LHC: configuration 2025/26, intensity ramp-up, polarity reversal, optics

X. Buffat, H. Bartosik, C. Bracco, R. Bruce, F. Cerutti, A. Donadon Servelle, R. De Maria, Y. Dutheil, S. Fartoukh, L. Giacomel, S. Kostoglou, A. Lechner, B. Lindstrom, E. Maclean, L. Mether, N. Mounet, Y. Papaphilippou, K. Paraschou, T. Persson, S. Redaelli, M. Solfaroli, G. Sterbini, H. Timko, R. Tomas, J. Wenninger, C. Zannini

...based on the contributions of many others, thanks to them as well!

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- IR configuration
- Magnet failure
- Operational cycle
- Filling scheme, bunch intensity and performance
- High intensity tests
- Conclusion

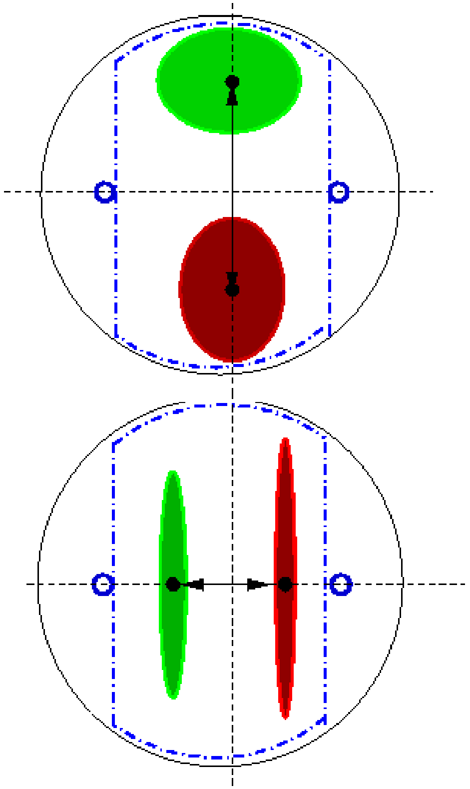
IR1/5 configuration

- Strategy:
  - Survival of the triplets is critical
  - Maintain forward physics and maximise data taking as much as possible
  - Minimize commissioning overhead between 2025 -2026

    → **Rotation of the crossing angles in IRs 1 and 5** with **reverted triplet polarity only in IR5** (Nom-H / RP-V)

    → Rotation of roman pots, change of settings and local aperture

Exemple: IP1



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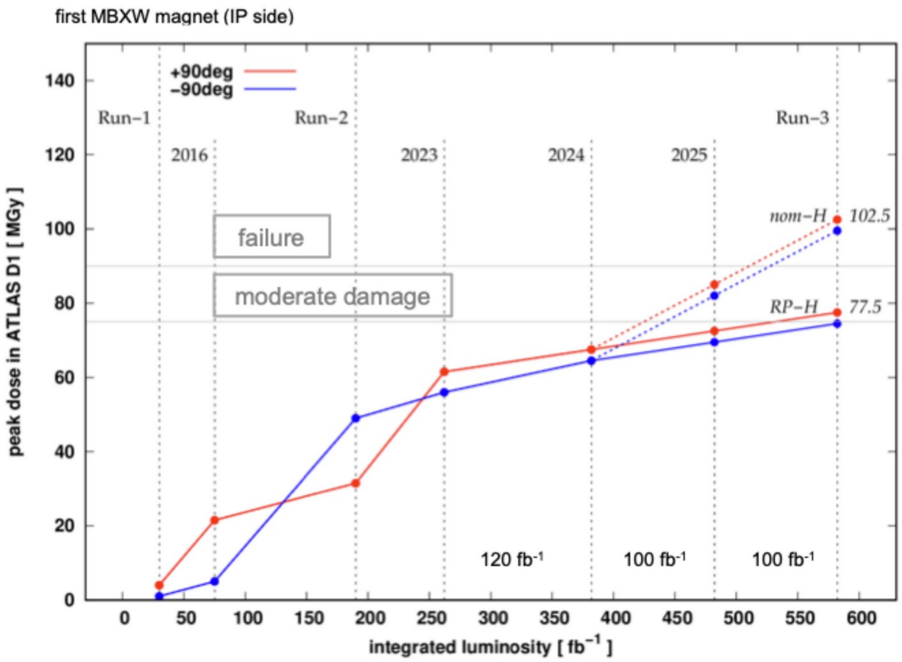

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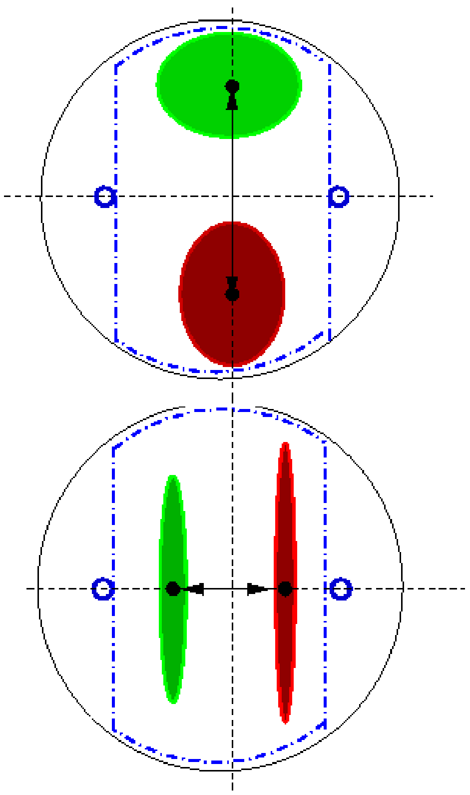

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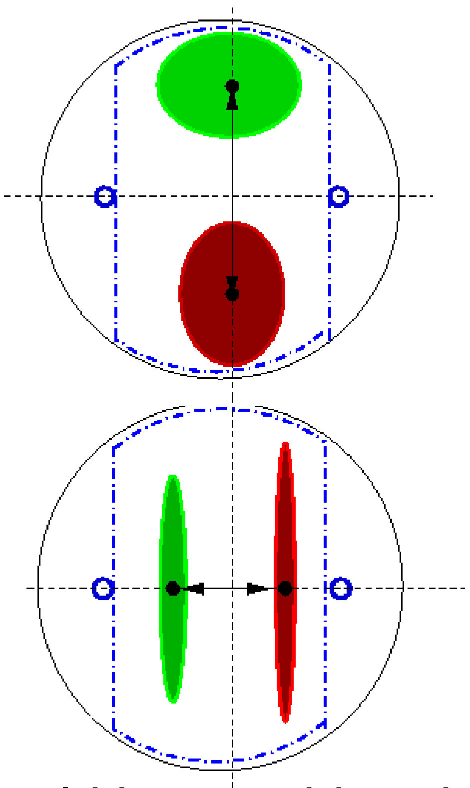

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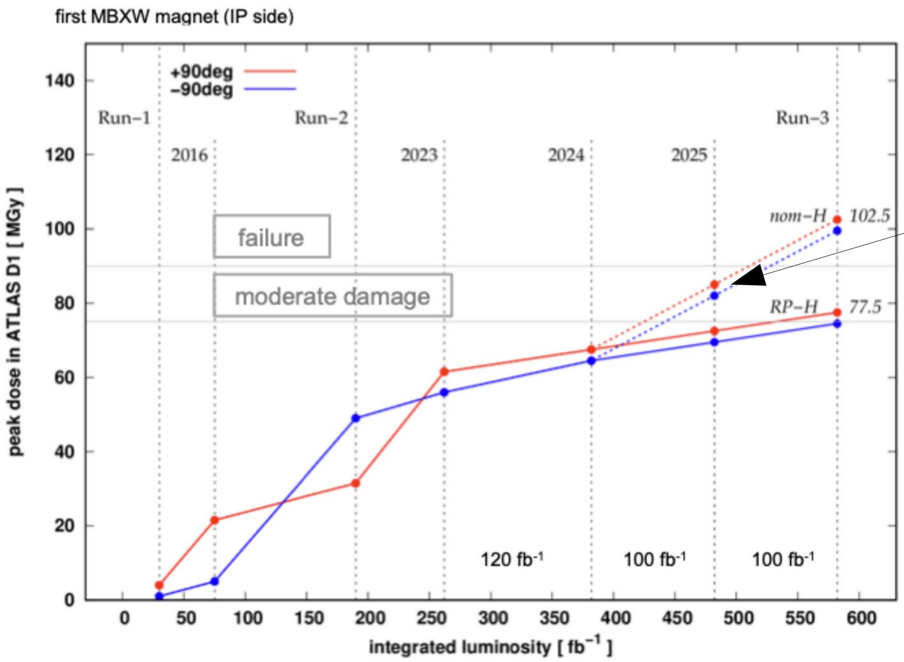

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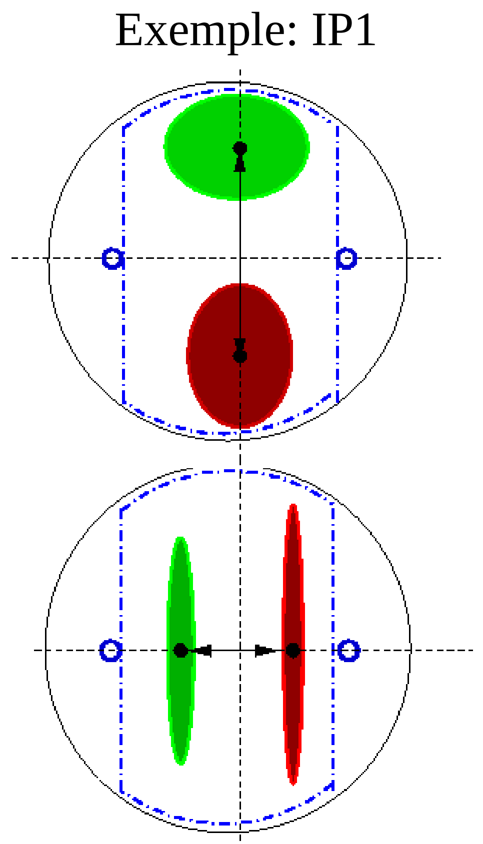

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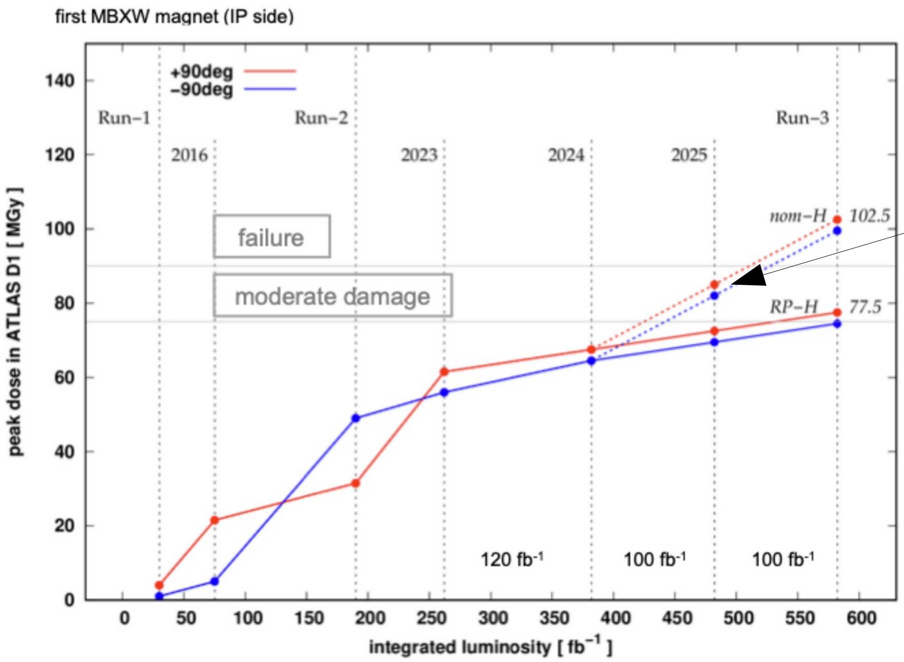

- Exchange with spare should be considered for the YETS 2025-2026
- Moderate risk for 2025
  - Replacement of a spare → 7 weeks of work in the tunnel
  - Possibility to run with the first D1 module disconnected (~1 shift of work in the tunnel), increasing the strength of the remaining 5 modules (per IP side) and the MCBHX3

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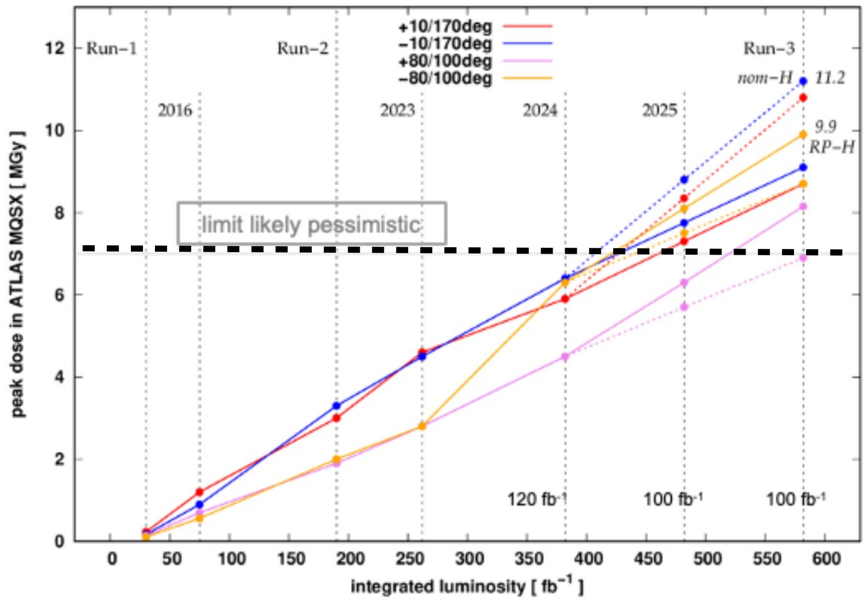

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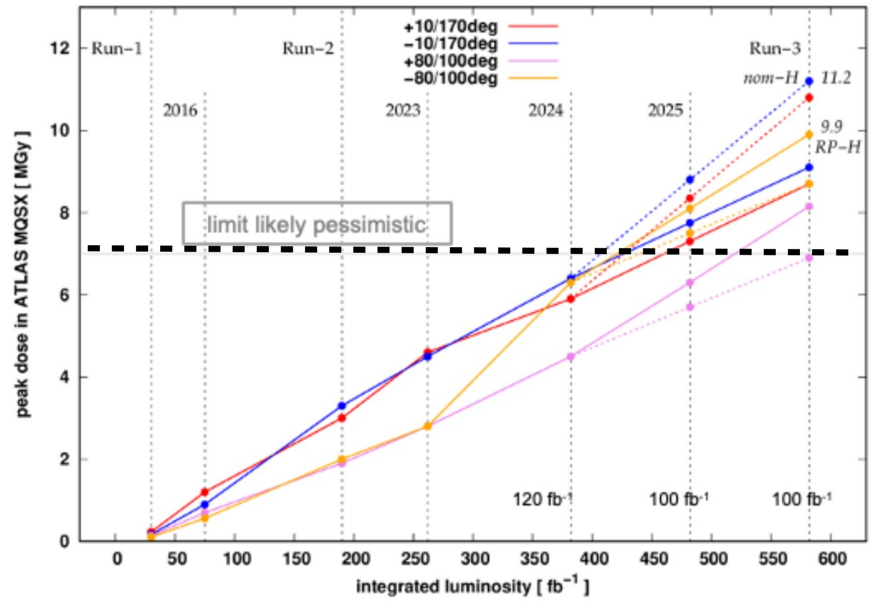

G. Arduini, et al., LHC Triplet Task Force Report, CERN-ATS Report-2023-0004

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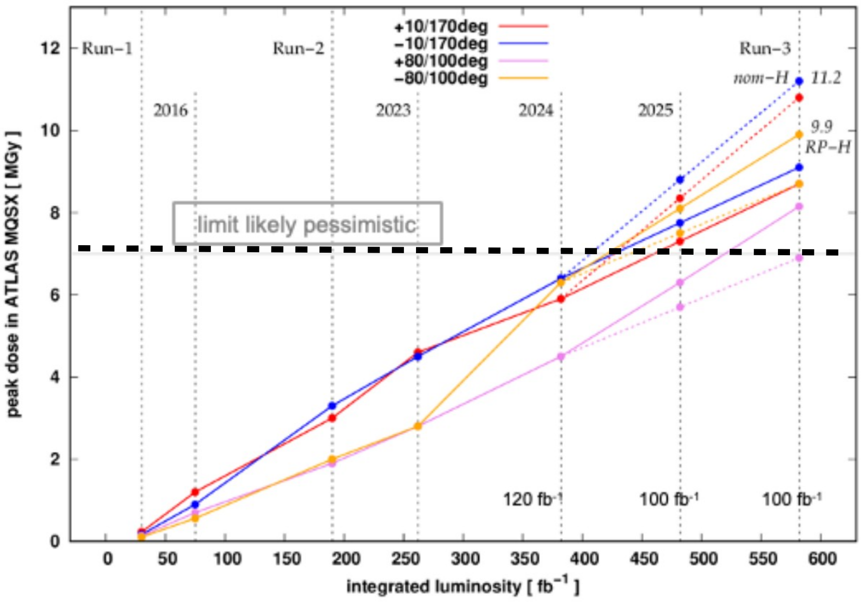

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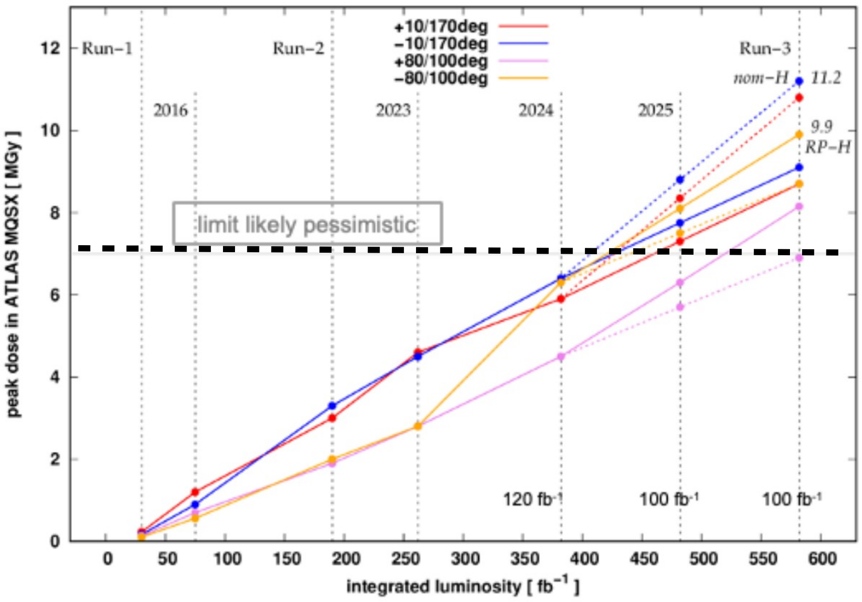

- Overall such events (either D1 or other magnet failures) could lead to few days of down time
  - **Some combinations of failures have a significant impact on the performance** (limited β* reach, lifetime degradation)

