Beam loss limitations: overview and proposal of changes

Sara Morales and Belen Salvachua on behalf of SY-BI-BL

Thanks to BLMTWG, OP, MPP, Collimation, ABT

14th HL-LHC Collaboration Meeting – Genoa – 09/10/2024

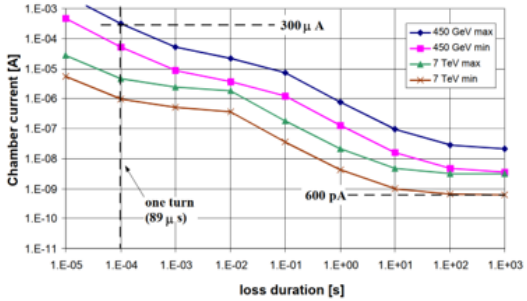
Overview of presentation

- LHC Beam Loss Monitoring (BLM) system
- Limitations observed during injection and 2022 proton DS quench test
  - Proposed BLM system modifications
- Optimization of BLM thresholds: allowed beam lifetime and power loss at the IR7 and IR3 collimators
  - LHC BLM system calibration

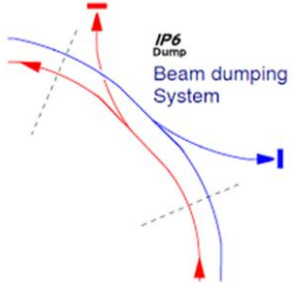
Disclaimer: this presentation is based on presentations at other meetings, mainly at the 200th HL-LHC TCC, BLMTWG joint meeting with MPP and Collimation WG, 99th, 100th and 101st BLMTWG meetings and 180th ColUSM

LHC BLM System

Continuous detection and monitoring of beam losses



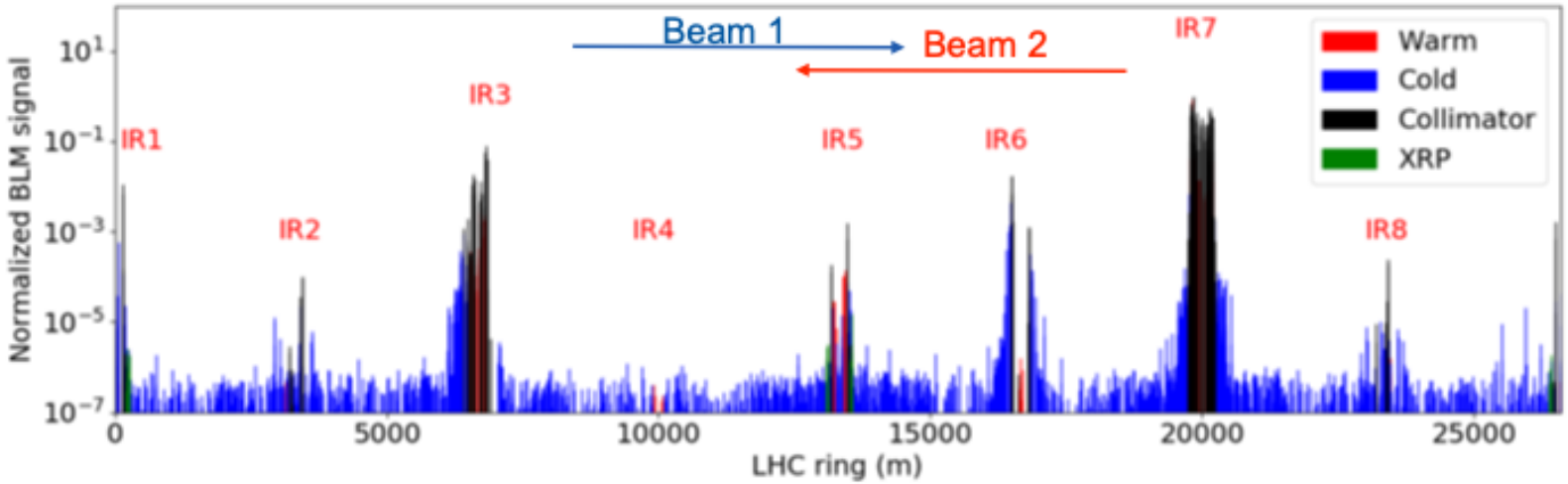
Comparison of measured losses with predetermined thresholds (dependent on energy and loss duration)



Beams extraction if losses above the thresholds

LHC BLM System

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

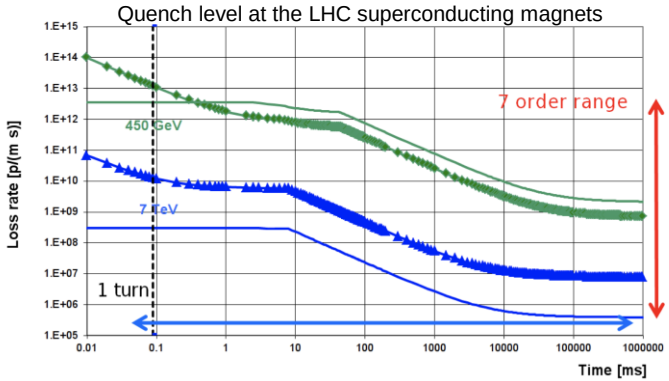


~4000 BLM detectors placed downstream the most likely loss locations
Ionization Chambers (IC), Little Ionization Chambers (LICs), Secondary Emission Monitors (SEMs), Diamond-based BLMs (dBLMs)

LHC BLM System

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)

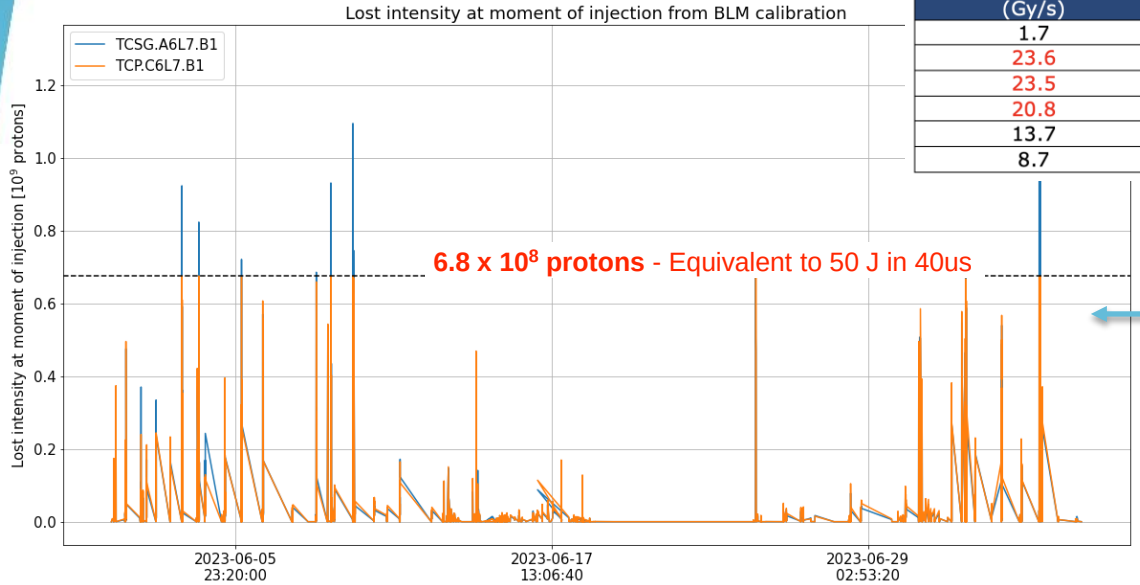


BLM type	Conversion Gy/BLMbit	Ratio to IC
IC	3.62×10^{-9}	1
LIC	5.07×10^{-8}	14
SEM	2.53×10^{-4}	69890

Estimated before the start of the LHC

Limitations: fast losses during injection

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

What power loss should be allowed for regular injection losses?

Limitations: fast losses during injection

Design report

Mode	T [s]	Lifetime [h]	Loss Rate [p/s]	Power Loss [kW]
Injection	Continuous 10	1.0 0.1	0.8 x 10^{11} 8.6 x 10^{11}	6 63
Ramp*	1	0.006	1.6 x 10^{13}	1200
Top energy	Continuous 10	1.0 0.2	0.8 x 10^{11} 4.3x10^{11}	100 500

LHC Run 3

Mode	T [s]	Lifetime [h]	Loss Rate [p/s]	Power Loss [kW]
Injection	Continuous 10	1.0 0.1	14 x 10^{11} 70 x 10^{11}	100 500
Ramp*	1	0.006	1.6 x 10^{13}	1200
Top energy	Continuous 10	1.0 0.2	0.8 x 10^{11} 4.3x10^{11}	100 500

HL-LHC

Mode	T [s]	Lifetime [h]	Loss Rate [p/s]	Power Loss [kW]
Injection	Continuous 10	1.0 0.1	24 x 10^{11} 140 x 10^{11}	200 1000
Ramp*	1	0.006	1.6 x 10^{13}	1200
Top energy	Continuous 10	1.0 0.2	1.6 x 10^{11} 8.6 x10^{11}	200 1000

* Ramp: Losses distributed between IR3 and IR7

New IR7 collimator threshold model implemented for Run 3 -> LHC-BLM-ECR-0072:

- BLM thresholds adjusted regarding reviewed specifications (MPP/Collimation/BLMTWG) in collimators from losses in the entire IR7 collimation system
- **Main focus on circulating slow losses**

Specifications for fast losses at injection in one turn are based on equipment failures**:**

- Discussed with OP that **a limit of 10^{11} protons lost during injection** would be reasonable

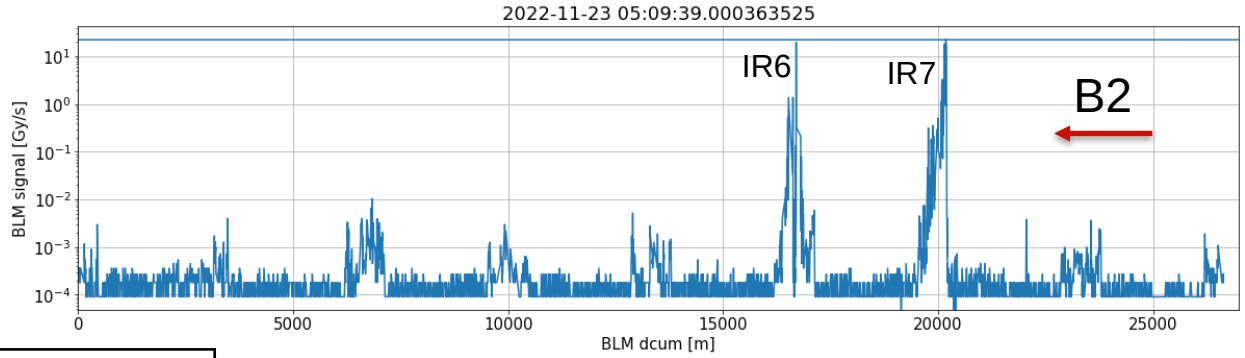
A factor of 150 reduction in BLM sensitivity would be needed to allow this

Limitations: fast losses during the quench test

In 2022, there were 5 DS quench attempts with Beam 2, aiming at 1MW losses (HL-LHC specifications):

- Two of them dumped due to the BLM at TCLA.B6R7.B1 (sensitive to losses from Beam 2 primary collimators) reaching the saturation limit in RS01 (40us).

