Power deposition studies for crystal-assisted Pb collimation

WP5
Collimation

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Introduction – Heavy ion challenge for collimation

Reduced efficiency of the collimation system for heavy-ion runs compared to protons mainly due to ion fragments leaking to the dispersion suppressor region downstream of IR7.

Moreover, the number of ions per beams will go from 1.54e11 (733 bunches) in Run 2 to 2.23e11 in Run 3.

Still, the collimation system must sustain a flux of 3.64e8 lost ions per second during 10 seconds (0.2h Beam Life Time scenario) without quenching. Hence the novel crystal collimation setup is planned to be used.

Study of the power deposition in SC magnets (IR7-DS) during **heavy-ion** runs by means of FLUKA shower simulations.

Content:

1) FLUKA benchmark of heavy ion collimation losses at 6.37 ZTeV with (MD) and without crystal (2018 fills).

2) Breakdown of the isotopes causing the energy deposition in the DS during crystal and standard collimation.

3) Assessment of energy deposition inside SC magnets during HL-LHC operation at 7 ZTeV with and without crystal.

Introduction – Collimation principle (simplified picture)

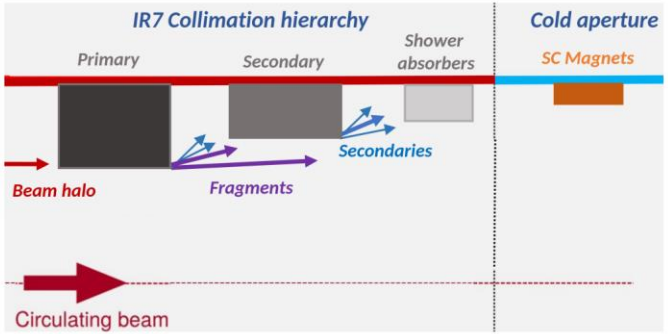


FIG. 1. Working principle of the standard collimation system. Figure inspired by Ref. [7]

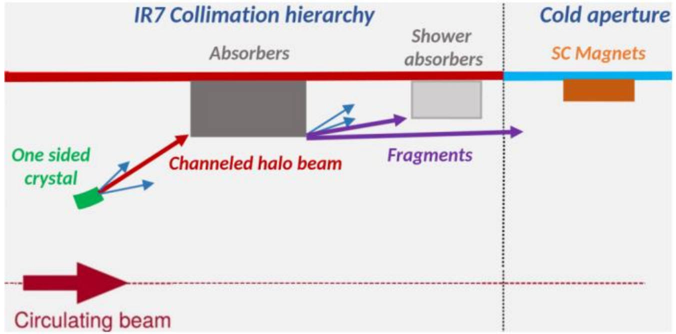


FIG. 5. Working principle of the crystal collimation system. Figure inspired by Ref. [7]

- Standard collimation uses hierarchy of collimators to intercept the beam halo and the subsequent particle shower.
- Crystal collimation relies on a few millimeter long crystal to deflect the beam halo on absorbers.

[7] High-Luminosity Large Hadron Collider (HL-LHC). Technical design report. (2020 p 87-114)

Crystal collimation - FLUKA implementation

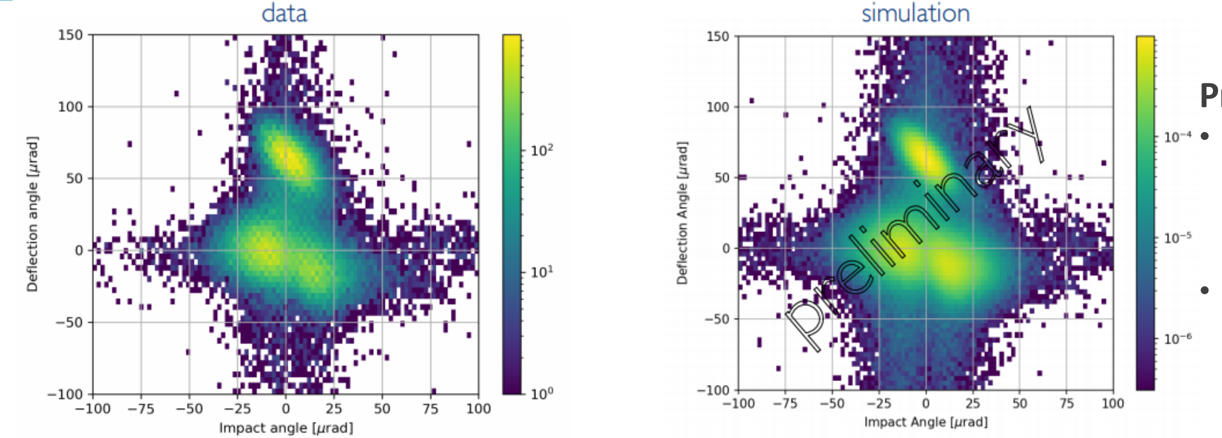


Figure: Benchmark of FLUKA heavy-ion crystal channeling [2]

Previous FLUKA benchmark:

- Heavy-ion channeling for Xe54+ 150A GeV in H8 geometry [2] (~20m) gave very similar deflection pattern on a target.
- Several improvements implemented to the original driver by P. Schoofs [1] (2014)

FIG. 2. Strip crystal with its titanium holder.