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Operational cycle

450 GeV: Run 2 injection optics (with phase knob)
but **reverting to nominal IR1 and to RP in IR5**)

Ramp: combined with anti-telesqueeze: β^*=2 m & r_{Tele} =0.5 EoR
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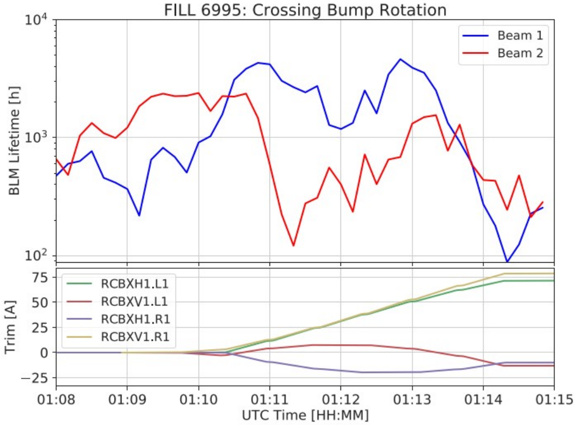

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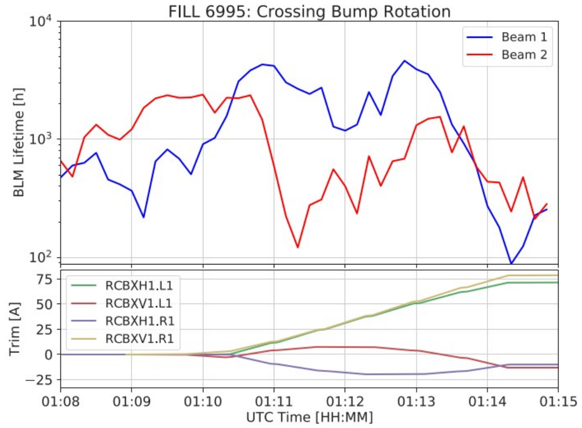

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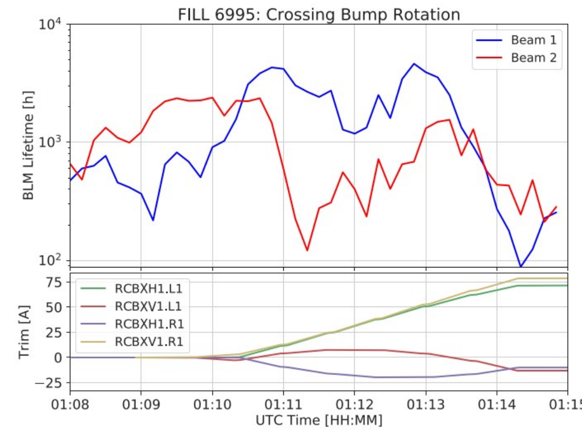

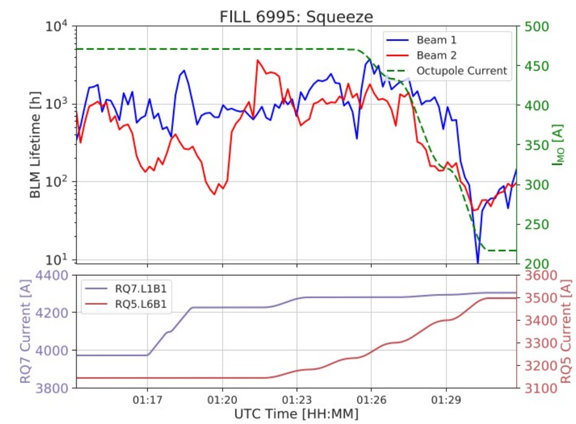

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Crossing angle reduction: 160 µrad → 110? µrad

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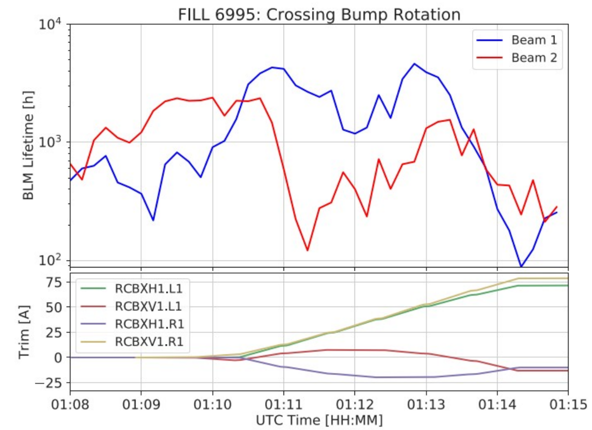

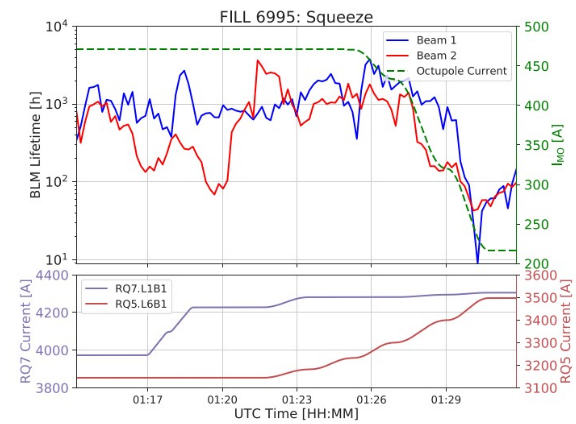

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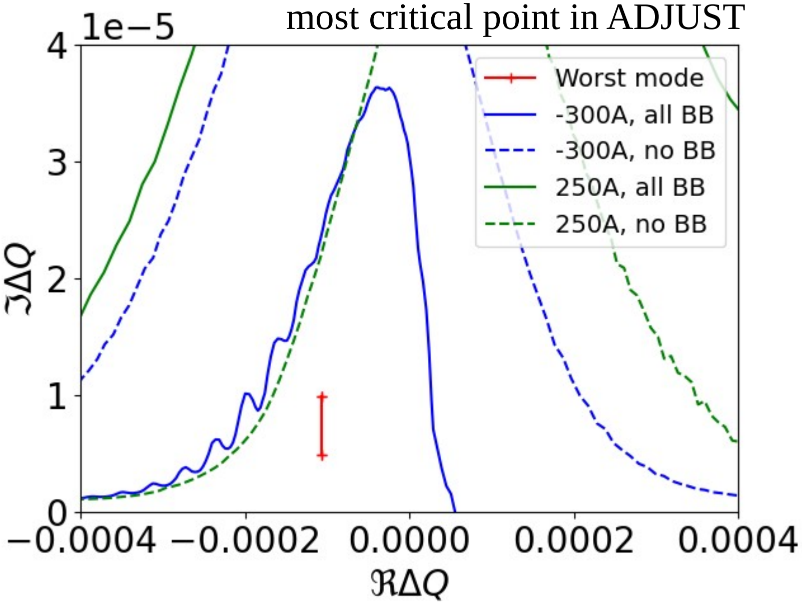
Transverse stability diagram at the most critical point in ADJUST



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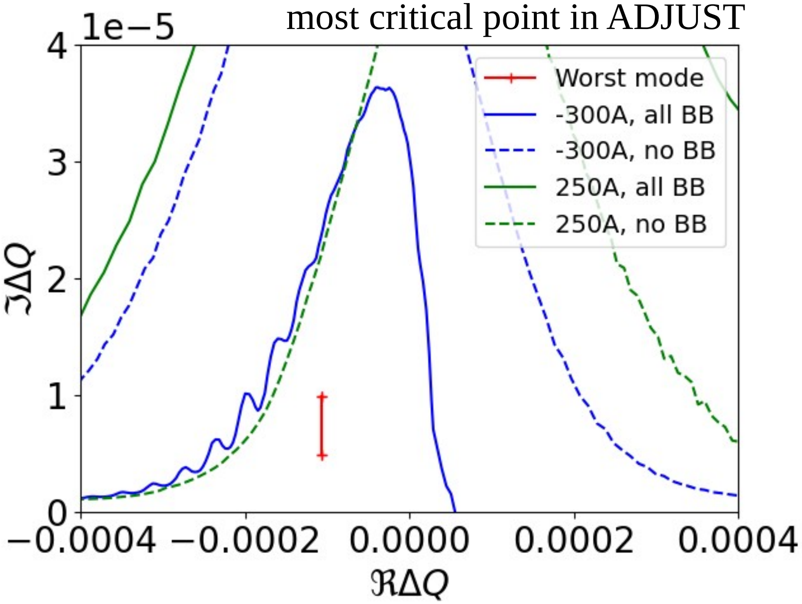

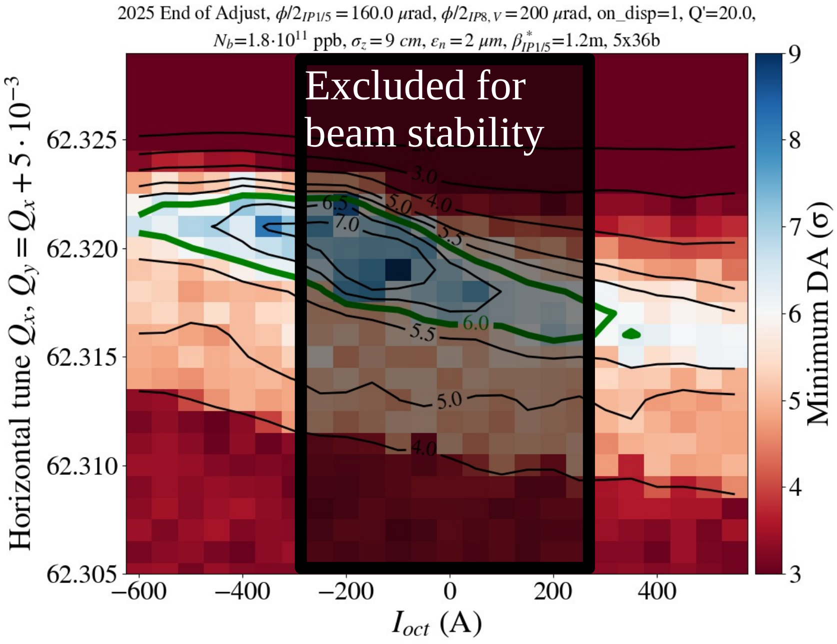

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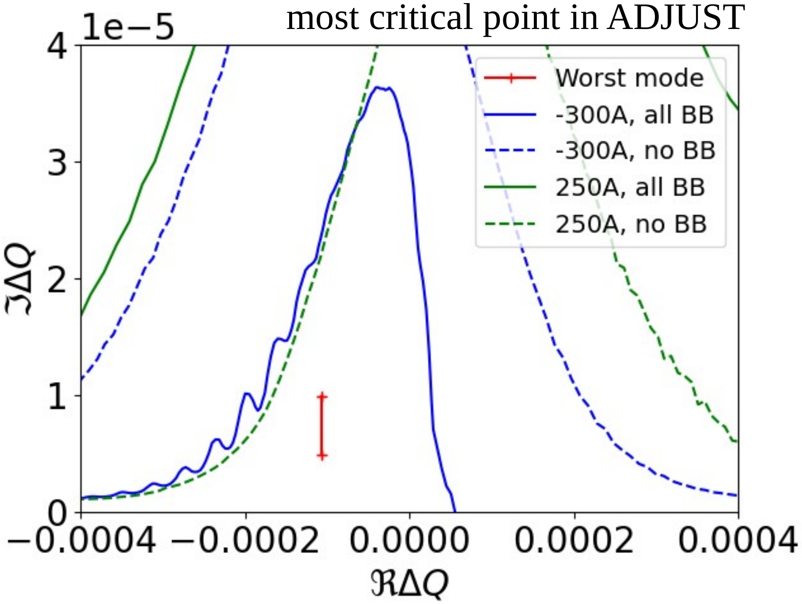

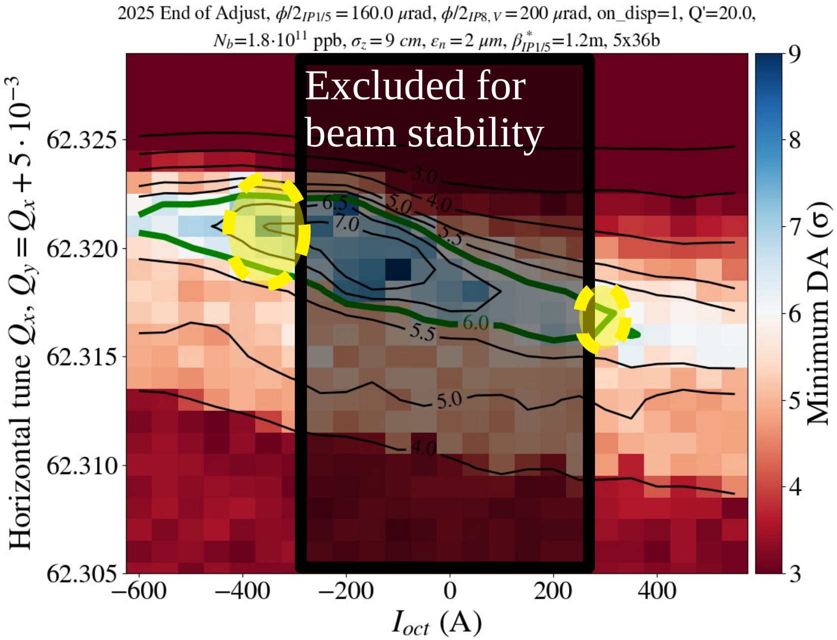

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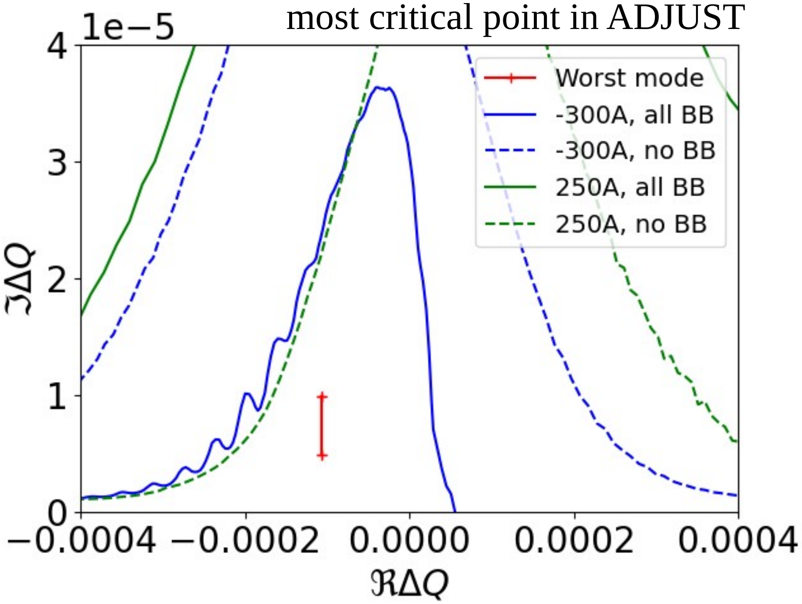
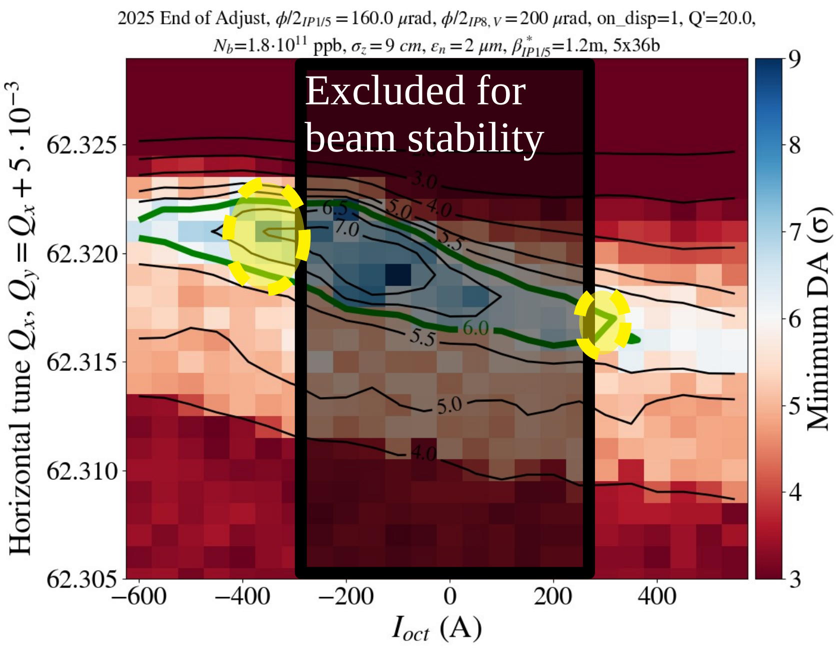
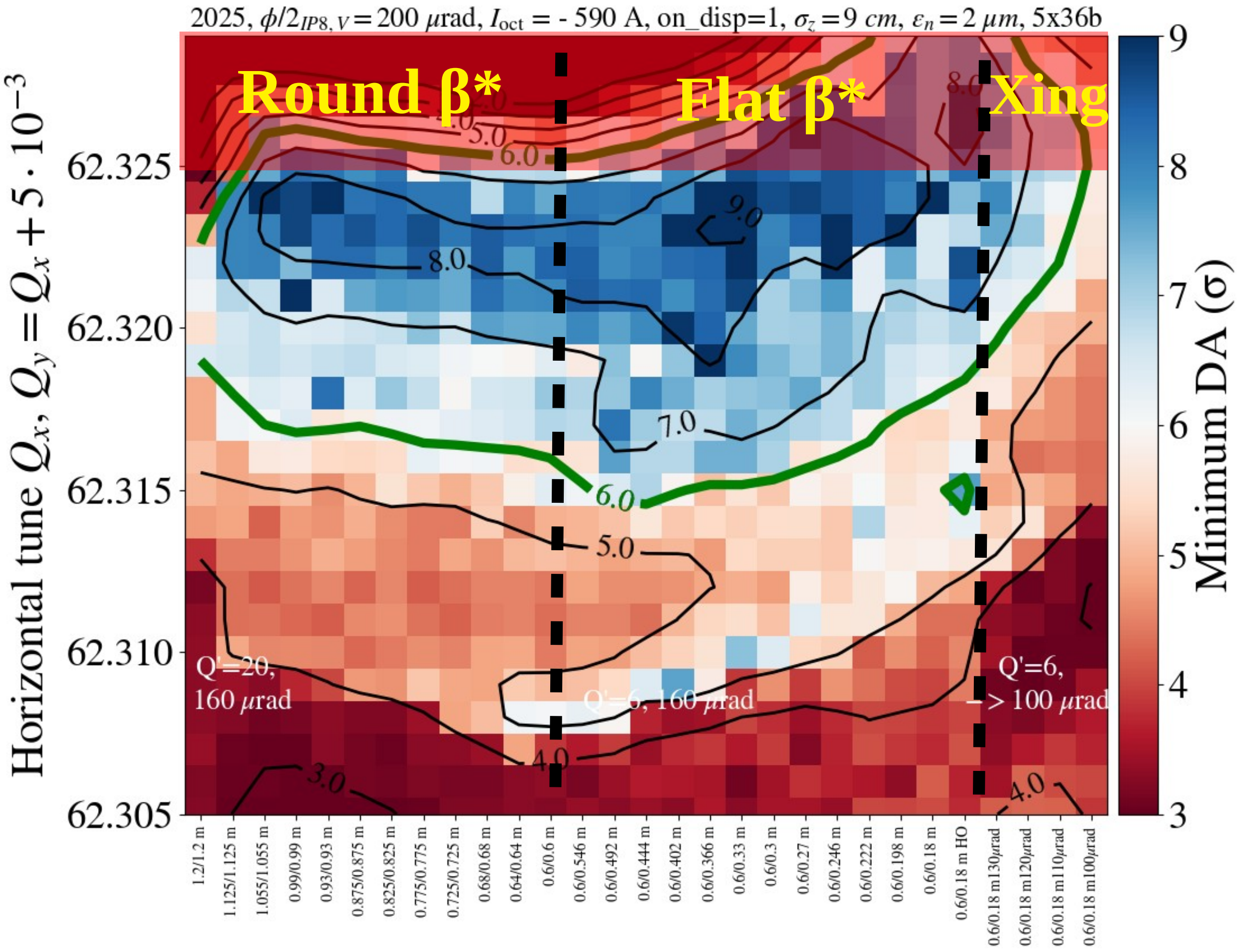




