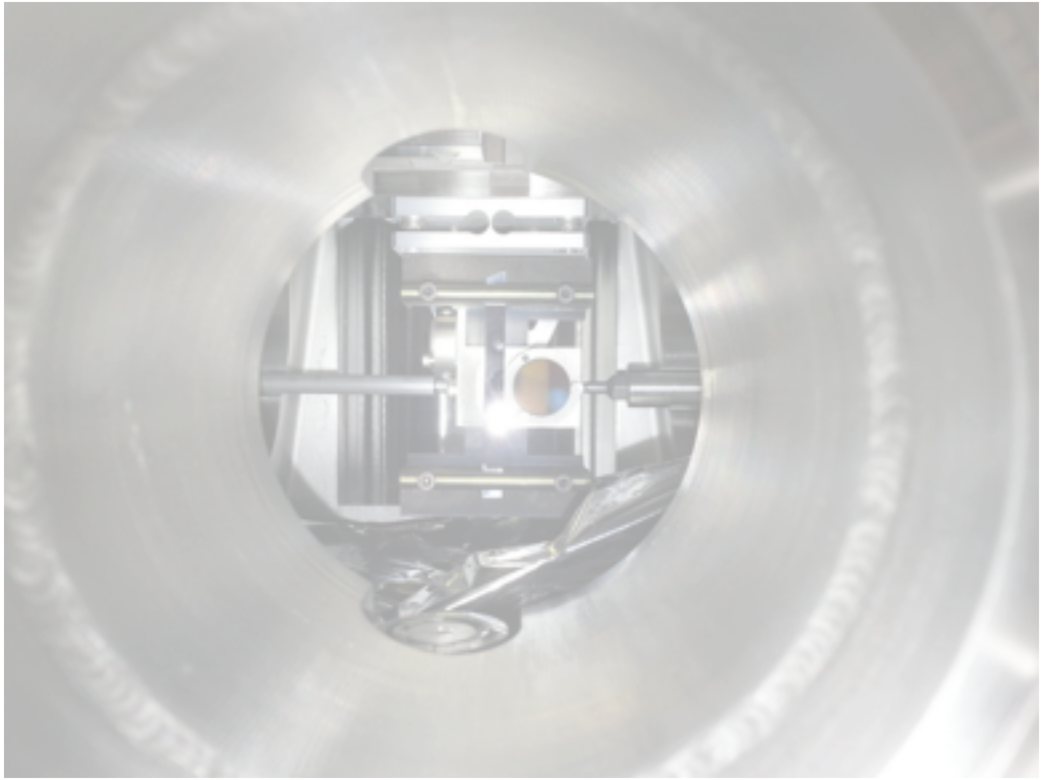
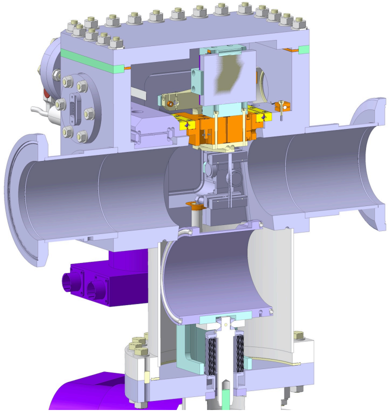


LHC Crystals

<u>Prototype system has been integrated in the LHC collimation layout</u>

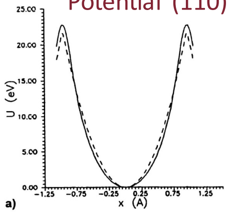
Two goniometers (one horizontal and one vertical) were installed in 2014 in positions where a secondary collimator could be used as absorber

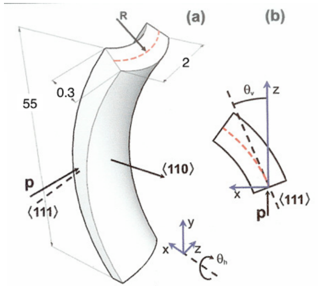


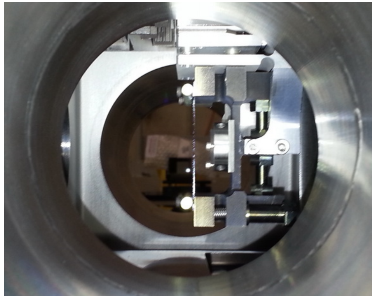
The goniometers are based on piezo-electric technology, and are able to achieve 0.1 µrad of accuracy

ST

Potential (110)

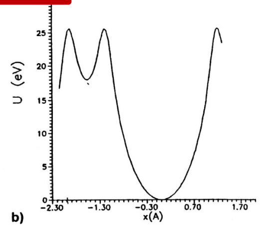


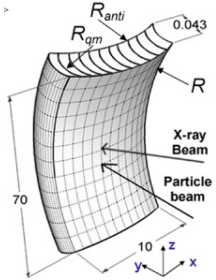


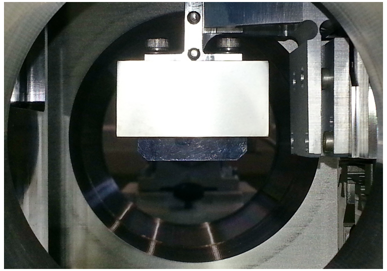


QM

Potential (111)





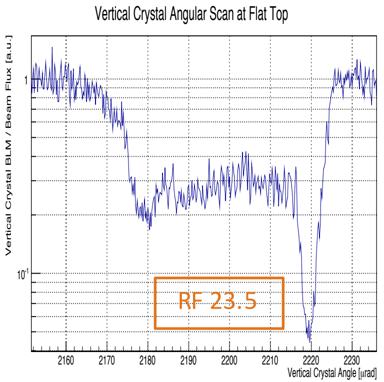


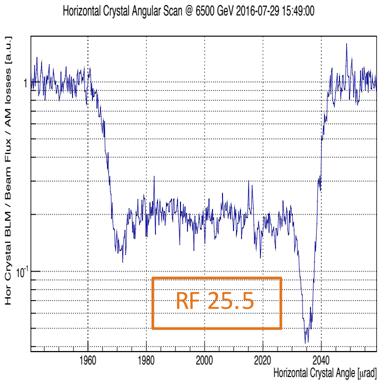
The bending for strip (ST) given by mean of anti-clastic forces.
Quasi-Mosaic (QM) exploit the quasi-mosaicity effect.

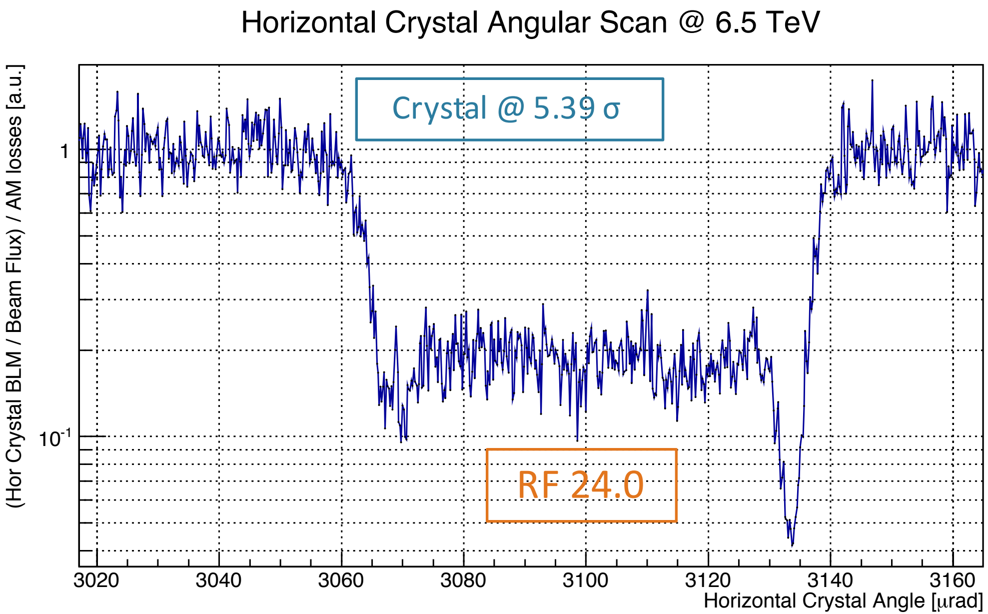
Horizontal Angular Scan @ 6.5 TeV

First observation of channeling at 6.5 TeV ➔ *World Record!*

In July both vertical (QM) and horizontal crystal (ST) were tested at flat top showing a reduction similar reduction factor