Current implementation:

- Is adjusted to fit crystal specification determined experimentally [3]
- Likelihood of inelastic nuclear collision reduced during channeling (EMD not suppressed)

[1] P. Schoofs thesis "Monte Carlo Modeling of Crystal Channeling at High Energies" - 2014
[2] R. Rossi - FLUKA Crystal Module Benchmark ColUSM #132
[3] L. Esposito – FLUKA crystal module and embedding in the coupling ColUSM #132

Benchmarks

Benchmark – Simulation scenario

Collimators	Crystal	2018 B1	2018 B2
TCPs	9	5.5(L)/5(R)	5
$TCSGs_{upstream}$	8.6	6.5	6.5
TCPC	5	/	/
$TCSGs_{downstream}$	6.5	6.5	6.5
TCLAs	10	10	10

Table 1: Collimation halfgaps as defined in [1] during 2018 crystal tests and heavy-ion fills.

- FLUKA simulation based on SixTrack inputs provided by R. Cai
- Crystal MDs at 6.37 ZTeV in 2018 to investigate its efficiency with a few bunches.
- This test was used to assess the accuracy of the FLUKA energy deposition simulation of crystal collimation.

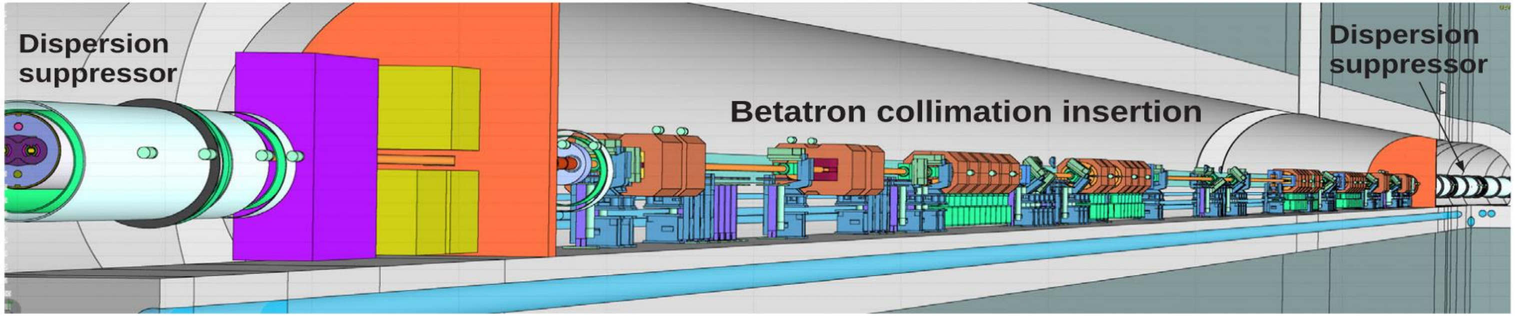
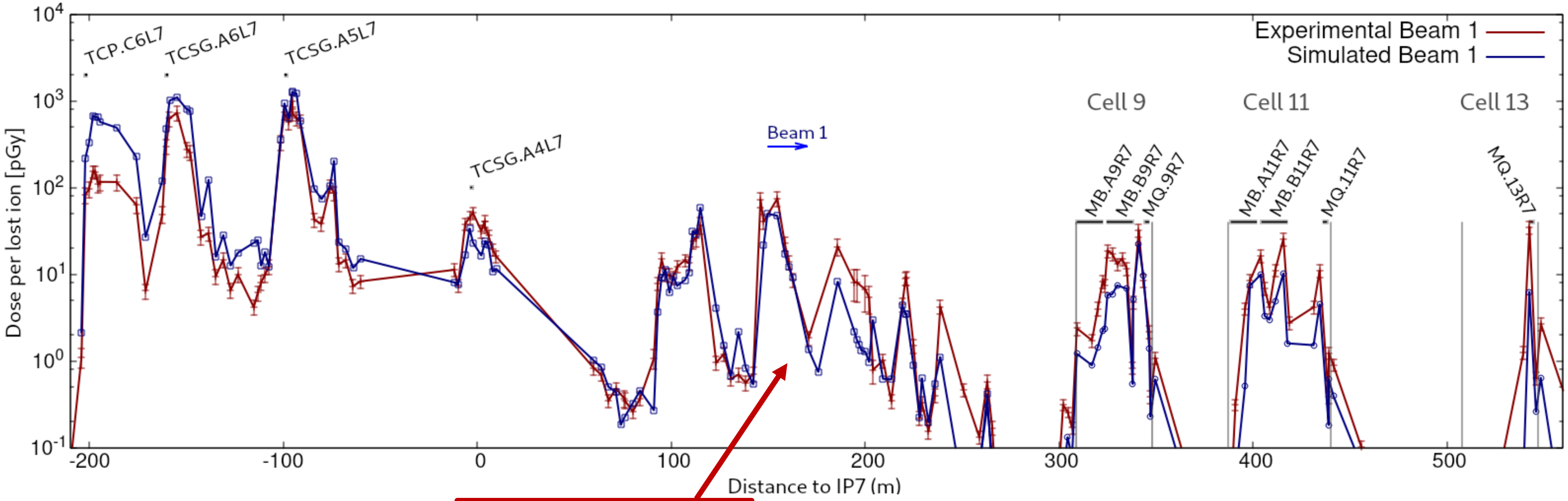