- Proposal: Operate the full cycle with the negative polarity of the octupoles, but keep the cycle compatible with the positive polarity in case of unexpected issues
  - A full cycle was already tested in MD with trains
  - Thanks to their neglibile impact on the orbit and optics, the octupoles are not subject to validation. Fall-back can be performed in 2-3 shifts (tune optimisation)

Luminosity levelling

- Thanks to stability coming along with the head-on collisions, the chromaticity can be reduced after ADJUST, thus improving DA / lifetime
  - → Successfully integrated in the operational cycle
  - → High chroma still required during emittance scans



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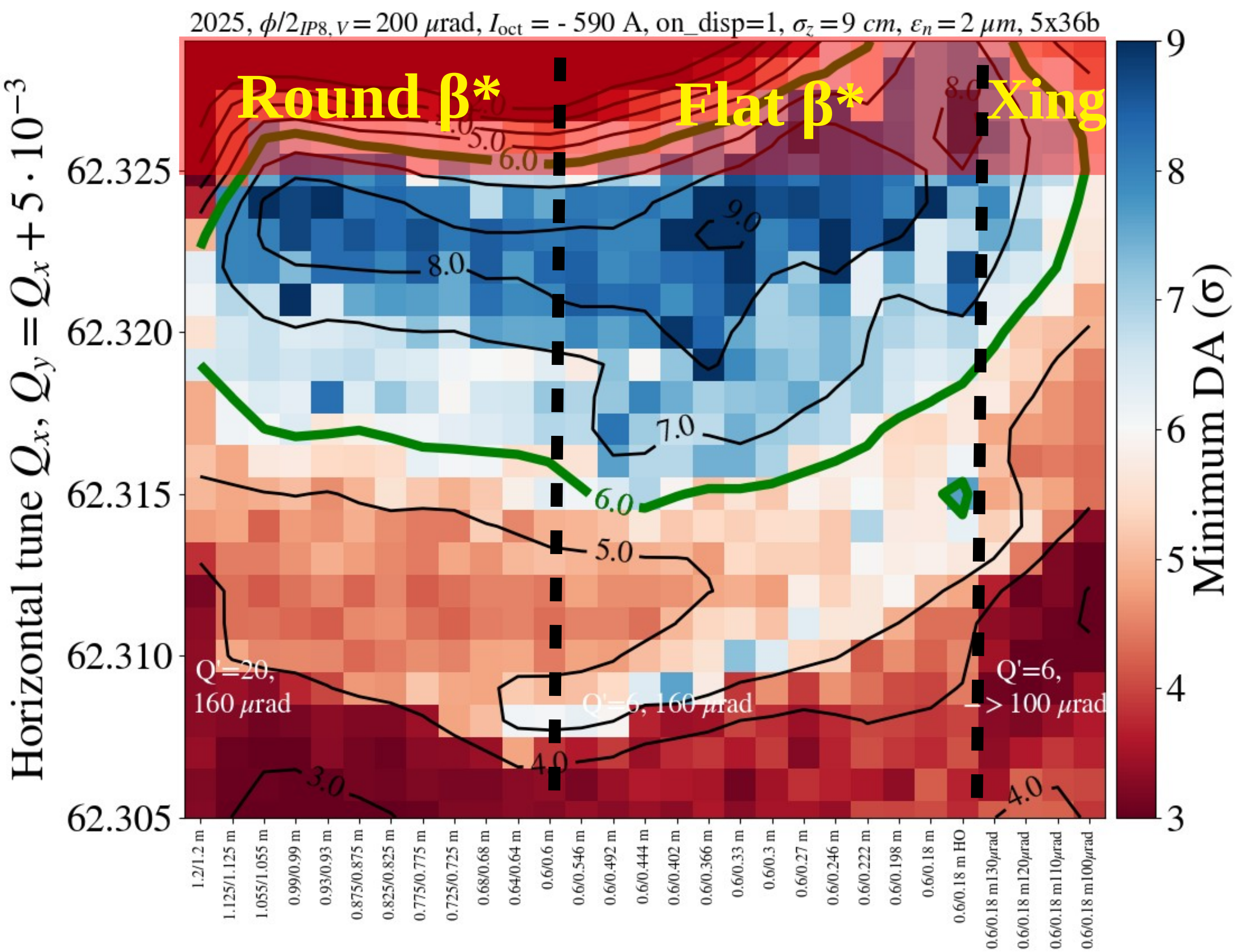

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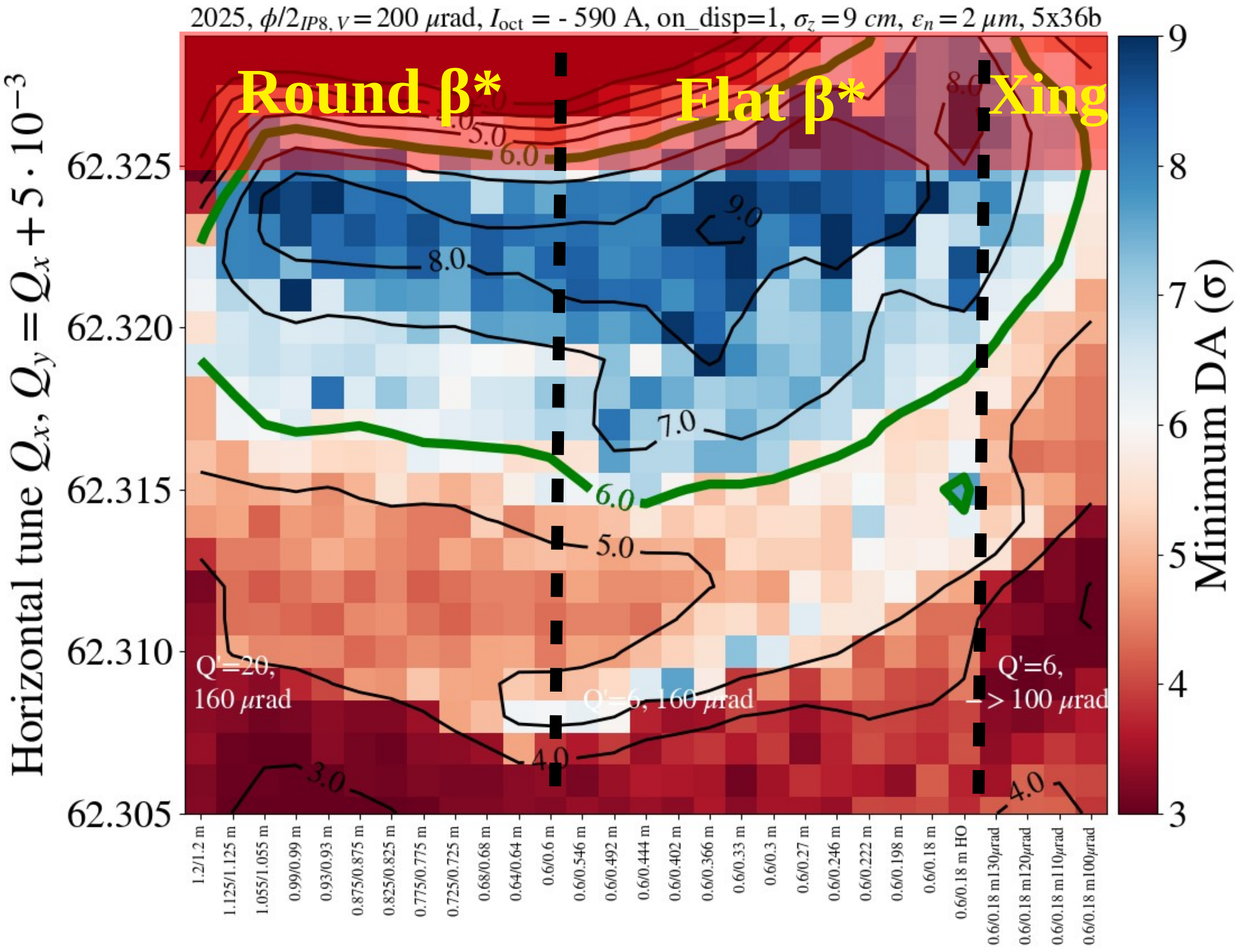

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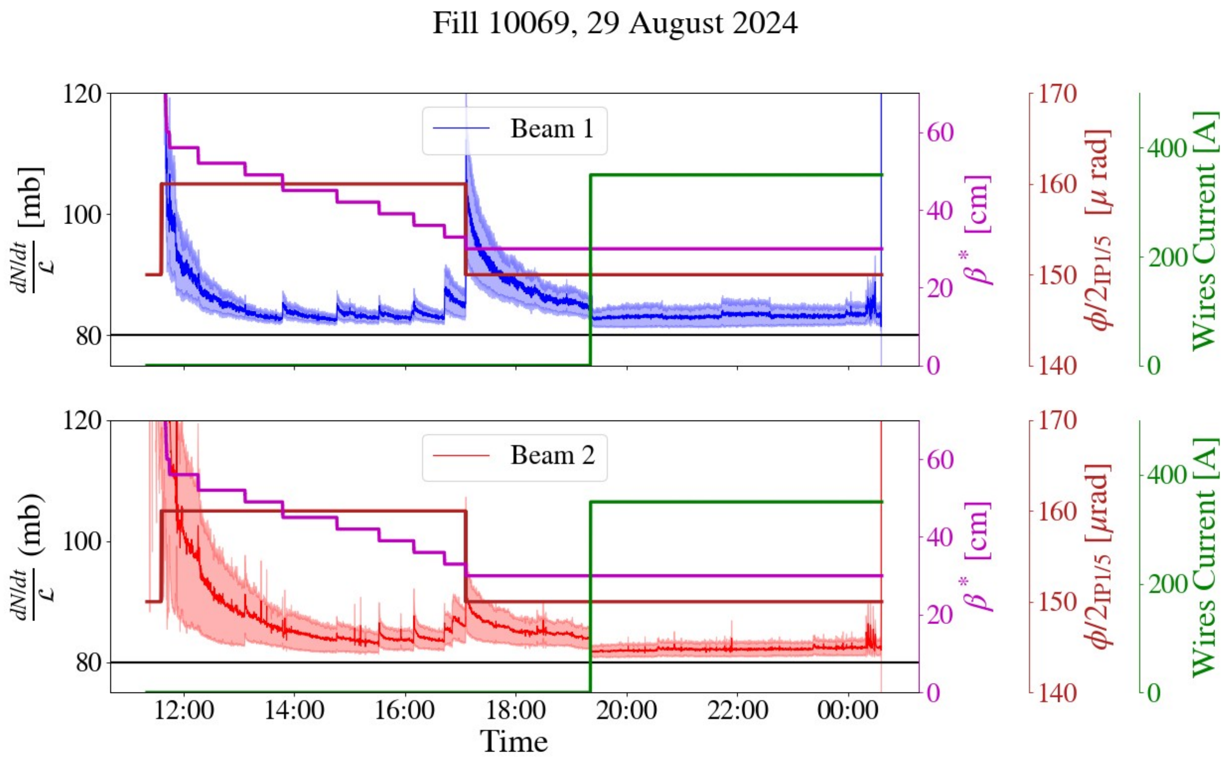
  → The cycle can be prepared in 2025 to ease 2026 commissioning
- HL-LHC will greatly profit from the experience with negative polarity and pushed beam-beam configuration (Losses in ADJUST with large beam-beam parameter, strong octupoles due to crab cavity impedance, beam quality preservation with low β*)

Beam-beam wire compensators

- The B1 and B2 **BBWCs were used in 2024** production fills at EoL (β^*=30 cm, $\phi/2$=150 urad) to improve the beam lifetime (1-2 h gain in lifetime) and σ_{eff}.

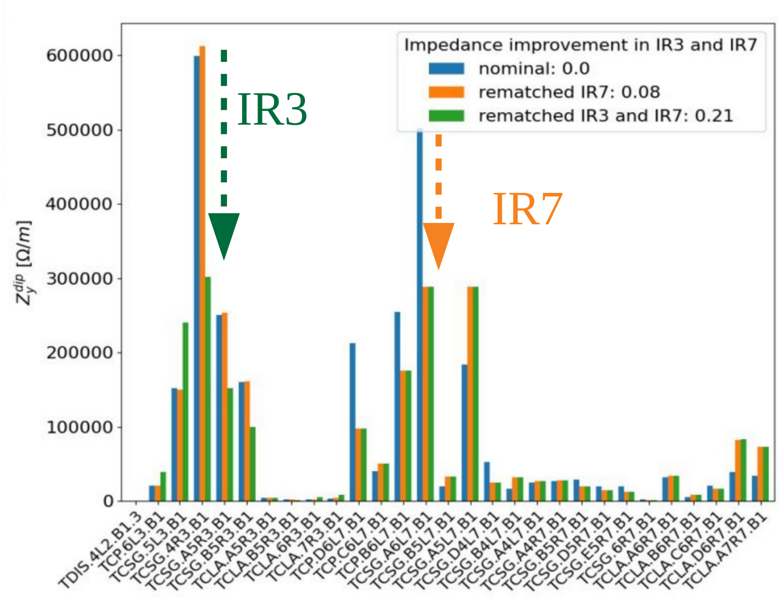


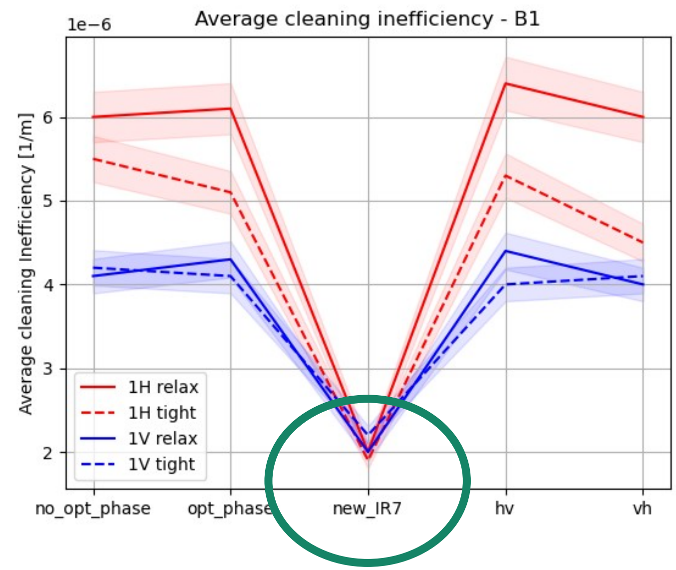
BUT with **2025** optics and the crossing plane change in IR1/5, the BBWCs (V in IP1 and H in IP5) will **not be in the beam crossing planes**.

Non-local compensation is being investigated targeting DA improvement at β^*=60/18 cm for 100<$\phi/2$<160 urad: depending on the simulations results, **one could switch ON the BBWSs after the final β^* step** is reached and during the crossing anti-leveling (similar configuration tested in Run3 MDs).

Collimation optics

- New optics / settings for the collimator insertions reduce the impedance and improve the cleaning, as fallback scenario to improve cleaning with missing 11T in HL-LHC





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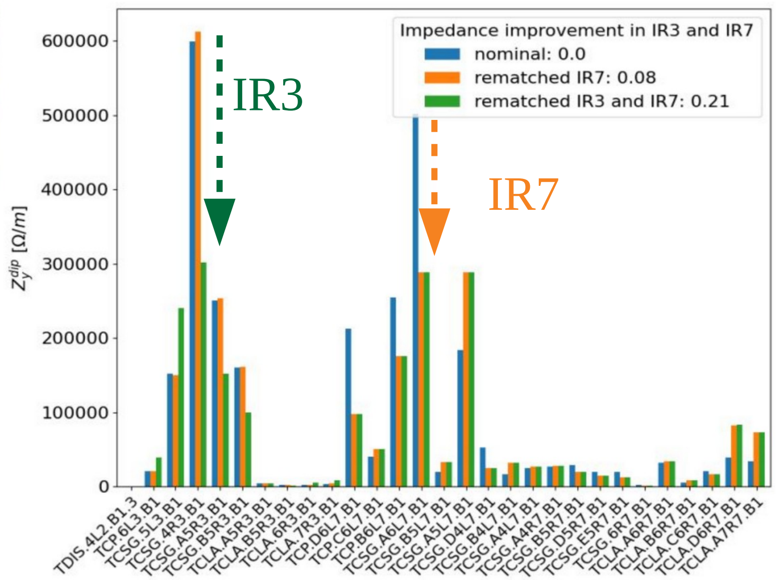
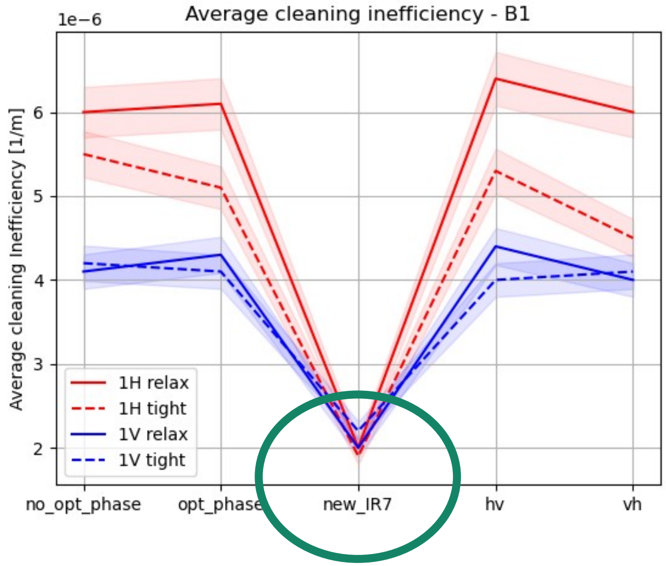
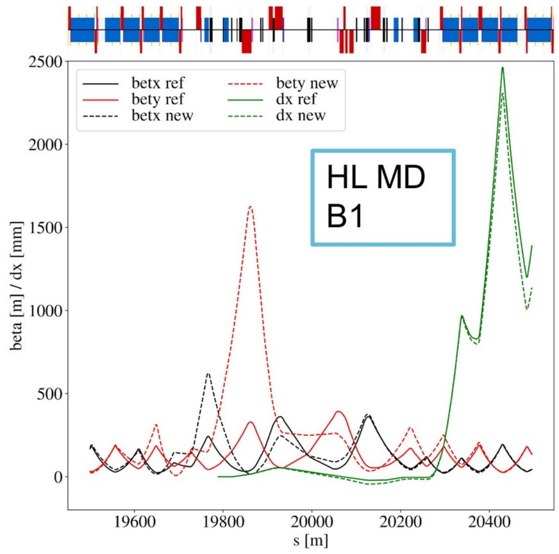




