Research supported by the High Luminosity LHC project

Evaluation of power deposition in HL-LHC with crystal-assisted heavy ion collimation

11th October 2023

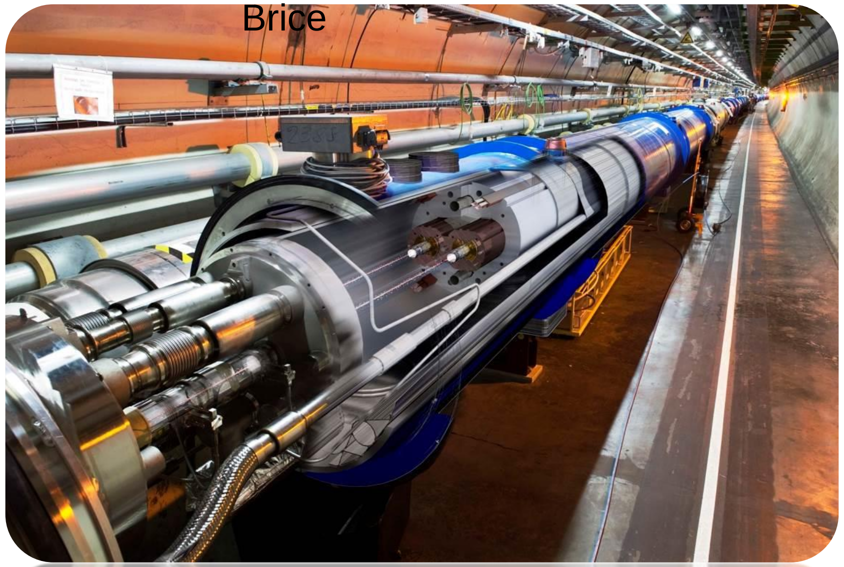
V.Rodin, R.Bruce, R. Cai, M. D'Andrea, L. Esposito, A. Lechner,
D. Mirarchi, J.B. Potoine, S. Redaelli, P. Schoofs

Main goal and content

LHC betatron halo collimation system was designed to prevent magnet quenches during periods of reduced **beam lifetime**. Lead ions are subject to electromagnetic dissociation (**EMD)** and **inelastic scattering** in collimators producing many secondary fragments, which can leak into the adjacent dispersion suppressors (**DS**).

This year LHC began ion operation with **HL-LHC** settings, for this reason, a better understanding of the quench margin in these DS magnets is needed, considering the increased beam current and the resulting higher beam losses of up to a few tens of kW**.**

CDS, Image by M. Brice

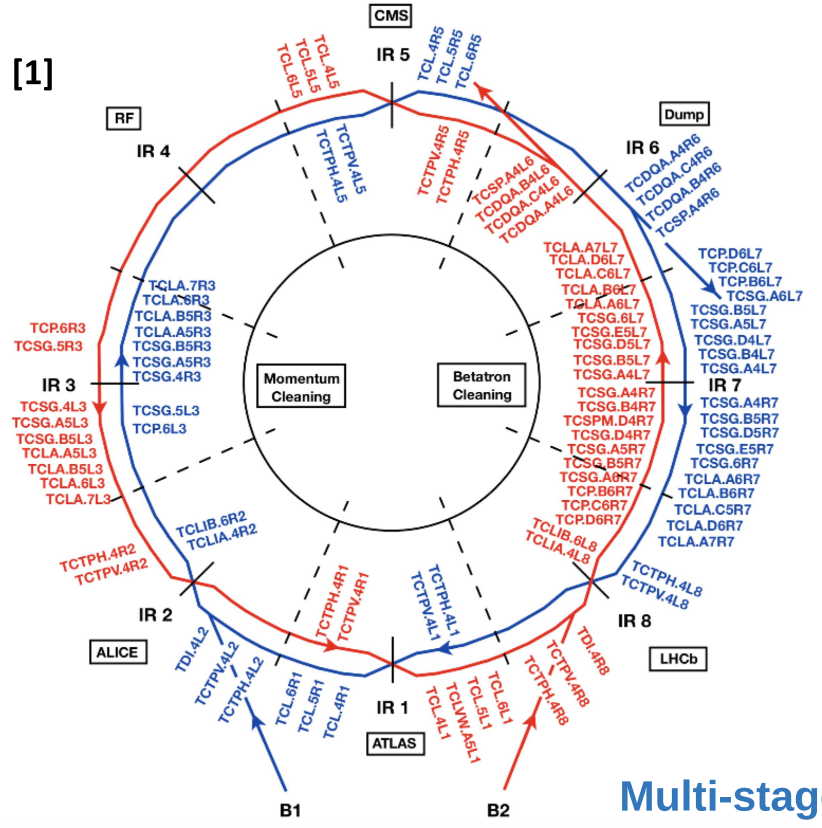


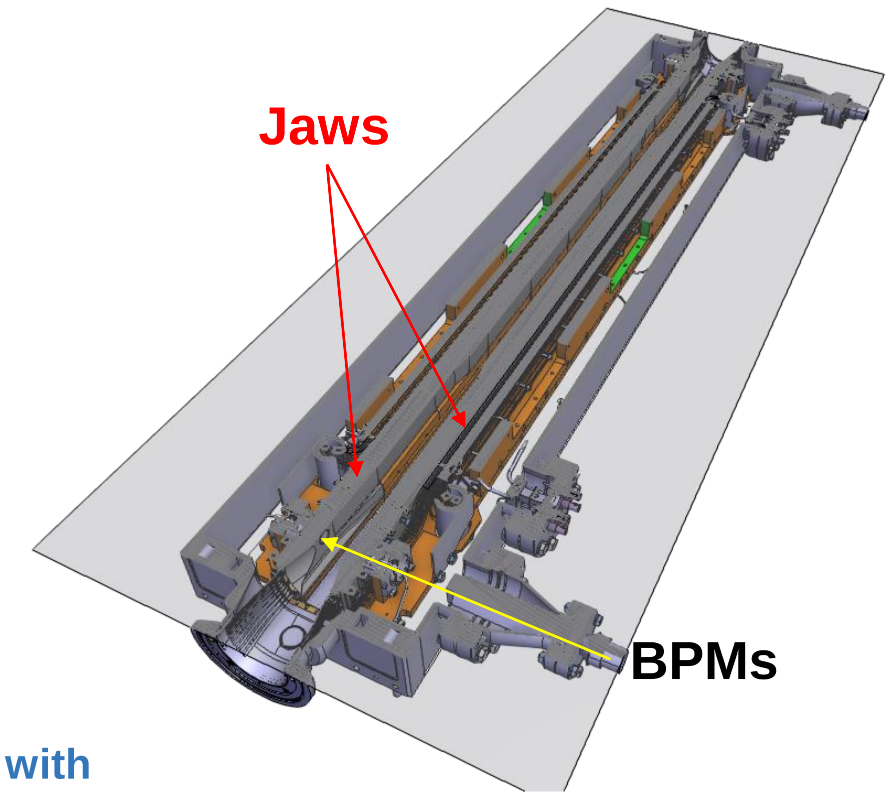
- Introduction: LHC collimation system and detection of losses
- Simulation workflow
- Investigation of power deposition in DS with FLUKA simulations:
- Comparison with previous studies

Introduction: LHC collimation system

Collimation system need to withstand effects of power deposition during nominal machine operation but also in case of abnormal (fast) beam losses. Power deposition in collimators is calculated using simulation tools and it provides insight into consequences of design or beam optics changes

[1]





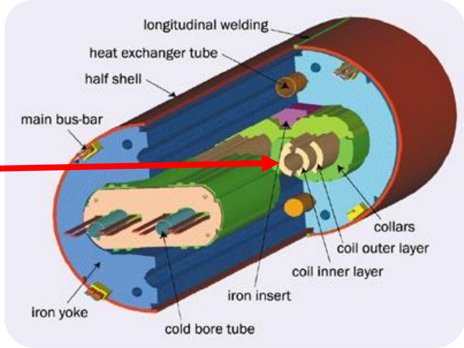
Multi-stage system with ~50 collimators per beam

[1] Data-driven cross-talk modeling of beam losses in LHC collimators, (G. Azzopardi)

Standard collimation system in LHC

Stored energy in the machine for protons: [1]

- **LHC** design: **360 MJ** ⟶ **400 MJ** (present) ⟶ **700 MJ** (HL conditions)