Figure: Betatron collimation insertion region model (IR7) used in FLUKA [2]

[1] Simulations of heavy-ion halo collimation at the CERN Large Hadron Collider: Benchmark with measurements and cleaning performance evaluation (N. Fuster Martinez)
[2] Validation of energy deposition simulations for proton and heavy ion losses in the CERN Large Hadron Collider (A. Lechner)

Benchmarks – Beam 1 standard collimation



Factor 5 TCPs

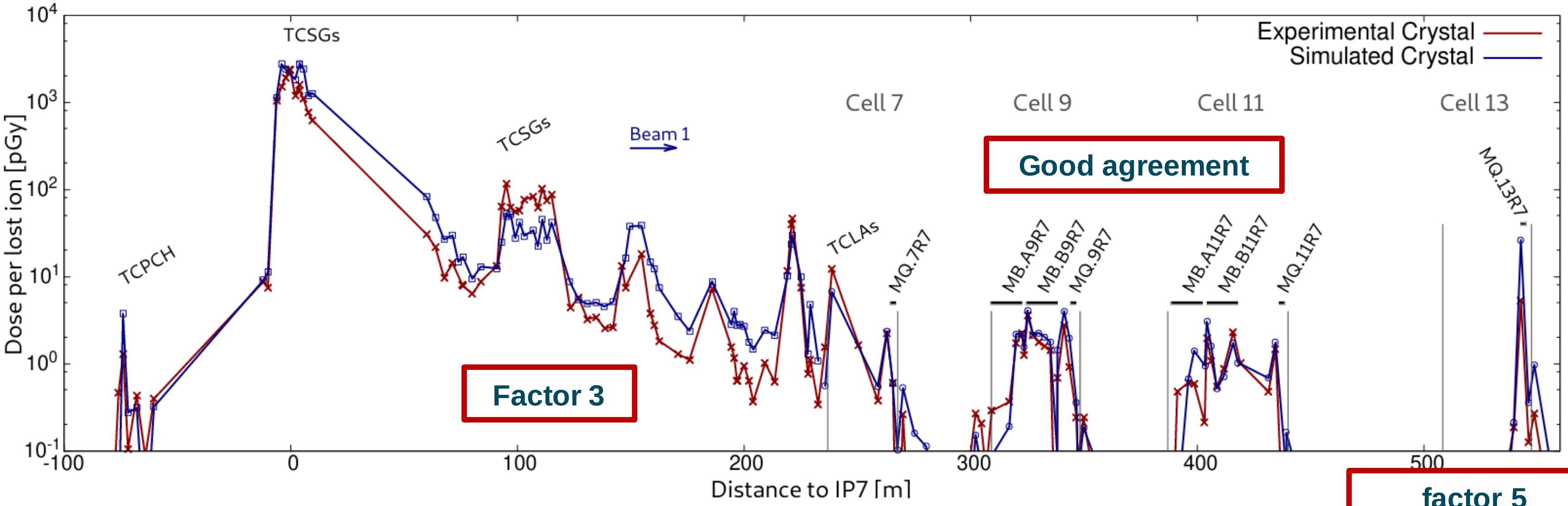
Beam 2 cross-talk

Cell 9/11 : factor 2

Cell 13 : factor 5 underestimation

- Absolute comparison
- First benchmark of BLM signals in IR7 during operational losses for Beam 1 (10 Hz events)
- Compared to 2015 benchmark (Beam 2): Better agreement in the DS (factor 5) – worse at the TCPs (factor 3)

Benchmarks – Beam 1 crystal collimation simulation



factor 5 overestimation

- Crystal MD on the 27/11/18 at 14h24 - B1H
- Remarkably good agreement in the DS
- Measurement reduced by up to a factor 8 at the highest BLM signal in cells 9/11
- Gives great confidence in the simulation tool to reproduce crystal physics for beam 1

Benchmark summary

	Crystal collimation		Standard collimation
	Beam 1	**Beam 2**	**Beam 1**
Cell 7-8	1	1	2
Cells 9-11	1	1	2
Cell 13	1/5	/	5

Those factors should be applied to the simulation of the energy deposition in the magnet coils

Isotope breakdown (EMD/Inelastic)

Losses breakdown – isotopes contribution

$$^{208}\mathrm{Pb}^{82+} + ^{12}\mathrm{C} \underset{\sigma_{\mathrm{nuclear}}}{\rightarrow} {}^{A_X}\,\mathrm{X}^{Z_X+} + ^{A_Y}\,\mathrm{Y}^{Z_Y+} + N_p\mathrm{p} + N_n\mathrm{n} + \ldots$$

$$^{208}\mathrm{Pb}^{82+} + ^{12}\mathrm{C} \underset{\sigma_{\mathrm{EMD}_m}}{\rightarrow} {}^{208\text{-}m}\,\mathrm{Pb}^{82+} + ^{12}\mathrm{C} + m\mathrm{n}$$

