Studies of crystal collimation for heavy ion operation at the LHC

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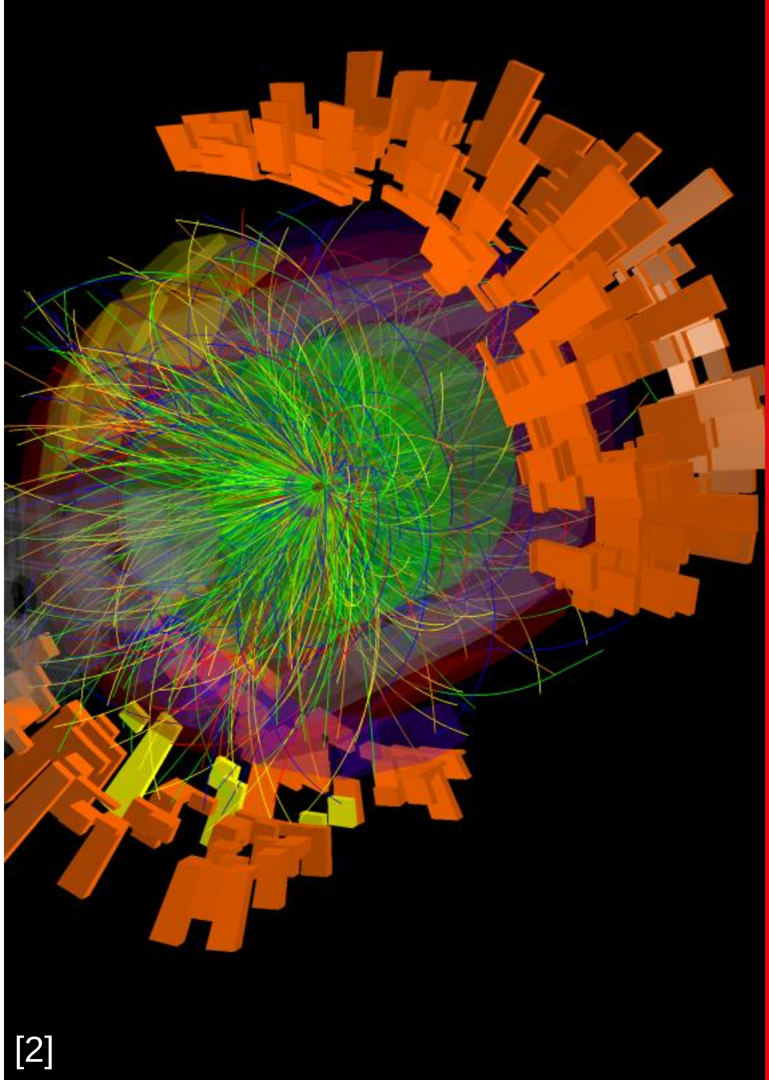
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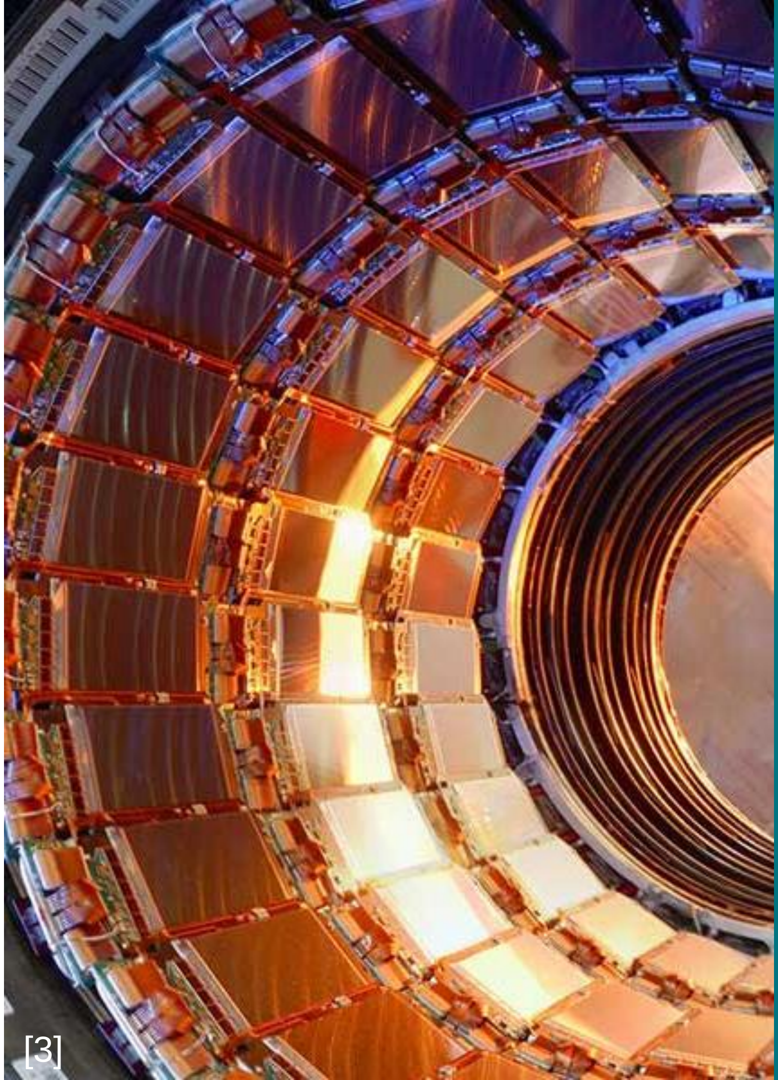
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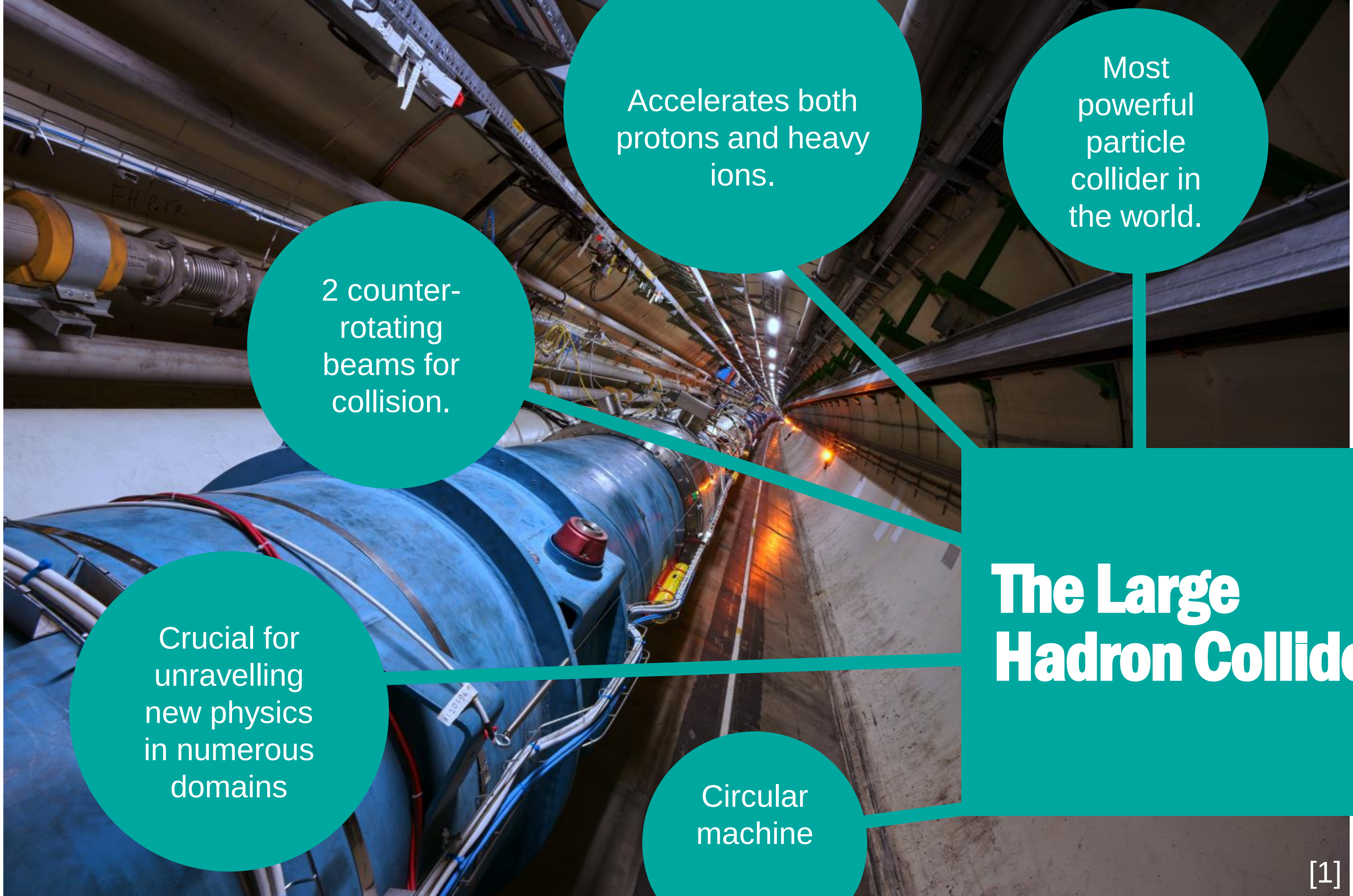
Introduction & building of the simulation framework

The Large Hadron Collider



- Accelerates both protons and heavy ions.
- Most powerful particle collider in the world.
- 2 counter-rotating beams for collision.
- Crucial for unravelling new physics in numerous domains
- Circular machine

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Collimation system

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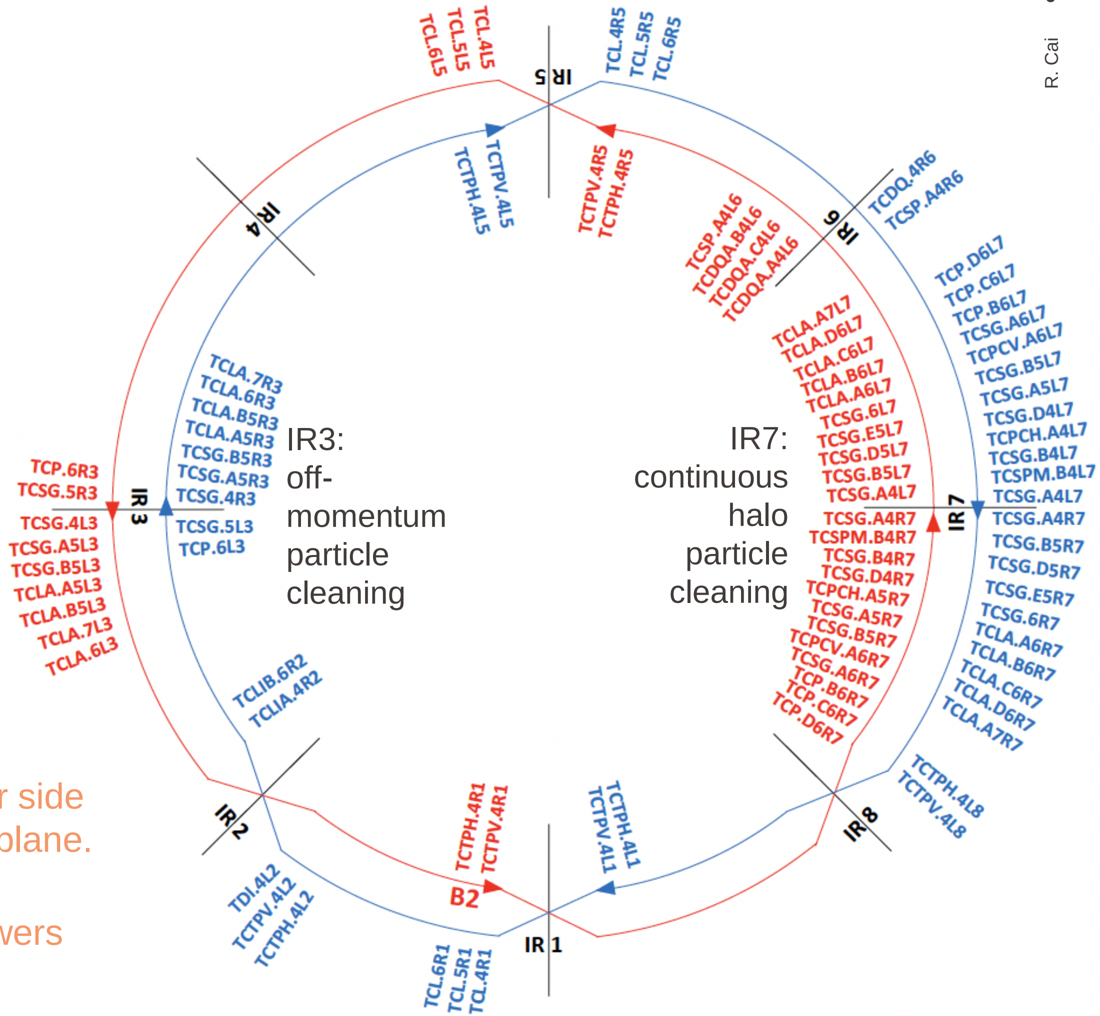
Particles circulate at very high energies.

If not controlled, may hit and damage beam pipe.

Risk of ”quench” superconducting magnets (lose superconducting properties)

Collimation system to prevent damage with safe particle interception.

- 100+ collimators.
- 2 parts (jaws) per collimator (one per side of beam) in horizontal/vertical/skew plane.
- 2 regions for collimation (IR3, 7).
- Multi-stage system for hadronic showers and secondary particles.



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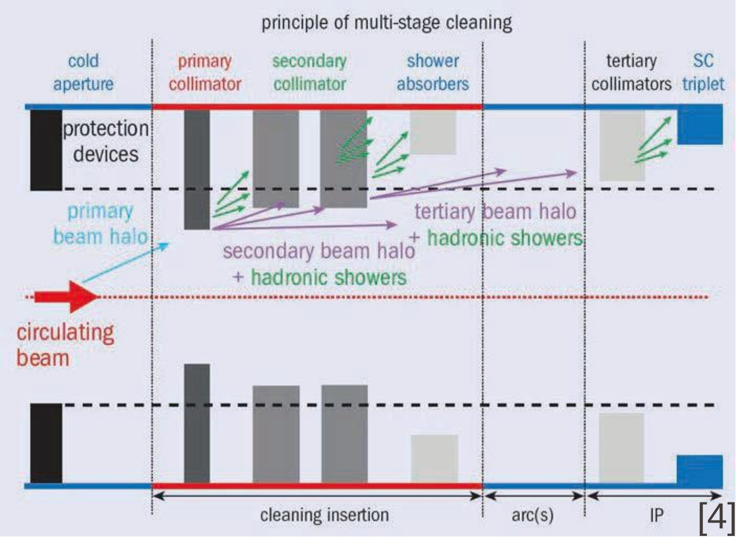
Main families of collimators:

Name	Role	Hierarchy
TCP	Intercept primary particles	1
TCS	Intercept secondary particles	2
TCT	Intercept tertiary particles	3
TCLA	Shower absorbers	4

Hierarchy: 1 = closest to beam, 4 = furthest to beam

Based on the scattering of particles to larger orbits.



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Ion collimation upgrade: crystal collimations

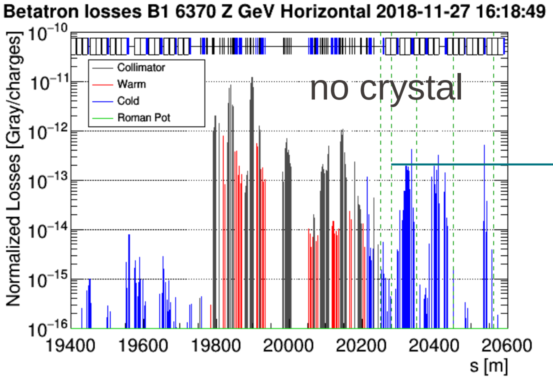
Ion collimation is challenging due to fragments with different magnetic rigidity.

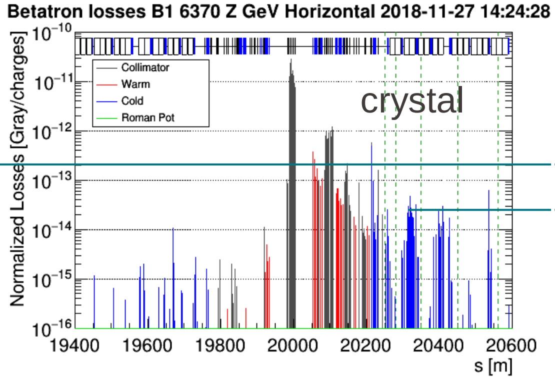
The stored beam energy is planned to increase from ~13 MJ to ~20 MJ. Without improvement, the total energy risks to be limited to 10 MJ/beam.

Previously planned mitigation through TCLD collimators, requiring the installation of 11 T dipoles, has been deferred

Deployment of crystal collimation for Run 3.

Need for a systematic simulation framework





Previous tests found decrease in losses

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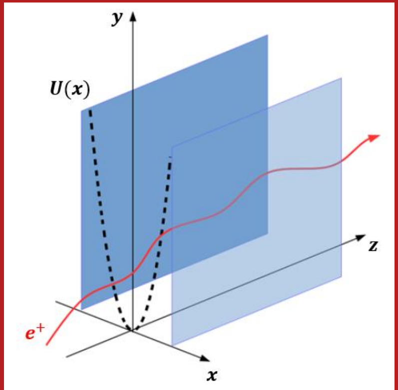
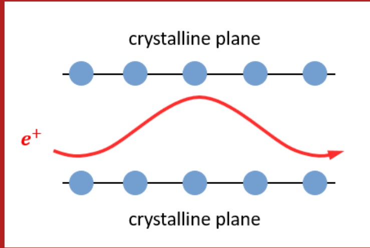
Crystal channeling



Crystal channeling exploits the harmonic potential of the crystalline structure.

An incoming particle that satisfies channeling condition undergoes harmonic oscillation within the crystal.
Channeled particle experience decreased fragmentation.



For a straight crystal (planar channeling), the following condition must be fulfilled:

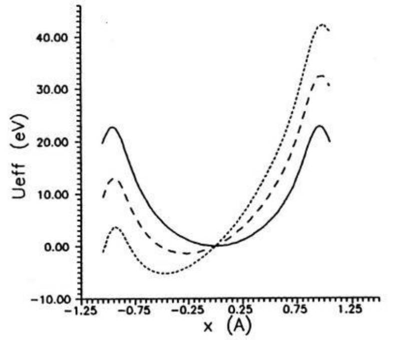
- $\frac{pv}{2}\theta^2 < U_{max}$, or $\theta_{in} < \theta_c$,

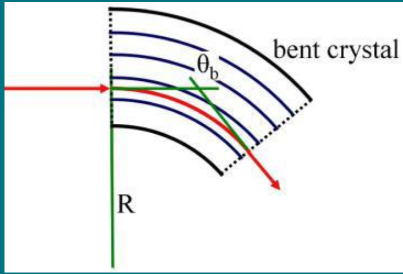
where $\theta_c = \sqrt{2U_{max}/pv}$ is the critical angle and U_{max} is the maximum of the crystal potential.

For a bent crystal:

- $\theta_c^b = \theta_c(1 - R_c/R)$,

where $R_c \propto pv$ is called critical radius and R is the bending radius of the crystal.





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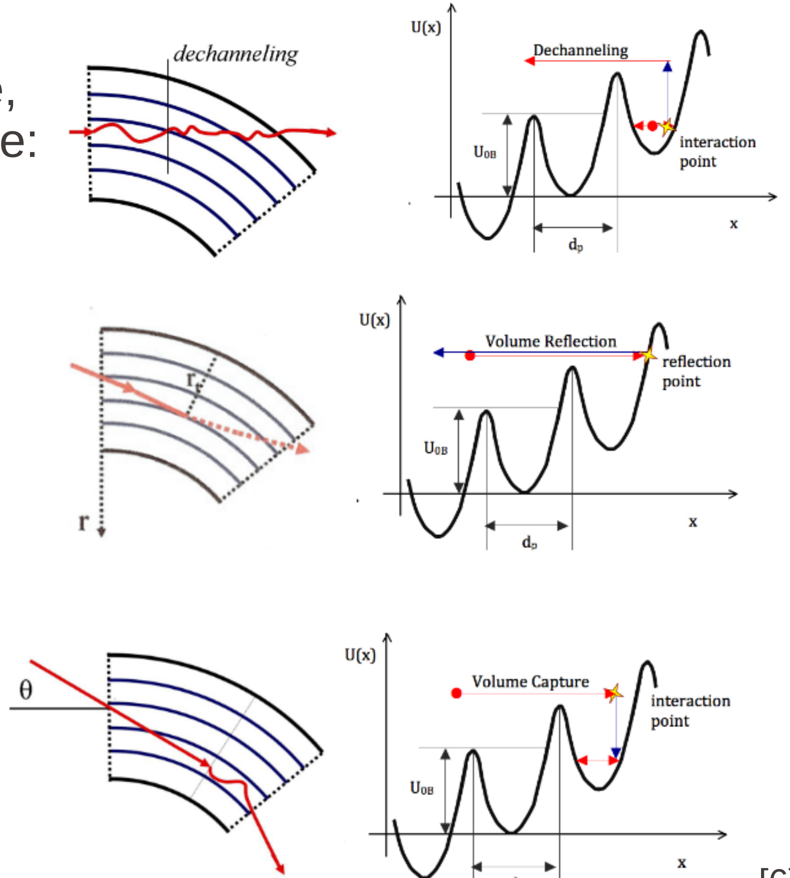
Crystal channeling

When a particle is not in channeling mode, other coherent phenomena may take place:

Incoming angle	Possible phenomena
$\theta_{in} < \lvert\theta_c\rvert$	**Channeling**(CH), **Dechanneling**(DC): the particle interacts with electrons and nuclei and loses channeling condition.
$\theta_c < \theta_{in} < \theta_b$	**Volume reflection** (VR): when a particle's momentum is parallel to a crystal plane, it gets literally reflected. **Volume capture** (VC): the particle, due to interactions regains channeling condition
$\theta_{in} > \theta_b$, $\theta_{in} < -\theta_c$	**Amorphous**(AM)

θ_b is the bending angle of the crystal.



