Status of the LHC

Jorg Wenninger BE/OP

161st LHCC OPEN Session

Mar 3rd, 2025

Outline

2024 run highlights

2025 configuration

Beam intensity

2025 schedule

Oxygen run preparation

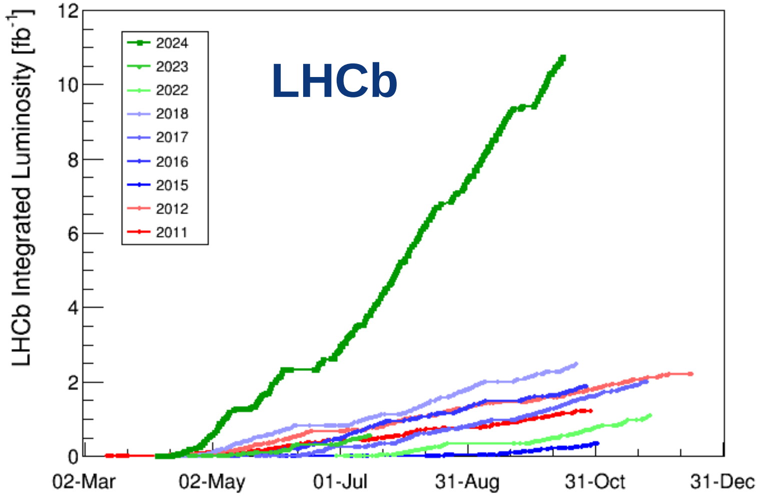
2024 pp

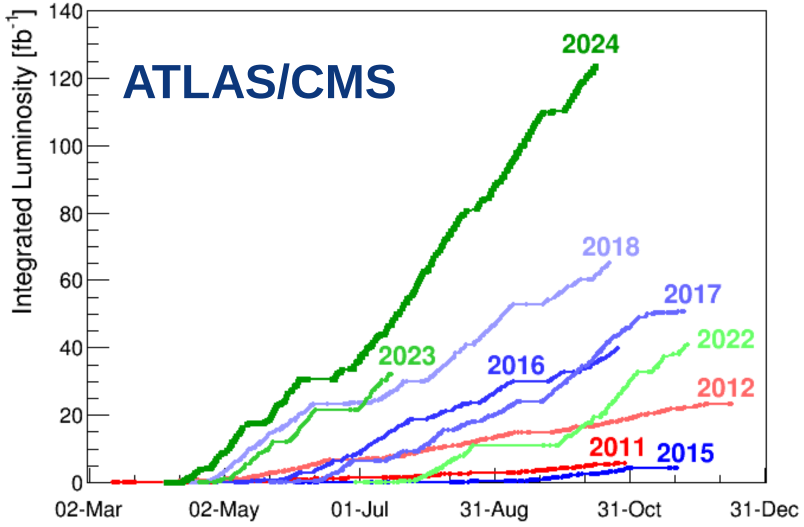
124 fb^{-1} in ATLAS/CMS

11 fb^{-1} in LHCb

67.5 pb^{-1} in ALICE

Most productive year !

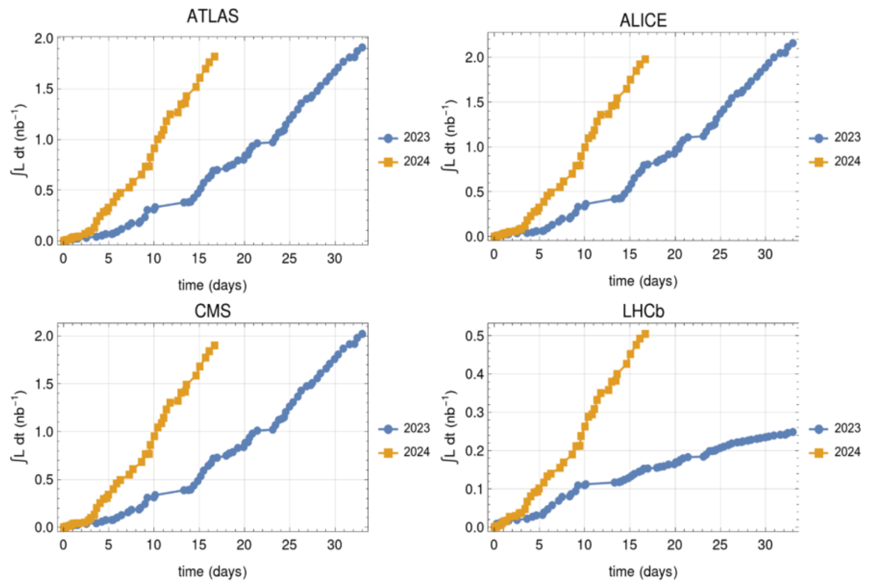




2024 AVG rate = 0.83 fb^{-1}/24h

2024 highest rate = 1.5 fb^{-1}/24h (midnight to midnight)

2024 ions



IP1/2/5: similar int. luminosity as 2023, achieving the target of 1.9 nb^{-1}

IP8: ~ double of the 2023 luminosity

~2h of levelling at 6.4 x 10^{27} cm^{-2} s^{-1}

~30% higher intensity with performance **beyond HL-LHC targets**

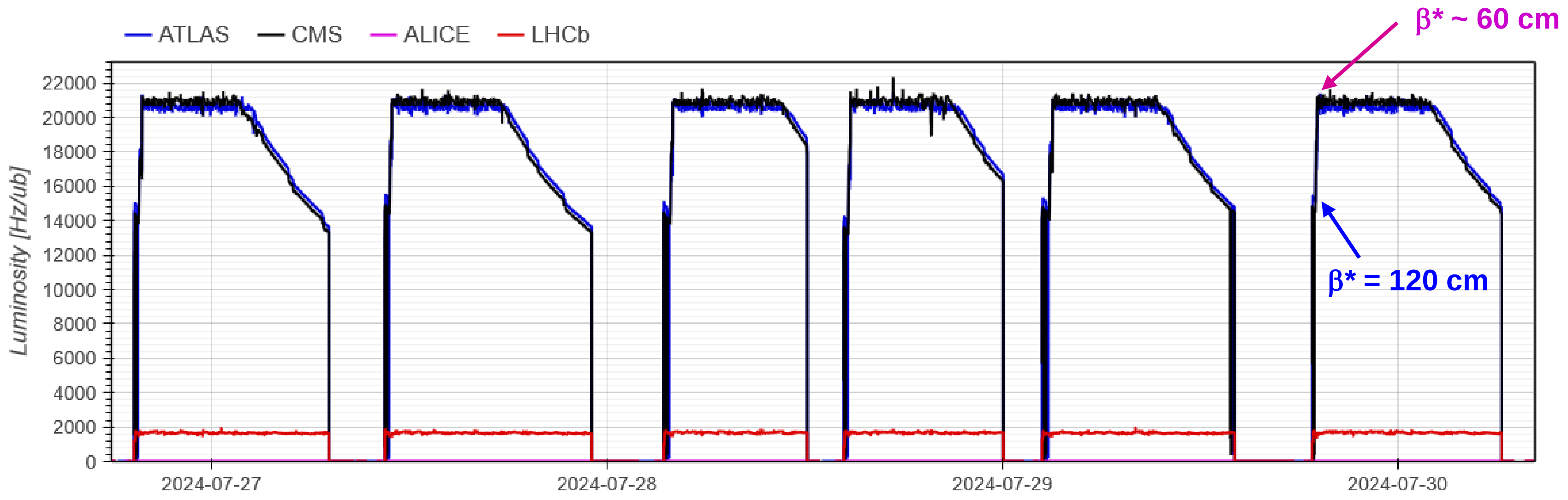
Levelling in physics

Combined (β* + offset) **levelling** allowed for

- **6-7 hours levelling** with BCMS beams.
- **Well balanced** luminosity between CMS and ATLAS thanks to combined levelling (but also risk of hiding normalization errors and real differences).

LHCb levelled **through the entire fill.**

Increasing the bunch intensity will extend further the levelling time (start at lower β*).



Beam status - intensity

LHC is operated with train of 1.6×10^{11} ppb:
Run3 target of 1.8×10^{11} not yet achieved.

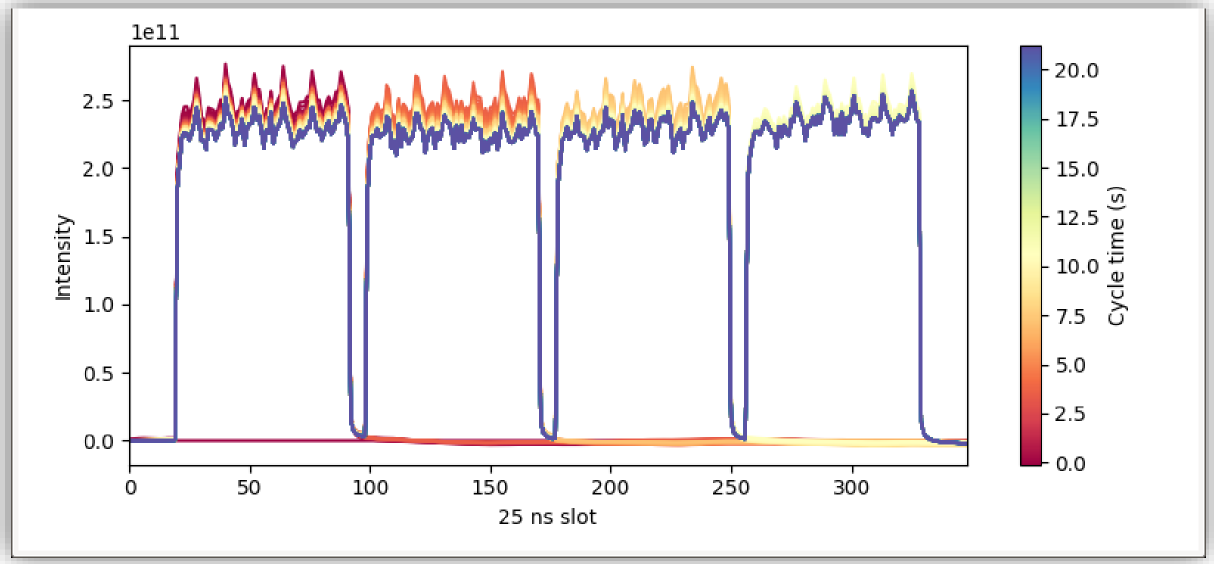
The injector chain achieved LIU target parameters at SPS flat top in 2024.

