Behavior of the LHC vacuum systems in 2022

G.Bregliozzi on Behalf of BVO Section
17/01/2023 TE-VSC Seminar

Outline

- Coming out from LS2 activities
- RUN3 Overview
- LHC Commissioning
- Luminosity production
- 2022 Main limitations
- Beam Vacuum Performance
- Future planning

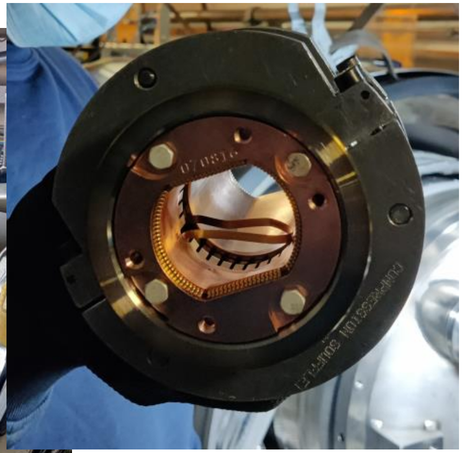
Coming out from the LS2 activities

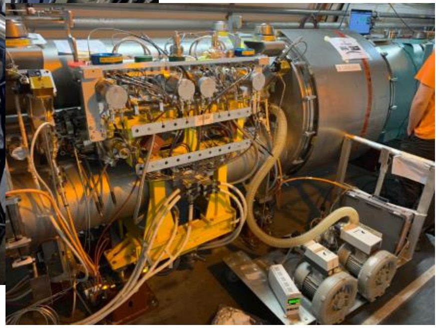
Coming out from the LS2 activities: YETS21/22

Installation of new C/C + Ti window and new fixed supports in CTD68 and CTD62

BSRTMB.D5L4 support and tank installation (WP13)

TCPC crystal collimator installation (WP5)





BGC works (WP13)

ATLAS experimental beam vacuum IP1.X

New Small Wheel – side C (nSW-C) installed by end of 2021

- **TE-VSC removed the vacuum layout for the LHC special run (2021) in ≈ 3 days**.
- Installation of the operational layout by January 2022.

Installation of the VT and VJ aluminum chambers

ATLAS experimental beam vacuum IP1.X

ATLAS EXPERIMENT

Bake-out & NEG activation of the IP1.X performed by February 2022.

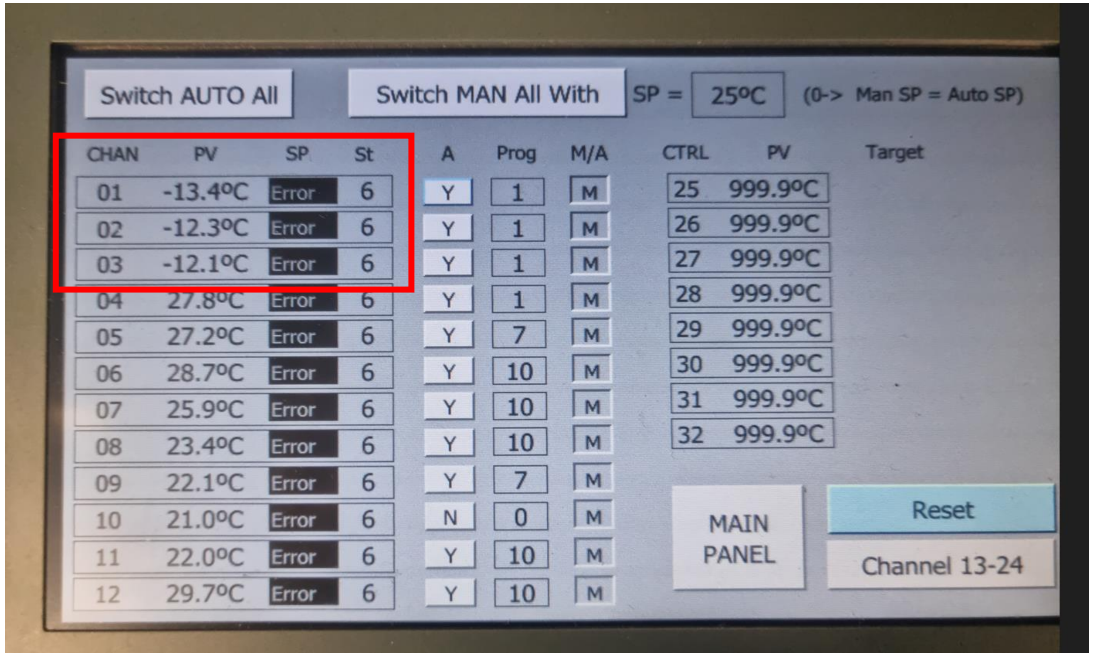
ATLAS tracker stays in place (including pixel detector).

- Complex DSS protection matrix put in place by ATLAS.
- **8 days process** (ATLAS running non-stop shifts).

18m of the IP1.X under active cooling

We are basically baking a fridge without melting the ice-cream inside ☺

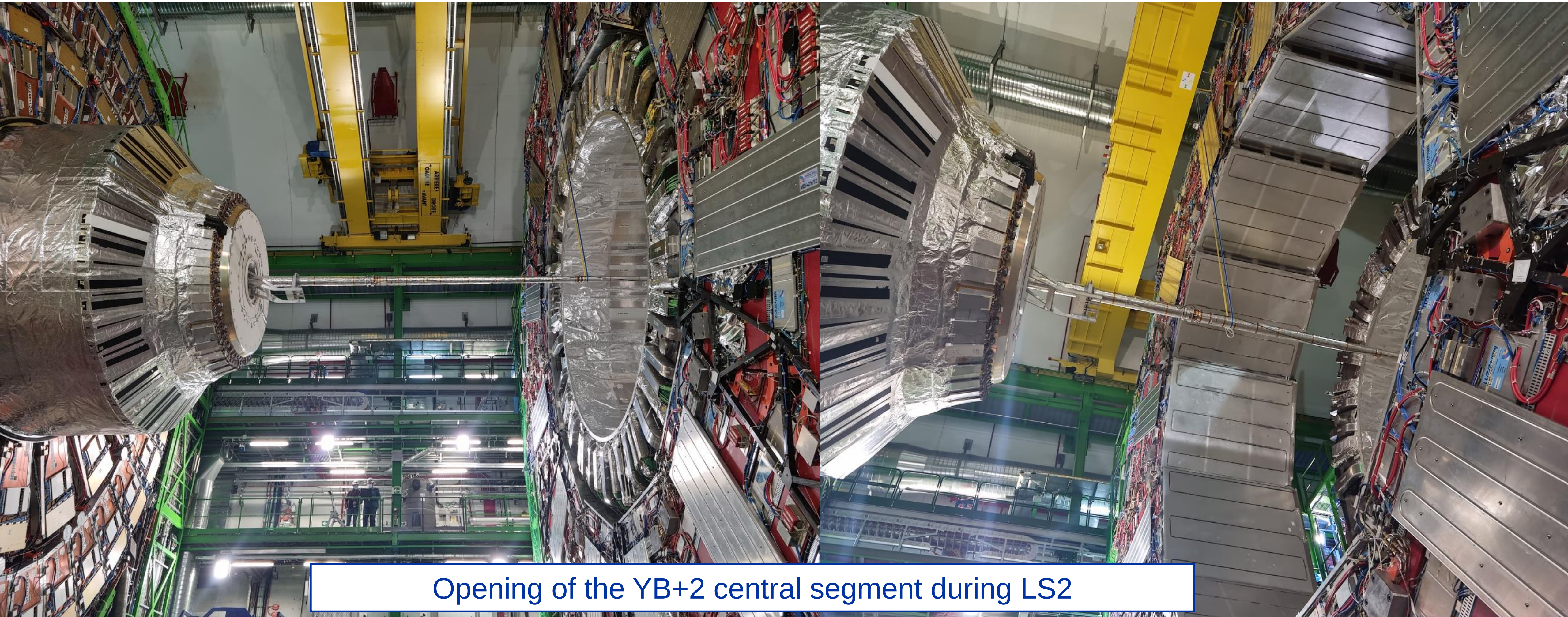
Overheating may cause permanent damage of the tracker.



CMS experimental beam vacuum IP5.X

IP5.X vacuum sector recommissioned (installation, bake-out & NEG activation) by May 2021.

- CMS required special opening to investigate post-SR2021 observations by beginning 2022.

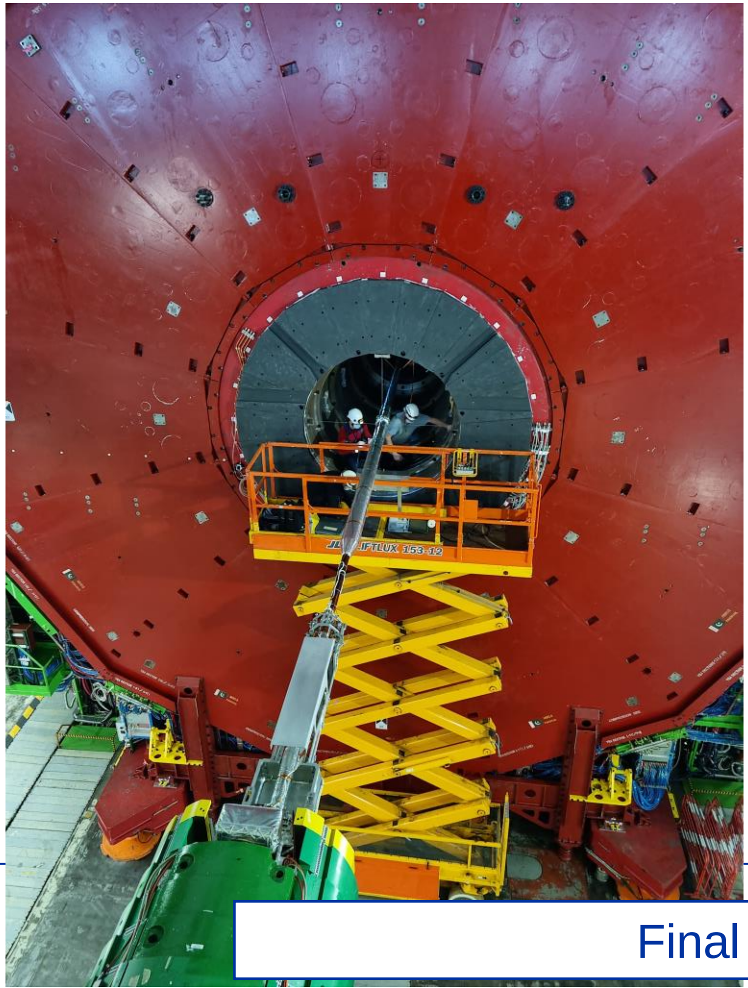


Opening of the YB+2 central segment during LS2

CMS experimental beam vacuum IP5.X

Experiment reclosed for Run 2022 by March 2022.

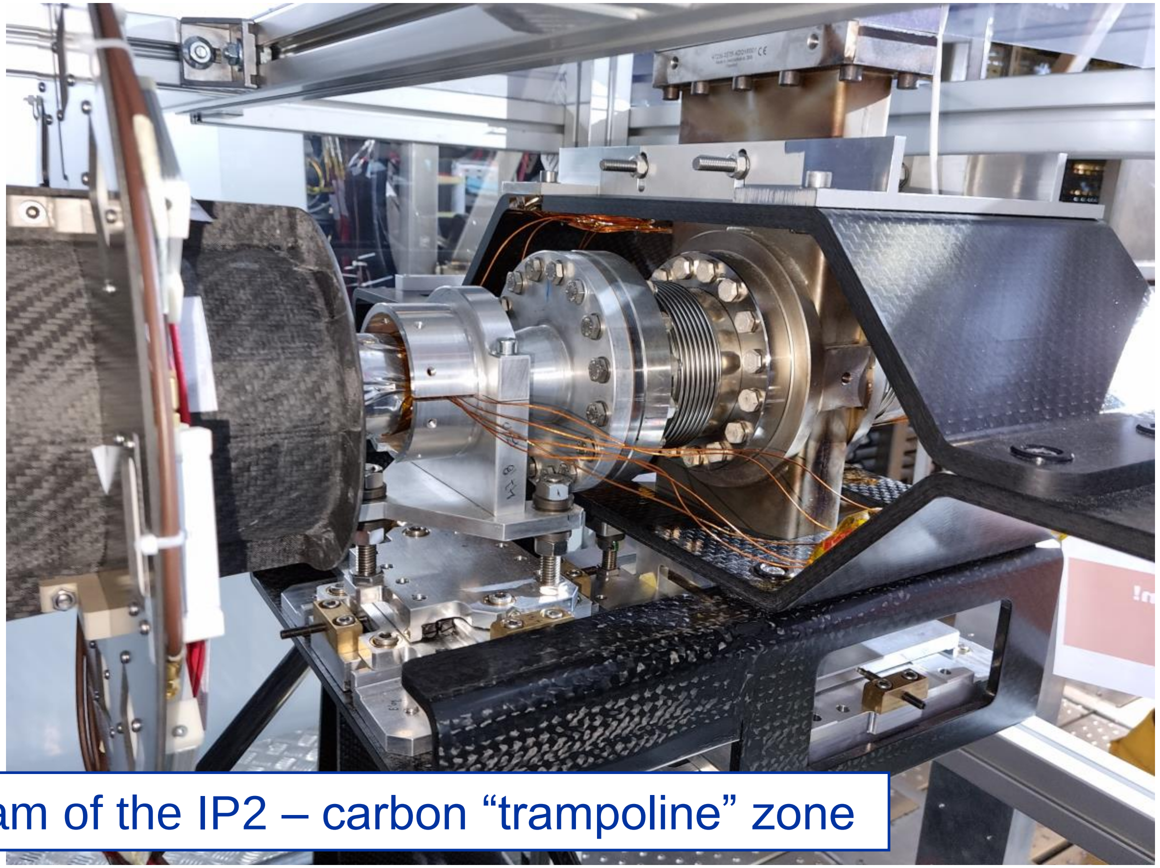
- Standard heavy involvement of TE-VSC team on site.



Final alignments prior the Run 3

ALICE experimental beam vacuum IP2.X

Mechanical support for additional activities with central region (new tracker tested during the special run 2022).



Central chamber upstream of the IP2 – carbon “trampoline” zone

LHCb experimental beam vacuum IP8.X

VELO detector (C – side) installed 02-2022.

VELO detector (A – side) installed 05-2022 (from Ne venting to pump-down <24h).

Installation of the VELO A-side

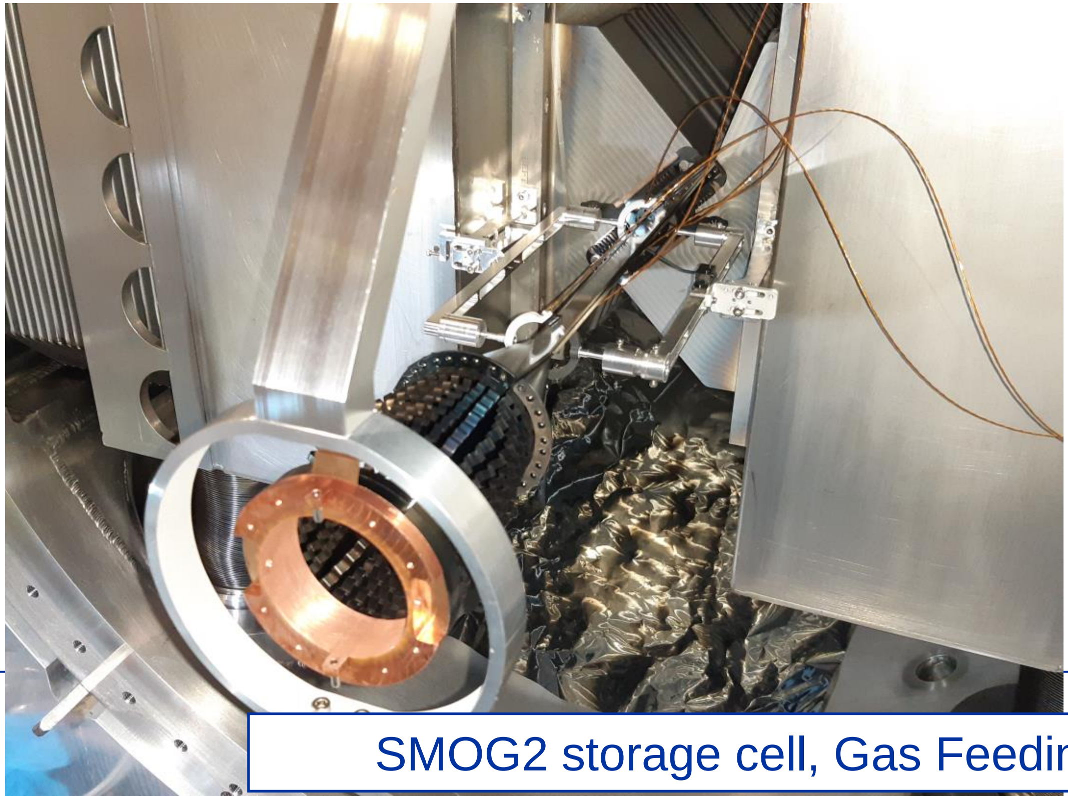
LHCb experimental beam vacuum IP8.X

SMOG & GFS system installed in March 2022.

- *SMOG – System for measuring overlap with gas; GFS – Gas Feeding System (SMOG injection platform)*

System allows injection of 4 different gases (He, Ne, Ar, H_2).

Two injection modes (VELO vessel – SMOG 1, Storage cell – SMOG 2).



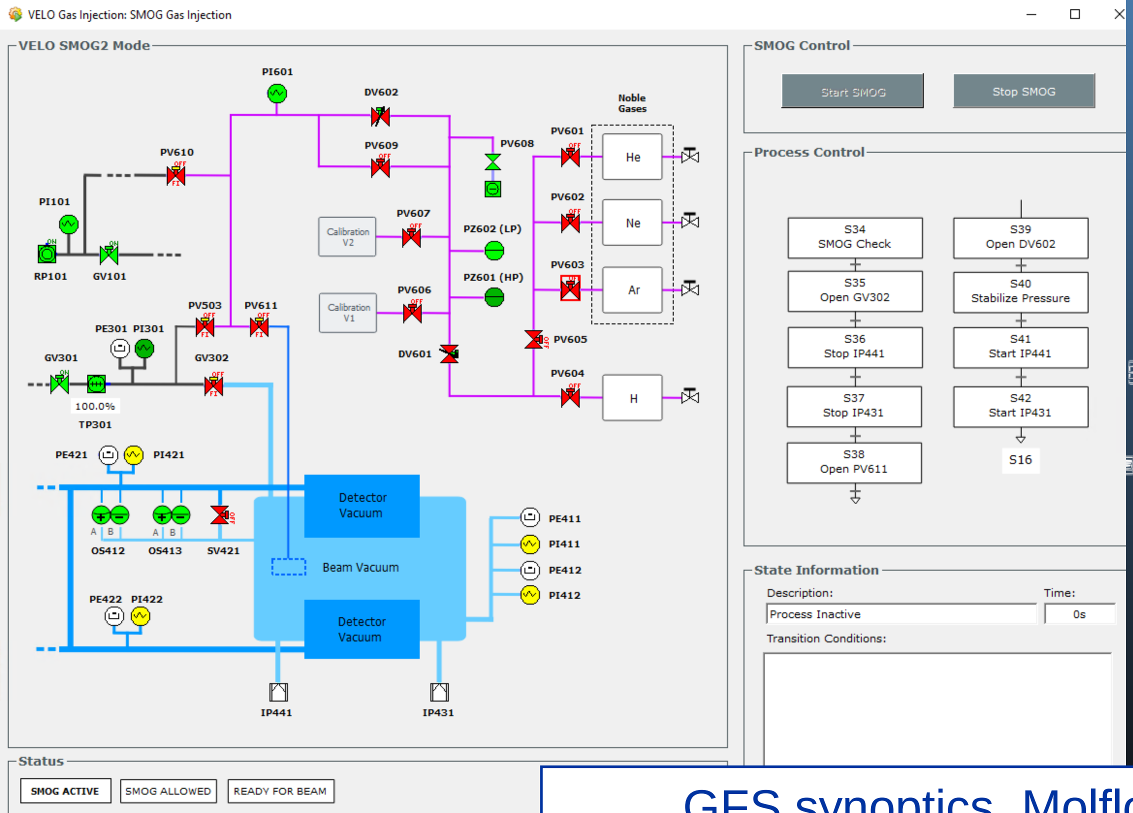
SMOG2 storage cell, Gas Feeding System (UX85 table)

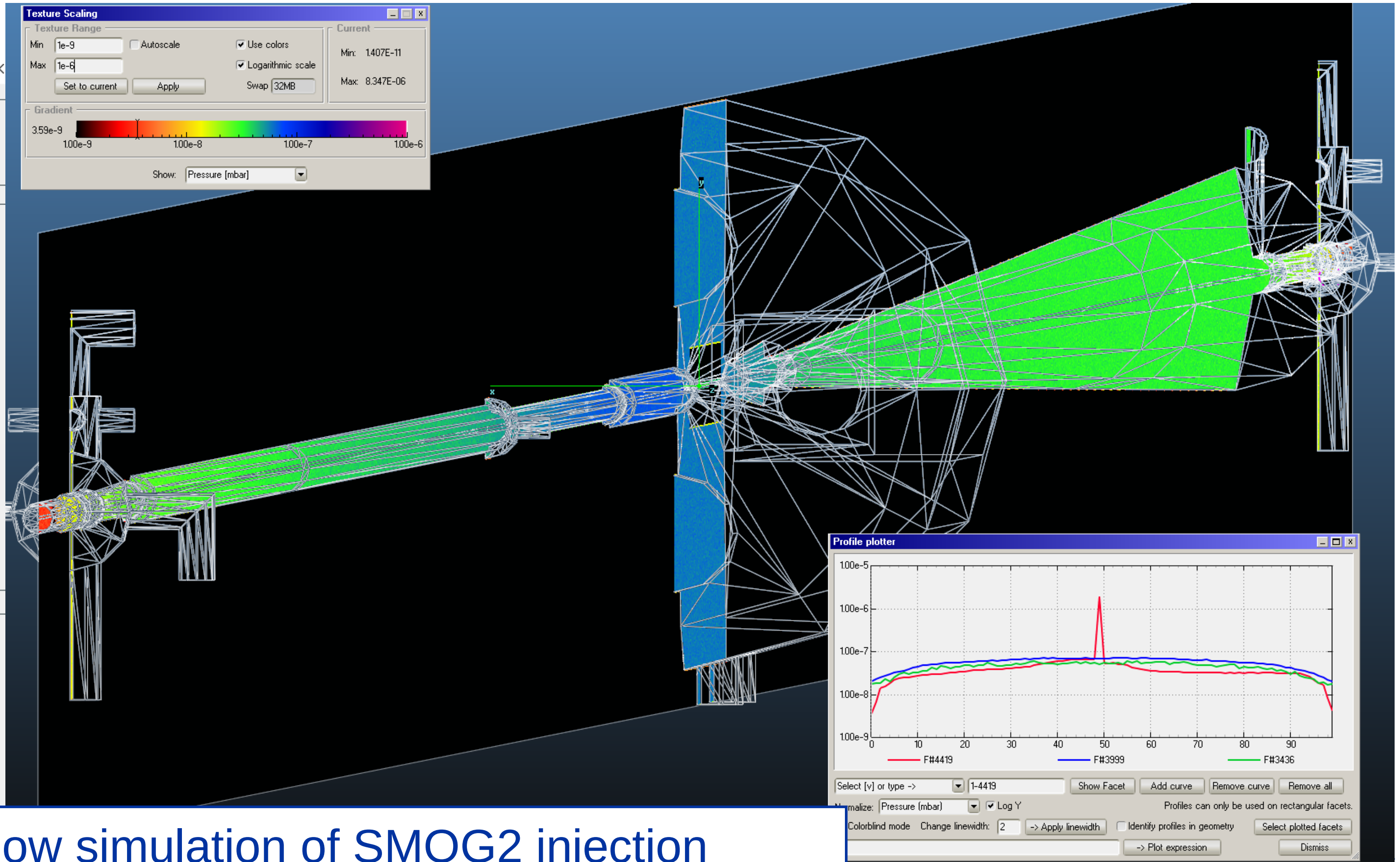
LHCb experimental beam vacuum IP8.X

New control system implemented by ICM.