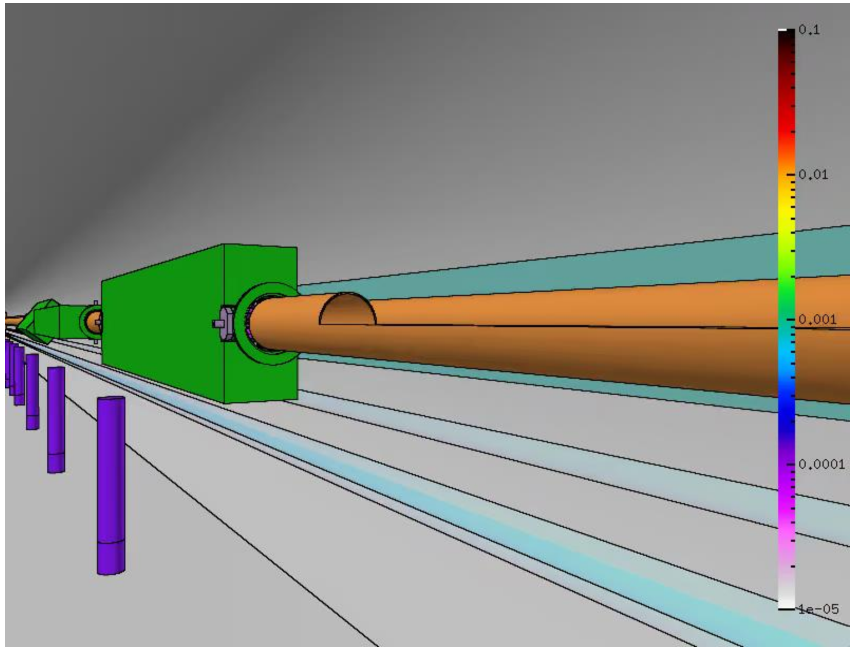


Superconducting magnets (T = 1.9 K)

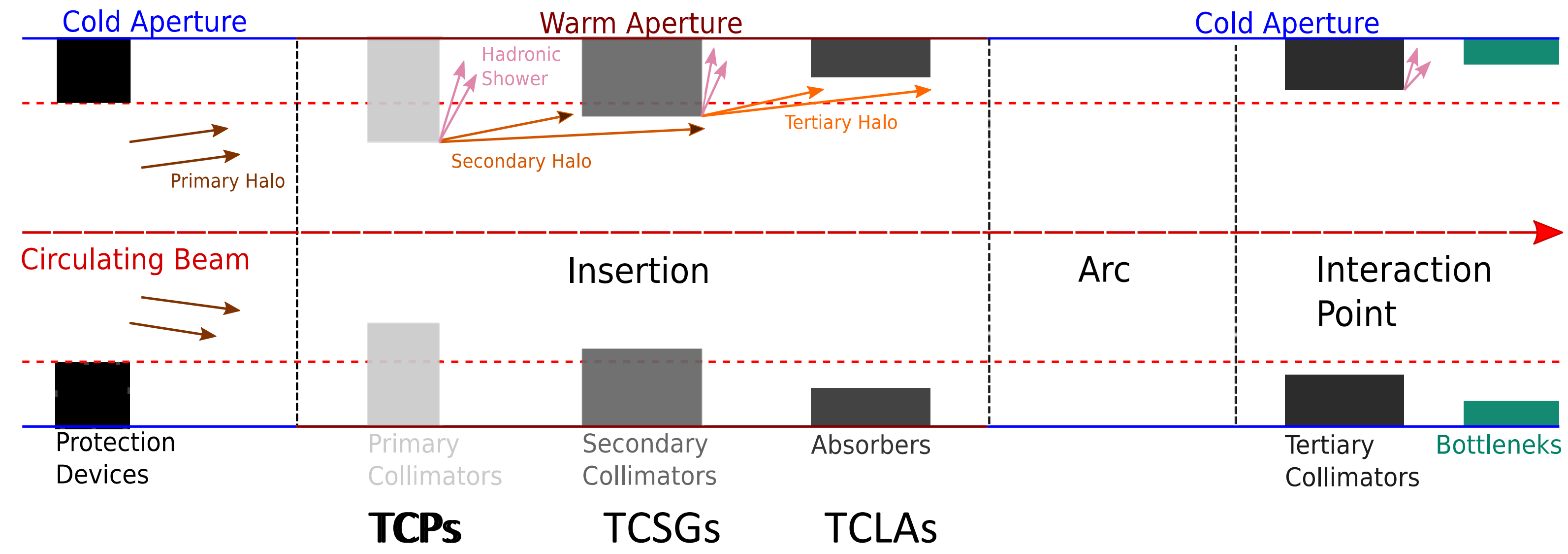
- quench limit ~ **15-50mJ/cm^3**

Collimation system is needed!

η = 10^{-4} is the actual performance in LHC



[2]



System tasks

- **Halo cleaning**: Reduction of the risk of magnet quenches
- **Concentration of losses/activation in controlled areas**

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

[1] LHC dipole production begins to take off CERN Courier

[2] Beam Cleaning and Collimation Systems (S. Redaelli)

Crystal assisted collimation system in LHC Run 3

Stored energy in the machine for ions:

- HL-LHC design: **20 MJ**

Beam energy:

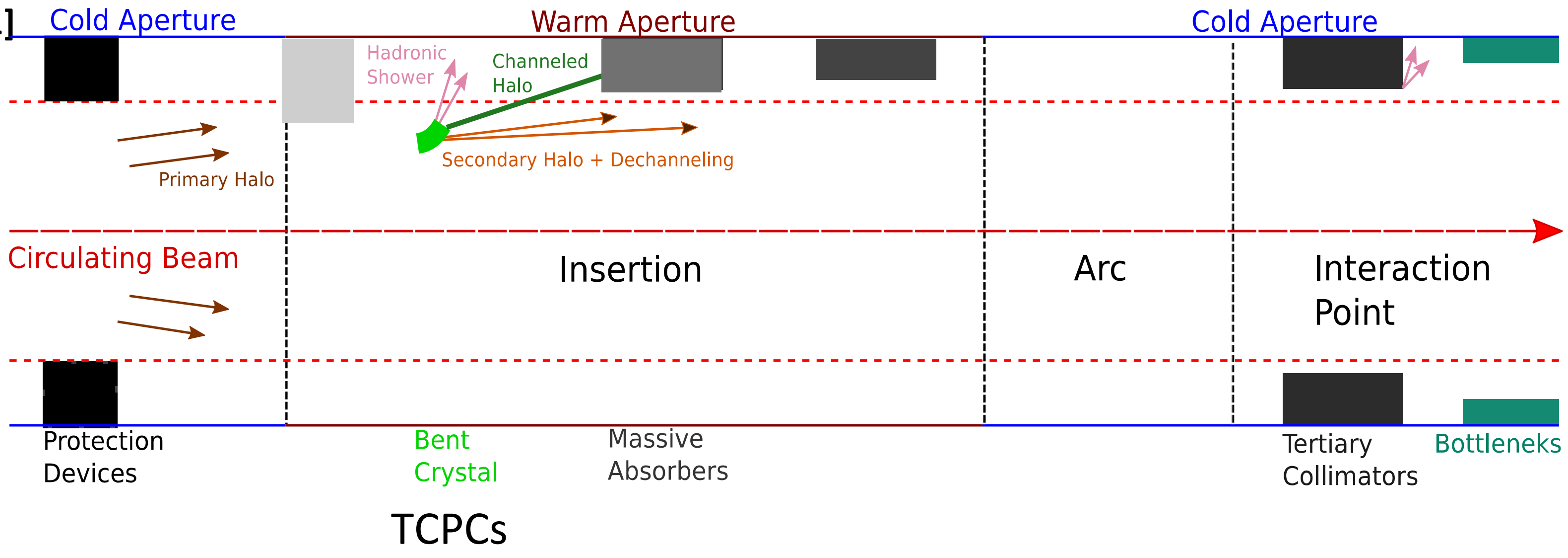
- 6.37 ZTeV → **6.8 ZTeV**

Expected that the maximum allowed power loss without quenching is 35-60 kW

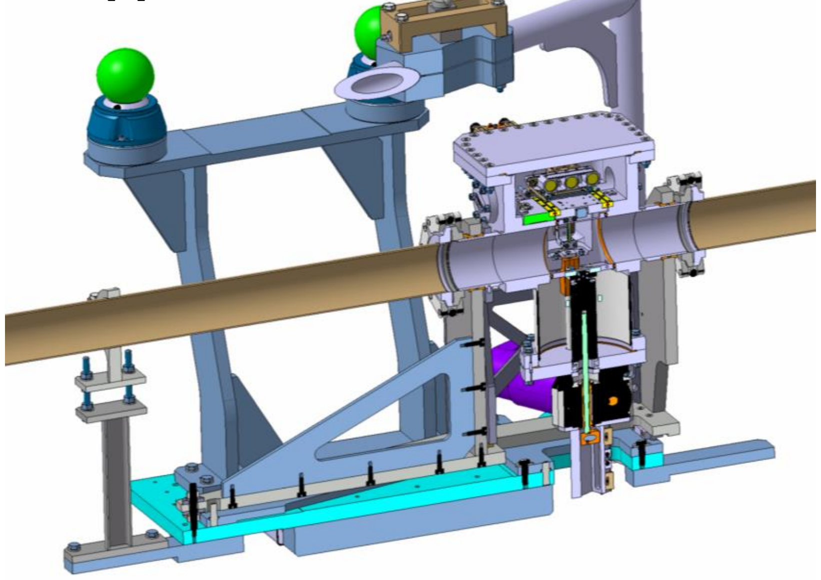
Collimation system with crystal as baseline for HL-LHC

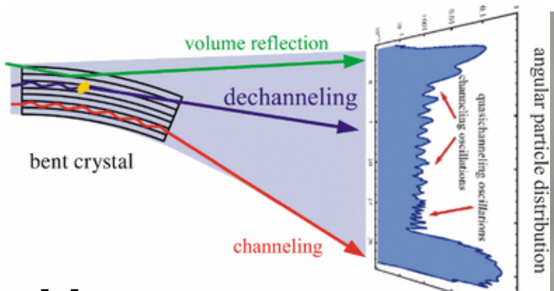
- Single side jaw collimation in horizontal and vertical plane of each beam