- 4x72b @ 2.3×10^{11} p/b with a bunch length of 1.65ns at 450 GeV/c.

Trains of ~2.2×10^{11} ppb (36b, 48b, 8b4e) were **injected into the LHC** in 2024.

- < 1000b / beam (2024 intensity limit).
- Focus: RF capture and e-cloud studies.

LIU beam in the SPS



K. Li, JAP '24 Montreux

Outline

2024 run highlights

2025 configuration

Beam intensity

2025 schedule

Oxygen run preparation

Triplet radiation and optics

Radiation doses to the inner triplet magnets **approach / exceed estimated damage levels** (large uncertainties !).

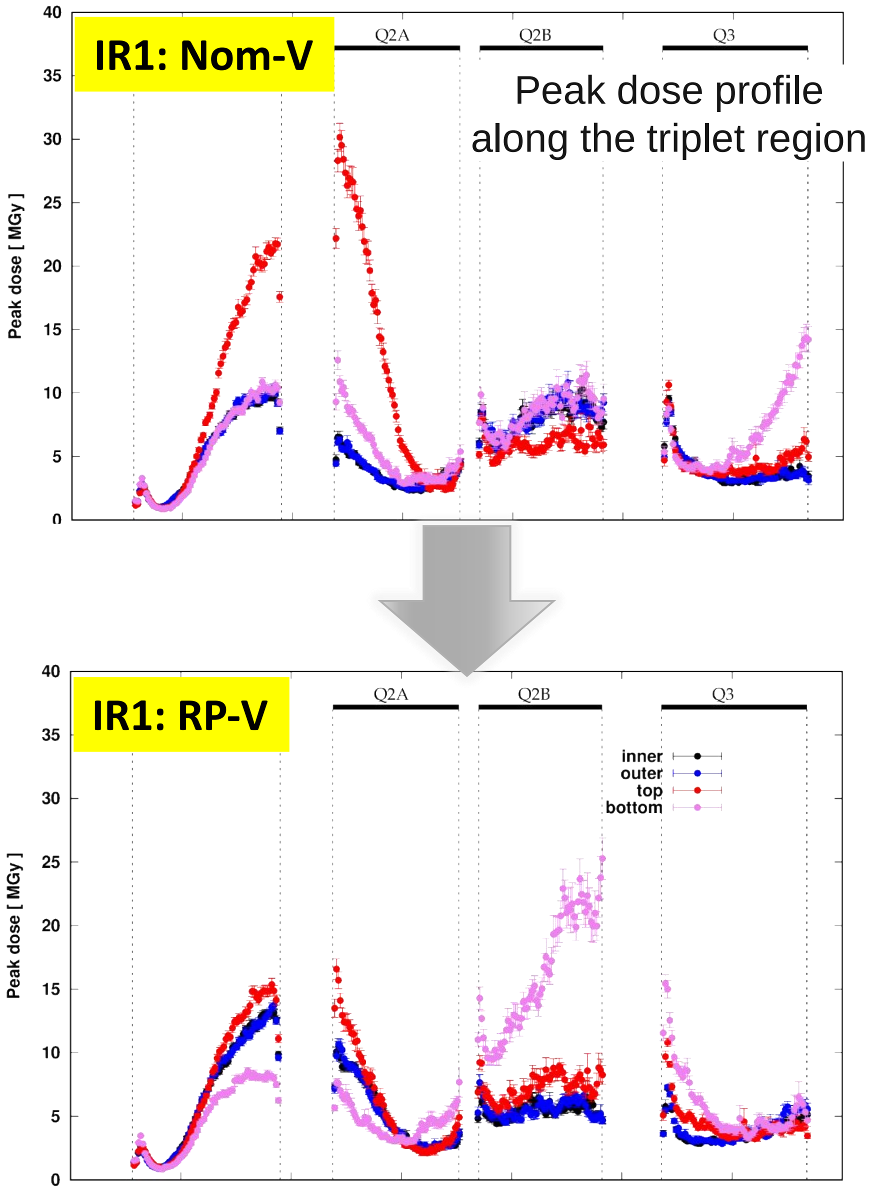
The **dose can be spread** over different azimuths by:

- Changing crossing angles (sign, plane),
- Inverting the triplet quadrupole polarities (RP optics).

In **2024** we operated with **RP optics in IP1** leading to **significant background increase for Forward Physics**.

For **2025**, pursuing the mitigation strategy, we have opted for **RP optics in IR5** and **nominal optics in IR1** and **flipped crossing planes**.

- **Flat optics** ($\beta^*_x \neq \beta^*_y$) is required to ensure an equivalent performance reach with flipped planes.
- Simulations indicate good conditions for FP.

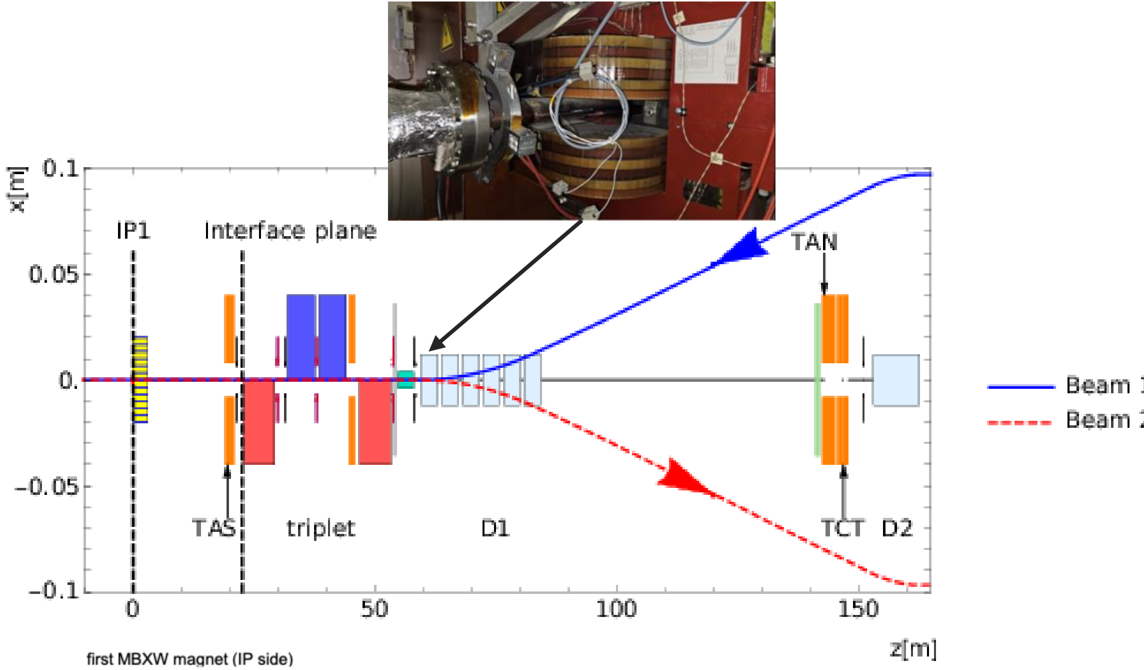


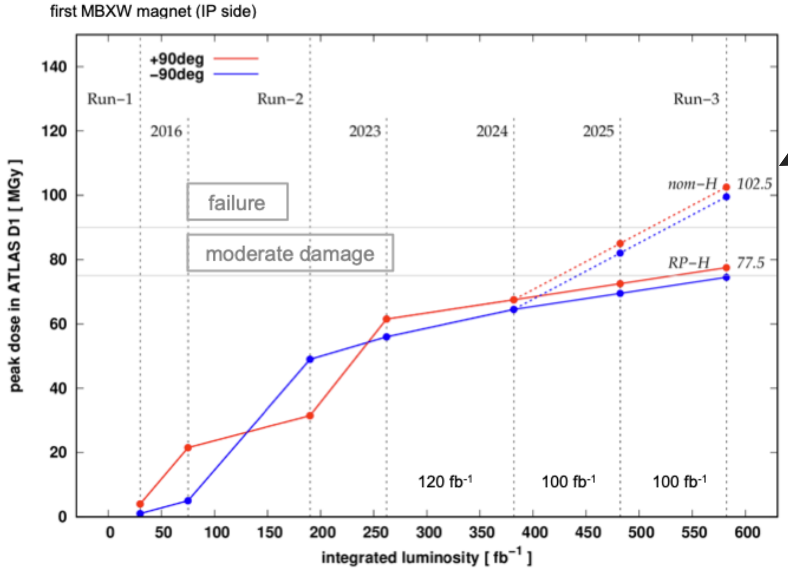
IT radiation levels

The **D1 separation dipole strings** (6 normal conducting magnets / IP side) are installed just behind the LHC ITs in IR1 and IR5.

Radiation hot spot in the vertical plane in IR1 is (was) a concern for the 1st magnet.

- Projected to **exceed the damage limit** in 2026 (insulation for high voltage).
- Due to the slow LHC cycle **with low inter-turn and coil to ground voltages**, exceeding the limits is considered a **low risk**.
- Backup plan: operation with 5 oo 6 magnets combined with an orbit bump.





2025 IR1 configuration (nom-H)

Why flat optics ?

