Simulations of crystal collimation processes for 6.8 Z TeV lead ion beams at the LHC

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Background and motivation

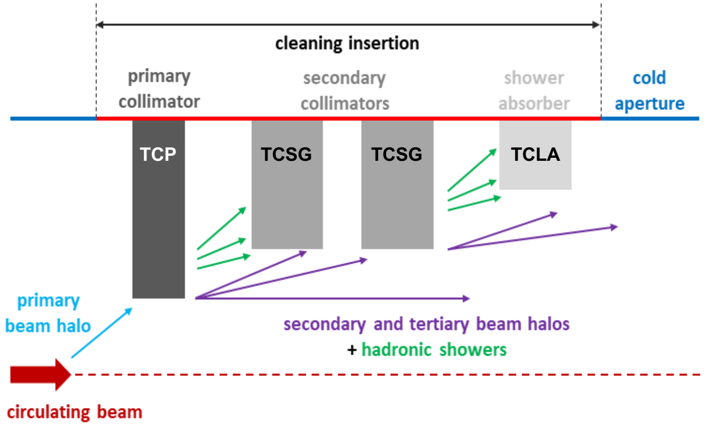
LHC collimation

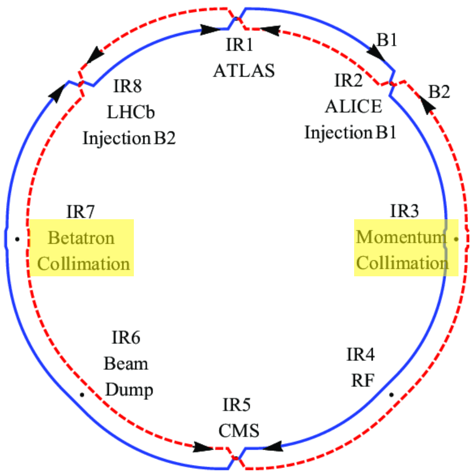
Collimation system

- High amount of stored beam energy circulate in the LHC (up to 410MJ for protons and ~20MJ for Pb).
- Potential risk of quench in the super magnetic regions in the dispersion suppressor region (DS).
- Multi-stage collimation system (50+ per beam) built for protons and ions.

Heavy-ion challenge

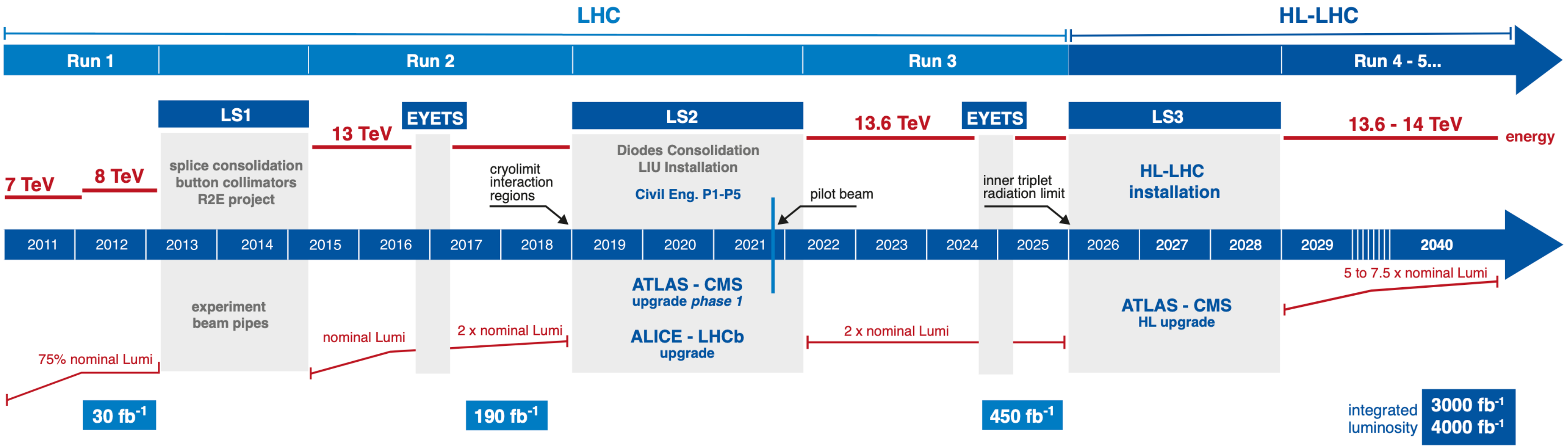
- Ion interaction with collimator material gives rise to fragmented particles with different magnetic rigidities.
- Heavy-ion collimation efficiency is worse.
- Observed and simulated: ~2 orders of magnitude worse performance.





P.D.HERMES

New challenges



For future LHC Pb operations: stored beam energy reaches **20 MJ**

2018: already with lower energy of 12MJ - **numerous beam dumps** from beam loss monitors (BLM)

For design min. beam lifetime - collimation debris induces **power load beyond quench limit** of SC dipoles

Mitigation through **HW upgrade** had to be **deferred**

Deployment of **crystal collimation** as a solution to overcome possible limitations.