LHC BLM RS01 signals at the last attempt (**that reached 666kW**) at the moment of the dump



RS01	Units	BLM expert name
23.35	Gy/s	BLMTI.06R7.B1E10_TCLA.B6R7.B1
18.44	Gy/s	BLMTI.06R7.B1E10_TCLA.A6R7.B1
15.85	Gy/s	BLMTI.06R7.B2I10_TCP.B6R7.B2
13.25	Gy/s	BLMTI.06R7.B2I10_TCSG.A6R7.B2
10.09	Gy/s	BLMTI.06R7.B2I10_TCP.C6R7.B2
9.23	Gy/s	BLMAI.06R7.B2I10_MBW.B6R7
8.36	Gy/s	BLMTI.06R7.B1E10_TCSPM.6R7.B1
5.74	Gy/s	BLMTI.06R7.B1E10_TCSG.6R7.B1
3.33	Gy/s	BLMTI.05R7.B2I10_TCSG.A5R7.B2

Highest BLM RS01 signals at the last attempt (666kW)

A factor of 2 reduction in BLM sensitivity would be enough to reach 1MW
(Can be confirmed with Beam 1 quench test this year)

Mitigations: system modifications

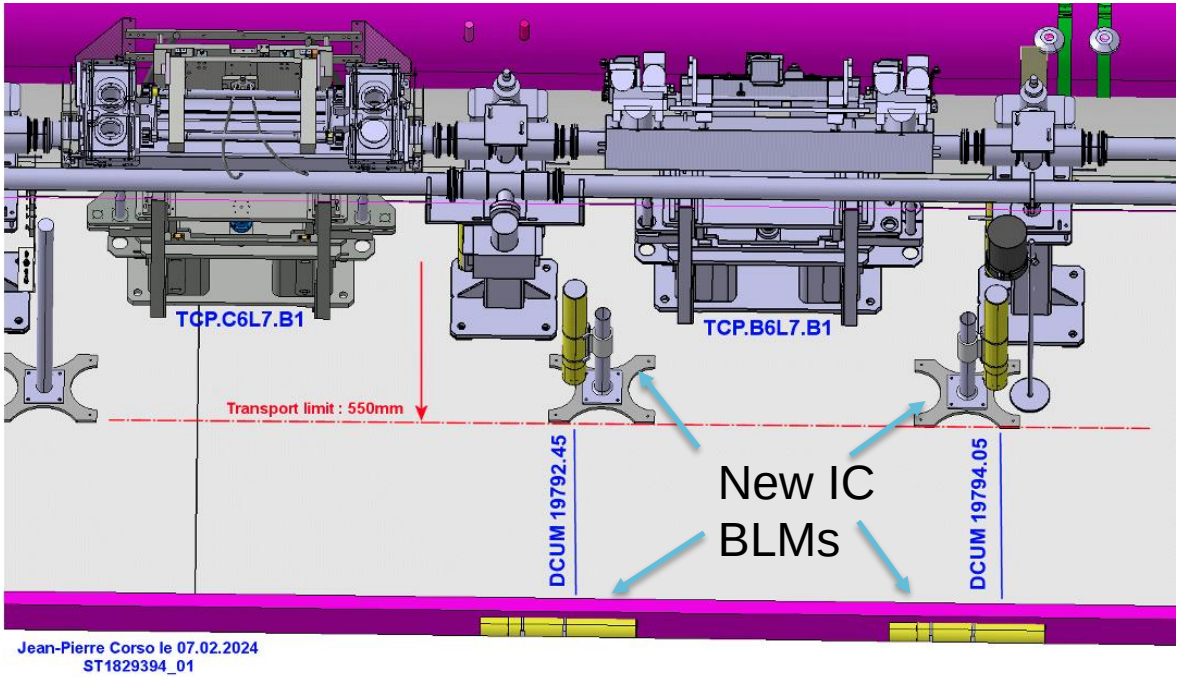
System modifications proposed in order to **partially mitigate these limitations for B1** and **study and determine the strategy for LS3** -> **Done over the 23-24 YETS, LHC-BLM-EC-0019**

1. **Installation of transversally displaced ICs** in order to reduce its response and eventually move the interlock functionality to them
    1. **2 IC BLM at 30/40 cm for the TCP.C and TCP.B** —> best compromise between integration and expected response reduction from FLUKA simulations
    2. **3 IC BLM installed in the tunnel passage WALL**, about 2 m transversal displacement from the beam pipe for TCP.C, TCP.B and TCLA.B
2. **Replacement of 10 SEM detectors by LICs** in the 6L7 area
    1. Verification of the reduction in sensitivity and stability of the detectors
    2. Complemented with simulations of signal response

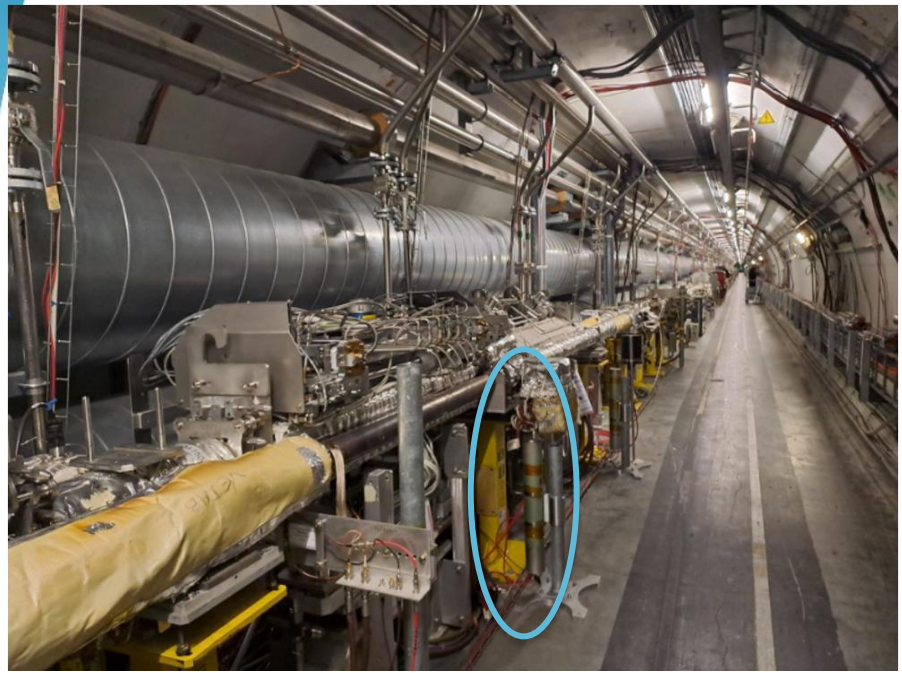
} On-going

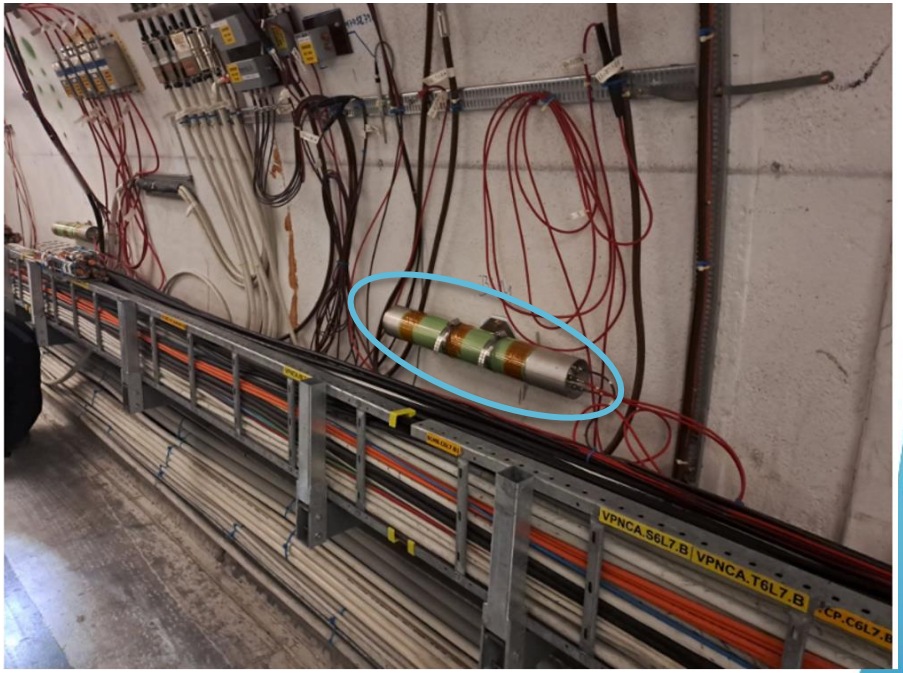
Mitigations: system modifications

B1



Mitigations: system modifications



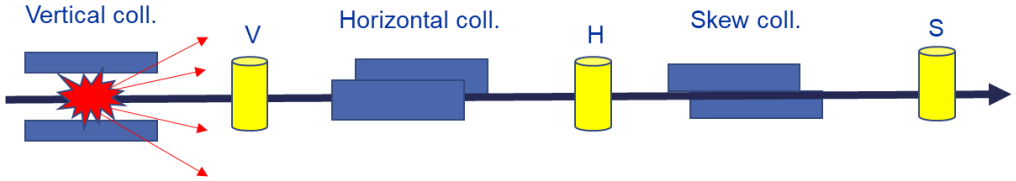


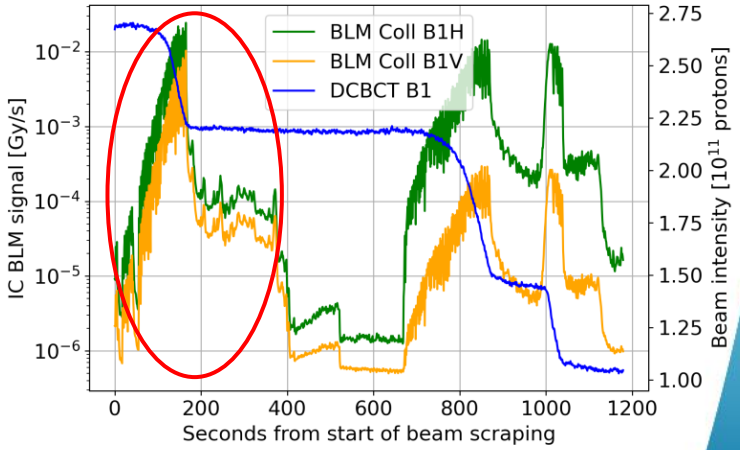
Mitigations: system modifications

From the first studies during 2024 (pilots impacting on closed collimators), it was observed that:

- The IC BLM displaced by 30/40 cm **do not show** any significant improvement
- The IC BLM on the WALL **show a reduction** on their response -> **saturation at minimum ~ 3x10^{10} p**

Further studies of response reduction from the dedicated beam scraping tests for BLM calibration:



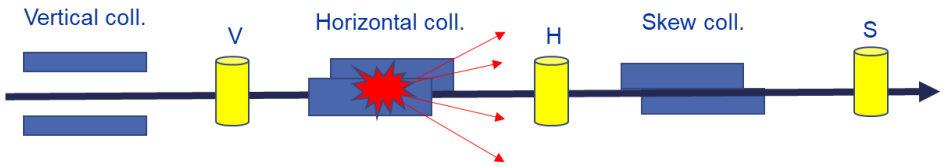


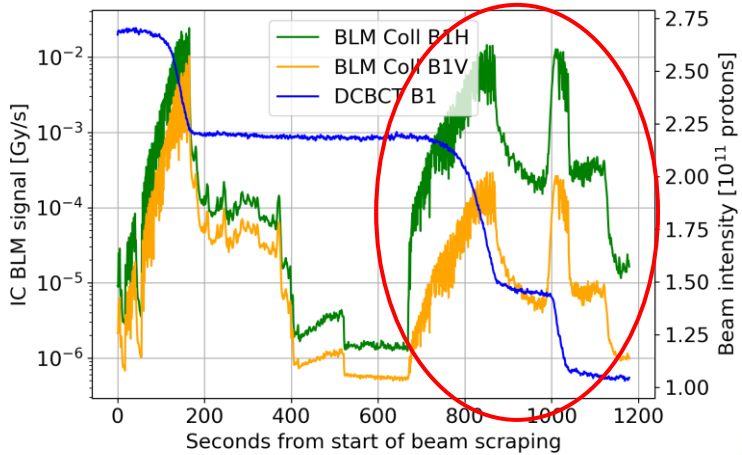
Mitigations: system modifications

From the first studies during 2024 (pilots impacting on closed collimators), it was observed that:

- The IC BLM displaced by 30/40 cm **do not show** any significant improvement
- The IC BLM on the WALL **show a reduction** on their response **-> saturation at minimum ~ 3x10^{10} p**

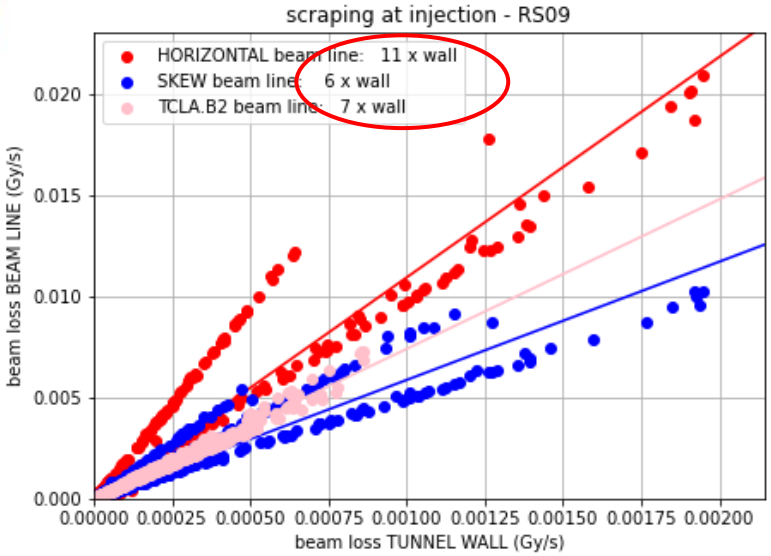
Further studies of response reduction from the dedicated beam scraping tests for BLM calibration:

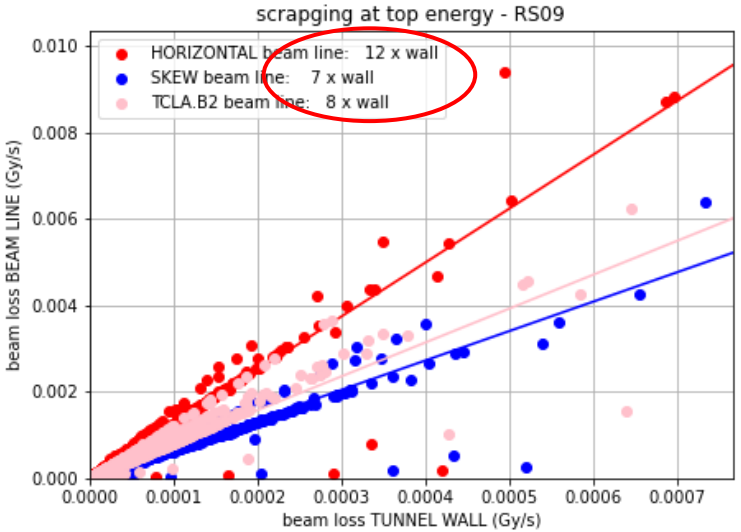




Mitigations: system modifications

Further studies of response reduction from the dedicated beam scraping tests for BLM calibration:

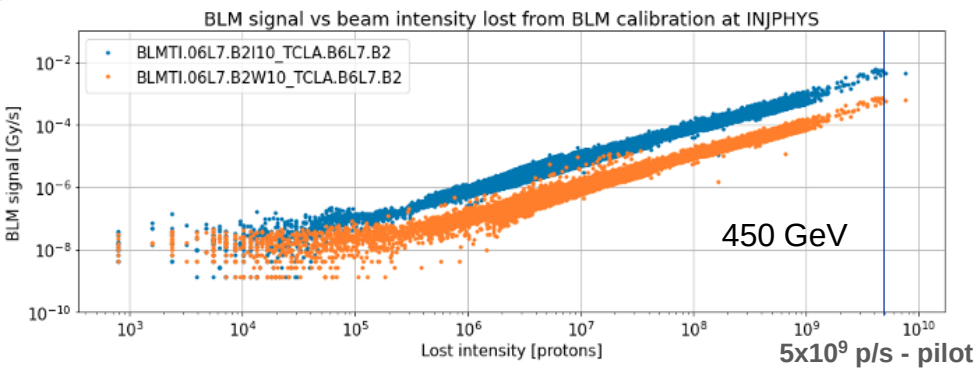




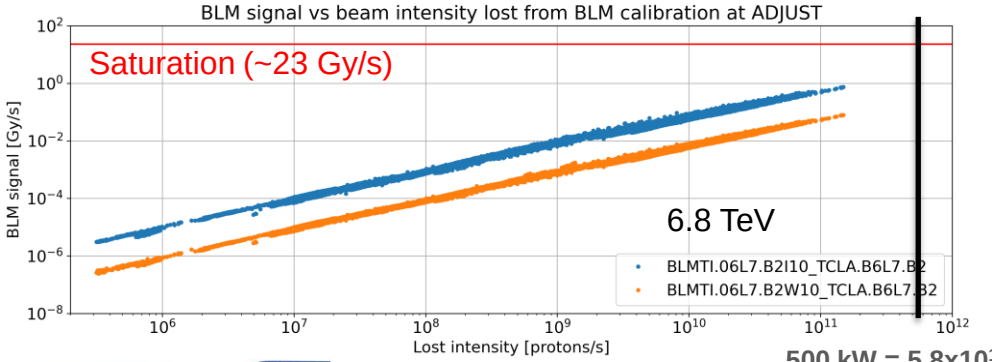
- Similar signal reduction is found at injection and at top energy.
- Ratio depends on the location of the primary impacts, showers reaching either detector vary.
- **Beam Line = [5 -10] x WALL**

Mitigations: system modifications

Further studies of sensitivity of the new detectors before moving the interlock functionality:



5x10^9 p/s - pilot



500 kW = 5.8x10^{11} p/s

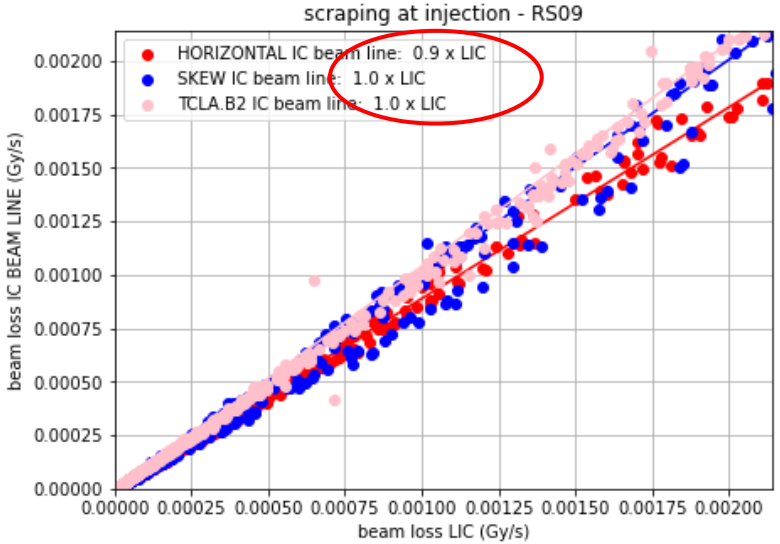
IC BLMs on the wall show lower signals (as expected) but are still sensitive to losses lower than 10^6 protons/s at the collimators

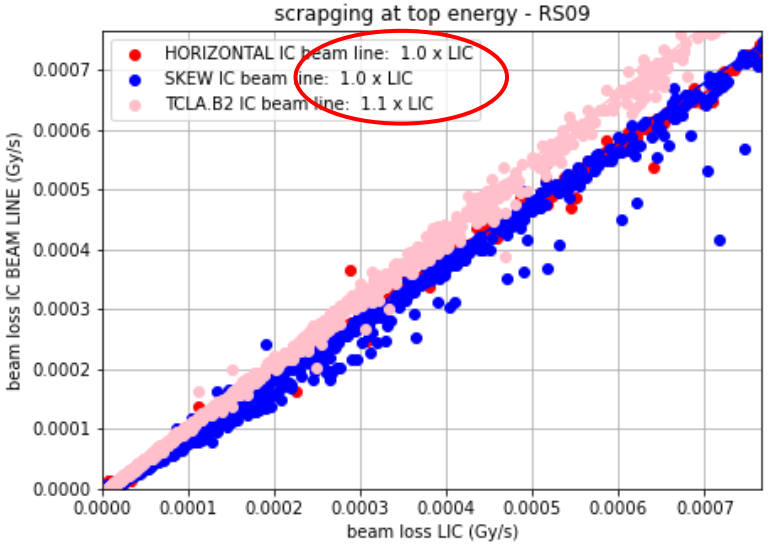
In the BLMTWG joint meeting with MPP and Collimation WG it was agreed to move the interlock functionality to the 3 IC BLMs on the WALL, effective since 23/04/2024, LHC-BLM-ECR-0080

No limitation observed in 2024, but note that the injection scheme changed to reduce the losses

Mitigations: system modifications

Response comparison of the **LIC and IC signals** during the beam scraping test for BLM calibration:





- Very similar signals observed at the IC and equivalent LIC (the sensitivity factor initially estimated for the conversion from BITs to Gy is adequate)
- **IC = 14 x LIC**

Summary of possible mitigations for fast losses

		IC Beam Line	IC Tunnel Wall	LIC Beam Line	LIC Tunnel Wall
	Beam Impact [p]	**6.8×10^8**	**3×10^{10}**	**$14 \times 6.8 \times 10^8 = 9.5 \times 10^9$**	**$14 \times 3 \times 10^{10} = 4 \times 10^{11}$**
Fast Loss INJECTION	**1×10^{11}**	150	3.5	10	0.25
	Power Loss TCLA.B [kW]	**666**	**7 x 666**	**14 x 666**	**7x14x666**
Fast losses TOP ENERGY	1000 + 20%	2	0.25	0.15	0.02

Injection losses, assuming 10^{11} protons for maximum tolerable in 1 turn :

- With IC BLM on the WALL a factor of 3.5 reduction in sensitivity would be needed - **could be achieved with LICs on the WALL**
- This configuration would need to be applied to more monitors in IR7, not only the 3 done over YETS 23-24

Summary of possible mitigations for fast losses

		IC Beam Line	IC Tunnel Wall	LIC Beam Line	LIC Tunnel Wall
	Beam Impact [p]	**6.8×10^{8}**	**3×10^{10}**	**$14 \times 6.8 \times 10^{8} = 9.5 \times 10^{9}$**	**$14 \times 3 \times 10^{10} = 4 \times 10^{11}$**
Fast Loss INJECTION	**1×10^{11}**	150	3.5	10	0.25
	Power Loss TCLA.B [kW]	**666**	**7 x 666**	**14 x 666**	**7x14x666**
Fast losses TOP ENERGY	1000 + 20%	2	0.25	0.15	0.02

Top energy losses, considering the 1MW specifications for HL-LHC:

- **Moving the IC to the wall or using the LIC on the beam line** seems to be sufficient.
- Will be tested during the B1 DS quench attempt later this year

Thresholds: Allowed power loss at collimators

New IR7 collimator threshold model implemented for Run 3 -> LHC-BLM-ECR-0072

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

Beam lifetime and power loss regularly monitored to verify correct thresholds settings

Thresholds: Allowed power loss at collimators

New IR7 collimator threshold model implemented for Run 3 -> LHC-BLM-ECR-0072

$$\mathrm{AppliedThresholds}(E, t) = \mathrm{MasterThreshold}(E, t) \times \mathrm{MF}$$

32 energy levels (EL), ranging from 0 GeV to 7.9 TeV

12 integration times or Running Sums (RS), ranging from 40us to 84s

From 0 to 1

	Duration	Master thresholds	Applied thresholds (MF=0.4)	Applied thresholds (MF=0.6)
RS09	1.31 s	500 kW	200 kW	300 kW
RS10	5.24 s	500 kW	200 kW	300 kW
RS11	20.97 s	239 kW	96 kW	143 kW
RS12	83.89 s	100 kW	40 kW	60 kW

Now

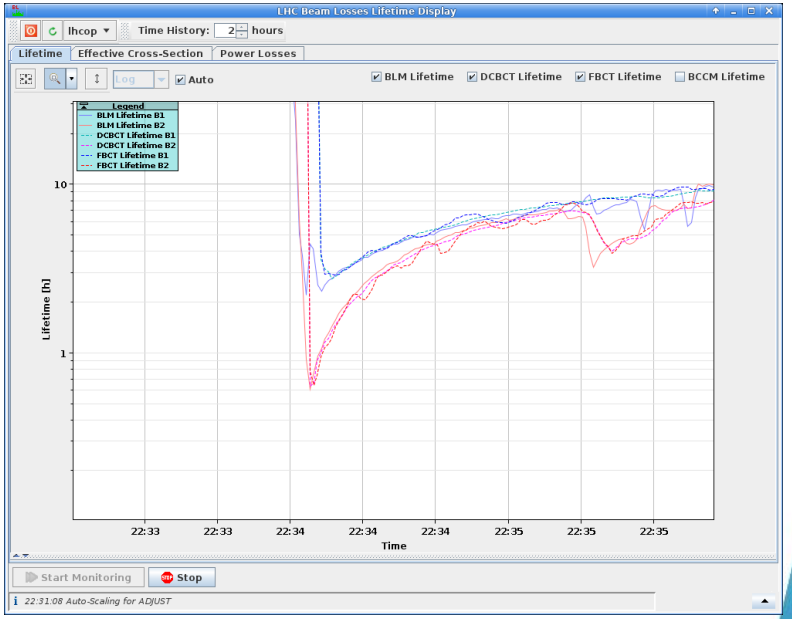
LHC BLM system calibration

The LHC BLM system can also be used as a diagnostics tool to improve accelerator performance when calibrated.

