LHC Operational Experience with Heavy Ion Beams

19/10/2018 – HL-LHC Crystal Collimation Day

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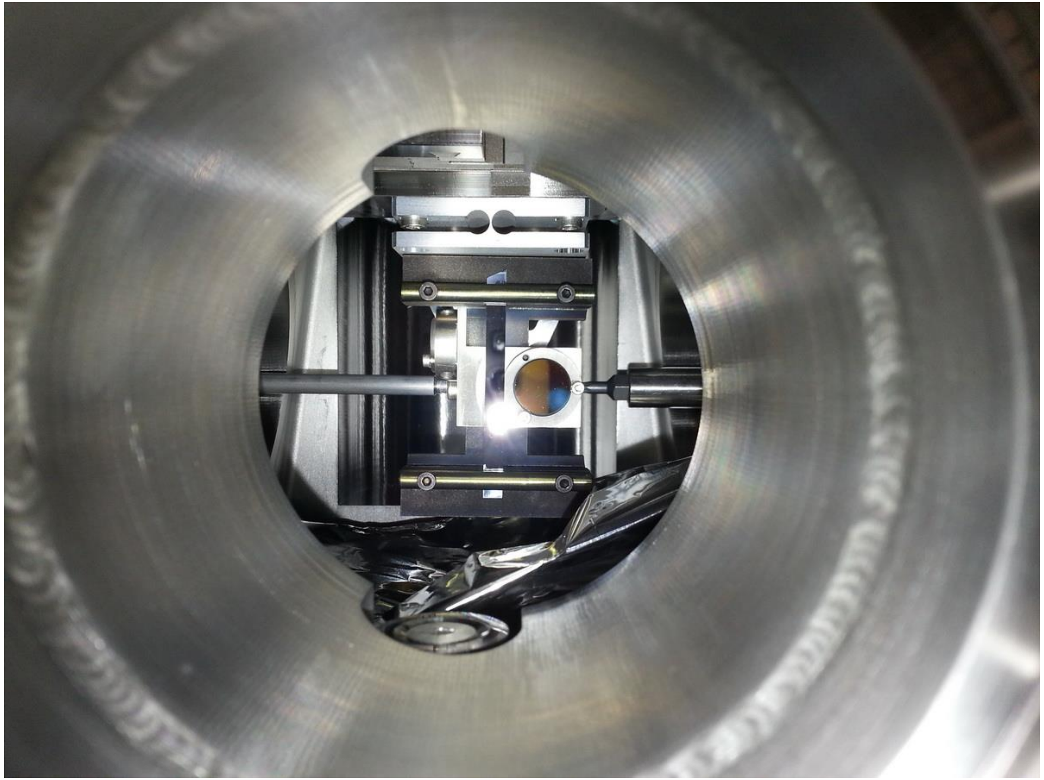
Acknowledgments: UA9 Collaboration, EN-SMM, BE-ABP, EN-STI, BE-OP

Outline

- Review of measurements performed with ion beam
  - Crystal angular scans
  - Collimator linear scans
- Cleaning with Xe ion beams
- Cleaning with Pb ion beams
- Proposed settings strategy and plans for tests in 2018
- Conclusions


Strip silicon crystal installed on the horizontal B1 goniometer in LHC.

Heavy Ion Tests Overview

Test with heavy ion carried out from 2015 to 2017 (one per year)

A total of 36 h were allowed with ion beams

~ 20h used for measurements

Details about procedures, analysis and results are presented in MD notes:

- CERN-ACC-NOTE-2018-0004
- CERN-ACC-NOTE-2018-xxxx

A report on Xenon beam measurement in the doctoral thesis:

- CERN-THESIS-2017-424

ID	Date	Particles	Energy	Main Program
MD#1	30/08/2015	Protons	450 GeV	First channeling characterization in LHC with both B1 crystals
MD#2	06/11/2015	Protons	450 GeV & 6.5 TeV	First observation of channeling at LHC top energy with B1 horizontal crystal
MD#3	02/12/2015	Lead Ions	450 ZGeV	Channeling characterization with lead ions with both B1 crystals
MD#4	29/07/2016	Protons	450 GeV & 6.5 TeV	Channeling characterization and cleaning measurements at top energy for both B1 crystals
MD#5	30/10/2016	Protons	450 GeV to 6.5 TeV	Crystals as primary collimator during the energy ramp, in channeling orientation
MD#6	29/11/2016	Lead Ions	450 ZGeV & 6.5 ZTeV	Channeling characterisation and cleaning measurements with lead ions at LHC top energy with both B1 crystals
MD#7	02/07/2017	Protons	450 GeV & 6.5 TeV	Channeling characterisation with both B1 & B2 crystals
MD#8	15/09/2017	Protons	450 GeV	Characterisation of horizontal crystal on B2
MD#9	13/10/2017	Xenon Ions	450 ZGeV & 6.5 ZTeV	Channeling characterisation and cleaning measurements in LHC with Xe ions

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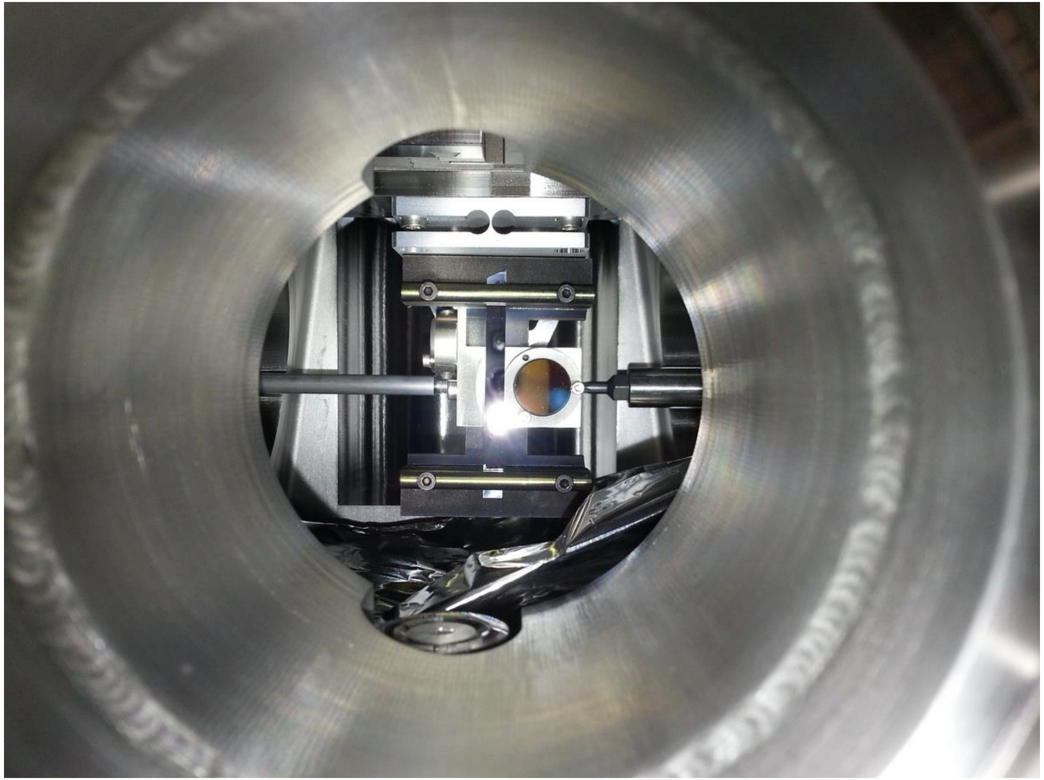
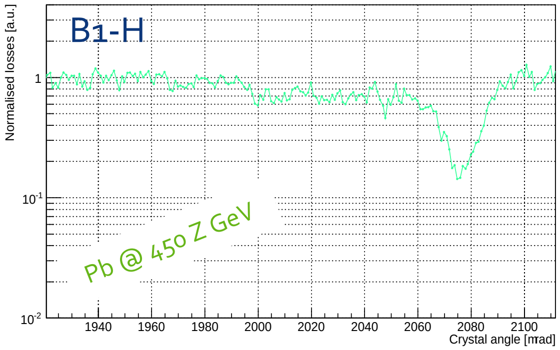
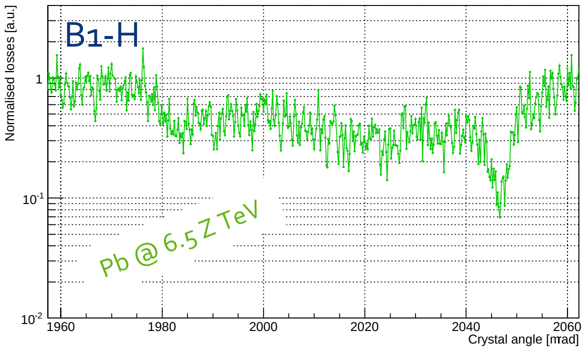


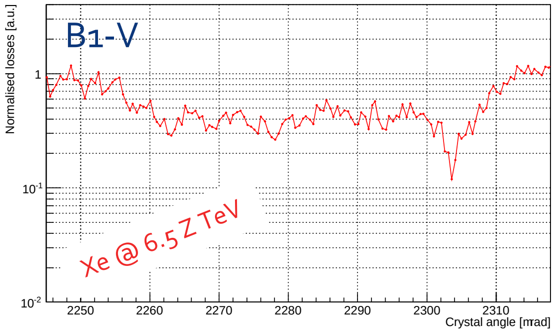
Strip silicon crystal installed on the horizontal B1 goniometer in LHC.

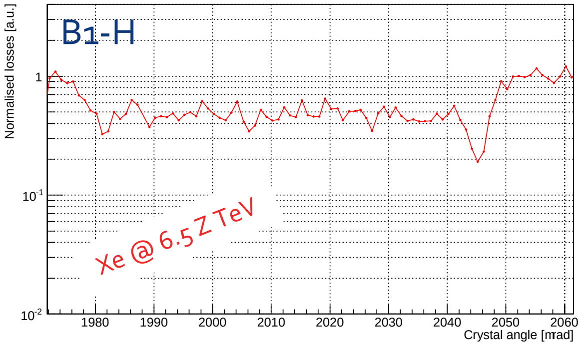
Ions Angular Scans

Channeling with ion beams of such energies observed for the first time in LHC





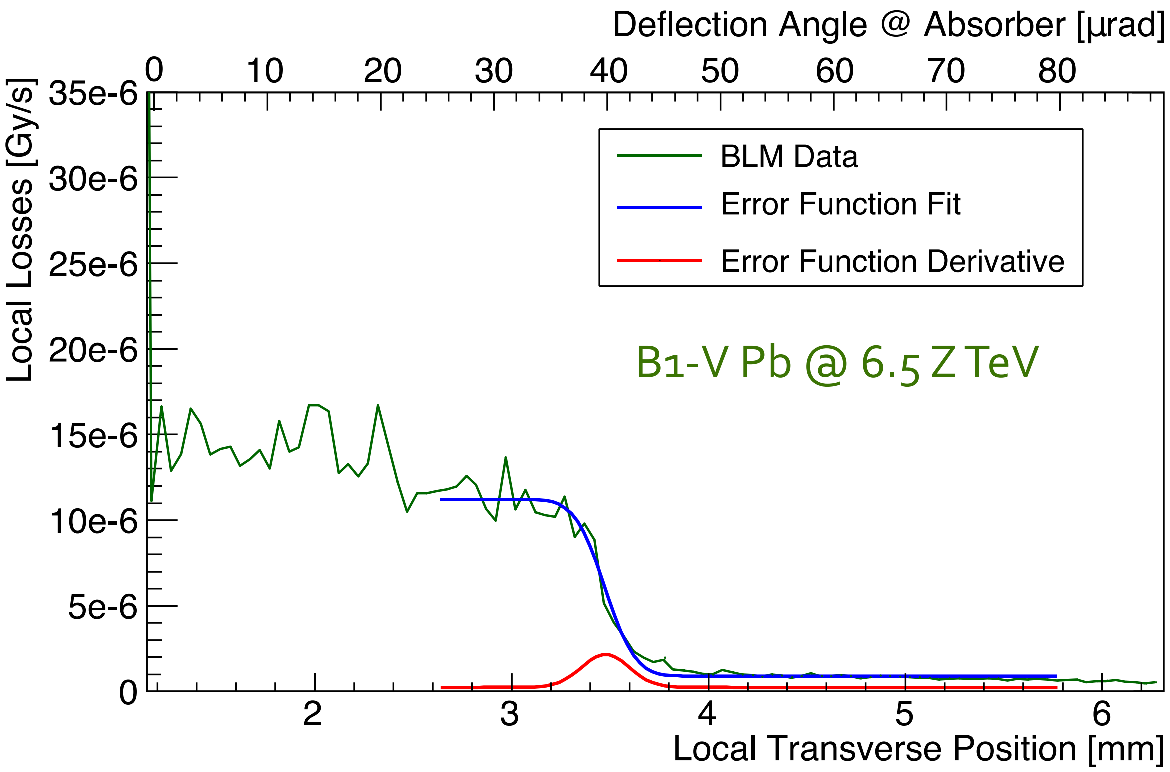




Ions Collimator Scans

As for proton beams the observables are:

- Bending angle ~ 40 μrad
- Multi-turn efficiency ~ 65 %



Overview

Crystal	ID	Bending Angle [μrad]	Multi-Turn Efficiency [%]	
			@ 450 Z GeV	@ 6.5 Z TeV
B1-H	STF75	63.2 ± 1.7	75 ± 5	37 ± 3
B1-V	QMP34	39.8 ± 2.3	86 ± 3	64 ± 3
B2-V*	QMP52	56.5 ± 1.5	-	-

* No linear scan with ion beams available

For each crystal it has been evaluated:

- the deflection angle (is averaged over all the measurements, both protons and ions)
- The Multi-Turn channeling efficiency (averaged on Xe and Pb measurements)