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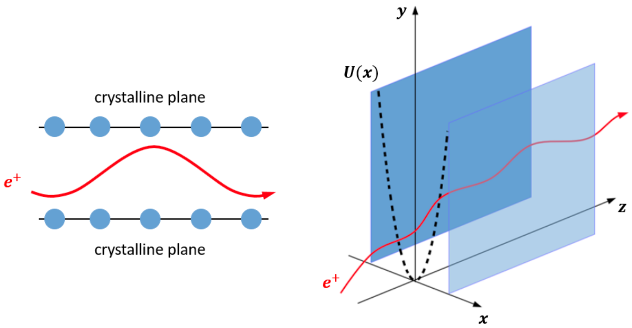
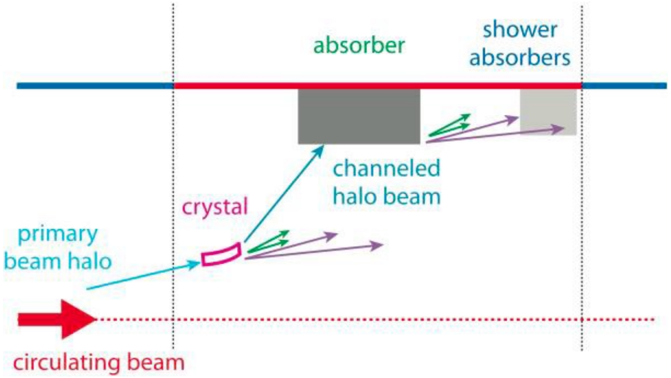
Crystal collimation

A bent crystal is used as primary collimator → It traps halo particles within its crystalline structure → It provides a fixed angular kick → The particles are sent to a downstream absorber





M. D'ANDREA

S. REDAELLI

For the current status of crystals installed, please refer to the presentation by M. D'Andrea in this conference.

Motivation for simulation effort

To…

…better understand measurements and study crystal collimation for Pb ions

…explore better collimation configurations with crystal collimators

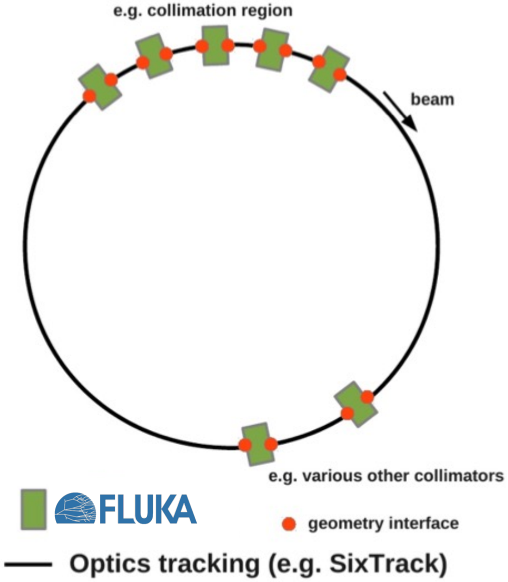
…predict performance in future machine configurations

→ a well-built and benchmarked simulation framework for heavy ions is needed.

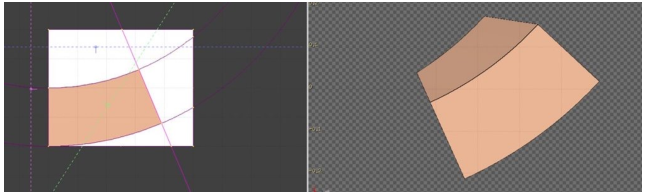
Simulation framework implementation

Main components of the implementation:

- Built upon the existing **SixTrack-FLUKA coupling.**
  - SixTrack is necessary to correctly model the **magnetic tracking** and the **full collimation system** (50+ devices).
  - **State-of-the-art tools** provided by the particle-matter interactions in FLUKA are crucial for ion collimation.
- Uses the **FLUKA crystal** routine*.
- Defined and inserted four **strip crystals** in the FLUKA Element Database for the LHC.
- Created relevant **link files** between the crystals and the accelerator lattice.
- **Updated crystal models** to the latest measurements.



E. SKORDIS



*for details on the FLUKA crystal routine please refer to P. Schoofs' presentation in this conference.

Benchmark of the simulation framework

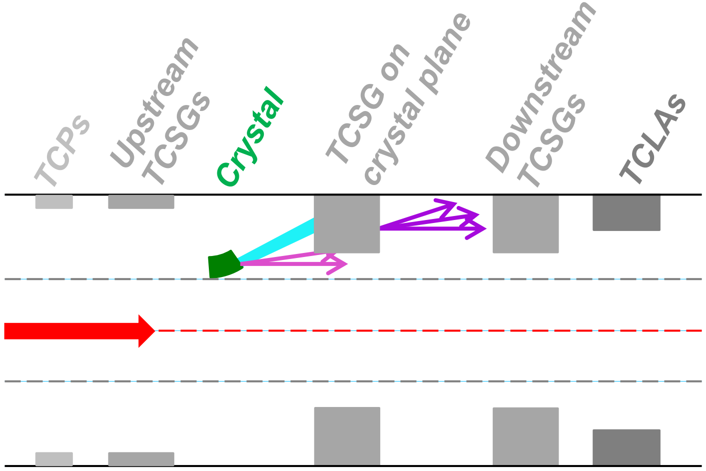
Framework benchmark
Proton

Benchmark configuration:

- 60 million 6.5 TeV proton.
- 2018 at flat-top in the Beam 1 horizontal plane.
- Crystal characteristics :

Bending angle [μrad]	65
Type	110
Material	Si
Length [mm]	4

- Collimation setup:

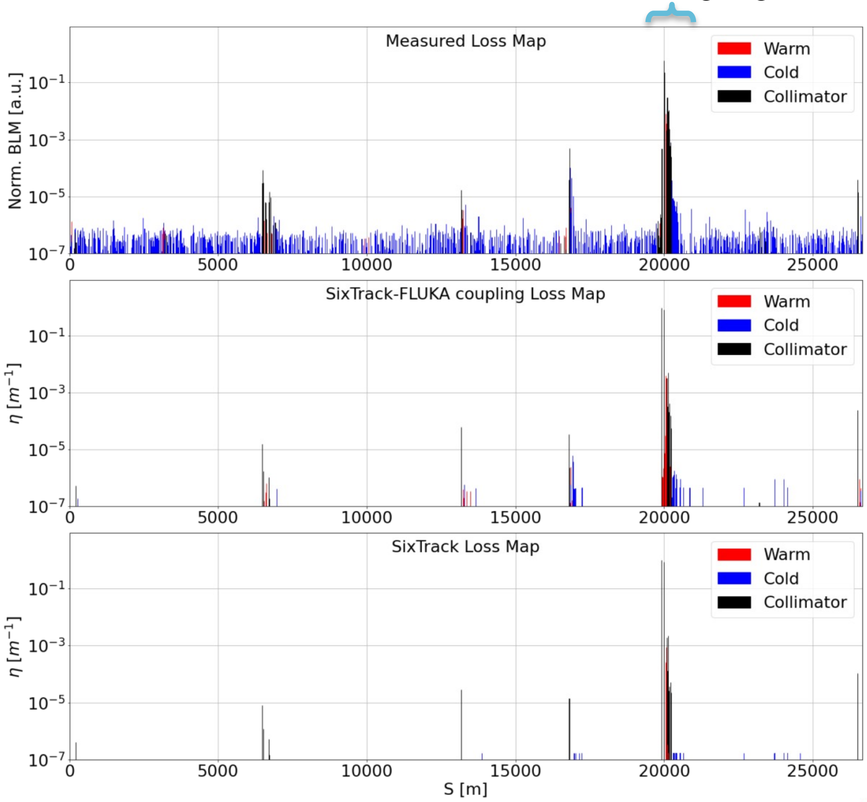


M. D'ANDREA

Framework benchmark Proton

- A loss map benchmark has been done with
  - experimental data;
  - the SixTrack built-in crystal routine (handles protons only)*.
- Loss map:
  - **Measured:** BLM signals normalised to the total loss.
  - **Simulated:** energy deposition at each element nomalised with the total energy lost and element length.

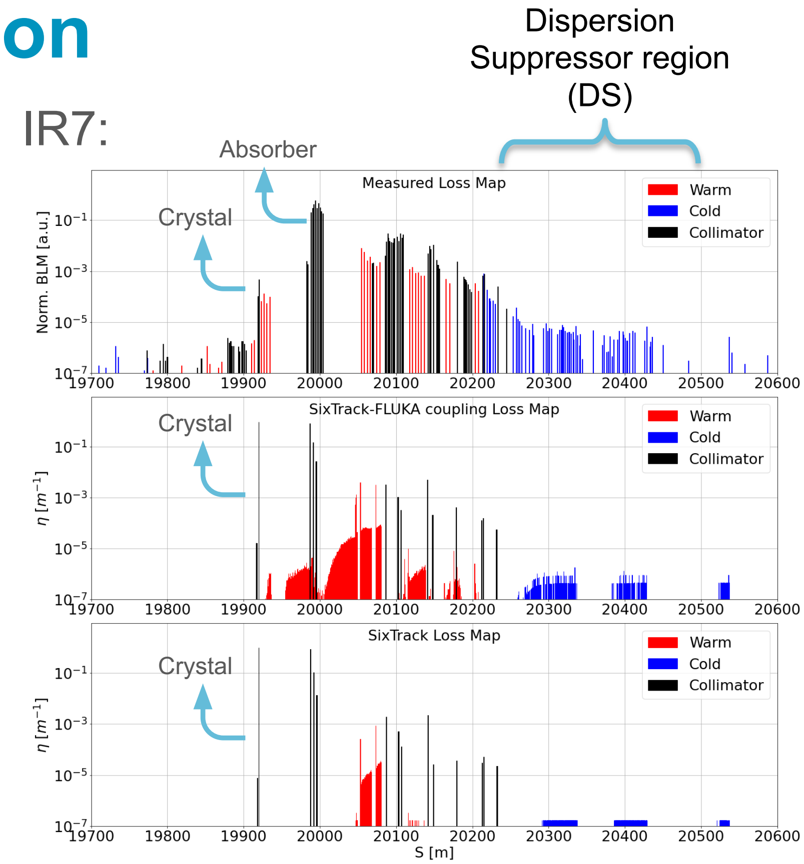
IR7: Cleaning region



*details and benchmarks in:
Crystal implementation in SixTrack for proton beams
A crystal routine for collimation studies in circular proton accelerators
Reducing Beam-Related Background on Forward Physics Detectors Using Crystal Collimation at the Large Hadron Collider

