First operational use of crystal collimation at the Large Hadron Collider with high intensity and high energy heavy-ion beams

D. Mirarchi, O. Aberle, A. Abramov, R. Bruce, R. Cai, M. Calviani, M. D'Andrea, Q. Demassieux, K. Dewhurst, M. Di Castro, L. S. Esposito, S. Gilardoni, P. D. Hermes, B. Lindstrom, A. Lechner, E. Matheson, J.-B. Potoine, S. Redaelli, G. Ricci, V. Rodin, R. Seidenbinder, S. Solis Paiva, L. Bandiera, V. Guidi, A. Mazzolari, M. Romagnoni, M. Tamisari, Y. Gavrikov, Y. Ivanov

Channeling 2024, 9th September 2024, Riccione, Italy

Outline

Outline

I. Introduction
II. Operational deployment
III. 2023 heavy ions run
IV. Conclusions

Introduction

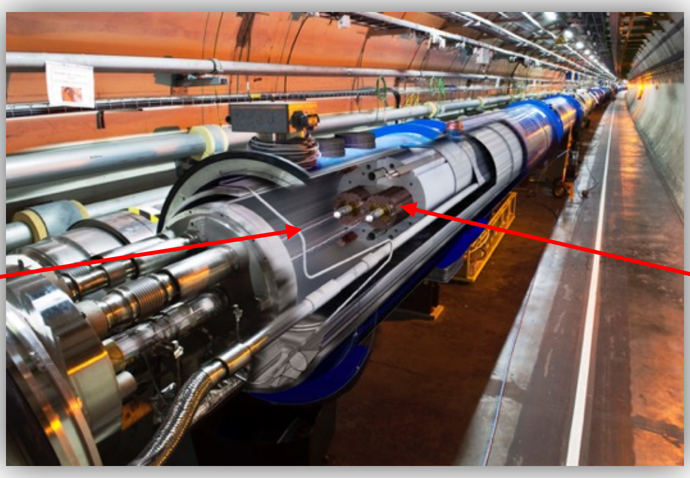
- *The LHC: biggest and most powerful particle accelerator ever built*

  → What does it mean?

Stored energy

LHC reached ***> 400 MJ***

Airbus A320 at ~110 km/h



Very sensitive machine:
~ 10^{10} between stored energy and quench limit!

Quench limit

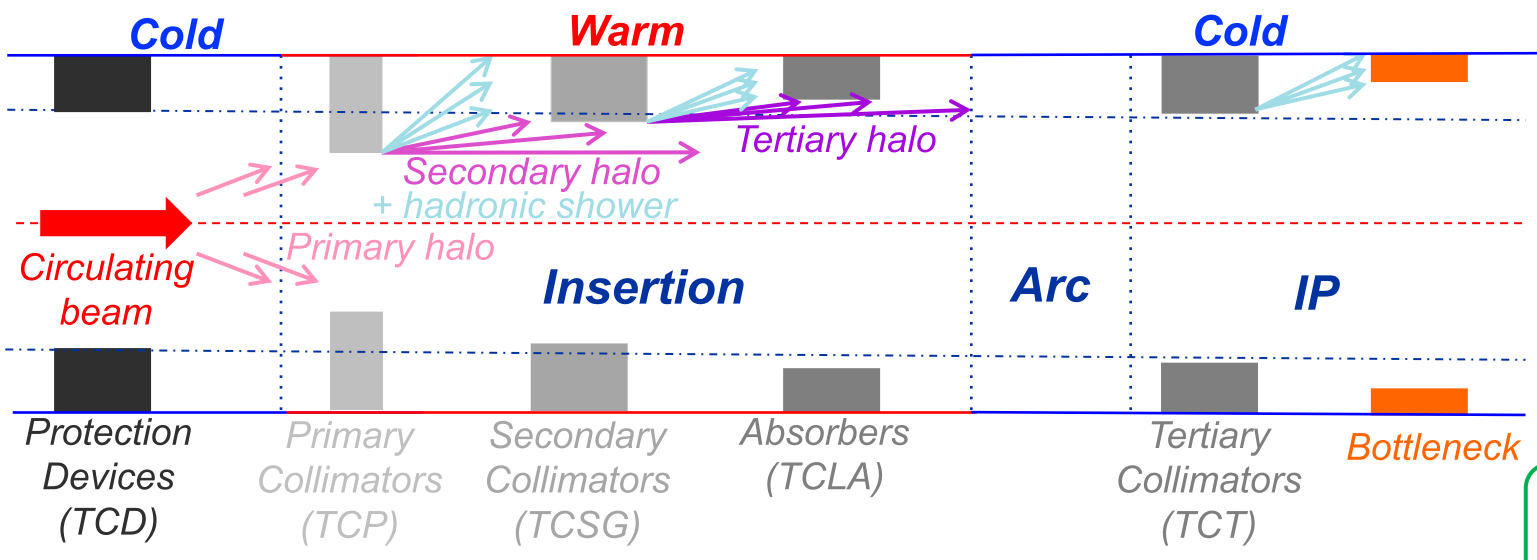
15-50mJ/cm³

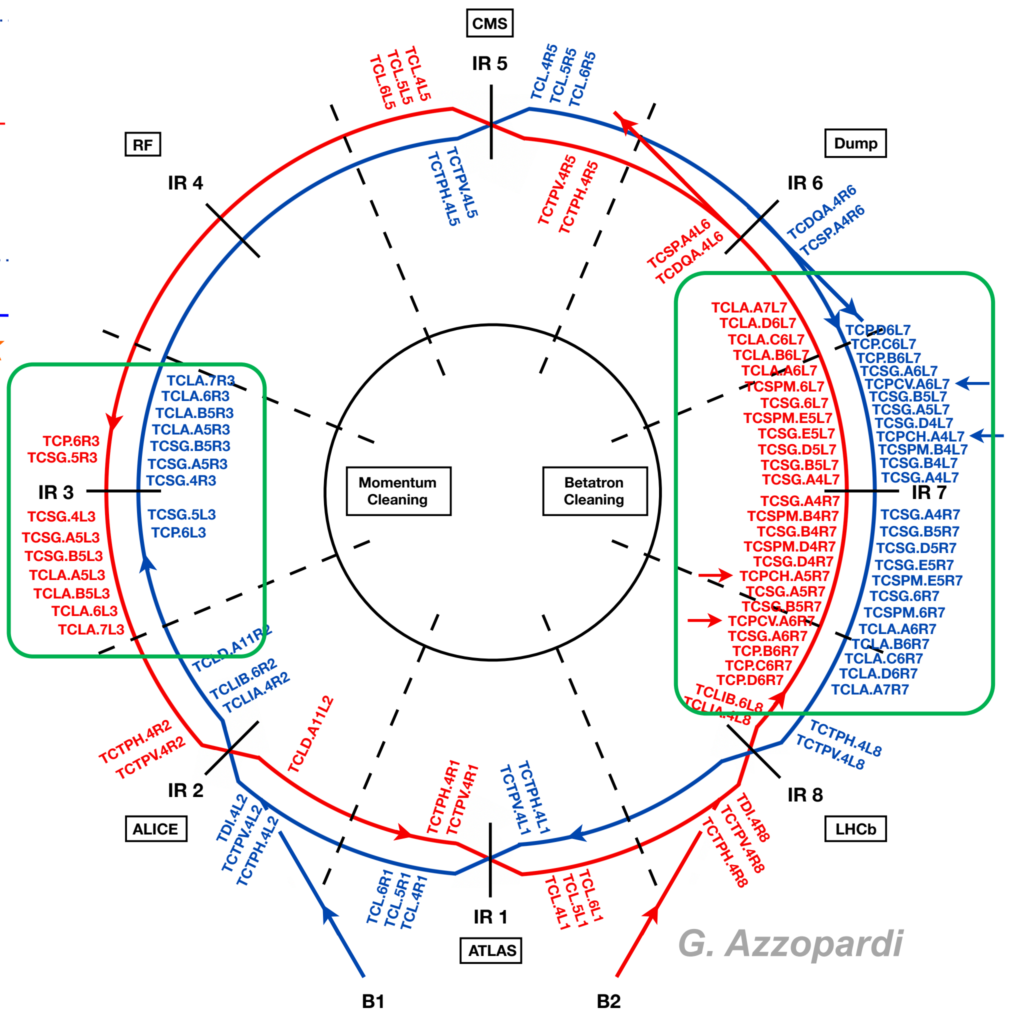
Ladybug at 10 km/h

Highly efficient collimation system needed for a safe beam disposal at any time!