- Global intensity calibration:
  - BLMs not sensitive to the plane of losses
  - Less sensitive to changes in collimation settings
  - Losses in IR7 collimators (betatron)
  - Beam lifetime calculation

$$I = I_0 e^{\frac{-t}{\tau}} \rightarrow \tau = \frac{I}{dI/dt}$$

$$\frac{dI}{dt} = \alpha \cdot \sum_n BLM_n$$



LHC BLM system calibration

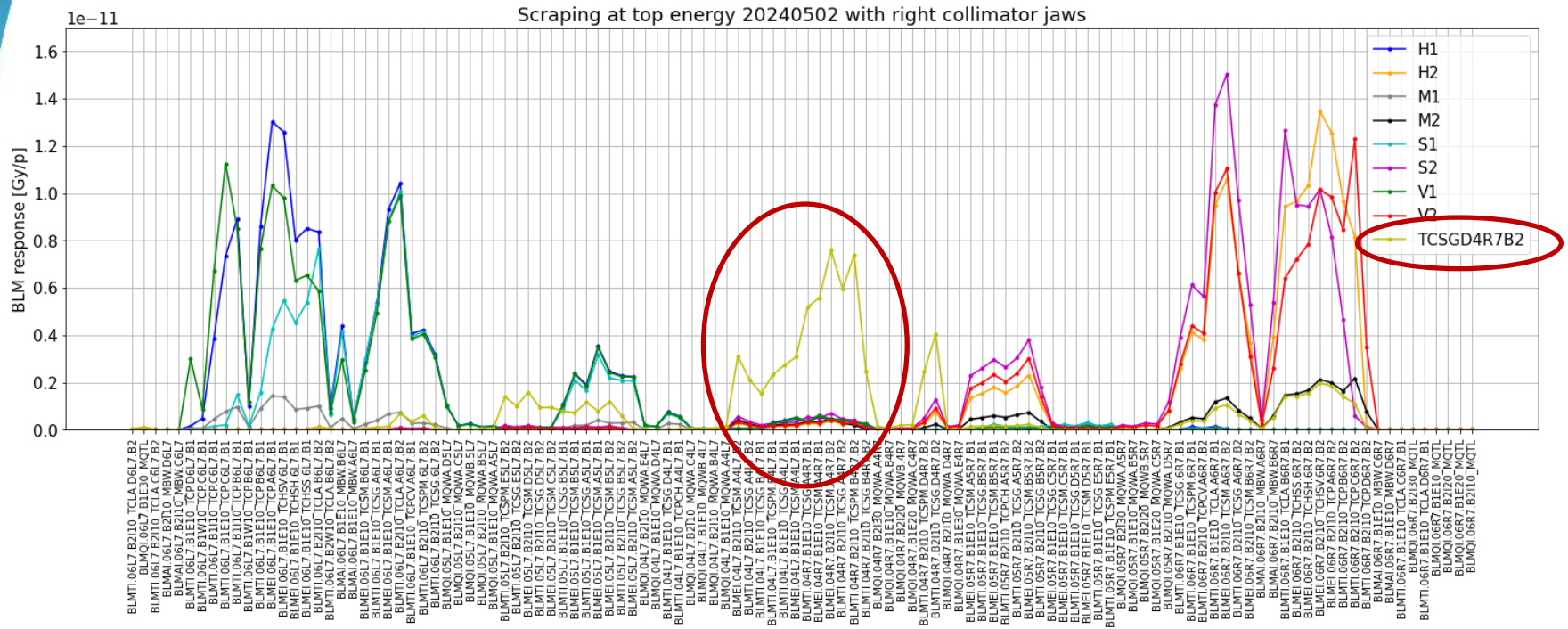
The LHC BLM system can also be used as a diagnostics tool to improve accelerator performance when calibrated.

- Loss plane decomposition calibration:
  - BLMs sensitive to the plane of losses
  - To be re-calculated after every change in optics or collimation settings
  - Losses in IR3 and IR7 primary collimators (betatron + off-momentum)
  - Plane of primary losses in the TCPs

Data from beam scraping with independent collimator jaws! This year including also the TCSG.D4R7.B2 (suspect of breaking the collimation hierarchy)

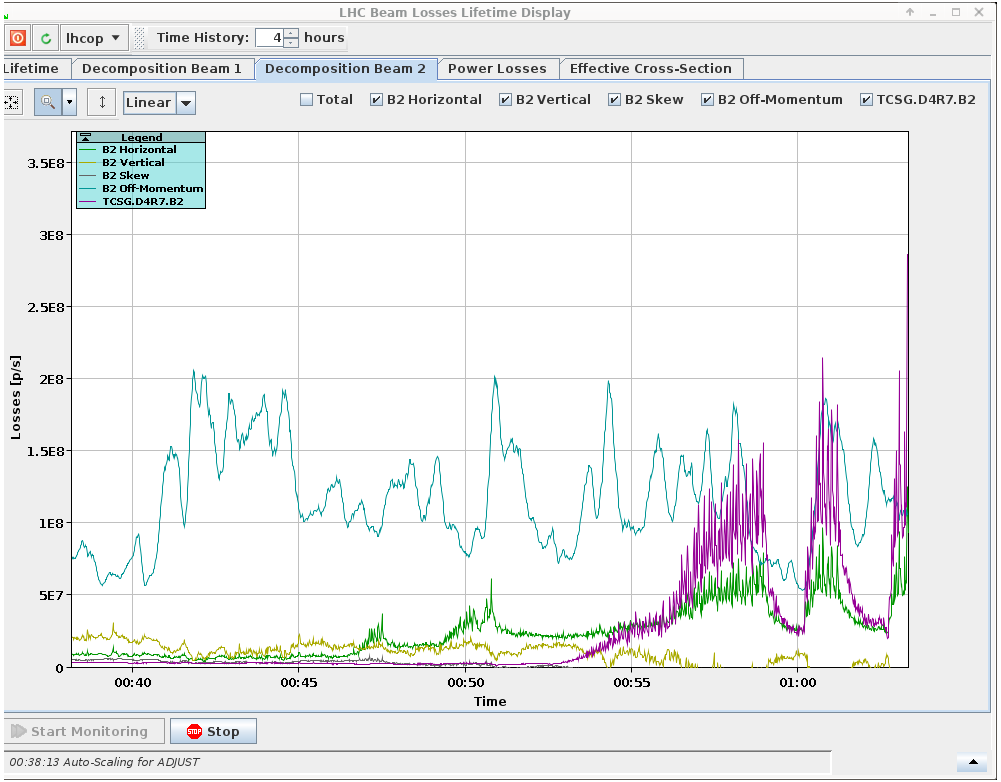
Details about the LHC BLM system calibration presented at past LBOC meetings!

LHC BLM system calibration – Scraping top energy



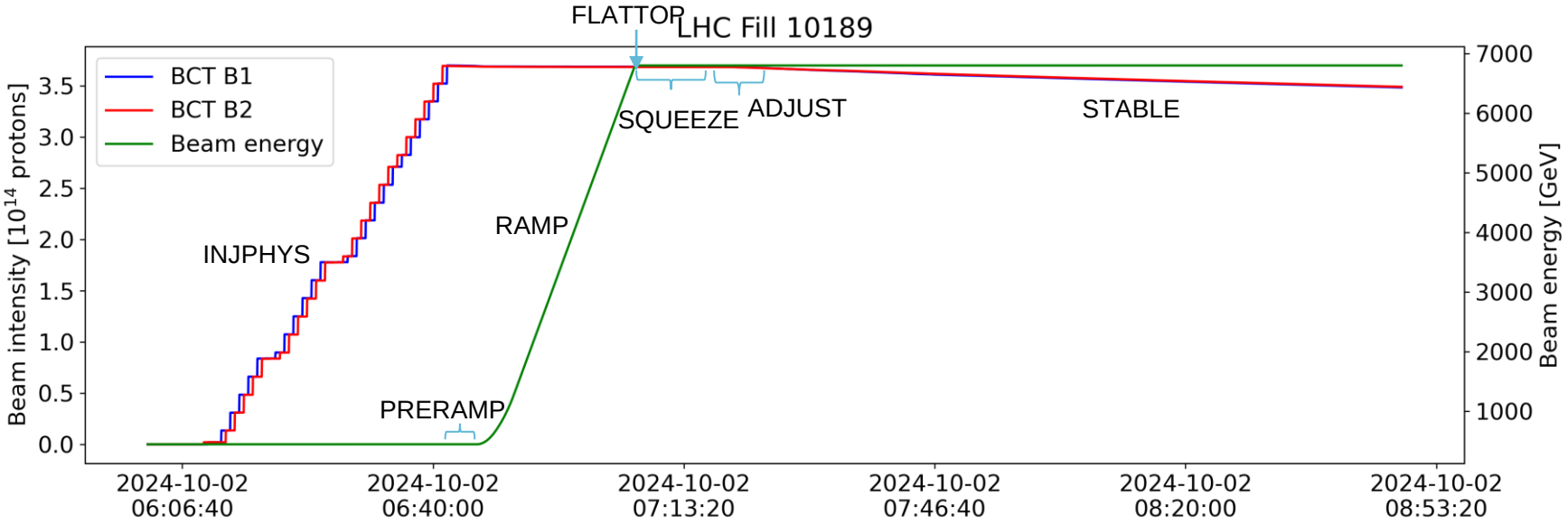
Pattern from impacts on the TCSG.D4R7.B2
(hierarchy breakage at top energy)!

LHC BLM system calibration – Scraping top energy



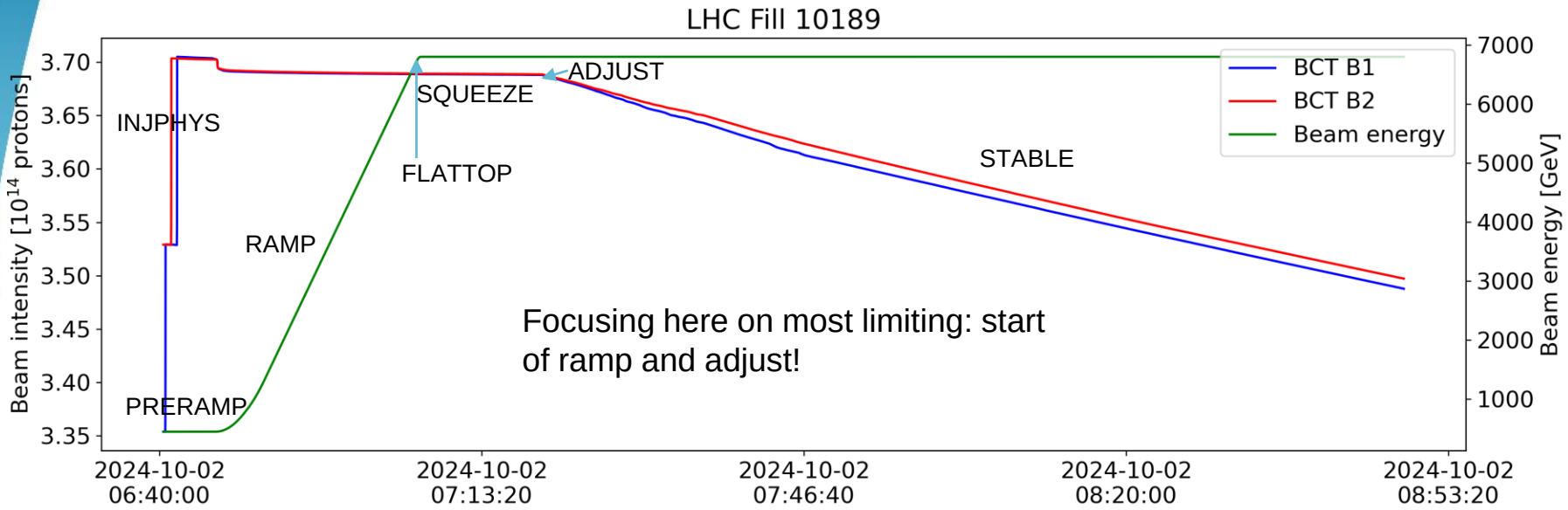
Loss plane decomposition calibration at top energy updated to include impacts on the TCSG.D4R7.B2!
Used to assess collimation hierarchy breakage