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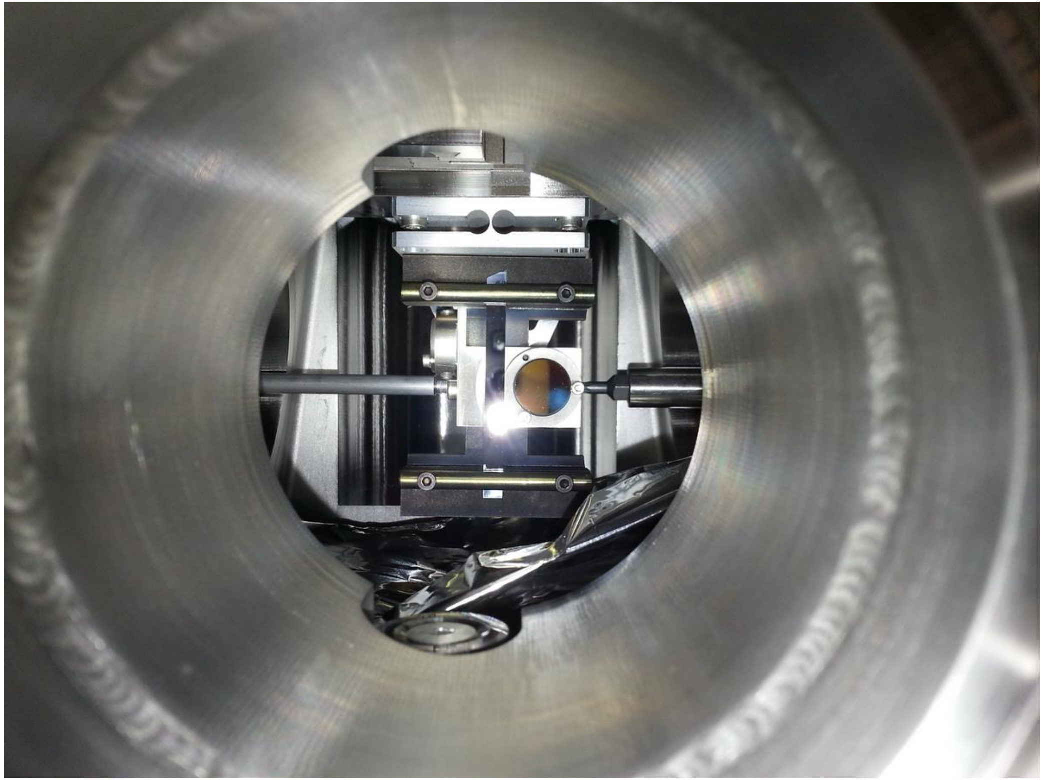
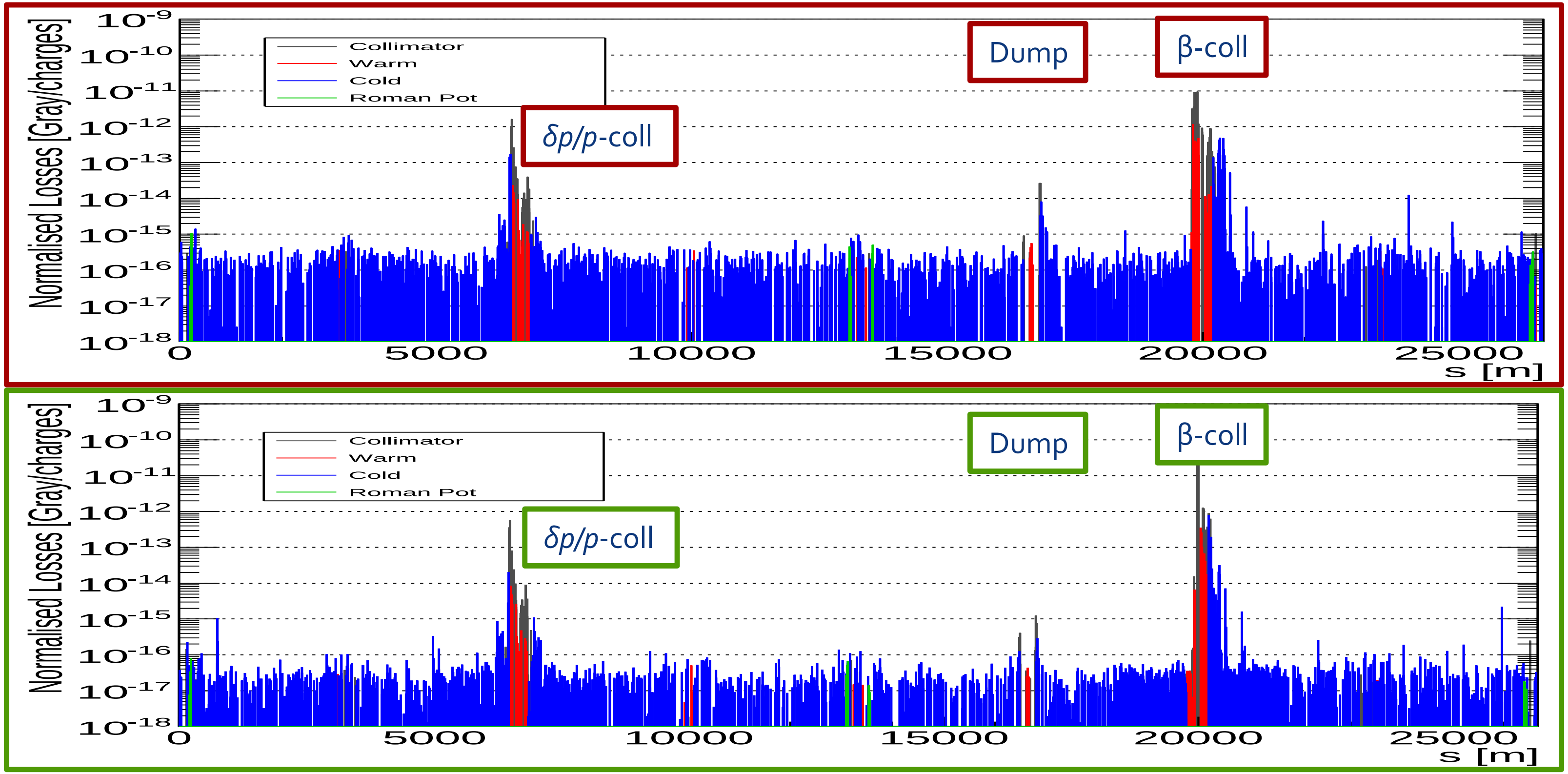


Strip silicon crystal installed on the horizontal B1 goniometer in LHC.

Crystal Collimation Xenon Cleaning

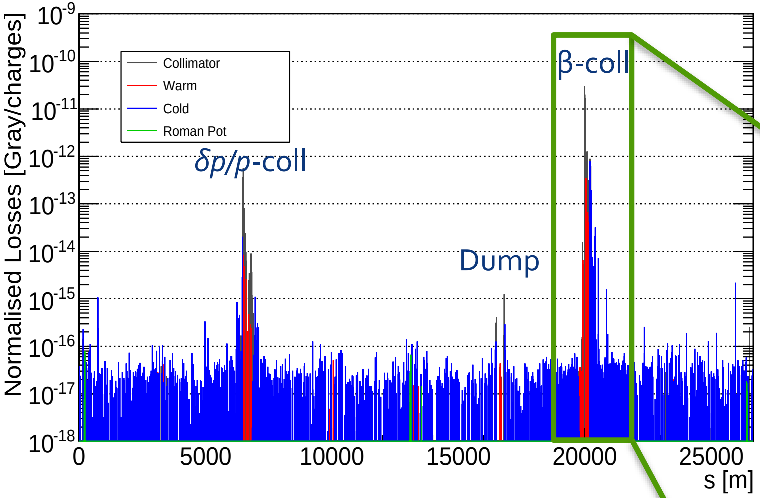
Standard

Crystal

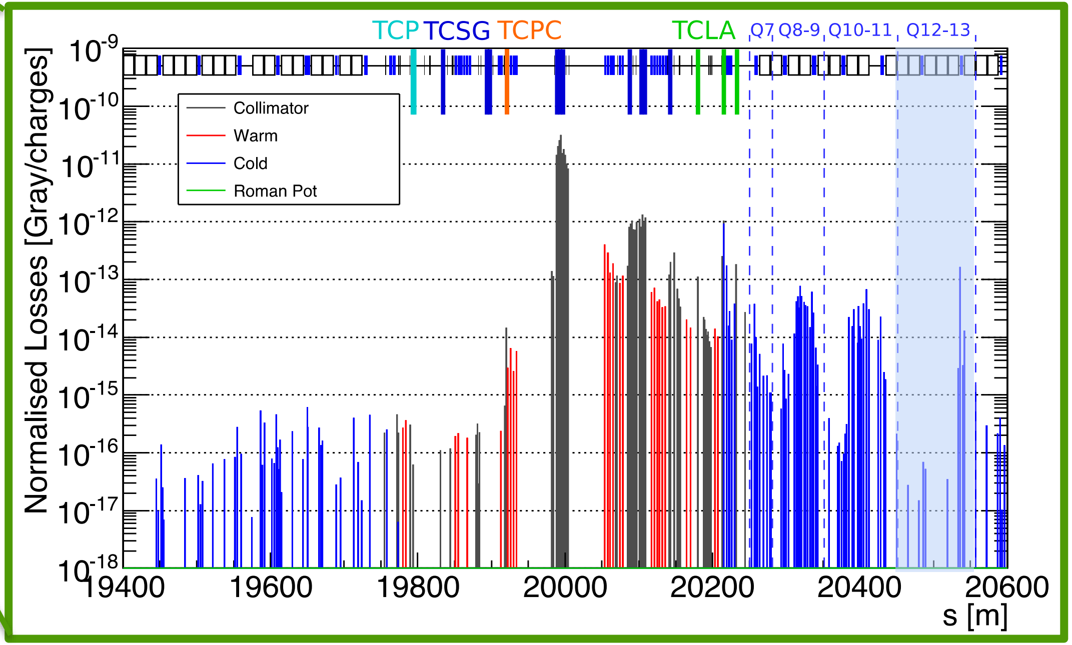


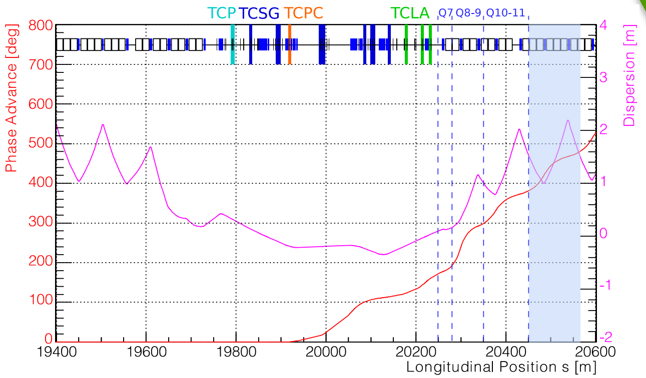
Looking at loss maps along the ring: no dangerous peaks with crystal