[1]



[3]





[2]

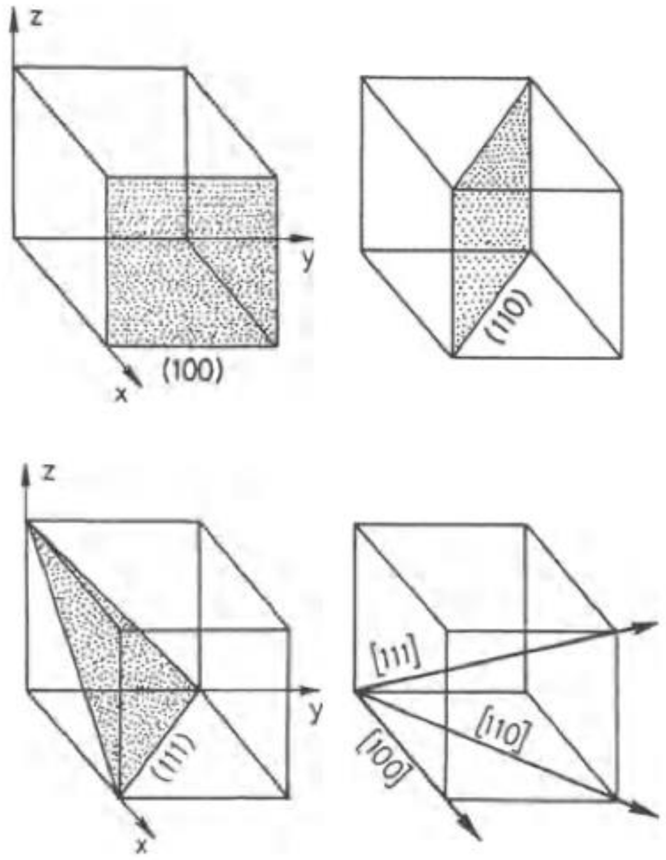
[1] Beam Cleaning and Collimation Systems (S. Redaelli)

[2] Planar channeling and quasichanneling oscillations in a bent crystal (A. Sytov)

[3] LHC Crystal collimator design (I.L. Garcia)

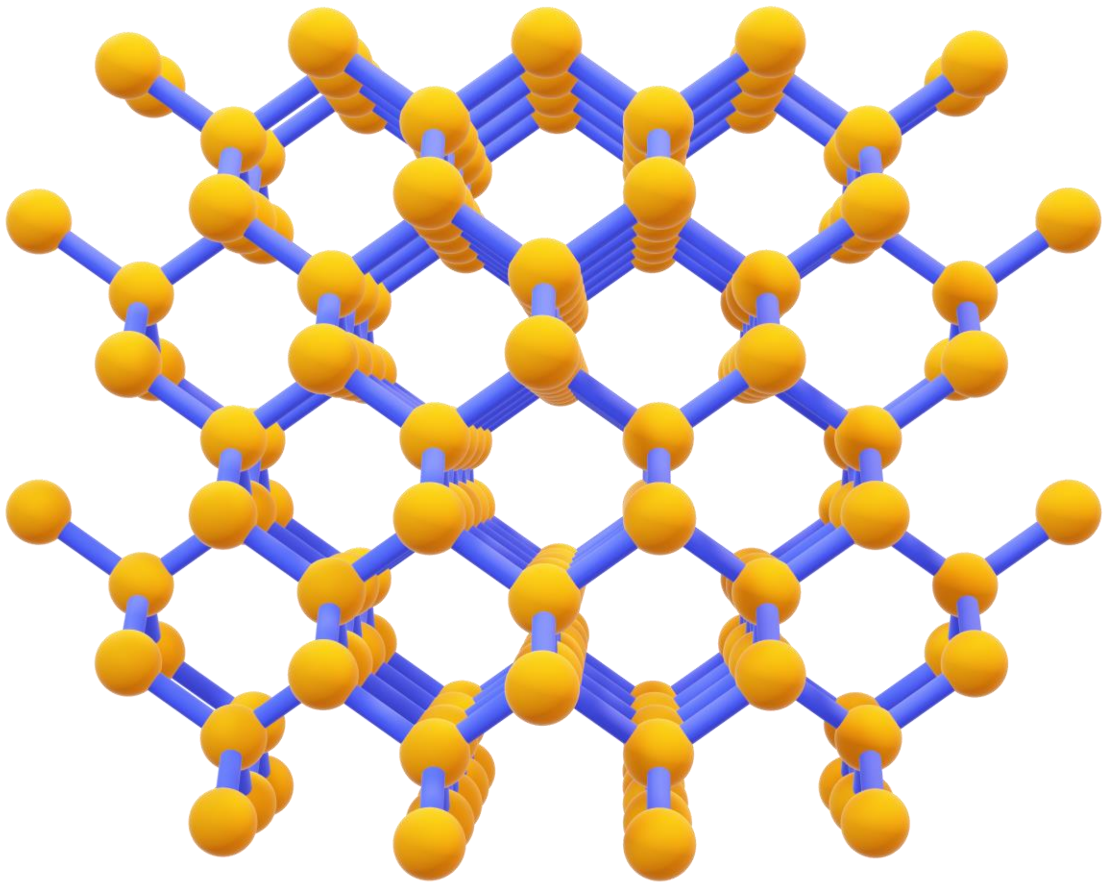
Crystal Channeling: Main concepts

[1]



Miller indices:

- Lattice planes (110) and (111) are most efficient



Diamond Crystal structure (C, Si, Ge, W)

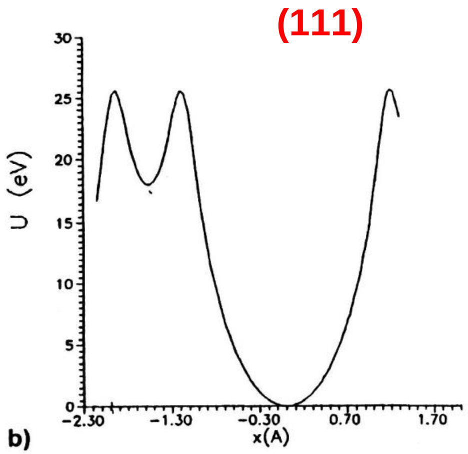
[1] Crystal Channeling and Its Application at High-Energy Accelerators (V.M. Biryukov)

Crystal Planar Channeling

Channeling condition is defined from the particle transverse momentum and the electrostatic potential generated by the atoms of the crystalline structure