The **IT beam screen shape is asymmetric**, arranged for a larger aperture in the “standard” crossing plane.

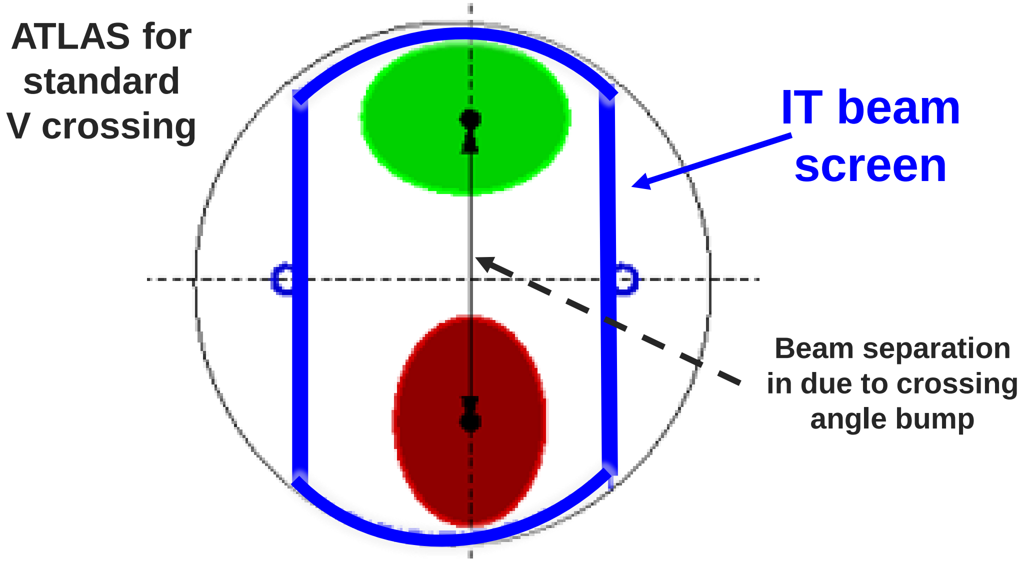
- Accommodates the **beam separation** due to the crossing angle bump to reach the **same β* in both planes**.
- Beam size in IT quadrupoles is $\propto 1/\sqrt{\beta}$

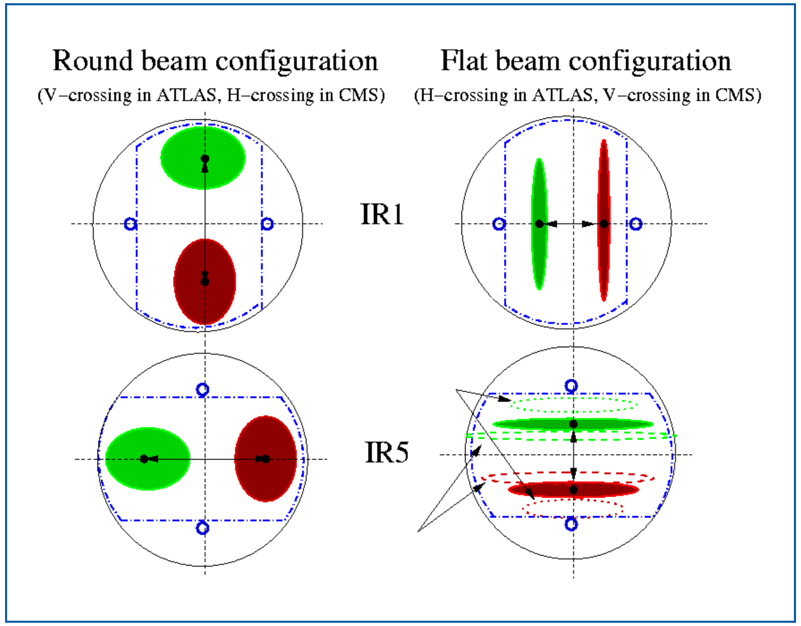
For **rotated crossing planes**:

- **Less aperture** in the rotated crossing plane: **minimum β* increases from 30 cm to 60 cm**.
- **More aperture** in the rotated separation plane: **minimum β* decreases from 30 cm to 18 cm**.

Luminosity is ~equivalent (smaller loss due to crossing angle for flat optics):

$$L \propto 1/\sqrt{\beta_x \beta_y} \qquad \sqrt{60 \times 18} \approx 33$$





2025 machine cycle

Stable beams

2025 cycle

Inject, ramp, squeeze to 120/120 cm → Flip crossing planes – IR1,5,8 → Collide at 120/120 cm → β* levelling to 60/60 cm → β* levelling to 60/18 cm

Round optics

ATLAS: V → H
CMS : H → V
LHCb : H → V

Flat optics

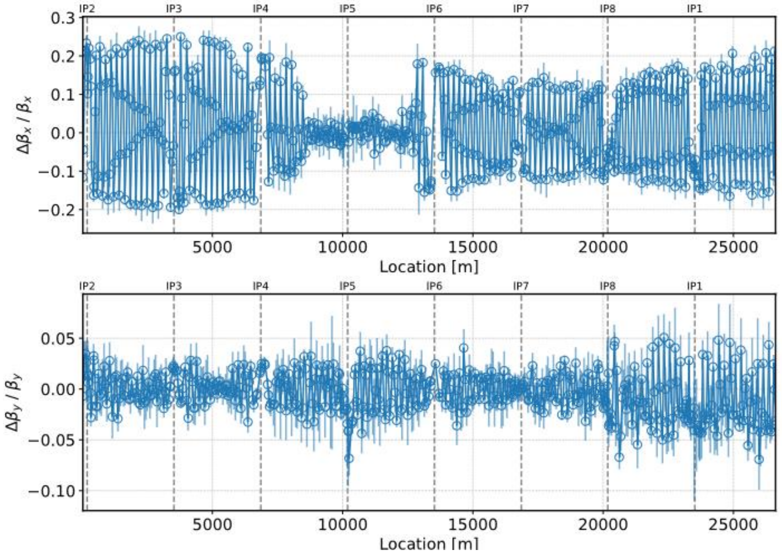
ATLAS: 18 cm in V
CMS : 18 cm in H

Flat optics configurations were already **tested in MDs**.

No issues expected, but **new optics corrections** will have to be established for **all configurations**.

The **apertures** must be checked to confirm choice of crossing angles and of minimum β* in the separation plane.

- Never had bad surprises in Runs 2 & 3.



B1 beta-beating @ 60cm x 18cm, uncorrected (B2 ~10-12% peak beat-beating) - 2024 MD

Outline

2024 run highlights

2025 configuration

Beam intensity

2025 schedule

Oxygen run preparation

Towards higher / HL-LHC beam intensities

The end of Run 3 offers a **last window** to **probe HL-LHC level beam intensities in the LHC**.

- **Critical investment into the success of HL-LHC** which is not just new triplets and crab cavities !
  - Most of HL-LHC is… LHC. No changes in the arcs.
- Our experience has shown that **increasing intensity** can reveal **unexpected limitations**.
  - Synchrotron radiation monitor mirrors, (old) TDI injection dumps, vacuum modules, roman pots.

1st ingredient: **demonstrate regular operation at 1.8×10^{11} ppb**.

- Intensity reach and smooth operation, LHC and injectors → to be done in 2025.

2nd ingredient: explore the **intensity range up to 2.3×10^{11} ppb** with ≥ **2000 bunches** in the machine.

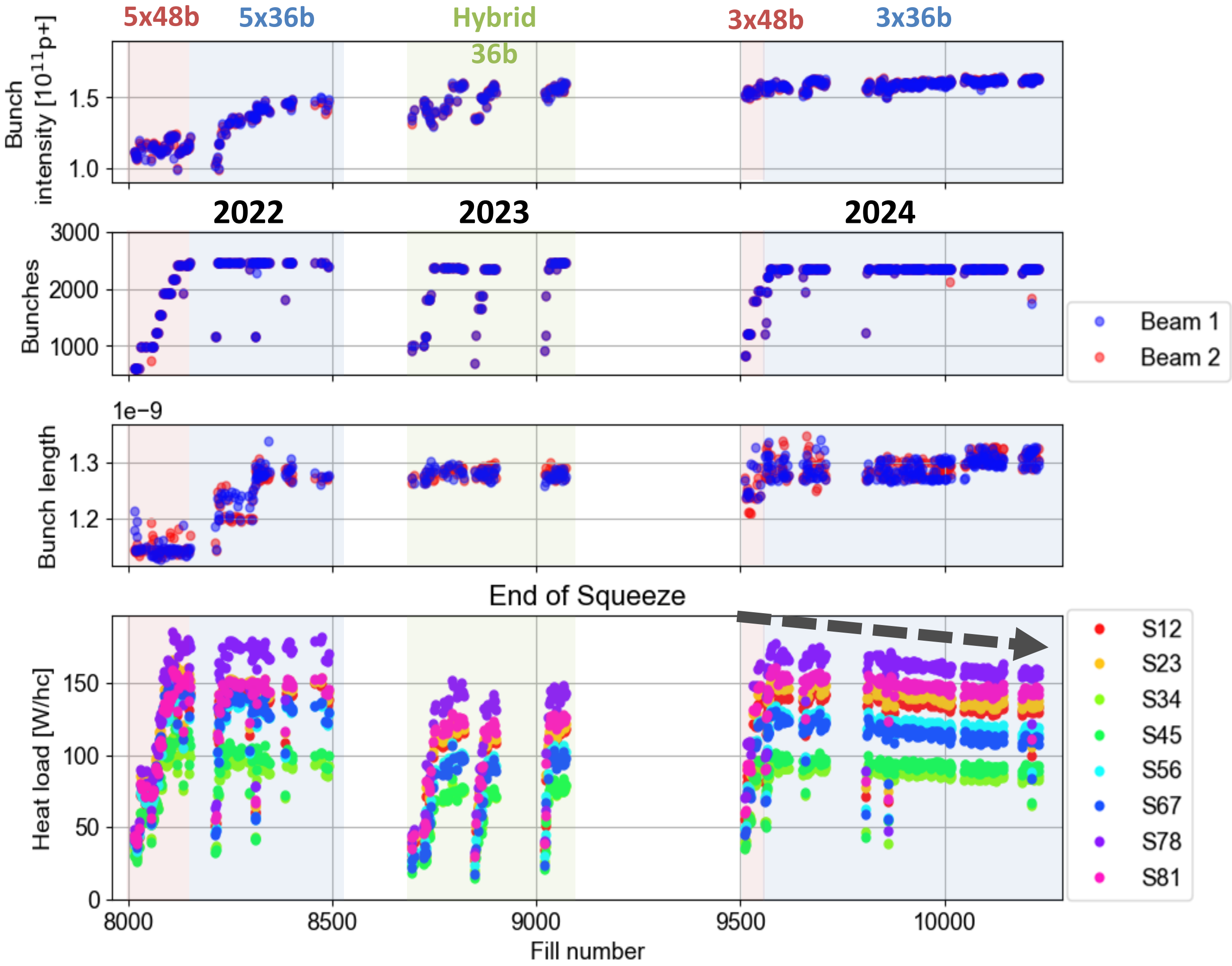
- Beam dynamics issues at 2.3×10^{11} ppb can be tested with partially filled LHC – no issue.
- Define test windows balancing the potential risks to components. Tests can be performed below 2 TeV (limitations on dump protection elements).