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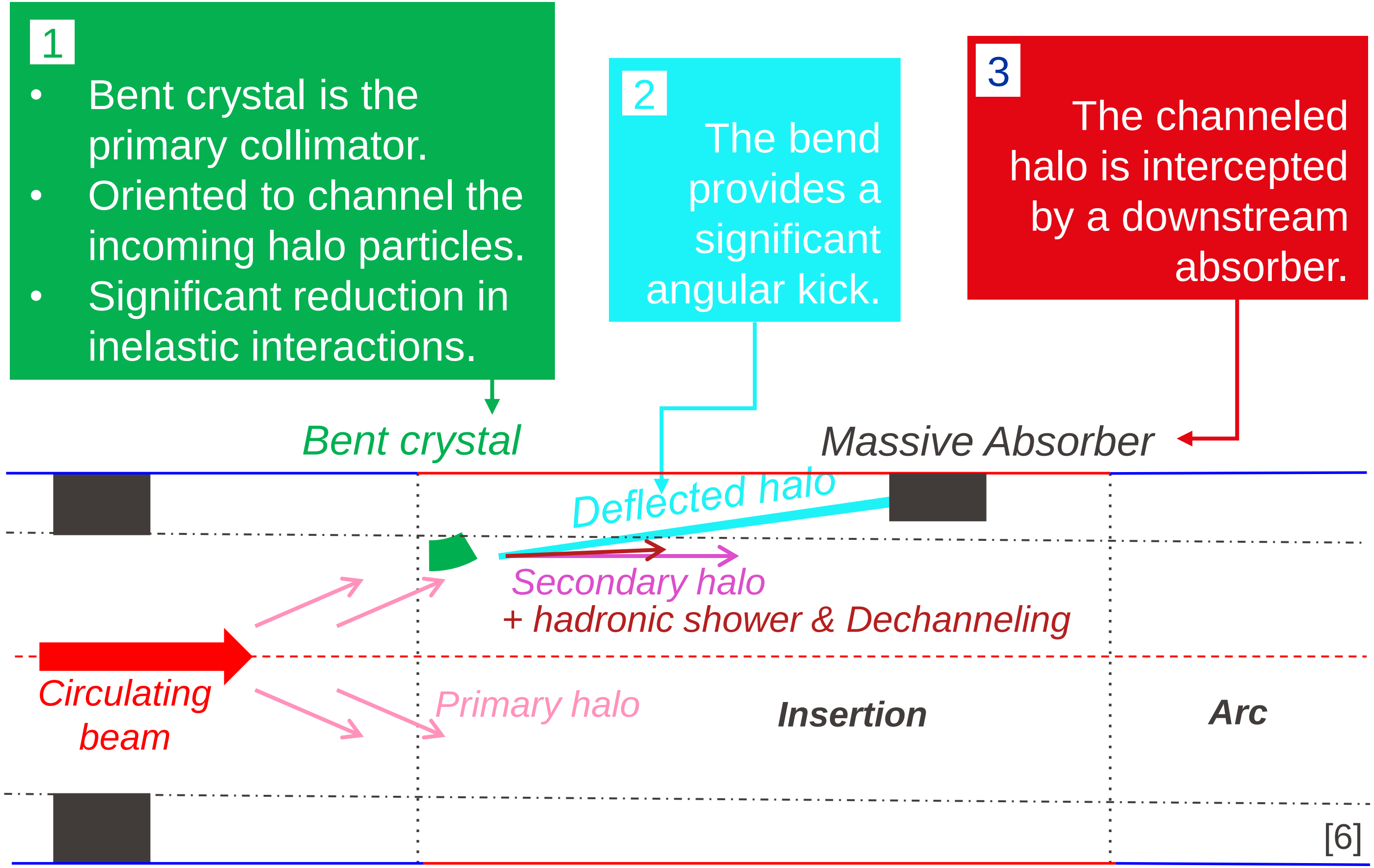
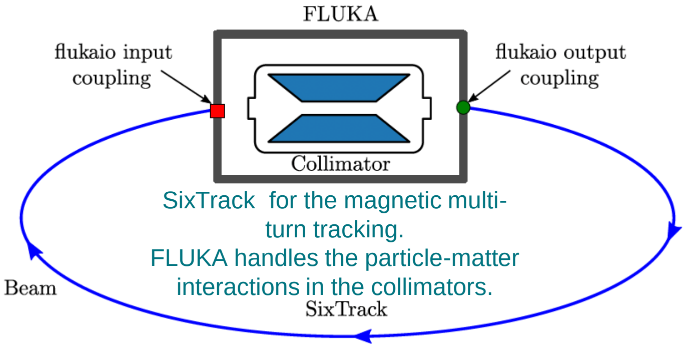
Crystal collimation



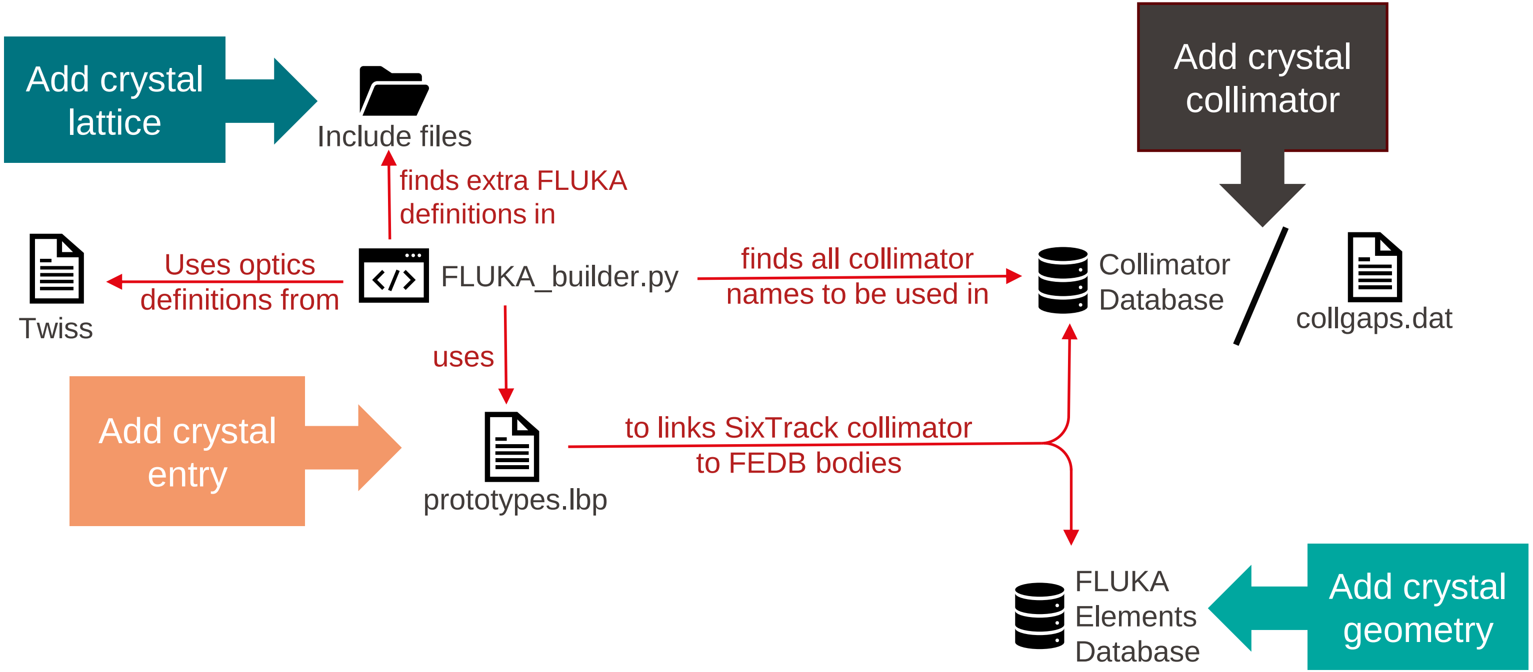
There are currently 4 Si crystals (one per plane)

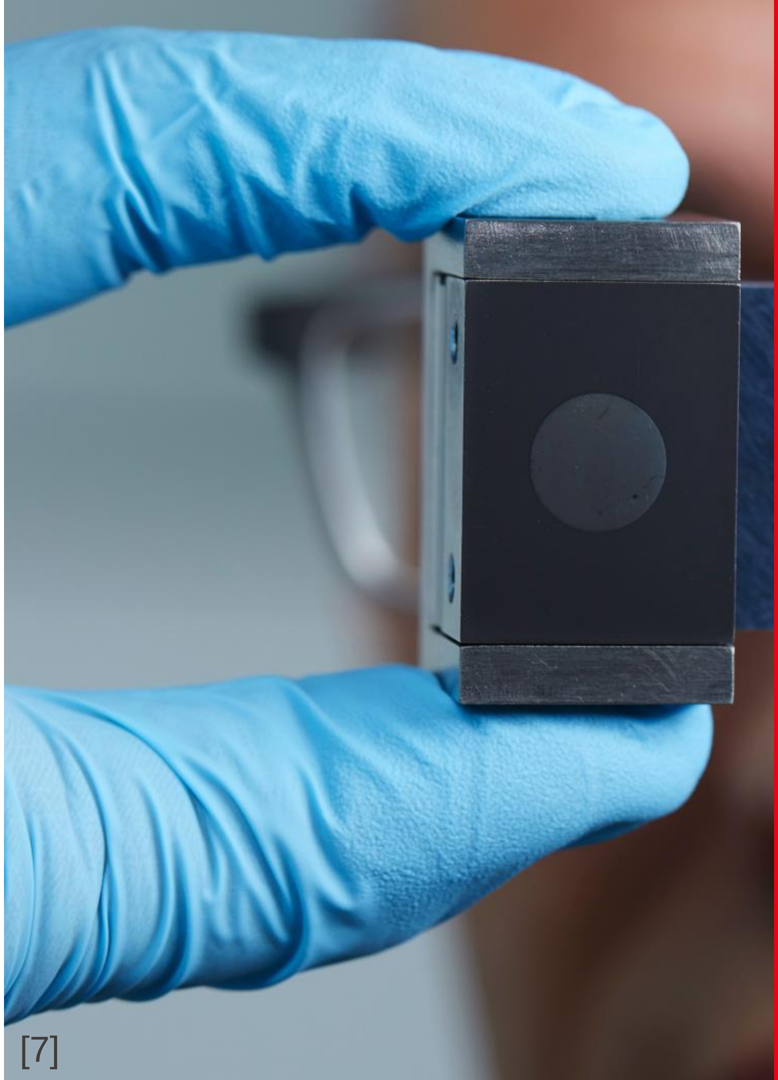
Building of the simulation framework

Crystal collimation for ions is built on the existing SixTrack-FLUKA Coupling.



Main changes to include crystal:





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Benchmark of the simulation framework

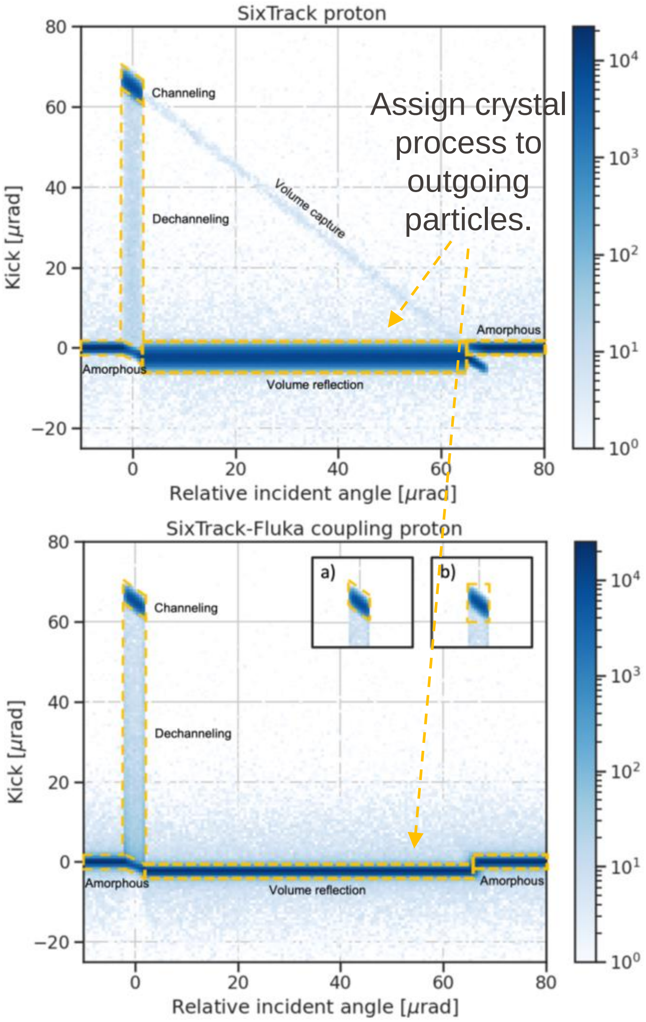
EPFL

Proton benchmark: Single pass

- SixTrack standalone can also simulate crystal for protons but not for ions.
- Aim: compare crystal interaction of FLUKA at high energies with SixTrack.
- Particles simulated to pass through the crystal only once.

Initial distribution	• 6×10^6 initial protons
	• 6.5 TeV.
	• Uniform distribution:
	  • -10 μrad < x' < 80 μrad
	  • -1 mm < x < 1 mm

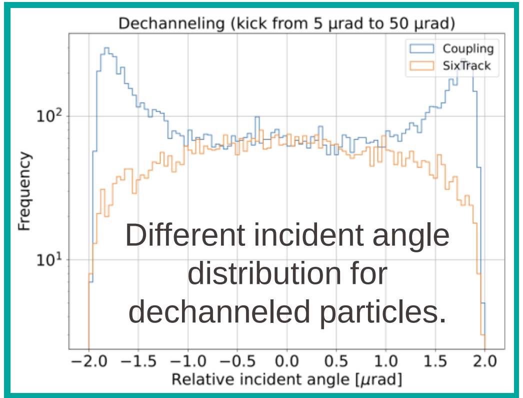
Plane	Beam 1 horizontal (B1H)
Crystal	• 64.5 μrad bending angle • 4 mm long • 2 mm wide • 50 mm tall • Type: 110 (strip crystal)



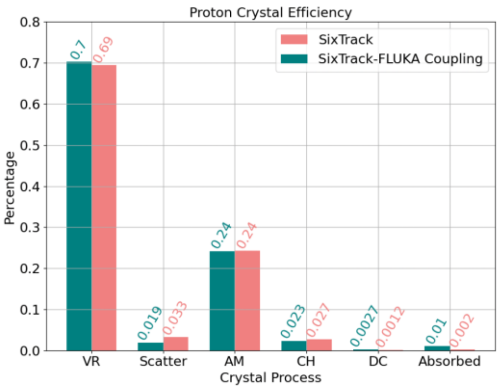
Proton benchmark: Single pass

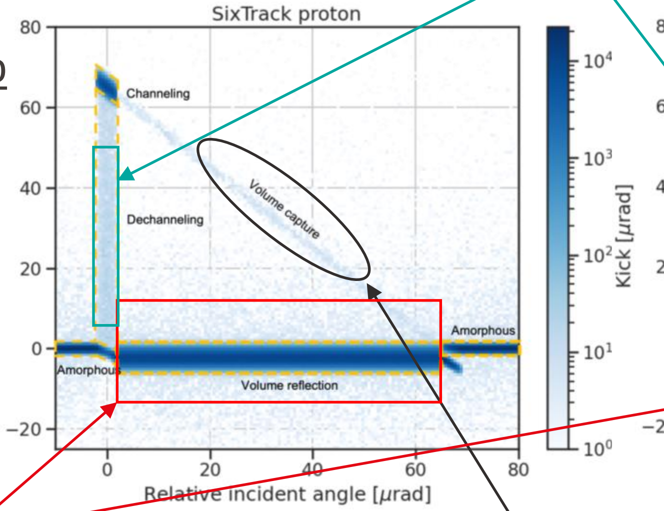
Overall, the two codes produce a similar pattern in angular kick vs incident angle.

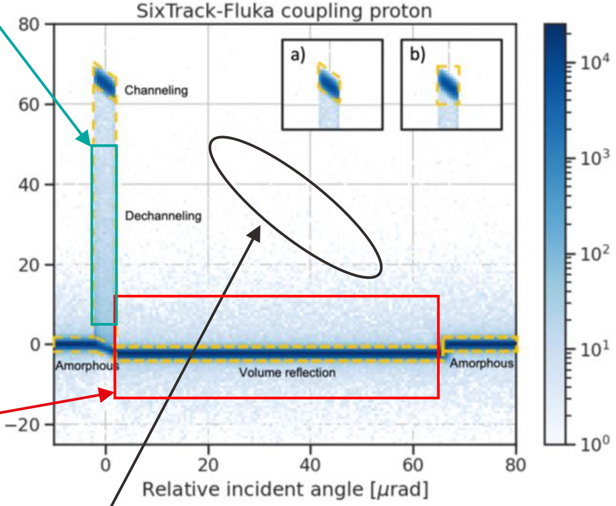
<u>Main differences have no experimental data to compare to</u>:



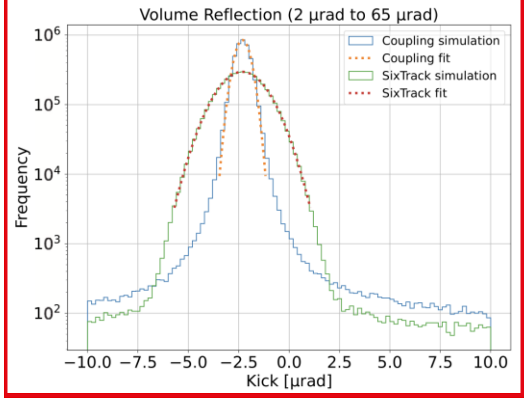
Different incident angle distribution for dechanneled particles.







Different angular kick distribution for volume reflection.

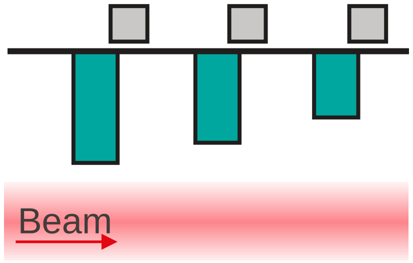


Absence of volume reflection in FLUKA at high energies.

Proton benchmark: Loss pattern

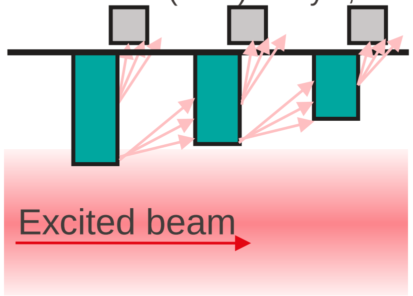
Collimation performance is assessed by looking at the particle loss pattern around the ring.

Measured loss pattern



Add white noise to excite beam

Particle loss measured on Beam Loss Monitors (BLM) in Gy/s, BLM(s)



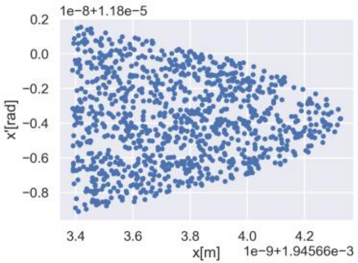
BLM Collimator

Plot loss map:

Measured inefficiency, $\frac{BLM(s)}{dI/dt}$ is plotted against s, where $BLM(s)$ is the BLM signal measured at the location s, I is the beam intensity, and t is time.

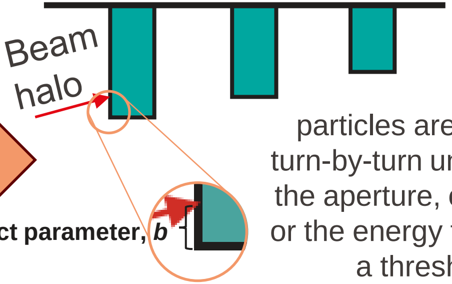
Simulated loss pattern

Create beam halo as pencil beam



Launch at primary collimator

Energy deposition recorded



particles are tracked turn-by-turn until they hit the aperture, collimator, or the energy falls below a threshold

Plot loss map:

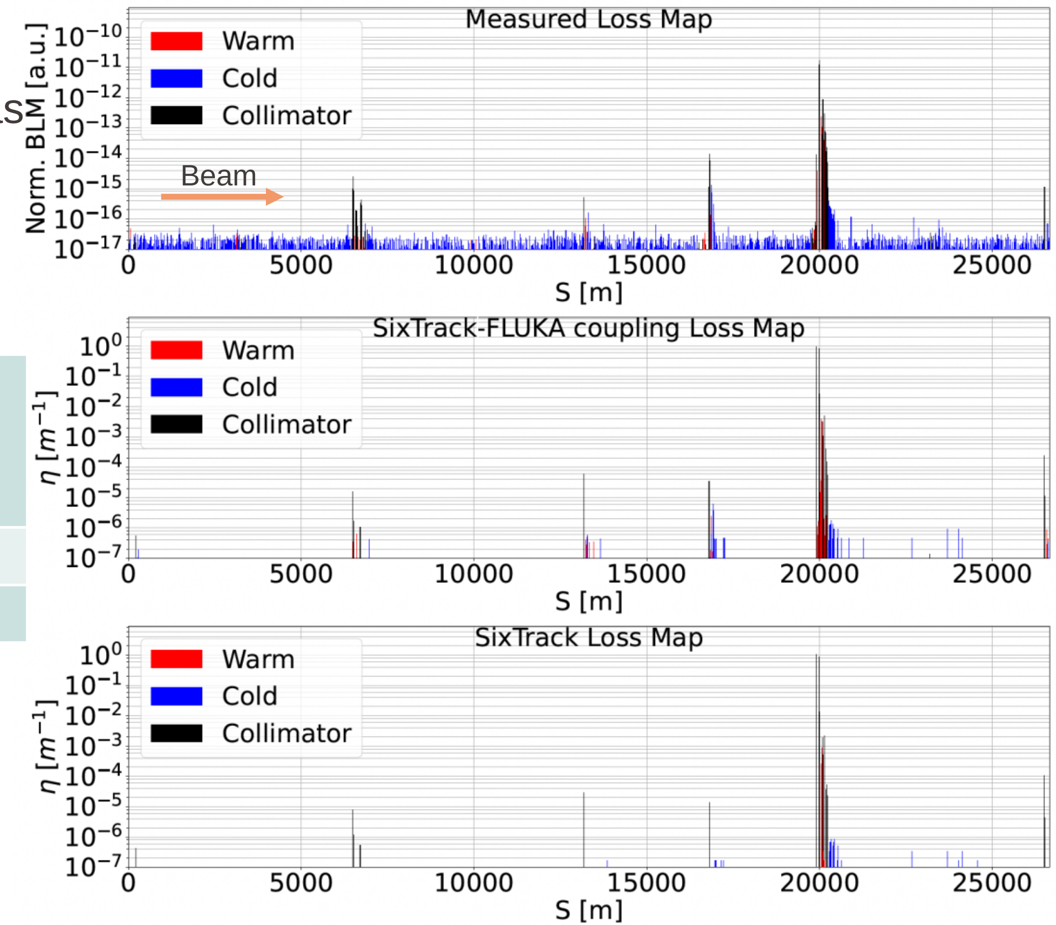
Simulated inefficiency, $\eta = \frac{E(s)}{lE_{tot}}$ is plotted against s in a simulated loss map, where $E(s)$ is the energy lost at s, l is the length of the element, and E_{tot} is the total energy lost.

