BLM Thresholds

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JAPW24 Session 2 “Beam dynamics modelling <-> Equipment”

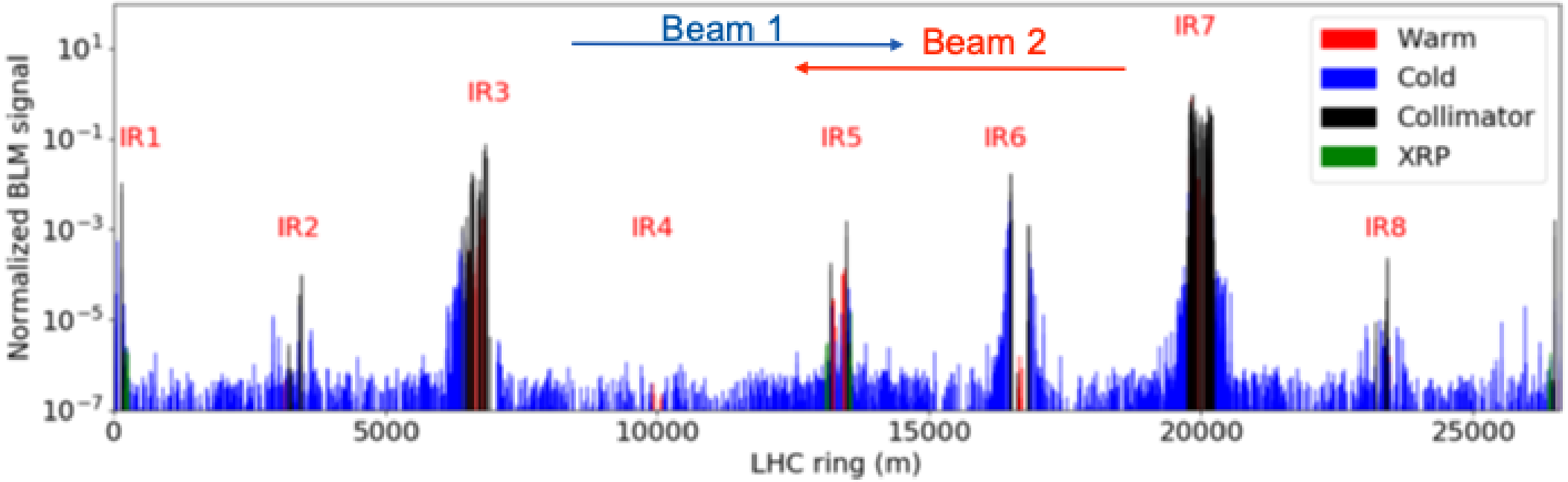
11/12/2024

Overview

- LHC BLM system
- LHC BLM thresholds strategy for Proton Runs
- Proton Run 2024: limitations and required changes
- PP Reference Run 2024: required changes
- Ion Run 2024: required changes

LHC BLM System

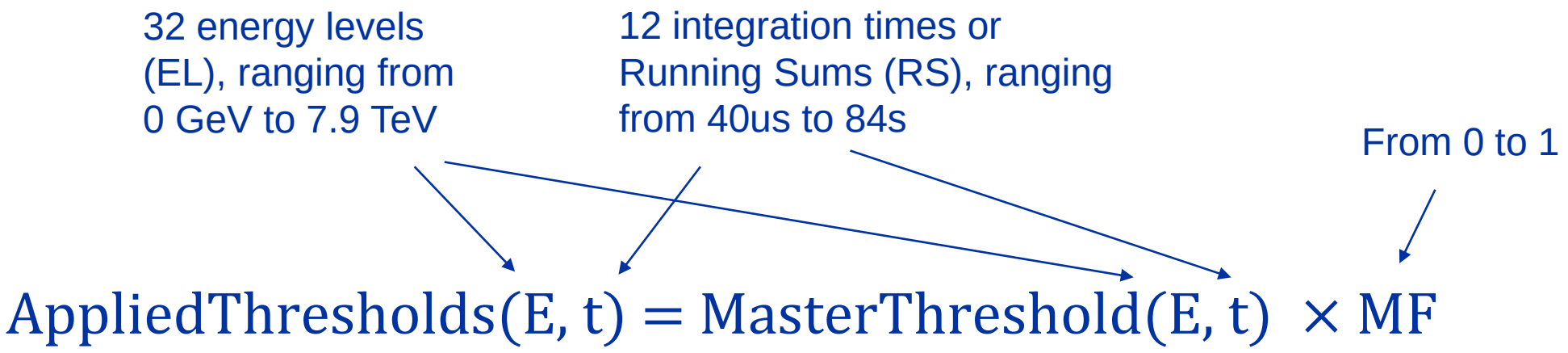
The main function of the BLM system is to protect actively the machine against energy deposition from beam losses -> **quench prevention and protection of devices**



~4000 BLM detectors placed downstream the most likely loss locations
Ionization Chambers (IC), Little Ionization Chambers (LICs), Secondary Emission Monitors (SEMs), Diamond-based BLMs (dBLMs)

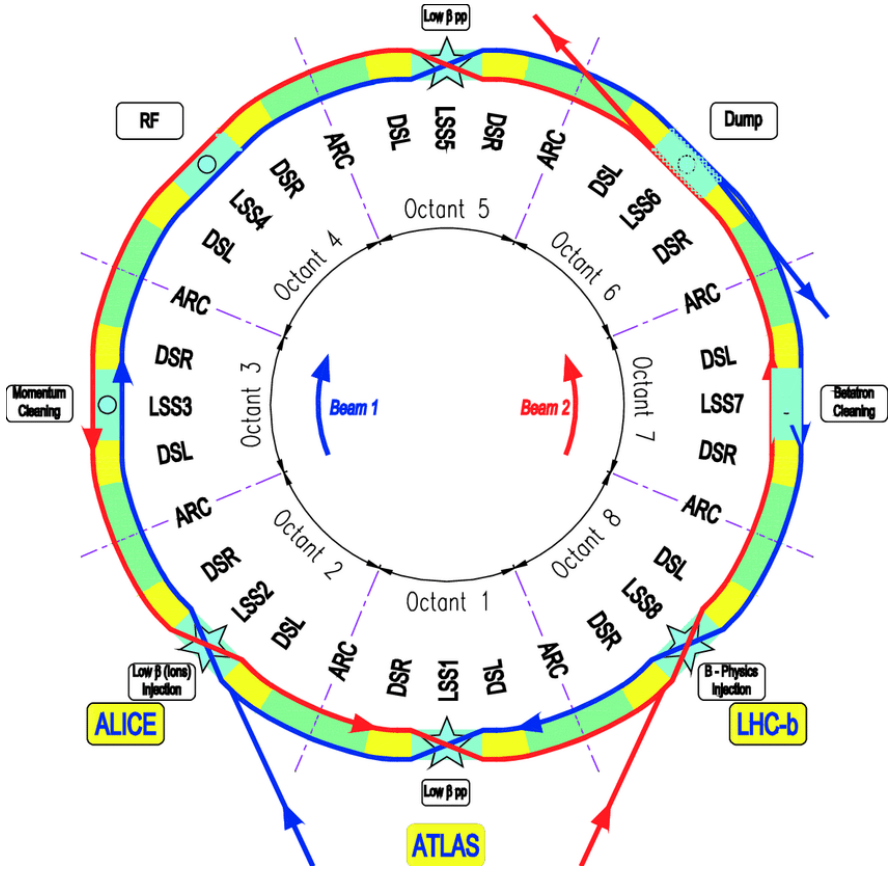
LHC BLM System: Thresholds

- **Master thresholds** according to different expected **loss scenarios and damage/quench limits**
  - **Beam losses modelling**
- BLMs grouped in master thresholds families, each BLM with a different **monitor factor (MF)**



Each BLM thresholds family will have implemented values for each RS (12) and each EL (32), making it a total of 384 values -> 1.5 million settings -> **critical settings management challenge**

LHC BLM System: Thresholds strategy for Proton Run



IR3 collimators/magnets and TCTs still using pre-LS2 models

- Superconducting magnets: Dust particles (UFOs) dominant source of transient beam loss events in the LHC arcs and DS
  - Master thresholds at 3x the quench level in short RS (40us – 2.5ms), and MF = 0.333
  - Thresholds reduced at selected locations which could be affected by hardware non-conformities

- Colliding IRs: BLM threshold families in the experimental insertions (IR1/5/8) have increased thresholds in the long RS (0.08s - 84s) to avoid constant warnings (30%) due to the physics debris leaking from the experiments
  - Increased thresholds only active at top energy

- IR7 collimators: BLM thresholds adjusted to the specifications for losses in the entire IR7 collimation system
  - Reviewed during LS2
  - IR7 warm and Q6 magnets are sensitive to IR7 collimation leakage -> thresholds aligned to IR7 collimation thresholds in the long RS (RS08-RS12) at the end of the ramp and at top energy

LHC BLM System: Thresholds strategy for Proton Run

Threshold Model

$$\text{Master Threshold}[RS][EL] = f_{\text{corrections}}\left(Q_{\text{BLM}}[RS][EL] \times N_{\text{p}}[RS][EL] \right)$$

$f_{\text{corrections}}(\text{thresholds}[RS][EL])$

A set of functions that allow for very flexible changes, so called ad-hoc corrections

$Q_{\text{BLM}}[RS][EL]$

Response Factor:
Expected BLM signal per proton lost

NEW from measurements!

