LHC Status Report

Tobias Persson
on behalf of the LHC operations team

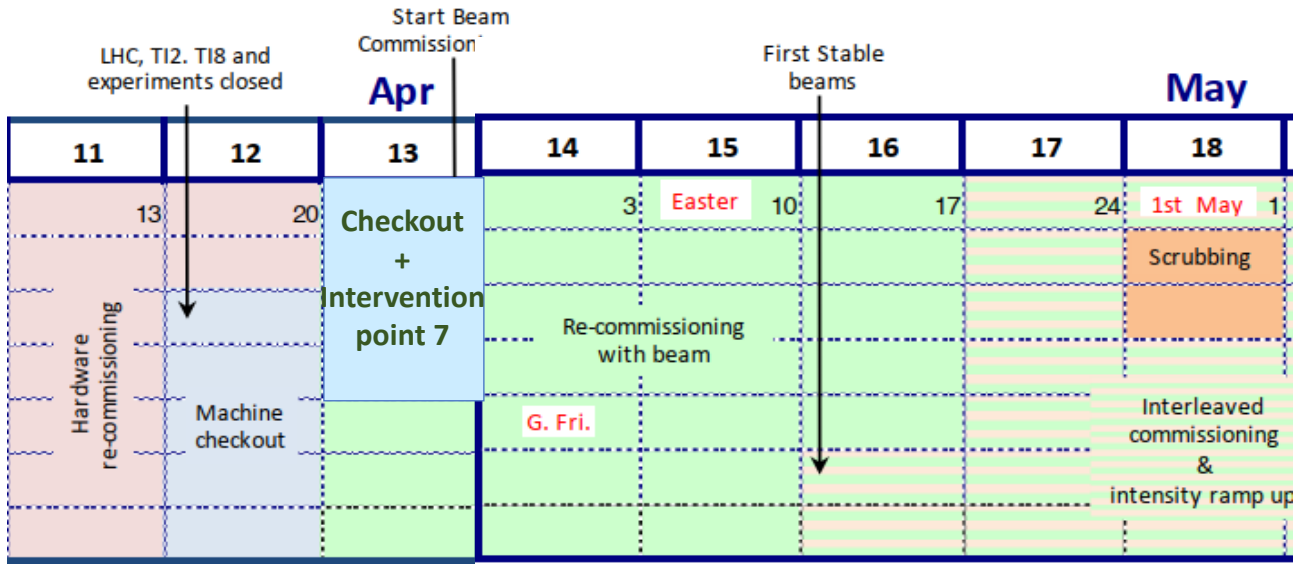
Outline

- Machine checkout
- Beam commissioning
- First stable beams in 2023
- Intensity ramp up and crossing angle adjustment
- Highlights in luminosity production
- 4L1 event and recovery
- Outlook

Machine checkout

Many checks of different system during the machine checkout:

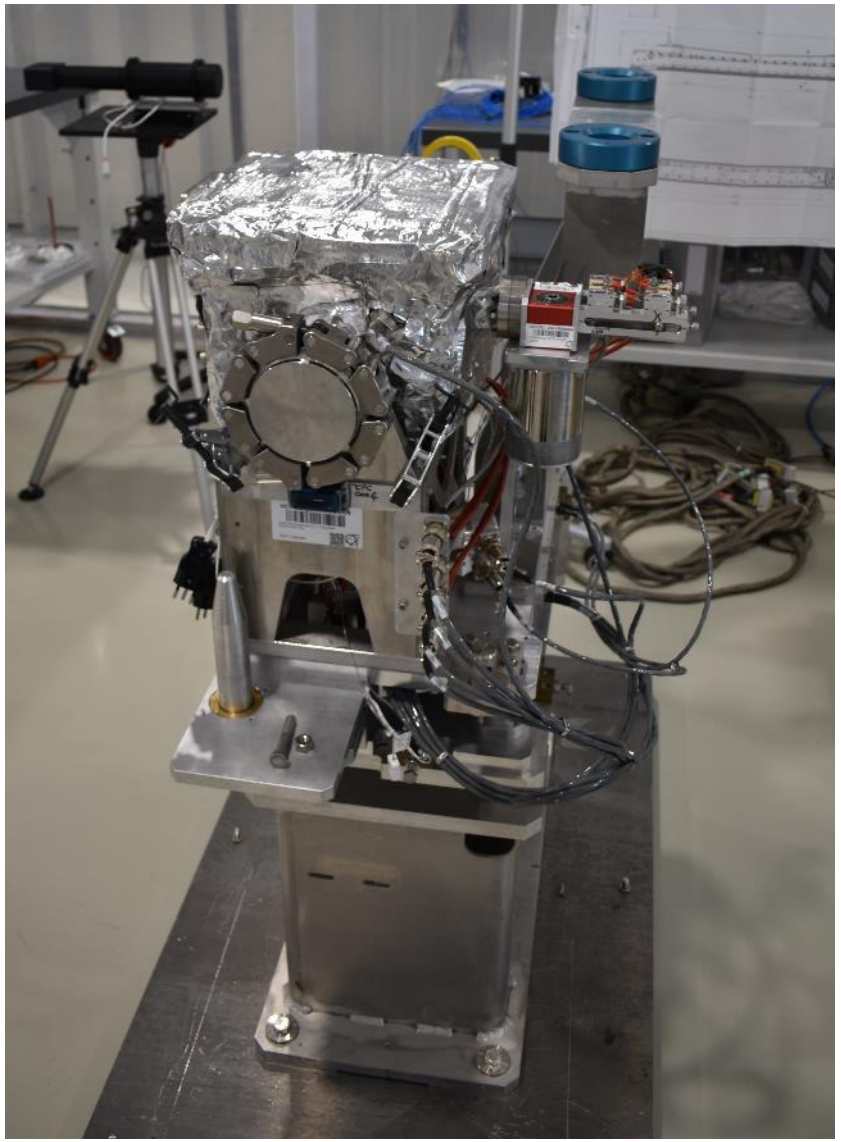
- Injection kickers
- Vacuum interlocks
- Interlocks and signal exchange with experiments.
- Beam instrumentation (Beam position monitors, Beam Loss Monitors, Tune measurements system).
- RF Low-level setup, Transverse damper
- Controls and sequences
- Collimators



A problem with a crystal collimator, was found and an intervention was needed. This delayed the startup with a few days.

Crystal collimator

- Installed in Feb 2023
- Baked and commissioned
- **Motor lost steps during hardware commissioning** (failure mode)
  - **Crystal halfway in**, could not be moved from outside
  - Intervention was needed and a replacement chamber was installed
    - Will be installed in TS1
  - Baseline for collimation in the Ion Run
    - Without it we can't reach the same nominal intensity for the ions

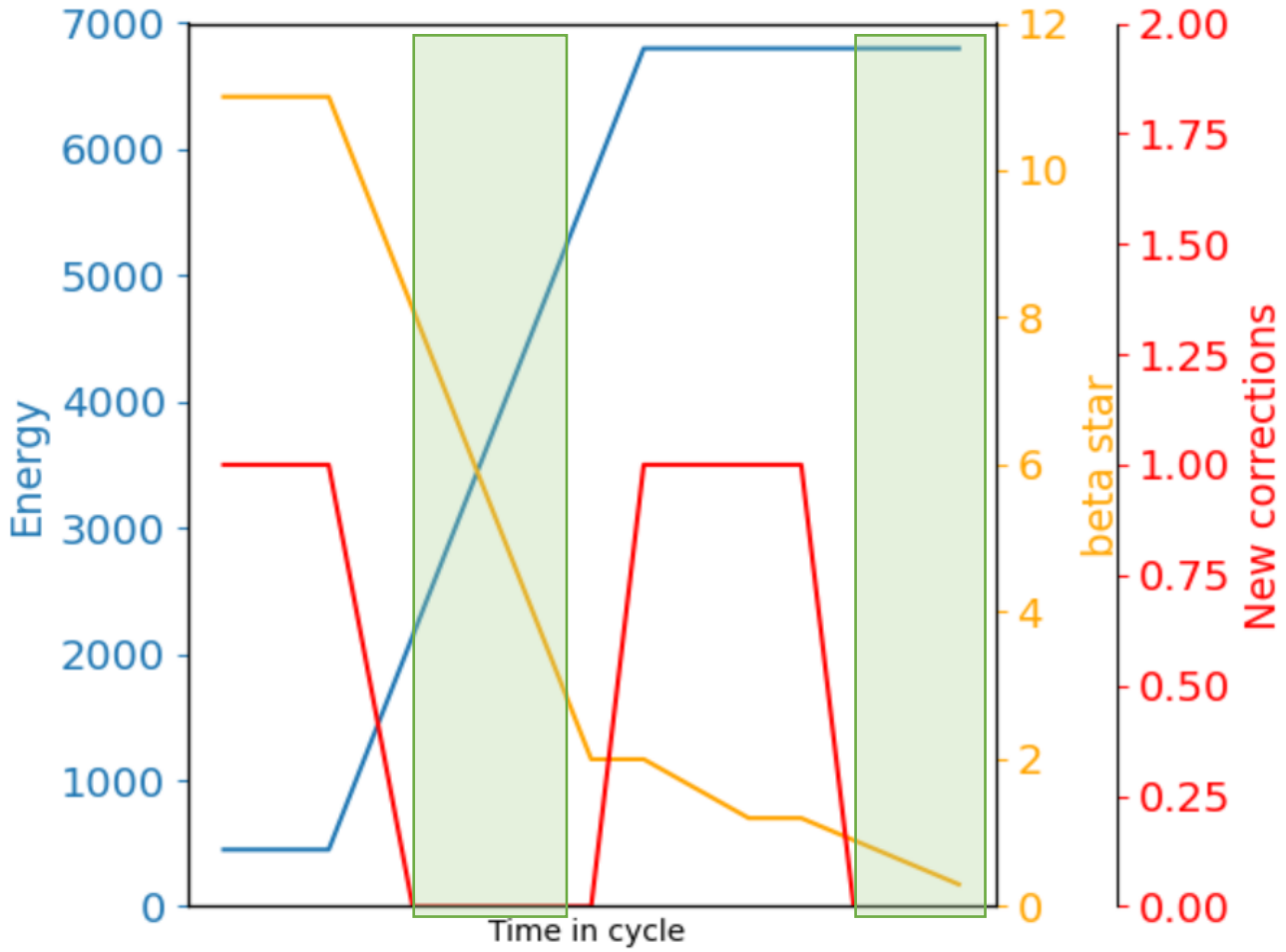


Beam commissioning

Why was the commissioning so short this year?

- Beam commissioning started **Tuesday March 28th**
- **21 days** for beam commissioning until first stable beam at 6.8 TeV in nominal cycle

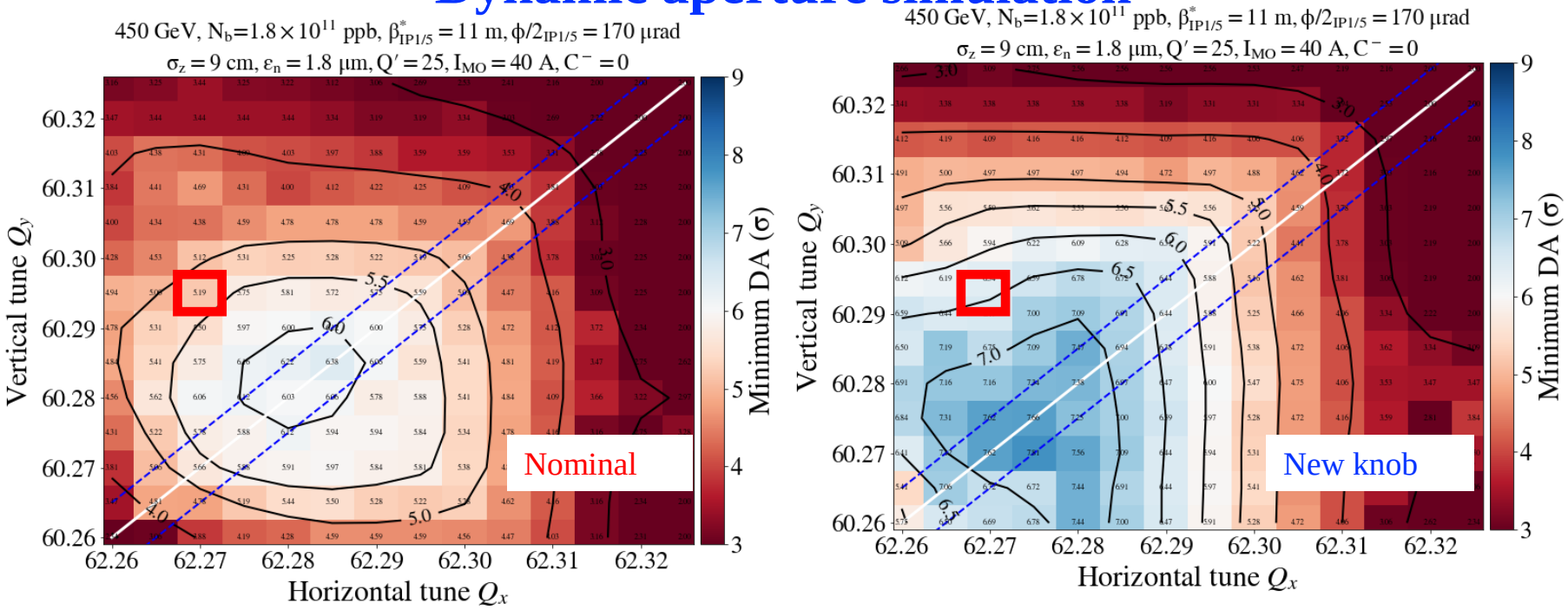
  Helped by a **very high availability of ~90%.**
  - **Including the 4 lost days → 72%**
    - **Rapture disc**
    - **Switch to high-heat load configuration for cryo**
- The new cycle was already extensively tested during MDs in 2022
  - Part of the cycle has also stayed the same
- Increased understanding and experience from 2022



Injection, what is different this year?

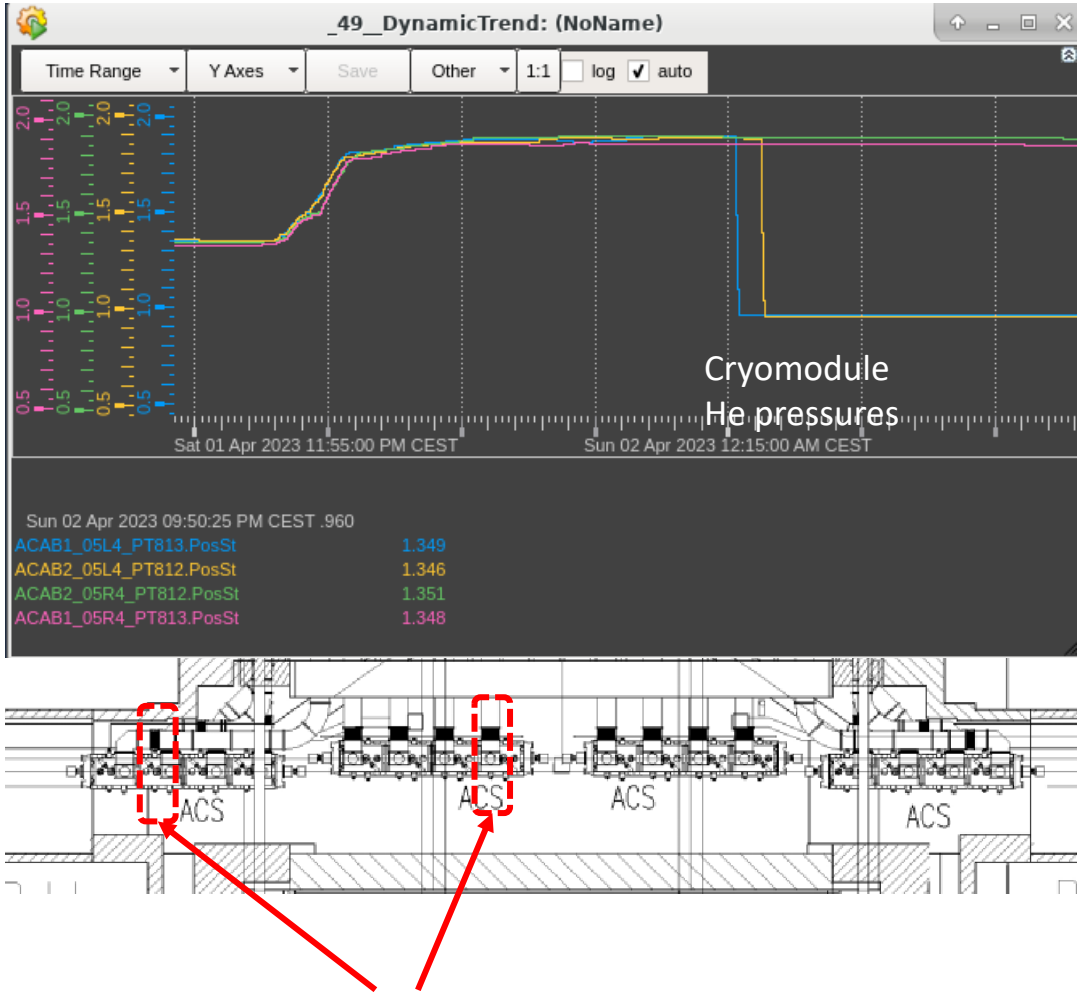
- New setting of the trim quadrupoles to change the phase advance to reduce the negative impact of the strong octupoles at injection needed to stabilize the beam
- Preliminary analysis show an improvement of life time at injection

