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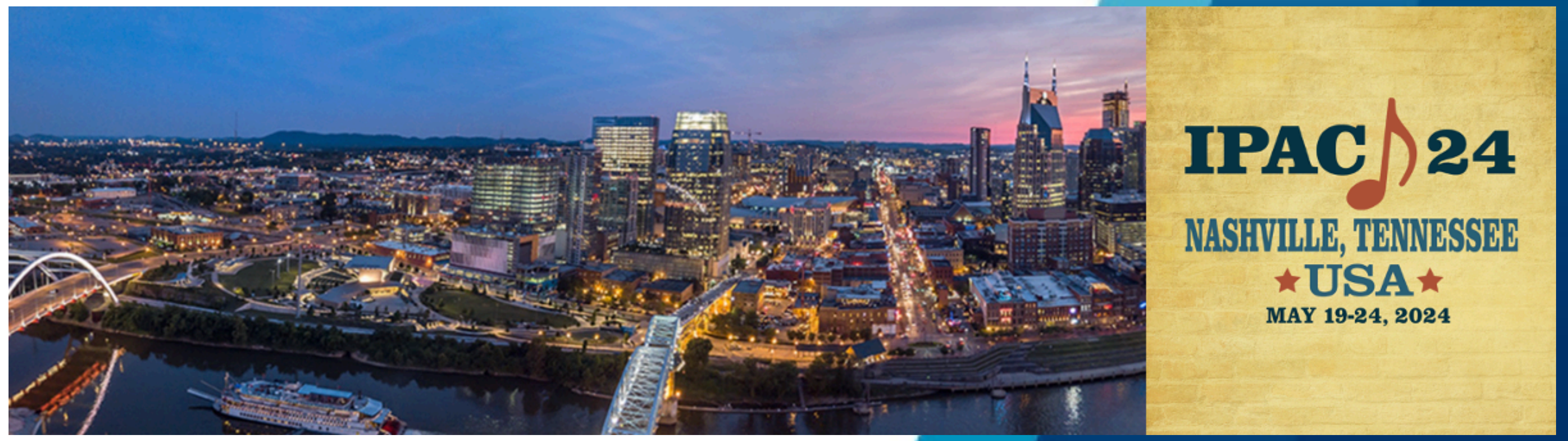
Crystal collimation of heavy-ion beams

Stefano Redaelli, BE-ABP, on behalf of the LHC Collimation teams

15th International Particle Accelerator Conference, IPAC2024
19-24 May, 2024
Music City Center, Nashville, TN, USA



Acknowledgements

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

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

BE-ABP | BE OP | BE CEM | SY STI

Funding acknowledgements LHC crystal:

UA9 collaboration:

Strong synergy with the Physics Beyond Collider study at CERN:

Measurements for forward physics experiments carried out in collaboration with TOTEM and ATLAS-ALFA

Authors

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CERN, Geneva, Switzerland
L. Bandiera, V. Guidi, A. Mazzolari, M. Romagnoni, M. Tamisari, INFN, Ferrara Section, Italy
Y. Gavrikov, Y. Ivanov

Recent PhD thesis works at CERN (simulations and/or measurements):

V. Previtali:	CERN-THESIS-2010-133 (2010, Collimation team)	— Sup. R. Aβmann
D. Mirarchi:	CERN-ACC-2015-0143 (2015, Collimation team)	— Sup. S. Redaelli
R. Rossi:	CERN-THESIS-2017-424 (2017, Collimation team)	— Sup. S. Redaelli
P. Schoofs:	CERN-THESIS-2014-131 (2014, FLUKA team)	— Sup. F. Cerutti
M. D'Andrea:	CERN-THESIS-2021-022 (2021, Collimation team)	— Sup. S. Redaelli
J.-B. Potoine:	CERN Thesis, https://theses.hal.science/tel-04486182	— Sup. A. Lechner
R. Cai:	CERN-THESIS-2024-045 (2024, Collimation team)	— Sup. R Bruce

Special thanks to W. Scandale

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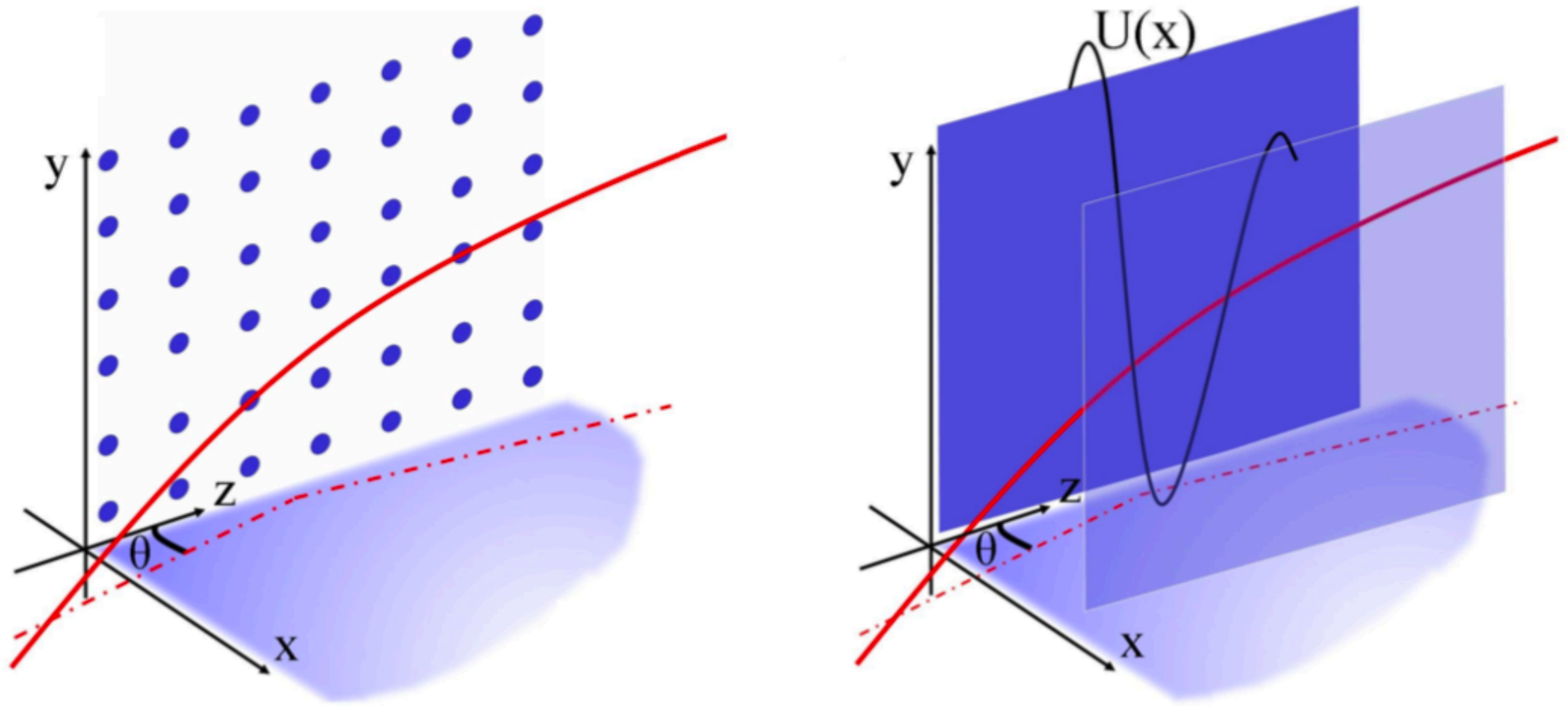
Introduction: Planar channeling in bent crystals

Pure crystals with regular lattices

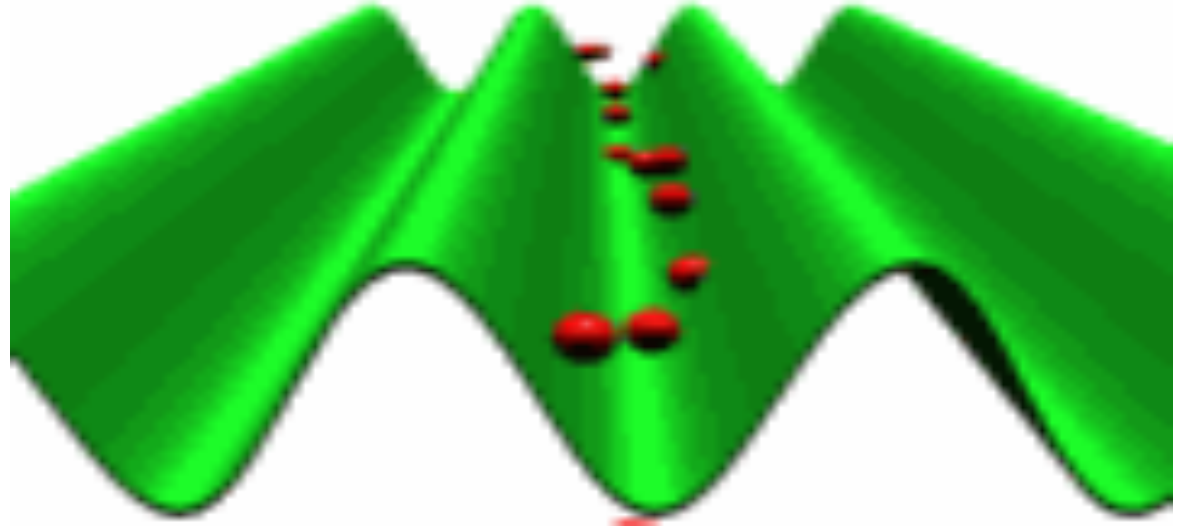


If the protons **have $p_T < U_{max}$**

⇕

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

Critical angle



Critical angle at the LHC energy frontier (Si crystals):

LHC 450 GeV = 9.4µrad

LHC 6.5 TeV = 2.4µrad

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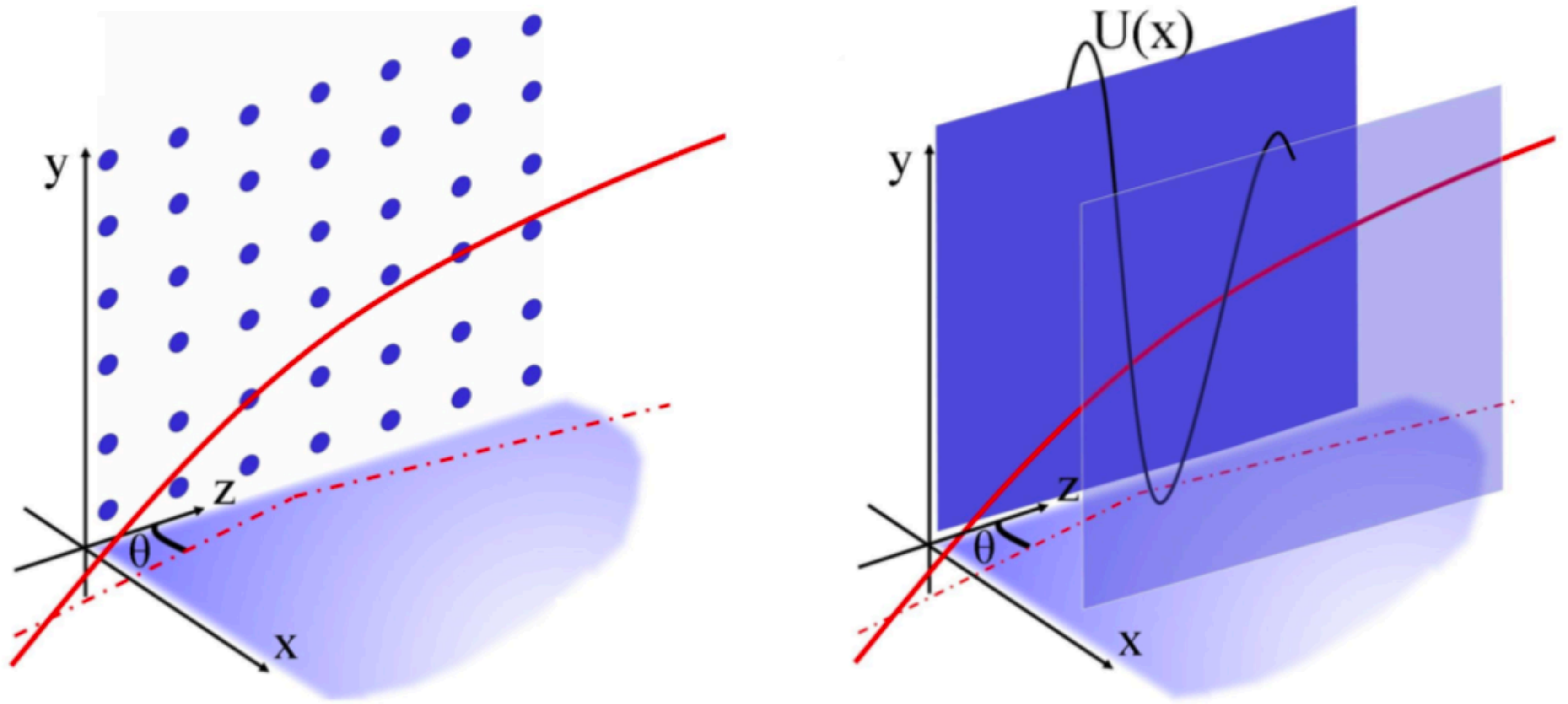

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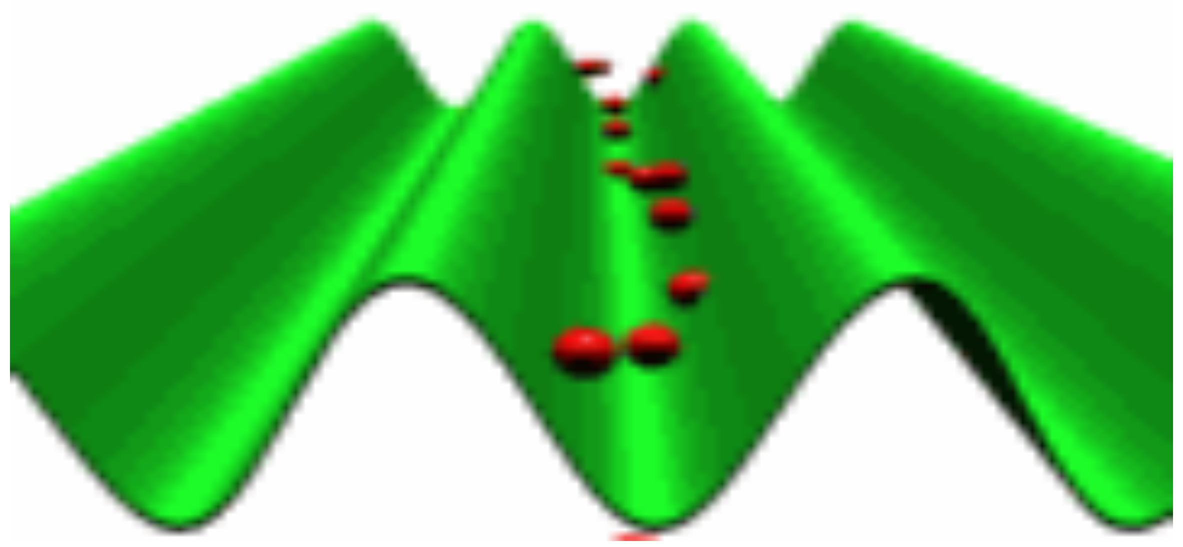

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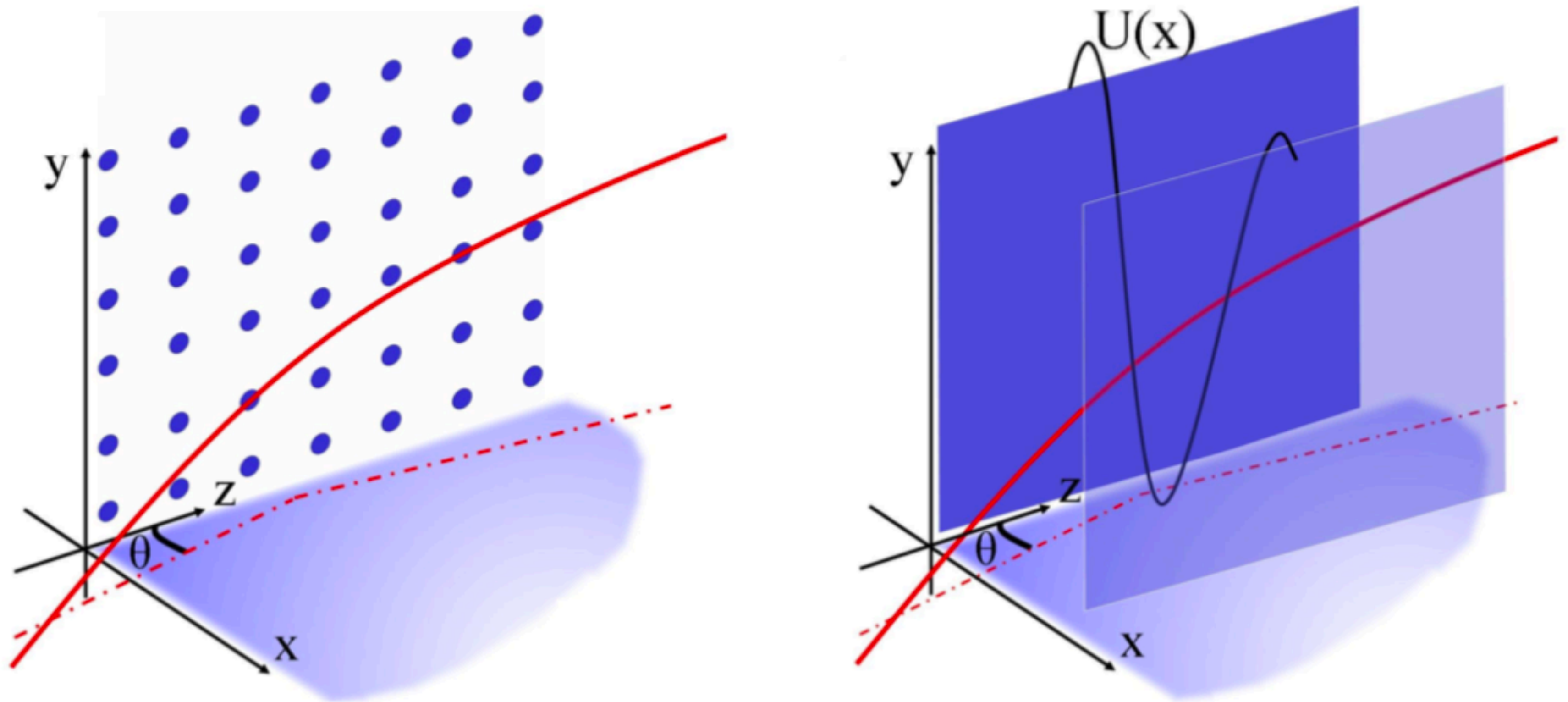

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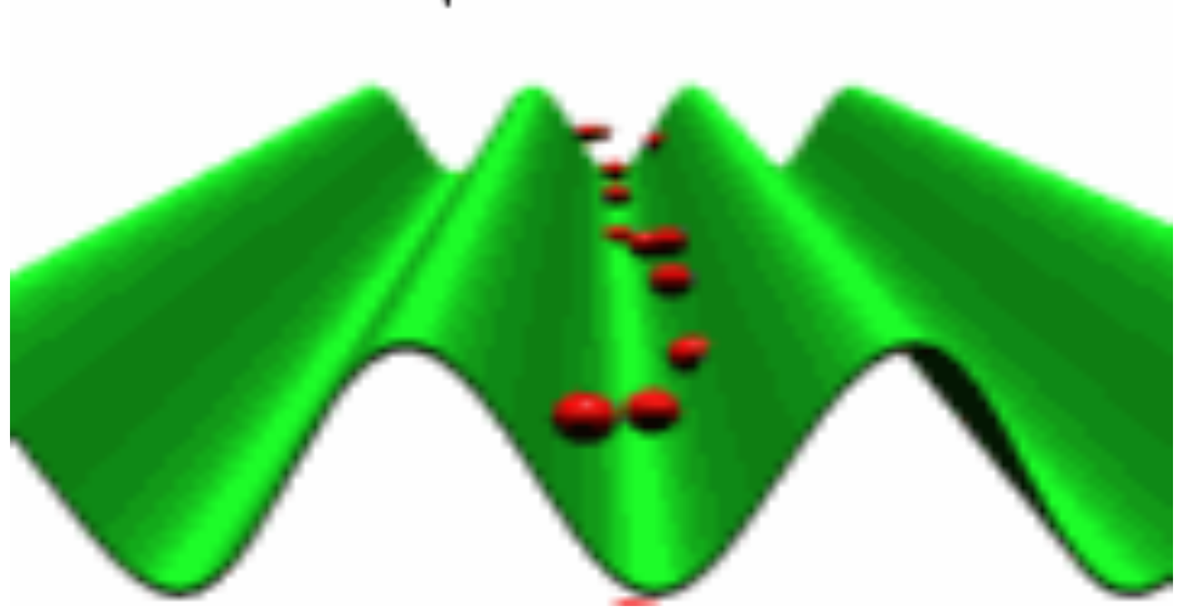

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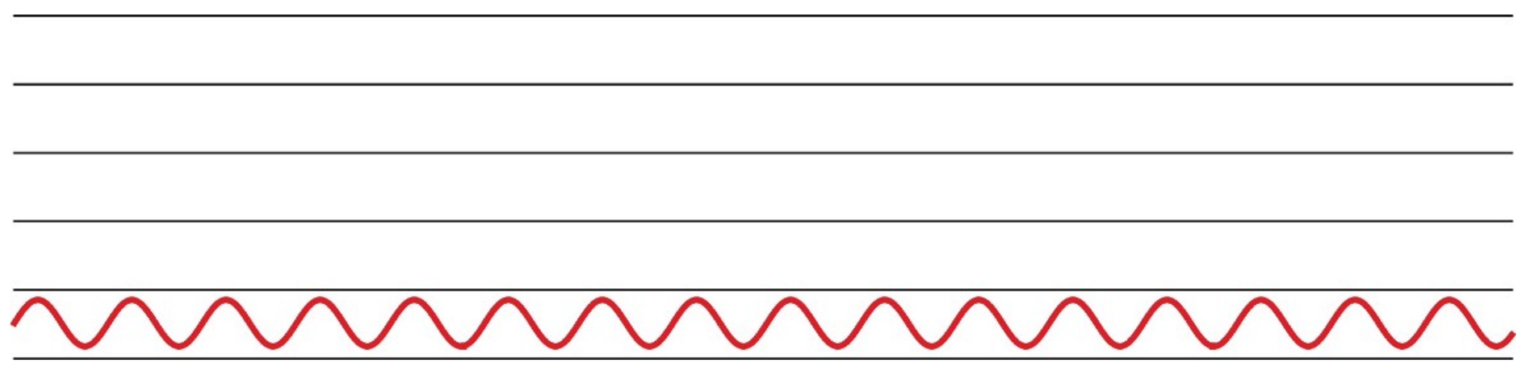
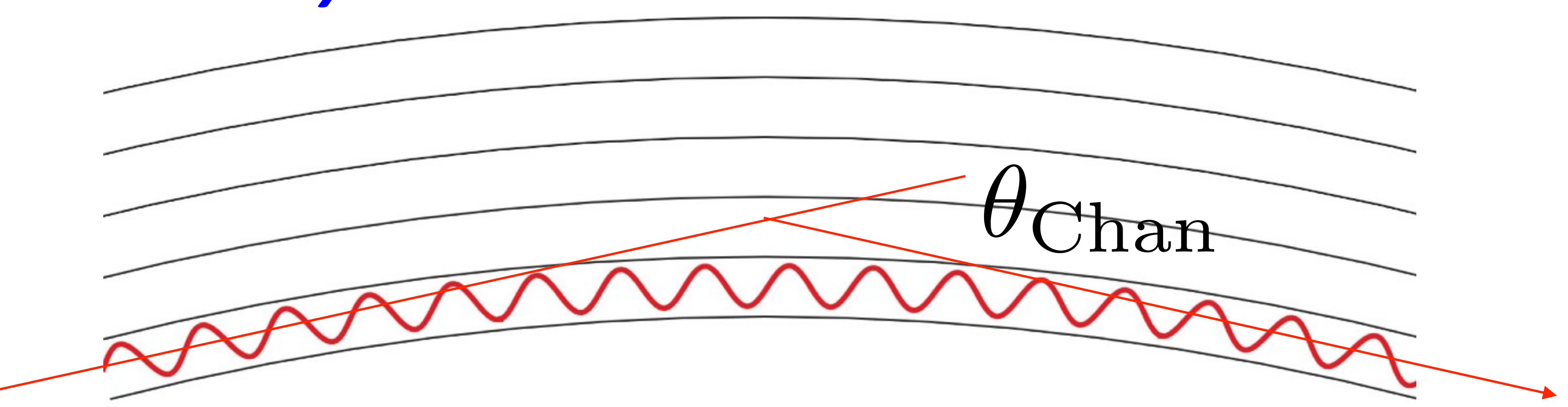
Straight crystal: oscillations between planes



Bent crystal



Bent crystal → net kick of the trajectory for particles trapped for the full crystal length!

Equivalent magnetic field close to **300 T** (4 mm crystal)

$$\theta_c = \sqrt{\frac{2U_{\max}}{pv}}\left(1 - \frac{R_c}{R}\right)$$

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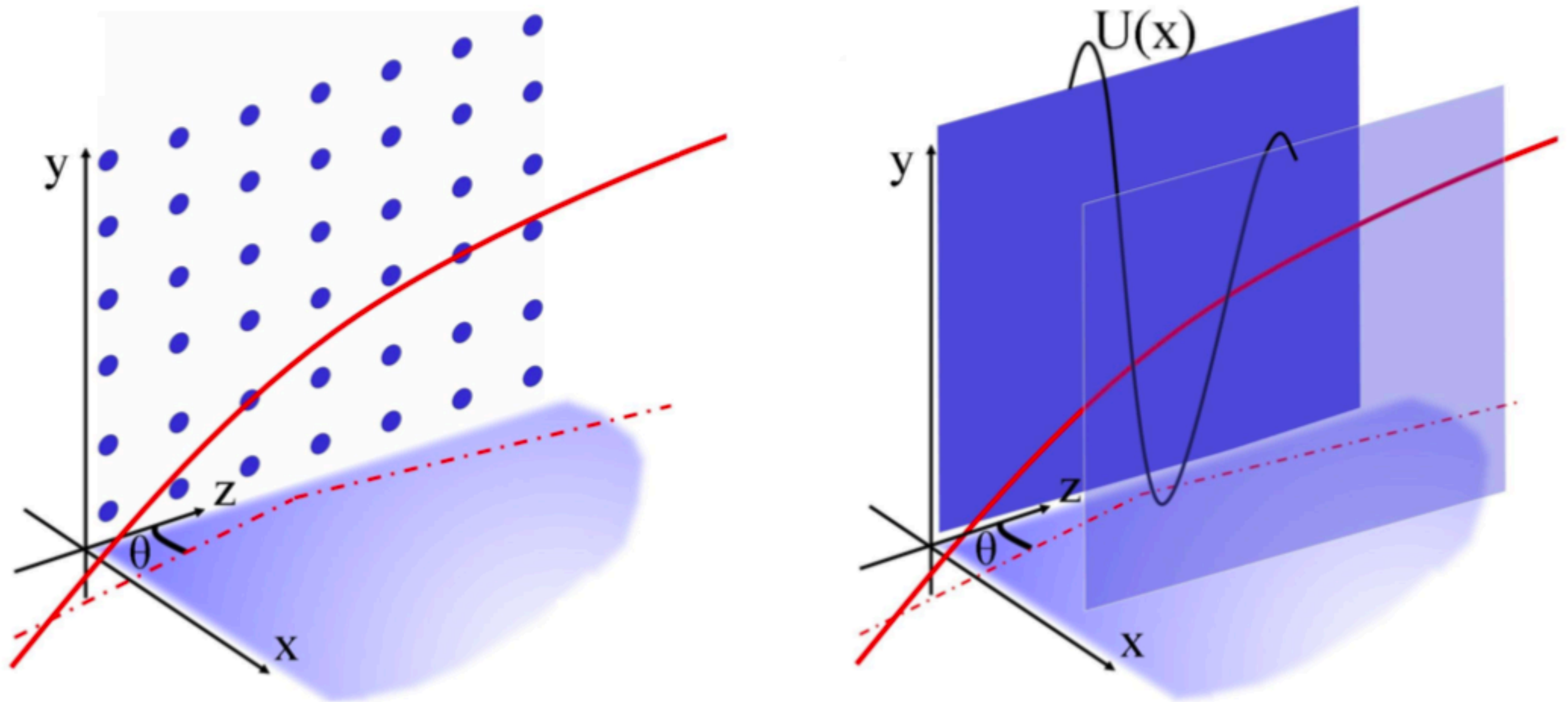

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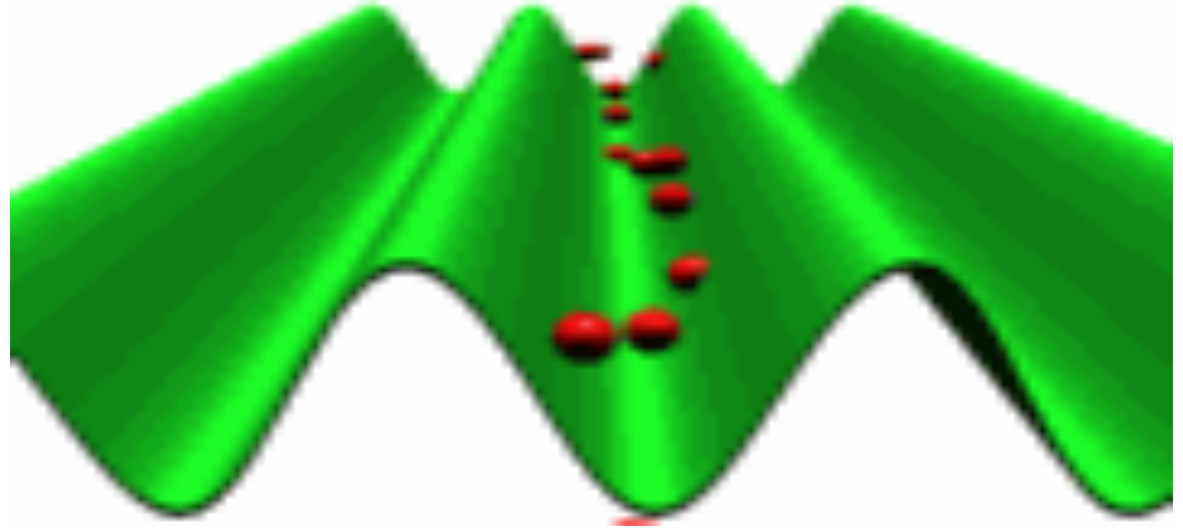

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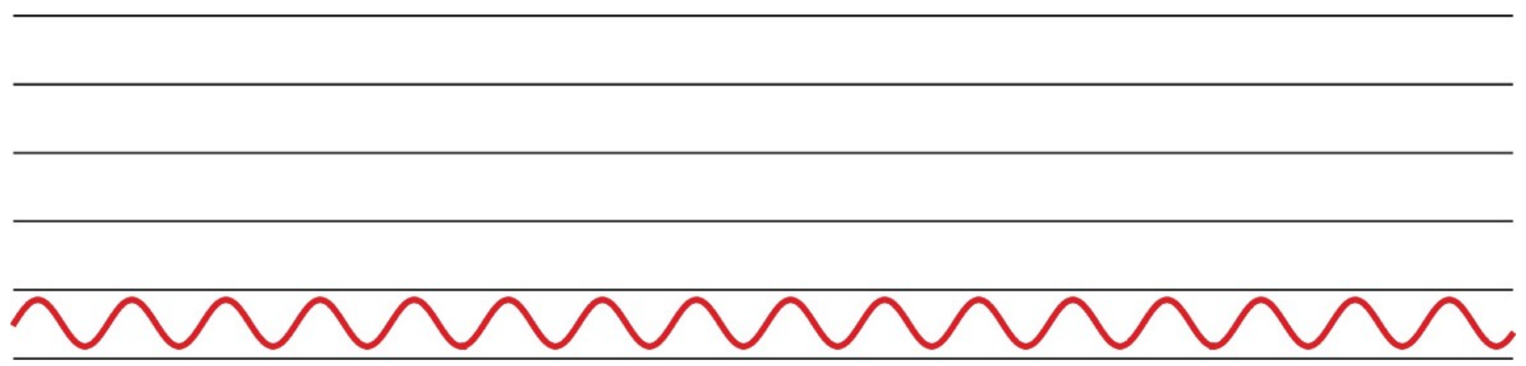

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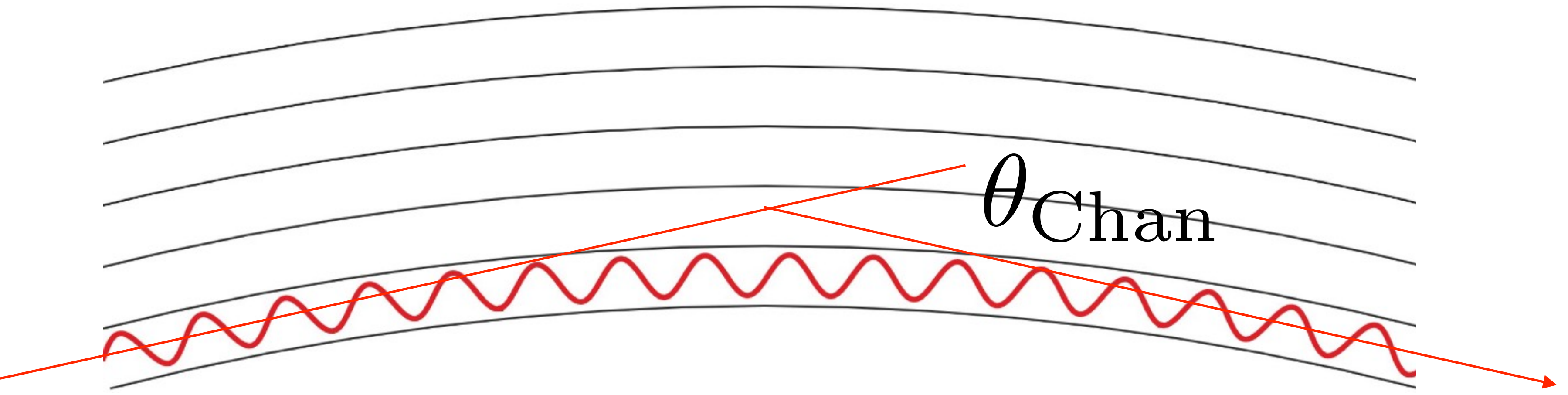

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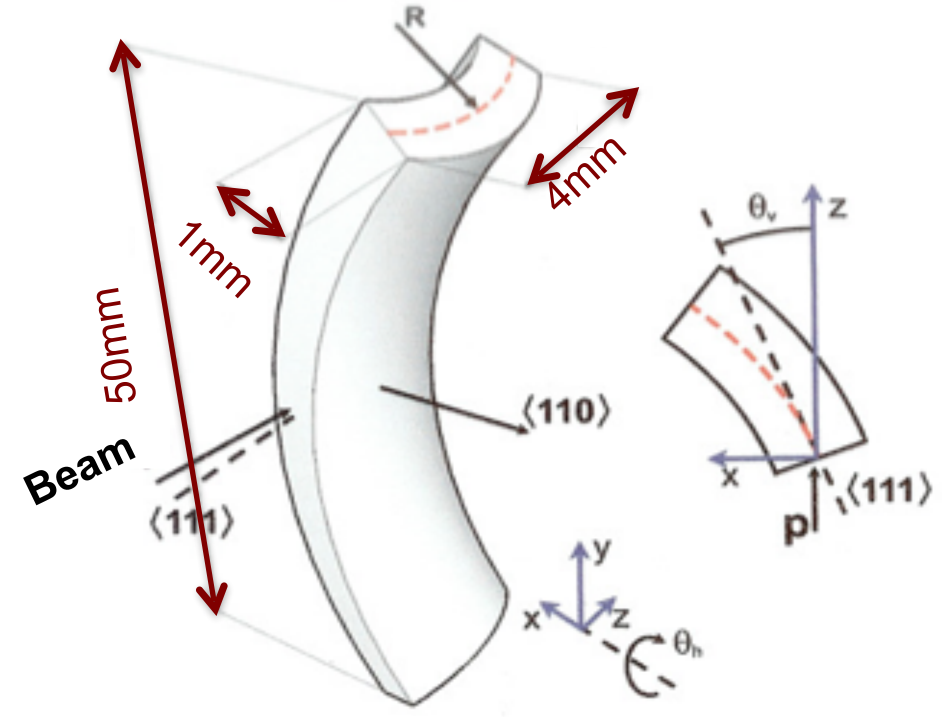
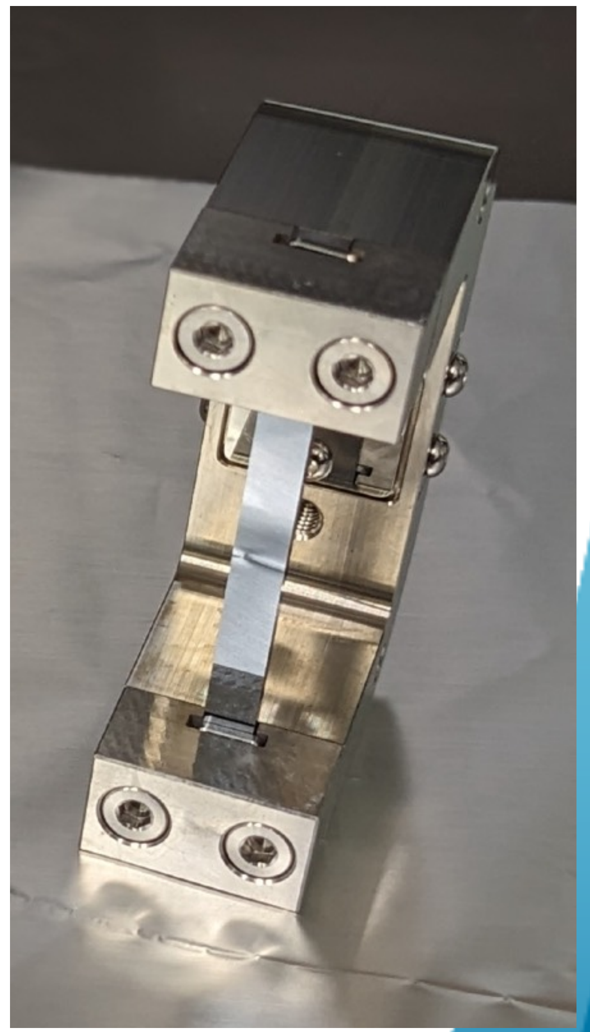
LHC design parameters for **Silicon crystals**

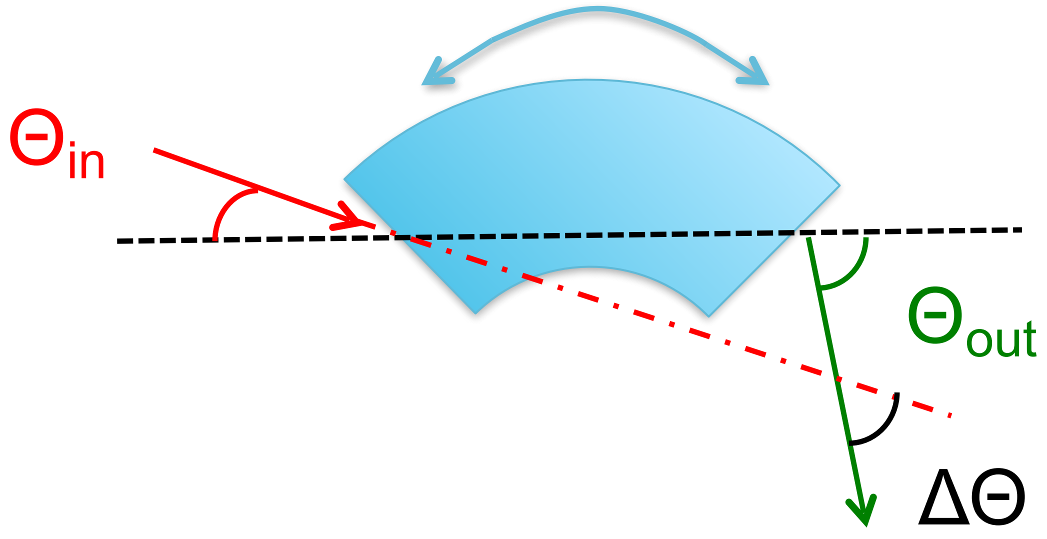


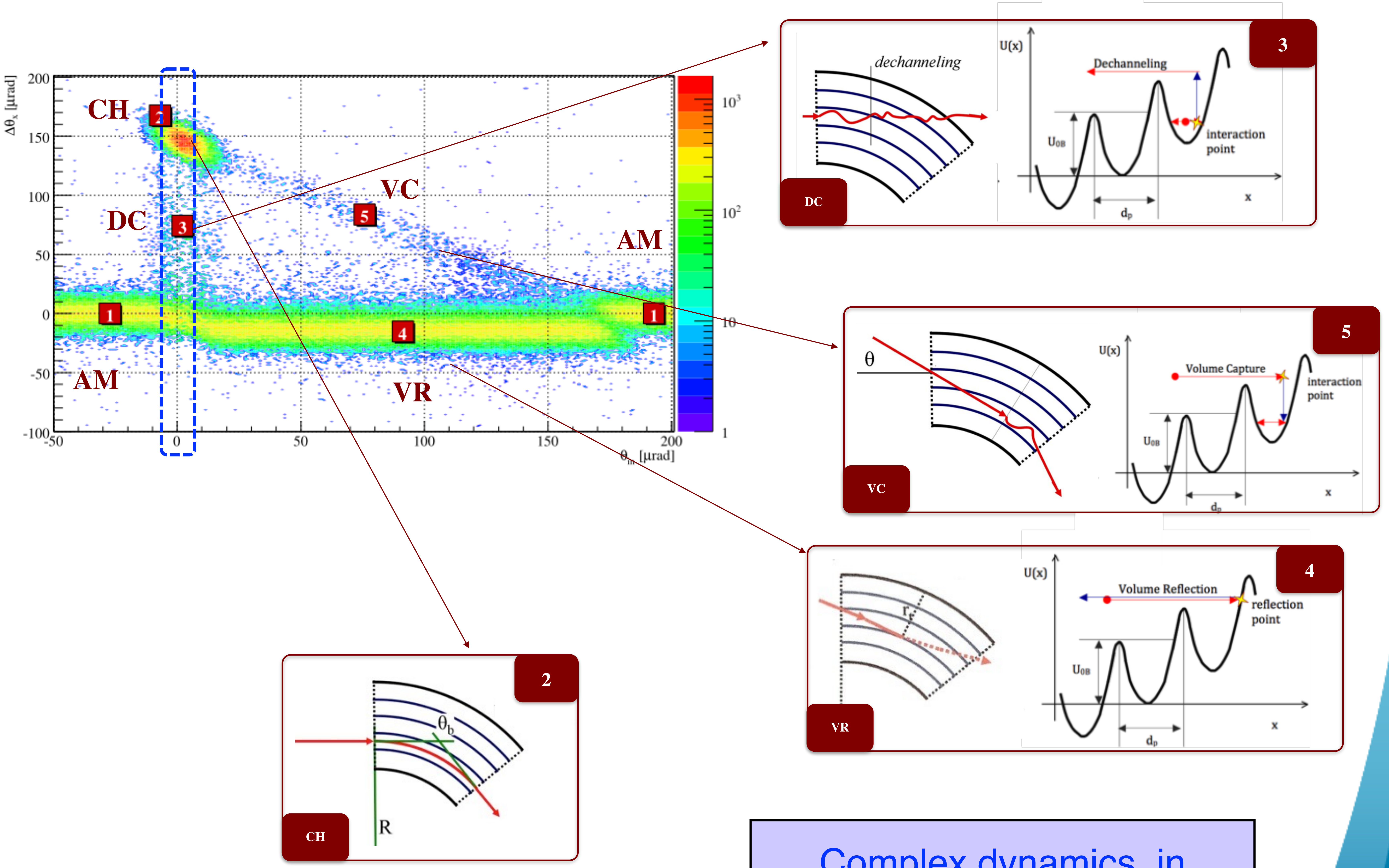
Bending 50μrad



Coherent interactions in bent crystals

From test beam on the CERN-SPS extraction line H8: (UA9 collaboration: see for example Phys. Rept. 815 (2019) 1-107)





Complex dynamics, in particular for heavy ions.

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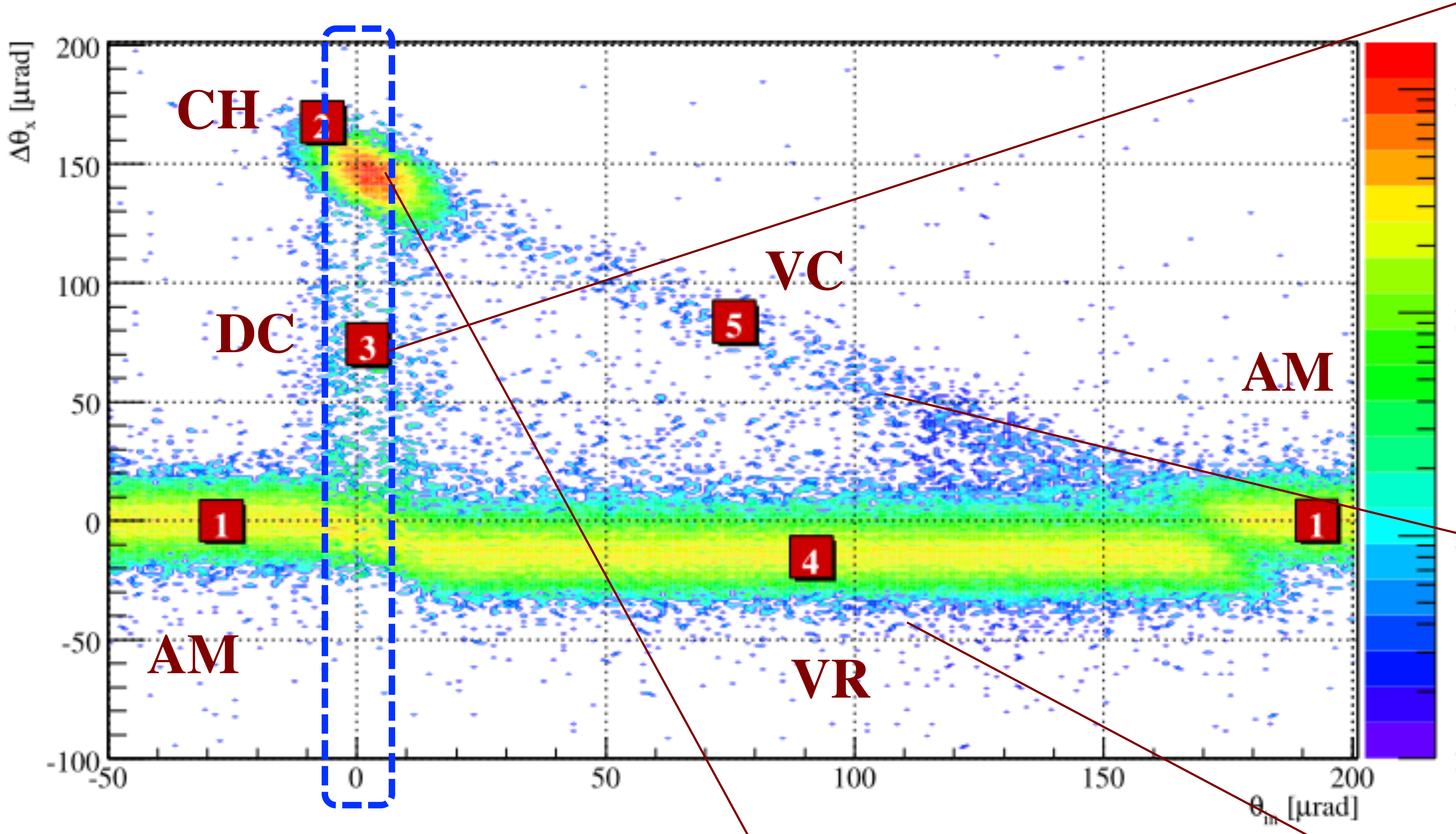
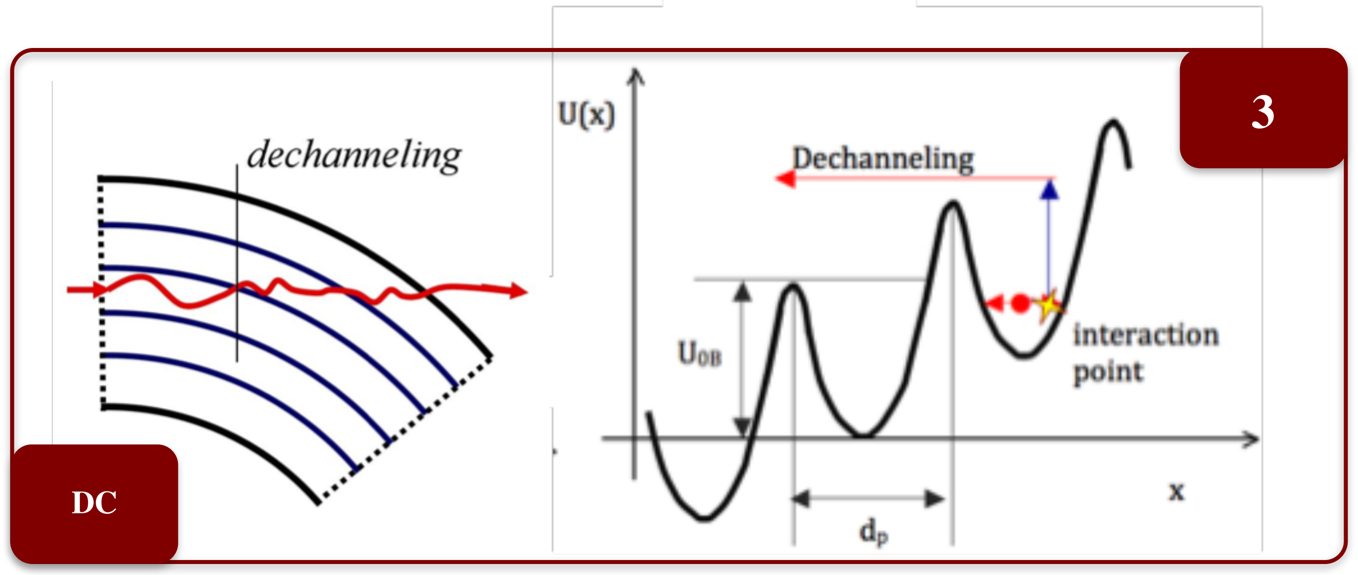
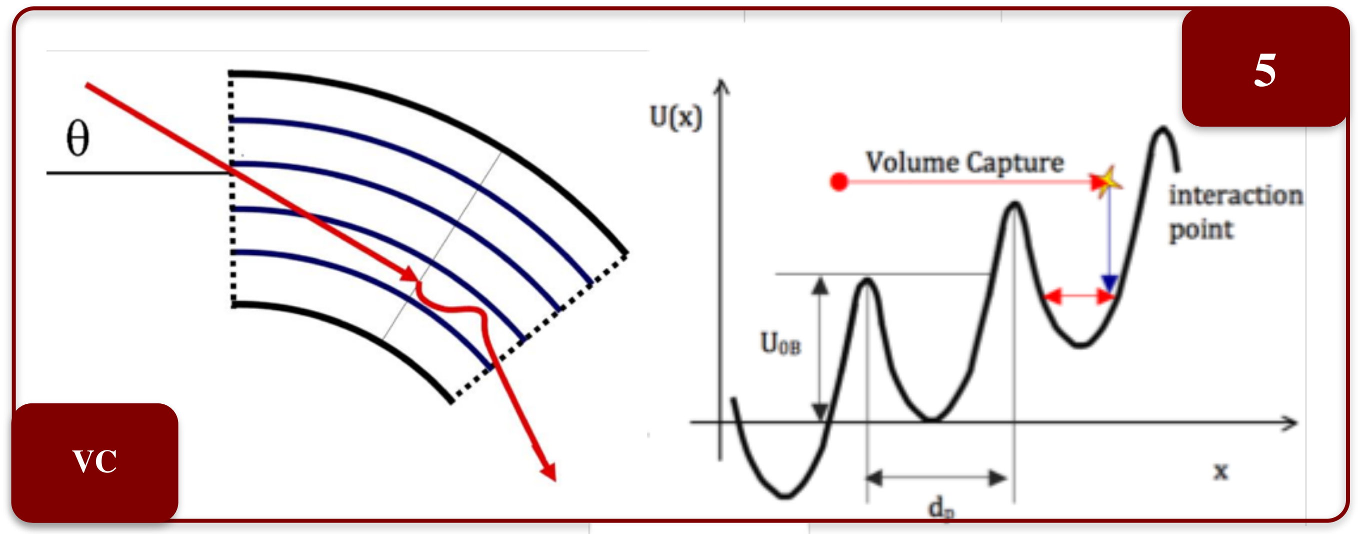
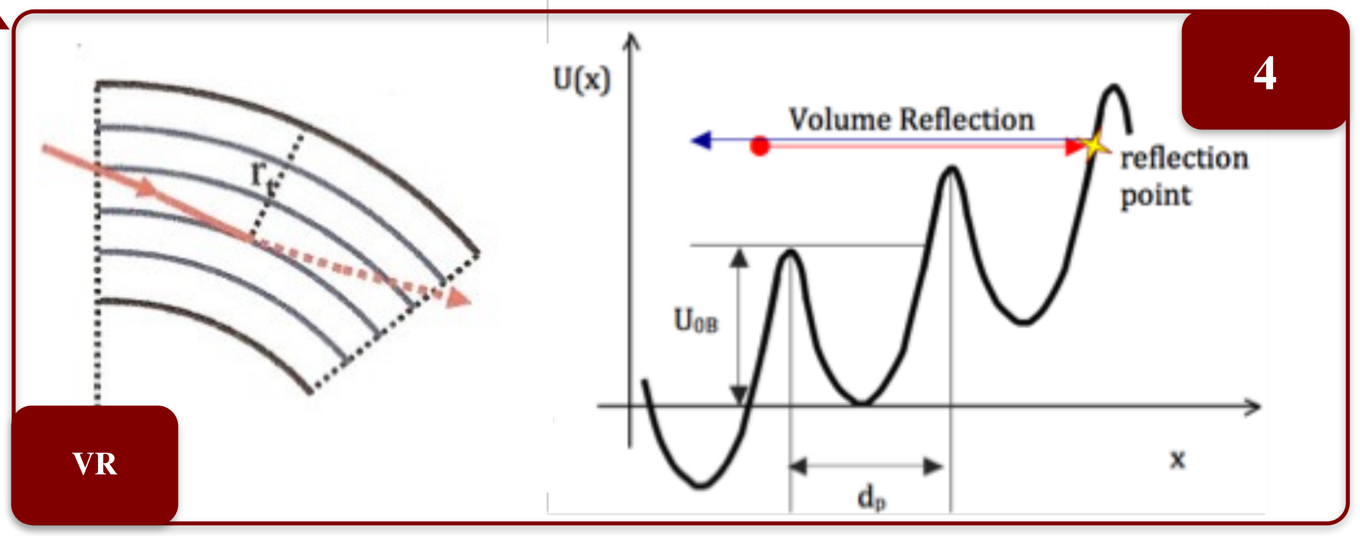
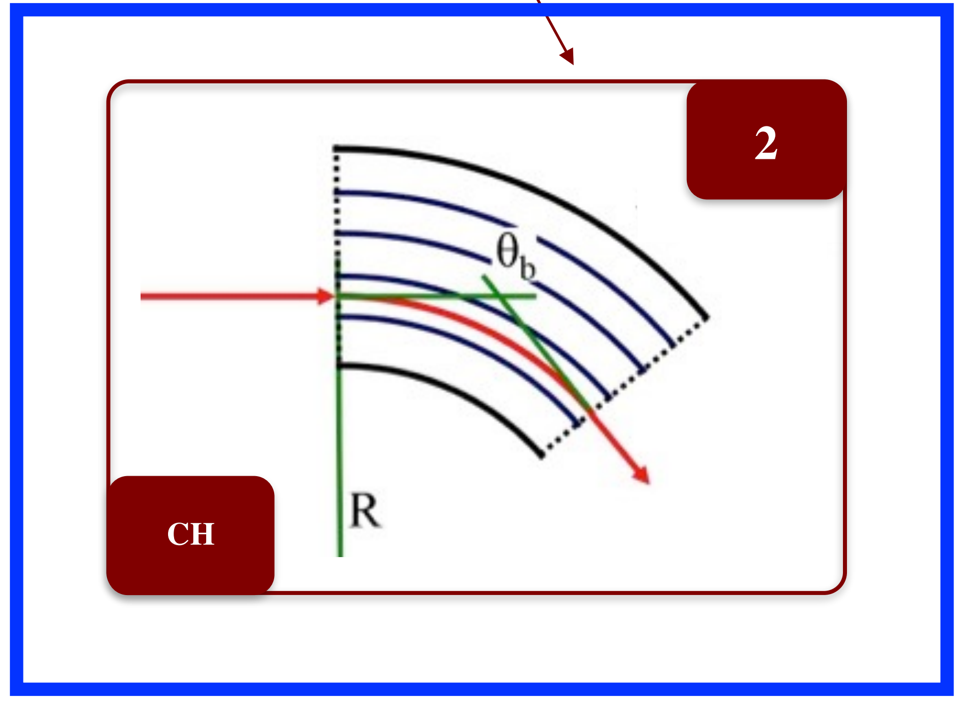


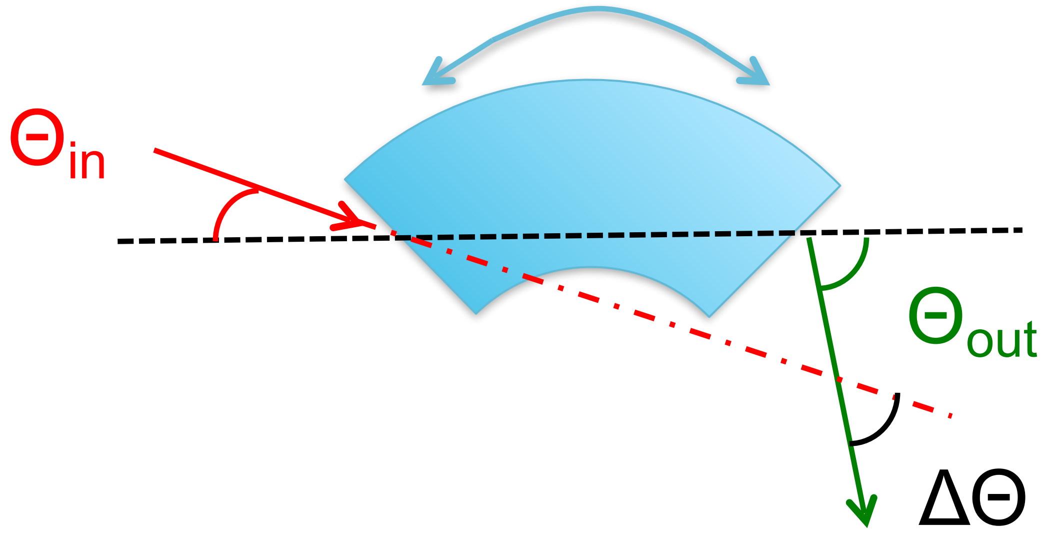






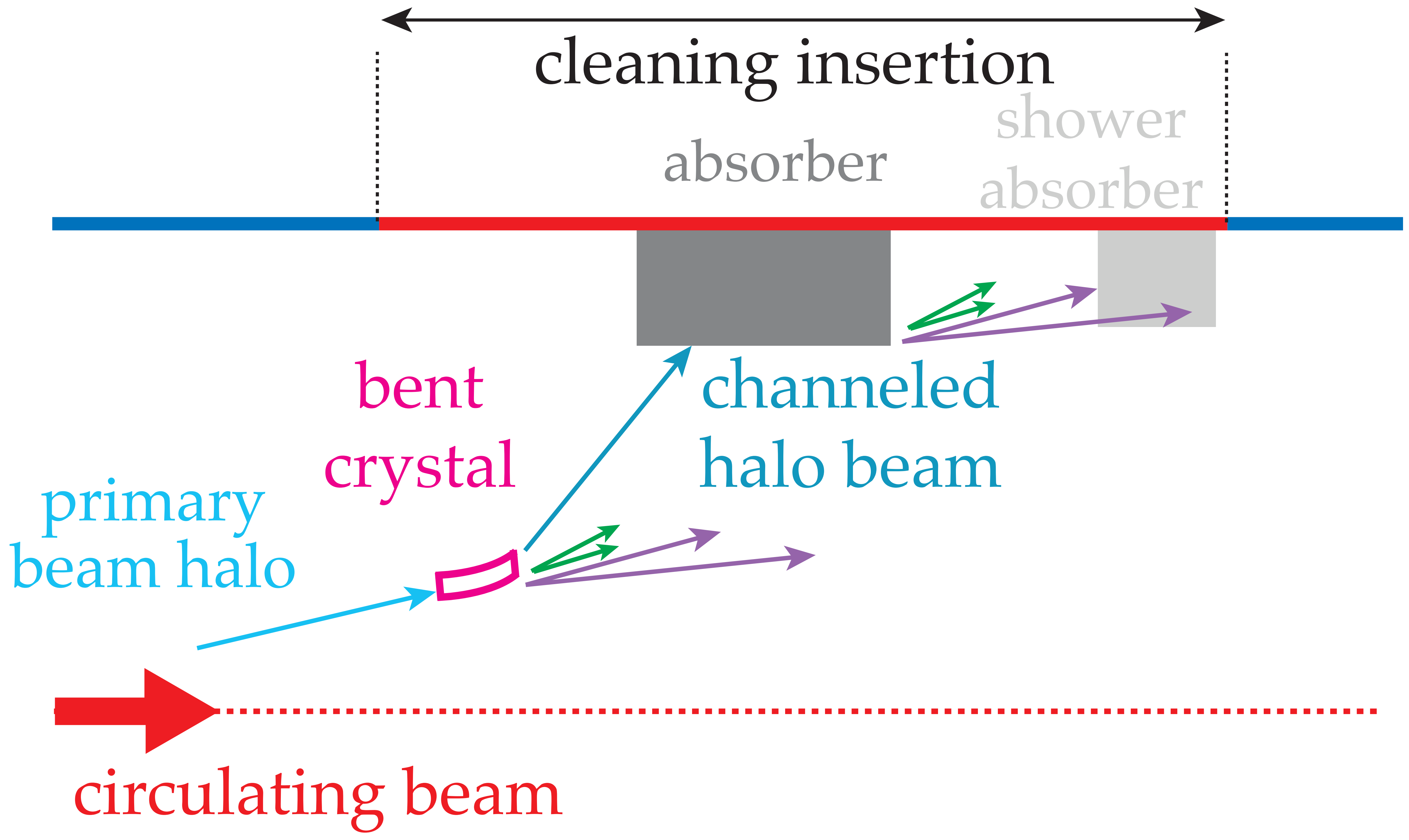
Collimation uses the channeling phenomenon in this angular region





Complex dynamics, in particular for heavy ions.