Ions Loss Maps

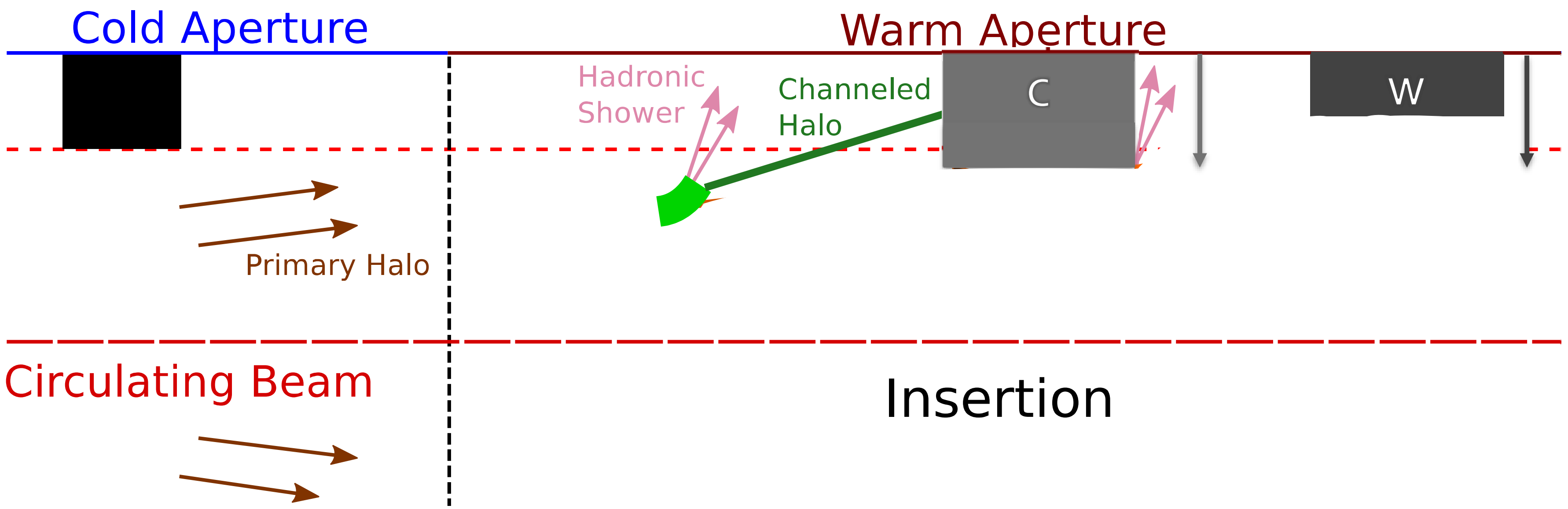


Extra region added for LM anlysis: Q12-13



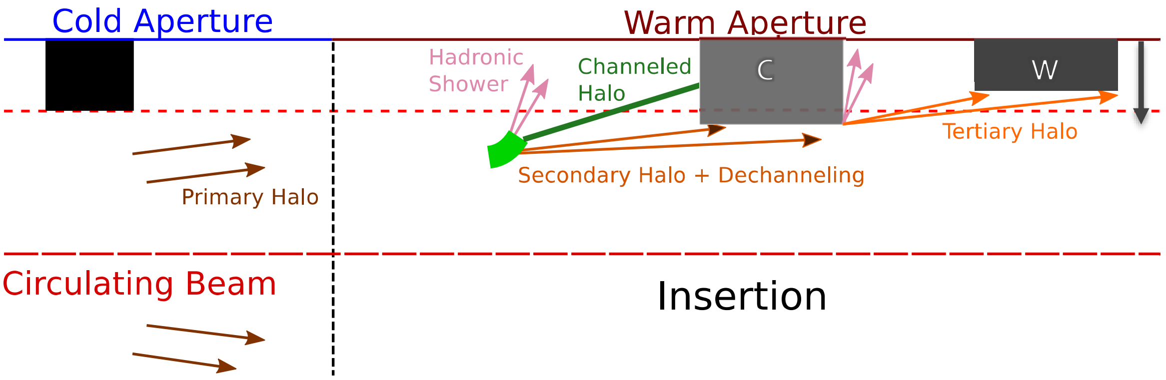


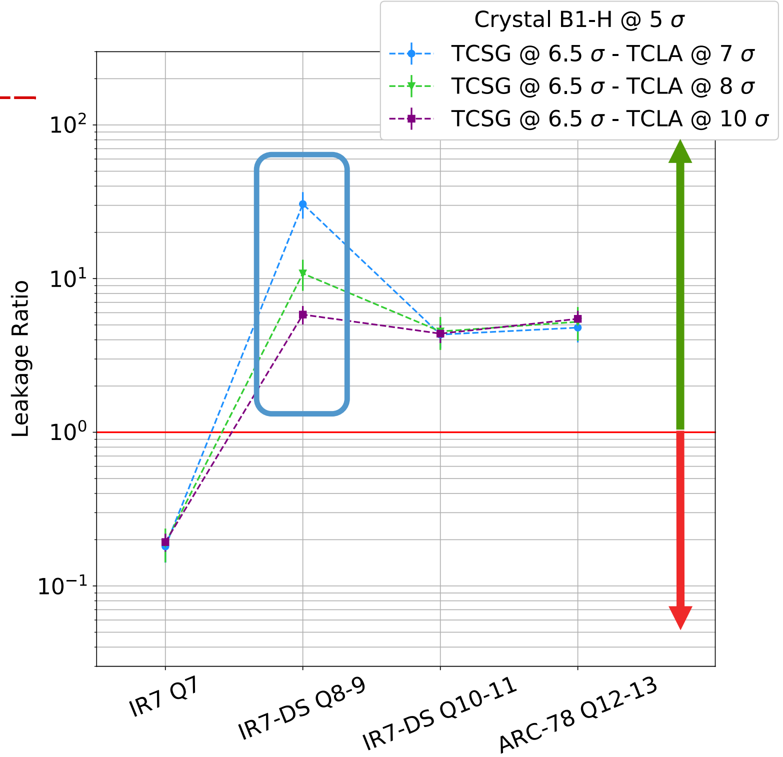
Crystal Collimation Concept for Xe Test



- B1-H showed large dechanneled population at low deflection angles
- Indication (SPS & LHC) of higher losses when C collimator is used as absorber

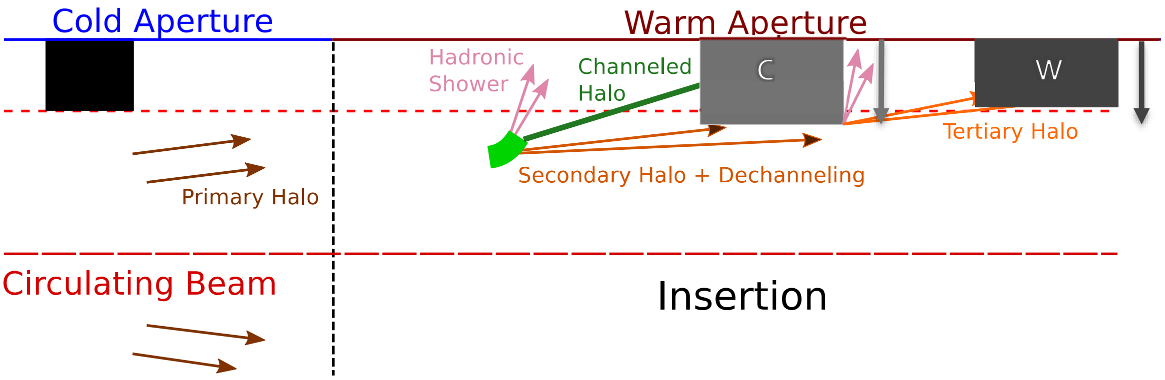
Different Absorber Collimator Apertures

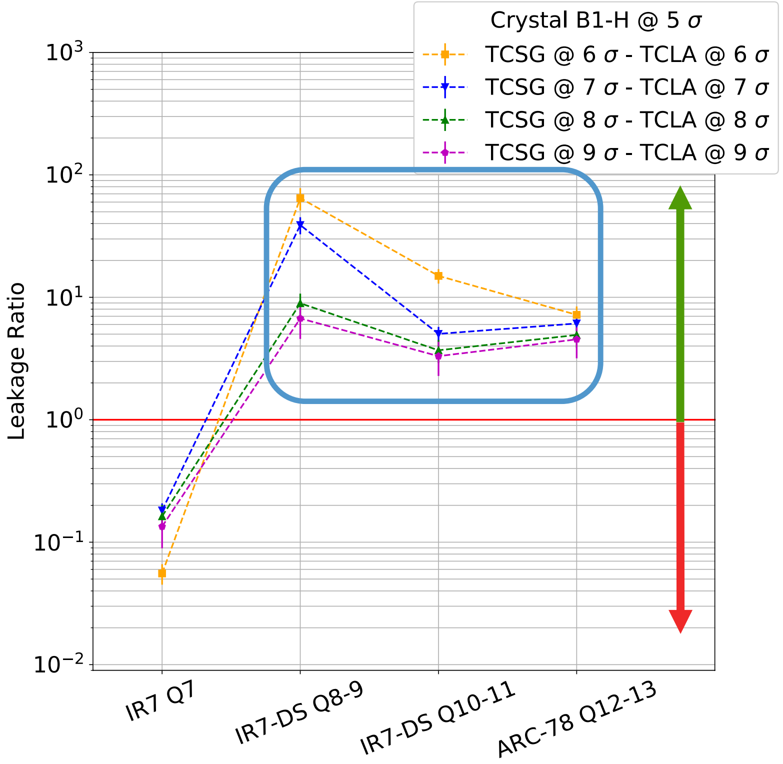




Tighter absorber collimator settings correspond to an improvement of leakage at first dispersive peak

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





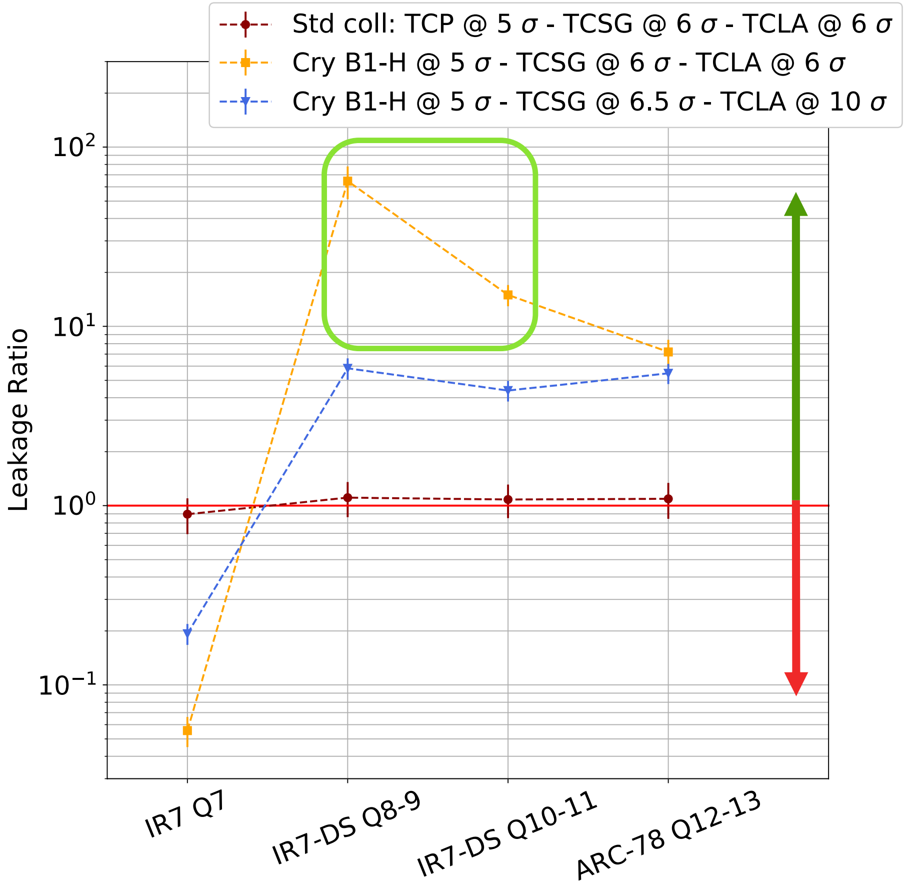
Tighter settings of both secondary and absorber collimators improve cleaning in both DS and ARC regions

B1-H wide dechanneling distribution escapes the downstream collimators and it is lost in both DS and ARC

Crystal Collimation Xenon Cleaning

When standard collimation is used with tight settings, only a small difference is observed in Q7 (more showers), while a large difference observed for crystal collimation

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



Comparison with QM crystals

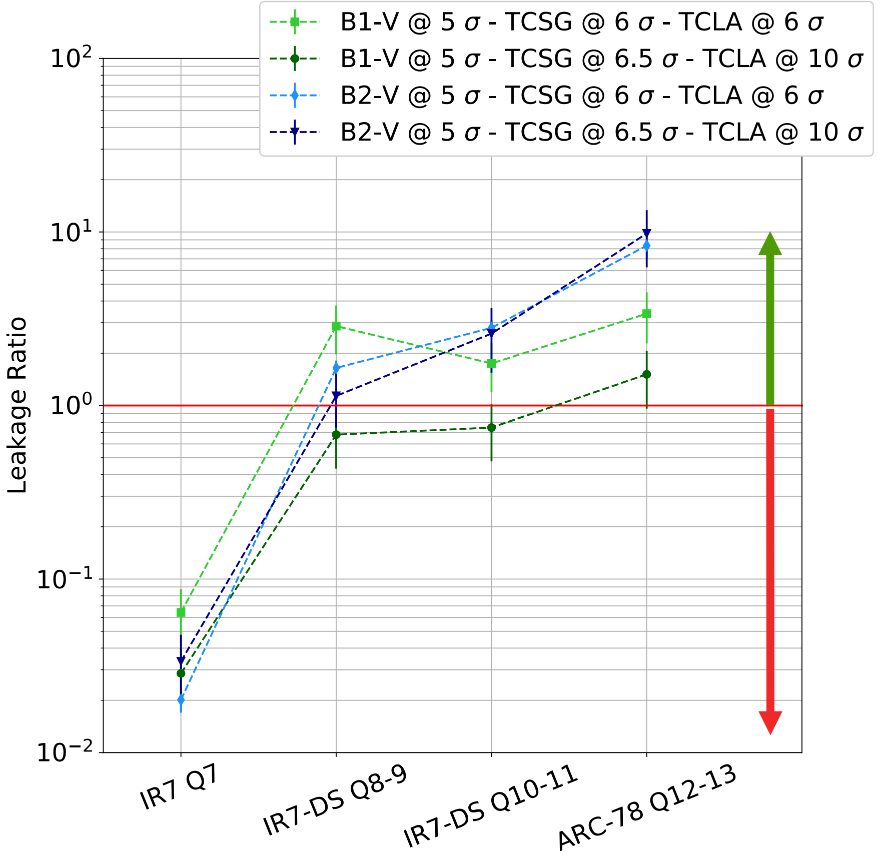
With QM crystals, with same tight settings, the same magnitude of improvement is not observed

To consider:

- Both QM are mounted on vertical plane
- B1-V and B2-V show better results with protons

Might be indication of differences between the two technologies (ST vs QM), with heavy ions at such energies