$N_{\text{p}}[RS][EL]$

Damage limits:
Maximum number of protons allowed.

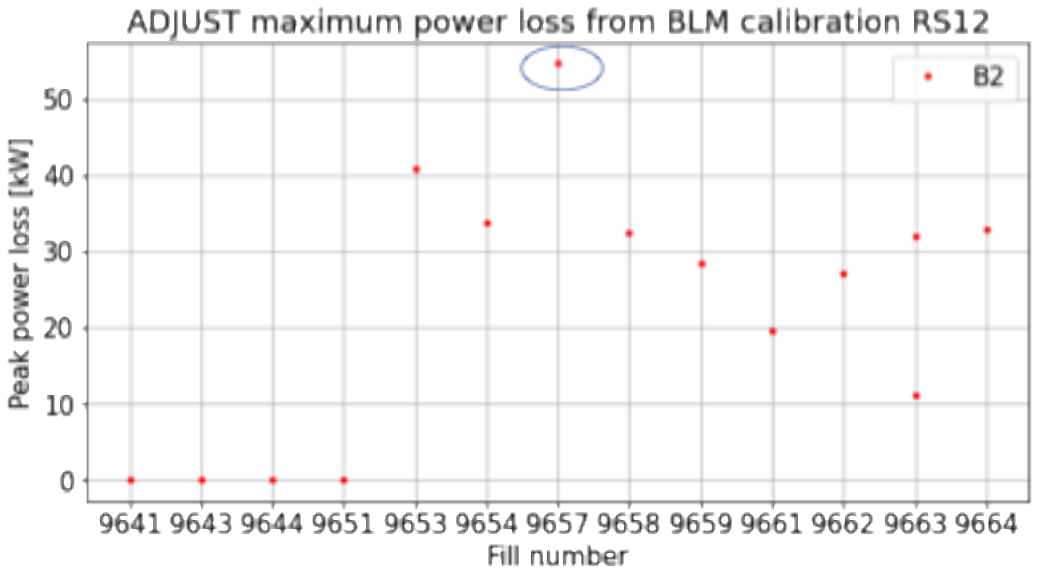
Updated values

	Duration	Master thresholds	Applied thresholds (MF=0.6)
RS09	1.31 s	500 kW	300 kW
RS10	5.24 s	500 kW	300 kW
RS11	20.97 s	239 kW	143 kW
RS12	83.89 s	100 kW	60 kW

Beam lifetime and power loss regularly monitored to verify correct thresholds settings -> BLM calibration (BCT signals when calibration is not possible, but signal averaging needed over several seconds)

Proton Run 2024 - Adjust

- Moment of **highest losses in IR7 throughout the cycle** -> beams brought into collision
- At the start of the 2024 proton run, **RS12 BLMs reaching warning and even dump levels for B2**
- MF = 0.6, allowing 60kW in RS12 for Run 3 -> **BLM thresholds well aligned with the allowed power loss in RS12 for Run 3** using the BLM calibration with RS12

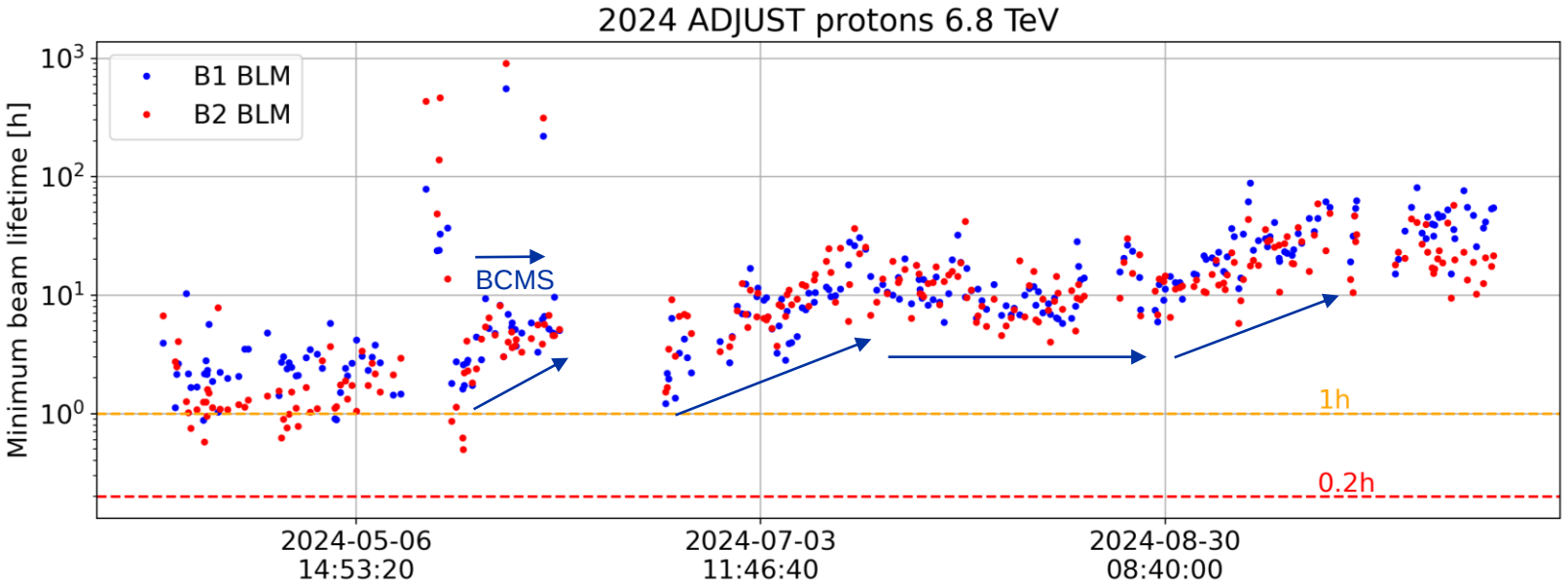


- Thresholds increased by a factor of 2 at selected BLMs in IR7 -> Change applied 25/06/2024, LHC-BLM-ECR-0081
- **Today, BLM RS12 in IR7 collimators set according to HL-LHC specifications, but the collimation acceptance limits for slow losses (RS12) for HL-LHC need to be reviewed if it could be increased further (LS3)**