Thresholds: Allowed power loss at collimators



INJPHYS (circulating beam, after TDIS open), PRERAMP, RAMP, FLATTOP, SQUEEZE, ADJUST and STABLE selected for beam lifetime analysis

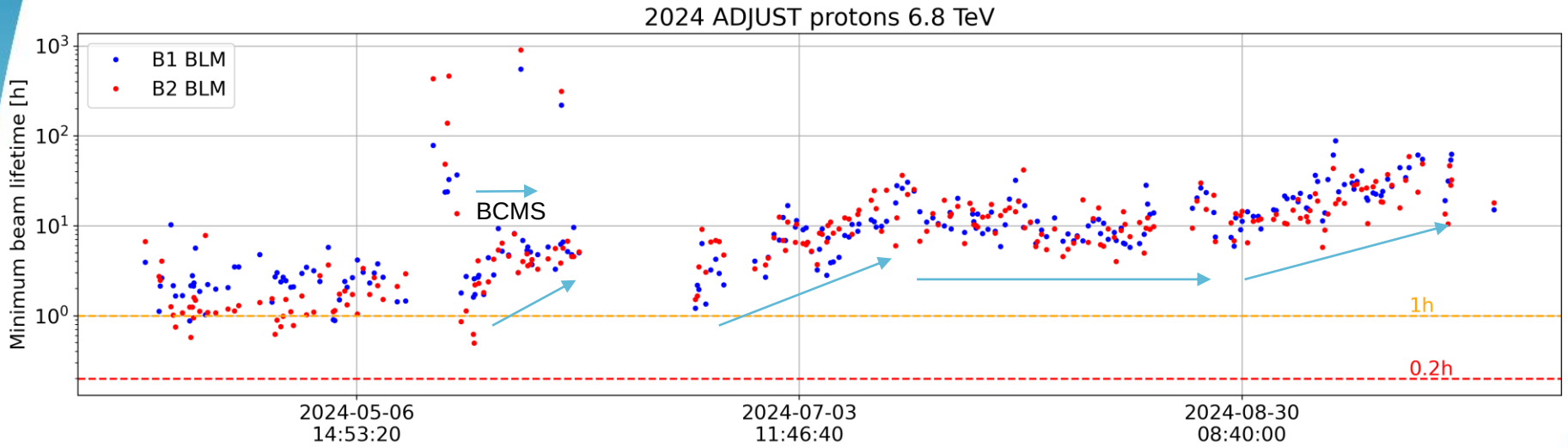
Thresholds: Allowed power loss at collimators



Beam lifetime analysis from collimation losses in IR3 + IR7 (BLM loss plane decomposition calibration)

BLM global intensity calibration for the ramp (excluding start of ramp)

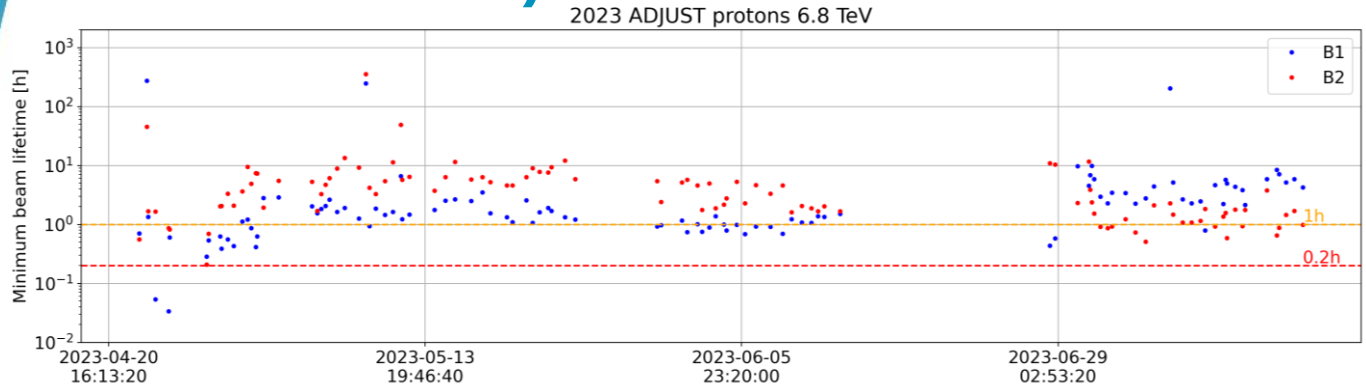
ADJUST during 2024 – Minimum beam lifetime (from BLM calibration)

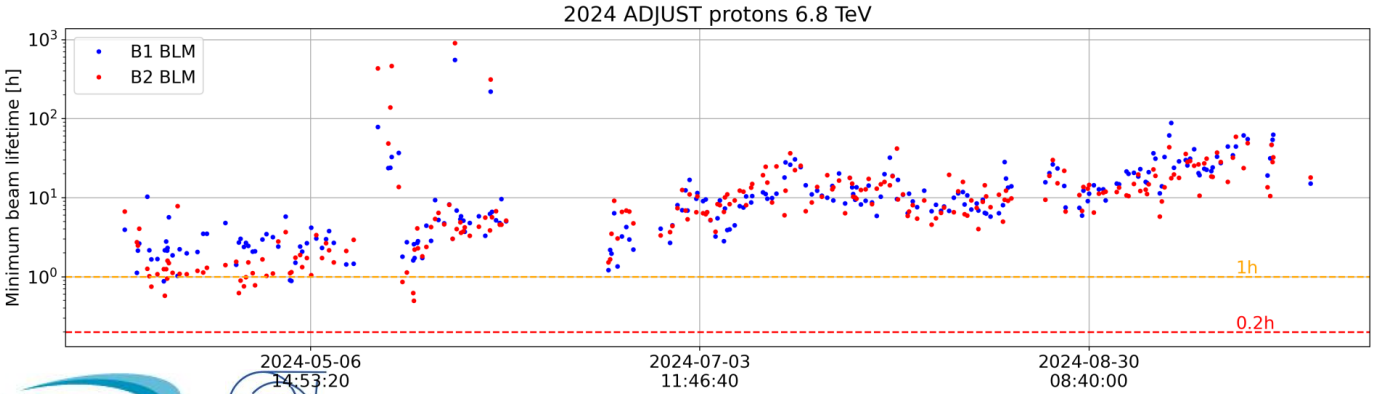


Some beam lifetime values below 1h at the beginning, improving along the year, with BCMS beams.

Consistent with observations by Sofia Kostoglou, discussed in Tuesday PM WP2/5/7 session, correlation with reduction in beam tails

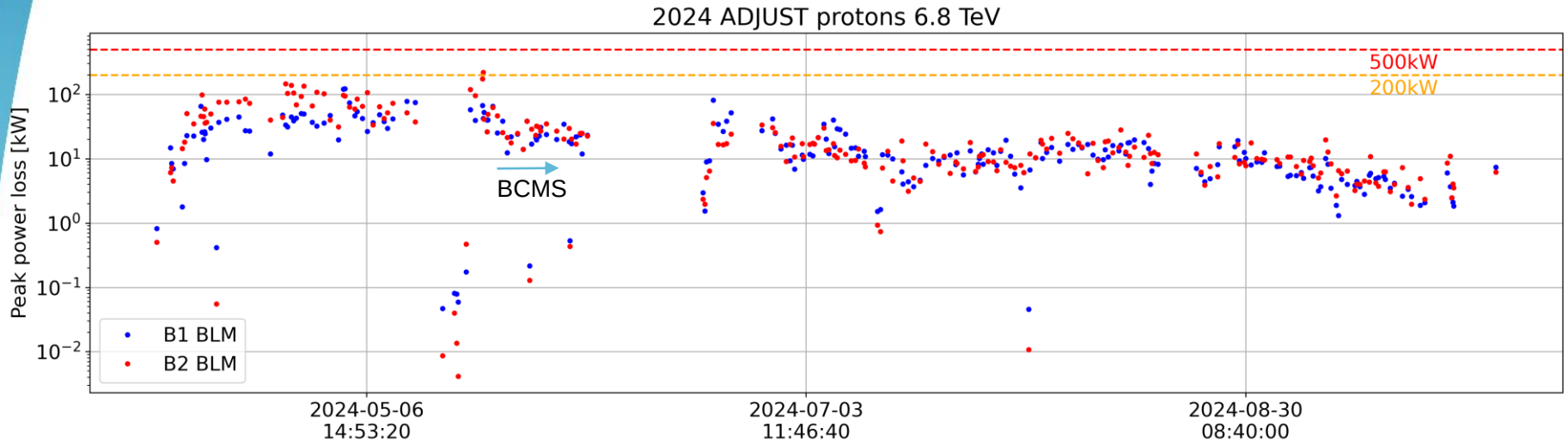
ADJUST during 2024 – Minimum beam lifetime (from BLM calibration)





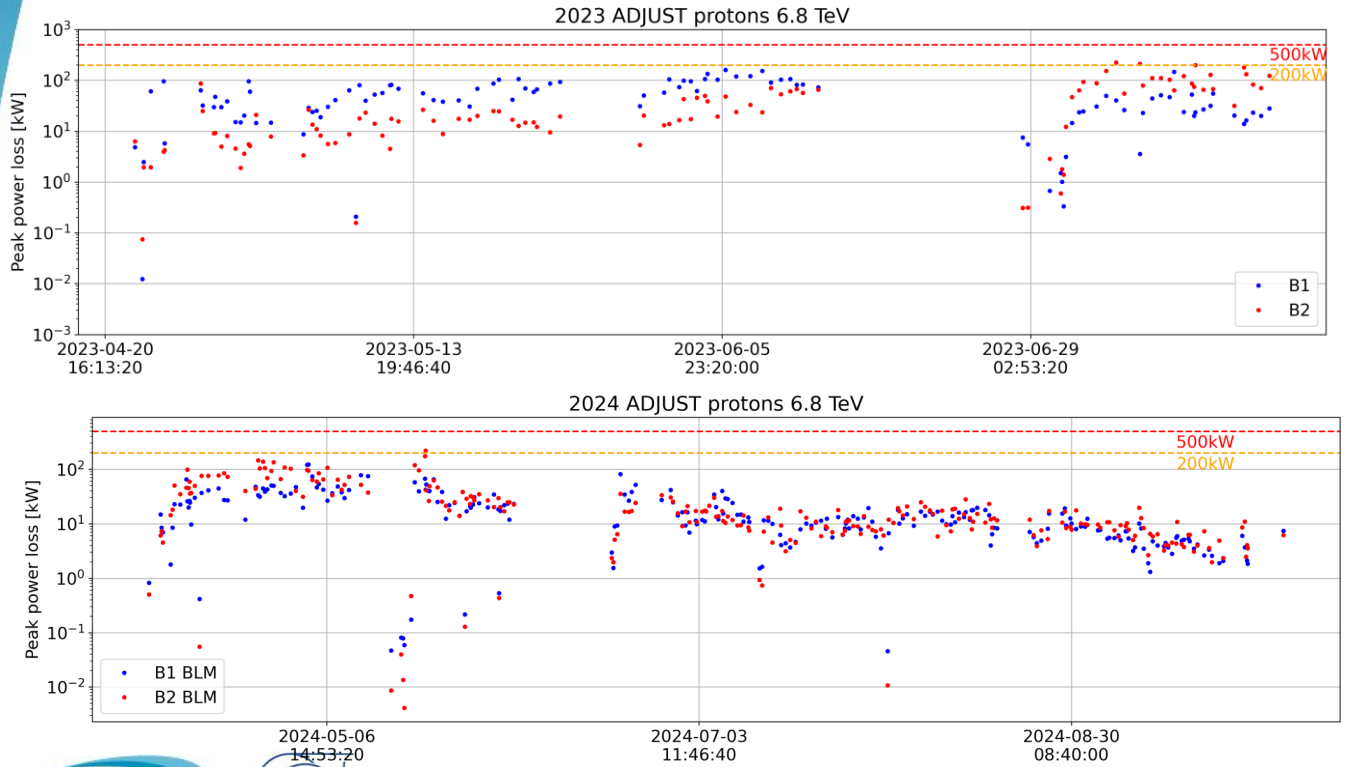
Better situation in 2024

ADJUST during 2024 – Peak power loss (from BLM calibration)



In general peak power loss below 200kW. Few cases around 200kW for B2. Decreasing along the year, with BCMS beams.