Intensity limitations : heat load

L. Mether, JAP '24 Montreux

Operational limitations due to **heat load**:

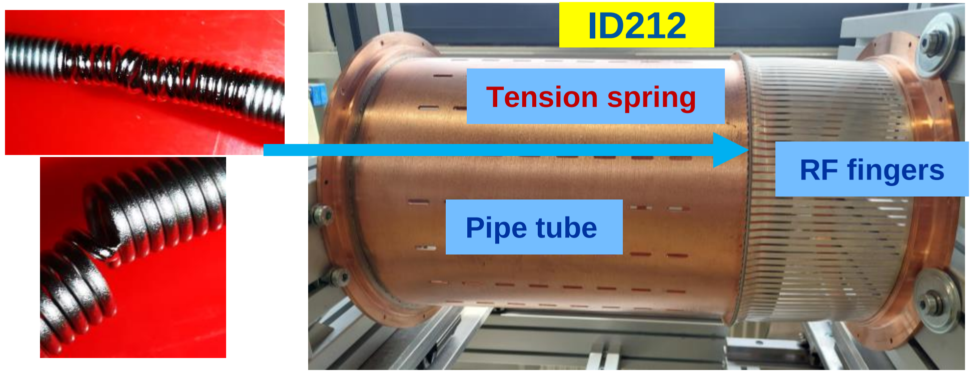
- **IT heat load – luminosity debris:**
  - Peak **luminosity ≤ ~2.1×10^{34} cm^{-2} s^{-1}**
- **Arc heat load – e-cloud**:
  - **Limitation** on train length, total number of bunches and bunch intensity.
  - **Limited** by **~170 W/half-cell in sector 78** (+10 W for operational margin)
  - Gained **~10% margin** due to conditioning during 2024 operation → to be used in 2025.



Intensity limitations : vacuum modules

Vacuum module failure in cell 4L1 (June 2023):

- **~5 days lost**
- **Bunch intensity limited** to 1.6×10^{11} p/b in 2023/2024.



2023 JAP talk, C.Antuono & P.Krkotic

Problem traced to **localized heating of the tension spring** of diameter 212 (**ID212**) modules for:

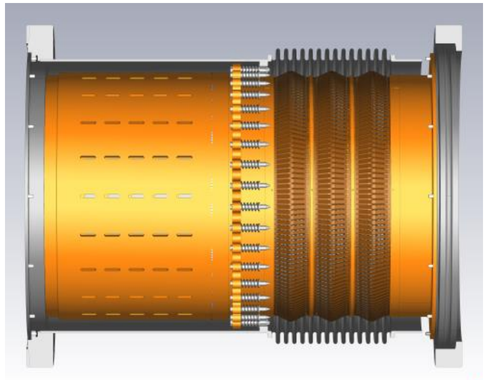
- **non ideal contact fingers/tube**
- **two beams**
- **beam offsets**

} **aggravating factors**

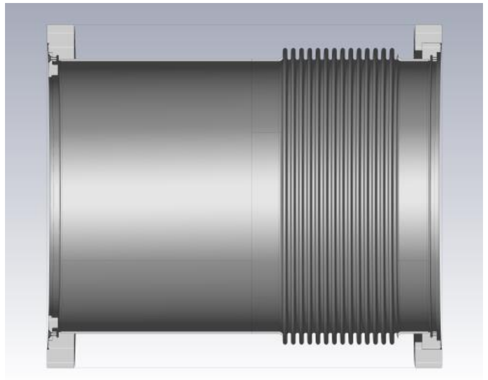
Consolidation campaign by TE-VSC, completed during the present YETS 24-25.

- 4 modules left in **single beam configuration (no offset)**.

Deformable RF fingers (DRF)



Optimized unshielded bellows

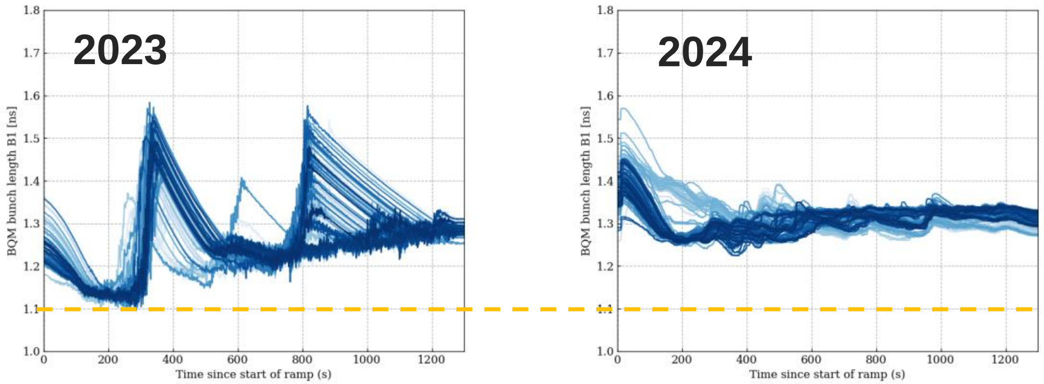


Intensity limitations : vacuum modules

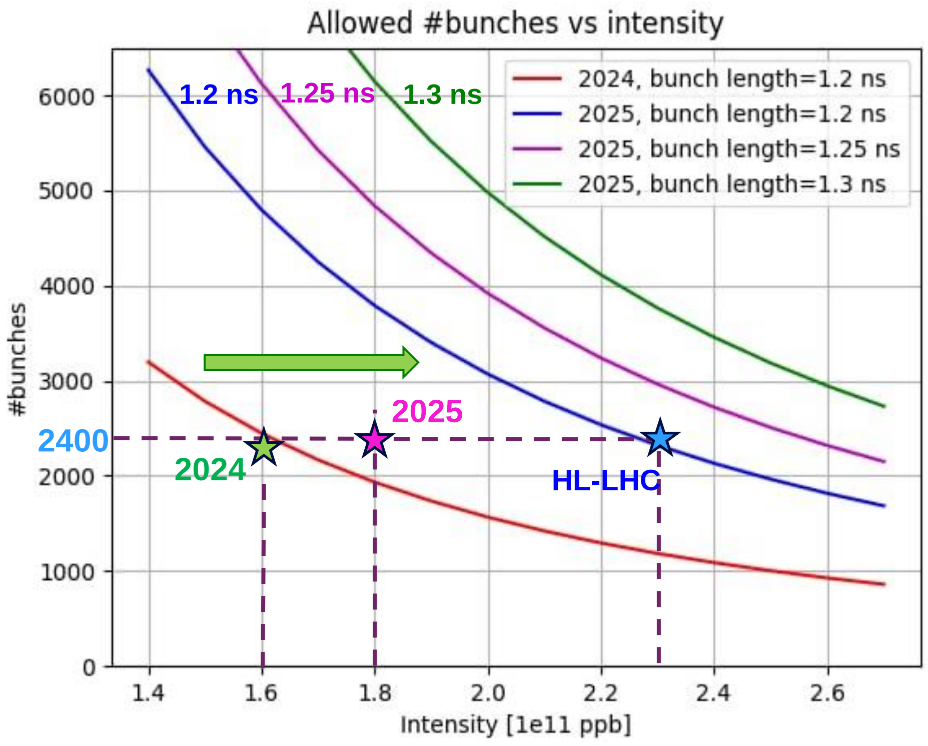
For 2025 there is **no intensity limitation** due to ID212 modules provided the **bunch length ≥ 1.2 ns**.

- For 2400 bunches: limit ≈ **2.3×10^{11} ppb**.
- **The limit increases by ~10%** per **50 ps** step in bunch length.
- > 40% gain from 2023 (1.1 ns minimum) to 2025 (~ 1.3ns).

Improved control of bunch length provides **safety factor** in power deposition



We must remain BELOW the curves !