To be further investigate in 2018 Pb tests



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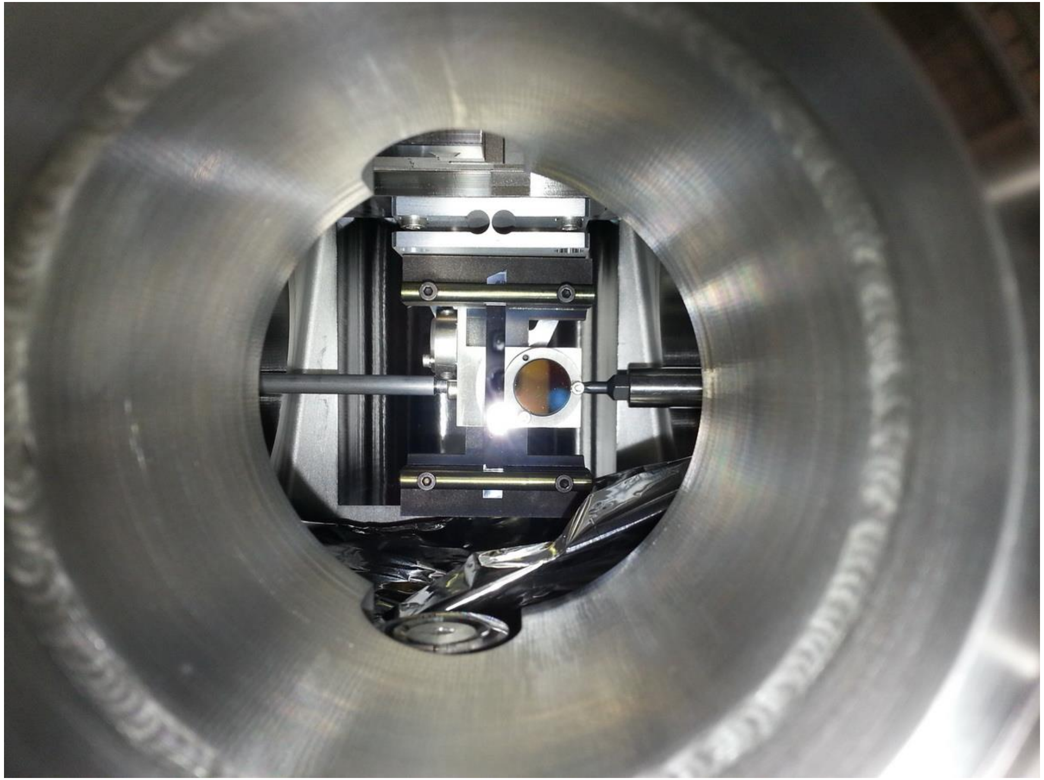
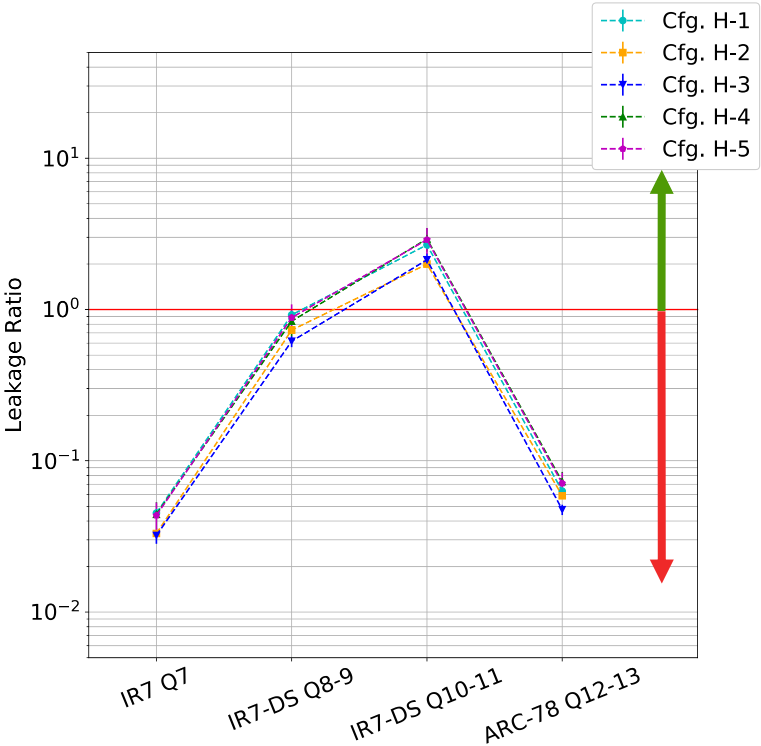
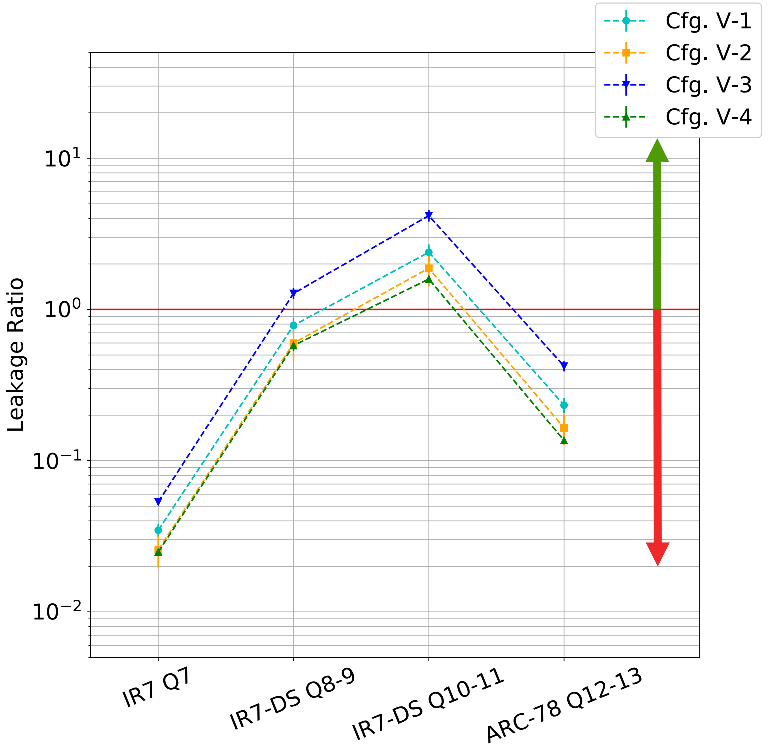


Strip silicon crystal installed on the horizontal B1 goniometer in LHC.

Pb Ion Cleaning Results

No significant improvement in any configuration tested with Pb beams





C and W absorbers closed up to the nominal aperture (7.5 and 11 σ)

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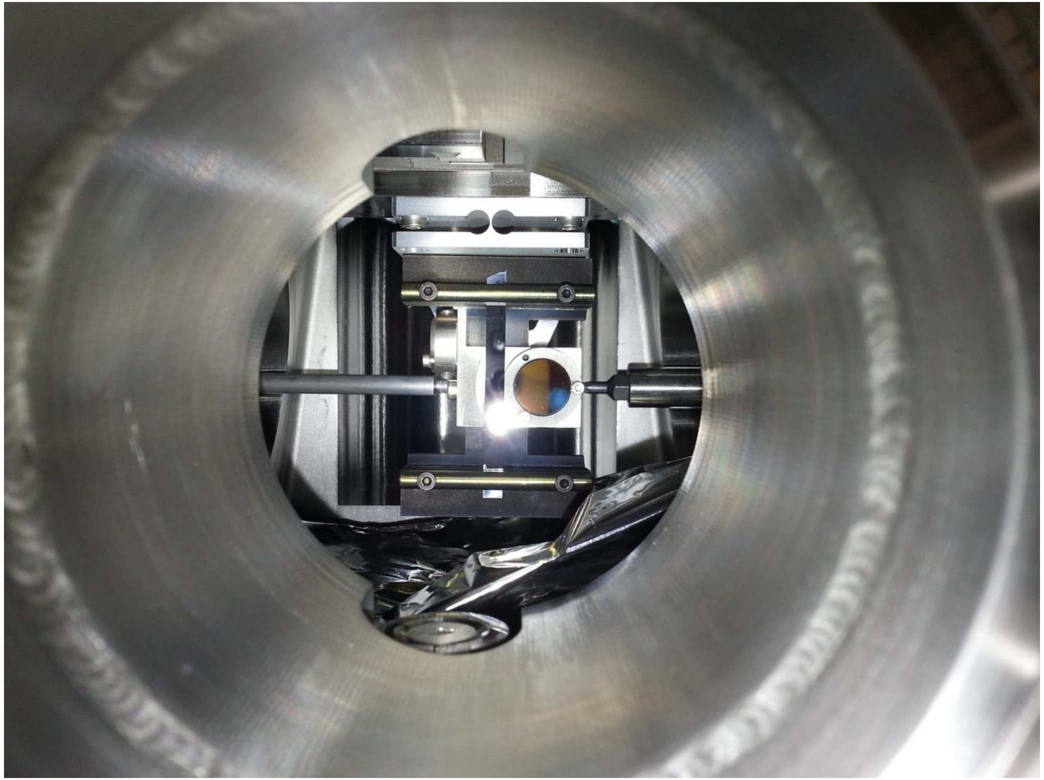

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Pb ions test in 2018

The crucial tests will be held in November this year

- Operational Tests (as an End of Fill test)
- Machine Development Tests

The main objective will be to measure cleaning performances with same tight configuration tested with Xe

Collimator Configuration	Standard Reference [σ] Nominal	Tight	Horizontal Crystal [σ] 1	2	3	4	5	6	7	8
TCPs	5.0	5.0	Out	Out	Out	Out	Out	Out	Out	Out
TCSG Upstream	6.5	6.0	Out	Out	Out	Out	Out	Out	Out	Out
TCPCH.A4L7	Out	Out	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
TCSG Downstream	6.5	6.0	Out	6.0	7.0	8.0	9.0	6.5	6.5	6.5
TCLAs	10.0	6.0	6.0	6.0	7.0	8.0	9.0	7.0	8.0	10.0

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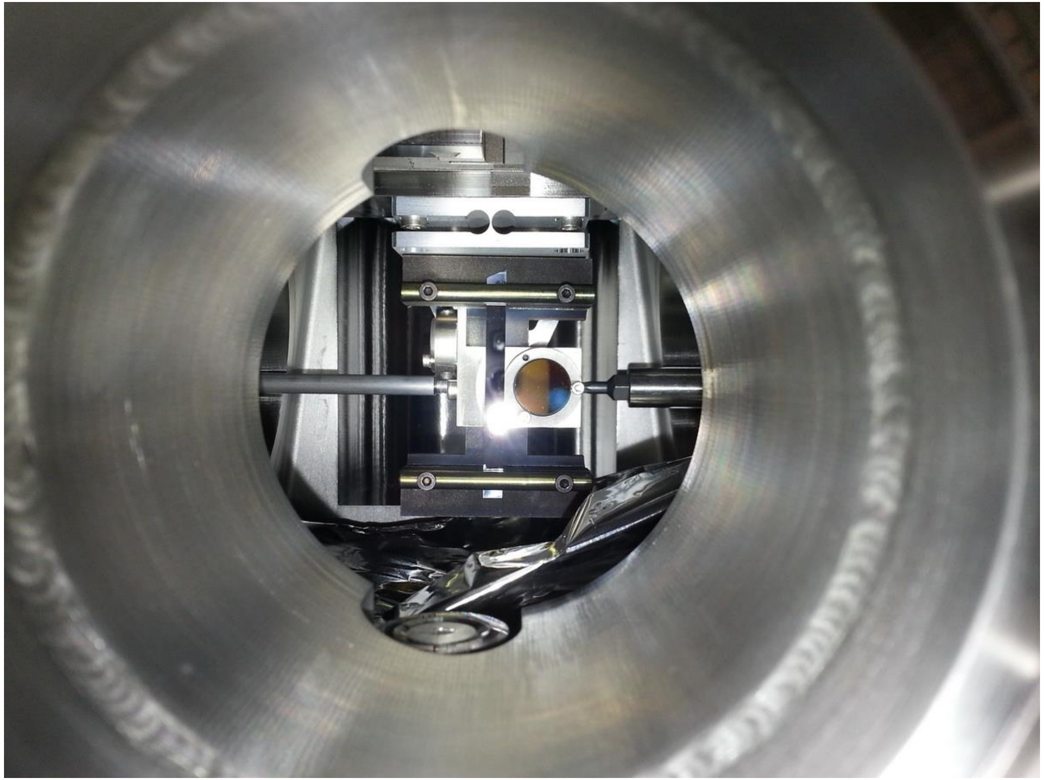

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Conclusions

- ✓ Crystal channeling with heavy ion beams of such energies observed for the first time
  - Observations coherent with previous SPS measurements with heavy ions
  - Crystal's bending angles and multi-turn efficiency characterised as for proton beams
- ✓ Cleaning test with Xe ions showed an improvement higher than a factor 10 in DS, and clarified several points:
  - B1-H crystal feature needs tighter absorber settings to compensate the large dechanneled population
  - Debris coming from secondary collimators (C) is observable at the first dispersive peak in DS, closing absorber collimators (W) improve cleaning
  - No improvement with QM crystals up to now, might indicate difference with ST technology at these conditions

Final Goal:

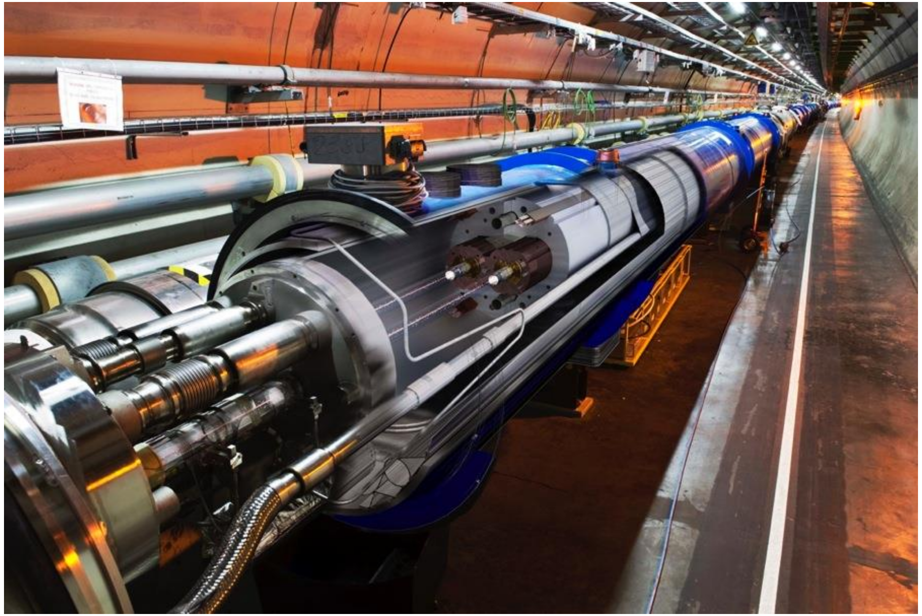
- ❑ Achieve with Pb the improved cleaning observed with Xe beams

BACKUP

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!

η = 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

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

Where are we?