Dynamic aperture simulation



Rupture disc burst 2nd of April 2023

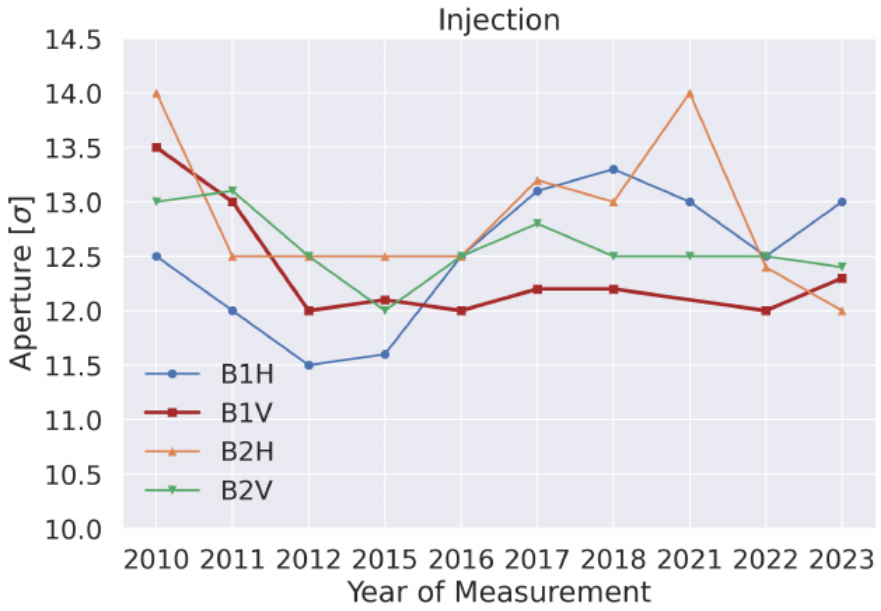
- Following a power cut in IP4:
  - 2 rapture discs burst
    - The rapture discs are crucial for certain failure scenarios
- Replaced only 4 hours later
  - Thanks to the fast intervention and reactions from everyone involved we were able to have back the RF conditions already on ~2.5 days after the incident

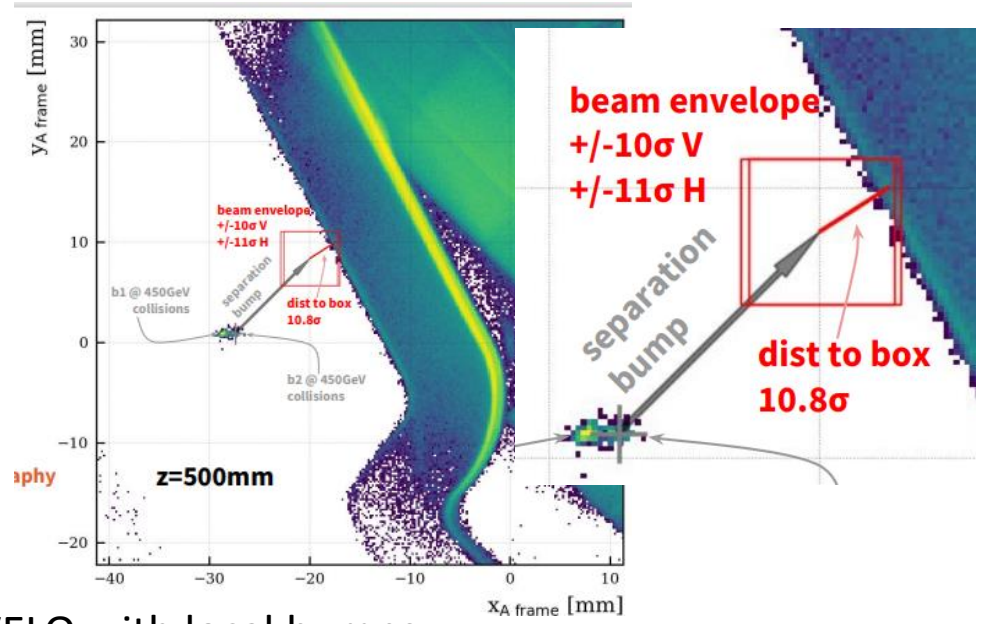


Rupture discs opened on C2B1 and C5B2

Aperture

- Good aperture, as in previous years
- Sufficient aperture & protection by collimation system throughout cycle
- Injection: LHCb VELO is **not** the bottleneck
  - Confirmed by tomography and by local aperture measurements



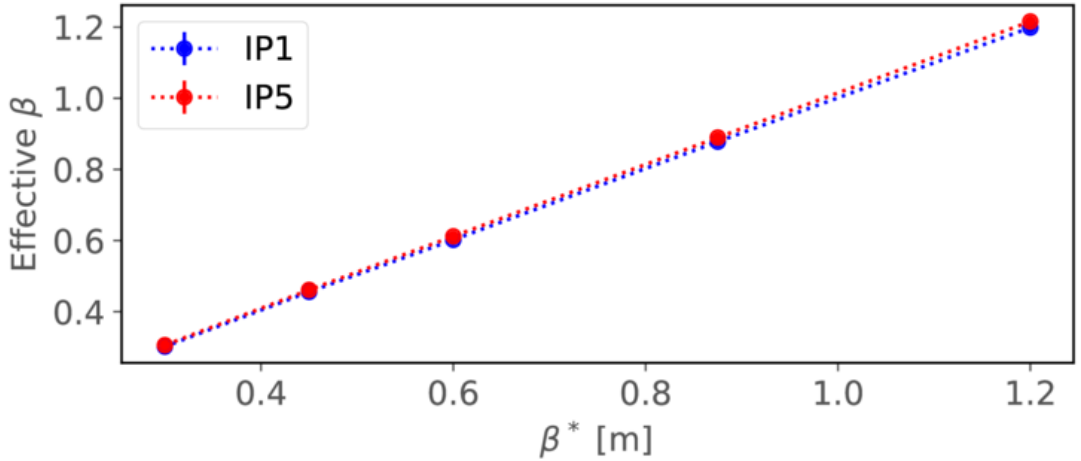


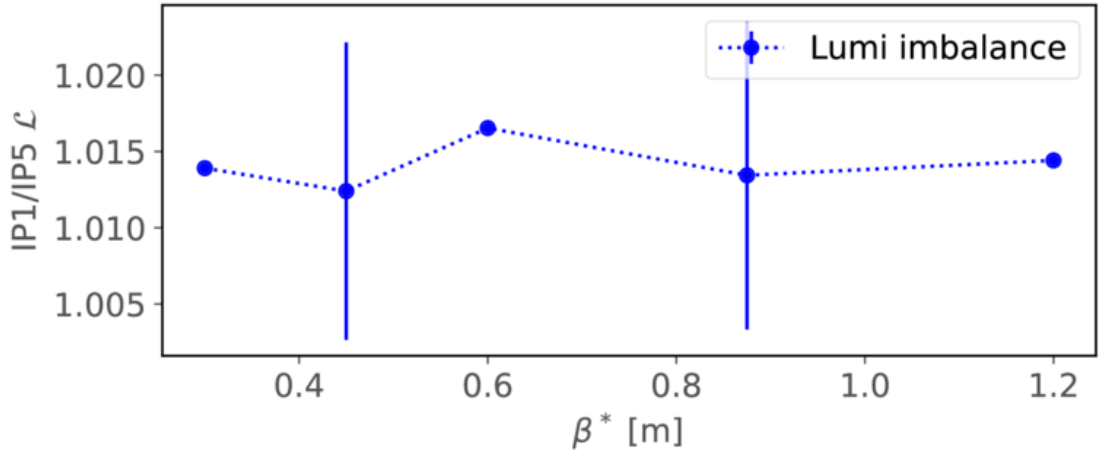
Probe the VELO with local bumps
Results consistent with tomography

β* and luminosity

$$\sigma(s) = \sqrt{\epsilon \cdot \beta(s)}$$

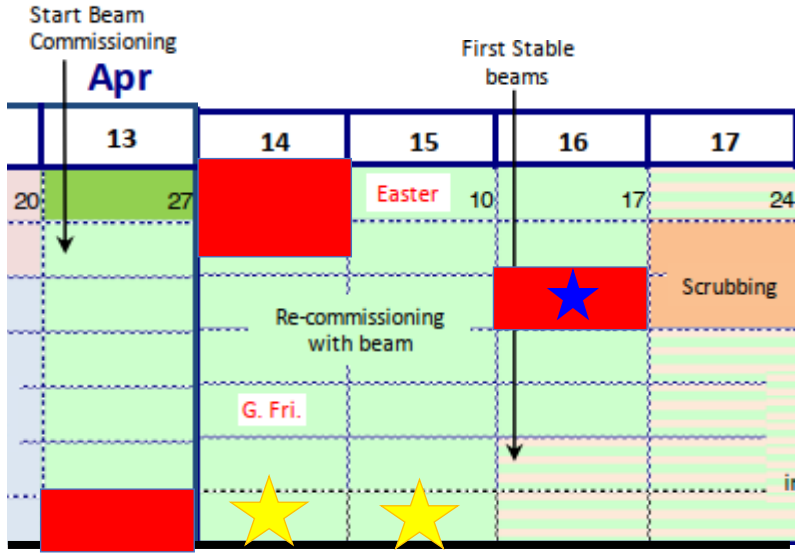
- The β-beat was measured and corrected throughout the cycle
- The β* was measured from 1.2m down to 30 cm using k-modulation
  - 3 times larger β* levelling range compared to 2022!
- Analysis indicates a ~1.5% higher luminosity from β* for ATLAS
  - To reduce error bar more measurement would be needed





Ion commissioning already started!

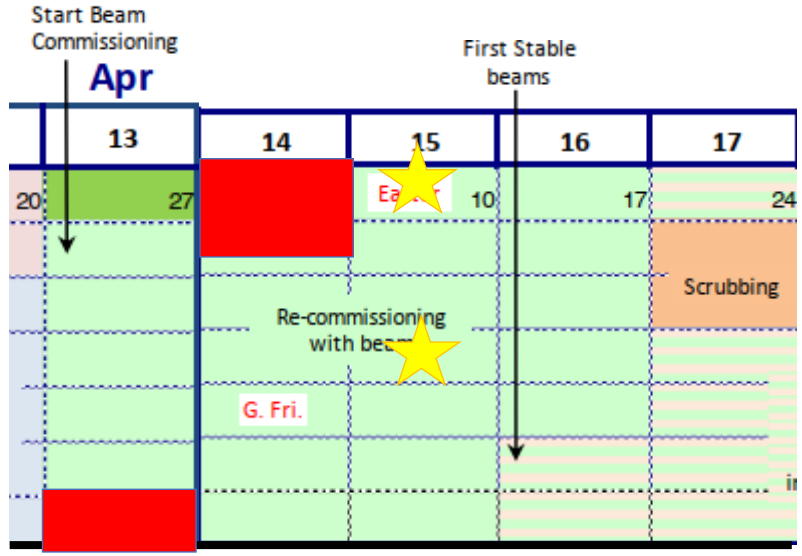
- IP1/2/8 are squeeze to 50 cm already in the ramp
- Optics corrections already calculated
- To do:
  - Switch on separation and crossing schemes.
  - Collimation setup
  - Inject Pb ions…



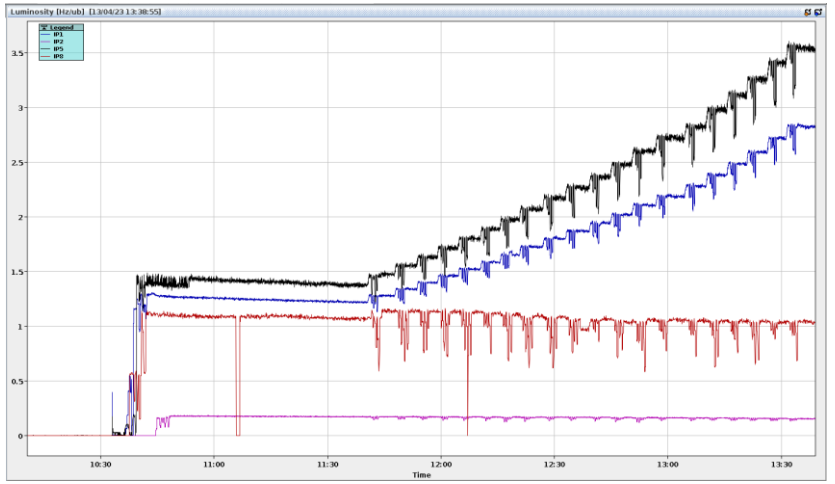
After corrections	B1x	B1y	B2x	B2y	β* effective	Lumi relative to IP2
IP1	0.52	0.53	0.49	0.51	**0.51**	**0.985**
IP2	0.50	0.50	0.52	0.50	**0.505**	**1**
IP5	0.48	0.50	0.51	0.51	**0.5**	**1.01**

Collisions at 6.8 TeV

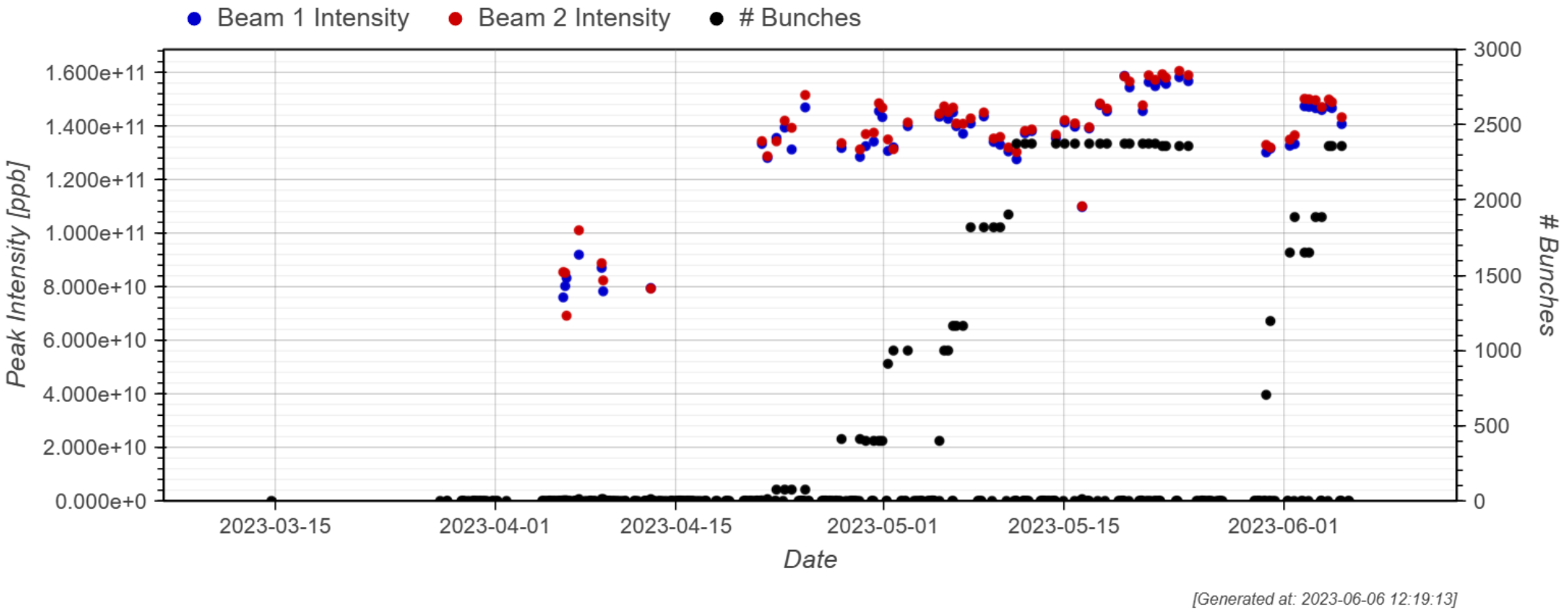
- The **vdm cycle** was quickly recommissioned to establish **first collisions at 6.8 TeV** on Easter Monday
  - Based on correction for tune, chroma and β-beat from 2022
- First **low β collisions** at 1.2 m took place 3 days later, immediately followed by β* levelling to 30 cm