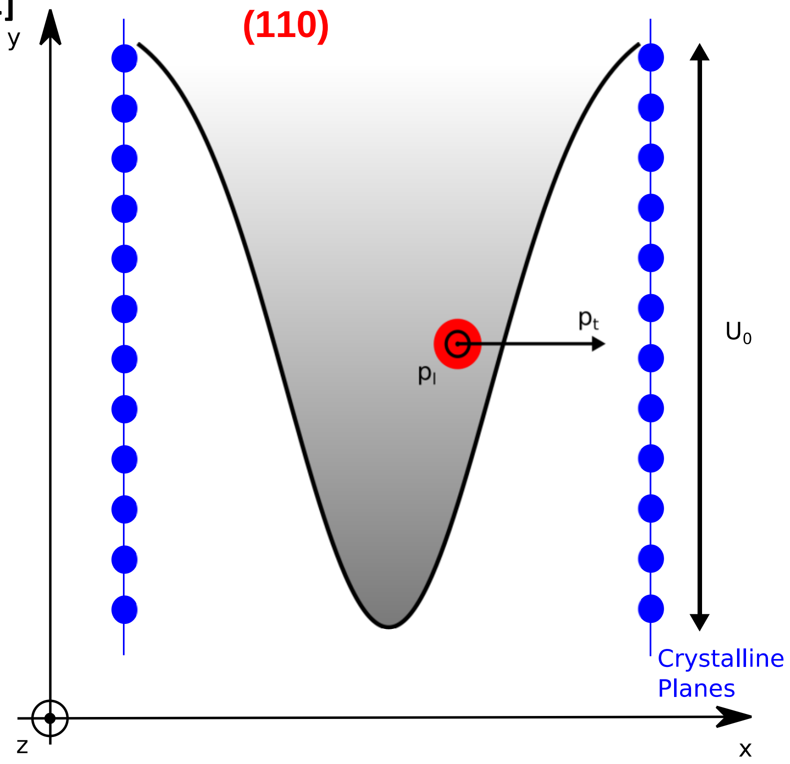
Critical angle

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

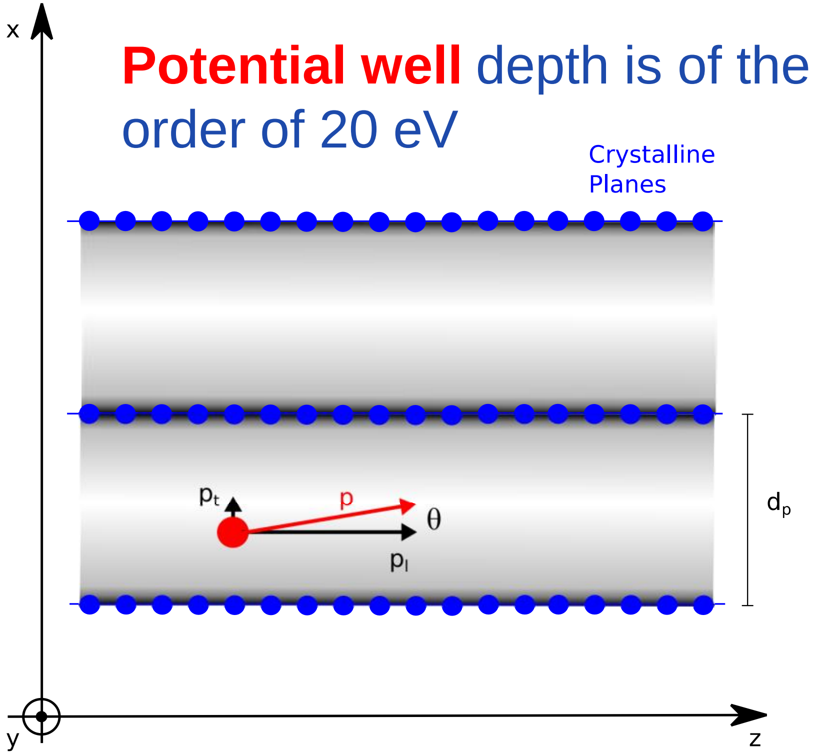


Energy	θ_c
500 MeV	282.8 μrad
120 GeV	18.3 μrad
180 GeV	18.0 μrad
270 GeV	12.2 μrad
400 GeV	10.0 μrad
450 GeV	9.4 μrad
6.5 TeV	2.5 μrad
7 TeV	2.4 μrad
50 TeV	0.9 μrad

[1]



Potential well depth is of the order of 20 eV

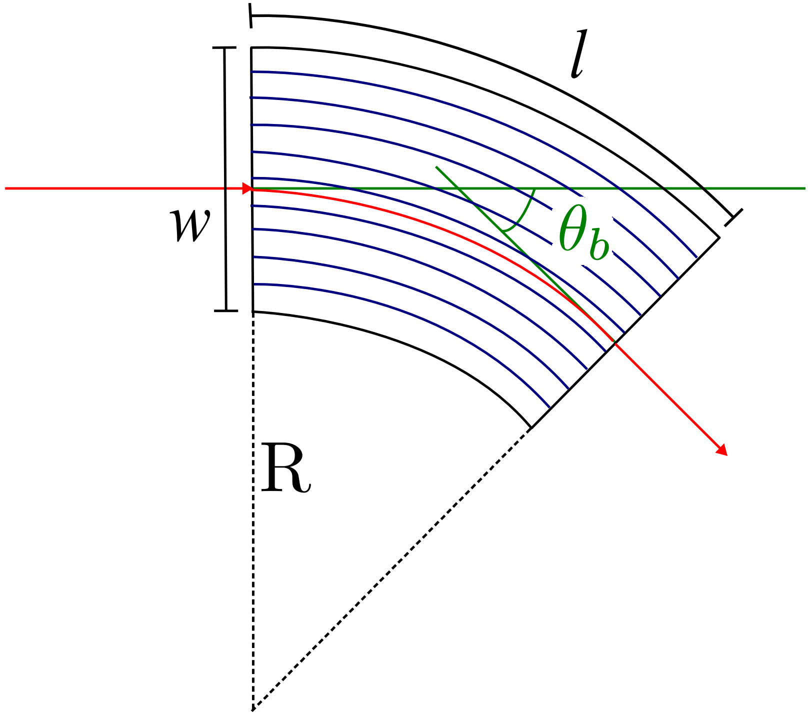


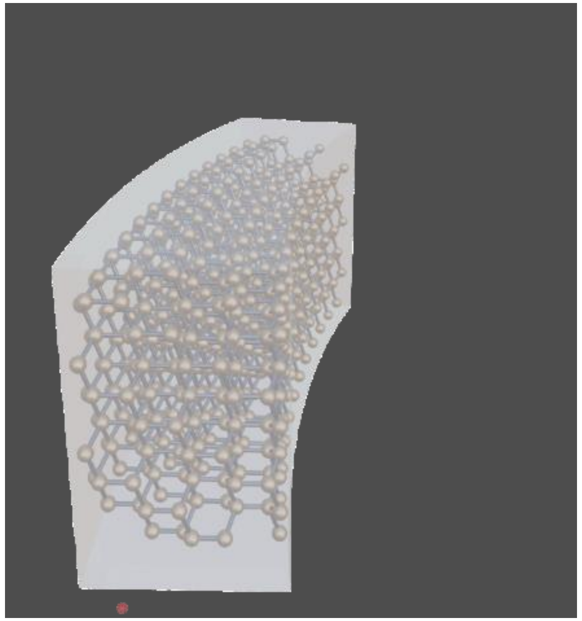
[1] Experimental Assessment of Crystal Collimation at the Large Hadron Collider (R. Rossi)

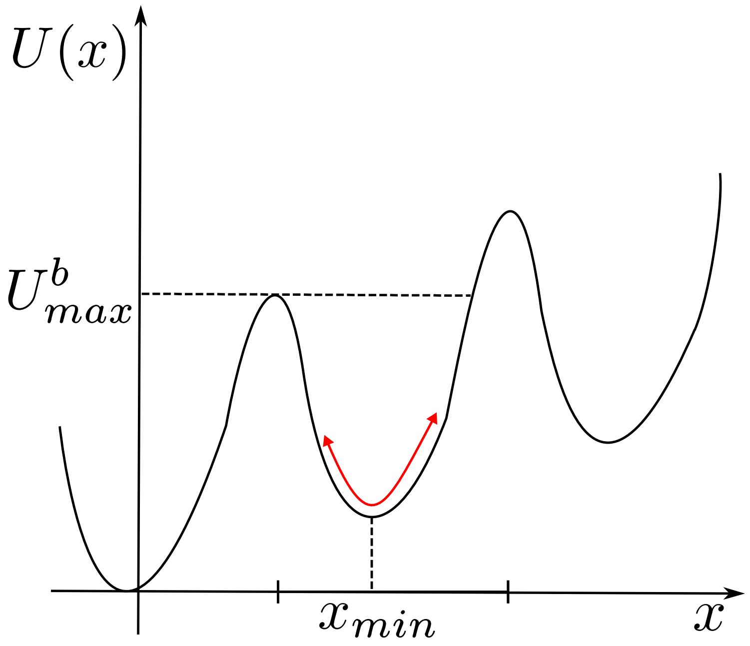
Channeling in Bent Crystals

The particles are trapped in a channel, hence if a curvature is given to the lattice the particles direction will be modified by $\boldsymbol{\theta_b = l/R}$

The bending induces a centrifugal term that deforms the straight potential with an additional term depending on both the crystal curvature and the particles energy:







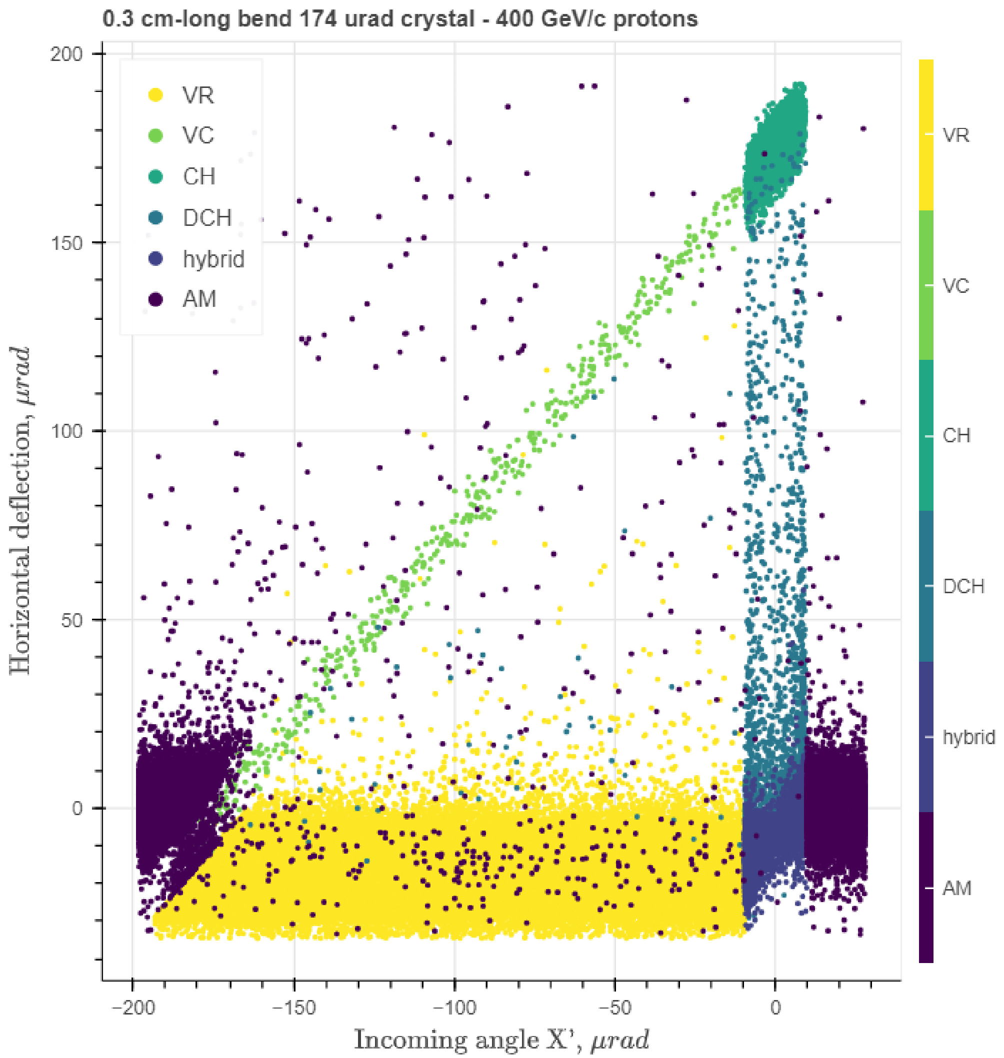
Beam manipulation with bent crystal

Two coherent effects could be used for beam deflection in particle accelerators:

- Channeling → (**CH**) larger deflection with smaller efficiency and smaller angular acceptance
- Volume Reflection (**VR**) → smaller deflection with larger efficiency and larger angular acceptance

Several other effects are present

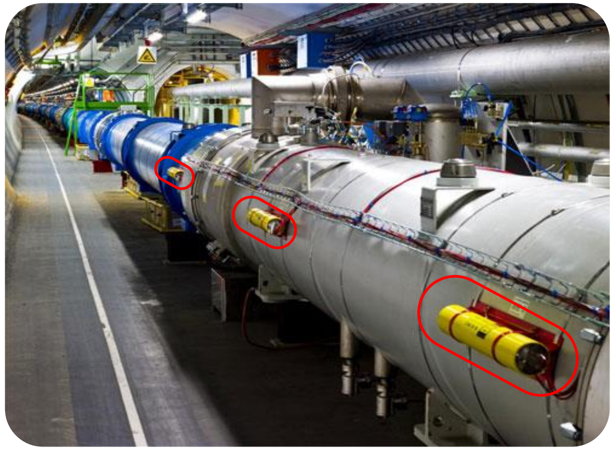
- Volume Capture (**VC**) → capture downstream the crystal and partial deflection with small probability
- Dechanneling (**DCH**) → lose of channeling conditions downstream the crystal due to inelastic interaction
- And transitions…



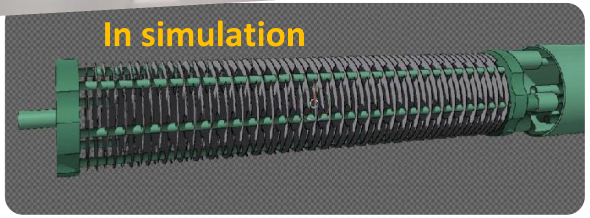
Introduction: Beam Loss Monitoring (BLM) system

- About 4000 ionization chambers are installed around LHC ring
- Each BLM is placed close to element of interest.
- For some MBs ~ every 2 m

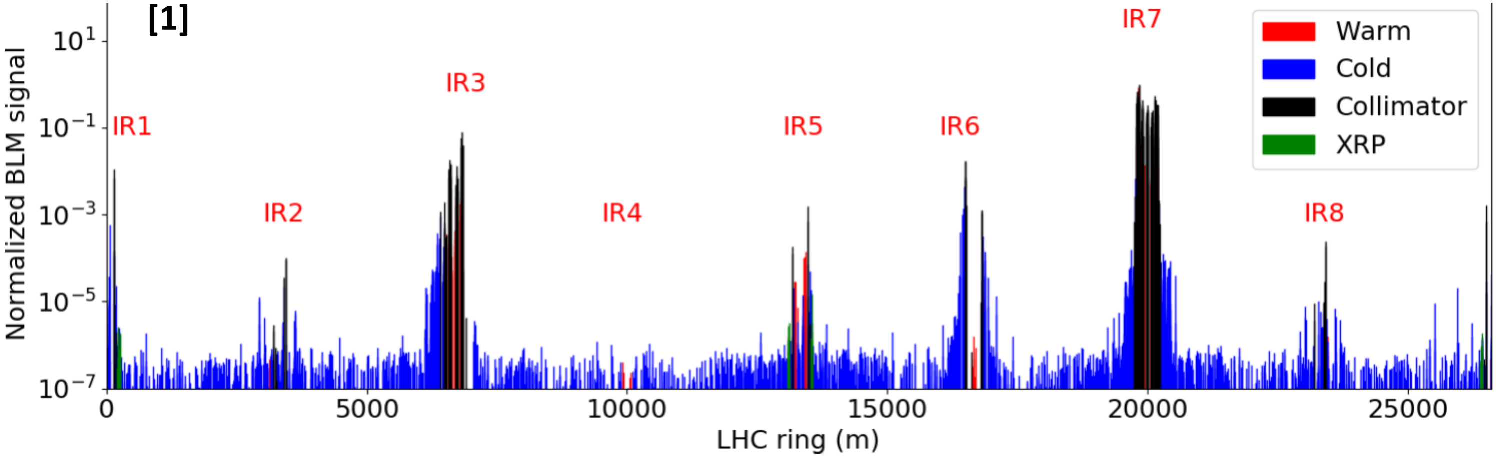
CDS, Photo by M. Brice

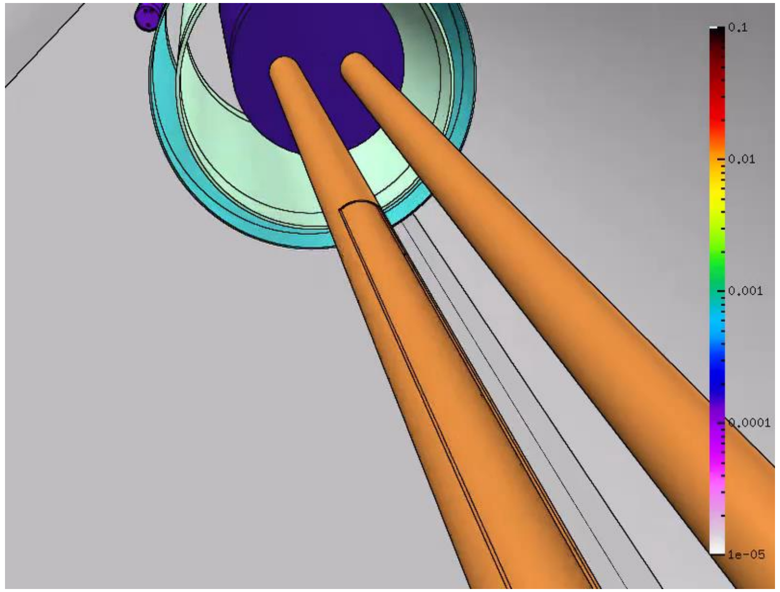


[1] **In picture**



- BLM ionization chambers (ICs) are filled with pressured nitrogen (1.1 atm)





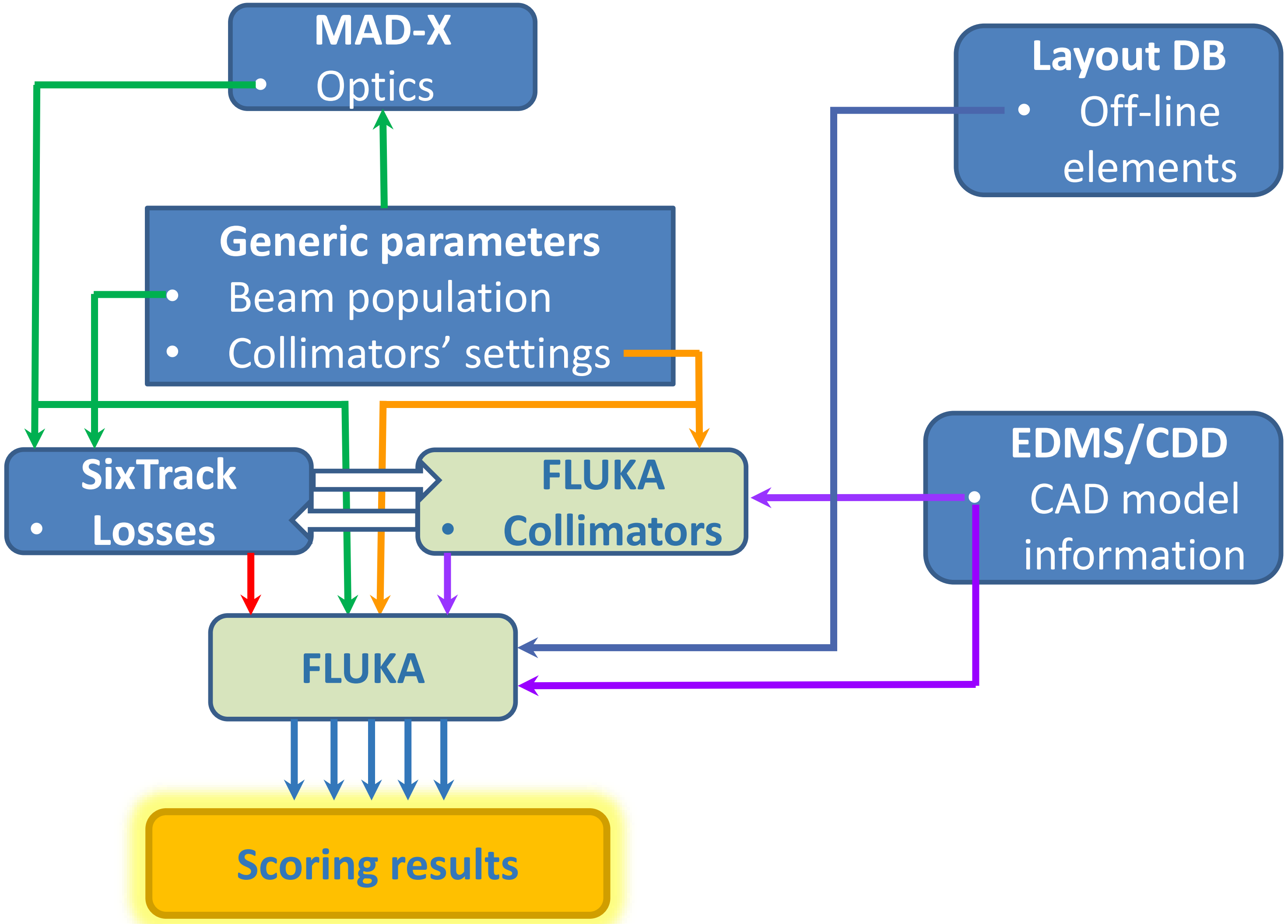
- Full ring can be characterized via a "loss map" that show how losses are localized