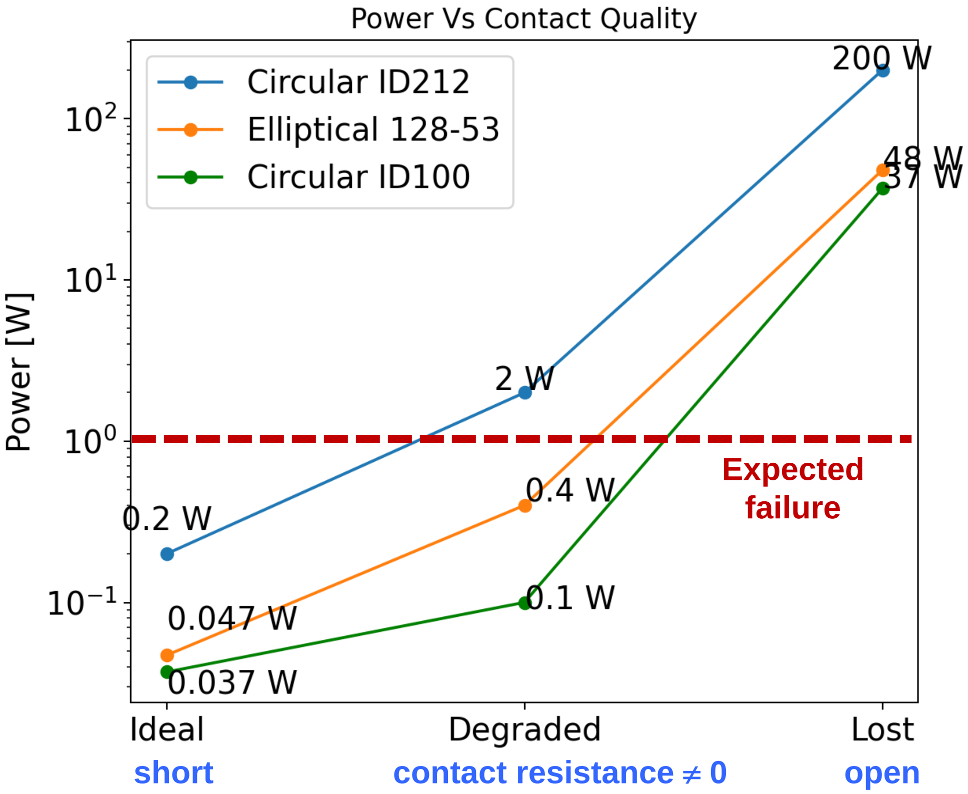


C. Antuono, M. Neroni, JAP '24 Montreux

Intensity limitations : other factors

Other **vacuum modules**:

- **Circular modules** with **smaller diameter** are less critical.
- **Elliptic modules** (IR1/5) are the most critical modules, but less critical than ID212. **Failures cannot be excluded for modules with degraded contact quality.**
  - Those modules will be **removed during LS3**.



Vacuum activity in a sector of point 4 and at the TCLD collimators (BFPP beam for ions) around point 2.

- Intermittent activity during operation and MD.
- Activity not directly correlated to intensity.

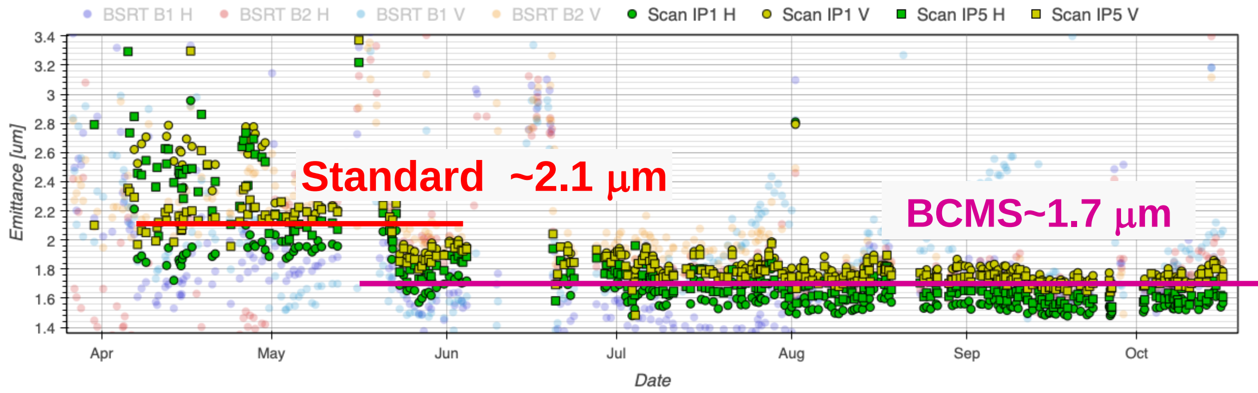
Such activity could **limit the intensity** due to associated **beam losses or high vacuum levels**.

Beams and filling schemes

With **n×36b** filling patterns, **standard 25ns** and Batch Compression, (bunch) Merging and (bunch) Splitting (**BCMS**) beams are **interchangeable**

Optimized BCMS beam deployed in May 2024:

- **> 10% brightness improvement.**
- Lower tails beneficial for losses and lifetimes.



36b train BCMS schemes will be the baseline for 2025:

5x36b : max. no of collisions, ≤ **~1.6×10^{11} ppb**.

4x36b : compromise, ≤ **~1.7×10^{11} ppb**.

3x36b : 2024 scheme, up to **1.8×10^{11} ppb**.

	N_b	Collisions IP1/5	Collisions IP2	Collisions IP8	S78 heat load [W/hc] 1.6e11	S78 heat load [W/hc] 1.8e11
5x36b	**2496**	2484	2132	2280	**168**	**181**
4x36b	**2460**	2448	2089	2227	164	**177**
3x36b	**2352**	2340	2004	2133	156	**168**

Outline

2024 run highlights

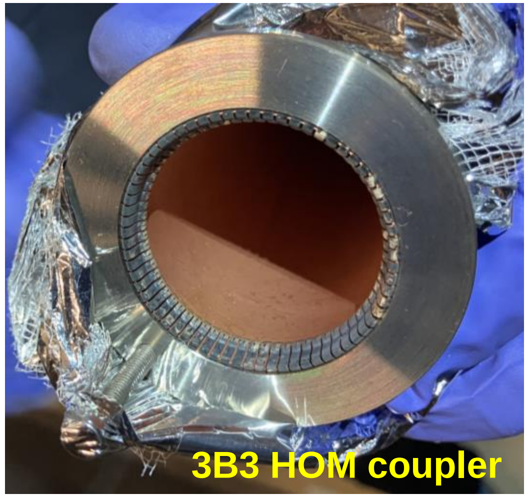
2025 configuration

Beam intensity

2025 schedule

Oxygen run preparation

YETS 2024/25 : RF

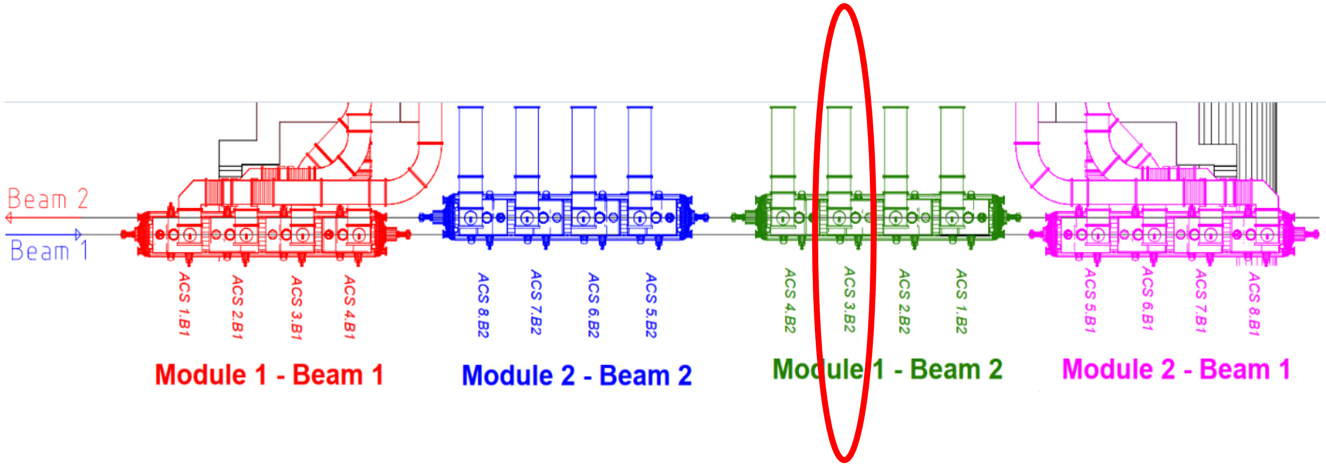


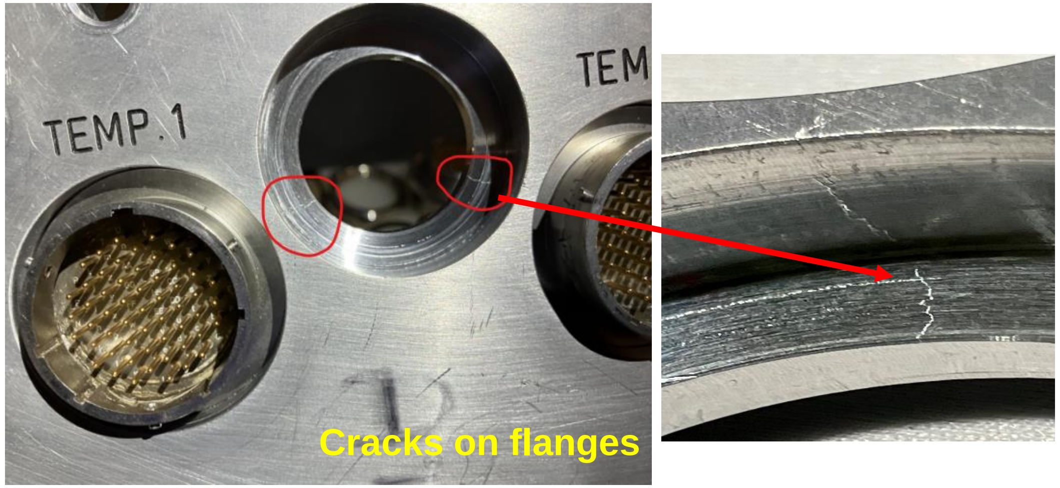
K. Turaj, LMC #501

YETS activities are on track, latest issues (cryo pt 6, EN/EL pt 6, LHCb PZ85 elevator) should be resolved soon.

