Update on collimation losses and halo limitations

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On behalf of WP5 & LHC Collimation teams

14th HL-LHC Collaboration Meeting, Genoa, Italy
07.10.2024

Collimation Challenges in HL-LHC

Quench Risk

IR7 DS (betatron collimation losses) and IR1/IR5 (collision debris)

Beam Halo

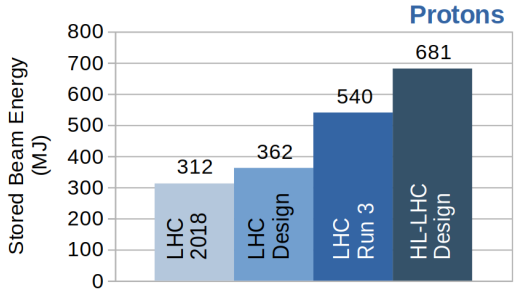
Threat to system integrity with fast failures

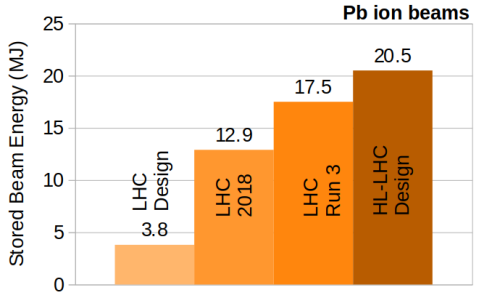
Impedance

Beam stability issues with higher beam intensities

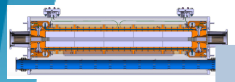
Heavy Ions

Quench risk (collimation & collision), backgrounds

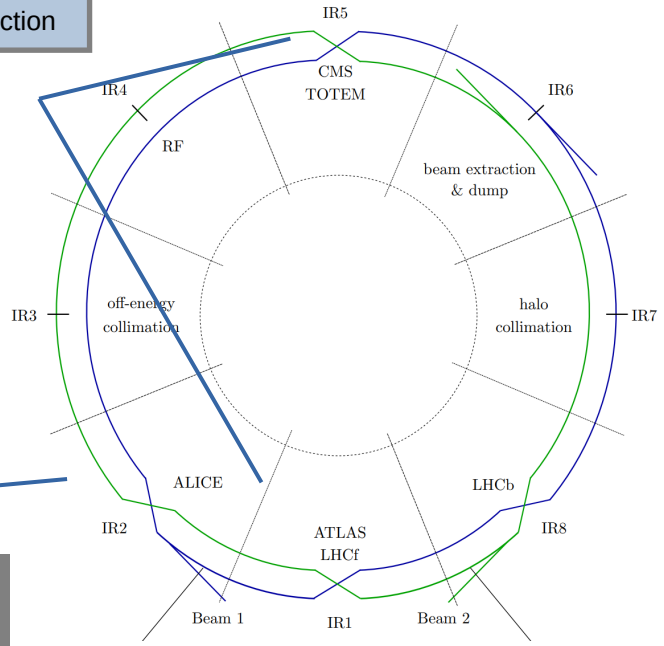


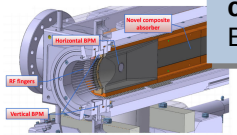


HL-LHC collimation system upgrades



IR1/IR5 Collimation
Quench & HW protection

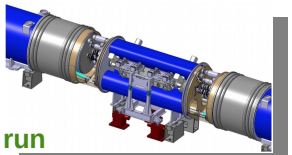




Low-impedance collimators
Beam stability

Phase I installed in LS2
Used routinely in Run 3

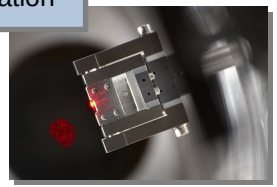
DS Collimators
Ion debris control



Installed
Used in ‘23 Pb run

Crystal collimators
Heavy-ion collimation

IR7



Installed
Used in 2023 Pb run

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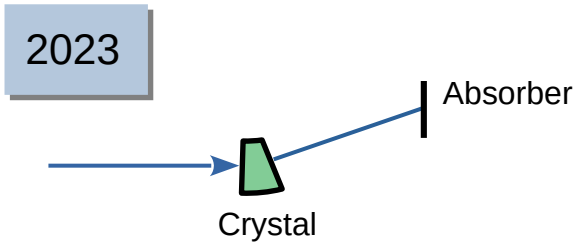
2023 Collimation Highlights: Pb Ions



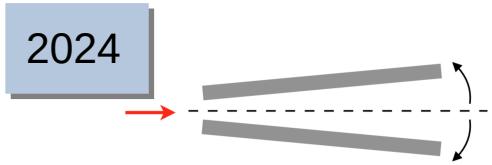
First operation with TCLD collimators in IR2

- Factor 6 higher luminosity in ALICE

First physics operation with crystal collimation

- Cleaning performance improved by factor > 5
- Issue with optimal crystal angle drift during fill