[1] Beam diagnostics for studying beam losses in the LHC (B.Salvachua)

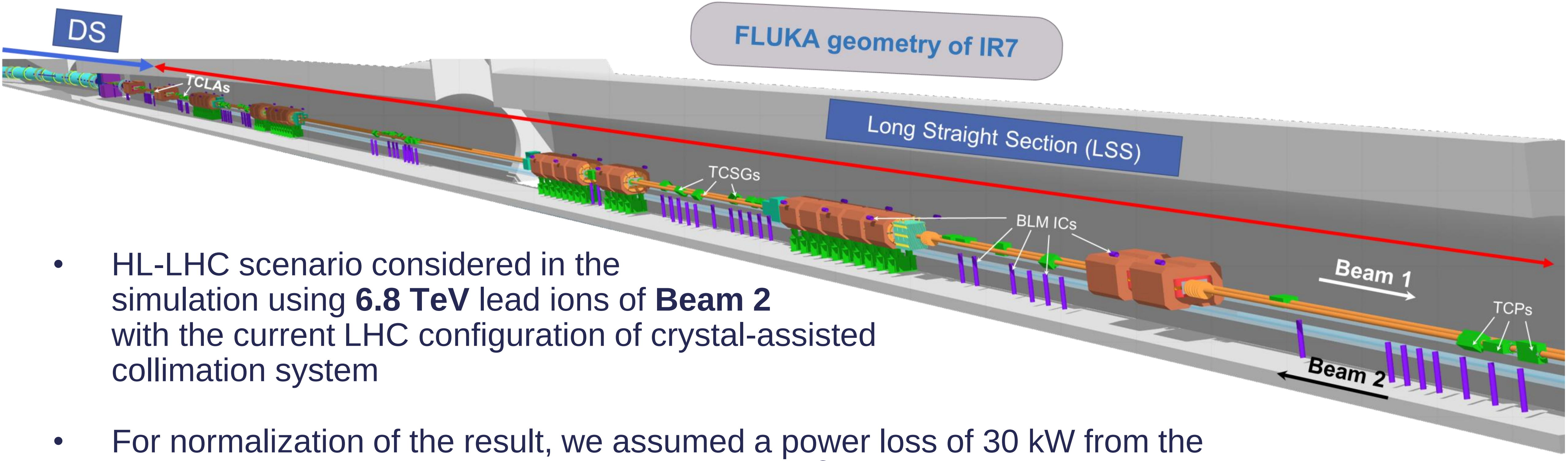
Global simulation workflow : Schematic view

Required input:

- Generic parameters
- Optics input from MAD-X
- Losses from SixTrack
- Drawings and materials from EDMS and CDD
- Location of elements from CERN layout database
- Simulation in Fluka (Geometry + Loss distribution)



Case study: Power deposition with 6.8 ZTeV ions in Run 3



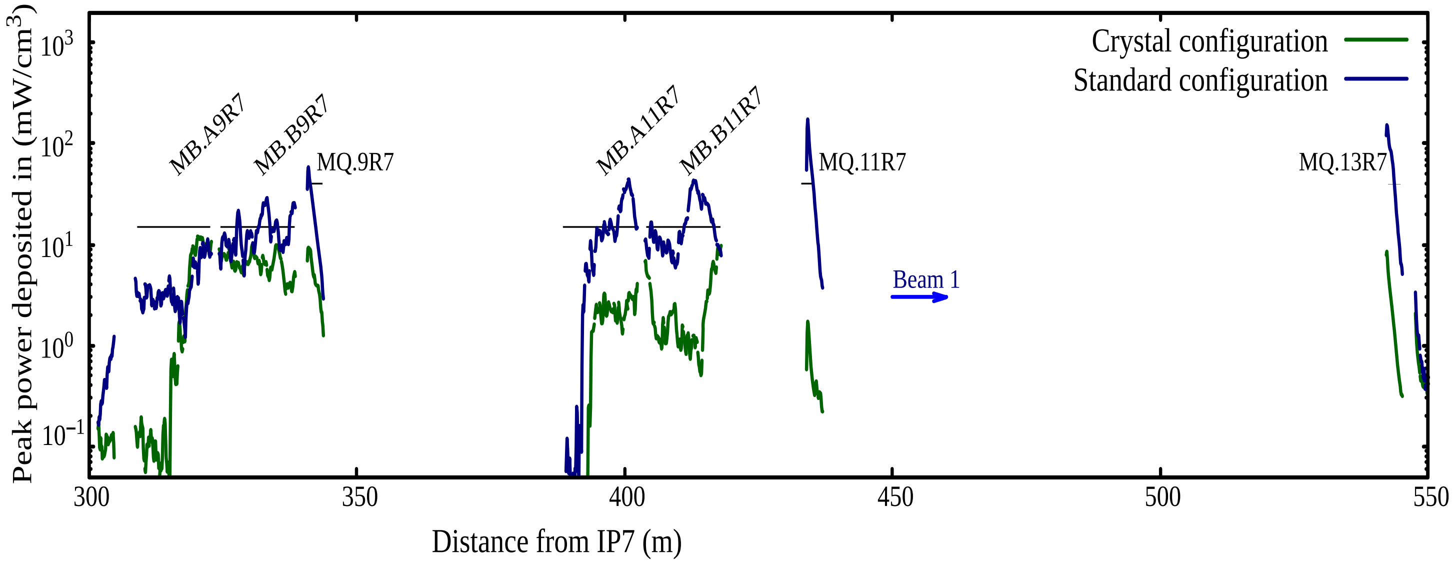
- HL-LHC scenario considered in the simulation using **6.8 TeV** lead ions of **Beam 2** with the current LHC configuration of crystal-assisted collimation system

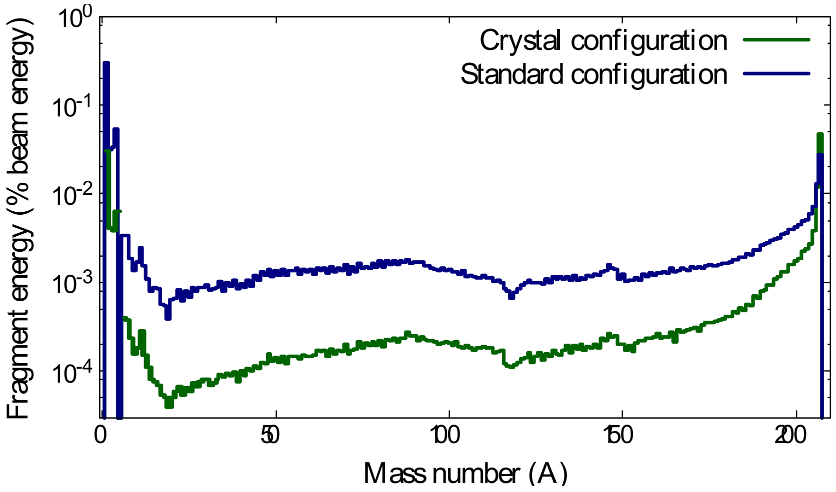
- For normalization of the result, we assumed a power loss of 30 kW from the beam, corresponding to the loss rate of **3.1×10^8** lead ions/s, defined from BLM loss map thresholds