The crystal collimation concept



Bent crystal as primary collimator deflects halo particles coherently to a single absorber (per beam and plane)

Promises of an ideal crystal collimation scheme

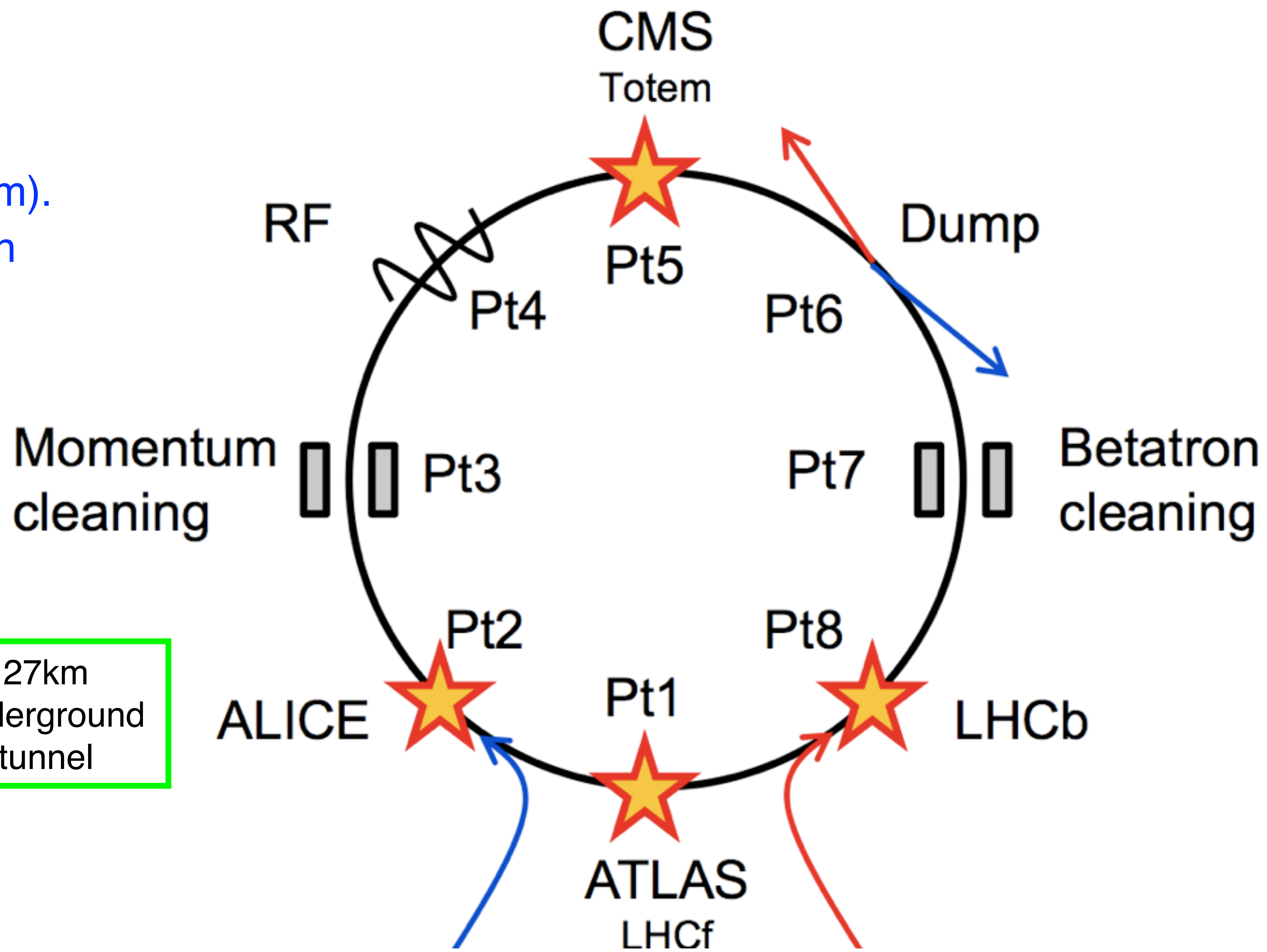
- Improved halo-cleaning performance
- Minimal collimation impedance (large absorber's gap)
- Reduced complexity — less collimators needed

The LHC and its High-Luminosity upgrade (HL-LHC)

Layout

- 8 arcs (~3 km)
- 8 straight sections (~700 m).
- Two-in-one magnet design
- 4 interaction points (IPs): IP1, IP2, IP5, IP8
- IP2/IP8: beam injection
- IP6: beam dump region
- IP4: RF (acceleration)
- IP3/IP7: beam cleaning

27km underground tunnel



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LHC Collimation Project CERN

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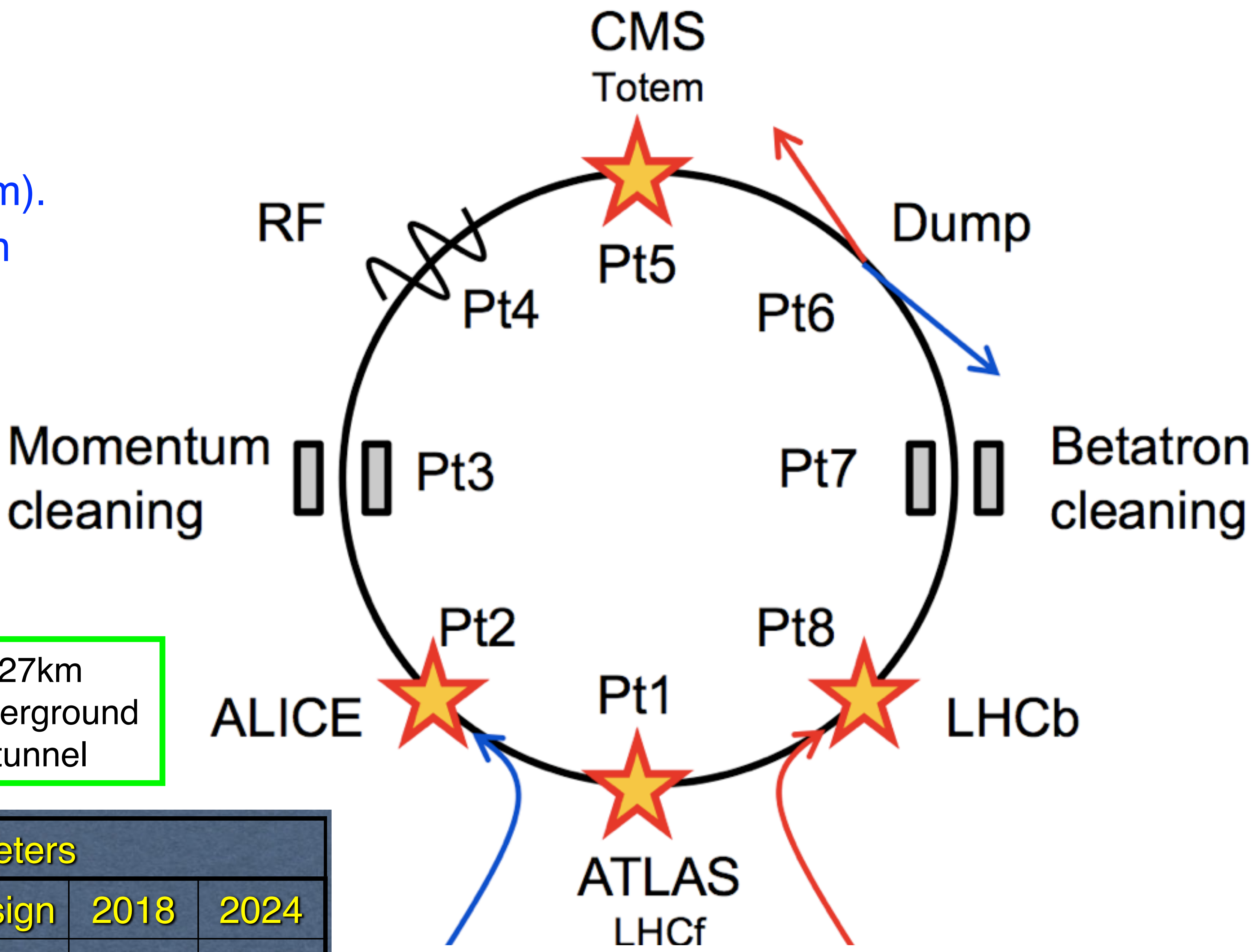

Nominal LHC parameters			
	Design	2018	2024
Injection energy (TeV)	0.45	0.45	0.45
Top energy (TeV)	7	6.5	6.8
Particles per bunch, I_b (10^{11})	1.15	1.2	1.6
Number of bunches per beam	2808	2560	2352
Stored beam energy, E_b (MJ)	362	300	410
Beam current (A)	0.58	0.48	0.56
Transverse emittance (µm)	3.75	2.1	1.8

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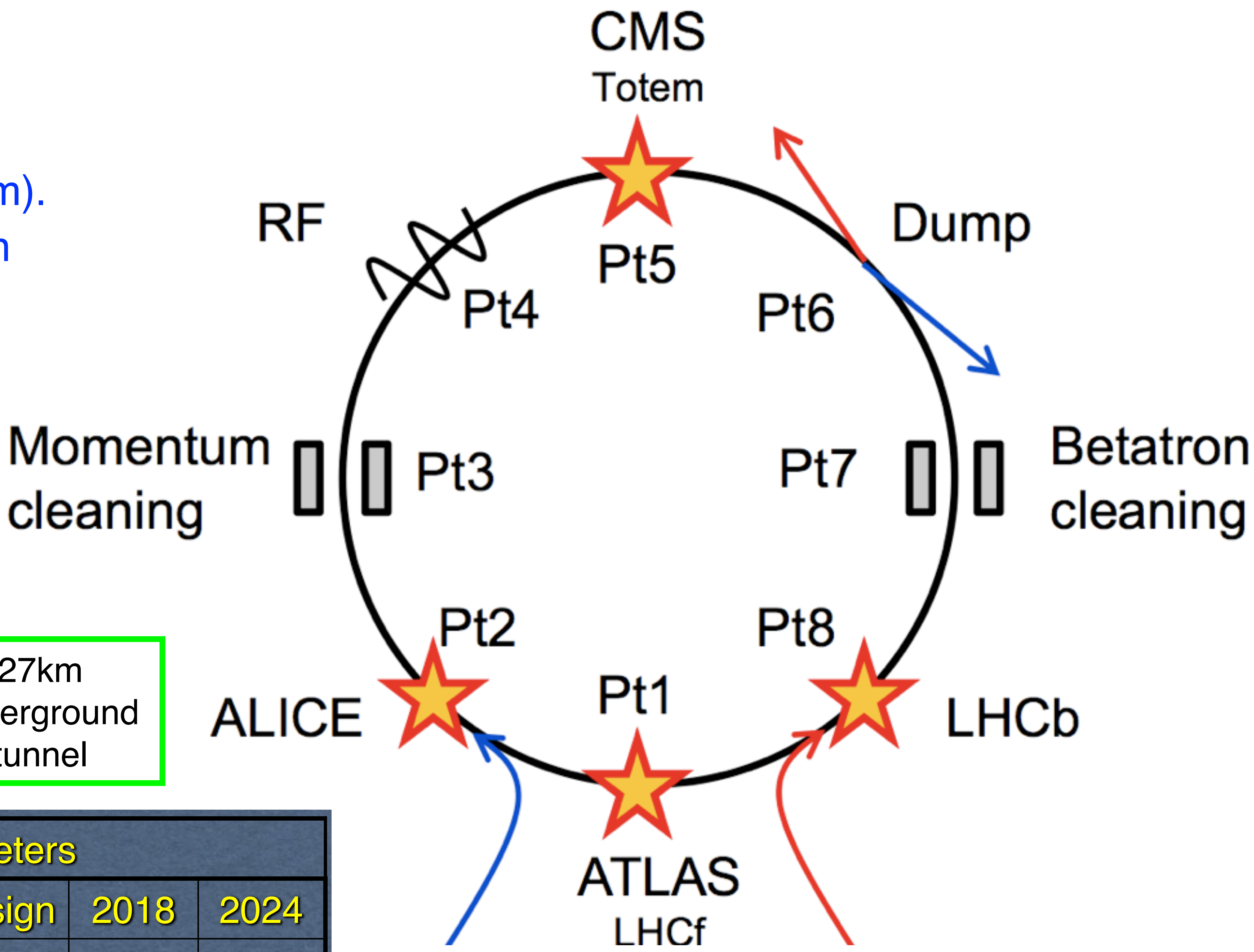

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Target beam upgrades

Protons (Run 4 starting 2029)

I_b [10^{11} p] : 1.15 → 2.20

E_b [MJ] : 362 → **690**

Lead ion beams (Run 3: now!)

I_b [10^{8} Pb] : 0.7 → 1.8

N_b : 592 → 1240

E_b [MJ] : 3.8 → **20.5**

Ion run report: TUBD2

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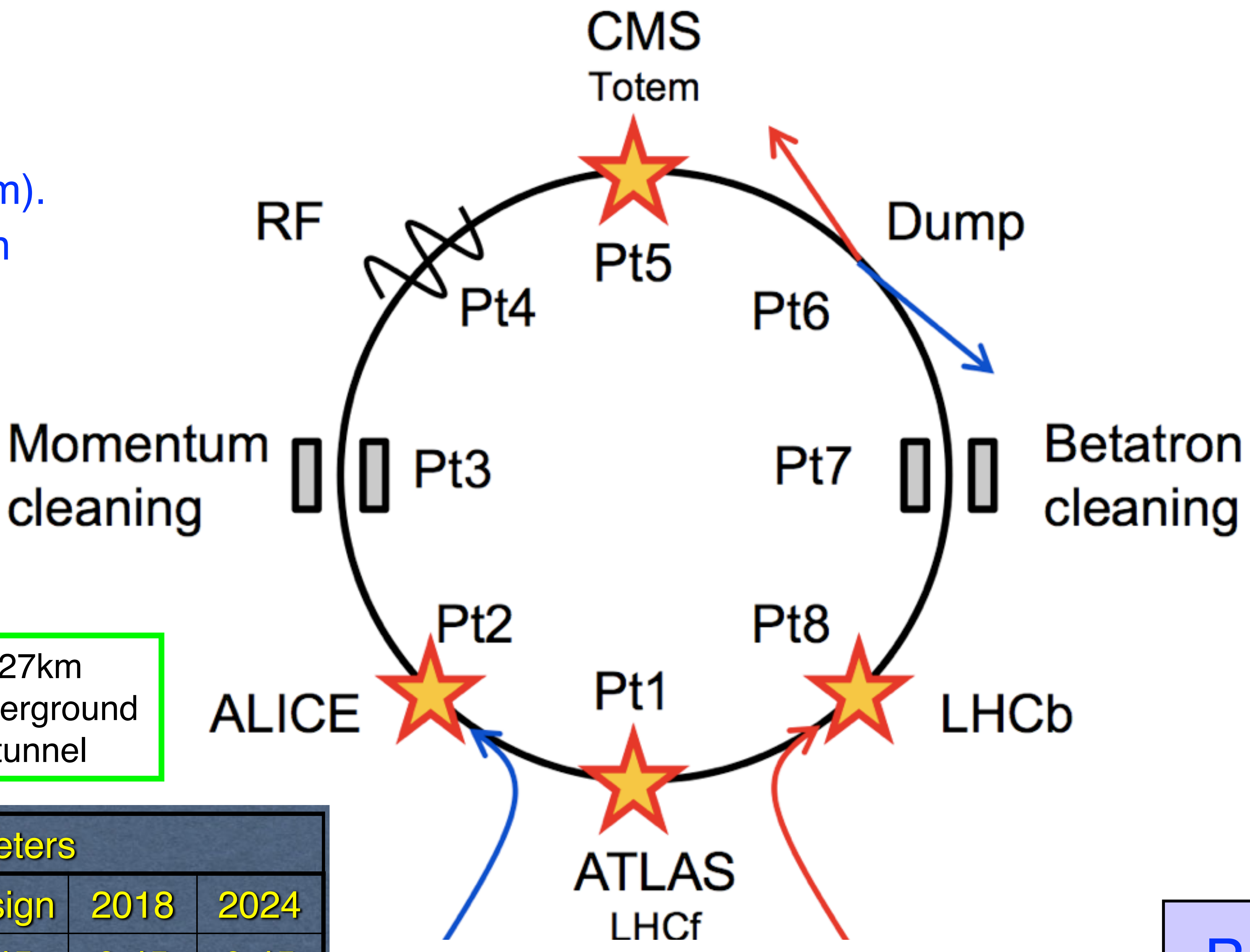

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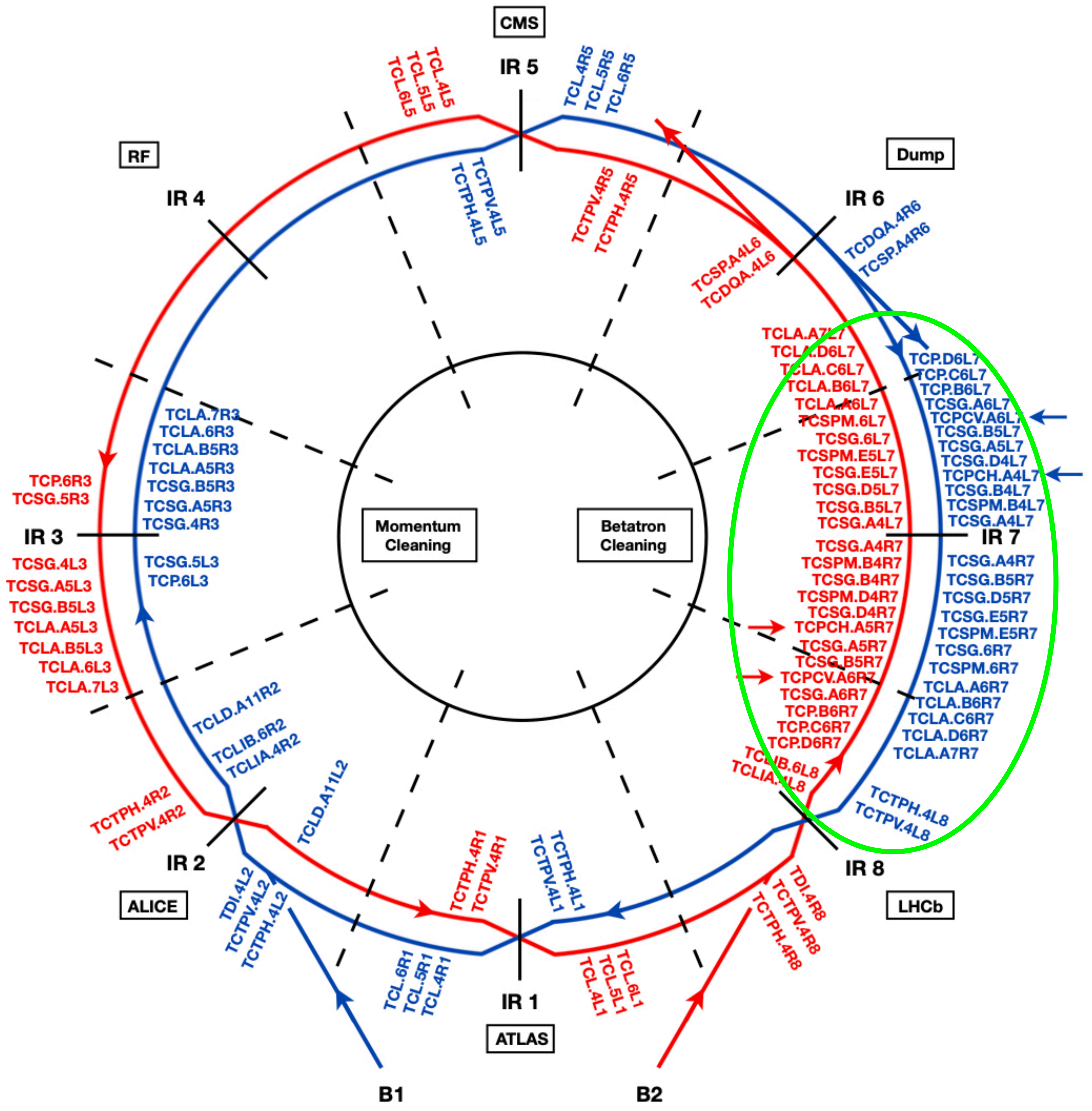
Beam collimation is a critical challenge for the HL-LHC!

Ion run report: TUBD2

LHC collimation system



It fulfils various critical roles

→ betatron halo cleaning (IR7)

→ off-momentum cleaning (IR3)

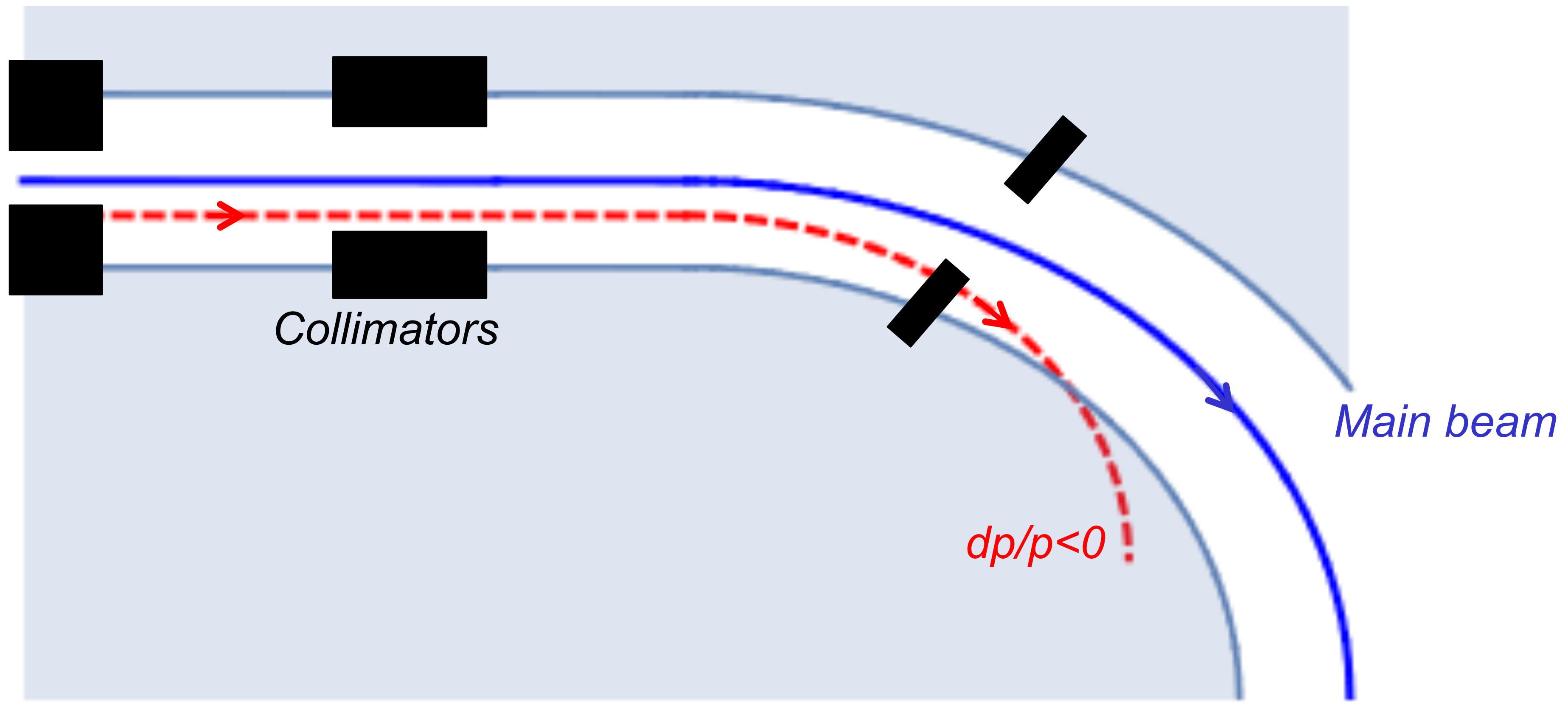
→ Inner triplet and detector protection

→ Disposal of physics-debris product

Run 3 system includes more than 100 “cleaning” collimators.

Crystal collimation scheme addressed the improvement of the betatron halo cleaning in IR7.

Collimation challenges at the high-luminosity LHC project



Interaction with the collimators causes a change of rigidity.
Beam losses occur in the cold dispersion suppressors.

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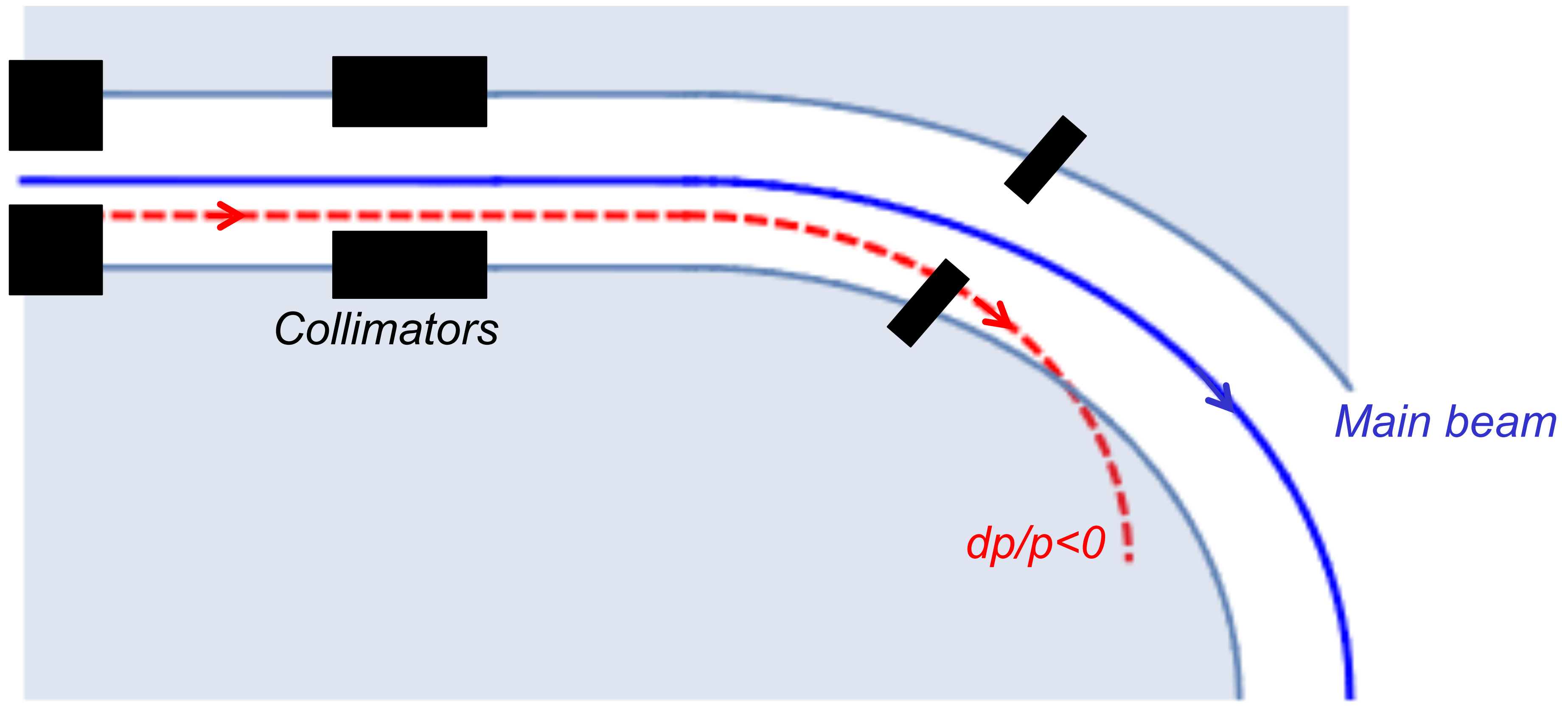

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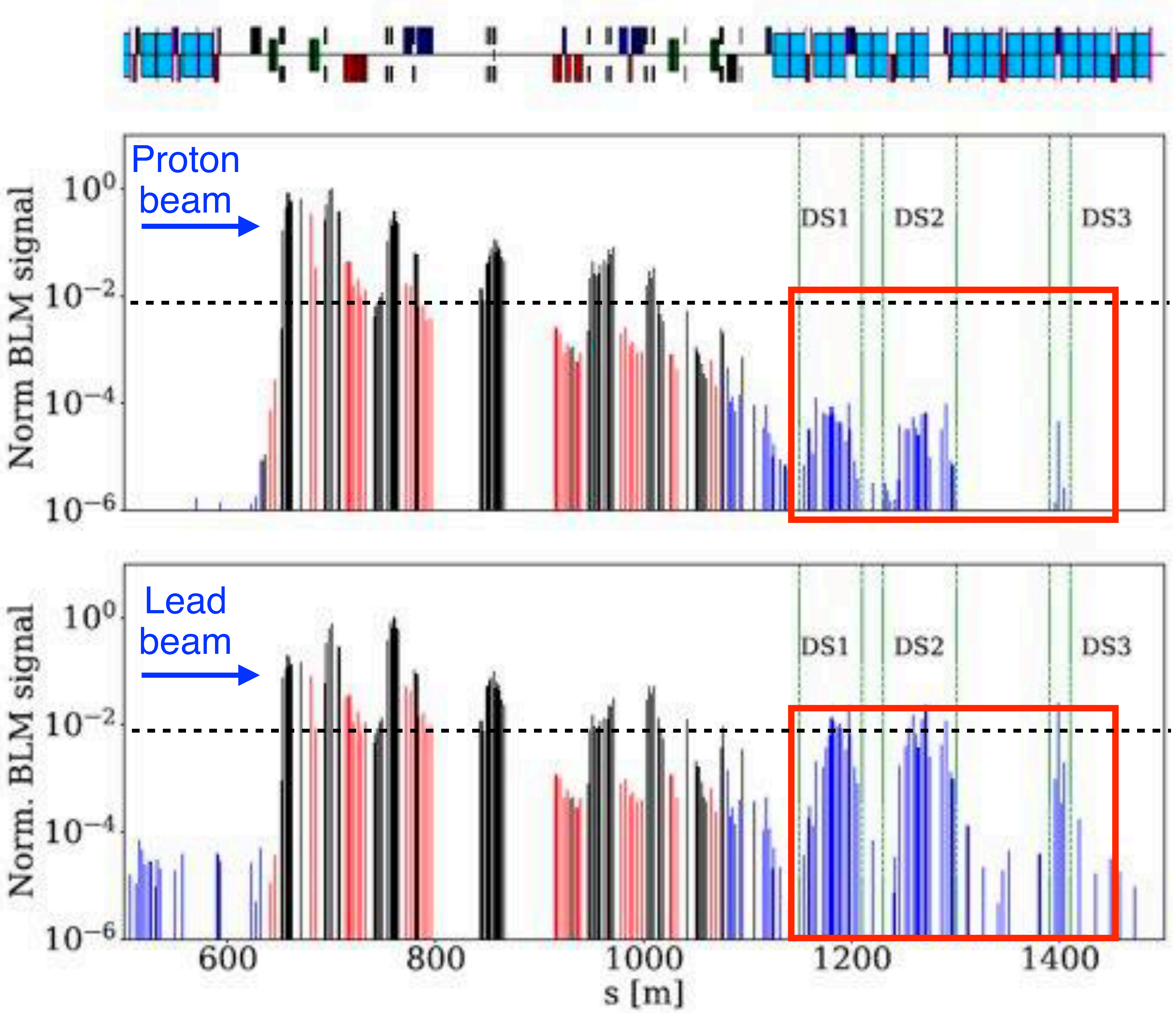

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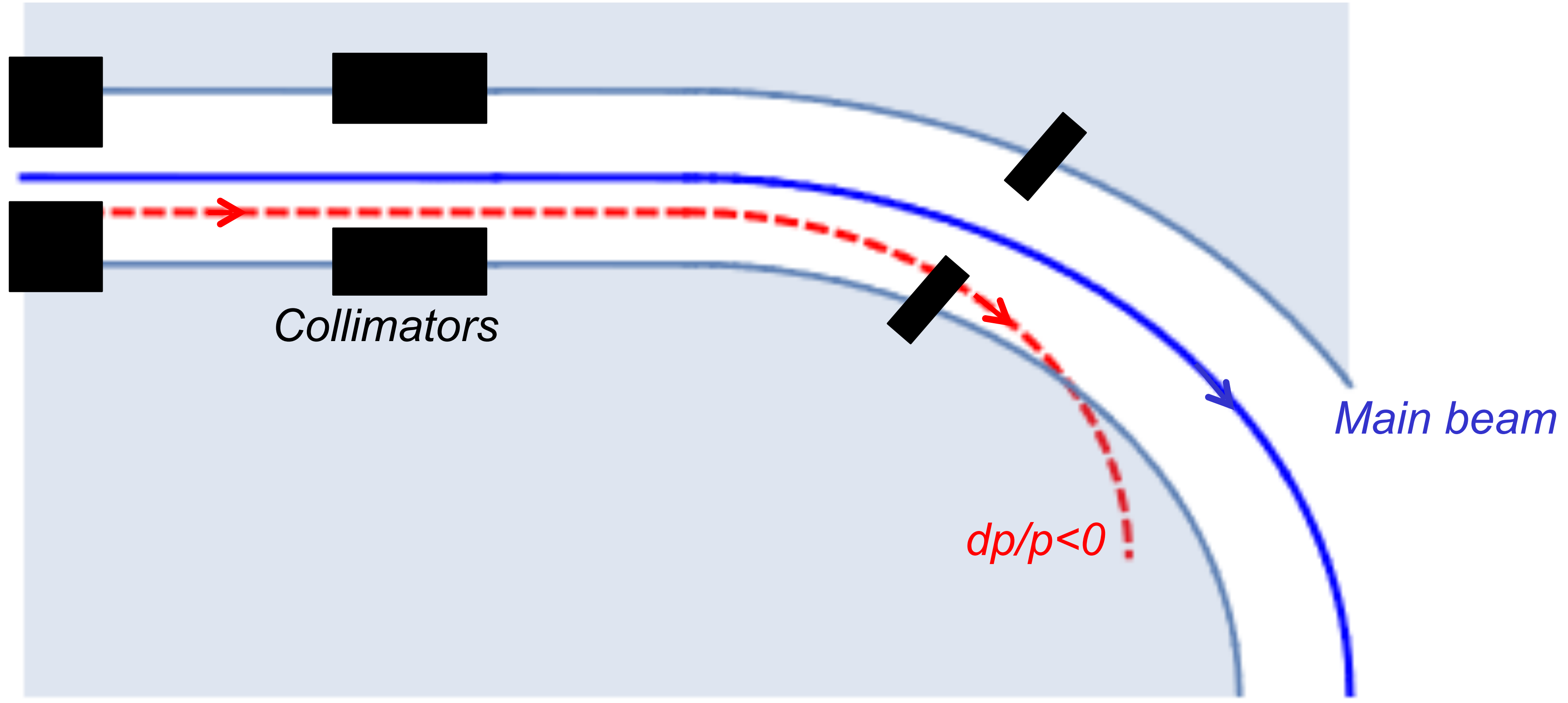

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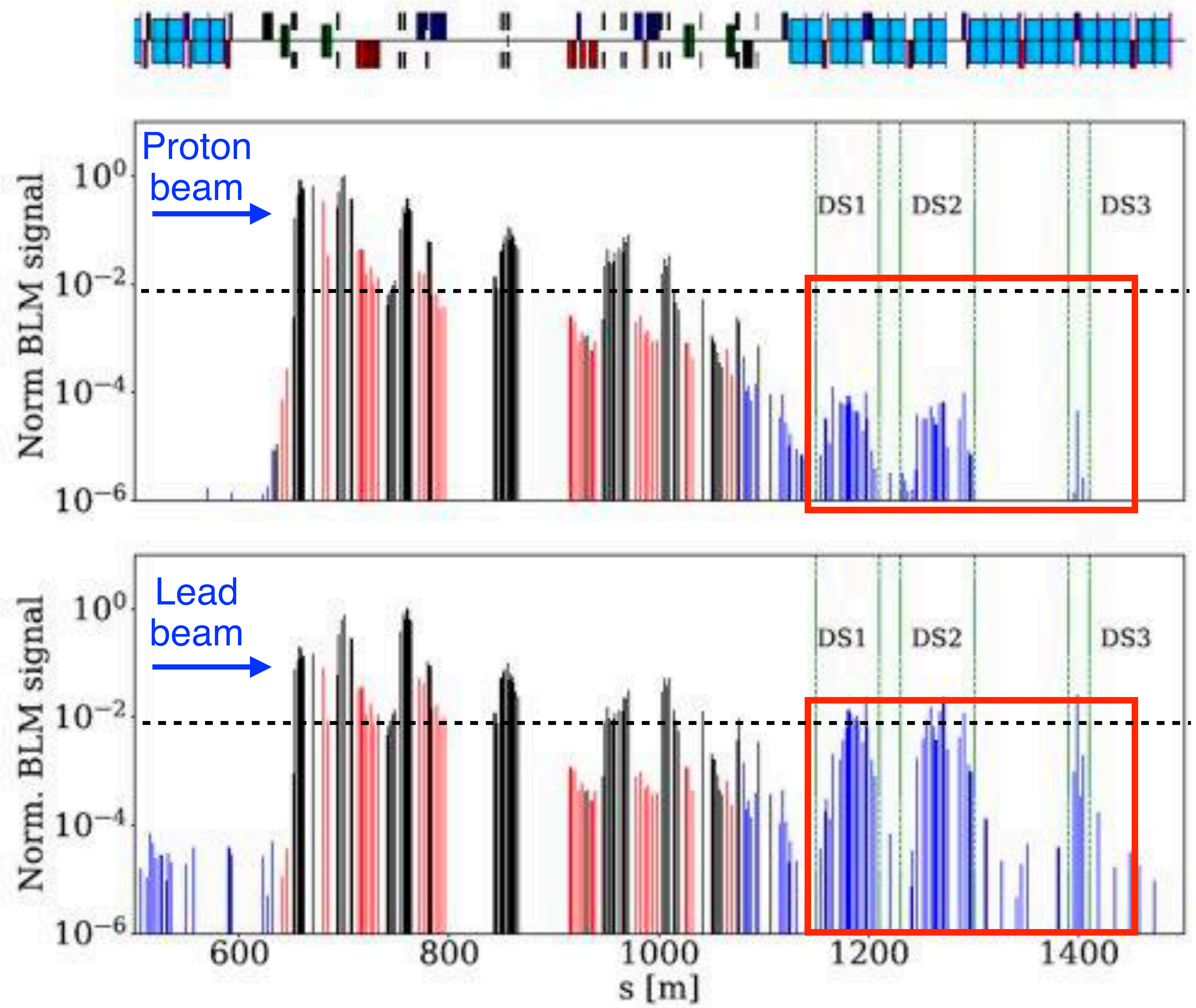


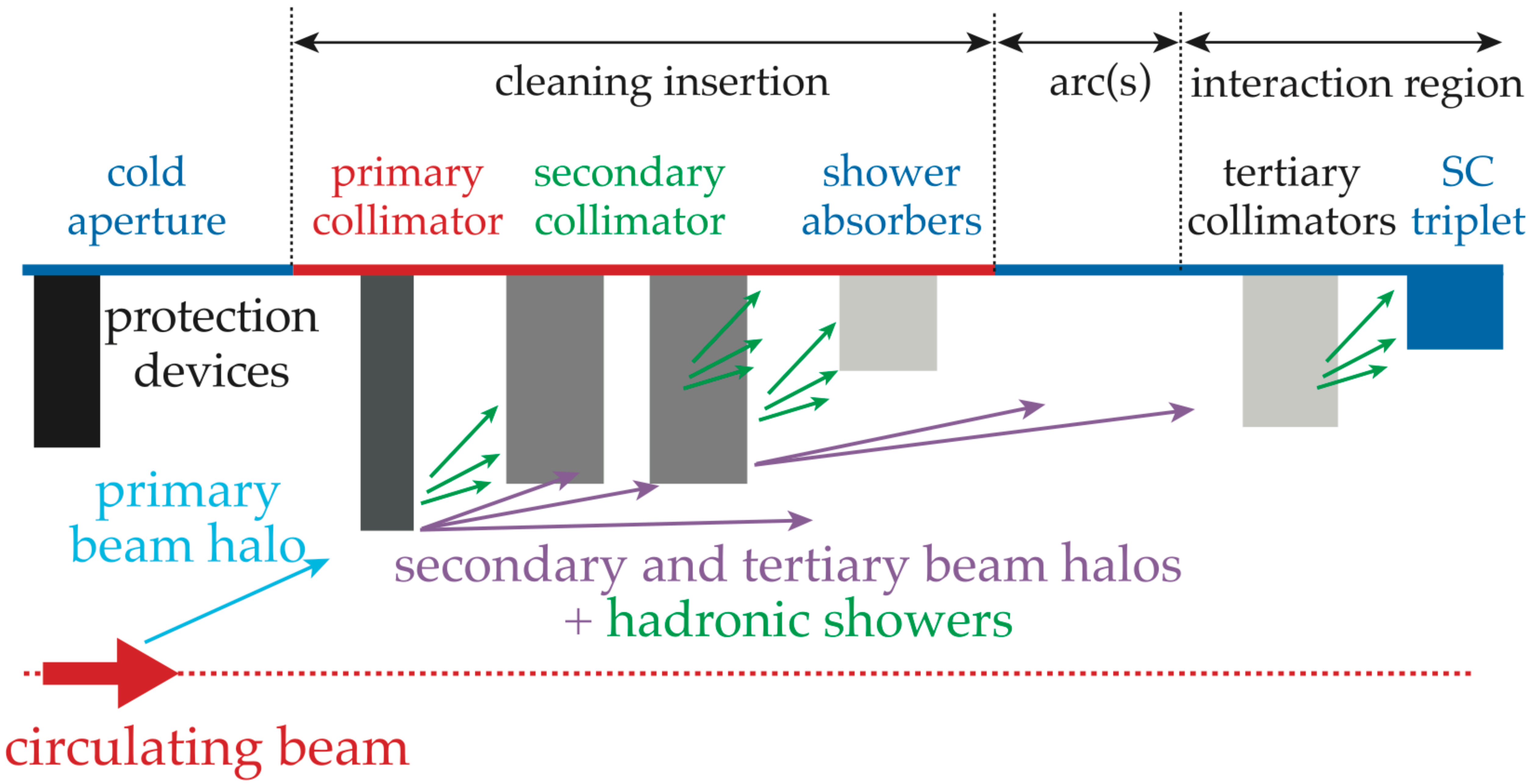
Projected collimation performance at the HL-LHC:

OK for proton beams!

Not OK for lead ions.

Despite of the ~30 times lower stored beam energy!

Multi-stage and crystal-based collimation schemes



Crystal collimation for ion beams:

1. No impedance concerns
2. No need of additional absorbers

(Proton beams: studied extensively, however not planned for upgrade. Only compatible with special runs at low intensities).

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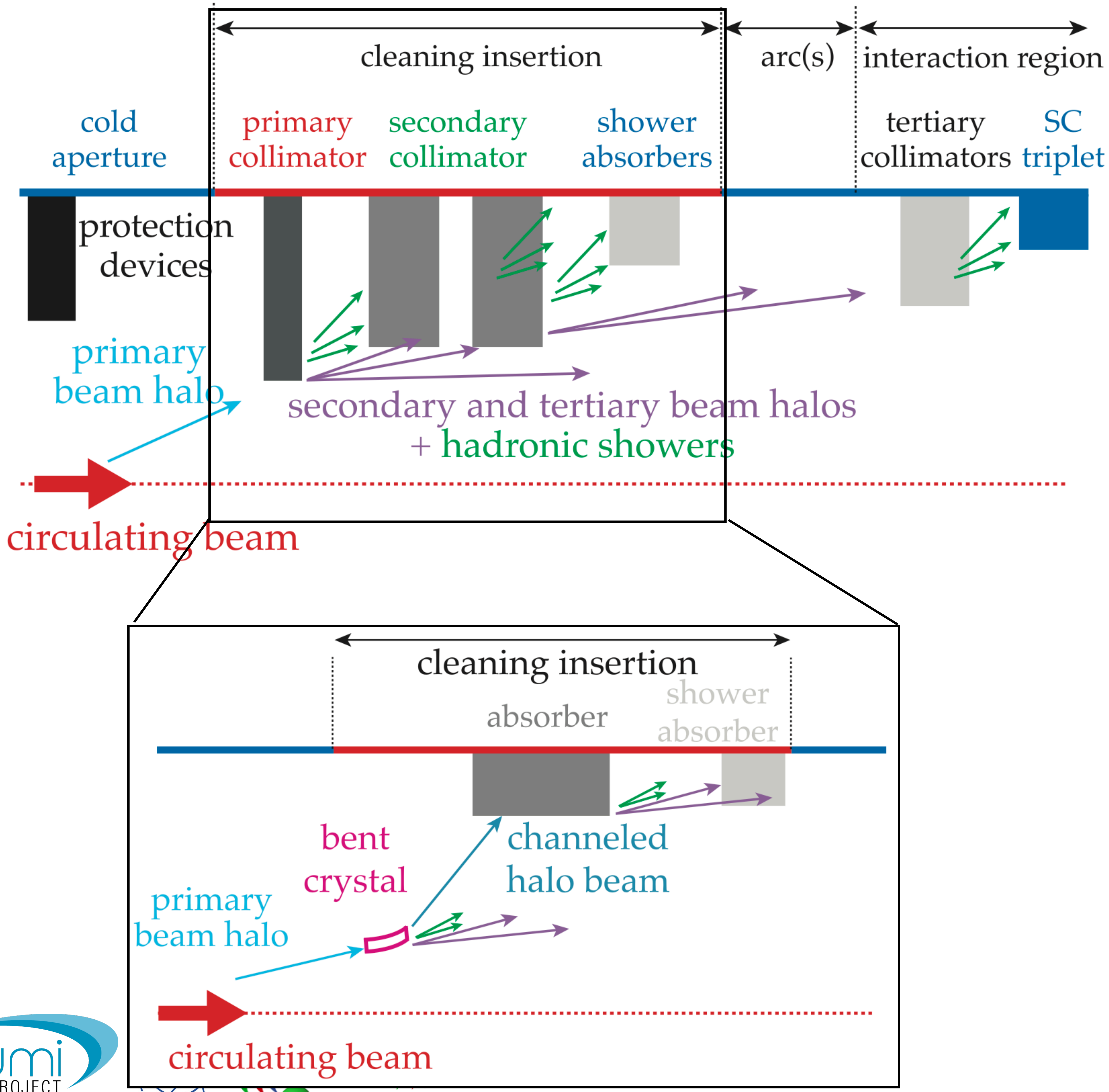

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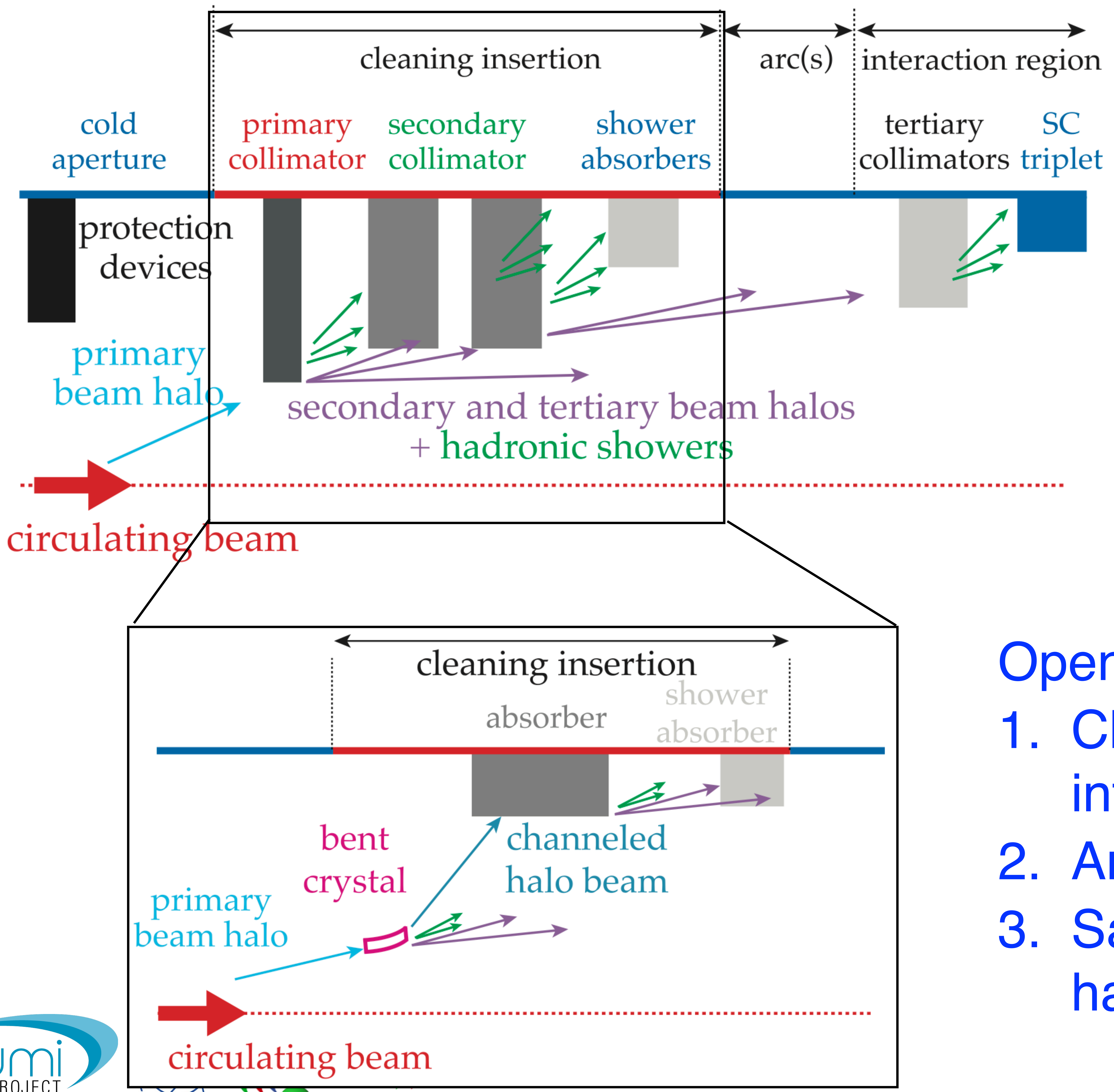

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Open points and challenges:

1. Channeling for the energies/particles of interest?
2. Angular control within sub-micro radians?
3. Safe and efficient disposal of channeled halo: can we improve cleaning?