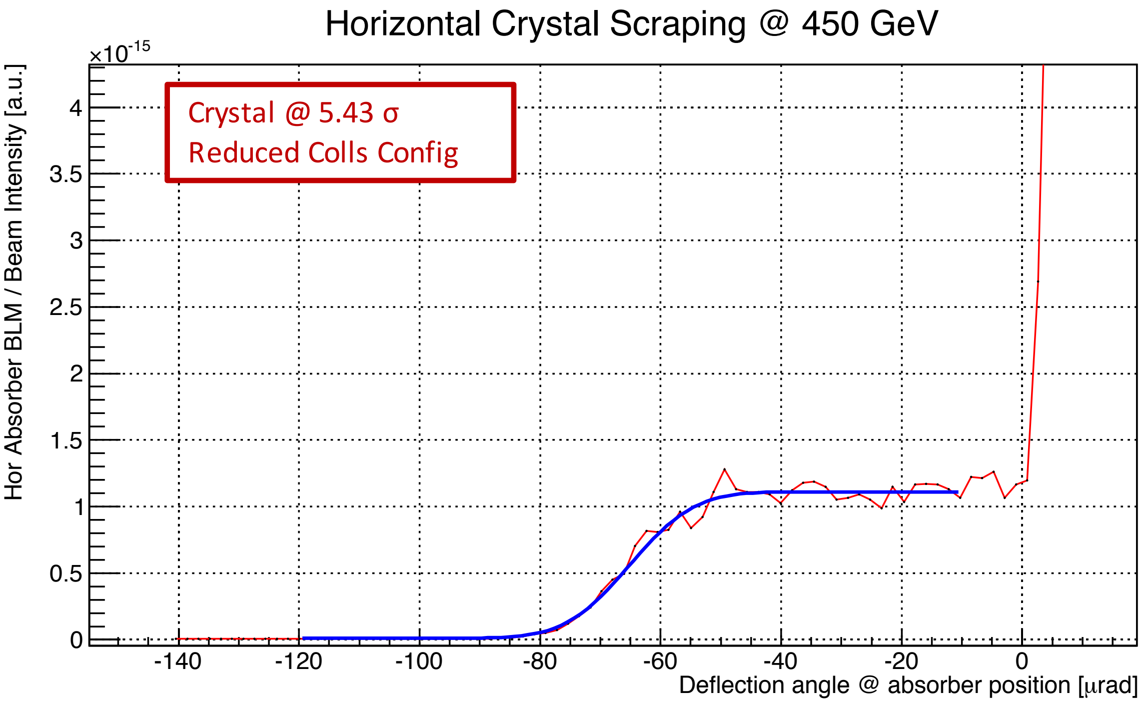
Losses recorded with BLM at goniometer position normalized to beam flux and to loss rate in amorphous

$$RF = \frac{loss_{AM}}{loss_{CH}}$$

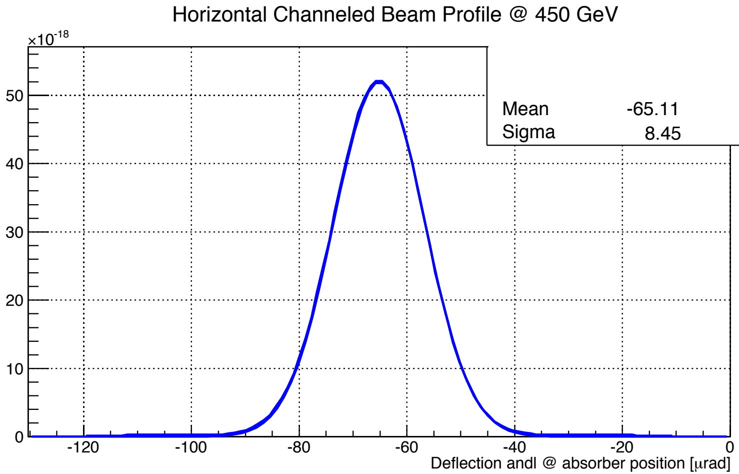
Horizontal Scraping @ 450 GeV

Losses recorded with BLM at goniometer position normalized to beam.
The X axis is converted in deflection angle using

$$\theta_k(s_{coll}) = \frac{x(s_{coll}) - \sqrt{\beta_{coll}/\beta_{cry}}\, x_{cry}\cos(\Delta\phi)}{\sqrt{\beta_{cry}\beta_{coll}}\,\sin(\Delta\phi)}$$