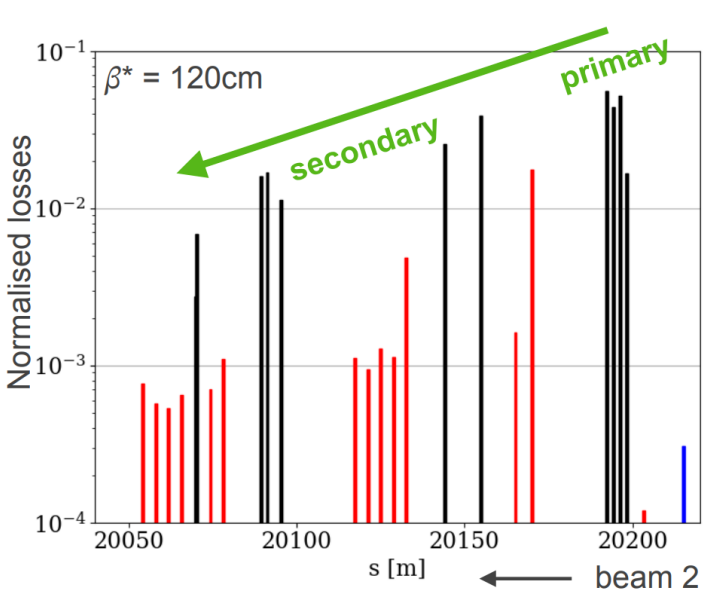
2024 Collimation Highlights

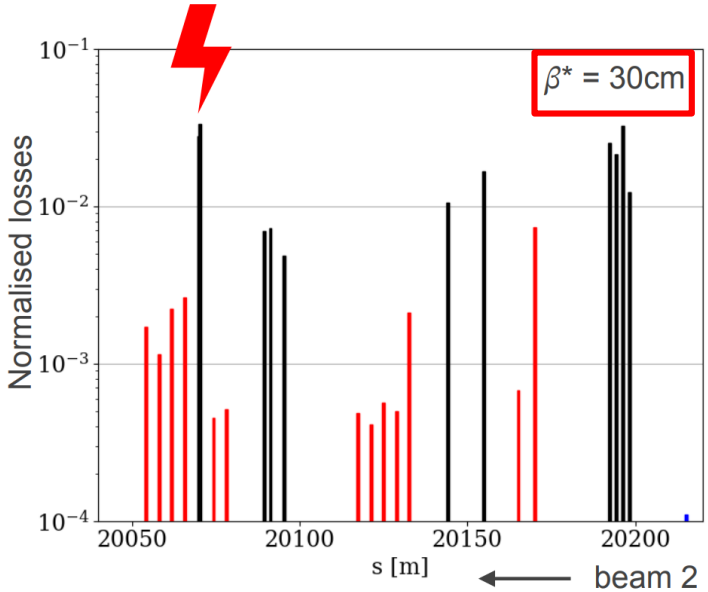


First deployment of **full collimation hierarchy with tilt angles**

- Excellent cleaning performance
- Important ingredient for tighter hierarchy & smaller β*
- IR7 loss distribution issue → next slides

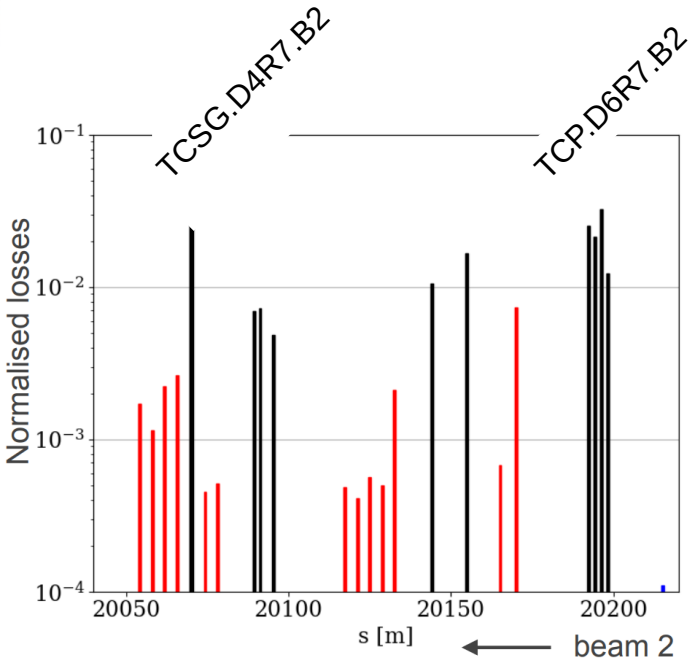
2024 Loss Distribution Issue





Courtesy of F.F. Van der Veken

2024 Dispersion / Local Optics Issue



Courtesy of F.F. Van der Veken

- Apparent breakage of collimation hierarchy
- Issue occurred at end of luminosity levelling (32.5cm → 30cm at intensities ~1.3x10^{11})

- Identified as
  - Beam-beam driven
  - High vertical dispersion at TCSG
  - Unfortunate phase space properties (increased $3Q_y$)

2024 Dispersion / Local Optics Issue

- Resolution after understanding of main effects involved:
  - **Reduced local dispersion**
  - **Reduced chromaticity and a3 correction**
- Illustrates the potential complexity of LHC collimation optimization

- **Good understanding achieved –**
  but must be studied in more detail for HL-LHC

Talks by E. Hamish Maclean (Tuesday)
And C.E. Montanari (Wednesday)

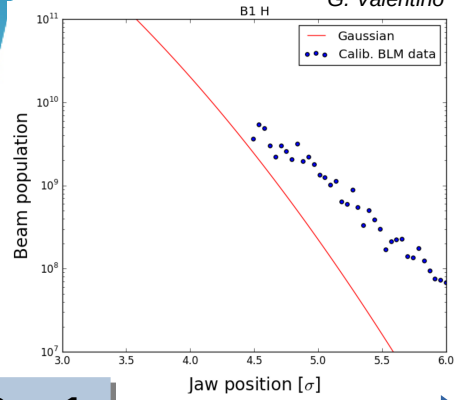
HL-LHC Collimation Status

Transverse Beam Halo

Assuming nominal σ with ε_N=3.5μm rad

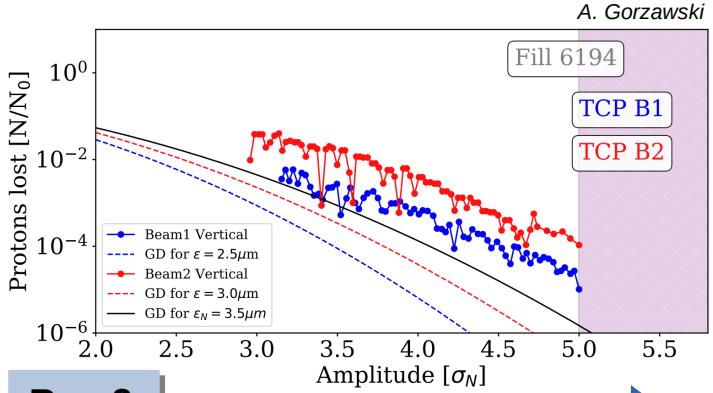
Halo Population

G. Valentino



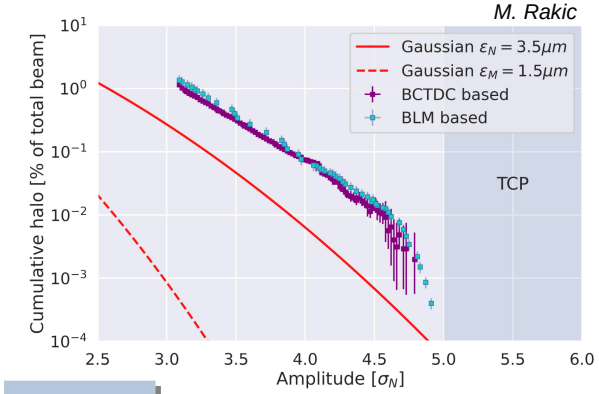
Run 1

A. Gorzawski



Run 2

M. Rakic



Run 3

- **Measured by collimator scraping**
- **Overpopulated halo:** found to 5% beyond 3σ in previous (Run 2) analyses
- **Potential threat for HL-LHC** if scales to post-LS3 beams – mitigation HW unavailable
- **Motivates** further **measurements**, extended **analysis**, exploring **alternative mitigation**