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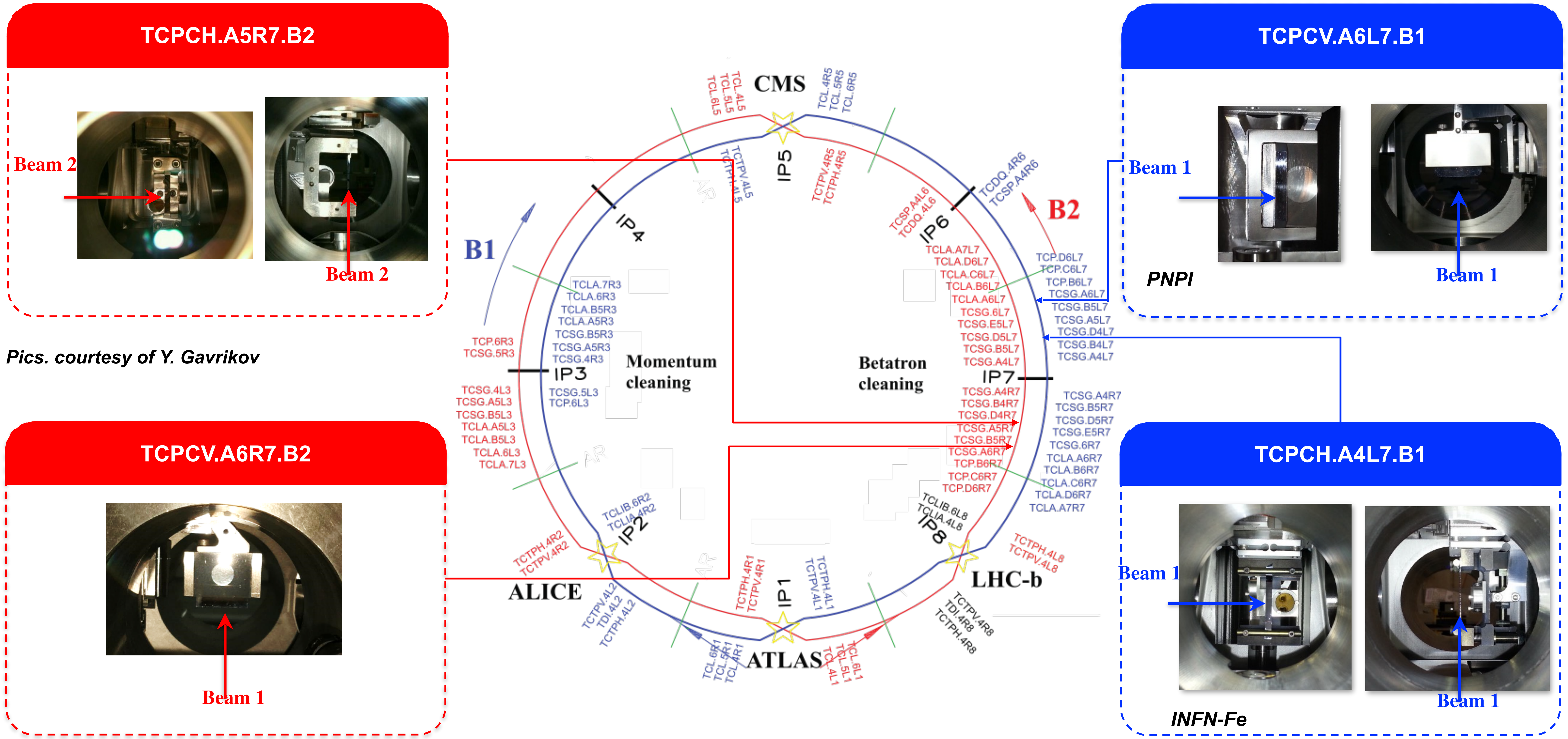
LHC crystal collimation test stand (2015-2018)

Four crystals installed in the LHC: two per beam, one per plane



Pics. courtesy of Y. Gavrikov

D. Mirarchi

Thanks to R. Losito

More information: Crystal collimation day (2018)
https://indico.cern.ch/event/752062

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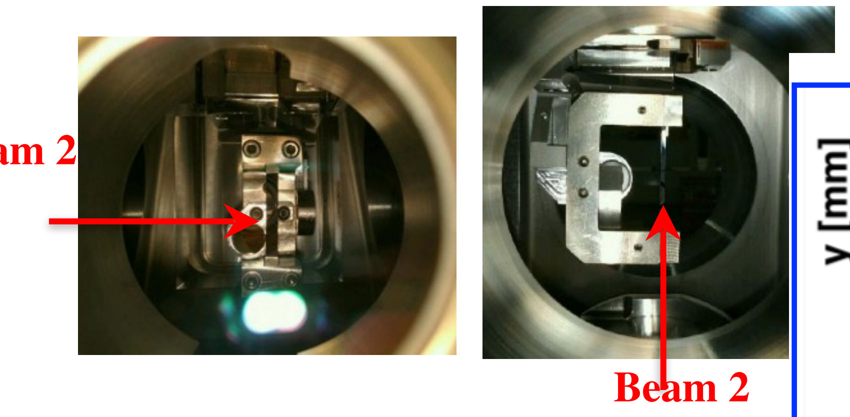
TCPCH.A5R7.B2



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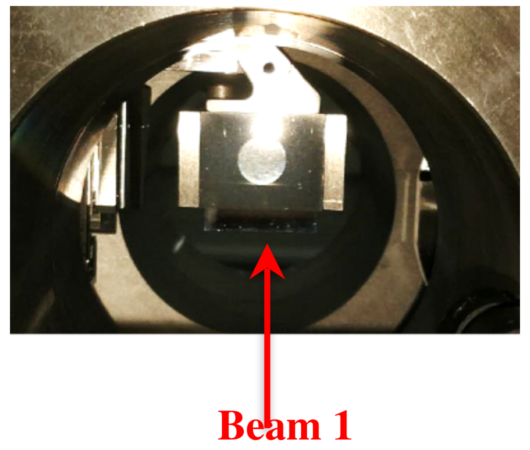

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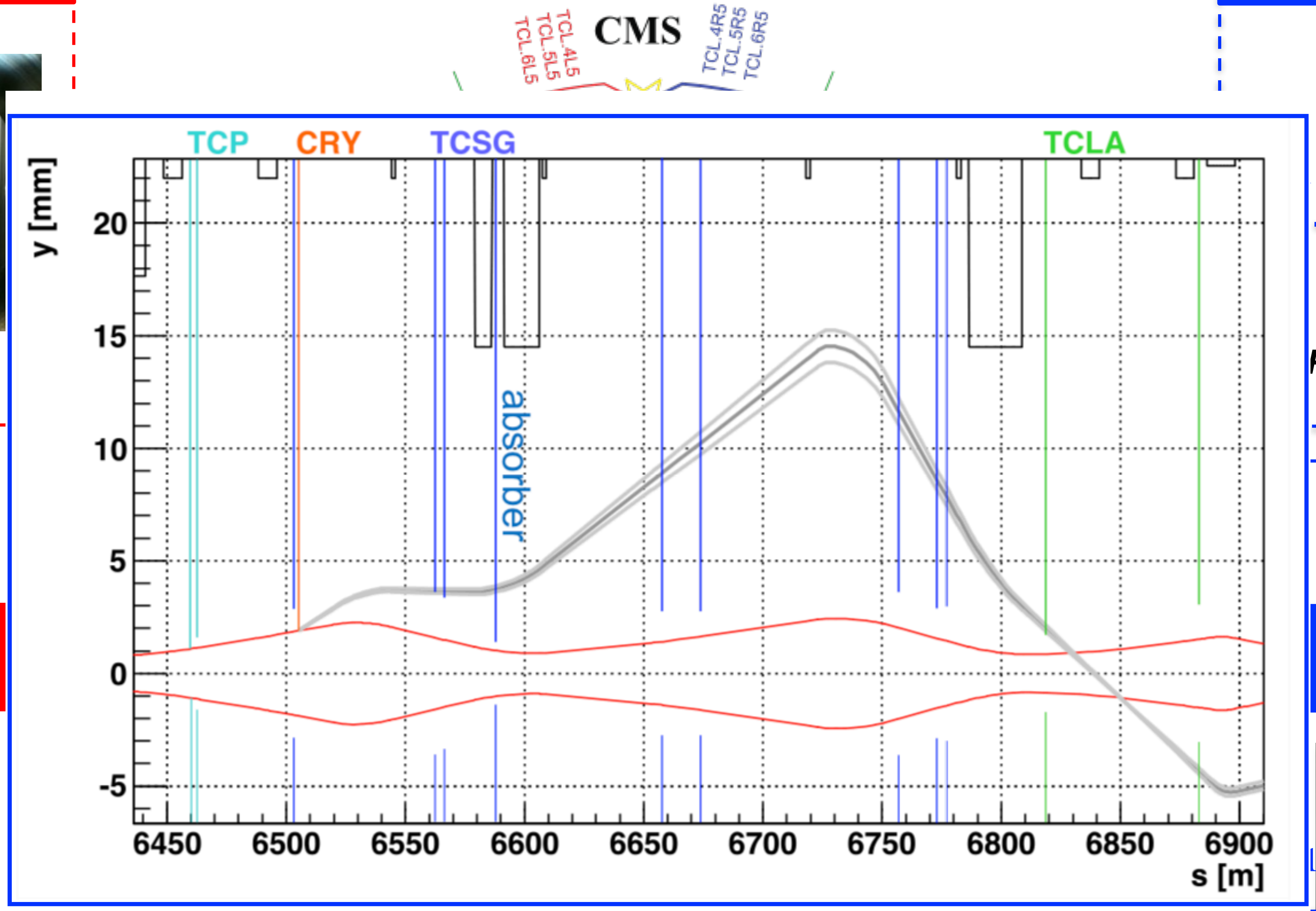
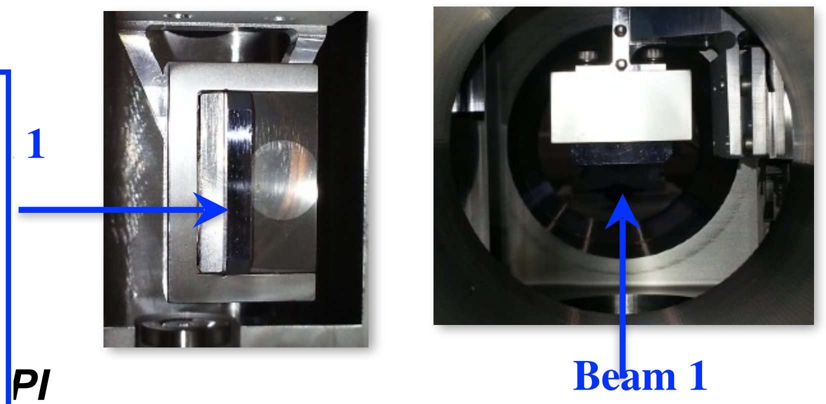


TCP = primary collimator
TCSG = secondary collimator
TCLA = shower absorber

TCPCV.A6L7.B1



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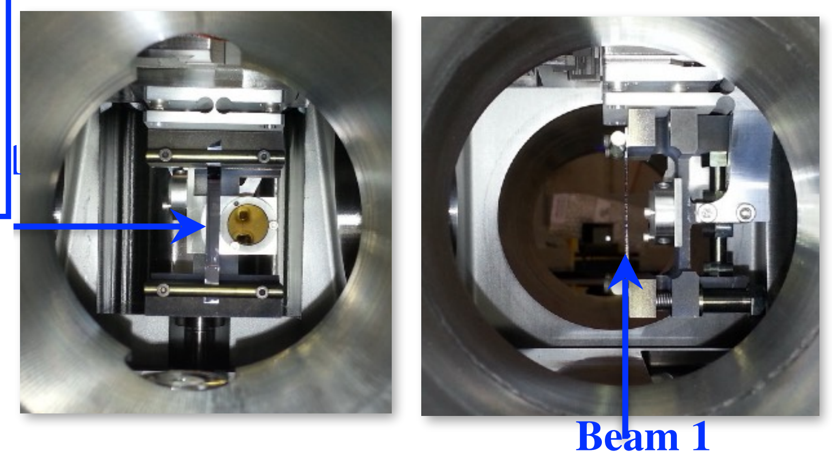

INFN-Fe

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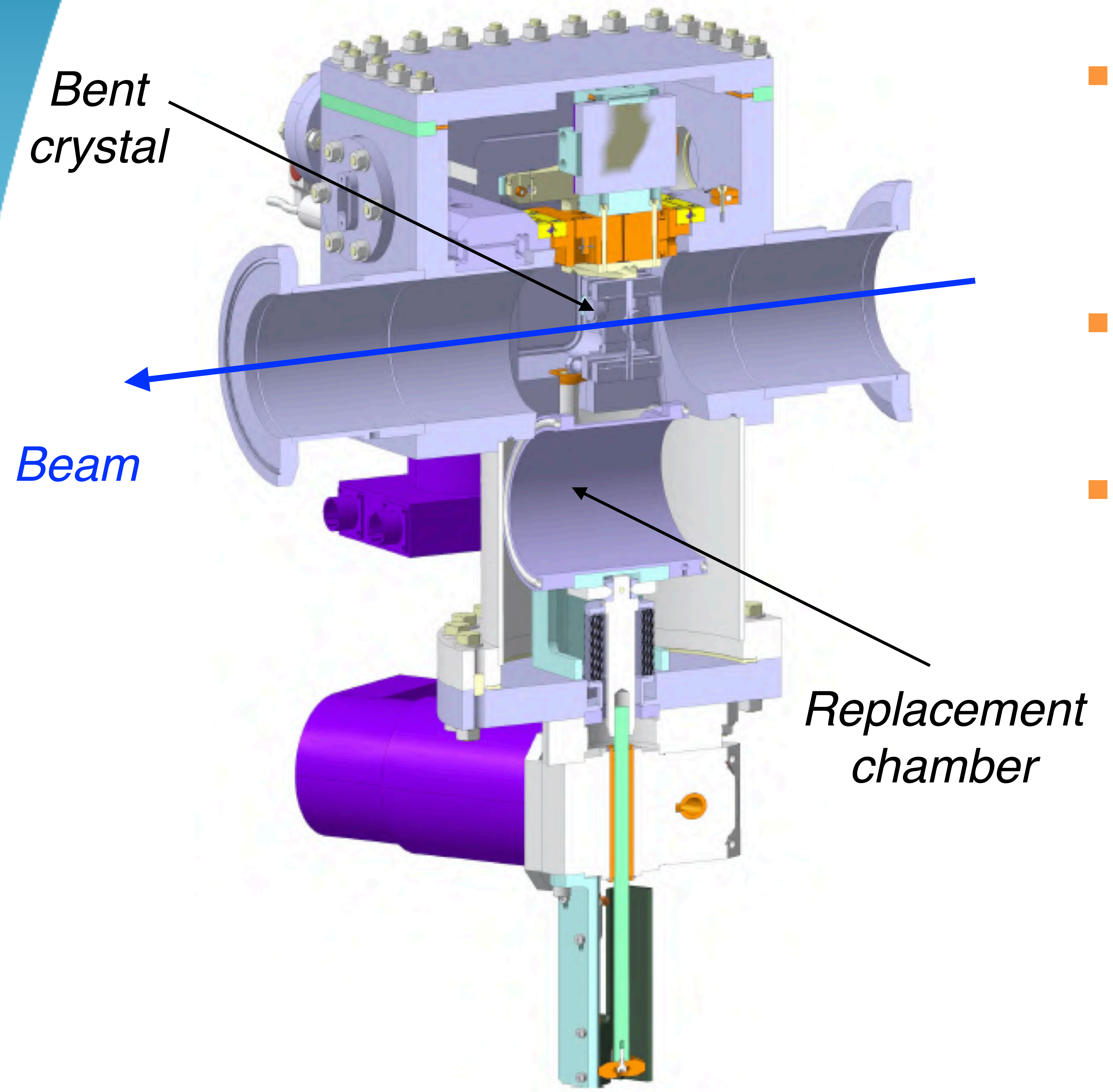
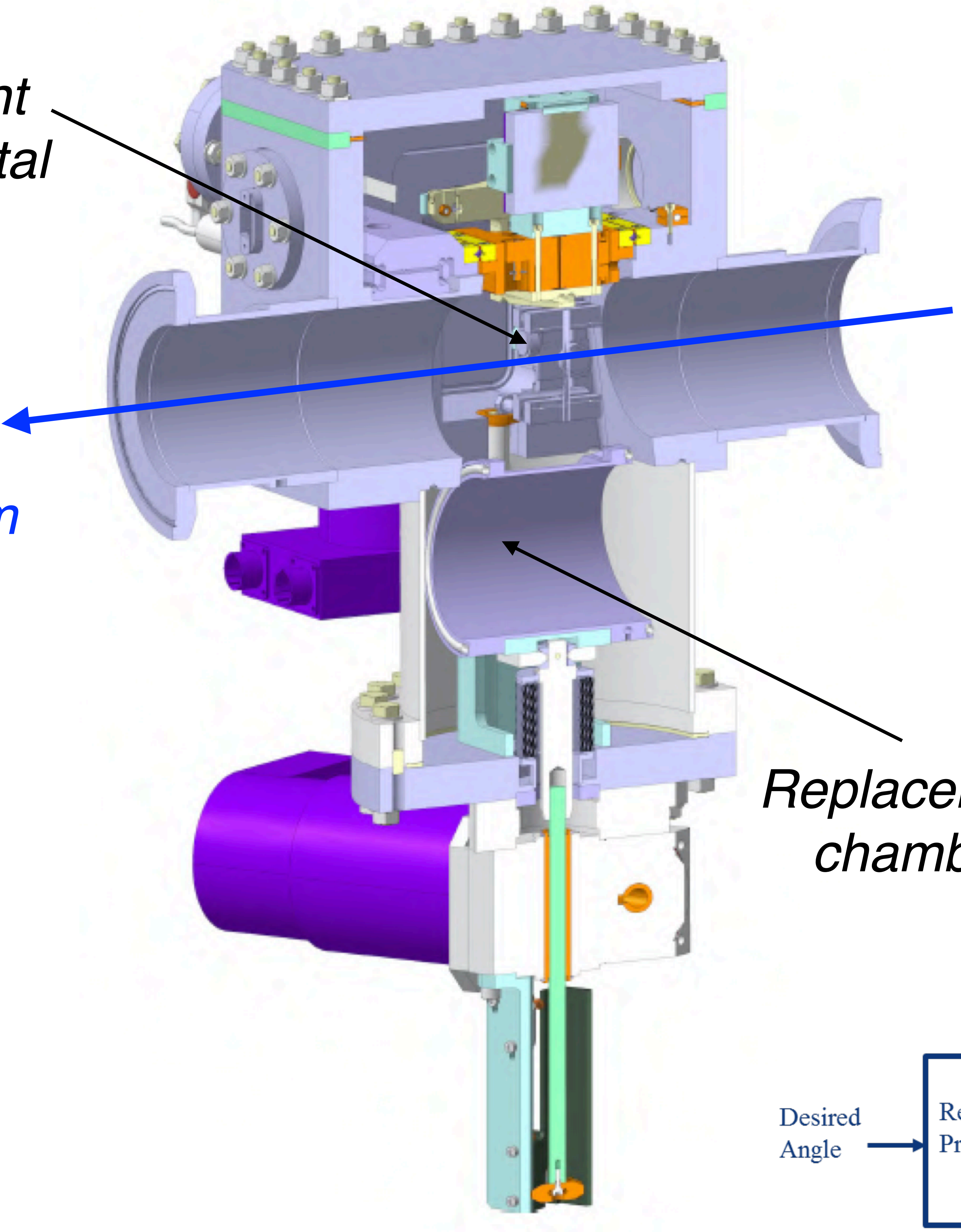
The crystal collimator assembly (TCPC)



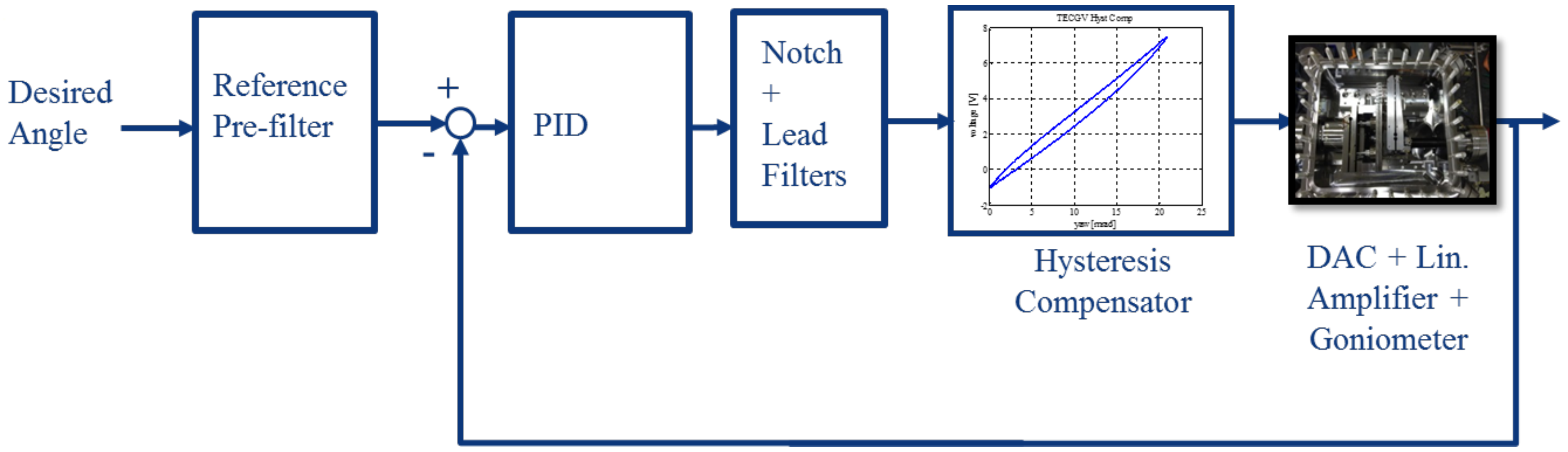
- "O" shaped replacement chamber avoids impedance issues during high intensity proton beams
  - Crystal can only access the beam if "O" chamber is OUT
- Stepper motors for linear movements (derived from collimation system)
- Interferometer-based piezo-controller for angles
  - Works with a closed-loop feedback that provides a **sub-µrad precision**

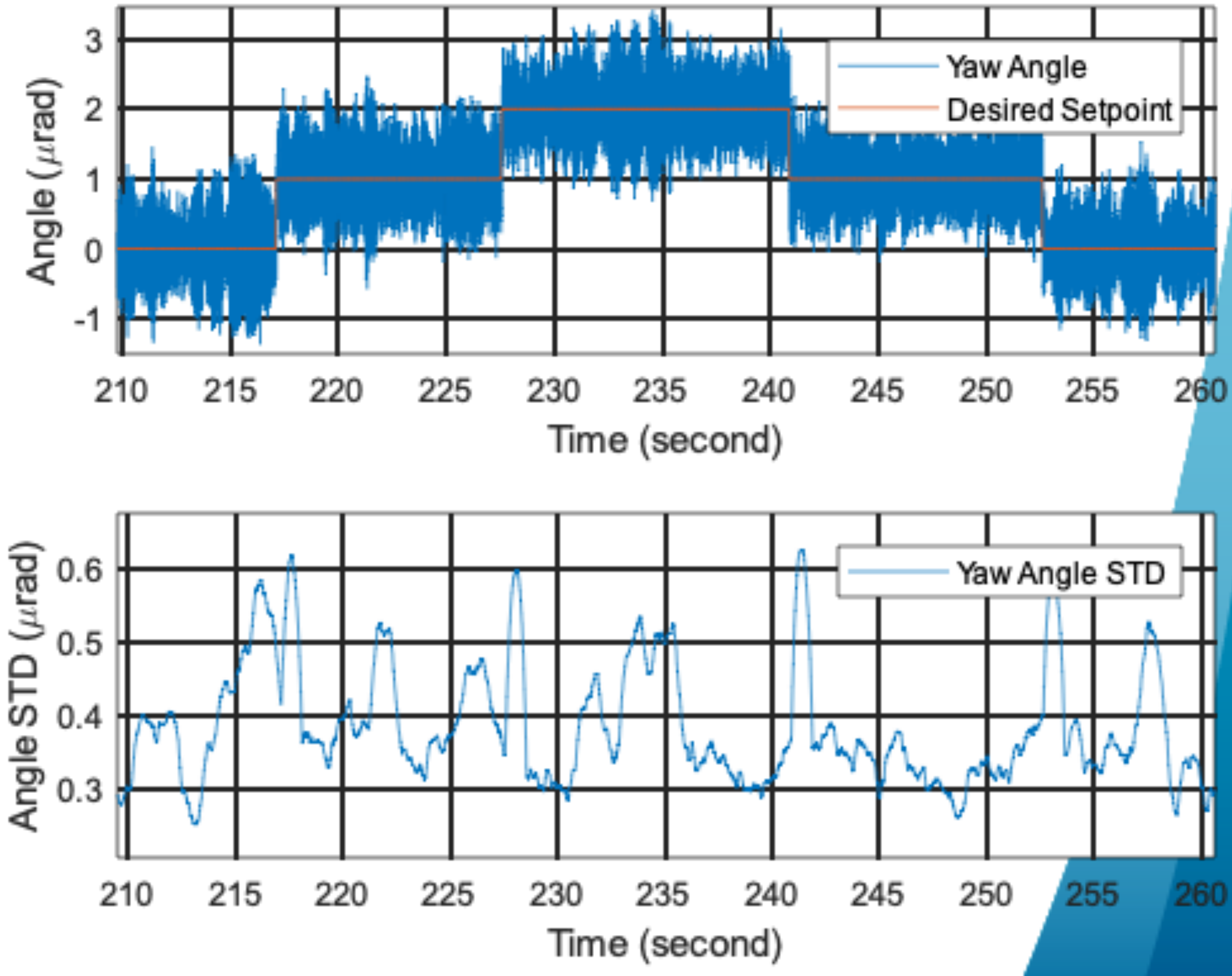
The crystal collimator assembly (TCPC)



- "O" shaped replacement chamber avoids impedance issues during high intensity proton beams
  - Crystal can only access the beam if "O" chamber is OUT
- Stepper motors for linear movements (derived from collimation system)
- Interferometer-based piezo-controller for angles
  - Works with a closed-loop feedback that provides a **sub-µrad precision**

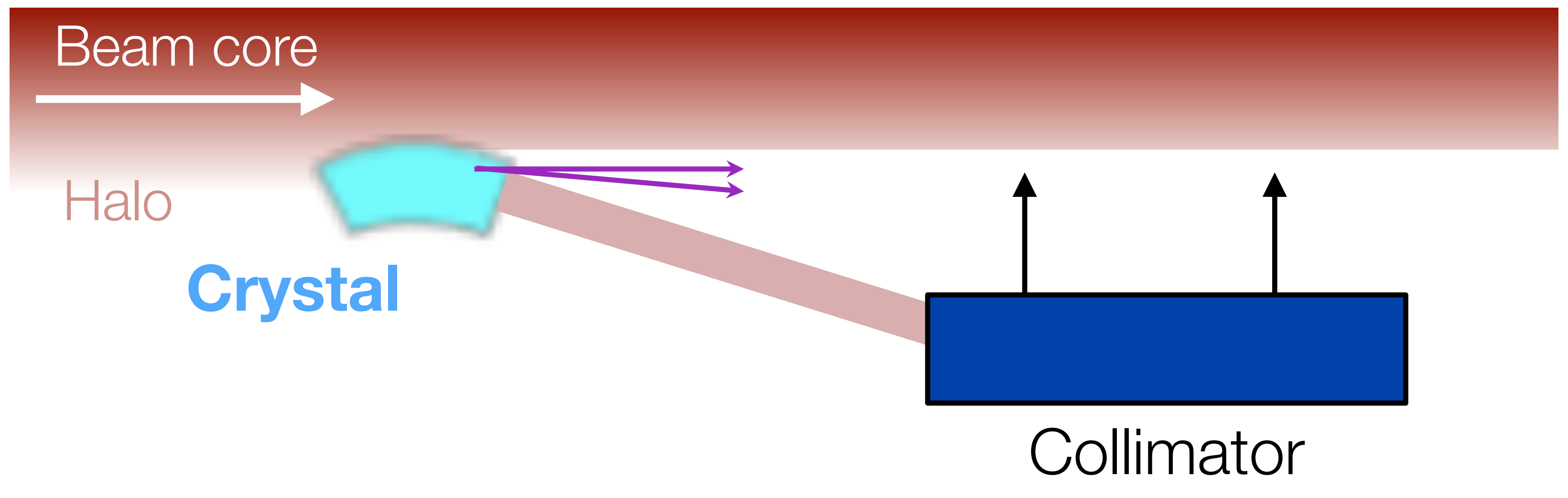
Unique setup in accelerators





Courtesy A. Masi

Key measurements with circulating beams



1) Crystal angular scans
2) Linear scans with downstream collimator
3) Loss maps to check full-ring loss distributions (controlled beam excitations in difference configurations)

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Easier to get machine time and we are studying other interesting applications!

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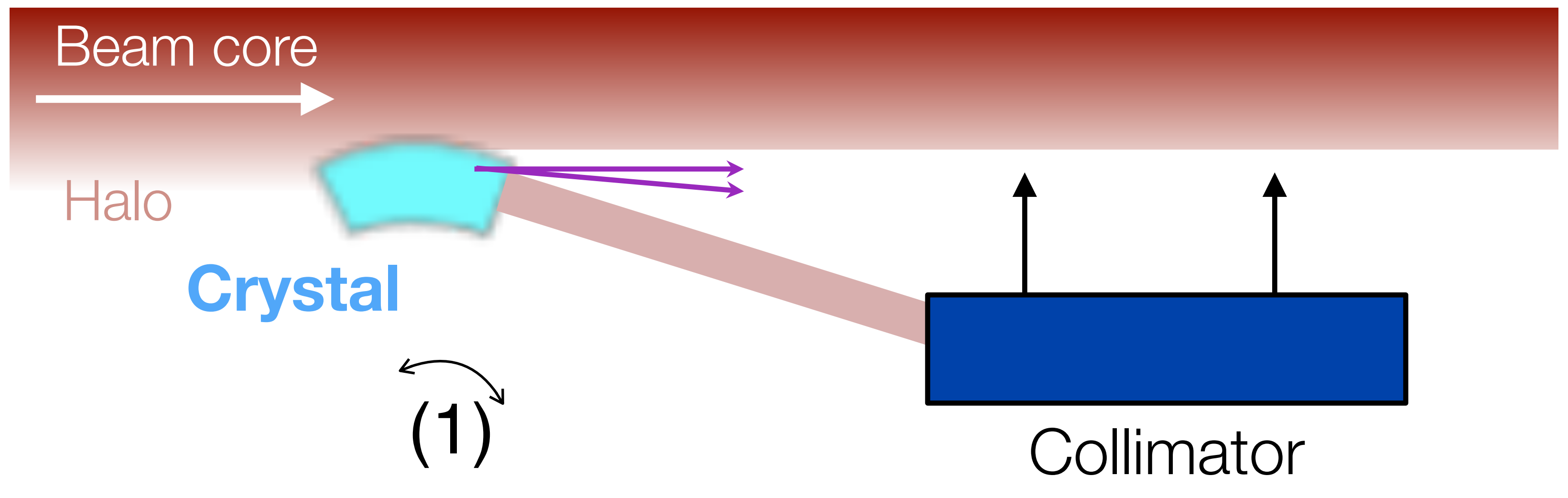

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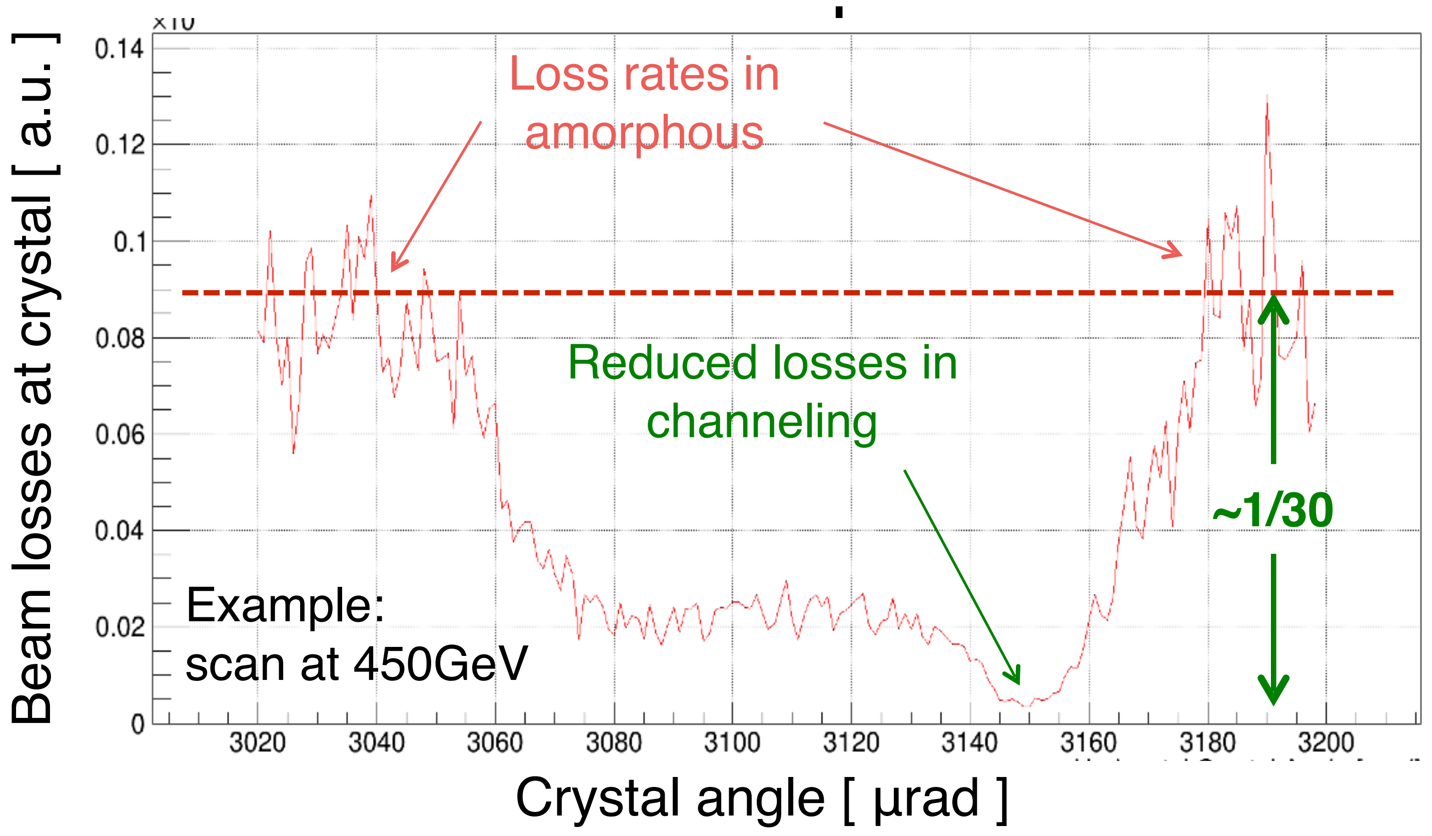

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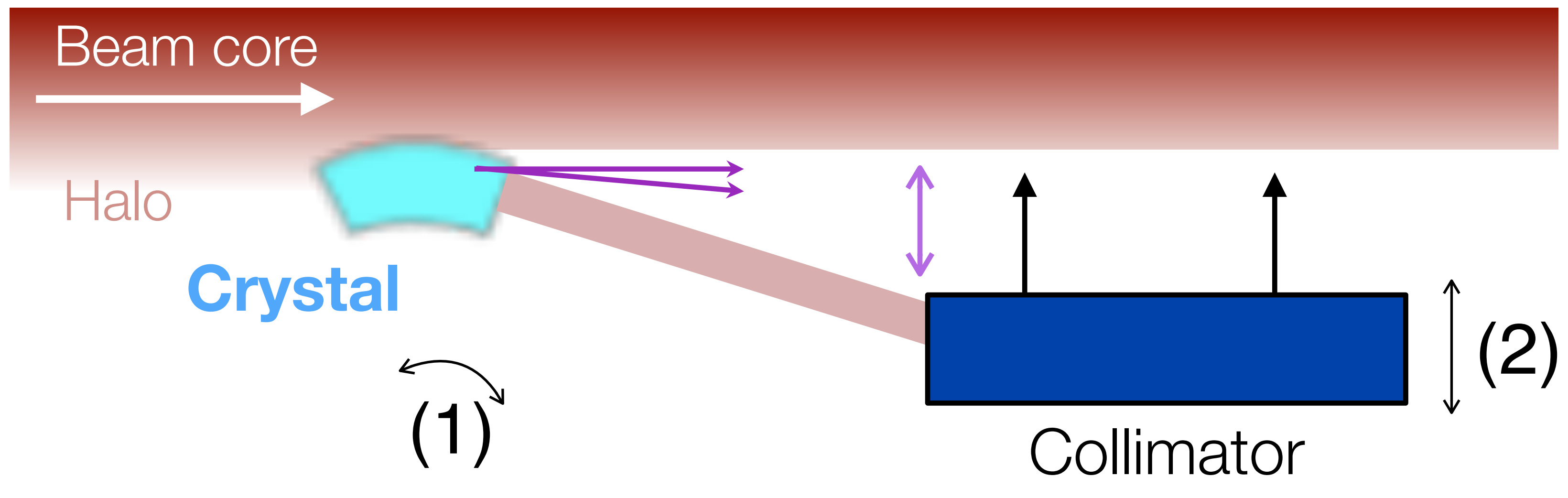

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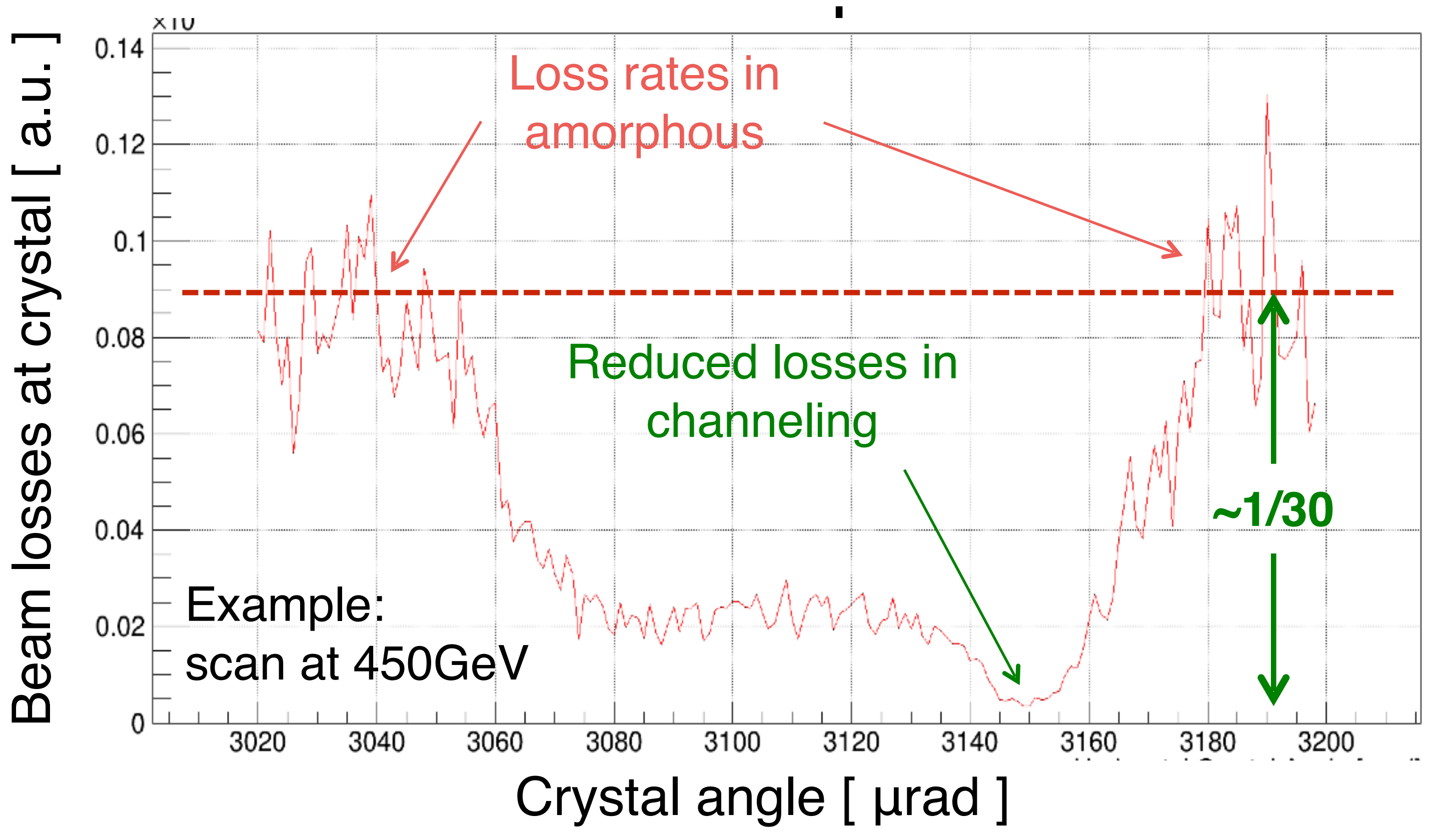
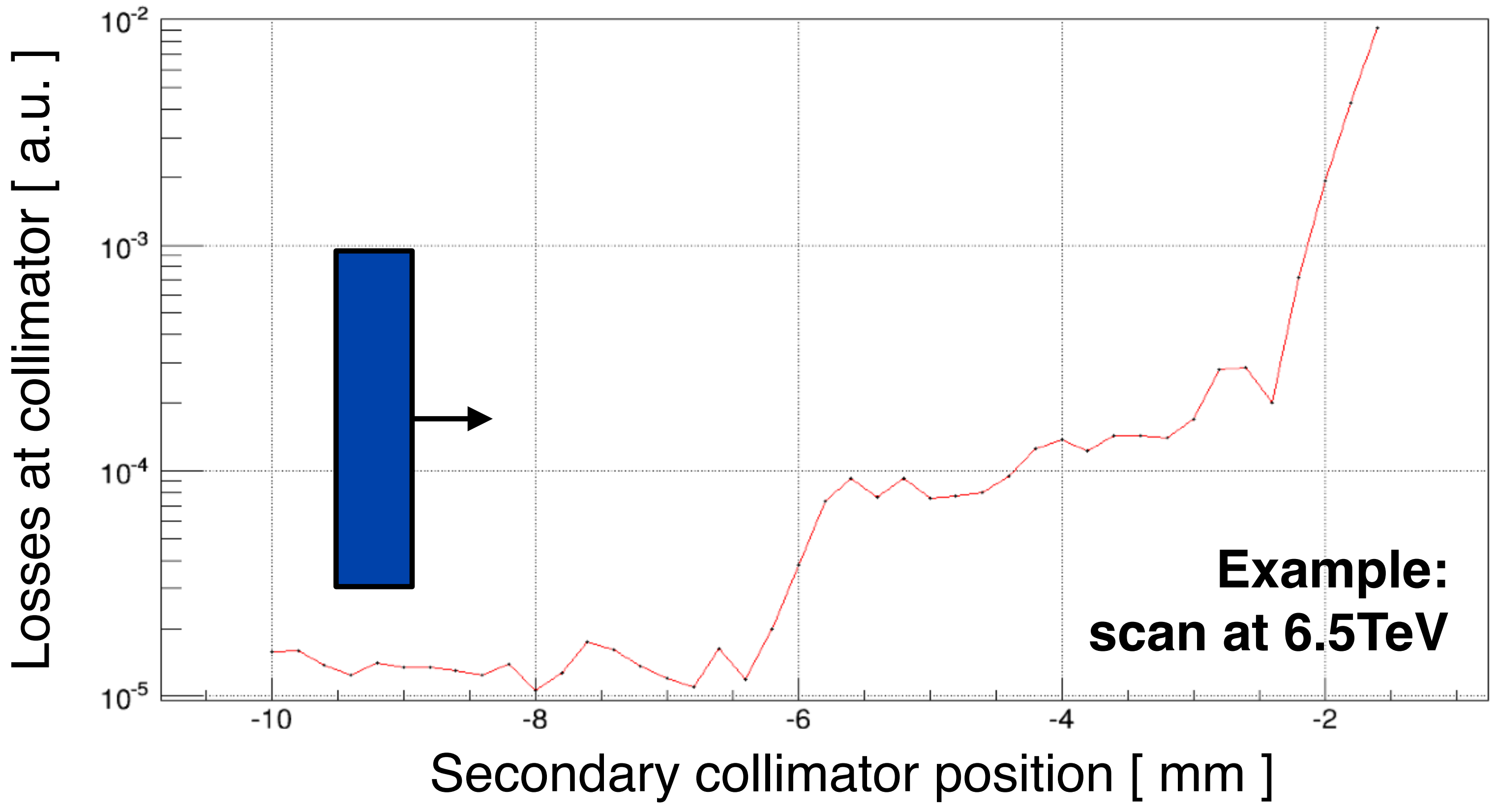


(2) **Linear collimator scan**: measures the profile of the channeled halo.