Proton benchmark: Loss map

- Crystal collimation with crystal as primary collimator is assessed.
- Simulation done with SixTrack standalone and with SixTrack-FLUKA Coupling.

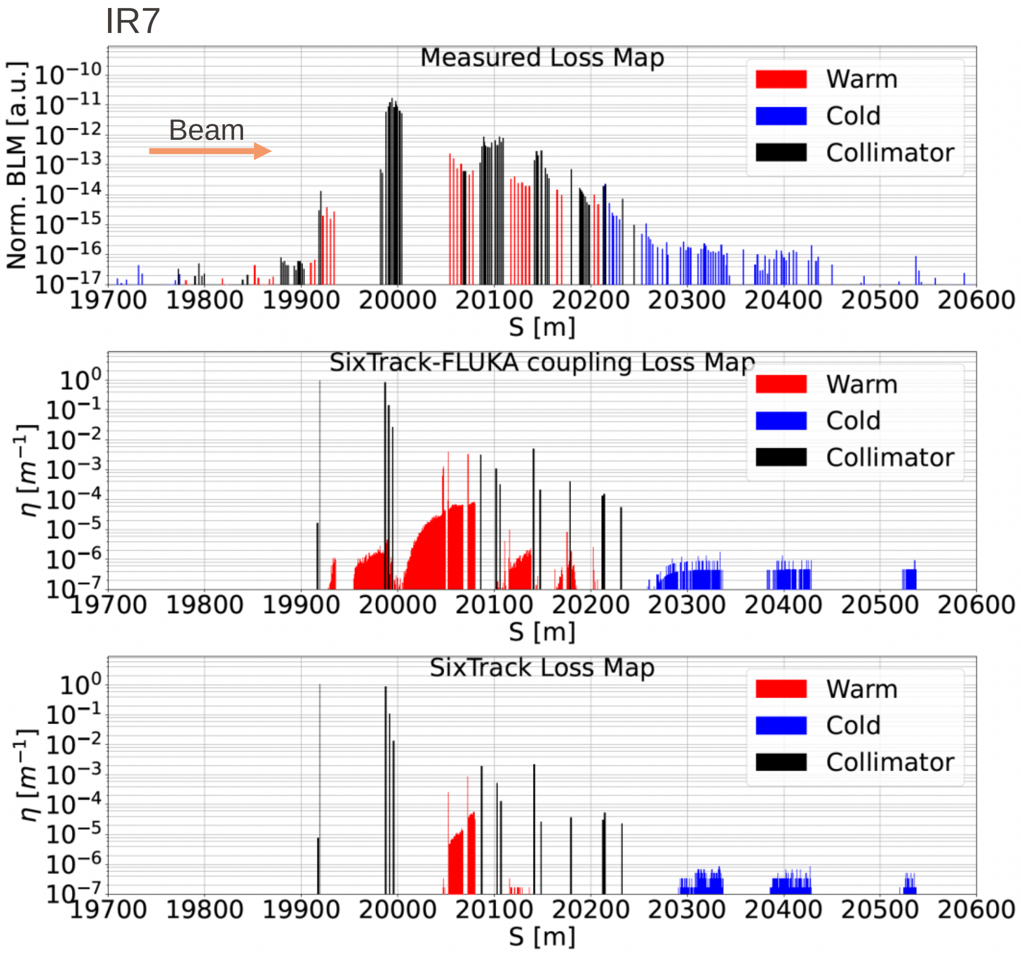
Initial distribution	• 60×10^6 initial protons • 6.5 TeV. • Pencil beam • 1 µm impact parameter
Plane	B1H
Crystal	64.5 µrad bending angle

- A good agreement is found between the measured loss map and the ones simulated by the two tools.



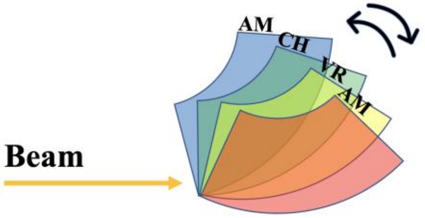
Proton benchmark: Loss map

- Some differences due to particle shower not simulated.
- Differences in warm losses between the tools is due to different transport energy threshold.
- Spike at the crystal is due to the normalization to length (4 mm).



Proton benchmark: Angular scan

- Used to find the channeling orientation of the crystal with respect to the beam and to probe the crystal.
- The crystal is slowly rotated in the bending plane and the BLM signal at the crystal is recorded.

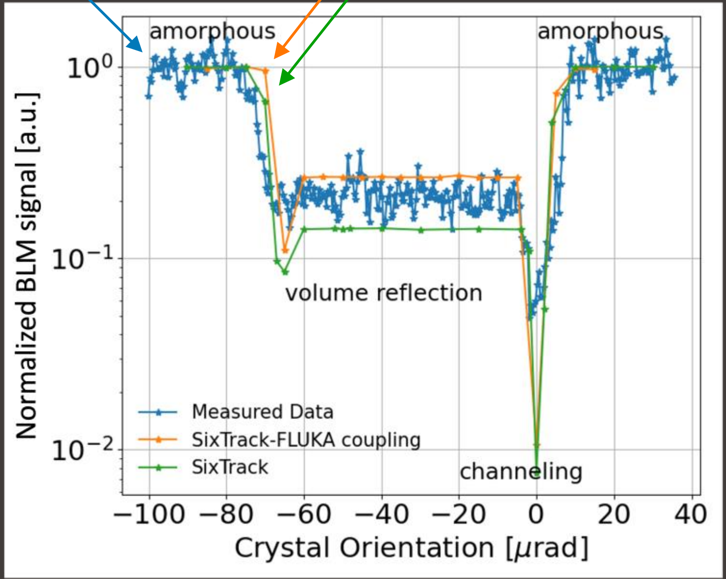


Simulations were done with the SixTrack standalone and the SixTrack-FLUKA Coupling at different crystal orientations:

Initial distribution	• 6×10^6 initial protons/simulation • 6.5 TeV. • Pencil beam • 1 µm impact parameter
Plane	B1H
Crystal	64.5 µrad bending angle

Measured BLM$_{crystal}$ signal at the is normalized to the BLM$_{crystal}$ signal in AM orientation.

Simulated energy deposition at the crystal is normalized to the energy deposited at the crystal when in amorphous orientation.



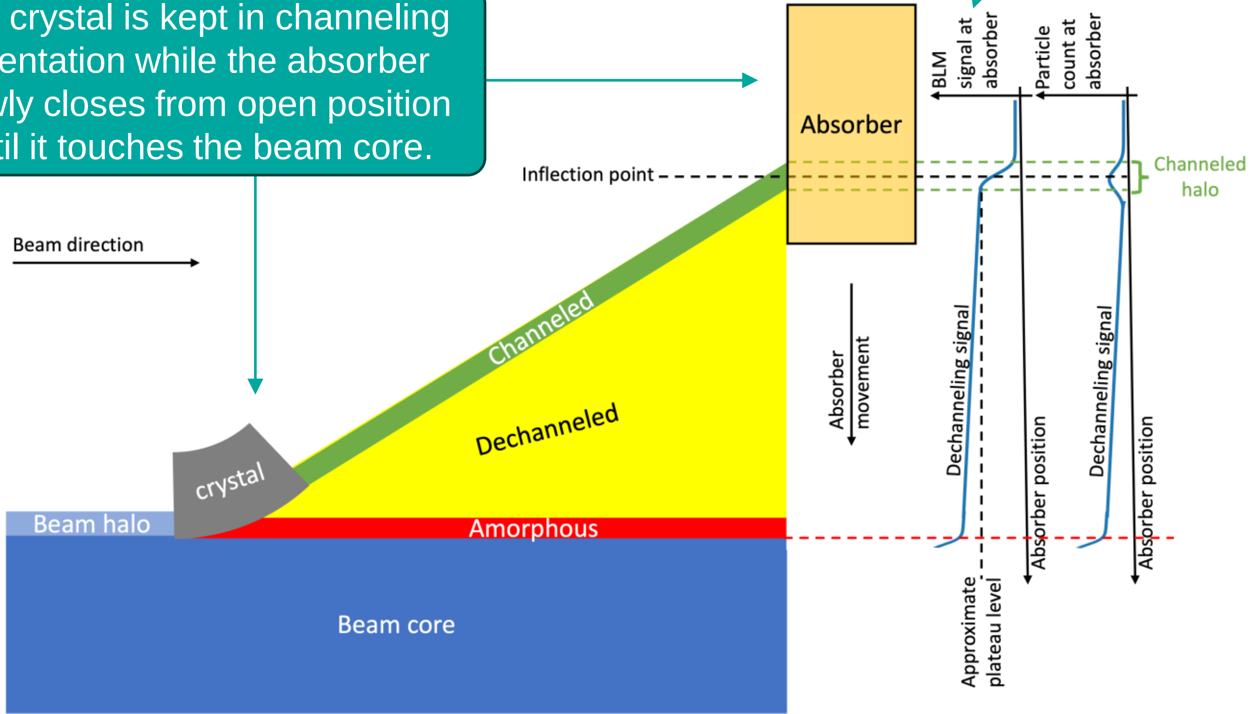
- A qualitatively good agreement is found between simulations and data.
- The level of accuracy is comparable to previous benchmarks.

Proton benchmark: Linear scan

Useful to measure the multi-turn channeling efficiency and the crystal bending.

The BLM signal at the absorber is recorded at each step.

The crystal is kept in channeling orientation while the absorber slowly closes from open position until it touches the beam core.



Proton benchmark: Linear scan

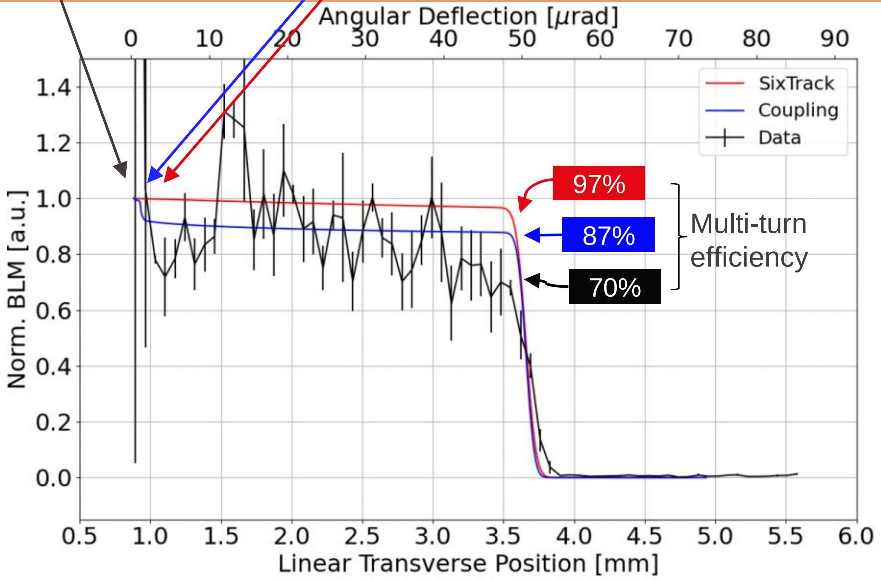
Simulations were done with the SixTrack standalone and the SixTrack-FLUKA Coupling:

Initial distribution	• 3×10^5 initial protons • 6.8 TeV. • Pencil beam • 1 µm impact parameter
Plane	Beam 2 vertical (B2V)
Crystal	• 51.1 µrad bending angle • 4 mm long • 2 mm wide • 50 mm tall • Type: 110 (strip crystal)

- The simulations reproduce measured data reasonably well. Both codes overestimate slightly the multi-turn efficiency. However, the high energy linear scans are very noisy (±15%).

Measured BLM signal is normalized to the signal just before touching the core to cover the entire beam tail.

The simulated particle impact distribution on the absorber is integrated from open position and normalized to the cumulative count just before the beam core.



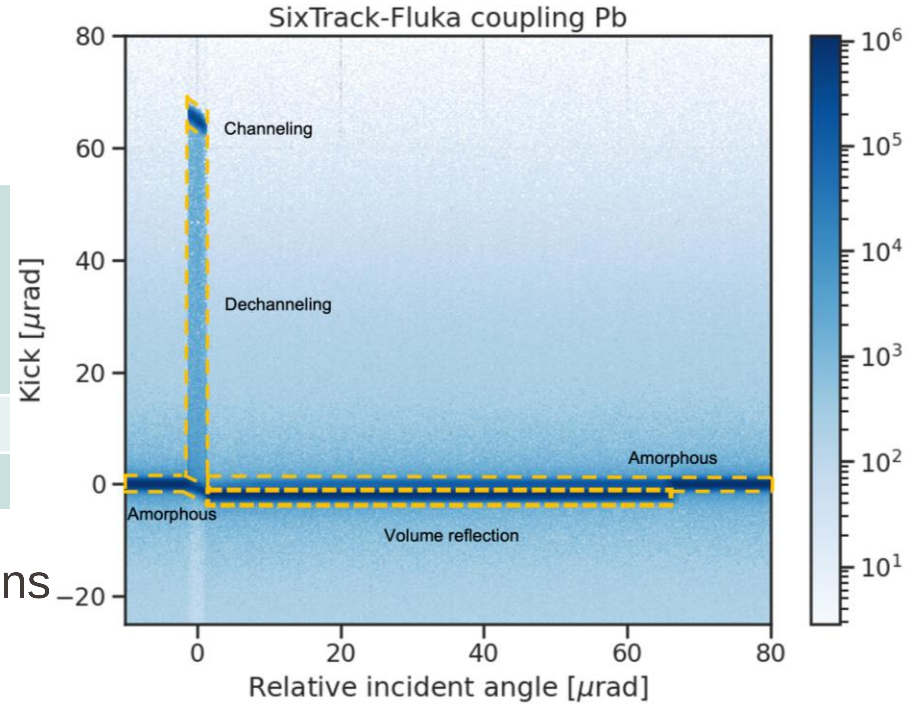
Heavy ion benchmark: Single pass

- Exploratory single pass simulation done with the SixTrack-FLUKA Coupling.

Initial distribution	• 6×10^6 initial lead ions
	• 6.37 Z TeV.
	• Uniform distribution:
	  • -10 µrad < x' < 80 µrad
	  • -1 mm < x < 1 mm

Plane	Beam 1 horizontal (B1H)
Crystal	• 64.5 µrad bending angle

- Same analysis as the one for protons used.
- Heatmap weighted with energy.

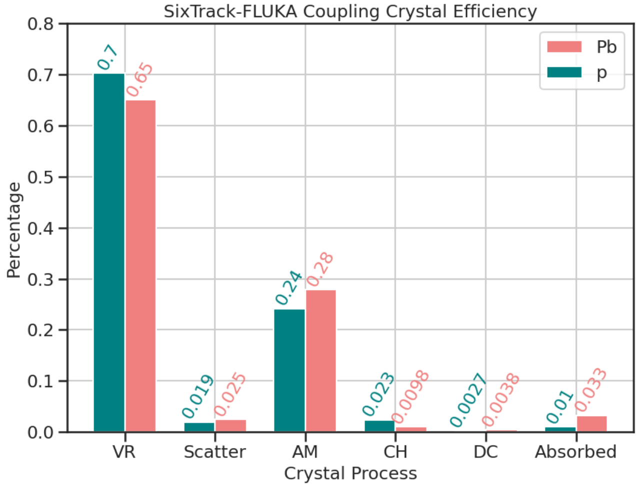


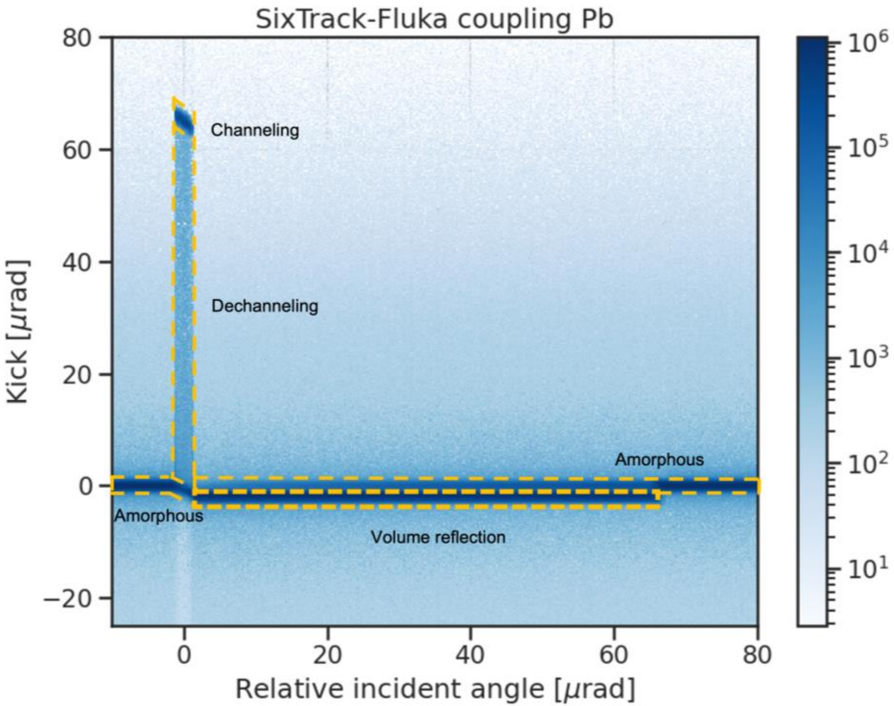
Heavy ion benchmark: Single pass

- Clearly defined regions for the various crystal processes.

Main differences compared to protons:

- Decreased percentage of CH.
- Decrease in VR and increase in AM (especially in the VR region)





Heavy ion benchmark: Loss pattern

Loss pattern benchmark done for Pb ions with SixTrack-FLUKA Coupling:

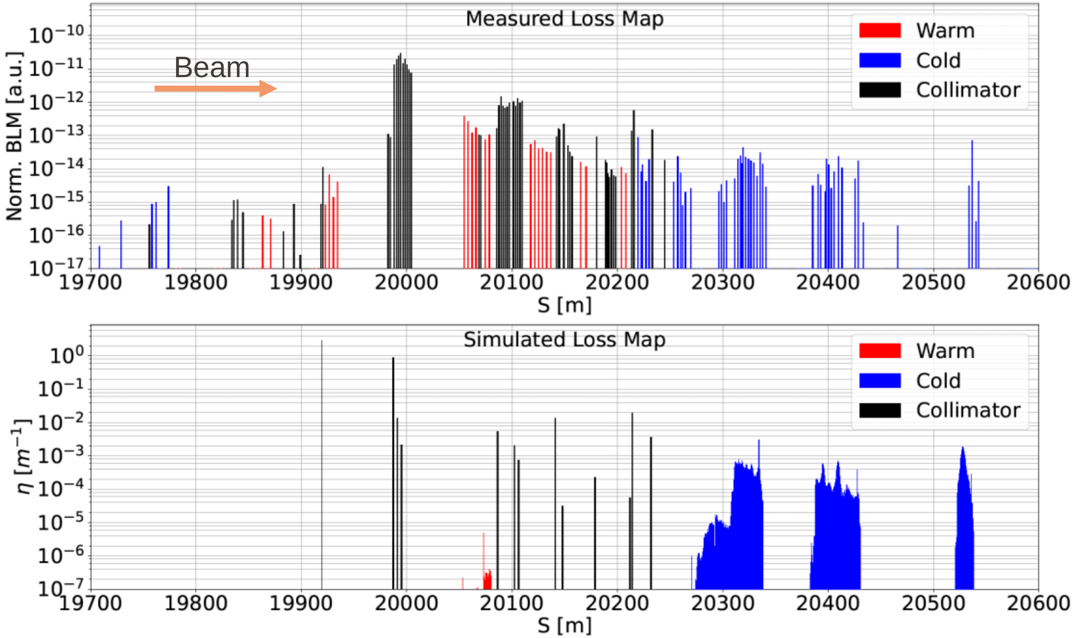
Initial distribution	• 6×10^6 initial lead ions. • 6.37 Z TeV. • Pencil beam • 1 µm impact parameter
Plane	B1H
Crystal	64.5 µrad bending angle

- Same analysis method used as for protons.
- Good qualitative agreement between measured and simulated data.

Heavy ion benchmark: Loss pattern

- Good reproduction of the order of magnitude of cold loss.
- Similar considerations done for the proton benchmark are applicable here.
- Benchmark has been carried out for other setups and planes with similar results.

IR7



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Heavy ion benchmark: Improvement factor

- Benchmark to assess accuracy in predicting crystal collimation improvement over standard collimation.
- Improvement factors applied to the most prominent loss clusters in the DS.
- Average and maximum improvement factors:

$$\bar{I} = \frac{\bar{\eta}_{CH,AM}}{\bar{\eta}_{STD}}, \ \max(\mathrm{I}) = \frac{\max(\eta_{CH,AM})}{\max(\eta_{STD})}$$

- Simulations done to reproduce 2022 machine development tests: standard, crystal in CH, and in AM.