Revised Run 2 Measurements

Fill number	No. of Bunches	Final collimator position [σ] / Halo content [%] B1H	B1V	B2H	B2V	Halo content [%] at 3.0 [σ] B1H	B1V	B2H	B2V
4910	313	4.1	3.9	4.0	4.1				
		0.1	1.2	0.7	1.0				
5105	2076	3.8	3.1	3.1	3.4				
		0.0	1.7	0.9	0.2				
5834	900	3.0	3.0	3.1	3.1	4.6	2.5		1.4
		4.6	2.5	1.4	1.4				
5848	1741	3.2	/	3.1	/				
		8.7	/	8.1	/				
5849	2029	3.2	/	/	3.1				
		5.3	/	/	1.3				
6052	2550	3.7	3.3	3.5	2.8				2.8
		3.0	5.2	1.0	5.5				
6194	224	2.3	2.4	2.1	2.2	6.2	1.5	0.1	1.8
		29.5	7.9	6.8	19.6				
7221	2550	/	3.0	/	3.2		5.6		
		/	5.6	/	0.6				
7264	2550	2.9	3.1	3.3	2.8	1.5			1.0
		2.4	0.6	1.0	2.1				
7392	300	3.5	2.0	2.9	2.0		0.7	4.4	0.2
		10.0	9.4	5.7	2.5				

Courtesy of M. Rakic

Run 3 Halo Measurements (Selection)

Fill number	Stage	No. of Bunches	Final collimator position [σ] / Halo content [%] B1H	B1V	B2H	B2V	Halo content [%] at 3.0 [σ] B1H	B1V	B2H	B2V
8233	EOF	200	3.0	3.1	3.2	3.1	0.3	0.2	0.3	0.6
			0.4	**0.2**	**0.3**	**0.6**				
8313	EOF	1200	3.1	3.5	3.0	3.6	1.2		0.2	
			1.2	**0.6**	**0.3**	**1.4**				
8387	EOF	2462	3.5	3.7	3.7	3.4				
			0.9	**0.3**	**0.1**	**0.7**				
9754	INJ	624	2.8	2.8	2.7	2.7	3.3	1.5	1.8	1.8
			4.7	**2.8**	**4.0**	**4.5**				
9756	INJ	624	2.8	2.9	2.7	2.7	3.6	1.7	2.0	2.0
			5.0	**2.4**	**3.7**	**3.9**				
9808	EOF	1238	2.6	/	2.6	/	0.8		0.3	
			2.6	**/**	**1.1**	**/**				
9996	EOF	2351	3.1	3.2	3.2	3.5				
			0.7	**0.1**	**0.4**	**0.2**				
10045	INJ	96	/	1.7	/	1.5		1.3		1.3
			/	**26.5**	**/**	**31.5**				