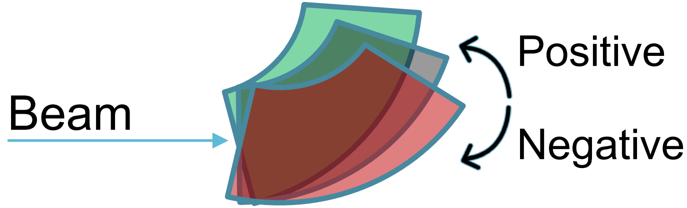
Framework benchmark Proton

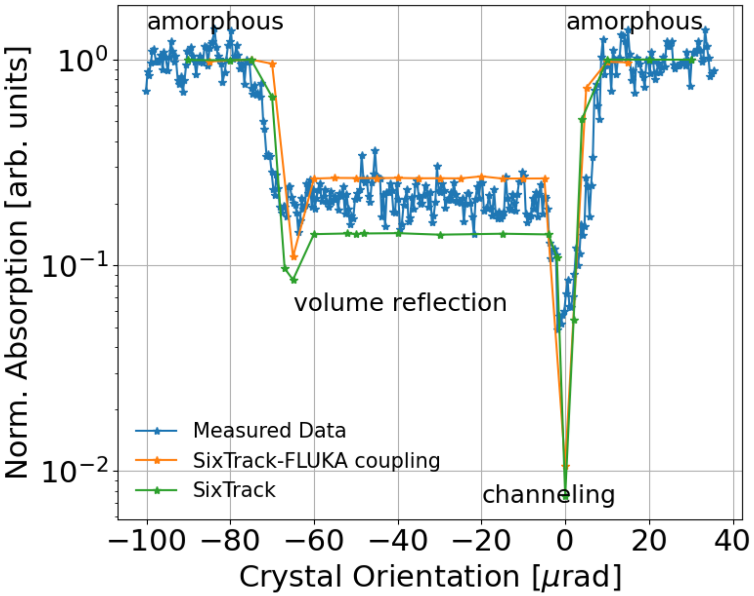
- The simulated peak in the crystal is due to the normalisation to its short length.
- The SixTrack-FLUKA coupling reproduced most of the loss locations correctly around the ring.
- In the dispersion suppressor region, the cold losses are reproduced with around 1 magnitude difference. However, full particle shower propagations were not included.



Framework benchmark
Proton

- In an angular scan
  1. the **orientation** of the crystal **is changed** with respect to the beam direction;
  2. the **BLM signal is recorded** as a function of orientation angle.
- The absorption is **normalised to** the **amorphous** orientation BLM signal.
- Simulation was done with the **full collimation** system and complete **multi-turn magnetic tracking**.
- The two tools have been compared with measured data with
  - overall satisfactory agreement;
  - the main **discrepancy** in the **volume reflection** section which necessitate further investigation. This may be due to the assumption of a perfect machine and effects from other ring collimators.





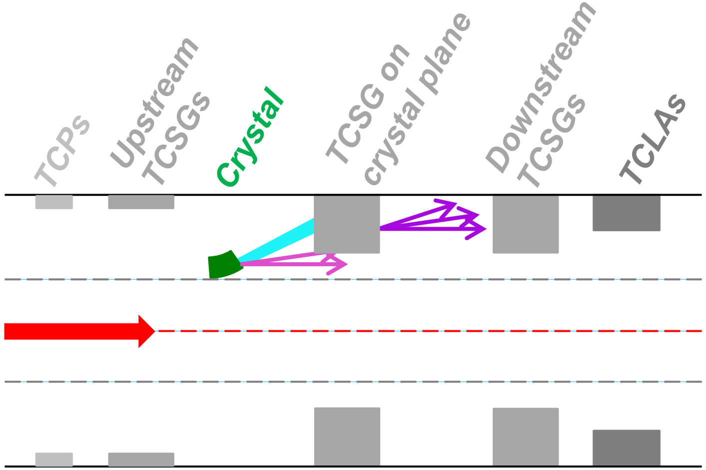
Framework benchmark
Pb ion

Benchmark configuration:

- 6 million 6.37 Z TeV proton.
- 2018 at flat-top in the Beam 1 horizontal plane.
- Crystal characteristics :

Bending angle [μrad]	65
Type	110
Material	Si
Length [mm]	4

- Collimation setup:



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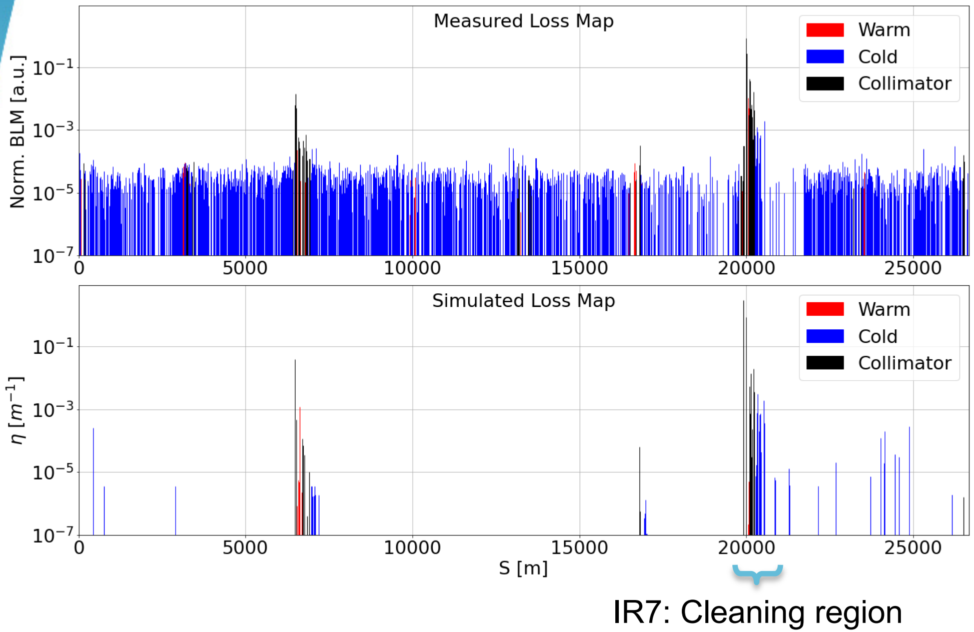
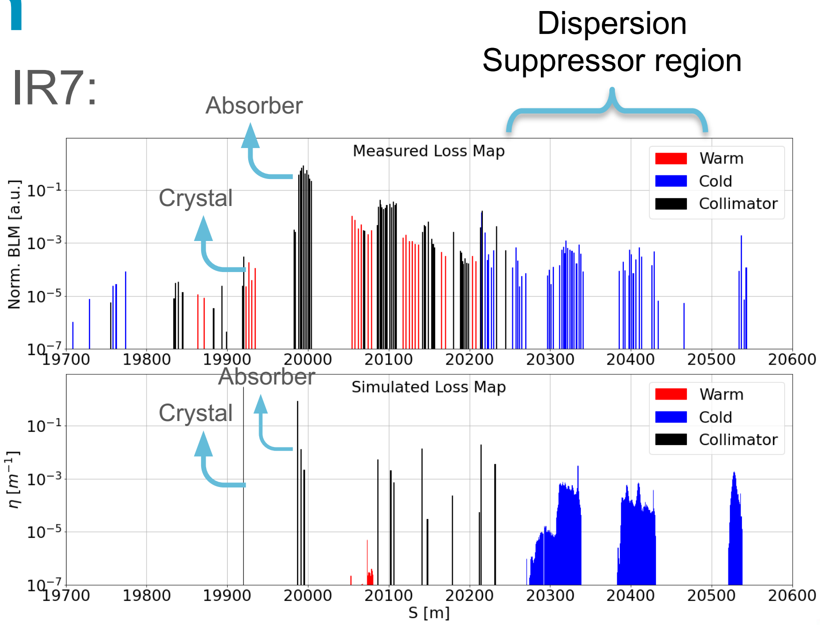
Framework benchmark
Pb ion

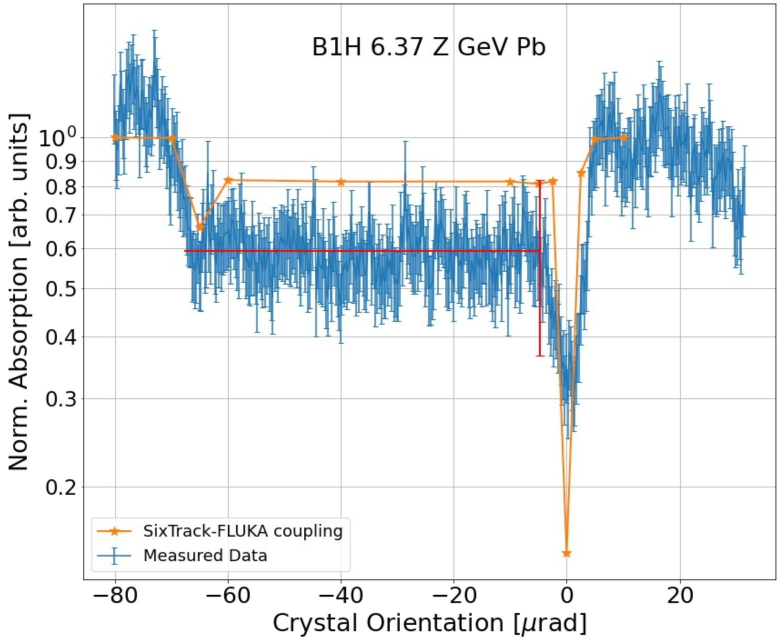




- The order of magnitude **of cold loss is well-reproduced** in the dispersion suppressor region.
- Highest losses in the absorber. Peak in simulated crystal loss is due to length normalisation.