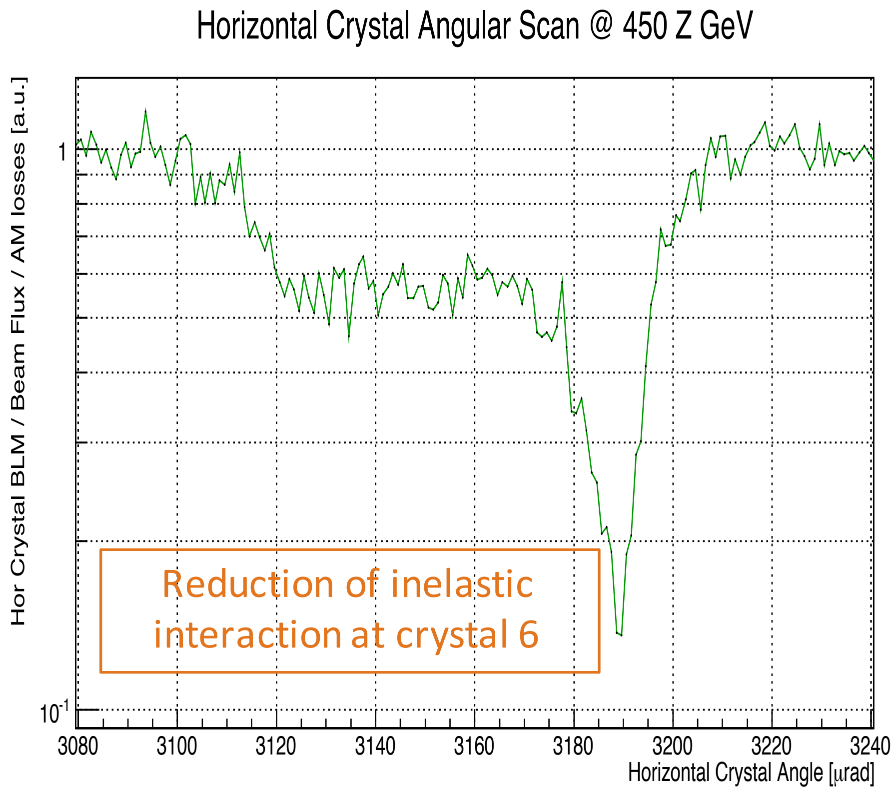


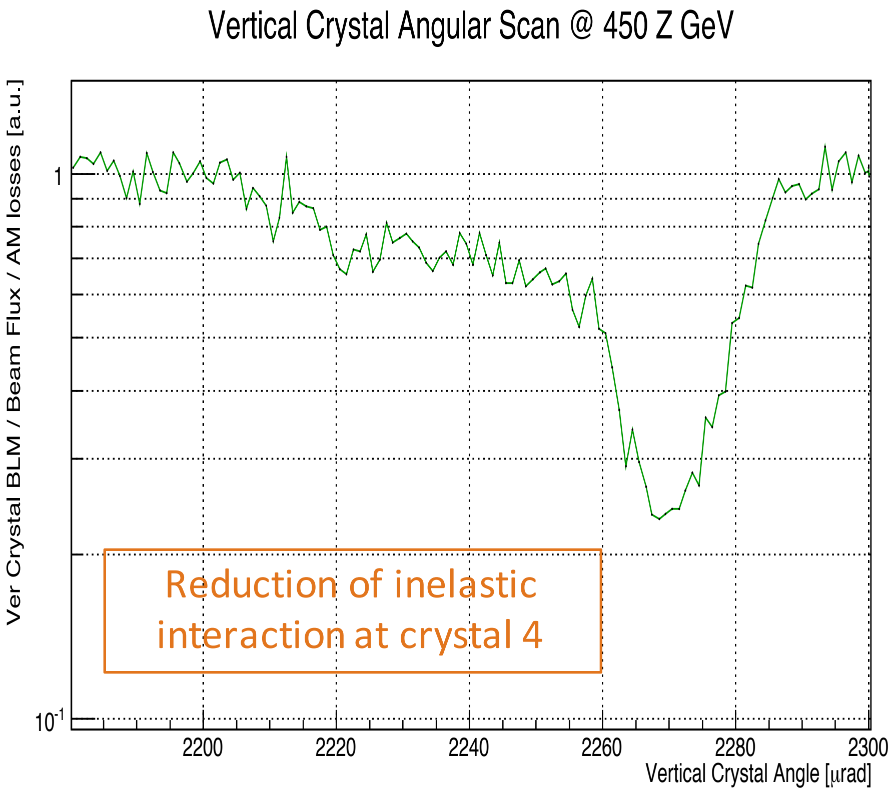
The error function fit gives info about the channeled beam properties as deflection angle and beam sigma



New investigations are ongoing to include the difference between nominal and measured beta function

Ions Angular Scans @ 450 Z GeV

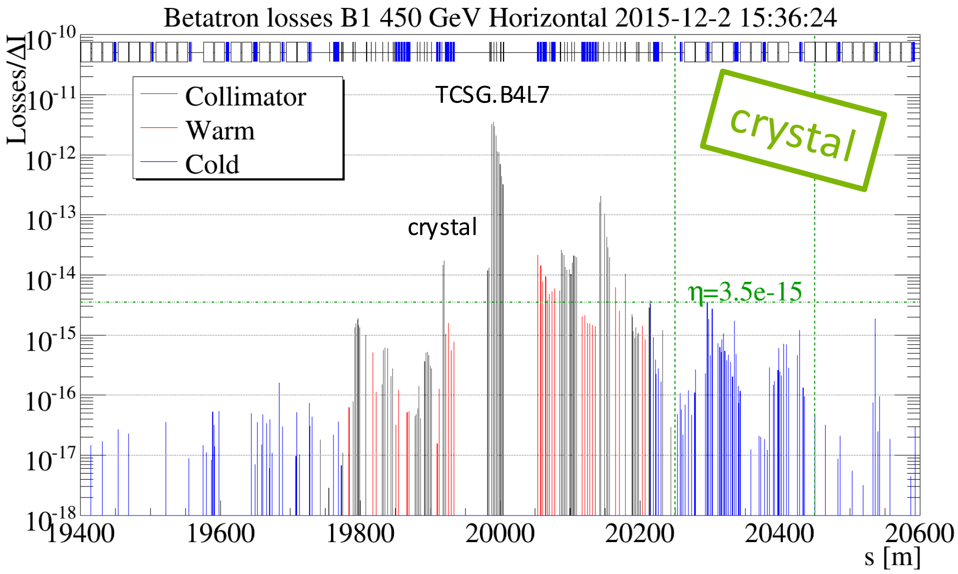


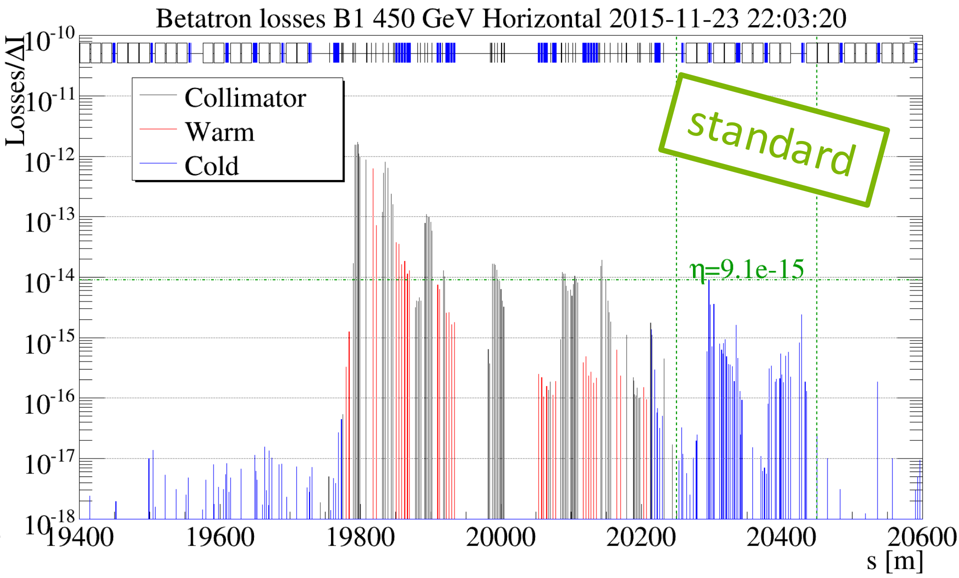


Losses recorded with BLM at goniometer position normalized to beam flux and to loss rate in amorphous orientation

Ions Loss Maps @ 450 Z GeV

Loss maps measurements was performed as during standard collimation tests





the leakage to IR7-DS is evaluated normalizing the BLM losses to the charges lost per second

the leakage to IR7-DS improves by a factor of about 2.6

better results are expected improving the clearance between crystals and TCSGs

note: the system is optimized for 6.5 TeV!