Intensive testing performed during 2022 (SMOG 1-2, different gases).

- Injection without beam; With beam – VELO open; With beam VELO closed)

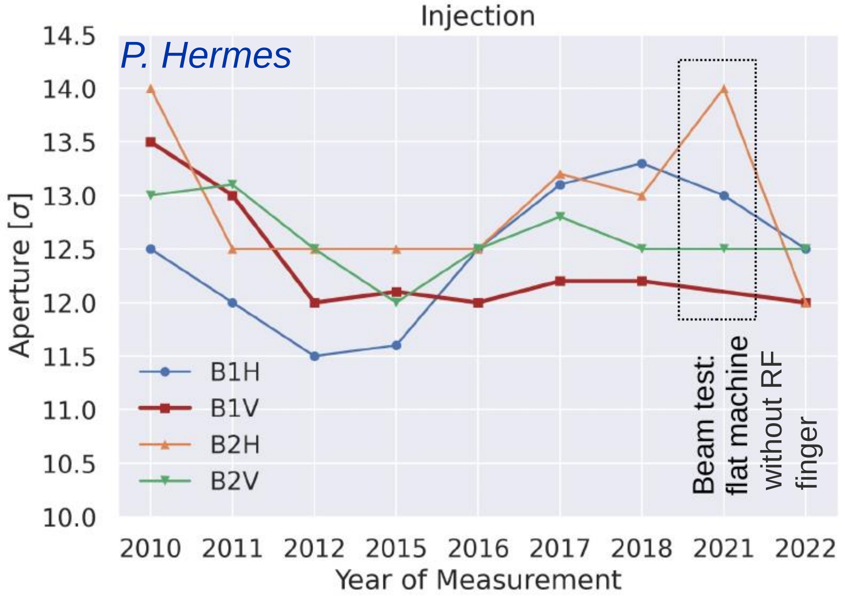




GFS synoptics, Molflow simulation of SMOG2 injection

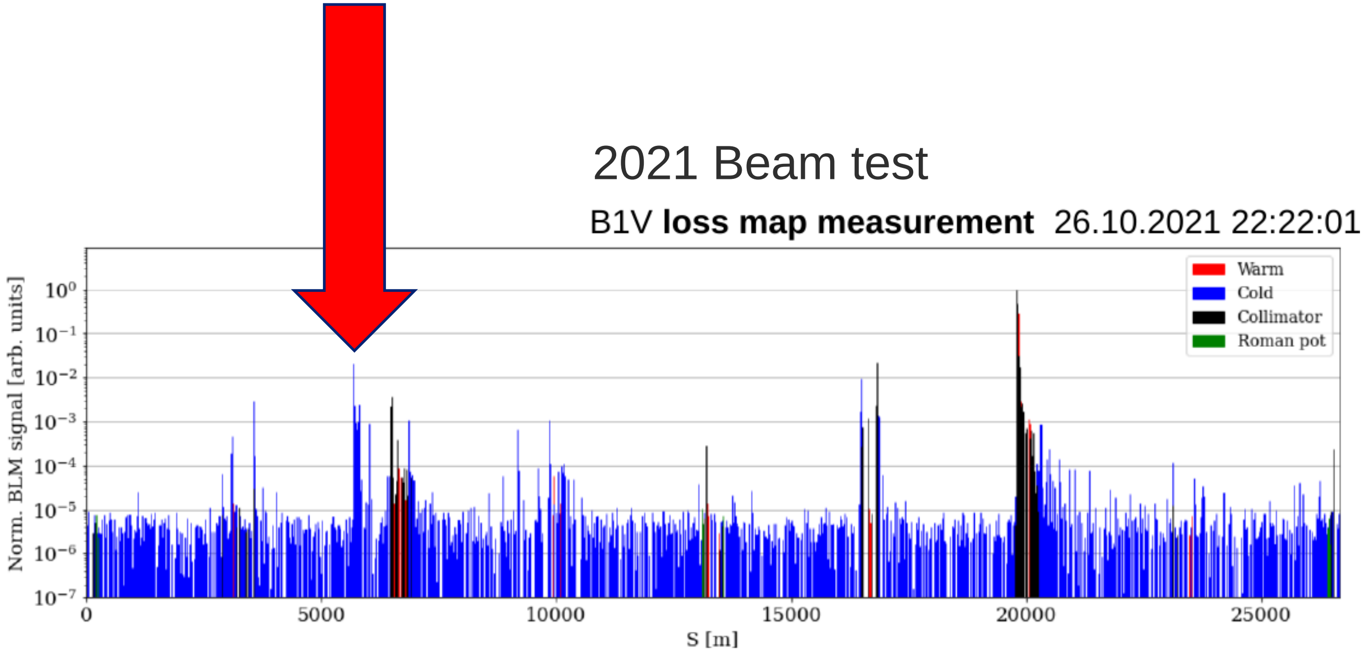
Beam aperture during reliability run in 2021

- **2021 beam test at injection showed high losses in cell 21L3 of ARC23**

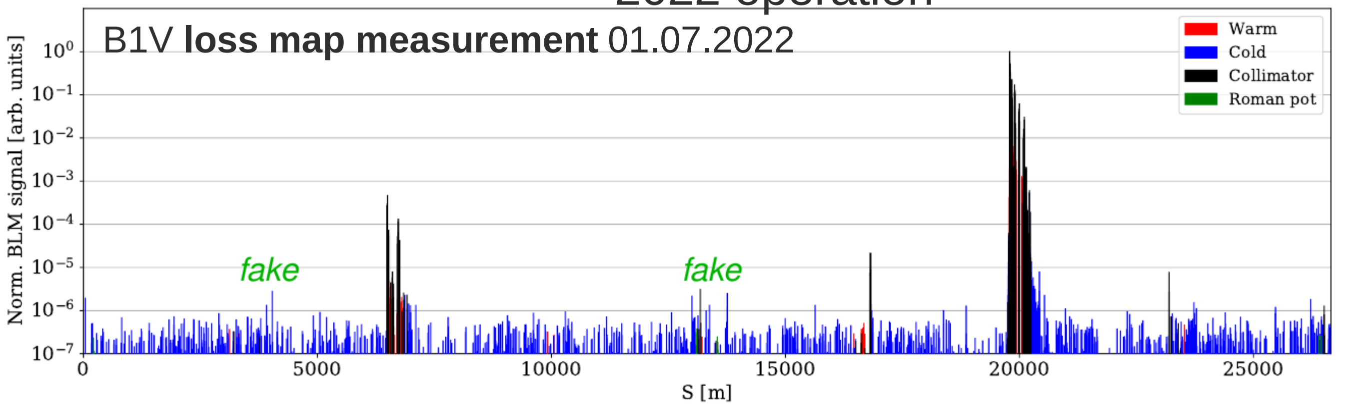


2021 Beam test

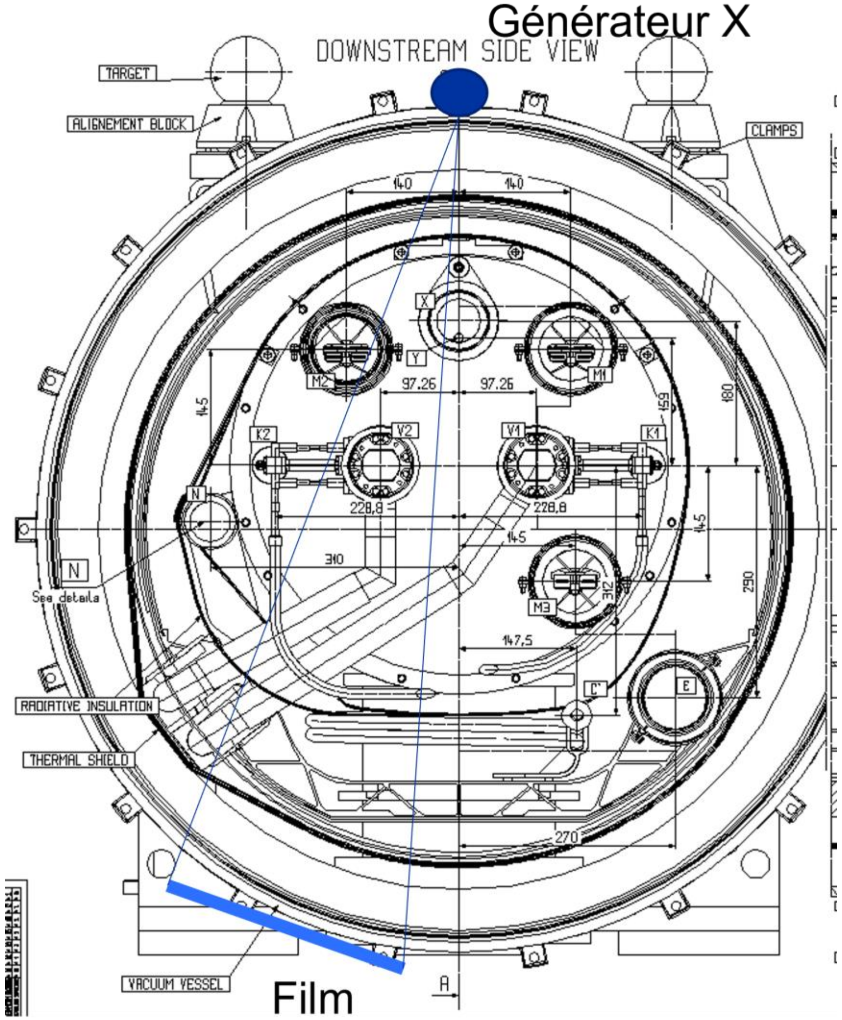
B1V **loss map measurement** 26.10.2021 22:22:01

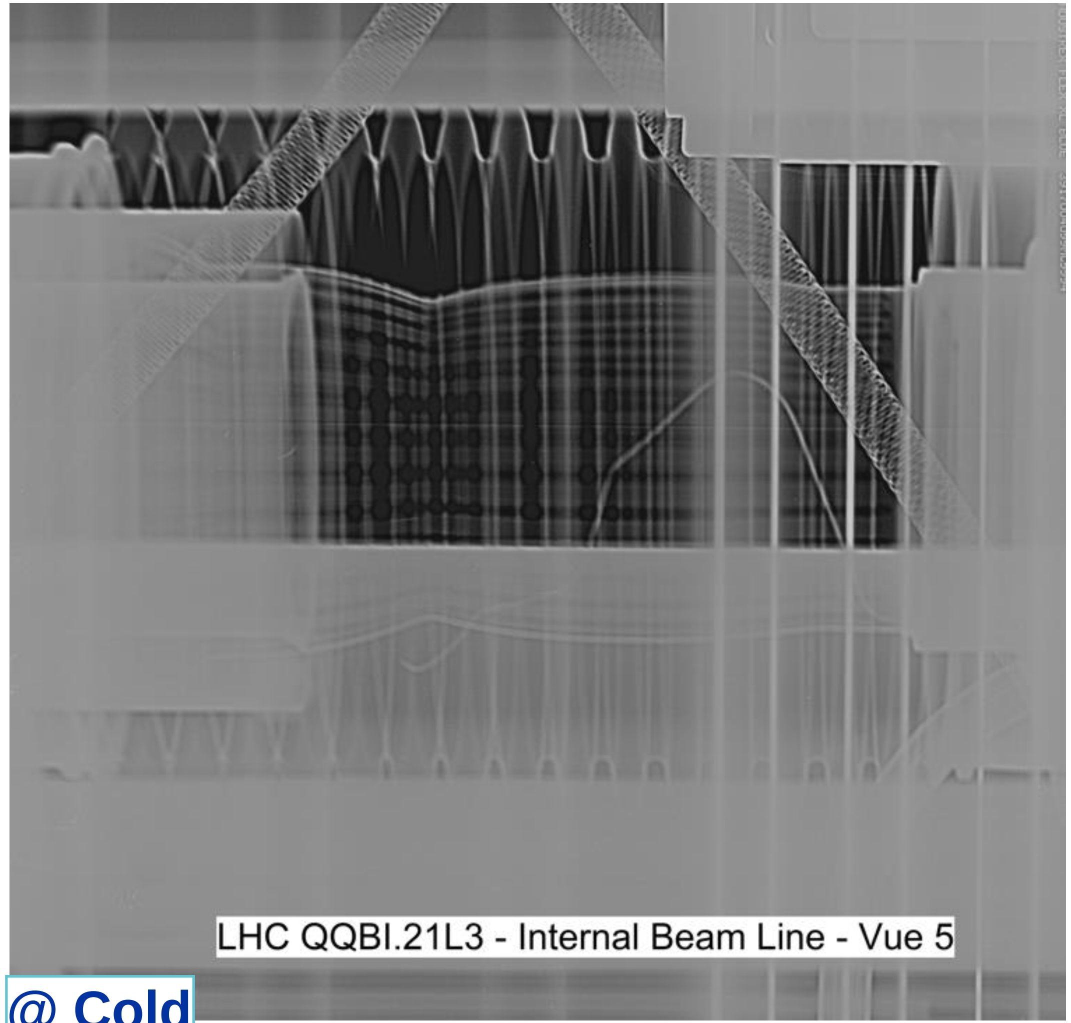


2022 operation



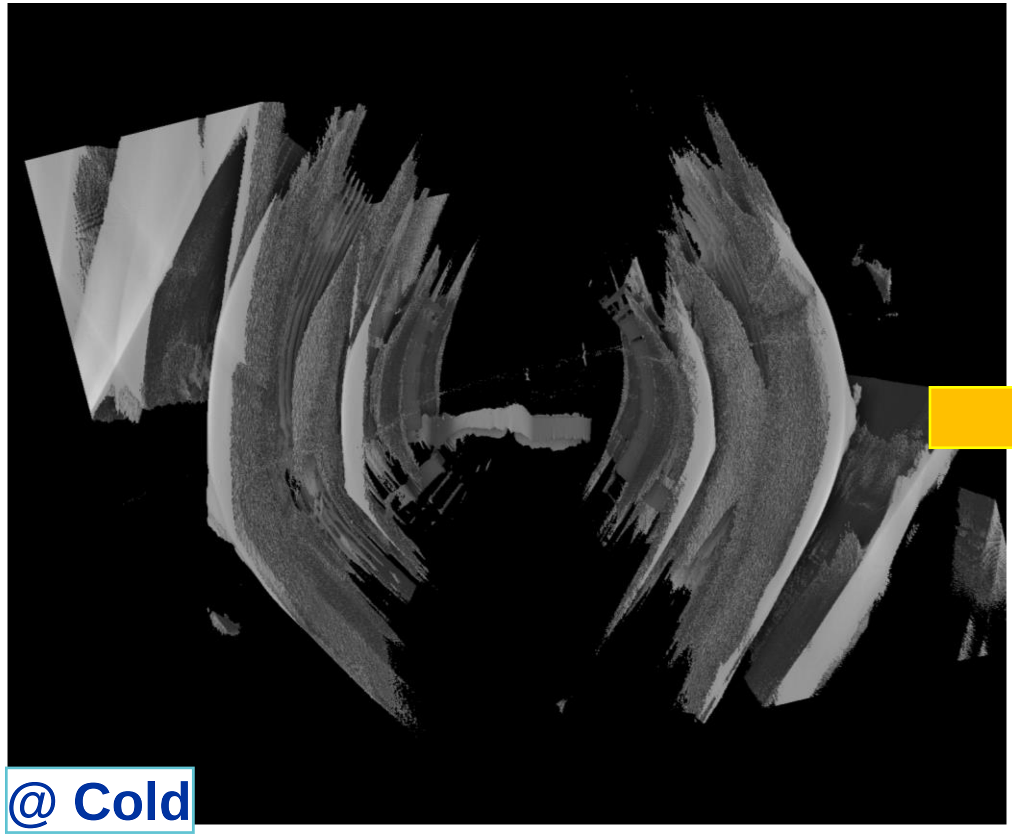
QQBI.21L3.V1: X-rays results



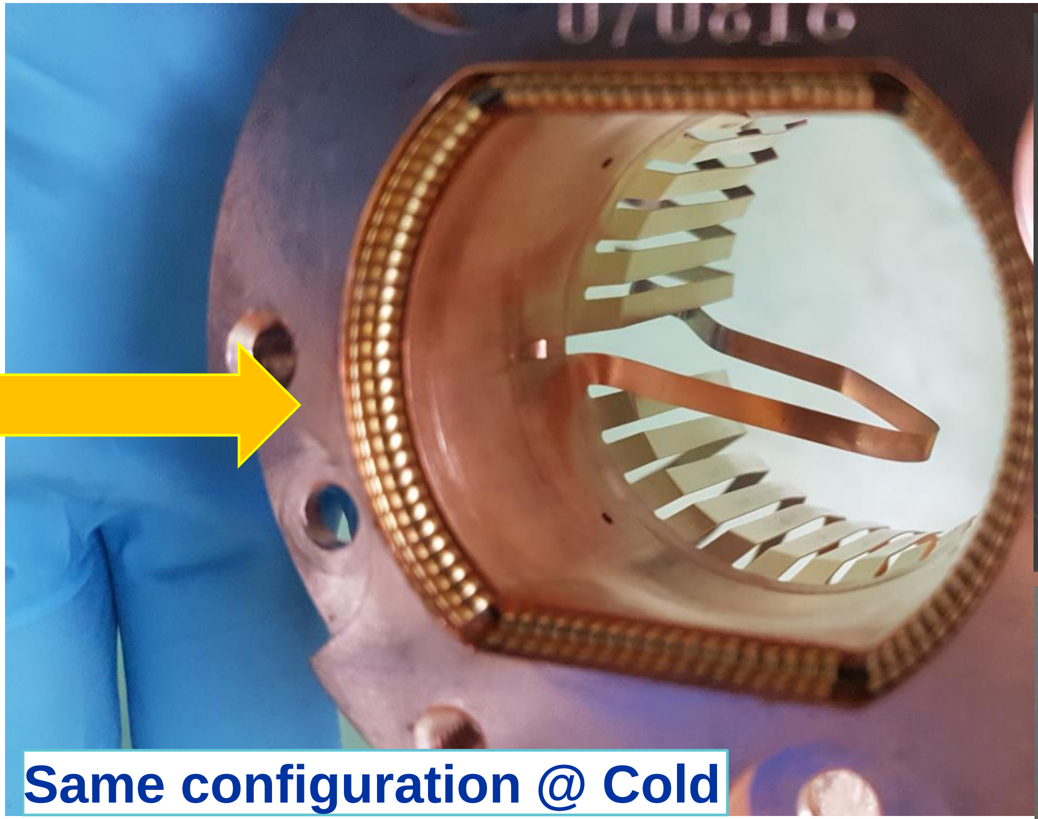


@ Cold

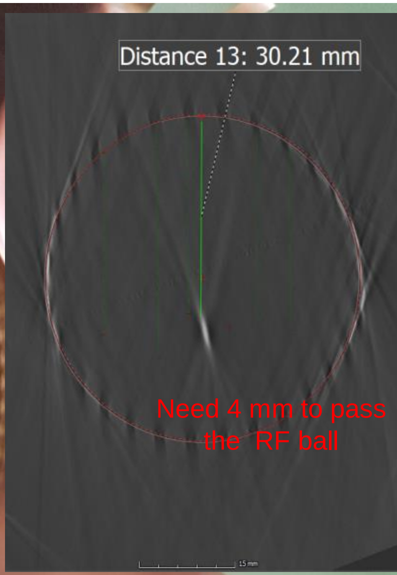
QQBI.21L3: Tomography Results vs Real Picture