Equations : Examples of Inelastic (top) and EMD (bottom) process

Physics Process	Unit	Si	CFC	MoGr
$\lambda_{nuclear}$	[cm]	4.82	3.67	3.05
λ_{EMD}	[cm]	8.07	27.22	22.32

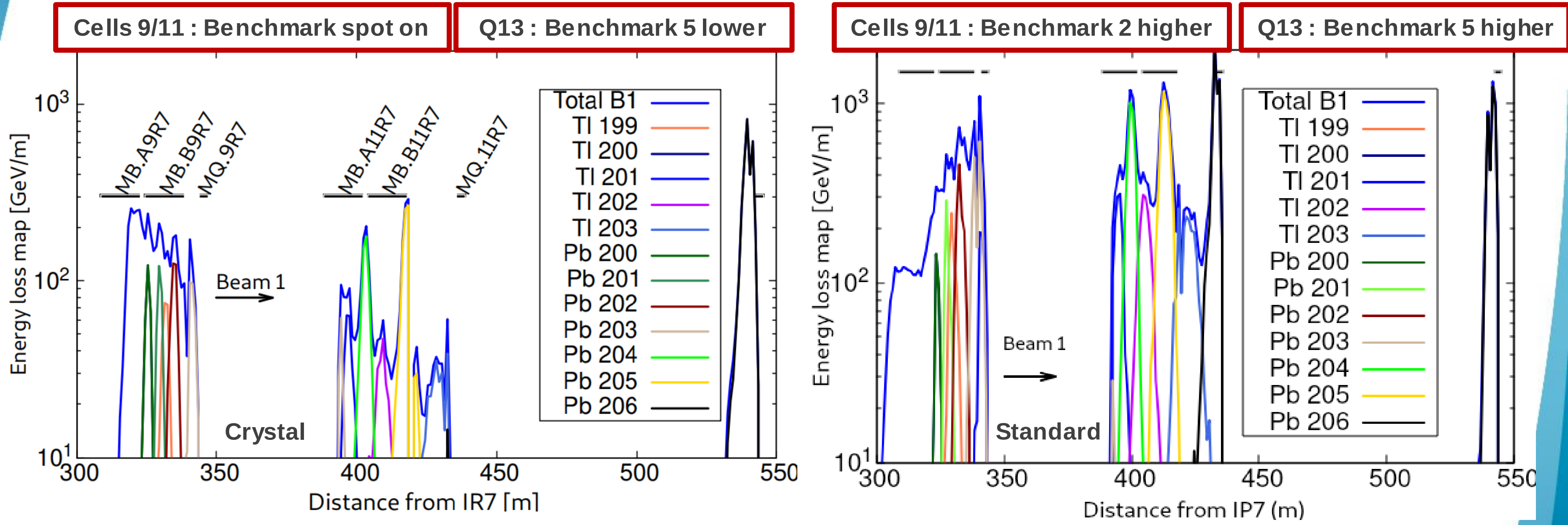
TABLE I. Characteristic of relevant interaction mechanisms for $^{208}Pb82+$ lead ions traversing different materials at 7 ZTeV.

Collimators	Crystal test	Standard HL	Crystal HL
TCPs	9	5	5
$\mathrm{TCSGs}_{upstream}$	8.6	6.5	6.5
TCPC	5	/	4.75
$\mathrm{TCSGs}_{downstream}$	6.5	6.5	6.5
TCLAs	10	10	10

Table 1: Beam 1 collimation apertures in units of the beam r.m.s σ at ϵ_N^P =3.5 μm during 2018 test and for standard/crystal HL-LHC heavy-ion runs

- Investigation of losses for 2 different HL-LHC configurations (crystal/ standard) at **7 ZTeV**
- Standard collimation (MoGr -TCP) : nuclear interactions account for 85% of the primary particle collisions in the primary collimator
- Crystal collimation (Si - TCPC) : in amorphous nuclear interactions account for 60% of the primary particle collisions however there is a reduction of inelastic collisions during channeling in FLUKA

Losses breakdown – HL-LHC energy lossmap



- **BLM benchmark factors not applied**
- Same spatial distribution of isotopes between the two collimation
- Same isotopic distribution for Beam 2 collimation (not shown here)

Losses breakdown – physics process

Losses of fragments emerging from collisions in collimators/ crystal

	Crystal					Standard				
	EMD		Inelastic		BF	EMD		Inelastic		BF
	All	$Z \geq 80$	All	$Z \geq 80$	X	All	$Z \geq 80$	All	$Z \geq 80$	X
IR7	3.82	2.99	8.2	0.29		13.36	<0.01	78.08	3.01	
Channeled	81.61					-				
DS products	1.67	1.55	1.16	0.78		2.87	2.65	1.24	0.84	
Cell 7-8 [230-300]	0.16	0.11	0.25	0.098	1	<0.01	<0.01	0.03	<0.01	1
Cell 9 [300-350]	0.51	0.47	0.53	0.35	1	0.75	0.61	0.52	0.25	2
Cell 11 [390-440]	0.35	0.35	0.29	0.25	1	1.74	1.67	0.62	0.53	2
Cell 13 [510-550]	0.63	0.63	0.078	0.078	1/5	0.38	0.38	0.06	0.05	5
Other regions	3.27	3.27	0.27	0.25	-	3.91	3.87	0.5	0.45	-

TABLE IV. Breakdown of the energy lost on apertures during 7 ZTeV Beam 1 halo simulations for crystal and standard collimation in percentage of the total kinetic energy from the $^{208}Pb^{82+}$ ions simulated. Z correspond to the charge number of the created isotopes. Distances of cells [-] are in m from the center of IR7. BF correspond to the benchmark factor that should be applied on top of the energy lost.