Discussions in 99th BLMWTG

Proton Run 2024 - Adjust

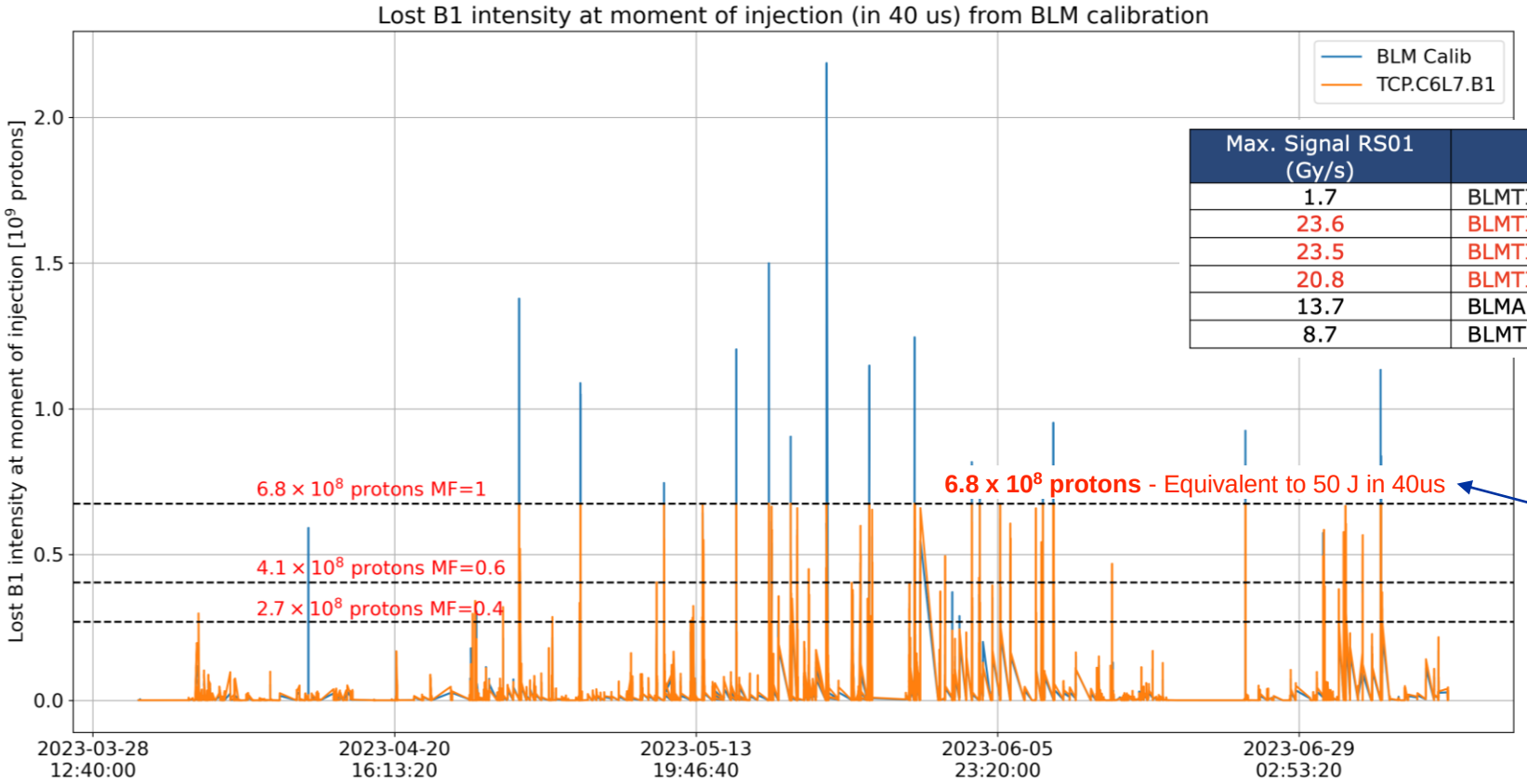
- Moment of **highest losses in IR7 throughout the cycle** -> beams brought into collision
- At the start of the 2024 proton run, **RS12 BLMs reaching warning and even dump levels for B2**
- The beam lifetime was indeed well below 1h at the start of the year, but **by the time RS12 (~83 s integration time) was triggering, the lifetime had already recovered**



Beam lifetime improving with the introduction of BCMS beams!
But there seems to be also another source of optimization

Proton Run 2024 - Injection losses

During the **2023 proton run, fast losses (40 us) in IR7 during the injection of B1** were reaching the saturation limit (23 Gy/s) of the IC detectors at the primary horizontal and skew primary collimators



Max. Signal RS01 (Gy/s)	IC BLM name	IC BLM dcum (m)
1.7	BLMTI.06L7.B1E10_TCP.D6L7.B1	19789.80
23.6	BLMTI.06L7.B1E10_TCP.C6L7.B1	19791.80
23.5	BLMTI.06L7.B1E10_TCP.B6L7.B1	19793.80
20.8	BLMTI.06L7.B2I10_TCLA.B6L7.B2	19807.98
13.7	BLMAI.06L7.B1E10_MBW.B6L7	19818.01
8.7	BLMTI.06L7.B2I10_TCLA.A6L7.B2	19839.12

Estimation of protons impacting the primary collimators during injection from BLM calibration

Several mitigations measures considered for the **EYETS 23-24 (short term)** and LS3 (long term)

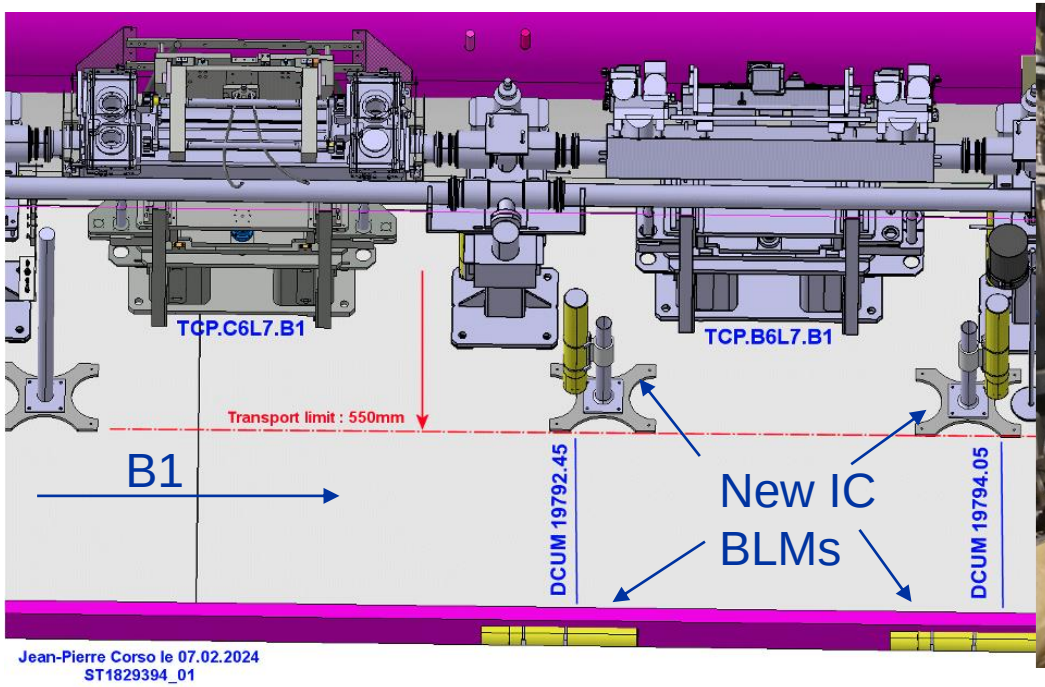
Proton Run 2024 - Injection losses – Actions during EYETS 23-24

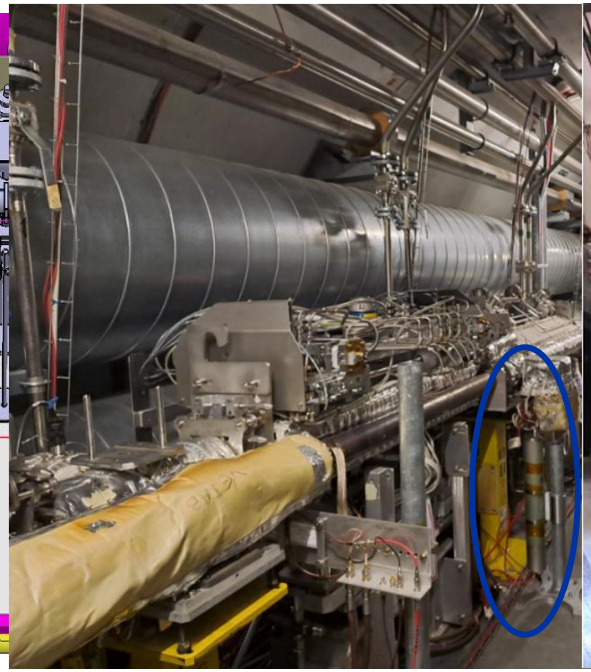
- Installation of additional BLMs in IR7, in the **internal side and tunnel wall** -> try to reduce the sensitivity for the most limiting cases (**TCP.C6L7.B1, TCP.B6L7.B1, TCLA.B6L7.B2**)