@ Cold

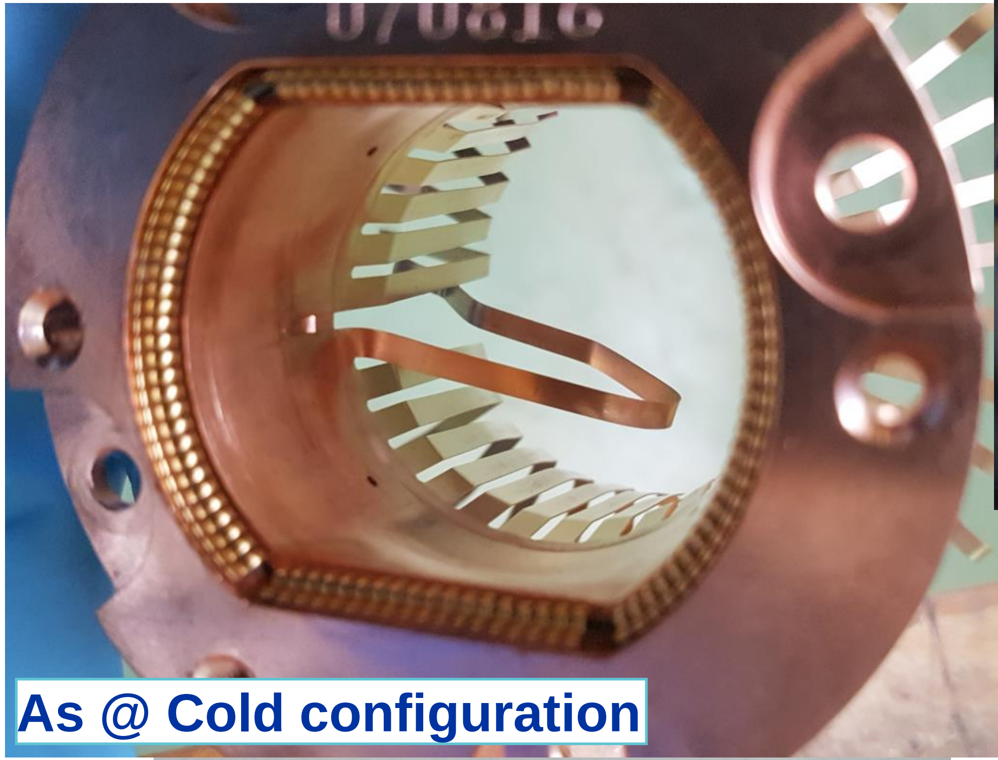


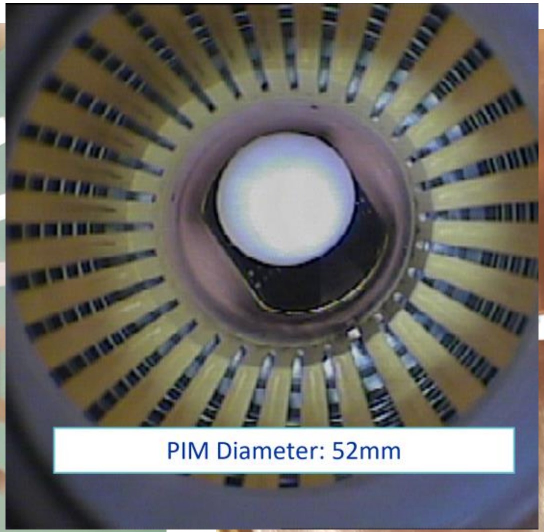
Same configuration @ Cold

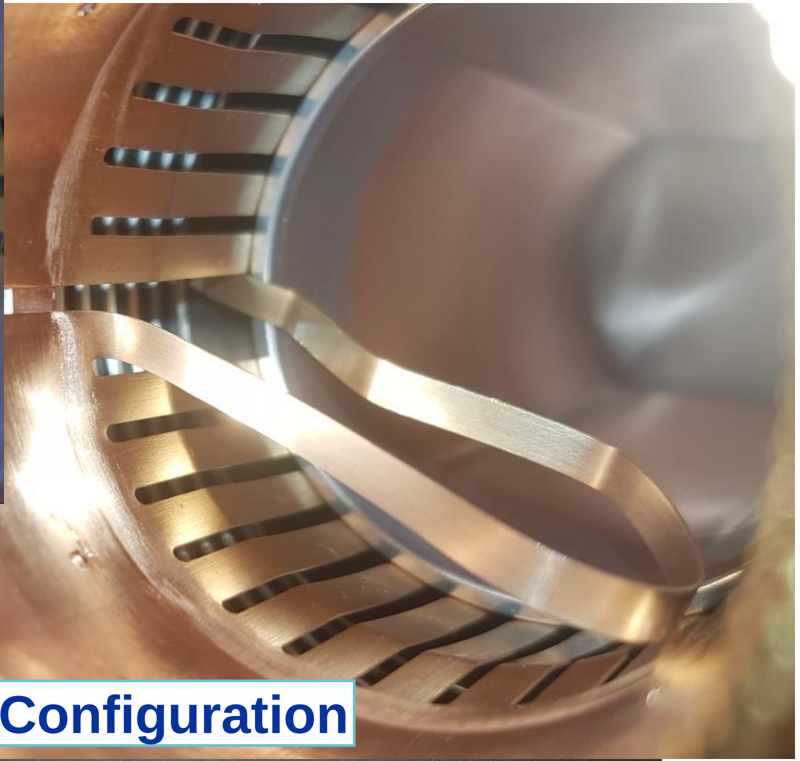


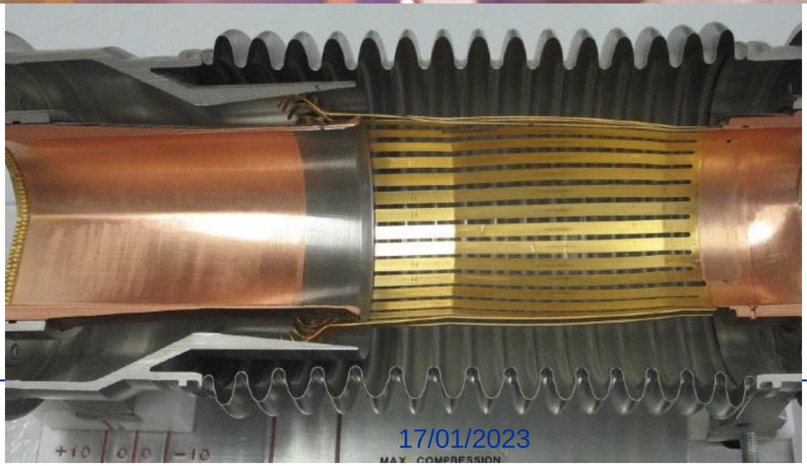
But……

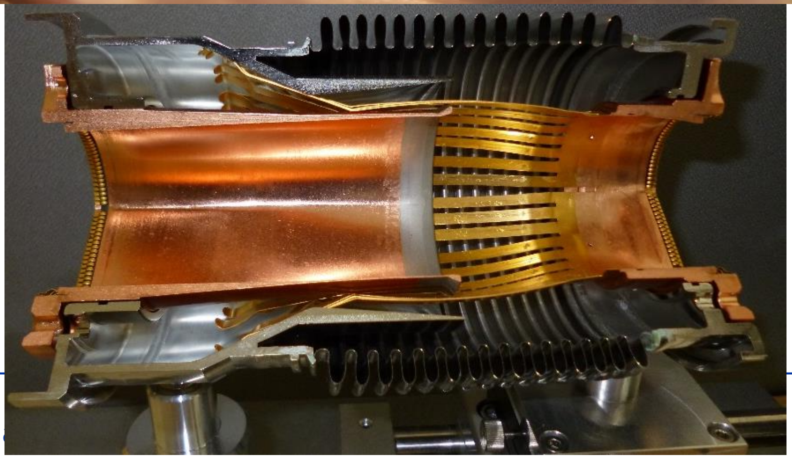
Different RF finger position vs machine configuration



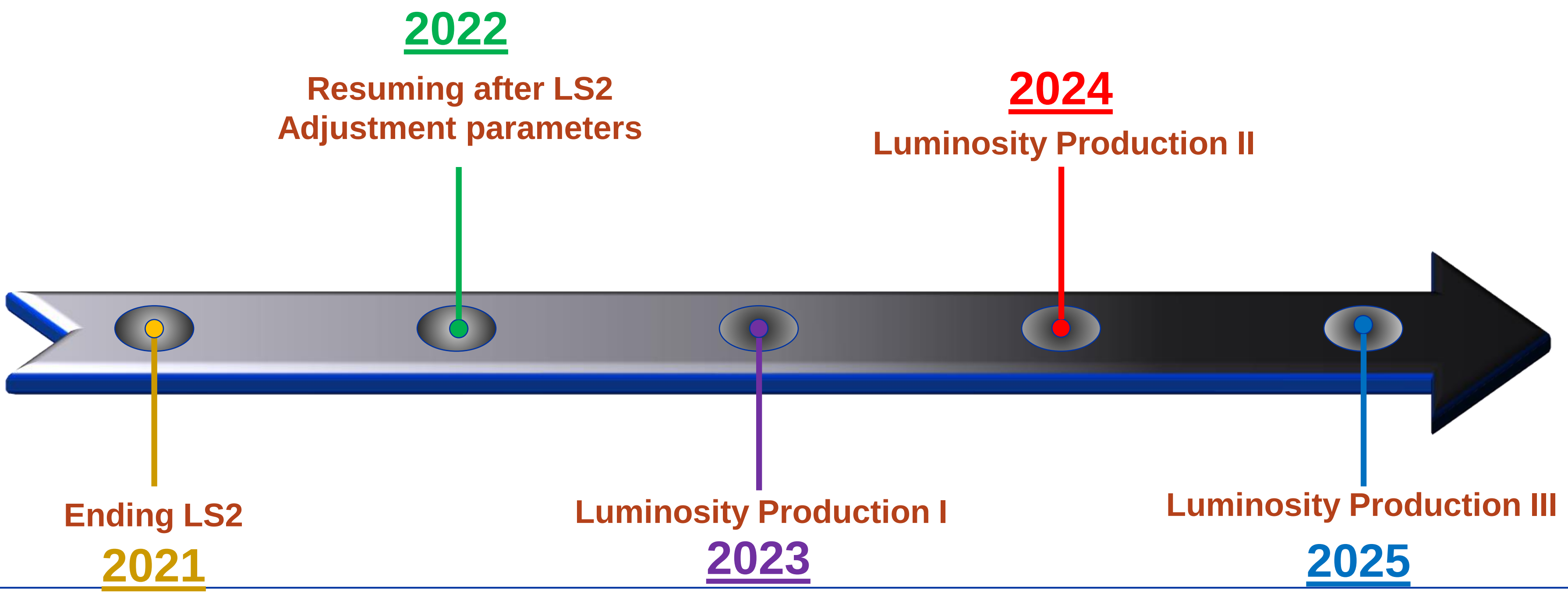









RUN 3


2022
Resuming after LS2
Adjustment parameters
2024
Luminosity Production II
Ending LS2
2021
Luminosity Production I
2023
Luminosity Production III
2025

Goals and constraints in Run 3 proton operation

- **Increased beam energy from 6.5 TeV to 6.8 TeV**
  - Initial magnet training to 7 TeV: bypass diode failure and an inter-turn short requiring thermal cycles in S23 and S78
  - Following risk analysis, target beam energy reduced to 6.8 TeV (limit quenches => limit risk for another thermal cycle)
- **Operational constraints:**
  - Limited triplet lifetime due to radiation dose – need to optimize energy deposition from luminosity
  - Need to level ATLAS/CMS luminosity at about 2×10^{34} $cm^{-2}s^{-1}$ due to cryogenic capacity, pileup <60
- **Max Run 3 LHC bunch intensity: 1.8×10^{11} p/bunch, ~2750 bunches (BCMS beam). Limitations:**
  - RF power at injection
  - The beam dump core/absorbers integrity – will be refined by observations during Run 3
  - Heating of the injection kickers
  - Potential limit from cryogenic capacity and heat load

R. Bruce

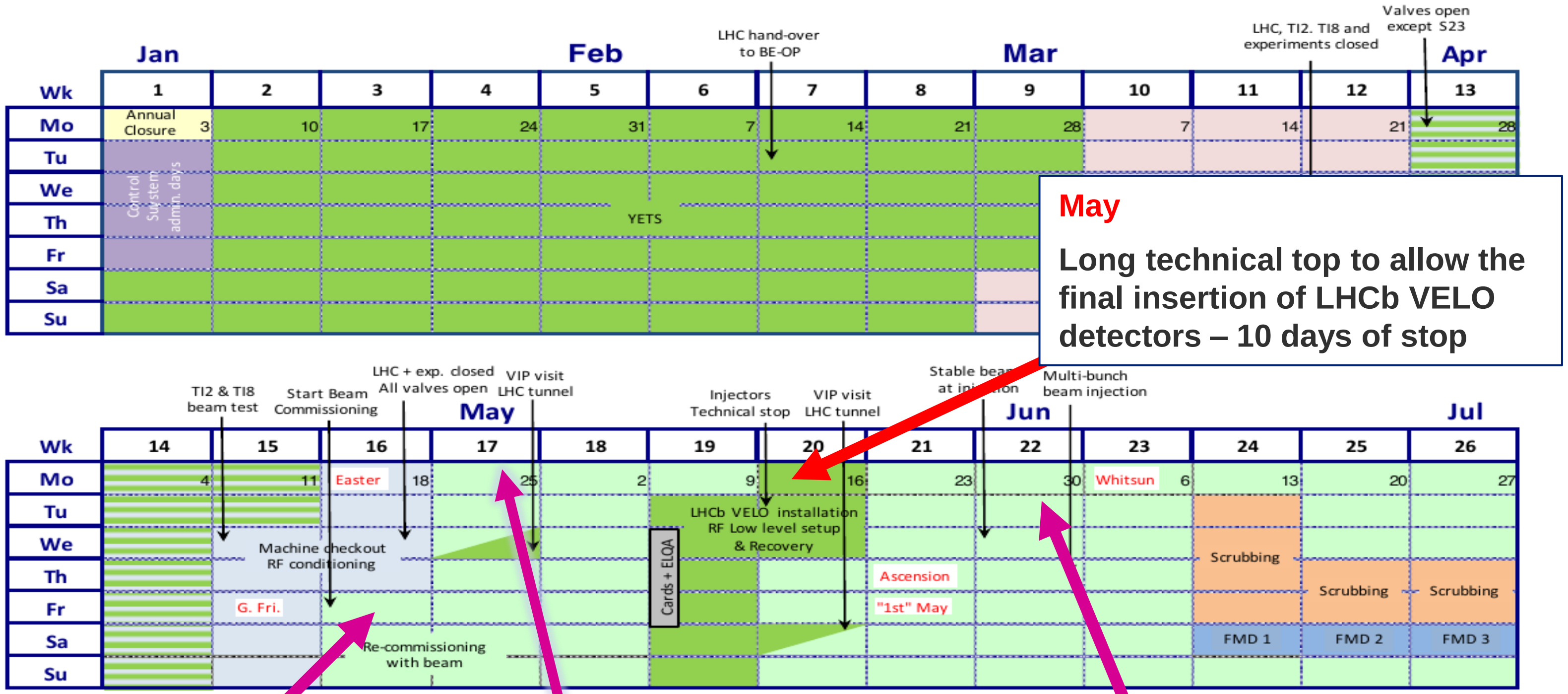
Which beam options for 2022?

- **BCMS beams for physics**
  - Up to **2462b** per beams with **≈ $1.45\cdot10^{11}$** proton per bunch
  - Ideally **5x48b** that could be stepped back to **5x36b** in case of high electron cloud activities
- **Mixed 8b4e + BCMS**
- **"Standard" 25ns beams for the scrubbing**
  - @ injection energy of 450 GeV

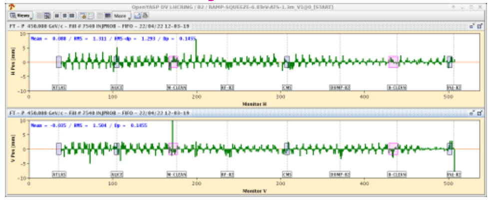
Batch Compression Merging and Splitting (BCMS) which offers significantly lower transverse beam size. This scheme increased the peak luminosity of the LHC by around 20% and set a new record of 1.2×10^{34} $cm^{-2}s^{-1}$.

Beam commissioning

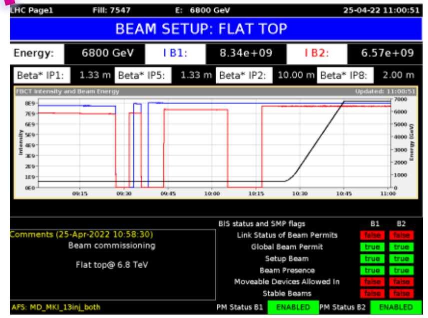
Beam commissioning 2022 – Q1 and Q2



April 22nd
First beam injection



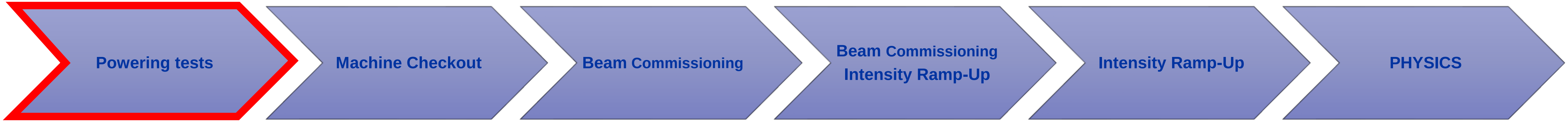
April 25th
First protons at 6.8 TeV

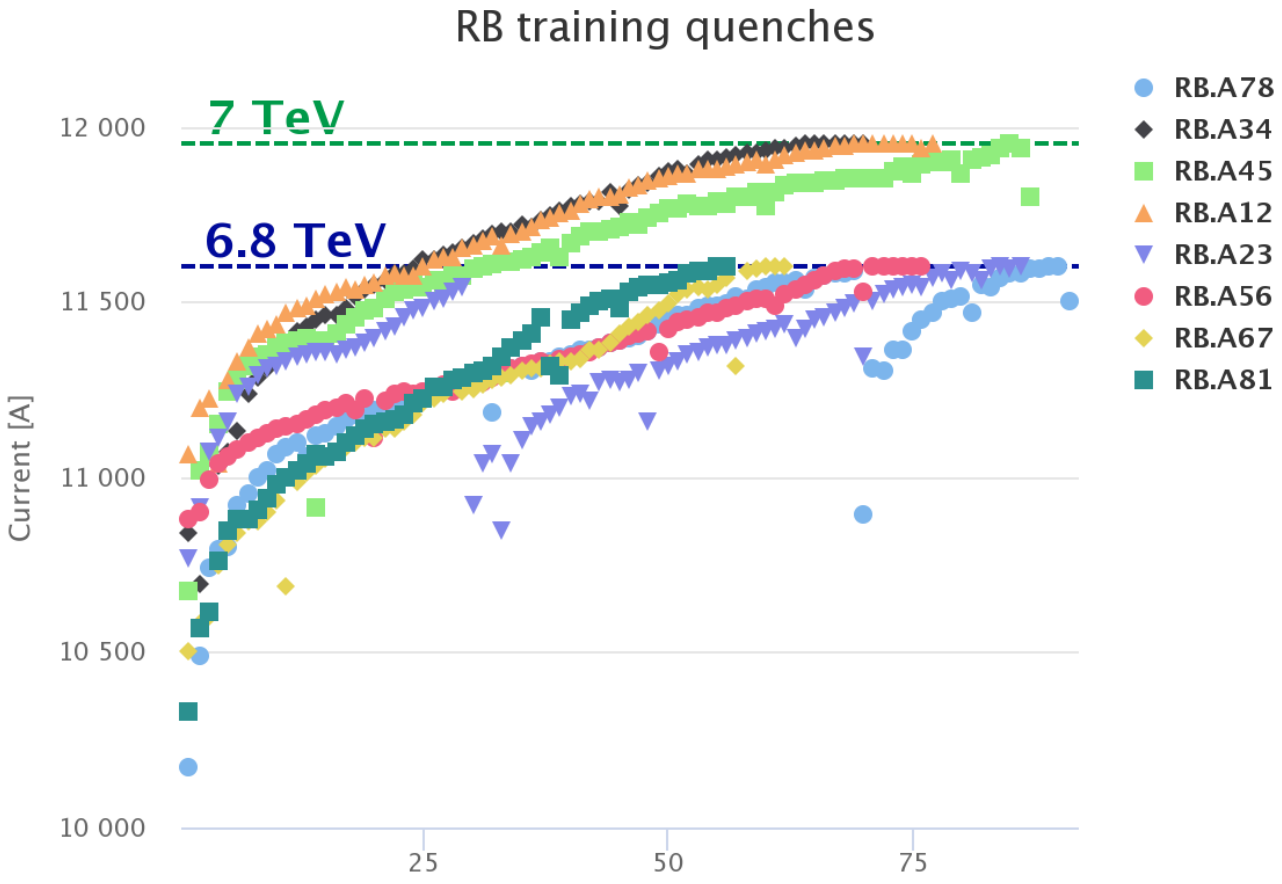


June 1st
Collisions at 6.8 TeV

- Initial delay: availability of LHCb VELO for installation, RF rupture disk failure following loss of cryo conditions
- Start of beam commissioning just after Easter
- Commissioning interleaved with scrubbing and machine development (floating MD)

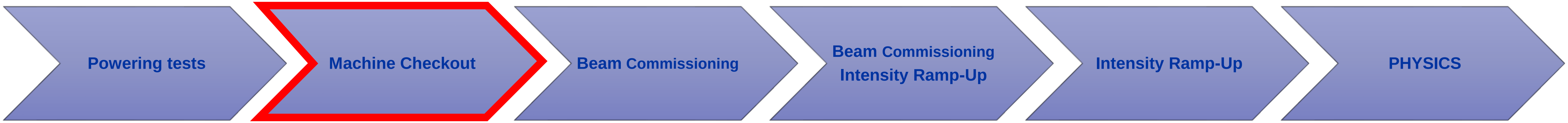
Beam commissioning

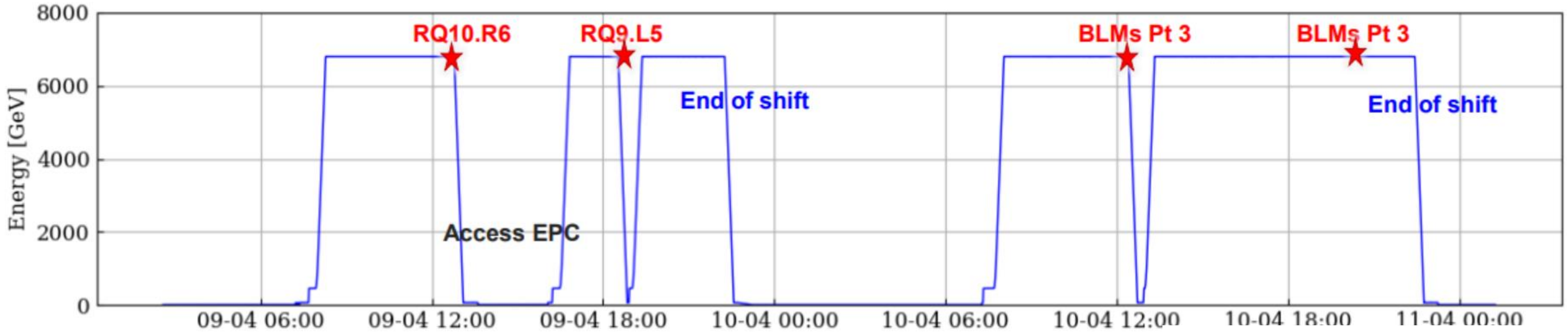




605 primary training quenches on the dipole circuits to prepare the LHC for 6.8 TeV operation. Completed on Thursday 14th April 2022.