- **BLM benchmarks factors not applied (column BF)**
- Losses in the DS coming mainly from EMD produced in the crystal/ primary
- Cell 9 losses evenly distributed between EMD and inelastic products
- Particles lost in other regions are mainly coming from EMD (Pb 207)
- Ongoing study to understand if collisions in crystal are during channeling or amorphous modes

Losses breakdown – DS isotopes contribution

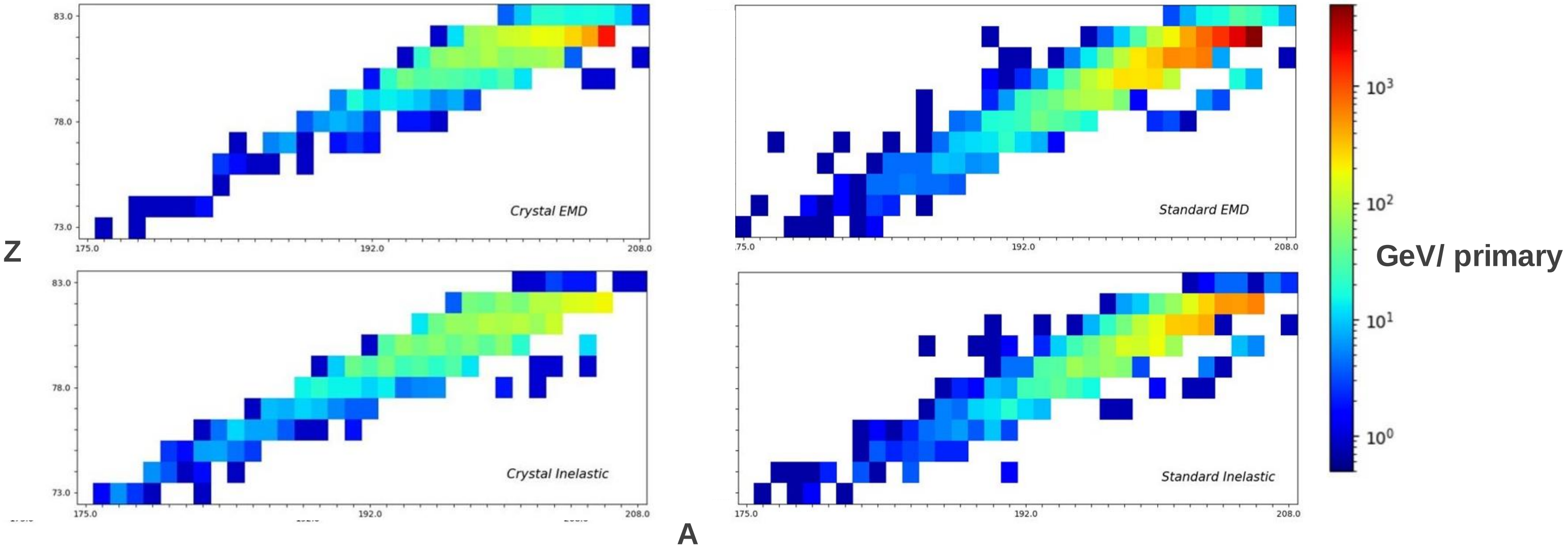


Figure: Comparison of the energy deposition per process of the different isotopes (72<Z<84 and 174<A<209) in the DS ([230;550~m] from IR7). Results are shown for B1 in the case of crystal collimation and standard collimation as defined Table [1] and are normalized by the number of heavy ion lost.

- **BLM benchmarks factors not included**
- Main energy deposition in the DS due to EMD process
- DS spectrum of crystal collimation wider in A
- DS spectrum of standard collimation wider in Z

Power deposition

Power deposition – Quench levels

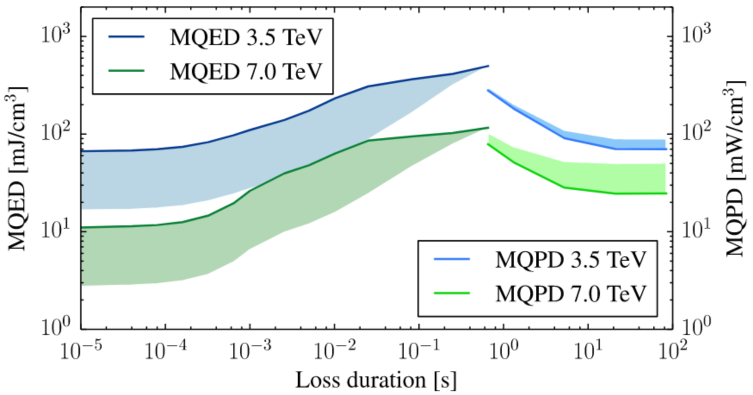


FIG. 24. Electrothermal quench level estimates for the inner layer of the LHC main bending magnet. [1]