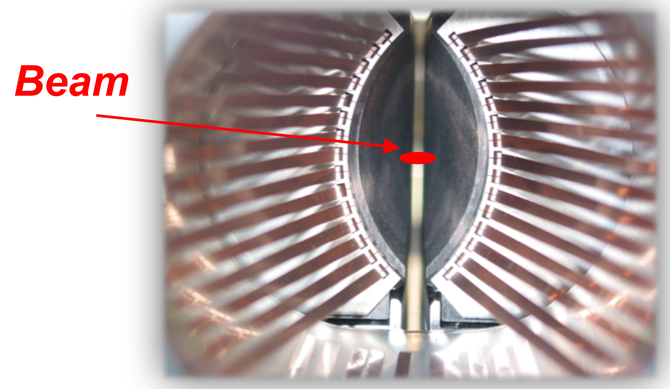
The LHC collimation system

Multi-stage cleaning with about 50 collimators per beam and two dedicated insertions





Movable collimators:
ensure required performance along the entire cycle



MDC PRS	L (mm)	IR7	R (mm)
	0.90	TCP.D6L7.B1	-0.59
	1.55	TCP.C6L7.B1	-1.09
	1.35	TCP.B6L7.B1	-0.93

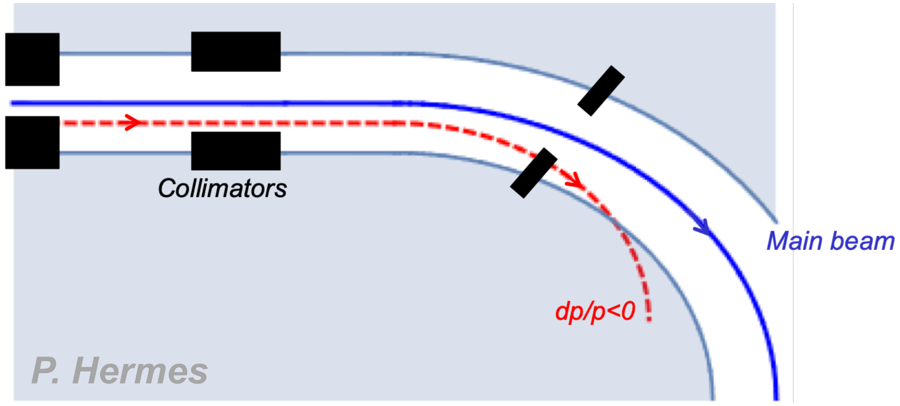
At 6.8 TeV/c: ~2 mm gap with 5 μm resolution!

Cleaning performance

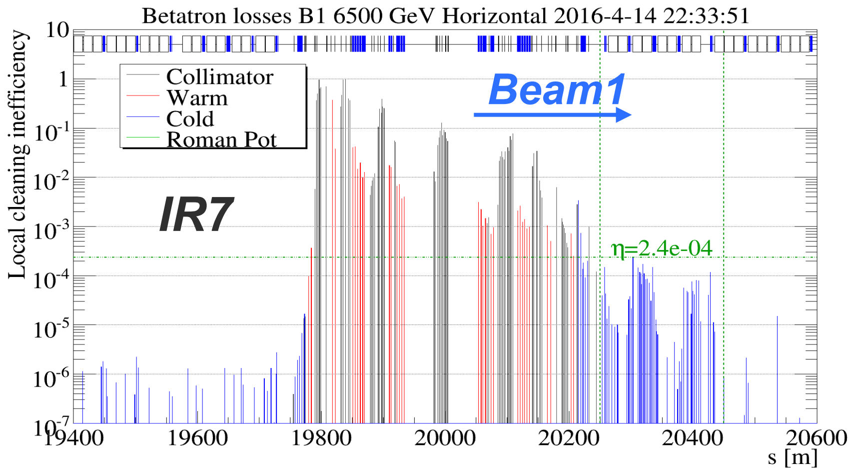
Main limitations:

1. **Interaction with the collimators** can causes a **change of rigidity**
2. **Beam losses** occur in the **first cold dipoles** seen

Performance** defined by **losses** on those **magnets w.r.t.** on **primaries

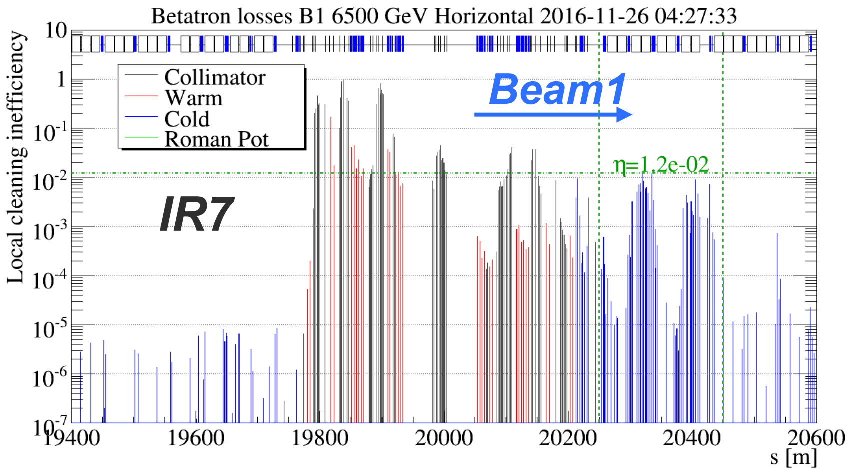


Proton beams: single diffractive events



Excellent performance: only ~10^{-4} of intercepted p able to emerge from insertion!

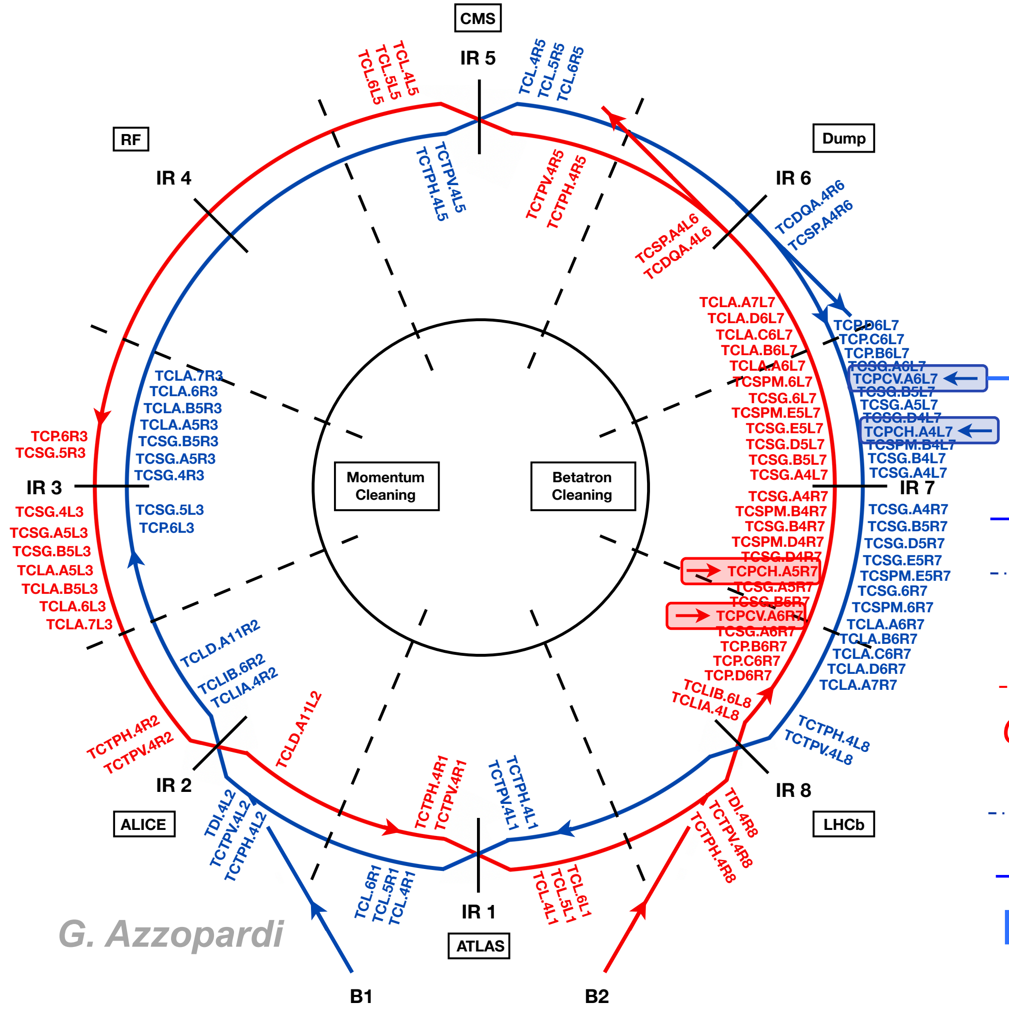
Ion beams: fragmentation and dissociation



~x10^2 worse cleaning than with p → **~x5 cleaning improvement** to reach **~20MJ target for Pb**