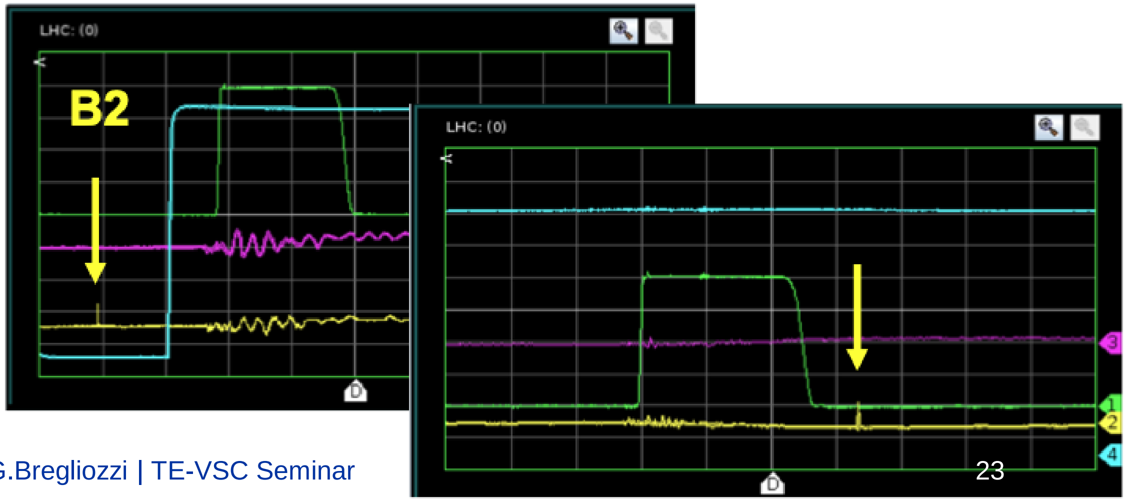
Beam commissioning



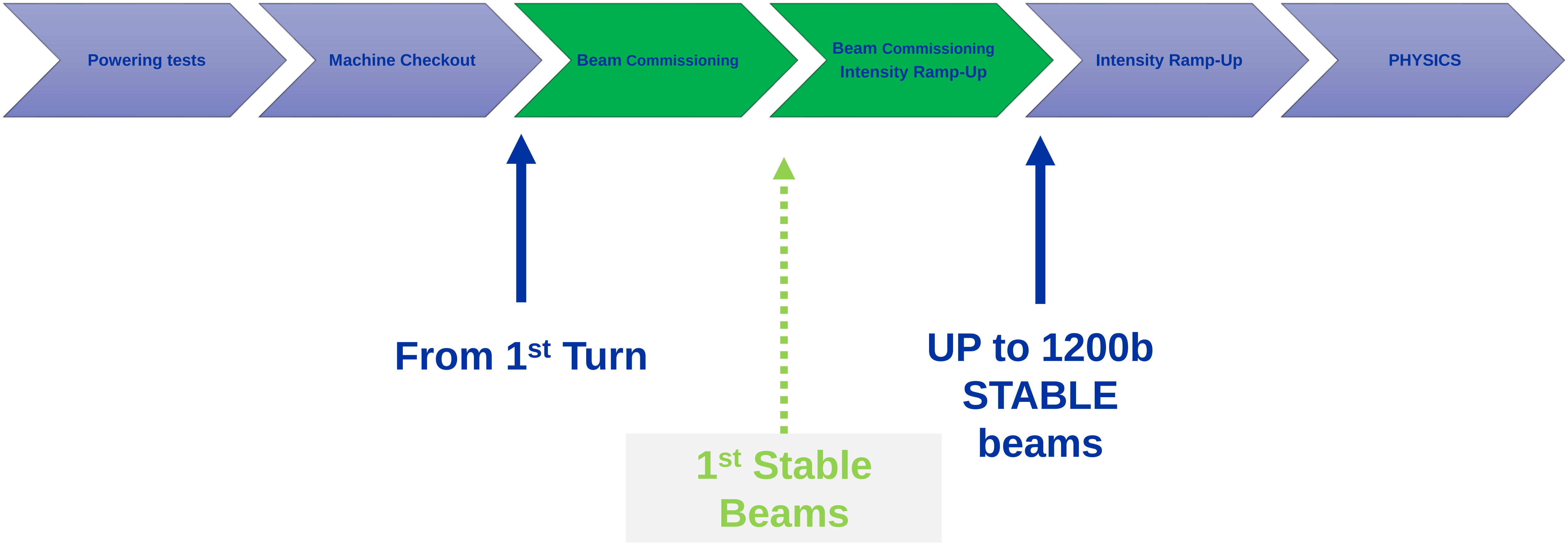


When we start cycling the full machine, ensuring all systems behave collectively well

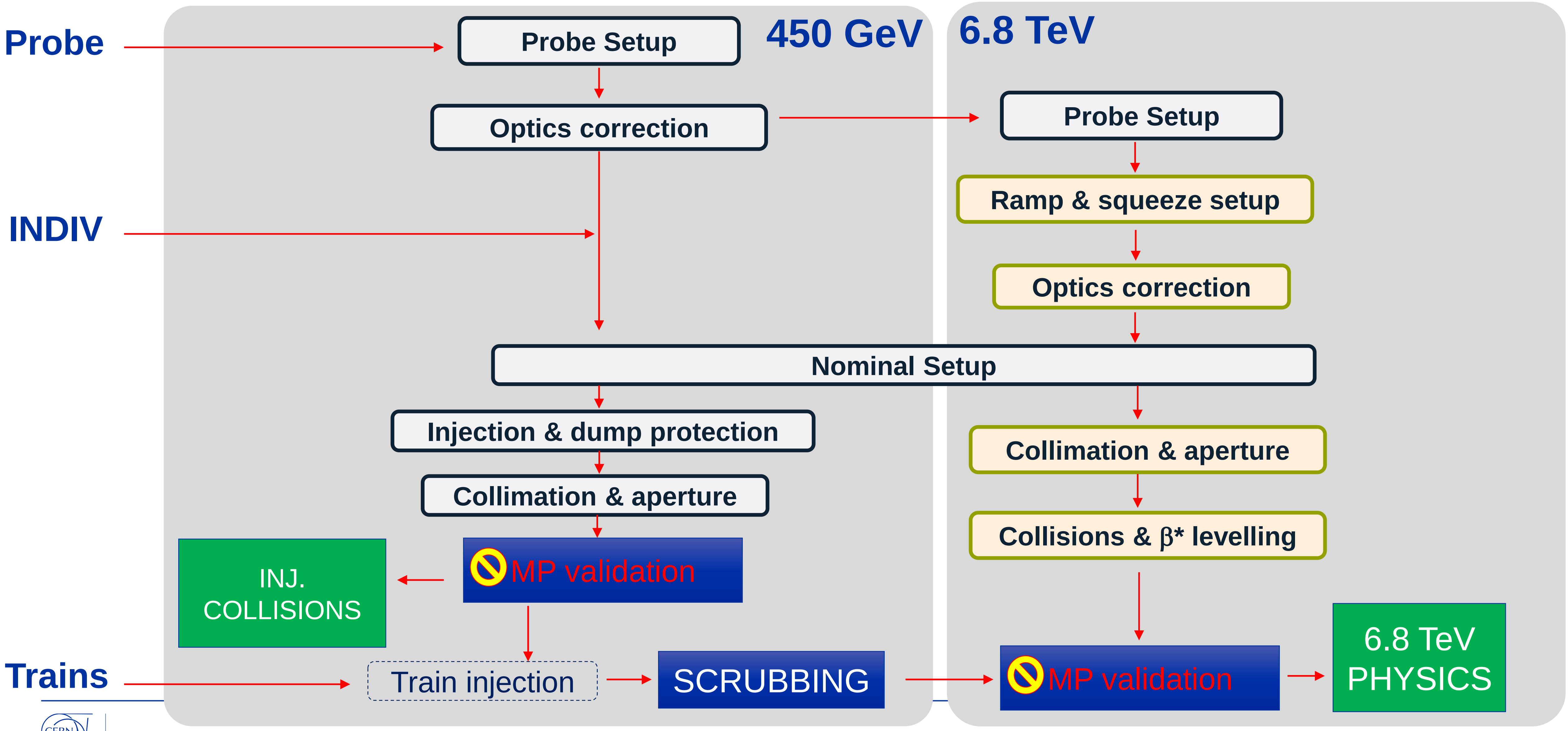
With beams knocking on the LHC doors!
(TL tests with beams to downstream TEDs)



Beam commissioning



Simplified commissioning flow



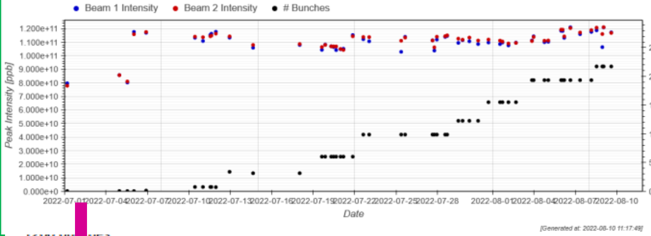
Luminosity production

Beam Pipe passing through the LHCb Muon detector

LHC operation 2022 – Q2 and Q3

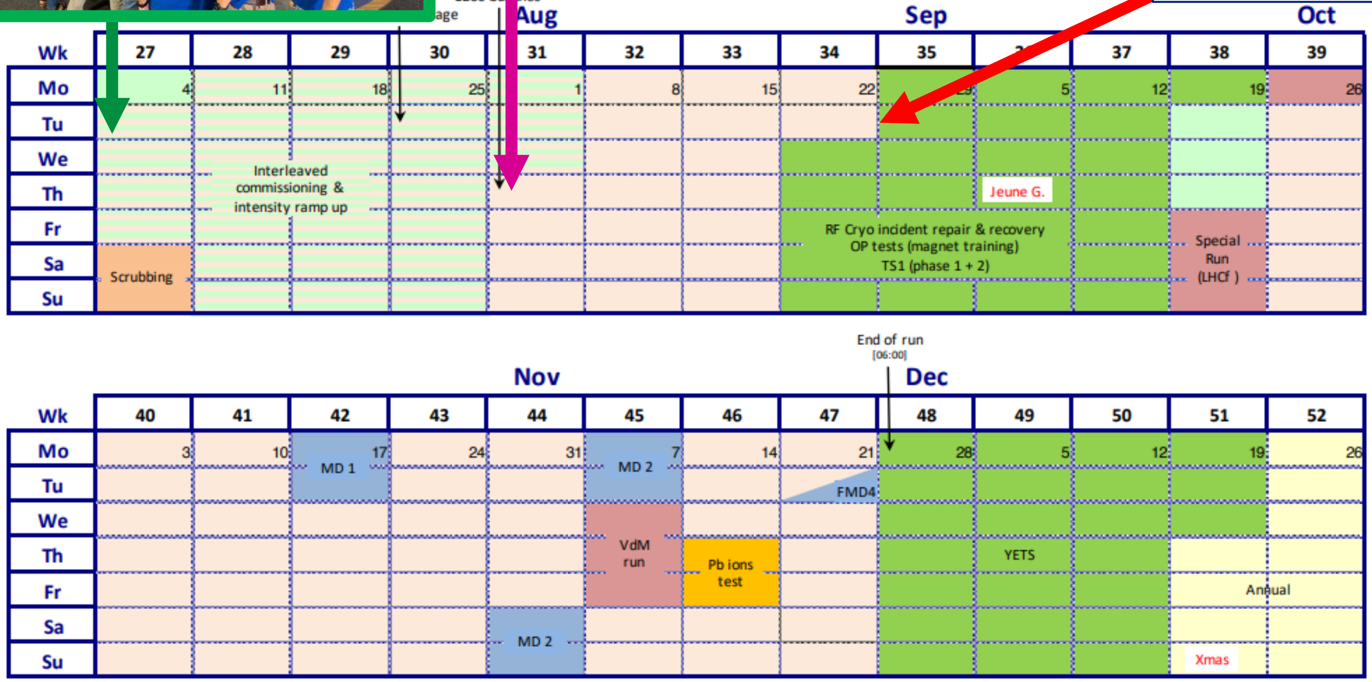
July 5th
Start of Run 3 physics

August 3rd
> 2000 bunches



August 23rd

Accidental cooling tower stop leads to helium release from RF cavities, failure of RF rupture disks – warm up and conditioning of RF cavities required – 3 weeks lost



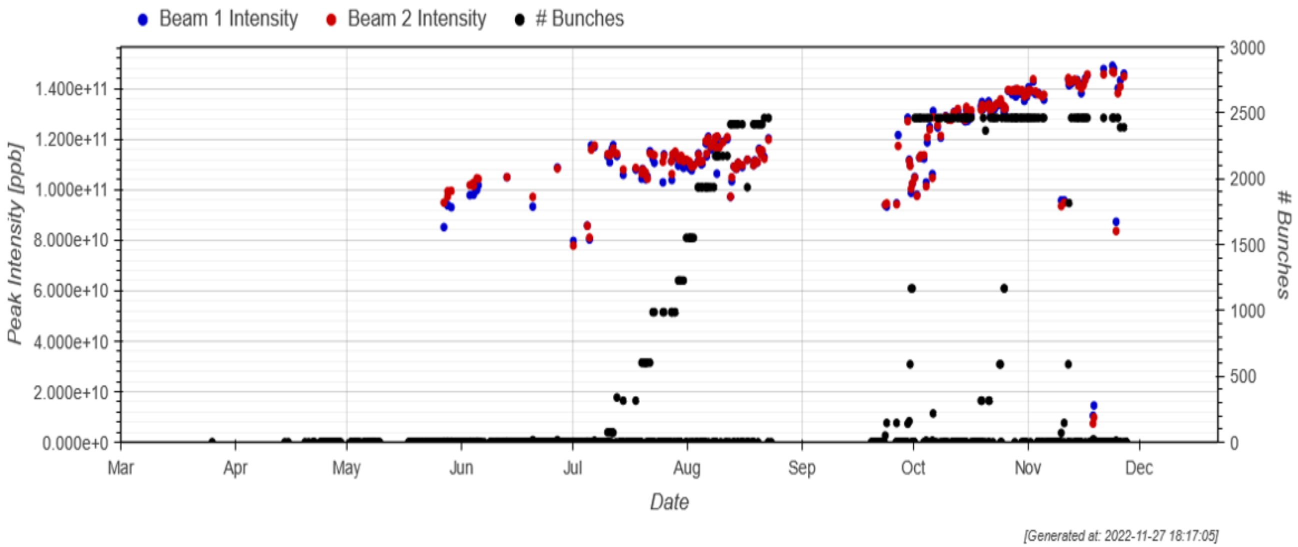
- First stable beams and media event on July 5th
- Intensity ramp-up with good luminosity production in spite of some issues
- Beam back in September after incident and RF conditioning
- In addition, 2022 run to be shortened by 2 weeks due to energy crisis

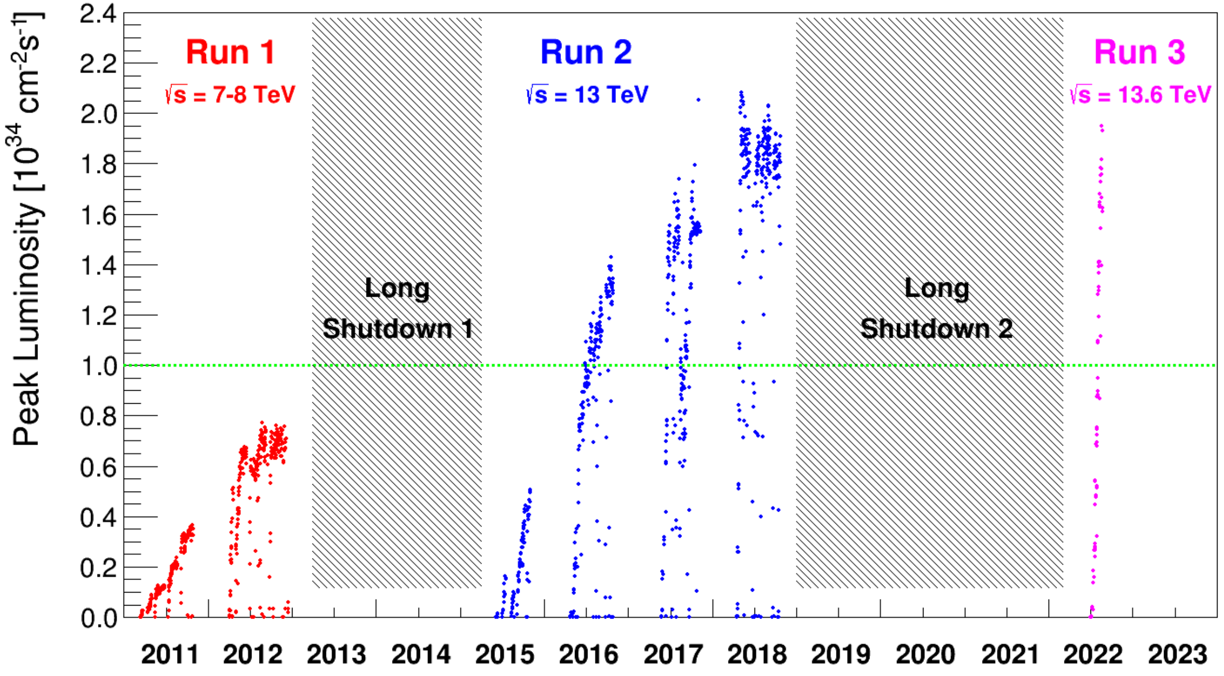
R. Bruce

LHC performance
Intensity ramp-up

- **Startup strategy: increase number of bunches at 1.2×10¹¹ p/bunch until machine is full, then push bunch intensity towards 1.5×10¹¹ p/bunch**

- **Very steep ramp-up of intensity and peak luminosity**
  - Not far from 2018 performance only after 1.5 months
  - Peak luminosity almost within target already
  - Reflects the excellent understanding of how to optimize and operate LHC

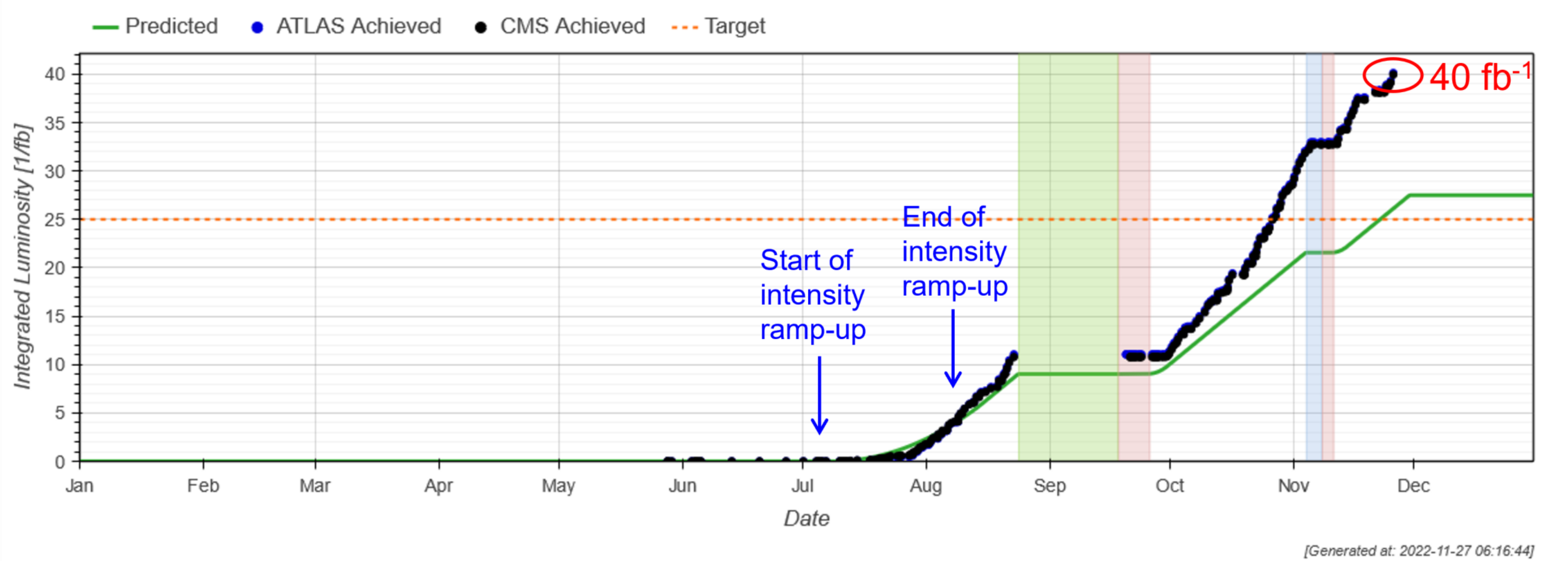




R. Bruce

Status of 2022 luminosity production

- **Luminosity production started to exceed the planning before the incident on 23/8**
- **Slope close to the best Run 2 periods**
- **Outstanding 40 fb^{-1} collected by ATLAS / CMS in 2022**



R. Bruce

2022 Main Limitations

UFO

Electron cloud & induced heat load

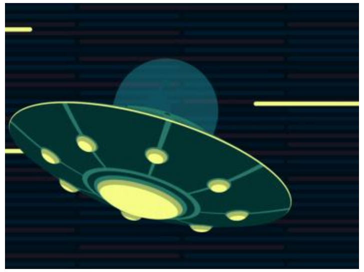
RF Burst disk accident

Beam induced heating

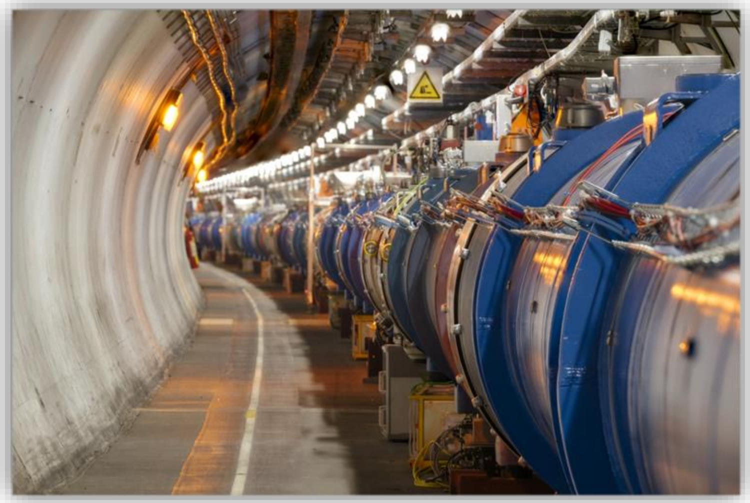
Beam Pipe near the central part of CMS Detector

UFO: Unidentified ~~Flying~~ Object

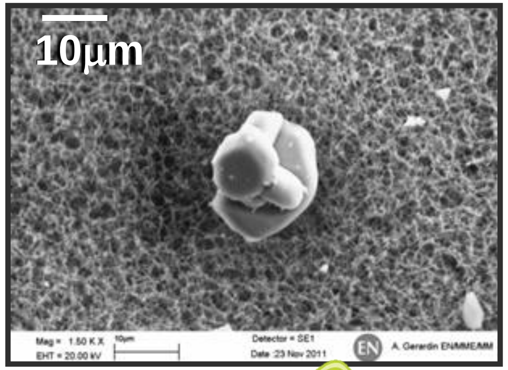
Can this



Stop this?