Framework benchmark
Pb ion

- An angular scan benchmark for Pb ions at 6.37 Z TeV reveals a good agreement.
- The volume reflection absorption level is higher than the observed mean.
- Simulation assumes perfect machine conditions.



The horizontal and vertical red lines represent respectively the mean and 2 standard deviations of the volume reflection.

Applications:
1) Simulation framework used for optimization

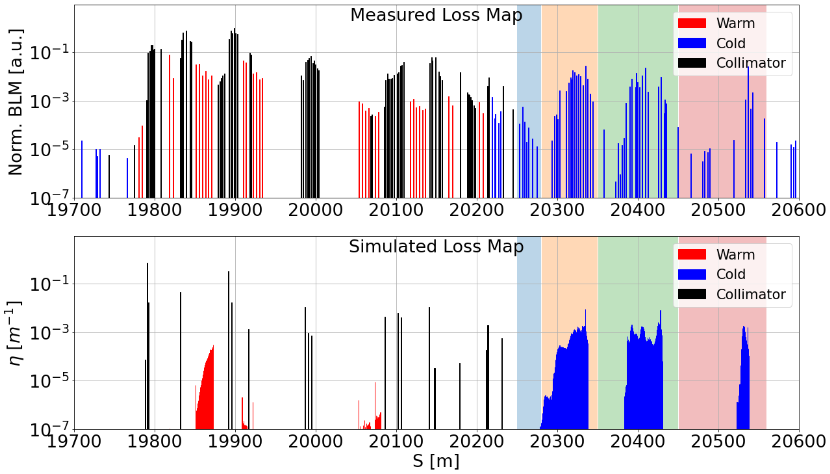
Crystal operational scenario comparisons

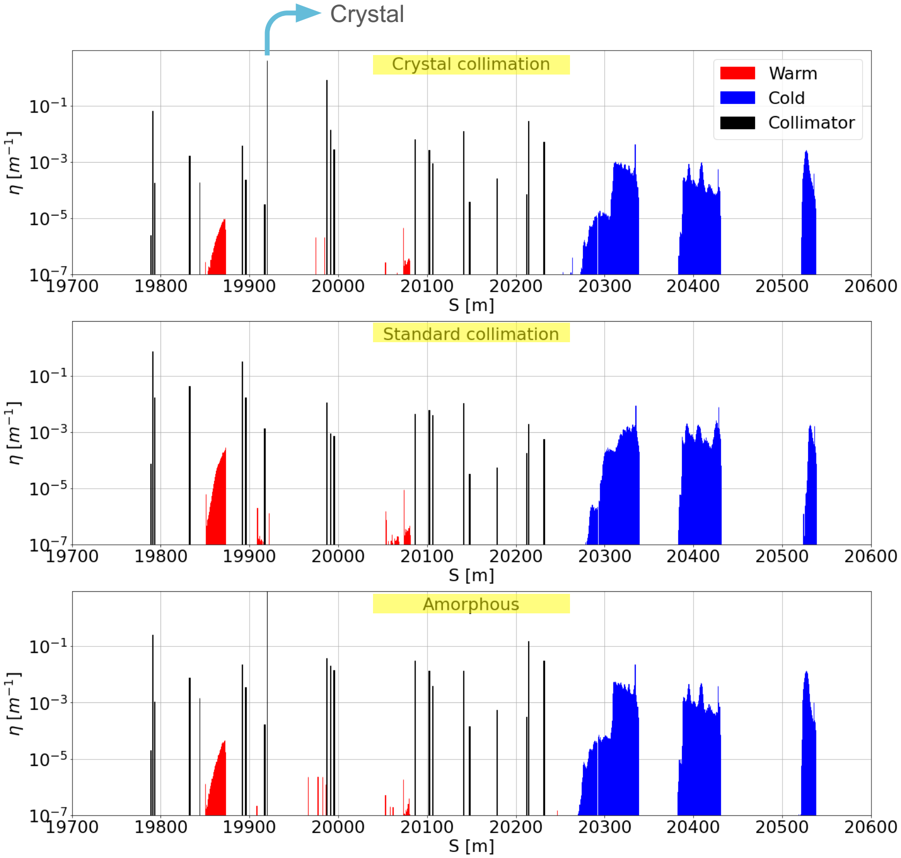
- The framework has also been used to compare different operational scenarios:
  - **Standard** collimation setup
  - Collimation setup with **crystal in optimal orientation**
  - Collimation setup with **crystal in amorphous orientation**
- The simulations follow the configuration of the 2018 physics Pb ion run.
- These simulations are useful to
  - evaluate the improvement of a collimation system with crystals starting from simulated data,
  - understand the risk in case of crystal failure or misalignment during the high-intensity operation at the LHC (critical for avoiding quenches or even damage at the LHC.