In recent years several Master/PhD works have been carried out in the Collimation Team towards a demonstration of the feasibility (simulations and/or measurements):

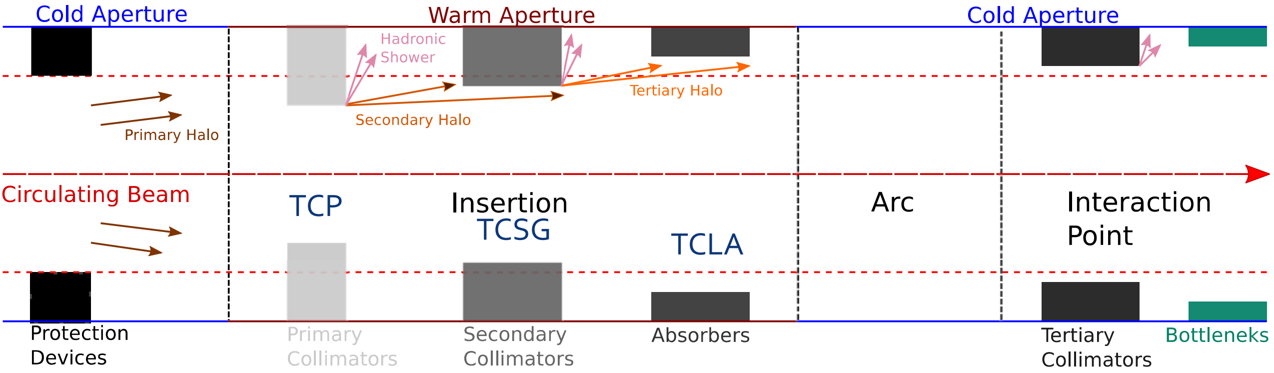
V. Previtali:	CERN-THESIS-2010-133 (2010, PhD)	*simulation code for SixTrack*
D. Mirarchi:	CERN-THESIS-2011-136 (2011, master)	*measurements on SPS*
	CERN-ACC-2015-0143 (2015, PhD)	*improvement of simulation tools and benchmark, design of the crystal system prototype installed in the LHC*
R. Rossi:	CERN-THESIS-2014-187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

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

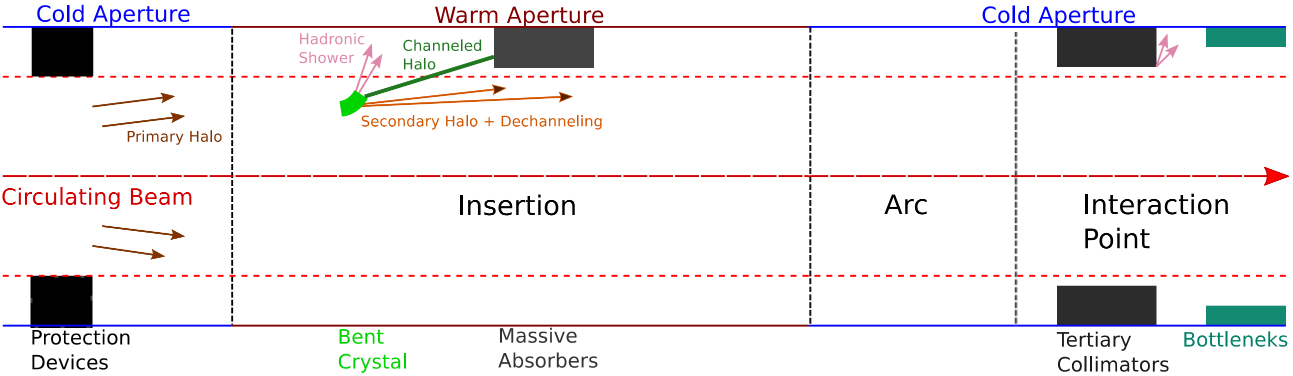


- **Halo cleaning**: reduce the risk of magnet quenches
- **Concentration of losses/activation** in controlled areas
  Avoid many hot locations around the 27km-long tunnel

Multistage 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

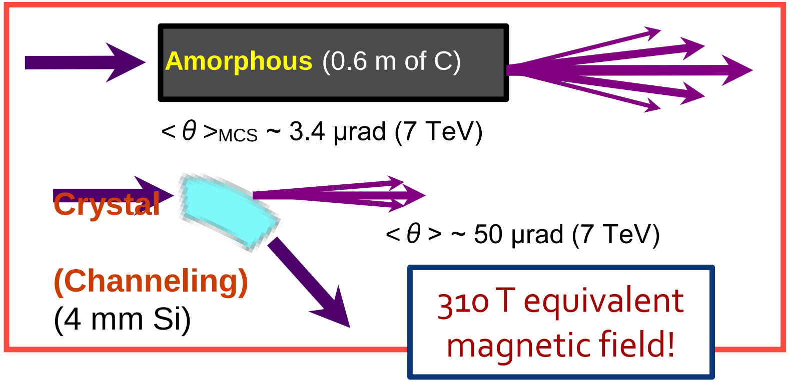


Advantages of crystal collimation at the LHC:

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

  Reducing off-momentum losses in DS
- Lower **impedance**;

  Less collimators at larger gaps



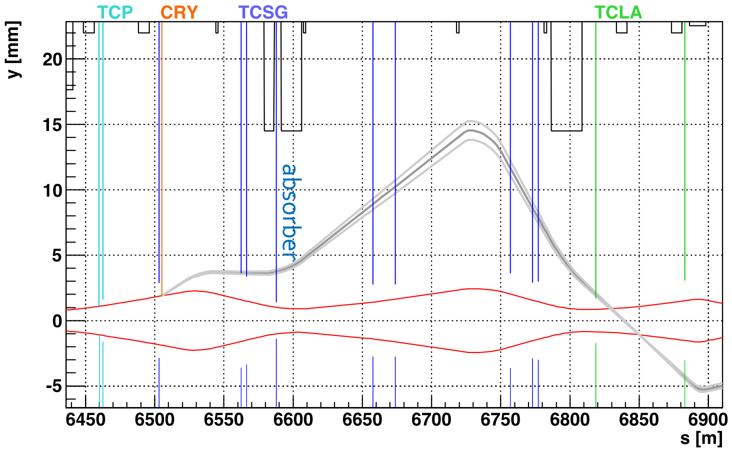
Crystal collimation *could improve the ion cleaning* and is one of the R&D subject for HL-LHC upgrade

Crystal Collimation Layout

Semi-analytical studies and full tracking simulations has been provided to find the best layout for the LHC test stand.

The major requirements (for both injection and flat top) have been studied [1]:

1. Intercept the channeled halo with enough clearance by the TCSGs downstream
2. Respect the aperture constraints
3. Collimation cleaning performances optimisation



Crystal request defined before 2014 restart:

- Bending angle: 50 μrad
- Length: 4 mm

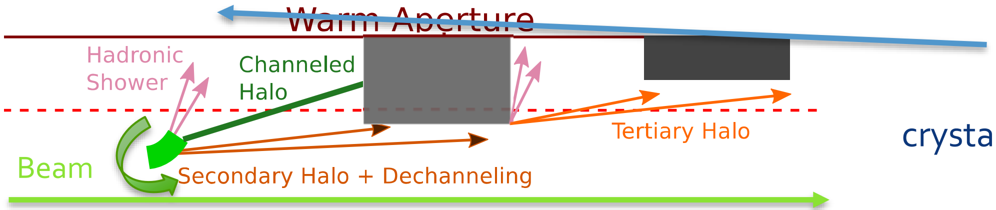
R[m]		θ_b [μrad]		
		40	50	60
l [mm]	3	~~75~~	~~60~~	~~50~~
	4	~~100~~	80	~~66.7~~
	5	~~125~~	~~100~~	~~83.3~~

R_c~15.6 m @6.5 TeV

[1] D. Mirarchi, et al., **Design and implementations of crystal collimation test stand at the Large Hadron Collider**, Eur. Phys. J. C, 77 (6) (2017), p. 424

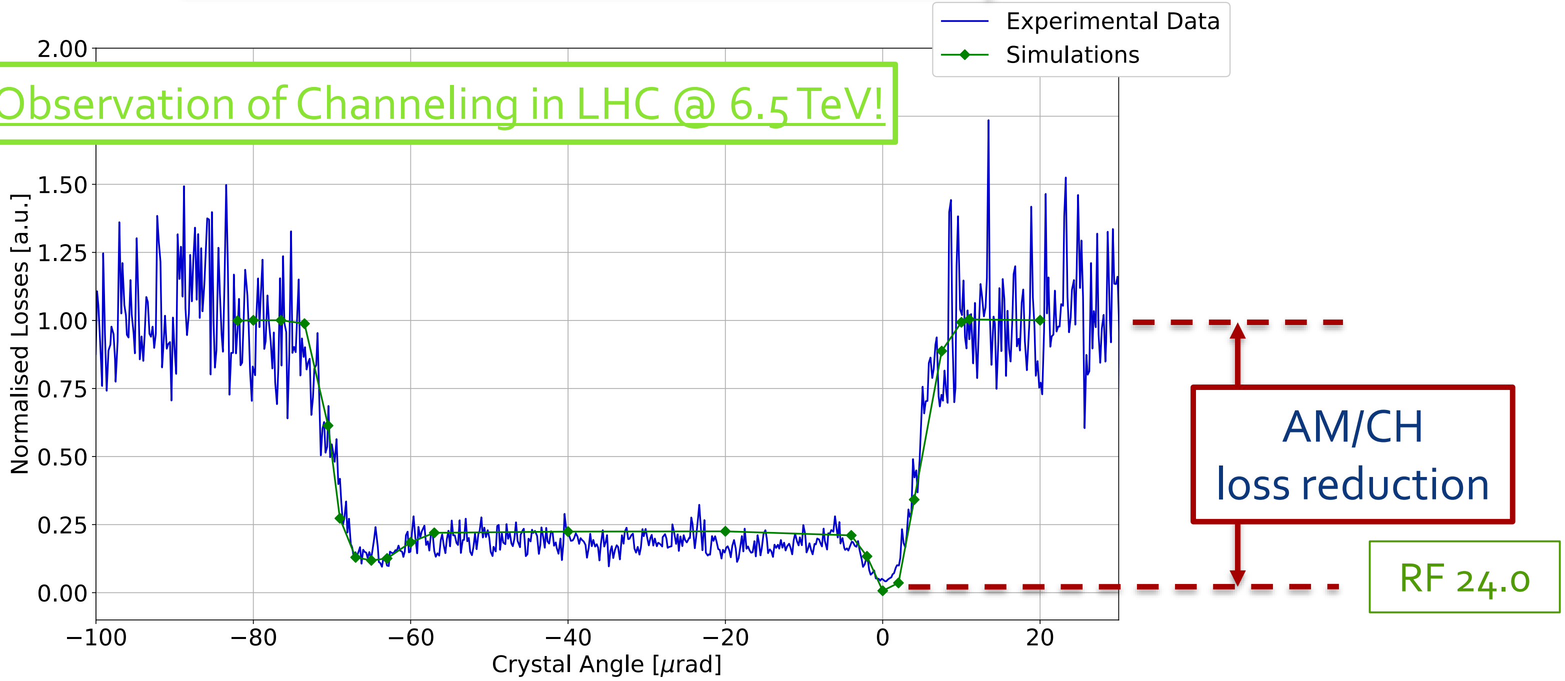
Channeling Observation

1. Angular Scan

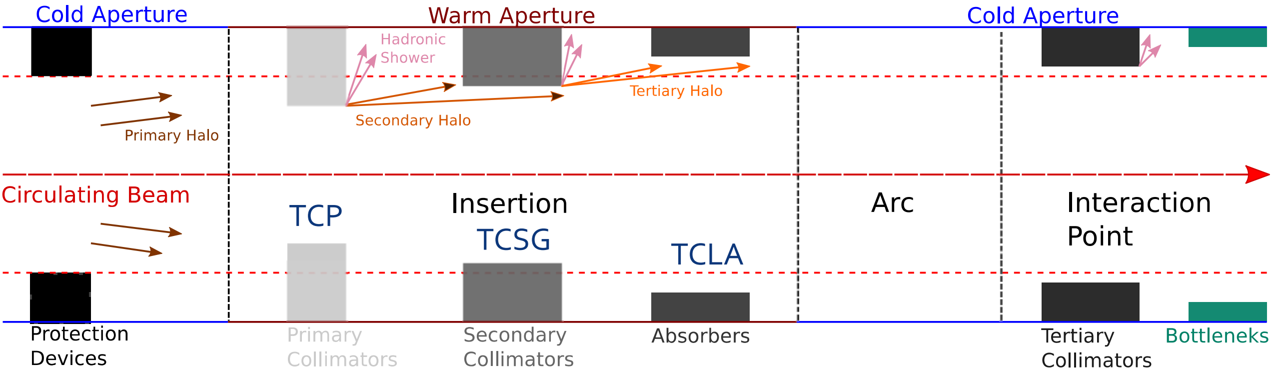


local losses
vs
crystal angular orientation

First Observation of Channeling in LHC @ 6.5 TeV!