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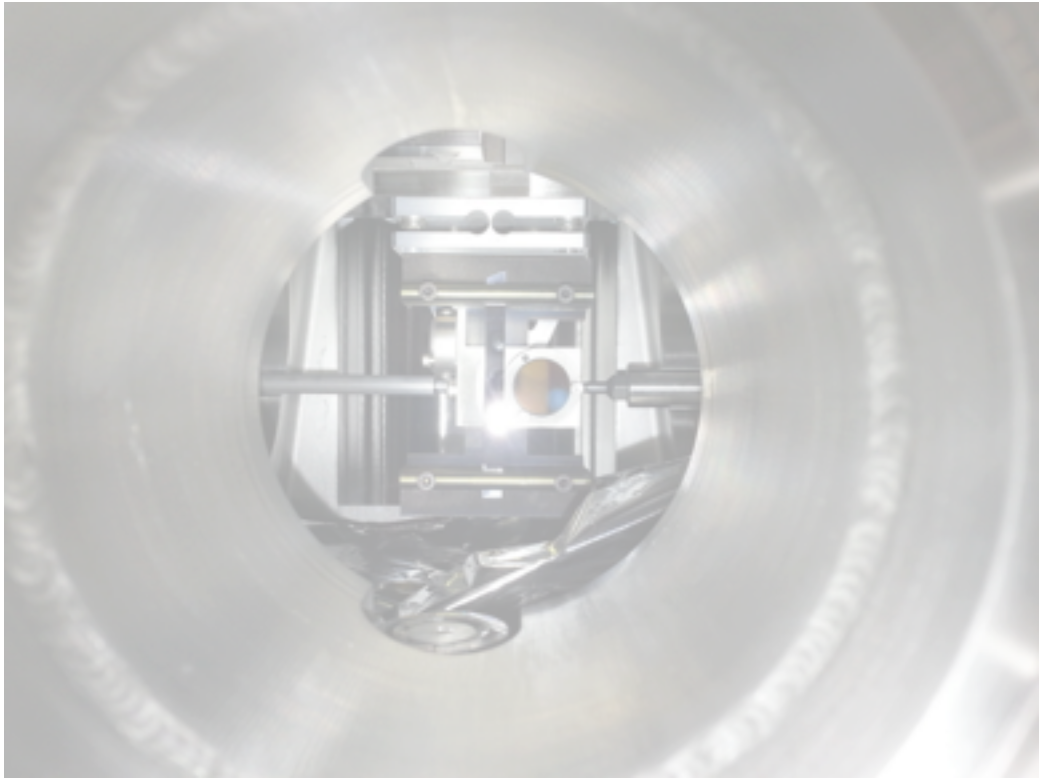
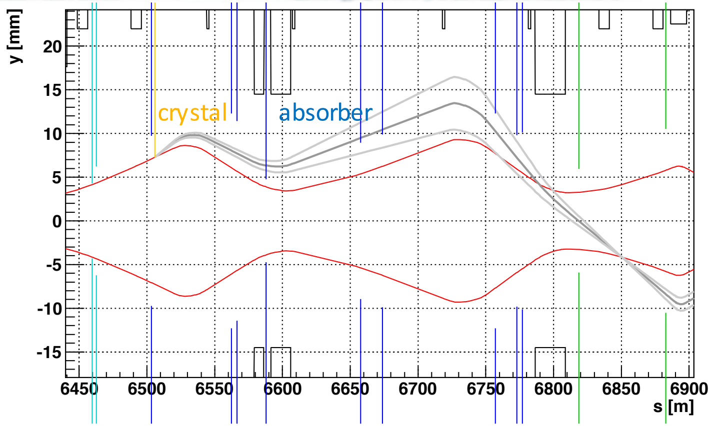
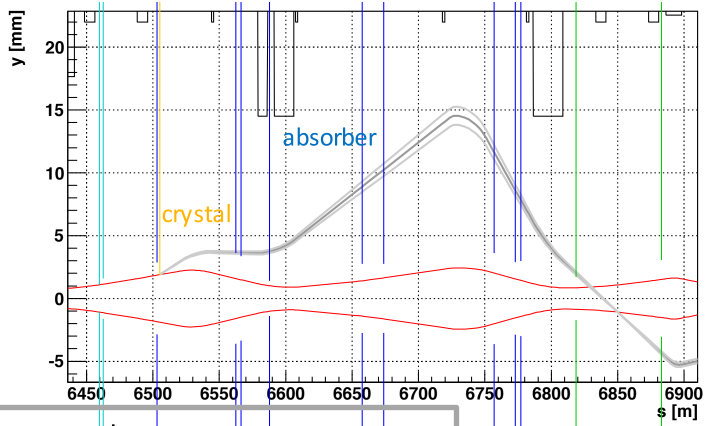


Crystal installation on beam 2

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

The possible available location where evaluated wrt the clearance obtained at the absorber collimator

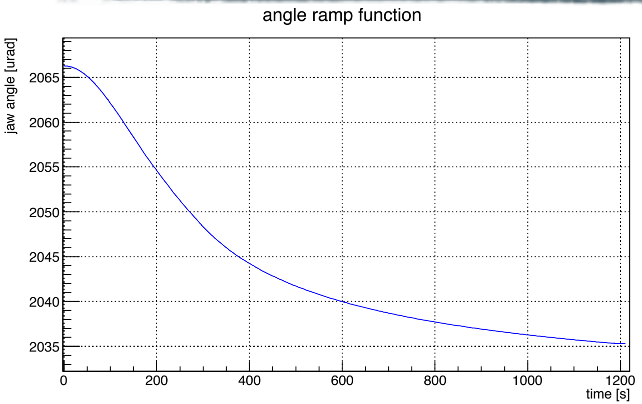


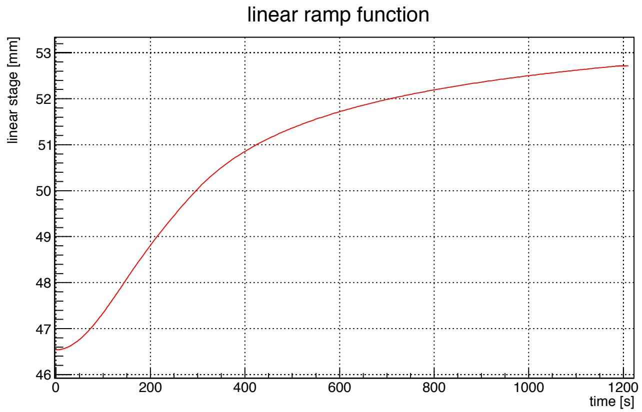


Two locations have been found and installation is foreseen for this winter shutdown

In figures the grey line represent the envelope channeled beam extract from a 50 µrad bent crystal.
The lighter line represent the kick plus (and minus) a critical angle, hence the channeled beam size envelope is represented

Energy ramp function for tests





In the next LHC MD crystal will be tested during the <u>energy ramp of LHC</u>

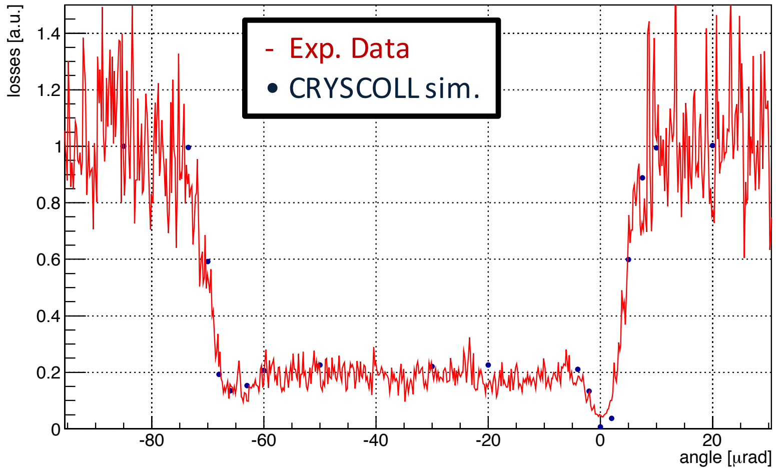
During the last MD of July the channeling orientation and the linear alignment has been measured

	Injection		Flat Top	
crystal	Linear [mm]	Angle [µrad]	Linear [mm]	Angle [µrad]
H	46.55 (5.71 σ)	2066.9	52.72 (5.53 σ)	2035.3
V	44.8 (5.68 σ)	2275.7	50.25 (5.47 σ)	2219.3

The energy ramp function was used to evaluate how the orientation angle and the linear stage has to vary to keep the crystal in the channeling condition during the E ramp

Simulations plan

To benchmark the simulation routines the scenarios of the measurements taken in LHC will be reproduced with the SixTrack code, as showed for the first flat top scan.