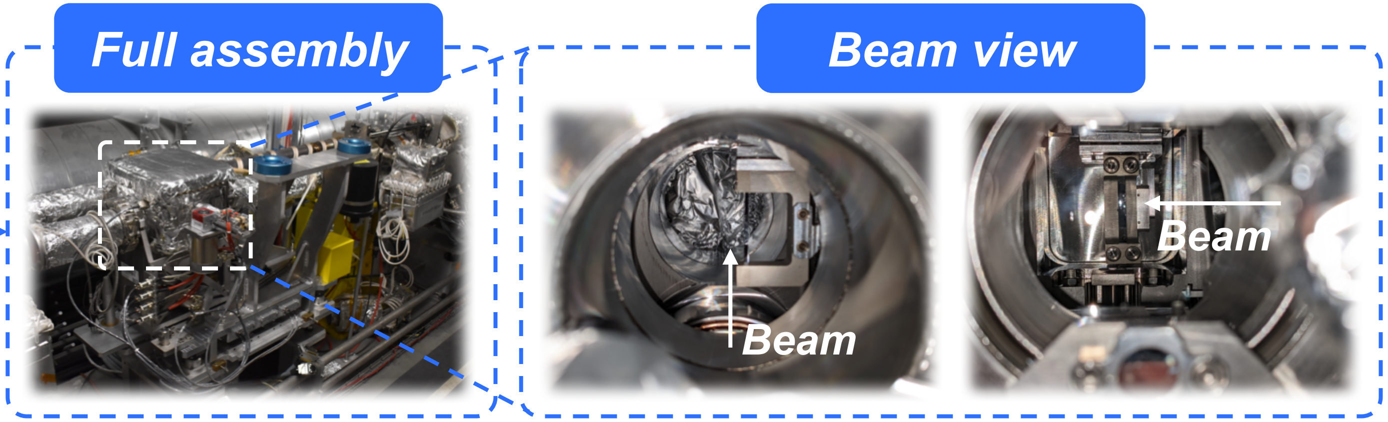
Crystal assisted collimation for LHC

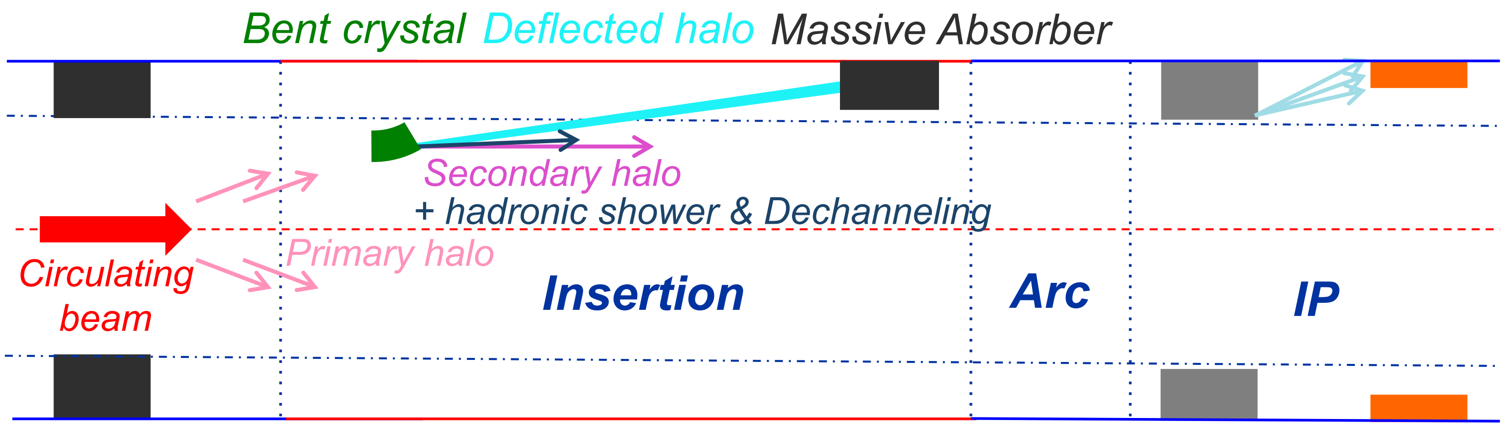
Four Strip (110) crystals installed in the betatron cleaning insertion: **two per beam, one per plane**



Full assembly

Beam view





Reduction of inelastic interactions at primary stage → **Reduced losses** on limiting locations

G. Azzopardi

Outline

I. Introduction
II. **Operational deployment**
III. 2023 heavy ions run
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Milestones at the LHC

2015

- **First p channeling** at the LHC: **450 GeV and 6.5 TeV** *(PLB 758 (2016): 129–133)*
- **First Pb channeling** at the LHC: **450 Z GeV**

2016

- **First** channeling during **energy ramp**
- **First** assessment of **cleaning performance** with p beams
- **First Pb channeling** at the LHC: **6.37 Z TeV** *(EPJC 81 (2021): 1-7)*

2017

- **First channeling of Xe at 450 Z GeV 6.5 Z TeV**, together with assessment of cleaning performance

2018

- **First** channeling during **squeeze** and **collision**
- **First** operational use in a **physics run** *(PRApplied 14.6 (2020): 064066)*
- **Operational tests** with **6.37 Z TeV Pb** beams *(PRAB 27.1 (2024): 011002)*

LS2

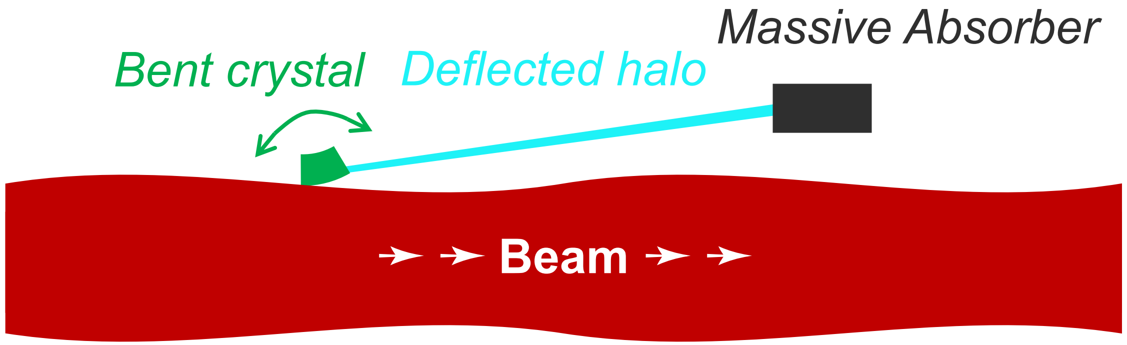
- Crystal collimation **baseline HL-LHC** upgrade for **heavy ions collimation**
- Installation of **two upgraded device**

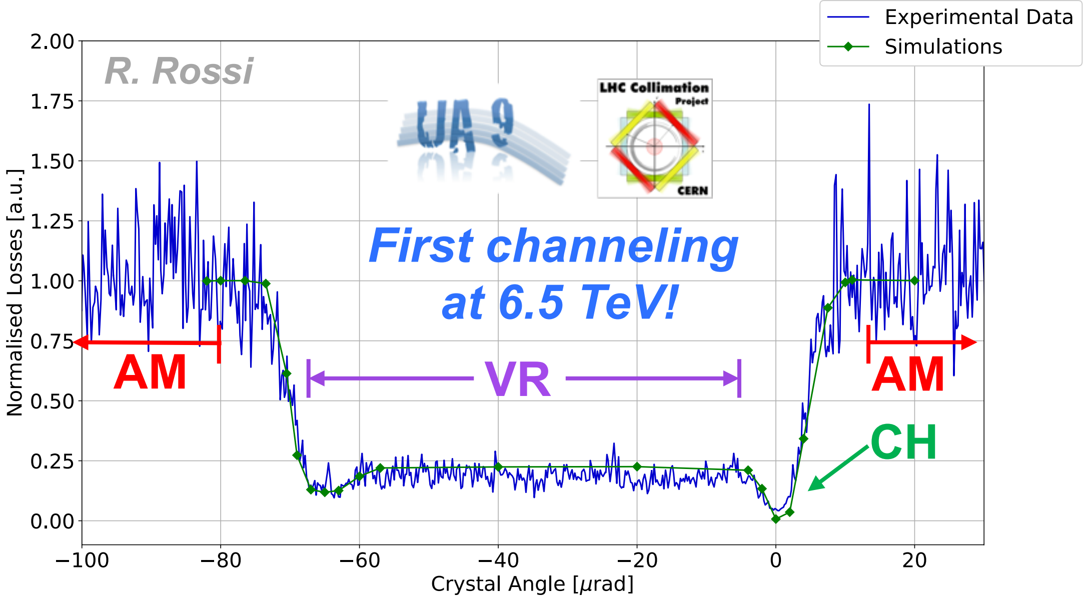
2022

- **Demonstrated x5 improved cleaning** with new devices
- Replaced **two remaining devices** with **upgraded** version

Main challenges – Identify channeling

Monitoring of **losses** at the **crystal** location as a function of its **angle**