Collimation System @ LHC



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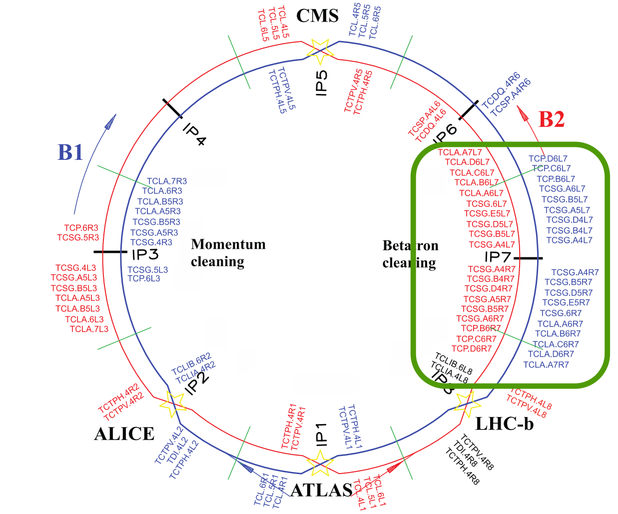

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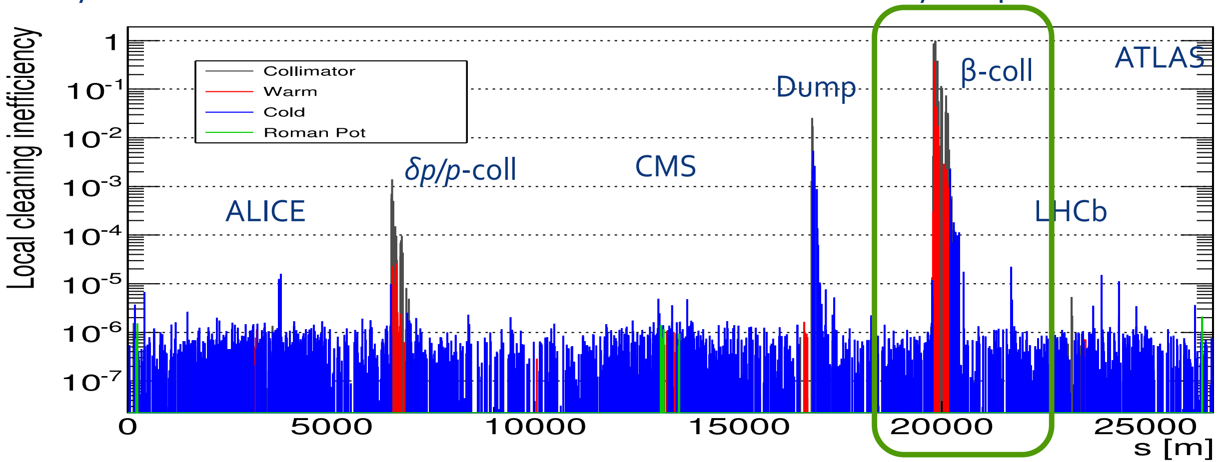


Main limitations

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

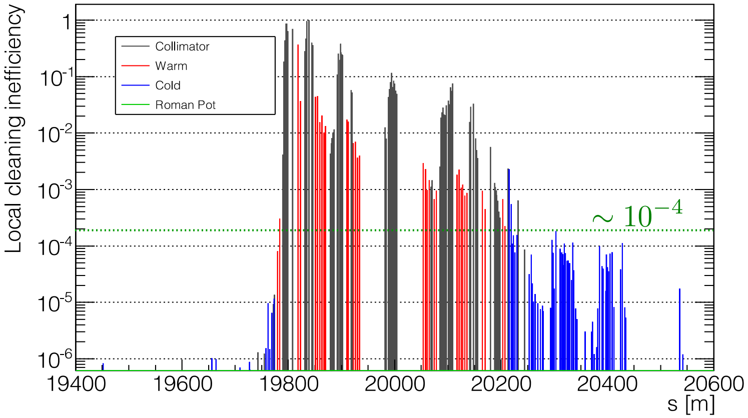
- Fragmentation and dissociation events

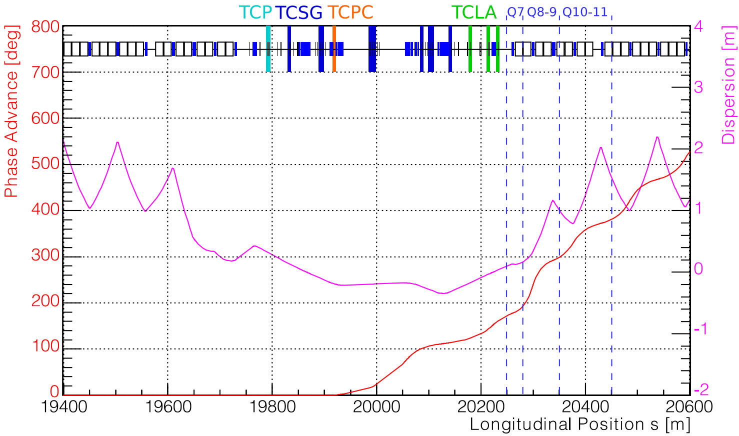
  particles with different magnetic rigidity (q/m) ➔ lost in the IR7-DS reducing of two order of magnitude the collimation system performance wrt to proton collimation

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

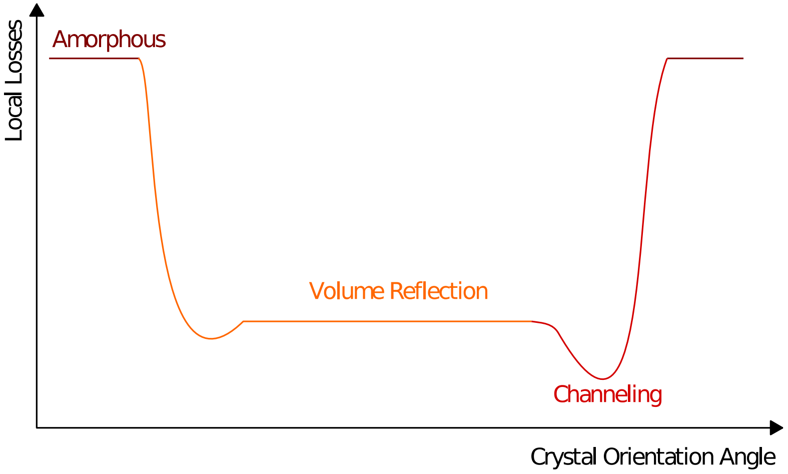
Impedance

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

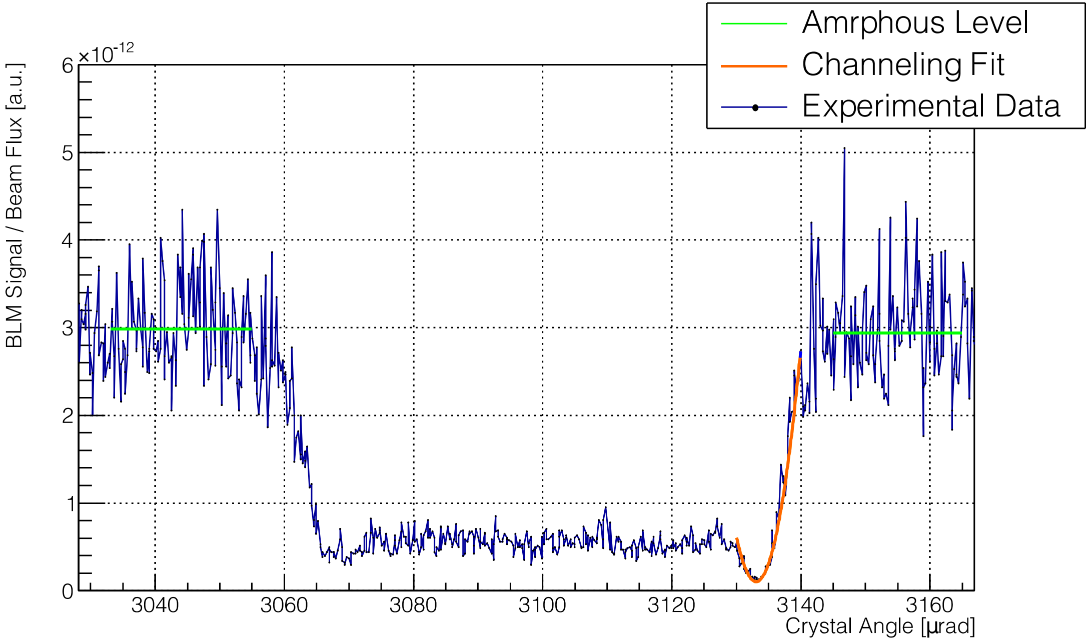




Angular Scans - Methodology



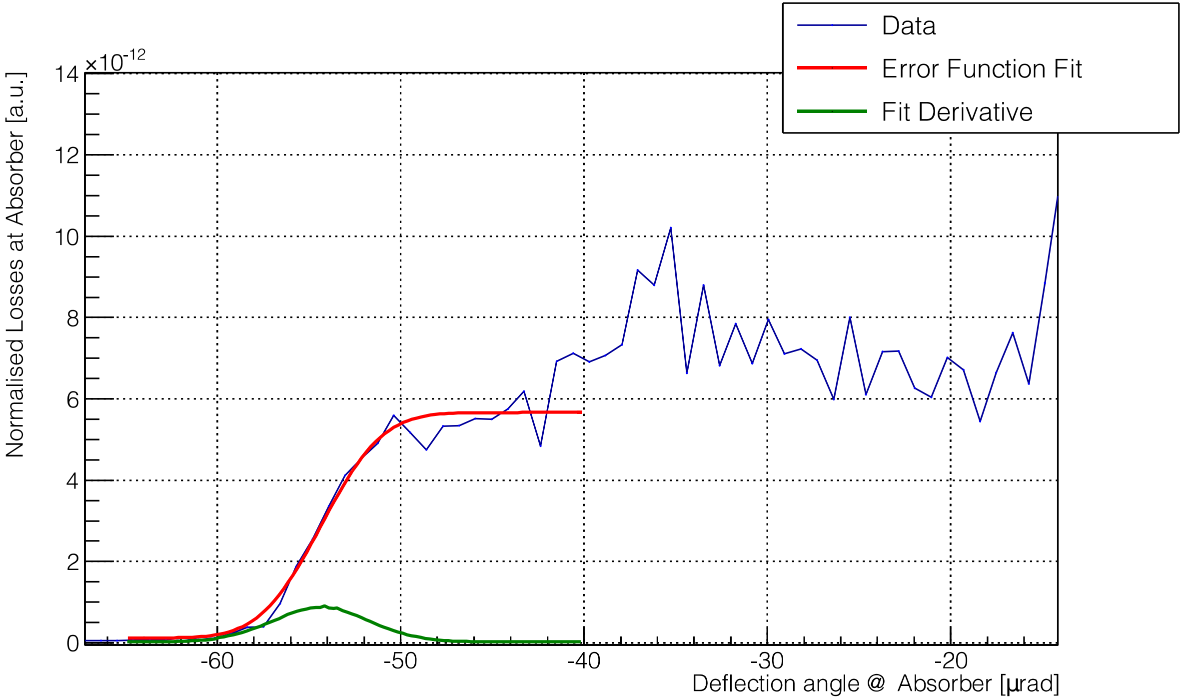
Fitting losses in Channeling with a parabolic function is the method used to evaluate both the best goniometer orientation for channeling and the average loss value in that point.



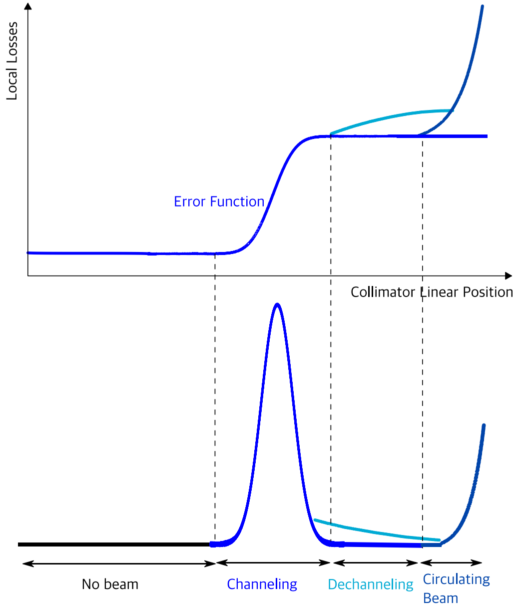
Halo Scraping - Methodology

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

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

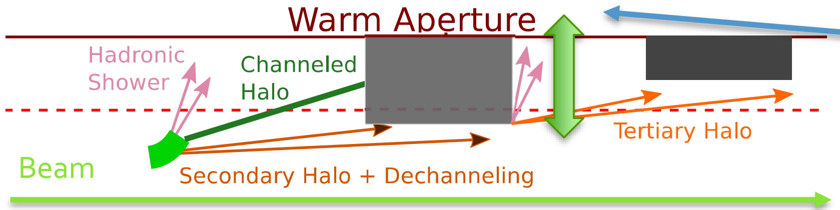


The error function fit gives info about the channeled beam properties as deflection angle and beam sigma