- Improved cleaning (-20% to -60%) and impedance (-20% to -30%) demonstrated in MDs

- The larger β functions are not compatible with the aperture at injection, they require a de-squeeze to be deployed during the ramp



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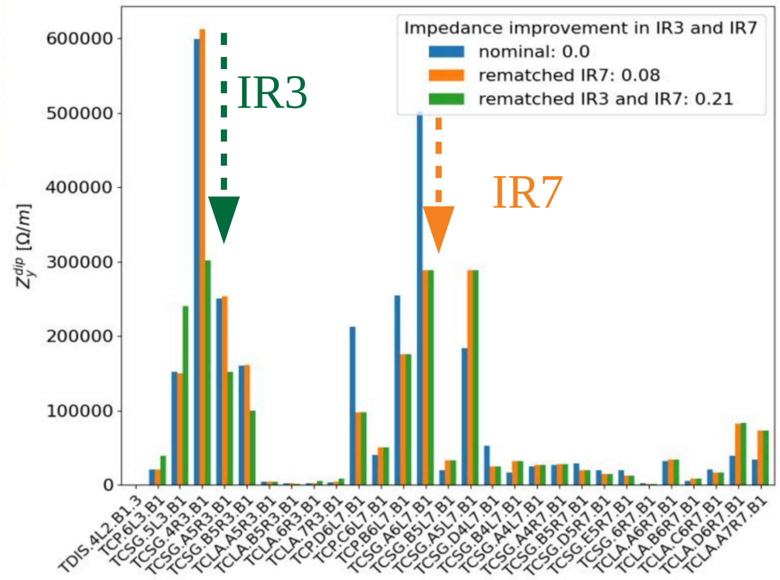

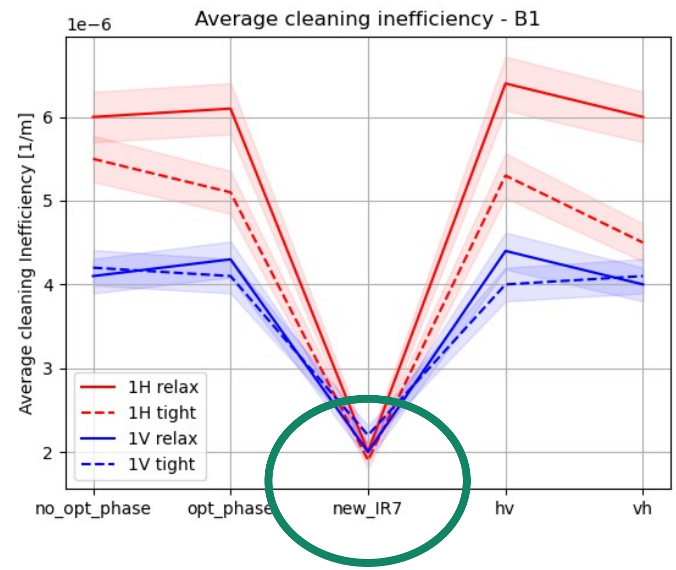

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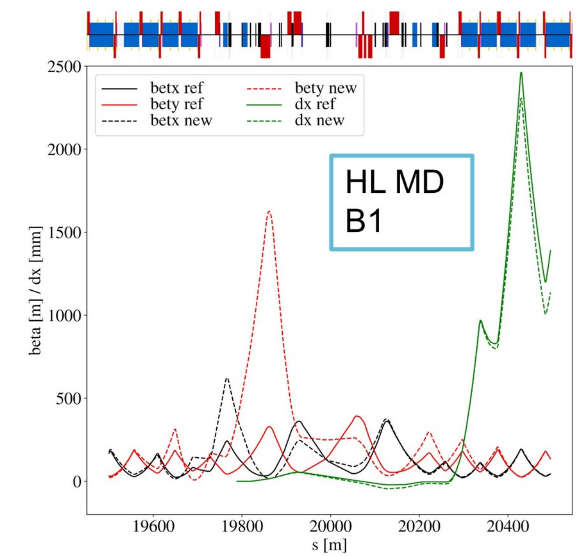

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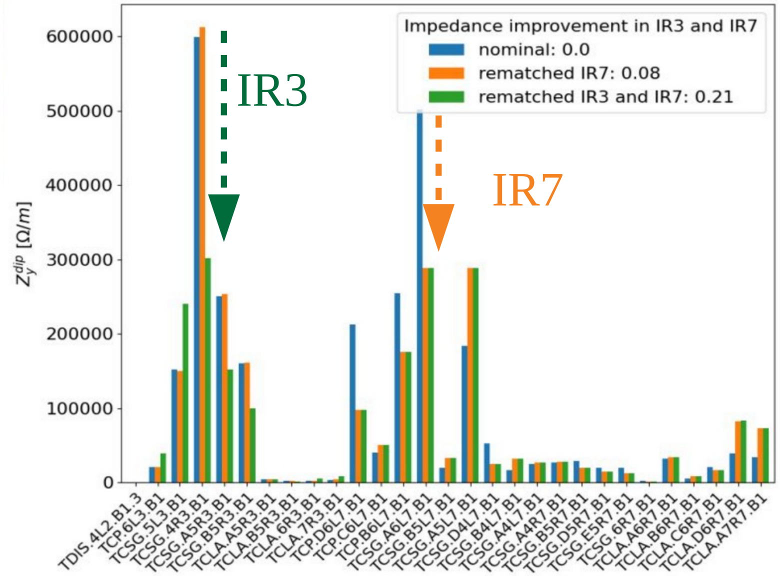

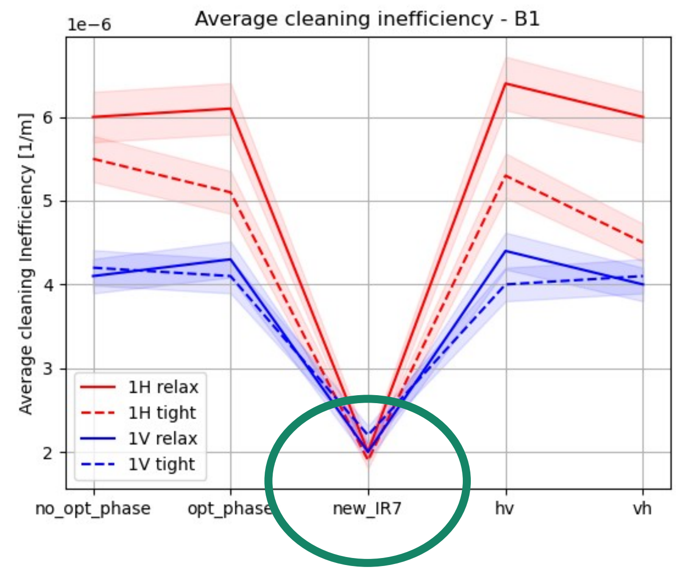

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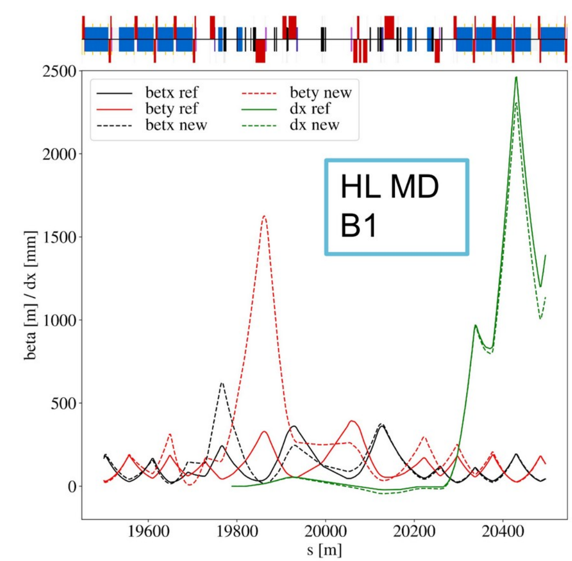
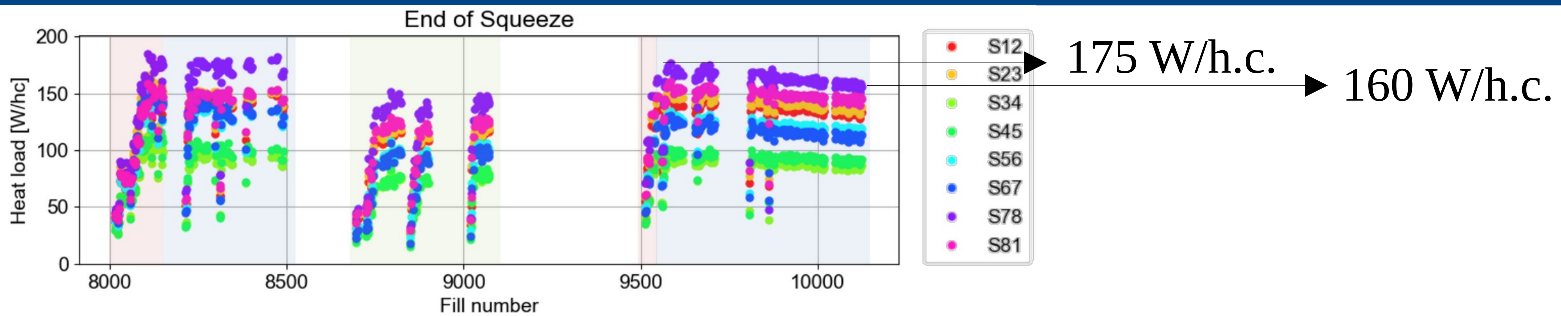
- The larger β functions are not compatible with the aperture at injection, they require a de-squeeze to be deployed during the ramp
  → Ramp & de-squeeze demonstrated in MD with the HL-LHC cycle
  → These HL-LHC optics could be integrated in the LHC's and validated in MDs in 2025 for a smooth integration in 2026 operation

- A similar de-squeeze is considered for IR4 to enhance the capabilities of the instrumentation



Bunch intensity and filling scheme, performance



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  → Ideal luminosity production **1.54 fb**$^{-1}$ / day***** (2024+9%) , max heat load: 171 W/h.c.

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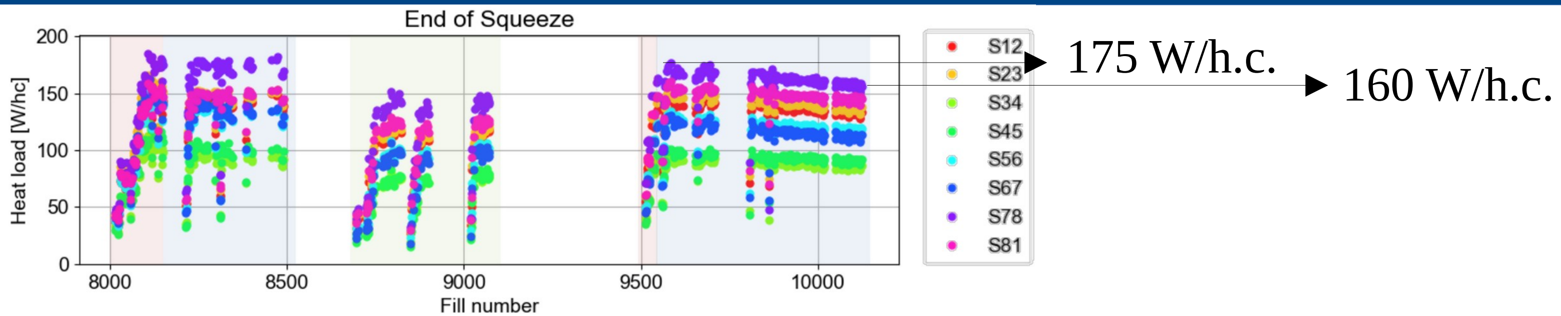

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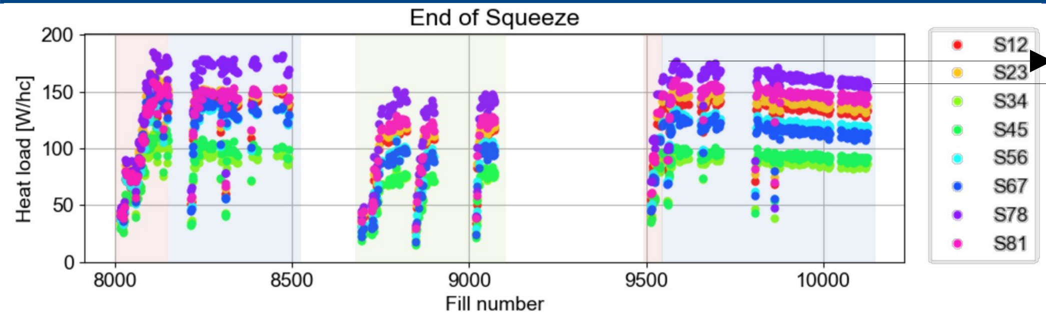

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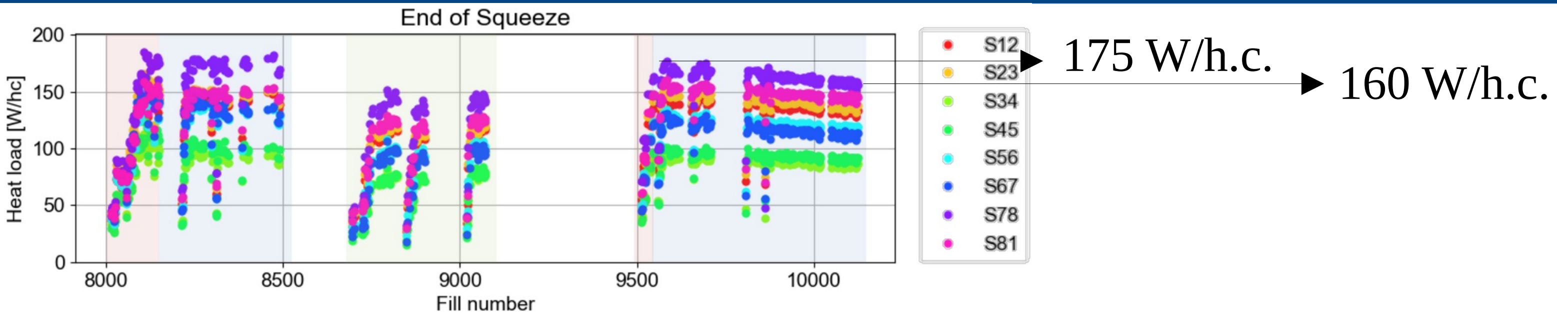

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→ Hybrid: Ideal luminosity production **1.51 fb^{-1} / day**, max intensity: $1.6 \cdot 10^{11}$p/b

Number of collisions at IPs 1 and 5: **+10%**, at LHCb: **+8%**

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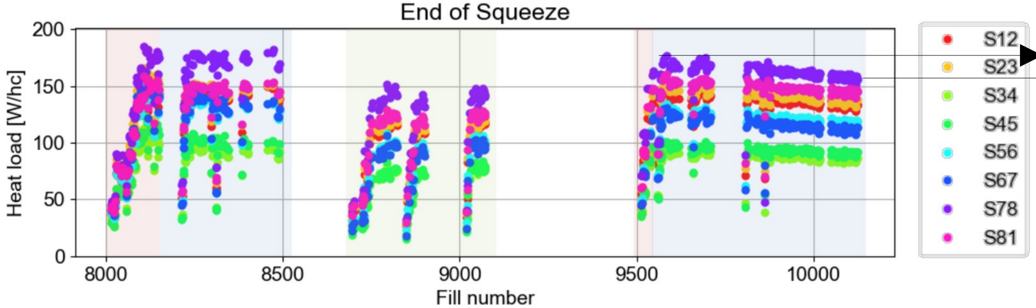

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Assuming 10% scrubbing at the end of 2025, the bunch intensity will no longer be limited by heat-load:

- **1.56 fb^{-1}/day** (2024+11%)
- **1.58 fb^{-1}/day** (2024+12%)

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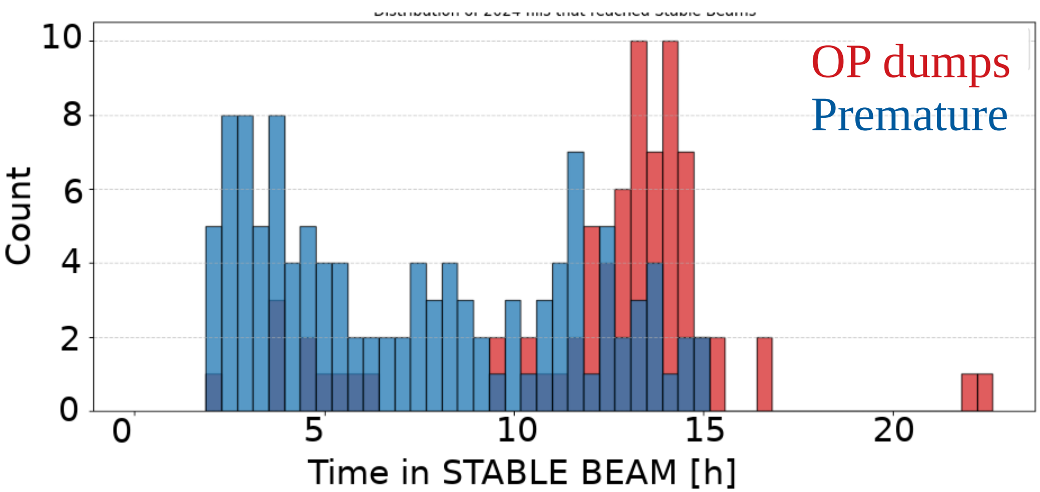

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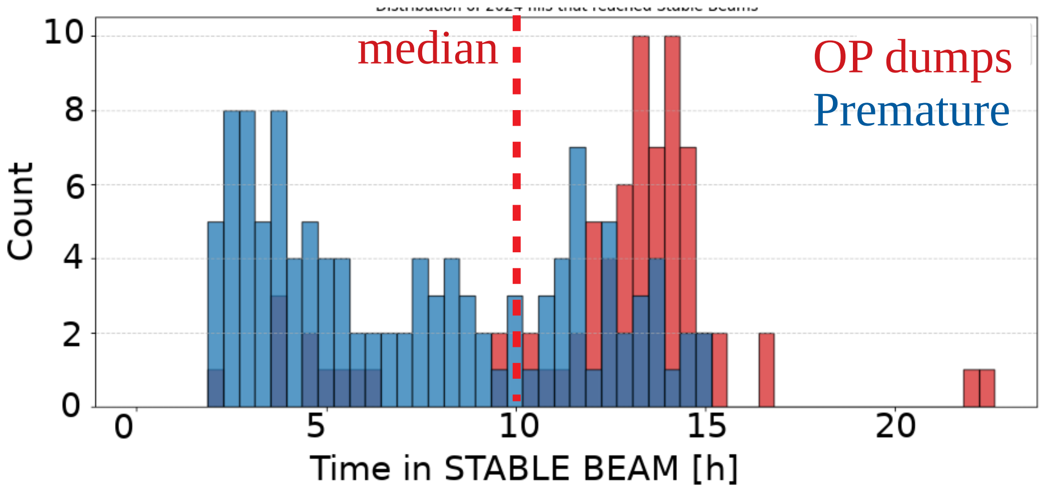