Crystal operational scenario comparisons

Beam 1:

Standard collimation





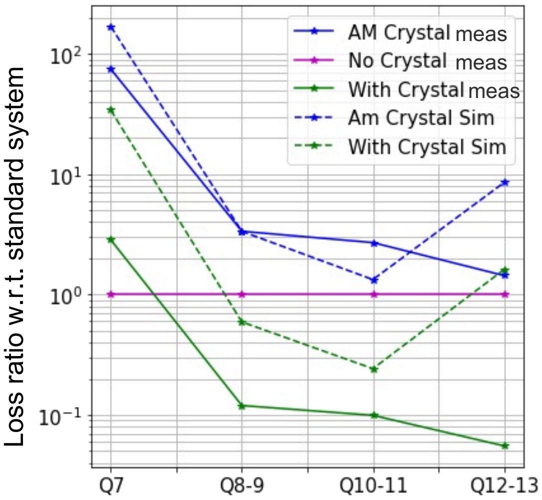
Crystal operational scenario comparisons

- **Losses are normalised to** the respective simulated or measured data with the **standard setup** (purple).
- **General trend** of performance hierarchy among the three configurations is **reproduced** by simulation.
- The simulated **amorphous** configuration also gives a **worse performance** than the standard system.

Simulation can be used for approximate predictions on future crystal configurations

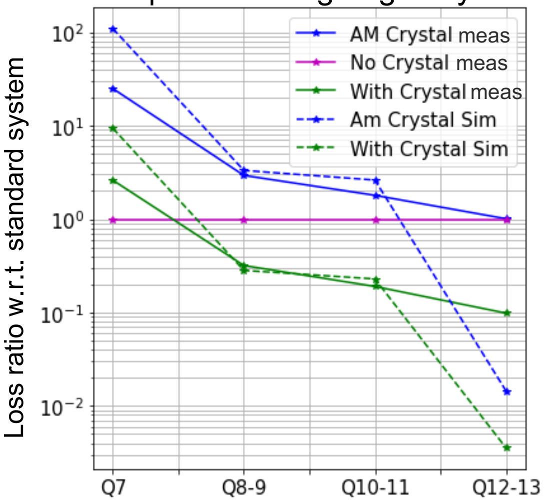
Beam 1 horizontal

65 μrad bending angle crystal



Beam 2 horizontal

36 μrad bending angle crystal



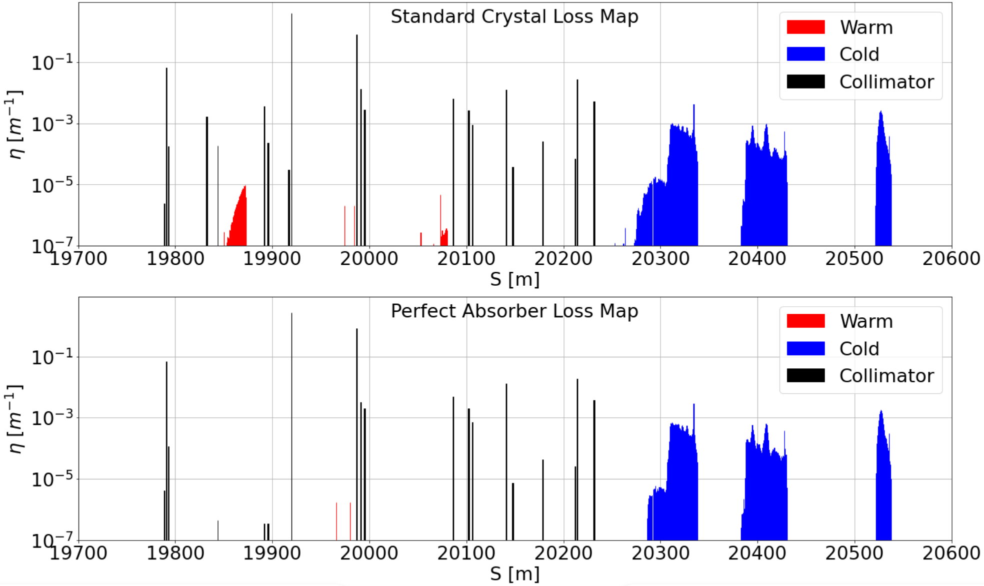
--- Dashed lines are the corresponding simulations for the measurement shown in the same color.

Applications:
2) Simulation framework used to better understand measurement results

Perfect absorber study

To know → How much DS losses come directly from the crystal → We can → Simulate with all collimators as black absorbers except for the crystal

Perfect absorber study



The small changes in the DS region between the two setups

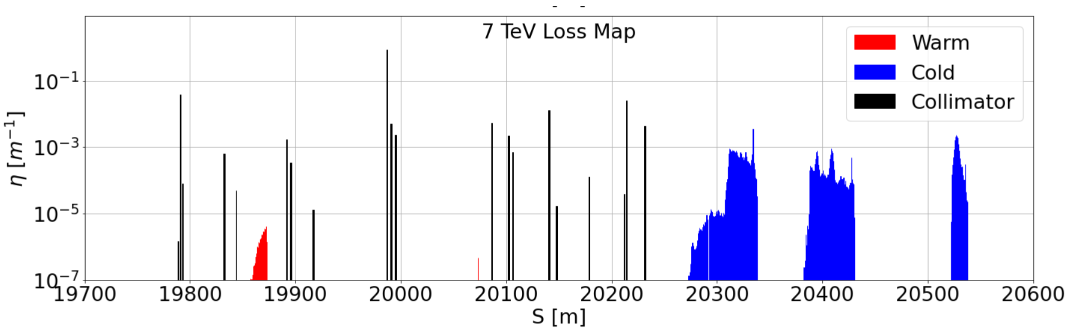
→

direct leakage from the crystal is by far dominating in Pb cleaning.