RF cavities activities and "surprises":

- **Burnt RF fingers** were identified and repaired on HOM coupler of **cavity 3B2**. This may cure recurrent RF HOM power faults and cavity quenches.
- **Cracks** were identified on 50% of some **instrumentation signal flanges.** Crash program to exchange 16 flanges (with better design) completed. No impact on restart with beam.





Schedule 2025

Beam back in PSB last week

Powering test preparations begin this week

Machine handed over to BE-OP March 13th

DSO safety tests March 13th and 14th

Experimental caverns closed on April 2nd

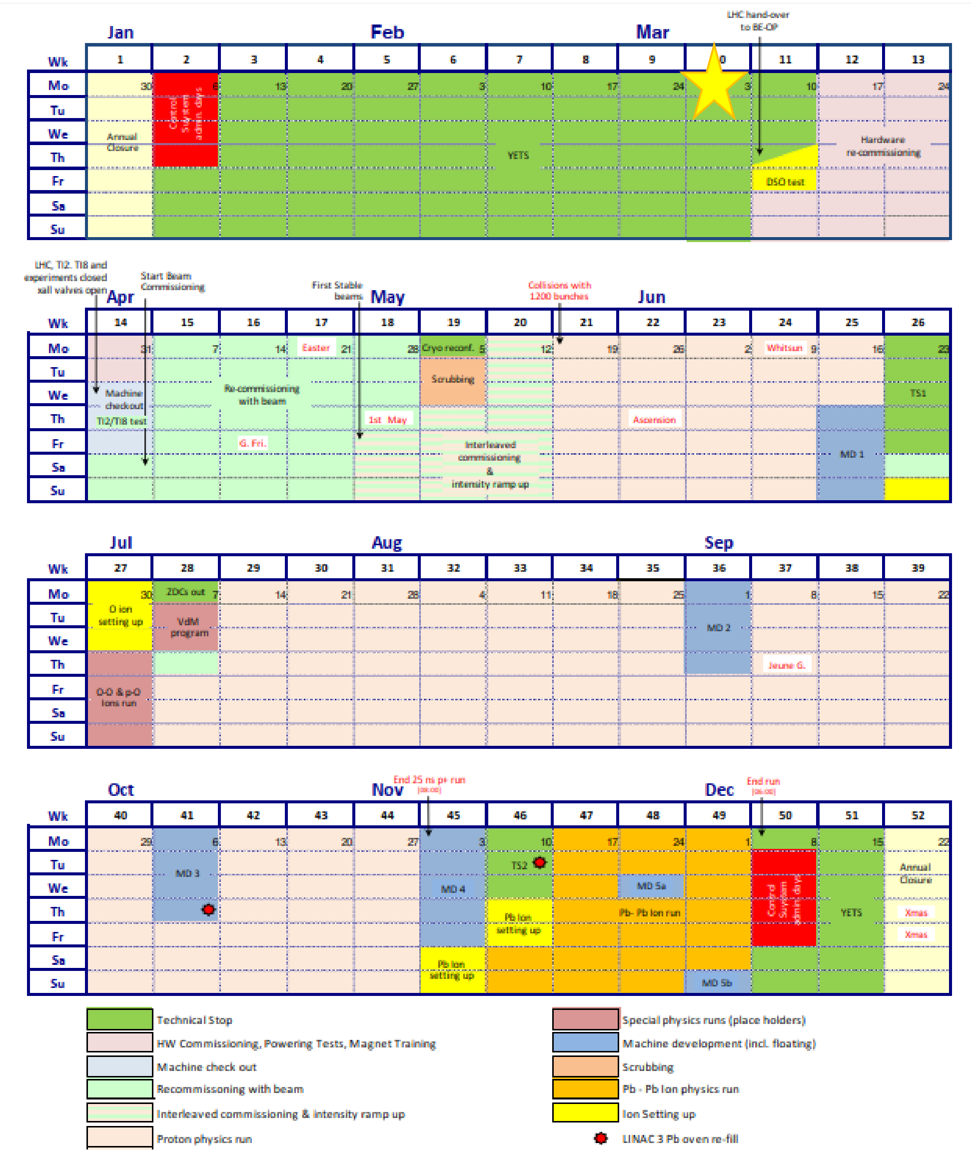
Transfer lines test on April 4th

Beam in LHC on April 4th or 5th

First stable beams at 6.8 TeV in week of May 1st

Intensity ramp up (no bunches) at 1.6×10^{11} p/b, full machine around mid-May.

Oxygen run during 1st week of July

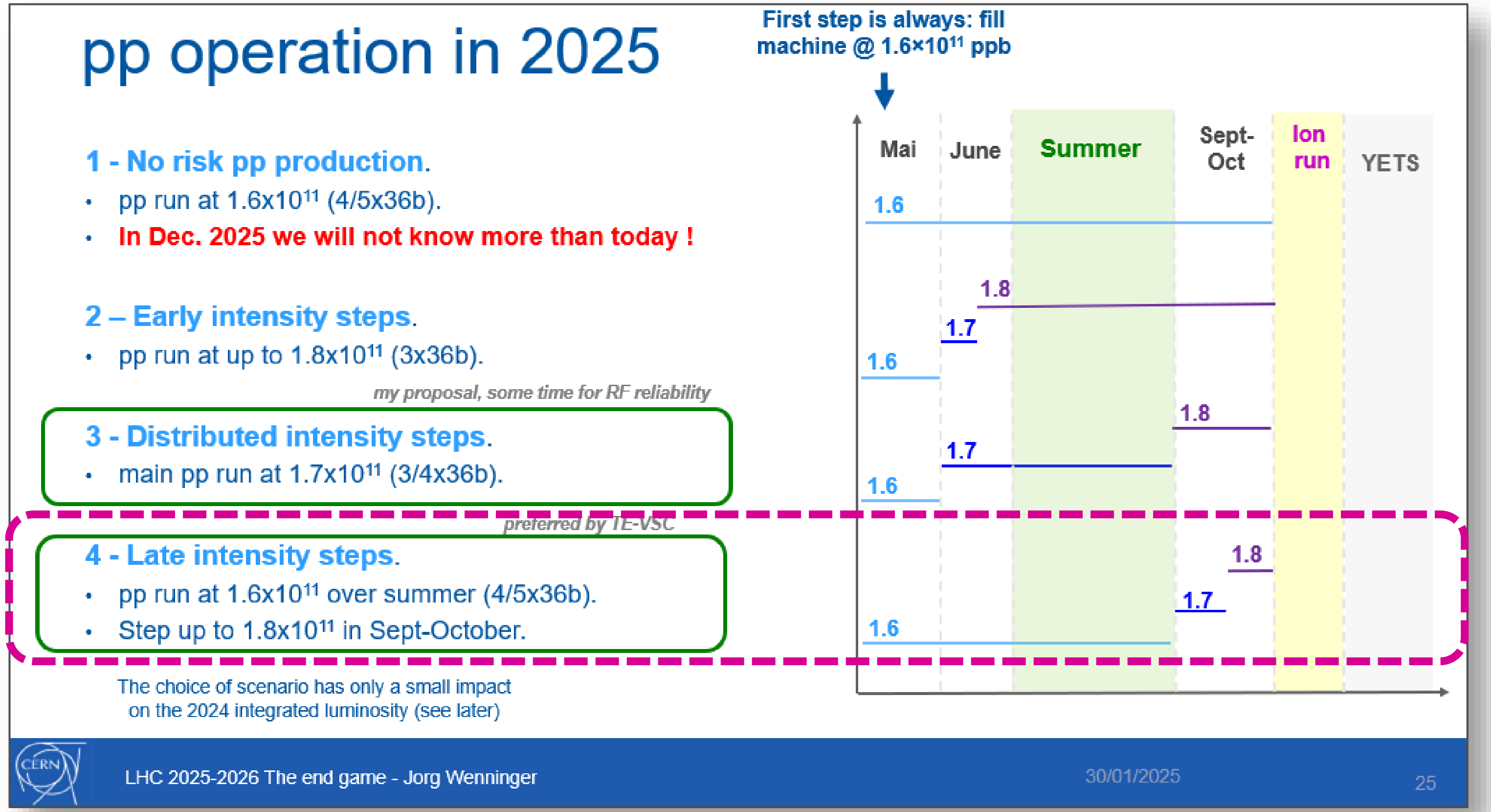


Intensity ramp up in pp physics

Chamonix 2025

Intensity ramp up scenarios were proposed @ Chamonix 2025.

Scenario # 4 was selected at the LMC (LMC # 501).