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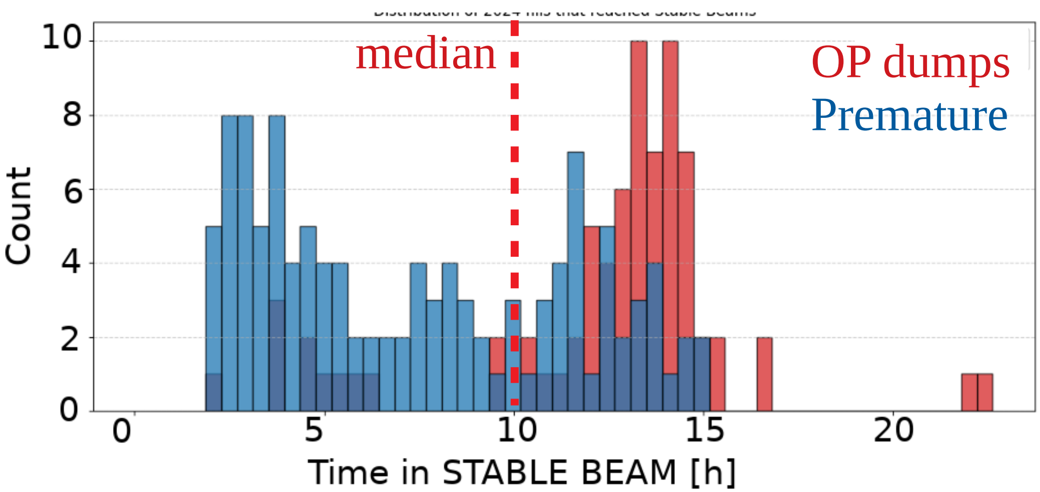
Bunch intensity and filling scheme, performance



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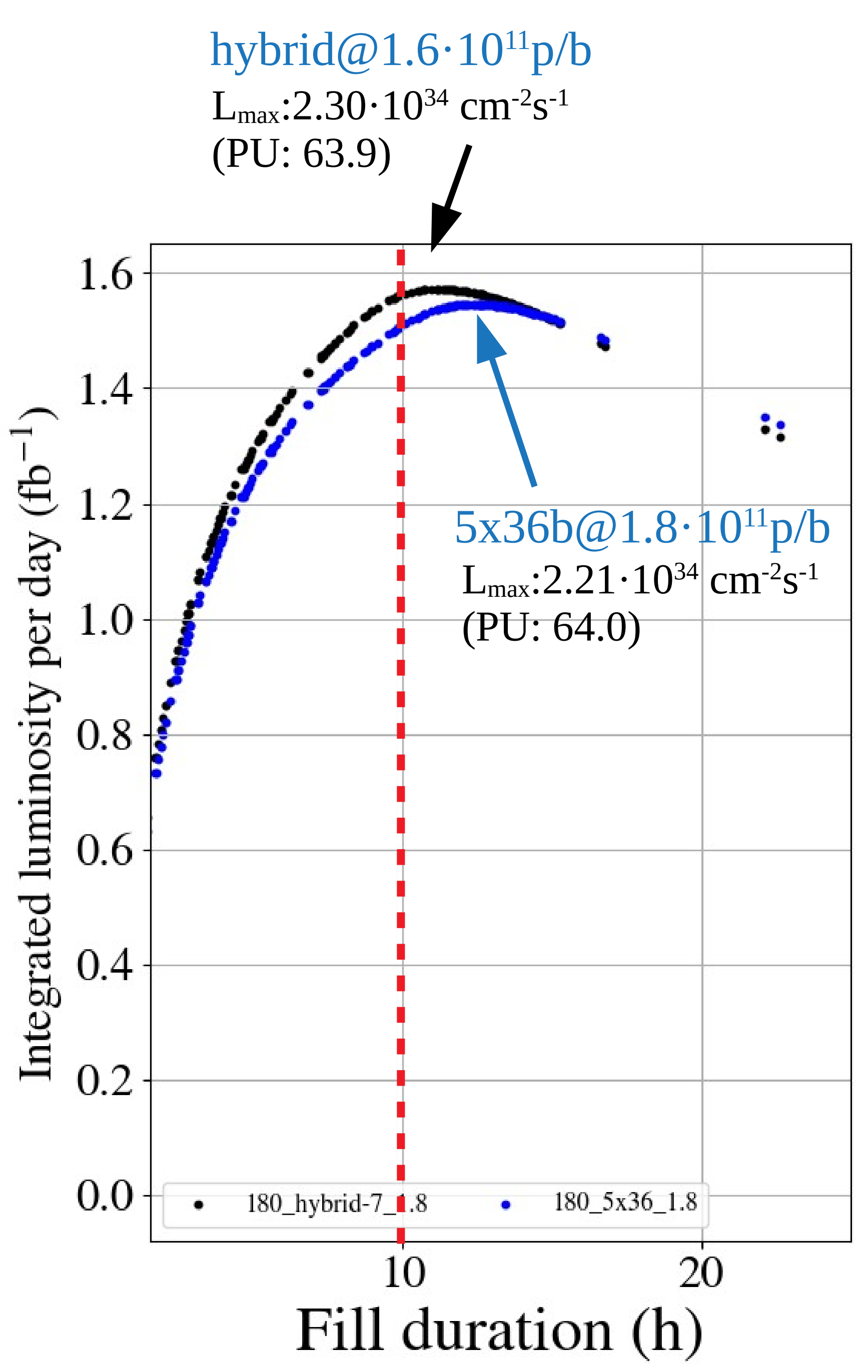

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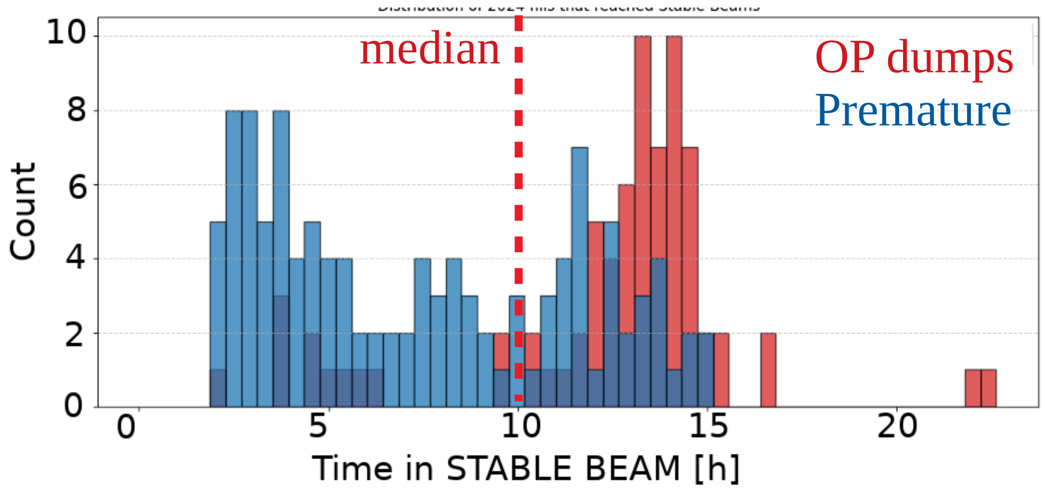

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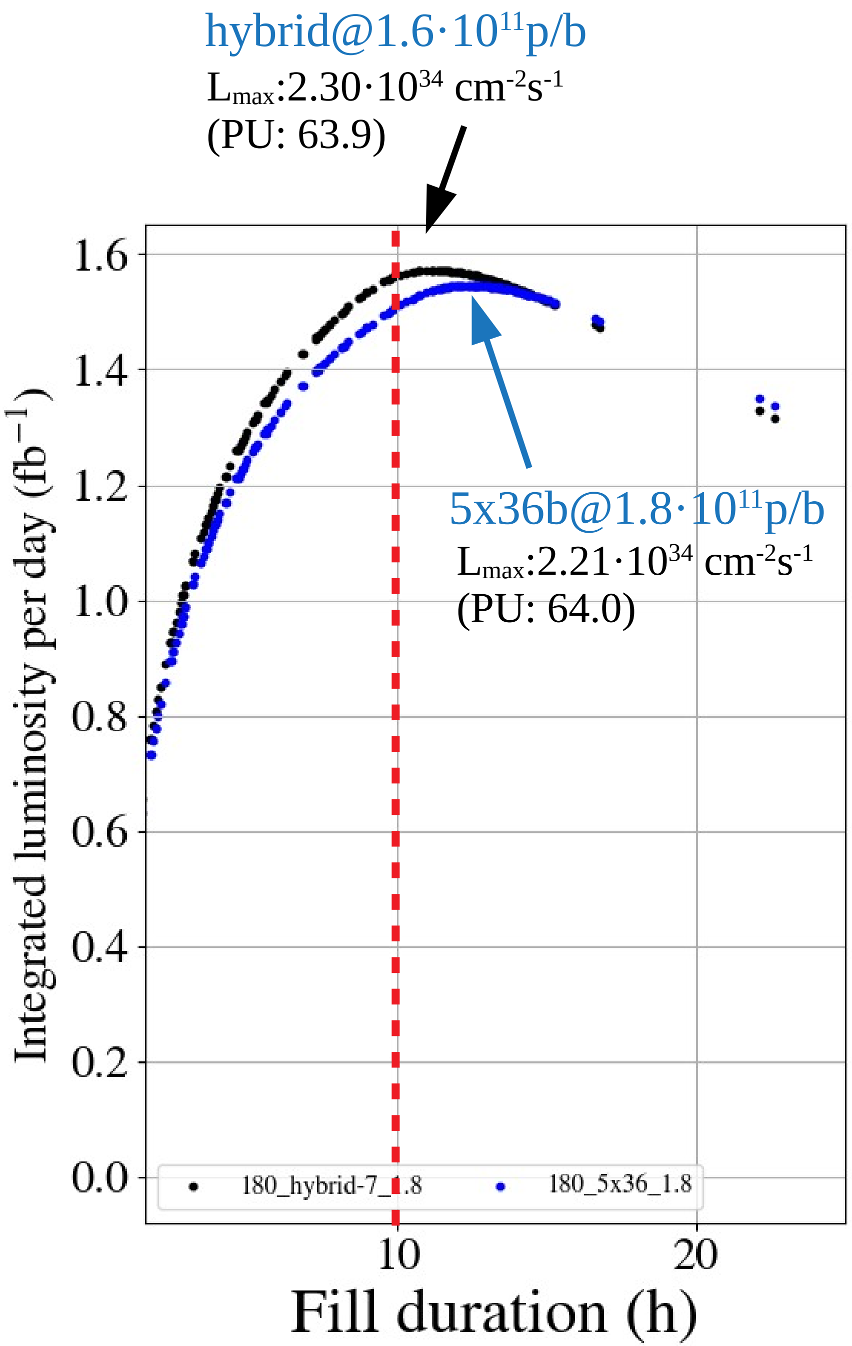

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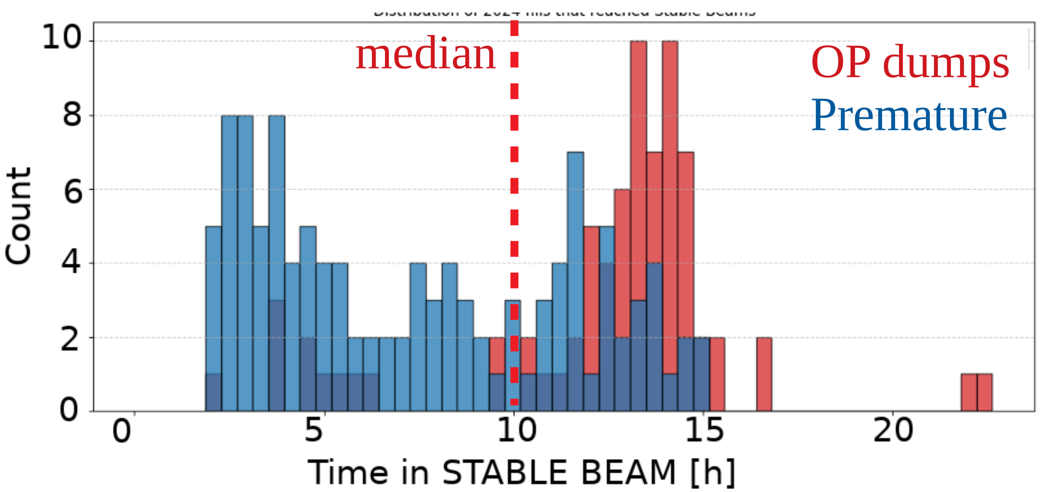

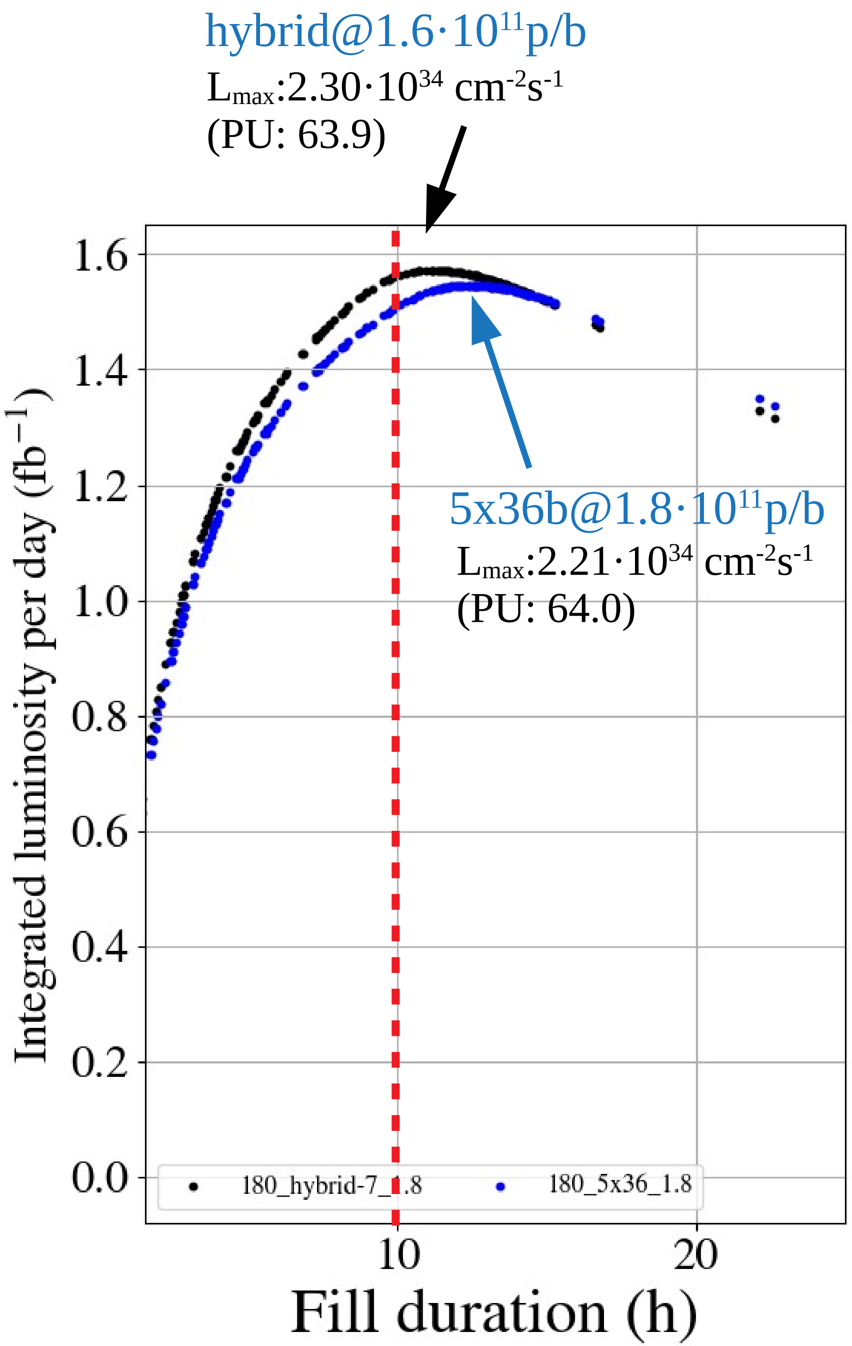

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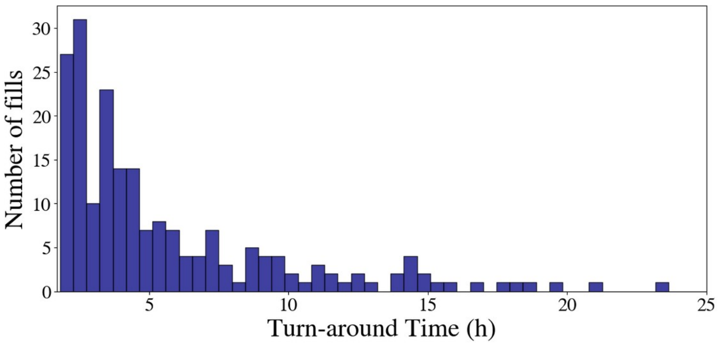
  - With such hypothesis, it is worth pushing for more bunches only if the high bunch charge can be reached

Bunch intensity and filling scheme, performance

- Expected integrated luminosity with 135 days of physics (applying the 2024 statistics of turn around times and premature dumps in SB): **~137 fb^{-1}**



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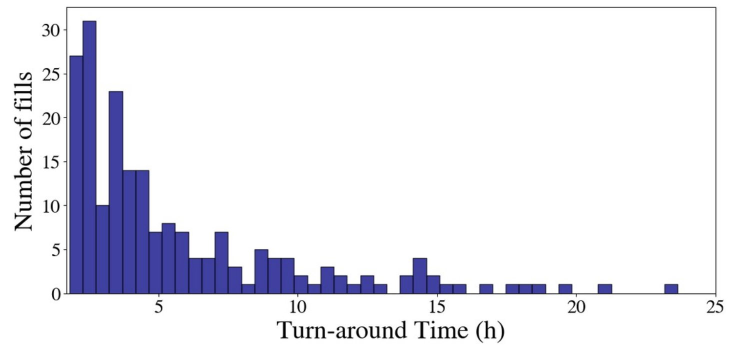

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4x36b → $2.6 \cdot 10^{13}$ p/inj

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Hybrid → $4.3 \cdot 10^{13}$ p/inj