- Investigation of steady states losses (t > 5s) assuming an HL-LHC 0.2 h beam life time
- Electro-thermal simulations for 7 TeV [1]:
  - MQ quench level : 50 mW/cm3 (pessimistic cooling model)
  - MB quench level : 20 mW/cm3 (pessimistic cooling model)
- BFPP quench test [2] at 6.37 ZTeV indicated 20 mW/cm3 for the MB : expected to be around 20% lower for 7 ZTeV

Some uncertainties for quench levels remains for 7 ZTeV

[1]Testing beam-induced quench levels of LHC superconducting magnets – B.Auchmann
[2]Bound-free pair production from nuclear collisions and the steady-state quench limit of the main dipole magnets of the CERN Large Hadron Collider (M. Schaumann)

Power deposition – Simulation losses

- **Steady states losses :**
  - the heat deposited by particle showers in the Rutherford cables has time to spread radially
  - Investigation of the radially averaged peak power density

- **HL scenario considered in the simulation:**
  - 0.2h BLT :
    - Intensity of up to 2.23e11 ions
    - Corresponding to a loss rate of 3.64e8 ions/s
  - New collimator materials:
    - TCSGs in MoGr except TCSG.A6L7 /TCSG.A5L7 which remained in CFC
    - TCP.D6L7/TCP.C6L7 in MoGr
  - Beam energy of 7 ZTeV

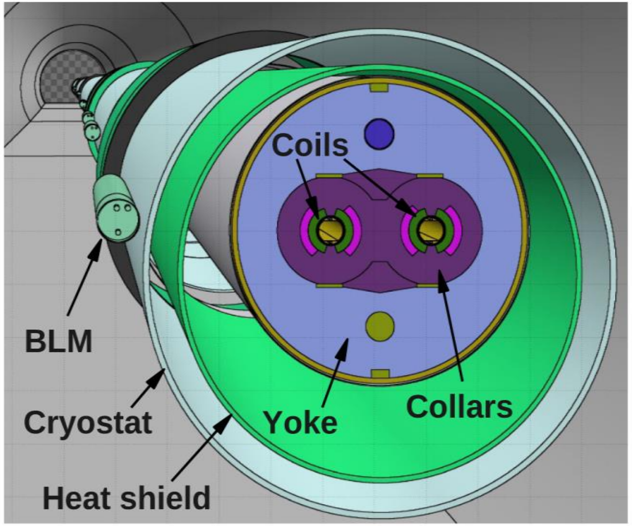
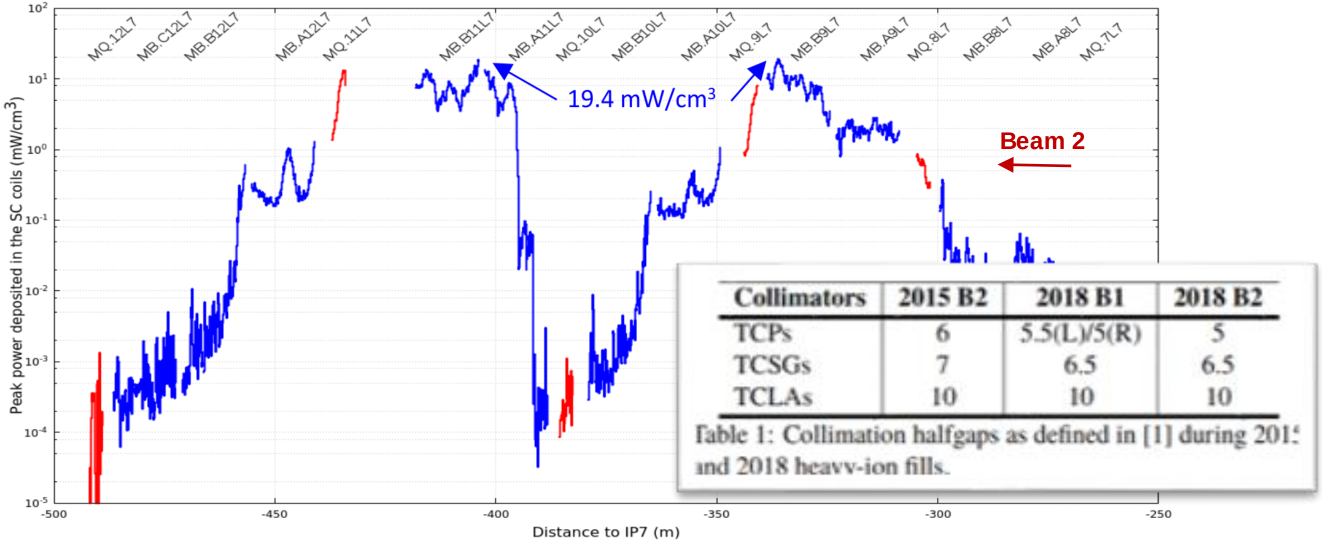