First β* levelling 120 cm to 30 cm

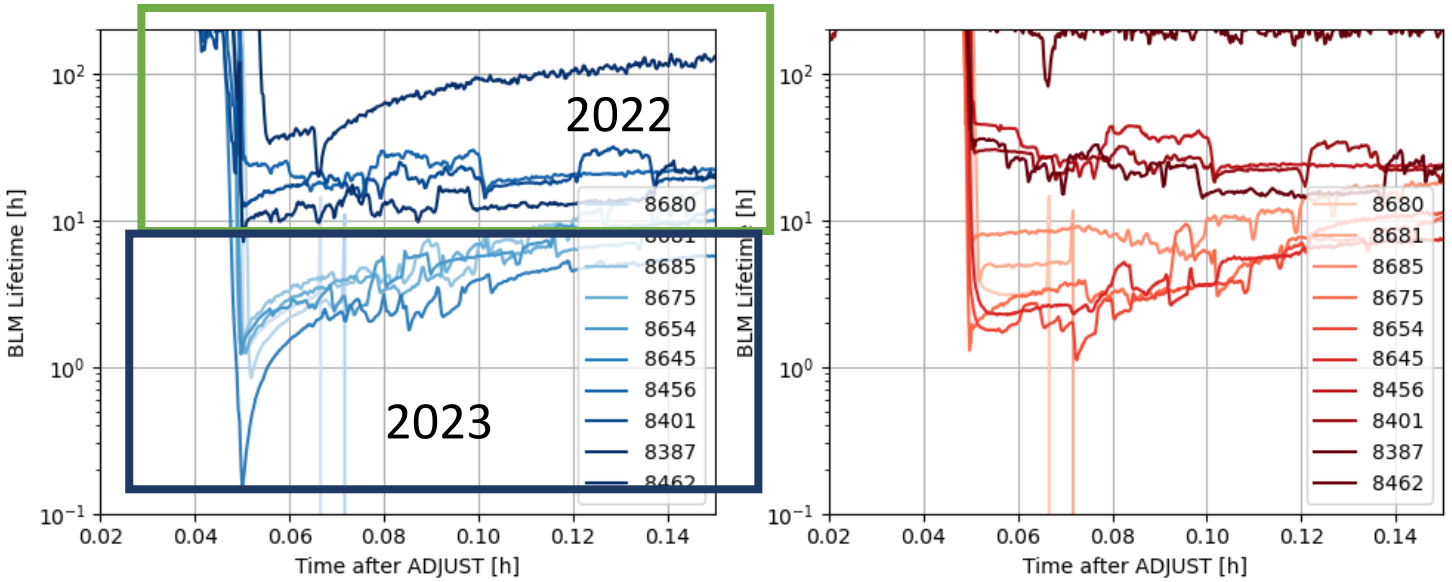


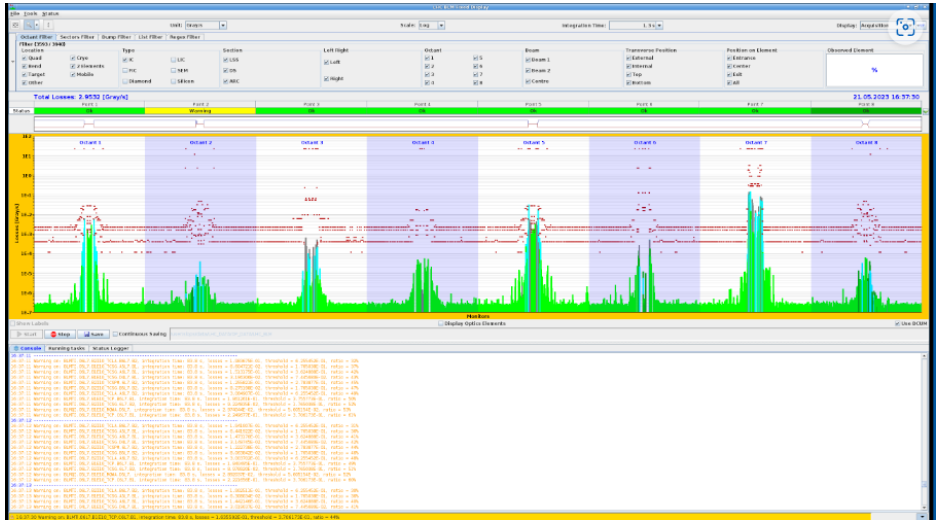
Intensity ramp up



Intensity ramp up

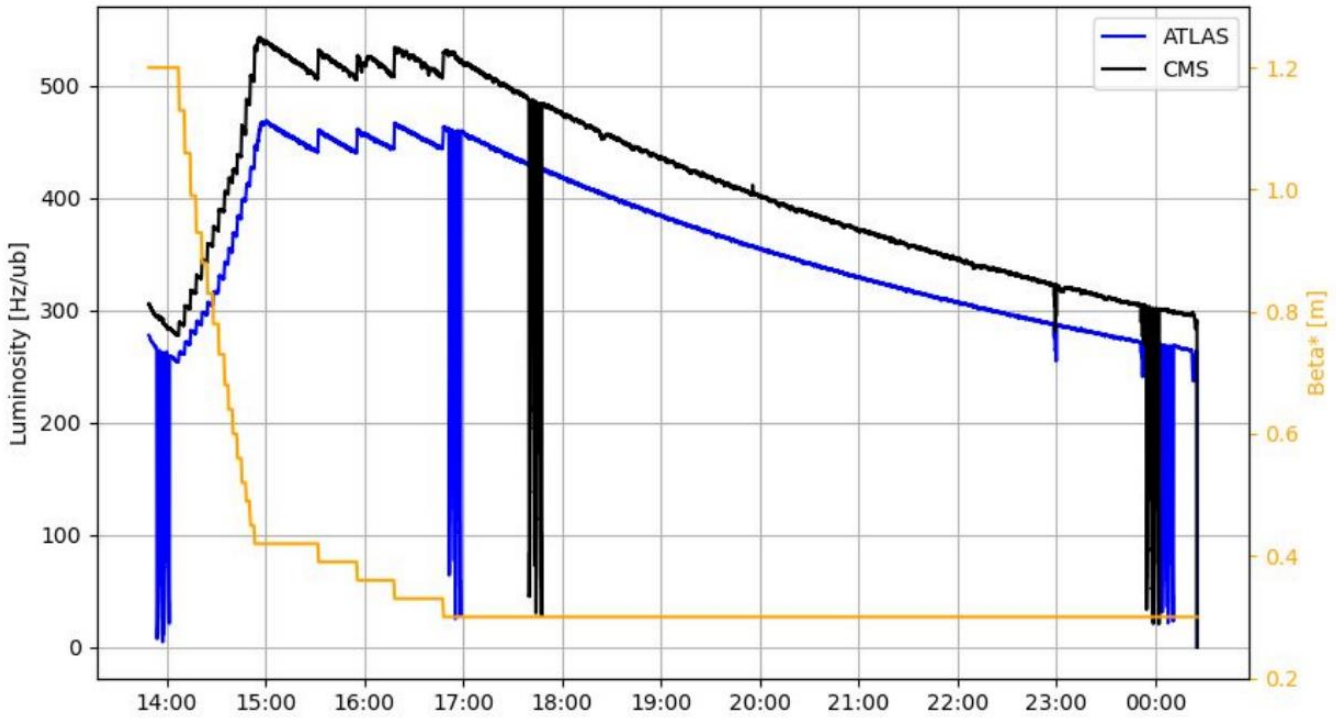
- During the intensity ramp up we got dumped due to losses when we went into collision
  - Collimator with an angle was retracted which fixed the issues **with the dumps coming from high losses** going in collisions
- Investigation ongoing to understand the worse lifetime when going to collisions
  - Not blocking any intensity increase



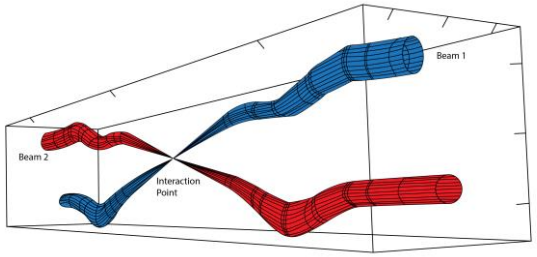


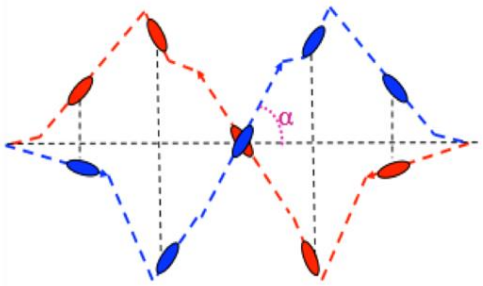
Luminosity in the early fills

- Significant difference between ATLAS and CMS
- At 30 cm the relative difference decreased
  - Sign that part of difference was due to crossing angle
  - Two independent beam position monitoring system also showed crossing angle was larger in ATLAS

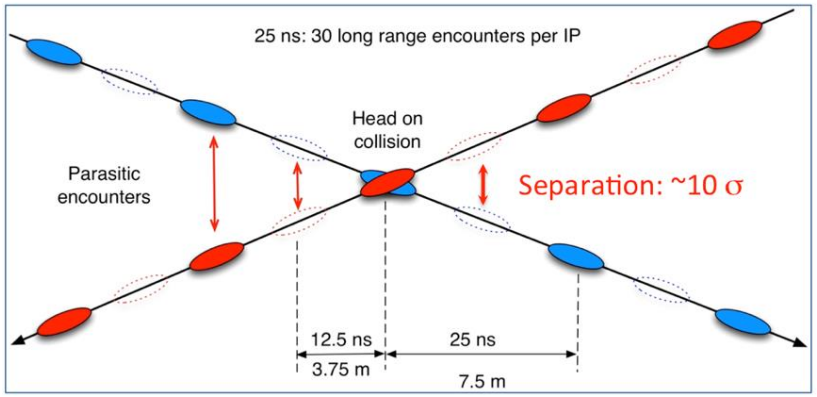


Crossing angle





- We need the crossing angle to reduce the parasitic encounters
- Has an impact on the luminosity
  - Larger crossing angle -> Less luminosity
- We just adjusted down the crossing angle for ATLAS by 10u rad and now the measured luminosity is much closer between ATLAS and CMS
  - Done at the same time as retracting the collimator
  - Saved time in terms of validation needed



$$\mathcal{L} = \frac{N_1 N_2 f N_b}{2\pi\sqrt{\sigma_{1x}^2 + \sigma_{2x}^2}\sqrt{\sigma_{2y}^2 + \sigma_{2y}^2}} \cdot$$

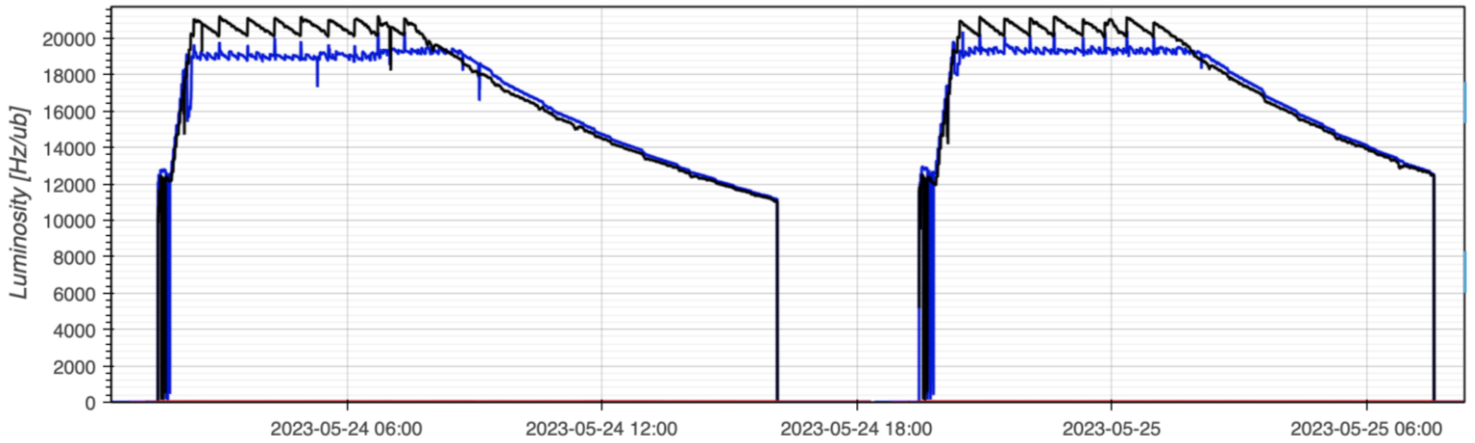
In case of a crossing angle one can calculate an approximative effective beam size following this formula

$$\sigma_{eff} = \sigma \cdot \sqrt{1 + (\frac{\sigma_s}{\sigma_x}\frac{\phi}{2})^2} \cdot$$

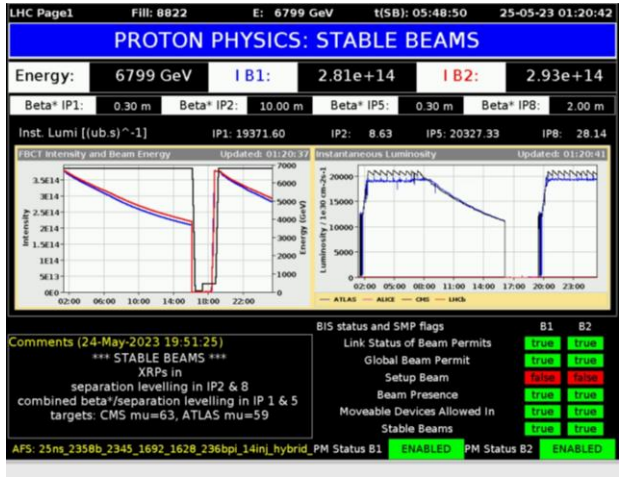
Physics fills performance end of May

- **New record:** Integrated luminosity: **~1.2 fb^{-1} in 24h !**
- Peak levelling just above 2.0 x 10^{34}cm^{-2}s^{-1}
- Pileup targets ATLAS/CMS = 63 / 59
  - Thanks to combined separation β* levelling and separation levelling we can deliver different pile up to ATLAS and CMS!
- Luminosity difference also reduce due to updated calibration factors

Max at start of stable beams: **409 MJ**
1.59 x 10^{11} p/b (Injected: 1.61)

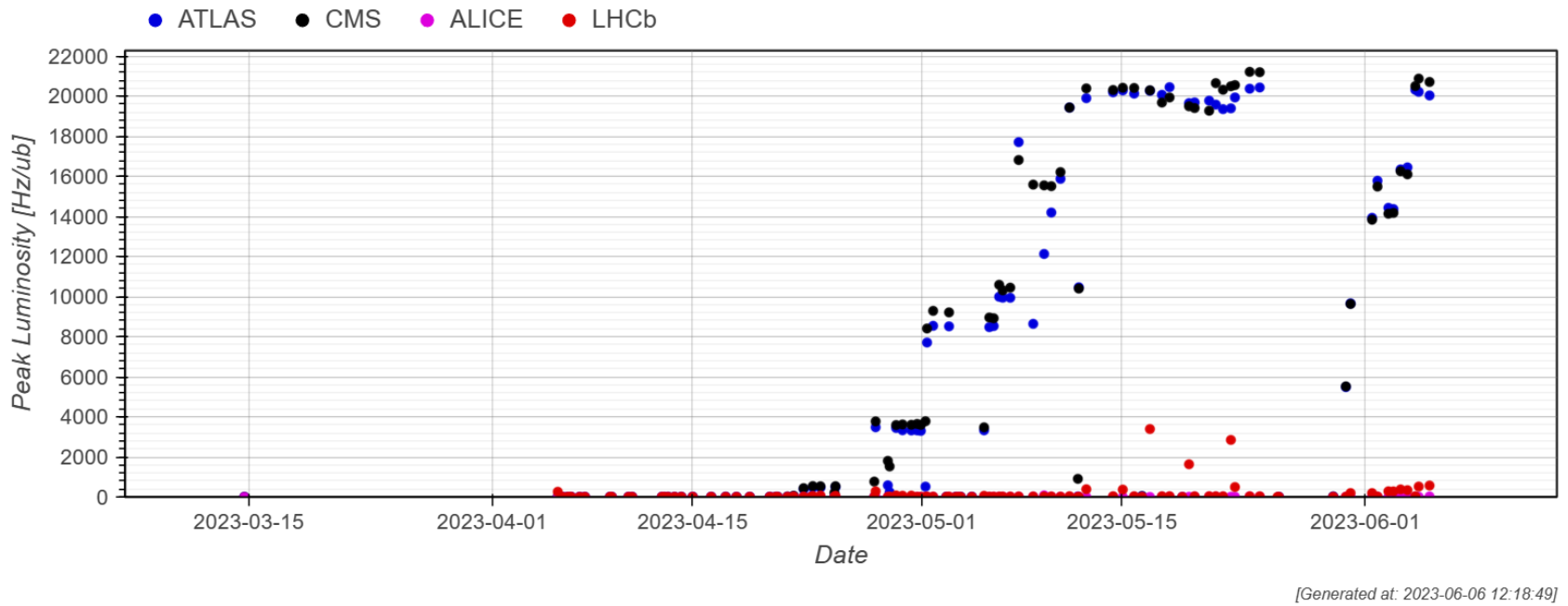


24th to 25th of May 2023



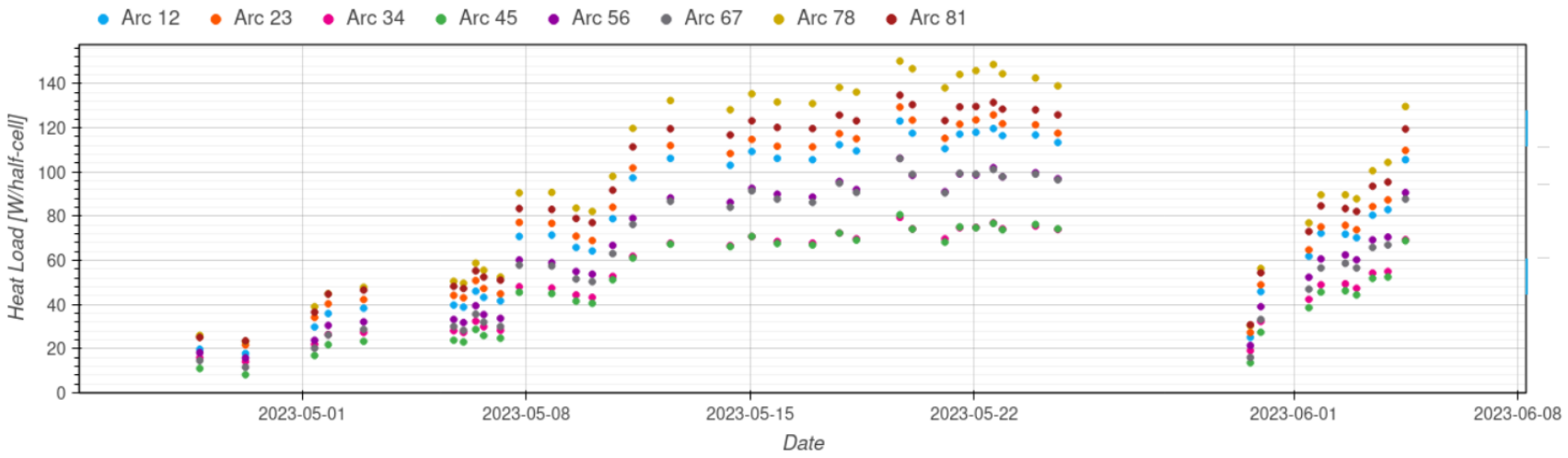
Peak luminosity evolution

- The pileup is limiting the peak luminosity at the moment, but we are also close to the cryogenic limit for the inner triplets
  - $2.2*10^{34}cm^{-2}s^{-1}$ is currently the maximum operational limit