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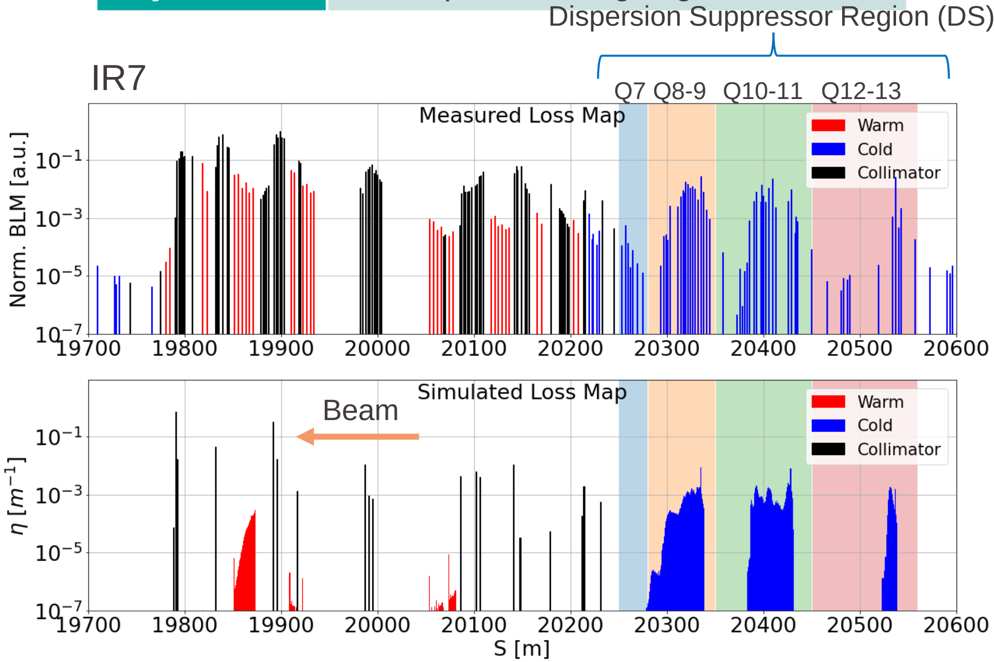
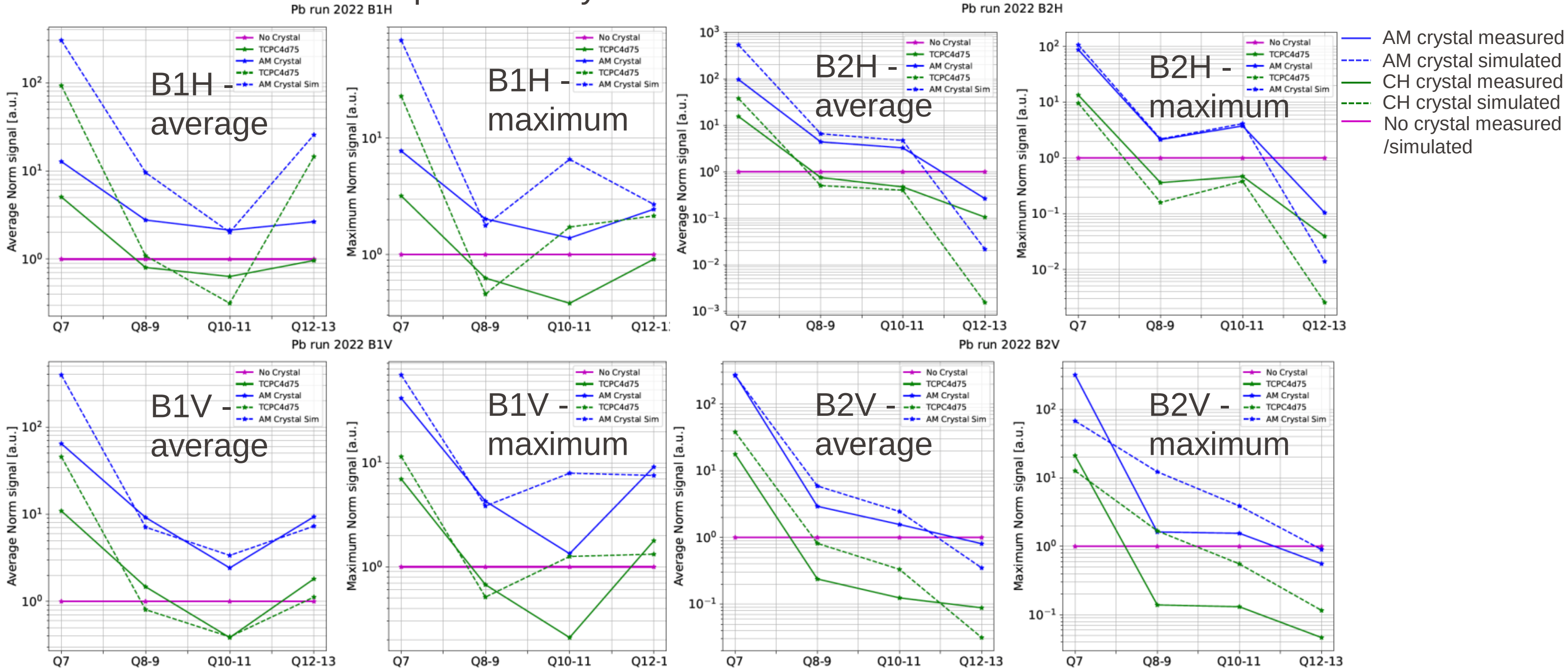
Initial distribution	• 6×10^6 initial lead ions / simulation • 6.8 Z TeV. • Pencil beam • 1 µm impact parameter
Plane	All
Crystal	50 ± 5 µrad bending angle



Heavy ion benchmark: Improvement factor

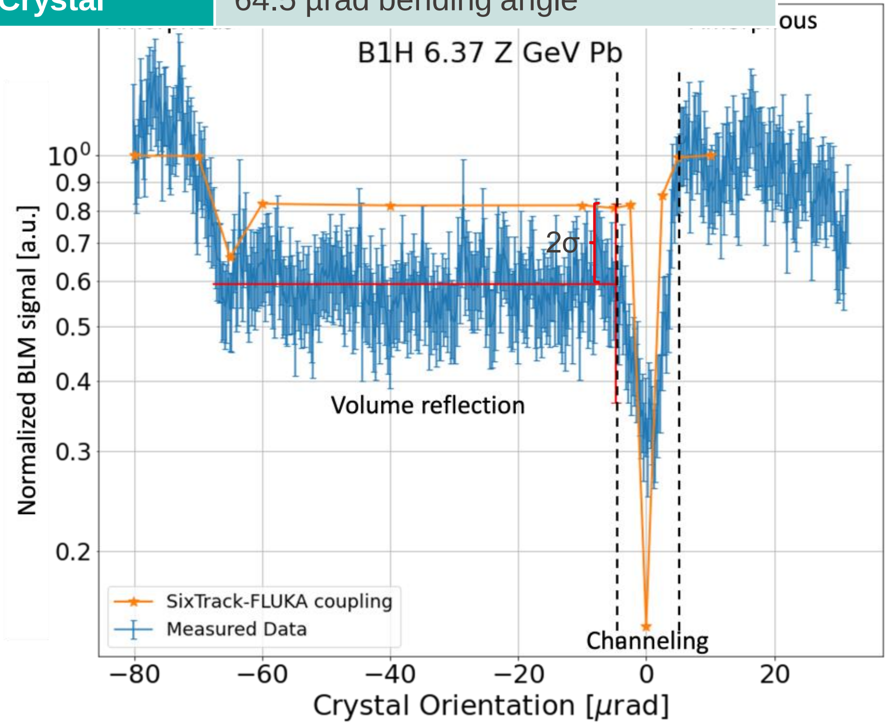
- Simulation achieves different degrees of accuracy for the various clusters. Q8-9 and Q10-11 tend to perform better.
- General trends can be predicted by simulations.



Heavy ion benchmark: Angular scan

- Angular scan benchmark was done with Pb ions.
- Same method of simulation and analysis as the one used for protons was used for ions.
- The level of accuracy in reproducing measurement is similar to that achieved with protons, except for VR.
- The predicted VR level lies ~2σ from measured VR level. However, VR regime is not used in operations.

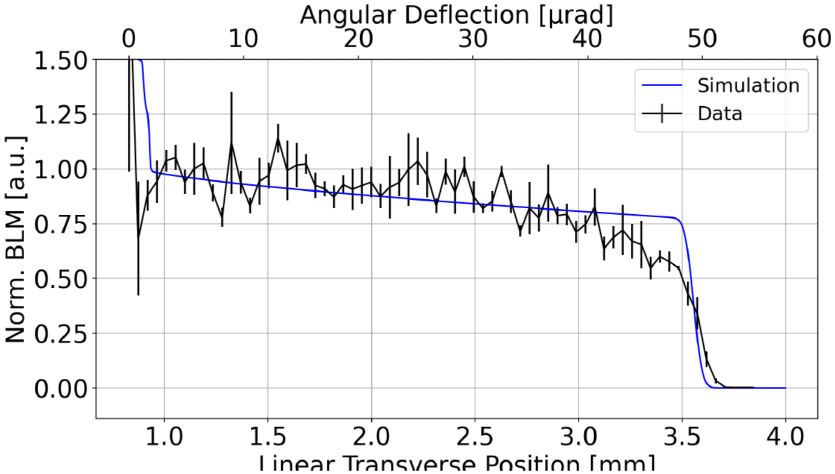
Initial distribution	• 6×10^6 initial lead ions/simulation • 6.37 Z TeV. • Pencil beam • 1 µm impact parameter
Plane	B1H
Crystal	64.5 µrad bending angle

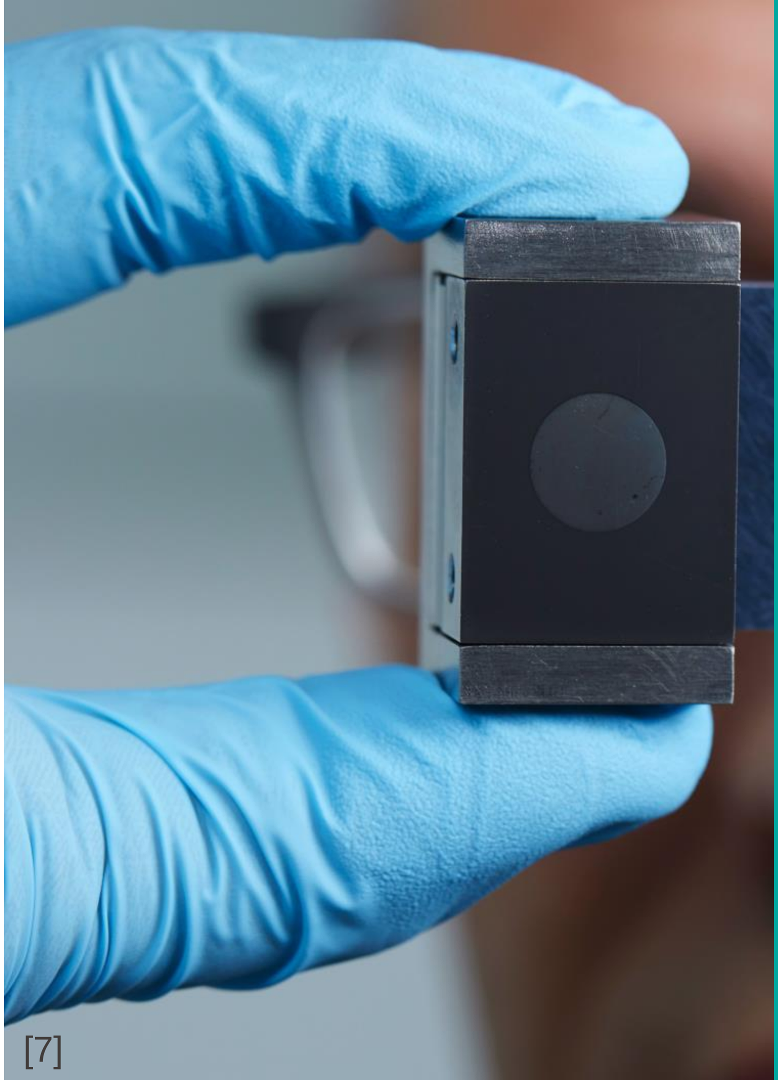


Heavy ion benchmark: Linear scan

Initial distribution	• 3×10^5 initial lead ions • 6.8 Z TeV. • Pencil beam • 1 µm impact parameter
Plane	Beam 2 vertical (B2V)
Crystal	• 49.7 µrad bending angle • 4 mm long • 2 mm wide • 50 mm tall • Type: 110 (strip crystal)

- Linear scan benchmark was done for Pb ions.
- Same method of simulation and analysis as the one used for protons was used for ions.
- Simulated data was weighted with energy.
- The multi-turn channeling efficiency measured is ~60%, while the simulated one is ~75%, similar to the proton benchmark.

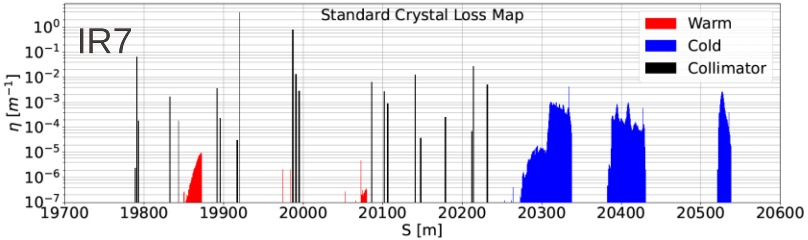


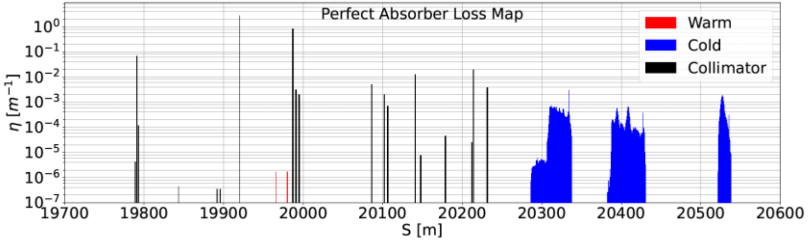

[7]

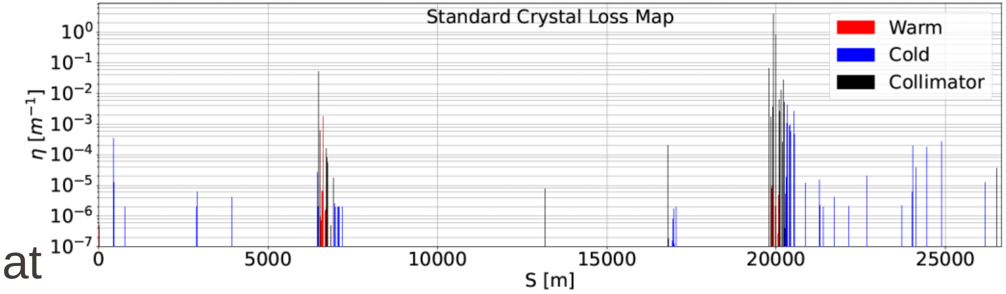
Crystal collimation studies

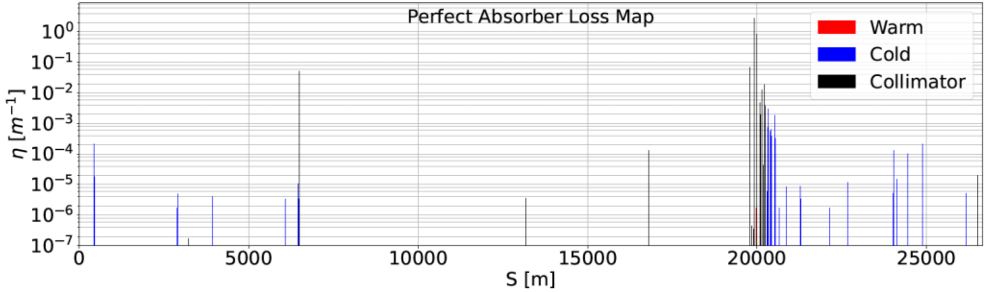
Characteristics of crystal collimation

- Goal: assess the contribution of losses leaking directly from the crystal to the DS.
- Simulation setup: all collimator materials set to perfect absorbers, except for the crystal.
- The black absorber loss map resembles closely the normal crystal loss map suggesting that direct losses from the crystal is the main source of cold loss.



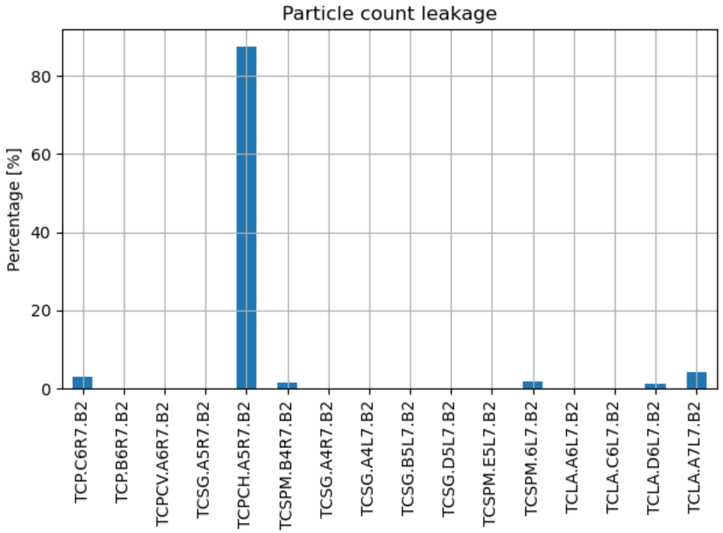


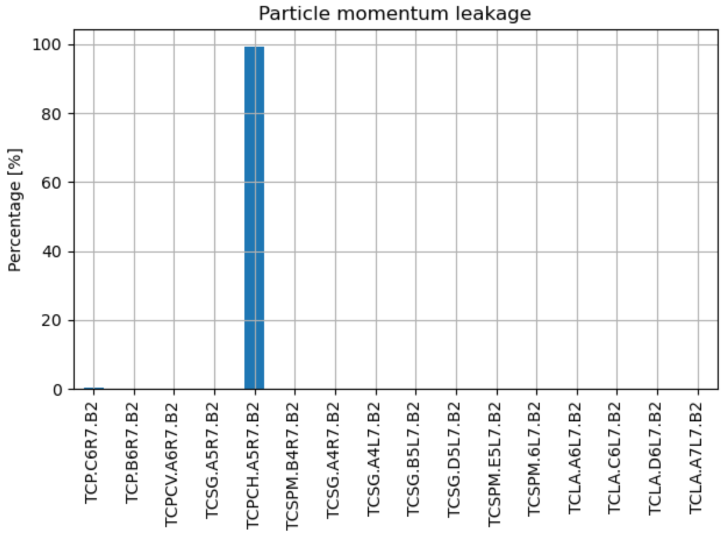




Characteristics of crystal collimation

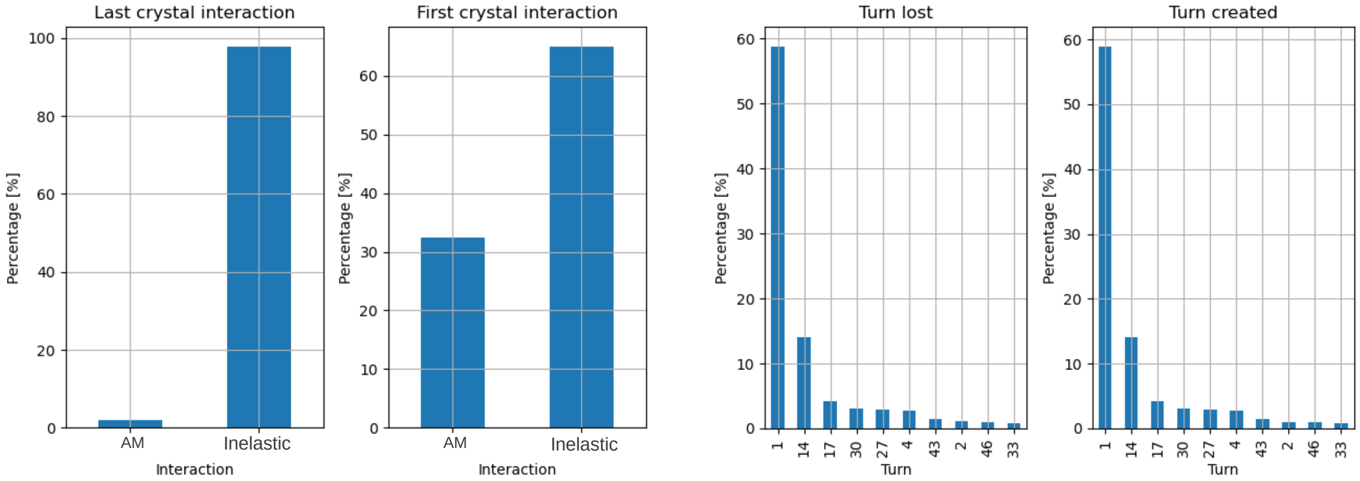
- A detailed particle track back confirms that most particles lost in the DS come from the crystal, especially when accounting for particle momentum.





Characteristics of crystal collimation

- The first crystal interaction of the particles lost in the DS are either amorphous or inelastic interaction.
- Almost 100% of the particles undergo inelastic interaction in the last passage through the crystal.
- Almost 60% of the particles are lost on the first turn.

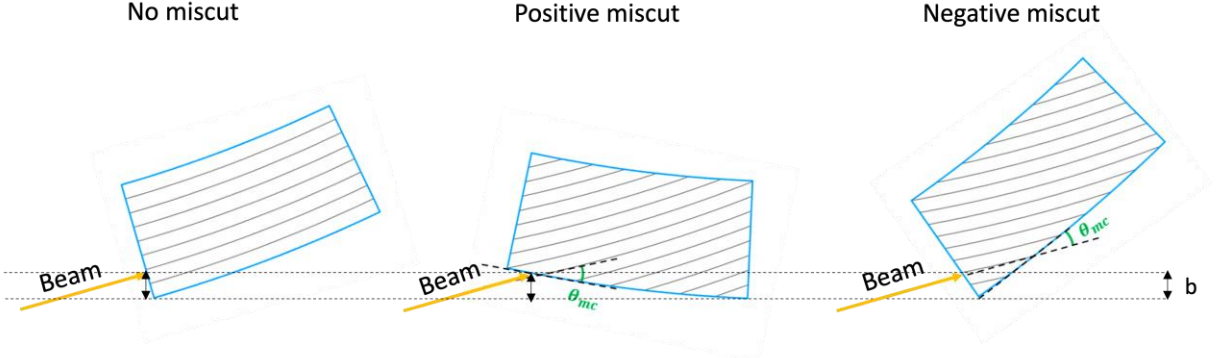


EPFL

Sensitivity studies: Crystal miscut

Initial distribution	• 6×10^6 initial lead ions/simulation • 6.8 Z TeV. • Pencil beam • 1 µm impact parameter
Plane	B2H
Crystal	45.4 µrad bending angle

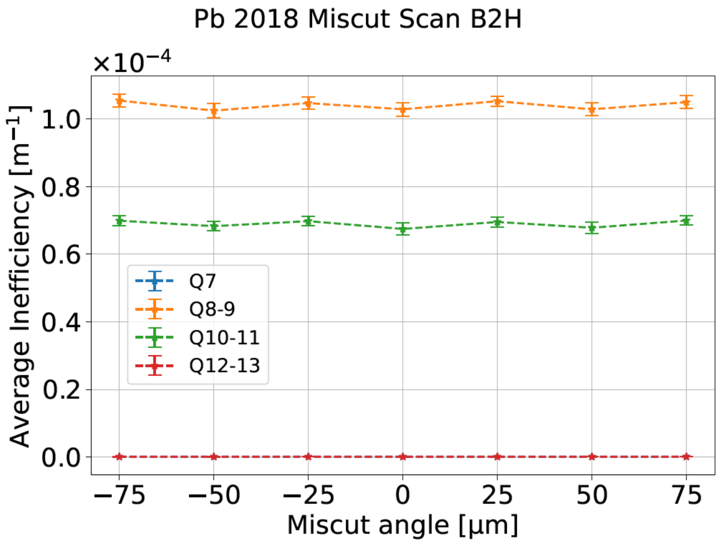
- Crystals have a miscut when the direction of channeling is not perpendicular to the incoming face.