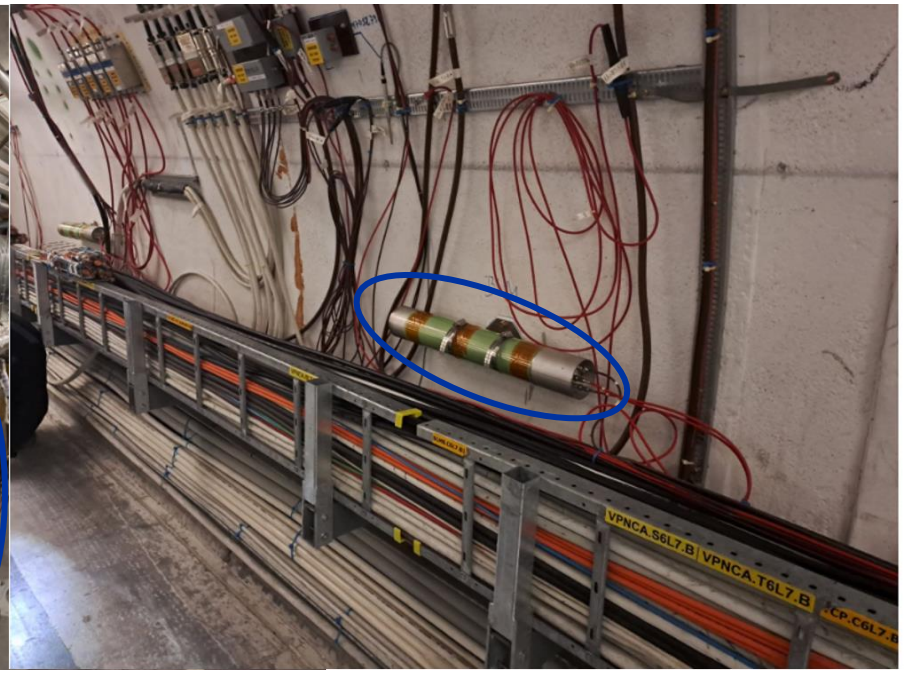
- Replacement of SEM BLMs by LIC BLMs ->

BLM type	Conversion Gy/BLMbit	Ratio to IC
IC	3.62×10^{-9}	1
LIC	5.07×10^{-8}	14
SEM	2.53×10^{-4}	69890

Estimated before the start of the LHC







Proton Run 2024 - Injection losses

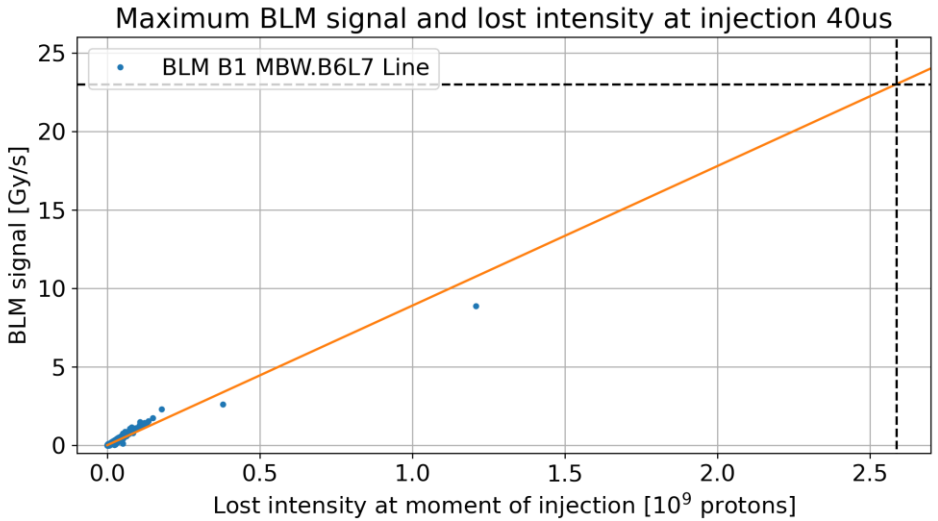
- Installation of additional BLMs in IR7, in the **internal side and tunnel wall** -> try to reduce the sensitivity for the most limiting cases (**TCP.C6L7.B1, TCP.B6L7.B1, TCLA.B6L7.B2**)

  It did for the ones on the wall! Signal reduction of a factor ~10, depending on the loss scenario
  Interlock functionality moved to the 3 IC BLMs on the WALL since 23/04/2024, LHC-BLM-ECR-0080

- Replacement of SEM BLMs by LIC BLMs

  Expected reduction in sensitivity of ~14 is observed, further studies and simulations on-going

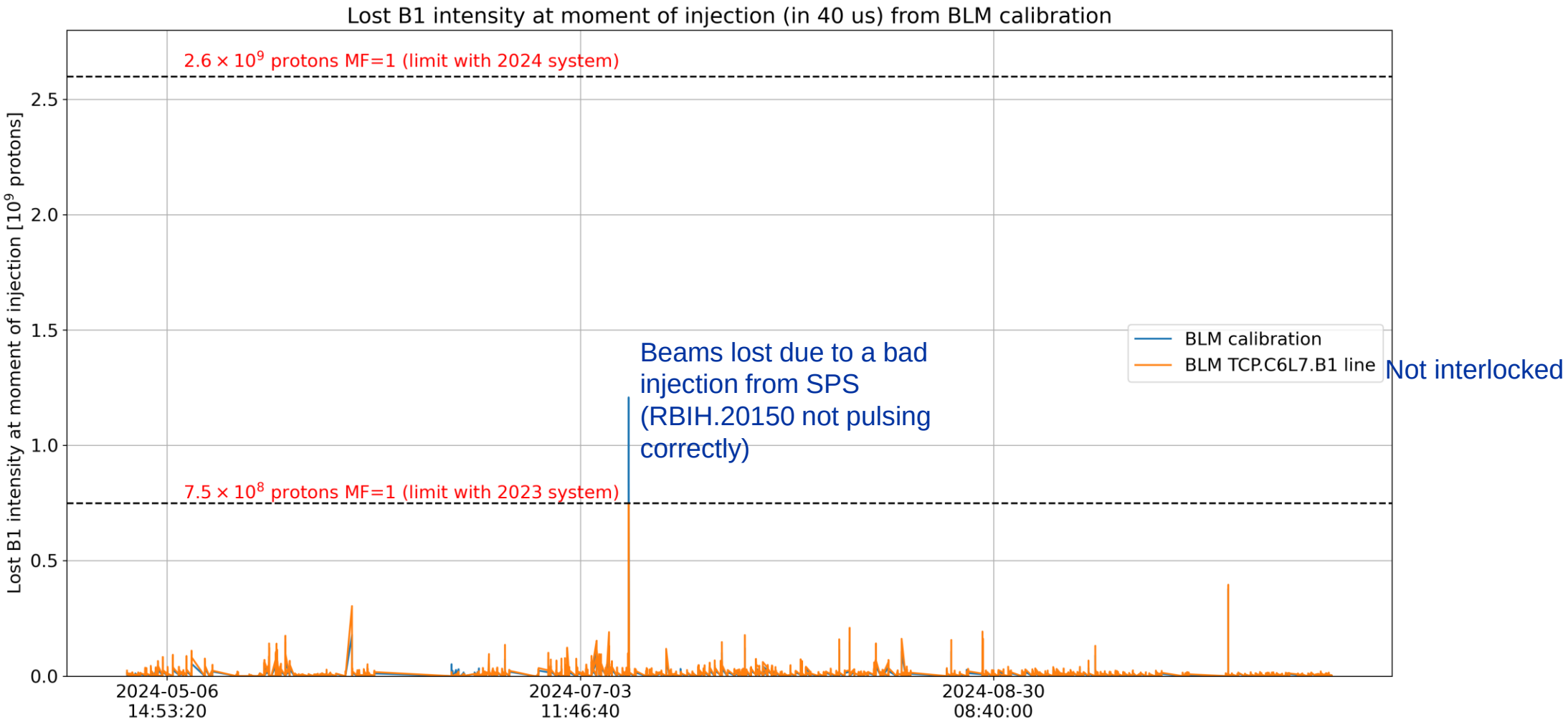
- **The current limitation is due to BLMs that were not moved to the wall**
  - **~2.6×10^9 protons lost in 40us -> For remainder of Run 3**
  - Agreed with OP that a reasonable limit for regular operation would be of around a nominal (10^{11} protons)
  - This is expected to be achieved with the installation of LIC BLMs on the wall -> Not before LS3



Discussions in BLMTWG joint meeting with MPP and Collimation WG and 200th HL-LHC TCC