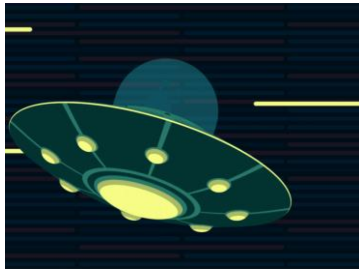
And this?



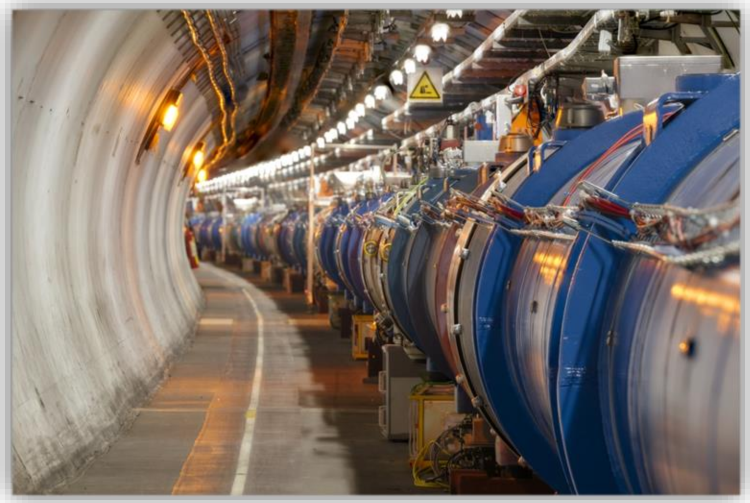
From 9th Evian Workshop, D. Mirarchi

UFO: Unidentified Falling Object

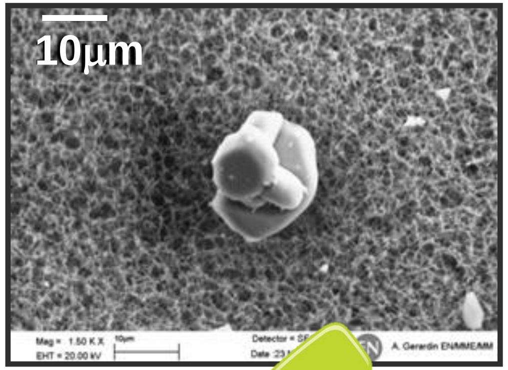
Can this



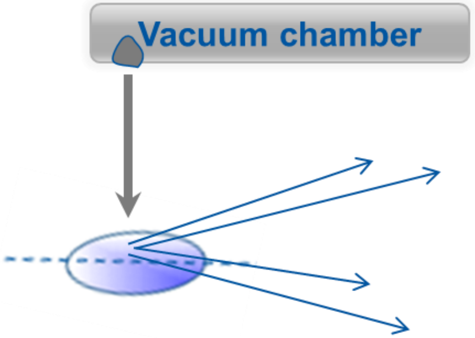
Stop this?



And this?



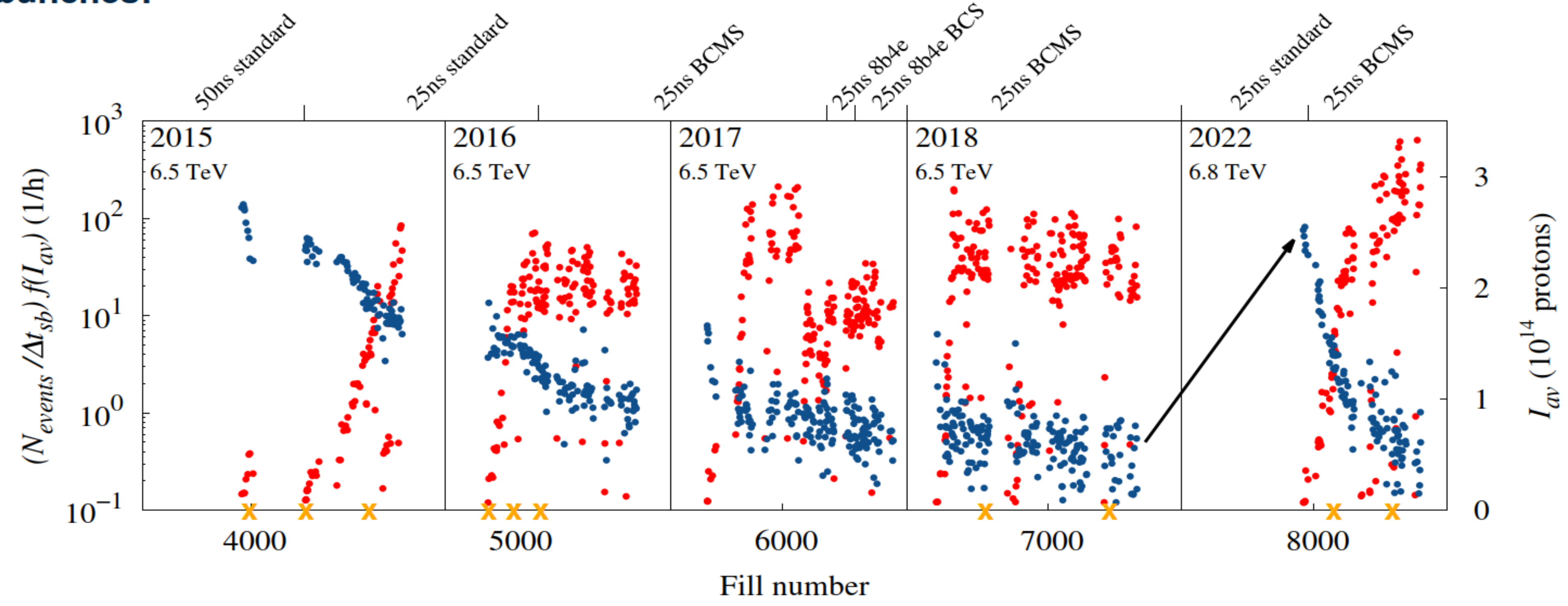
- **Unidentified Falling Object**:
  1. **Dust** particles falling into the beam (**at least tens of µm**)
  2. **Inelastic** proton-UFO **collisions**
  3. **Hadronic showers** and **energy deposition** on magnets **coil**
  4. **Quench**



D. Mirarchi

Beam UFO interactions events

70+ bunches:

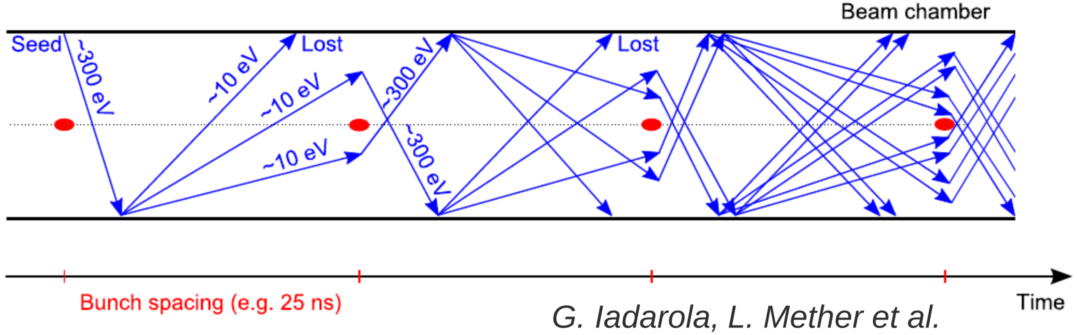


Blue dots = **UFO rate**, red dots = **fill-averaged intensity**, orange crosses = **quench**

- **In 2022, 23 beam dumps (1 quench) due to UFOs**
- **Important impact on availability this year, but the worst should be over by the end of 2022**

A. Lechner

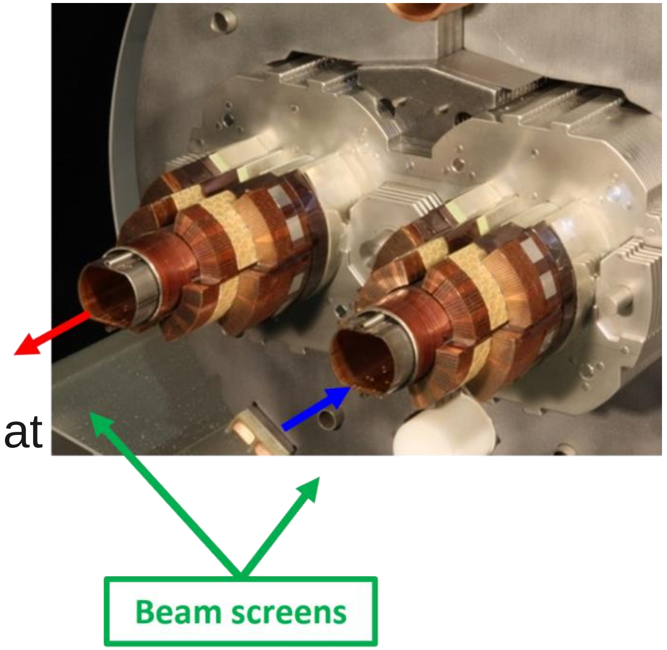
Electron cloud and heat load

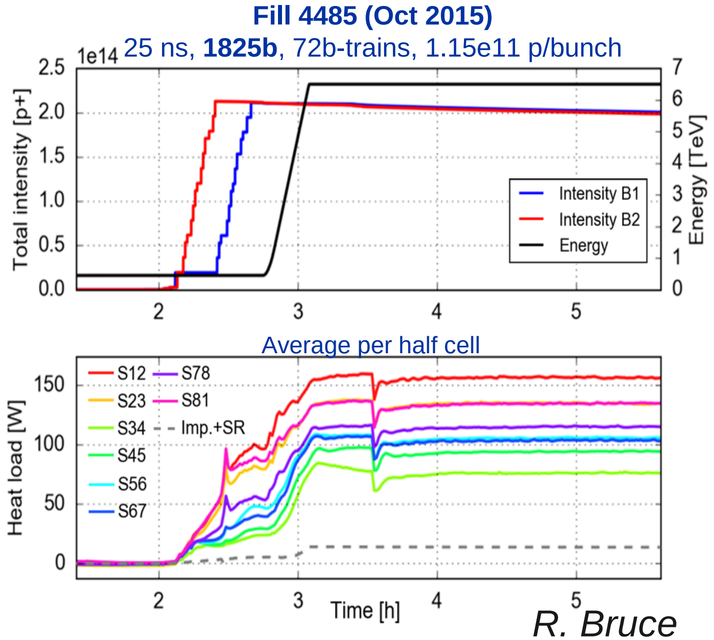


G. Iadarola, L. Mether et al.

- **Electron cloud**
  - Electrons accelerated by the beam, hitting the chamber and in turn releasing new electrons => avalanche effect
  - Consequences: heat load on chamber wall (main limit), instabilities, vacuum degradation, emittance blowup

- **Run 2**
  - Conditioning over the run
  - Significantly higher heat load observed in some LHC sectors: S12, S23 and S81 => degradation from Run1 to Run 2.
  - Studied by dedicated task force. Found chemical alterations in beam-screen surface at high-heat load locations (see 2022 Seminar of V. Petit)

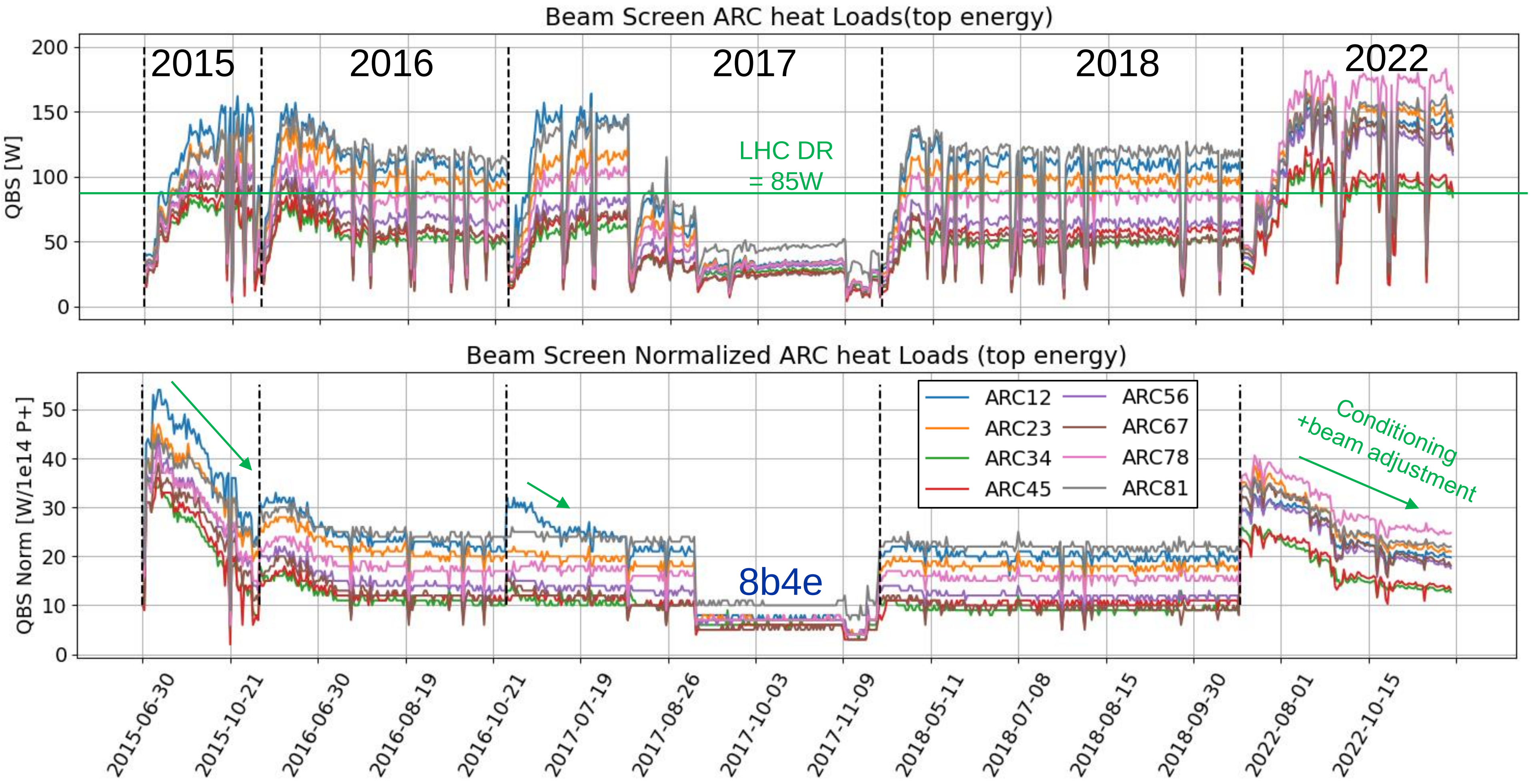




R. Bruce

Beam Screen heat load history @ top energy

5 years of operation @ 25ns

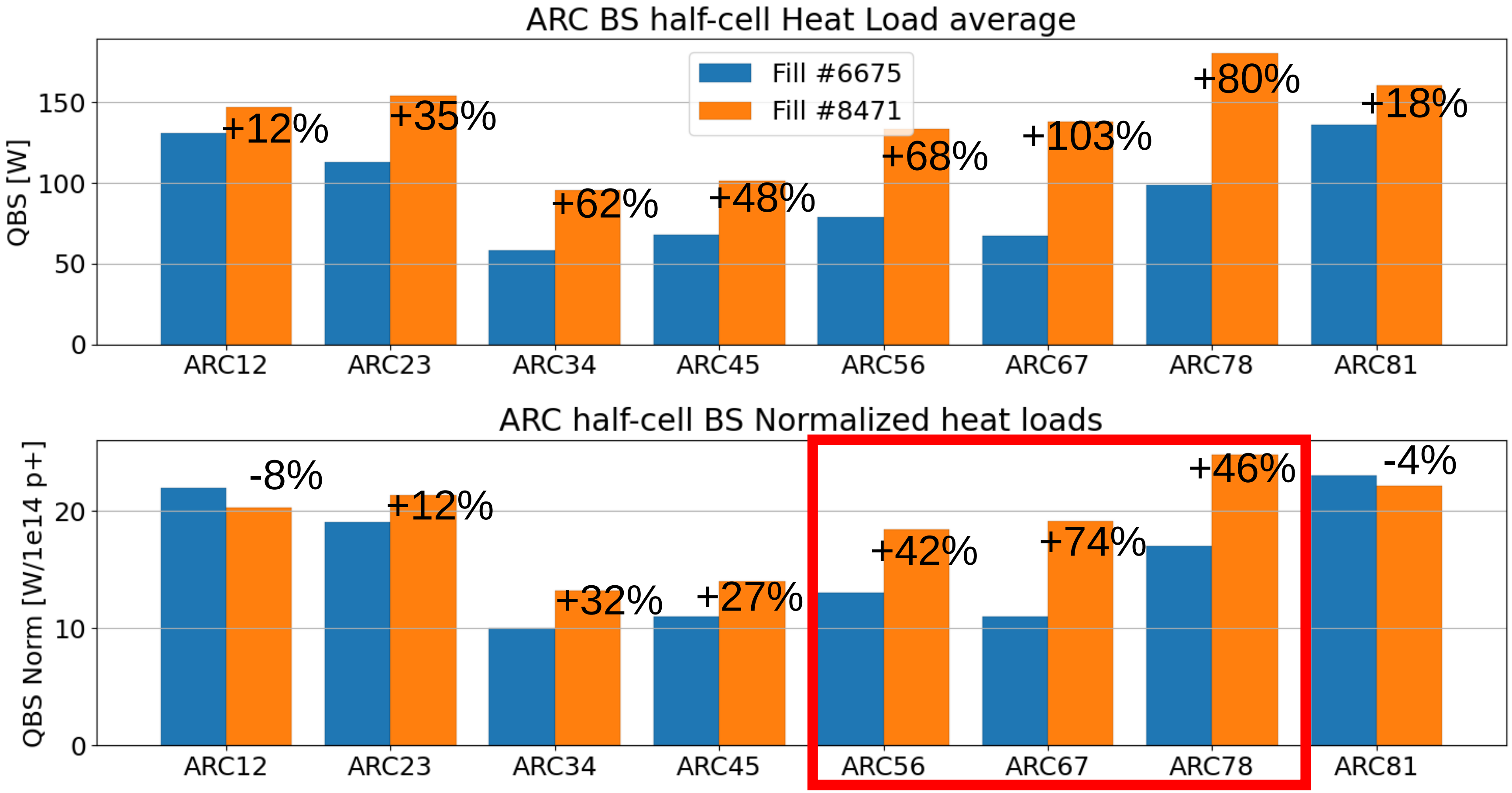


B. Bradu - Status on heat load analyses at the end of the 2022 run

B. Bradu

Fill comparison 2018 Vs 2022

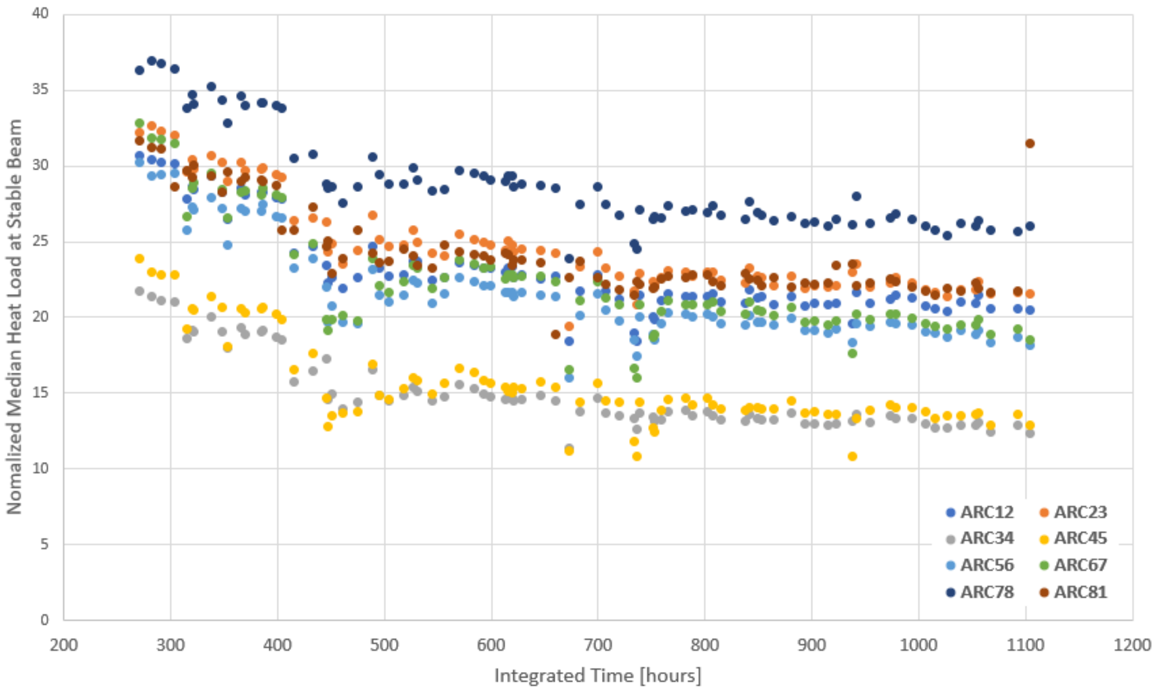
Fill #6675 (2018): 25ns_2556b_2544_2215_2332_144bpi_20injV (3x48b)
Fill #8471 (2022): 25ns_2462b_2450_1737_1735_180bpi_17inj_2INDIV (5x36b)