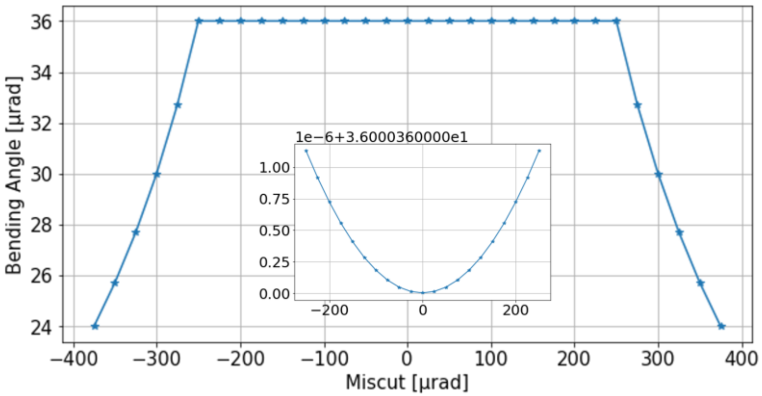


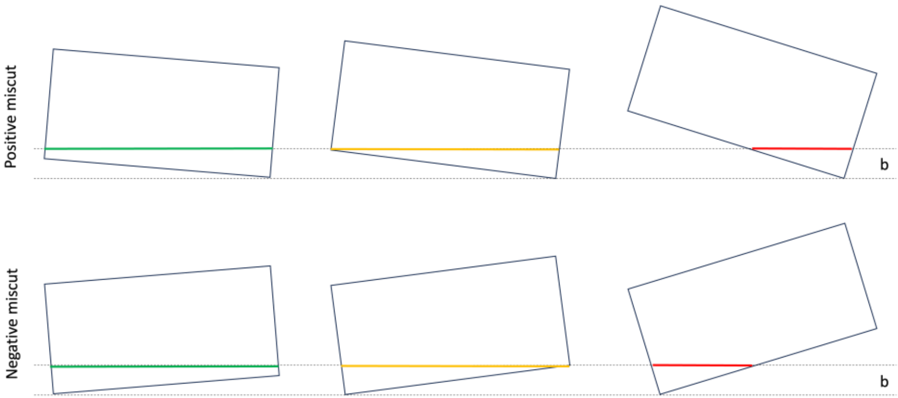
- Simulations have been performed to assess the influence of crystal miscut to the collimation performance.
- Initial distribution adjusted to maintain the same impact parameter.

Sensitivity studies: Crystal miscut

- Average inefficiency of the DS clusters suggest no change to collimator performance in the miscut range considered -75 to 75 µrad.
- This is likely due to the very small (10^{-6} µrad) change in bending angle in this range.



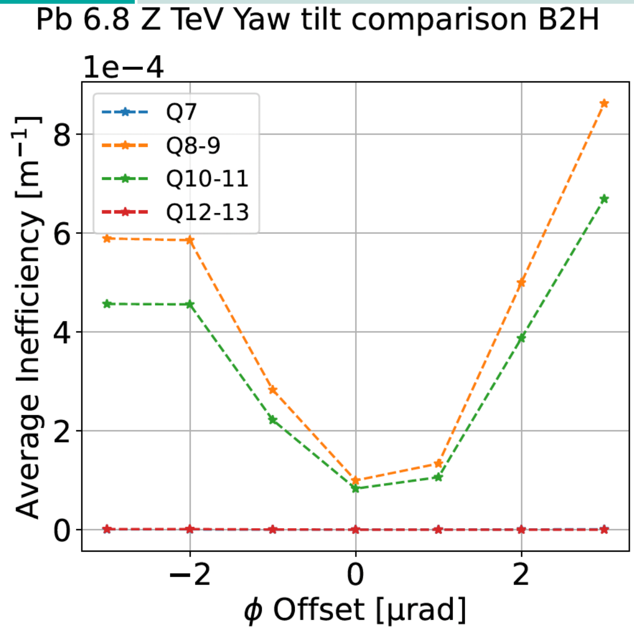




Sensitivity studies: Crystal orientation

Initial distribution	• 6×10^6 initial lead ions/simulation • 6.8 Z TeV. • Pencil beam • 1 µm impact parameter
Plane	B2H
Crystal	45.4 µrad bending angle

- Angular stability of crystal is crucial to maintain channeling.
- Study on the sensitivity of the collimation system with respect to small angular instabilities was done.
- The average inefficiency of some clusters reflect the shape of the channeling well.
- From perfect alignment to the limit of the next crystal regime, a worsening up to a factor of 4-6 can be expected.



EPFL

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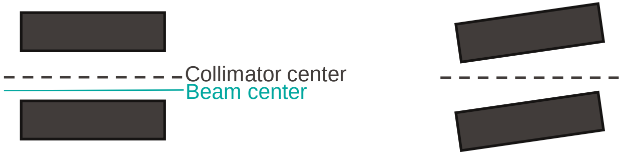
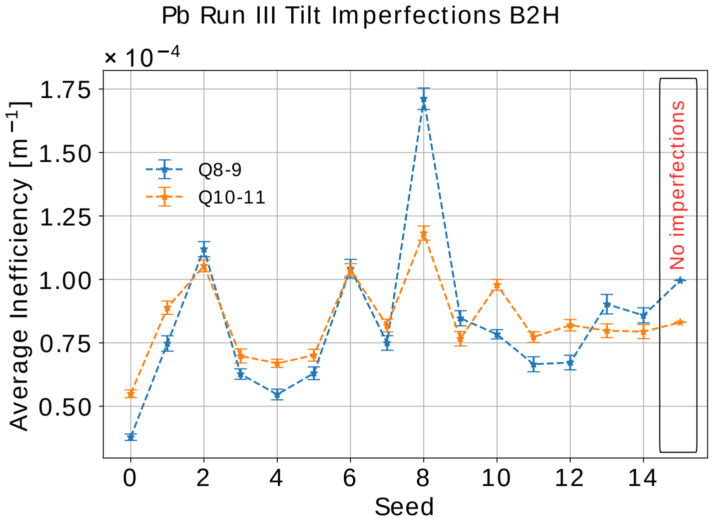
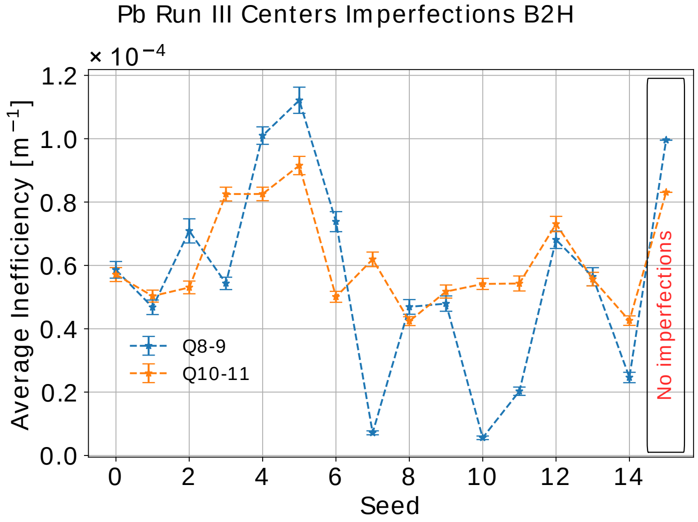
Sensitivity studies: Collimator imperfections

- During operations, there may be machine misalignments. Two kinds are simulated here: collimator center and tilt.



- Both studies give small performance oscillations around the performance of the perfect machine.

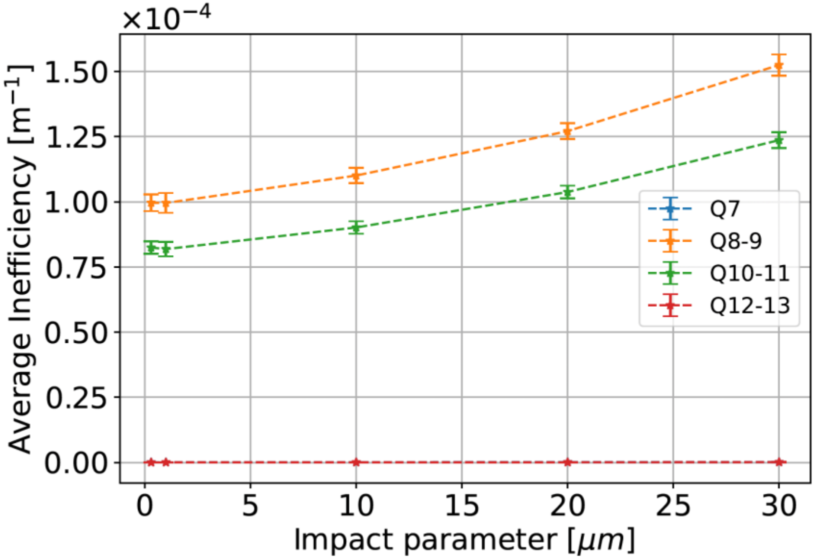




Sensitivity studies: Impact parameter scan

- Due to beam instabilities and other phenomena different diffusive mechanisms may happen. The impact parameter may change consequently.
- Simulations have been done to explore different impact parameters.
- For impact parameters up to 30 µm, the average inefficiency of clusters Q8-9 and Q10-11 worsens up to 50%.
- The worsening is likely caused by initial particles having larger impacting angles.
- This indicates that the crystal system is sensitive to impact parameter fluctuations.

Initial distribution	• 6×10^6 initial lead ions/simulation • 6.8 Z TeV. • Pencil beam • 1 µm impact parameter
Plane	B2H
Crystal	45.4 µrad bending angle



Configuration optimization: TCLA

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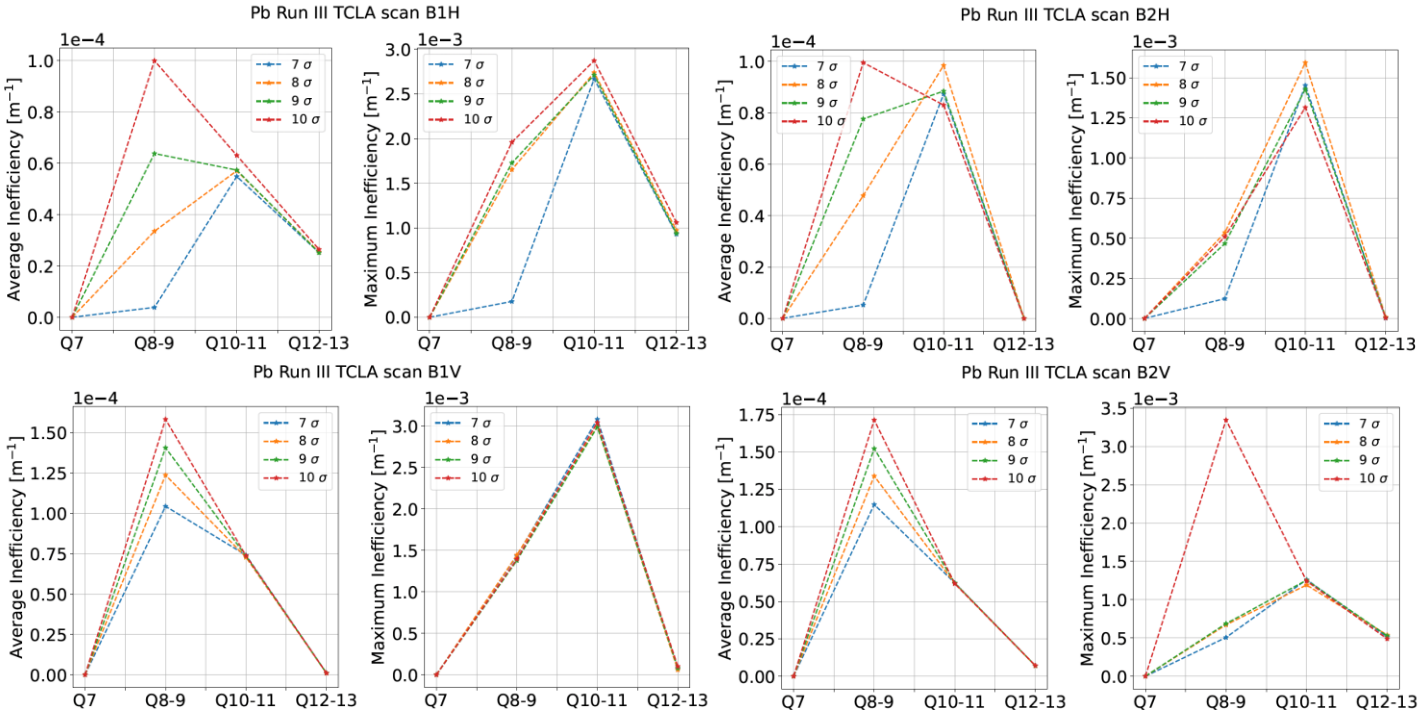
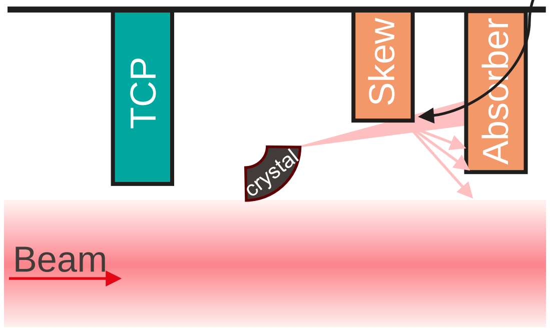
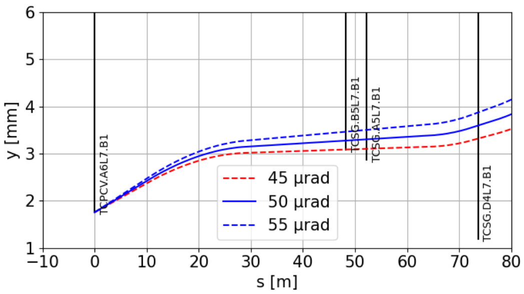
- Different TCLA collimator apertures are tested to improve performance.
- From 10 to 7 σ aperture, a consistent improvement was found in Q8-9.

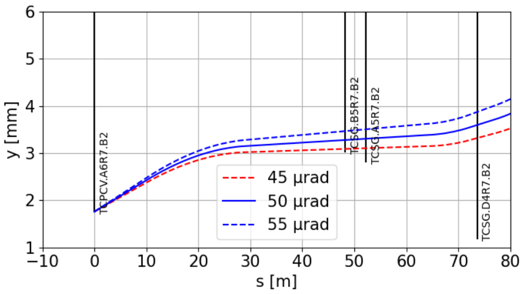


Configuration optimization: TCS

risk of grazing impacts in vertical planes on skew TCS collimators and increasing the probability of particles escaping the absorber.

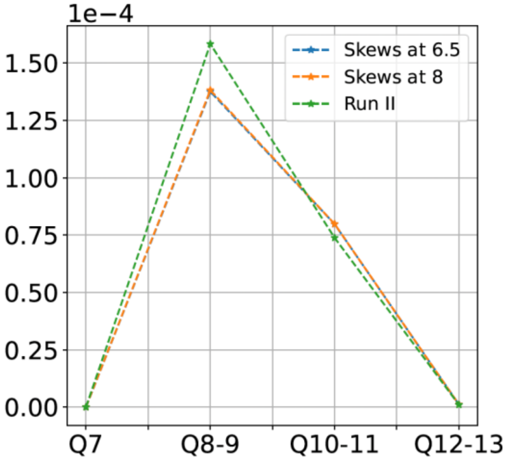




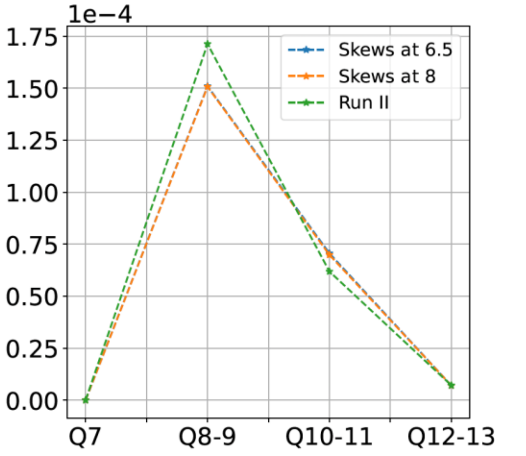


- Simulations were done to check closed (6.5σ) and open (8σ) skew collimators.
- No change in performance was found.

Pb 6.8 Z TeV configuration comparison B1V



Pb 6.8 Z TeV configuration comparison B2V



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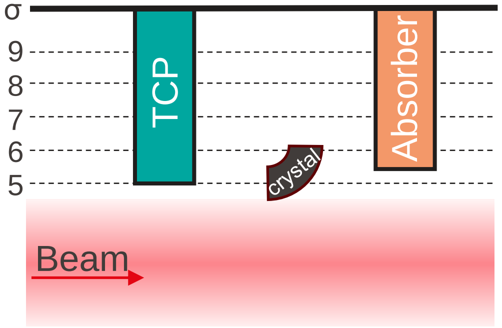
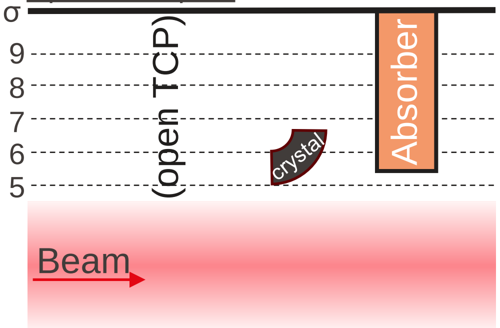
Configuration optimization: Upstream open

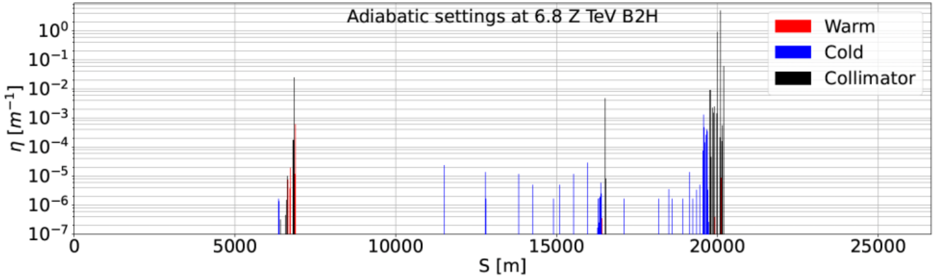
Two historical settings:

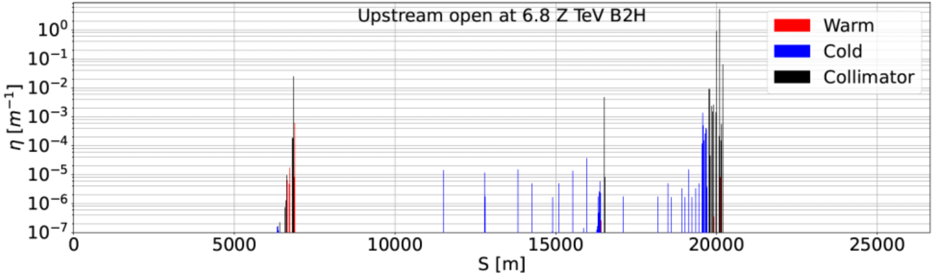
Adiabatic:

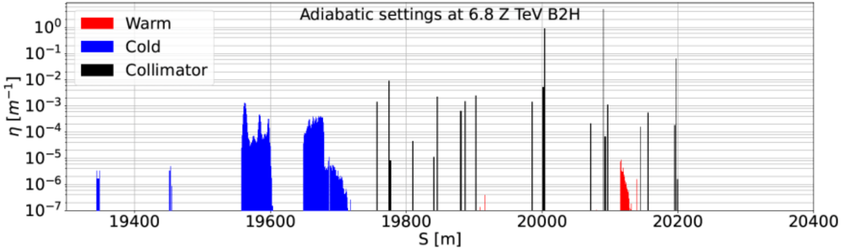


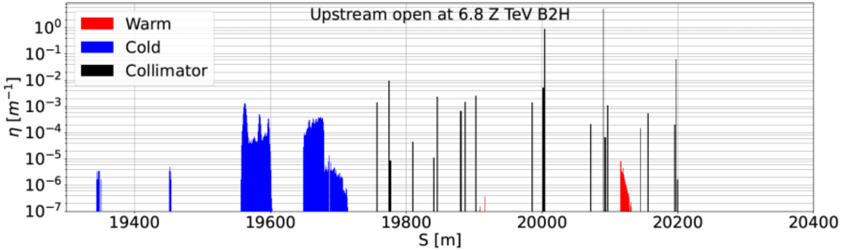
Upstream open:







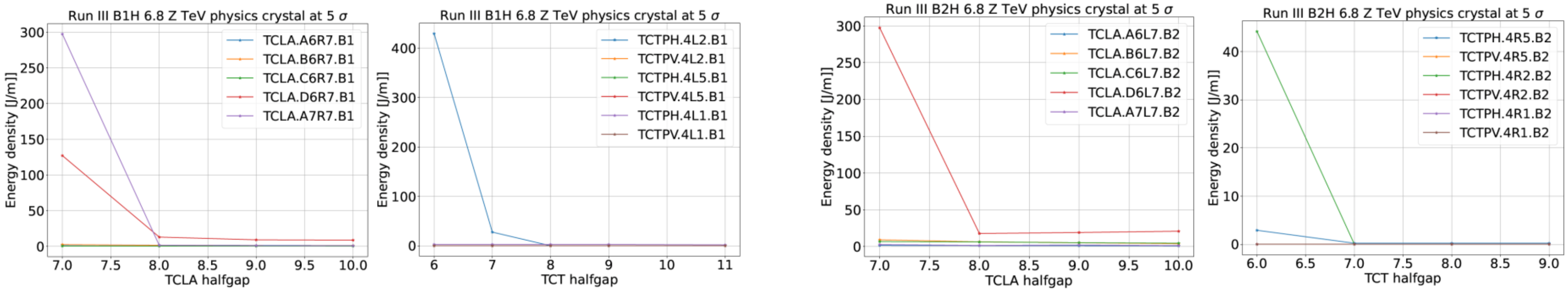




Simulation found no significant performance difference

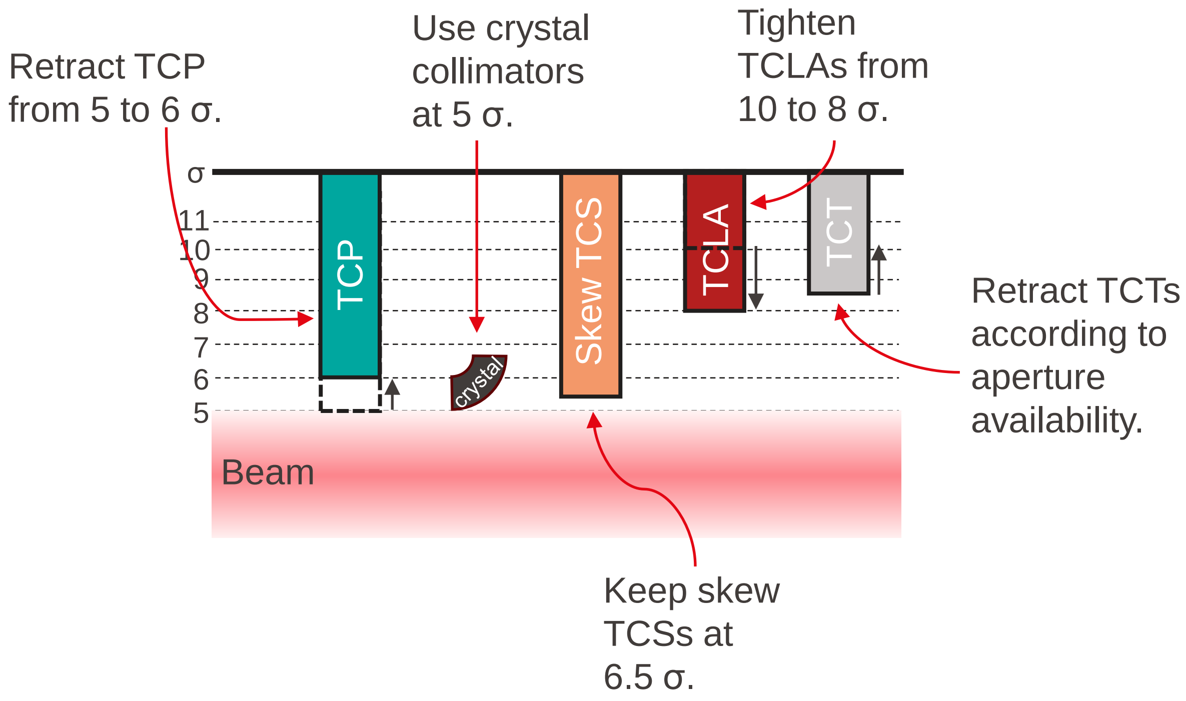
Machine failure: Asynchronous dump

- One of the most severe types of machine failure is asynchronous dump.
  - It occurs at beam extraction when the beam bunches receive an intermediate magnetic kick that is insufficient to be extract and may hit the machine aperture causing damage.
- This failure scenario has been simulated for various settings of the TCLA and TCT collimators.
- In all cases the total energy density is below ~400 J/m, well below the deformation limit of ~5.6 kJ.



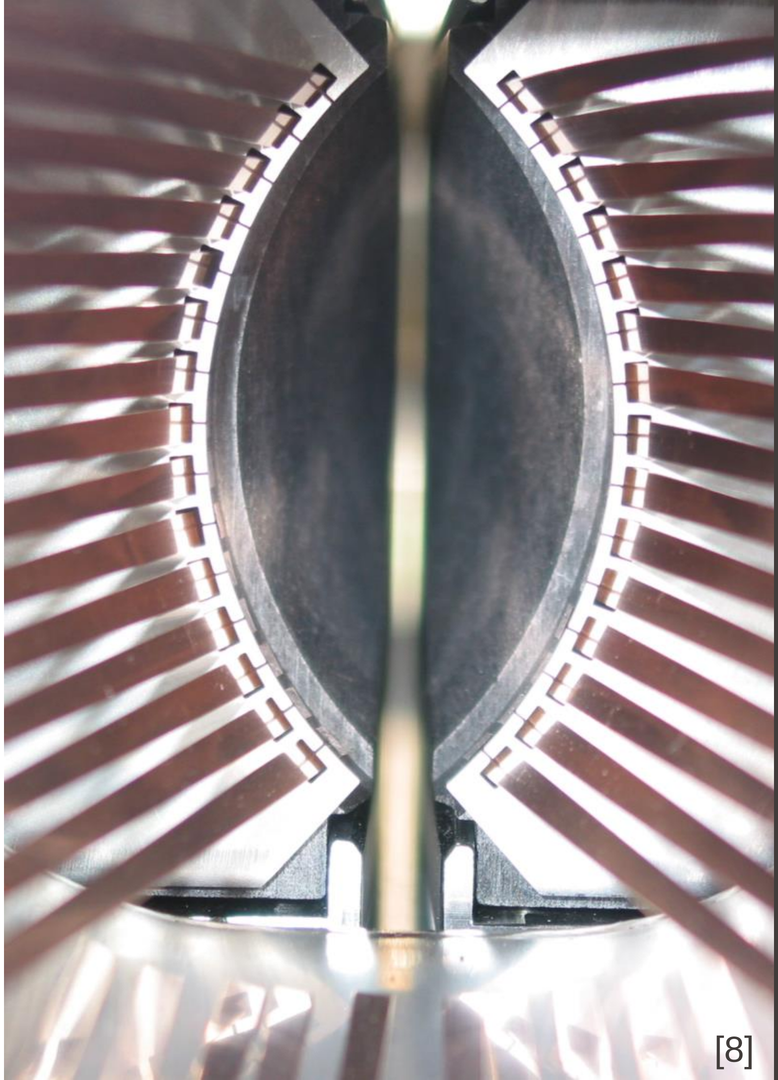
2023 ion run: Proposed configuration

Changes to the collimation system proposed (with respect to 2018):



2023 ion run: Operational experience

- First operational experience with crystals
- Crystal stability issues
  - Energy ramp
  - Reproducibility
  - Orbit oscillation
- Cleaning improvement found
- Successful real-time mitigation of high background signals in ALICE

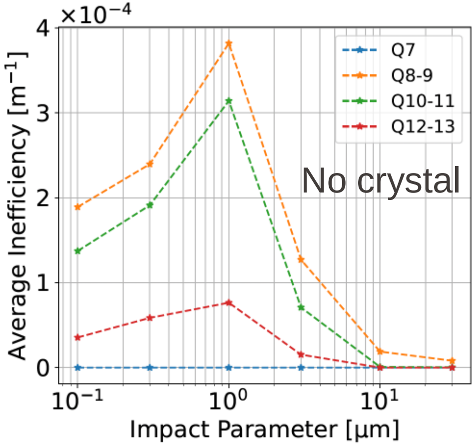

[8]

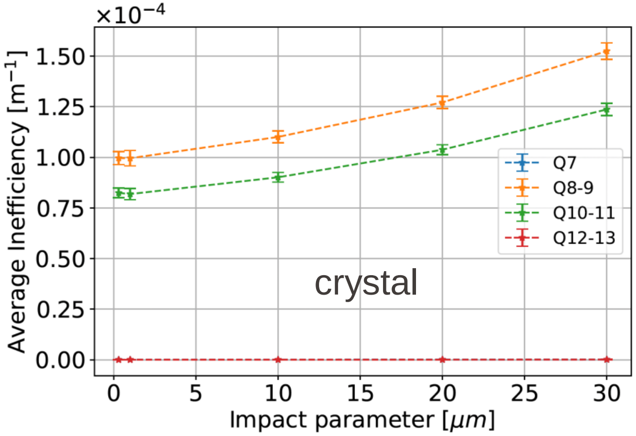
Standard collimation

Impact parameter scan

- Study on different impact parameters was done with impacts on the TCP.

Initial distribution	• 6×10^6 initial lead ions/simulation • 6.8 Z TeV. • Pencil beam • 1 µm impact parameter
Plane	B2H





- It is confirmed that the worst performance is found at 1 µm.
- Above ~3 µm, crystal collimation does not perform better.

Single jaw setup

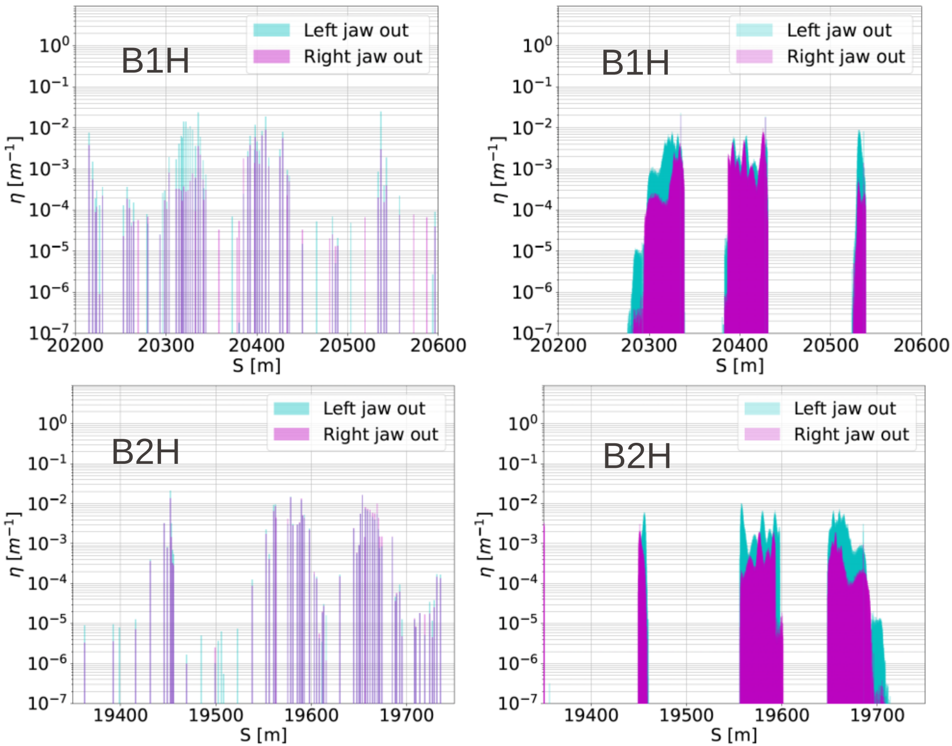
- Comparison of using one single jaw of the H primary collimator.
- Measurement done for both beams in 2018.

Simulation done for horizontal planes:

Initial distribution	• 6×10^6 initial lead ions/simulation • 6.37 Z TeV. • Pencil beam • 1 µm impact parameter
Plane	B1H, B2H

- It was found that only using the left jaw seems to give better performance

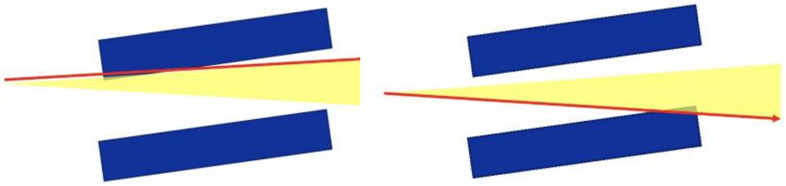
Measurement | Simulation

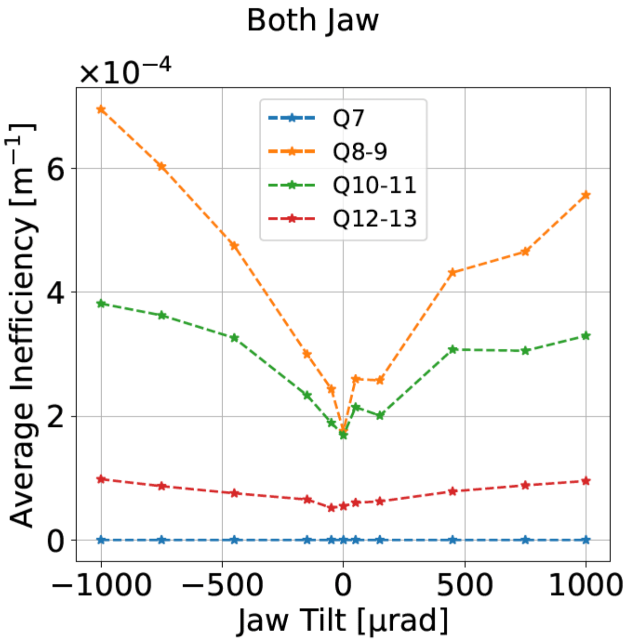


Jaw tilt study

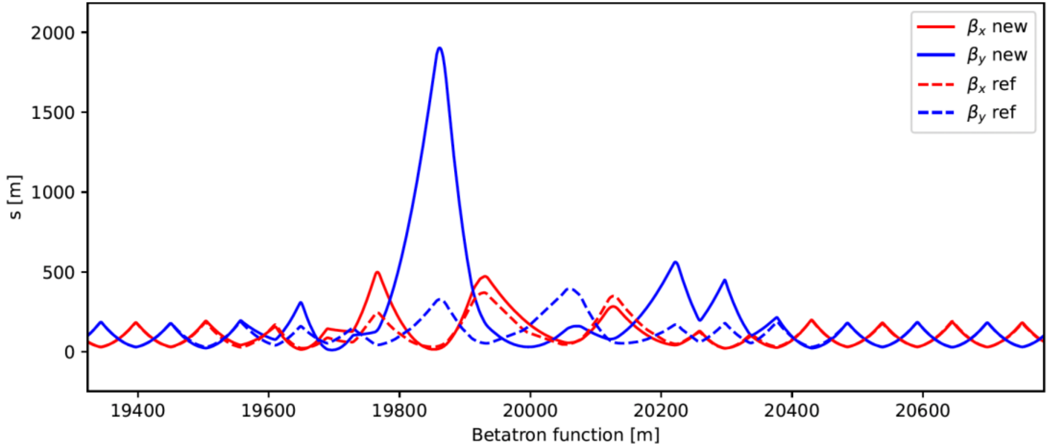
- Study on sensitivity of performance with respect to TCP tilt.
- Two jaws simulated separately, then combined.
- Systematic worsening observed with non-zero jaw tilt angles.

Initial distribution	• 6×10^6 initial lead ions/simulation • 6.37 Z TeV. • Pencil beam • 1 µm impact parameter
Plane	B2H





Optimized optics



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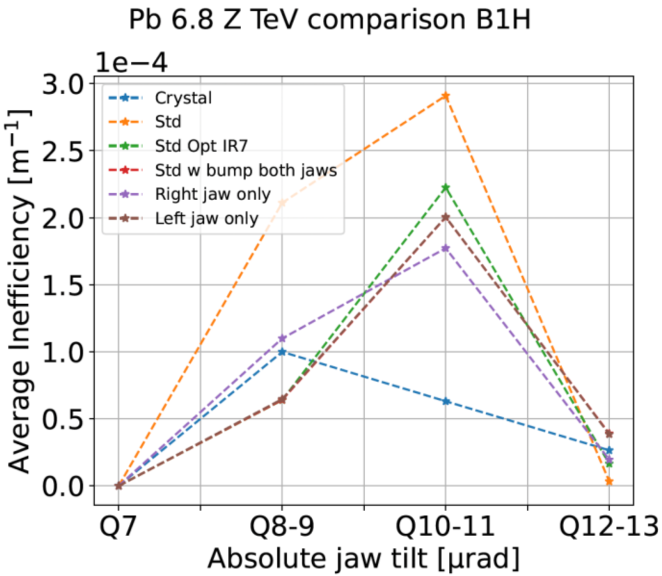
- New optics designed for proton to increase β in IR7.
- Orbit bump also added to increase single-pass dispersion.
- Various combinations were simulated.
- Overall crystal setup still gives the best performance.
- Collimation performance with new optics is better than previous optics.

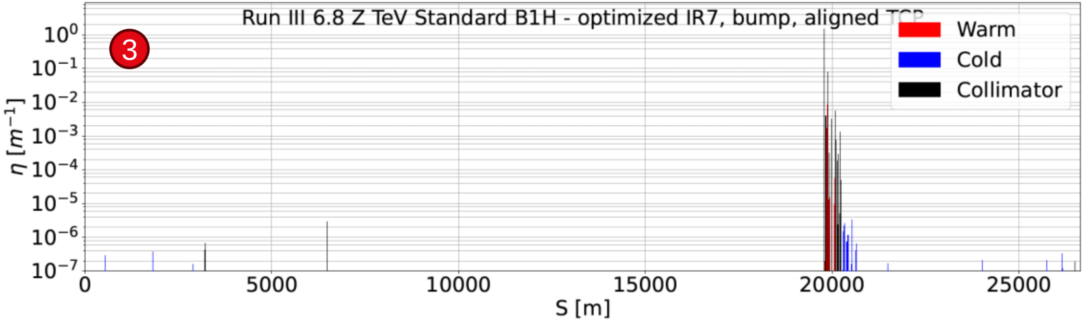


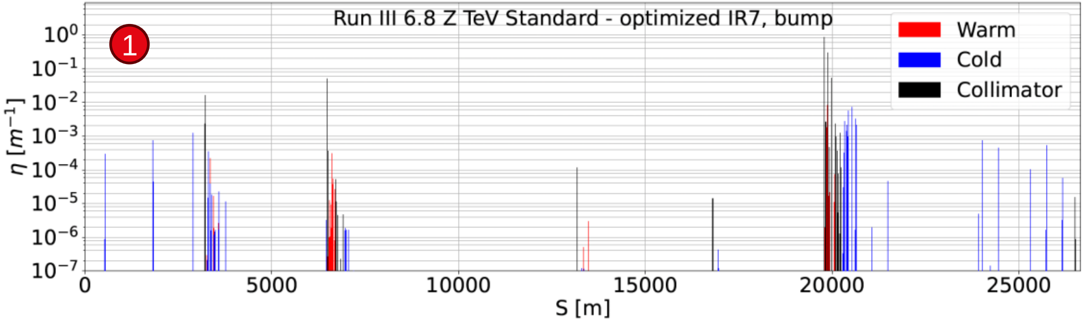
Aligned TCP

- To maximize the distance travelled in the collimator, a simulation with collimator jaws parallel to beam profile was done.
- Same impact parameter kept.

Initial distribution	• 6×10^6 initial lead ions • 6.8 Z TeV. • Pencil beam • 1 µm impact parameter
Plane	B1H

TCP alignment procedure:





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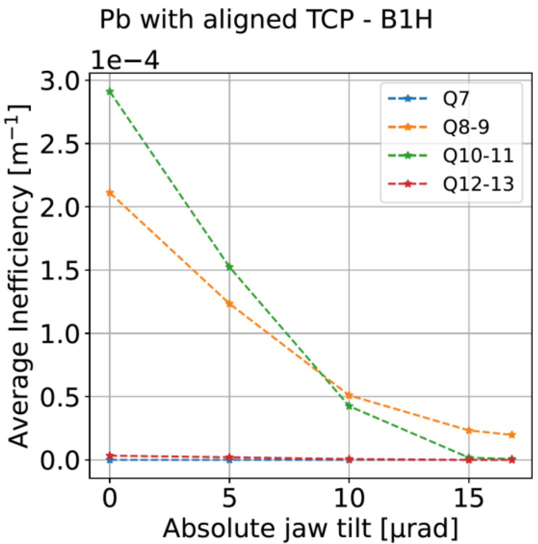
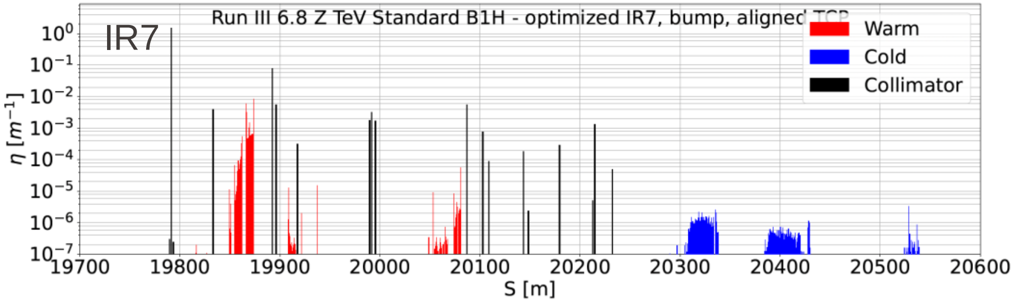
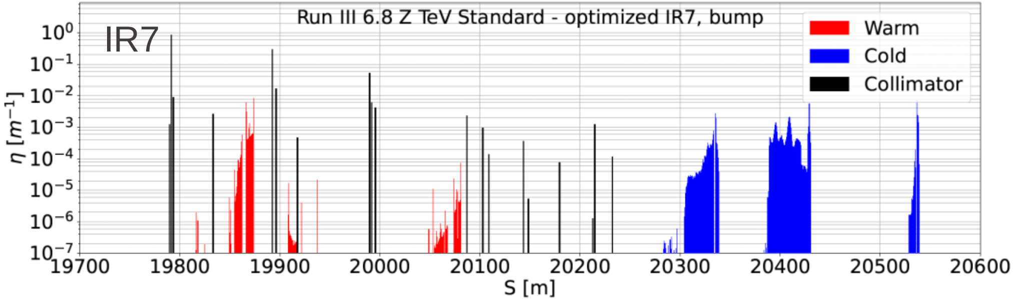
Aligned TCP

- Collimation performance with aligned TCP improves significantly (up to several orders of magnitude).
- Analysis with intermediate tilt angles also show improvement over parallel jaws.