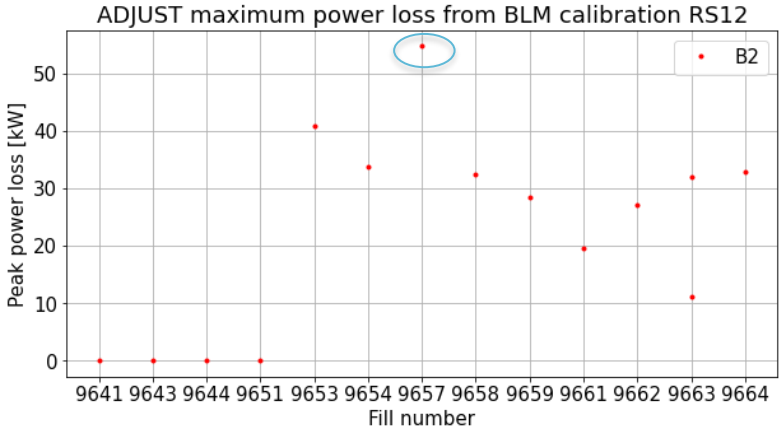
ADJUST during 2024 – Peak power loss (from BLM calibration)

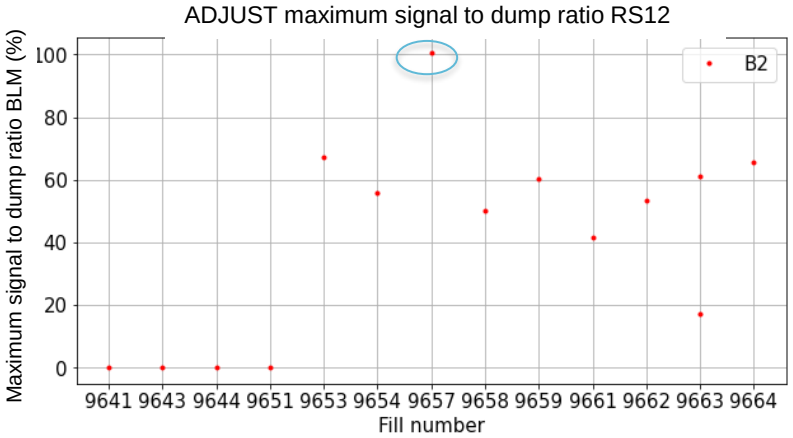


Better situation in 2024

Thresholds: Allowed power loss at collimators

- At the start of the 2024 proton run, **RS12 BLMs reaching warning and even dump levels for B2** at the start of **ADJUST** (most limiting BLMTI.06R7.B2I10_TCP.B6R7.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

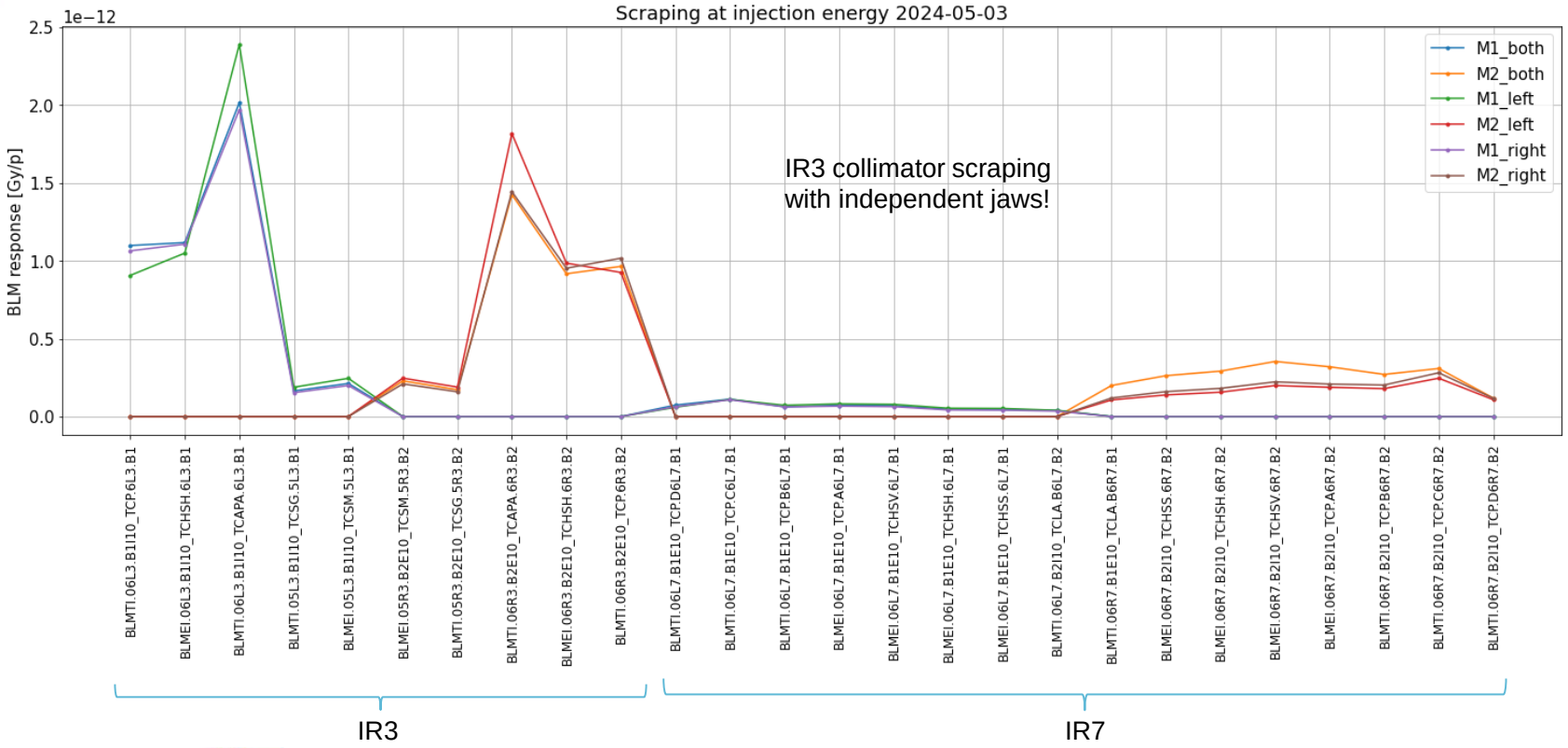




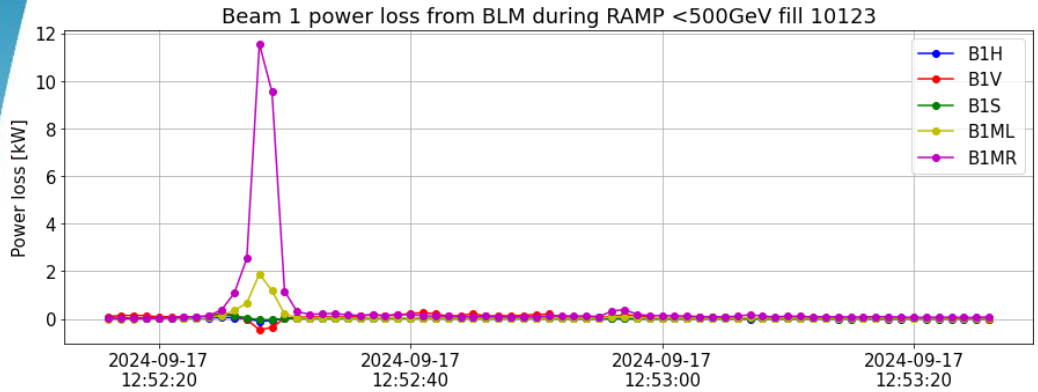
Thresholds: Allowed power loss at collimators

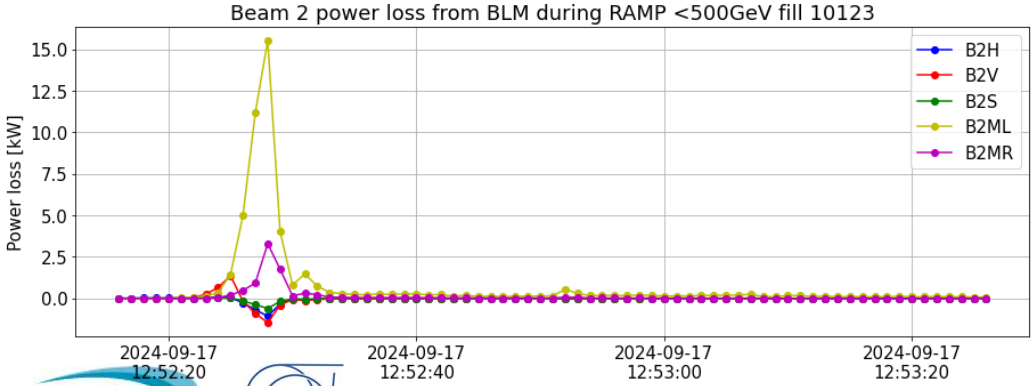
- The beam lifetime was then indeed well below 1h at the start of ADJUST when the beams are going into collisions, but **by the time RS12 (~83 s integration time) triggered, the lifetime had already recovered**
- It had been observed that for some fills, the BLM signal to dump ratio was:
  - RS12 at 40%
  - RS11 at 14%
  - RS09 at 10%
- It was decided at the 99th BLMWTG to increase RS12 thresholds by a factor of 2 at selected BLMs in IR7 to align it with the other RSs -> 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**

LHC BLM system calibration – Scraping at injection



LHC BLM system calibration – Scraping at injection



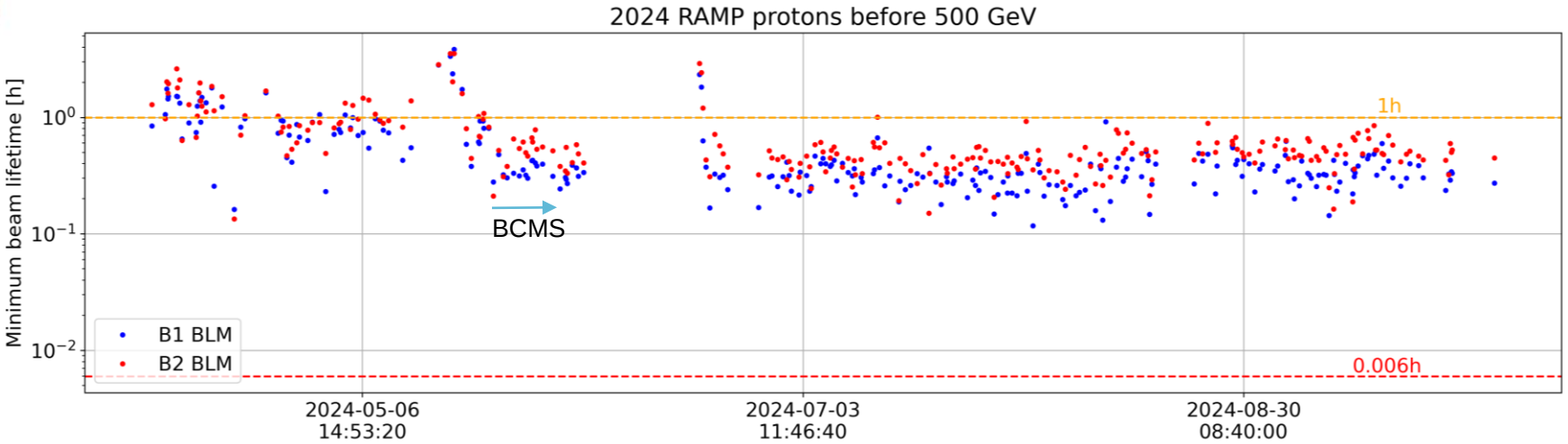


Loss plane decomposition calibration at injection updated to include impacts on left/right collimator jaws in IR3 at start of ramp! Can also see IR3/IR7 sharing!