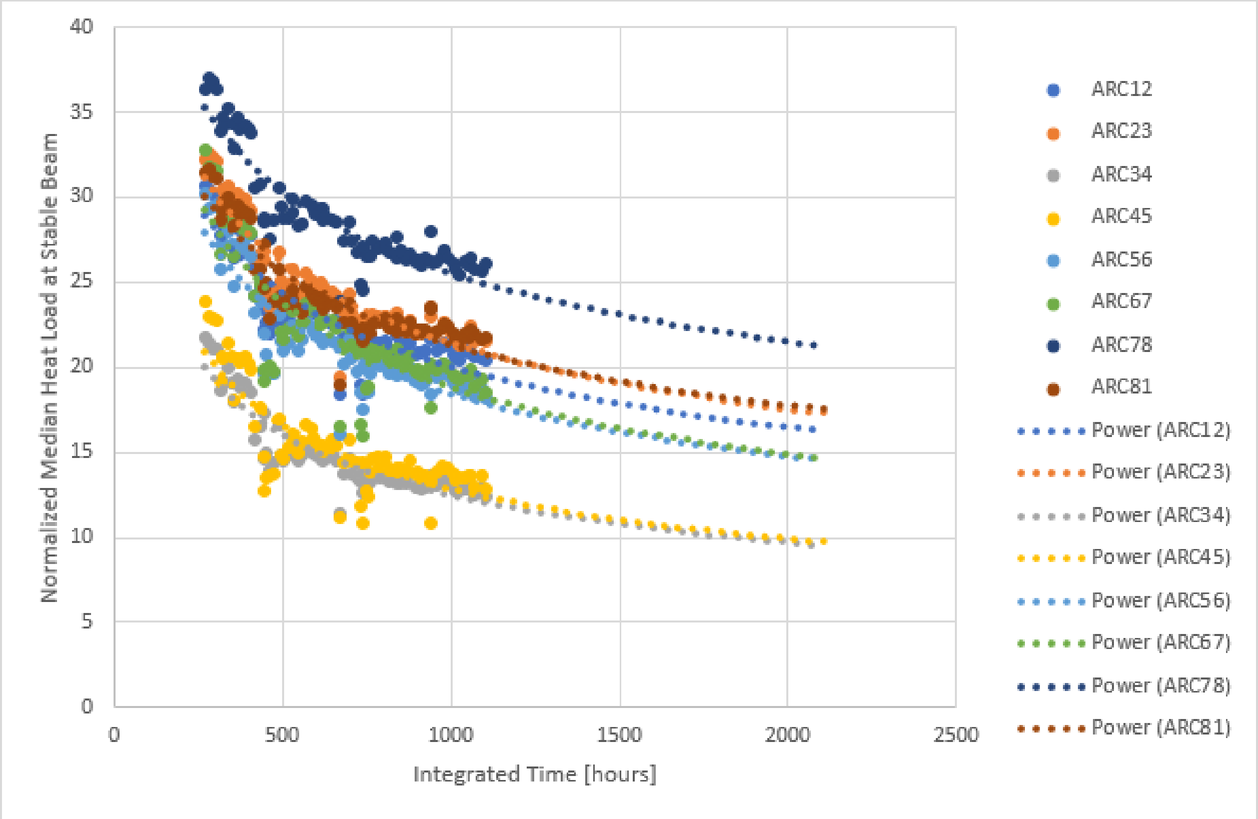
➔ LS1 provoked significant degradation of heat loads in S12 & S23 & S78 & S81
➔ LS2 provoked significant degradation of heat loads in S56 & S67 & S78

B. Bradu

2022 Heat Load Evolution



Cannot expect significant further scrubbing in S78



Mitigation under discussion:

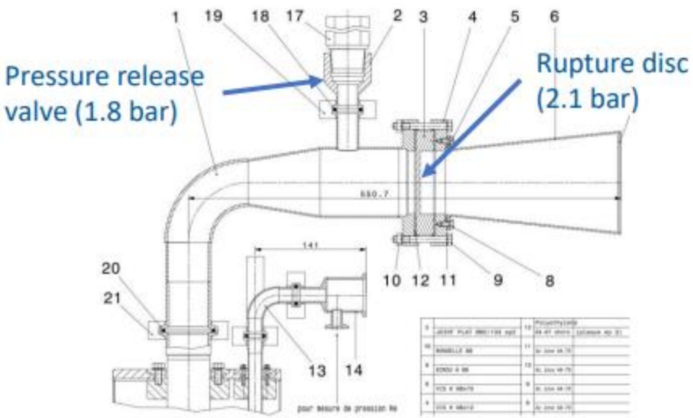
- Could change filling scheme to include “holes” (8b4e) – limited to about 1900 bunches in total
- Could use mix of 8b4e and standard 25ns beam
- Task force in place to study different surface treatments -> **Could have a clear impact for the HL-LHC upgrade**

RF burst disc incident

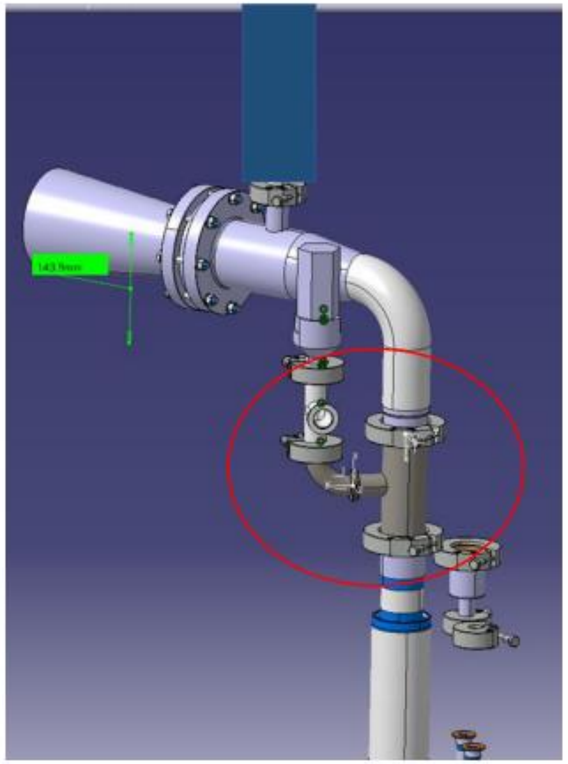
Time line

- 23rd of August @18h07: CV alarm indicating loss of communication from SF4 supervision
- 23rd of August @18:09: Loss of cryo conditions
- 23rd of August @18:19: M2B1 rupture disc burst, followed by M1B1, M1B2
- 23rd of August evening: All rupture discs replaced and cryomodules repressurized
- 24th of August @ 11h00: Decision to warm-up all cryomodules
- 24th of August: LMC#446
- 25th of August at 00:28: M2B1 disc burst again at 1.74 bara
- 26th of August: Degradation of the insulation vacuum
- 29th of August: RF Burst Disk Meeting
- 31st of August: LMC#447 and 13th Meeting of RF burst disk task force
- 6th of September evening: Installation of new release valve configuration
- 7th of September morning : Leak checks of valve assemblies at 1.5 bara and insulation vacuum
- 9th of September morning: He circuit purge and cool down started on all 4 modules
- 12th of September: Start of Rf conditioning
- 14th of September: LMC#448
- 19th of September evening: RF conditioning and LLRF checks completed

K. Turaj, LMC#449, 28th September 2022



Old safety valve configuration

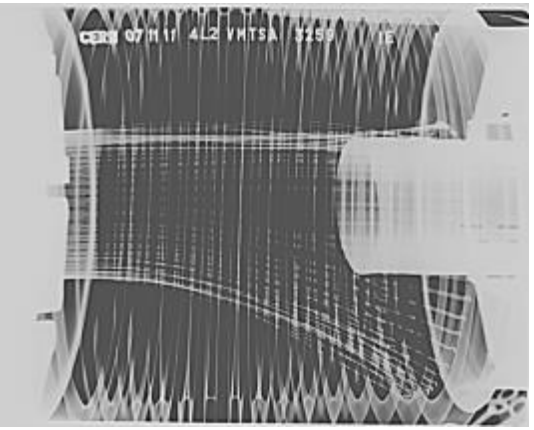


New safety valve configuration

Pressure release valves @ 1.7 bar

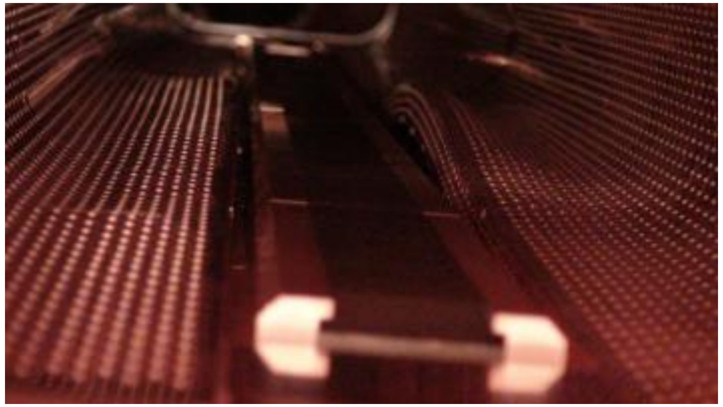
Reminder: Beam induced heating issues since LHC startup

Damaged vacuum modules
→ Design not robust



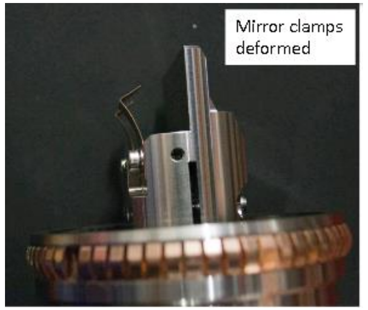
One injection kicker delays injection
→ Non conformity

Damaged injection collimators
→ Design not robust



2 collimators reached temperature interlock dump levels
→ Cooling non conformity
→ Spurious temperature readings

Damaged synchrotron light monitor
→ Design not robust



ATLAS-ALFA detector almost reached damage level
→ Design not robust

One single cryogenic module (Q6R5) has no margin for cooling, likely linked to TOTEM outgassing.
→ TOTEM ferrite not baked

→ Many actions taken by all involved equipment groups (especially during LS1 and 2015-2016 YETS)!

What has changed after LS2

Steady increase of intensity per bunch from nominal to ~1.45 10^{11} p/b

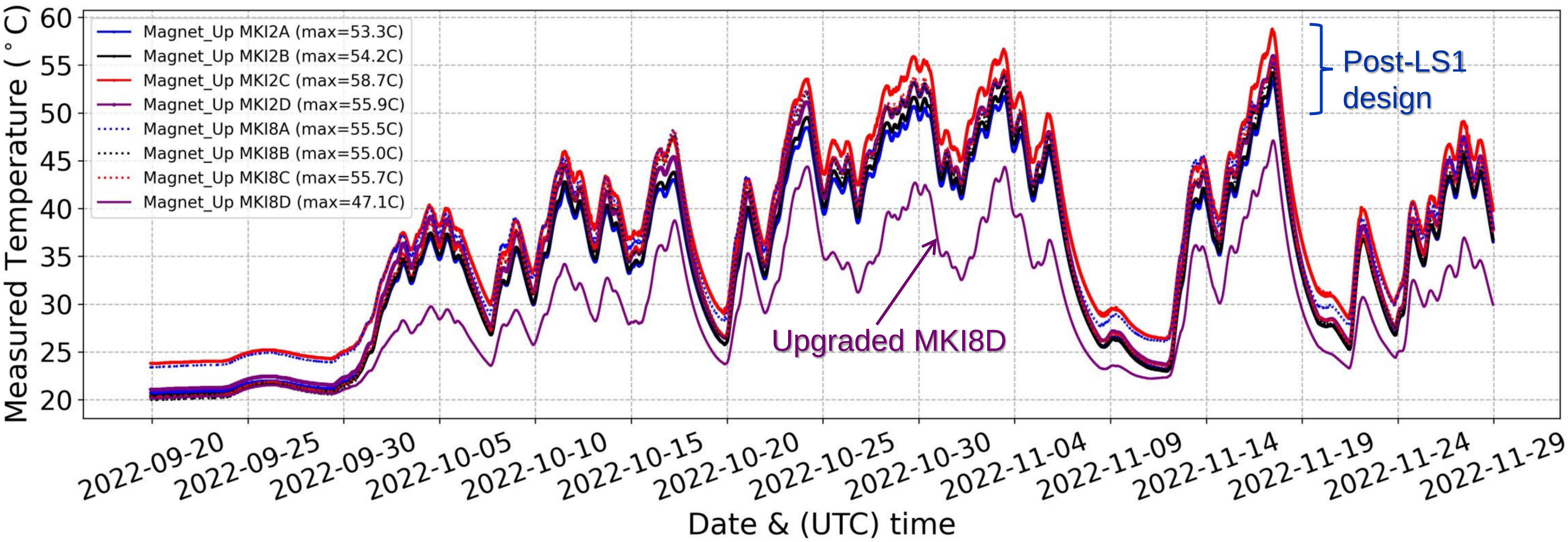
→ **Beam induced heating increased by ~50% compared to Run 2**

→ **Another ~50% increase expected to reach 1.8 10^{11} p/b**

Relevant equipment installed during LS2

- TDIS
- LHCb Velo upgrade
- TCLD
- New experimental chambers

MKI temperature



- Measured temperatures increase as expected with higher intensity and long fills
- Procedures followed, with fast turn-around, to increase SIS interlock thresholds as necessary.
- MKI8D (installed YETS 2017/18) included an upgrade to relocate a significant portion of beam induced power from the yoke to the 'RF damper': this element is not at pulsed high voltage.
- Lower yoke temperature for MKI8D → effectiveness of the upgrades demonstrated during LHC operation.

Vacuum spikes observed during the 2022 run

TCLDs

- Vacuum spikes observed on both 11R2 and 11L2 throughout the year (randomly in the fill) (largest during the scrubbing run in June)
- No correlation to movement of collimator, but some correlation observed with losses
- Xrays were performed during the LHC stop in Summer, will be redone on 11R2 during the YETS to investigates shadows seen on the Xrays

5R4

- Vacuum spikes observed at almost every fill during injection or the first part of the ramp, one dump at flat top during high intensity BCMS MD.
- Xrays will be performed on vacuum modules to check status of RF fingers (Dec 8^{th})

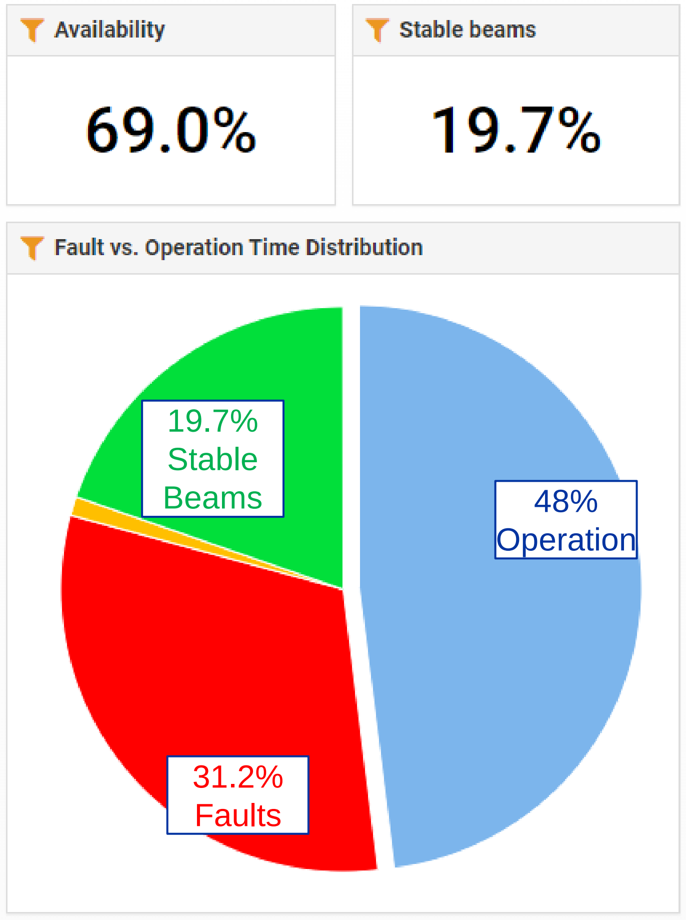
LHCb Velo

- Vacuum spikes observed when moving the Velo IN and OUT during stable beams
- Temperatures increase measured on the SMOG side with beam
- Visual inspection will be performed on the wakefield suppressor side during the YETS

UNDER ANALYSIS in the YETS


LHC Operation
Beam Vacuum Performances

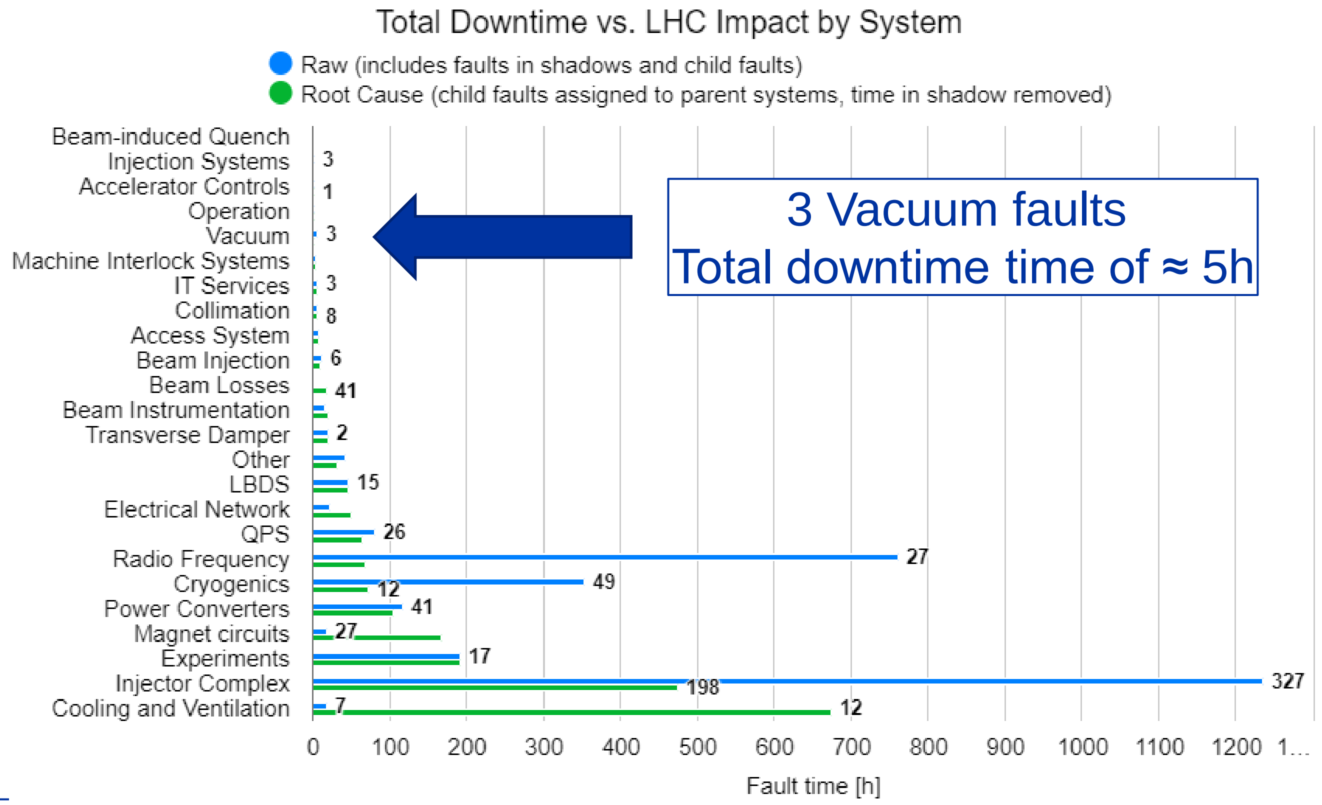
LHC Operation: Accelerator statistic



2h due to a TPG300
2h50min due to a sector valve card
15min : Ion pumps stopped for SMOG injection in IP8