[9]

Future scenarios

EPFL

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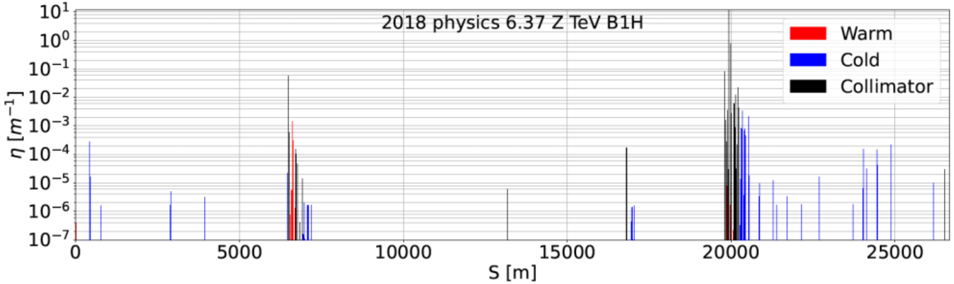
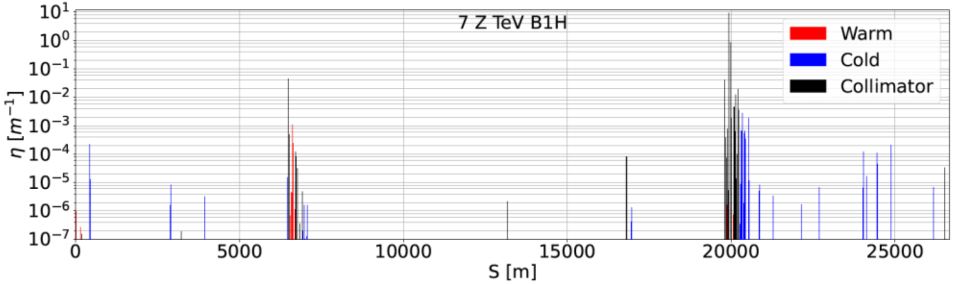
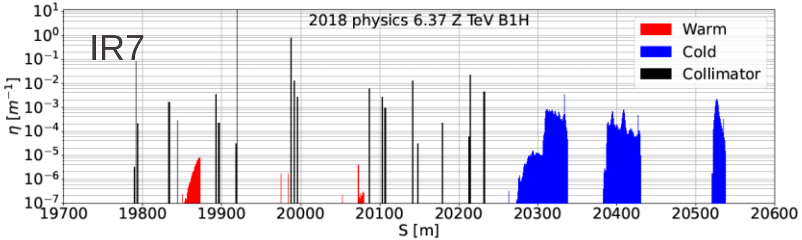
Higher energy case: HiLumi LHC

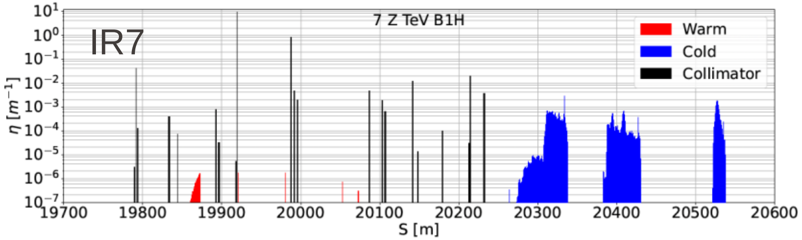
- Crystal collimation has been simulated at HL energy (7 Z TeV).
- No significant worsening thanks to a similar crystal acceptance.

Initial distribution	• 6×10^6 initial lead ions • 7 Z TeV. • Pencil beam • 1 µm impact parameter
Plane	B1H



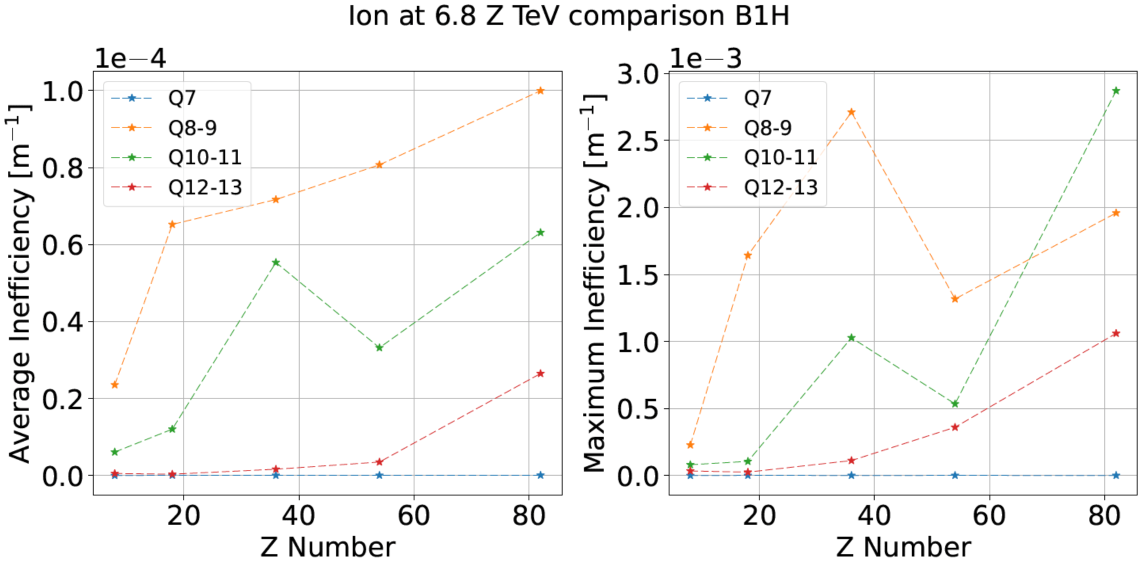






Crystal collimation for other ion species

- Operation with other ion species forecasted for the future.
- Crystal collimation simulated for $^{16}O^{8+}$, $^{40}Ar^{18+}$, $^{84}Kr^{36+}$, and $^{129}Xe^{54+}$.
- An increasing trend of the average inefficiency in the cold loss clusters have been found with increasing Z number.



Conclusion

Crystal collimation is planned for the ion run in Run 3.

A systematic simulation tool is needed.

framework for ion crystal collimation built

benchmark done with results deemed suitable for deployment

Crystal simulation framework used to perform

- Crystal collimation characteristic studies
- Sensitivity and machine failure studies
- Optimization studies
- Setup design for 2023 ion run
- HiLumi prediction
- Light ion predictions

Standard system studies done as backup

Results contributed to 2023 ion run

Thank you

[1]

References

[1] Image: https://home.cern/science/accelerators/large-hadron-collider

[2] Image: https://home.cern/news/news/accelerators/lhc-report-make-way-heavy-ions

[3] Image: https://www.lhc-epistemologie.uni-wuppertal.de/home.html

[4] G. Apollinari, I. BejarAlonso, O. Bruning, P. Fessia, M. Lamont, L. Rossi, and L. Tavian (editors). High-Luminosity Large Hadron Collider (HL-LHC): *Technical Design Report V. 0.1.* CERN Yellow Reports: Monographs. CERN-2017-007-M. CERN, Geneva, 2017. doi: http://dx.doi.org/10.23731/CYRM-2017-004. URL: https://cds.cern.ch/record/2284929.

[5] Marco D’Andrea. *Applications of Crystal Collimation to the CERN Large Hadron Collider (LHC) and its High Luminosity Upgrade Project (HL-LHC)*. PhD thesis, University of Padova, Feb 2021. URL : http://cds.cern.ch/record/2758839. Presented 23 Feb 2021.

[6] D. Mirarchi*. Crystal Collimation for LHC*. PhD thesis, Imperial College, London, Aug 2015. URL: http://cds.cern.ch/record/2036210.

[7] Image: https://home.cern/news/news/accelerators/crystal-cleaning-lhc-beam

[8] Image: https://lhc-collimation-project.web.cern.ch/pictures.php

[9] Image: https://www.ncbj.gov.pl/en/aktualnosci/lhc-mightiest-particle-accelerator-world-ready-run-2

Ion collimation

Challenge: ion fragmentation in collimators (not in protons)

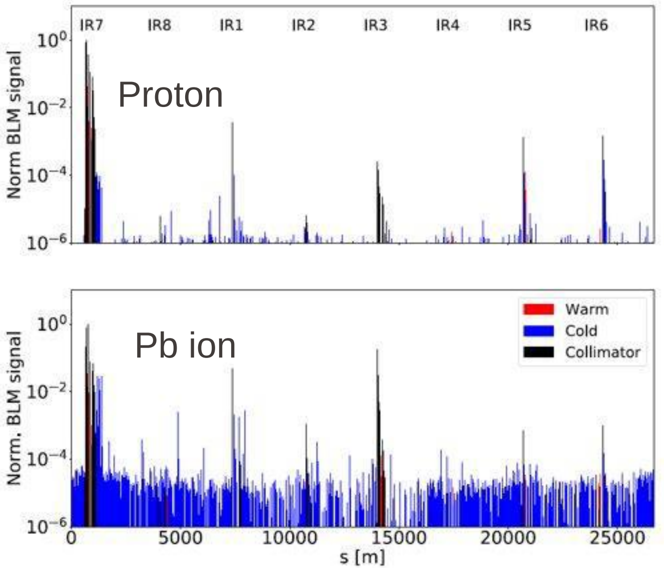
Produce particles with different charge-to-mass ratio

$B\rho = pq$, where B is the magnetic field, ρ is the bending radius, p is the momentum, and q is the charge.

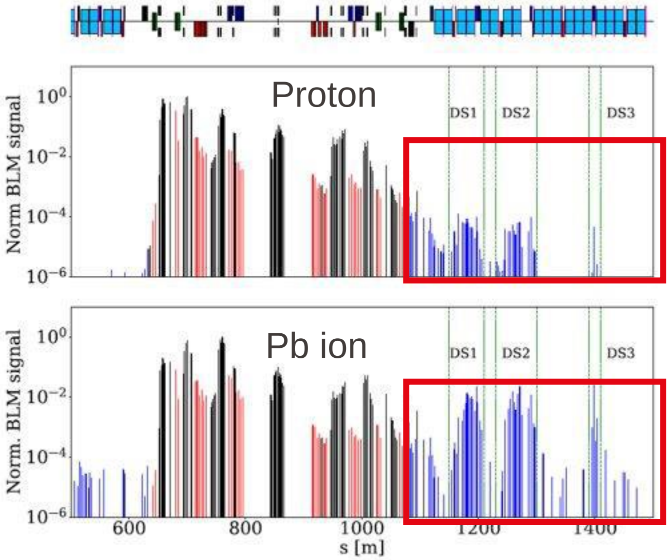
Risks of quench in strong magnetic field regions: e.g. IR7 Dispersion Suppressor (DS)

By comparing the energy deposited by protons and heavy ions along the ring, the performance worsened with Pb ions:

LHC ring:



Only the IR7 section:



Motivation

Crystal collimation for heavy ions is planned for Run 3

No systematic simulation tool exist for ion crystal collimation.

a well-built and benchmarked simulation framework for heavy ions is needed to…

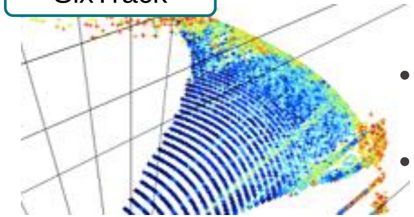
…efficiently study crystal collimation for Pb ions

…explore better collimation configurations with crystal collimators for Run 3

…predict future setups

Existing simulation tools

SixTrack

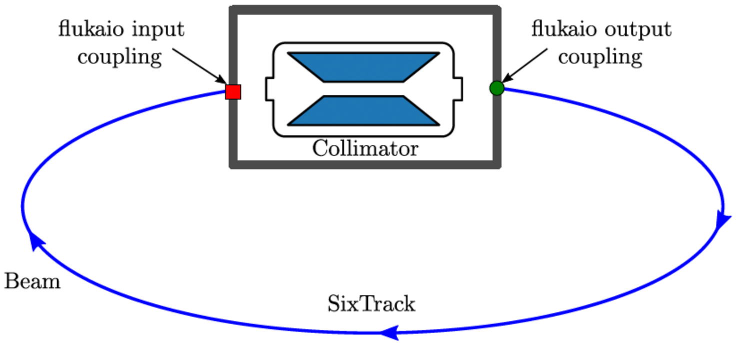


- A 6D symplectic particle tracking code.
- Used for proton and other ion collimation studies.
- Can handle thick and thin elements.

FLUKA

- A general-purpose Monte Carlo code
- Simulate particle-matter interactions, electromagnetic and hadronic showers.

SixTrack-FLUKA Coupling

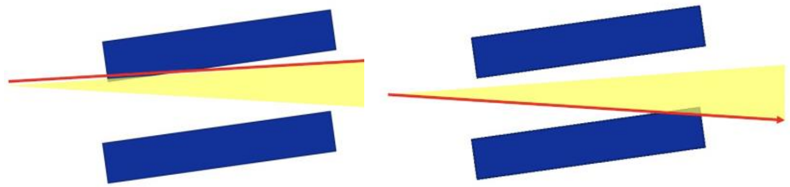


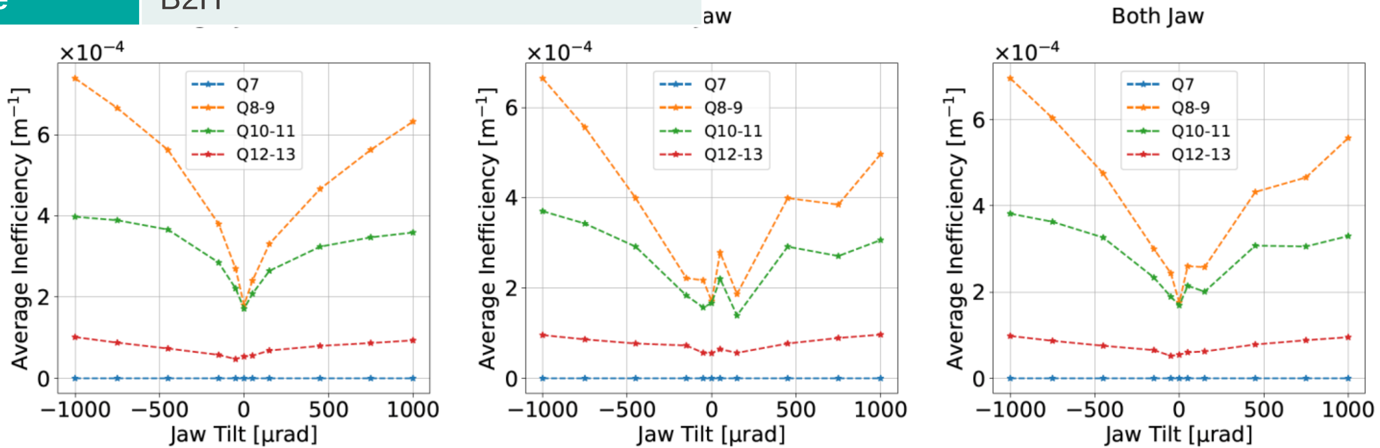
- A simulation framework that actively couples SixTrack and FLUKA.
- SixTrack is used for the magnetic multi-turn tracking.
- FLUKA handles the particle-matter interactions in the collimators.
- Particle information is exchanged at boundaries.

Jaw tilt study

- Study on sensitivity of performance with respect to TCP tilt.
- Two jaws simulated separately, then combined.
- Systematic worsening observed with non-zero jaw tilt angles.

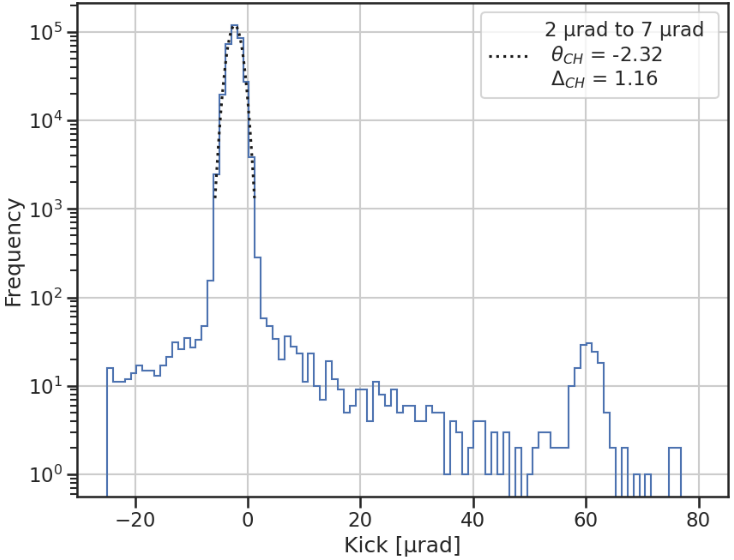
Initial distribution	• 6×10^6 initial lead ions/simulation • 6.37 Z TeV. • Pencil beam • 1 µm impact parameter
Plane	B2H





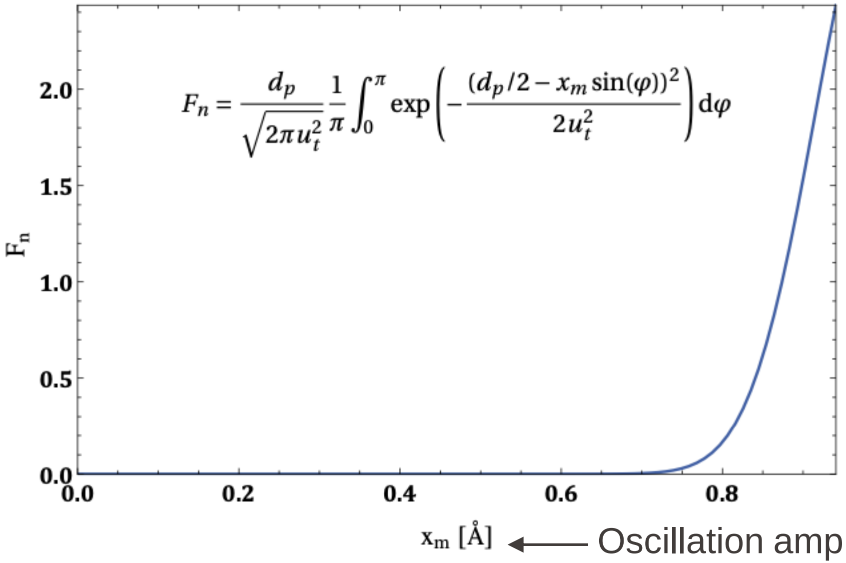
Proton benchmark: Single pass

- Angle division method



Nuclear interaction reduction in crystals

Same scaling factor, F_n, is applied to interaction cross-sections for both ions and protons.



Oscillation amplitude

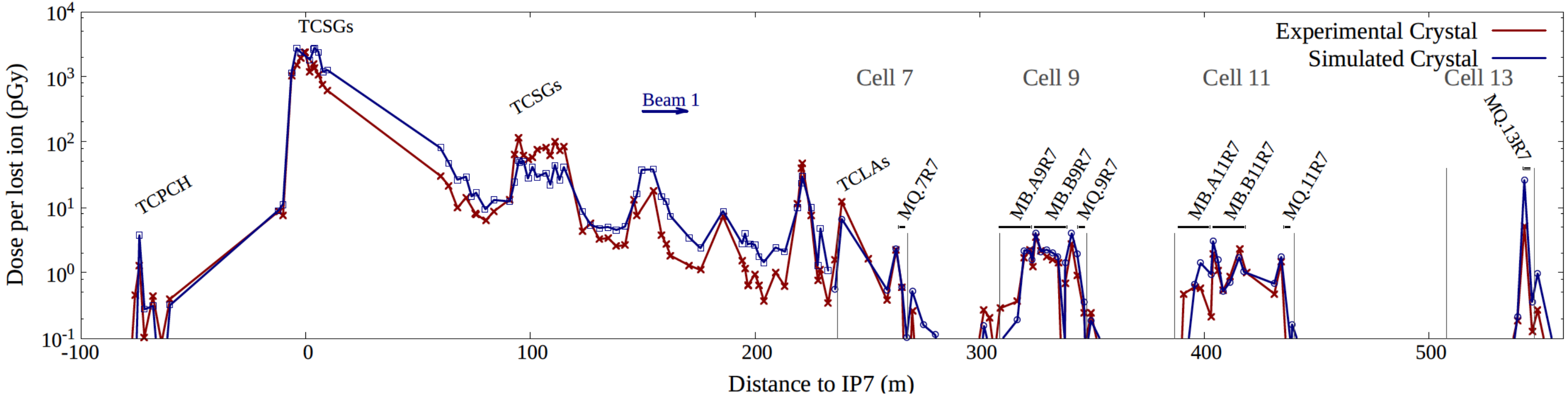
p [GeV/c]	θ_b [μrad]	$\sigma_{x'}$ [μrad]	$\%_{n,am}$	$\%_{n,ch}$	Reduction factor	% chann.	$\%_{n,tot}$
400	0	10	0.667(6)	0.0528(11)	12.6(8)	53.0(1)	0.342(5)
400	150	10	0.663(9)	0.0523(39)	12.8(9)	47.6(1)	0.371(4)
400	150	0	0.655(12)	0.0246(17)	25.4(1.7)	85.7(1)	0.115(7)
7000	0	2.4	0.674(6)	0.138(5)	4.88(19)	53.9(1)	0.385(5)
7000	50	2.4	0.661(5)	0.135(6)	4.90(22)	20.6(1)	0.553(5)
7000	50	0	0.663(6)	0.0787(27)	8.43(30)	54.8(1)	0.343(5)

https://cds.cern.ch/record/1950908/files/CERN-THESIS-2014-131.pdf

R. Cai

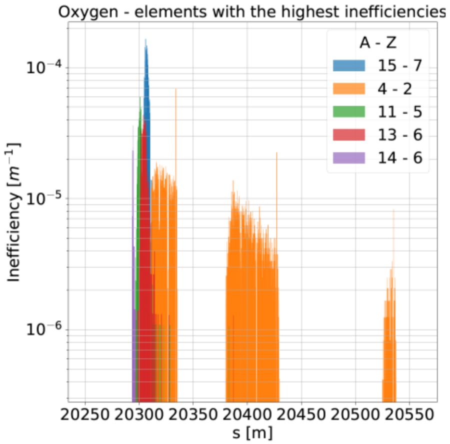
Heavy ion benchmark: Loss pattern

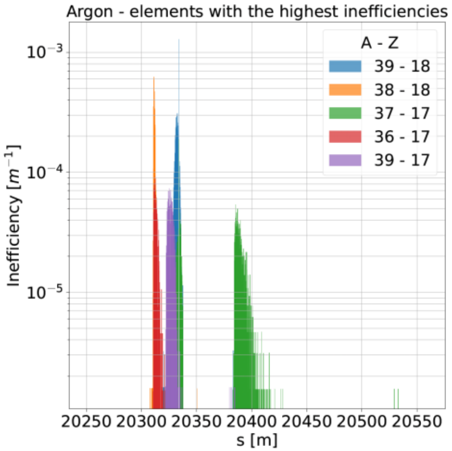
Absolute power deposition benchmark for crystal collimation:

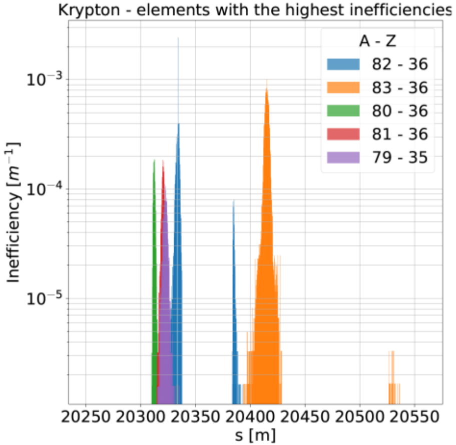


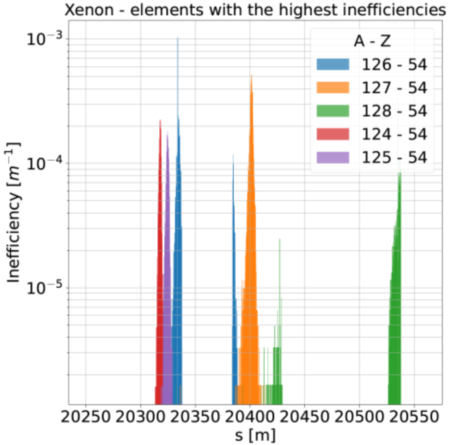
Crystal collimation for other ion species

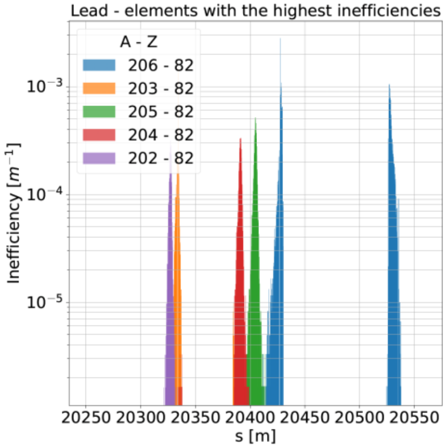
- Isotope distribution







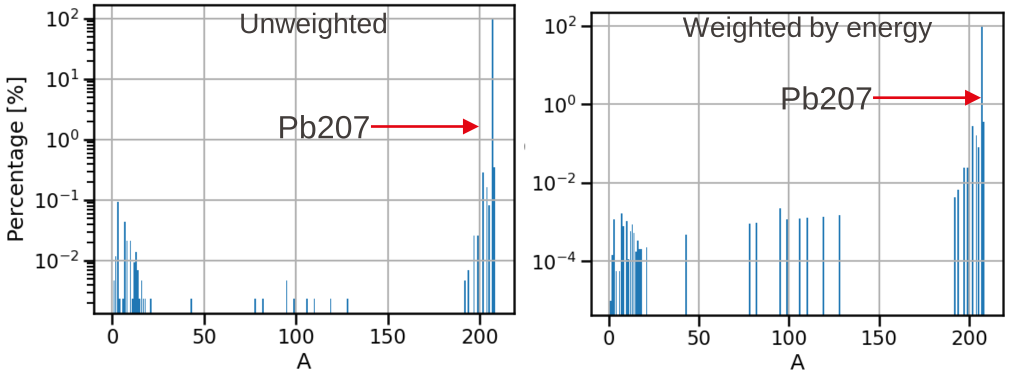


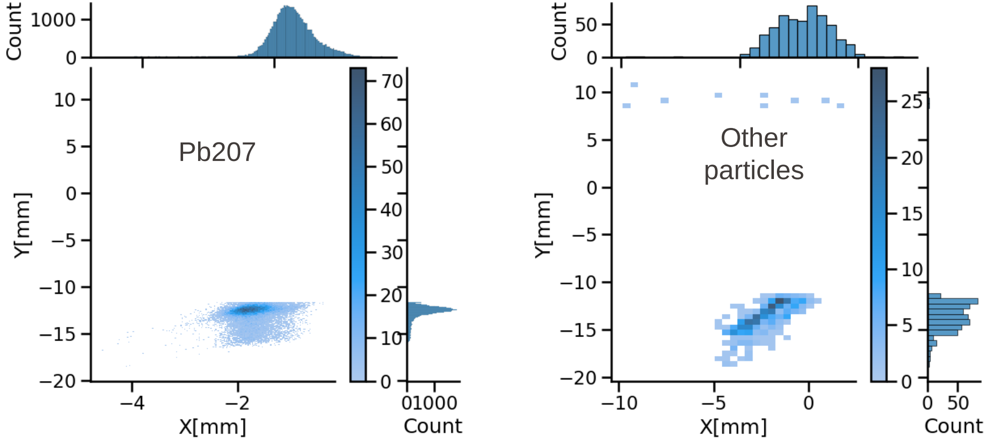


Investigation of the particles lost in TCT

- 98.7% of the particles hitting the TCTs are Pb207.
- Particle impacts peak at 1-2 mm depth. However, the spread covers several mm.
- > 99% of particles impact on the bottom (right) jaw, but a few impacts are seen on the top (left) jaw too. Background signal also dominated by bottom jaw.
- Impacts recorded on TCTs - can be provided as starting conditions in future FLUKA simulation of the shower towards ALICE

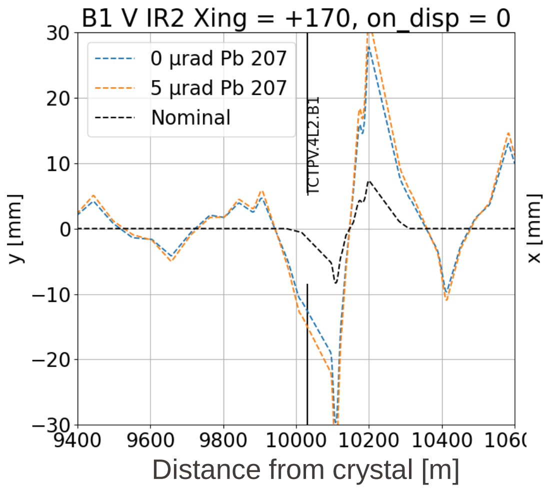
Simulated results:



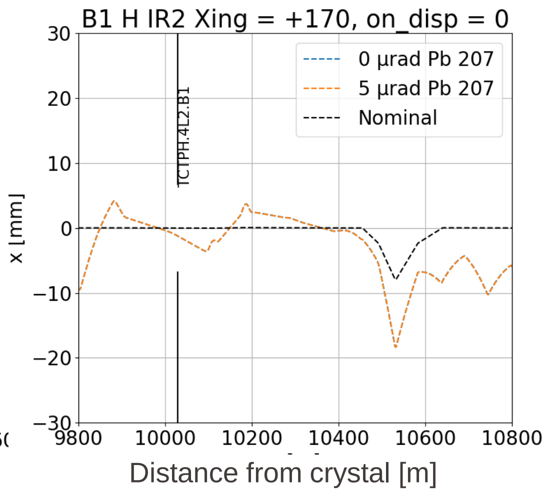


Nominal machine configuration

- ALICE background due to losses at bottom side of TCTPV.4L2.B1.
- Losses mostly constitute of Pb207.
- Losses originate from amorphous interactions and dechanneling in B1V crystal.
- Losses exacerbated due to ~270° phase advance.



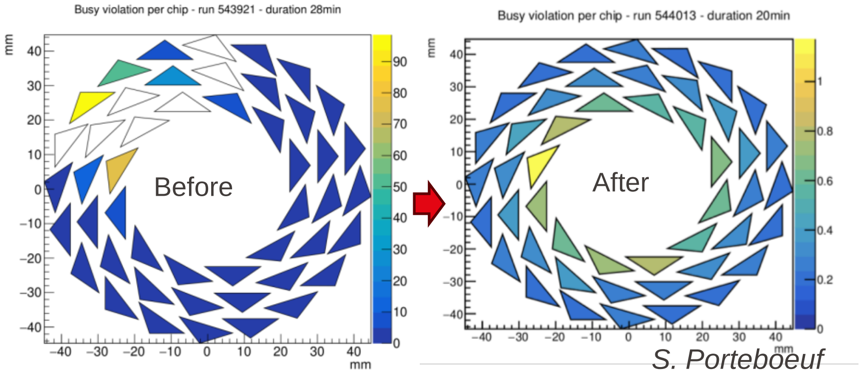
Trajectory in the vertical plane in IR2 of Pb207 exiting from vertical crystal



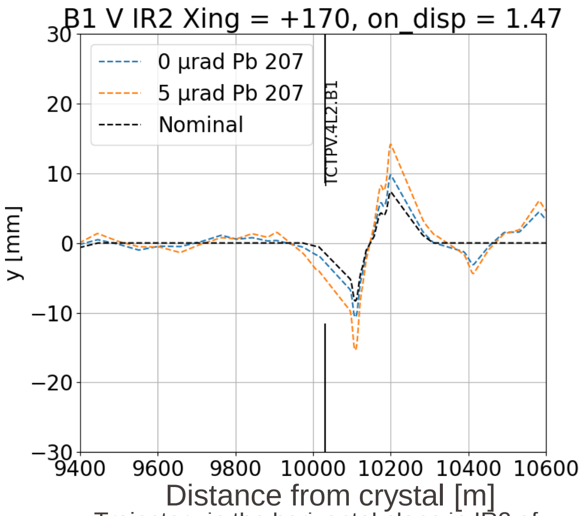
Trajectory in the horizontal plane in IR2 of Pb207 exiting from vertical crystal

After adding orbit bump

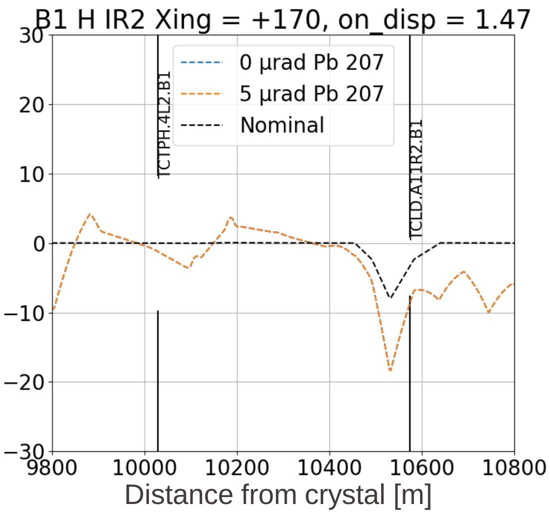
- Local orbit bump can be applied to IR1,2 with the on_disp function used for protons.
- The particles previously responsible for losses in TCTV2 miss this collimator.
- Particles intercepted by TCLD downstream.



Chips of ALICE inner tracking system

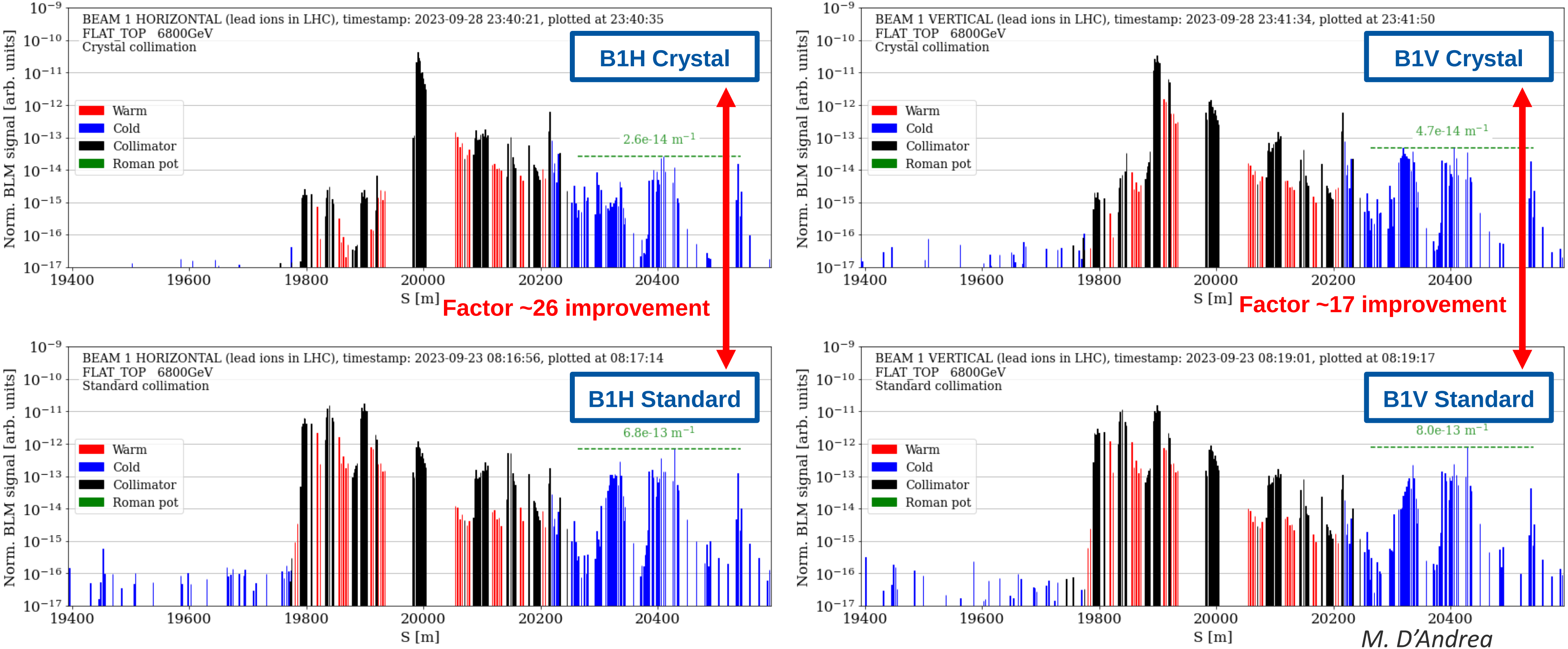


Trajectory in the horizontal plane in IR2 of Pb207 exiting from vertical crystal



Trajectory in the vertical plane in IR2 of Pb207 exiting from vertical crystal

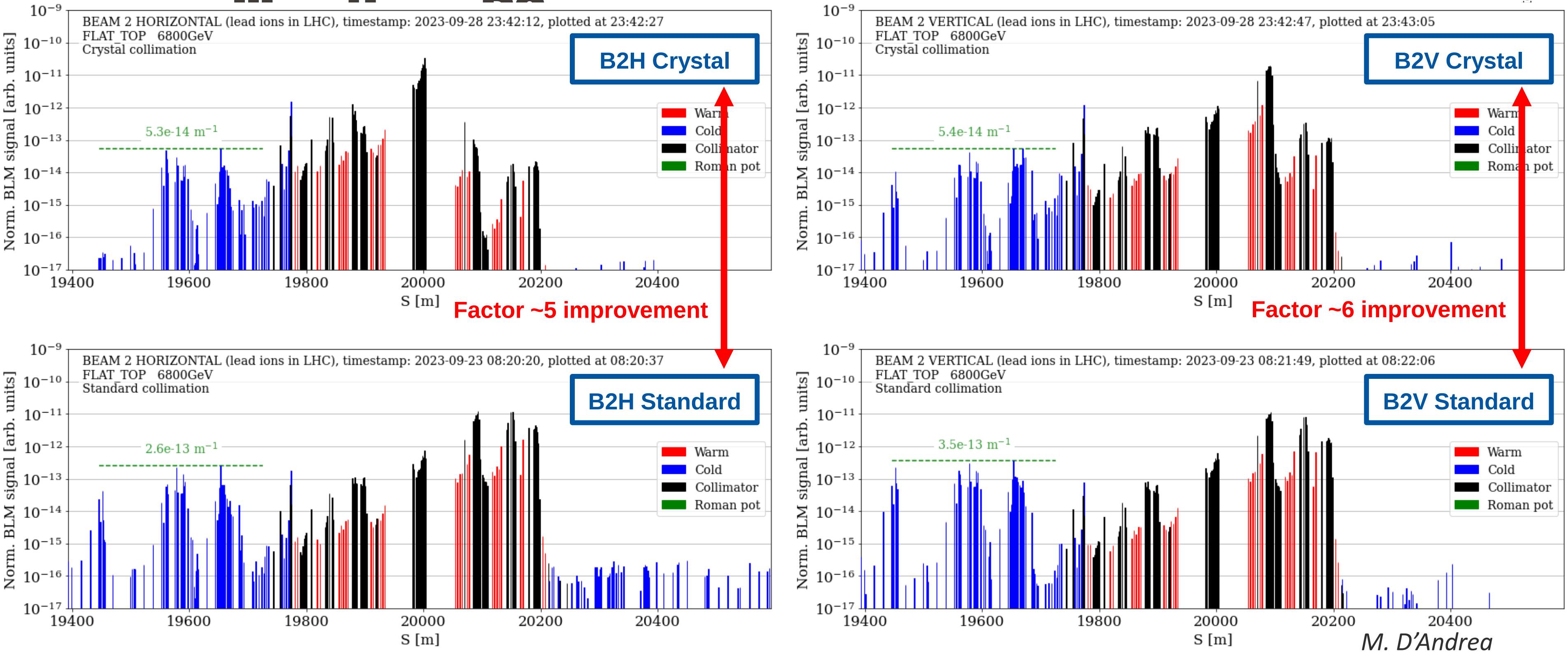
Performance improvement with crystal



M. D'Andrea

EPFL

Performance improvement with crystal



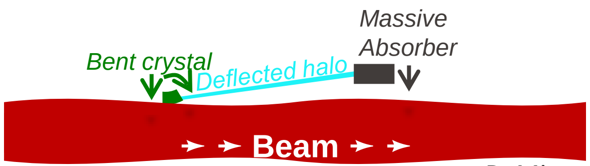
M. D'Andrea

EPFL

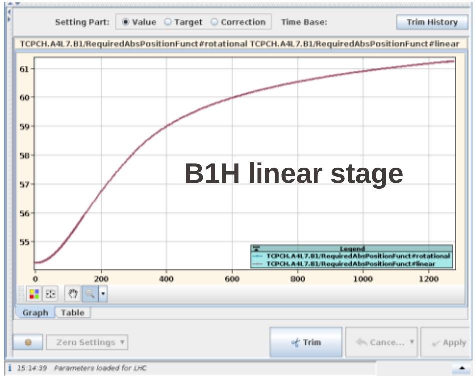
Collimation during energy ramp

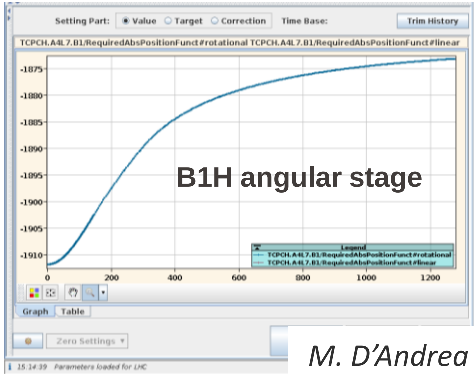
CHALLENGE

- Combined squeeze + ramp
- Change of beam size and divergence during ramp.
- The crystal must follow the beam envelop in transverse and angular position.
- Channeling acceptance reduces from ~10 to ~2 µrad.



D. Mirarchi





M. D'Andrea

SOLUTION

- Reference settings at injection and flat-top used to generate ramp function in control system.
- **Successful functioning achieved during machine development.**

LOSSES DURING ENERGY RAMP

- Important losses observed during operational energy ramp – significant slowdown.
- Crystals not in perfect channeling orientation may have worsened the situation.
- Many mitigations applied…
- Not well understood – investigation in progress.
- More from the collimation side in next slides…

R. Bruce

EPFL

Reproducibility of optimal channeling

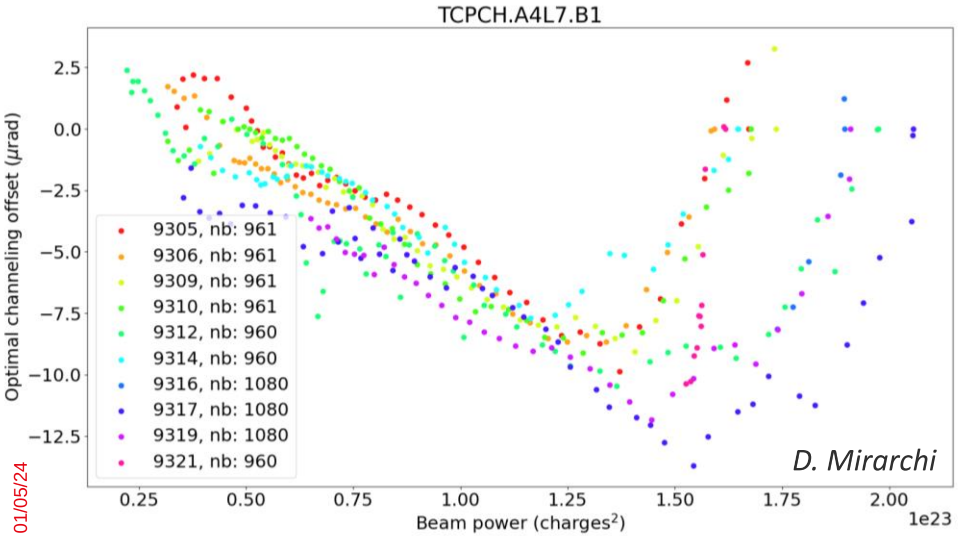
Drifting crystal angle during
- Flat-top
- Ramp (likely, but no monitoring)
- 10 Hz events

Degraded cleaning

Not well understood

Possible dependence on temperature

Mitigations deployed:
- Automatic crystal realignment at top energy
- Ramp function update
- Increase in bunch length



Investigations in progress:
- Detailed analysis
- Simulation and measurement of impedance on spare crystals.
- Component deformation exploration.
- …

Improvement challenges:
- Better real-time control.
- Implementation during energy ramp up.
- …

Collimation for 10Hz events

SITUATION

- 10 Hz orbit oscillations are back for B1H as in 2017-8
- 8 dumps + some "near misses".
- Not fully understood.

WHAT IT MEANS FOR CRYSTAL COLLIMATION

Orbit oscillations means potential impact angle out of crystal acceptance, $\theta_c \sim 2.1$ µrad.

OVERALL

- With crystal collimation could tolerate higher oscillations (40-85 µm) than with standard system.
- Issue not solved yet.
- Possible idea: change collimation hierarchy…

WHAT WE FOUND

- Impact angle changed by:

Orbit angle from oscillations ~ θ_c

+

Orientation change from orbit offset ~ 0.2-0.4 µrad

→ Oscillations brings artificially crystal out of optimal channelling.

- Crystals are at the limit or out of channeling at moment of dump.