Courtesy of M. Rakic

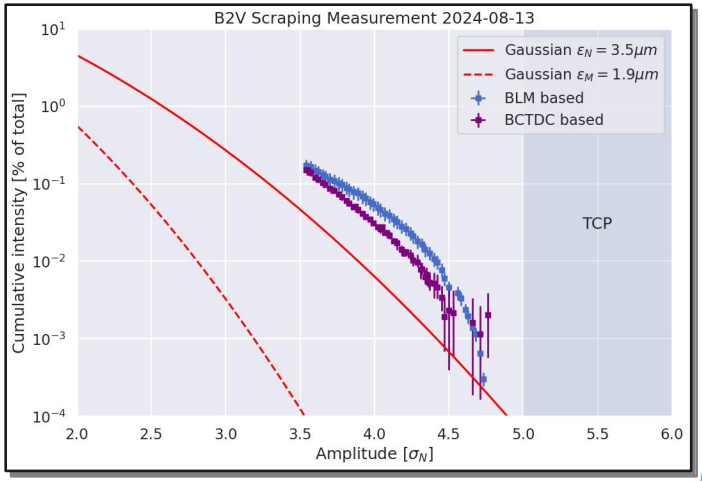
Run 2 vs. Run 3 Data

Run 2

- **High population** (>5% at >3σ) **confirmed** for isolated cases

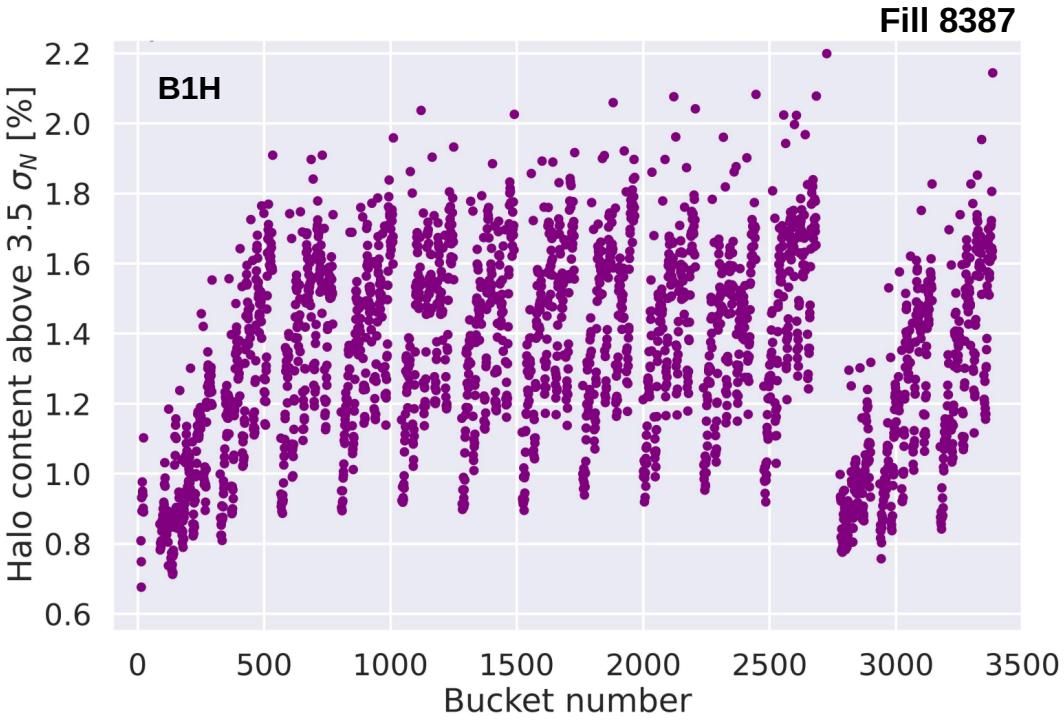
Run 3

- Above Gaussian (assuming 3.5 µm rad) but **less populated than Run 3**
- Higher halo population at injection (in MDs)
- Mostly smaller emittances than HL-LHC (2.5 µm rad)
- Remaining uncertainty on scaling to 2.5umrad



Courtesy of M. Rakic

Bunch-by-bunch halo analysis

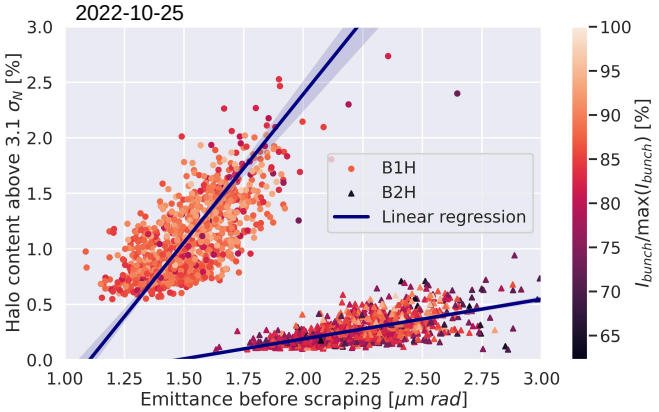


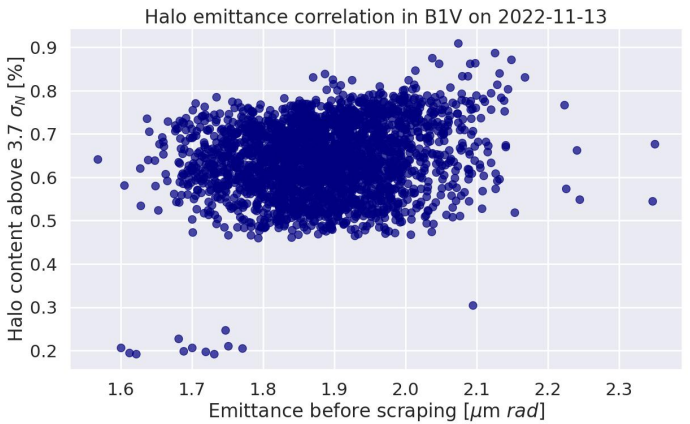
- Bunch-by-bunch variation observed in F-BCT analysis
- **Simply linked to emittance?**

Courtesy of M. Rakic

Courtesy of M. Rakic

Bunch-by-bunch halo analysis

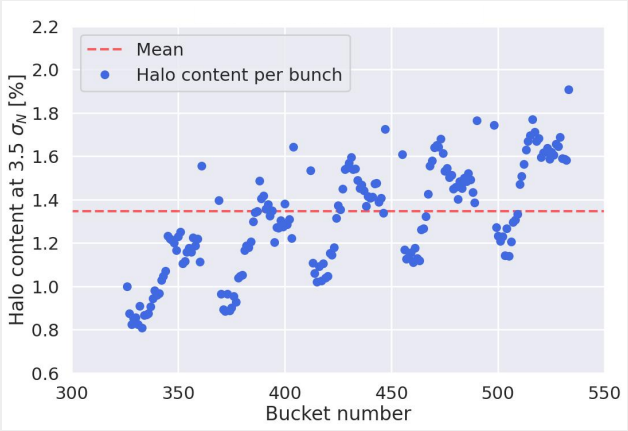




- Correlation observed in some measurements, uncorrelated in others
- Different correlation strength for different planes
- No clear conclusion

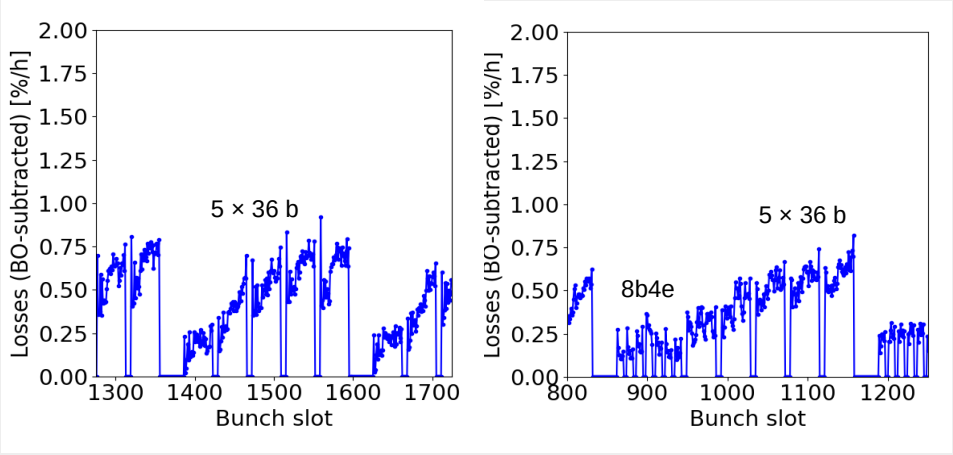
Electron cloud hypothesis

Measured beam halo



Courtesy of M. Rakic

E-cloud driven losses after hours in collision



Courtesy of K. Paraschou

Is halo linked to electron cloud effects?