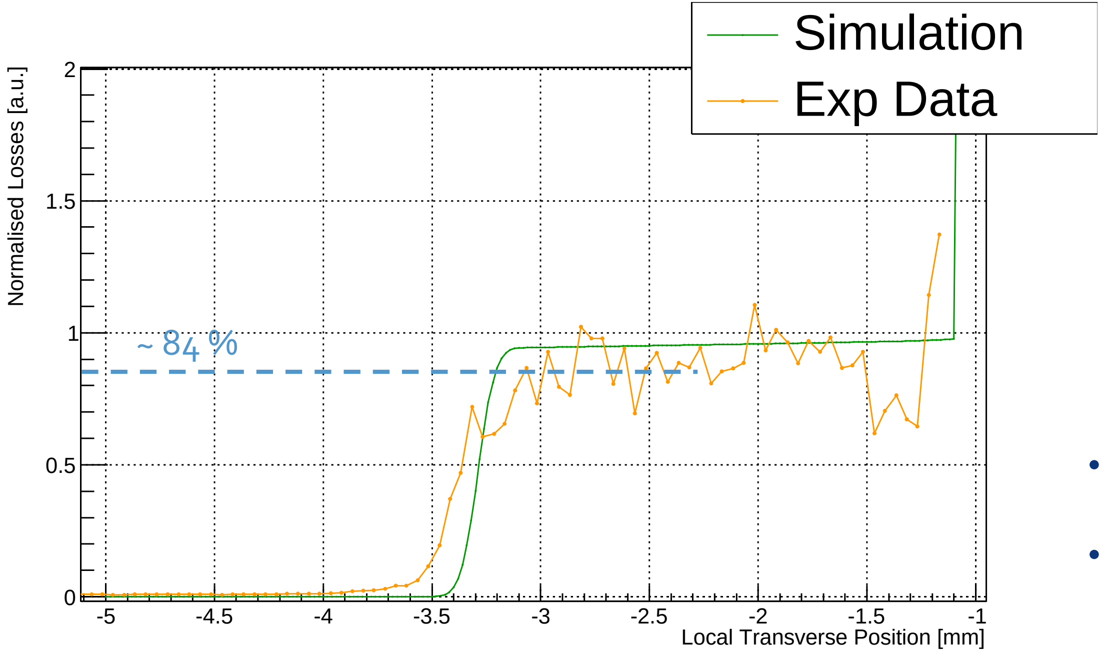


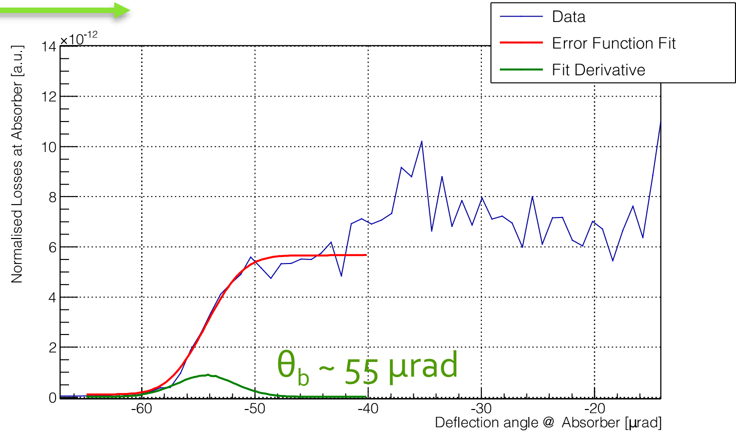
Channeling Observation

2. Absorber Scan



local losses
vs
collimator transverse position

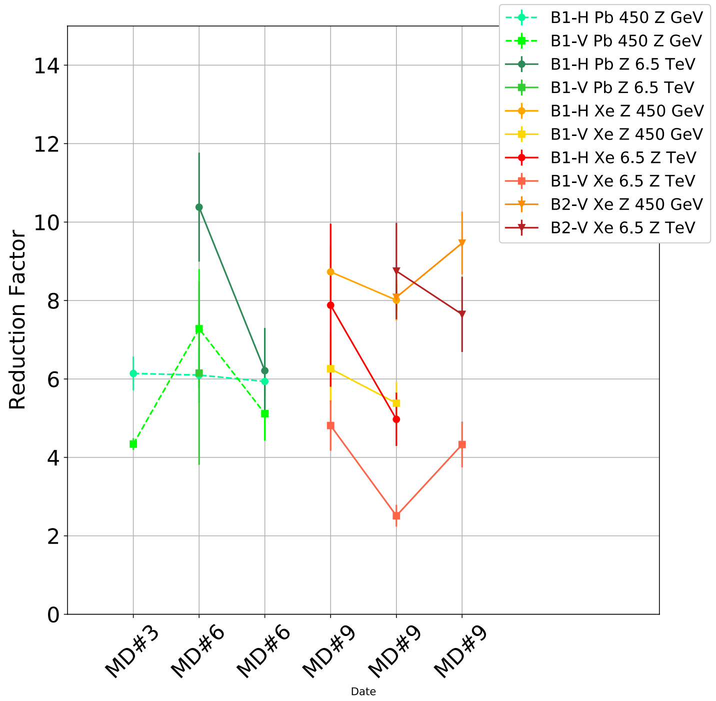




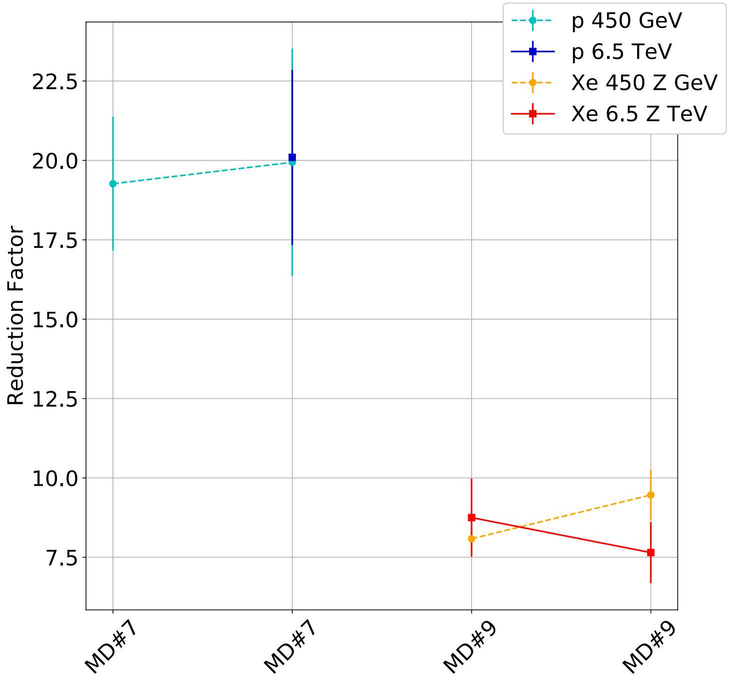
- With Transport Matrix can be evaluated the deflection angle
- Losses at channeling plateau, normalised to the primary beam spike, can evaluate the multiturn channeling efficiency

Ions Angular Scans

Channeling Reduction Factors in agreement between xenon and lead ions observations.

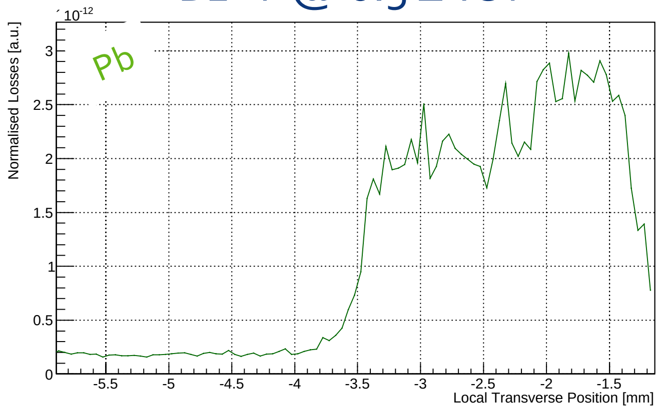


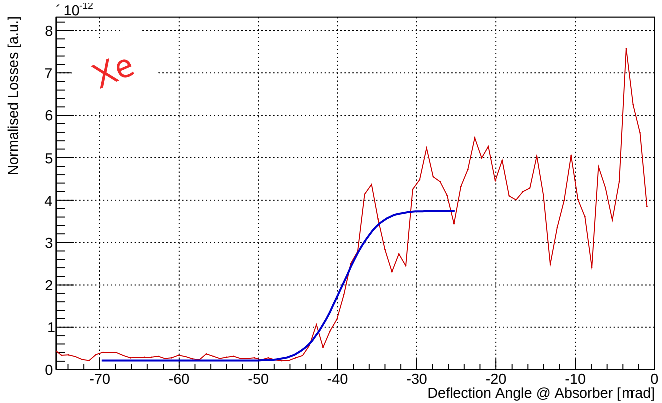
In comparison with protons, the reduction factor is about a factor ~2 lower.



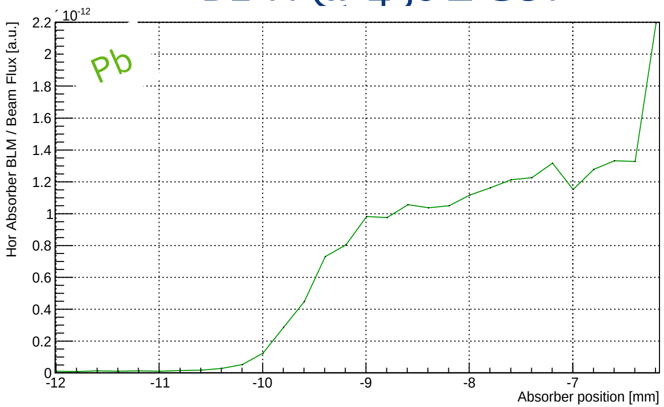
Ions Collimator Linear Scans

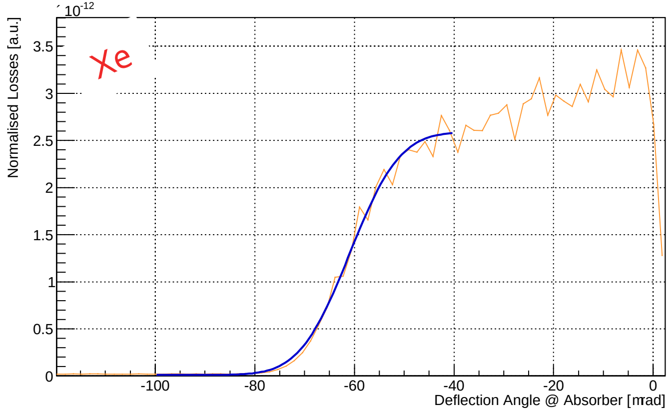
B1- V @ 6.5 Z TeV





B1-H @ 450 Z GeV

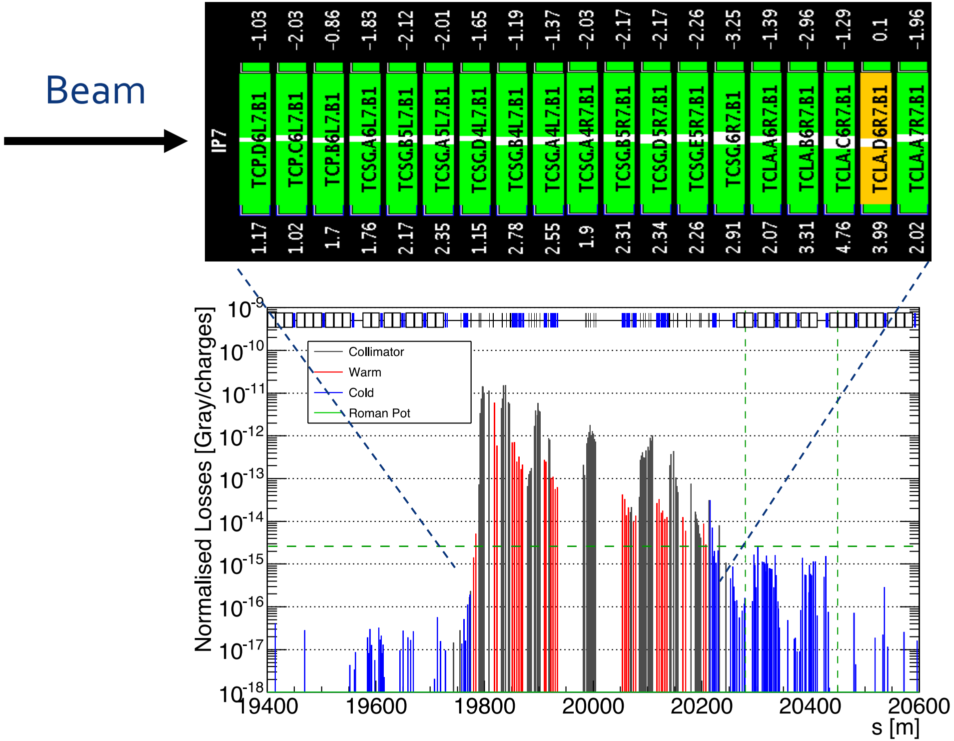




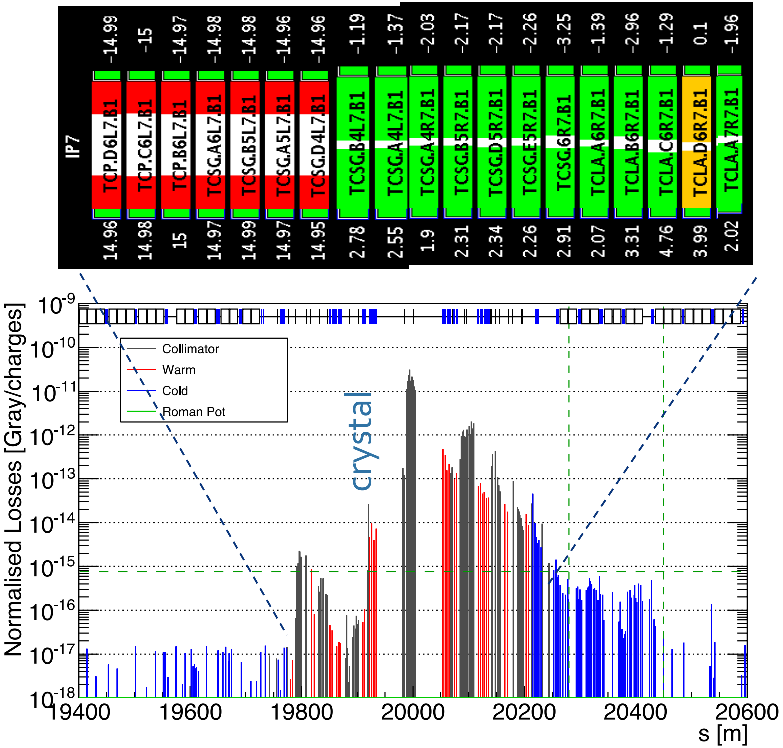
All measurements confirmed proton observations about bending angle for each crystals