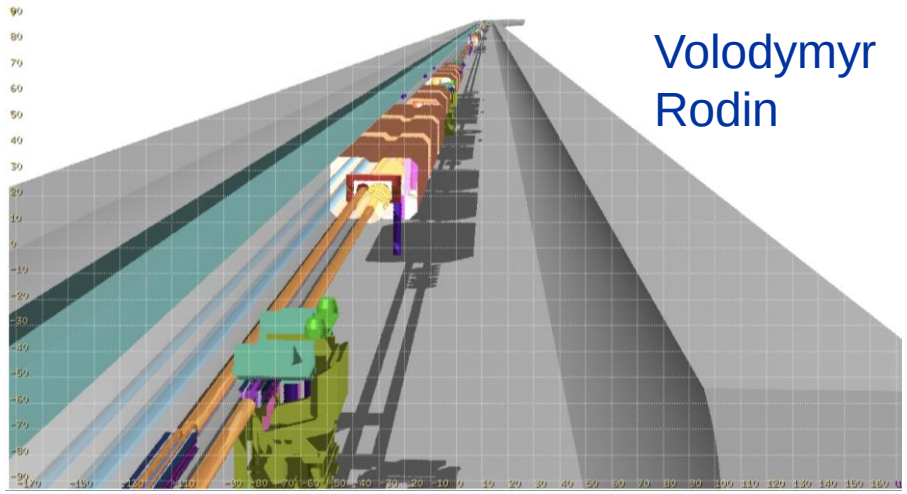
Proton Run 2024 - Injection losses

This year, much lower injection losses -> different injection scheme

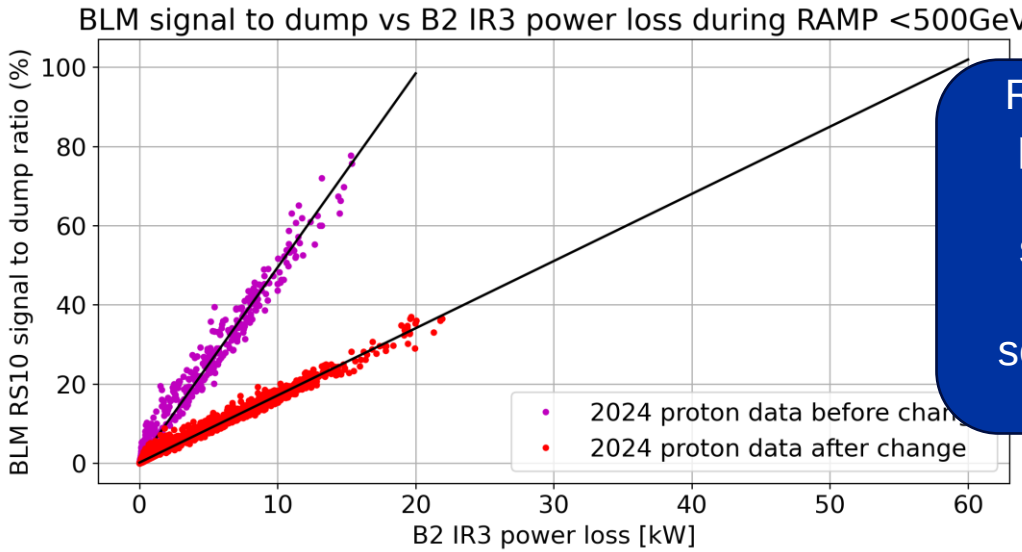


Proton Run 2024 – Start of ramp losses

- Moment of **minimum beam lifetime overall** in the LHC during regular operation -> Losses in **IR3 (mainly) and IR7**
- IR3 BLM thresholds currently under study to provide a model similar to IR7 -> Based on tracking (SixTrack), energy deposition (FLUKA) and thermo-mechanical simulations (Ansys)
- Main limitation in the 2024 proton run at the start of the ramp **was** in the Q6L3 BLM RS10 (~5.2s integration time)
- Threshold increased by a factor of 2 as a **temporary measure before studies are completed** -> Changes implemented on 25/06/2024, LHC-BLM-ECR-0082



Volodymyr Rodin

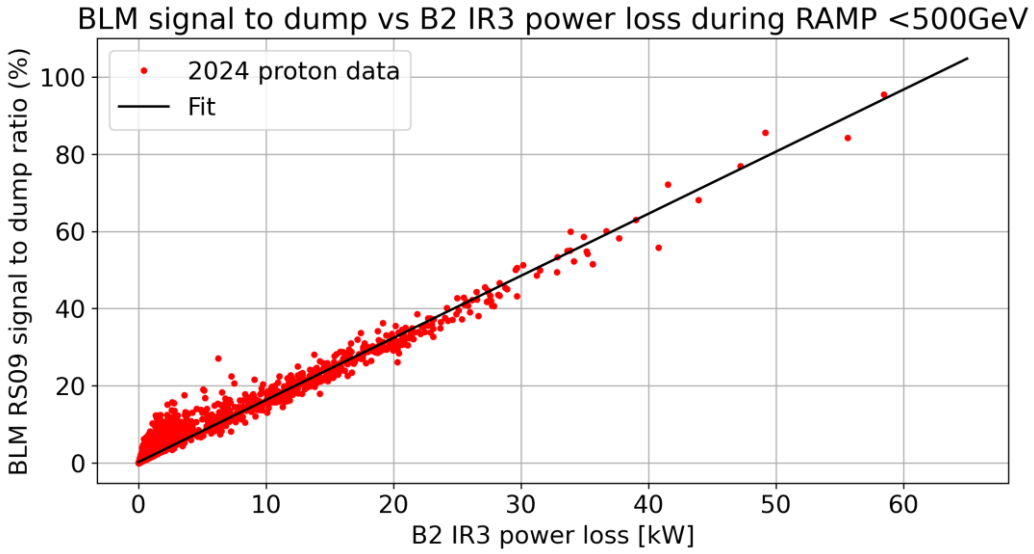


RS10 limit at a power loss of 60kJ for ~5 seconds now (20kJ for ~5 seconds before the change)

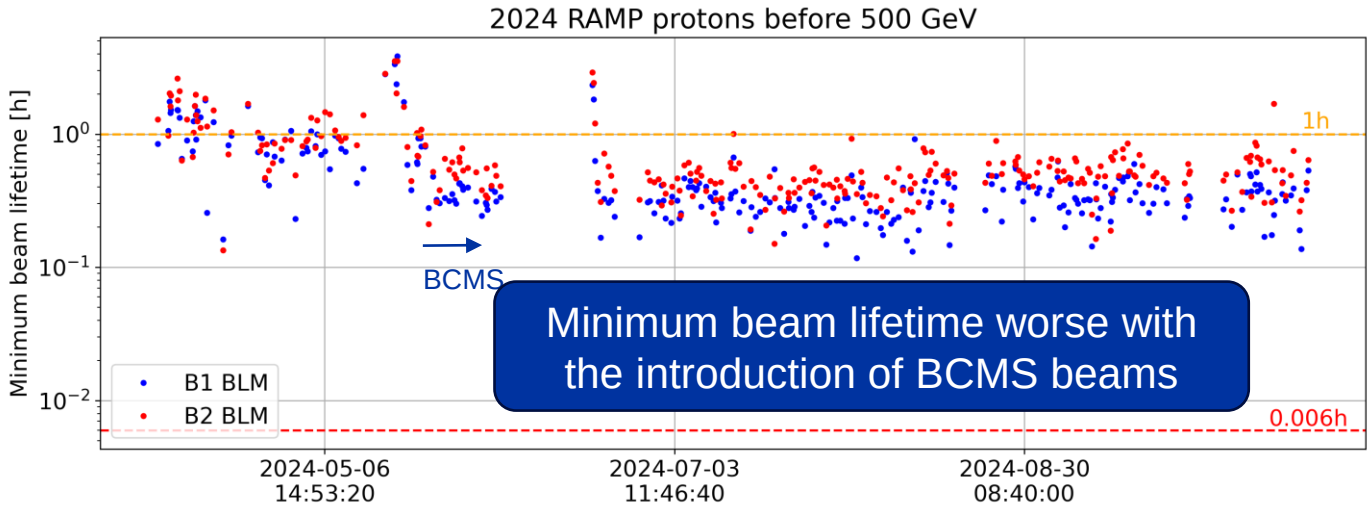
Discussions in 100th and 101st BLMTWG meetings

Proton Run 2024 – Start of ramp losses

- Moment of **minimum beam lifetime overall** in the LHC during regular operation -> **IR3 (mainly) and IR7**
- IR3 BLM thresholds currently under study to provide a model similar to IR7 -> Based on tracking (SixTrack), energy deposition (FLUKA) and thermo-mechanical simulations (Ansys)
- Main limitation now in the same detector but RS09 (~1.3s integration time)