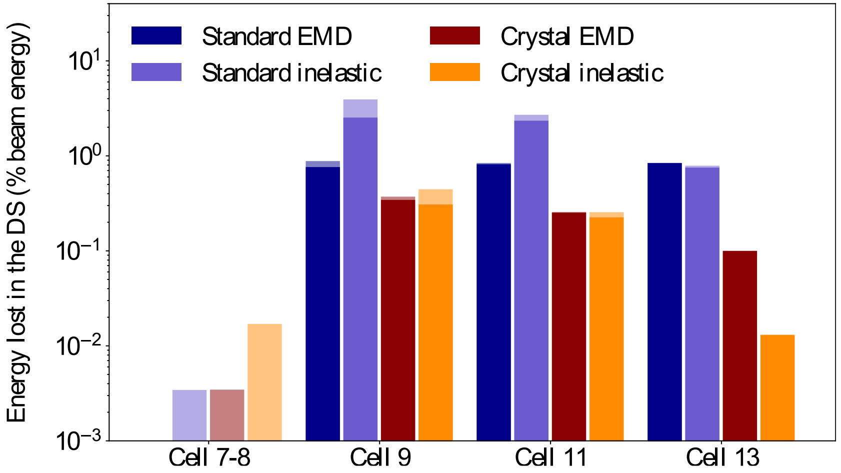
- 3D scoring in polar coordinates system was defined for each superconducting dipole or quadrupole with resolution 3 mm × 2 deg ×10 cm

Crystal-based collimation system: Cleaning performance

- Reference study for comparison [1], with previous version of HL-LHC configuration (**HL22**) and different crystals at **7 ZTeV**
- Crystal collimation decreases peak power deposition in DS superconducting coils by factor >3 for most of the magnets





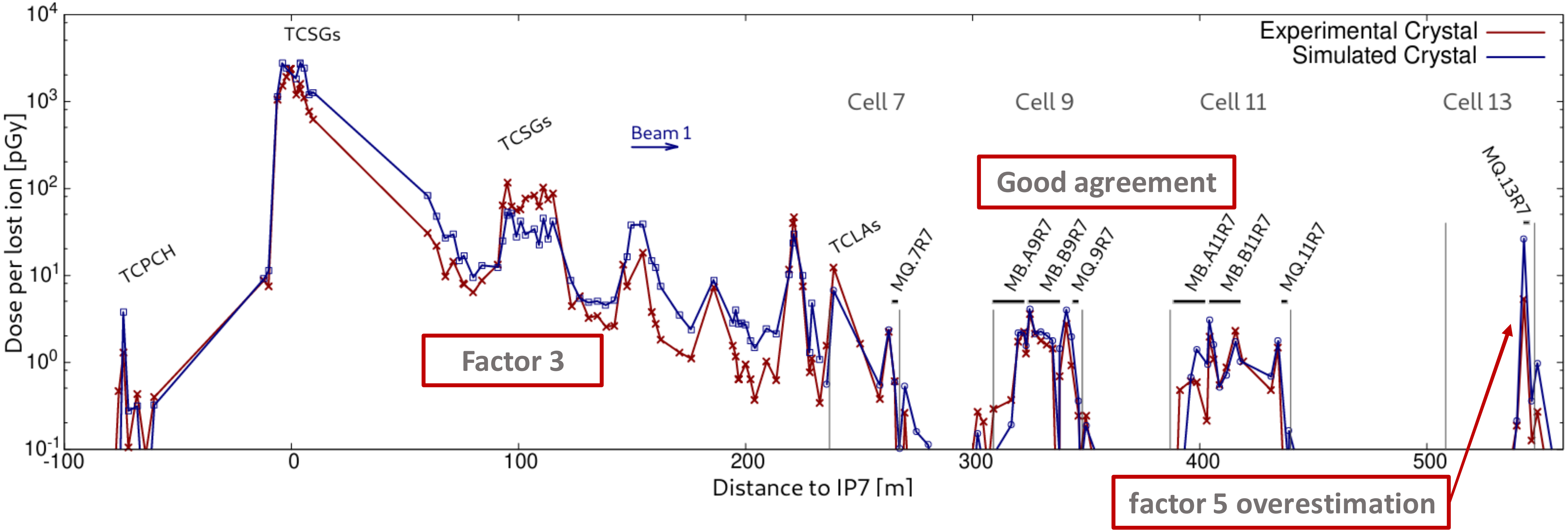


- Leakage of ion fragments into DS was decreased

J. B. Potoine *et al* Phys. Rev. Accel. Beams **26**, 093001

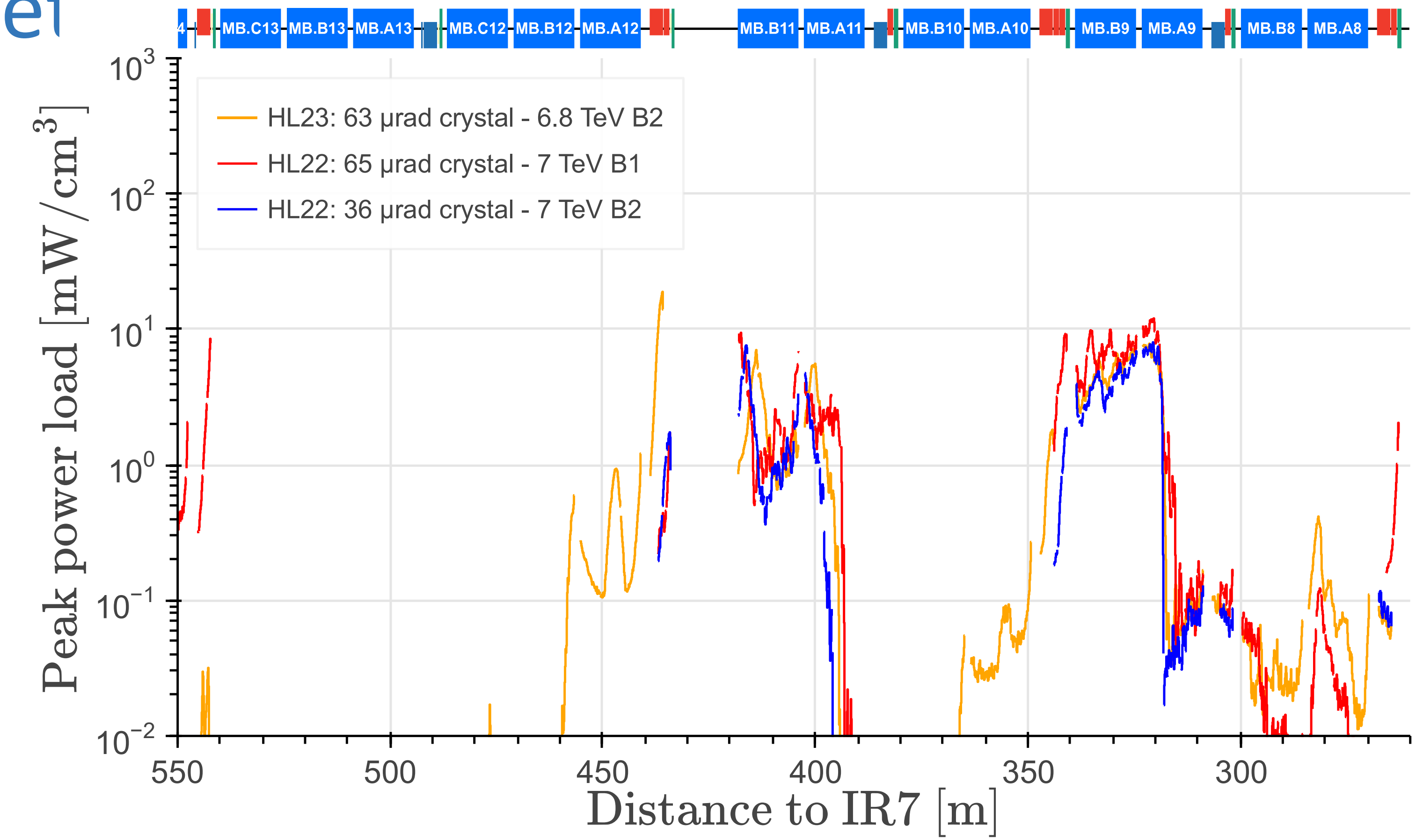
Crystal-based collimation system: BLM benchmark

- Crystal study of the **27/11/18 MD** at **14h24** – **B1**, artificial beam generation in **horizontal plane**, **Run 2** collimation system settings with ion beam at **6.37 ZTeV**
- Quite good agreement in the DS