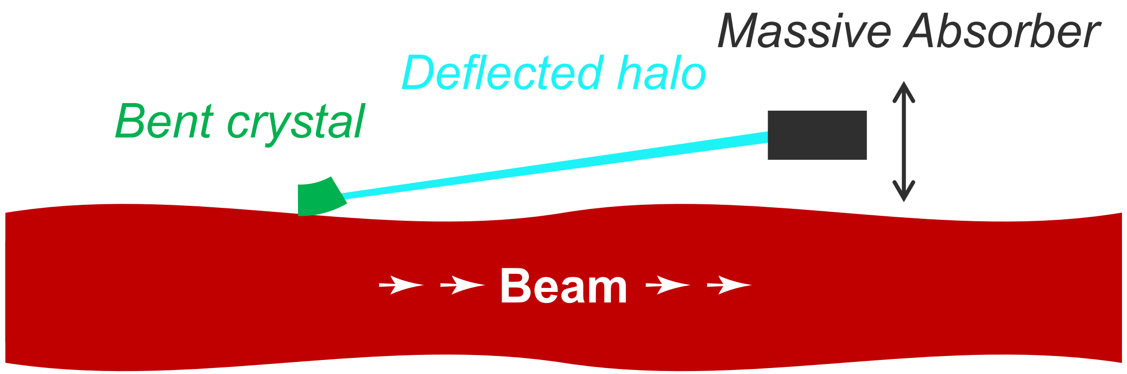


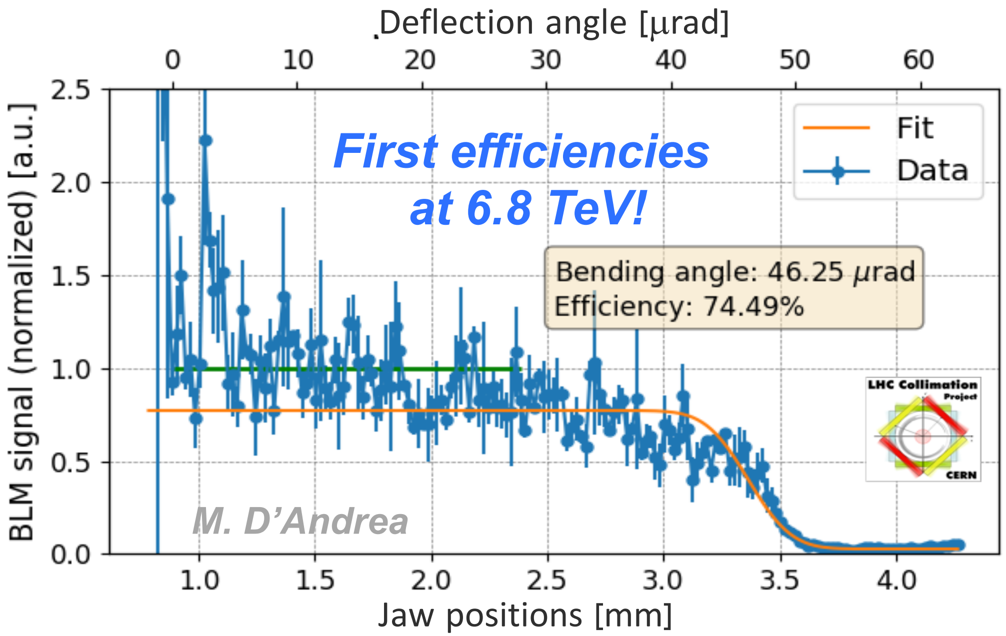


- **Main outcomes:**
  - ✓ Optimal **channeling orientation** depending on transverse crystal position (**minimum of losses**)
  - ✓ Crystalline **lattice quality** (depth of well due to **reduction of nuclear interaction rate**)
  - ✓ **Qualitative** evaluation of **geometrical bending** (**well extension**)

Main challenges – Validate crystal performance

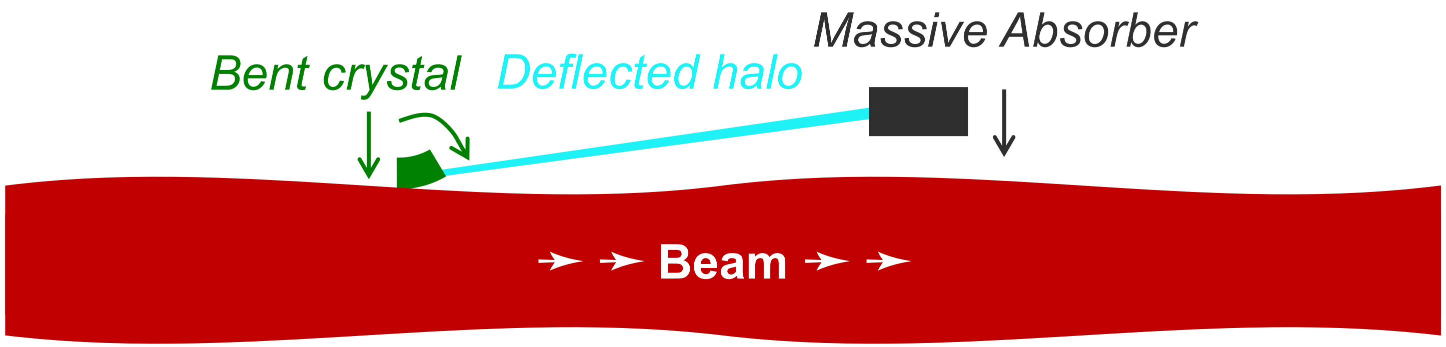
Monitoring of **losses** at **absorber** as a function of its **position**, while crystal in channeling





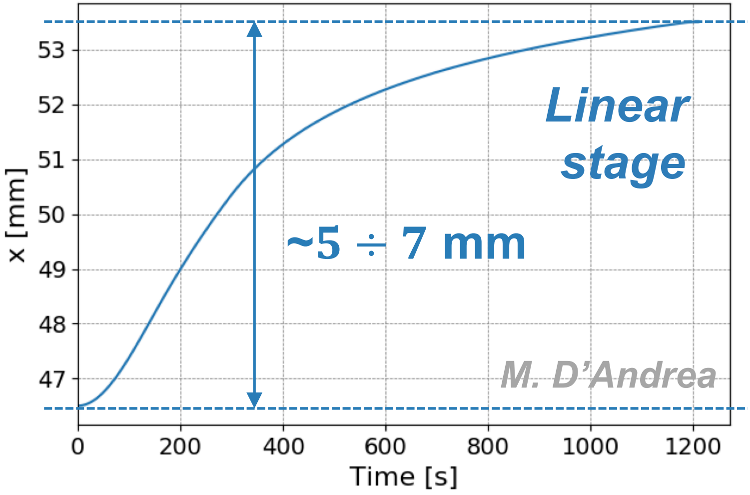
- **Main outcomes:**
  - ✓ **Multi-turn channeling efficiency** depending on transverse crystal position (**error function plateau**)
  - ✓ Geometrical **crystal bending** (**displacement of channeled halo**)

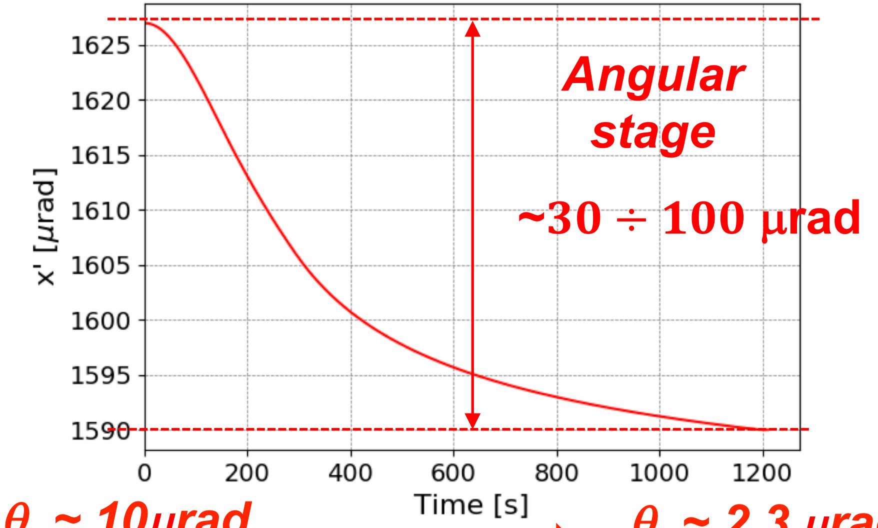
Main challenges – Keep the channeling during ramp



Beams **shrinking** when **increasing energy** (adiabatic damping)

$$x(t) = x_c - \left[n_{inj} + \frac{n_{ft} - n_{inj}}{\gamma_{ft} - \gamma_{inj}}(\gamma(t) - \gamma_{inj})\right]\left[\tilde{\sigma}_{inj} + \frac{\tilde{\sigma}_{ft} - \tilde{\sigma}_{inj}}{\gamma_{ft} - \gamma_{inj}}(\gamma(t) - \gamma_{inj})\right]\frac{1}{\sqrt{\gamma(t)}}$$