RS09 limit at a power loss of ~60kJ in ~1s



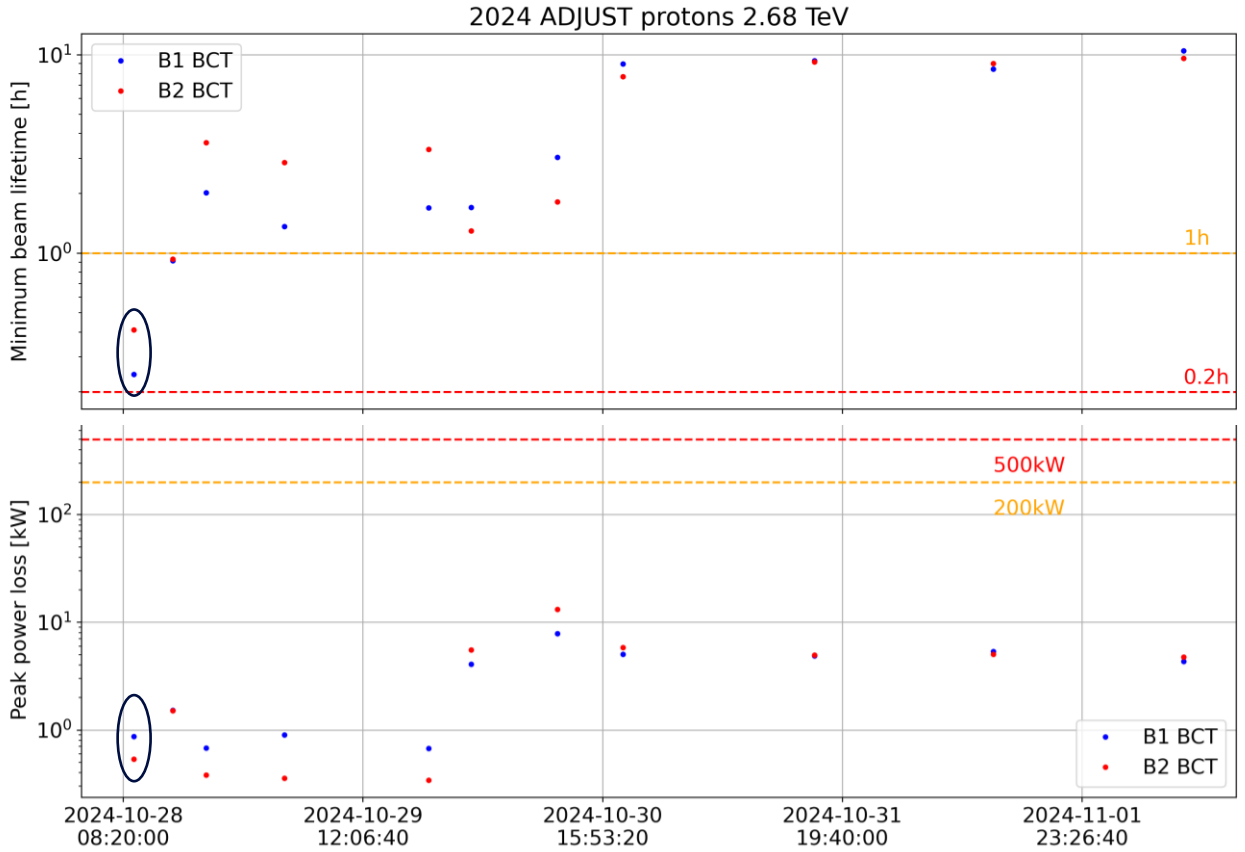
Minimum beam lifetime worse with the introduction of BCMS beams

Estimated quench levels for slow losses at the MQTL (LS1 values) are much lower compared to other magnets (see 101st BLMTWG meeting) -> limits homogenized already this year for the Ion Run, providing more margin

PP reference Run 2024: required changes

- Colliding IRs: Different energy for stable beams! -> Changes to avoid constant warnings in BLMs during collisions
  - Still, some BLMs <40% at start of collisions -> **Not limiting -> No additional changes done**

- IR7 collimators: Allow 500kW losses in master thresholds at 2.68 TeV -> Based on loss maps, thanks to OP for advancing!
  - Low lifetime, but also low equivalent power losses! -> **No BLM dumps**



Changes applied on the 21/10/24, LHC-BLM-ECR-0084

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- Colliding IRs: Different energy for stable beams! -> Changes to avoid constant warnings in BLMs during collisions
  - Still, some BLMs <40% at start of collisions -> **Not limiting -> No additional changes done**

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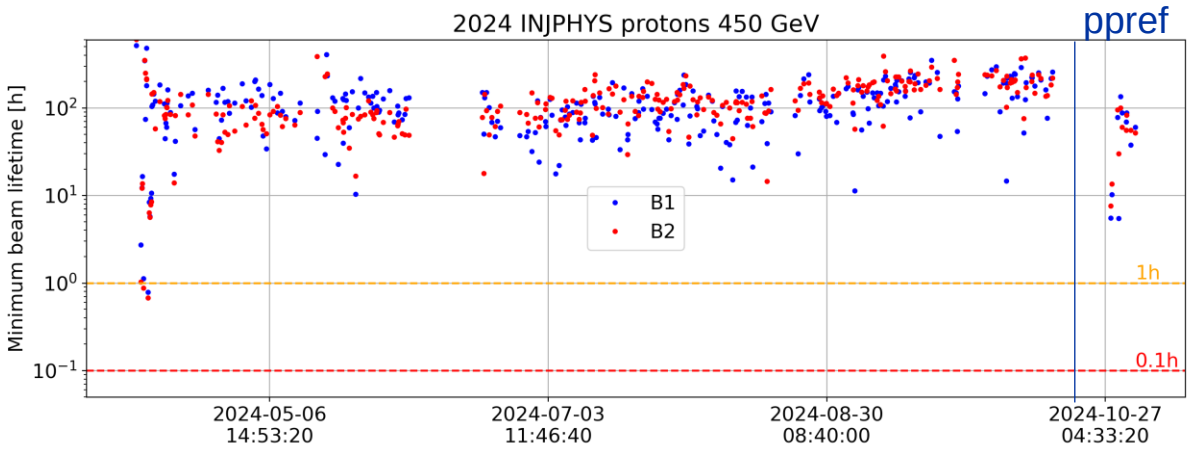
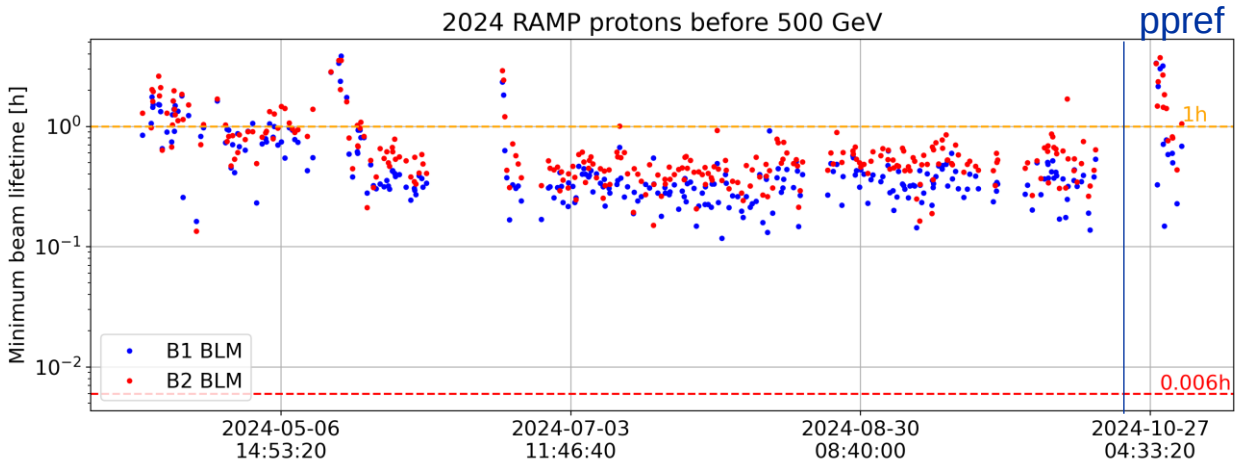