Dedicated MD proposed and performed in 2024

Halo vs e-cloud MD 2024

Courtesy of M. Rakic

Merit

Study of halo for **different beam flavors**

Outcome

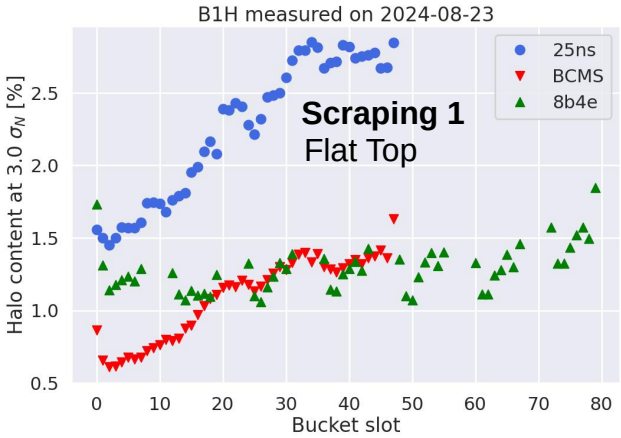
E-cloud effect confirmed! Likely from triplets

Complex setup: limited time in collision

Plan

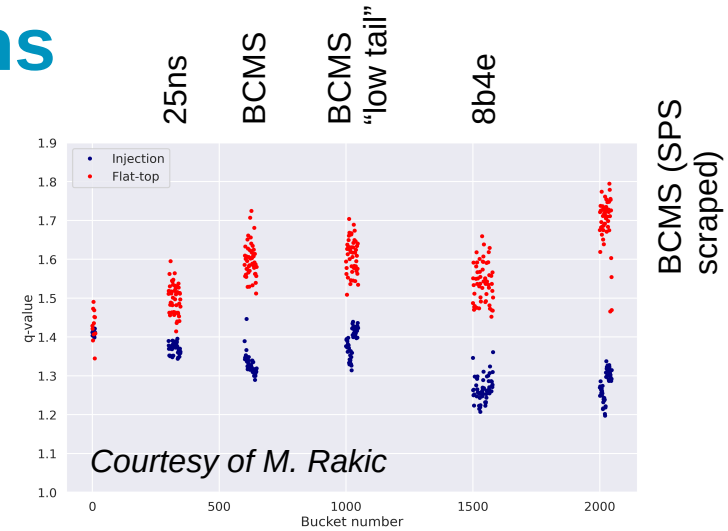
Repeat in MD5

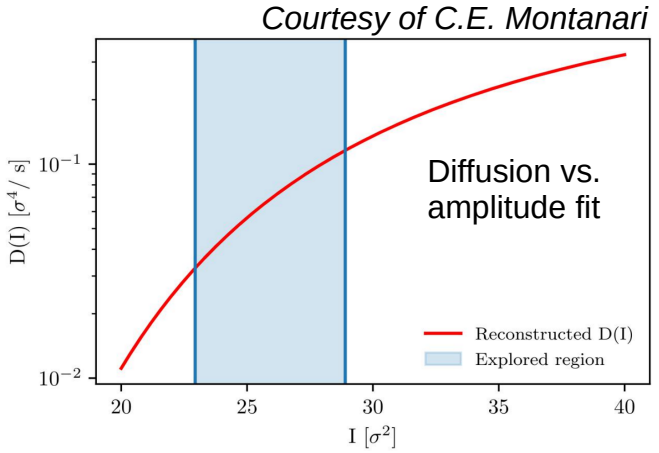
Longer collision phase & injection measurements



Halo Modeling & Simulations

- Simulations crucial: estimate impact of missing HELs
- **Starting over to review** using q-Gaussian
- Models used for simulations
  - Diffusion & halo formation
  - Depletion
  - Failure scenarios
- Increased efficiency: Xtrack with GPU





Talk by C. E. Montanari (Wednesday)

Halo monitoring in HL-LHC

Talk by J. Pucek (Wednesday)

- Halo monitoring is crucial
- Dedicated WG (BI, ABP, MPP) est. 2024
  - Applications
  - Specifications
  - Review of R&D and prototypes
  - MD plans (coronagraph)

LHC Coronagraph MD

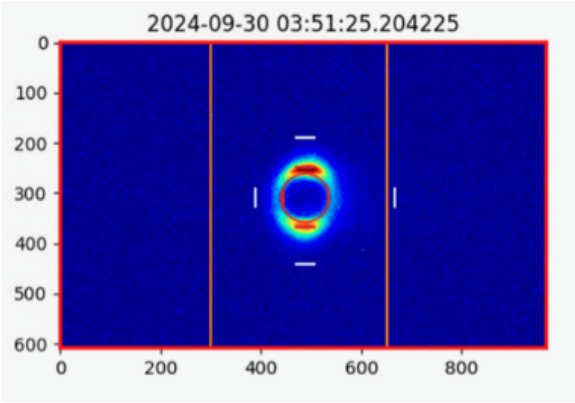


Figure: Courtesy of J. Pucek

Conclusions: Beam Halo

- **Halo with missing HEL remains critical** : work in progress
  - Less halo measured in Run 3
  - Detailed review & new measurements performed
  - Estimate of criticality & possible performance impact ongoing