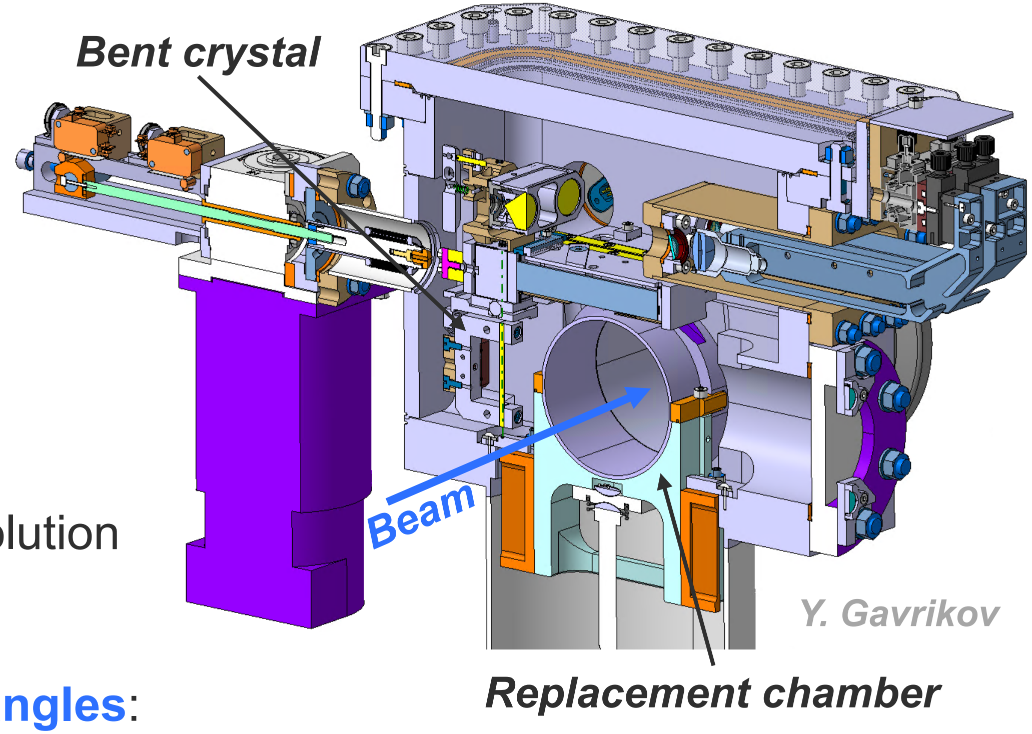


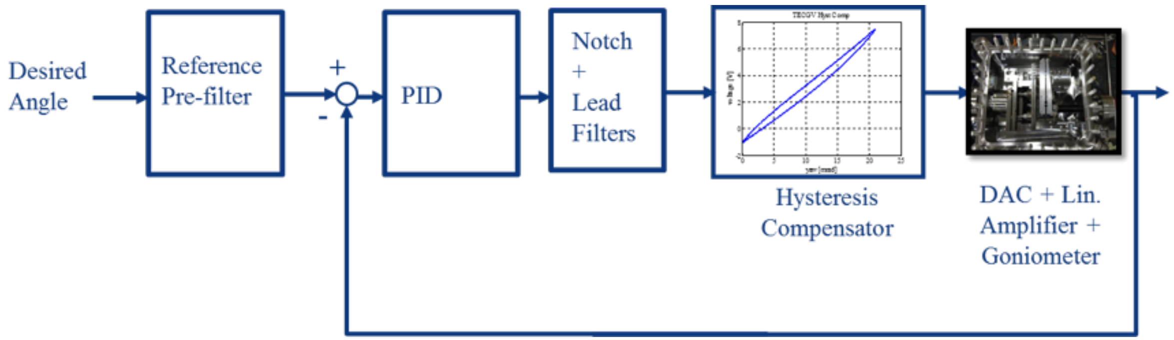


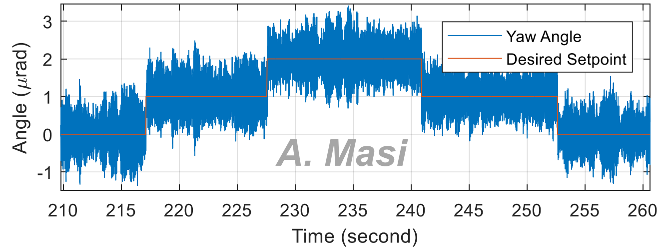
$\theta_c \sim 10\mu rad$ 450 GeV → $\theta_c \sim 2.3\ \mu rad$ 6.8 TeV

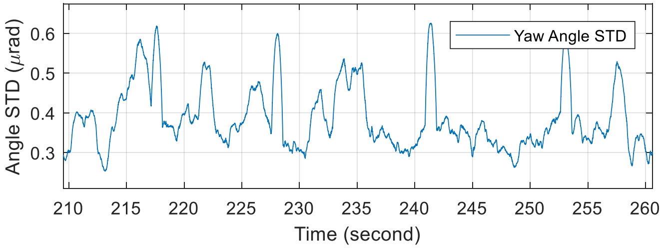
Piezo goniometers

- **State-of-the-art control** on linear and angular position:
  - ✓ "O" shaped **replacement chamber** avoids impedance issues during high intensity proton beams
  - ✓ **Stepper motors** for **linear** movements ensures **5 μm** resolution (derived from collimation system)
  - ✓ Interferometer-based **piezo-controller** in closed loop for **angles**:
    - ➢ **RMS** angle **stability $0.3 \div 0.6$ μrad**
    - ➢ **Peak-to-peak** angle **stability ~1 μrad**









Operational deployment

Crystals are **orchestrated in harmony** with all the other components of the Large Hadron Collider!

CCC (CERN Control Centre)

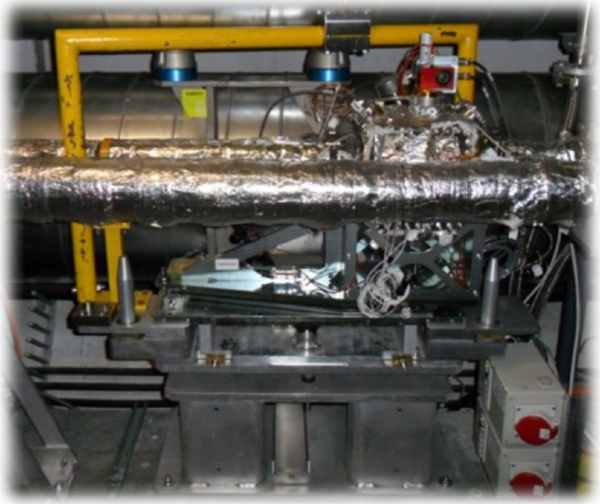
High level applications for **settings** and **device handling**

Java python

FEC (Front-End Card)

Dedicated **Front-End** Software Architecture

Device

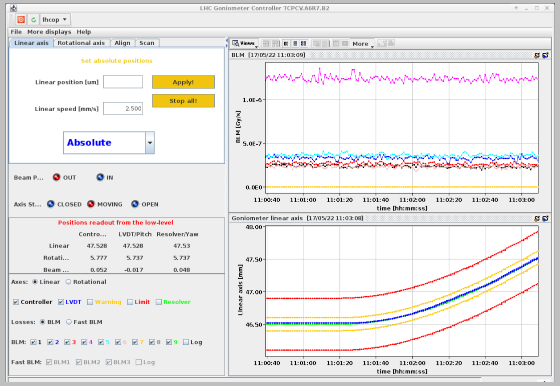


Low-level device handling

FPGA

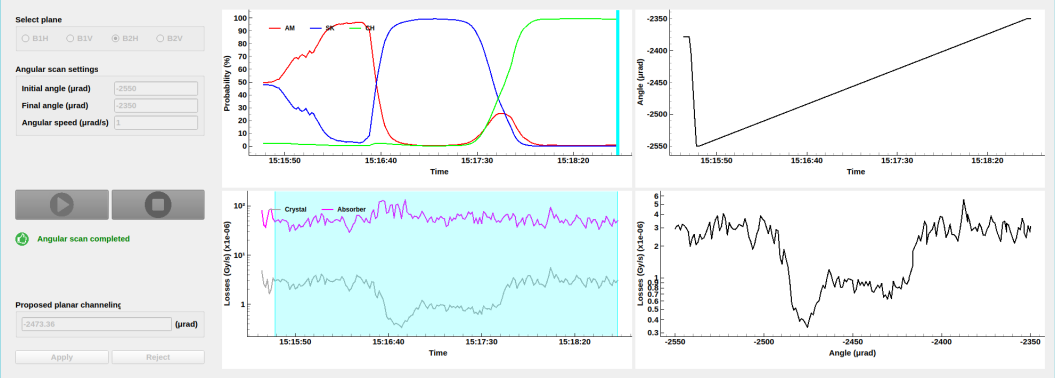
Main high level tools for device handling

Expert application



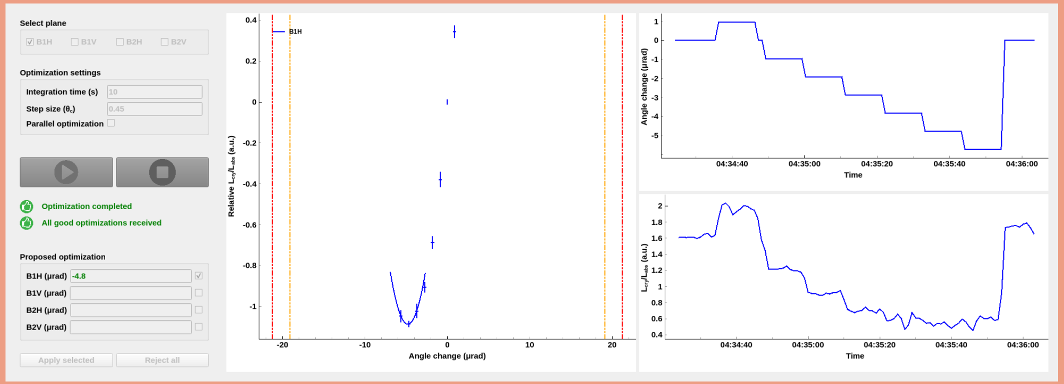
✓ Manual handling of devices

Fast identification of crystalline planes orientation



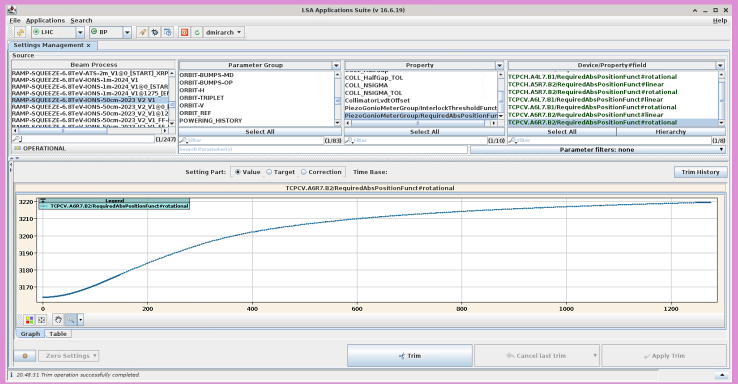
✓ Loss pattern recognition based on 1D-CNN