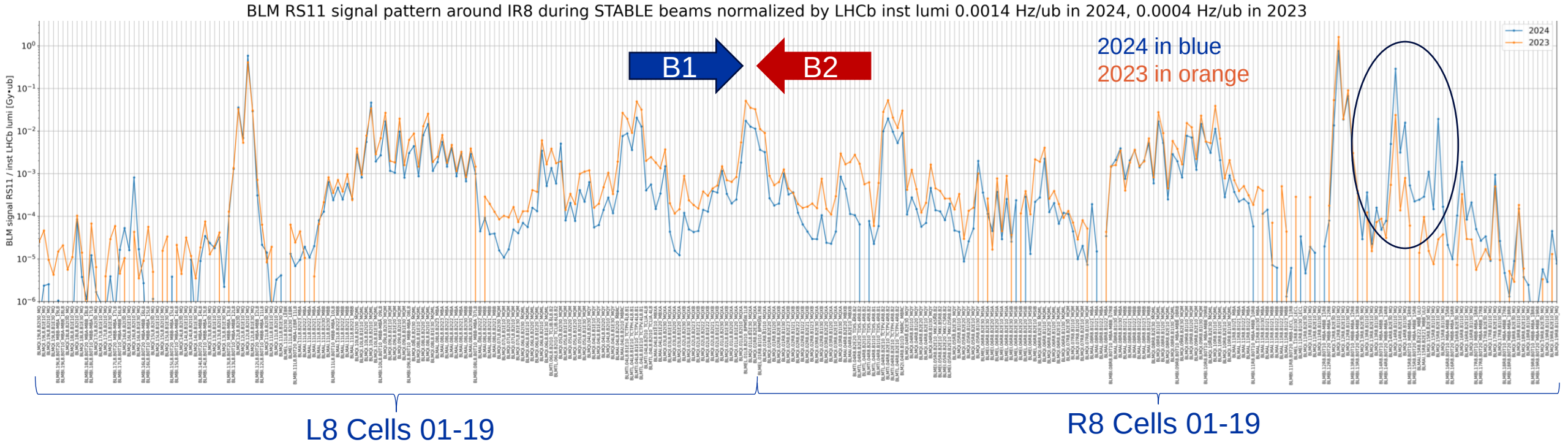
Same collimation settings at injection energy, only difference is the absence of the phase knob -> Can compare directly beam lifetime at flat bottom and start of ramp

Pb ion Run 2024: required changes

- Superconducting magnets in IR7 DS: BLM thresholds set to the signals recorded during the 2015 Pb collimation quench test

- Colliding IRs: BFPP losses -> Measured loss patterns look similar as in 2023 -> Start with 2023 thresholds configurations
  - Still, some BLMs <40% at start of collisions -> **Not limiting, no additional changes**
    - Two BLMs in IR5, reduced thresholds due to non-conform bypass diodes
    - One BLM in 14R8 -> Not expected BFPP losses
      - Analyzing possible correlations with ATLAS, LHCb luminosity and others…

Changes applied on the 04/11/24, LHC-BLM-ECR-0085



Pb ion Run 2024: required changes

- Crystal collimation: Different loss patterns in IR7 and fragment leakage to TCTs and TCLDs
  - In 2023, even though there were dedicated thresholds for the ion run:
    - Limitations in **intermediate running sums** during 10-Hz loss events and loss of CH orientation
    - **18 BLM dumps** in physics fills (9 in ramp, 9 at top energy)
    - Mostly at **Q6R7** (7x), **TCLDs** (4x) and **TCTs** (4x)
    - Needed to carry out 15+ threshold changes **during** the run
    - Remained prudent for TCT, TCLD and Q6 thresholds due to some uncertainty about the acceptable power deposition

  - In 2024, for IR7 (collimators and DS):
    - Dedicated BLM thresholds set to provide redundant protection for CH, AM, and VR (new!)
    - CH set at 60kW (50kW in 2023), AM at 15kW and VR at 15kW
    - Same 2023 dedicated families used, incorporating corrections from 2024 loss maps -> Thanks to OP for advancing!
      - New bottleneck in DS (Q8) -> New family created
    - New curves considered for intermediate running sums

Proposal of BLM thresholds for the 2024 Ion Run presented and accepted at the 497th LMC and 255th MPP meeting, discussed in several BLMTWG meetings: 18th October, 23rd October, 29th October, 1st November, 6th November

Pb ion Run 2024: required changes

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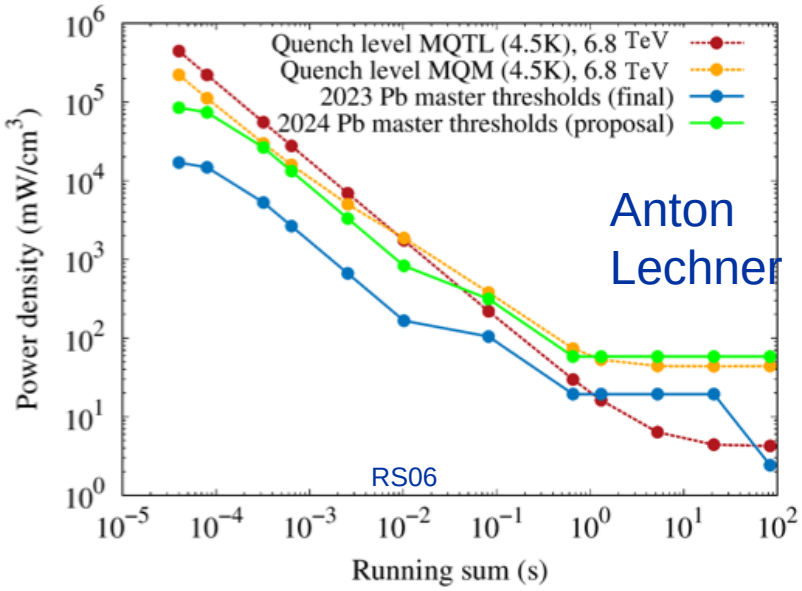
    - Needed to carry out 15+ threshold changes **during** the run
    - Remained prudent for TCT, TCLD and Q6 thresholds due to some uncertainty about the acceptable power deposition

  - In 2024, for Q6 in IR7:
    - Thresholds were based on quench level curves from LS1
    - Studies to understand actual quench margin
    - Consider MQM quench levels for new thresholds



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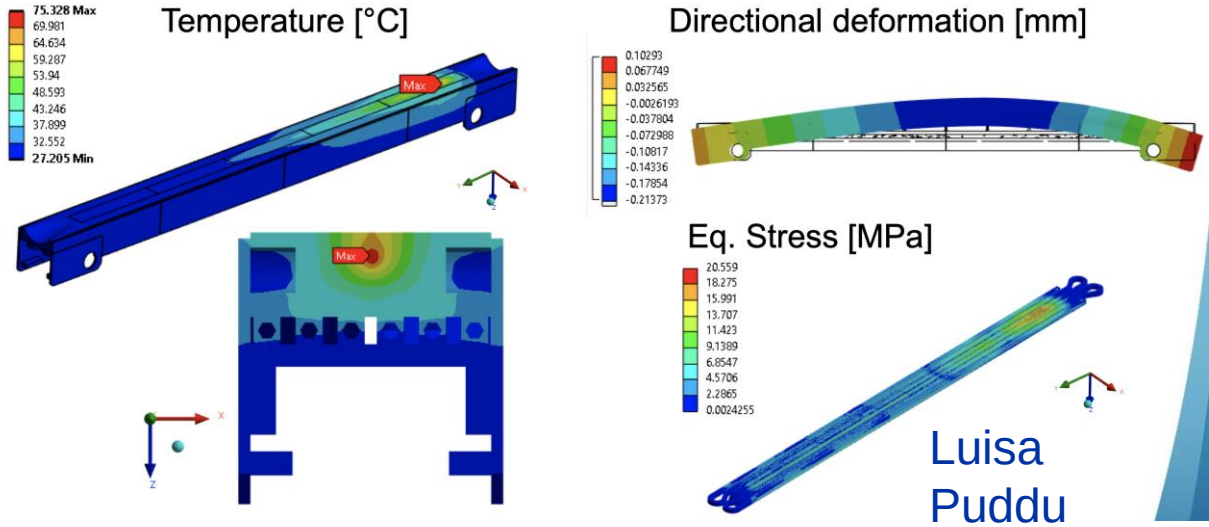
    - Needed to carry out 15+ threshold changes **during** the run
    - Remained prudent for TCT, TCLD and Q6 thresholds due to some uncertainty about the acceptable power deposition

  - In 2024, for TCTs and TCLDs:
    - Reviewed in intermediate and long running sums with dedicated studies
    - Master thresholds in TCTs increased by factor 3, TCLDs by a factor of maximum 4 (RS06)
    - Based on tracking (SixTrack), energy deposition (FLUKA) and thermo-mechanical simulations (Ansys)

Similar study planned for protons!