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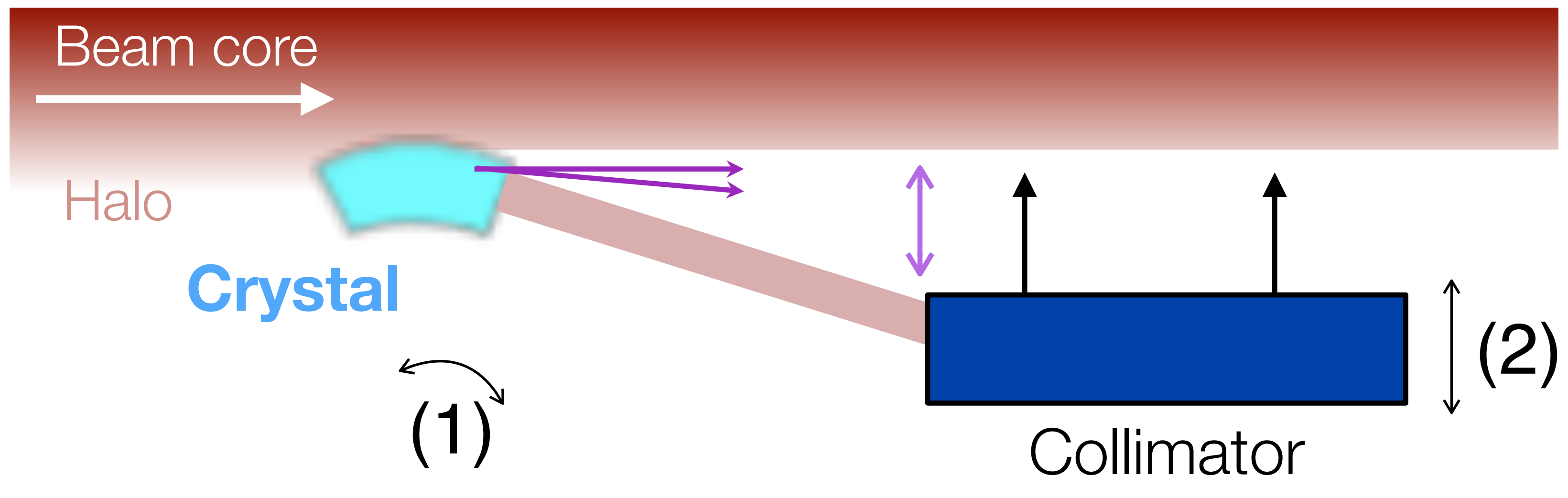

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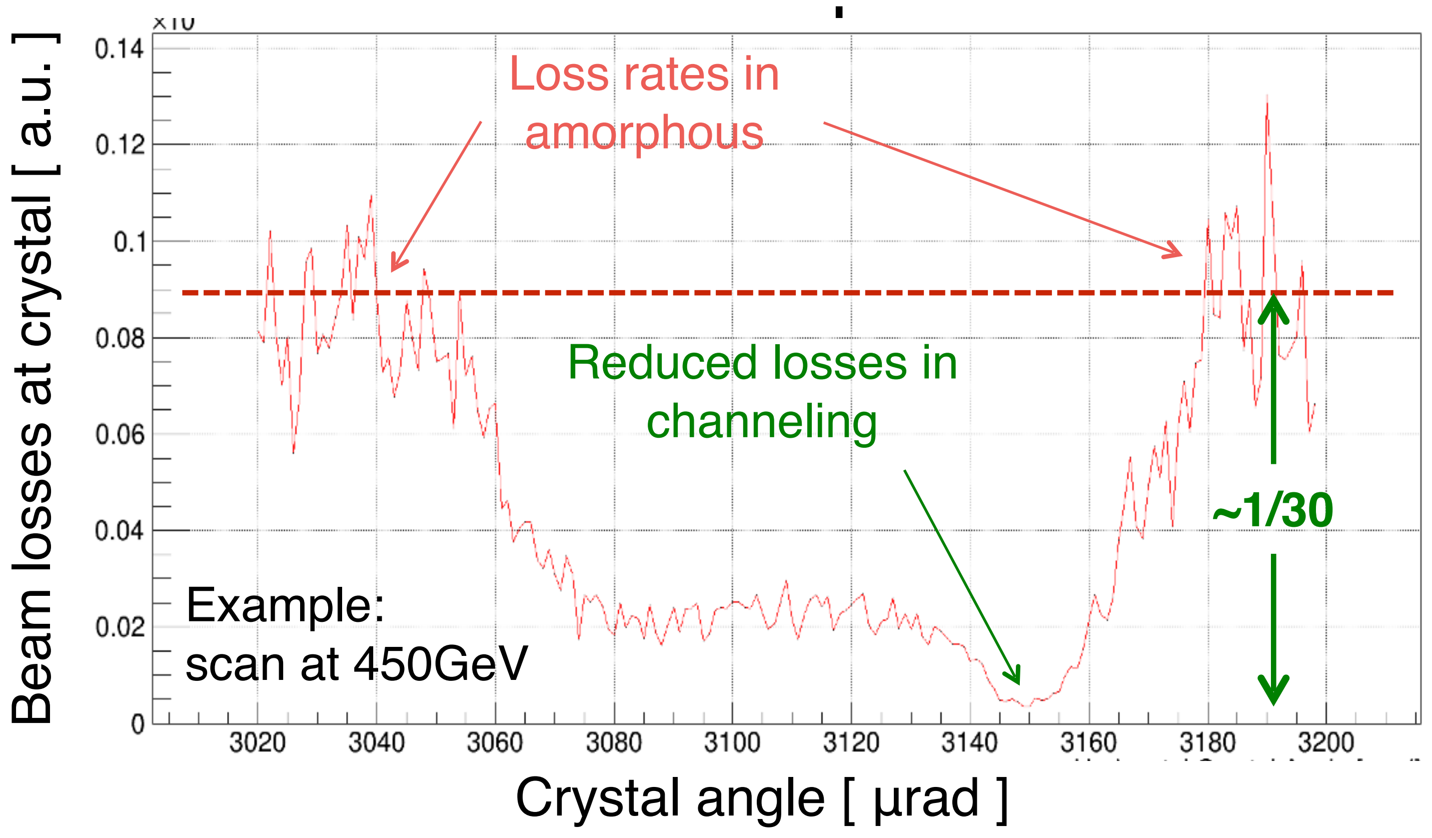

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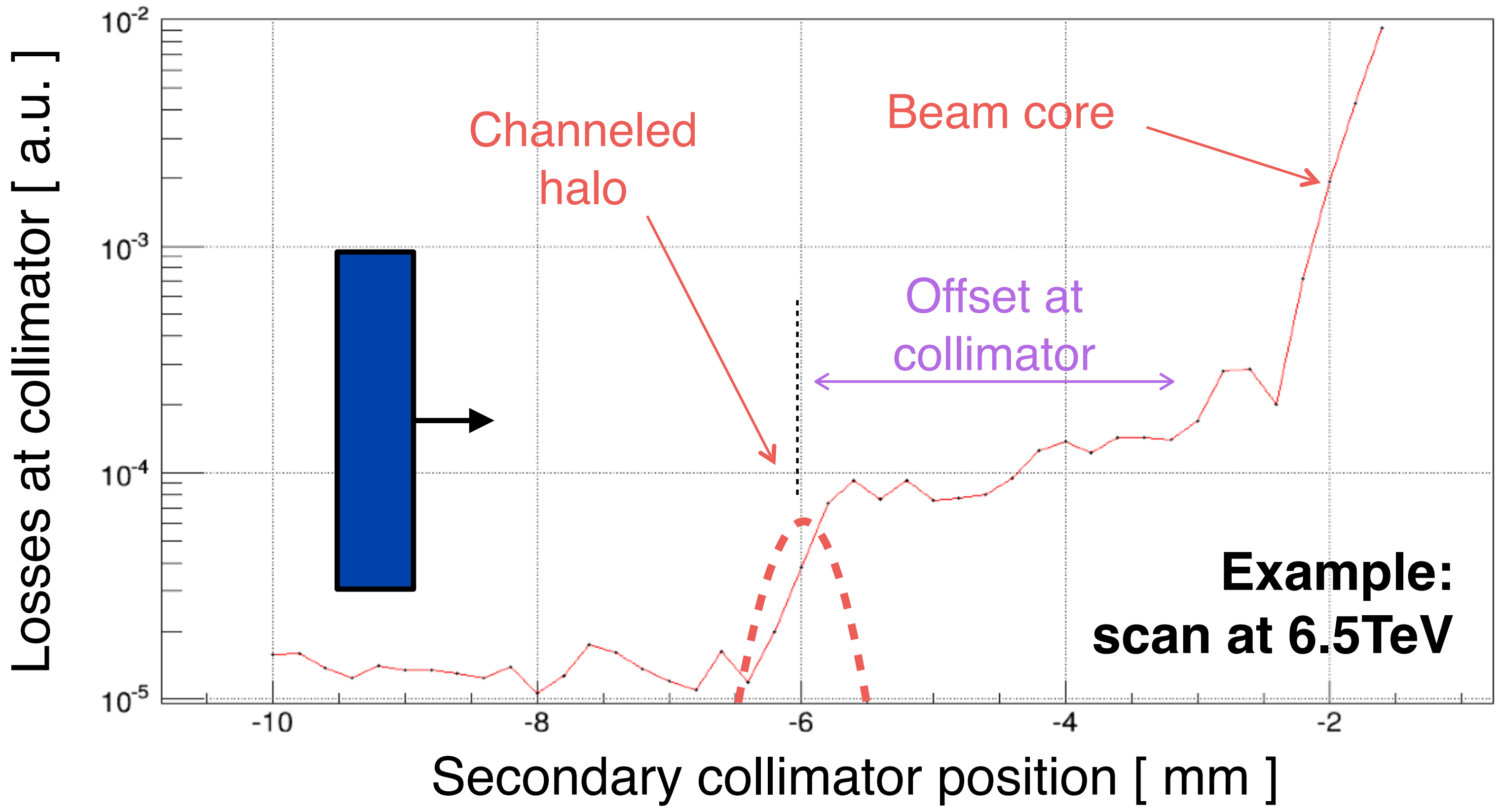

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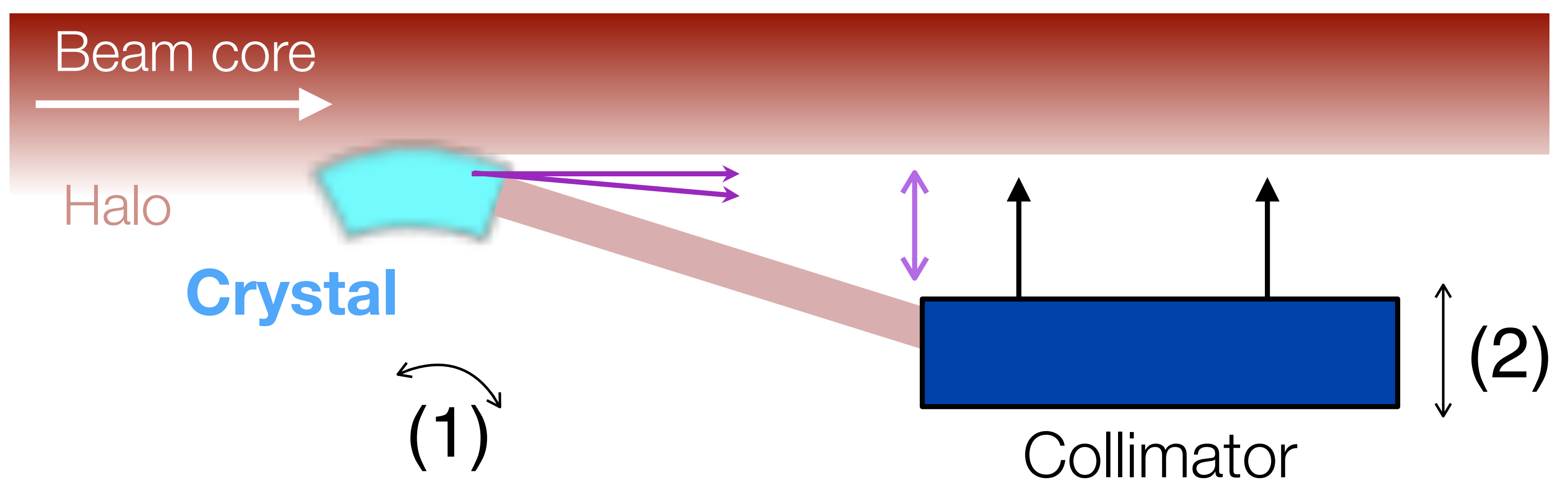

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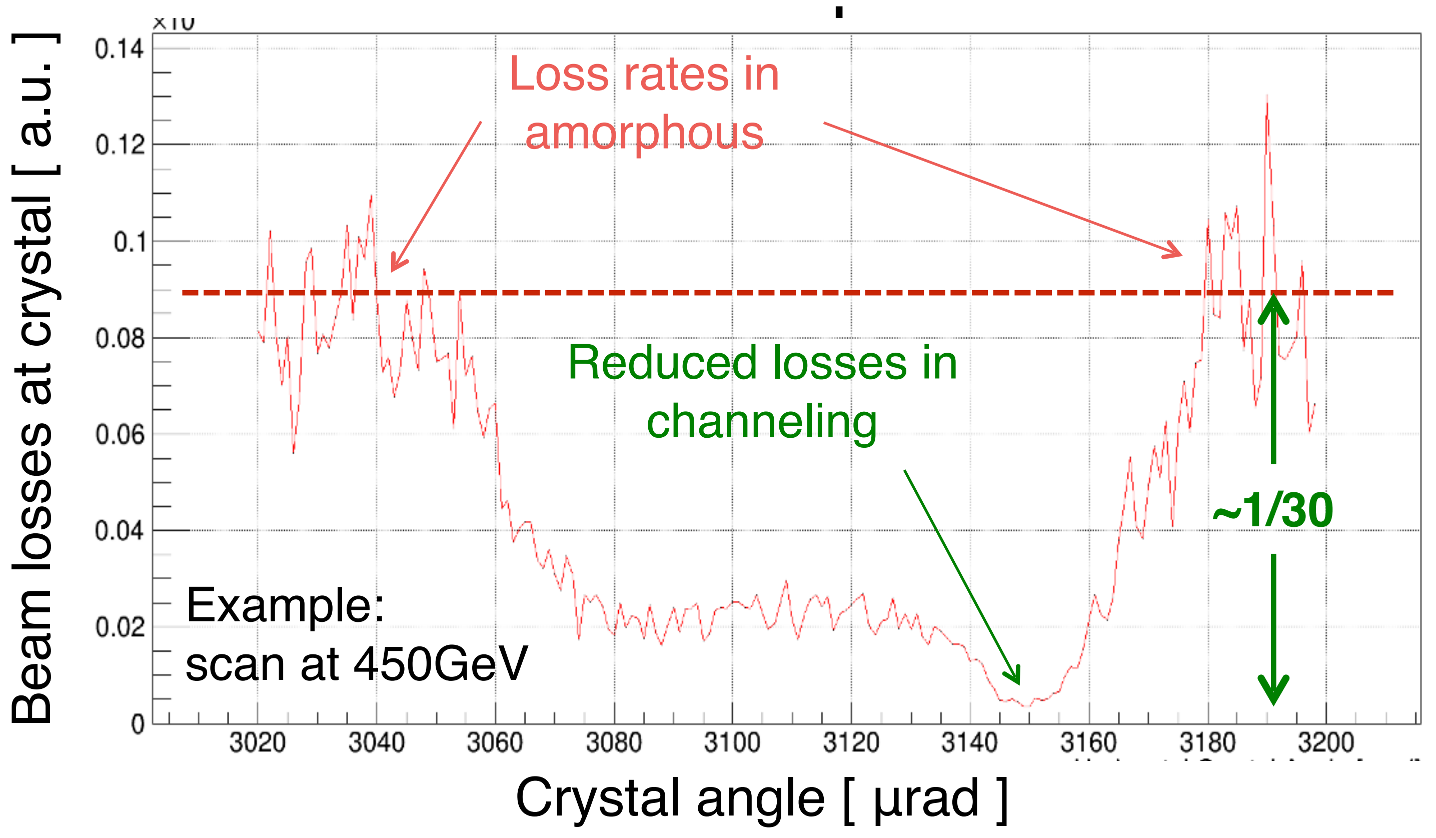

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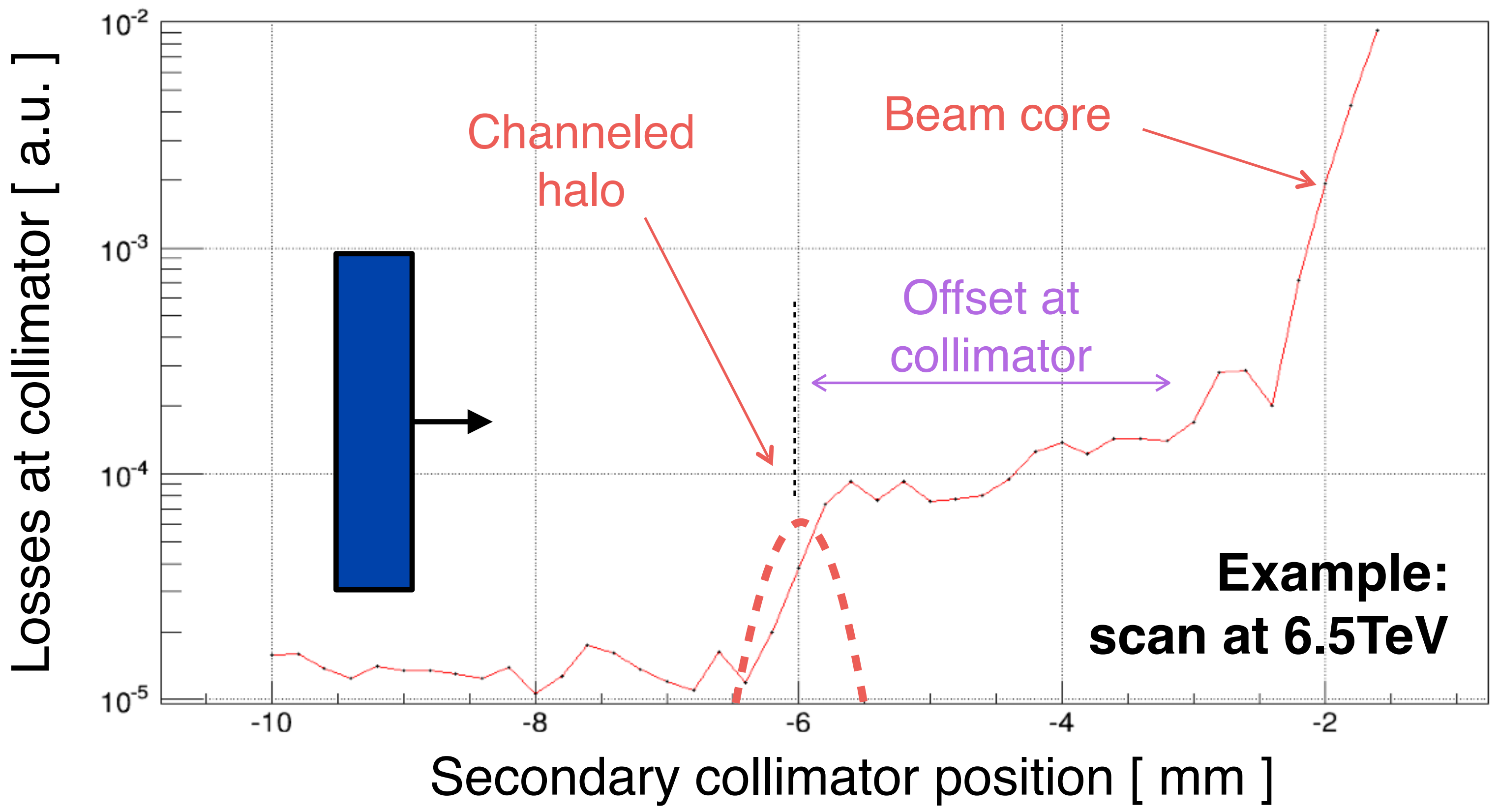

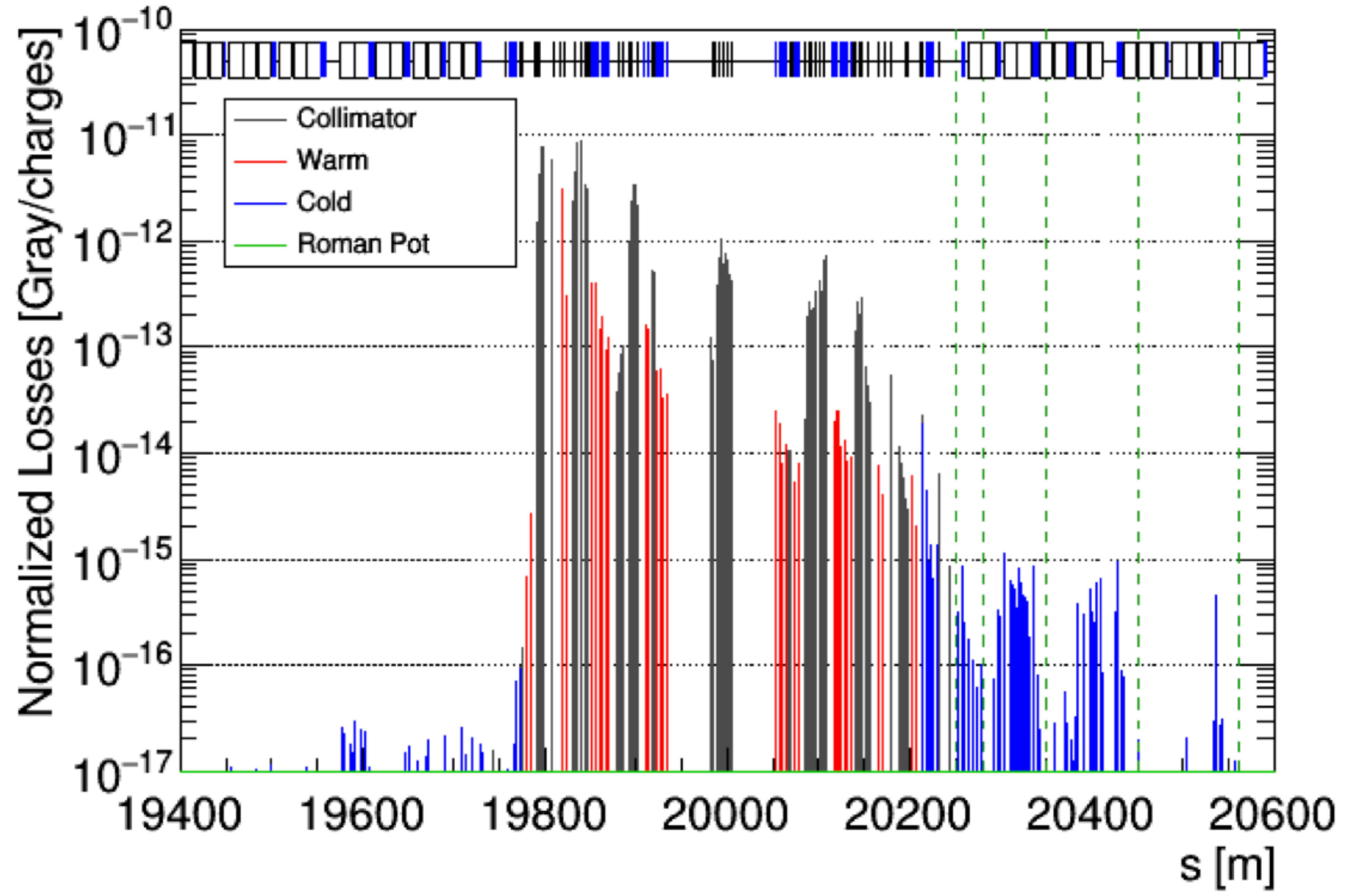

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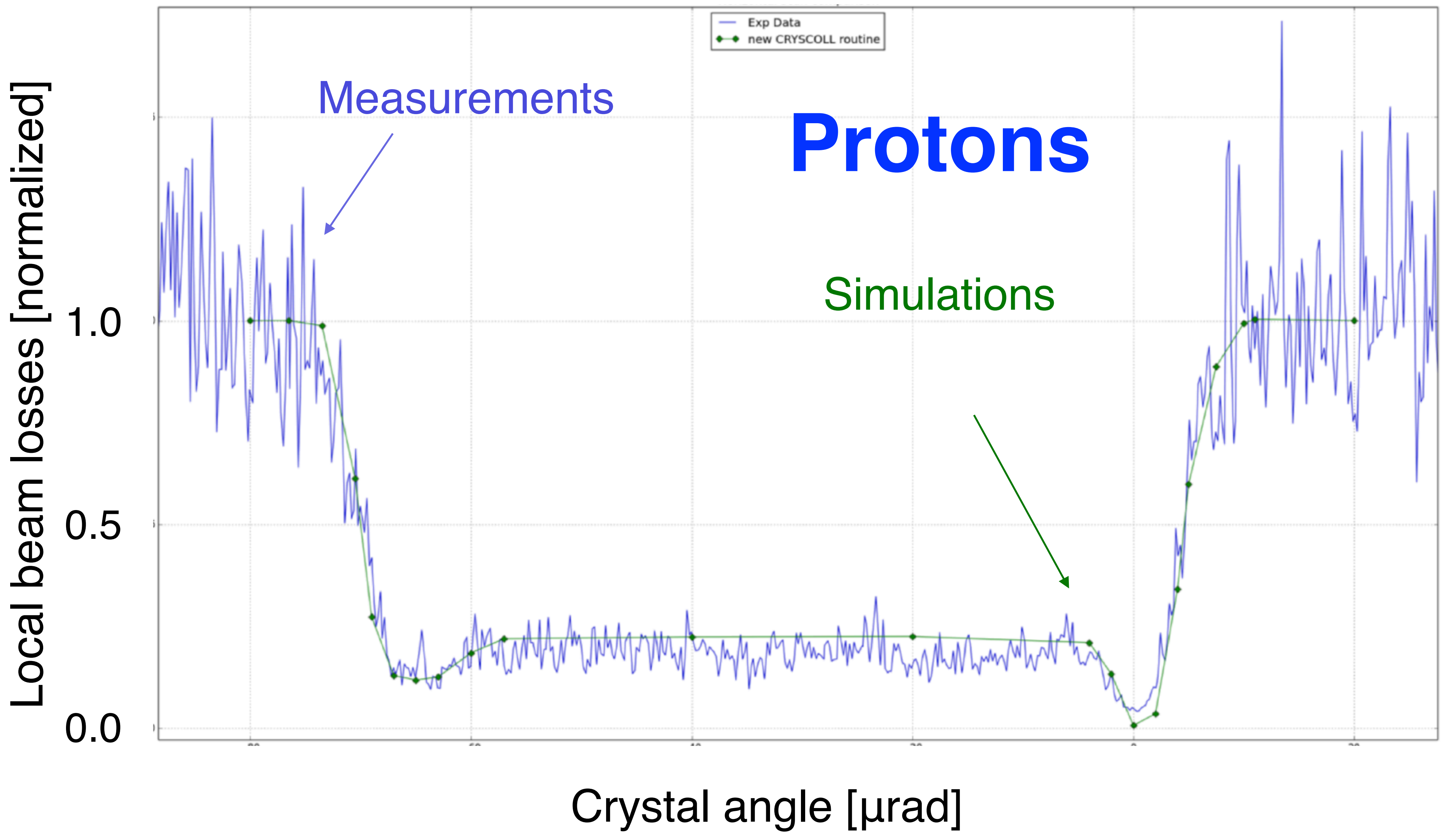
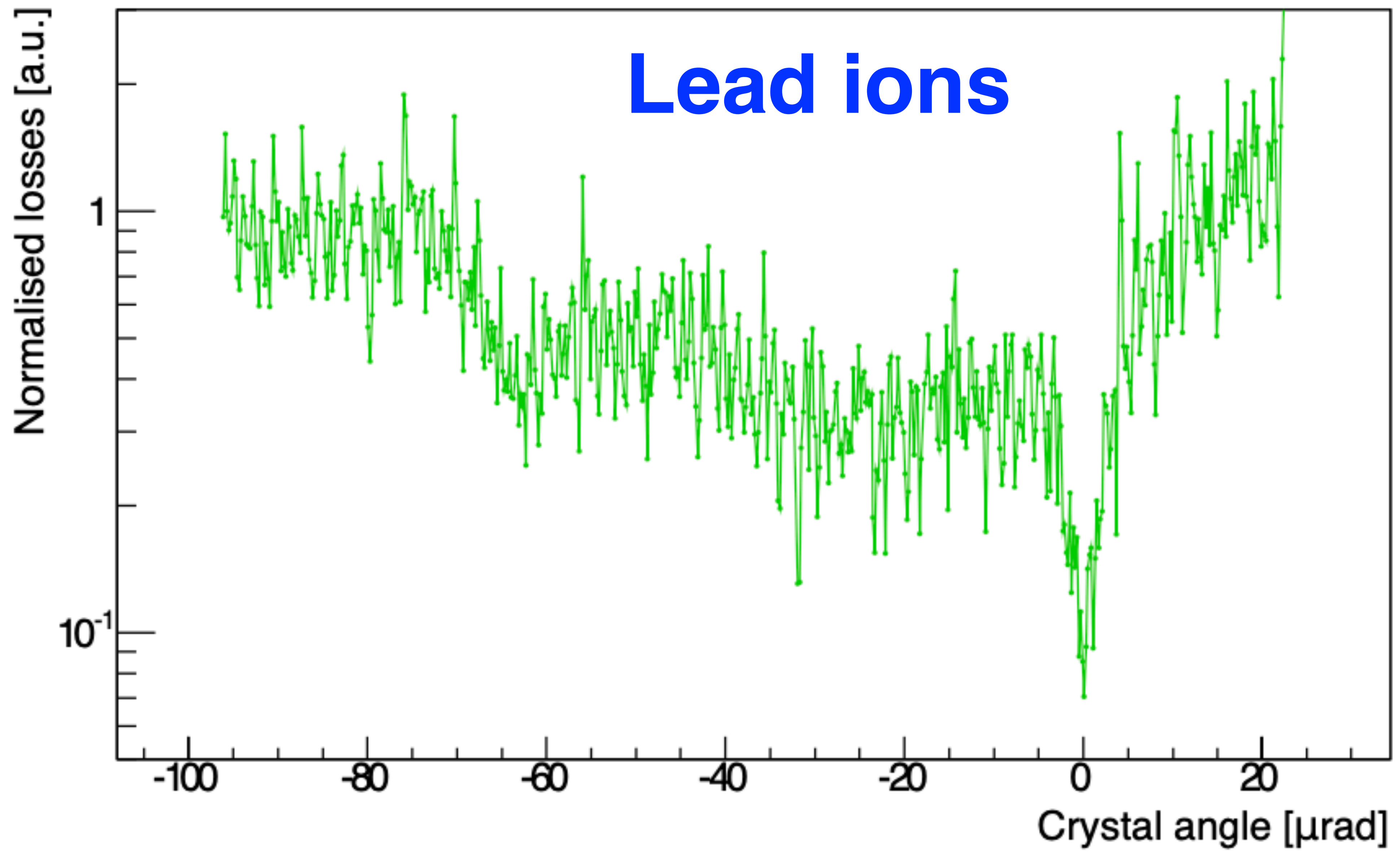
First channeling observations at 6.5 (Z) TeV



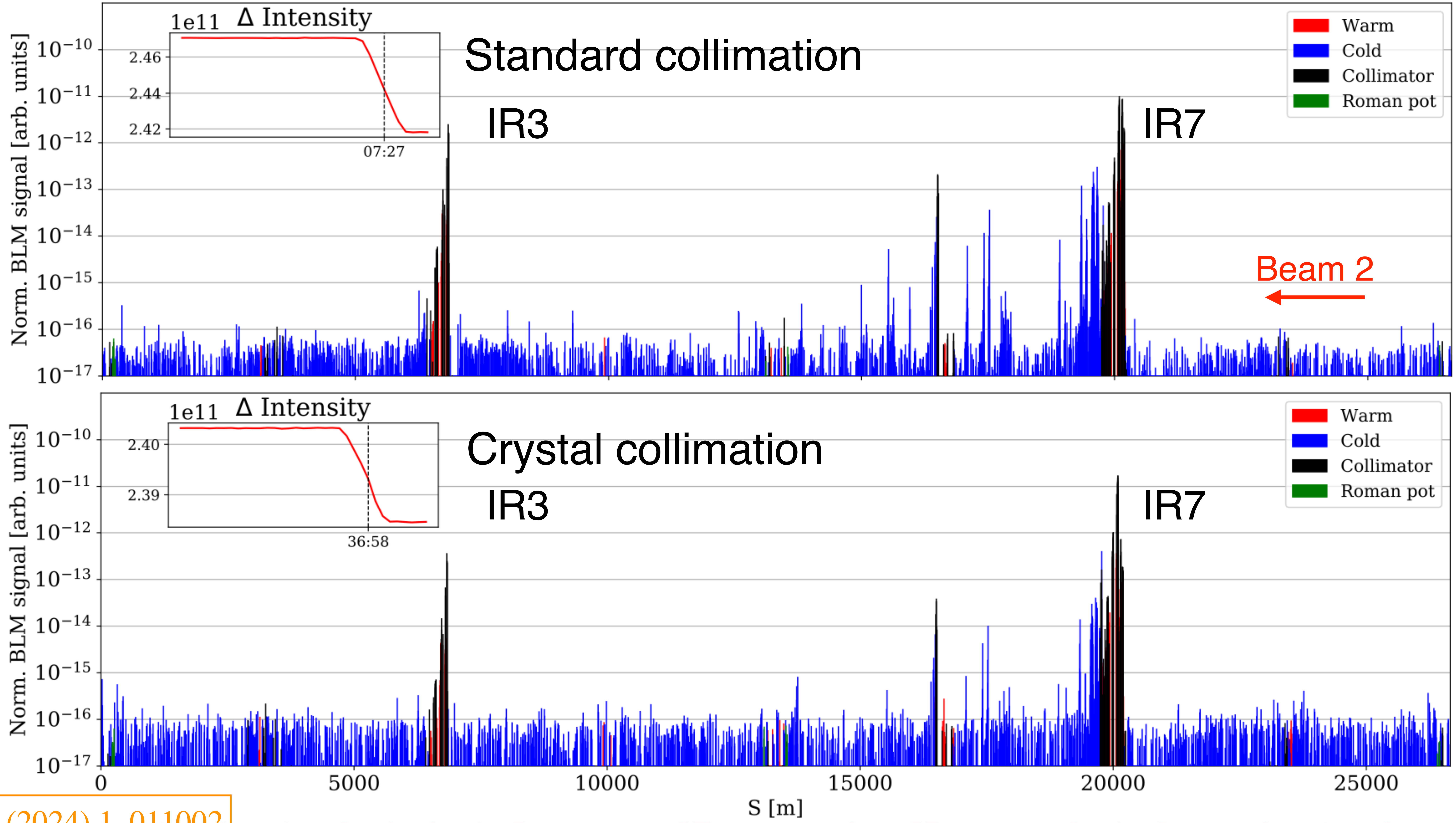
Phys. Lett. B, vol. 758, pp. 129–133, 2016



Eur. Phys. J. C, vol. 81, no. 2, 2021

- Excellent achievement — channeling observed for p, Pb and Xe beams at 6.5 Z TeV!
- Crystal orientation for channeling established reliably and in a reproducible way.
- Quality of crystals was good
  - Although a few devices were out of specs (bending angle/alignment) and were replaced.

Pb ion collimation cleaning, 6.8 Z TeV



M. D'Andrea

PRAB 27 (2024) 1, 011002

Empirical comparison indicated in the test stand gains up to a factor >5 for the best crystals

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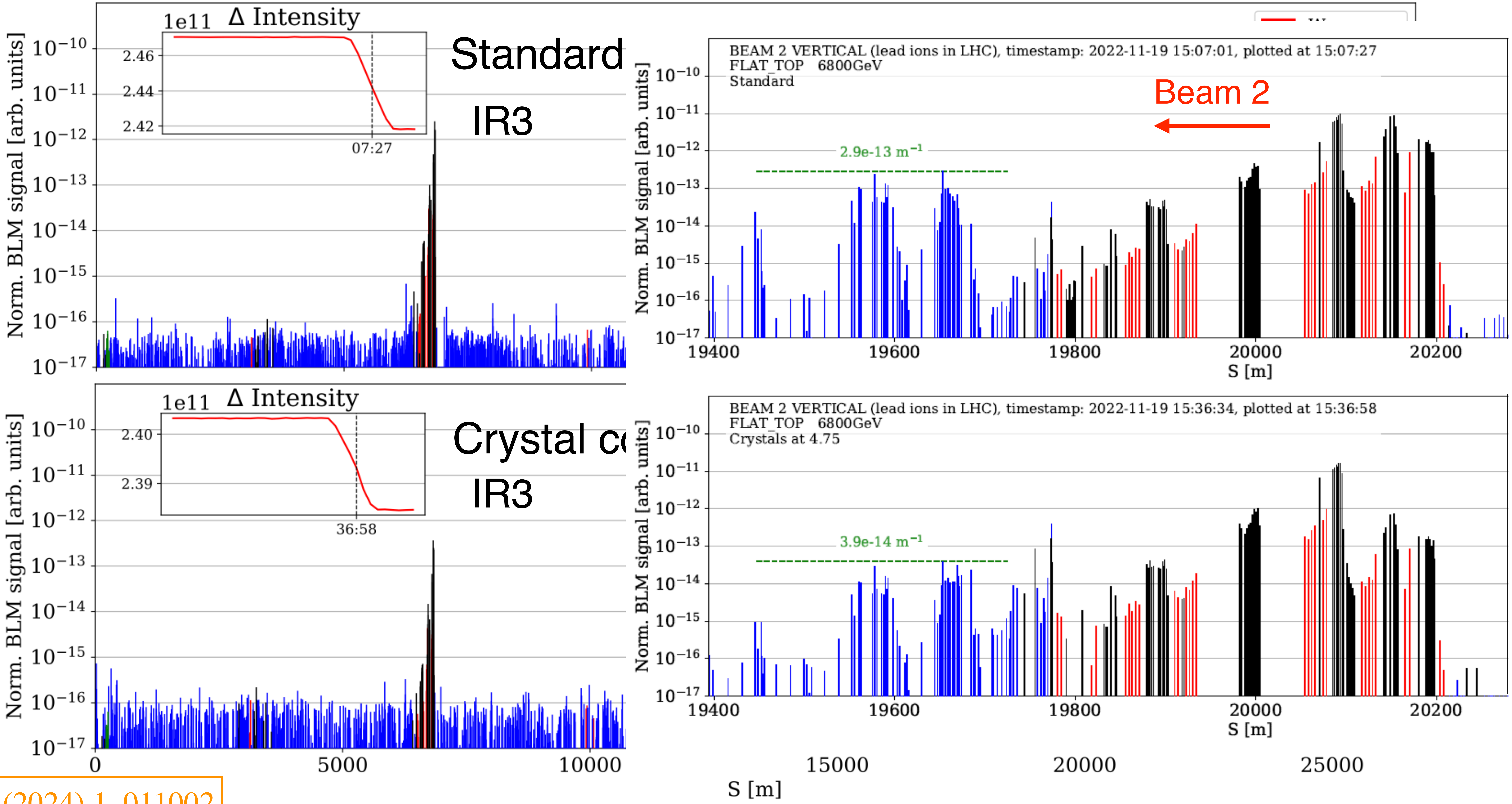

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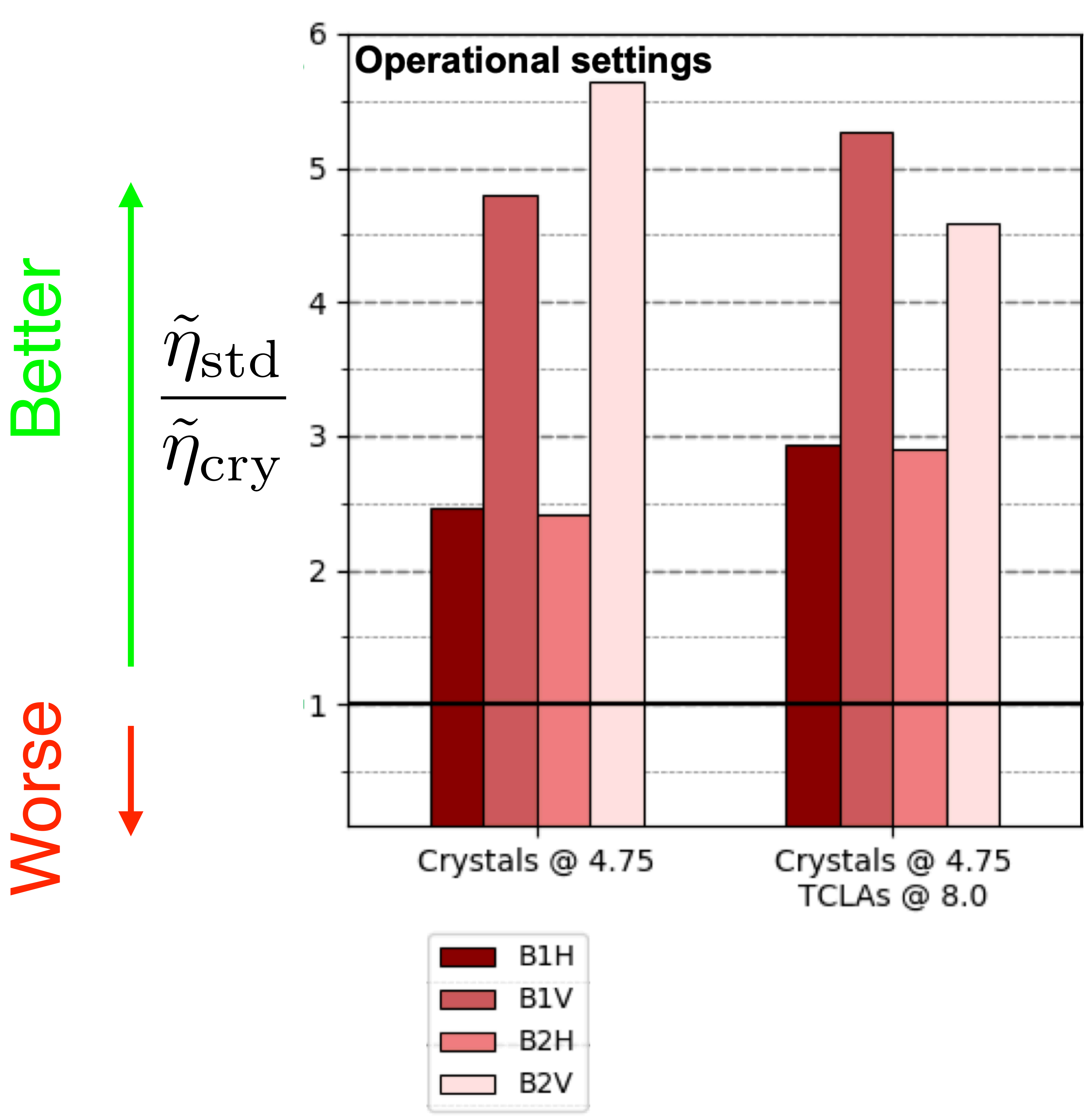

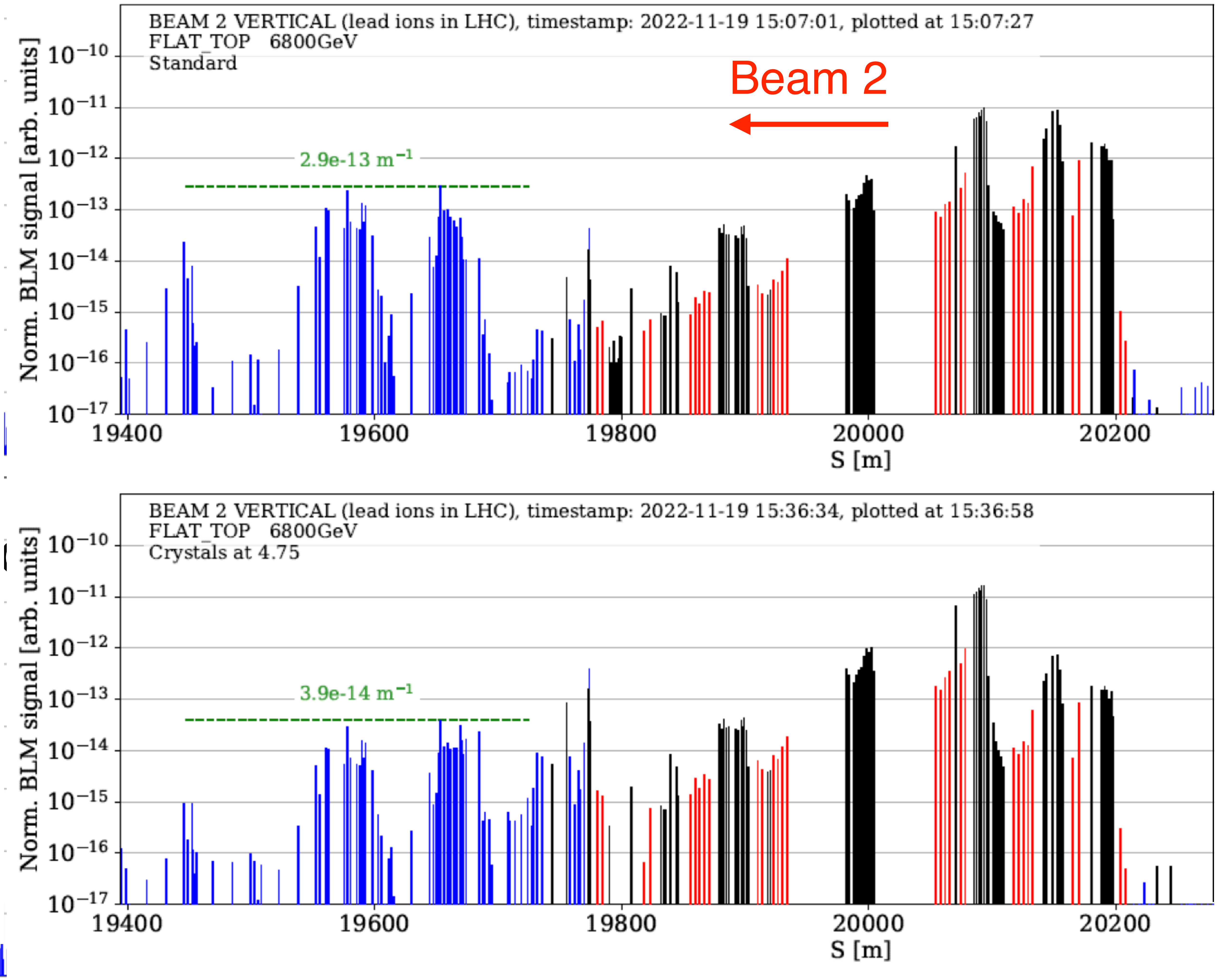

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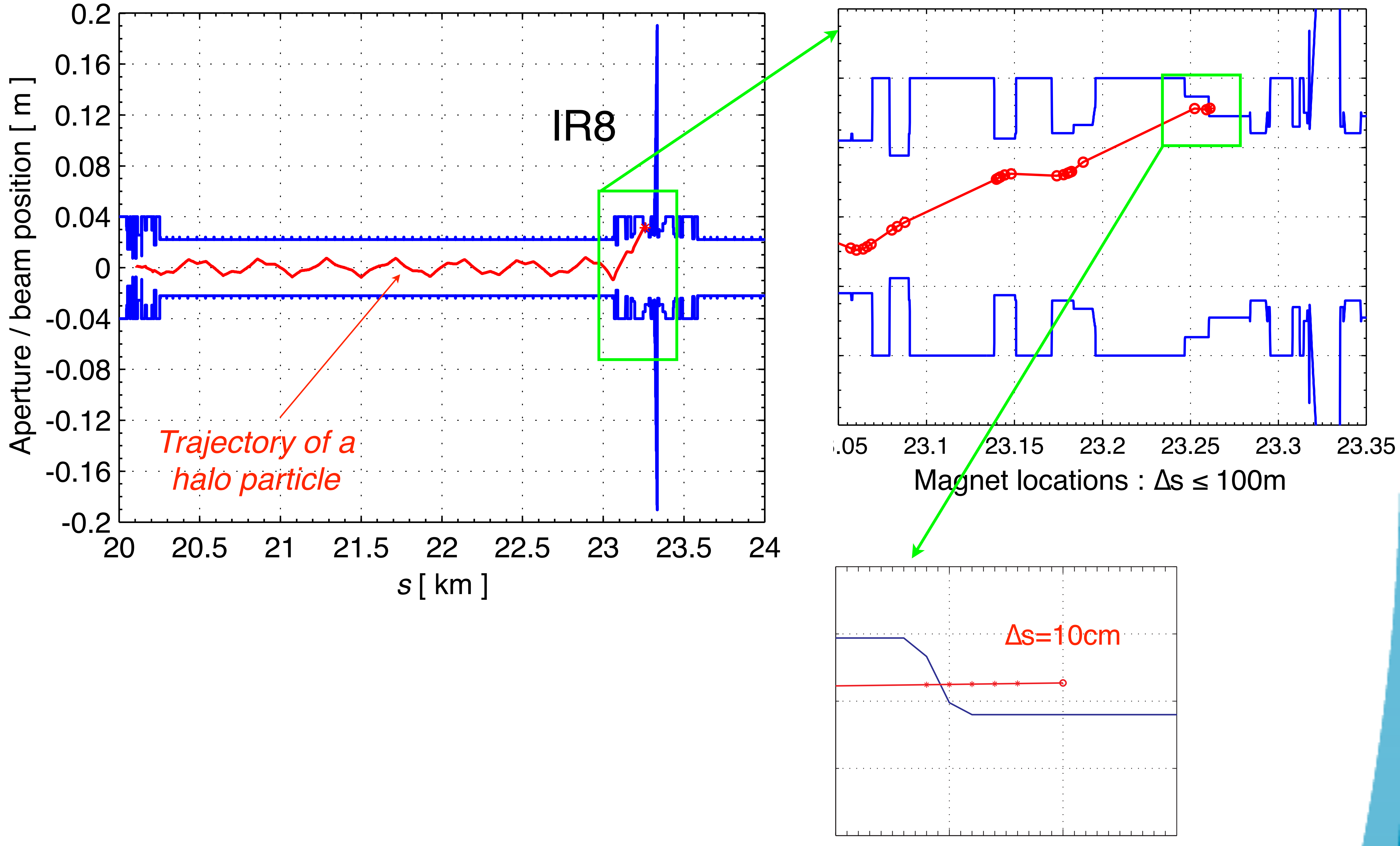
Simulation challenges for LHC beam collimation:

- Accurate tracking of particles with large amplitudes and energy deviations
- Interactions with collimator materials
  - Ions: complex physics and multiple products
- Coherent effects and scattering in crystals
- Detailed LHC aperture (27 km, 10cm bins)
- Speed for statistics on ~10^{-6} loss levels!
  - → *10-20M particles for 100-1000 turns*
  - → *interaction with ~50 collimators/turn*
- Model the relevant imperfections



Interpolation: Δs=10cm
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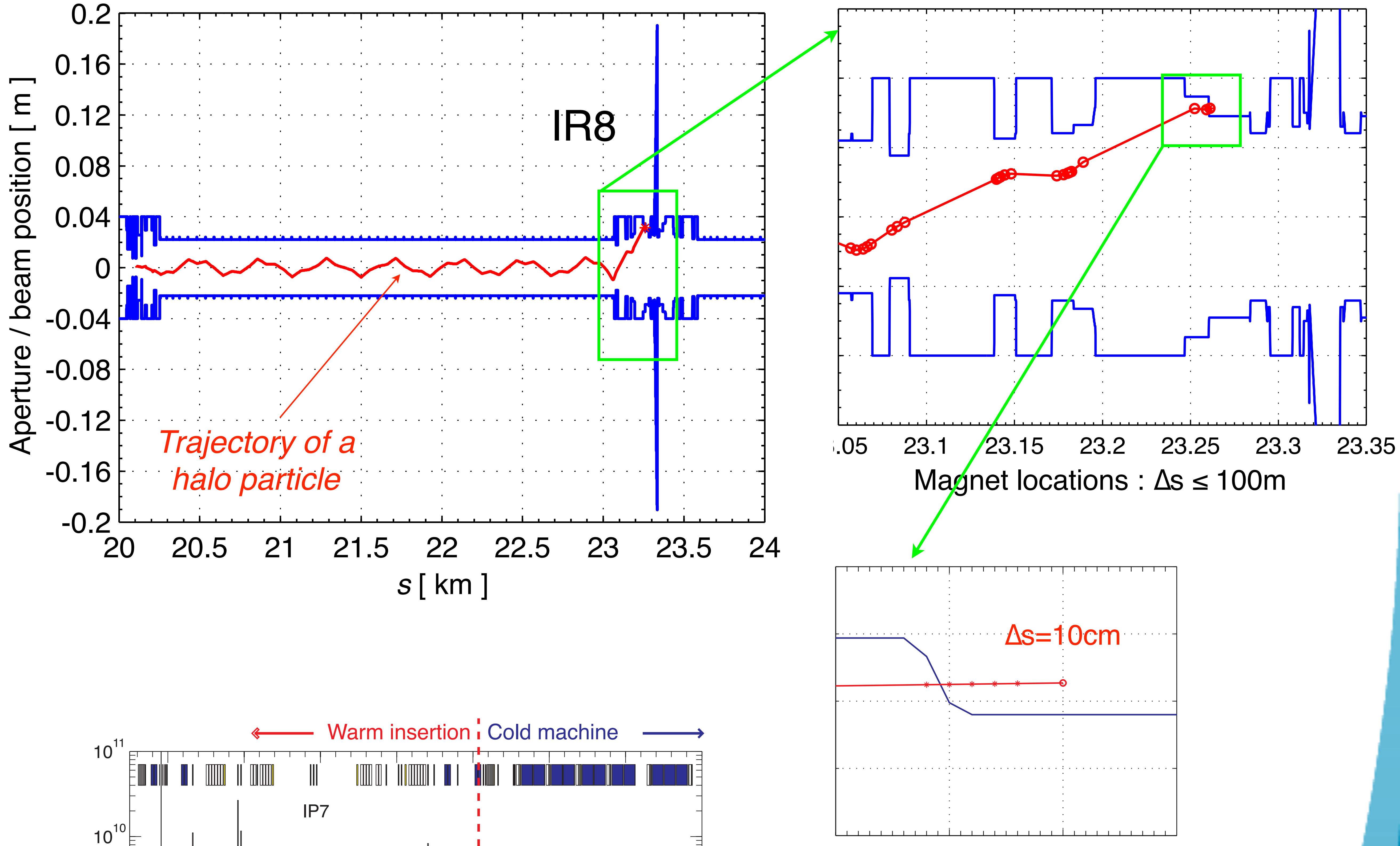

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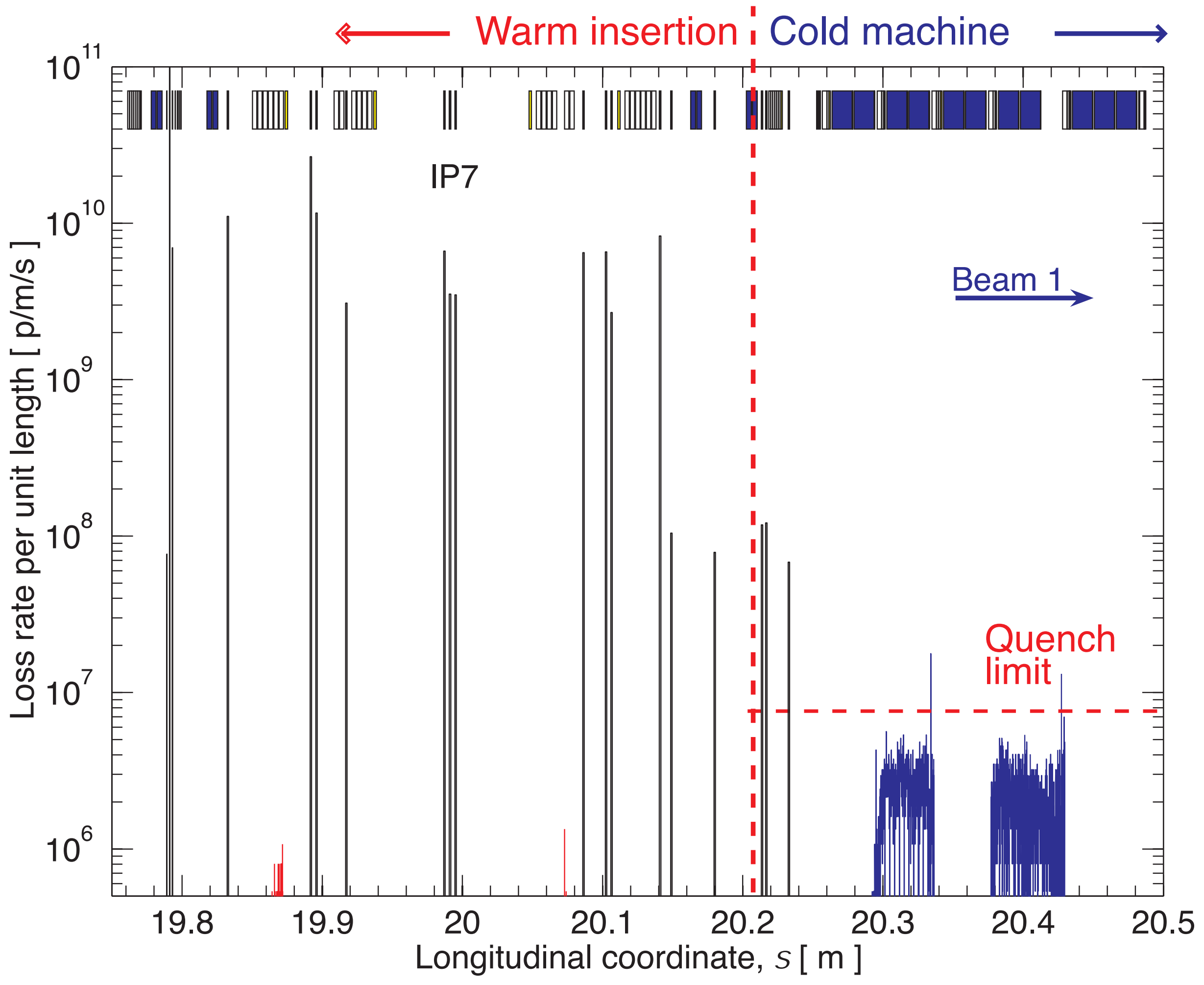
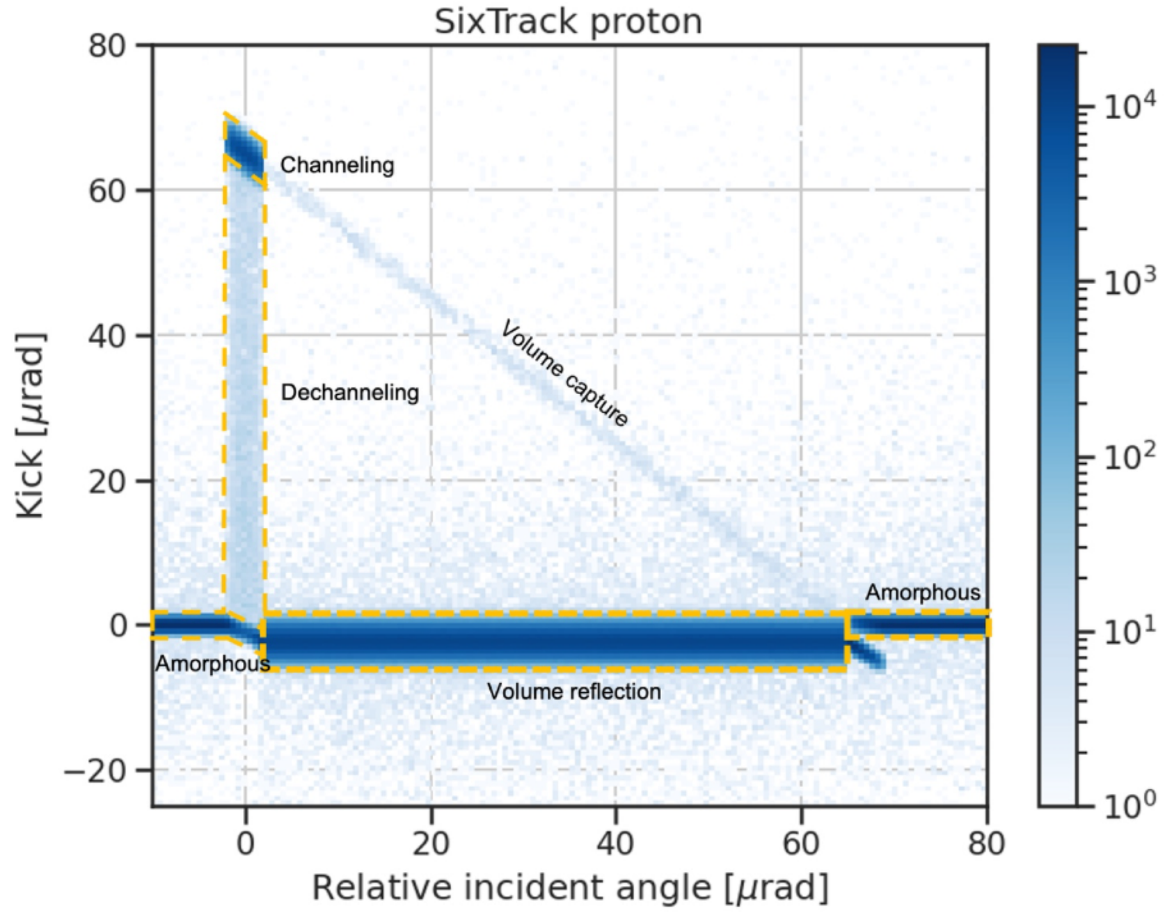


Simulation setups for LHC collimation studies

Sixtrack with K2 routine

Native implementation of a monte-carlo crystal routine for protons only.