Simulations most important results are undergoing

- Angular scans of crystals
- Linear scans with absorber collimators
- Loss maps in Channeling and with standard system

Of course each bullet has to be considered for both energy (injection and flat top) and for both plane (H & V)

Benchmarking the simulation code is the fundamental step to begin the studies on the final layout for a possible crystal collimation system for HL-LHC

Also UA9 SPS results will be used to benchmark the simulation code

Conclusion

✓ First part of thesis focused on data taking and experimental results:
  - Channeling observed for the first time at the LHC with protons and ions at 450 GeV
  - Channeling observed with protons at 6.5 TeV (world record)
  - Tests with ions showed a reduction of particle leakage on dispersion suppressor in IR7, already at 450 Z GeV
  - Energy ramp functions for operation cycle produced to be tested soon

Goals for the next year:

- ❑ Continue experimental activities and finalize open issue in data analysis

  The most important will be the test with ion beam @ 6.37 Z TeV (this december)
- ❑ Complete simulations to benchmark code with experimental data
- ❑ Detailed design work for the LHC not yet started (final part of the thesis).

  However, applied tools for a first new design layout for B2

  to be implemented at the end of this year

BACKUP

Crystal Channeling

Lindhard: “In the ipothesis of low impact angle, the potential generated by the crystalline plane can be approximated by a continouns potential.”

Channeling : Tansverse momenta < potential well

The channeling condition can be defined as

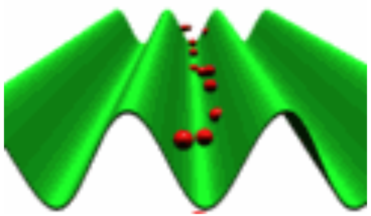
$$\frac{p^2c^2}{2E}\theta^2 + U(x) \leq U_{max}$$

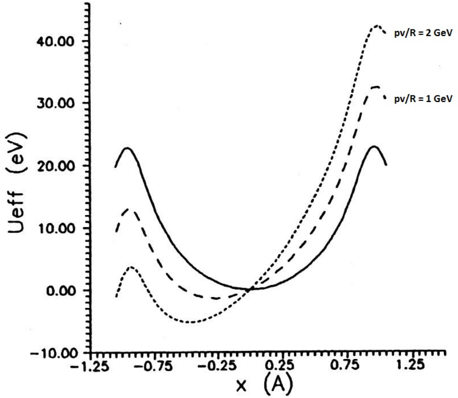
So we can define a condition to undergo channeling condition

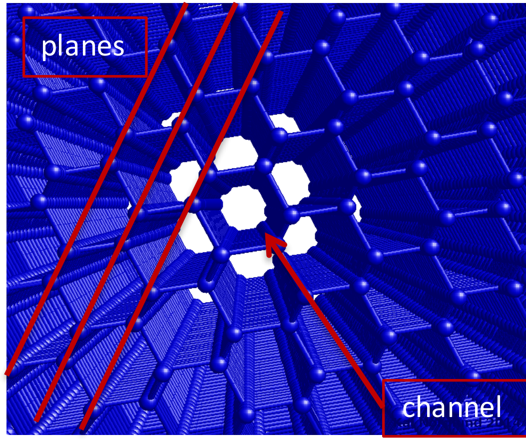
Case	Energy [GeV]	θ_c [μrad]
SPS coast	120	18.3
SPS coast	270	12.2
H8	400	10.0
LHC inj.	450	9.4
LHC top	6500	2.5
LHC top	7000	2.4

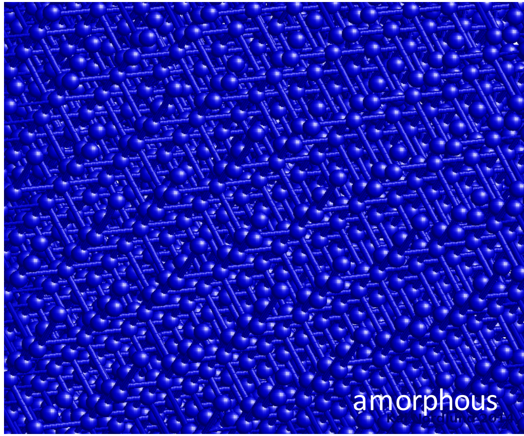
Critical angle

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







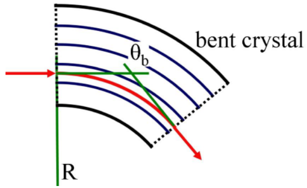


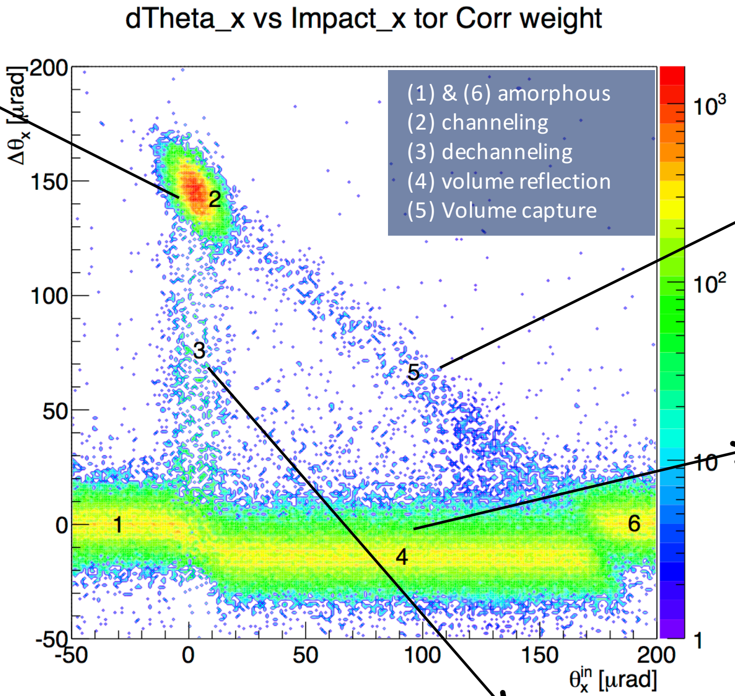
The particles are trapped in the channel, hence if a curvature is given to the lattice the particles direction will be modified by $\theta_b = l/R$

Coherent effect in bent crystals

Planar channeling (PC)

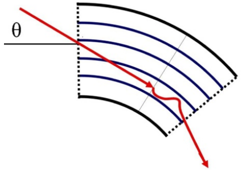
Particles are channelized, if impact angle is lower then the critical one, and deflected





Volume Capture (VC)

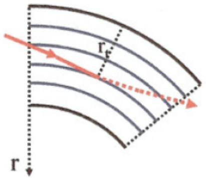
Particles are channelized at a certain depth in crystal volume



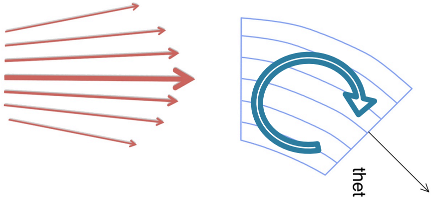
Volume Reflection (VR)

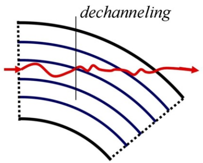
Particles are deflected by the potential well, at a certain depth in crystal colume.