Used to benchmark power deposition studies (see talk by Volodymyr Rodin Thursday AM WP5/7/14 session)

Studies on-going to update the IR3 collimator model similarly to IR7 -> could provide more margin for start of ramp losses

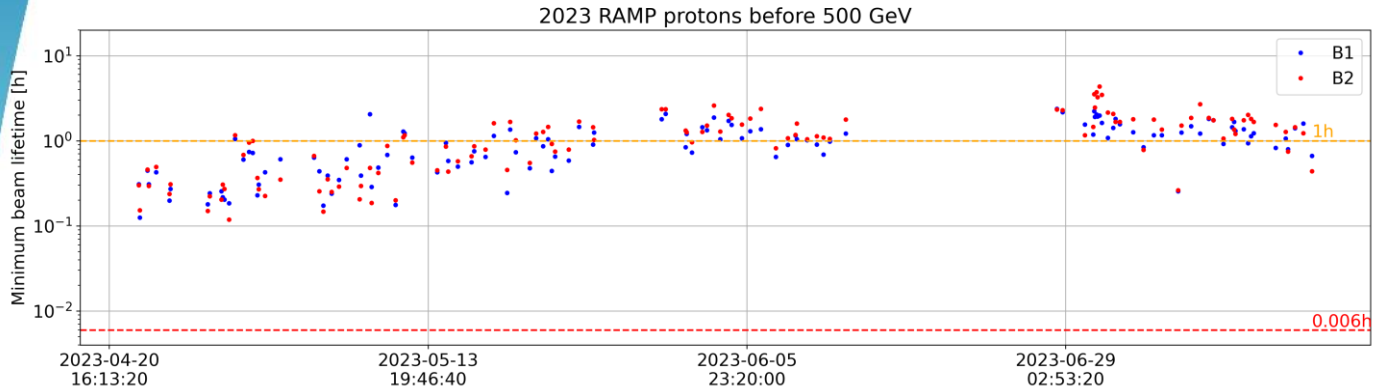
RAMP (before 500 GeV) during 2024 – Minimum beam lifetime (from BLM calibration)

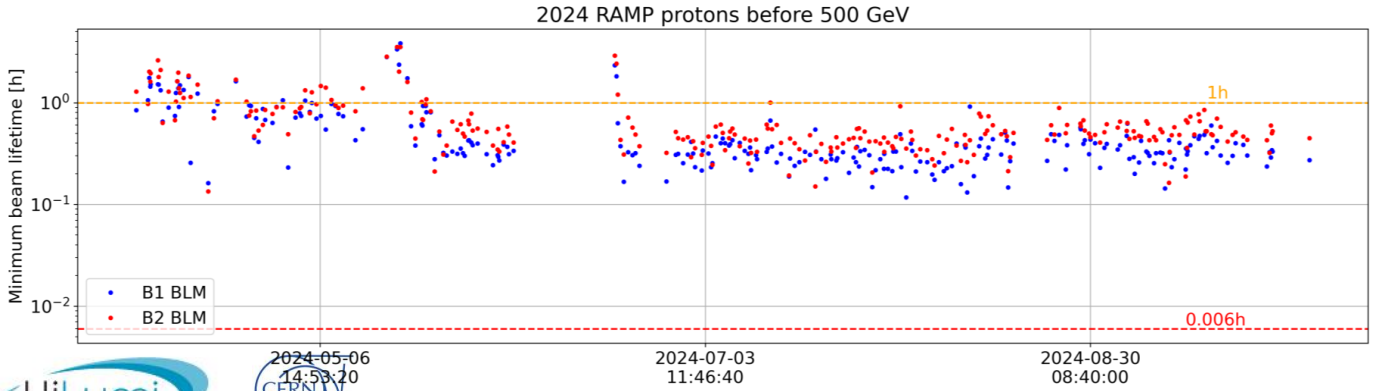


Acceptable beam lifetimes of ~20 s (~0.006h) at the start of the ramp in LHC design specifications (capture losses). In all cases minimum beam lifetime well above the limit. Seems to worsen with BCMS beams.

Consistent with observations by Birk Karlsen-Baeck, discussed in Thursday AM WP2/4 session, correlation with bunch length evolution at flat bottom

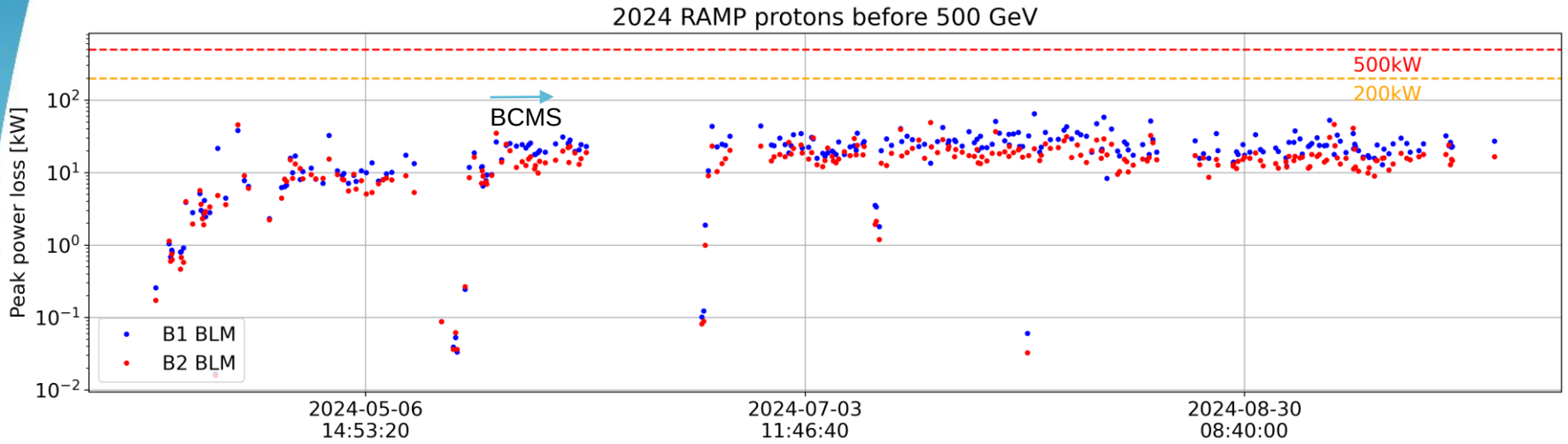
RAMP (before 500 GeV) during 2024 – Minimum beam lifetime (from BLM calibration)





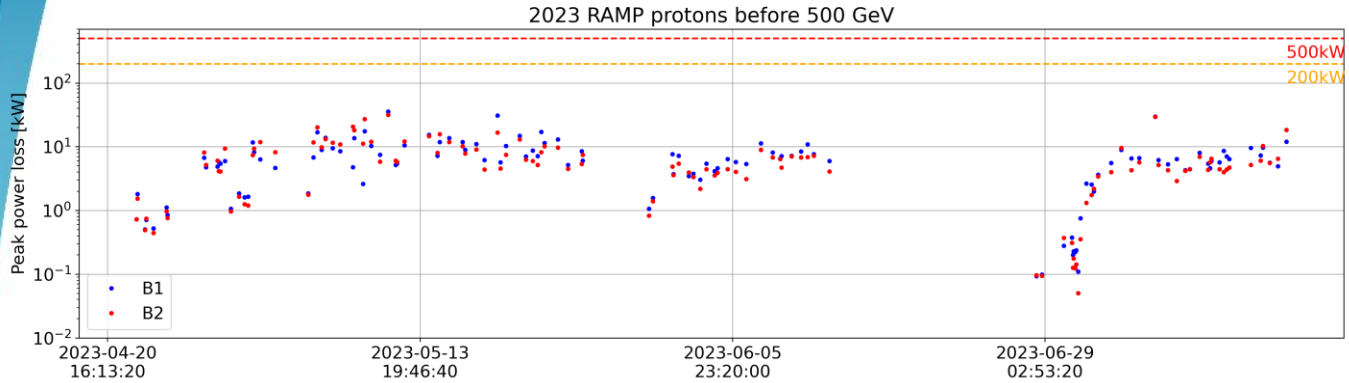
Worse situation for B1 and B2 in 2024

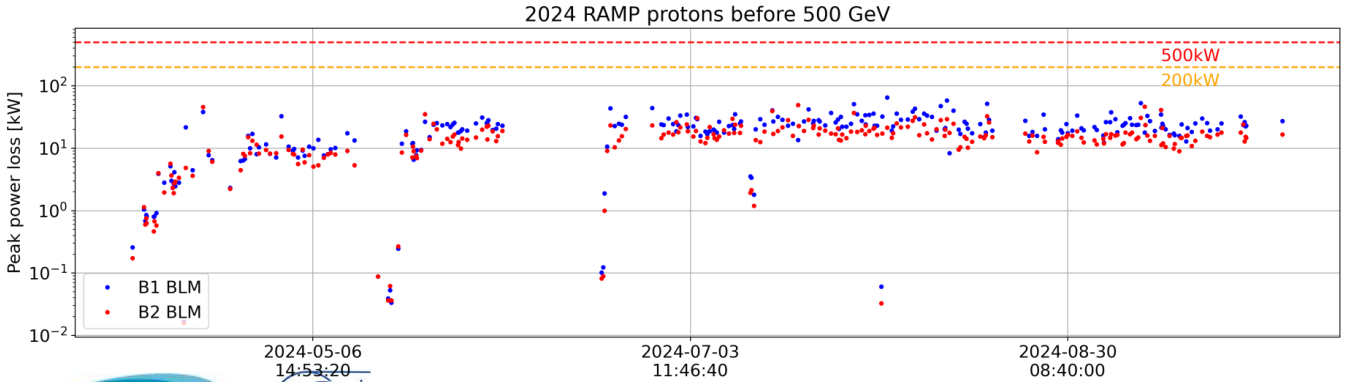
RAMP (before 500 GeV) during 2024 – Peak power loss (from BLM calibration)



Peak power loss between 10-50kW for most fills, few cases a bit higher but not reaching 100kW.
Seems to worsen with BCMS beams.

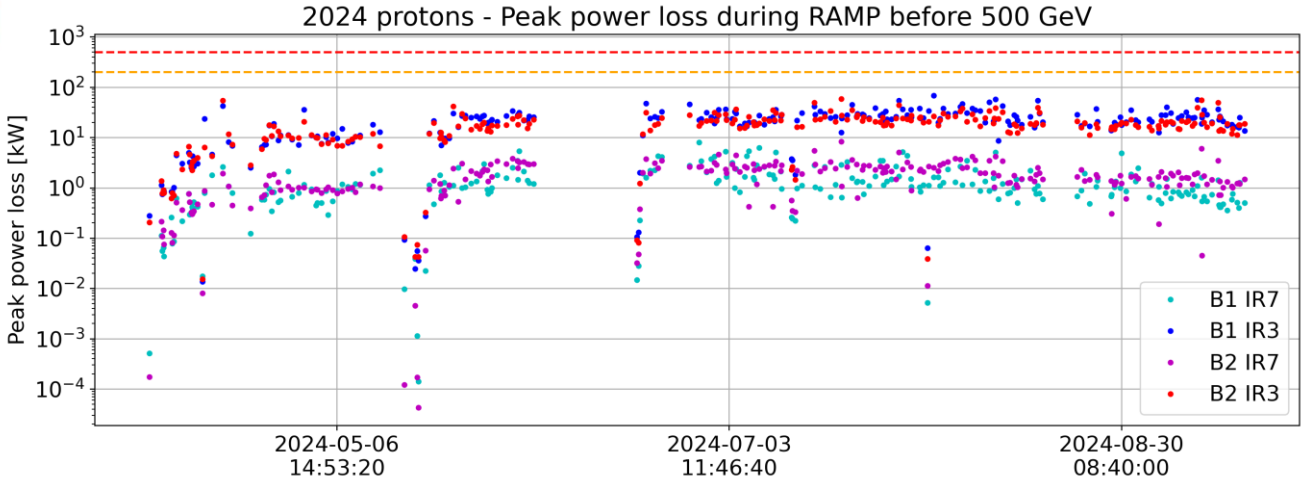
RAMP (before 500 GeV) during 2024 – Peak power loss (from BLM calibration)





Worse situation for B1 and B2 in 2024

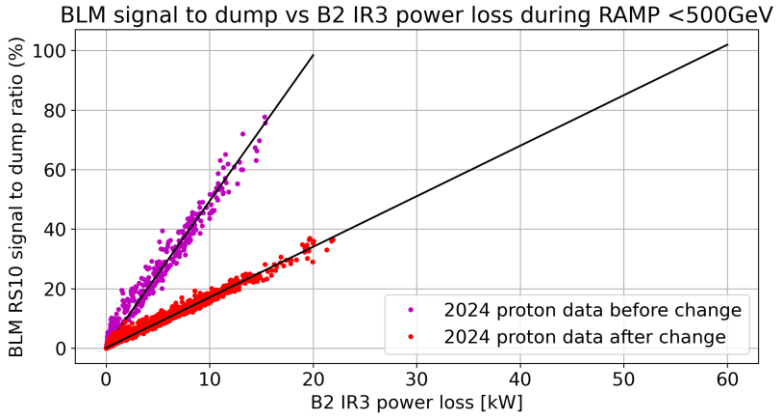
RAMP (before 500 GeV) during 2024 – Peak power loss (from BLM calibration) sharing between IR3 and IR7