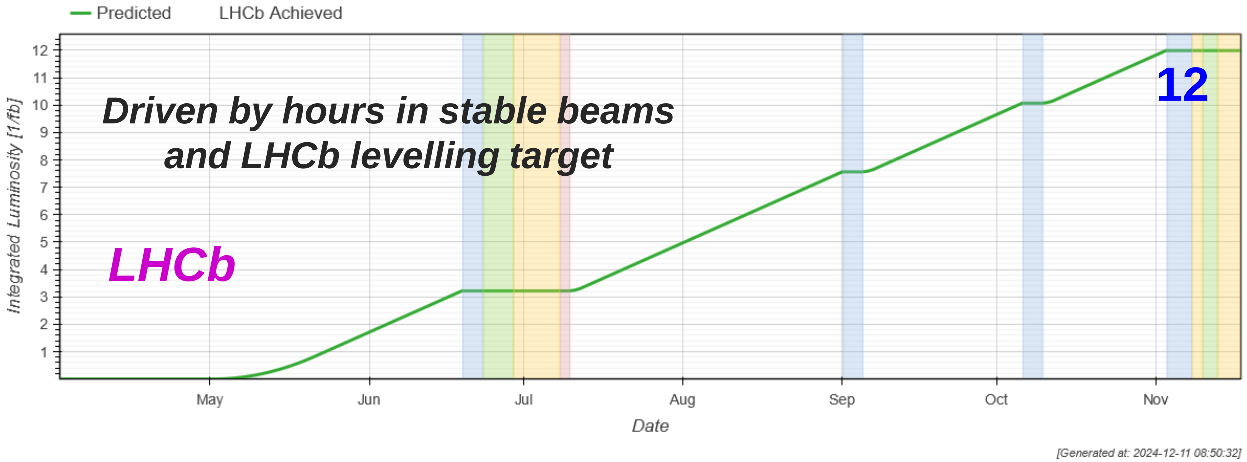


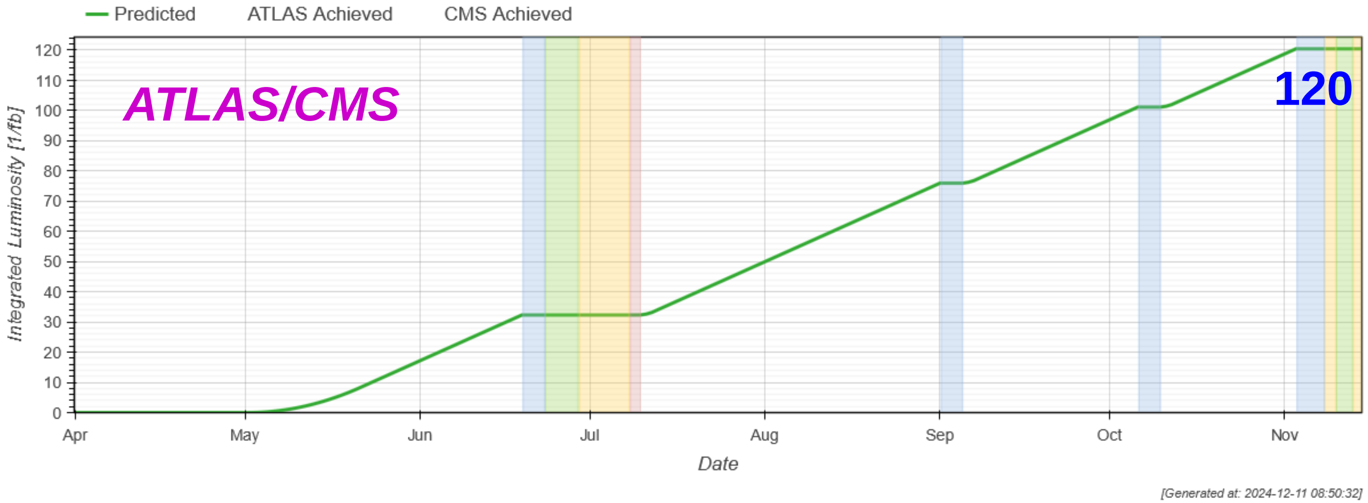
Performance estimates

For scenario #4 filling schemes based on **4x36** are the preferred choice.

Expected performances:

- **ATLAS/CMS: ~120 fb^{-1}**
- **LHCb: ~12 fb^{-1}**
- **ALICE: ~50 pb^{-1}**





HL-LHC intensity in 2026

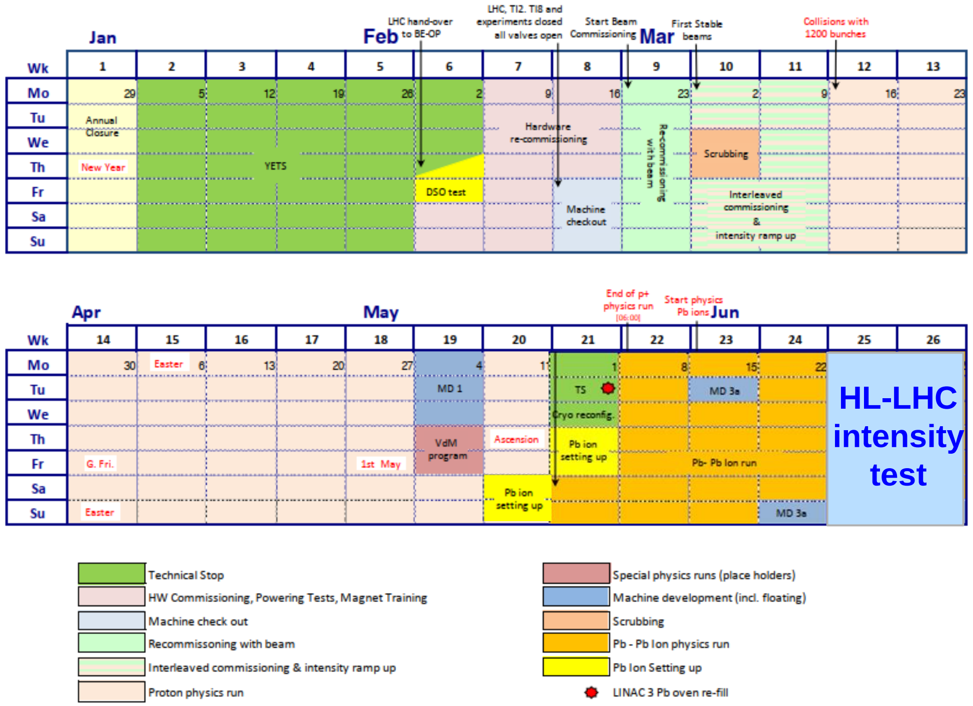
A **HL-LHC high intensity test** was proposed at Chamonix at the end of Run 3

- **Advance the ion run by 2 weeks**.
- Step up to **full machine at 2.3×10^{11} ppb**.
- **No risk to the physics program in case of failures**, but we "sacrifice" some physics operation to invest into the future.
- Collisions are not needed but would be possible. Collisions may however impact access date to caverns/detectors.

Two weeks should not be considered very long: this is pretty much a minimum for the intensity step that we consider here.

- Proposal to combine this with a low pileup run.

Discussions are just starting.



Outline

2024 run highlights

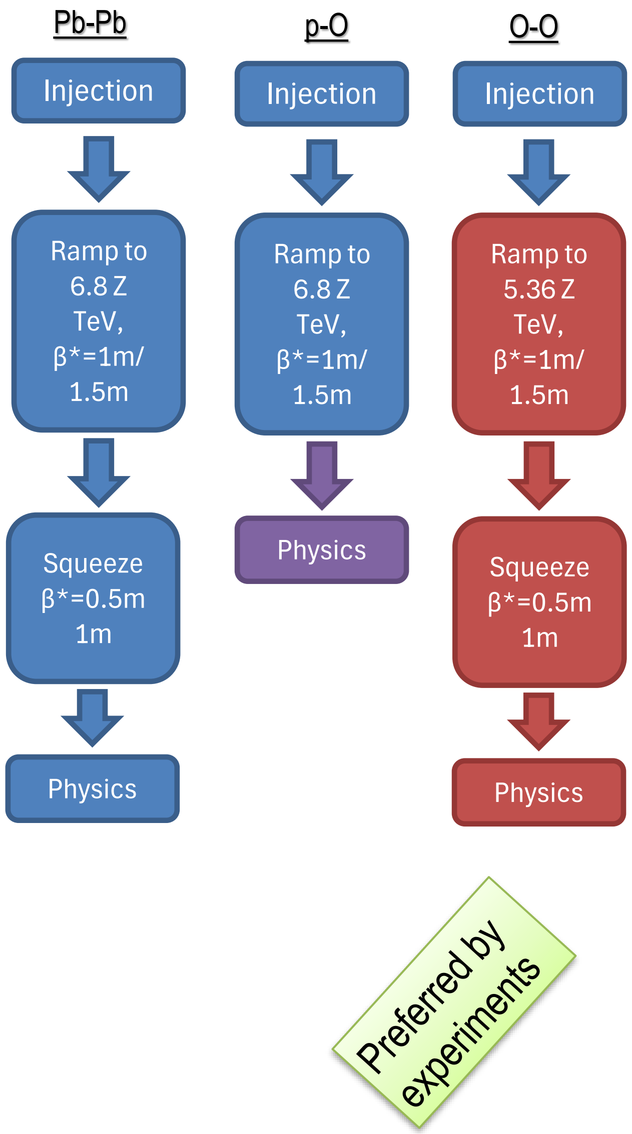
2025 configuration

Beam intensity

2025 schedule

Oxygen run preparation

Oxygen run

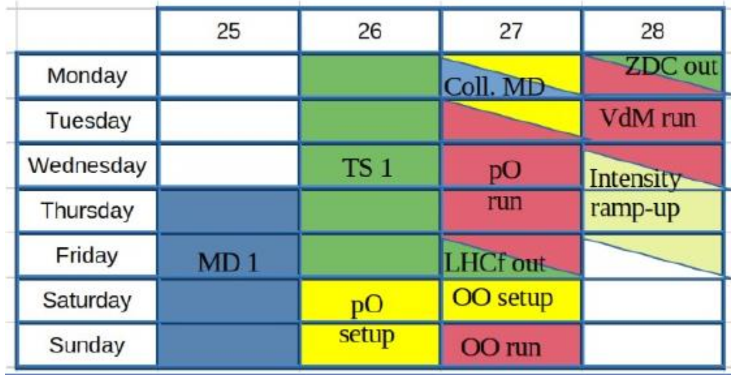


8 days allocated for Oxygen run for setup and physics run.

Initial machine-side plan relied on a **single machine configuration** for PbPb, OO and pO to minimize setup overhead.