The VR deflection is opposit to CH deflection and it's about $1.6*\theta_c$



Single pass measurements with 400 GeV protons.
During an angular scan the crystal shows different choerent effect due to the bending.
In this case a strip crystal (110) with a 2 mm lenght anlong the beam and a curvature of 144 μrad.





Dechanneling (DC)

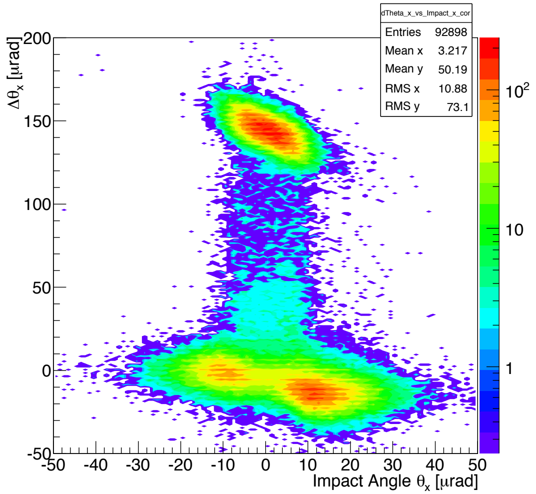
Particles exit from channeling condition at a certain depth in crystal and get a lower deflection

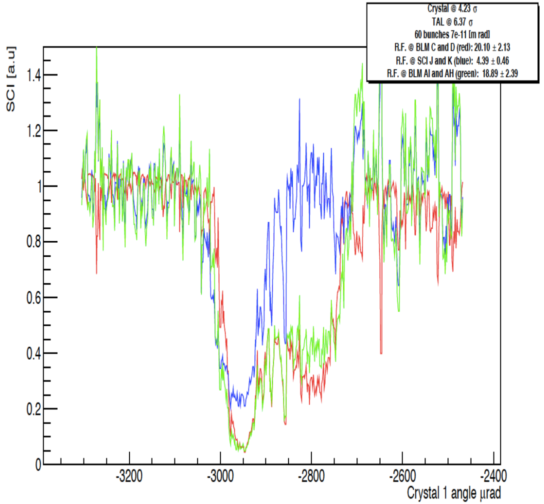
UA9 Experiment

The UA9 Collaboration investigates how tiny bent crystals could assist and improve the collimation process in the Large Hadron Collider (LHC) at CERN in view of future ultra-high luminosity operation.

Recap of results relevant for LHC beam tests

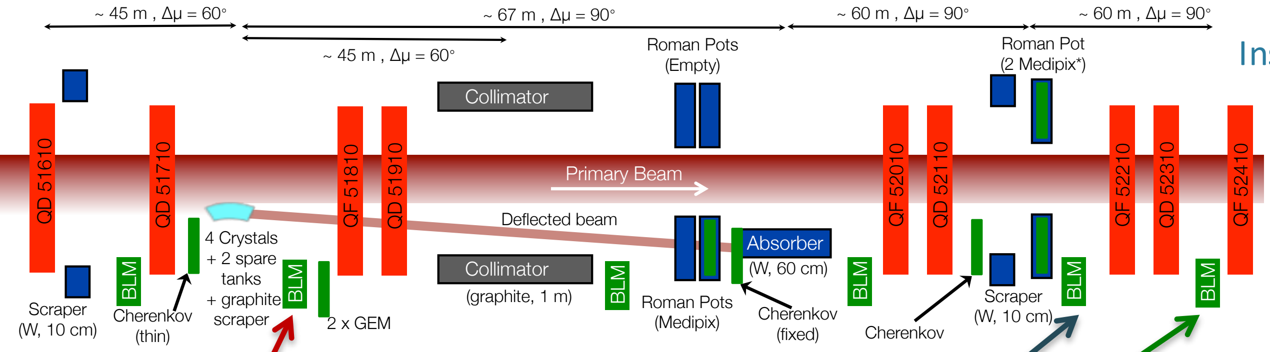
Characterization of coherent interaction between high-energy particles and bent crystals performed in SPS H8 extraction line.	Principle of crystal-assisted collimation is investigated at the CERN SPS with stored beams of protons or lead (Pb) ions.