Optimization of channeling orientation



✓ Achieved required resolution of 0.1 θ_c

Operational handling



✓ Settings in LHC database and automated motion

Simulation tools

Tracking

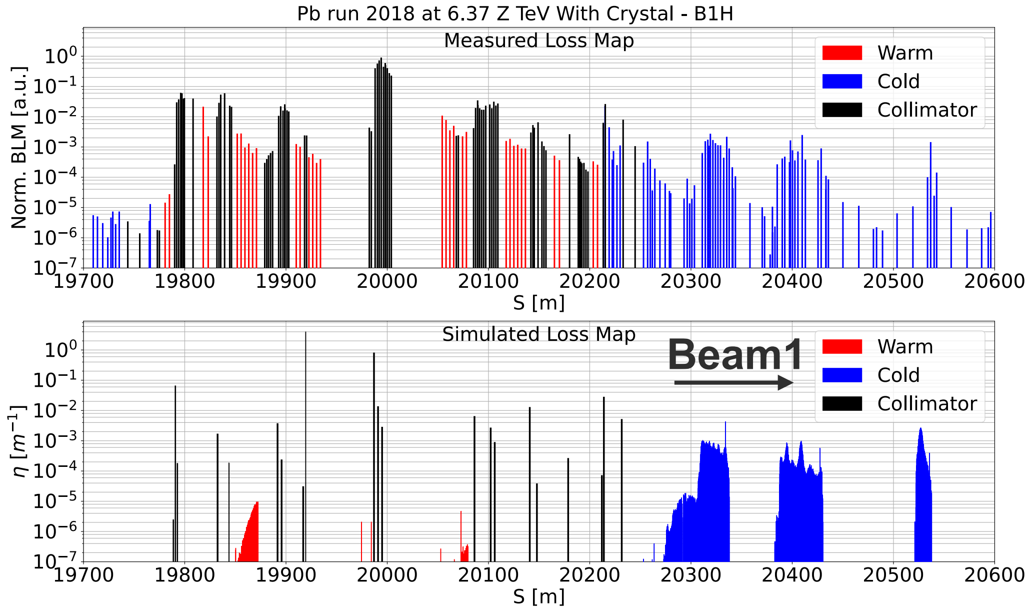
Main features:

- **6D** symplectic **tracking** trough LHC **lattice**
- Particle – matter **interaction**
- Geometrical machine **aperture**

Main outcome:

✓ **Loss pattern** around entire ring

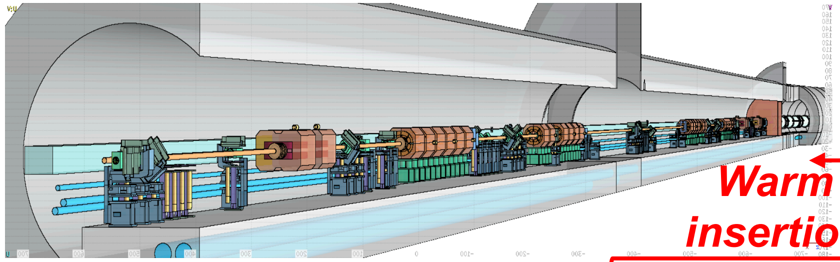
R. Cai
CERN-THESIS-2024-045



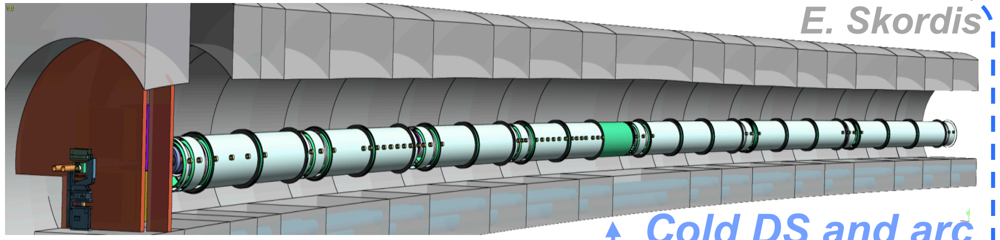
Energy deposition

Main features:

- Full **showering**
- Detailed **geometry**

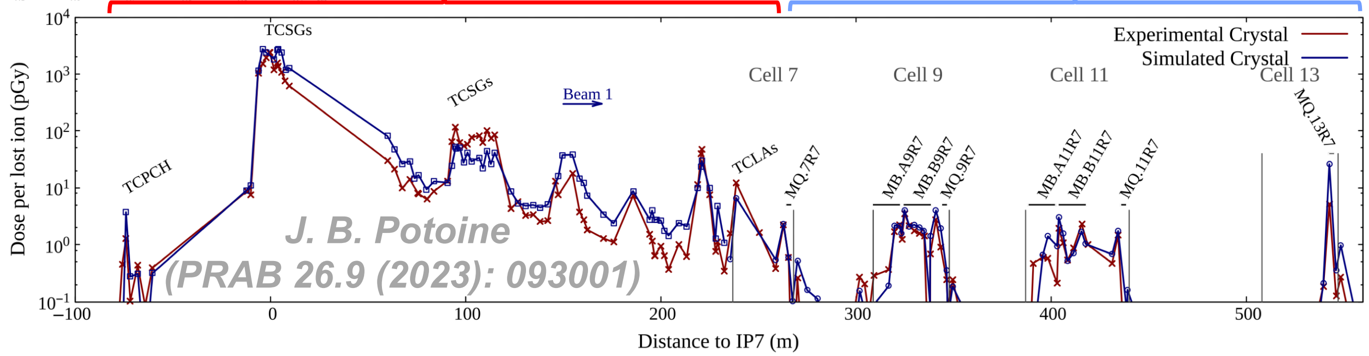


E. Skordis



Main outcome:

✓ **Expected signal** Beam Loss Monitor (i.e. power loss in magnet coils)



J. B. Potoine
(PRAB 26.9 (2023): 093001)

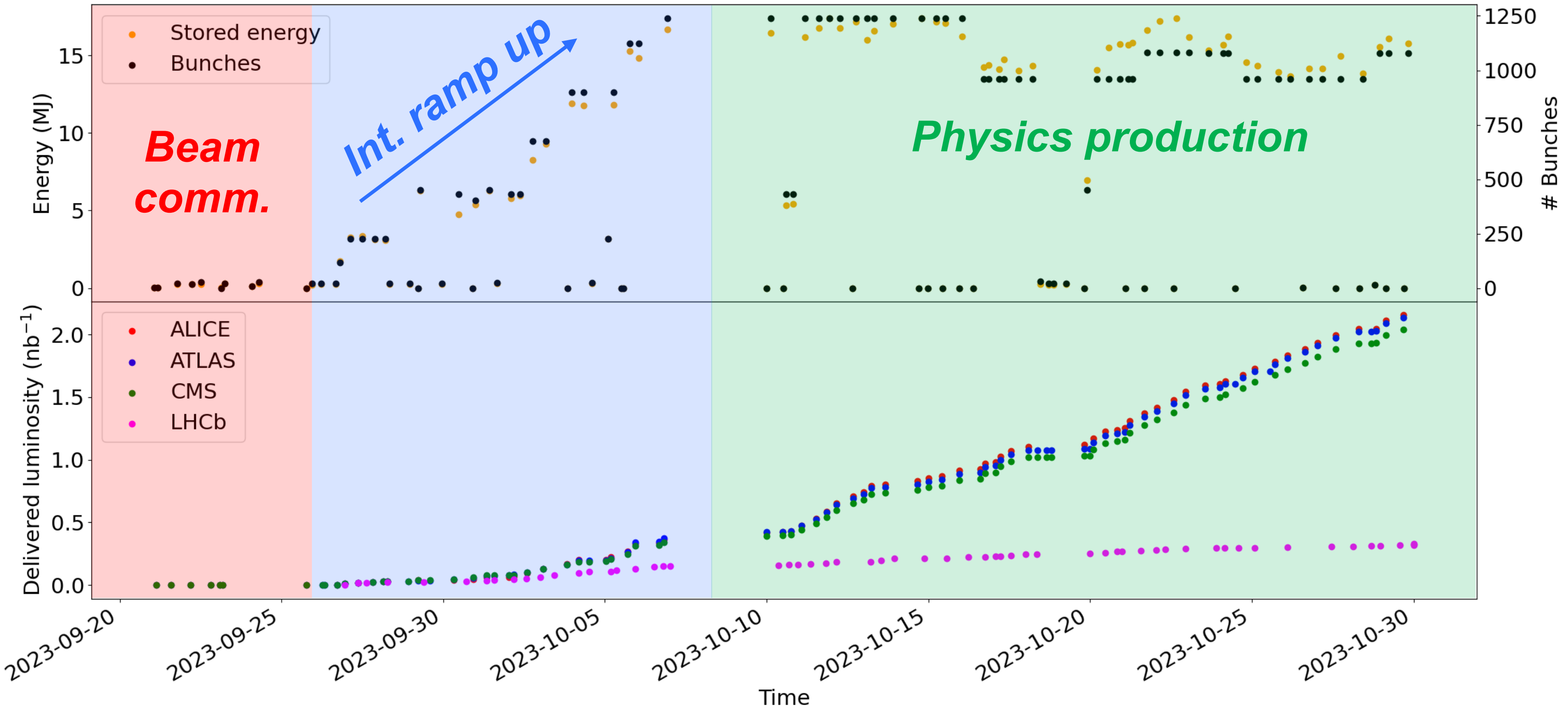
Outline

Overview

Few weeks/year of the LHC devoted to **heavy ion physics**

Dynamic LHC schedule (energy crisis, unscheduled stop):