- **The requests from the experiments** are however **incompatible** with this simple plan (LHCf $\beta^* \geq 1$m, OO at 5.36 TeV).
- We will need **3 distinct configurations** for PbPb, OO and pO, trying to optimize the overlap.

Plan by LPC



Luminosity targets in nb^{-1}

	p-O	O-O
ATLAS	1.5	≥ 0.5
ALICE	(5)	0.5
CMS	3	0.8
LHCb	2	0.5

Oxygen run (2)

R. Bruce, N. Triantafyllou, LBOC #176

First estimates for the expected integrated luminosity indicate that **some targets are difficult to reach**. Time estimates range between **7d** (perfect availability) and **9d**.

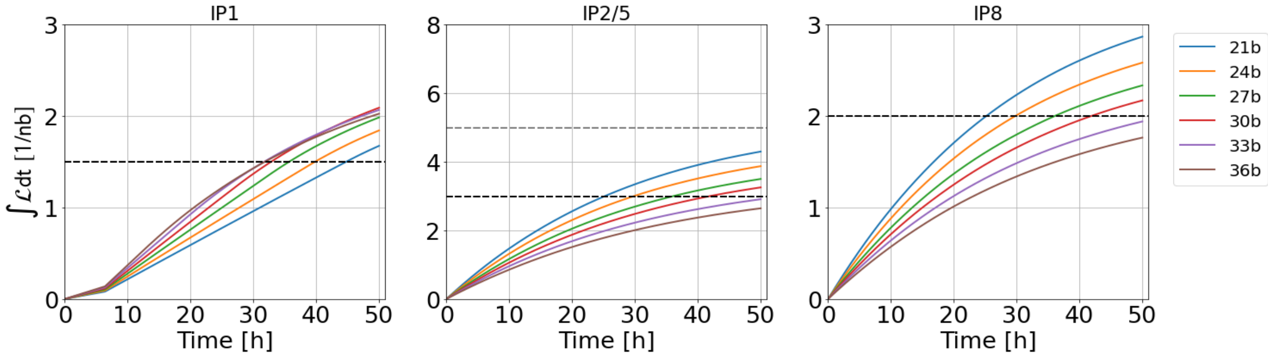
- Total time = 3.5 days of setup, 3.5 days of run, plus in-efficiency.

We consider **increasing the beam intensities** (~50%) at the price of a slightly increased setup time. Discussions ongoing.

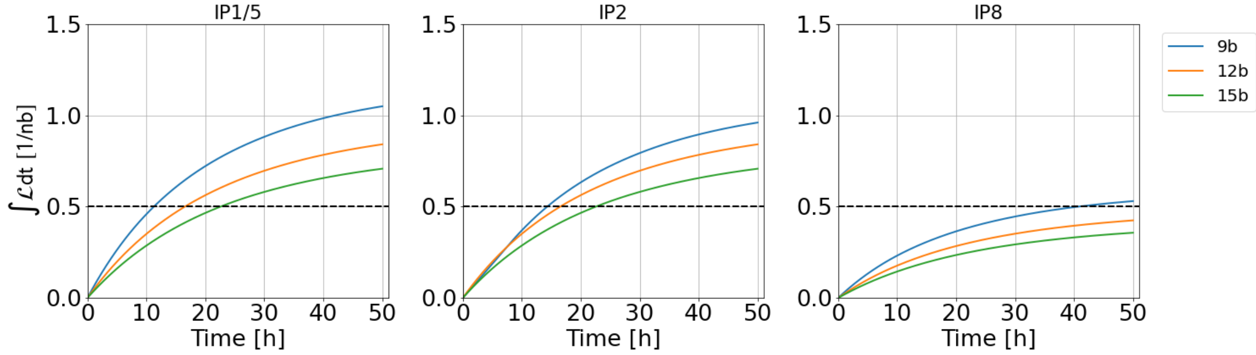
NeNe run does not fit into the time frame.

- No overhead wrt OO on machine side.
- Machine just needs to know: GO or NO-GO !

pO 6.8 Z TeV, $\beta^*_{IP1/2/5}$ = 1m, β^*_{IP8} = 1 .5m



OO 5.36 Z TeV, $\beta^*_{IP1/2/5}$ = 0.5 m, β^*_{IP8} = 1 m



Summary

- The 2025 pp configuration will be adapted to **limit radiation** to the triplet magnets and to **improve conditions for forward physics** in IR1.
  - Triplet polarity in IR1 back to “normal”, in IR5 to “reverse”.
- For pp operation the expected performance is **~120 fb-1 for ATLAS/CMS** and **~12 fb-1 for LHCb**.
- After summer, the intensity per bunch will be pushed to **1.8×10^{11} ppb**.
- The **oxygen run boundary conditions are complex**: iterations are needed to converge to a performance and configuration that fits into the time frame.

Spare slides

Intensity limitations - scaling

With a partial ID212 consolidation, the **bunch Intensity was limited to 1.6×10^{11} ppb** in **2024**.

For N_b bunches of intensity I_b, the **heating power P** scales with:

$$P \sim N_b I_b^2 f(\text{bunch length } \sigma_l) \quad \text{with } df/d\sigma_l < 0$$

Scaling with N_b depends on bema type

Importance of bunch length control

Power increase with respect to 2024 for **2025 candidate filling schemes**.

- Range : 5 – 25%

	N_b	Relative beam power 1.6e11	1.7e11	1.8e11	2.3e11
5x36b	**2496**	1.06	x	x	
4x36b	**2460**	1.05	1.18	x	
3x36b	**2352**	1	1.13	1.26	2.05

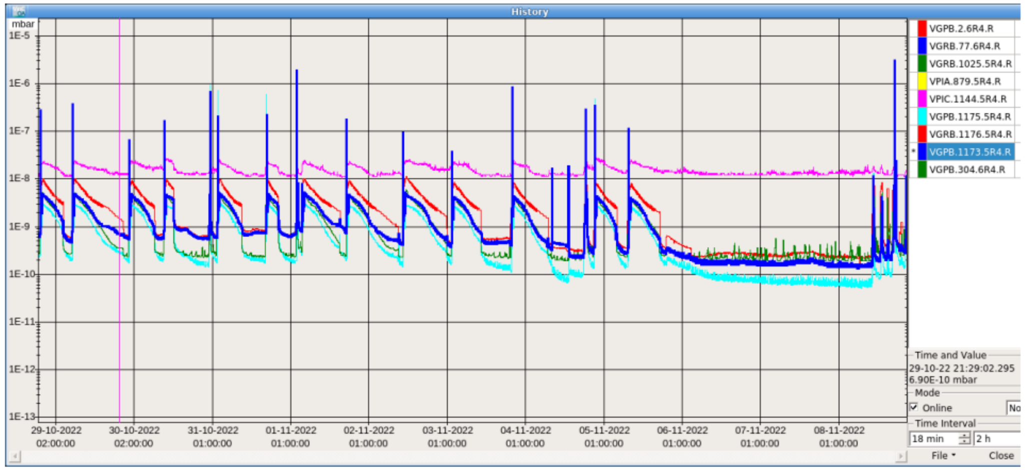
KEY numbers: **5%** **15%** **25%** **100%**

Vacuum spikes – point 4 and TCLDs

Pressure spikes close to interlock thresholds recorded during MDs in **vacuum sector ER4** with trains of 2.3×10^{11} ppb.

Possible cause: a non-conformity of a Schottky monitor.

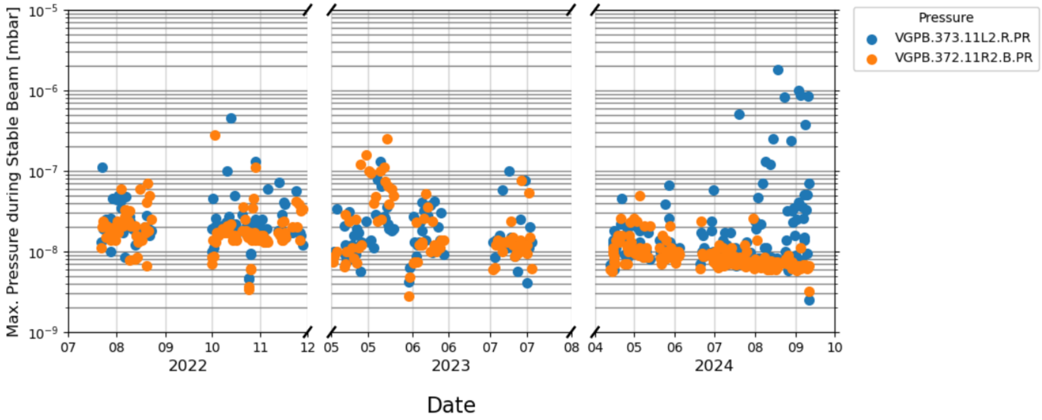
There is **margin to increase the interlock thresholds**.



Pressure spikes were observed on the **TCLDs** during pp and Pb operation, more pronounced on B2 in 2024.

No correlation with jaw movements (TCLDs not moved during the pp cycle with beam) or with jaw temperatures.

No clear correlation with bunch / beam intensity.



C. Antuono, M. Neroni, JAP '24 Montreux

N. Triantafyllou, Coll. WG #285

A limitation of the beam intensity cannot be excluded !

- Vacuum and/or beam loss.

Intensity step validation

How long should we operate until a step is validated for heating aspects?

- No simple answer.
- Some cases are ~ immediate, the **ID212 failure in 2023** occurred after **~7 cycles** at similar intensities.

Approximately **1 week of operation** could be considered sufficient to validate an intensity step for **heating**.

- One can consider to step back after such a period in case of availability issues on some equipment (injection kicker heating…).
- **RF group request to operate N×month at 1.8×10^{11}** *see also H. Timko, 2nd session*

During **2025 MDs**, the heating power should **not exceed the level validated in regular operation**.

May 2023

ID212 failure