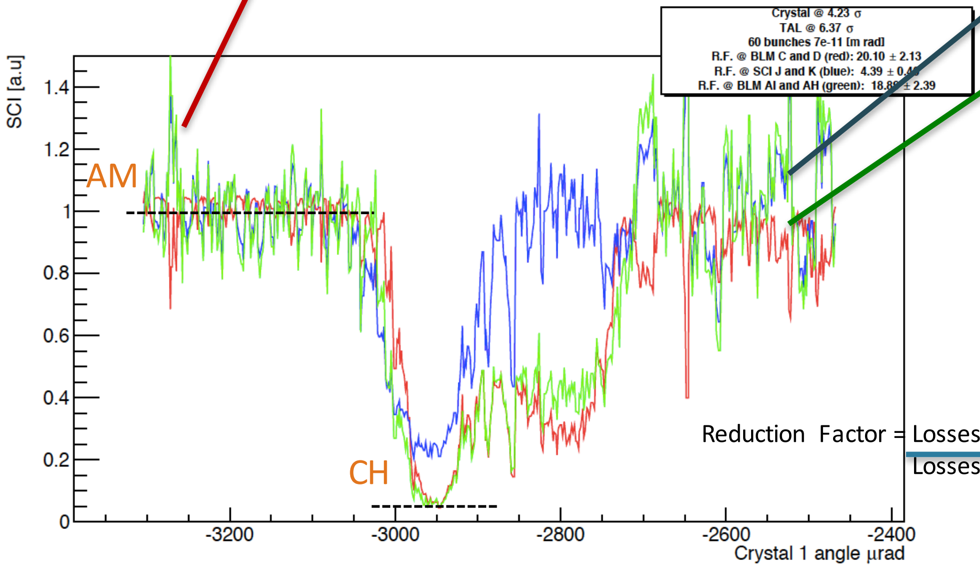




UA9 SPS collimation

Instrumentation Layout in LSS5 in the SPS





$$\text{Reduction Factor} = \frac{\text{Losses AM}}{\text{Losses CH}}$$

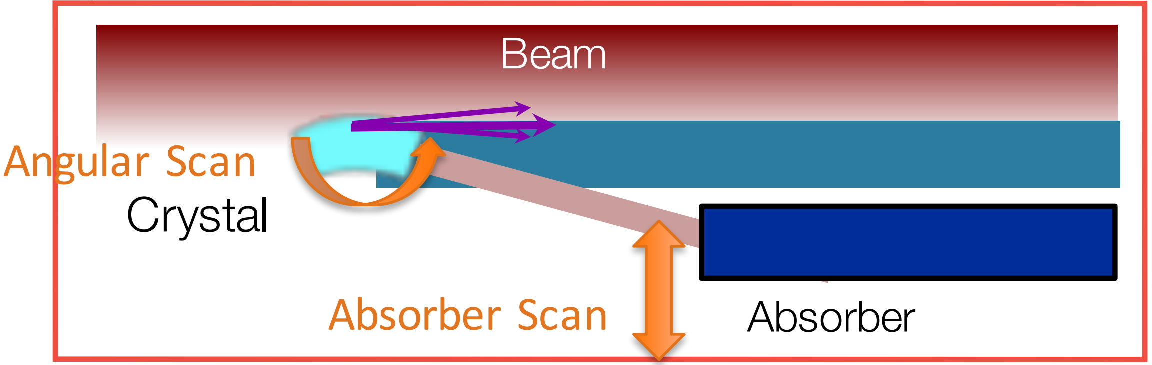
Well established hardware and layout

- Fast alignment
- Clear loss reduction in CH orientation

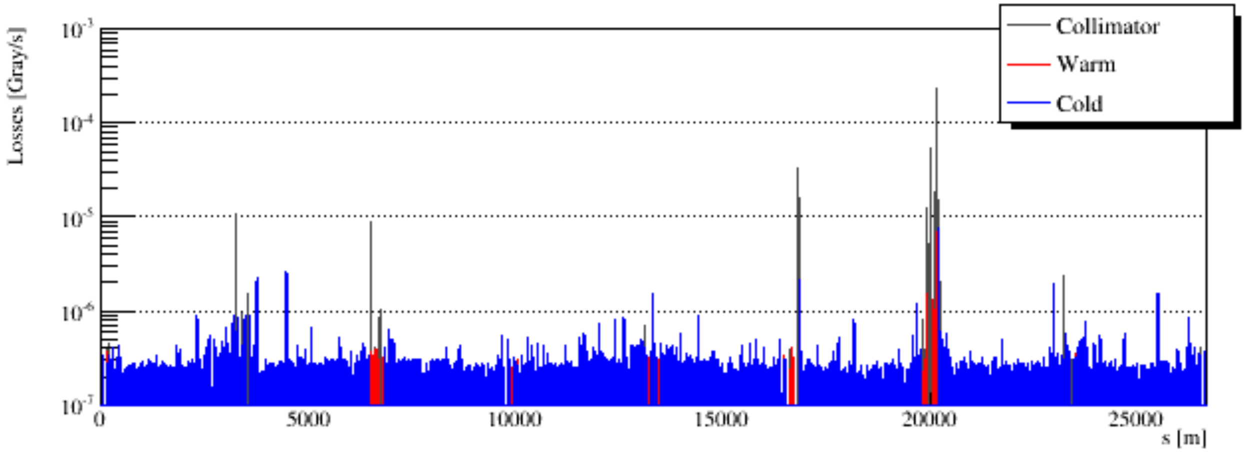
Initially used to prove crystal channeling in circular machines;
now useful test bench for detailed collimation studies in the LHC

List of measurements

- Fast angular scan on whole goniometers range
  - Identification of channeling orientation
- detailed angular scan around angles determined with the measurement above
  - indication of optimal channeling orientation, scans repeated in different fills to test the system stability
  - measurement of nuclear interaction rate at the crystal, characterization of local losses for different working regimes
  - measurement of reduction of nuclear interaction rate (AM/CH) and measurement of crystal bending angle (extension of VR region)
- Crystal placed in optimal channeling orientation and linear scans with selected TCSG is performed
  - study the extracted beam profile, deflection angle, and multiturn channeling efficiency
  - validation of expected crystal orientation
- Loss map with reduced set of collimators in IR7 (all collimators upstream the crystal retracted of … sigma)
  - validation of working principle with reduced number of collimators
  - comparative studies w.r.t. present collimation system



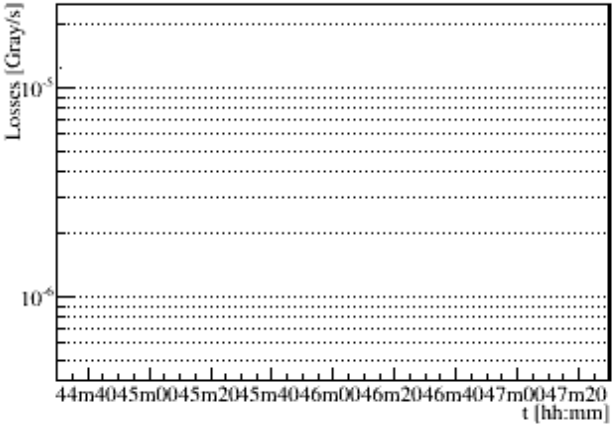
Loss Map Horizontal plane

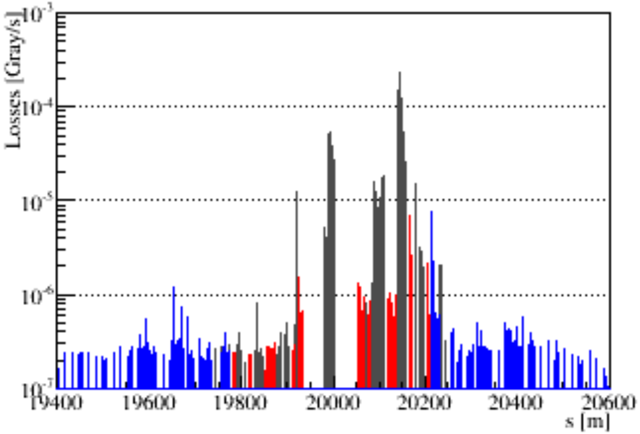


Raw data

The picture shows losses on the whole machine during an angular scan, with the reduced settings of collimators.

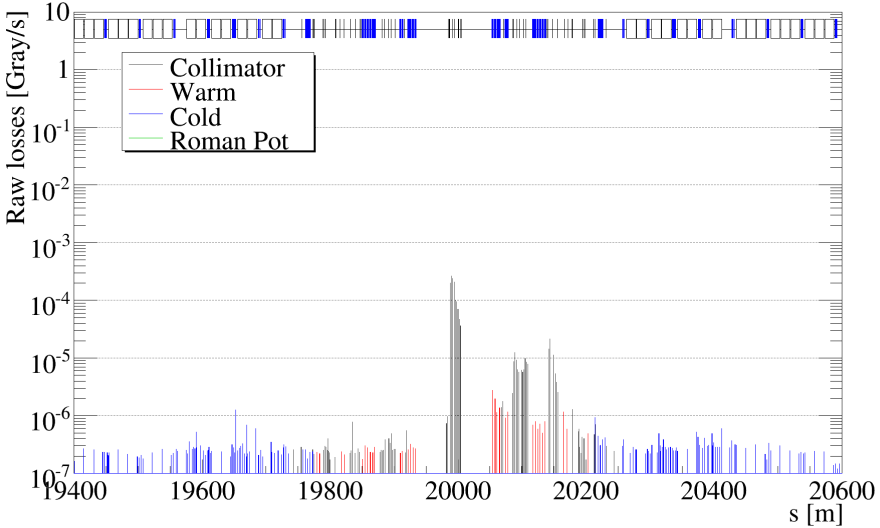
Preliminary – pending detailed calibration