Heat Load

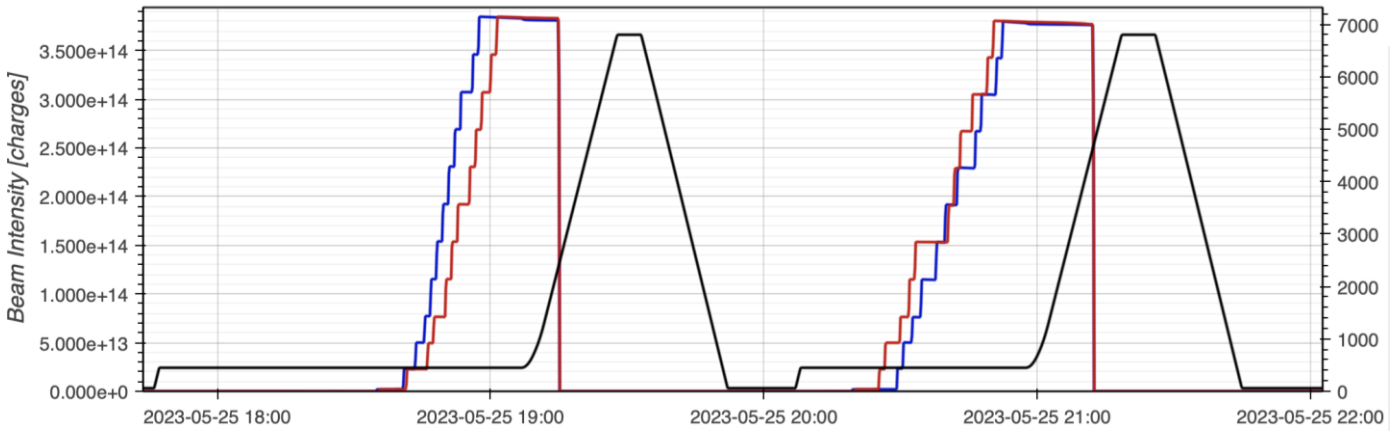
- The heat load is under control even for the highest intensity fill we are below 150W/half cell
  - Up to 183W/half-cell in 2022 even though the total intensity was very similar
- Thanks to **hybrid filling scheme** (mixture of 8b4e and 36 bunch train)
  - First time we use in normal operation
  - Significant effort from the injectors to make this happen!

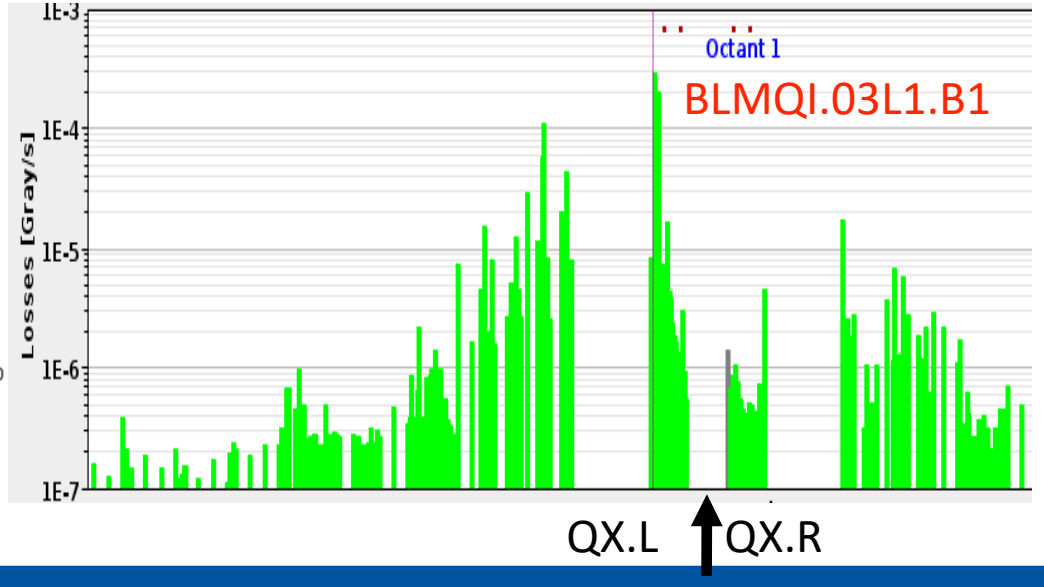


4L1 event

4L1 event

- Evening of the 25th of May the beam was dumped during the ramp due to losses
  - The highest losses were at Q3.L1

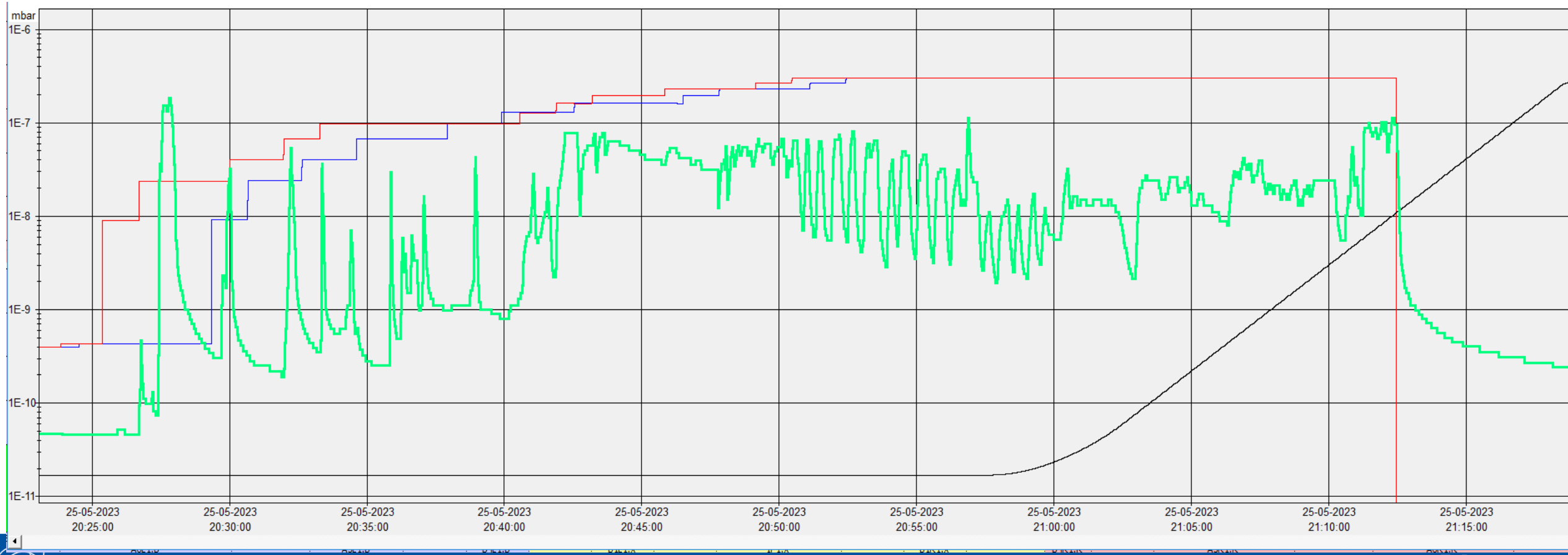




4L1 issue

- The issue was not present the day before

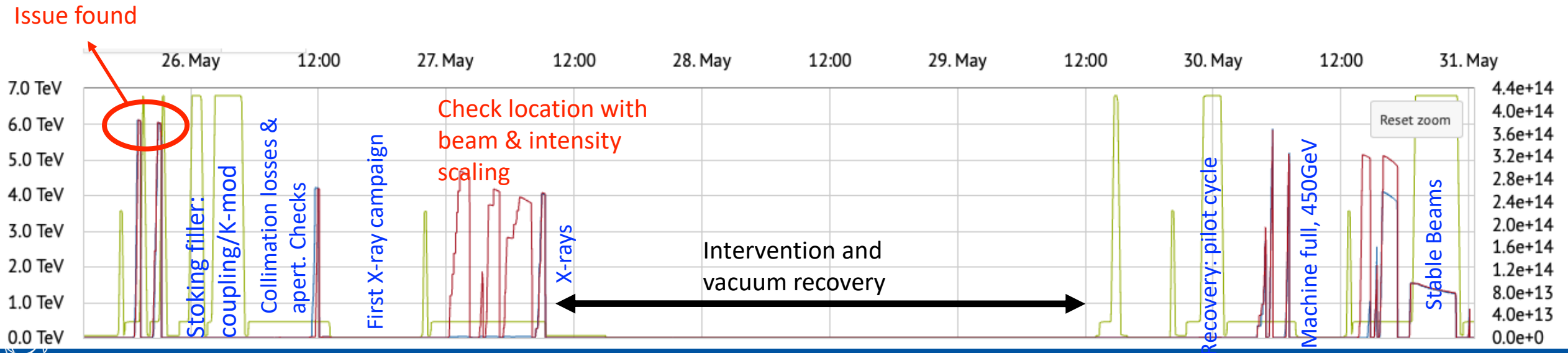
Already issues at injection with the vacuum
High intensity operation was stopped after this!



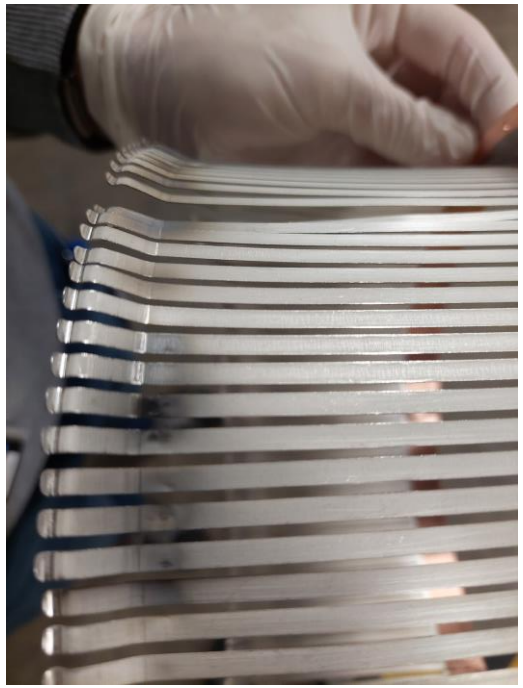
Intervention on 1L4

- After the high intensity was stopped a validation that there were
  - Loss maps
  - Aperture measurements
- X-ray campaign was launched to find the source day after
  - The source was found to be “module 5” located left of IP1
- Intervention to exchange was started ~2 days after the issue was first and vacuum pumping started as soon as it was finished

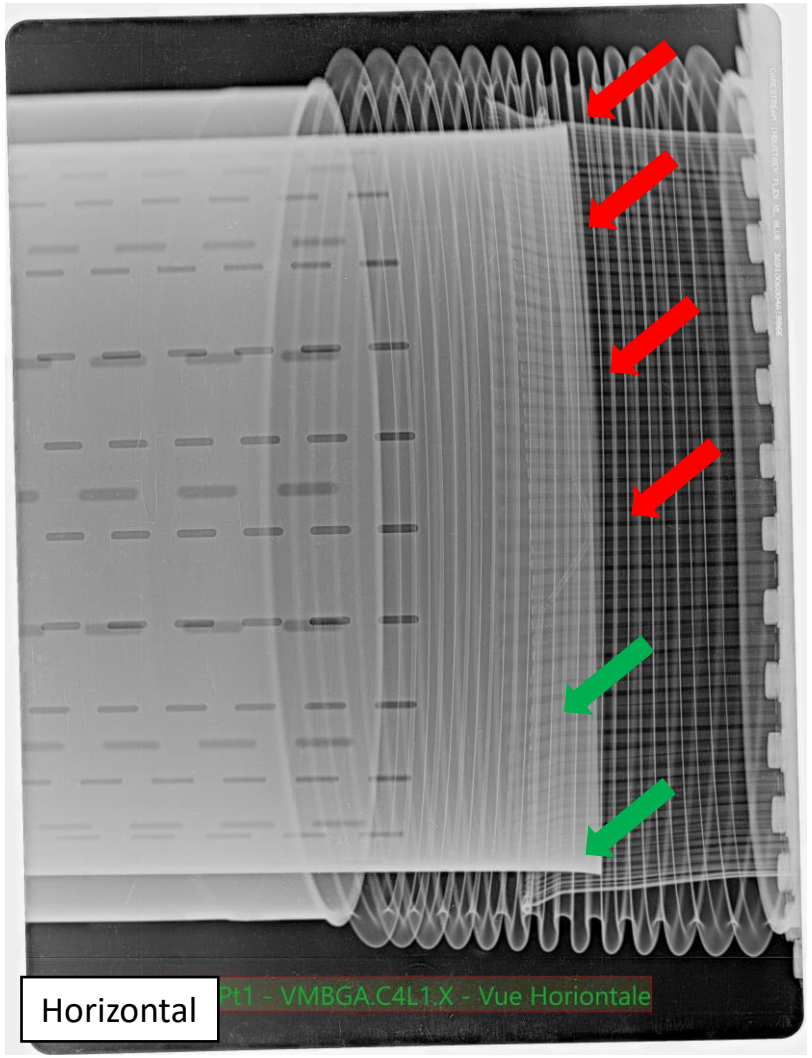
Many thanks to all the people involved, in particular VSC, MME, RP, CEM, BI and may other



Module 5 X-ray and photos after opening

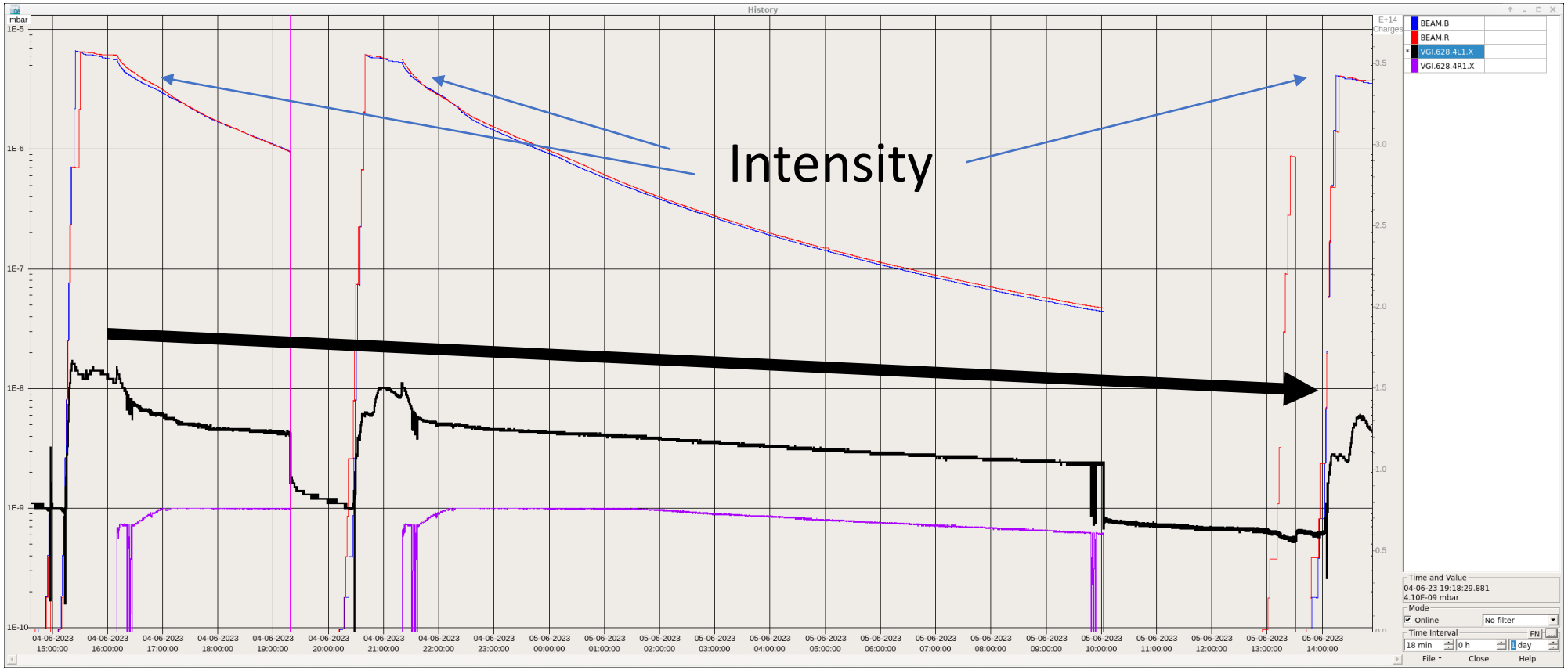


Clear sign of the spring heating, possibly this is the source of the problem



Preliminary, analysis ongoing!