Applications:
3) Simulation framework used to predict

7 Z TeV Pb ion simulations

- Simulation at 7 Z TeV with detailed shower propagation finds that the crystal collimation is able to maintain **power density below** the HL-LHC quench **limits**.
- Presently, we are working on demonstrating this experimentally.



Conclusions

- A simulation framework has been built for heavy-ion crystal collimation: Unprecedented for a machine with the collimation systems of the complexity used in the LHC!
- The LHC loss pattern and angular scans have been benchmarked for protons and Pb ions with good agreement and can be used to study and optimize the performance in future configurations.
- The tool has been used to reproduce the enhanced collimation efficiency coming from the crystal collimator for Pb ions.
- Thanks to this simulation framework, it was possible to understand that direct leakage from the crystal contributes greatly to DS losses.
- Future scenarios such as 7 Z TeV Pb ions have been simulated successfully with crystals.

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Thank you!

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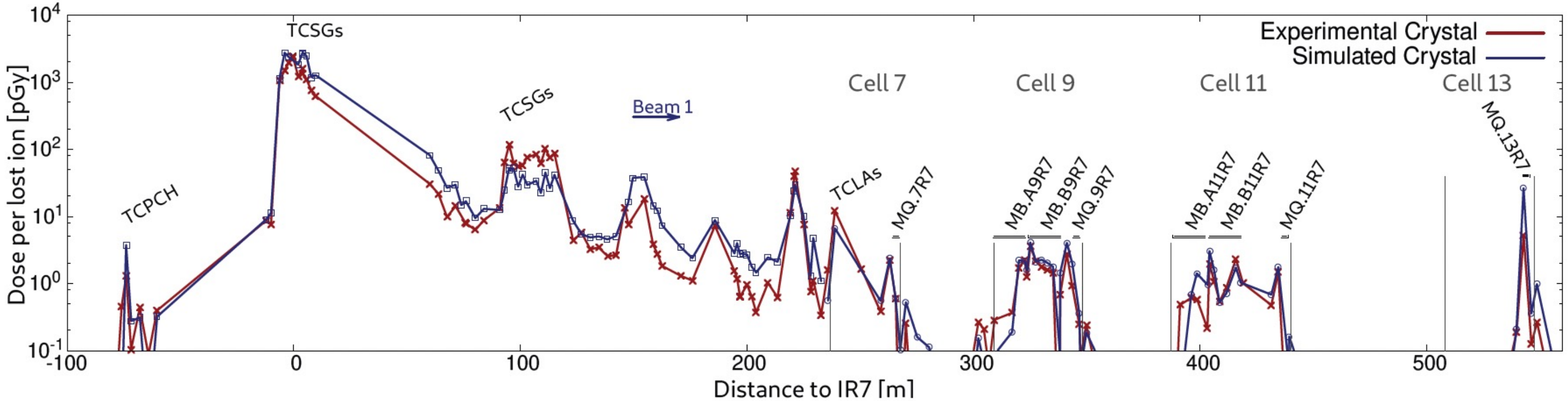
Backup

Power deposition benchmark for ion crystal collimation



- Simulated and experimental BLM signals for crystal-based Pb collimation in IR7 (6.37 Z TeV). The beam direction is from left to right.
- According to the latest analysis, the power deposition level will stay below the quench level.

J. B. POTOINE

Experimental evidence of crystal efficiency

Global leakage ratio: $\frac{\max \eta_c^{STD}}{\max \eta_c^{CRY}}$

where $\max \eta_c^{STD}$ and $\max \eta_c^{CRY}$ are the maximum cleaning inefficiency for the standard and crystal collimation.

Results of 2018 cleaning measurements with Pb ions

Crystal	Maximum normalized BLM signal [a.u.]		Global leakage ratio
	Standard	Crystal	
B1H	$(5.81 \pm 1.03) \cdot 10^{-13}$ Q8-9	$(7.30 \pm 0.15) \cdot 10^{-14}$ Q8-9	8.0 ± 1.4
B1V	$(1.95 \pm 0.07) \cdot 10^{-13}$ Q8-9	$(6.39 \pm 0.05) \cdot 10^{-14}$ Q12-13	3.1 ± 0.1
B2H	$(2.76 \pm 0.39) \cdot 10^{-13}$ Q12-13	$(7.89 \pm 0.78) \cdot 10^{-14}$ Q8-9	3.5 ± 0.6
B2V	$(2.25 \pm 0.01) \cdot 10^{-13}$ Q8-9	$(1.46 \pm 0.36) \cdot 10^{-13}$ Q8-9	1.5 ± 0.4

All crystals have been replaced

M. D'ANDREA