Peak power loss around 10 times higher in IR3 wrt IR7 -> Similar values for B1 and B2, less power loss in IR7 specially for B1 in recent fills

Thresholds: Allowed power loss at collimators

- Main limitation in the 2024 proton run at the start of the ramp **was** in RS10 (~5.2s integration time) BLMQI.06L3.B2E10_MQTL -> reaching 80%
- It was decided at the 100th BLMTWG meeting to set RS10 to RS09 at the Q6 IR3 BLMs only at injection energy to gain a margin of around 2 in allowed power losses as a **temporary measure before energy deposition studies are completed** -> Changes implemented on 25/06/2024, LHC-BLM-ECR-0082

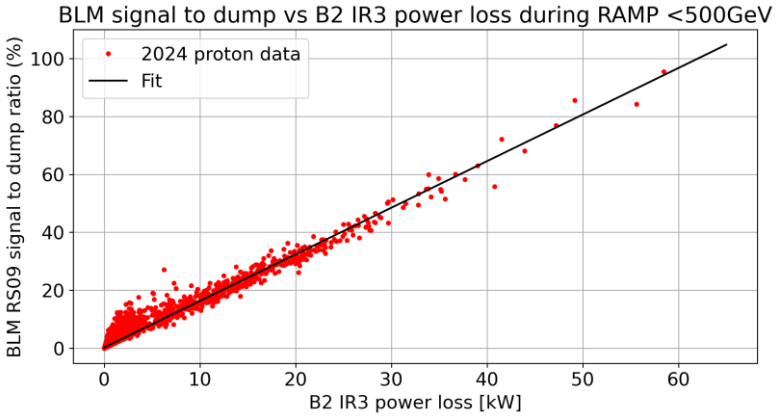


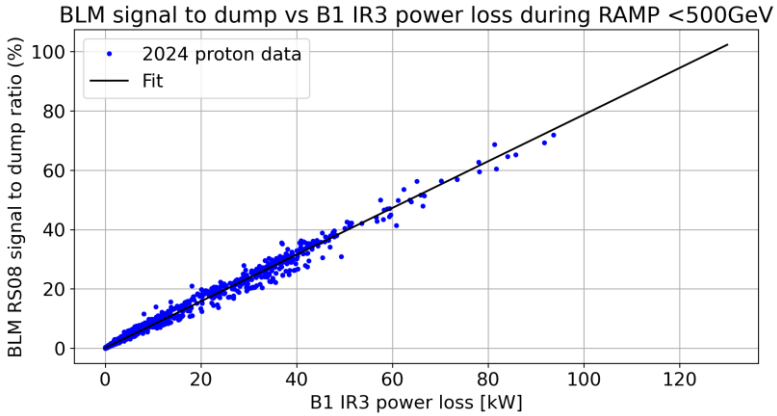
B2 -> RS10 signal to dump ratio from BLMQI.06L3.B2E10_MQTL -> Dumping at 60kJ for ~5 seconds now (20kJ for ~5 seconds before the change)

It has been observed that the estimated quench levels for slow losses at the MQTL (LS1 values) are much lower compared to other magnets -> assessing possibility of homogenizing limits (see 101st BLMTWG meeting)

Thresholds: Allowed power loss at collimators

- Main limitation now in the same detector but RS09 (~1.3s integration time) and in the RS08 (~655ms integration time) of BLMTI.05R3.B1I10_TCLA.A5R3.B1 and BLMTI.05L3.B2E10_TCLA.A5L3.B2





B2 -> RS09 signal to dump ratio from BLMQI.06L3.B2E10_MQTL -> Dumping at ~60kJ lost in ~1s

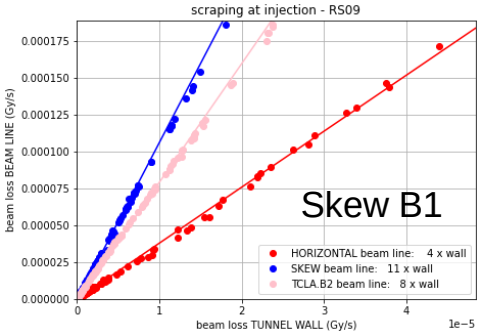
B1 -> RS08 signal to dump ratio from BLMTI.05R3.B1I10_TCLA.A5R3.B1-> Dumping at 85kJ lost in ~655ms

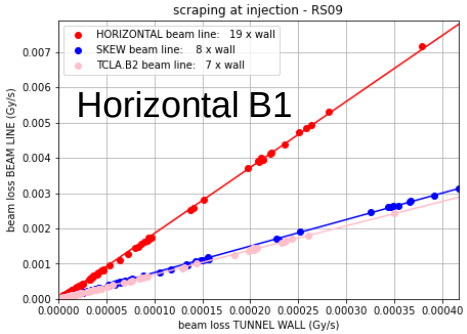
Conclusions

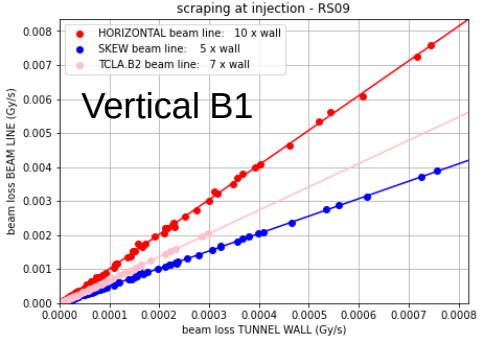
- Assuming 10^{11} protons for maximum tolerable losses in 1 turn during injection, the development of a new detector prototype would not be in the critical path, but the installation of LIC detectors on the WALL
  - Start production of LIC detectors
- Losses of 1MW (HL-LHC specifications) at the IR7 collimators could be reached with IC detectors on the WALL or LIC detectors
  - To be verified during the Beam 1 quench test happening soon
- The IR7 BLM thresholds model was updated during LS2 to align it with the latest collimation specifications
  - The BLM thresholds are well aligned with the intended allowed power loss in IR7 collimator
  - RS12 BLM thresholds are now aligned to HL-LHC specifications to cope with limitations during ADJUST
  - Beam lifetime and power loss in ADJUST well within the specifications, improving with BCMS beams
- On-going studies to update the IR3 BLM thresholds model, hoping to provide more margin to start of ramp losses
  - The main limitation has been mitigated before the studies are completed
  - Beam lifetime and power loss at the start of the RAMP worsening with BCMS beams

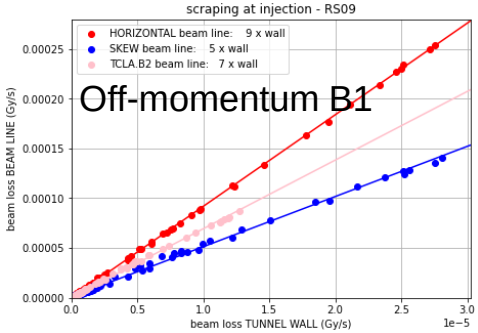
Backup slides

Additional fits from Scraping Test







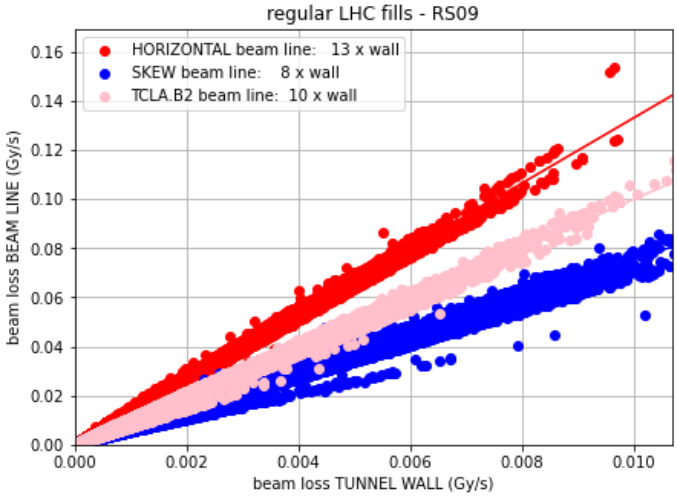


Ratio between BLM in beam line and BLM on the WALL changes depending on the location of the primary impacts.

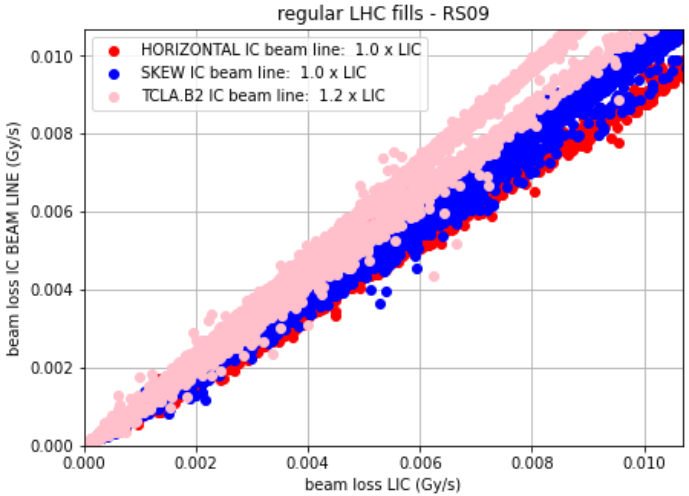
This is also observed in the rest of BLMs in the Beam Line

Additional fit from regular fills

These includes ALL data between 15th July 2024 and 30th July 2024, injection and top energy.



IC Tunnel WALL



LIC

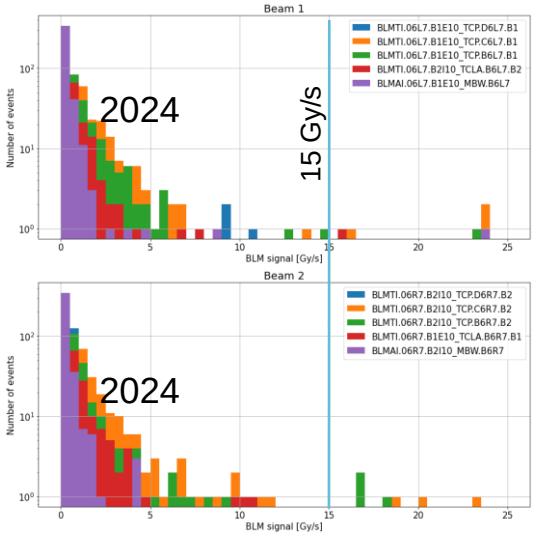
Maximum RS01 measurements

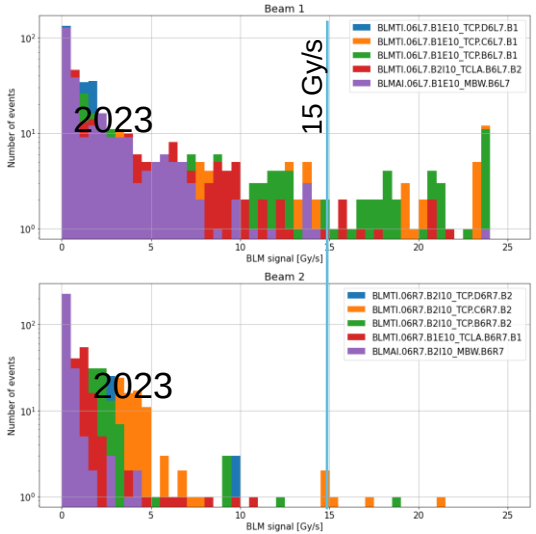
- Maximum signal on the RS01 in ALL fills (injection and top energy) for 2024 and 2023

2024:
4 fills > 15 Gy/s in RS01
9536: QH fired B9L2
9704: PC in TI2 -> Quench MB IR2
9524: Machine Test - SPS scraping not working properly
9704: Machine Test - Loss map

2023:
43 fills above 15 Gy/s, specially in Beam 1

* Based on these numbers the assumption of **1x10^{11} protons maximum loss during injection** incorporates a very large margin.





15 Gy/s at injection in RS01 for TCP.C is approx. 5 x 10^{8} p

* Discussed with J.Wenninger and M.Solfaroli