FIG. 1. Geometry model of a main arc dipole embedded in the LHC tunnel, with a BLM mounted on the outside of the magnet cryostat. [1]

[1] Validation of energy deposition simulations for proton and heavy ion losses in the CERN Large Hadron Collider (A. Lechner)

Power deposition – Reminder standard collimation Beam 2

Factor 3 coming from previous B2 benchmarks not included:



Collimators	2015 B2	2018 B1	2018 B2
TCPs	6	5.5(L)/5(R)	5
TCSGs	7	6.5	6.5
TCLAs	10	10	10

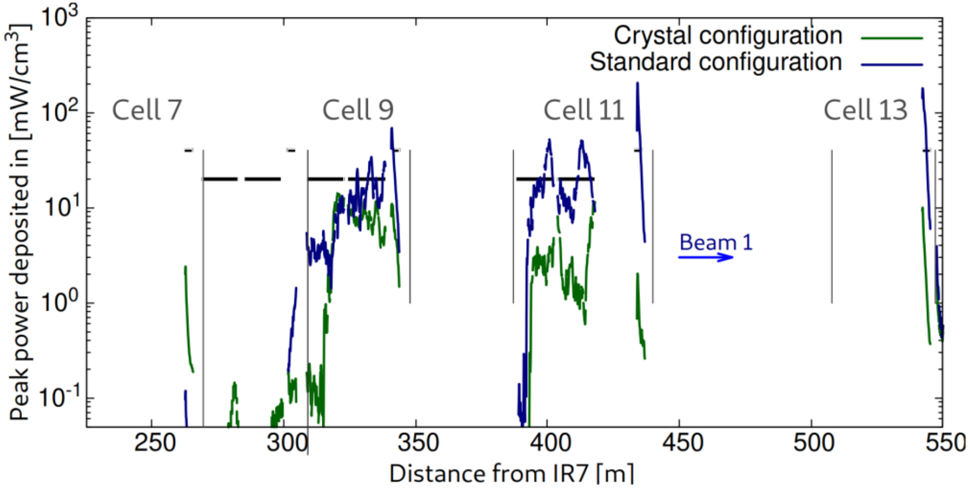
Table 1: Collimation halfgaps as defined in [1] during 201… and 2018 heavy-ion fills.

Figure: Radially-averaged peak power deposition [mW/cm3] in magnet coils along beam 2 with an 0.2h HL BLT [2]

- Power deposition done in 2018 for HL-LHC standard collimation
- Power deposition a factor 3 above quench limits (20 mW/cm3 for MBs)

[1] Simulations of heavy-ion halo collimation at the CERN Large Hadron Collider: Benchmark with measurements and cleaning perfomance evaluation (N. Fuster Martinez)
[2] Energy deposition from collimation losses in IR7 dispersion suppressor (C. Bahamond)

Power deposition – crystal vs standard quench margins



BLM benchmark factors applied !!

Crystal collimations provide a reduction of:

- At least a factor 1.5 for the MBs
- At least a factor 4 for the MQs

Assuming HL-LHC beam parameters, the power deposition for losses on Beam 1 should remain below the expected quench limits in case of a 0.2 h beam lifetime

Conclusion

- Crystal collimation losses in the DS are well reproduced by FLUKA BLM benchmarks
- Losses in the DS are coming almost exclusively from inelastic/EMD interactions in the crystal/ primary collimators.
- Satisfactory reduction of the power density in IR7-DS magnets with crystal collimation even though there is some uncertainties about the actual quench levels.
- A separate assessment for Beam 2 (crystal with different efficacity/ different beam settings) is ongoing.

Assuming HL-LHC beam parameters, the power deposition for losses on Beam 1 should remain below the expected quench limits in case of a 0.2 h beam lifetime using crystal collimation.