- ✓ Only **2 days** of test in **2022**
- ✓ **5 weeks** of run in **2023**



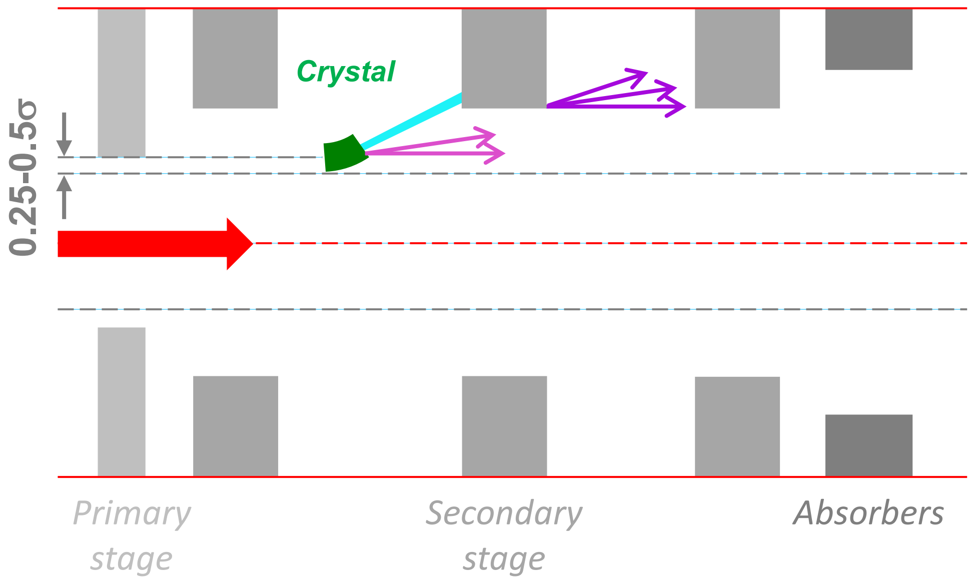
Only **4 days** dedicated to beam **commissioning** → Heavily relying on **preparatory activities with p beams** (e.g. optics corrections, crystals characterization, …)

Peak of **~17.4 MJ achieved**! (limitations in injectors and LHC prevented to reach target ~20MJ)

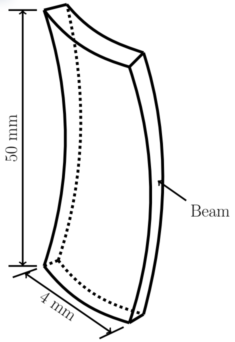
→ **Never deployed crystal** collimation with such **high intensity** and **high energy** beams, and for **so long**!

→ **Concerns** on long term **stability** due to very **tight channeling acceptance** at LHC top energy

Operational configuration for crystal collimation



Two producers: INFN-Fe and PNPI



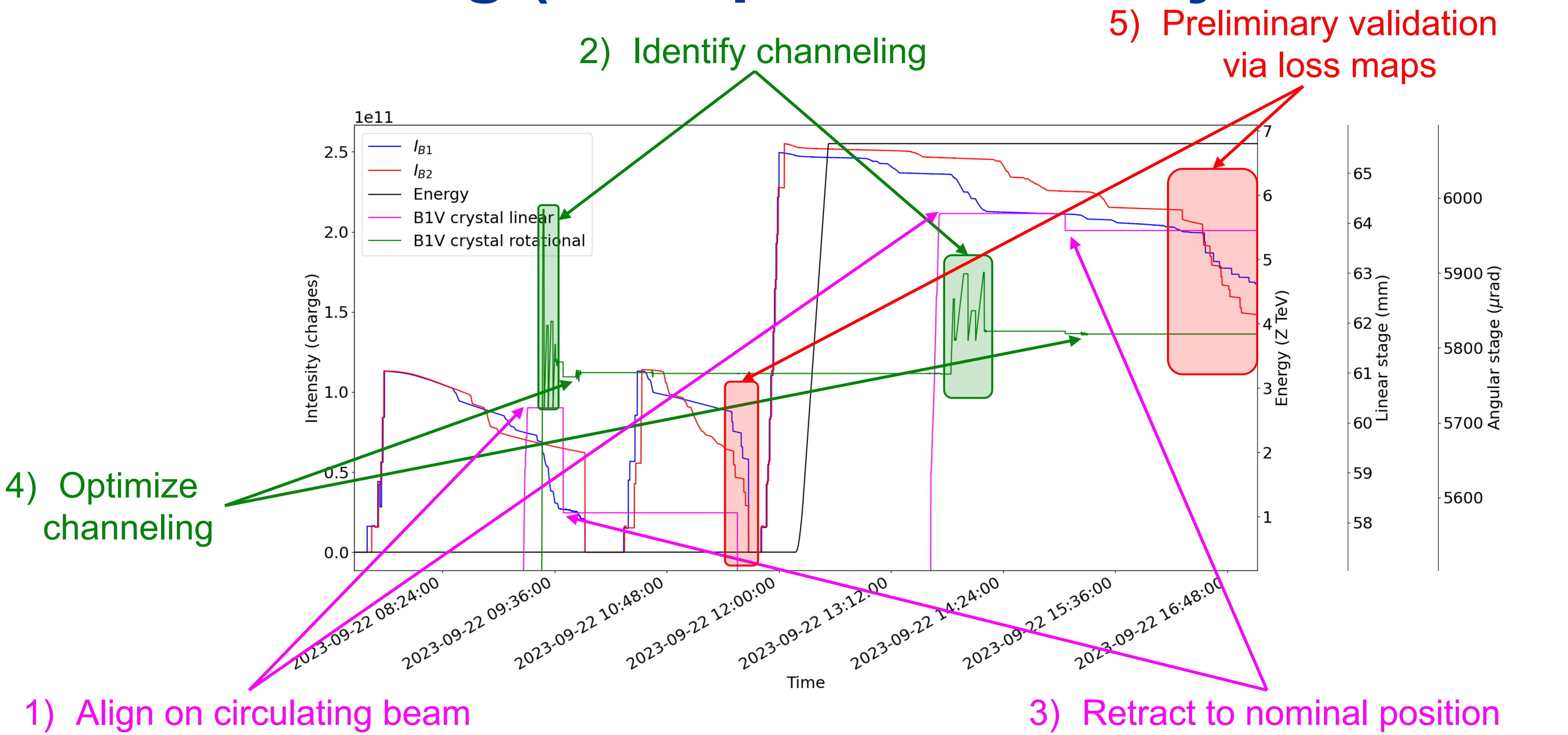
Design bending
50 ± 2.5 μrad $\equiv$ B ≈ 310 T @ 7 TeV!

Core strategy: **adiabatic** insertion

✓ **Crystal primary** stage **defining cleaning** performance

✓ **Standard system** fully in place to ensure **phase space coverage** for protection in case of failures

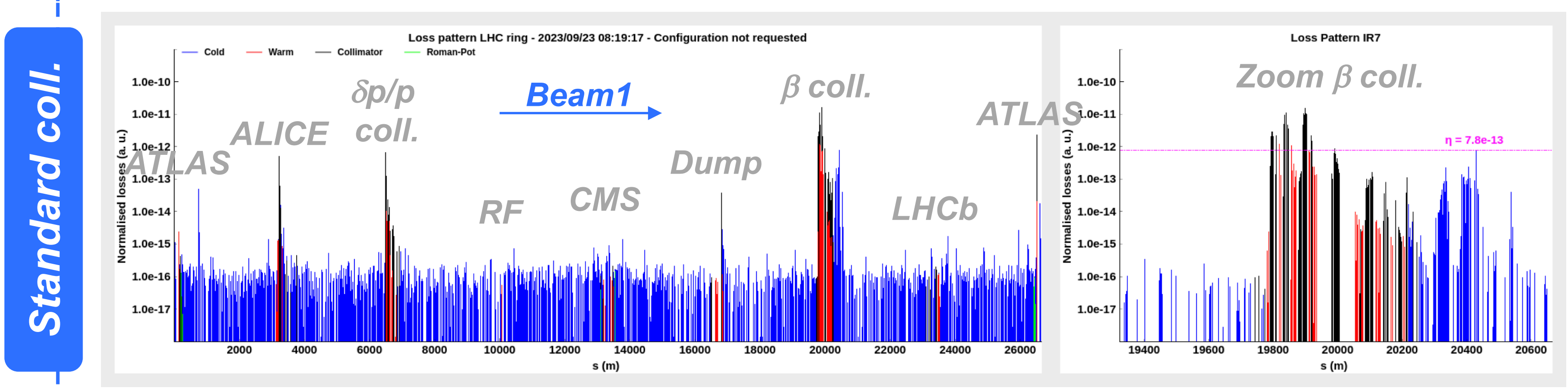
Commissioning (example vertical crystal on Beam1)