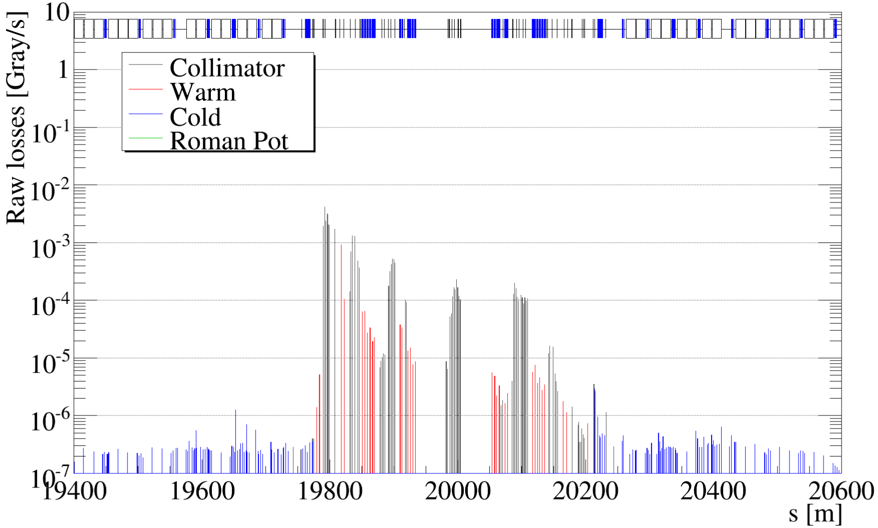




Daniele Mirarchi

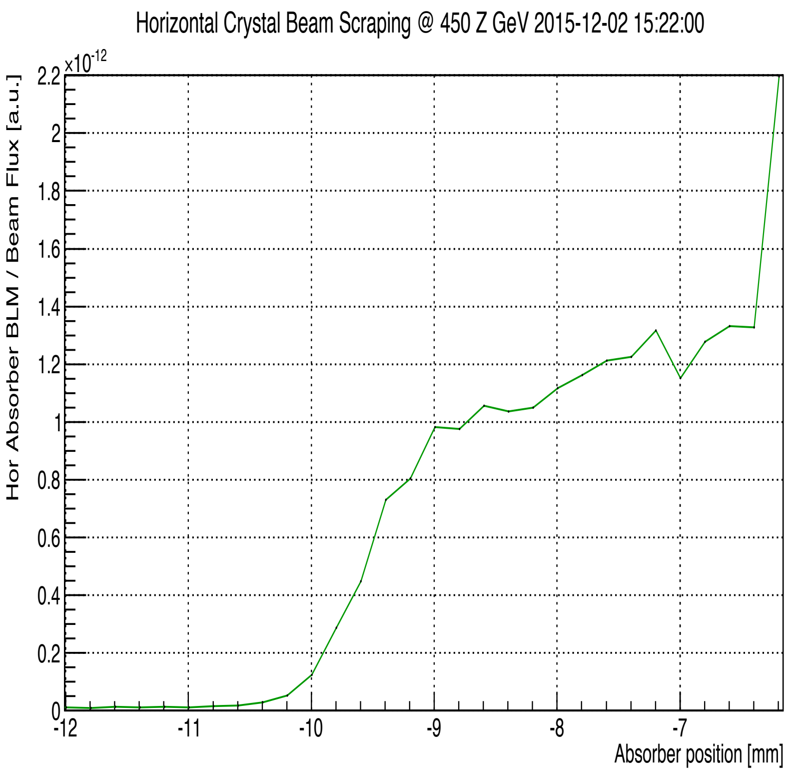
Loss Map comparison

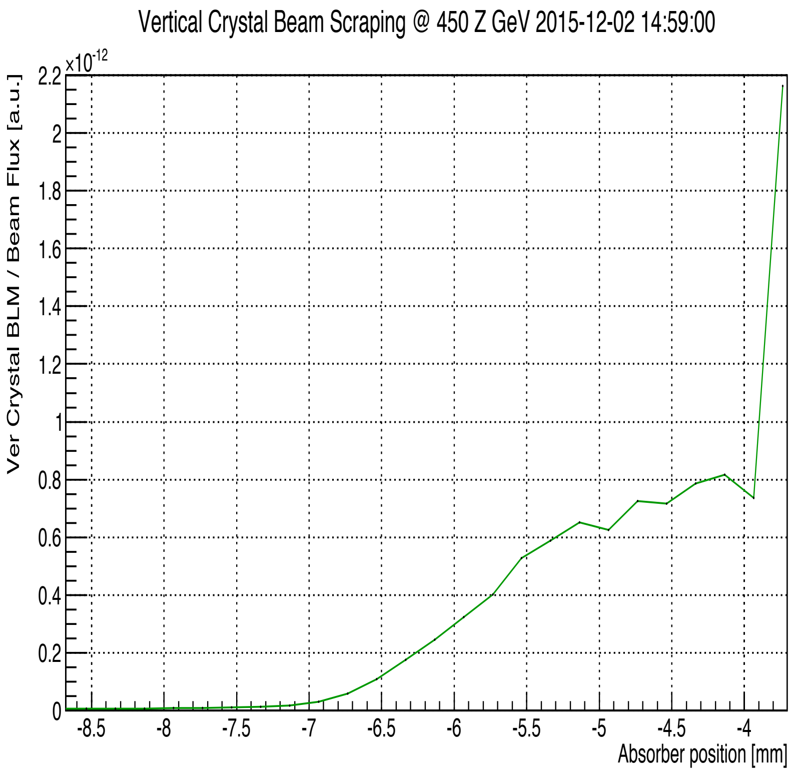




Preliminary – pending detailed calibration

Ions Channeled Beam Linear Scans

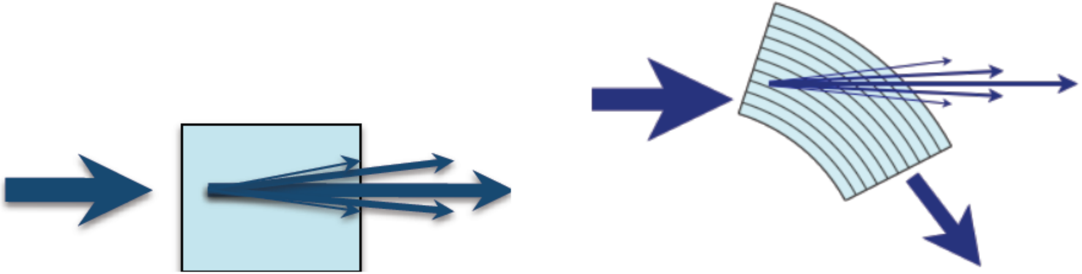




Losses recorded with BLM at each collimator position normalized to beam flux

Introduction

UA9 collaboration is studying the possibility of steering particle beam with bent silicon crystal to improve the actual LHC collimation system.



Various studies are required to achive this goal :

- Interaction characterization of charged particle with bent crystal
- Development of simualtion routine
- Experimental study of a crystal-assisted collimation system on SPS
- New detector development for beam flux measurment

UA9 just launched a working group with the CERN Extraction team to study an SPS beam extraction system with bent crystals.

H8 Crystal test Beam

The UA9 collaboration is studying techniques to steer ultra-relativistic beams with bent crystals to improve the collimation of proton and heavy ion beams at the LHC.

Measurements of key crystals properties (bending angle, channeling efficiency, etc..) are performed on the SPS extraction line (H8) with 400 GeV/c protons before testing crystals with circulating beams.

Data analysis main goal:

Consistently analyze all the crystals tested in H8 (total of 15 between 2010-2012).

- Compile a comprehensive statistical treatment of different crystals
- Identify "fine" systematic effects (e.g., transitions)
- provide inputs to crystal code developers

Immediate goal: compile list of experimental data for comparison with crystal simulations.

http://lhc-collimation-upgrade-spec.web.cern.ch/LHC-Collimation-Upgrade-Spec/H8_input.php

H8 experimental Layout

- Five silicon micro-strip sensors (active area 3.8x3.8 cm^2 in the x-y plane) are used to track the particles in the plane orthogonal to the beam direction before and after passing through the crystal.
- High precision goniometer is used to modify the crystal plane orientation with respect to the beam direction.