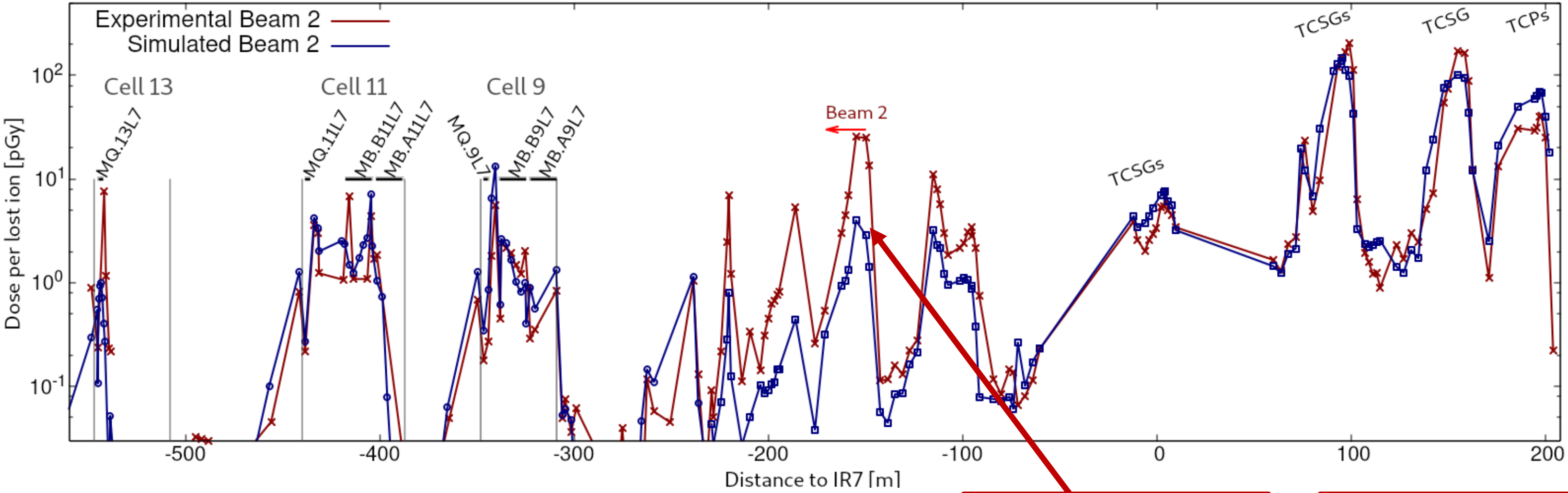
Backup
Benchmarks Beam 2

Benchmark summary

	Crystal collimation		Standard collimation	
	Beam 1	**Beam 2**	**Beam 1**	**Beam 2**
Cell 7-8	1	1	2	~1
Cells 9-11	1	1	2	~1
Cell 13	1/5	/	5	5

Those factors should be applied to the simulation of the energy deposition in the magnet coils

Benchmarks – Beam 2 Standard collimation



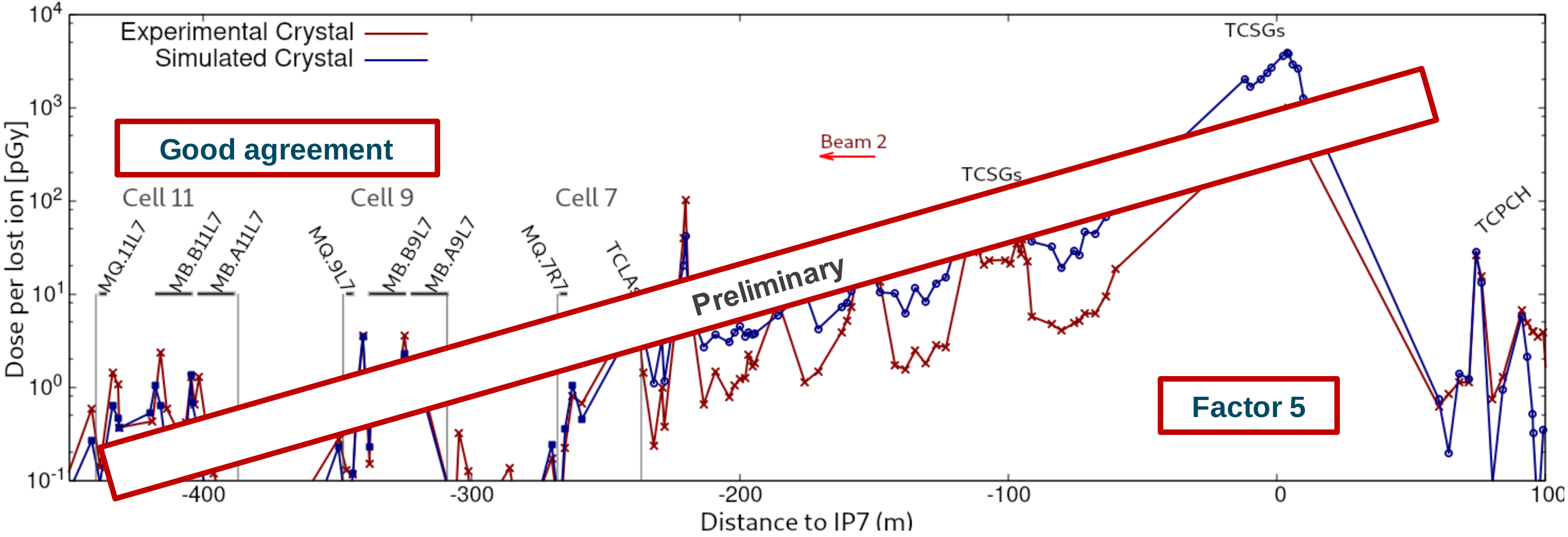
Cell 13 : factor 5 underestimation

Beam 1 crosstalk

Factor 2 TCPs

- Absolute comparison – around **30% precision on measurements.**
- Compared to 2015 benchmark (beam 2): Better agreement in the DS (factor 3) and at the TCPs (factor 3)
- Difference with 2015 simulation might be due to 2018 tighter collimators, which are here closer to HL-LHC settings

Benchmarks – Beam 2 Crystal collimation simulation



- Crystal study of the 27/11/18 MD at 14h27 - B2H
- Remarkably good agreement in the DS
- Reduces up to a factor 5 highest BLM signals in cells 9/11
- Presence of miscuts, angle of the impacting ions or lower channeling efficiency of the crystal could explain the Factor 5 in the LSS -> **investigation ongoing**