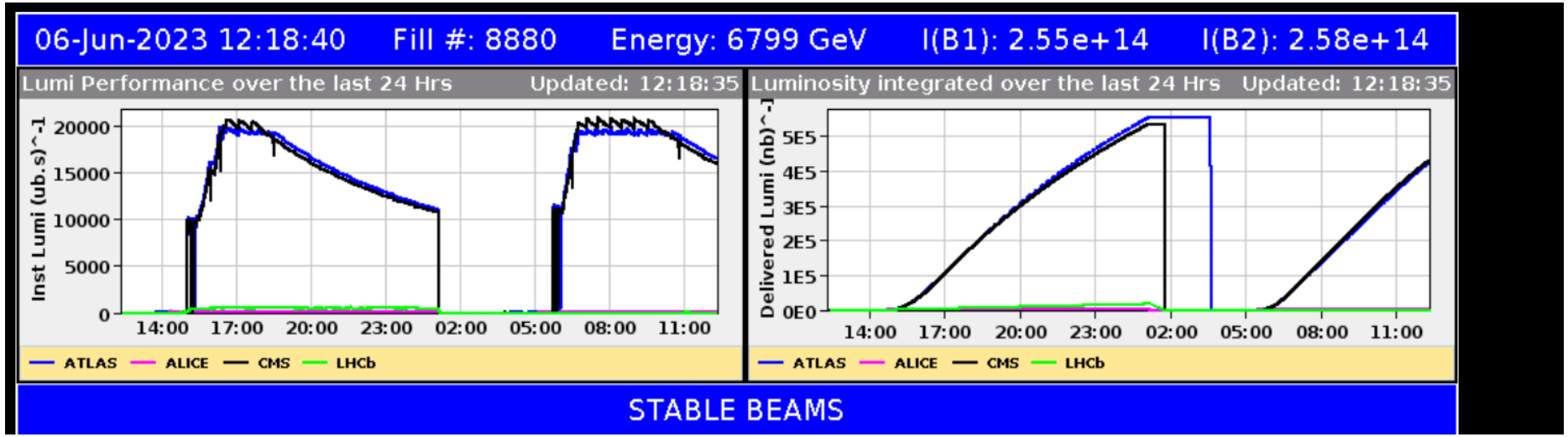
Recovery after intervention 4L1



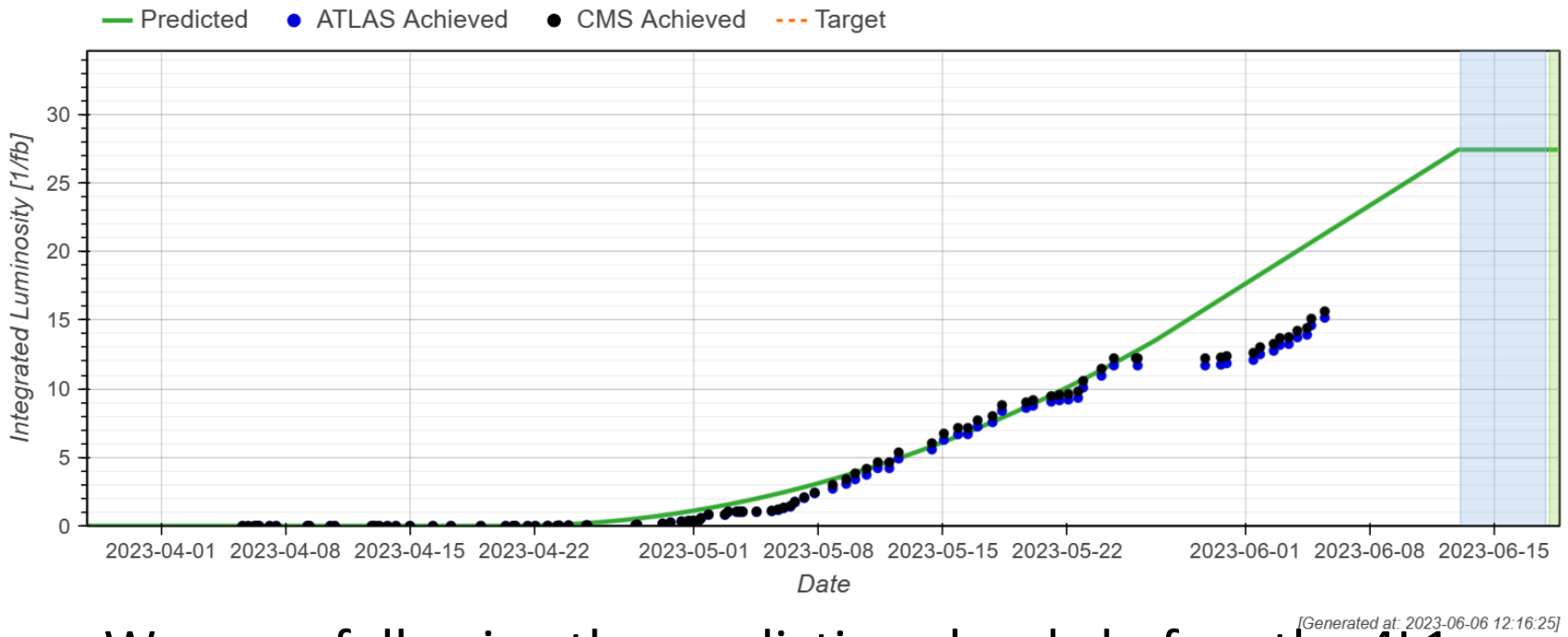
- Priority was to get the machine back to physics
- Vacuum conditioning with beam -> lower intensity for the first fills after intervention
- Vacuum still not as good as before but no longer limiting us to reach previous intensity

Almost back in the conditions before 4L1

- Even with these issue we are back to significant luminosity production!
  - Some difficulties to inject (not related to the event)
    - Significant scraping of the beam is needed in SPS
  - We will consolidate with bunch intensity below $1.6*10^{11}$ while we better understand the 4L1 event and why the large scraping in SPS is needed



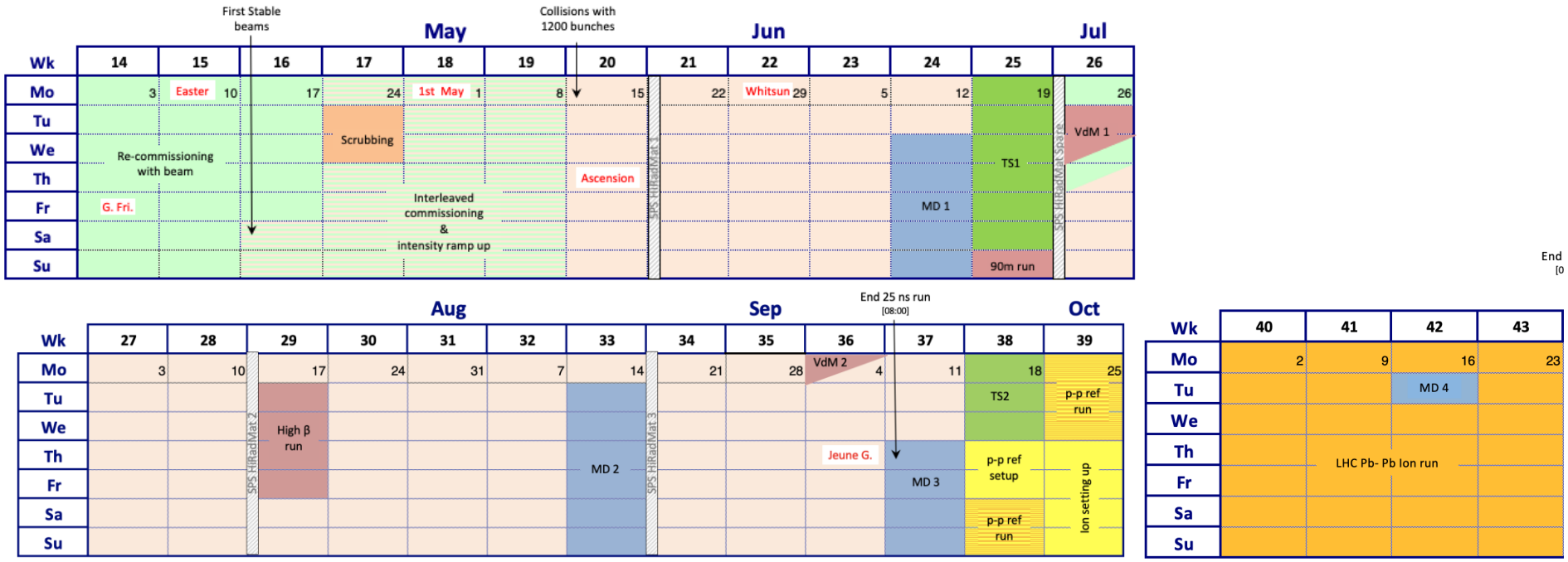
Luminosity production



- We were following the prediction closely before the 4L1 even
- Challenging “catch up”
  - Mainly determined by the number of faults we have

What is next?

- MD period starting next week followed by a technical stop
- Many interesting other runs ahead, e.g., high-β and ion run!
- The target is still to reach the $1.8*10^{11}$ for the nominal cycle this year
  - Will be in β* levelling for most of the fill!

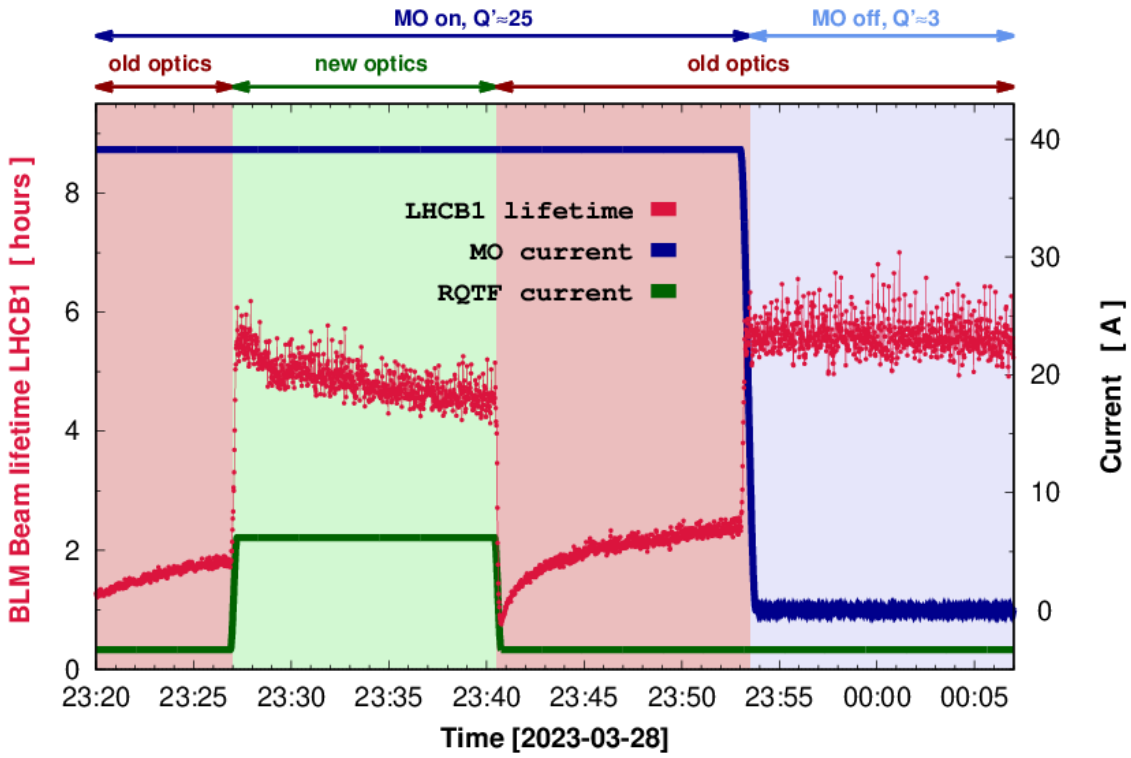


Conclusion

- A very efficient commissioning thanks to all the effort of all the teams involved
  - Profited from this period to anticipate activities, e.g., the ion commissioning
- After the adjustment of the crossing angles and updated calibration factors the luminosity is now very close between IP1 and IP5
  - Combined β* and separation levelling enable to operate at different pile up for ATLAS and CMS
- The hybrid bunch scheme enables us to go for even higher intensities without being limited by the heat load
- The issue in 4L1 is fixed and we are almost back to situation before the stop in terms of luminosity production!

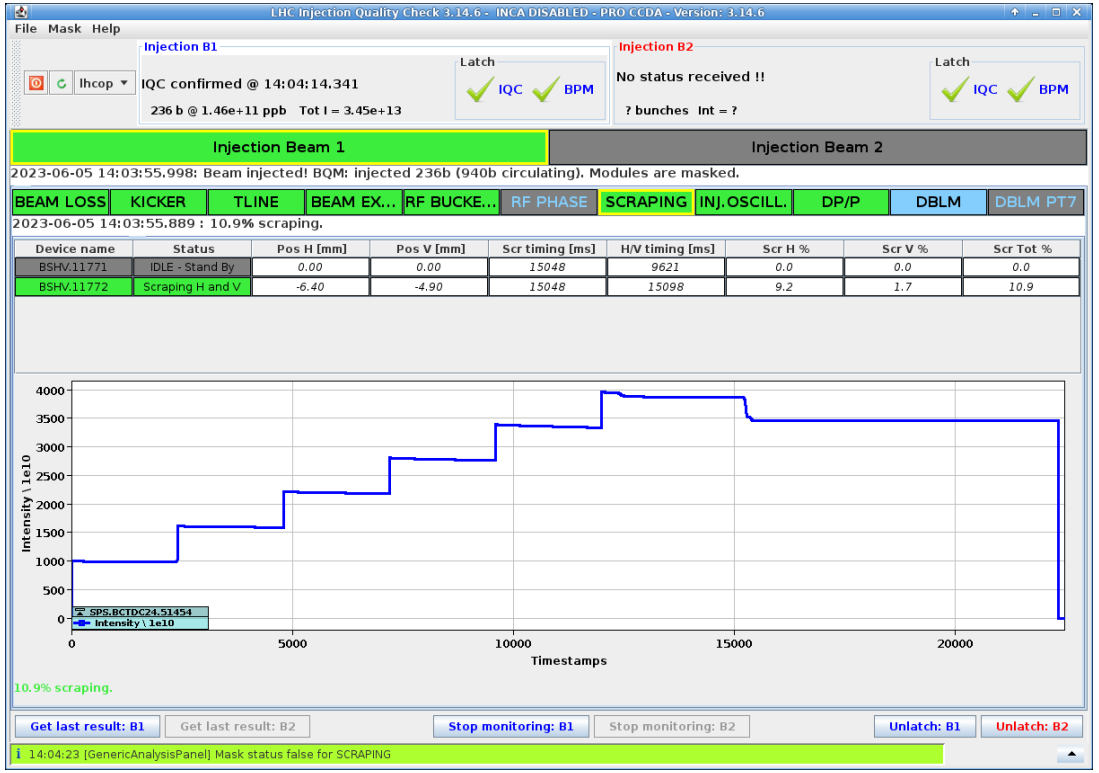
Backup

Clear improvement on lifetime with new optics



- Test was done with blown-up single pilots (low intensity bunches)
  - Different from normal configuration
- Not so easy to compare to 2022 for nominal configuration due to the fact that we use mixed (36b and 8b4e) filling scheme this year.
- Stay tuned for the results from the MD in the coming weeks when we will try to make a direct comparison!

Issues at injection



- Significant scraping of the beam needed in SPS to inject Beam 1
  - Much less is needed for Beam 2
- The temperature at the injection collimator for beam 2 (TDIS) close to threshold
- -> Pause injection and move out injection protection to cool down

Recovery after intervention 4L1

In the end the measured losses at injection were the best proxy for a successful ramp.