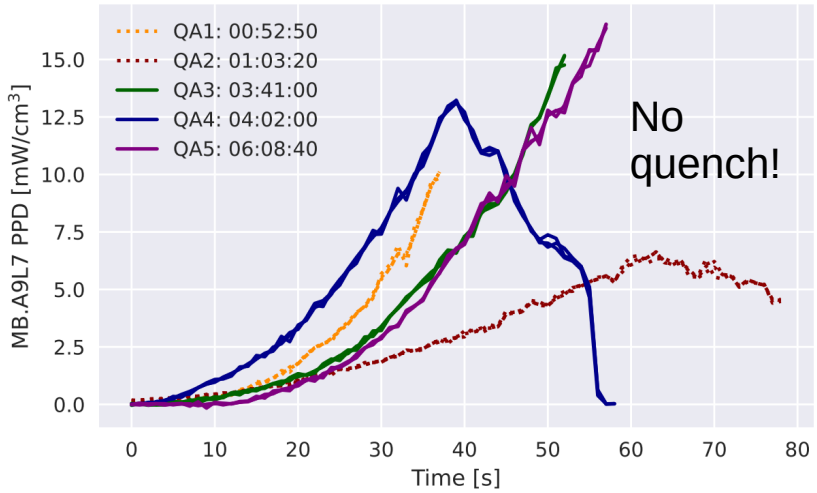
HL-LHC Collimation Status

Quench Risk

IR7 DS Quench Risk

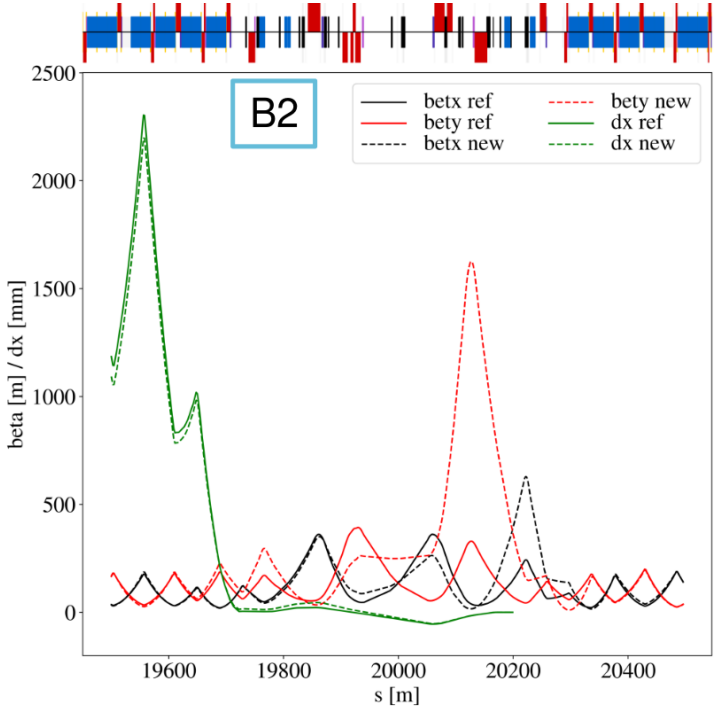
- Non-availability of IR7 DS collimators
- Issue with Pb ions with standard collimation (2015 Pb Quench Test)
- Crystal collimation installed as alternative mitigation strategy
- For protons likely no issue → nevertheless alternative mitigation studied (e.g. IR7 optics)
- Follow-up quench test (B1) planned 2024

2022 IR7 quench test (B2): 700kW, relaxed collimator settings



Updated IR7 Optics

Talk by B. Lindstrom (Tuesday)



- New optics developed in WP5 to increase β-functions at collimators
  - Improves impedance for given betatron cut
  - Improved collimation cleaning
- Increased single-pass dispersion TCP-TCSG: improved collimation cleaning
- Tested operationally in Mds: cleaning improvement up to ~67%!

Courtesy of B. Lindstrom

Conclusions: IR7 Quench Risk

Protons

- Seems under control with existing HW
- Additional margin thanks to new IR7 optics
- 2024 Quench Test expected to further reduce remaining uncertainties

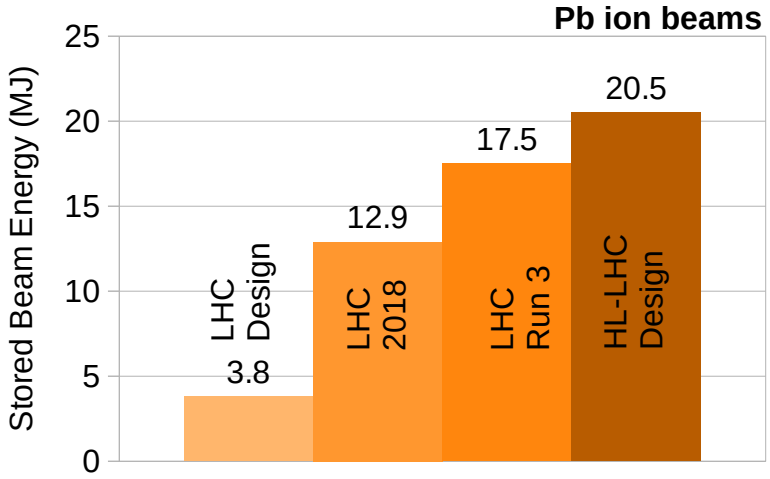
Heavy-Ions

- Quench risk with standard collimators
- Relies on crystal collimation

Heavy-Ion Operation

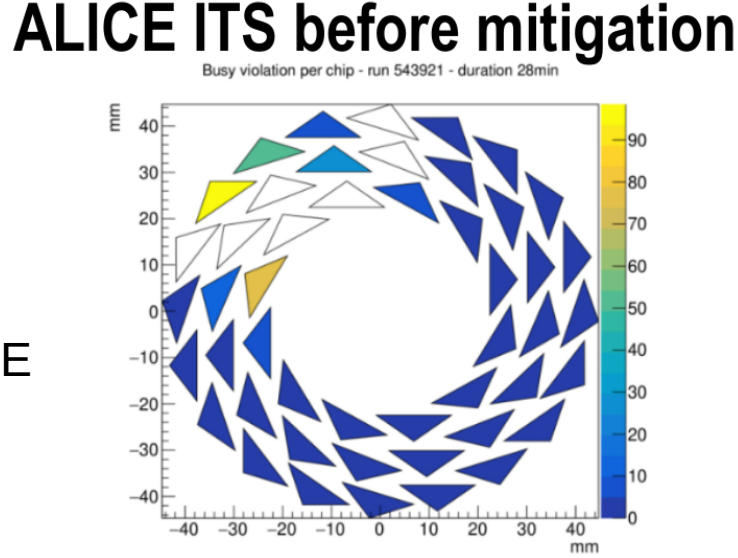
2023 Pb-Pb Run

- Slip-stacked 50ns beams used
  → **Pb HiLumi era has started!**
- Crystal setup and characterization very efficient (after replacement of one device during 2023)
- Excellent cleaning performance demonstrated!
- IR2 TCLD collimators / BFPP Bump
  → 6× higher ALICE luminosity
- Good system performance. But some issues encountered