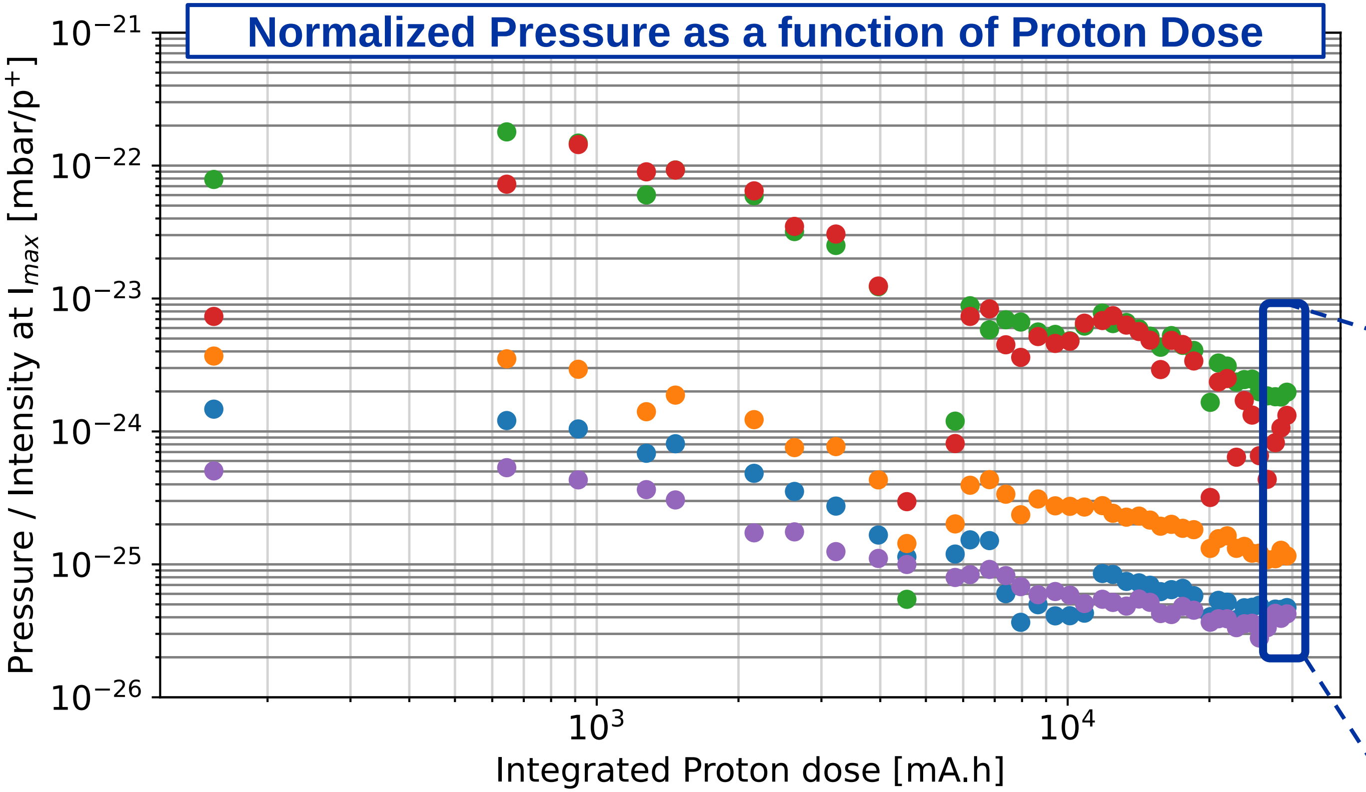
Mian faults that cause downtime:

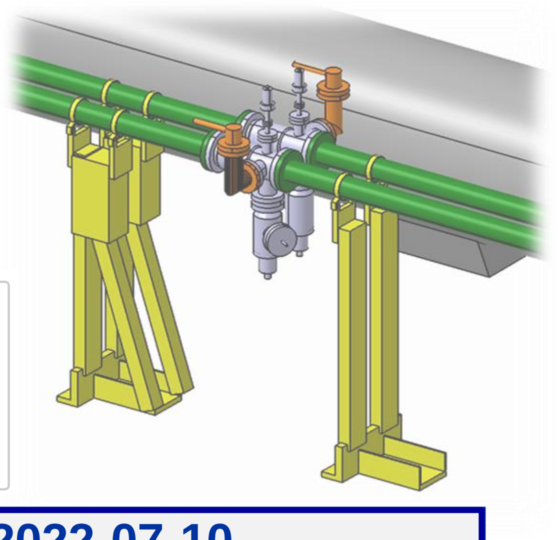
- Cryogenics and cooling tower incident on 23/8/2022
- Injector complex
- UFOs
- Training quenches in operation
- RF trips, klystron replacement
- Electric perturbations

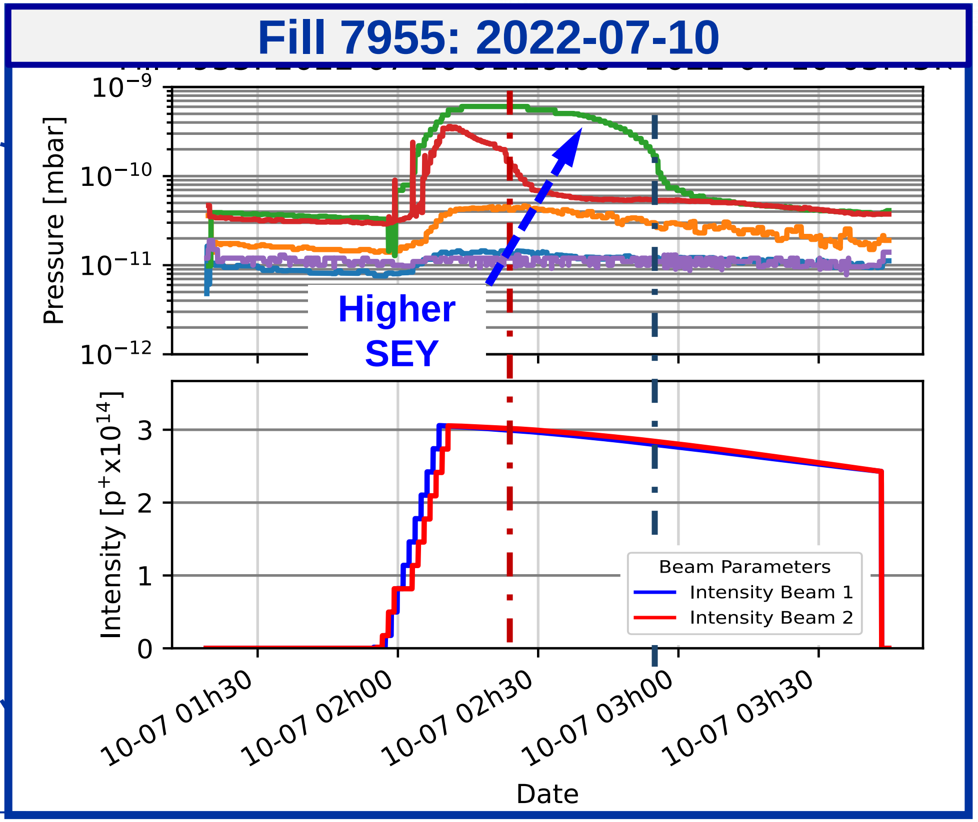


3 Vacuum faults
Total downtime time of ≈ 5h

LHC SCRUBBING RUN
History Dependence in Baked Sectors





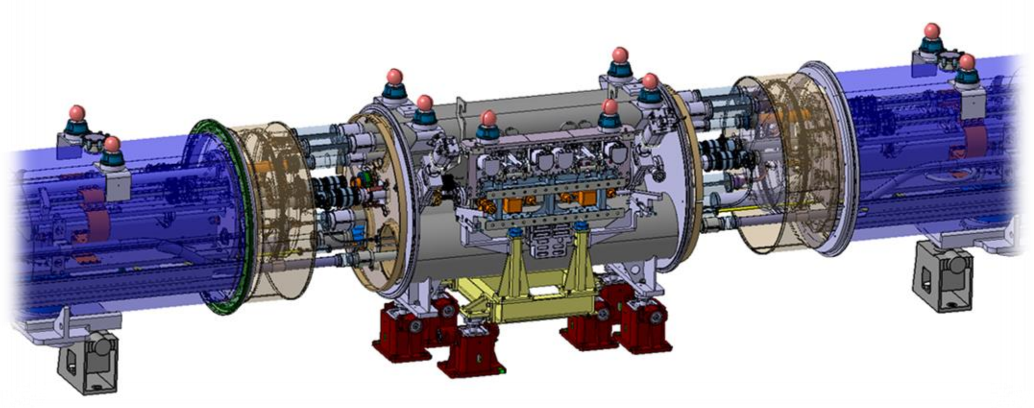


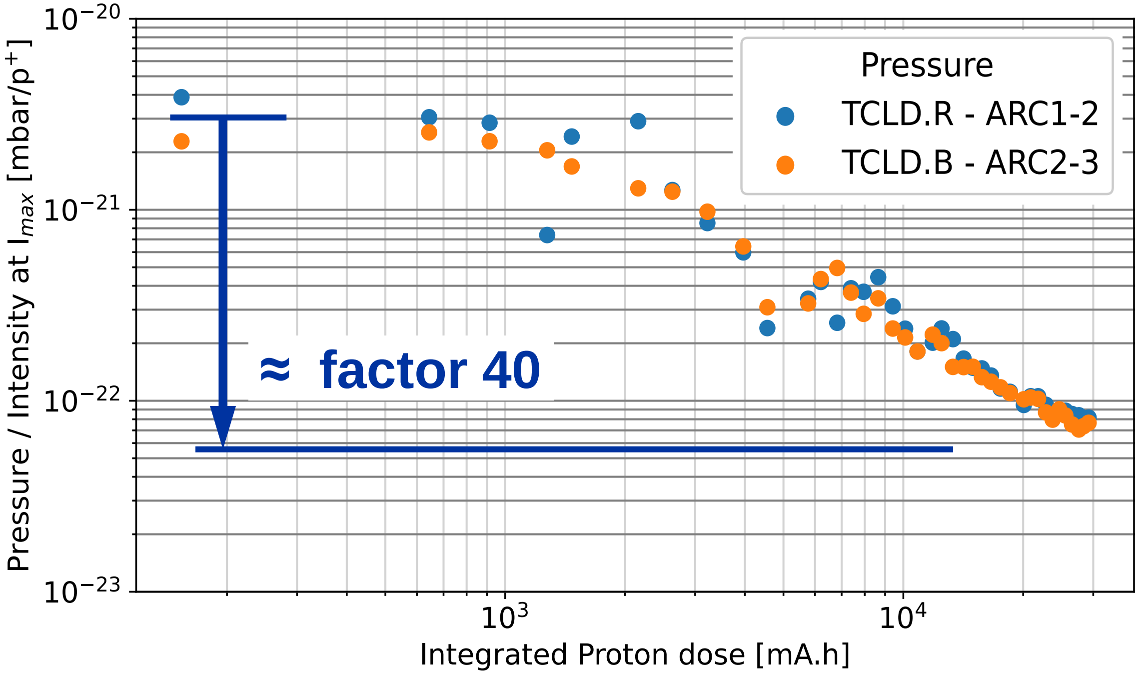
Vacuum performance analysis must consider sector history:

- Pressure measurements spanning 2 orders of magnitude.
- Differences between LS1 and sectors that were never vented are still seen.
- In some locations we are at the multipacting threshold for this intensity/energy.

LHC SCRUBBING RUN
TCLD Collimators

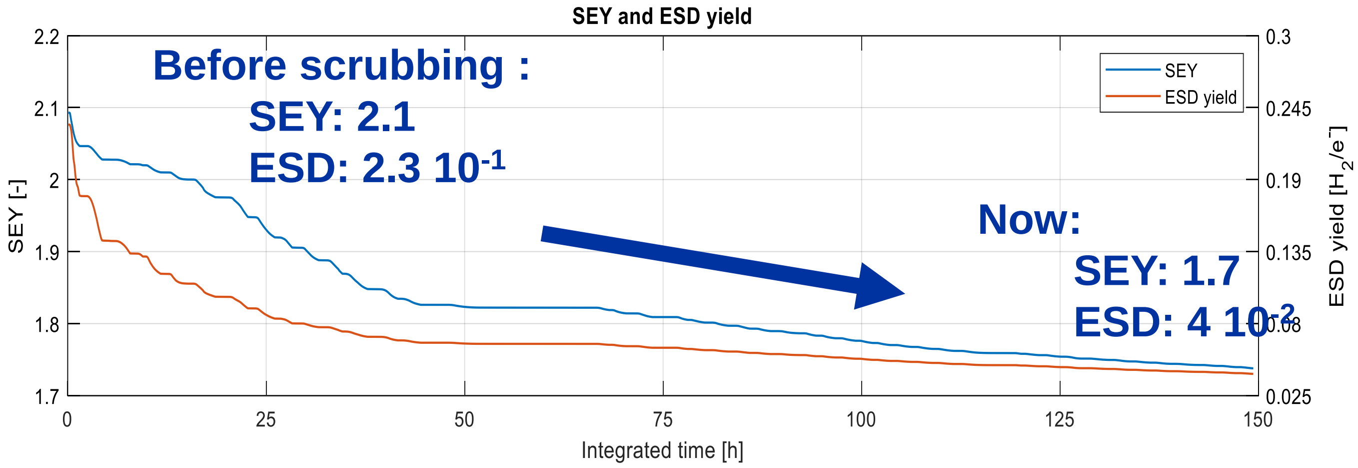
First room temperature sector in LHC ARCs



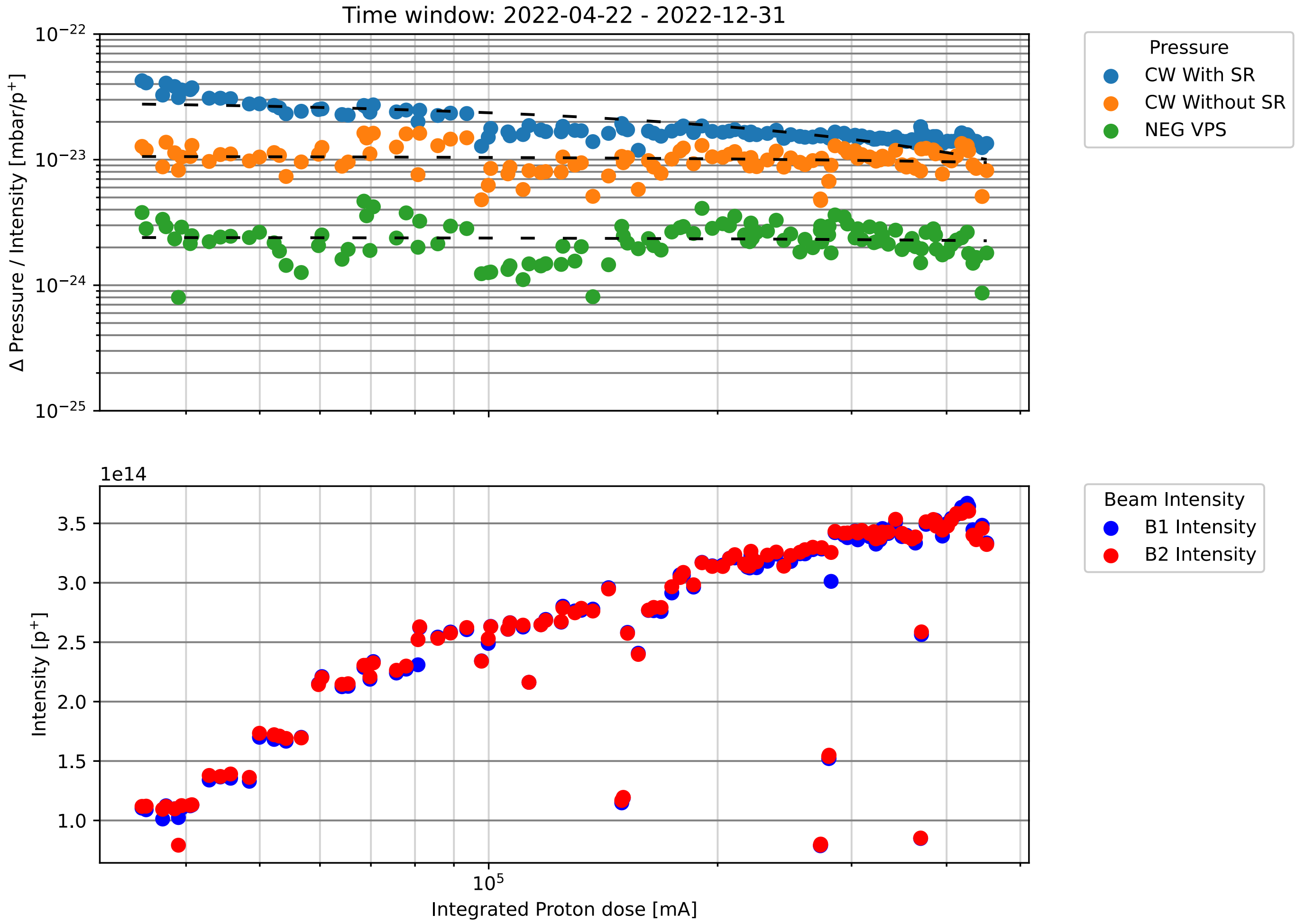


Factor 20 decrease of pressure at maximum intensity, down to low 10^{-8} mbar.

- **Completely un-scrubbed surface: known initial surface state**
- **Possible to estimate ESD and SEY from:**
  - Experimental conditioning curves.
  - TCLD pressure evolution



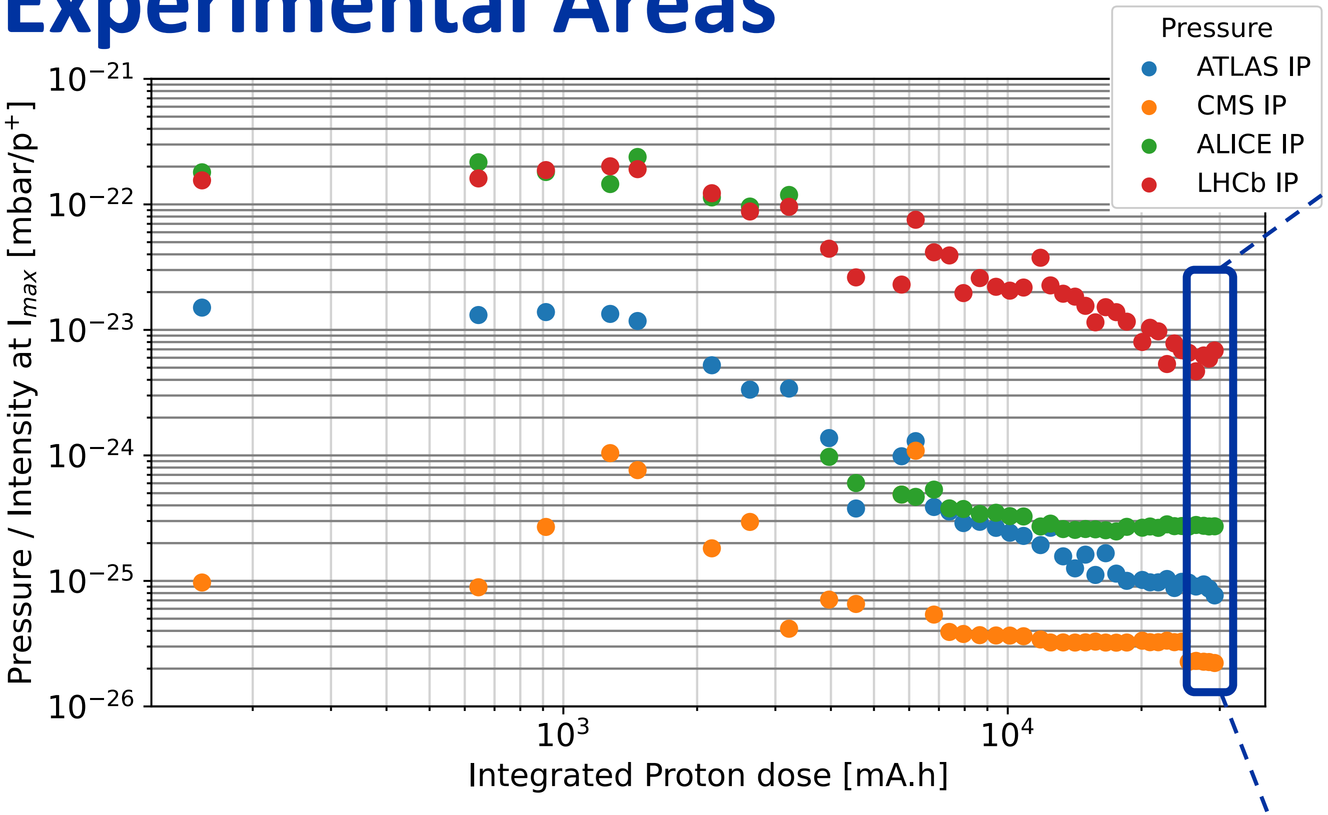
LHC VACUUM PERFORMANCE
Room temperature areas

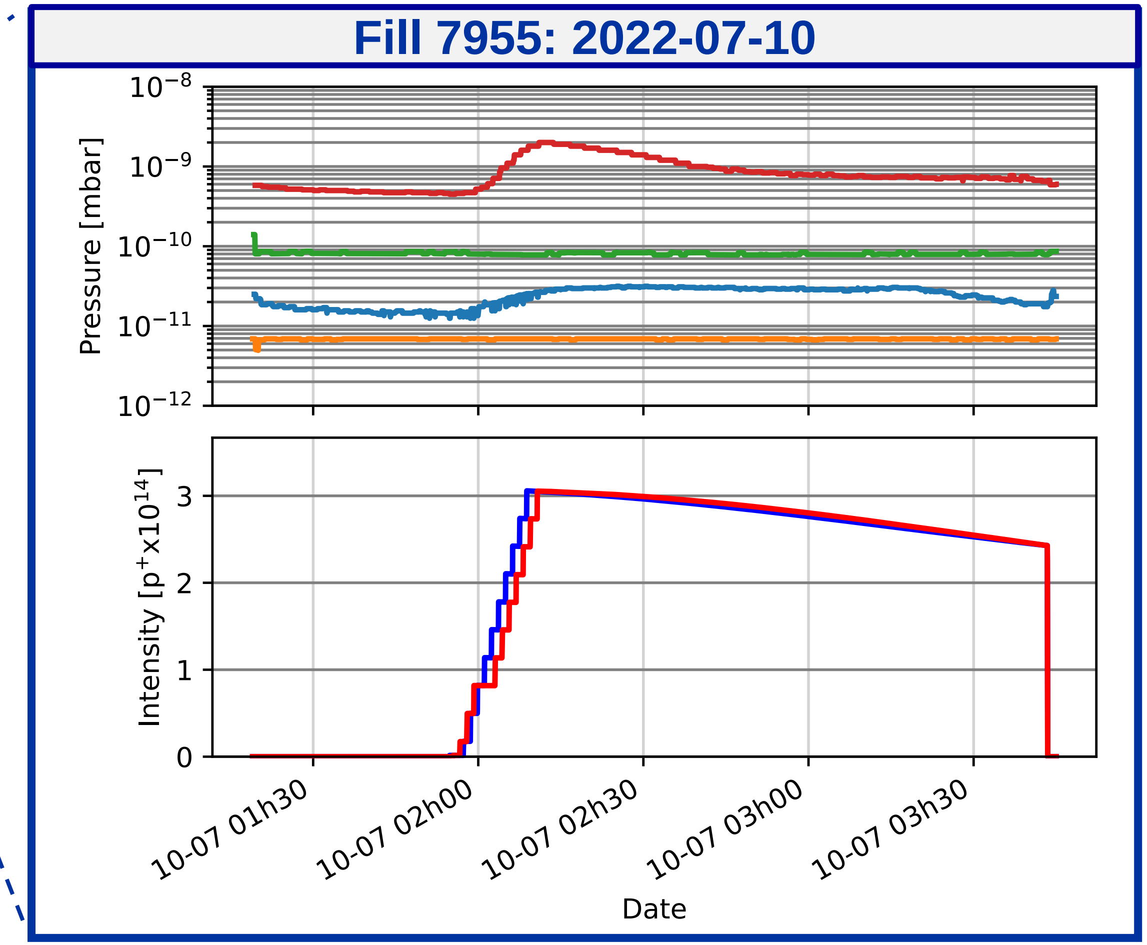


- NEG SVT: Dedicated **NEG** pilot sector -> Pressure ≈ $5 \cdot 10^{-10}$ mbar
- Cold Warm Transition **with Synchrotron Radiation** -> Pressure ≈ $5 \cdot 10^{-9}$ mbar
- Cold Warm Transition **without Synchrotron Radiation** -> Pressure ≈ $1 \cdot 10^{-9}$ mbar