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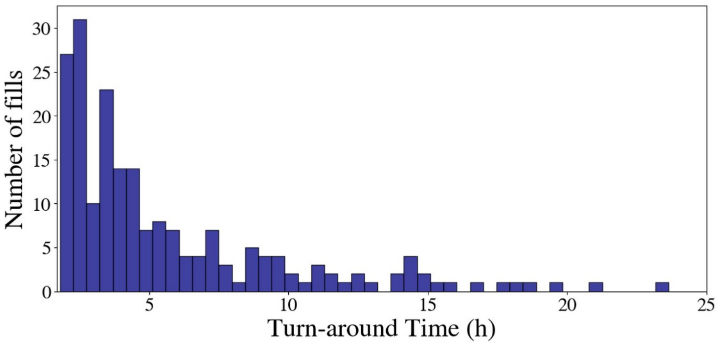

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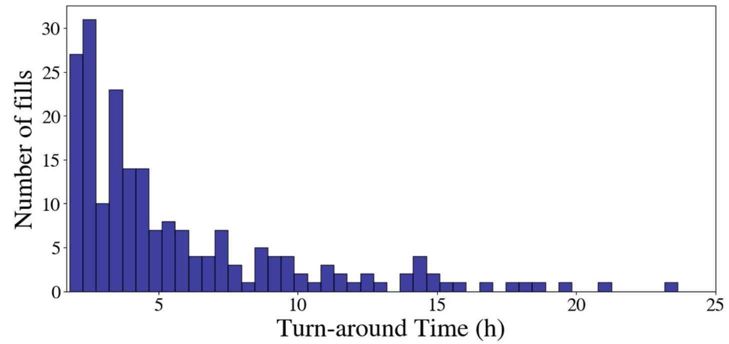

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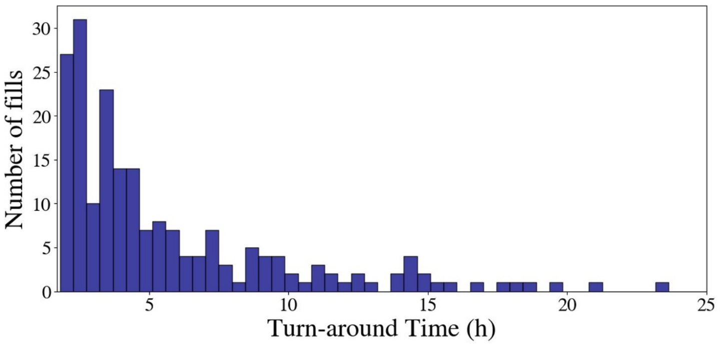

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- The hybrid scheme implies additional difficulties and preparation time in the injectors → Not for startup, but could be prepared in parallel to physics and used later in 2025 or in 2026

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High intensity tests

- Few pushed beams could fit for the full physics cycle until collision with $2.3 \cdot 10^{11}$ p/b:
  - 8b4e scheme: 1972b
    expected luminosity at β*=1.2m: $2.2 \cdot 10^{34}$ $cm^{-2}s^{-1}$ (PU~81)
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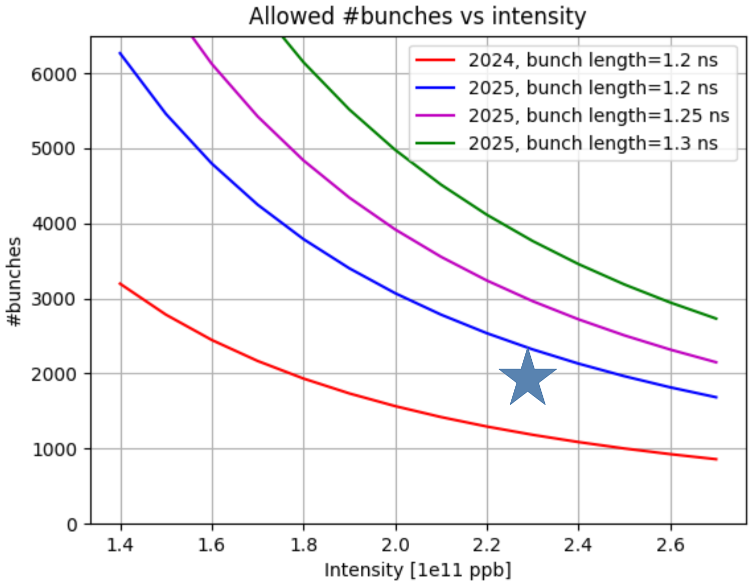

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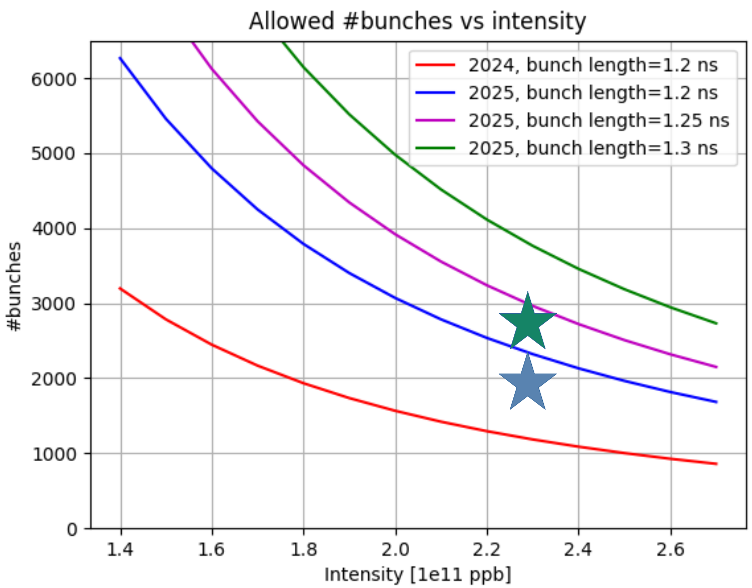

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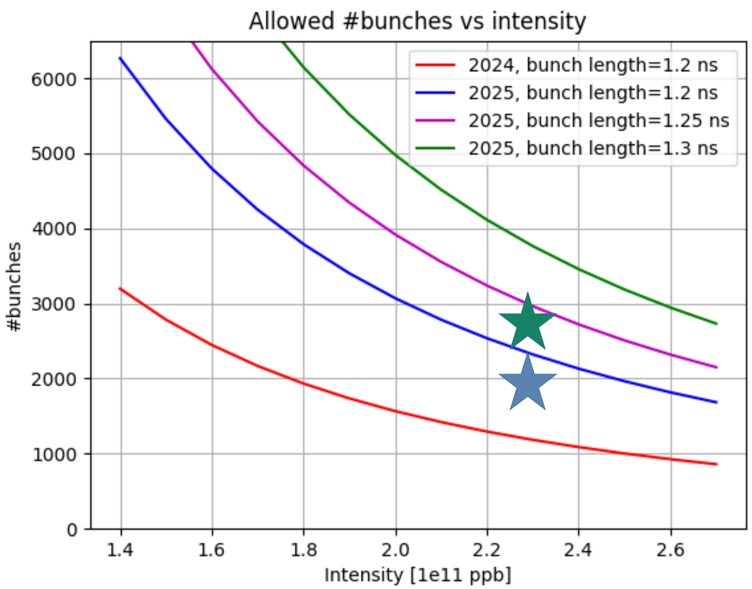

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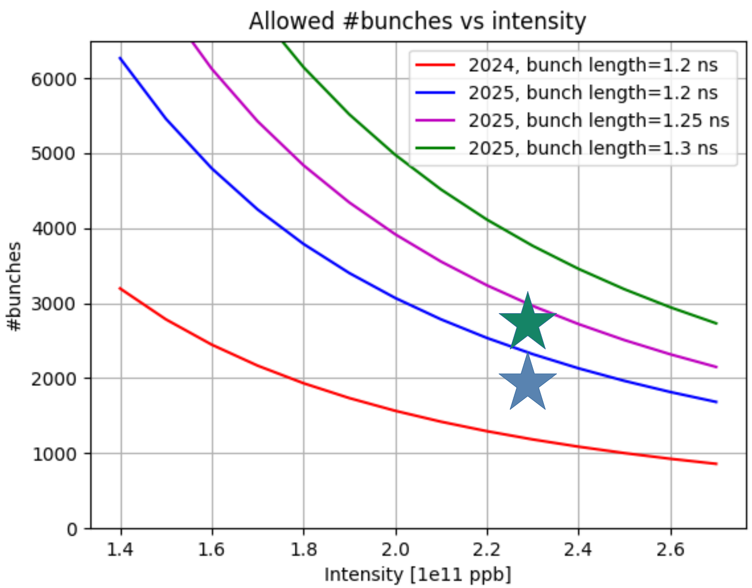

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- Tests with such beams are critical to assess the validity of the beam dynamics models, validate the operational procedures and **identify unexpected issues that could be addressed during LS3**
  - Instabilities
  - Beam-beam
  - Longitudinal dynamics, RF power / voltage
  - Losses through the cycle
  - E-cloud
  - Beam induced heating

→ Compromise on number of bunches may be found to minimise risk on equipment

→ Inherently necessitate additional risk on equipment

High intensity tests: Potential strategies

- No tests beyond operational beams in Run 3
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- Dedicated 'high intensity run' at the very end of Run 3 (after the ion run)

  → Additional time for re-setting up proton beams, intensity re-ramp-up

  → Impact on cool-down time before LS3. Note: Most critical items do not need collisions

Conclusion

- Yet another configuration of IRs 1 and 5 are needed to maintain the triplet alive until the end of Run 3
  - There are consequences for the forward physics experiments, but they can all be maintained
  - The new cycle features a rotation of the crossing angle plane in IRs 1 and 5 and flat β* levelling from 60 to 18cm
  - A set of IR magnets are reaching the predicted damage limit. **“La chance ne sourit qu'aux esprits bien préparés”**
  - The potential of the BBLR is probably jeopardised by the change of crossing plane, yet studies are ongoing.
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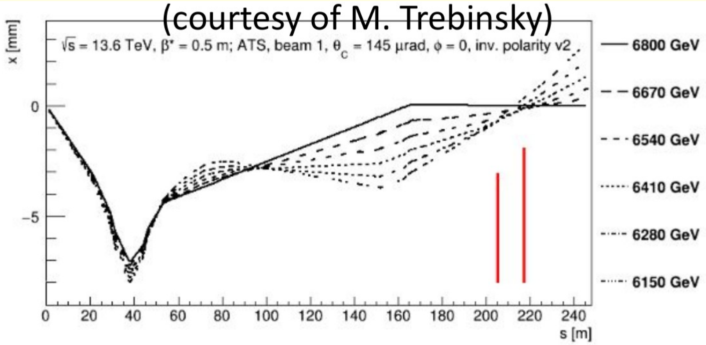
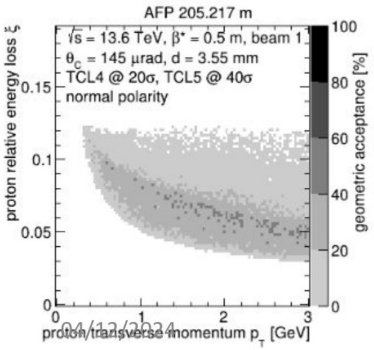
- Intensities beyond operational levels ($1.8 \cdot 10^{11}$ p/b) should be explored in view of HL-LHC, possibly in dedicated slow ramp up phases or during a high intensity run at the end of Run 3.

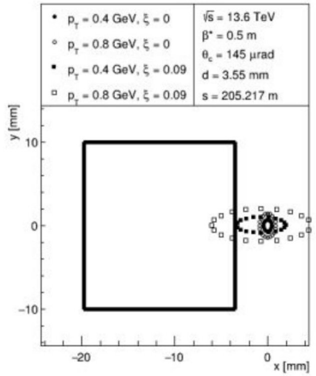
- **Exclusion (RPH for both IR1 and IR5)**

(i) RP-H kills the **single-pass dispersion** at the XRP (disaster for AFP/PPS) but also at the nearby TCL6 (DS losses & QPS!!)

AFP simulations for 2024 optics with H crossing
(courtesy of M. Trebinsky)

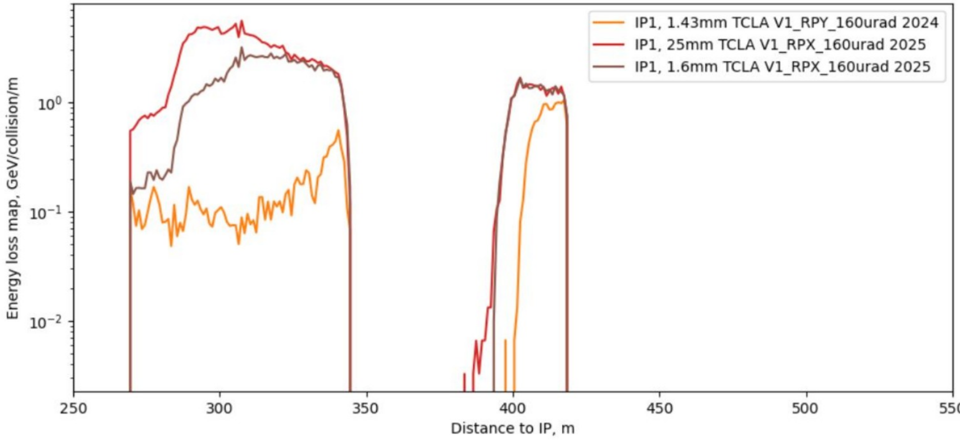






DS losses simulations in IR1 with RPH & RPV optics (V. Rodin)

Cell 8-9 [GeV/coll]	Half-cell 11 [GeV/coll]	
11	12	IR1 RP-V *1.43 mm* (2024)
119	28	IR1 RP-H *1.6 mm*
213	28	IR1 RP-H *25 mm*



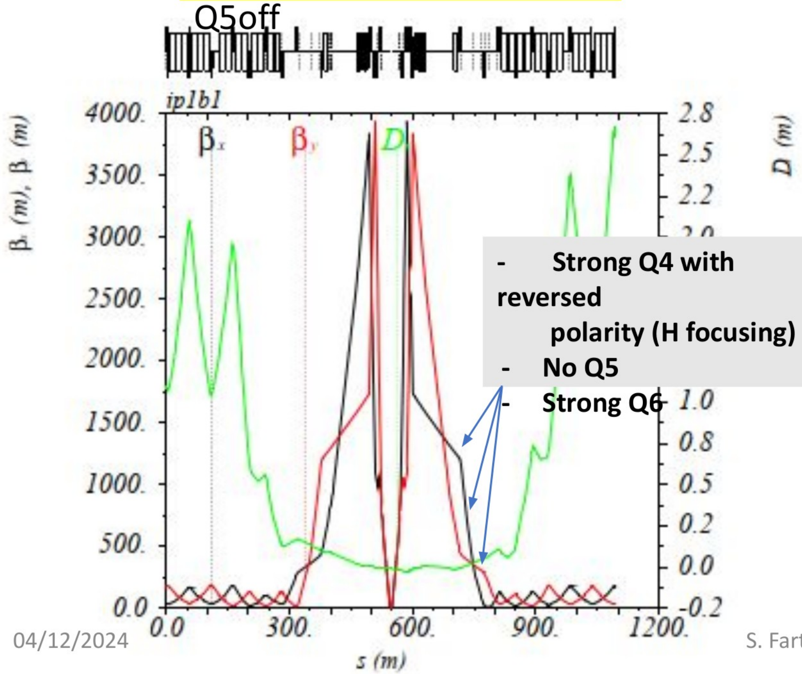
04/12/2024 S. Fartoukh, LMC 4

- **Exclusion (RPH especially for IR1)**

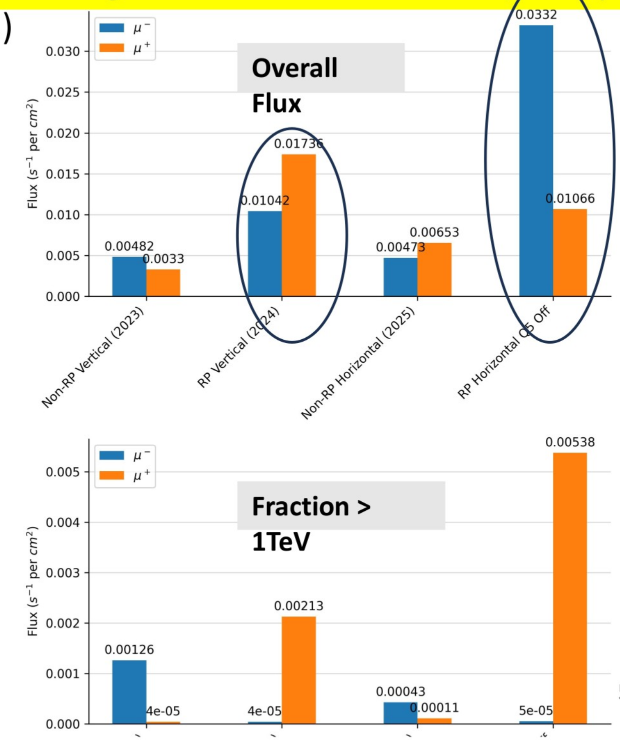
  (ii) RP optics (H or V) was discovered to increase the background to FASER/SND with μ^+ (especially > 1 TeV)

  - ~40% of it could be washed out by a **RP variant with strong Q4 and Q5 off**
  - but not the high energy μ^+ and at price of tripling the low energy μ^- for RPH(Q5off) w.r.t. 2024 (poor TCL6 effectiveness due to ~0 dispersion @ TCL6) [RPV(Q5off) not studied but irrelevant, see later]

RP optics variant with Q5off



Muon background to FASER detector (A. Keyken, RHU)



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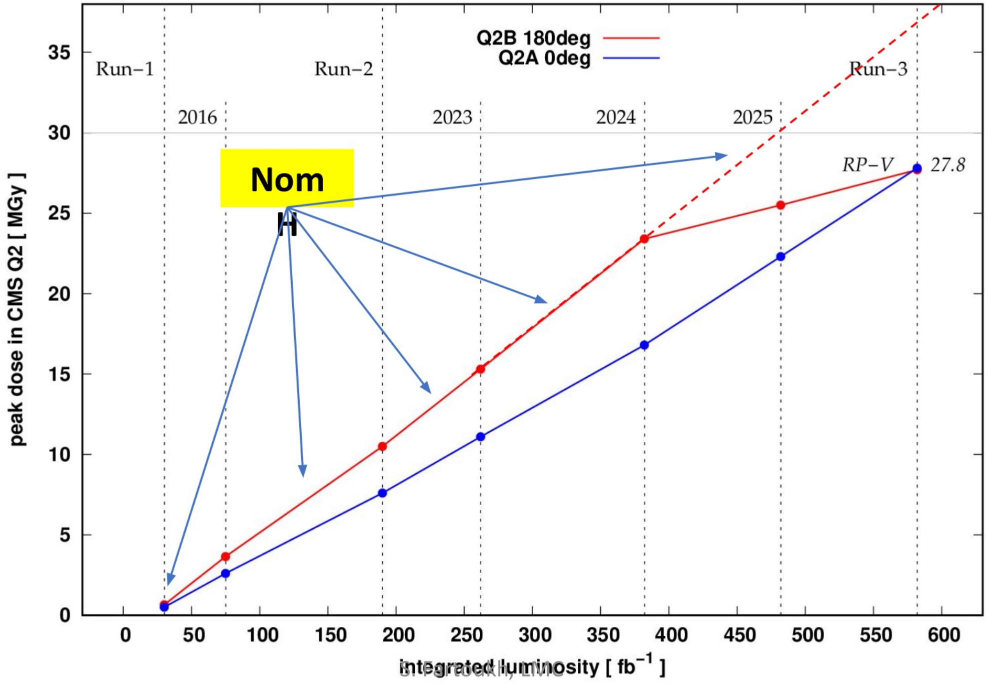
- **Exclusion (Nom-V)**