- the CCC adjusted machine filling to achieve <8E^{-6} Gy/s before ramping

Below is an indication of how the conditioning evolved over the weekend

Day	Fill #	# bunches	ppb	% RS12 threshold (3L1)	%RS7 TCTPH.4L1.B1 in collisions
Friday 2/6	8863	1650	1.5E11	87%	
Saturday 3/6	8865	1650	1.5E11	60%	
Saturday 3/6	8866	1886	1.5E11	55%	
Sunday 4/6	8870	1886 (2358b scheme)	1.5E11	72%	56%
Sunday 4/6	8872	2358	1.5E11	70%	56%
Sunday 4/6	8873	2358	1.5E11	56%	60%

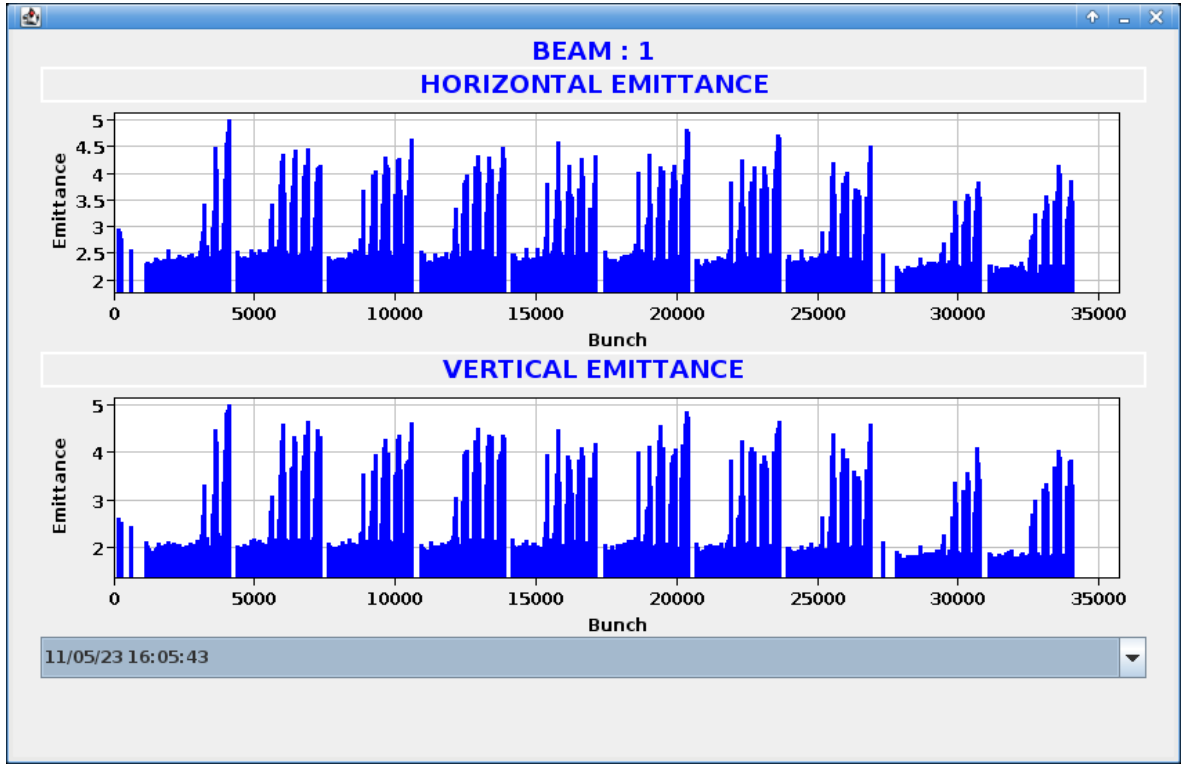
Recap of the CMS lumi calibration changes

- Also circulated on MM
- Luminosity update in 2023
  - Fill 8642: -1.9%
  - Fill 8675: -2.8%
  - Fill 8686: -2.0%
  - Fill 8728: +1%

Collimator and xing angle “retouche”

- Updated settings for TCSPM.E5R7.B1 (dumps going in collisions)
  - Moved the TCSPM.E5R7.B1 to 8.2 sigma
- Also applied a crossing angle correction at IP1 of 10urad (down)(IP1/5 imbalance)
  - Luminosities at IP1 and IP5 now well correlated
- Validation of the new settings agreed with Machine Protection Panel
- Two validation fills for loss maps
  - subset of βtron loss maps from flat top to 30 cm, off momentum loss maps at 30cm and asynch dump at 120cm and 30cm with roman pots in and the wires powered (only at 30cm).
- Step down in intensity to 400b (with ~1.5e11 ppb) for one fill
- Followed by a final 999b fill (also with 1.5e11ppb), before stepping to 1200b

Emittance blowup in B1 at 1.1 TeV



- In the fist two fills with 200ns spacing clear signs of e-cloud increase (1900b and 2400b)
- Sudden blowup of B1 around 1.1 TeV
- Increase of Q’ did not help
- Disappeared by itself due to conditioning
- Investigation lead to finding bug in FF of coupling correction

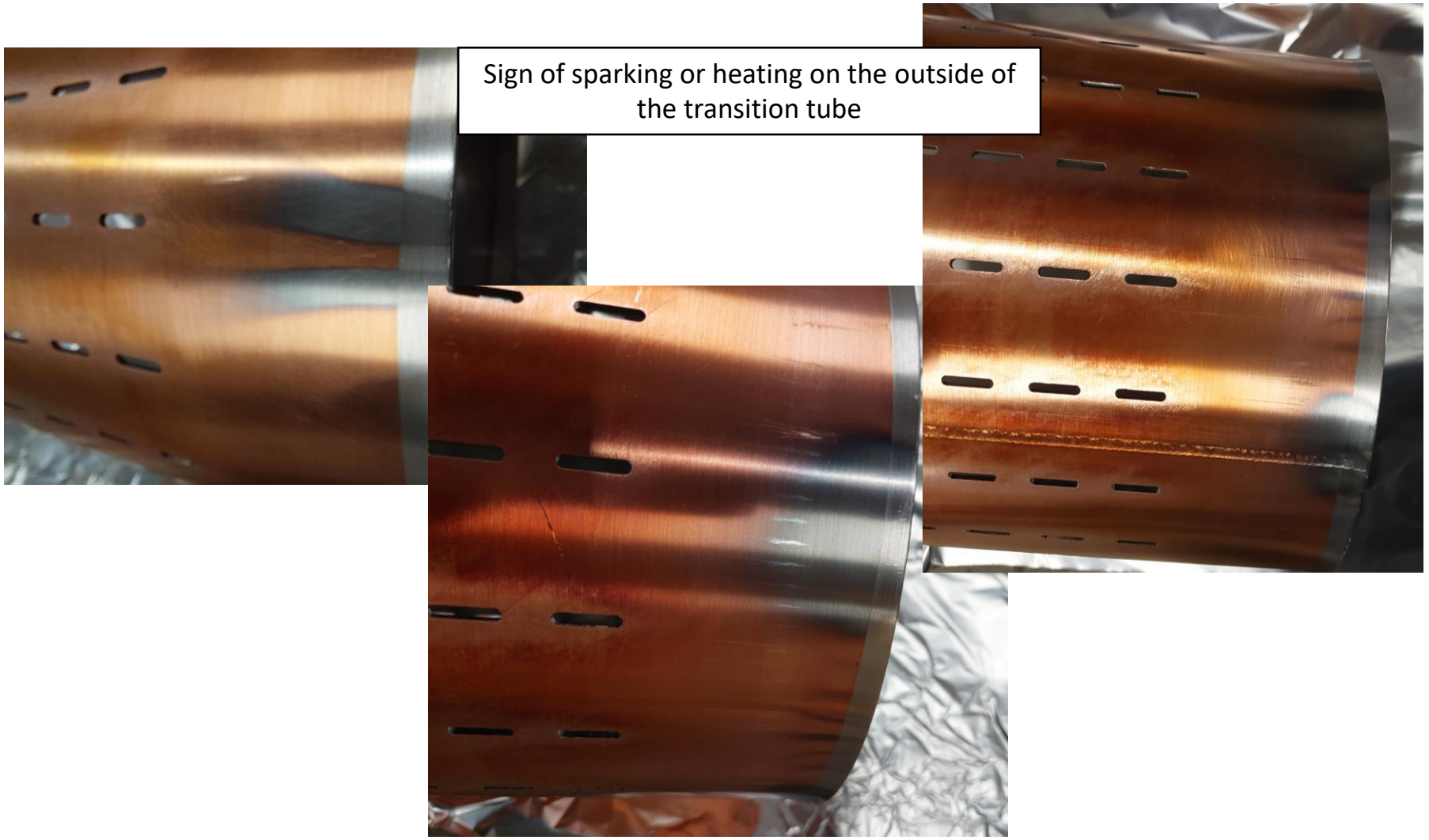
Slide from LMC, S. Redaelli

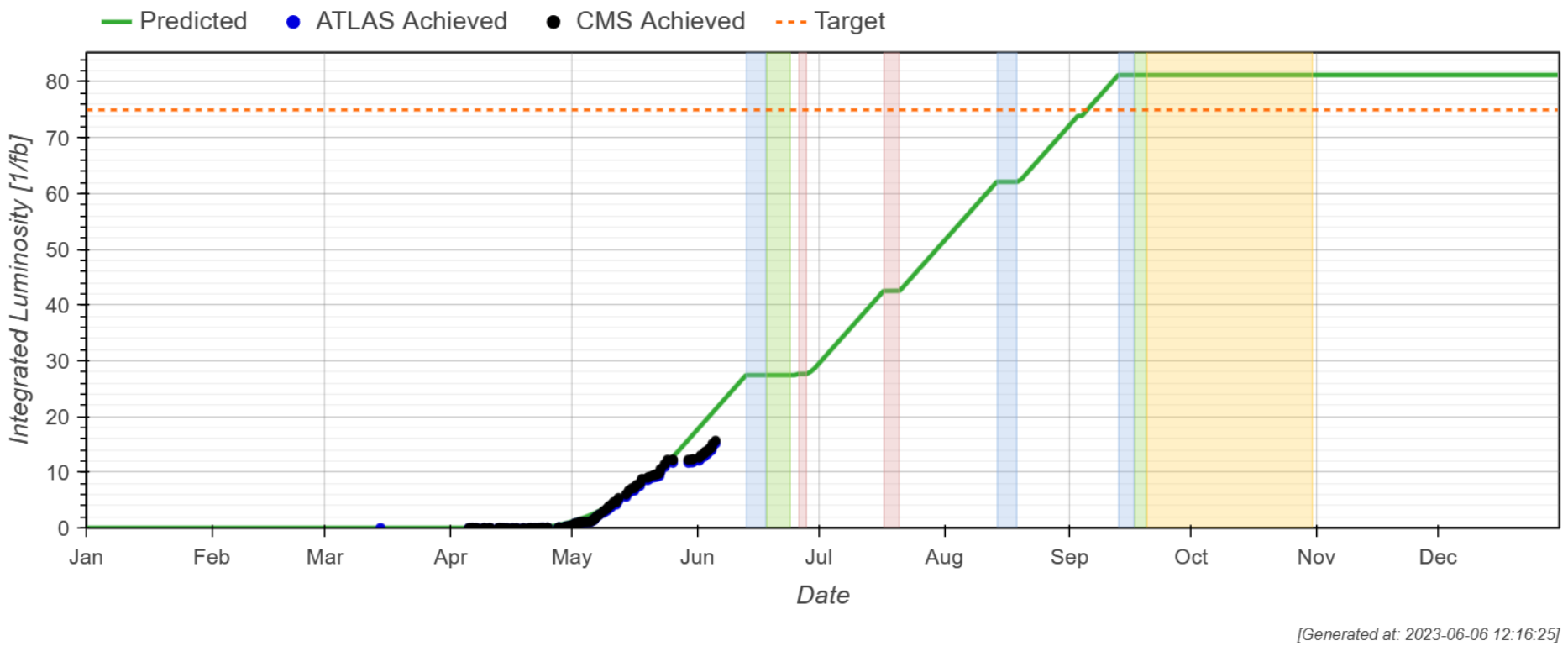
Beam measurements and intervention

- ☑ Friday: Beam checks: loss maps, “collimation losses” and aperture at 450GeV → Ok
  Access: first X-ray campaign, installation of BatMon and prep. for new BLMs → Ok
  Suspicious spring layout for “Module 5”. Cross checked with beam measurements.
- ☑ Sat.: X-ray of Module 5 from side → Confirmed issue. Started intervention to replace M5.
  Initial pumping; leak detection; continued pumping.
- ☑ Sun.: Given the good progress of pumping, could already launch the partial bake out!
- ☑ Mon.: Good progress. Access to remove equipment and opened valves → Ok for beam
  Over night: (1) full cycle with 3b; (2) filling the machine at 450G

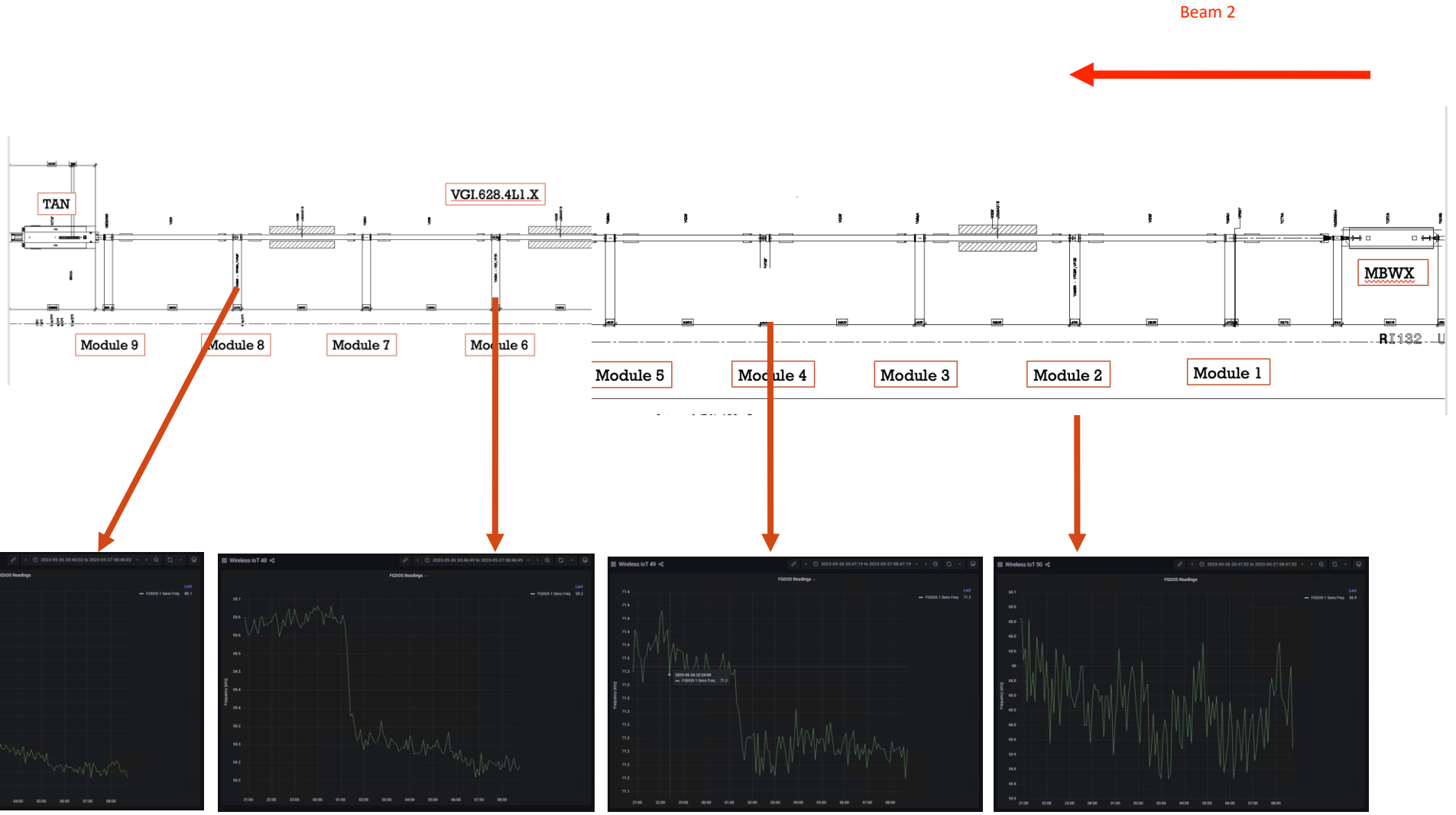
Many thanks to all the people involved, in particular VSC, MME, RP, CEM, BI and may other

Module 5: Transition tube




Predicted
ATLAS Achieved
CMS Achieved
Target
Integrated Luminosity [1/fb]
0
10
20
30
40
50
60
70
80
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Date
[Generated at: 2023-06-06 12:16:25]

Additional observations

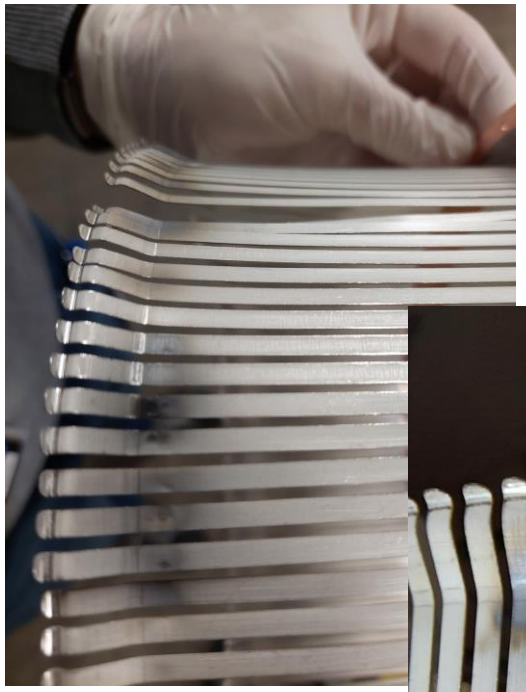


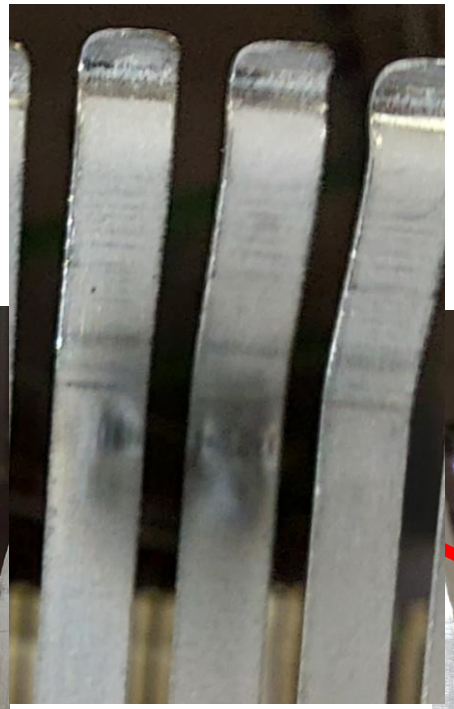
S. Danzeca

New BLM layout also deployed by BI: 3 new BLMs per side available and configured on Tue.