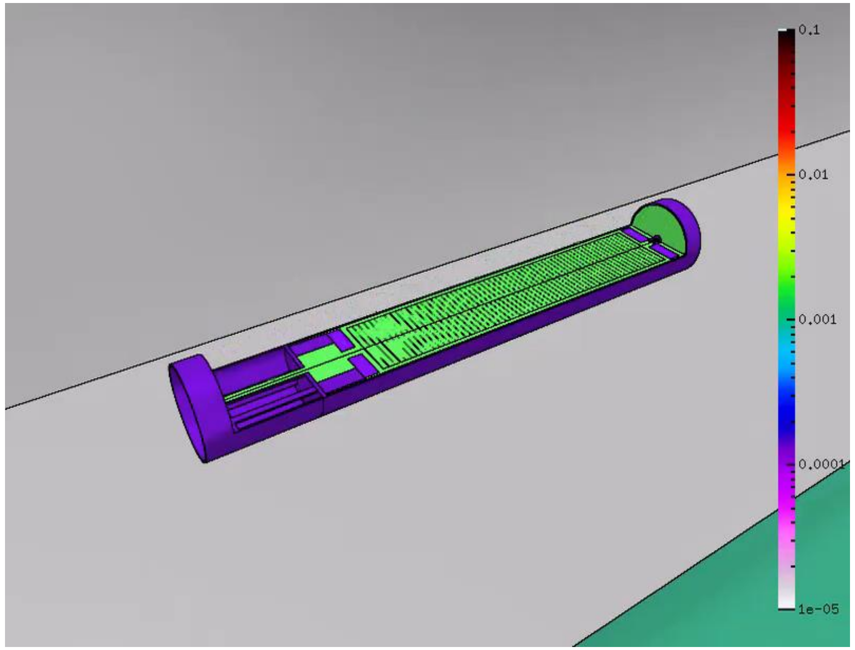


J. B. Potoine *et al* Phys. Rev. Accel. Beams **26**, 093001

Power loss density in both beams, side to side: old and new settings

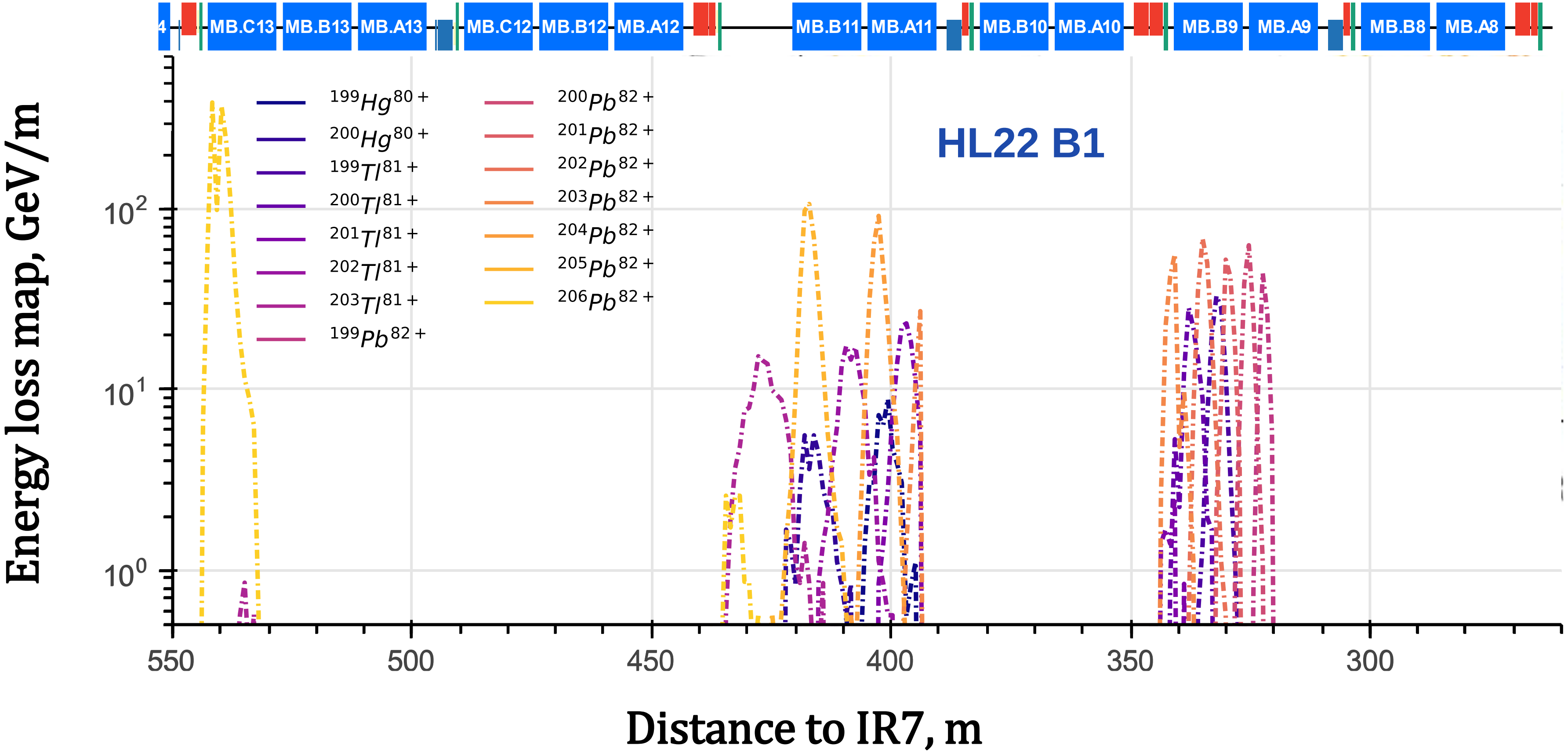


- Radially averaged value in the inner coil



- Normalization applied for direct comparison:
- Good match in loss pattern between **HL22 B1** and **HL23 B2**, when crystal bending is quite close

Fragment loss map analysis: HL22 B1 vs HL23 B2



- Normalization factors applied for direct comparison
- Value is shown per primary particle
- **Major shifts** for:

$206Pb^{82+}$ (MQ.11 → MQ13)
$201Tl^{81+}$ (MQ.9 → MB.A11)

- The displacement of some ion fragments further downstream is happening due to higher magnetic rigidity and also because of a slight asymmetry in optics between Beam 1 and Beam 2

Power deposition — Quench levels

Research supported by the High Luminosity LHC project

[1]

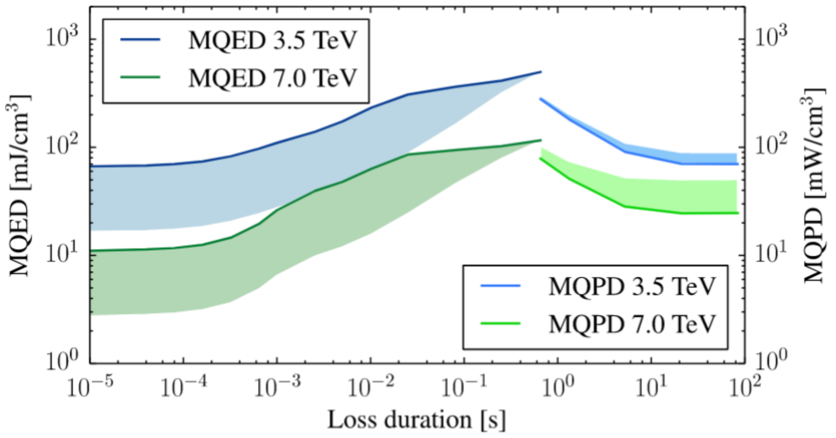


FIG. 24. Electrothermal quench level estimates for the inner layer of the LHC main bending magnet. Shading in the MQED

Electro-thermal simulations for 7 TeV [1]:

- MQ quench level : 50 $\mathrm{mW/cm^3}$ (pessimistic cooling model)
- MB quench level : 20 $\mathrm{mW/cm^3}$(pessimistic cooling model)

- Same order of value is assumed for protons

- **Still some uncertainties remain regarding actual quench level at 6.8 and 7 ZTeV**

[2]

Year	Type	Particle type (energy)	Quench	Time profile of loss rate	Reconstructed max. energy density in MB coils	Reconstructed energy density in MB coils (10 s average)
2015	BFPP (IR5)	Pb (6.37 ZTeV)	Yes	Const for 20 s	15-20 $\mathrm{mW/cm^3}$	15-20 $\mathrm{mW/cm^3}$
2015	Collim (IR7)	Pb (6.37 ZTeV)	Yes	Rising for 12 s	20-30 $\mathrm{mW/cm^3}$	13-19 $\mathrm{mW/cm^3}$
2015	Collim (IR7)	p (6.5 TeV)	No	Rising for 5 s	*20-25 $\mathrm{mW/cm^3}$ (x)*	
2022	Collim (IR7)	p (6.8 TeV)	No	Rising for 50 s	14-17 $\mathrm{mW/cm^3}$	12-14 $\mathrm{mW/cm^3}$

[1] Testing beam-induced quench levels of LHC superconducting magnets (B.Auchmann)

[2] BLM threshold strategy for the 2023 Pb run (A. Lechner, 96th BLM Thresholds Meeting (Pb run))

Summary & Outlook

- Power deposition distributions in the superconducting magnets were obtained using FLUKA for the HL-LHC baseline configuration for Run3
- Satisfactory reduction of the power density in IR7 - DS magnets with crystal collimation even though there is some uncertainties about the actual quench levels.
- Power deposition in DS dipoles (~12 mW/cm3) from Beam 2 losses should remain below the expected quench limits in case of a lifetime drop . Much larger margin for quadrupoles.
- Losses in the DS are coming almost exclusively from inelastic/EMD interactions in the crystal/ primary collimators.
- A separate assessment for Beam 1 (crystal with different channeling efficiency) is ongoing.

Thanks for your attention!

Any questions are welcome!

Comparison in location of ion loss and power deposition