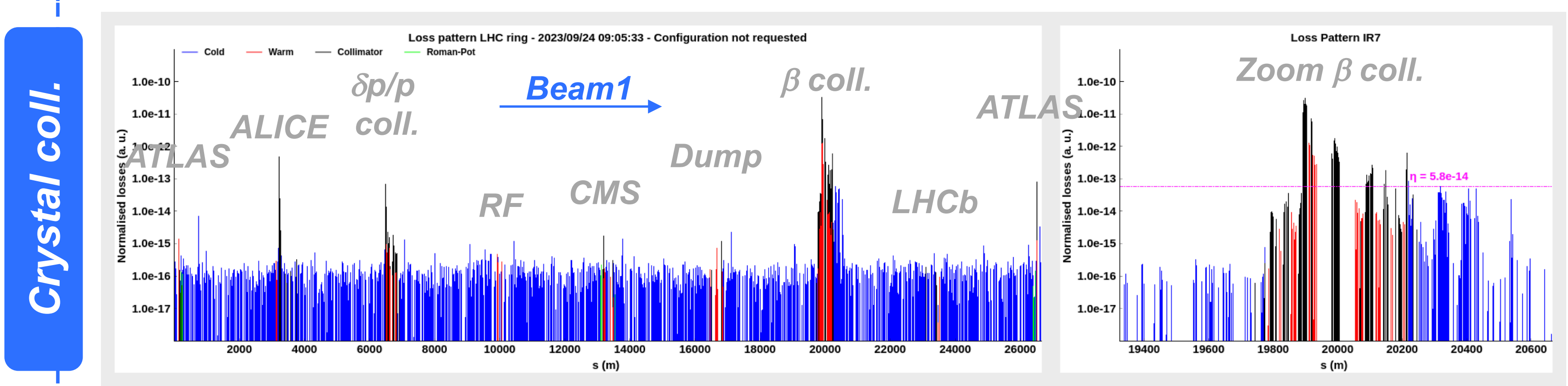


Smooth commissioning:

- ✓ ***All 4 crystals & full system commissioned in <12h***
- ✓ ***Energy ramp commissioned the 24^{th} Sept.***

Cleaning performance





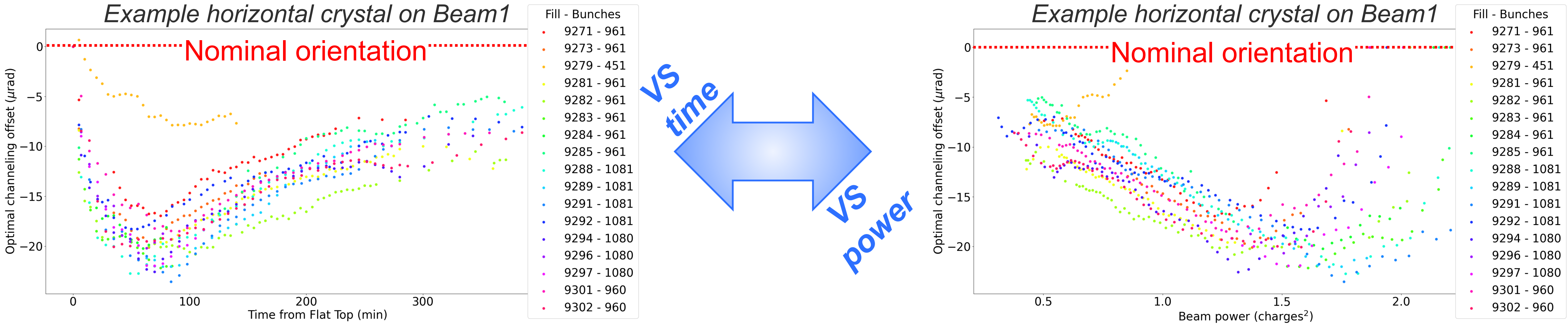
Thorough **optimization** of **entire system** along LHC

Plane	Gain factor
B1H	~13.7
B1V	~5.1
B2H	~4.9
B2V	~6.5

Target factor ≥ 5 **cleaning improvement achieved** in all planes!

Performance stability

- **Good overall stability** with no loss of **reference frame over 5 weeks**
  → Entire heavy ion run performed with **only 1 alignment** during **initial commissioning**!
- **Issue** detected: **drifts** in time of **optimum** crystal orientation **within a fill**
  → **Successfully mitigated** at top energy with **auto-pilot** deployment for a continuous automated optimization



Potential source: uncontrolled **heating by impedance** of a goniometer component leading to a change in crystal orientation not caught by interferometric loop

Outline

Conclusions

- The **LHC**: very **powerful** but very **sensitive** machine

→ Highly **efficient collimation** system needed for a safe beam disposal **at any time**!

- **Excellent** performance of standard **collimation** system with **p beams**

→ A factor **~x5** cleaning **improvement needed** to reach target stored energy with **Pb beams**

- **Crystal assisted collimation** deployed operationally in the LHC after a long and intense journey

→ Several **challenges overcome**; **state-of-the-art hardware**, **controls**, **handling**, and **simulation** developed

- **First operational use** of crystal assisted collimation with up **~17.4 MJ** with **6.8 Z TeV** beams for **5 weeks** in 2023!

→ **Achieved** required **improvement** of cleaning performance
Good overall operational **performance**, working on **orientation drift** with high intensity beams

Acknowledgments

Collimation results *are presented of behalf of the* ***WP5 collimation*** *upgrade teams within the* ***High-Luminosity LHC upgrade project*** *(HL-LHC). Special thanks to S. Redaelli, M. D'Andrea, R. Cai, R. Bruce.*

CERN groups involved in these crystal studies:
(support from many: vacuum, diagnostics, operations, services…)

BE-ABP

Beams Department | Operation

SY Accelerator Systems STI

Funding acknowledgements LHC crystal:

LHC Collimation Project CERN

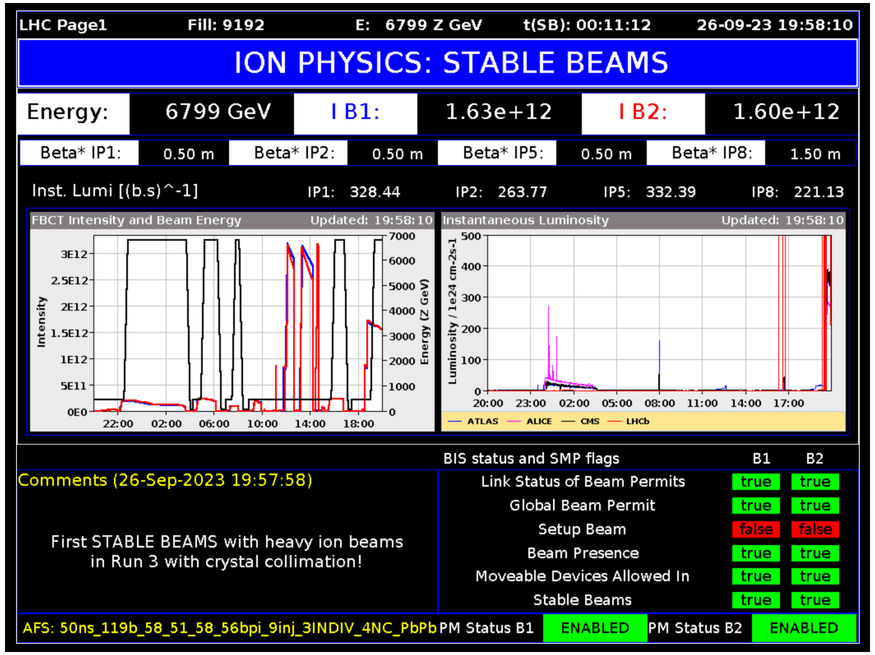
HiLumi HL-LHC PROJECT

UA9 collaboration:

Special thanks to W. Scandale

Strong synergy with the
Physics Beyond Collider study at CERN:

Physics Beyond Colliders



Outline

BACKUP

Crystals lifetime and damages

2021 JINST 16 P08015

- *Test of cystalline structure degradation as function of integrated dose:*
  1. 9 Crystals characterised at the H8 extraction line from SPS
  2. Irradiated with $2.5 \cdot 10^{21}cm^{-2}$ thermal neutrons at SCK-CEN BR2 reactor
  3. Characterisation repeated at H8

- Main outcome:
  - ✓ Reduction of single-pass channeling efficiency from ~67% to ~59% with an equivalent dose of >5.5 years of operations (with both p and Pb)
  - ✓ Replacement every LS may be envisaged but not strictly needed as multi-turn effect may compensate reduced single-pass channeling efficiency

Eur. Phys. J. C (2019) 79:933

- *Test of thermo-mechanical stresses in case of accidental irradiation during operations:*
  1. 2 Crystal characterised at the H8 extraction line from SPS
  2. Irradiated at the HiRadMat CERN facility with 2.5×10^{13} 440 GeV/c protons, with a pulse length of 7.2 μs.
  3. Characterisation repeated at H8

- Main outcome:
  - ✓ No reduction of single-pass channeling efficiency observed
  - ✓ No macroscopic damage, as cracks, vitrification or deformations in case of accidental beam impact at injection from the SPS, or due to an asynchronous beam dump at maximum energy.

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