Module 5: RF Fingers

However, there is clear sign of sparking or heating on the outside of the RF fingers





Clear sign of the spring heating, possibly this is the source of the problem

Module 5: Spring

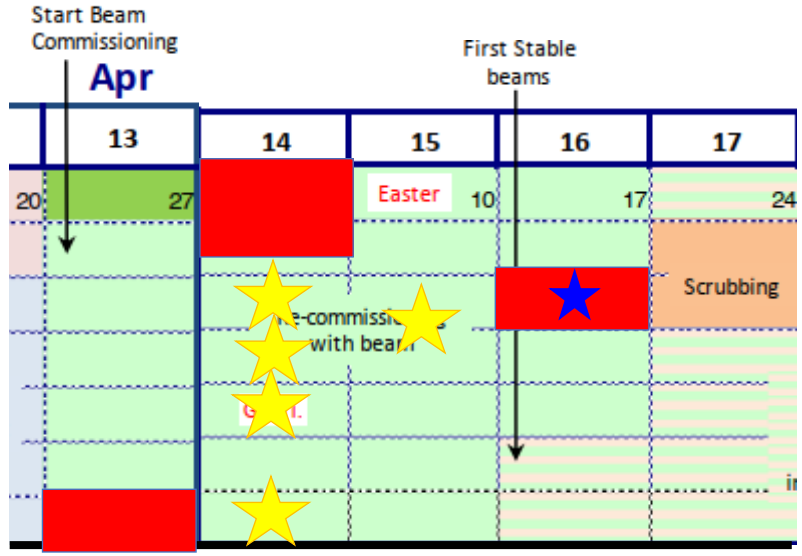
Completely plasticized spring (T > 500°C)

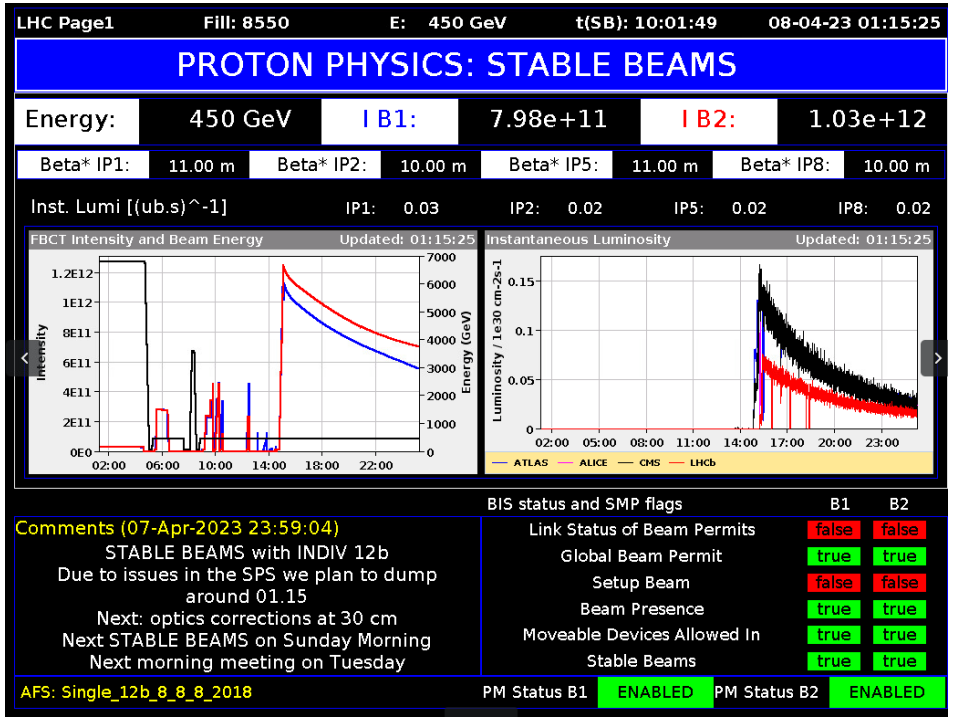
Sign of melting and evaporation

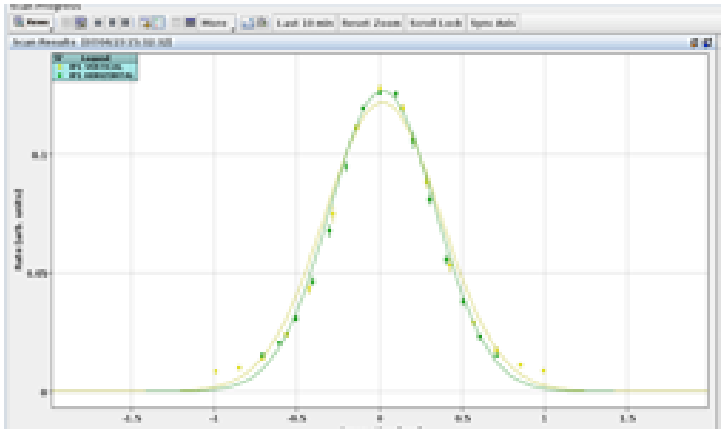
Collisions at injection

Four fills of stable beams were delivered at injection with nominal crossing scheme (+ 1 fill of setting up).

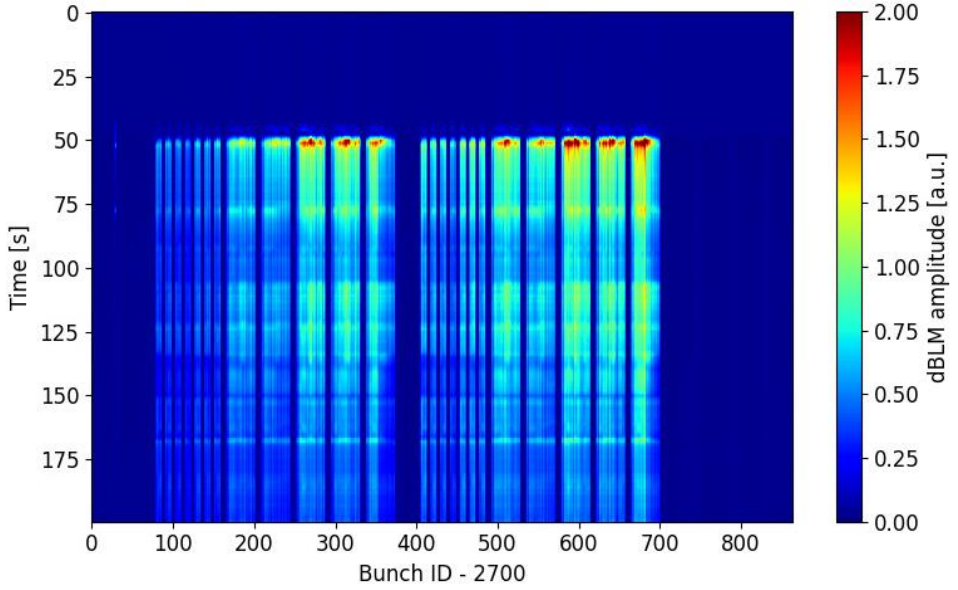
- First fill with 3 bunches, other fills with 12 bunches per beam.



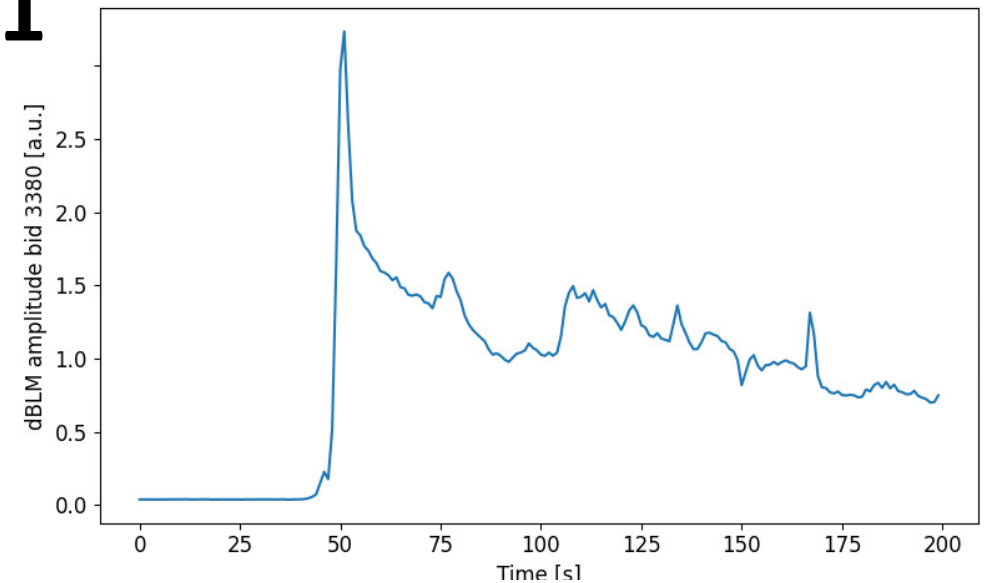


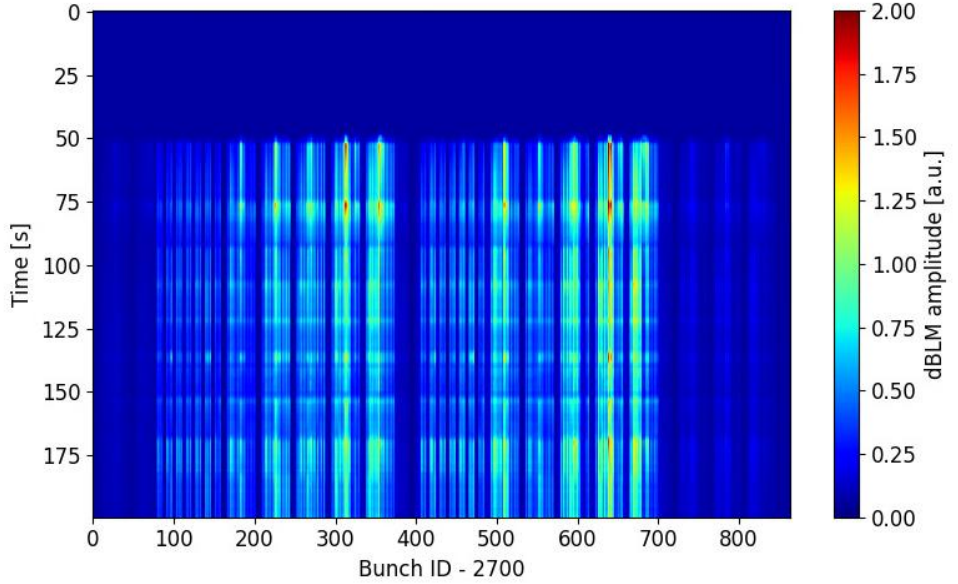


Losses going in collisions

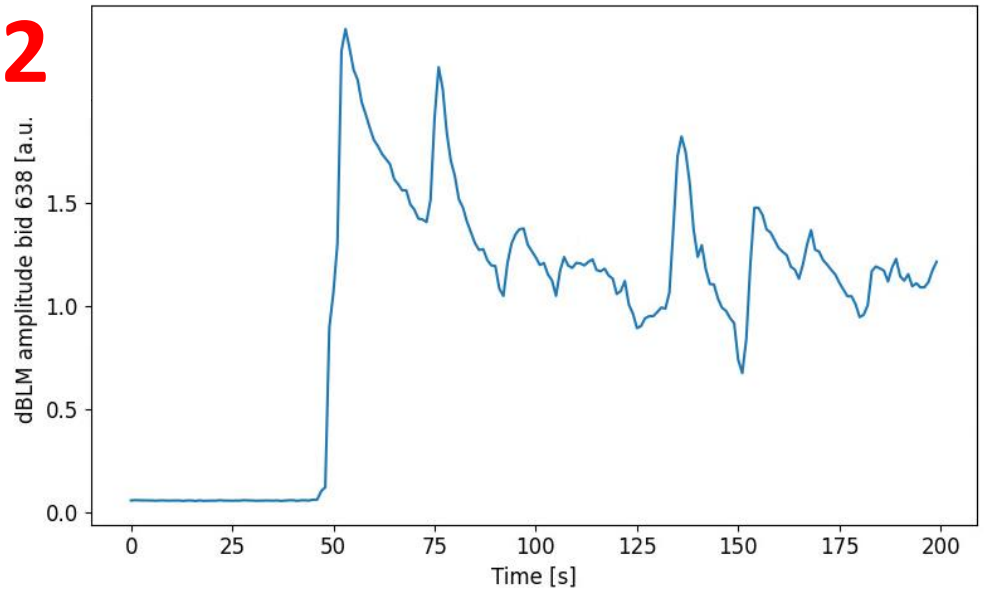


B1





B2



8b4e almost unaffected

Center of 36b batch most affected

Losses last few seconds

Dump on long RS (80s)

Much more pronounced on B1

Filling scheme and PU options for 2023

Luminosities predicted for various filling schemes and PU scenarios

Pure 8b4e not available in 2023

		8b4e	Hybrid 36b	Hybrid 48b	36b	48b
	I_b [10^{11}ppb]	2.1	1.8	1.7	1.5	1.2
	#IP1/5 bunches	1967	2380	2440	2484	2740
μ=54	$L_{peak,IP1/5}$	1.5	1.81	1.86	1.89	2.08
	$L_{int.,day}$ [fb^{-1}]	1.06 (-6%)	1.21 (+8%)	1.20 (+7%)	1.13	0.97 (-14%)
μ=60	$L_{peak,IP1/5}$	1.66	2.01	2.06	2.10	2.32
	$L_{int.,day}$ [fb^{-1}]	1.14 (+2%)	1.30 (+15%)	1.28 (+14%)	1.18 (+4%)	0.98 (-14%)
μ=65	$L_{peak,IP1/5}$	1.8	2.17	2.23	2.27	
	$L_{int.,day}$ [fb^{-1}]	1.21 (+7%)	1.36 (+21%)	1.34 (+19%)	1.22 (+8%)	
μ=70	$L_{peak,IP1/5}$	1.94	2.35	2.41	2.45	
	$L_{int.,day}$ [fb^{-1}]	1.27 (+13%)	1.42 (+26%)	1.39 (+23%)	1.25 (+11%)	

Max bunch intensity for a given scheme (heat load+TCDS)

Reference (~2022)

Target for 2023?

CONFIRMED

Note actual gain will depend a lot on how availability changes with bunch intensity and longer optimal fill length

Luminosity gains for 2023 wrt. 2022?