 The IR5 configuration (Nom-H since ever) needs to be changed in 2025 (IT radiation)

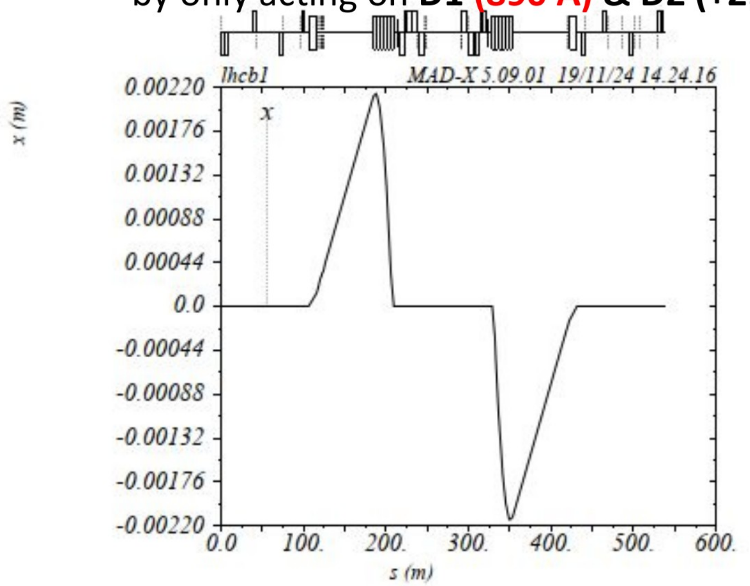
 With RPH excluded, we are left with RPV and NomV, both requesting similarly a rotation of the XRPs for PPS, with **only one polarity allowed for the X-angle (V-)**

 <u>For a fixed polarity of the V-crossing</u>, Nom-V has the **VERY WORST ratio** ***Radiation/Lumi of ~0.5 MGY/fb^{-1}*** **for D1:** **Q3 V-defocusing & V-crossing**

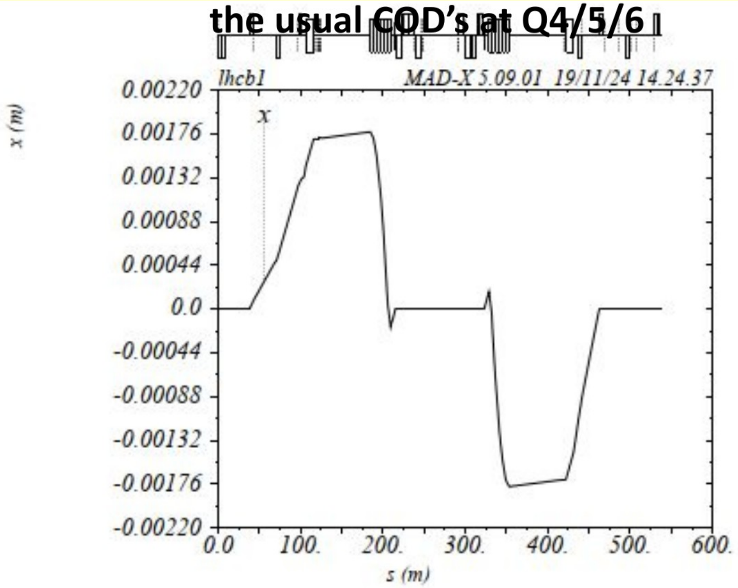


S. Fartoukh @ LMC 04.12.2024

MBXWA disconnected and restoring the ring geometry
by only acting on **D1** **(890 A)** **& D2 (+2.55%)**

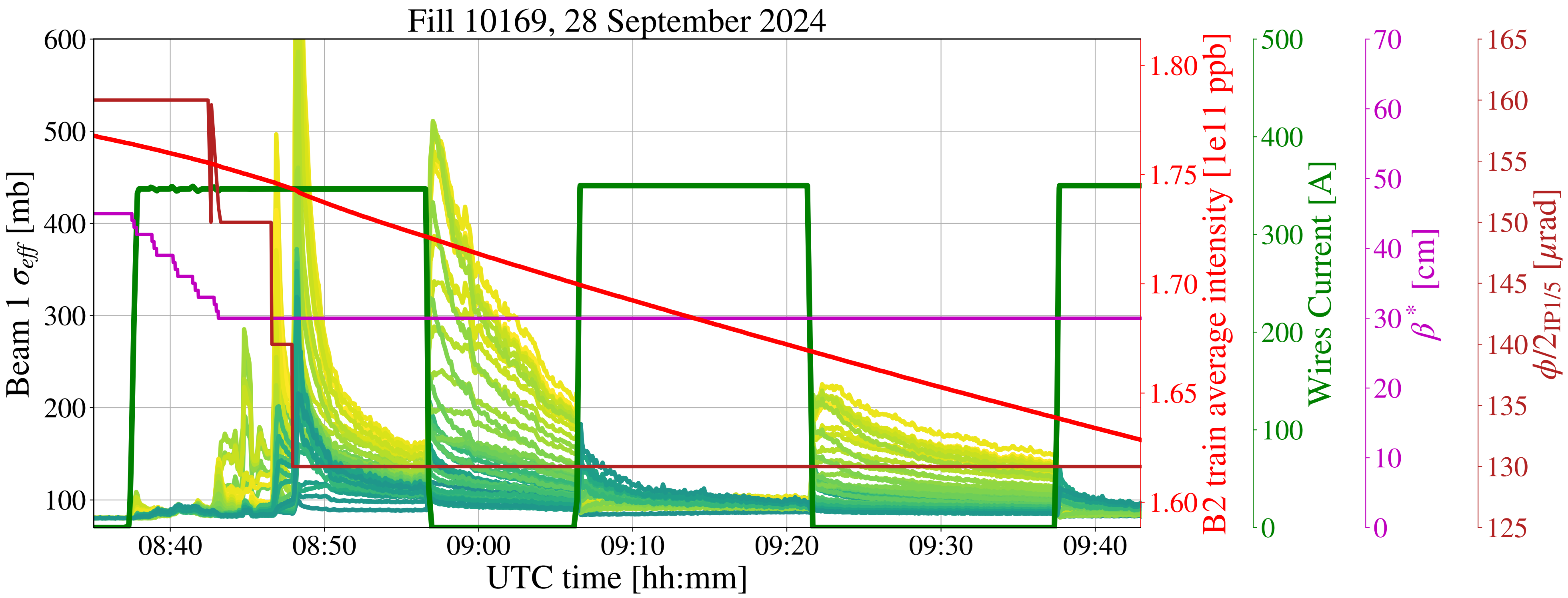


Idem, mitigating **D1** **(815 A),** **reducing D2 (-5%), using MCBXH3 (+250 A), and closing the bump with the usual COD's at Q4/5/6**



- Only works for H crossing because the H-Xing (always > 0) fights against D1: we are lucky !
- MCBXH3 is very well shielded for radiation by the MCSTX coils: we are lucky again !
- **Question: do we put it in preventively already beginning of next year ?**

BACKUP
BBWC MD in 2024 (G. Sterbini)



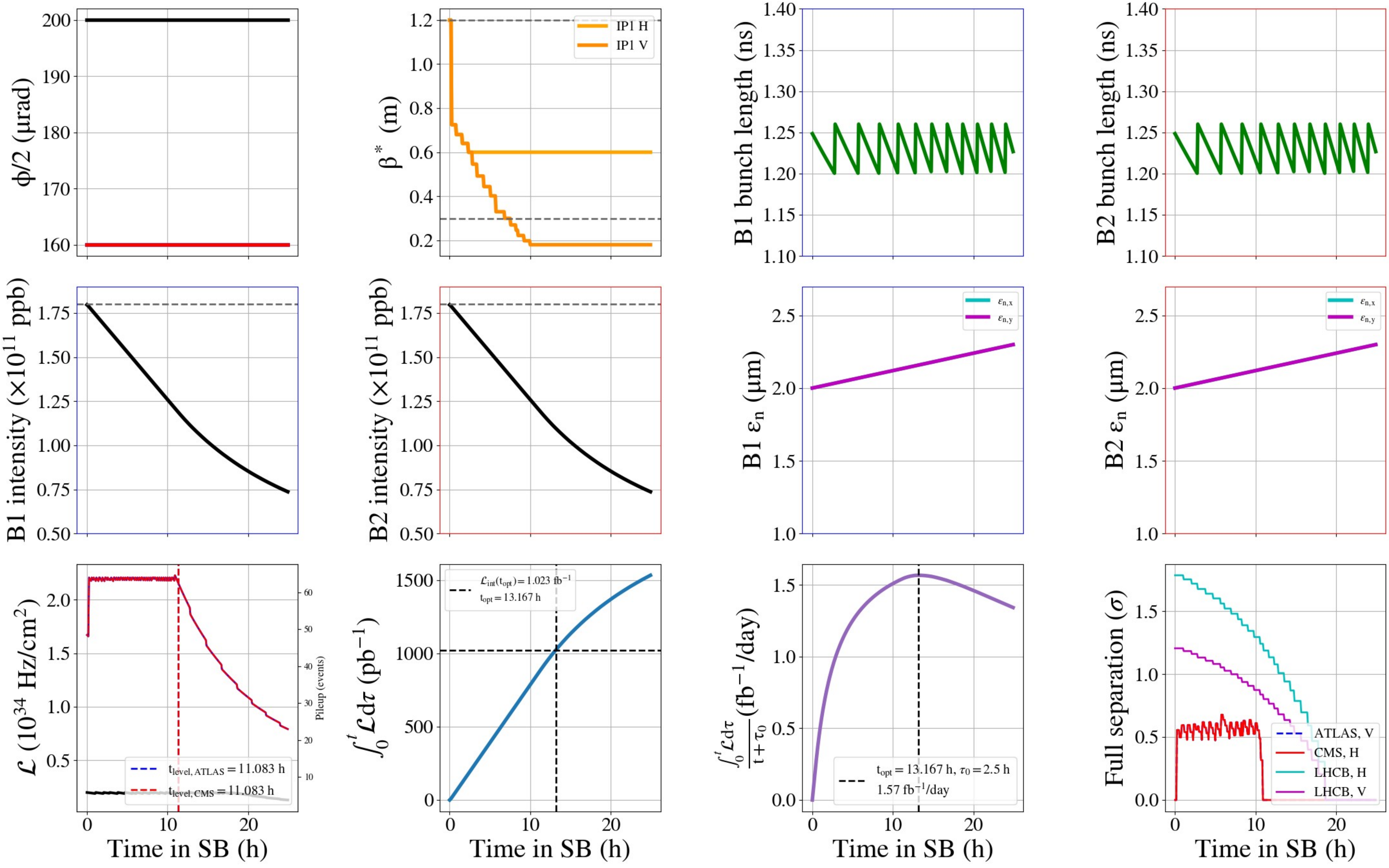
BACKUP

Bunch intensity and filling scheme, performance (L. Mether)

	N_b	Collisions IP1/5	IP2	IP8	Heat load [W/hc] 1.6e11	1.8e11	N_{bpi}	N_{inj}	SPS flat bottom [s]	Bunch intensity for 175 W/h.c. [10^{11} p/b]
3x48b	**2556**				187	201				
6x36b	**2604**	2592	2097	2059	177	191	216	13	18	1.57
Hybrid-7+47x48b	**2604**	2592	2224	2313	174	187	240	13	14.4	1.62
5x36b	**2496**	2484	2121	2260	168	181	180	16	14.4	1.71
4x36b	**2460**	2448	2005	2146	164	177	144	20	10.8	1.77
3x36b	**2352**	2340	2004	2133	156	168	108	24	7.2	1.8

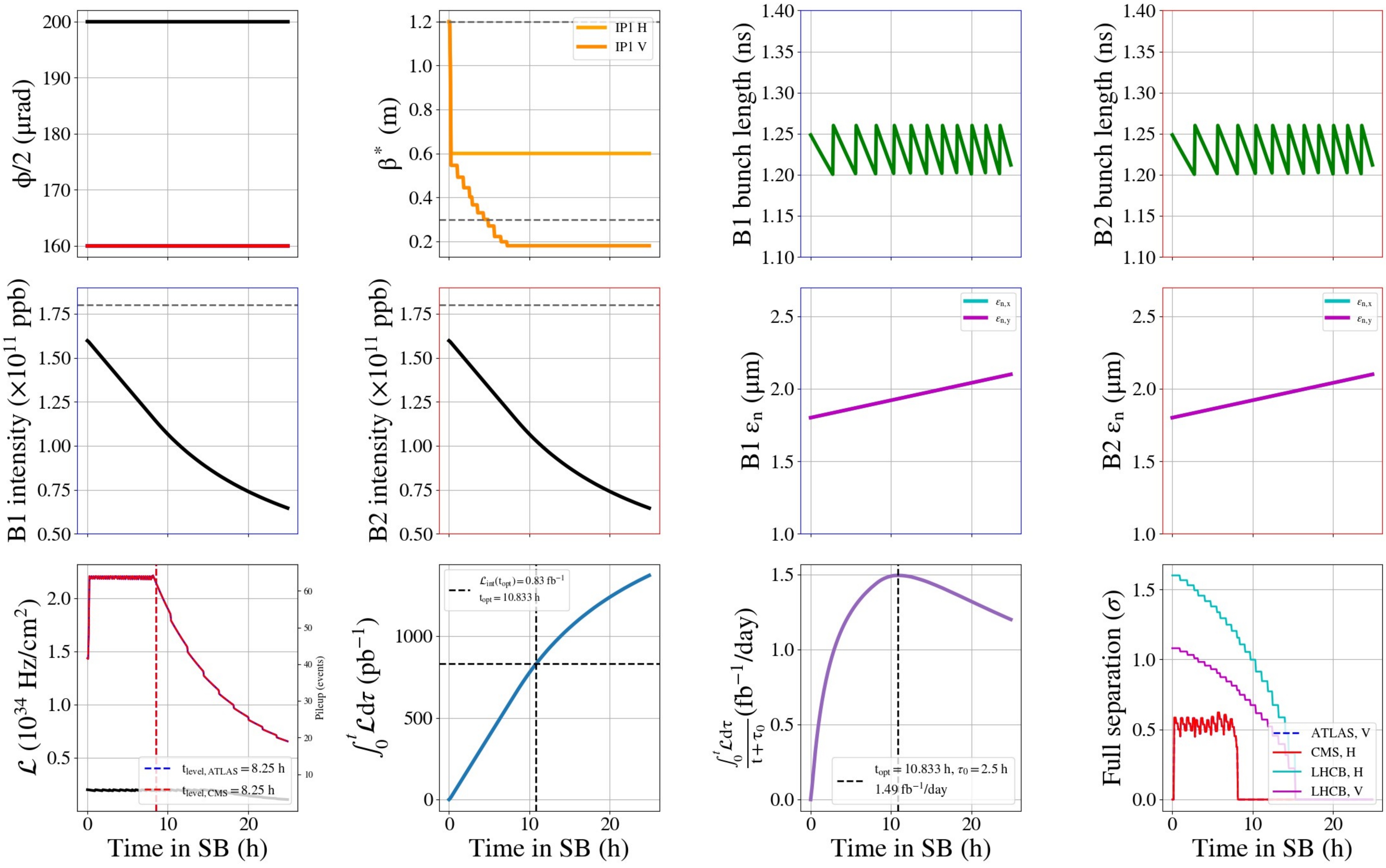
Backup

Parameters through the cycle ($1.8 \cdot 10^{11}$ p/b) (S. Kostoglou)

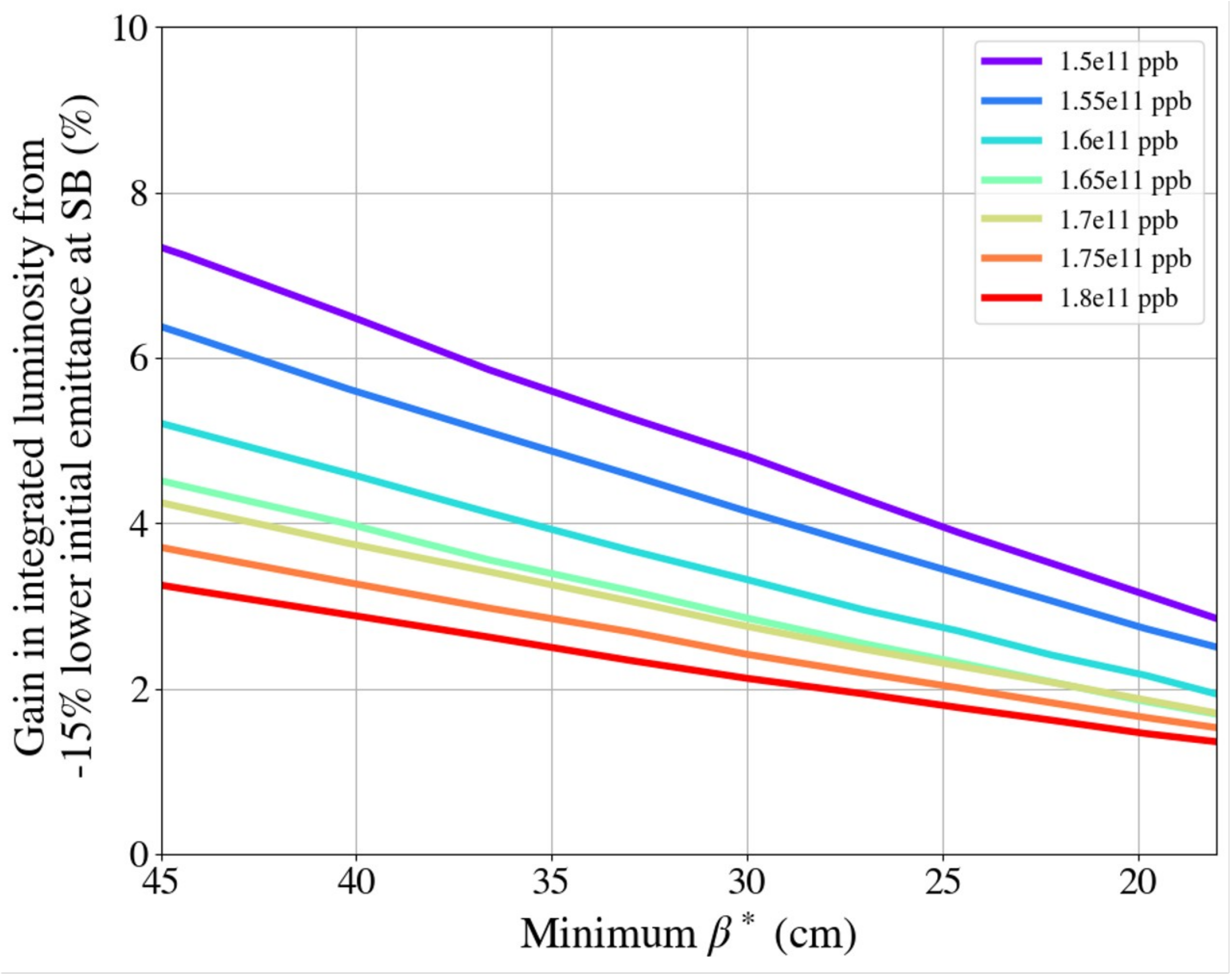


Backup

Parameters through the cycle ($1.6 \cdot 10^{11}$ p/b) (S. Kostoglou)