Collimation Loss Maps

Present IR7 — tight settings

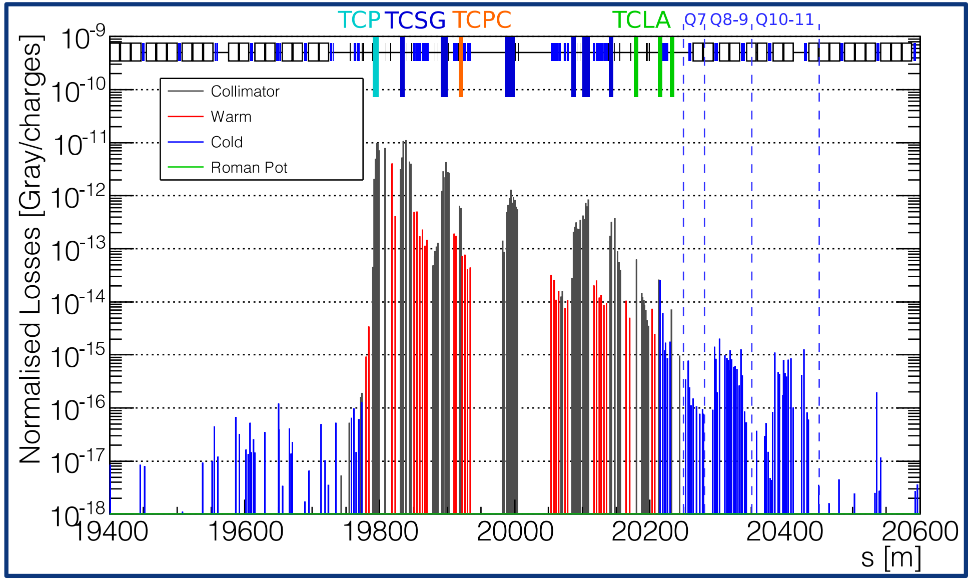


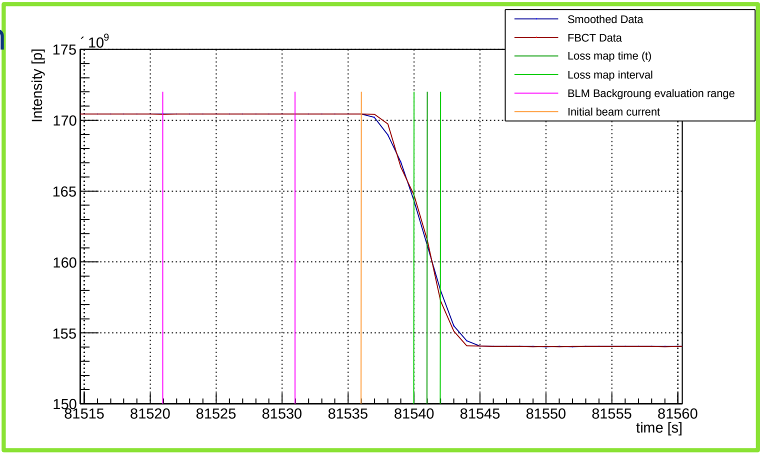
1 crystal, TCSG + TCLA

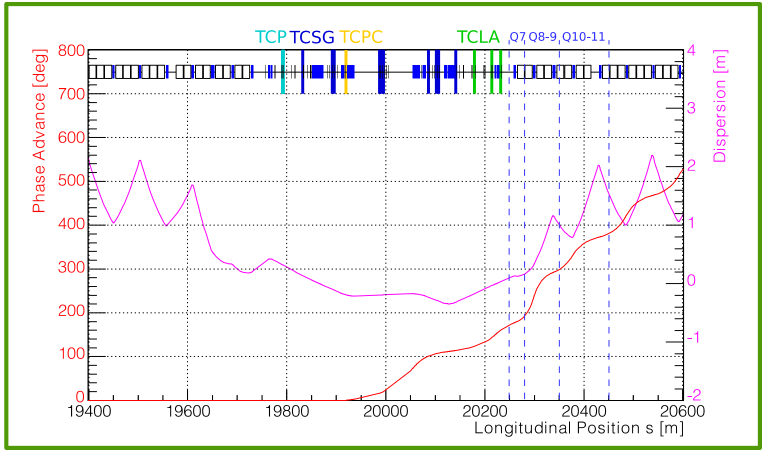


Collimation Cleaning - Methods

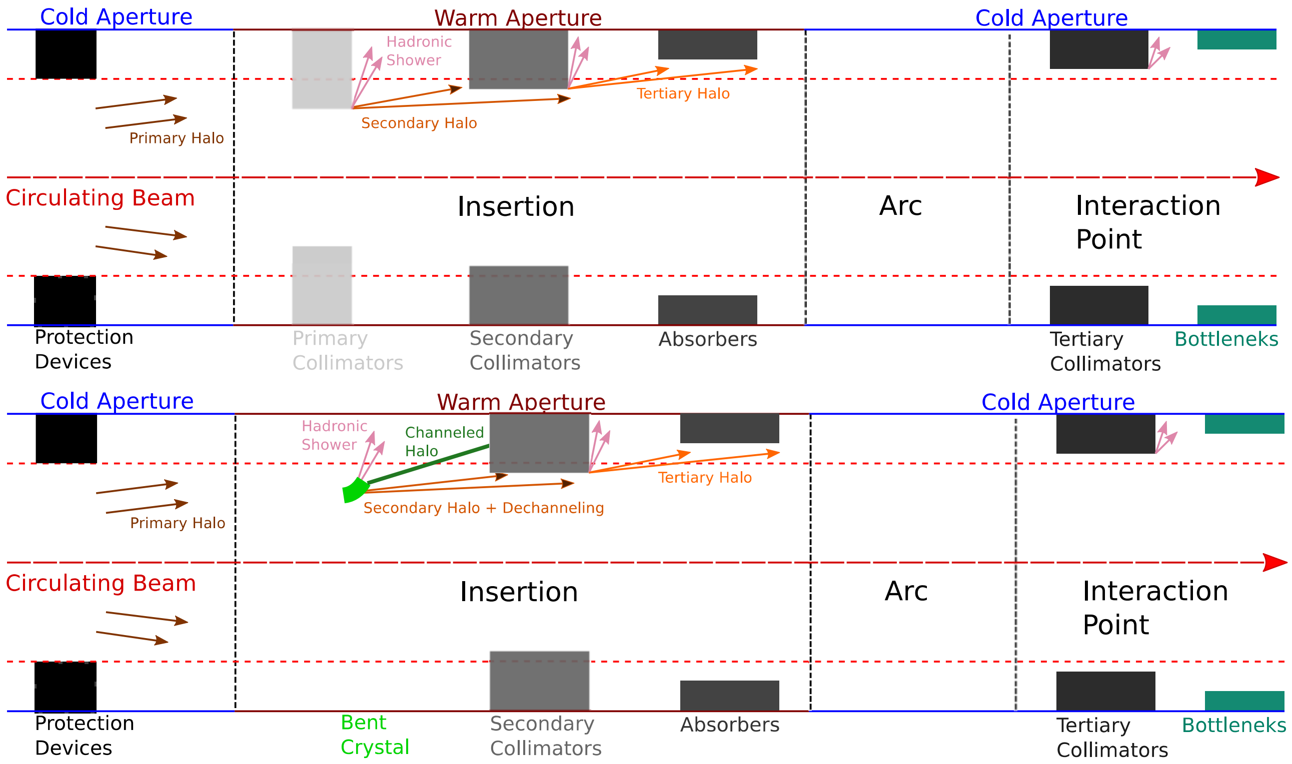
Normalisation to beam flux ➔ Particles lost in collimation system





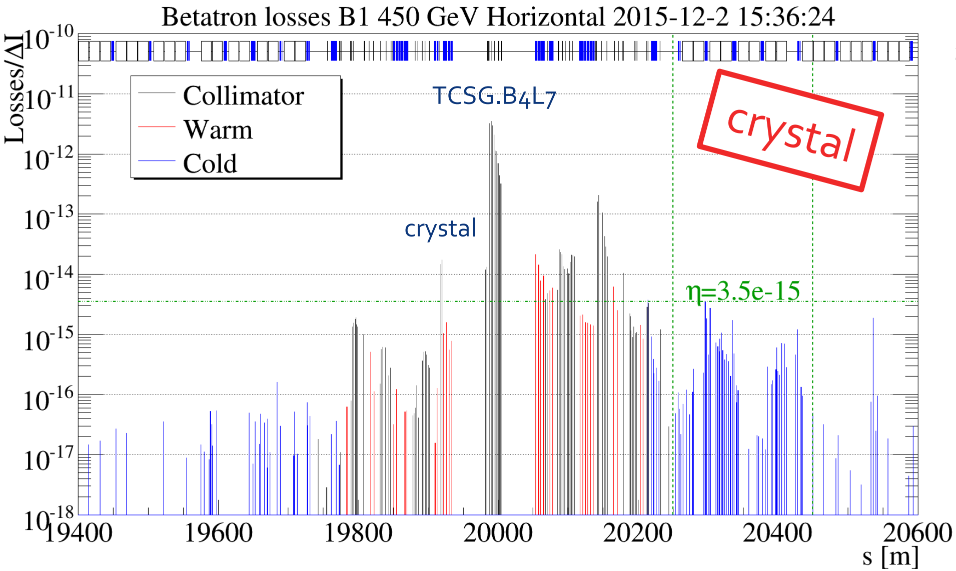


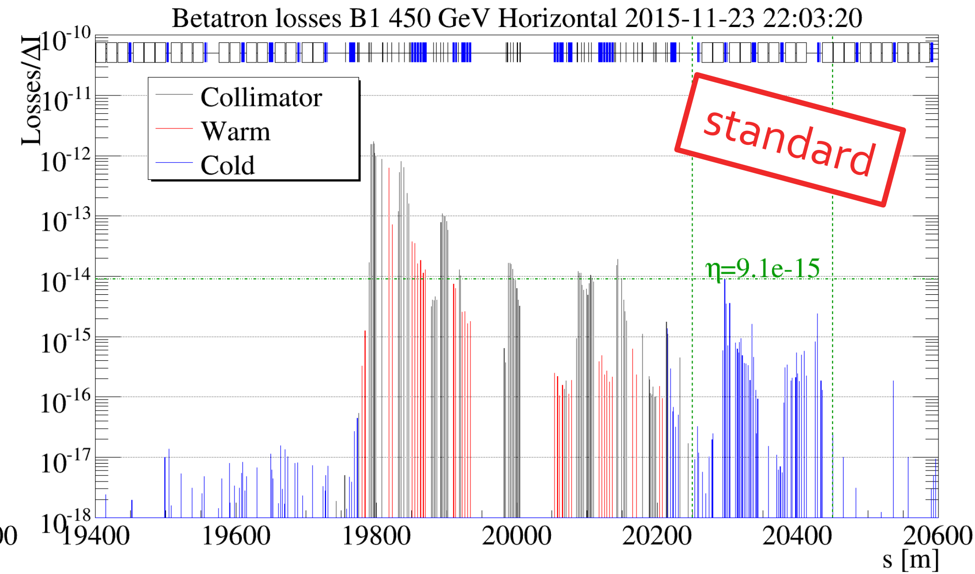
To compare the crystal collimation to the standard collimation <u>the leakage of particles</u> in specific region near to the <u>IR7-DS</u> is evaluated by normalizing losses to the beam flux.


Cold Aperture
Warm Aperture
Cold Aperture
Hadronic Shower
Tertiary Halo
Secondary Halo
Primary Halo
Circulating Beam
Insertion
Arc
Interaction Point
Protection Devices
Primary Collimators
Secondary Collimators
Absorbers
Tertiary Collimators
Bottleneks
Cold Aperture
Warm Aperture
Cold Aperture
Hadronic Shower
Channeled Halo
Tertiary Halo
Secondary Halo + Dechanneling
Primary Halo
Circulating Beam
Insertion
Arc
Interaction Point
Protection Devices
Bent Crystal
Secondary Collimators
Absorbers
Tertiary Collimators
Bottleneks

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

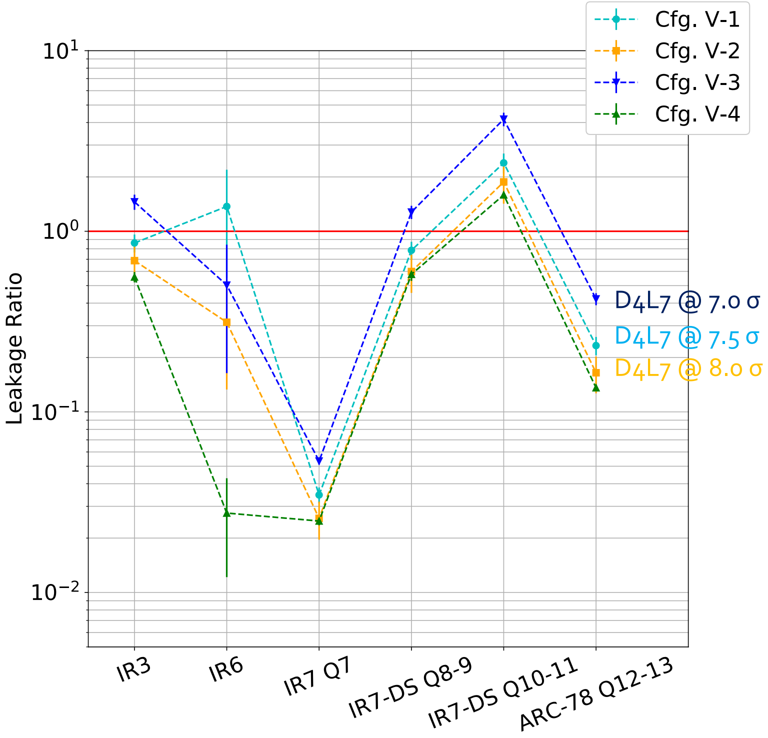
the leakage to IR7-DS improves by a factor of about 2.6

better results are expected improving the clearance between crystals and TCSGs

note: the system is optimized for 6.5 TeV!

Collimation cleaning setup

In lead ion test a small improvement were observed when the first secondary collimator was moved to tighter apertures.



With Xe was decided to explore different settings, using also TCLAs to different apertures.