CERN-2018-011-CP
NIM Phys. Res., Sect. B, v. 355, 2015



Sixtrack coupling FLUKA

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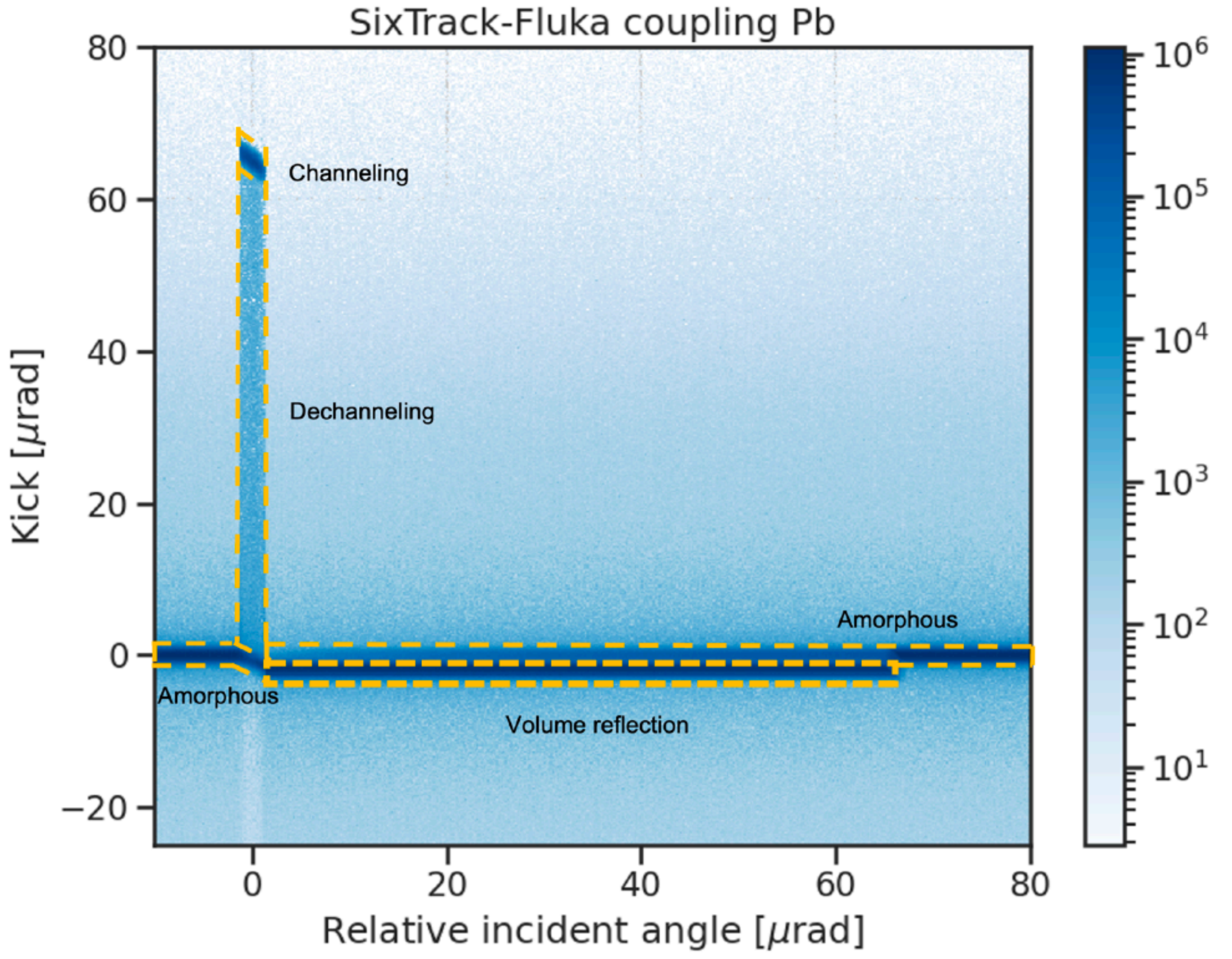
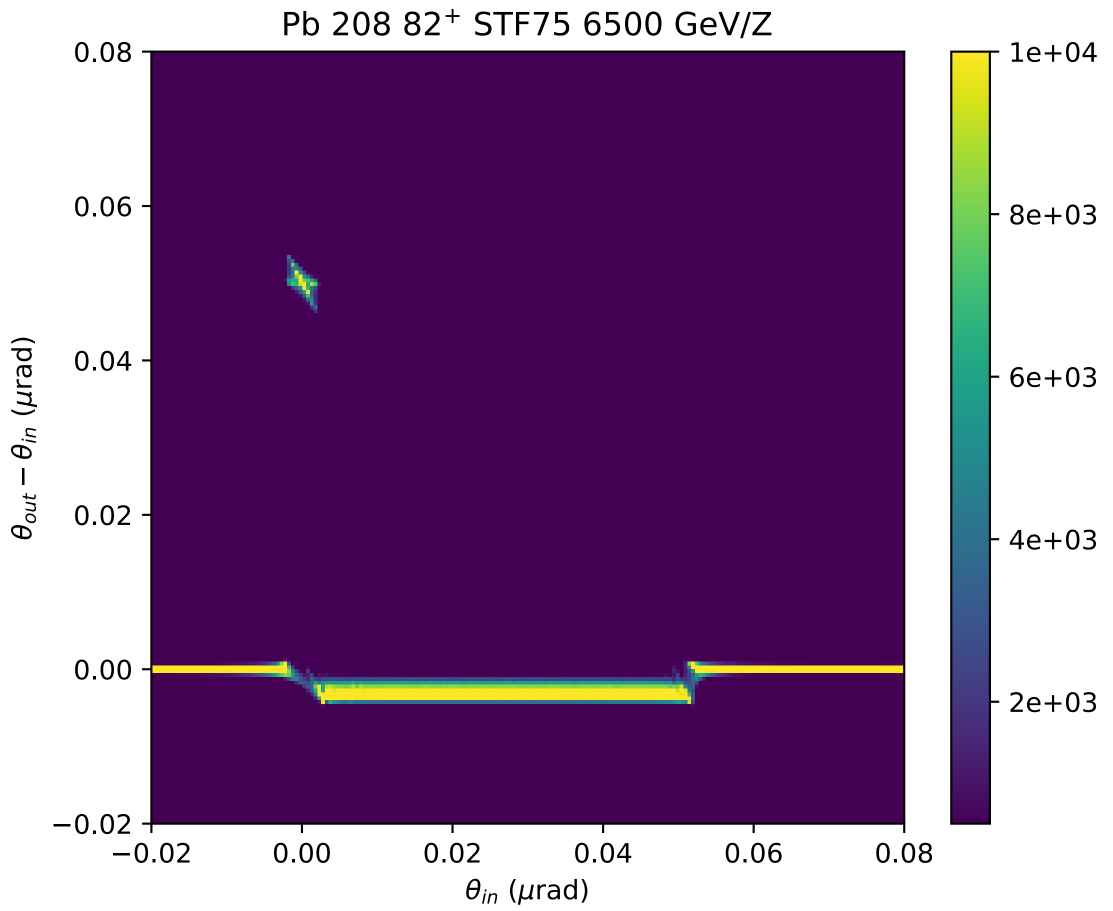
https://cds.cern.ch/record/1950908
Front. Phys., vol. 9, 2022



Sixtrack coupling Geant4

Relies on Geant4, including crystal routine developed in INFN-Fe. Protons and ions.

Eur. Phys. J. C (2014) 74:2998



Recent developments by L. Nevay

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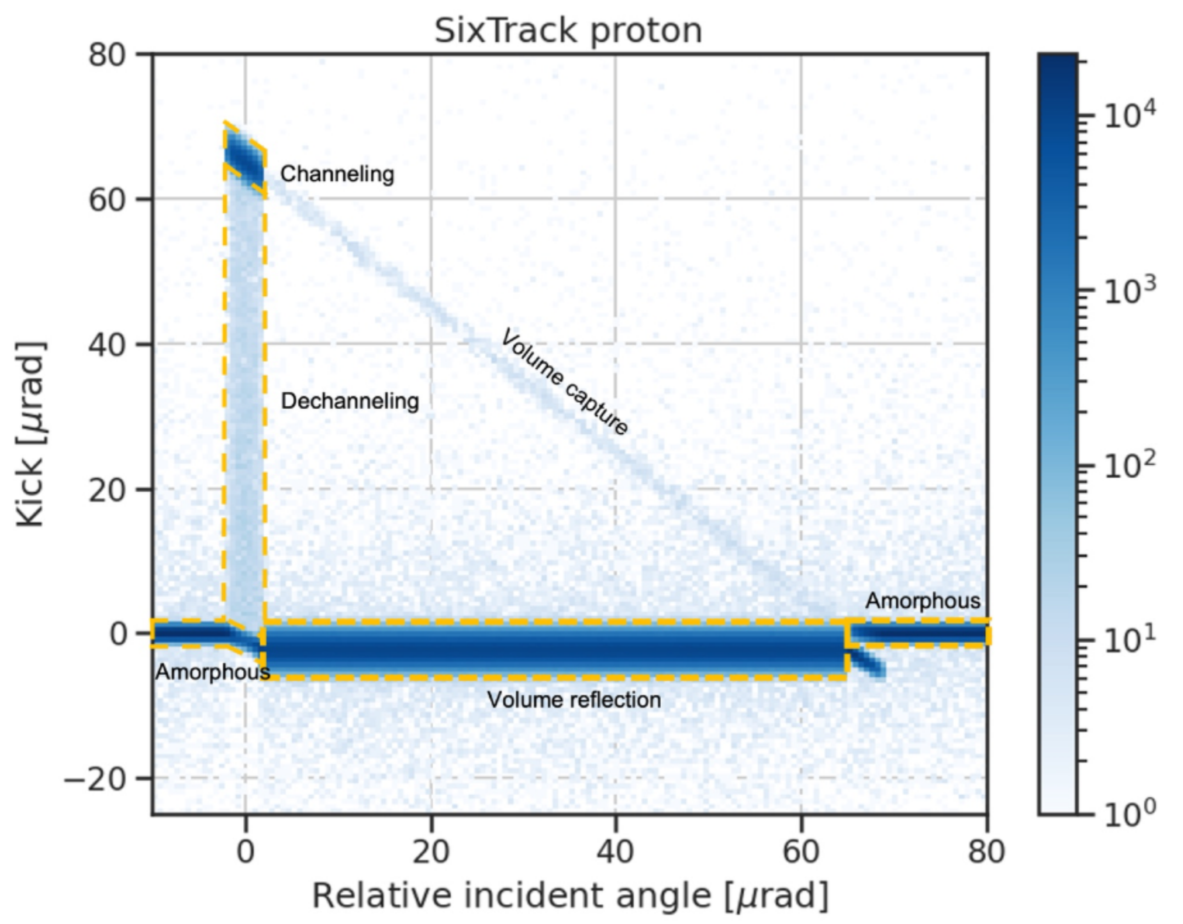

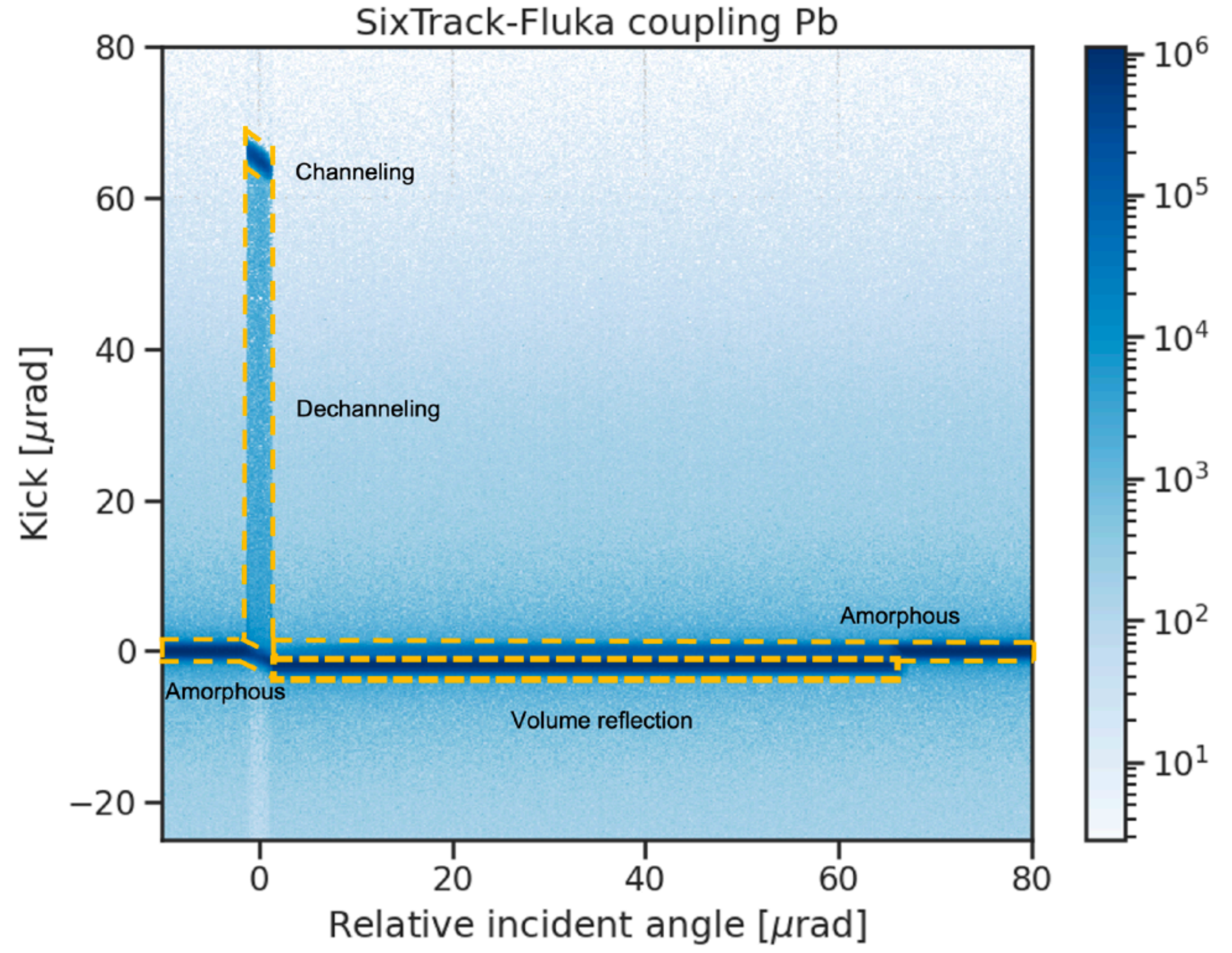

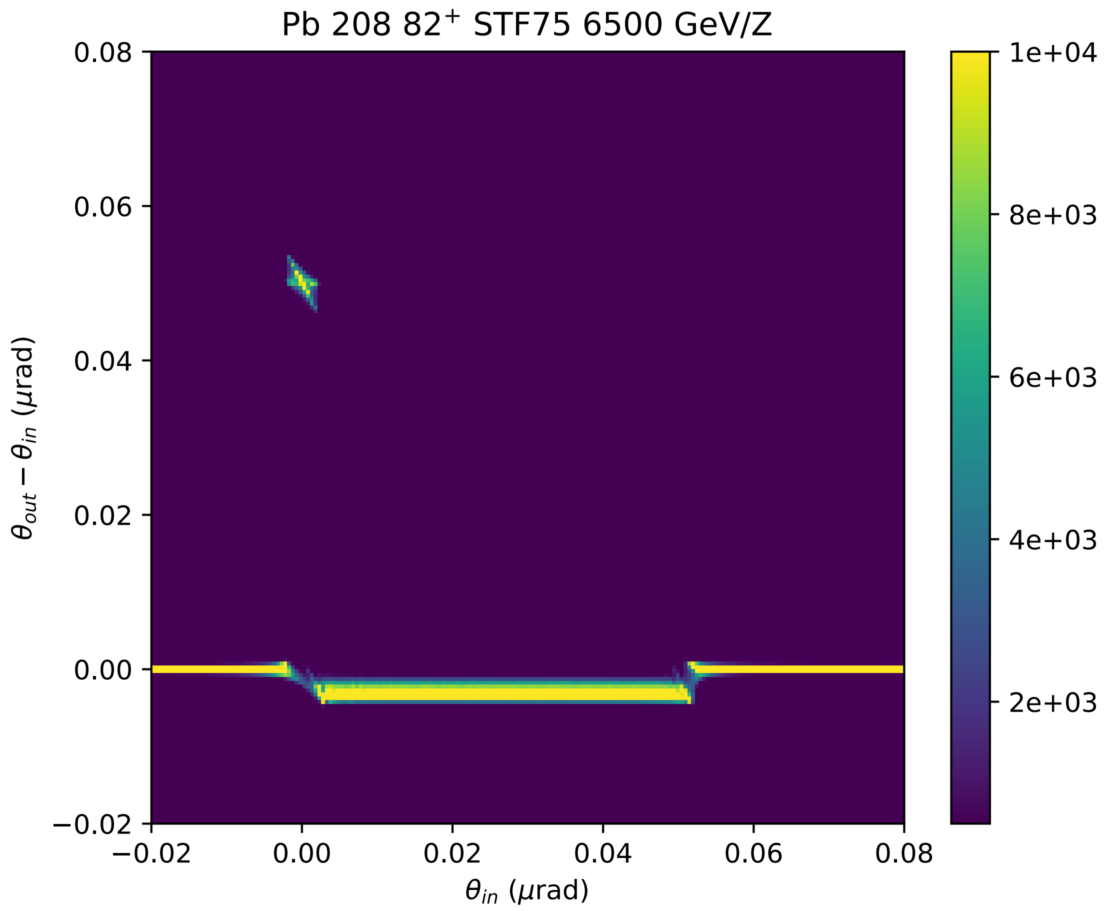

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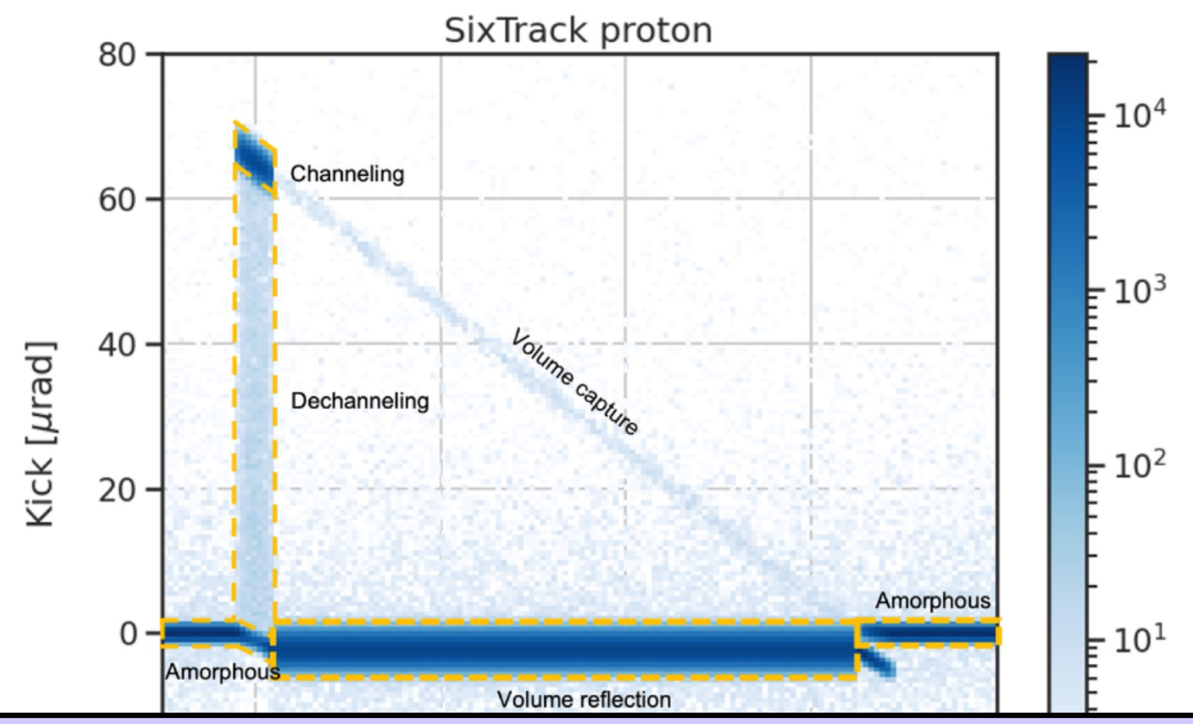

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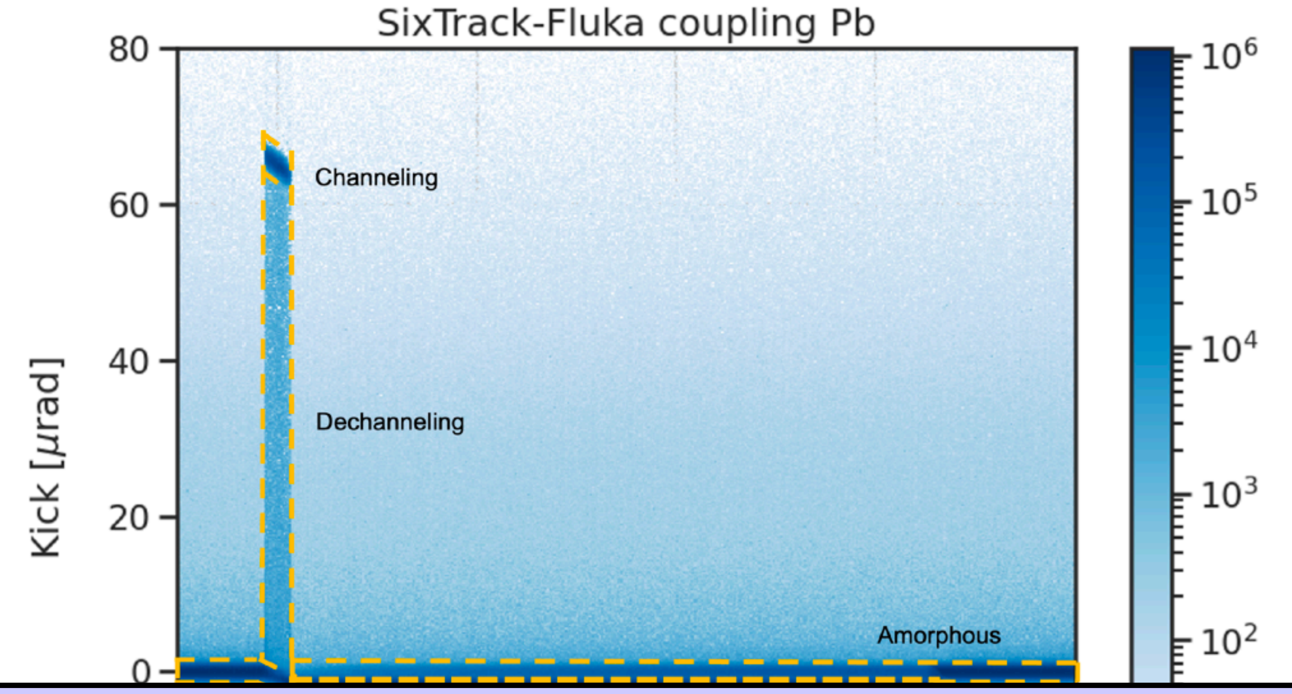

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Relies on Geant4, including crystal routine developed in INFN-Fe. Protons and ions.

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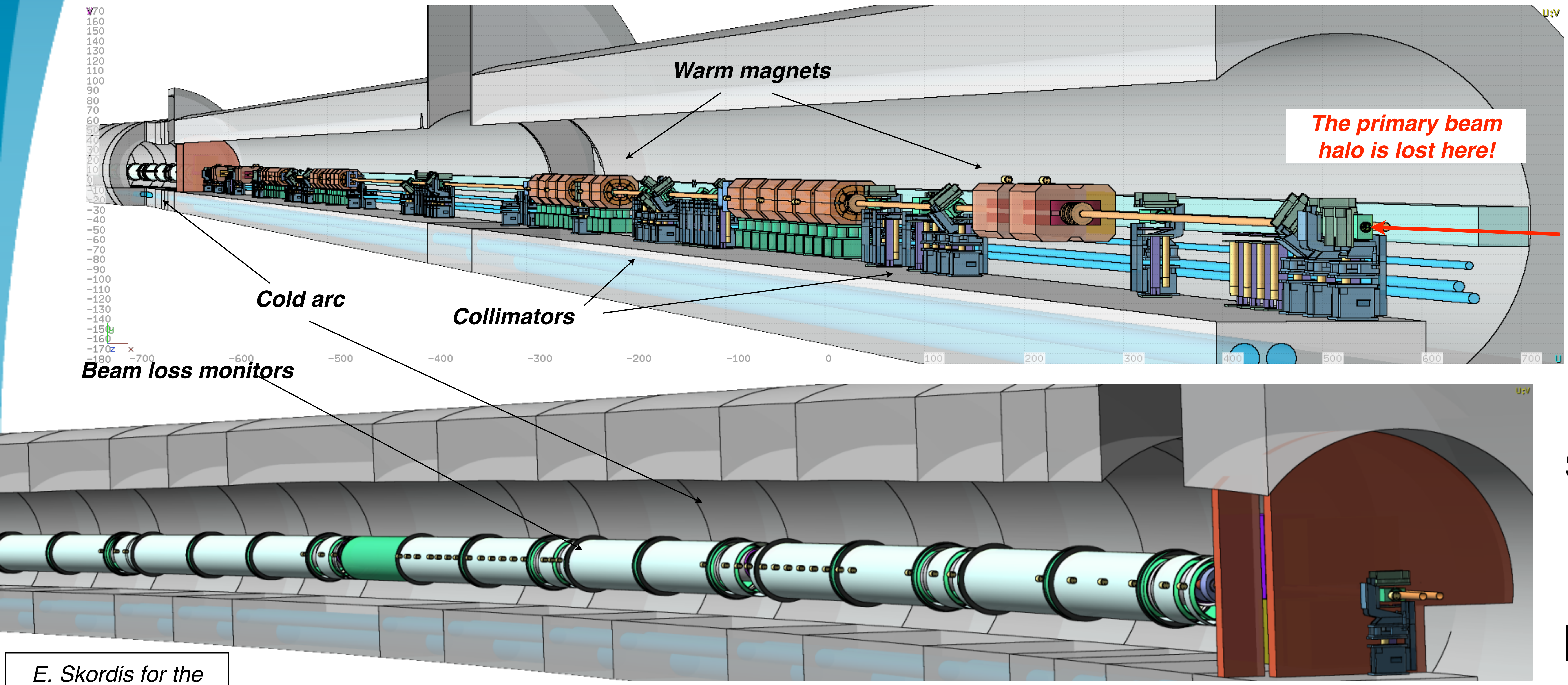
The CERN accelerator physics group is migrating most simulations to the **new XSuite package**.
Native Sixtrack and coupling to Geant4 already available and a first coupling to FLUKA under test.

FLUKA geometries for energy deposition studies



E. Skordis for the FLUKA team

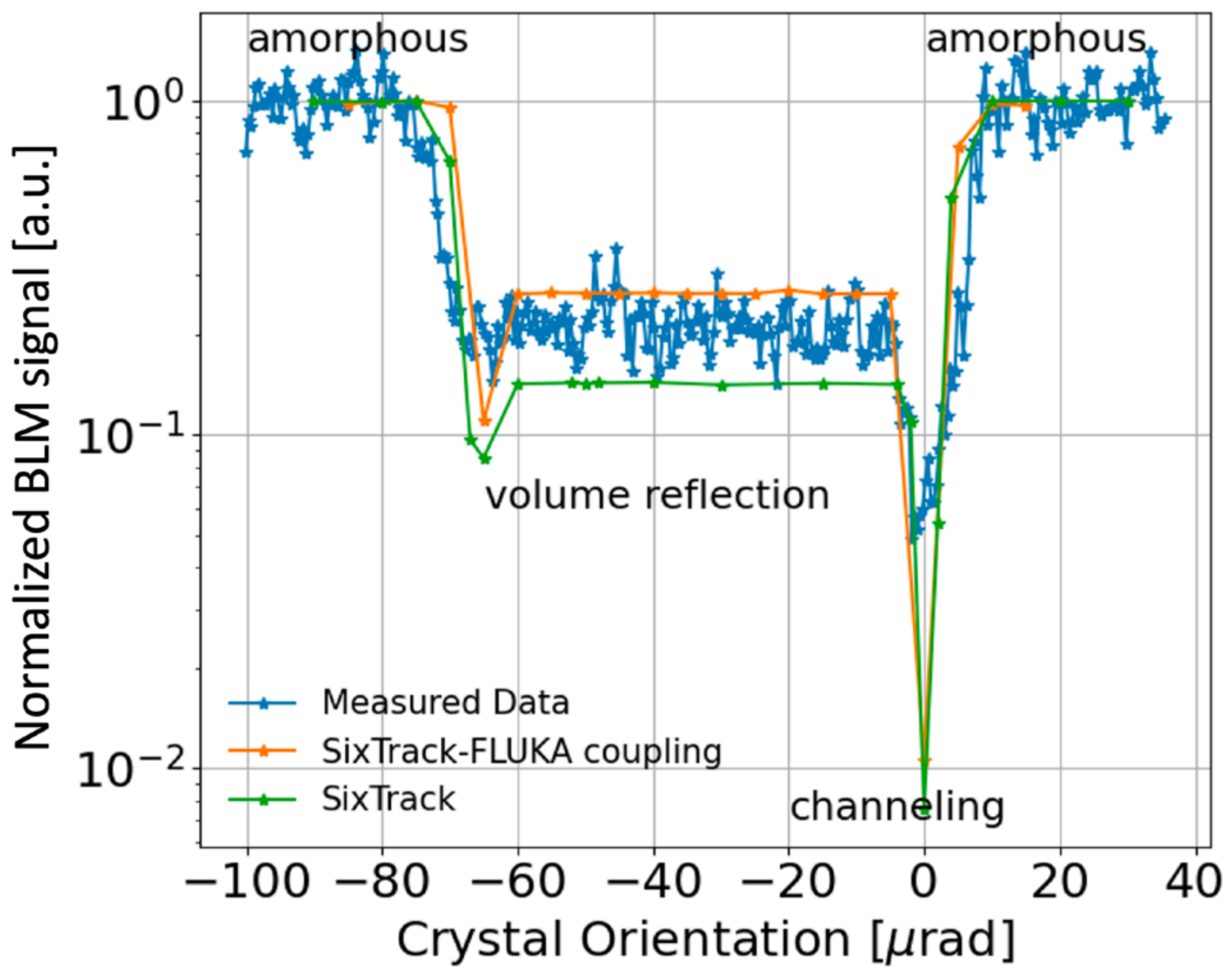
Model involves all relevant elements along about 700m metres of IR7 + downstream cold magnets.

Multi-year effort to build an IR7 model in FLUKA for energy deposition studies!

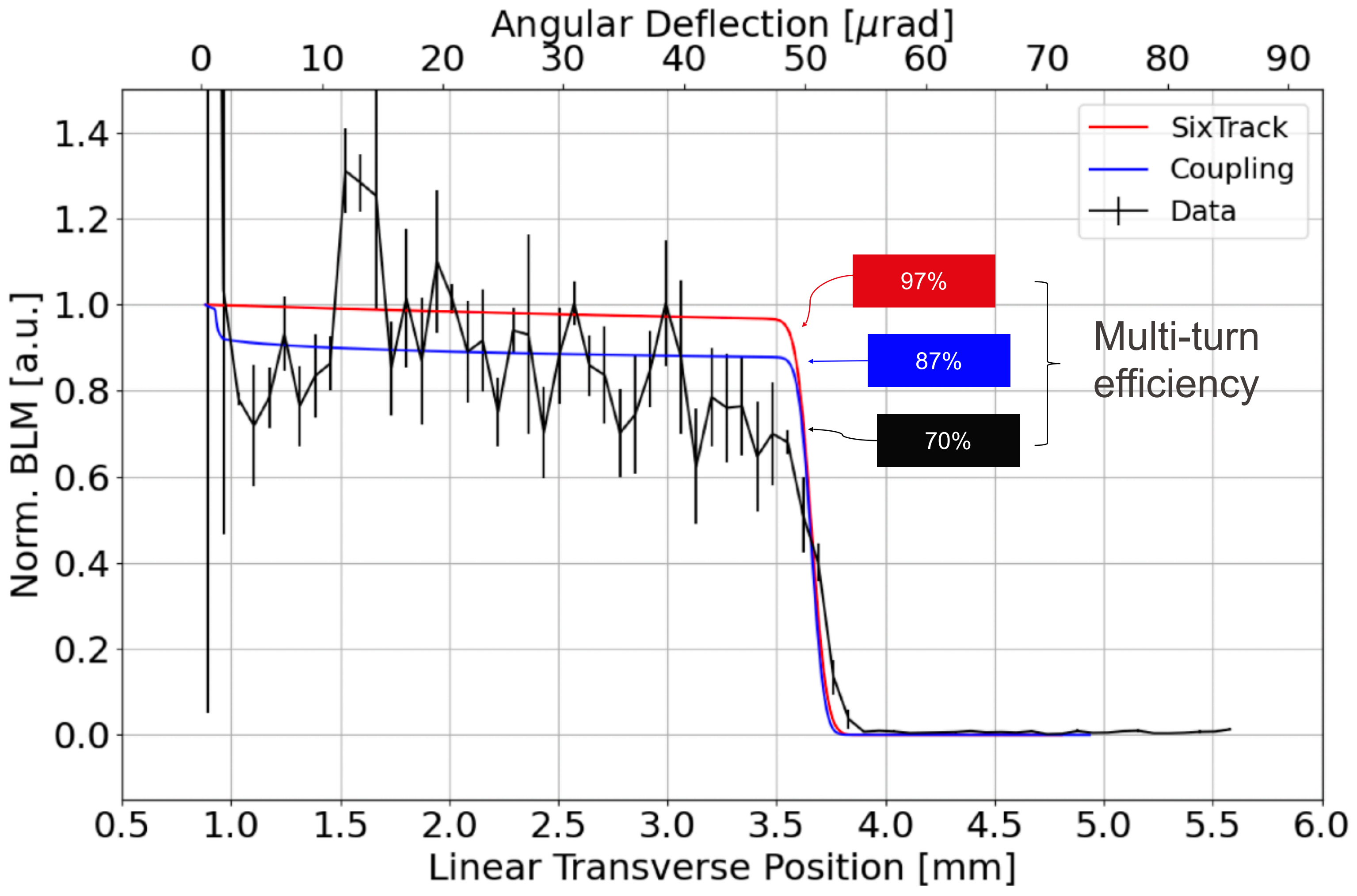
Simulation flow:
tracking with collimators
↓
losses used as input to shower simulations in FLUKA
↓
comparison to measure losses at ionisation chambers (BLMs)
↓
realistic assessment of power loss in magnet coils.

Crystal collimation simulations for proton halos

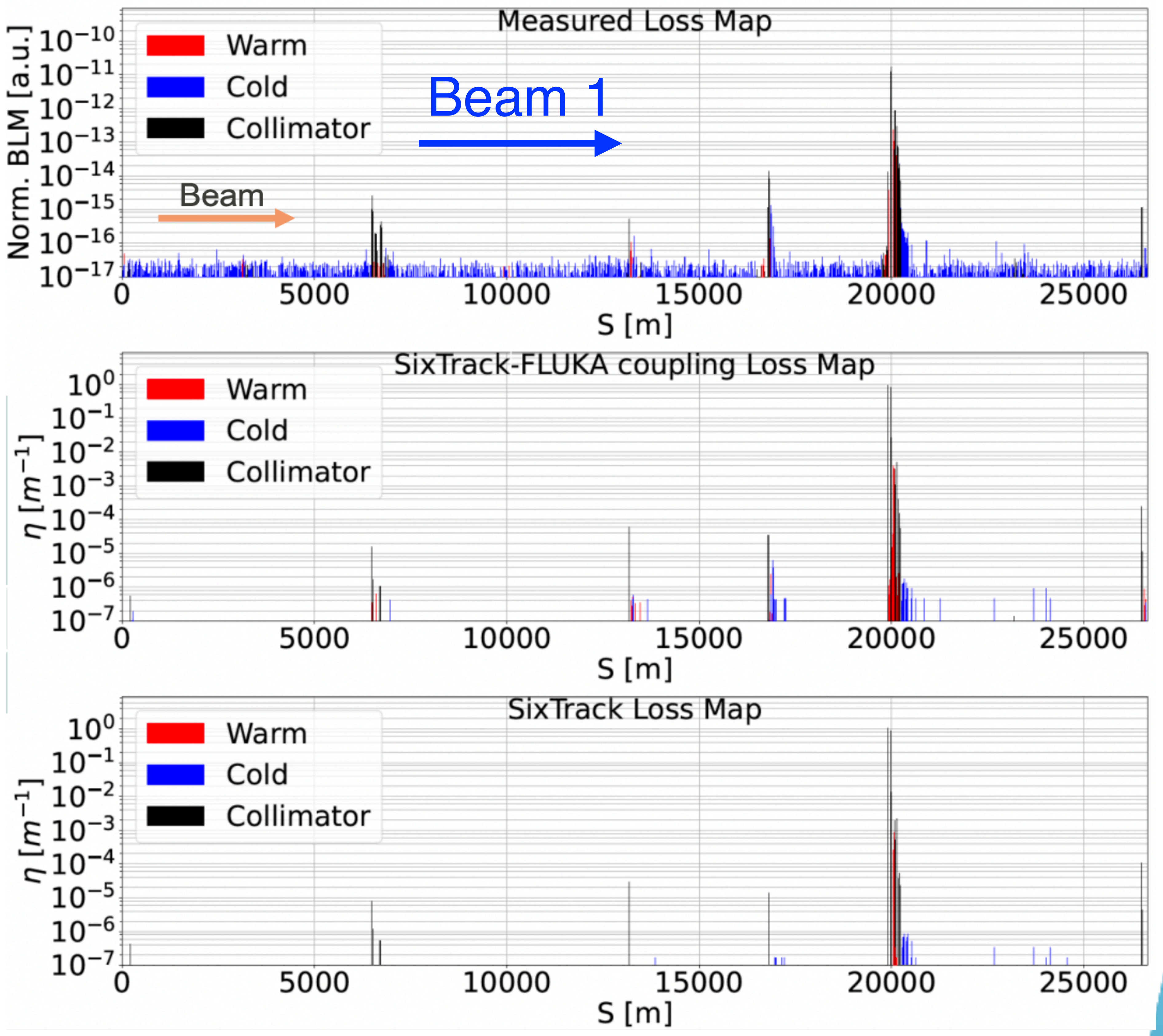
Angular scan



Collimator scan



Ring losses



- Very good agreement of both codes (SixTrack and SixTrack/FLUKA) with measurements!
  - Angular and linear scans look good
  - Complete ring loss maps!
- Notes: machine with no imperfections; measurements done with ionisation chambers outside vacuum, while simulations look at protons lost on aperture!

Simulations parameters:

- *6.5 TeV (2023 configuration)*
- *Multi-turn simulations with complete collimation system*
- *1 μm impact parameter*
- *Angular and linear scans + loss maps*
- *Perfect machine (no imperfections)*

Nucl. Instrum. Meth. A 1060 (2024) 169038

Crystal collimation simulations for proton halos

LHC Collimation Project CERN

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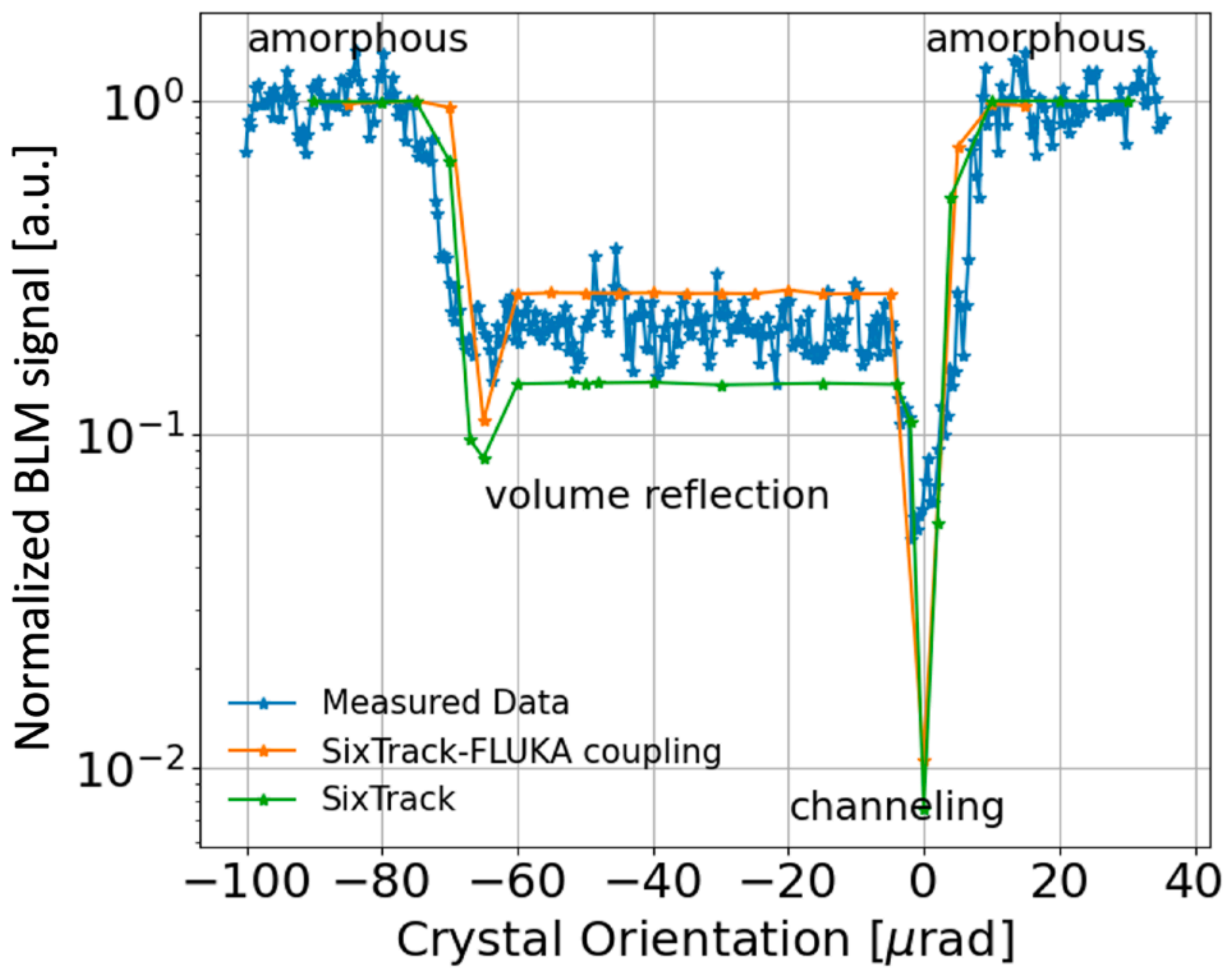

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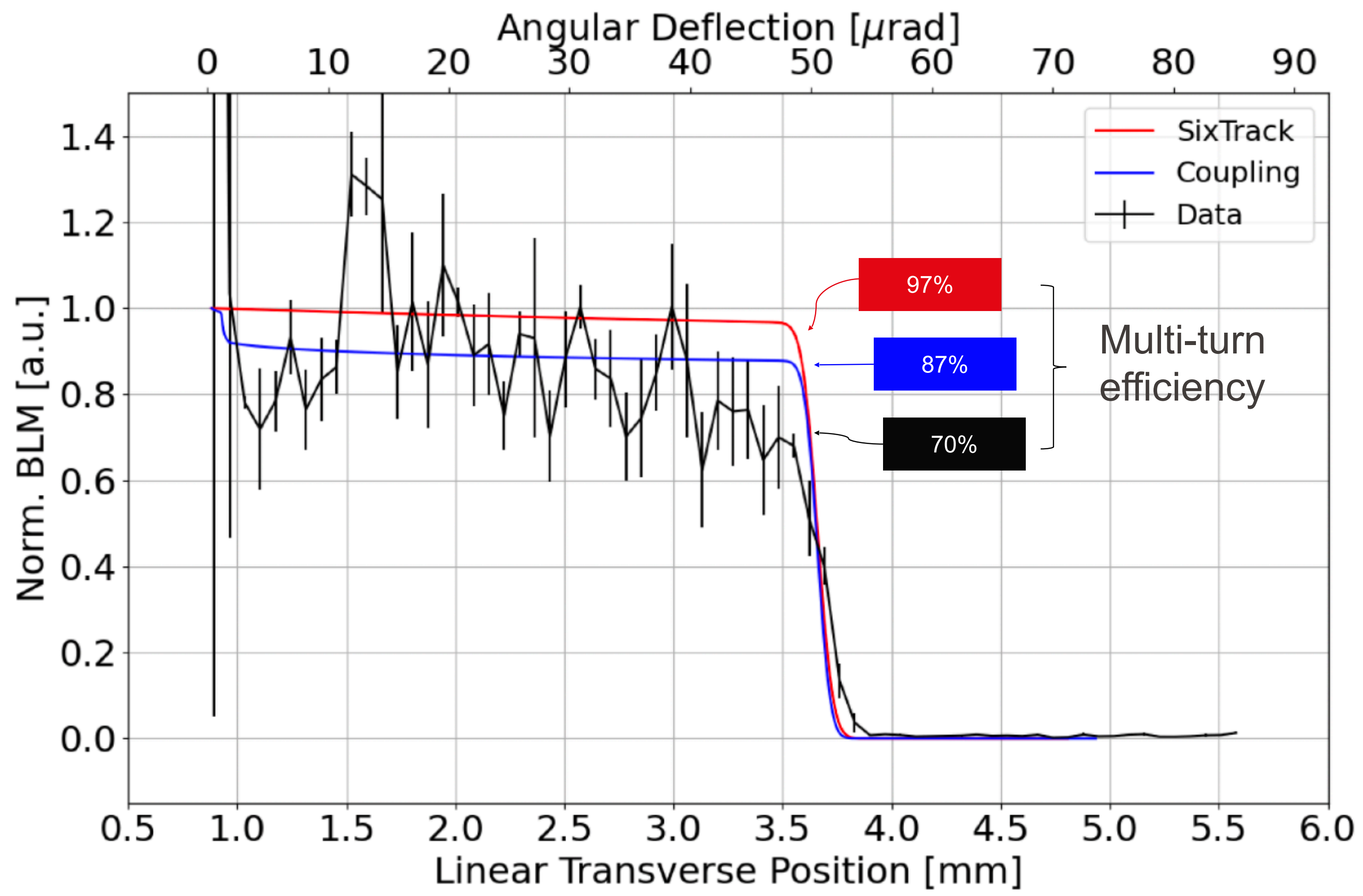

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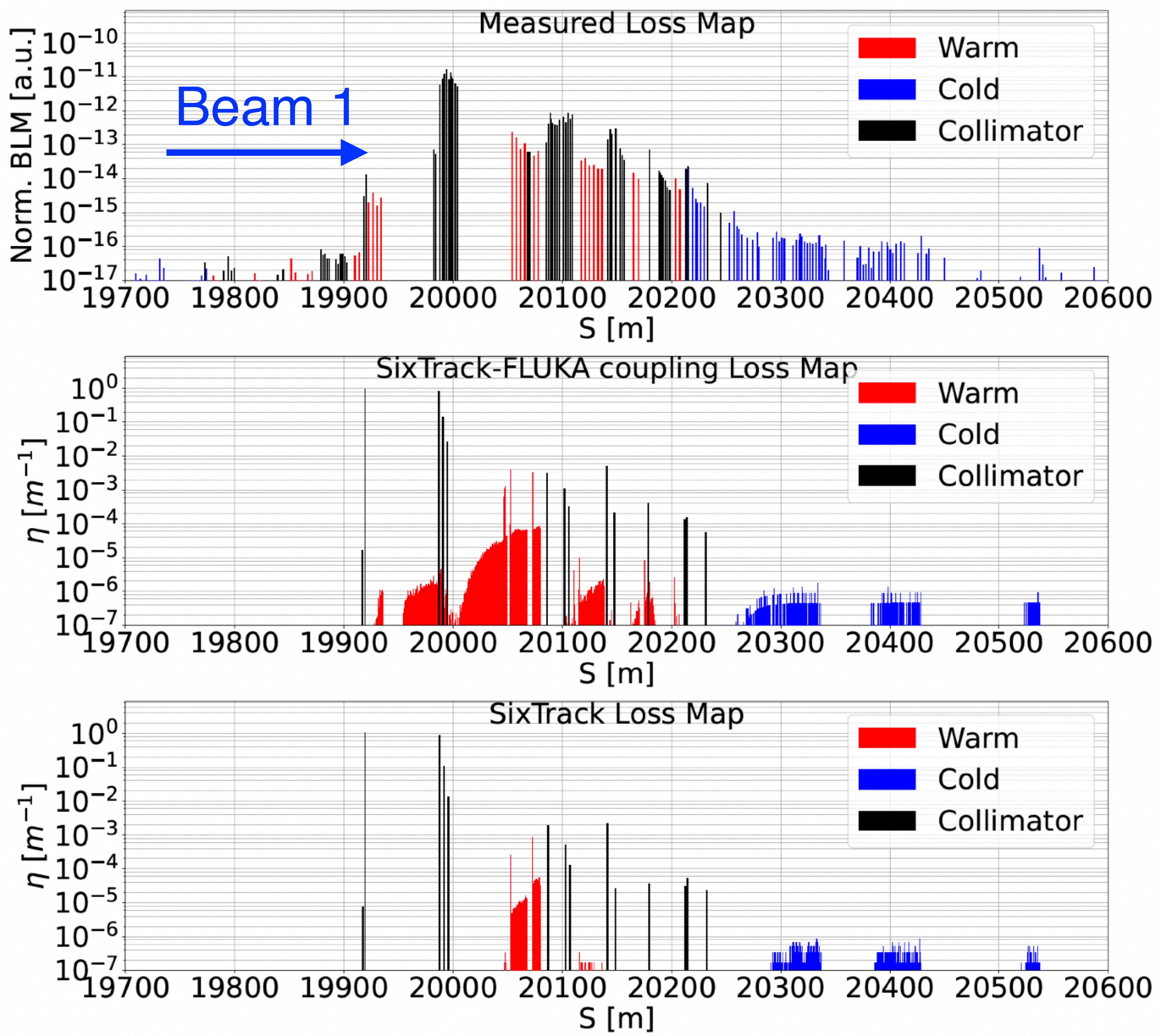

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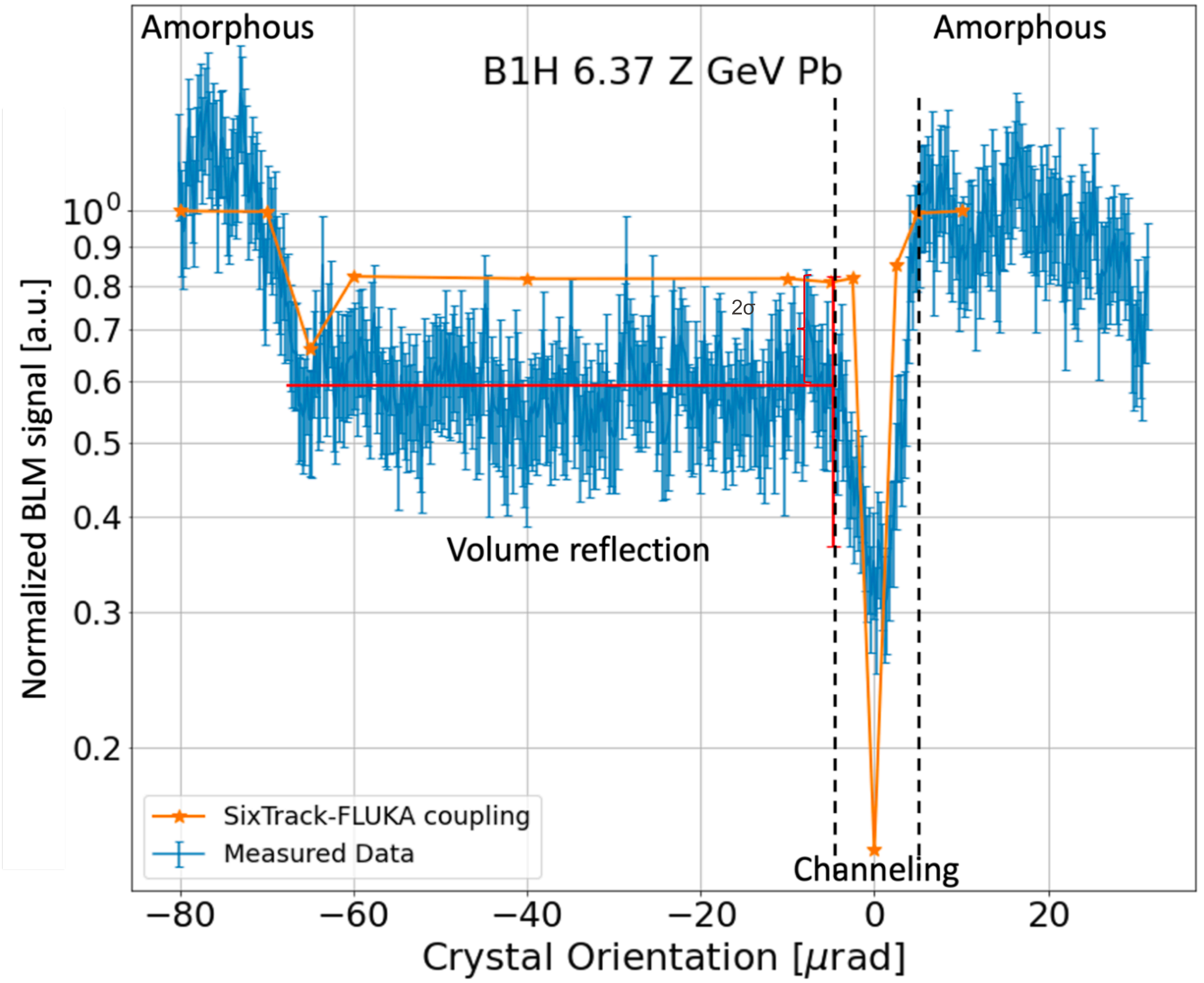
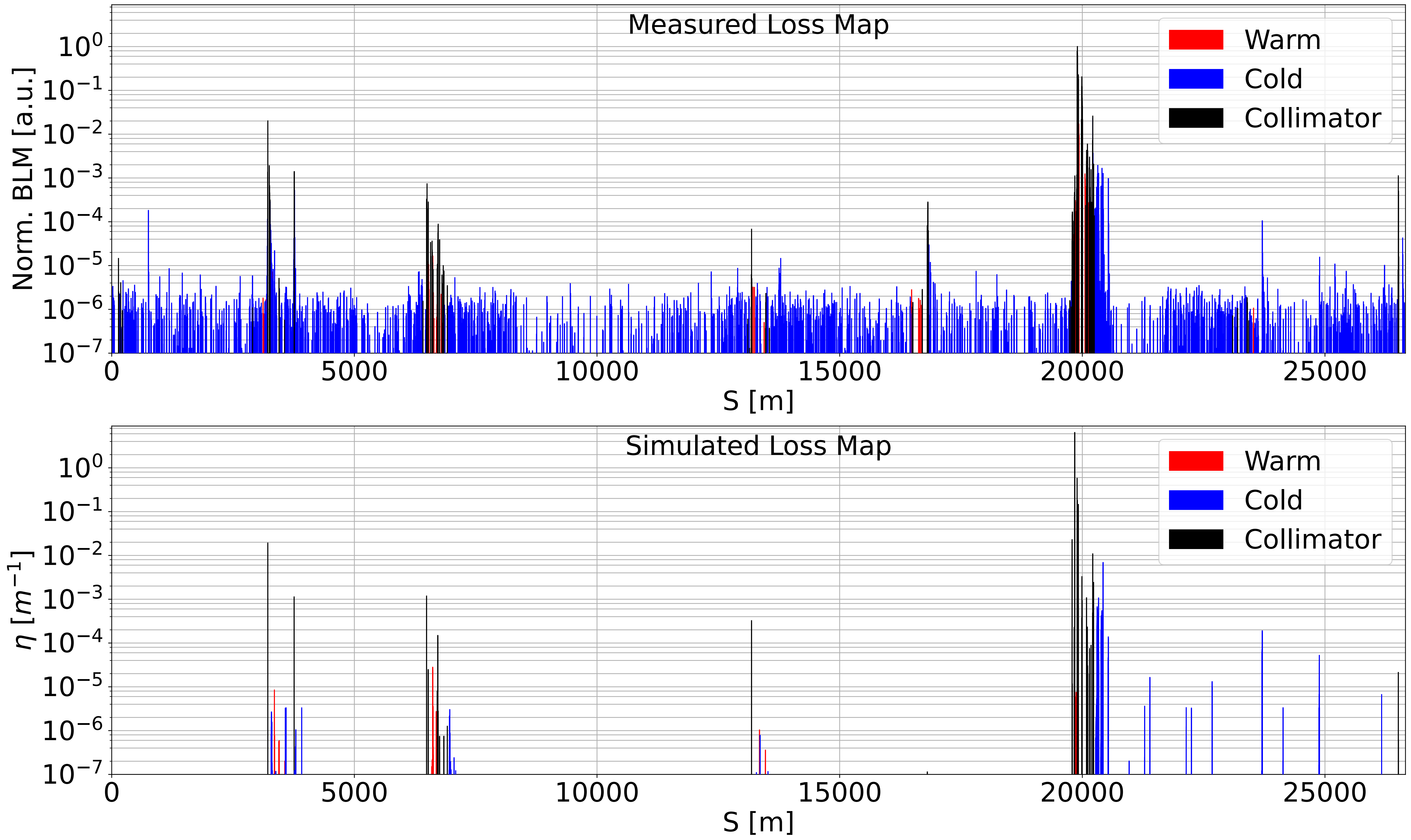
Simulation for lead ion beams



- Simulations with SixTrack/FLUKA coupling
- Angular scan well reproduced overall, with volume reflection discrepancy larger than for protons (under investigation)
- Very good qualitative agreement for full-ring and local IR7 losses.