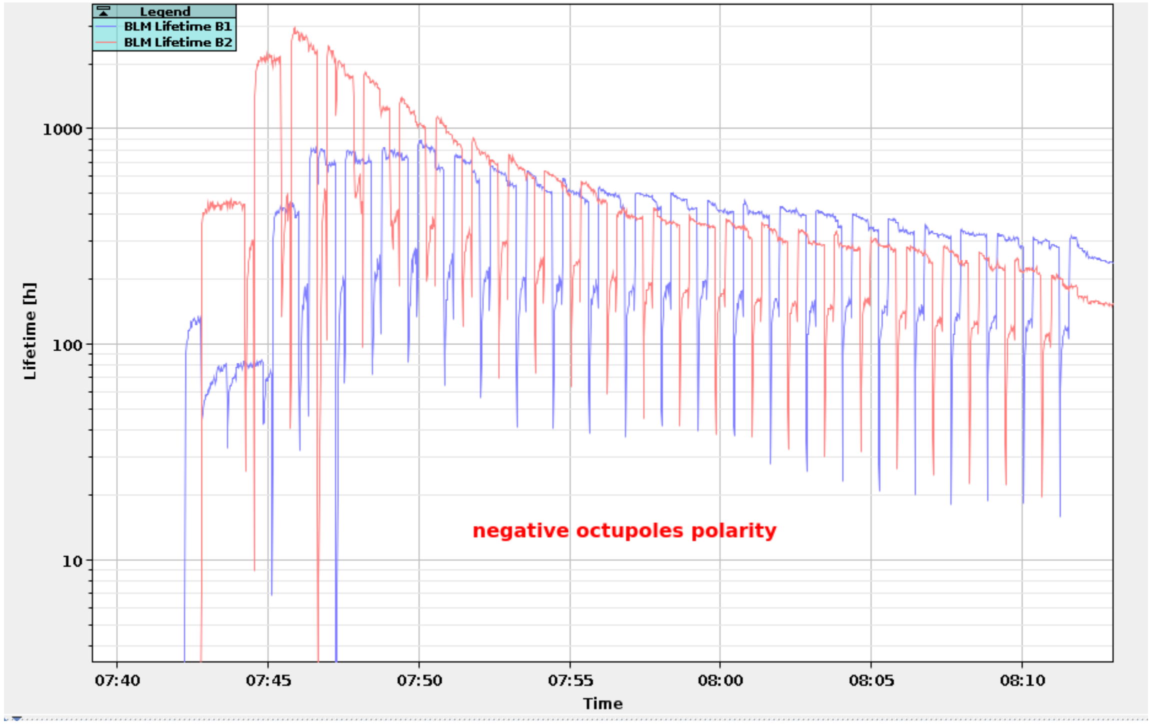


BACKUP
BCMS vs Std (S. Kostoglou)

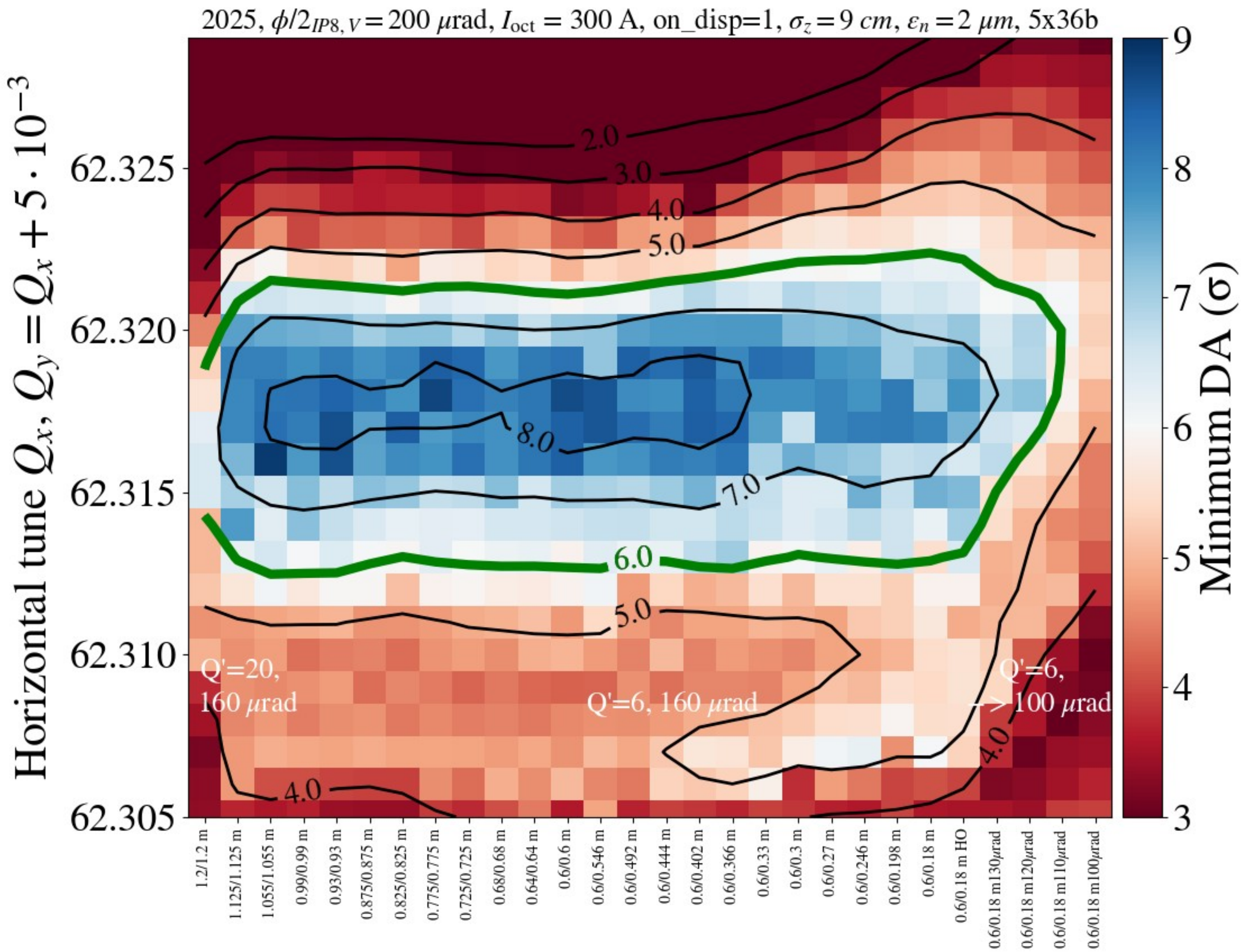


BACKUP
Lifetime at injection (K. Paraschou)

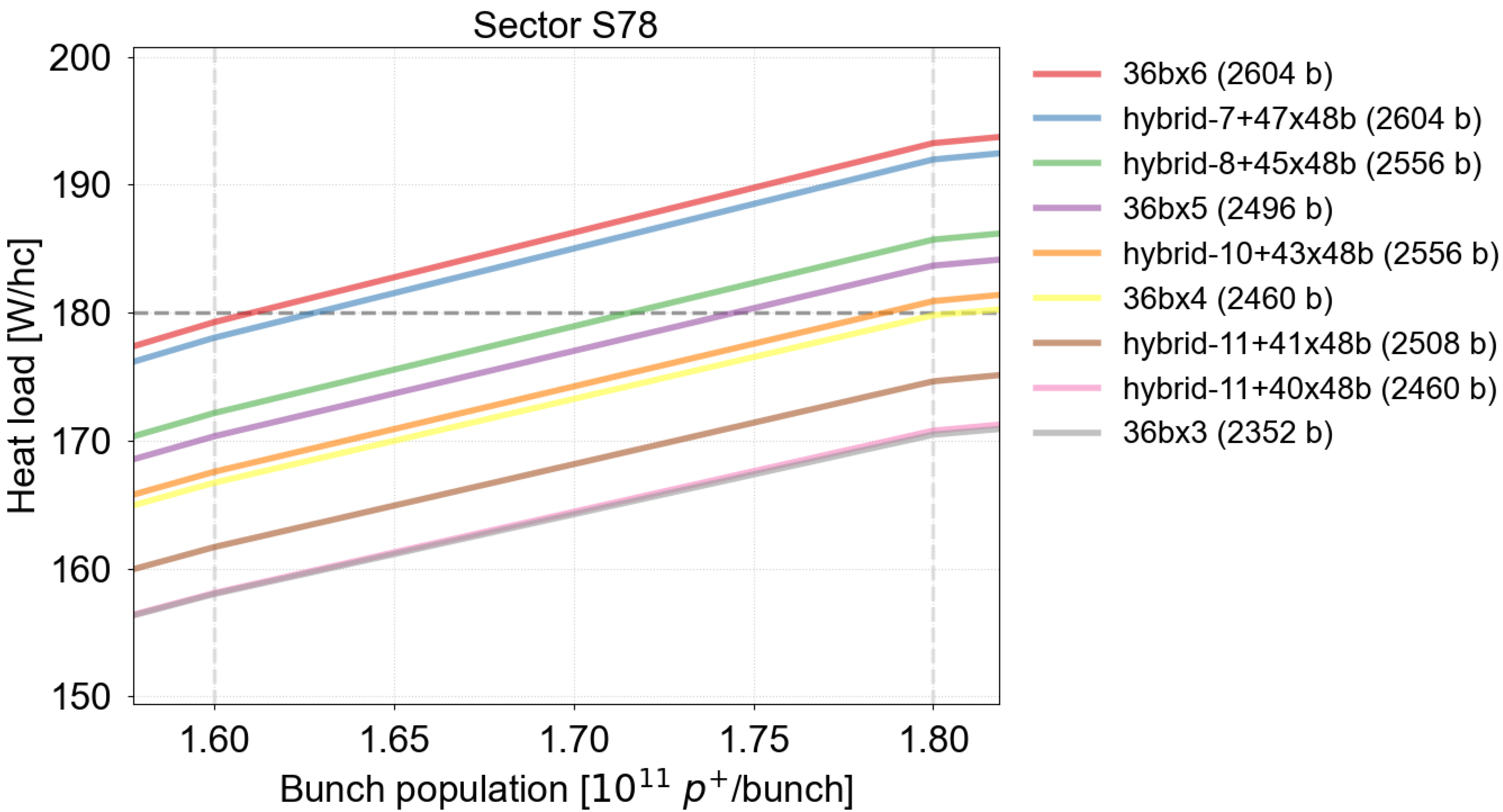
B1 knob: 3.2
B2 knob: 2.5
Tunes: 62.295/60.313

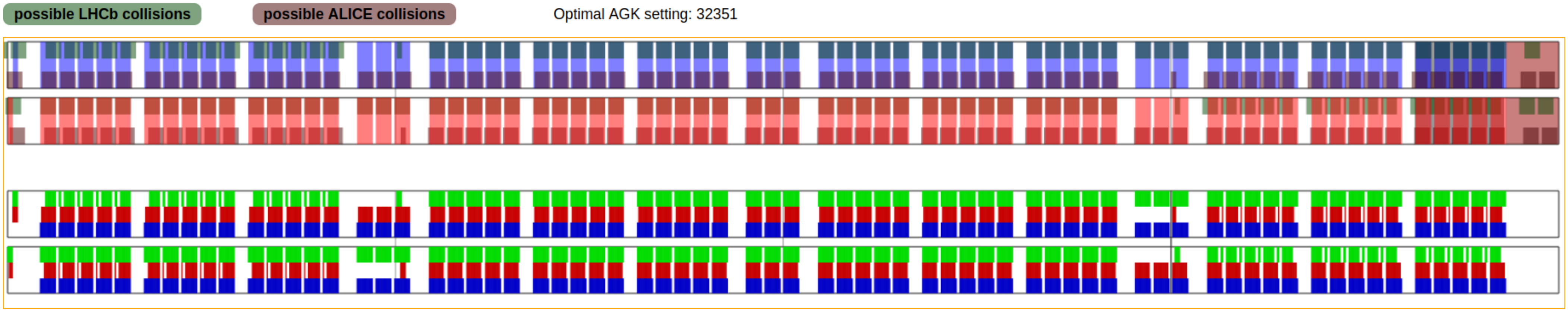


BACKUP
DA through luminosity levelling, positive octupole (S. Kostoglou)



Heat load (L. Mether)





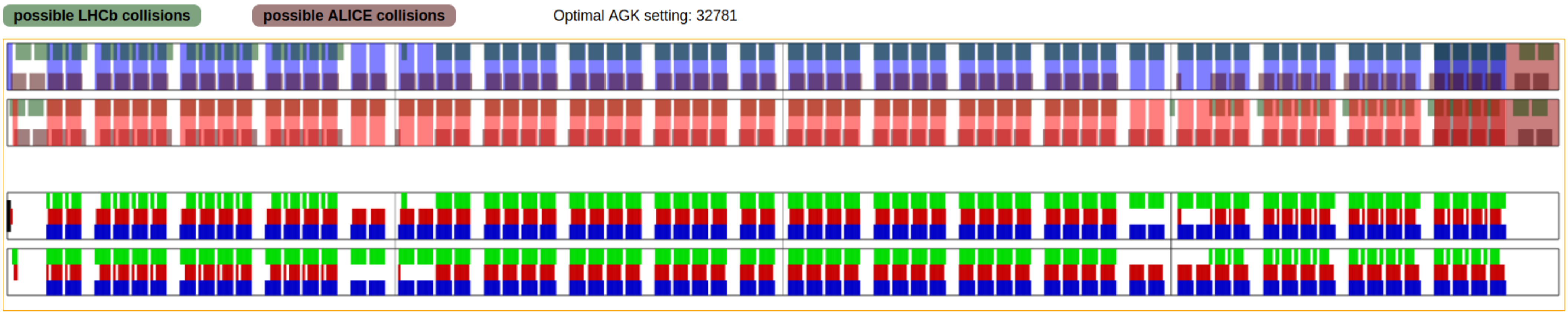
Beam Info	
Bunches B1/B2	2496 / 2496
Injections B1/B2	16 / 16

Collisions	
ATLAS/CMS	2484
ALICE	2132 (85.8%)
LHCb	2280 (91.8%)
Non Colliding B1	0
Non Colliding B2	0

B1 classes : 0:0 1:18 2:0 3:198 4:0 5:346 6:12 7:1922

B2 classes : 0:0 1:18 2:0 3:198 4:4 5:342 6:8 7:1926

BACKUP
4x36b



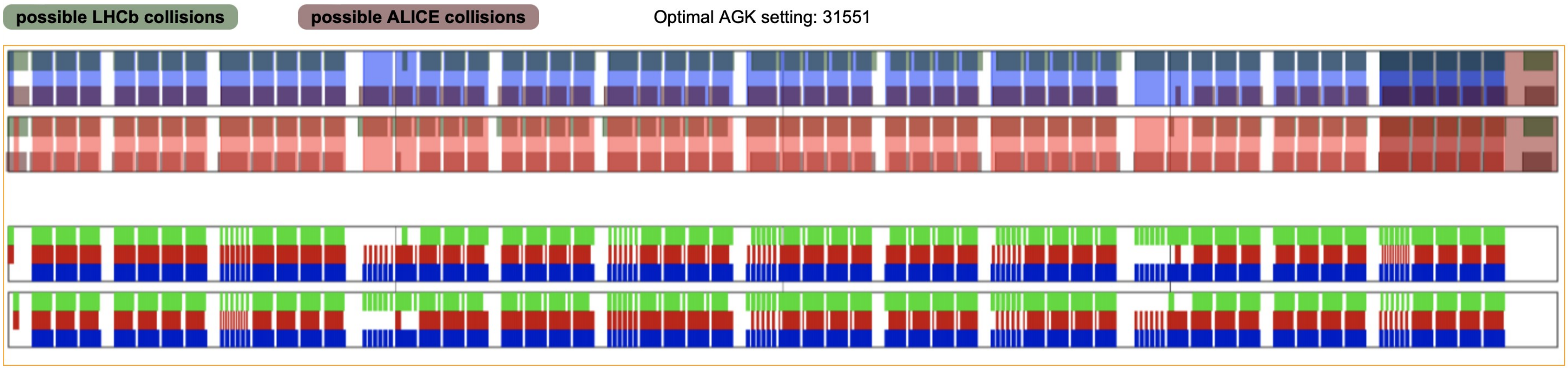
Beam Info	
Bunches B1/B2	2460 / 2460
Injections B1/B2	20 / 20

Collisions	
ATLAS/CMS	2448
ALICE	2005 (81.9%)
LHCb	2146 (87.7%)
Non Colliding B1	8
Non Colliding B2	0

B1 classes : 0:8 1:35 2:4 3:267 4:0 5:412 6:0 7:1734

B2 classes : 0:0 1:34 2:0 3:280 4:4 5:417 6:8 7:1717

Hybrid-7+47x48b



Beam Info	
Bunches B1/B2	2604 / 2604
Injections B1/B2	13 / 13

Collisions	
ATLAS/CMS	2592
ALICE	2224 (85.8%)
LHCb	2313 (89.2%)
Non Colliding B1	0
Non Colliding B2	0

B1 classes : 0:0 1:55 2:0 3:236 4:0 5:325 6:12 7:1976

B2 classes : 0:0 1:72 2:0 3:219 4:0 5:308 6:12 7:1993

BACKUP

Integrated luminosity and triplet lifetime

Radiation forecast and back up for D1 in IR1

S. Fartoukh @ LMC 04.12.2024

- **Radiation forecast for the IT&D1 in IR1 and IR5**

MAGNET	PEAK DOSE [MGy] BY THE END OF		
	2024	**2025**	**2026**
IT (Q2A) IR1	19.5	25	30.5
D1 IR1	67.5	85	102.5
IT (Q2B→*Q2A*) IR5	23.5	25.5	*28*
D1 IR5	61.5	68.5	73.5
LUMI [fb^{-1}]	**380**	**480**	**580**

04/12/2024 S. Fartoukh, LMC 9

Integrated luminosity and triplet lifetime

Radiation forecast and back up for D1 in IR1

S. Fartoukh @ LMC 04.12.2024

- **Radiation forecast for the IT&D1 in IR1 and IR5**

MAGNET	PEAK DOSE [MGy] BY THE END OF			
	2024	2025		2026
IT (Q2A) IR1	19.5	25	27.0	30.5
D1 IR1	67.5	85	91.5	102.5
IT (Q2B→Q2A) IR5	23.5	25.5	26.4	*28*
D1 IR5	61.5	68.5	70.3	73.5
LUMI [fb^{-1}]	**380**	**480**	517	**580** 587

04/12/2024 S. Fartoukh, LMC 9

Most optimistic integrated luminosity estimate: 137 fb^{-1} 70 fb^{-1}
* Yet not taking into account potential improvements in the 2026 cycle

- From R. Steerenberg @ LMC 04.12.2024: 2025 → 138 days / 2026 → 66 days