Pb ion Run 2024: required changes

- In 2023, even though there were dedicated thresholds for the ion run:
  - Needed to carry out 15+ threshold changes **during** the run
- In 2024:
  - Only one additional change during the run due to losses at the start of the ramp in Q8R3
    - Signal at warning levels in long RS, increasing with intensity
    - Magnet with a possibly non-conform bypass diode
    - The thresholds had already been increased by 30% in the longer RS in 2023
    - It was decided to increase by a factor of 2 in RS08-RS12 for EL 01-03 -> Up to 740 GeV
    - After setting RF@12MV -> less debunched beam, no more BLM warnings
      - Limitation overcome thanks to change of BLM thresholds and optimization of machine parameters
  - Injection losses reaching 65% in RS01 for IR2 and 80% for IR8
    - In some cases, even RS09 reaching warning levels
    - If needed, it would be possible to use the blindable functionality in these BLMs

Pb ion Run 2024: required changes

Thanks to the huge efforts by everyone involved in modelling the particle trajectories, simulating the energy and power deposition and the thermo-mechanical stresses, various BLM thresholds models have been updated and optimized, with almost no limitations from BLM thresholds during the 2024 Ion Run!

Thanks also to the efforts by many people in reducing the beam losses and limitations from last year!

Summary

- BLM thresholds set according to different expected loss scenarios and damage/quench limits
- It is important to follow continuously beam lifetime and power loss to verify correct thresholds settings
- Proton Run 2024: limitations
  - Injection losses: limit is now at ~2.6×10^9 protons lost in 40us due to interlock moved to BLMs at the wall for the three most limiting cases during 2023
  - Start of ramp: main limitation in Q6 at a power loss of ~60kW, studies on-going to update the IR3 BLM thresholds model, probably providing more margin
  - Adjust: RS12 IR7 BLM thresholds increased by a factor of 2, at HL-LHC specifications
- PP Reference Run 2024: changes needed due to the operation at a different energy in colliding IRs and IR7 collimators
  - Low lifetime observed during collisions, but also equivalent low power loss
  - Similar lifetime at flat bottom and start of ramp compared to the Proton Run (only difference phase knob)

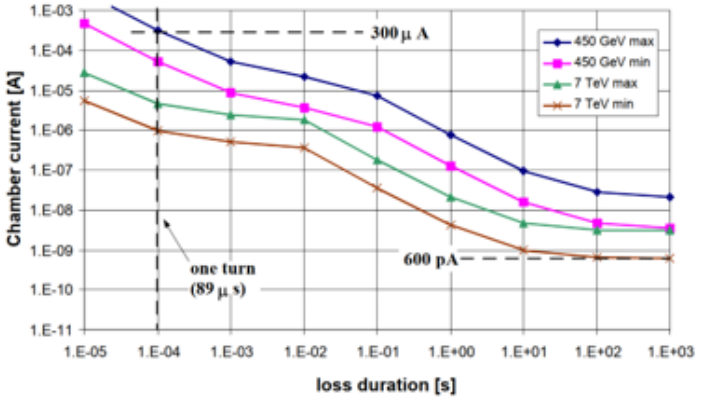
Summary

- Pb Ion Run 2024: changed needed due to BFPP losses and crystal collimation
  - Increased losses in R8 from cell 14 during collisions, source not clearly understood
  - Pb Ion Run 2023 limitations mitigated by:
    - IR7 collimators: limiting power loss in CH at 60kW, including VR in the thresholds and considering new curves for intermediate running sums
    - Q6 IR7: considering MQM quench levels for new thresholds
    - TCTs and TCLDs: reviewing the thresholds in intermediate and long running sums with dedicated studies
      - A similar study to be performed with protons
  - Limitation encountered at start of ramp in Q8R3, threshold increased by a factor of 2 and optimization of RF voltage
  - If needed, the blindable functionality in IR2 and IR8 could be used for injection losses

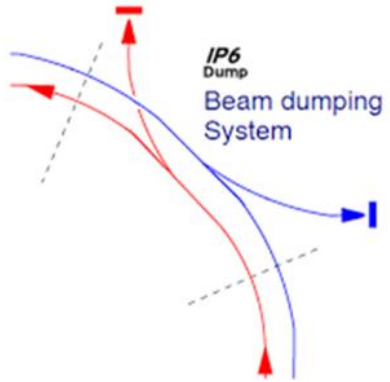
Backup slides

LHC BLM System

Continuous detection and monitoring of beam losses



Comparison of measured losses with predetermined thresholds (dependent on energy and loss duration)

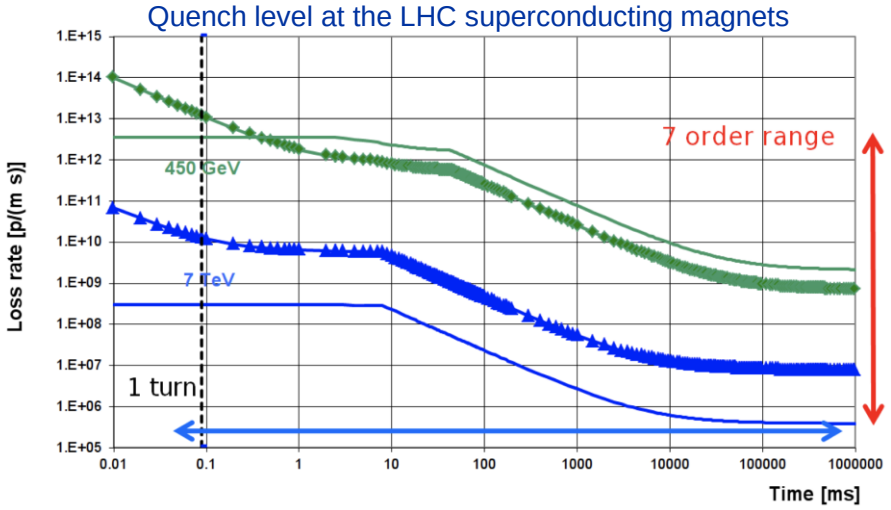


Beams extraction if losses above the thresholds

LHC BLM System

The dynamic range and choice of main detector were based on the expected quench levels before the start of the LHC:

- ~3600 Ionization Chambers (IC), 50 cm long, filled with nitrogen, 1.5 L sensitive volume
- Other detectors placed in areas where IC saturation might occur (collimation, injection…)
- CFC conversion with dynamic range > 10^8 (from 10 pA to 1 mA)
- Measurements in Gy/s in 12 moving windows ranging from 40 us to 83.9 s (Running Sums)



BLM type	Conversion Gy/BLMbit	Ratio to IC
IC	3.62×10^{-9}	1
LIC	5.07×10^{-8}	14
SEM	2.53×10^{-4}	69890

Estimated before the start of the LHC

BLM Thresholds proposal for the 2024 Ion Run

Power loss limits for the **master thresholds** RS09 (1.3 s) at top energy with the dedicated ion families

BLM Family Name	Power Loss Limit Channeling B1 / B2 [kW]	Power Loss Limit Amorphous B1 / B2 [kW]	Power Loss Limit Volume Reflexion B1 / B2 [kW]	
THRI_COLL_7_TCLA_LO_ION	113 / 131	20 / 25	31 / 36	IR7 collimators
THRI_COLL_7_TCSPM_LO_ION_H_CH	**66 / 74**	329 / 520	217 / 419	
THRI_COLL_7_TCSPM_LO_ION_V_CH	**63 / 59**	299 / 108	67 / 82	
THRI_COLL_7_TCSG_LO_ION_H_CH	**55 / 70**	257 / 396	148 / 301	
THRI_COLL_7_TCSG_ME_ION_V_CH	**63 / 72**	293 / 372	344 / 539	
THRI_COLL_7_TCSG_ME_ION_V_AM	90 / 174	**14 / 25**	**31 / 21**	
THRI_COLL_7_TCSPM_LO_ION_H_AM	118 / 92	**22 / 23**	**17 / 14**	
THRI.IP7.P1_MQTL_FT_ION_COLL	237 / 460	42 / 94	64 / 131	IR7 Q6
THRI.IP7.P2_MQTL_FT_ION_COLL	298 / 386	55 / 86	77 / 110	
THRI.IP7.P2_MB_ION_COLL	81 / 153	**15 / 30**	**23 / 42**	IR7 DS
THRI.IP7.P3_MB_ION_COLL	163 / 121	**20 / 23**	**36 / 48**	
THRI.ARDS_MBMB_ION_COLL	169 / 104	**21 / 19**	**39 / 40**	
THRI.ARDS.P1_MQ_ION_COLL	177 / 85	**18 / 15**	**31 / 20**	
THRI.ARDS.P3_MQ_ION_COLL	120 / 108	**16 / 15**	**30 / 23**	