Simulation for lead ion beams



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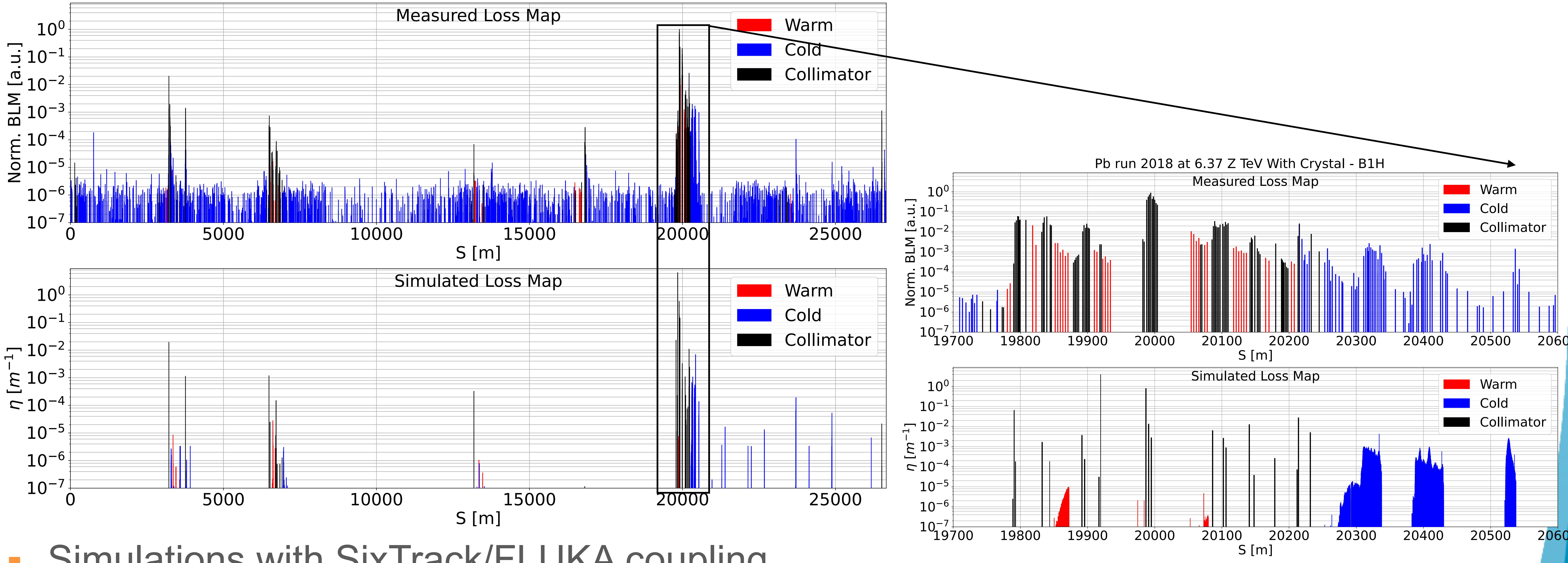

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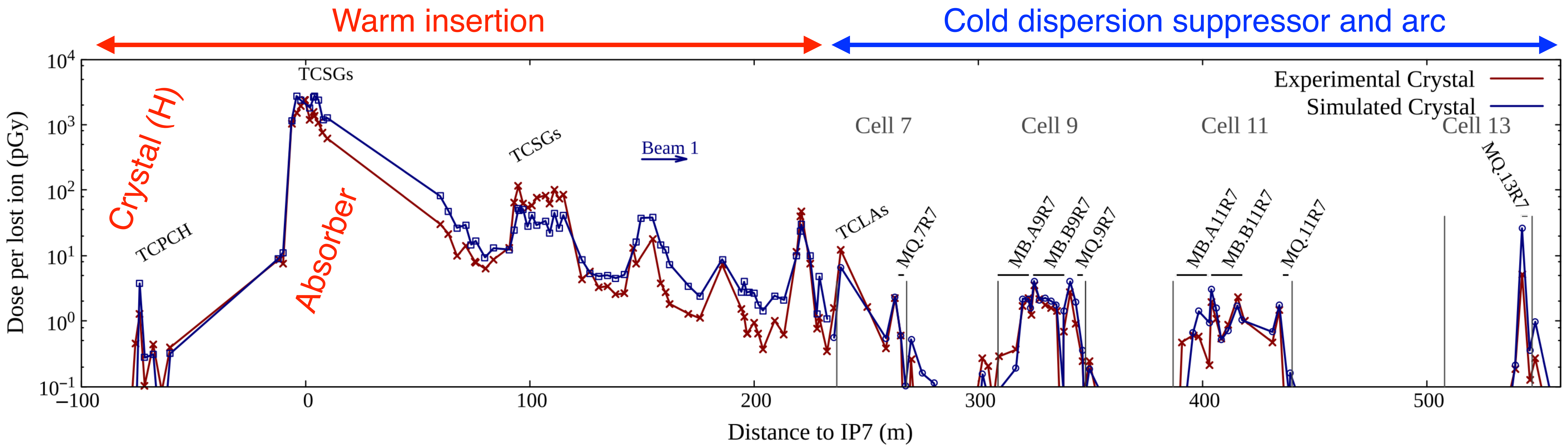
Energy deposition in the superconducting magnets

- Overall, excellent quantitative agreement when comparing simulated BLM signals.
- Losses in superconducting magnets are reproduced within a factor 5 for lead beams. (better for protons: ~factor 3).
- Extrapolation to run 3 configuration indicate that crystal collimation **improves the ion cleaning by a factor 3** at the limiting locations (more in other ring locations)
- Note: case for a perfect cleaning — errors to be studied.

*Run 2 lead-ion data used **in two companion PhDs** in the accelerator physics (M. Cai) and FLUKA (J.P. Potoine) teams at CERN. Extrapolations to 2023 configurations by V. Rodin.*

See also: TUPS39



PRAB 26 (2023) 9, 093001

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HL-LHC upgrade scope (deployed in 2022 and 2023)

- 4 re-designed, new crystal assemblies (TCPCs)
  - Improved design for reliability. Still based on the replacement chamber
- New produced crystals (same specs), all strip crystals.
- Same layout and longitudinal positions in IR7

Crystal length along the beam	4±0.1 mm
Crystal + support height	< 55 mm
Crystal + support weight	< 150 g[1]
Channeling plane	<110>
Channeling axis	<111> or <110>
Miscut for planar channeling	< 40 urad
Torsion	< 1 urad/mm
Bending	50.0±2.5 urad
Miscut for axial channeling	0±18 mrad
Dislocation density	< 1 cm^2

Two crystal producers: INFN-Fe and PNPI

Courtesy SY/STI, BE/CEM

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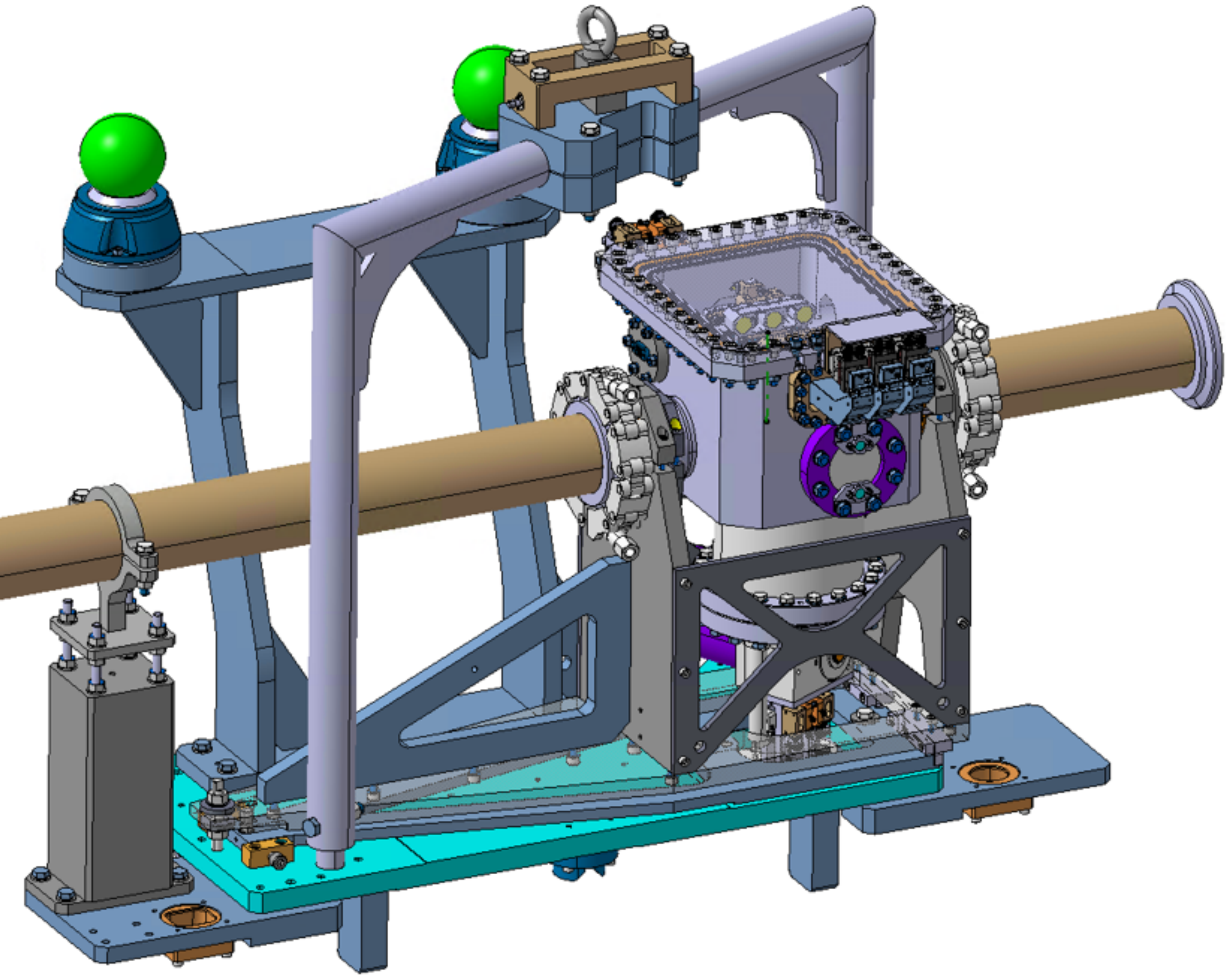

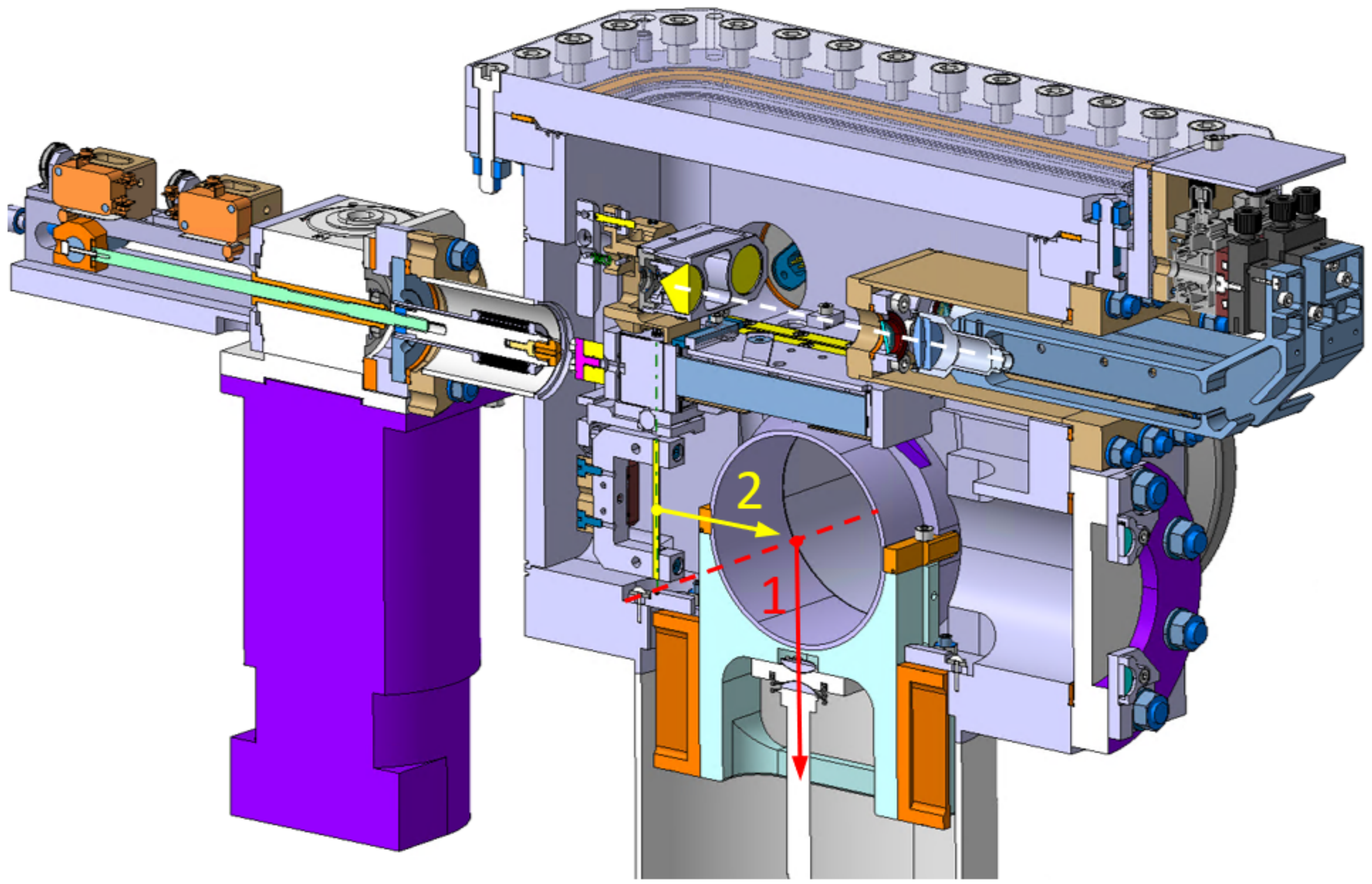

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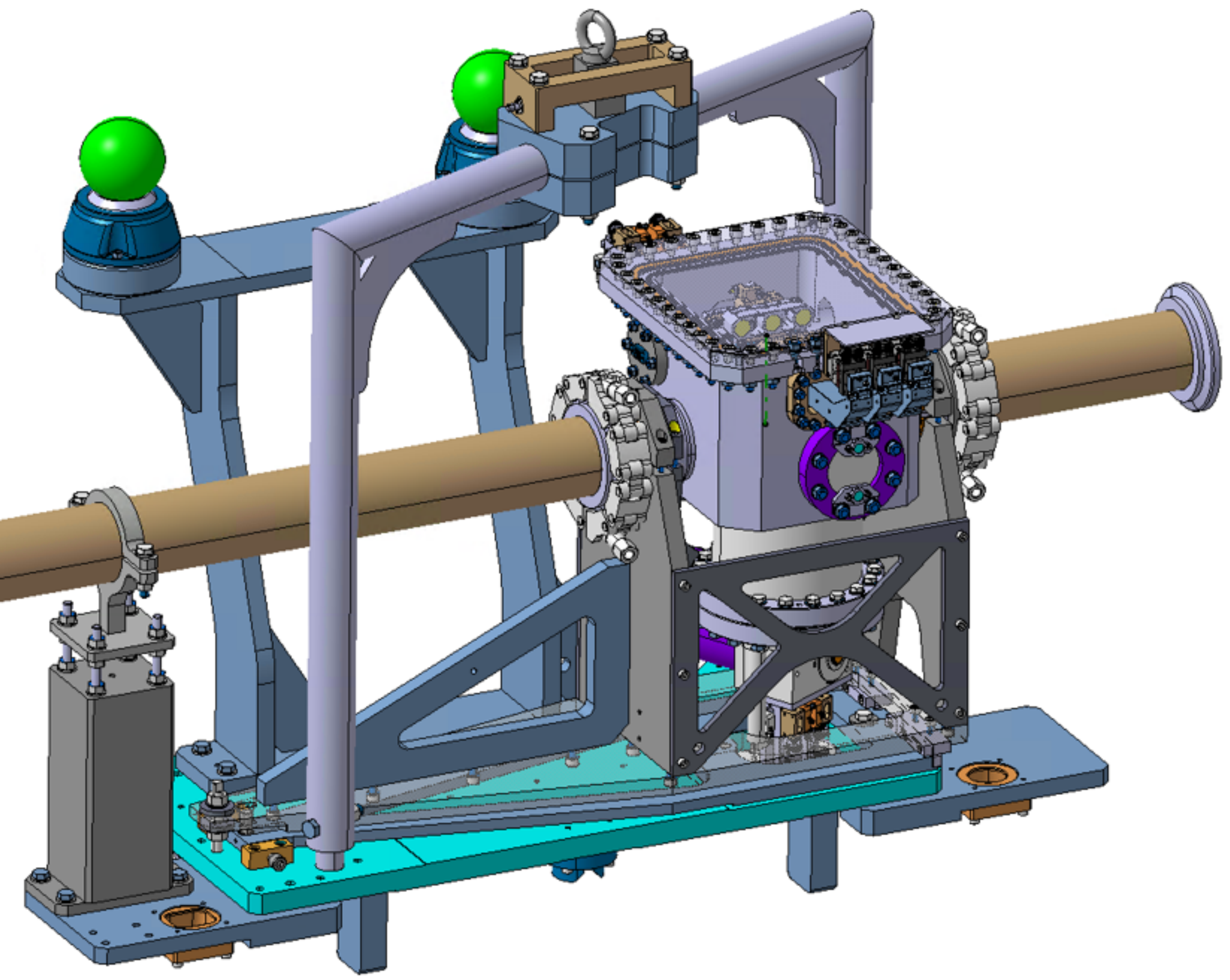
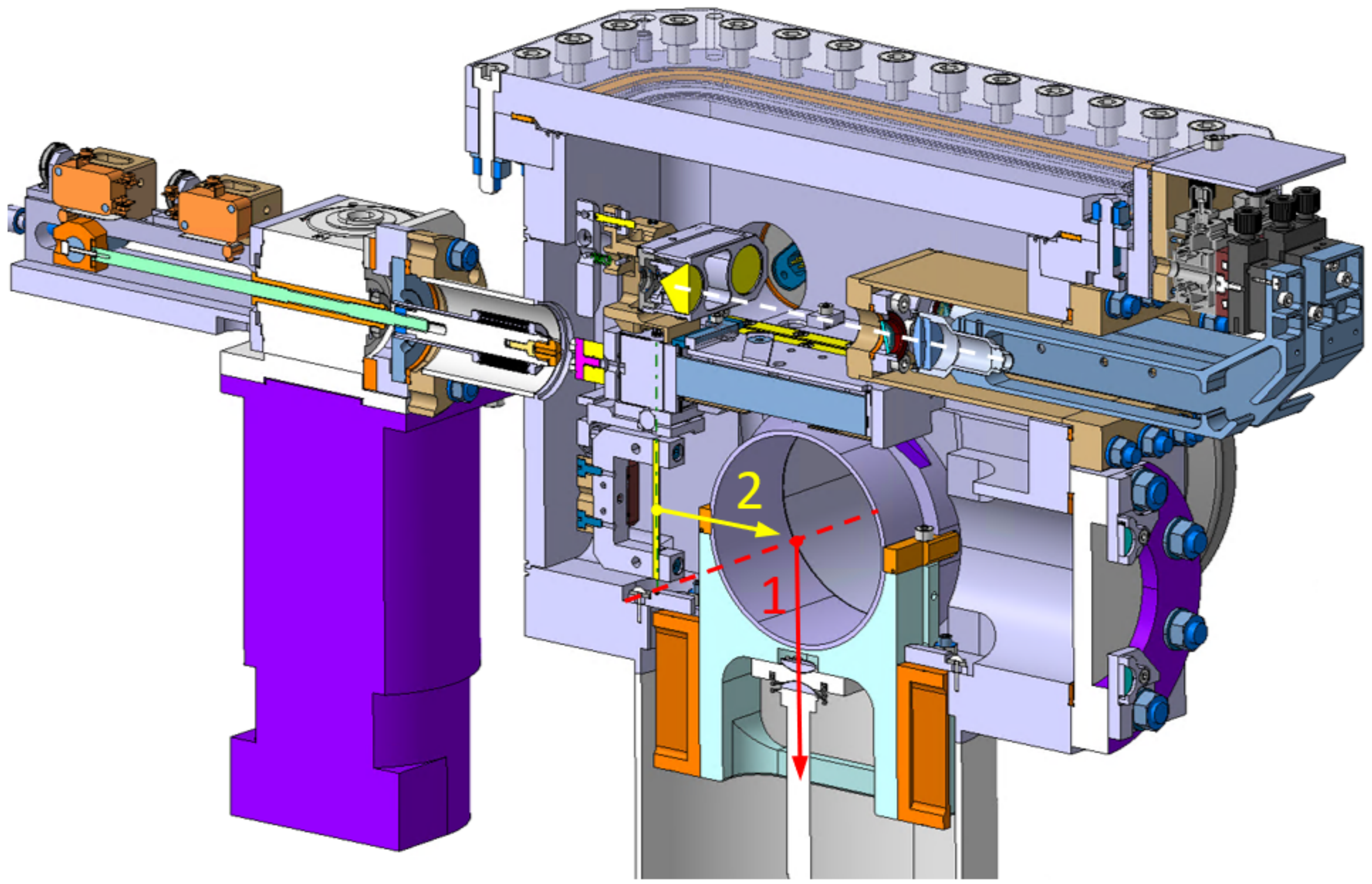
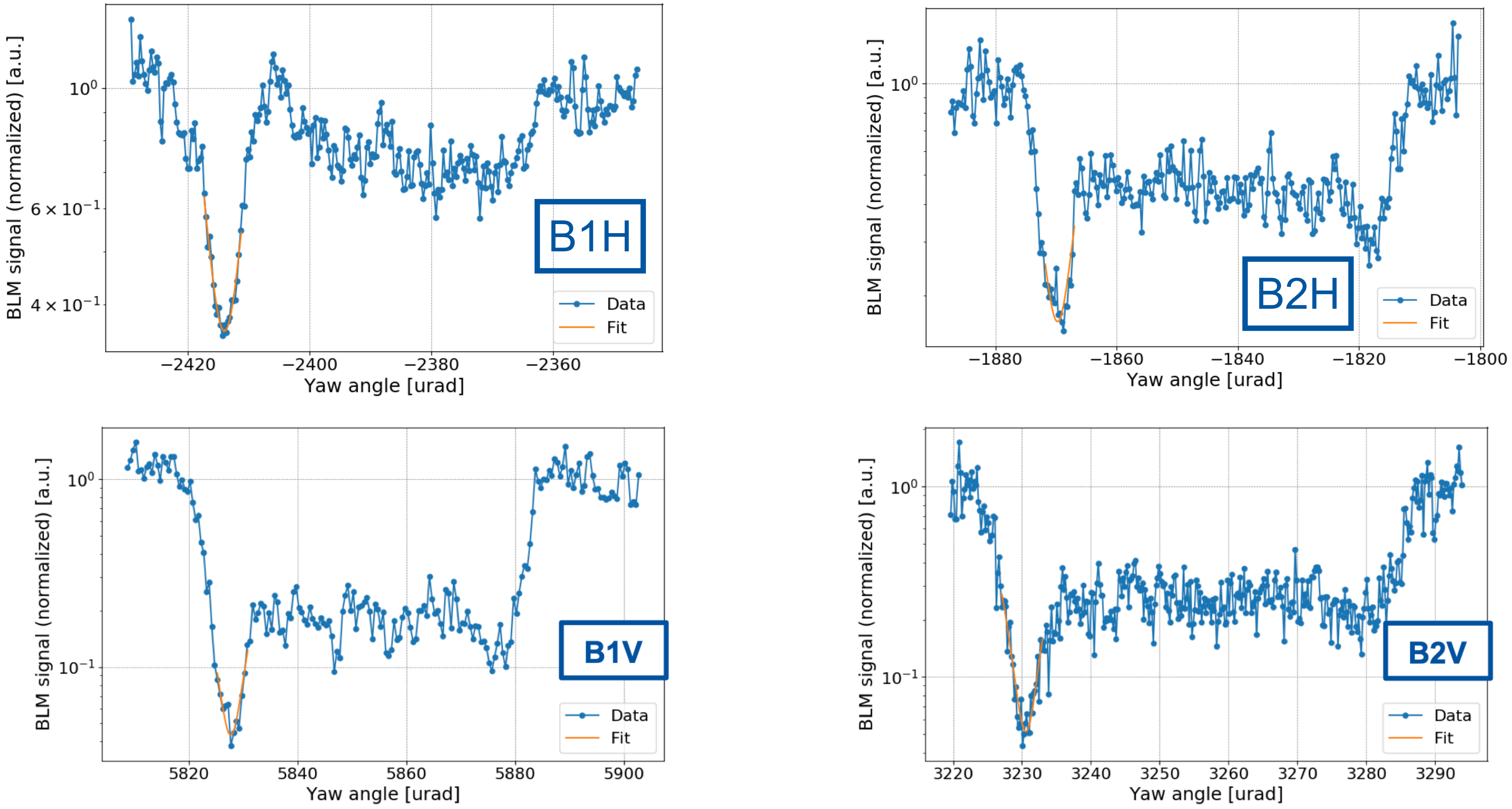




Two crystal producers: INFN-Fe and PNPI

Courtesy SY/STI, BE/CEM

Validation of the new bent crystals with 6.8TeV protons

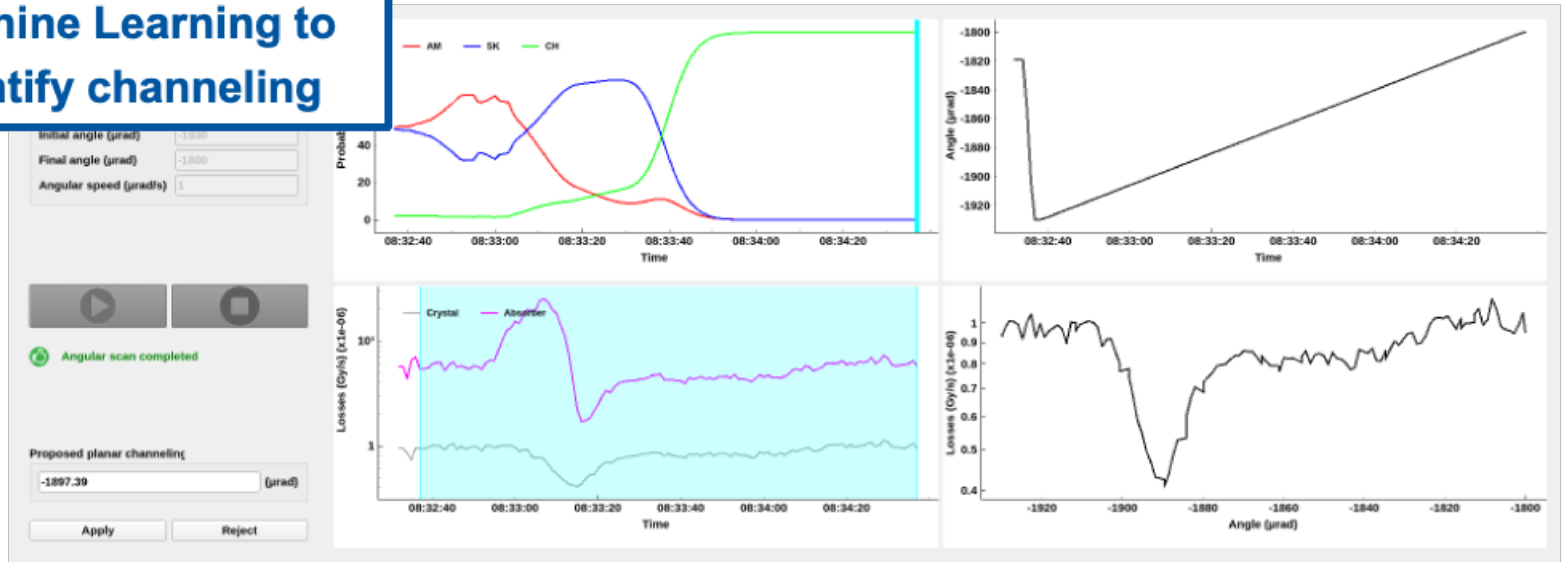


Courtesy M. D'Andrea NIM A, vol. 1060, p. 169 062, 2024

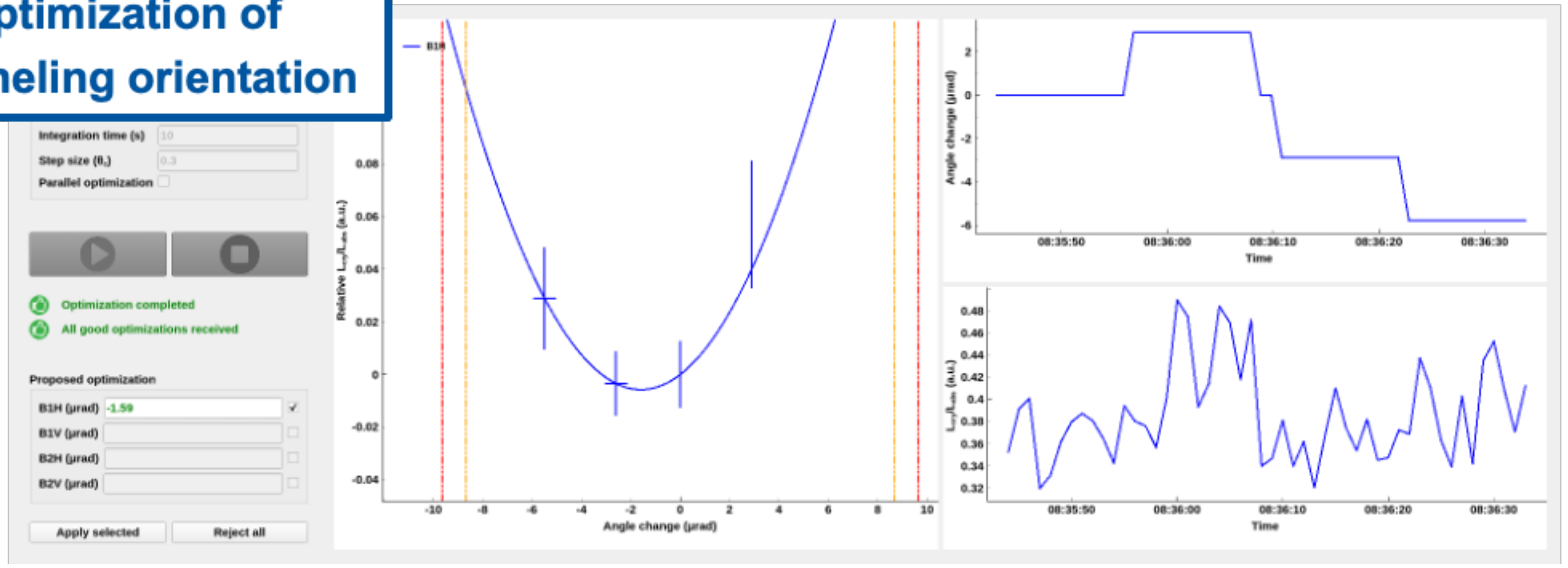
- All the 4 new crystals are well in specifications as installed!
- Excellent quality, with miscut < 2μrad for 3 crystals and ~ 6 μrad for one.
- Goniometer controls working as expected.

Automated crystal setup, assisted by machine learning tools

Machine Learning to identify channeling



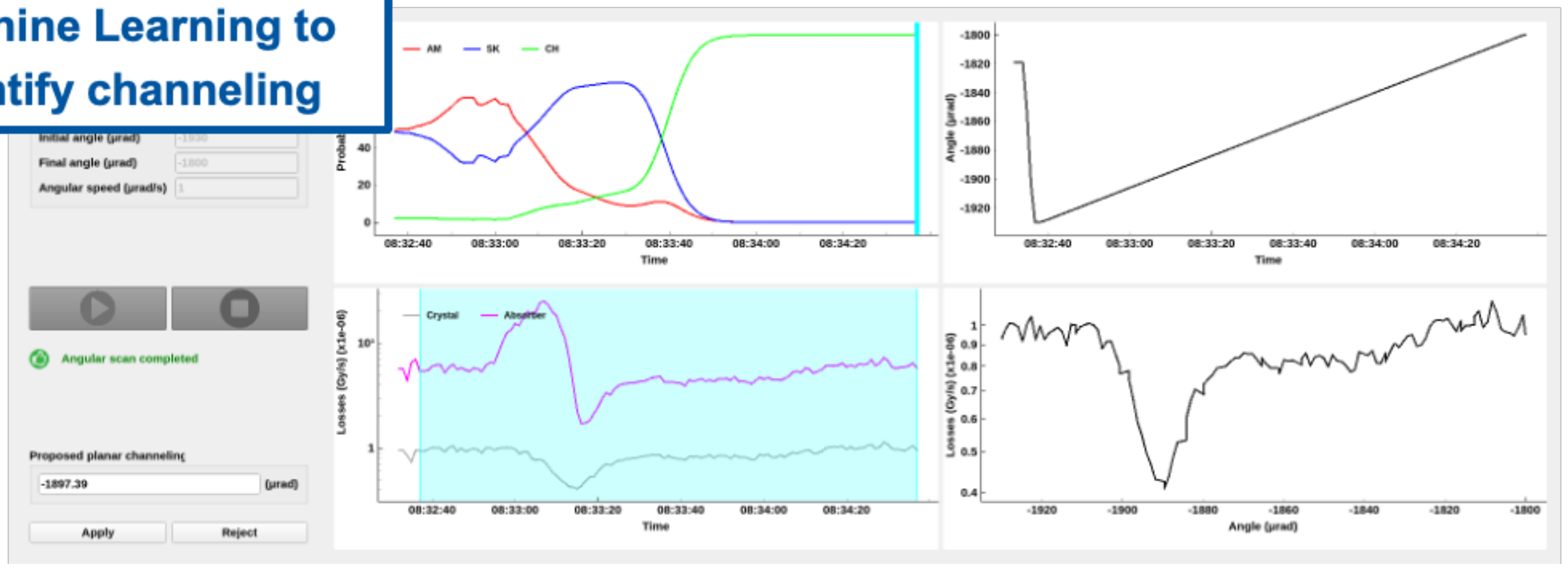
Optimization of channeling orientation



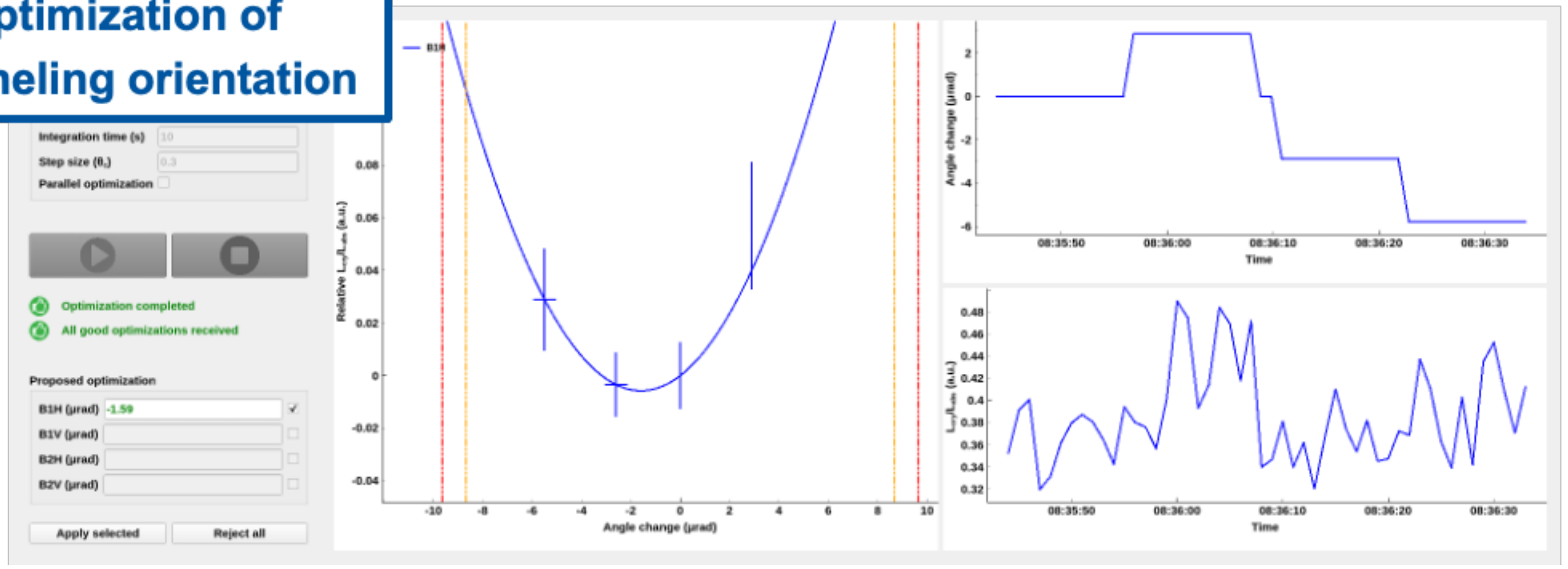
Courtesy D. Mirarchi, A. Vella, G. Ricci

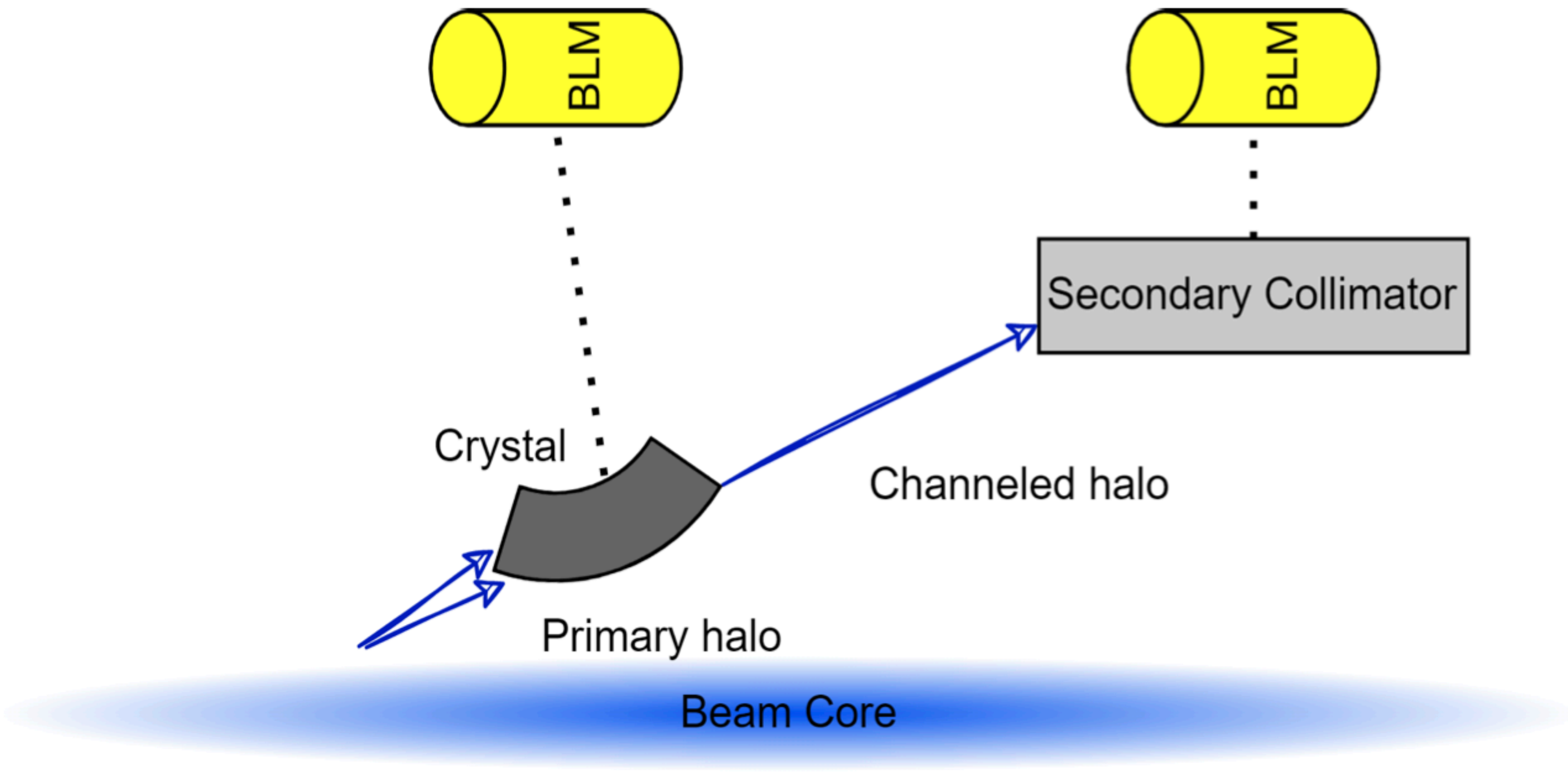
Automated crystal setup, assisted by machine learning tools

Machine Learning to identify channeling



Optimization of channeling orientation





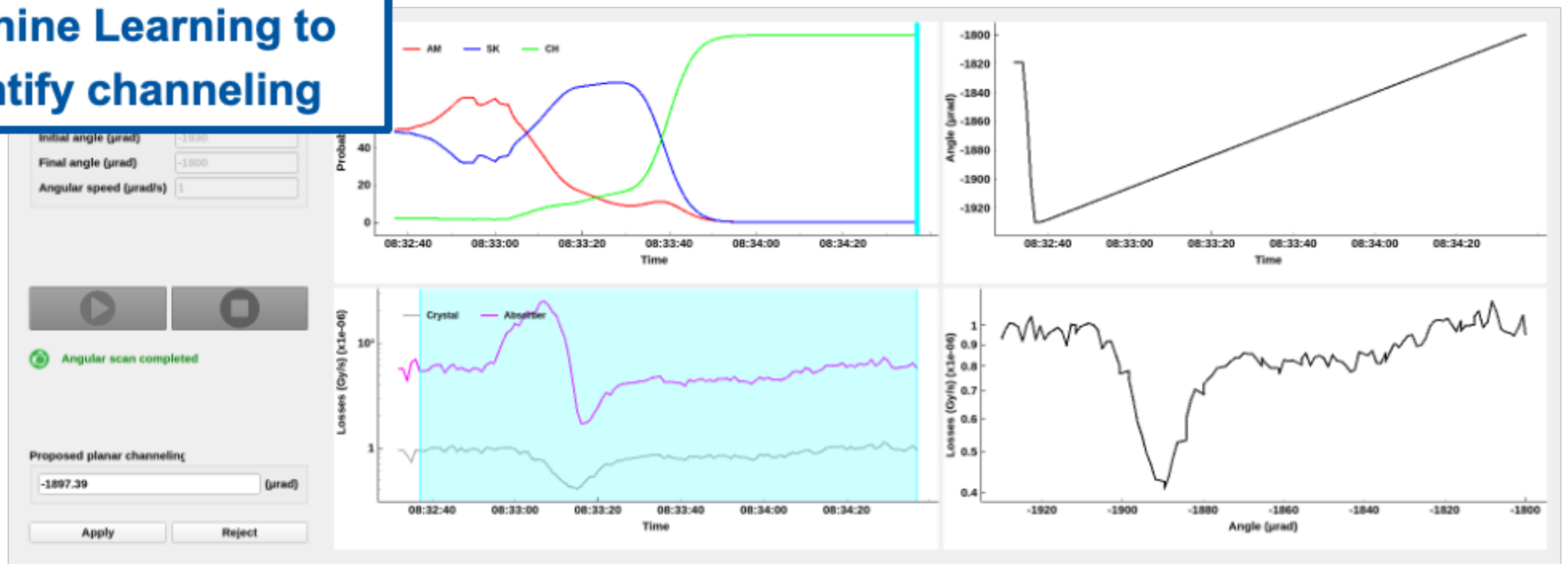
Courtesy D. Mirarchi, A. Vella, G. Ricci

TUPS42

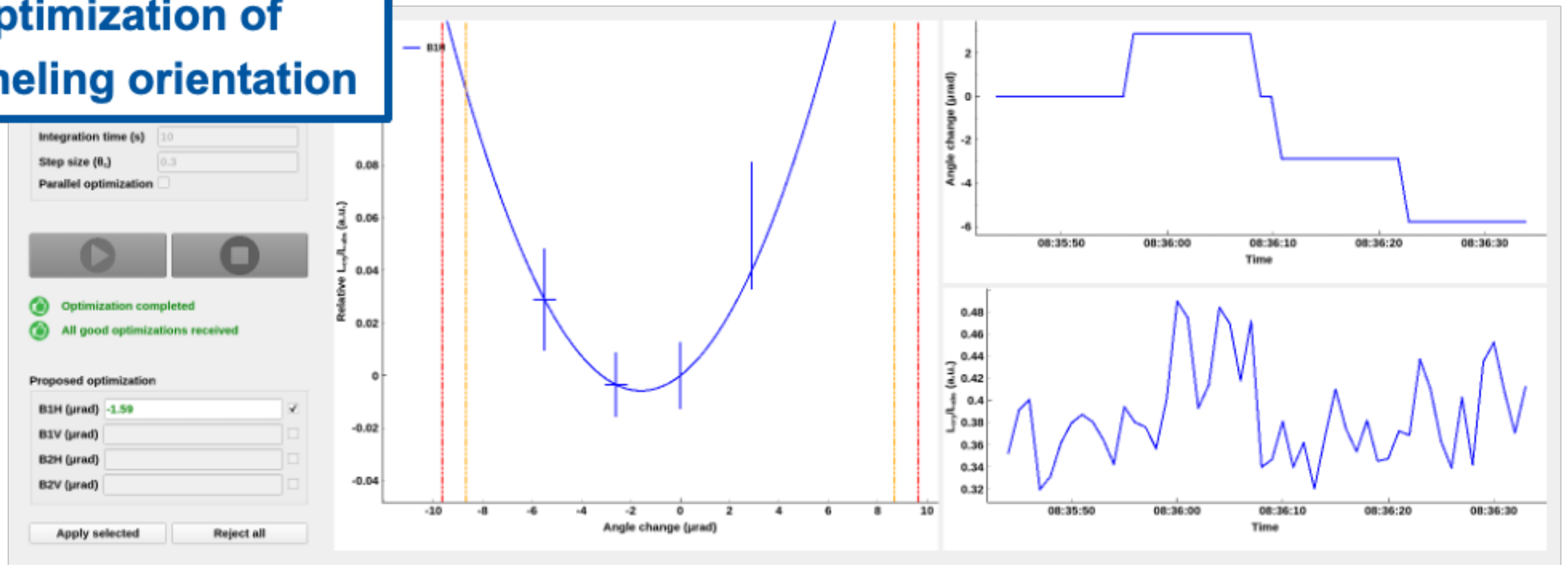
Automated crystal setup, assisted by machine learning tools

LHC Collimation Project CERN

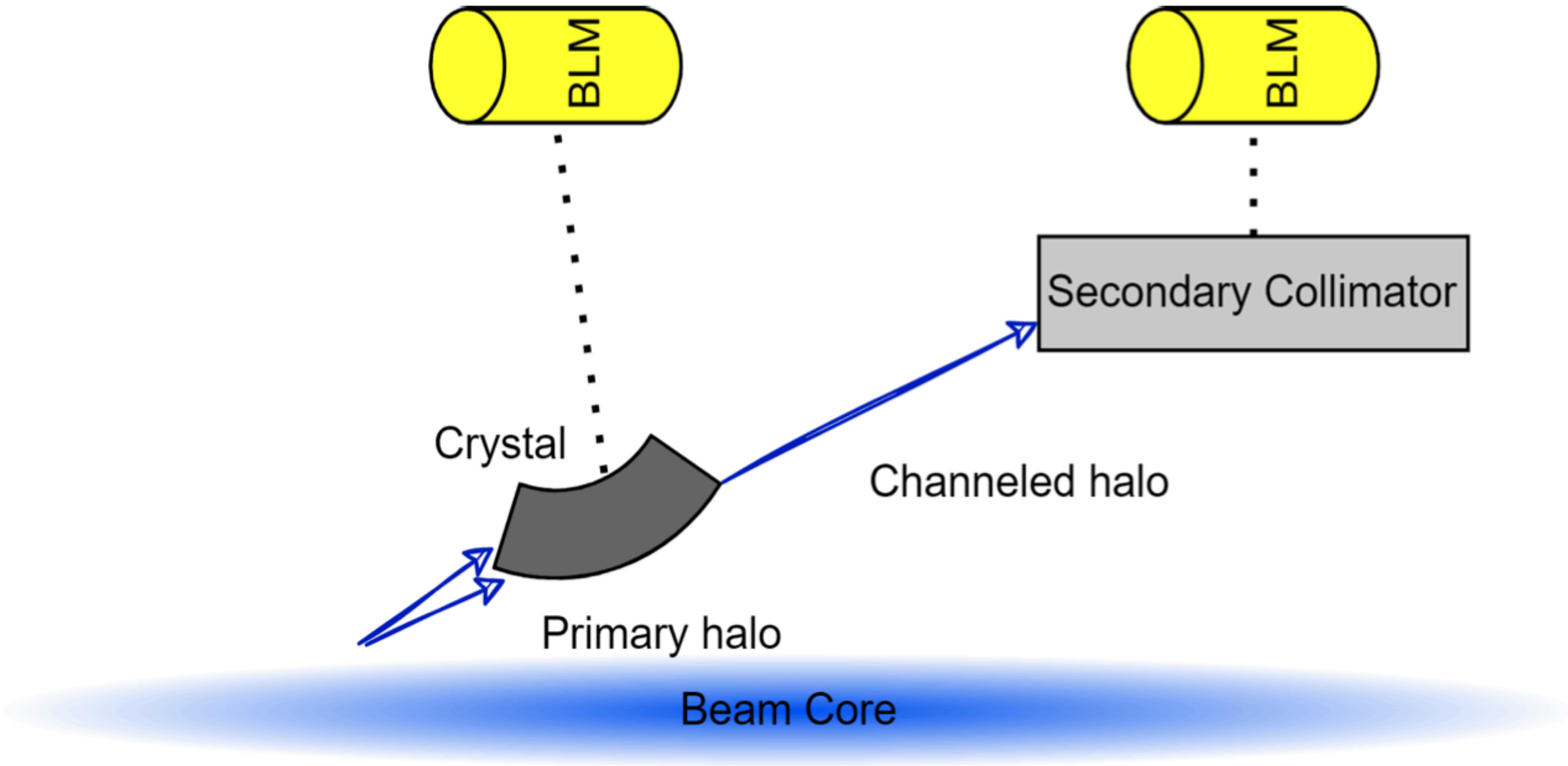
Machine Learning to identify channeling



Optimization of channeling orientation



Courtesy D. Mirarchi, A. Vella, G. Ricci



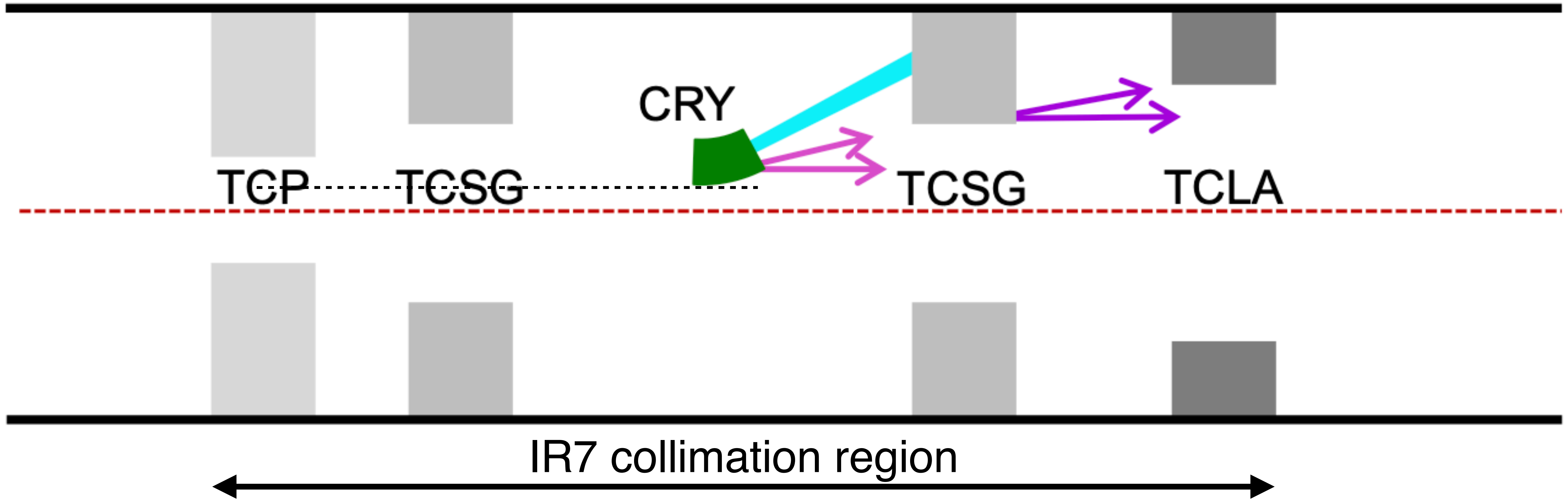
- Studying application of ML for real-time monitoring of loss of channeling (see later)
- Key inputs: BLM at key-collimator locations
- Target output: Crystal angular error from optimal channeling orientation
  - Through identification of the “amorphous” and channeling orientations
- Feed-forward neural network — FNN — being used; simulation framework to train the model