ALICE background in Pb operation

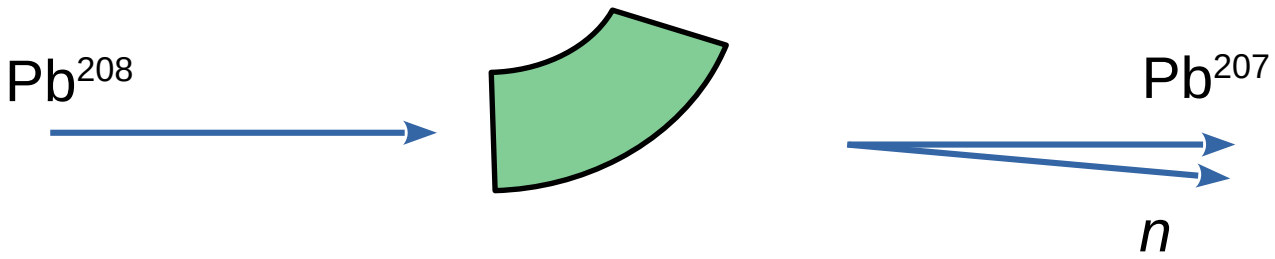
Strong background signal in ALICE



Severely affected data taking

ALICE background in Pb operation

Hypothesis: Electromagnetic Dissociation in IR7 crystal



ALICE background in Pb operation

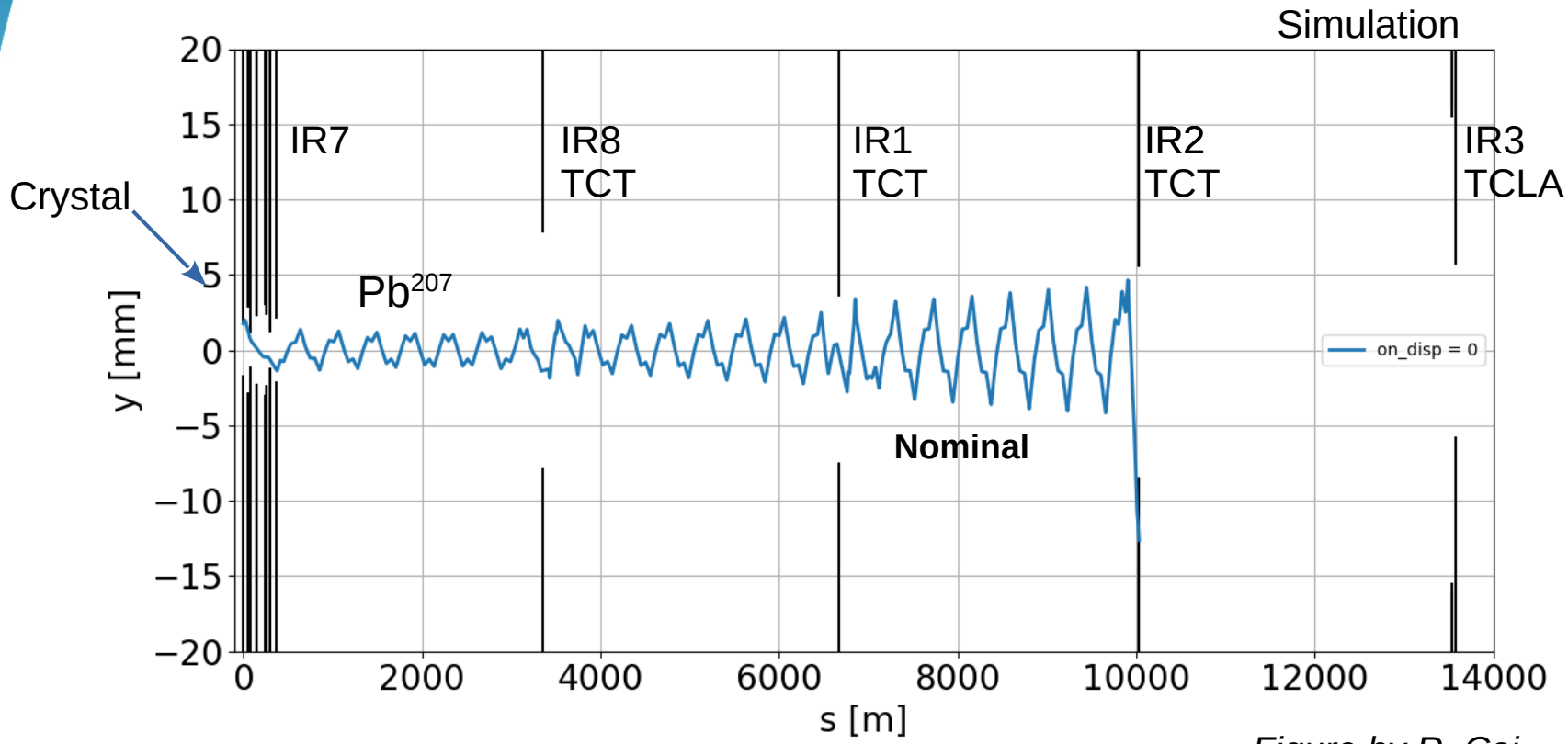


Figure by R. Cai

ALICE background in Pb operation

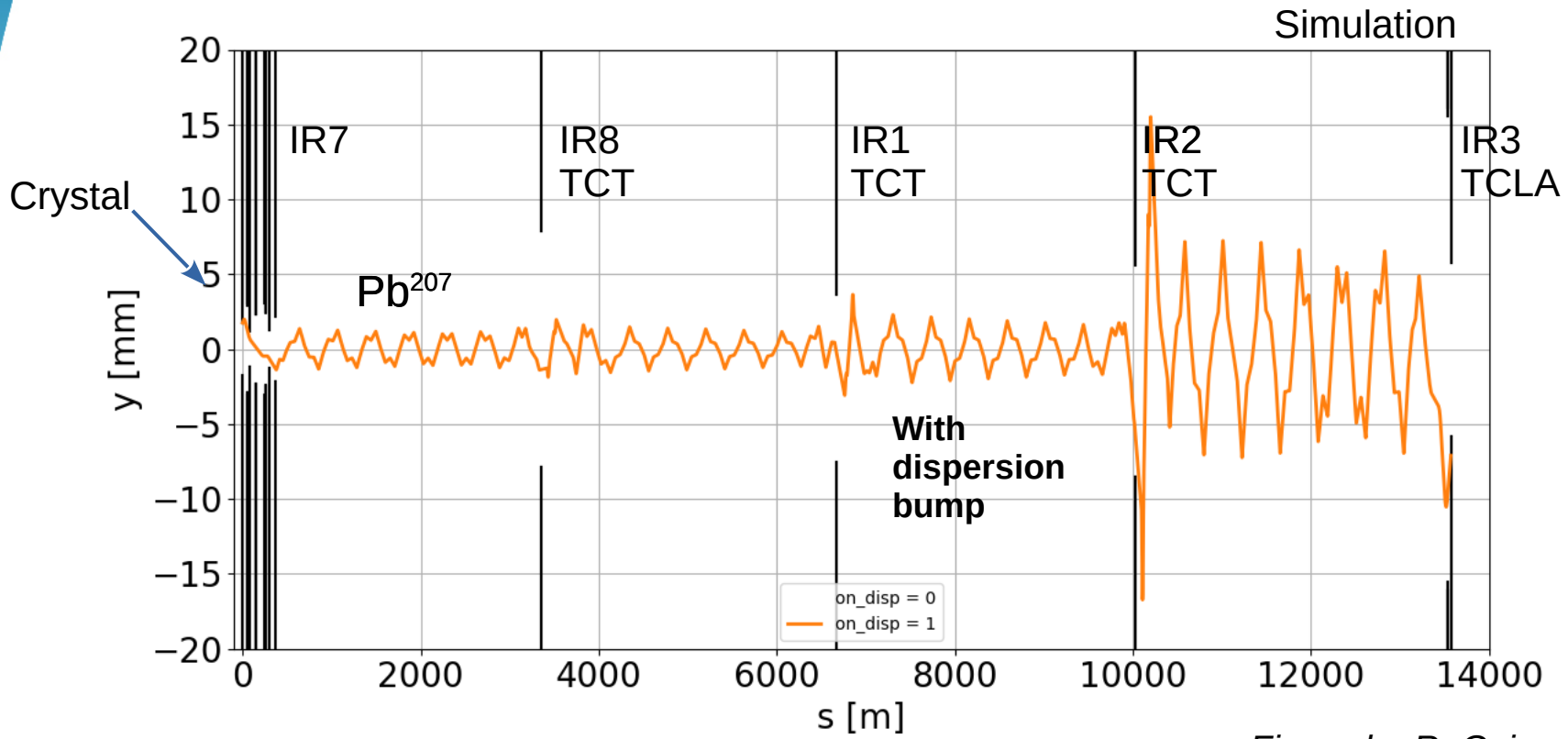
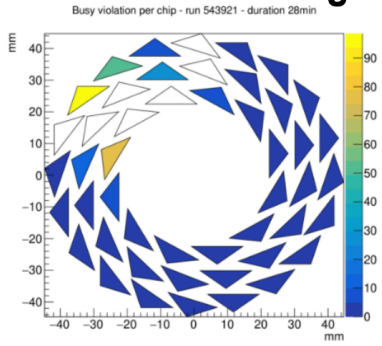


Figure by R. Cai

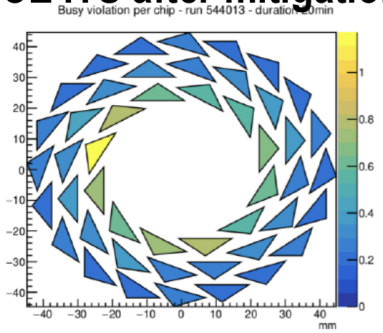
ALICE background in Pb operation

- Strong **background reduction** with dispersion bump
- Residual background from unknown origin remained but **data taking became possible**
- Example for improving understanding of potential issues in HL-LHC

ALICE ITS before mitigation

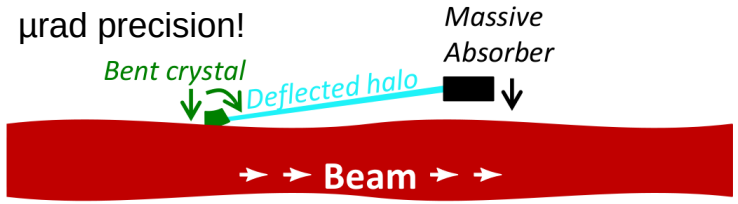


ALICE ITS after mitigation

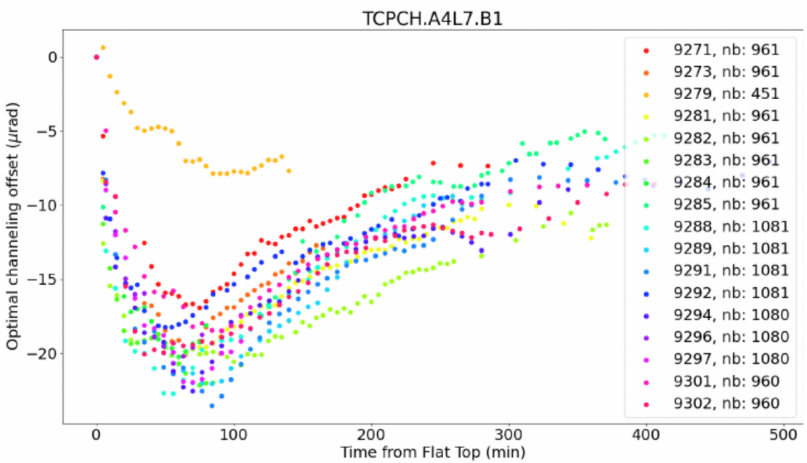


2023 Pb run: crystal collimation

- **Overall excellent cleaning performance**
- **But: optimal crystal orientation drifted**
  → reduced cleaning performance with time
- Possibly temperature, no solid conclusions
- Limited mitigation methods (automatic re-alignment, open collimator settings)
- **2024 objective: ensure compatibility with future Ion runs**



D. Mirarchi



Conclusions

- **Baseline collimation system upgrades well on track** & partially completed
  - Low-impedance upgrade partially completed: good performance!
  - TCLDs (IR2) installed and operated without issue
  - Crystal collimation operational with some issues → review required
  - IR1/IR5 hardware on track for installation in LS3
- **Absence of 11T dipoles likely not critical:**
  excellent system performance & revised IR7 optics
- **Halo with missing HEL remains critical** : work in progress
  - Less halo measured in Run 3
  - Detailed review & new measurements performed
  - Estimate of criticality & possible performance impact ongoing


HiLumi
HL-LHC PROJECT


CERN