1) Can gain ~8% by going from 36b scheme @I_b=1.5x10^{11}ppb to hybrid filling scheme @I_b=1.8x10^{11}ppb

2) Additional luminosity gains by increasing PU:

PU = 60 + 7% wrt. PU=54
65 + 6% wrt. PU=60
70 + 5% wrt. PU=65

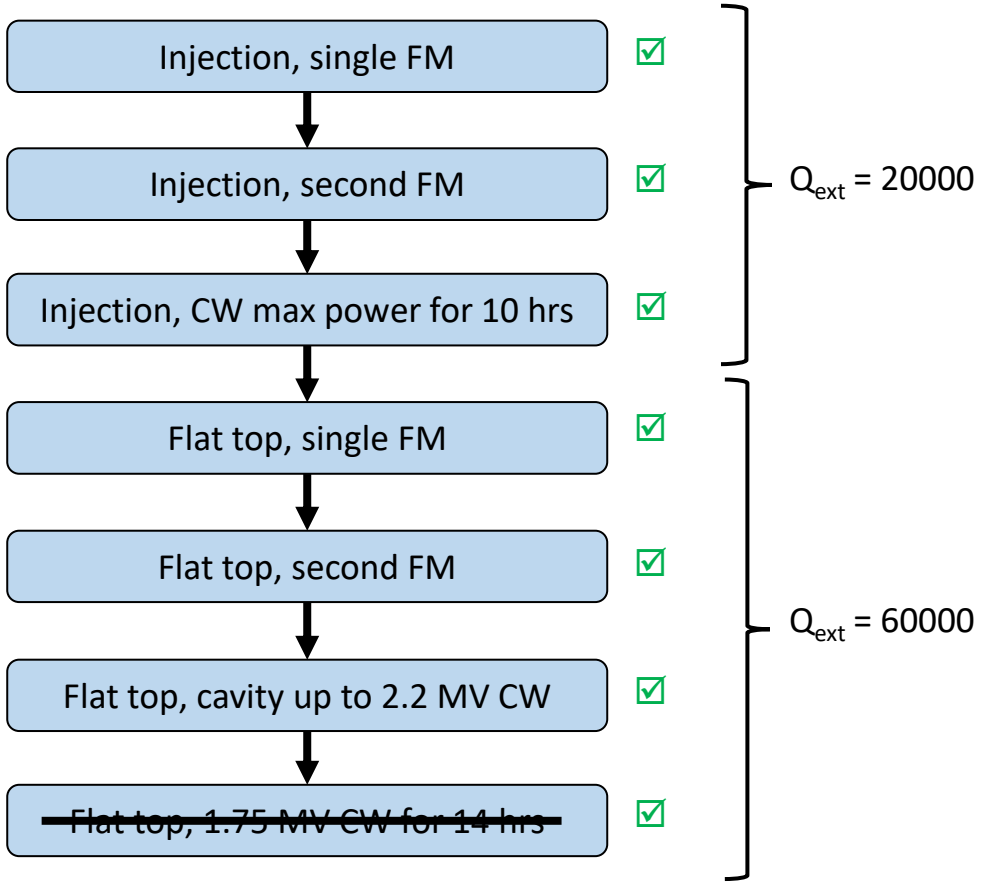
Observation on TCPCH.A4L7.B1

(HCTCPC_002-CR000004)

- Situation today:
  - Motor, interferometry system, LVDT, switches and external linear motion functioning ok
  - Replacement chamber in OUT position
  - **Internal linear stage is blocked at an intermediate position** (32 mm, hard point)
  - **Rotational stage still operating**
  - Linear movement interrupted (link between external and internal stages appears to be lost)

Recovery

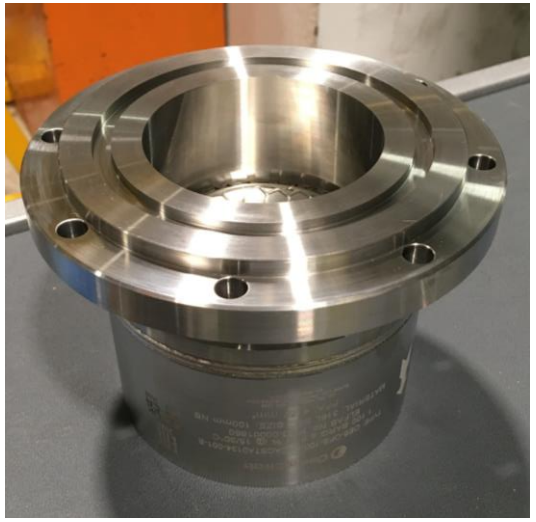
- Monday morning: Cryo conditions re-established for RF
  - Conditioning procedure launched to check cavity performance
  - Conditioning @ injection (20k) and flat-top (60k) coupler settings
  - Single and double RF frequency modulations
  - No significant degradation was observed, and the full conditioning cycle was completed in 24h
- Tue 09:00: RF ready for beam



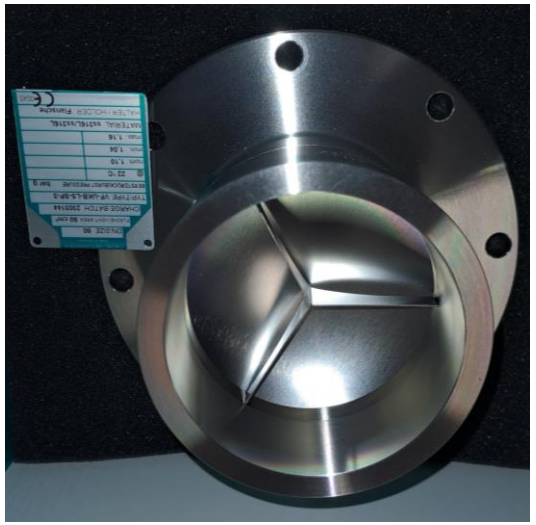
Conditioning procedure

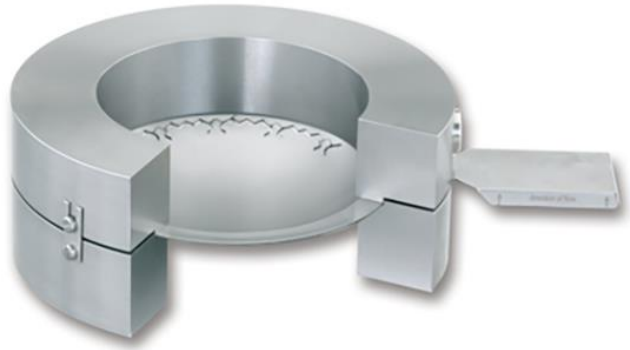
Rupture discs

- 2 batches of discs were purchased during YETS:
  - 18 stainless steel forward-acting discs (ELFAB)
  - 18 stainless steel reverse buckling discs (Paliwoda)
- Both types are specified as 1.10 barg +/- 5% rupture pressure
  - Certified minimum rupture pressure 1.045 barg
- The first batch (ELFAB) was individually tested up to 0.85 barg
  - 16 discs installed in LHC + 2 spares
  - 2 of these burst this weekend at 0.9 barg
  - The 2 spares were installed to replace the 2 burst discs
- The second batch (Paliwoda) is at CERN awaiting testing
  - Will be tested at higher pressure (maximum allowed working pressure, 0.99 barg)



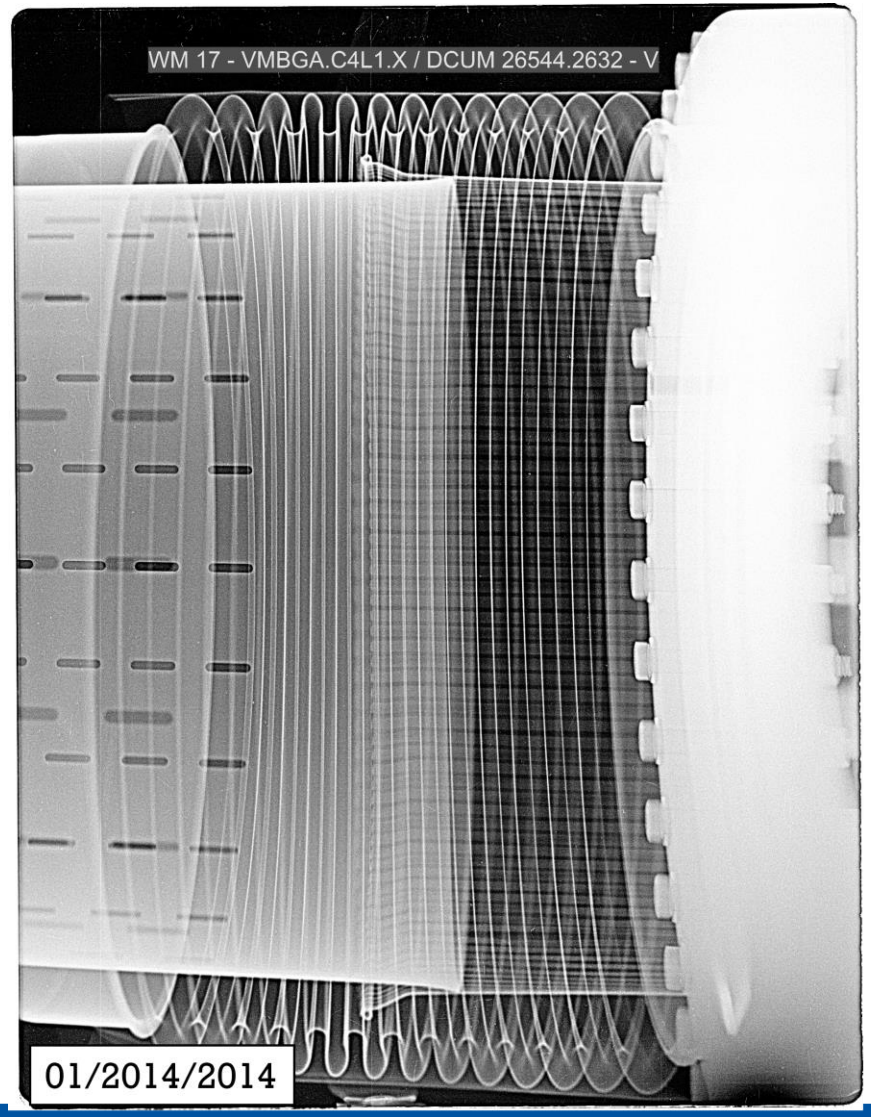
Forward-acting disc (ELFAB)

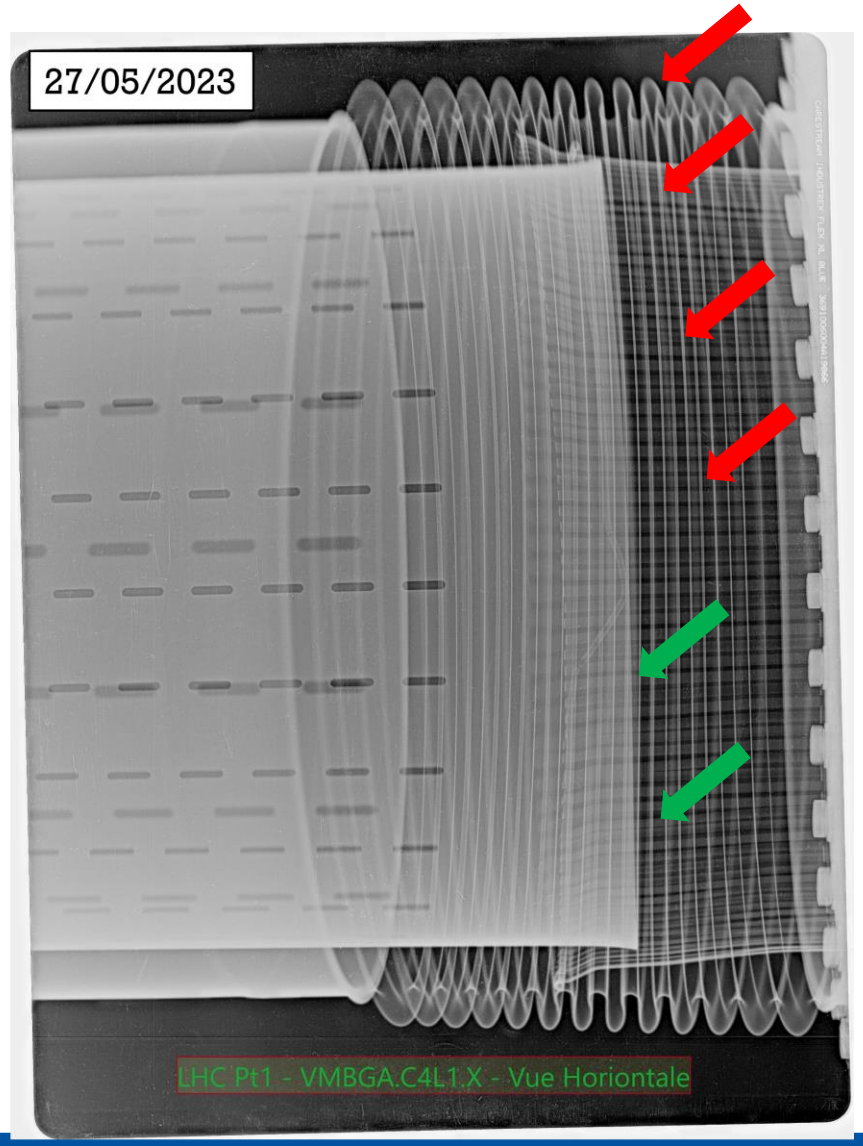




Reverse buckling disc (Paliwoda/Rembe)

Comparison X rays in 2014 vs 2023



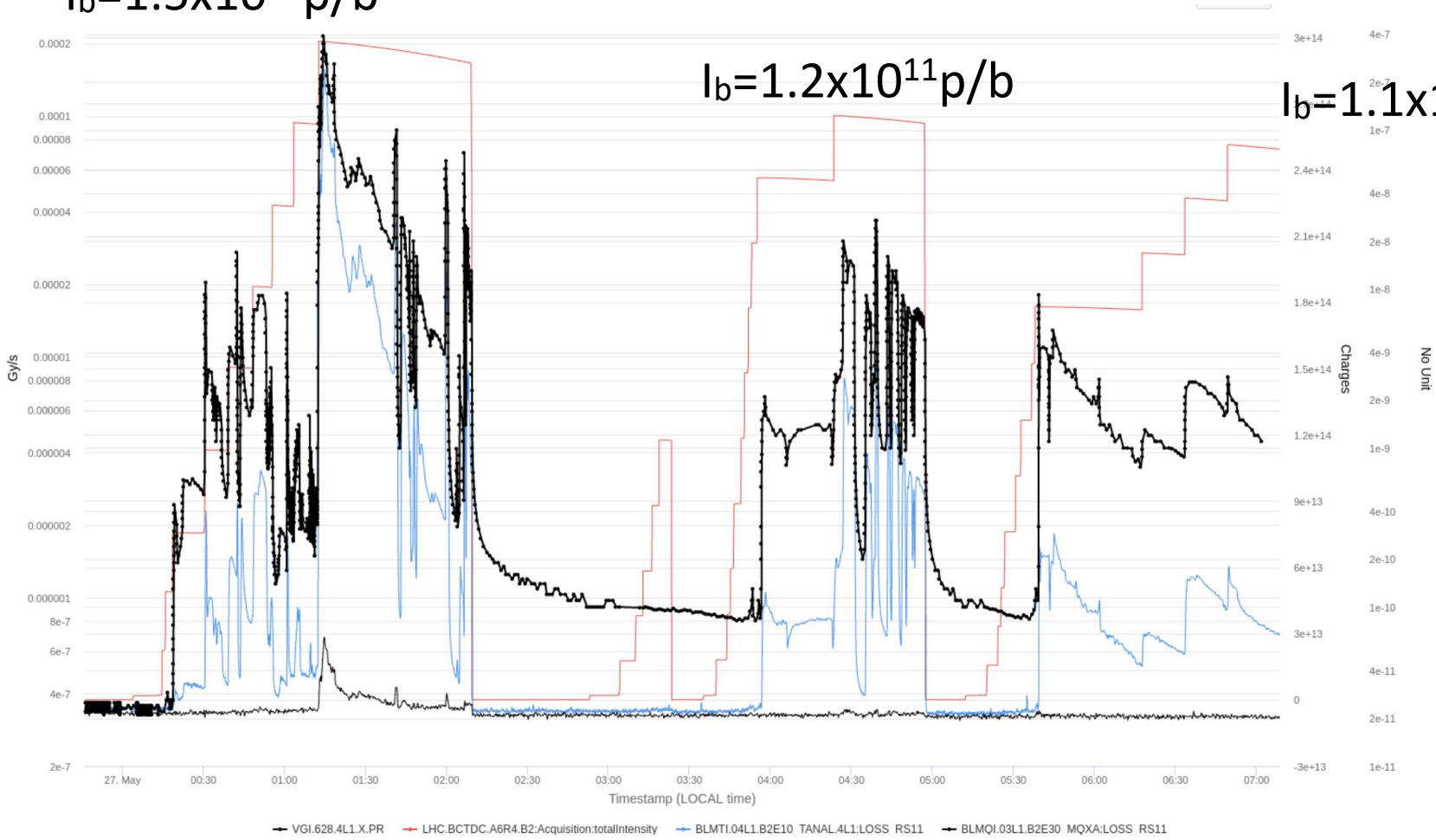


Confirmation of location with BatMons

I_b=1.5x10^{11}p/b

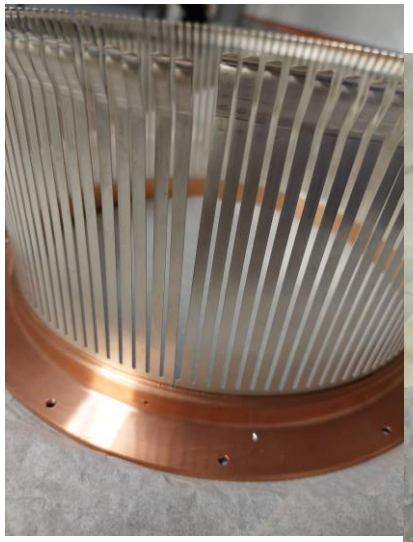
I_b=1.2x10^{11}p/b

I_b=1.1x10^{11}p/b



Measurements with one beam at a time indicated that the vacuum activity in the common region is triggered primarily by the Beam 2.

New Warm Module Type VMB & VAM



2023 plan

- 2023 is a short year due to early EYETS:
  - 13.5 weeks of pp physics
  - 4 weeks of ion physics
    + 1 week for pp reference run

Activity	Duration [days]	Ratio [%]
Beam Commissioning & Intensity ramp-up	47	21.7
Scrubbing	2	0.9
25 ns physics (>1200 bunches)	**97**	**44.7**
Special physics runs (incl. setting-up)	**7**	**3.2**
Pb-Pb ions & p-p ref. setting-up	6	2.8
Pb-Pb ions physics & p-p ref. run	**32**	**14.7**
Technical stop	8	3.7
Technical stop recovery	2	0.9
Machine Development blocks (incl. floating MDs)	16	7.4
Total:	**217**	**100%**