TUPS42

HiLumi HL-LHC PROJECT CERN IPAC24

Operational configuration for Pb ion run

Crystal scheme — "adiabatic" insertion in to the betatron system

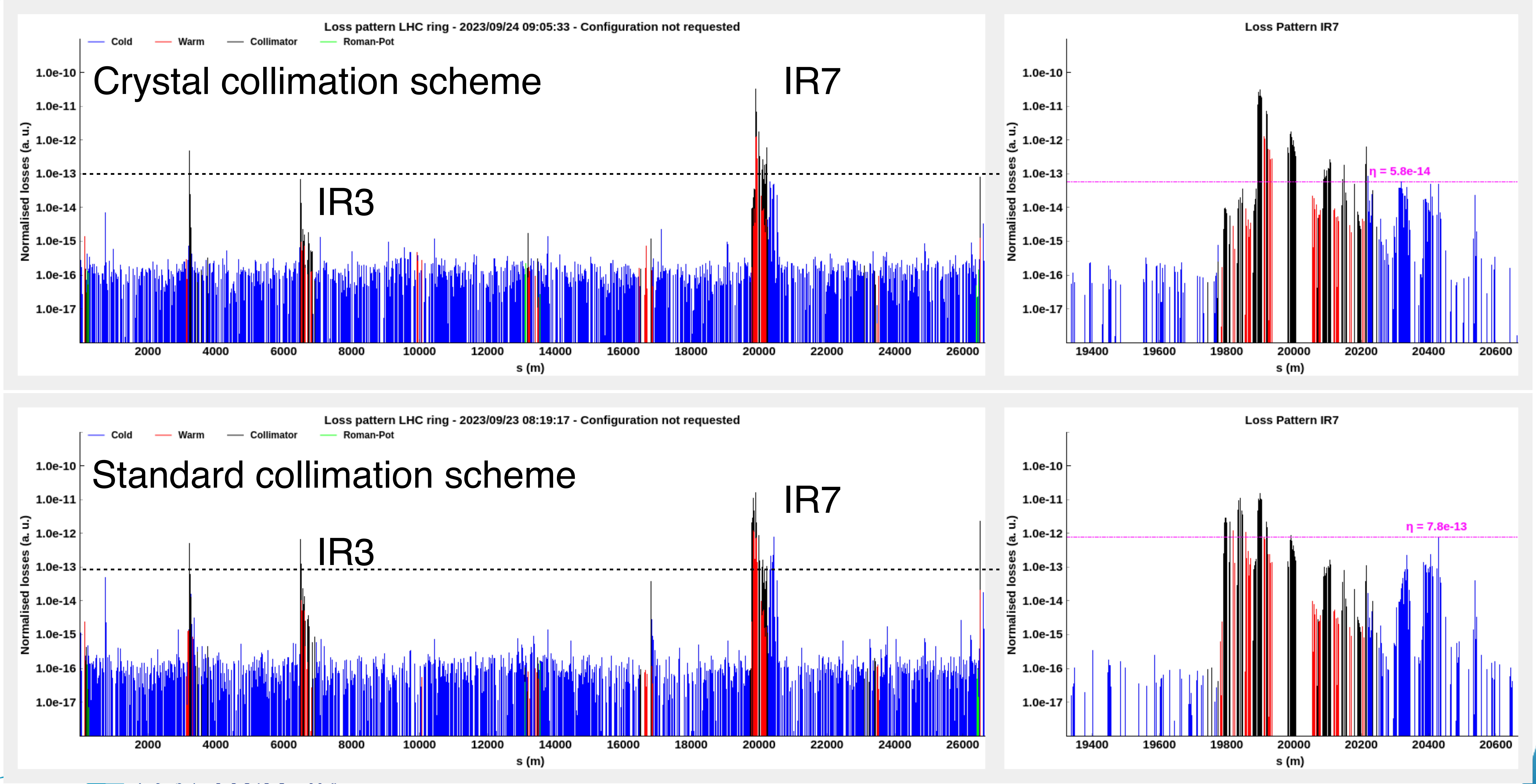


Collimator family	IR	Half-gap [σ]
TCPCH/V	7	4.75/5.0
TCP	7	6.0
TCS	7	6.5
TCLA	7	8.0
TCT	1/5/8	10.5
TCT	2	13.0 (B1)/10.5 (B2)

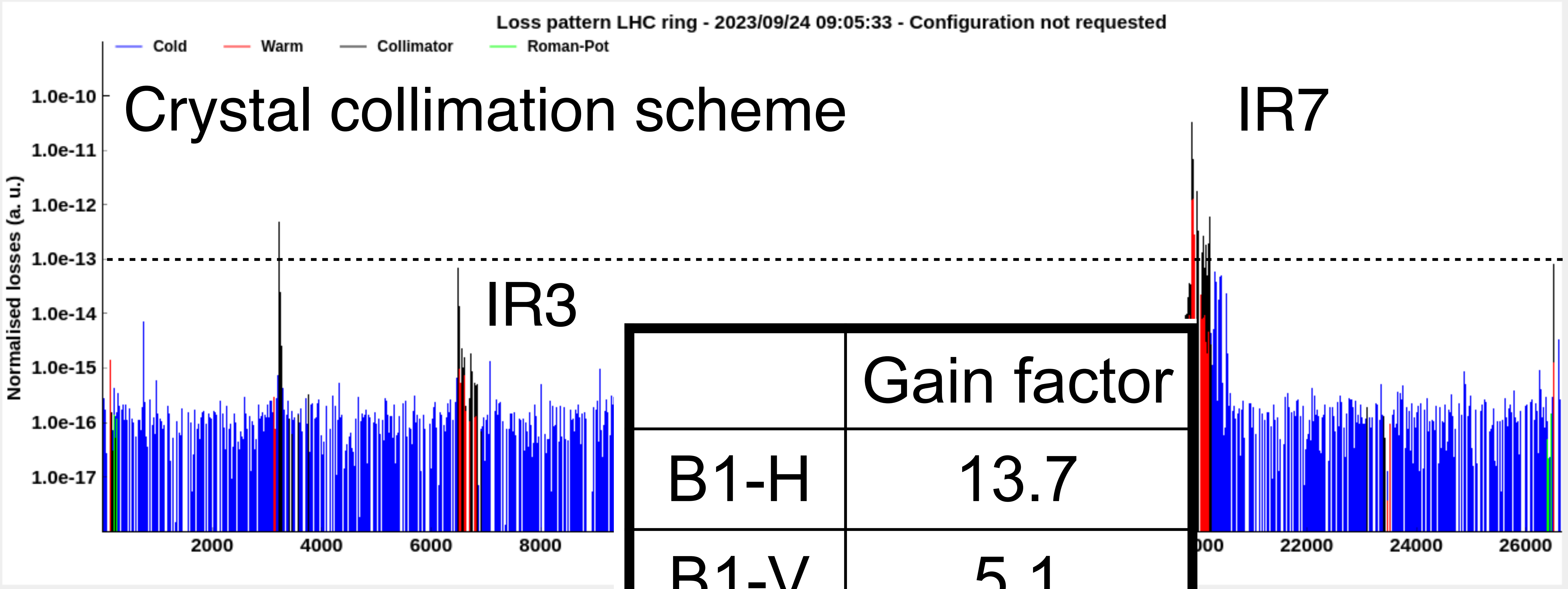
TCPC = crystal primary collimator
TCP = primary collimator
TCS = secondary collimator
TCLA = shower absorber
TCT = tertiary collimators (in experiments)

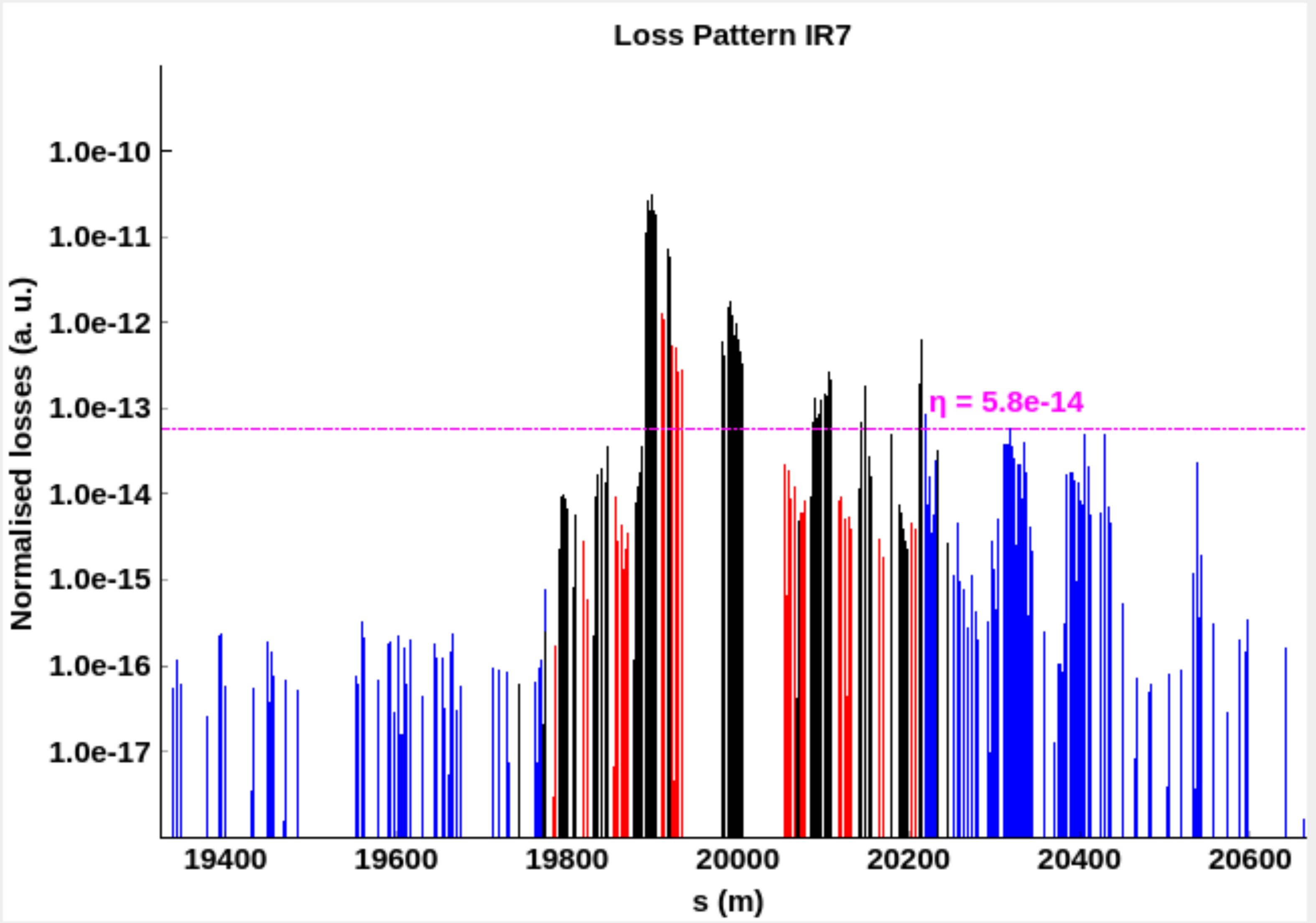
Conceived to improve cleaning while leaving in place standard collimation.
This approach ensures the phase space coverage for protection in case of failures.

Measured crystal collimation cleaning

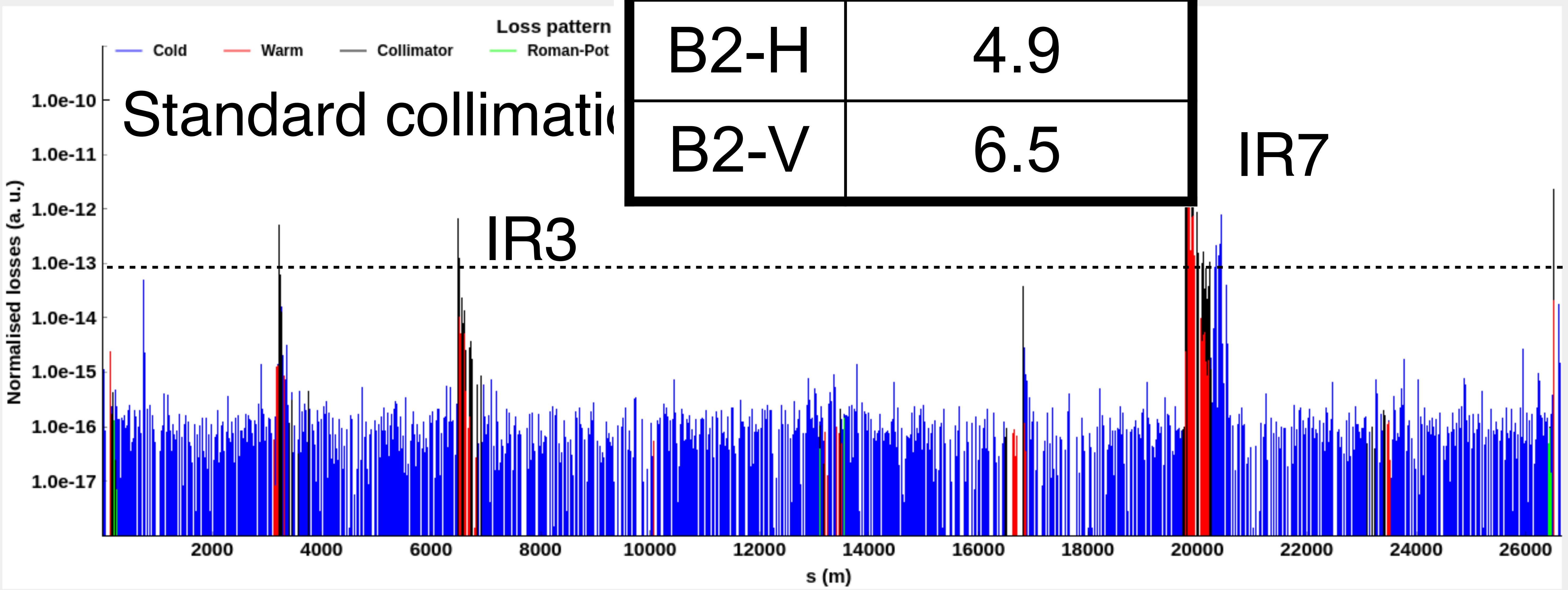


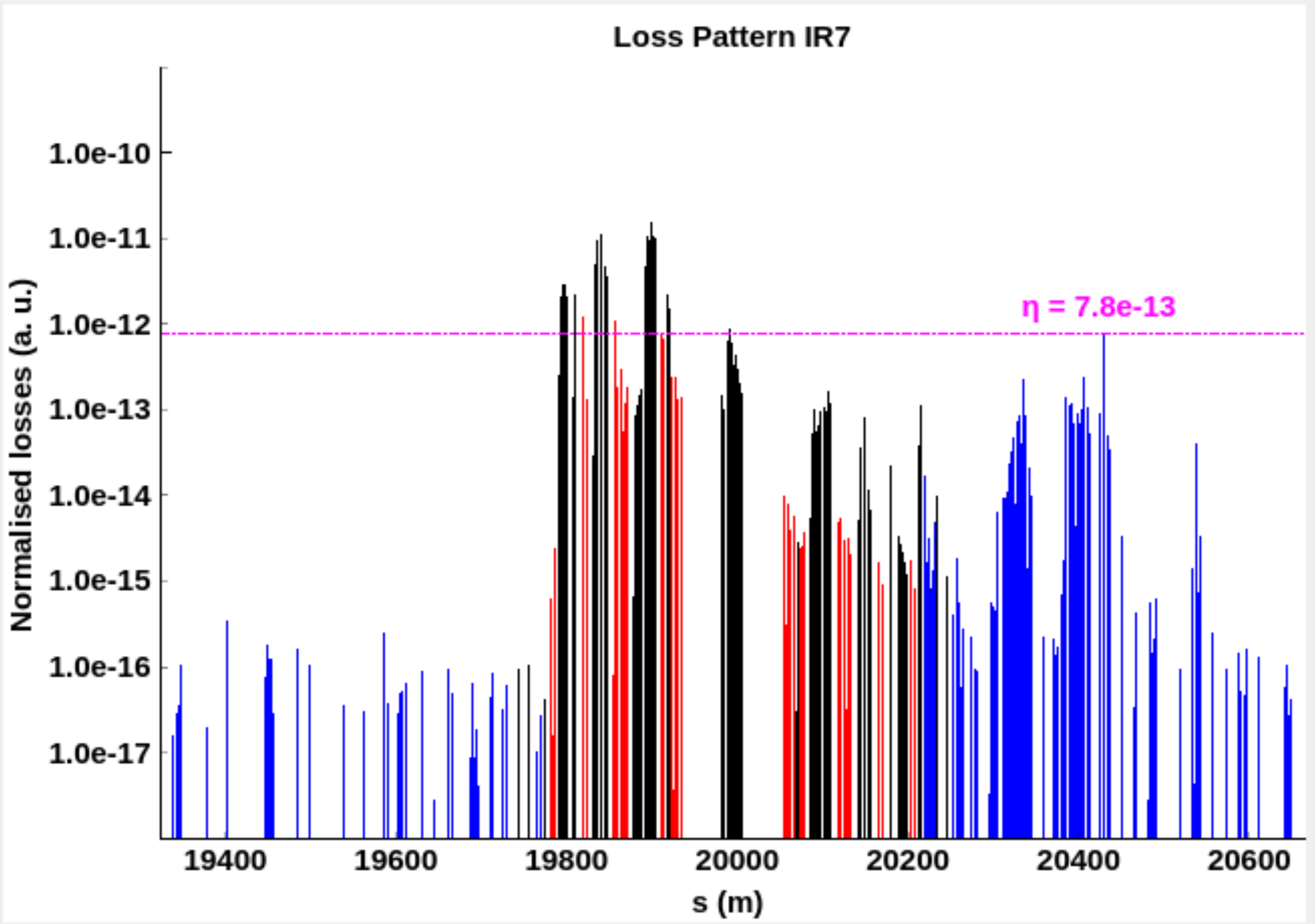
Measured crystal collimation cleaning



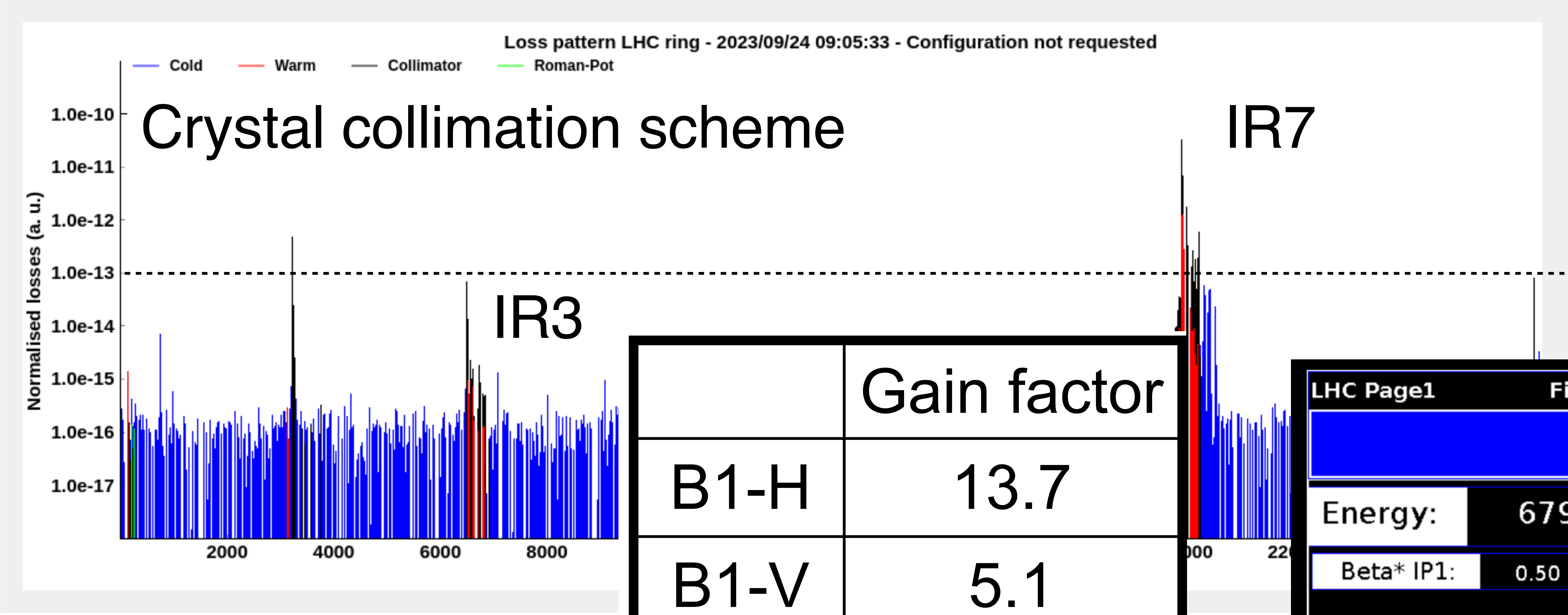


	Gain factor
B1-H	13.7
B1-V	5.1
B2-H	4.9
B2-V	6.5

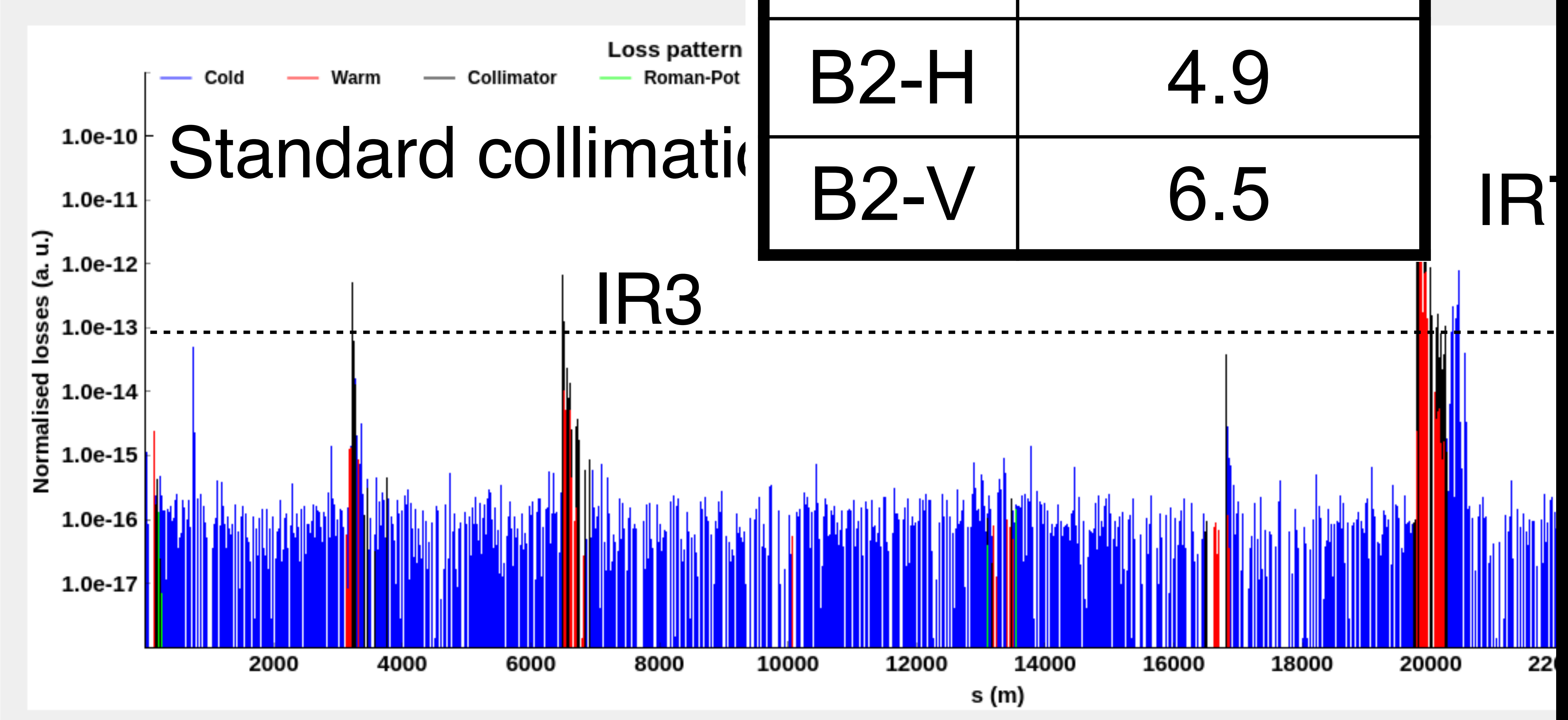


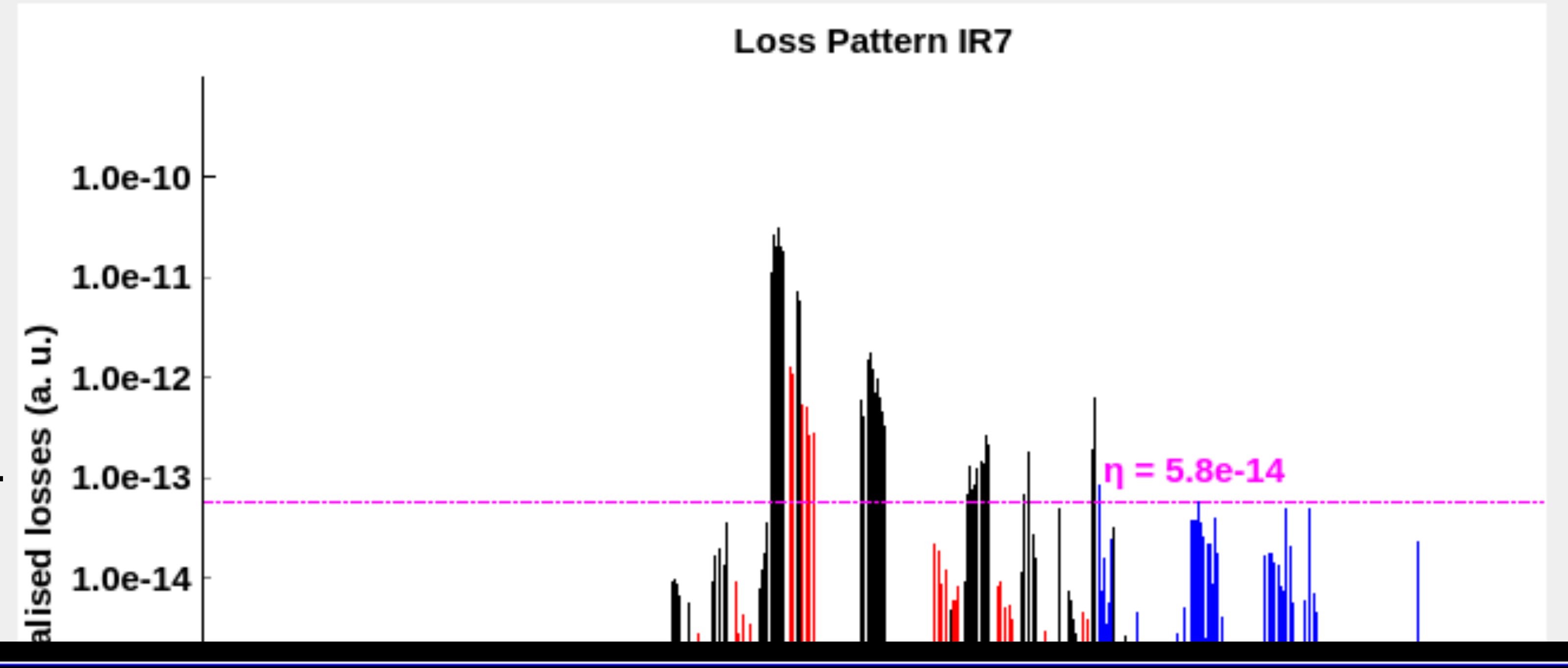


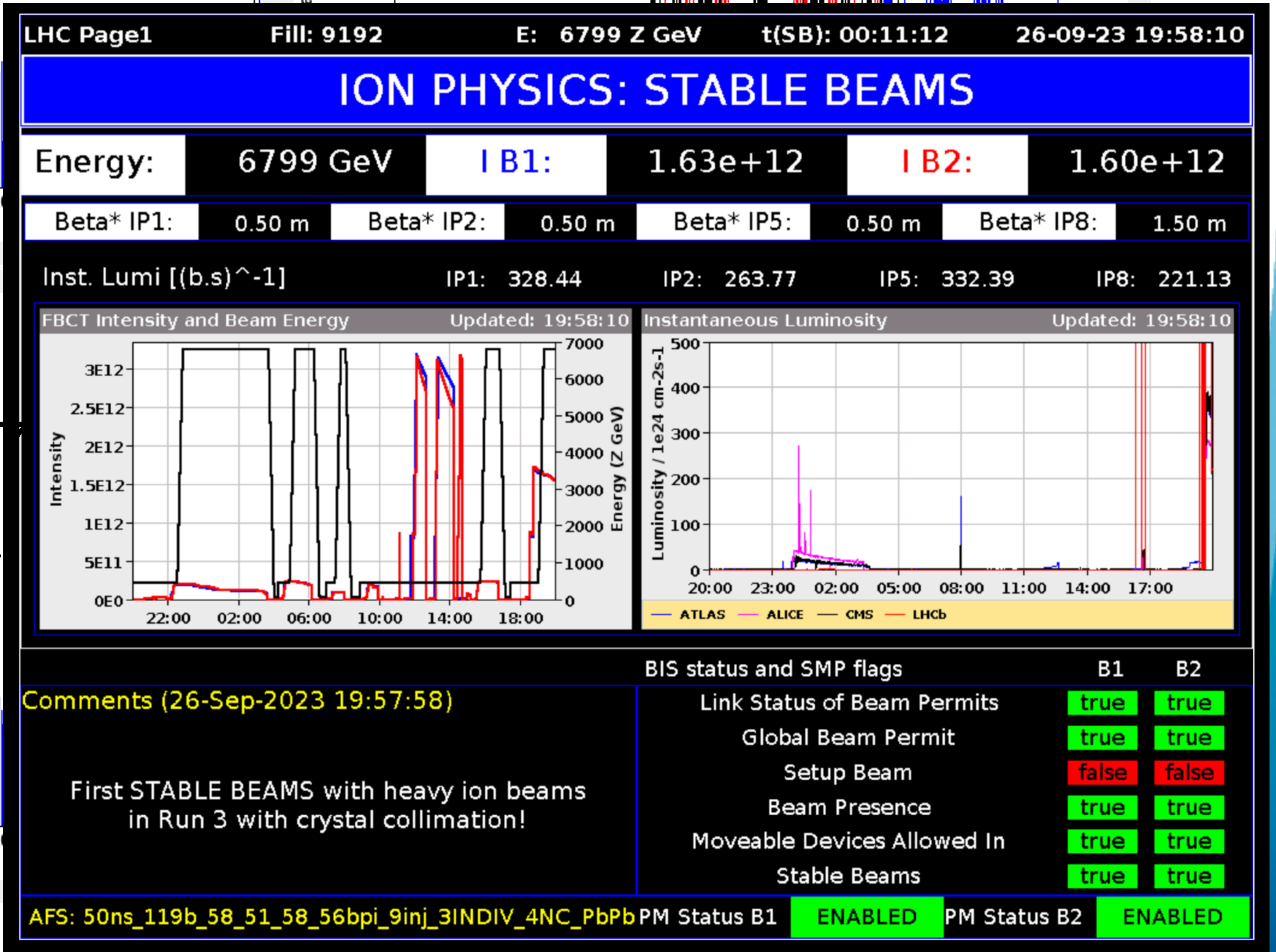
Measured crystal collimation cleaning



	Gain factor
B1-H	13.7
B1-V	5.1
B2-H	4.9
B2-V	6.5

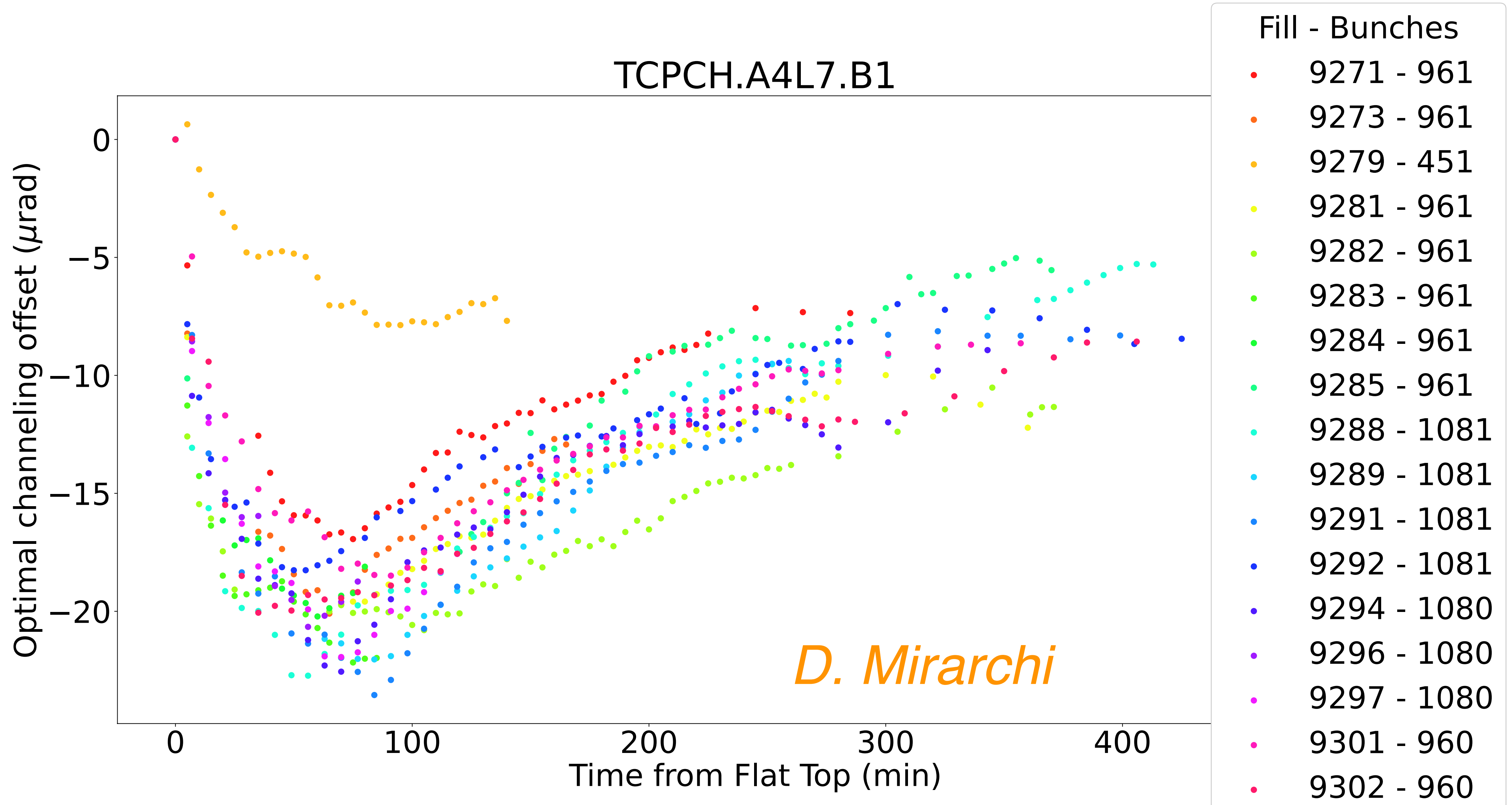






Overall feedback and issues encountered in 2023

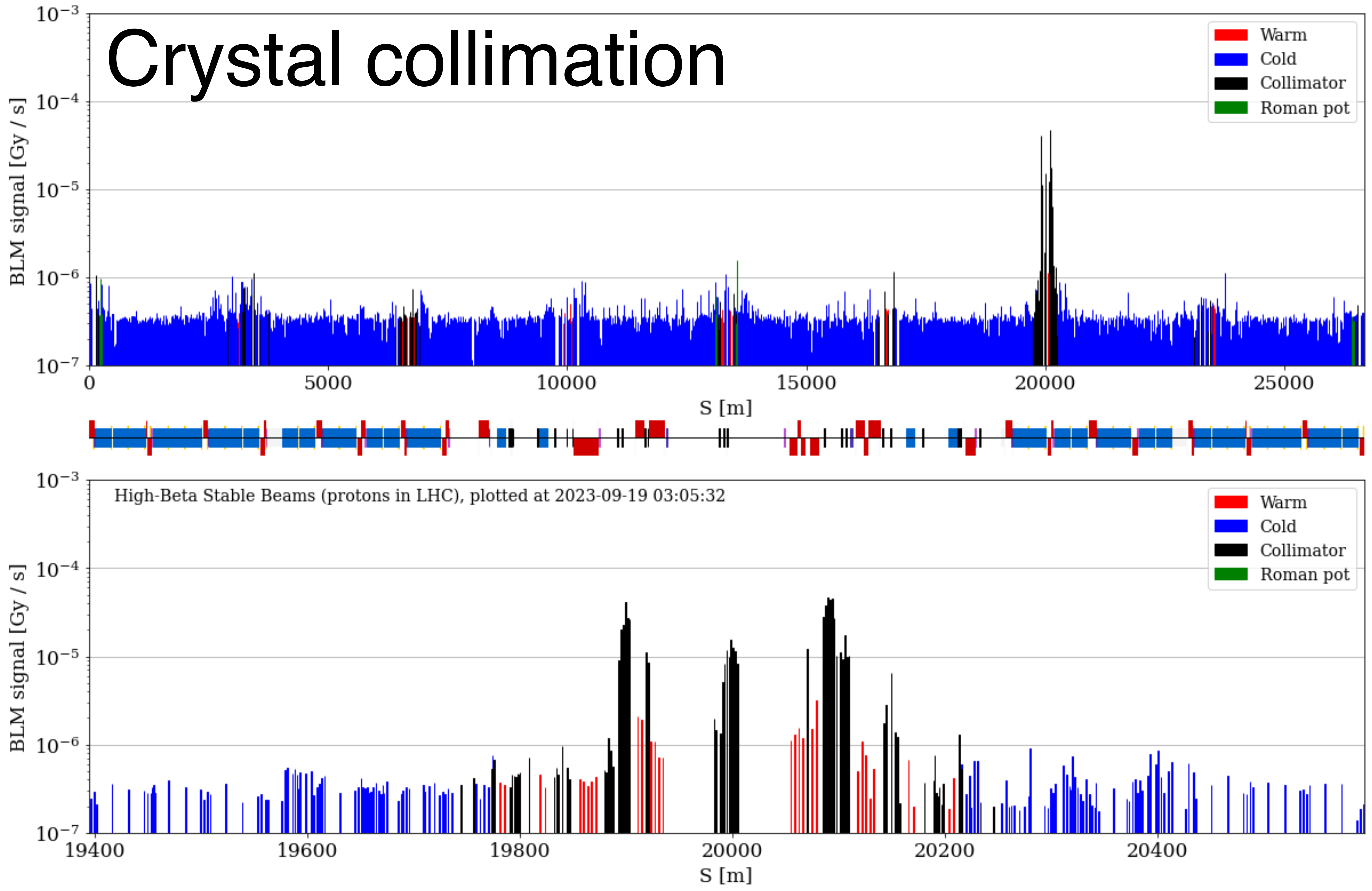
- Excellent cleaning performance, with gain of x5 or more in all planes
  - Crystal collimation used for the first time for the whole lead ion run
- Issue: peak performance could not be reproduced reliably because of **drifts in time of the optimum crystal orientation**. Source not yet understood.
  - Successfully mitigated by an automated re-alignment optimisation tool.
  - Feed-forward corrections also applied, but not reliable as variations fill-to-till too high
- Concern for future operations, in particular for the ramp. Studying real-time trims to feedback online to the angular controller. Very challenging as it needs a reliable detection of out-of-channeling orientation (simultaneously for all crystals).

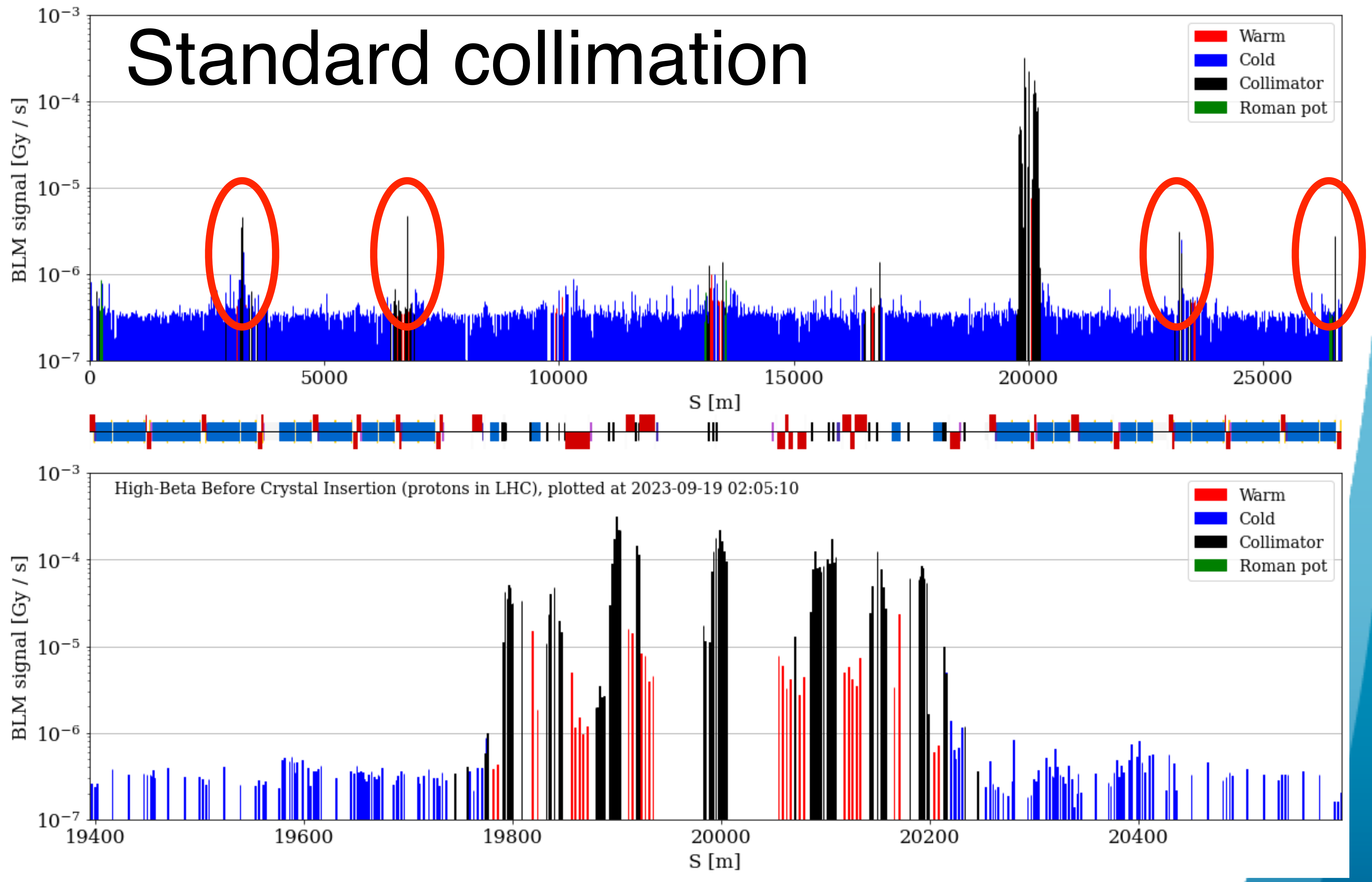


Potential source: Uncontrolled heating by impedance of a TCPC component leading to a change in crystal orientation.

Crystal collimation for background control (protons)

- Crystal collimation used to suppress backgrounds in the Roman pots in ATLAS-ALFA and TOTEM during a special run with high-β* run at 6.8 TeV in 2023
  - Optics with 3km/6km, Roman pots operating down to **3 beam sigmas**.
- Low burn-off → long fills up to 9h-10h. Crystal used reliably over ~2 weeks





See also: MOPC16

See also Phys. Rew. Applied 14, 064066 (2020)

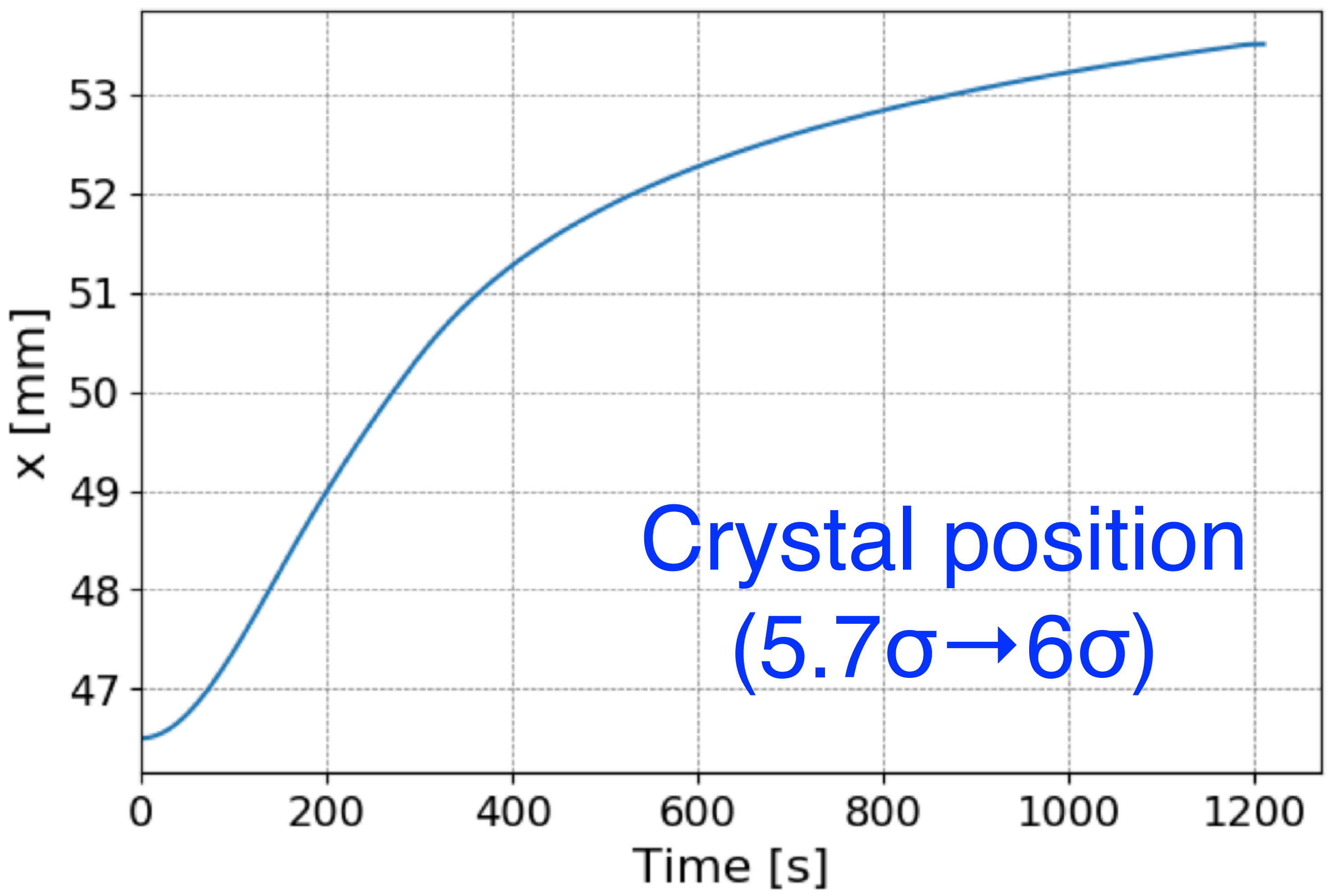
Conclusions

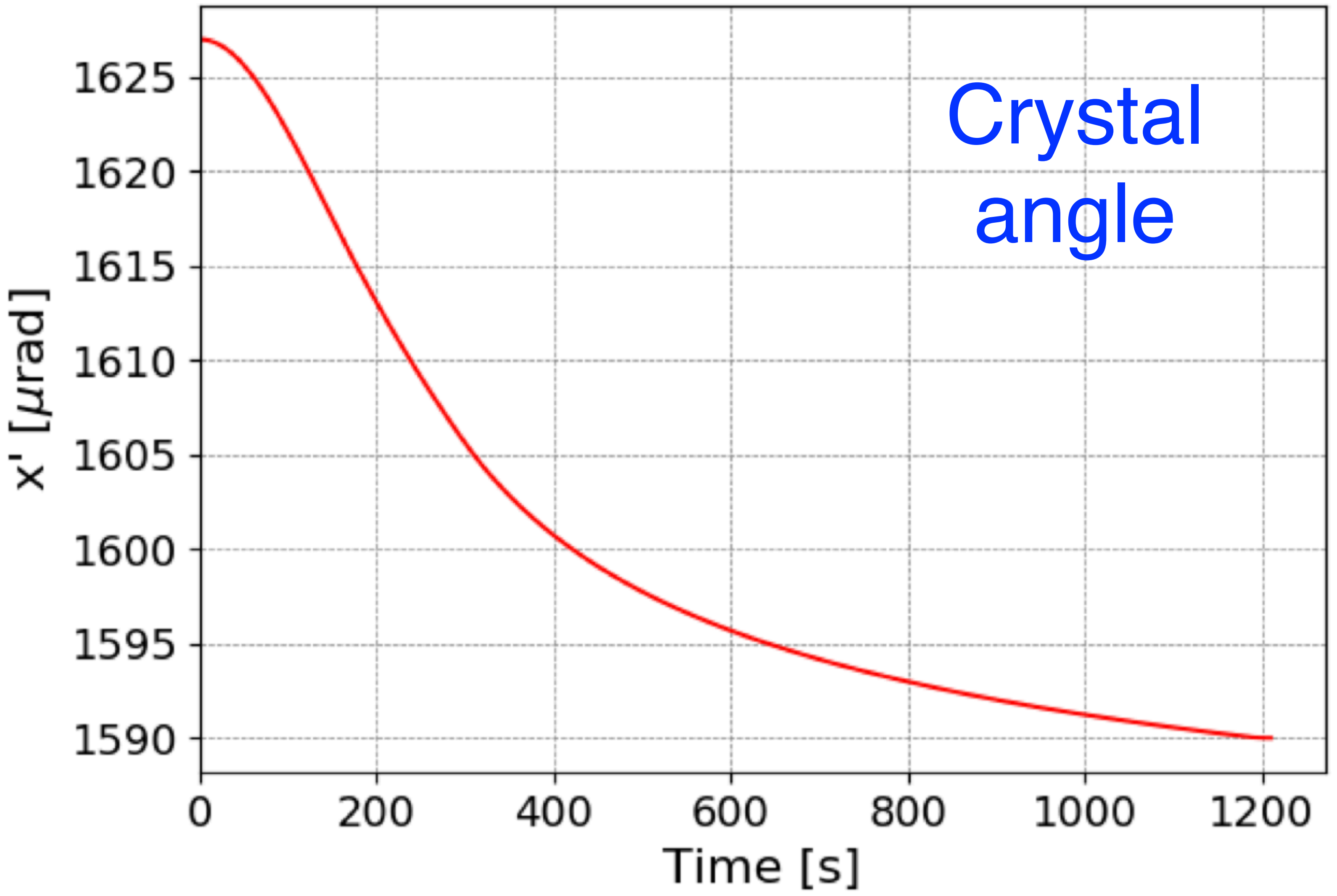
- Crystal collimation was deployed at the LHC for betatron cleaning of ion beams
  - Result of long lasting effort, possible thanks to engagement of many people and teams
- An exciting R&D in the LHC Run 2 (2015-2018) using a test stand in the collimation region, demonstrated the readiness of this scheme for the LHC
  - New hardware and control solutions can face the small acceptance in the multi-TeV range
  - Achieved rapidly the first channeling observations, longer journey to demonstrated collimation cleaning gains for ions beams (2018)
- Strong support from simulations — developed a solid simulation framework
  - We address satisfactorily the challenges of big accelerators with multi-stage collimation
  - Recent results indicate a very good accuracy between simulations and measurements
- Crystal-based scheme was deployed for the full 2023 lead ion run
  - Excellent cleaning performance with measured improvements of a factor 5 or more for each plane
  - Problem of stability of the crystal orientation
- Looking forward for a successful crystal collimation for the rest of Run 3
  - Controls and diagnostic improvements, assisted by ML, under study already for the 2024 run.

Reserve slides

Continuous channeling during the energy ramp

Energy ramp: 450GeV → 6.8 TeV



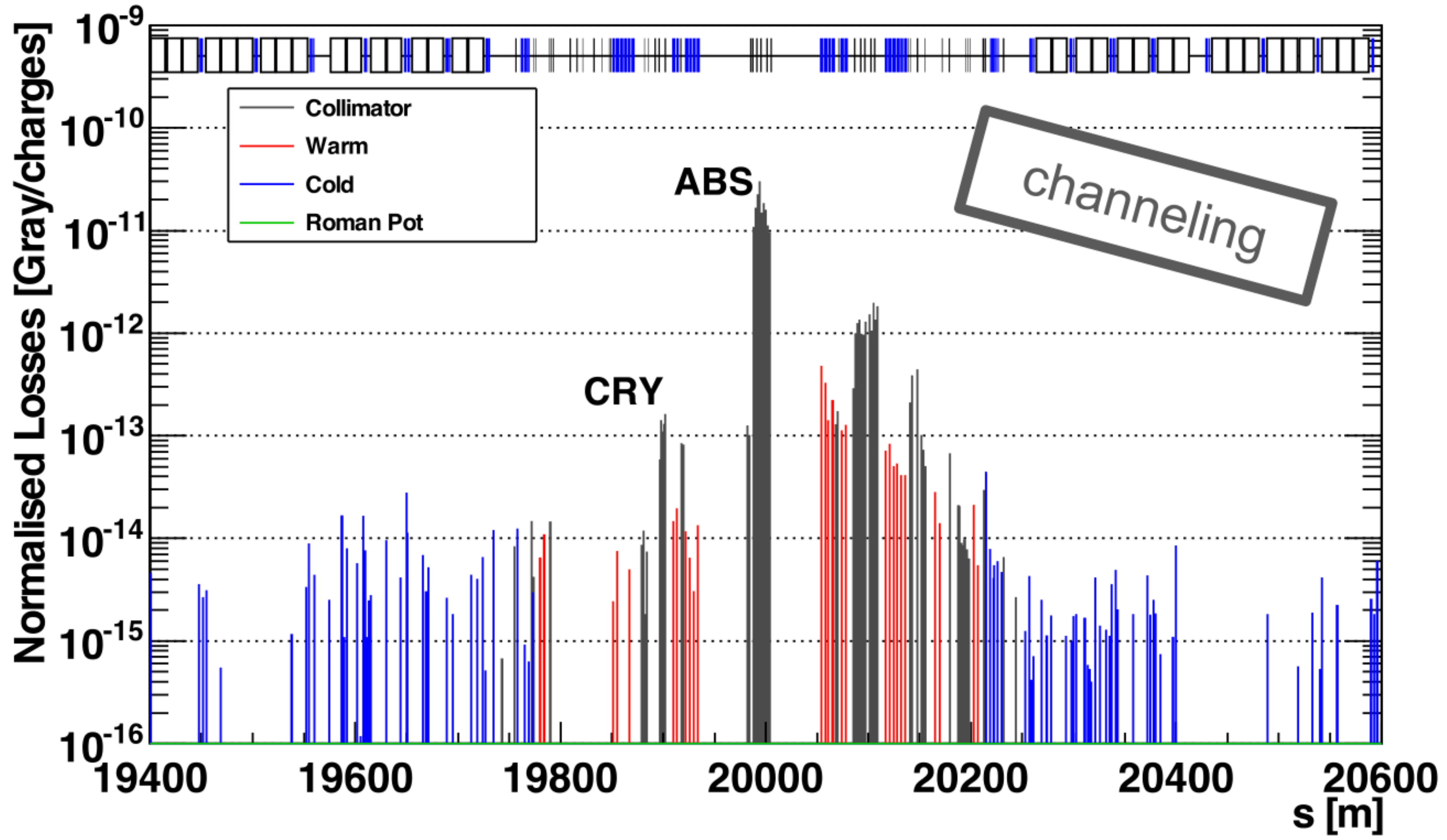


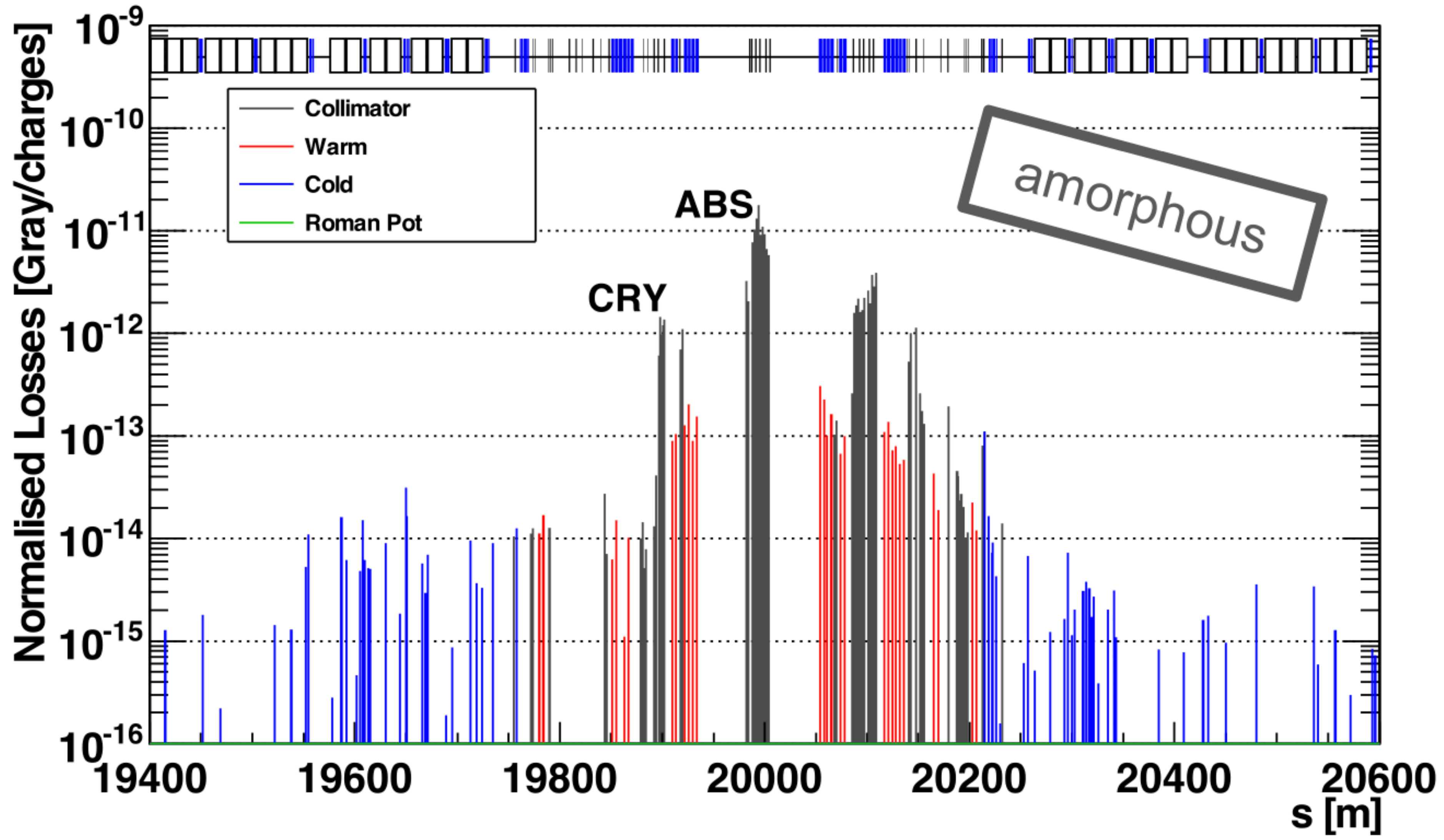
$$x(t) = x_c - \left[n_{inj} + \frac{n_{ft} - n_{inj}}{\gamma_{ft} - \gamma_{inj}}(\gamma(t) - \gamma_{inj})\right]\left[\tilde{\sigma}_{inj} + \frac{\tilde{\sigma}_{ft} - \tilde{\sigma}_{inj}}{\gamma_{ft} - \gamma_{inj}}(\gamma(t) - \gamma_{inj})\right]\frac{1}{\sqrt{\gamma(t)}}$$

Ramp functions equivalent to that of conventional primary collimators. Interpolation with time (γ) between beam-based settings at injection and top energy.

Goniometer can follow reference function for angle while preserving the ***sub-μrad accuracy****!*

Continuous channeling during the energy ramp





Well under control (ratio < 10^{-2}) for the whole ramp!

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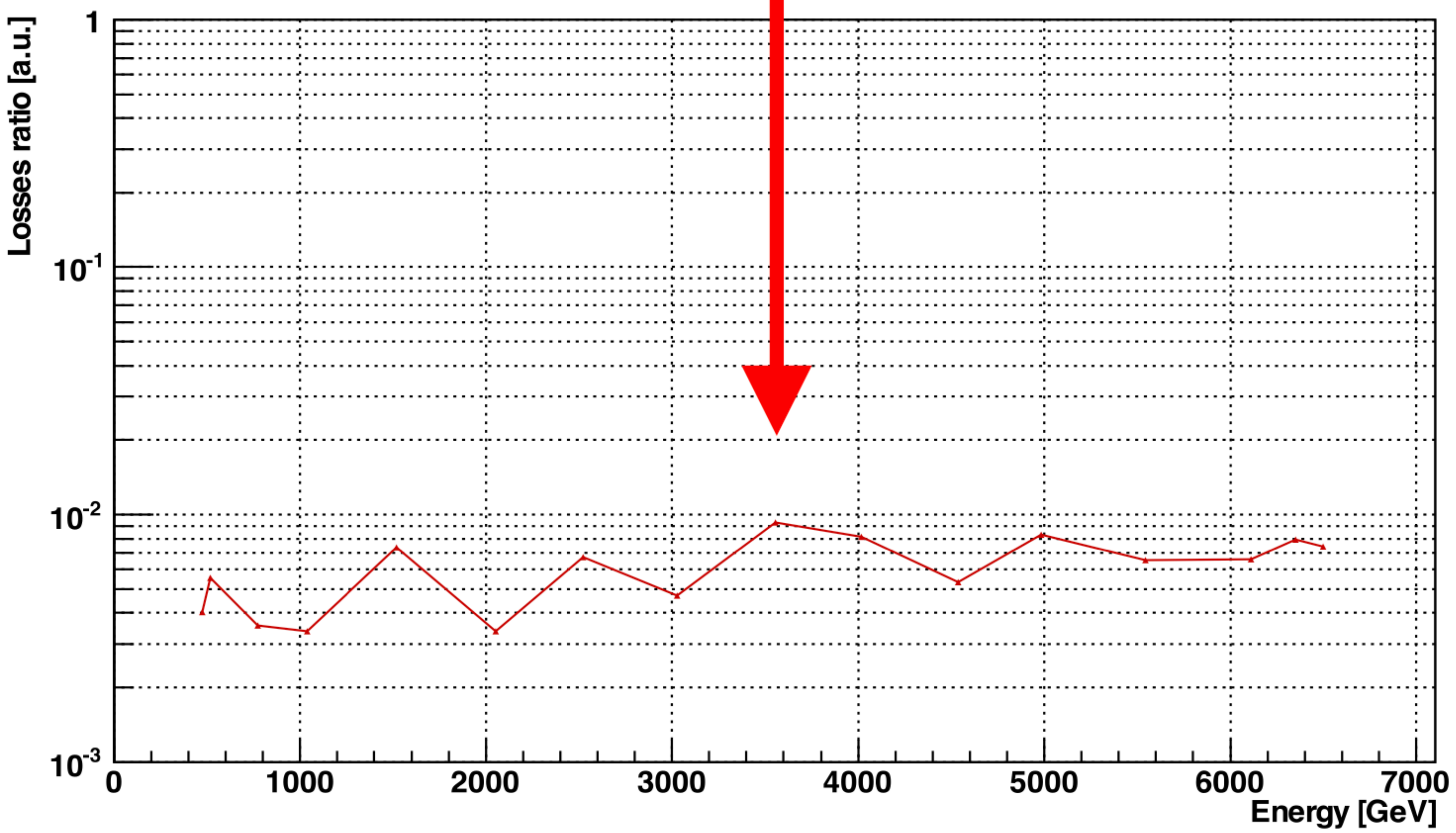
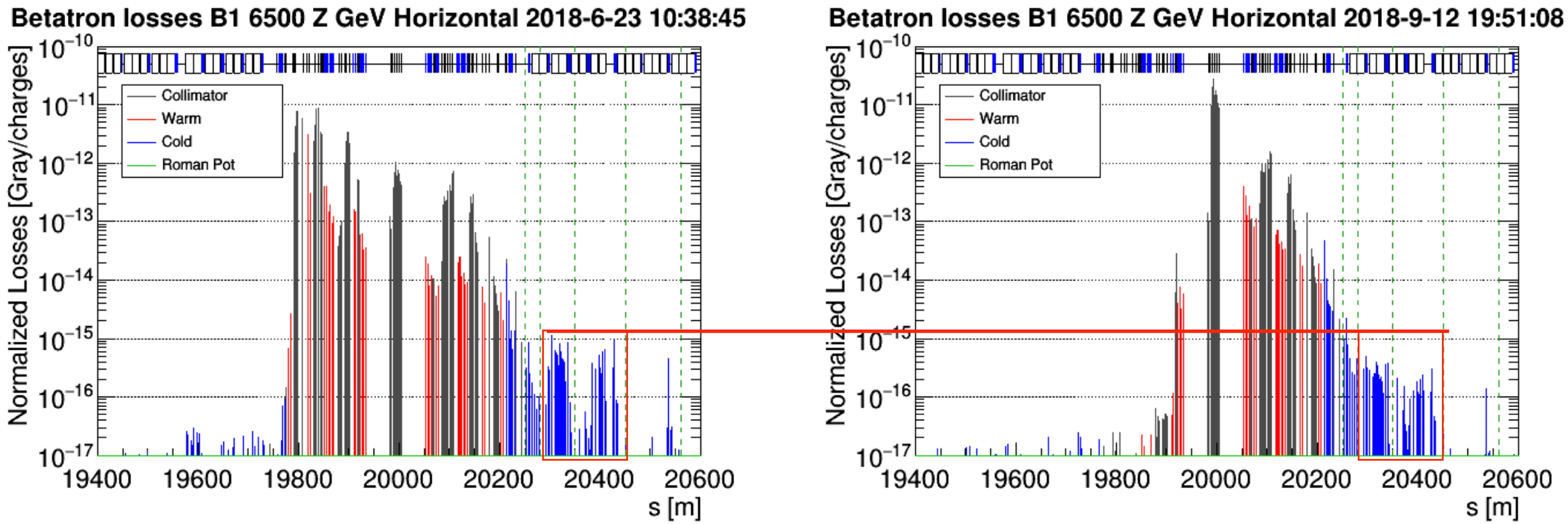
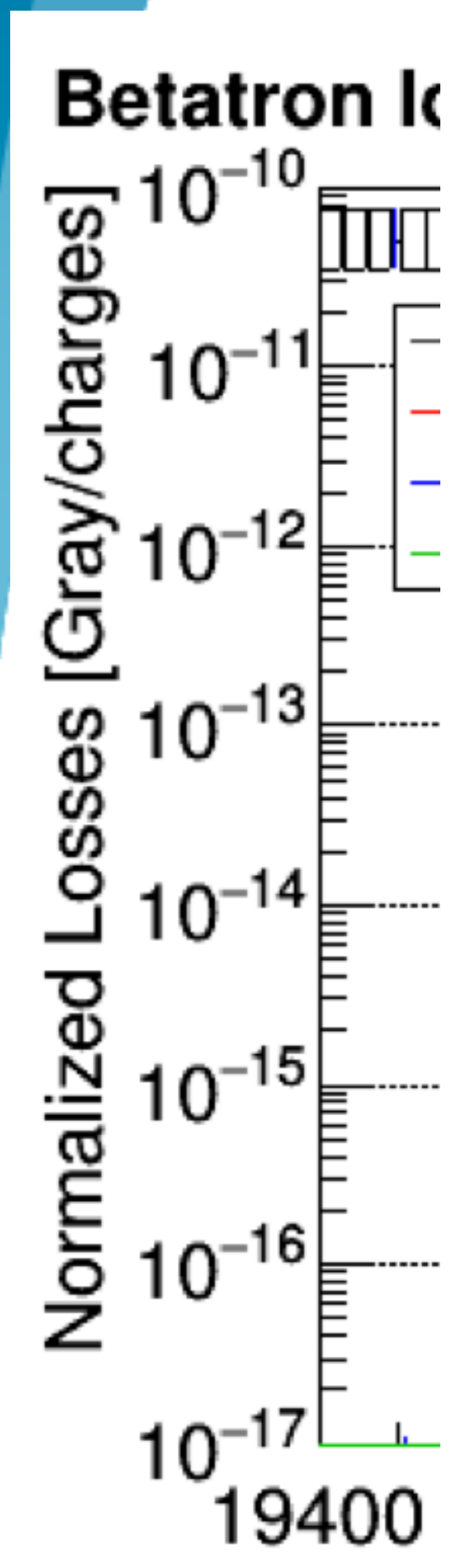


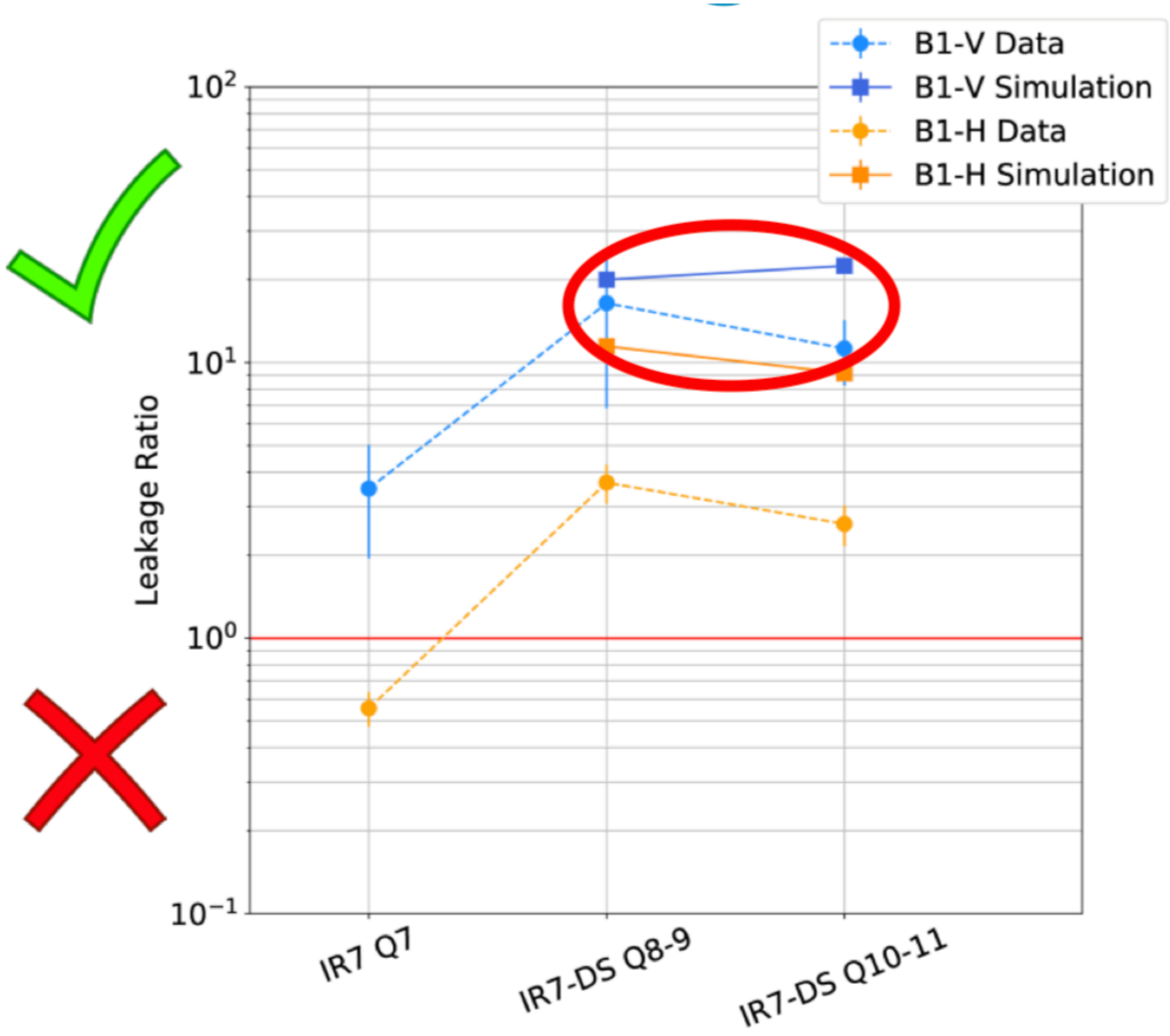
"Channeling factor indicator" calculated by looking at ratio of crystal and absorbers — demonstrated that we remain in channeling during the energy ramp.

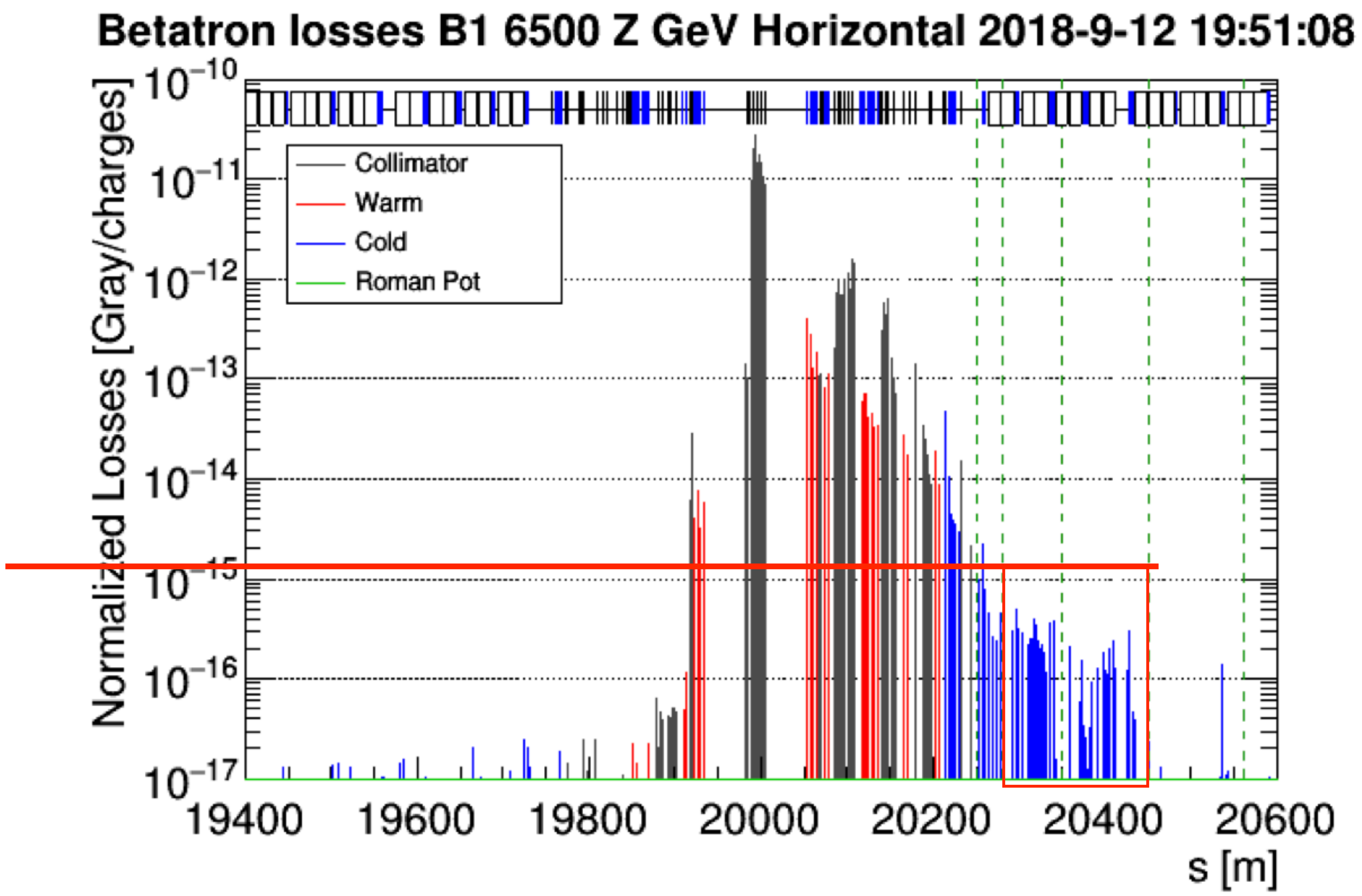
Collimation cleaning performance with protons



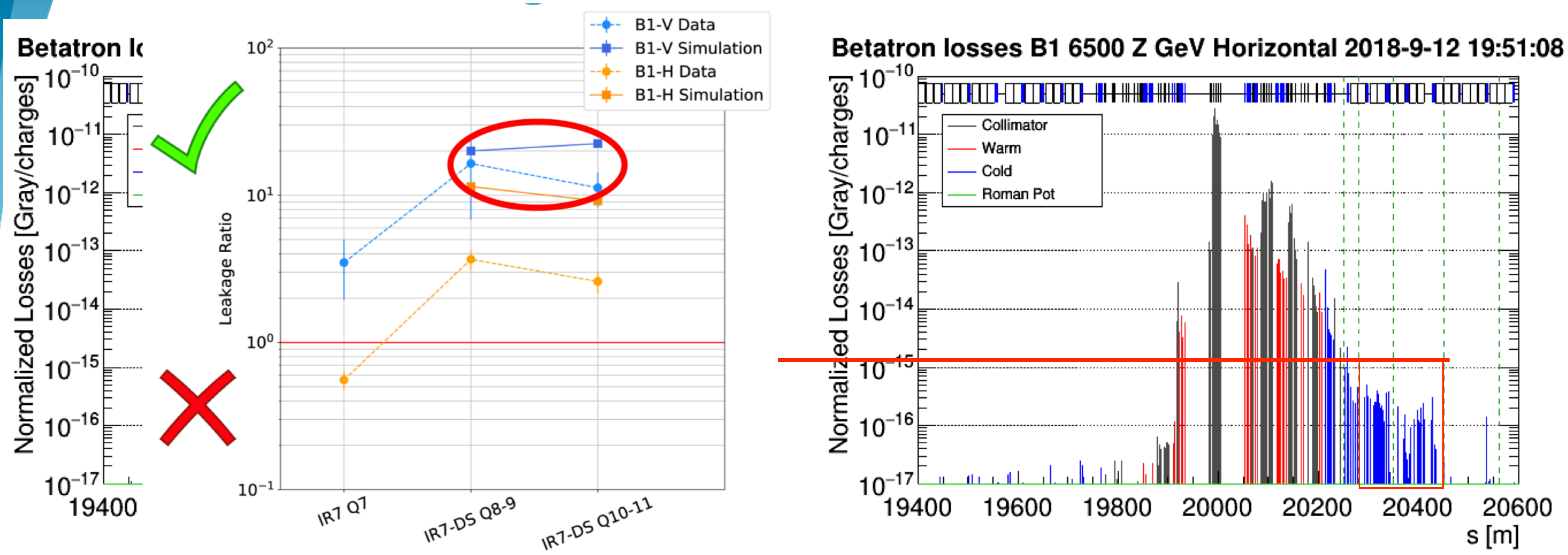
Collimation cleaning performance with protons







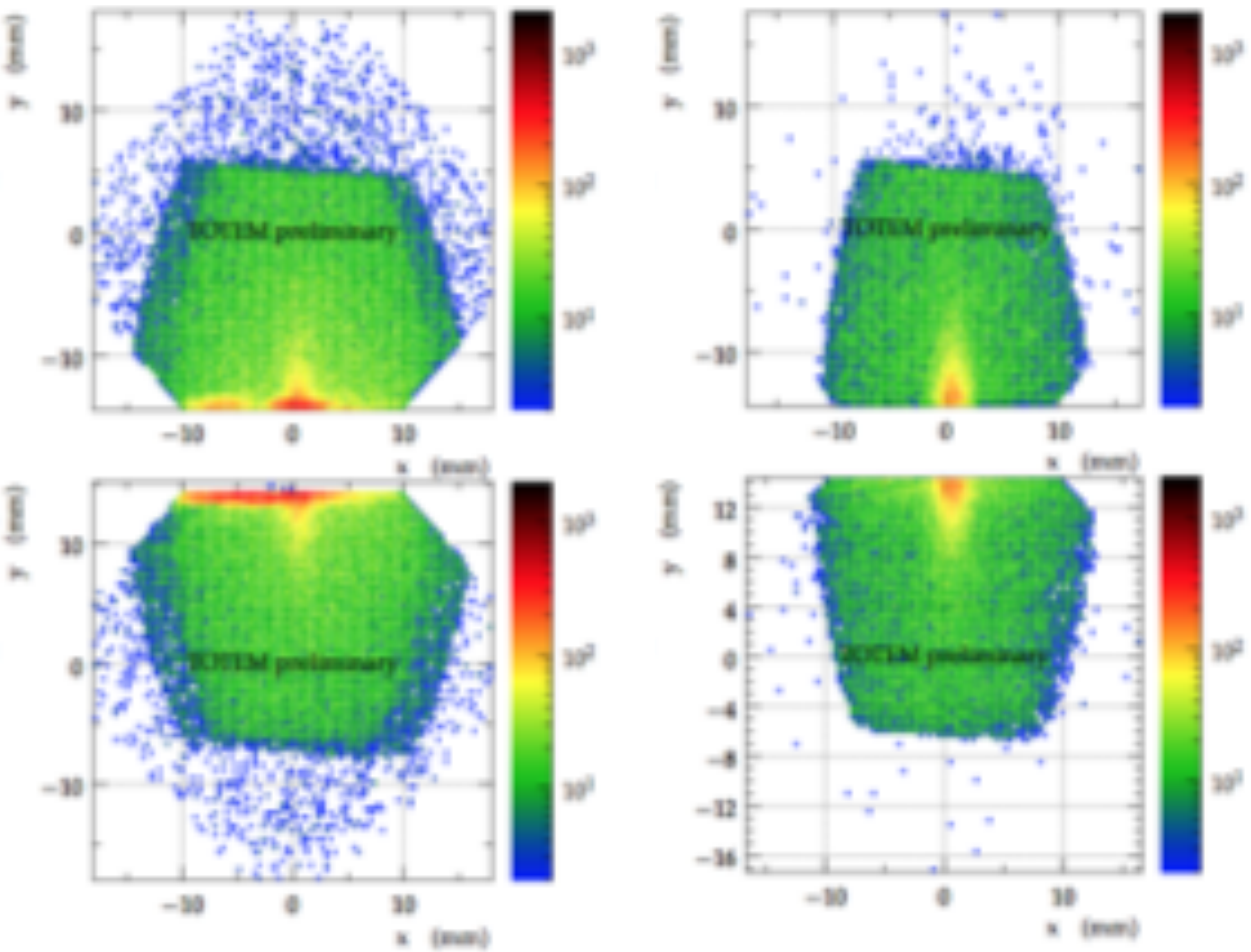
Collimation cleaning performance with protons



Crystal system not presently compatible with high intensities (impedance; absorber). Could be used successfully for special low-intensity runs for forward physics.

Simulations special high-β* run (450 GeV)

Standard **Crystal**



Courtesy of TOTEM (preliminary)

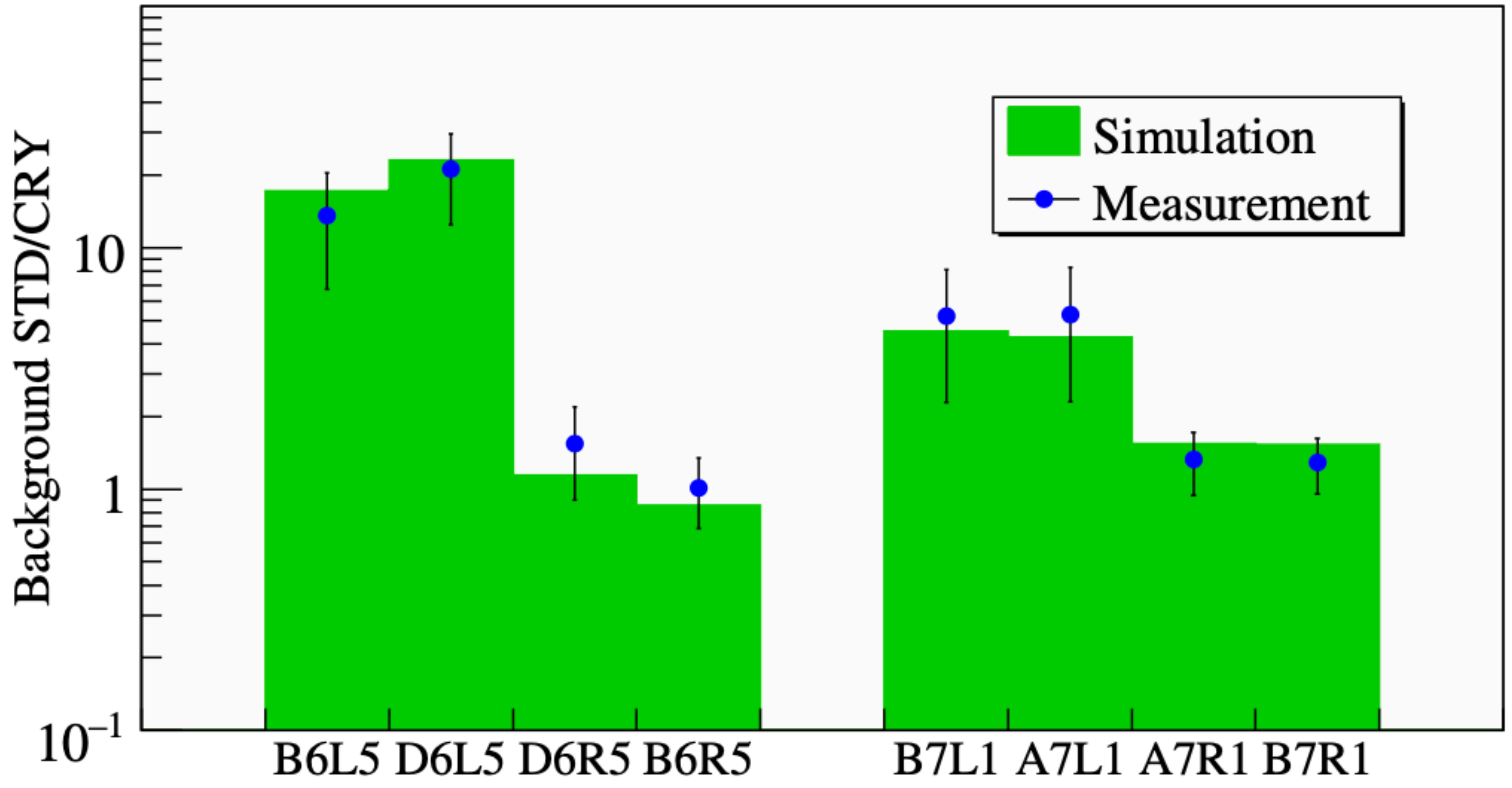
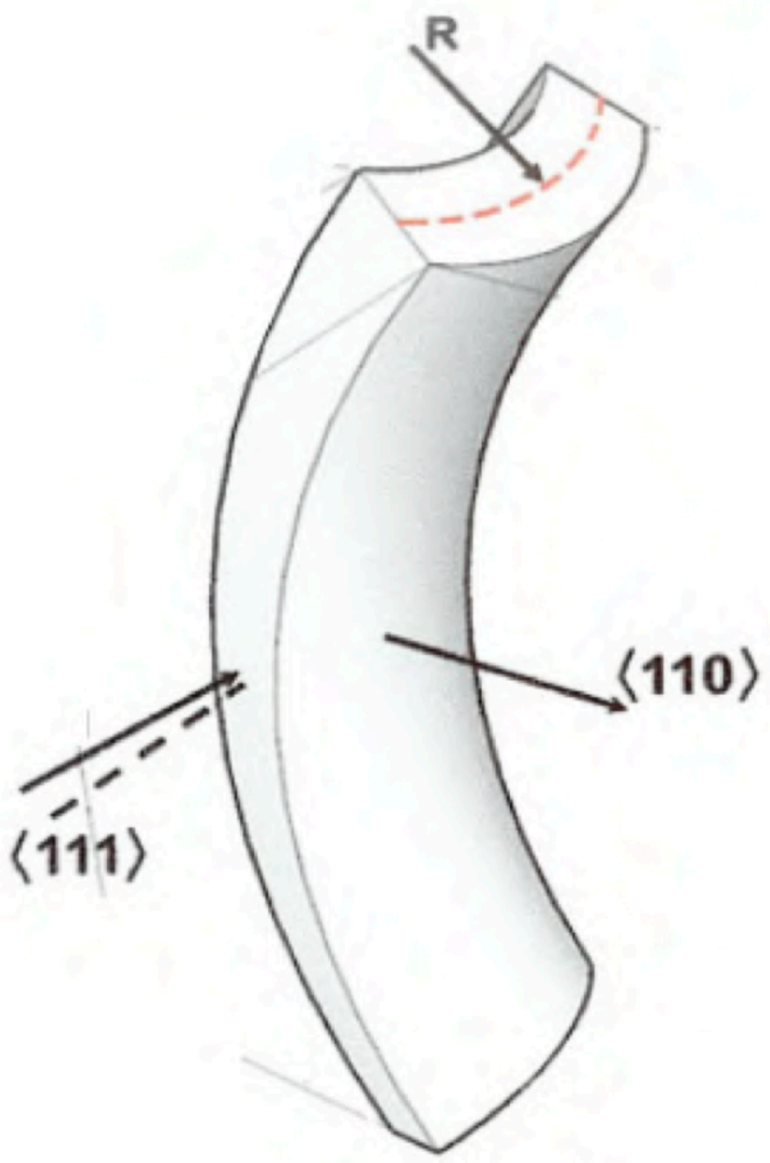
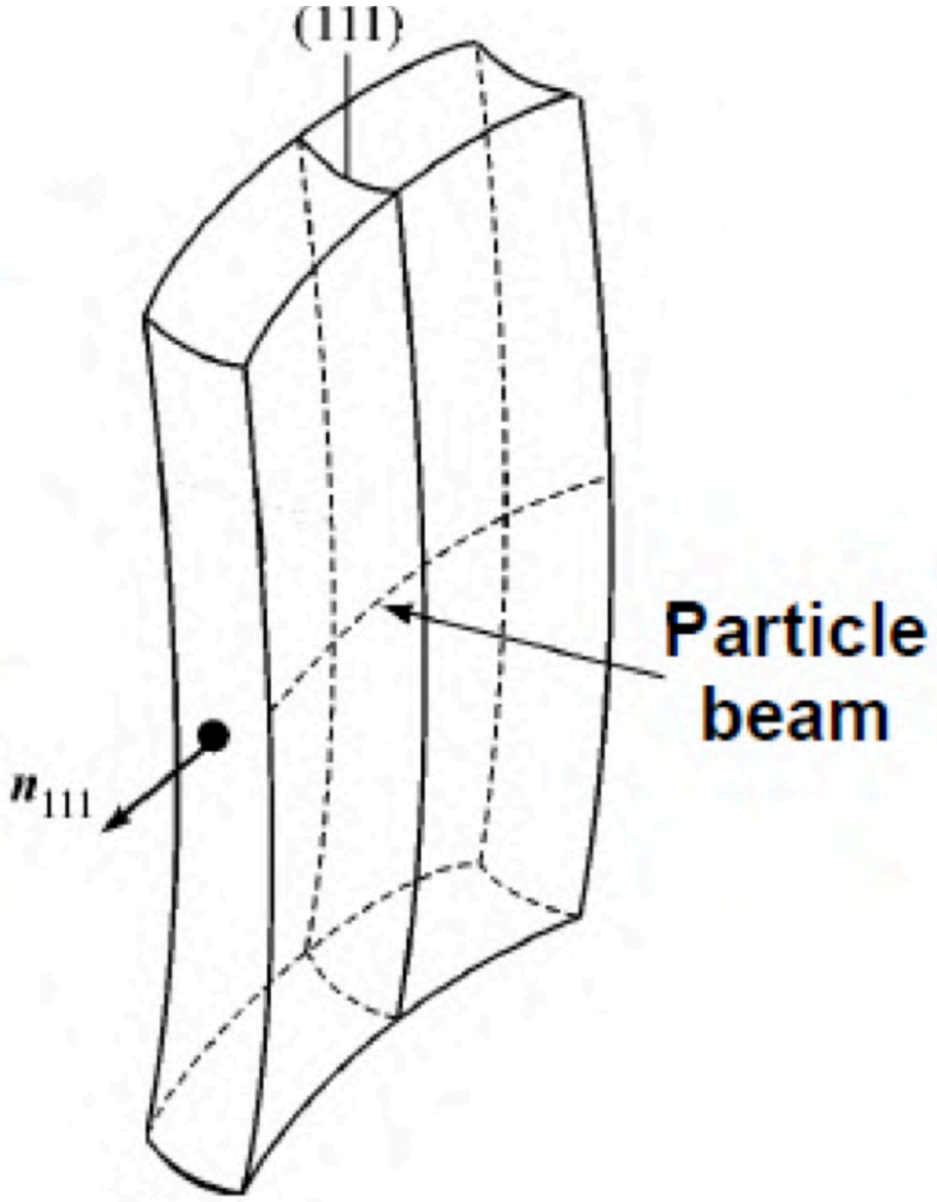
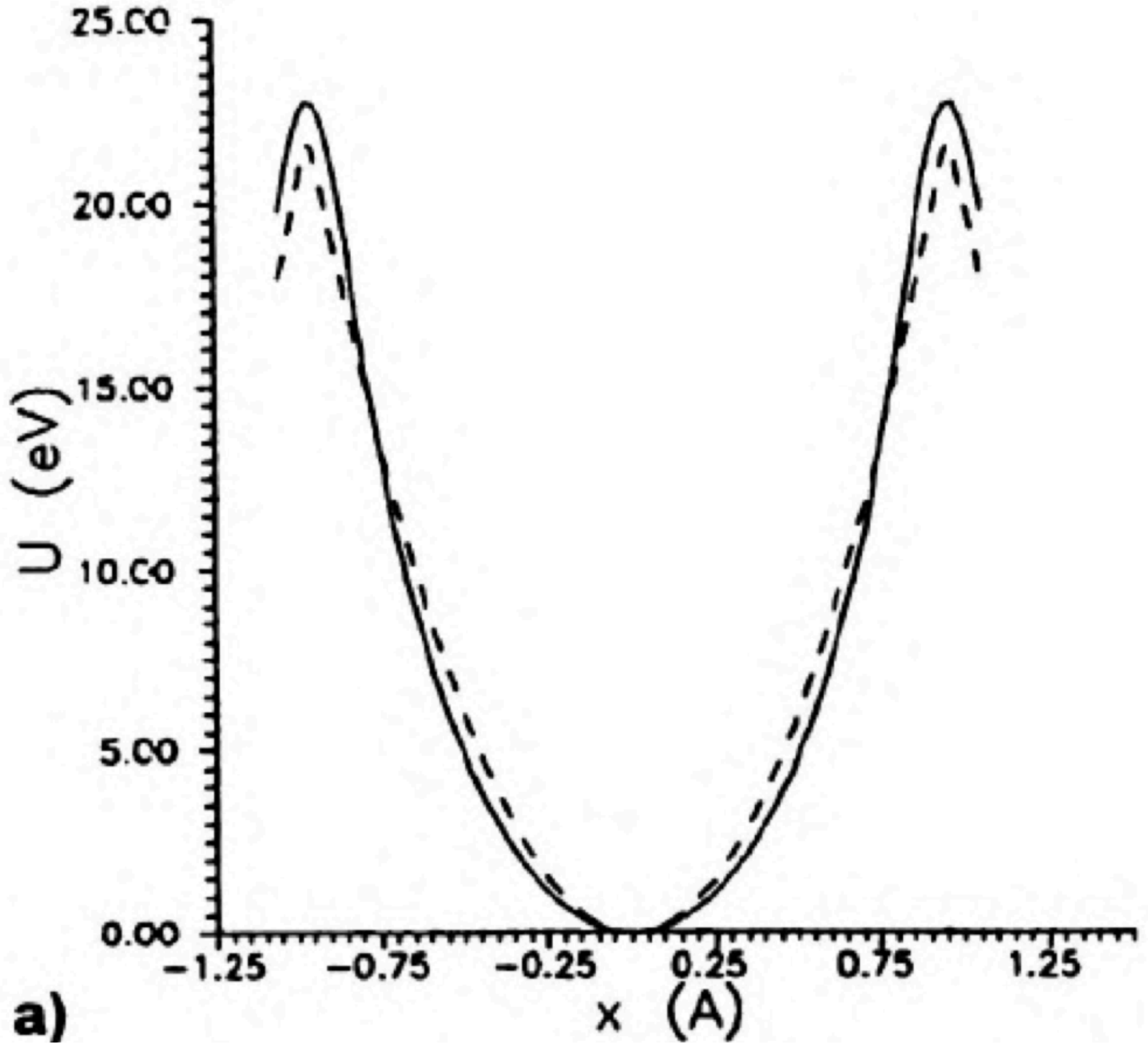


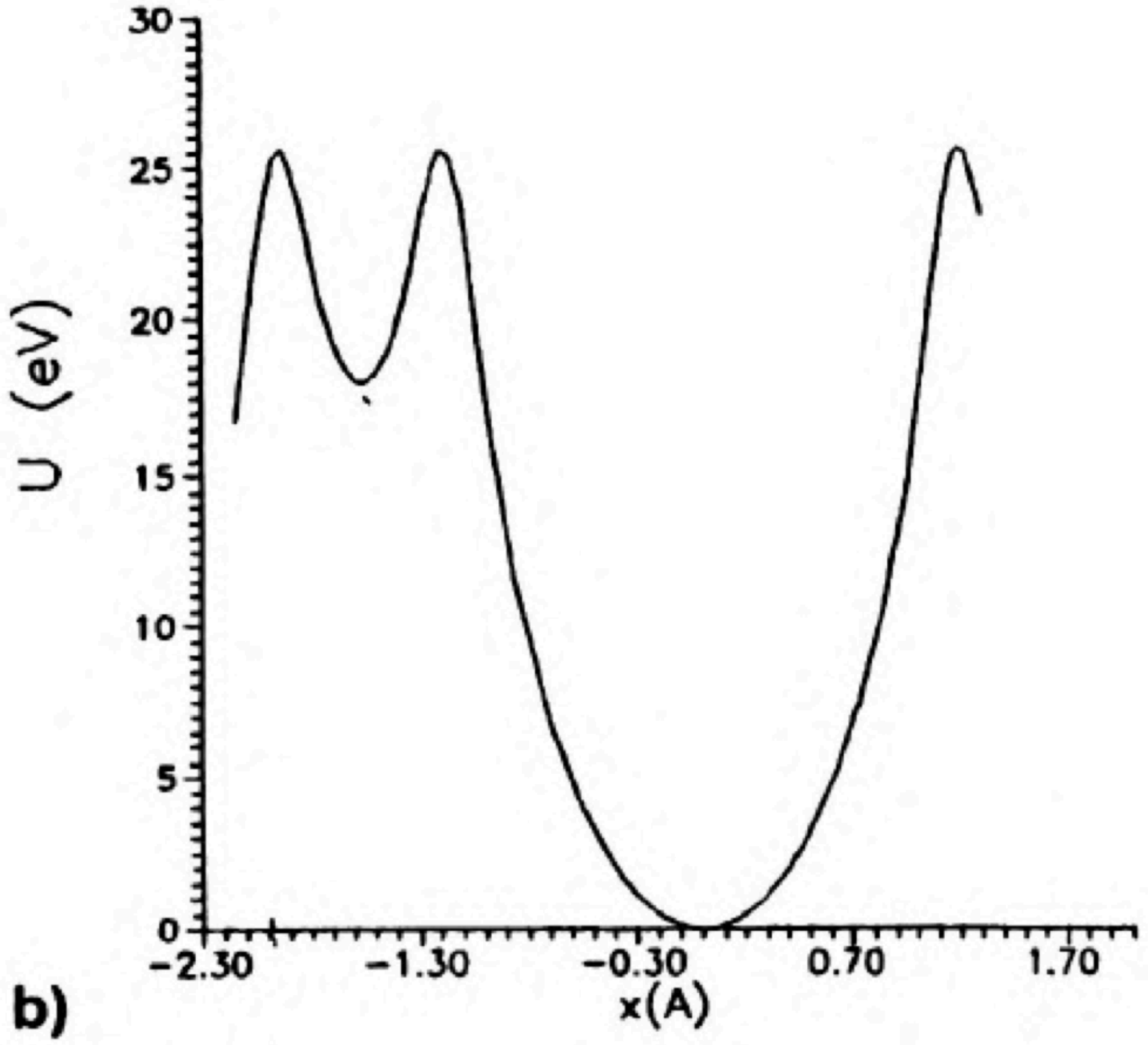
FIG. 10. Comparison between the measured and the simulated background ratio at the TOTEM and ALFA XRPs.

Strip and quasi-mosaic bent crystals



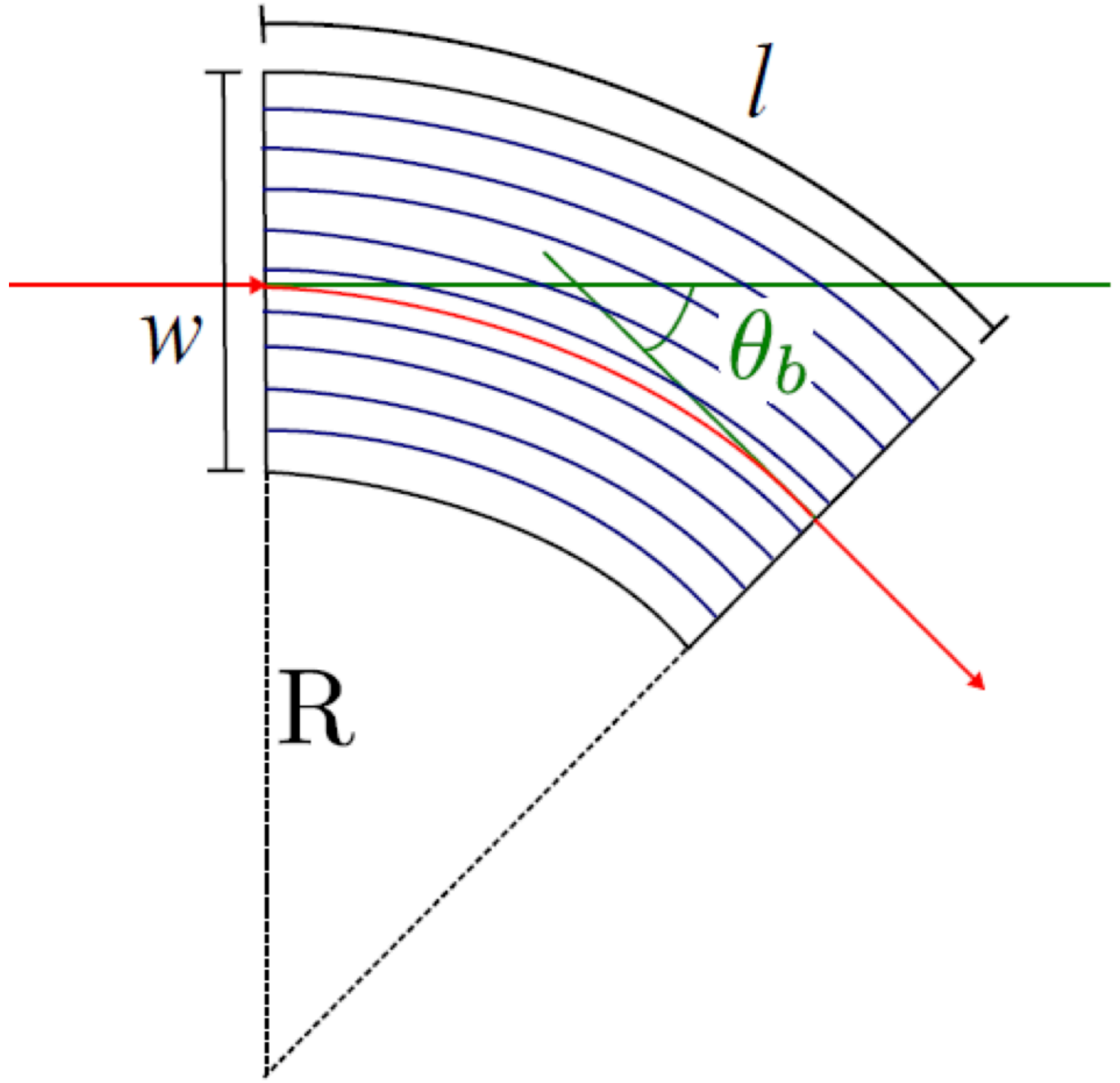




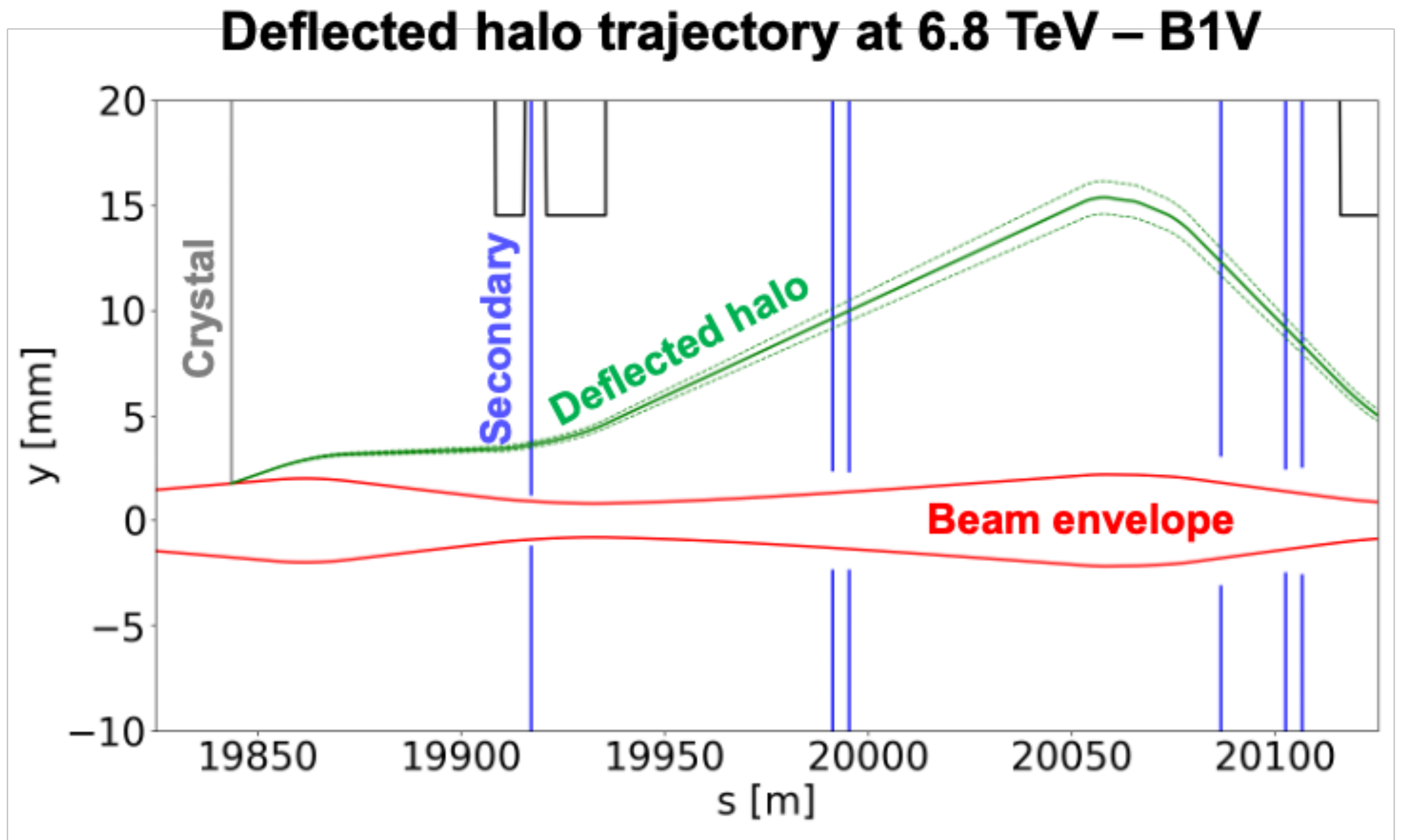


Critical angle and critical bending radius

Energy [GeV]	$\boldsymbol{\theta_c}$ **[μrad]**	$\boldsymbol{\lambda}$ **[μm]**	$\boldsymbol{R_c}$ **[m]**
120	18.3	33.0	0.3
180	18.0	40.5	0.4
270	12.2	49.6	0.6
400	10.0	60.3	1.0
450	9.4	64.0	1.1
6500	2.5	240.0	15.6
7000	2.4	250.0	16.8



Final LHC layouts



	Beam 1		Beam 2	
Name	TCPCH.A4L7	TCPCV.A6L7	TCPCH.A5R7	TCPCV.A6R7
Plane	Horizontal	Vertical	Horizontal	Vertical
s **[m]**	19918	19842	20090	20145
β_x **[m]**	342.1	30.5	201.6	30.5
β_y **[m]**	64.9	281.1	135.0	281.1
α_x **[rad]**	-2.05	0.24	-3.53	0.24
α_y **[rad]**	0.84	-2.63	2.36	-2.63
D_x **[m]**	0.03	0.15	-0.28	0.01
D_y **[m]**	0.10	0.12	0.22	0.32
Absorber	TCSG.B4L7	TCSG.D4L7	TCSG.B4R7	TCSG.D4R7