Conditioning/scrubbing of the internal surface due to photons and electrons bombardment

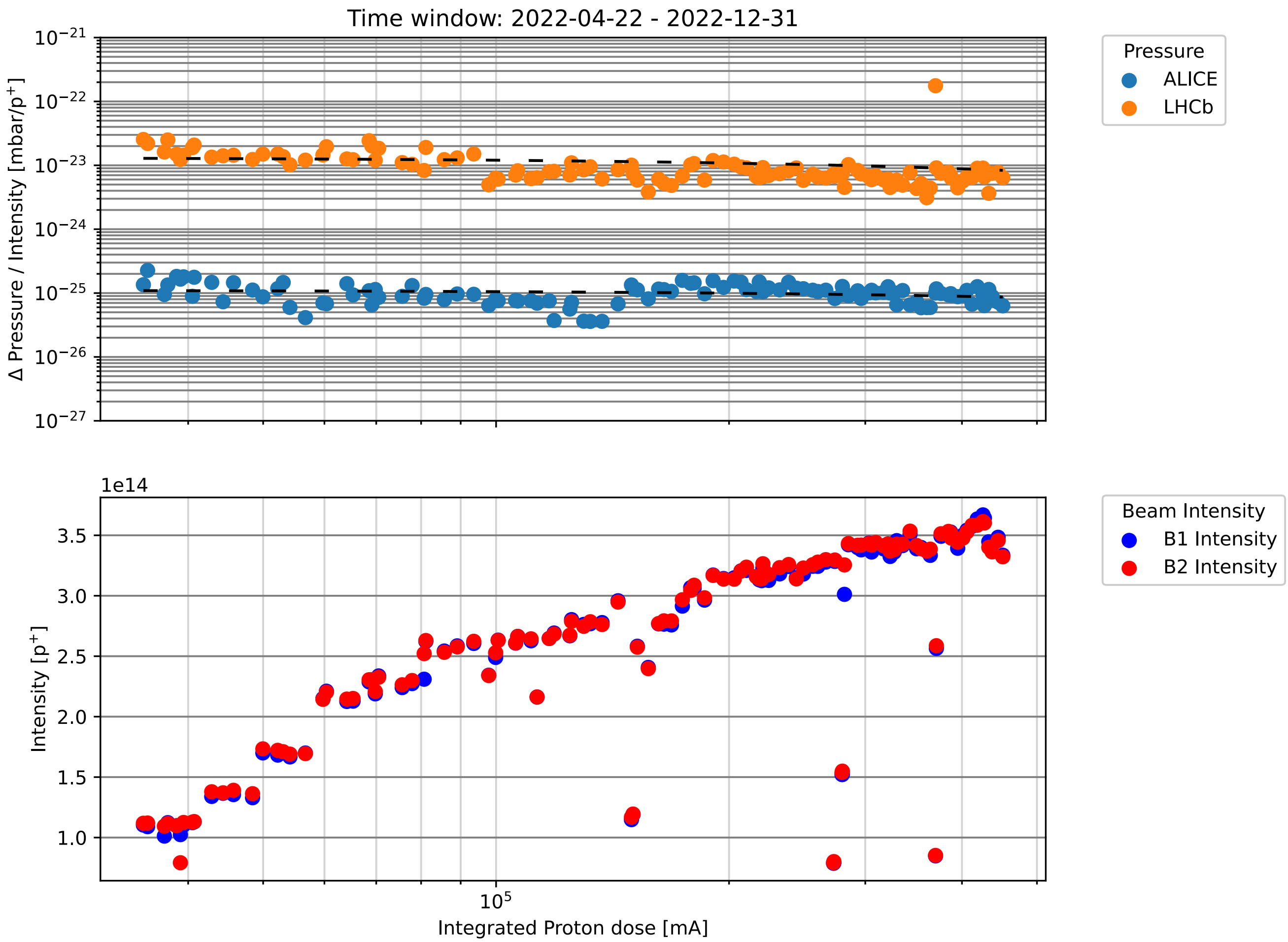
LHC SCRUBBING RUN
Experimental Areas





- **Conditioning observed in ATLAS and LHCb**
- **In CMS and ALICE:**
  - No visible multipacting if the solenoid ON
  - Pressure readings affected by magnetic fields

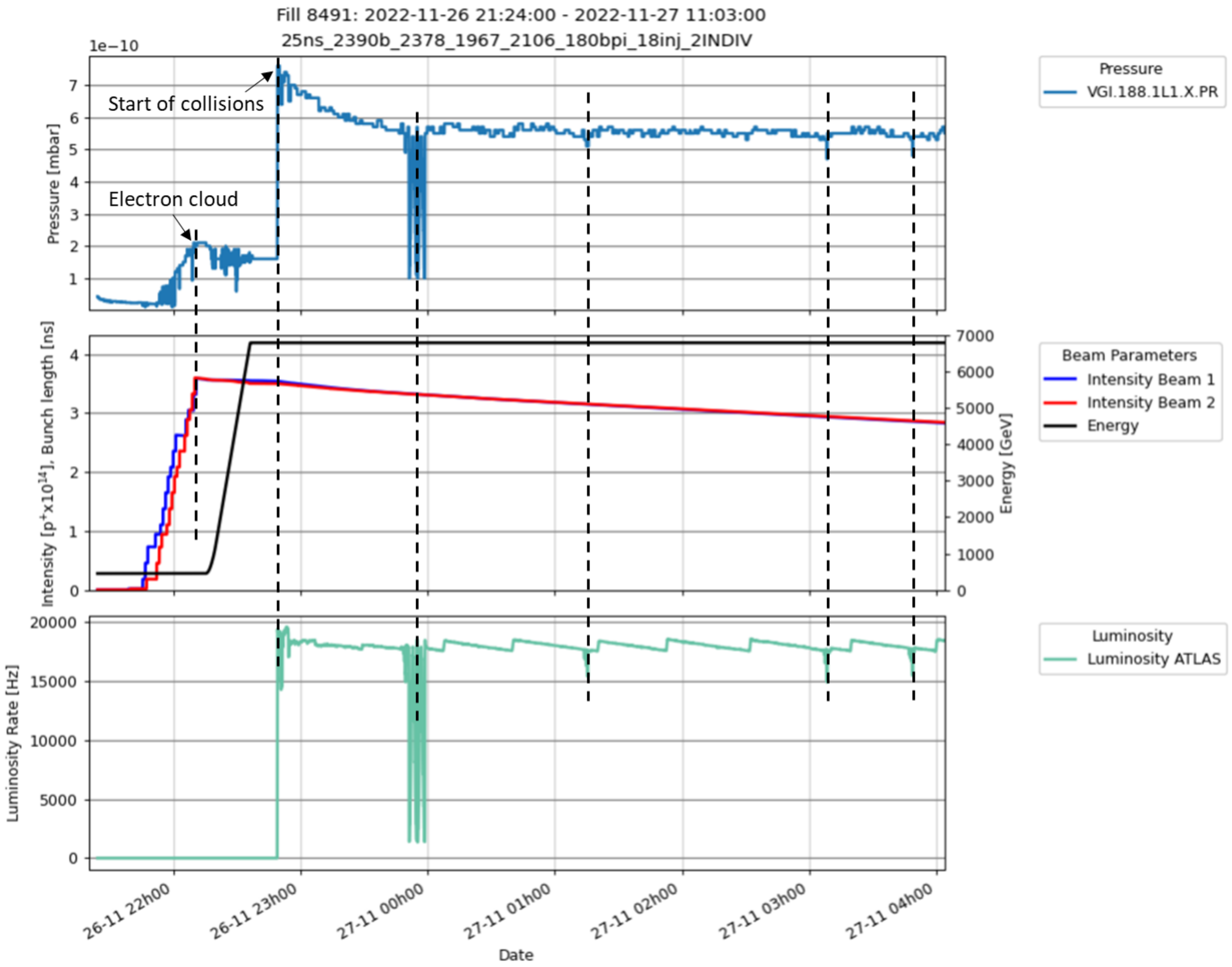
LHC VACUUM PERFORMANCE
Experimental Areas: ALICE & LHCb



- Pressure ≈ **10^{-9} mbar for LHCb**
- Pressure ≈ **10^{-11} mbar for ALICE**

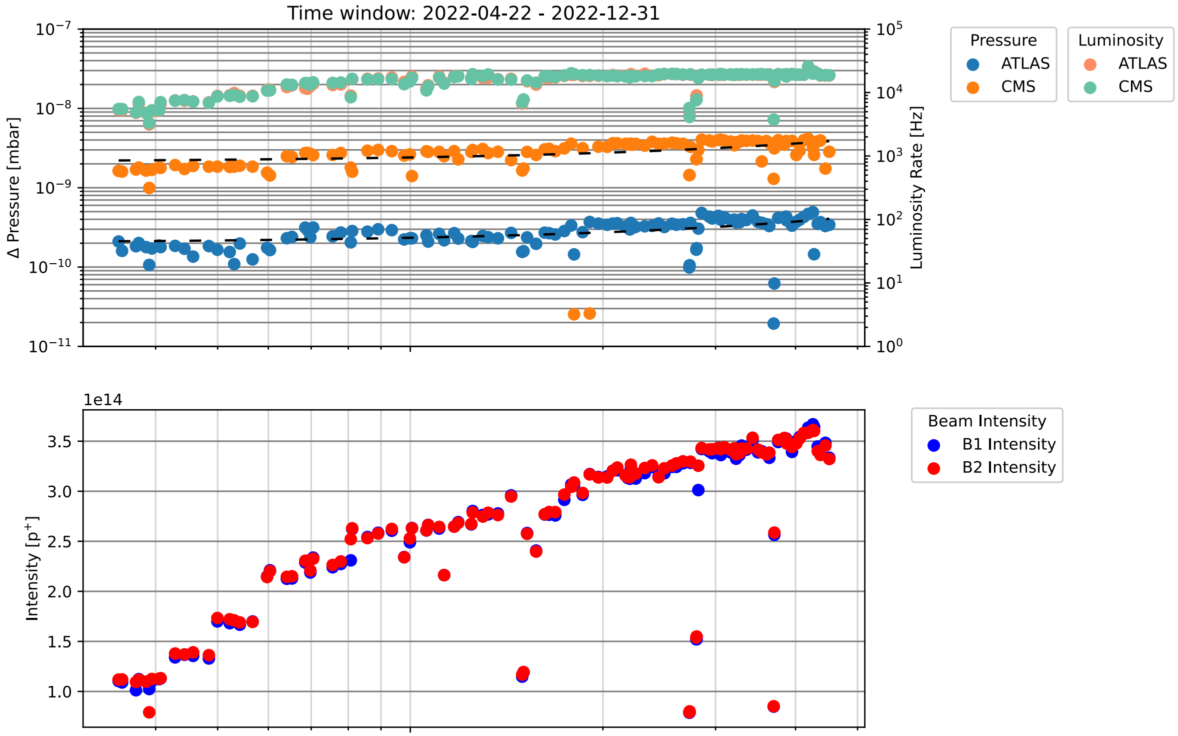
LHC VACUUM PERFORMANCE
Experimental Areas: ATLAS pressure as a function of beam parameters

- Typical pressure rise during a physics fill: ATLAS.
- Three main pressure peaks during one typical physics fill.
    1. Electron Cloud @ injection
    2. Synchrotron Radiation from the inner-triplets during ramp
    3. Related to collision.

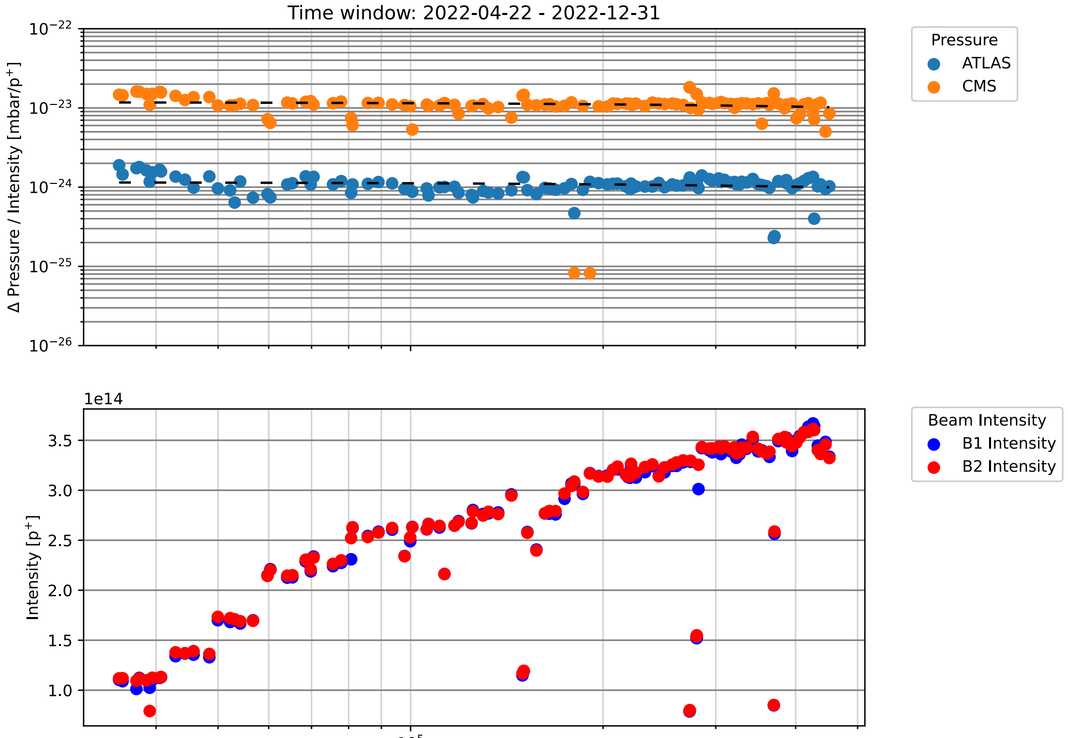


LHC VACUUM PERFORMANCE
Experimental Areas: ATLAS & CMS

Pressure evolution & Luminosity



Normalized pressure to intensity

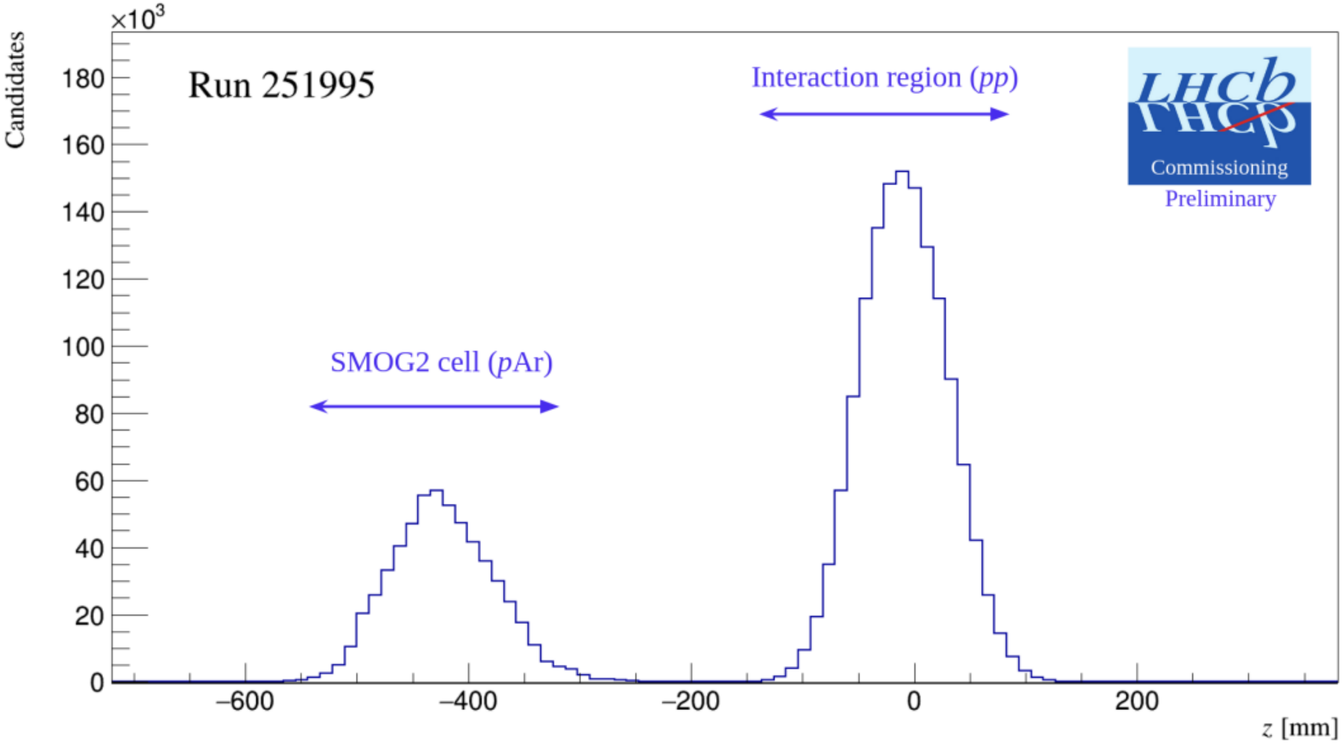


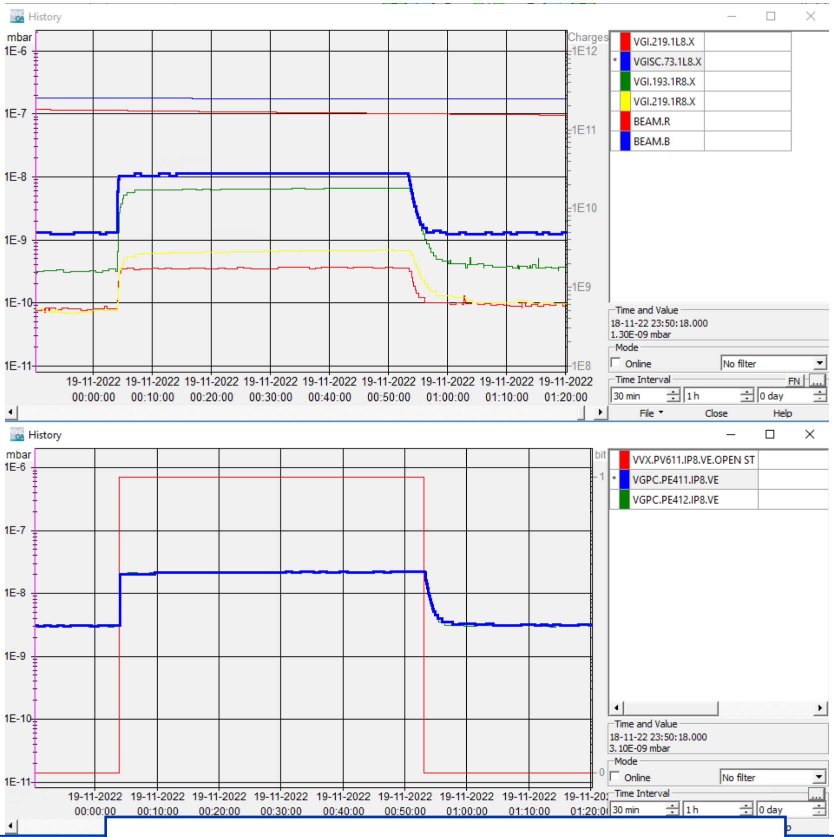
- ➢ **Pressure reading in the high luminosity experiments is dominated by induced noise on the cables of the gauges**
- ➢ **Around ATLAS & CMS what we are measuring is the luminosity (beams collision effects) more that gas density!**

LHCb experimental beam vacuum IP8.X

TE-VSC Support to the LHCb during 2022

- Injections in both SMOG 1 & 2 regimes for VdM Scans (for all experiments)

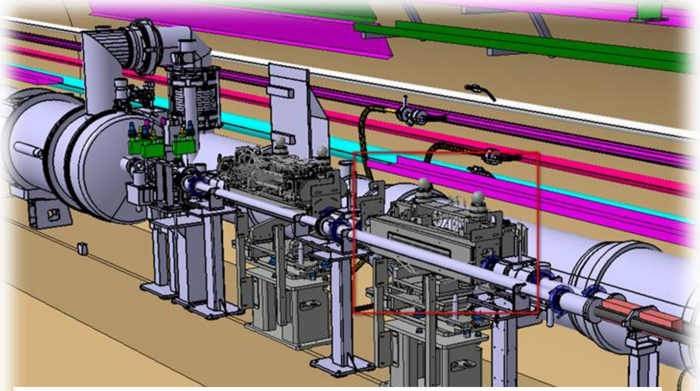




LHCb is the world first experiment taking data simultaneously in beam/beam & beam/gas regime
The second interaction point provided by TE-VSC ☺

SMOG2 Argon injection as seen by VELO and Machine

LHC YETS 22-23: Overview of Activities



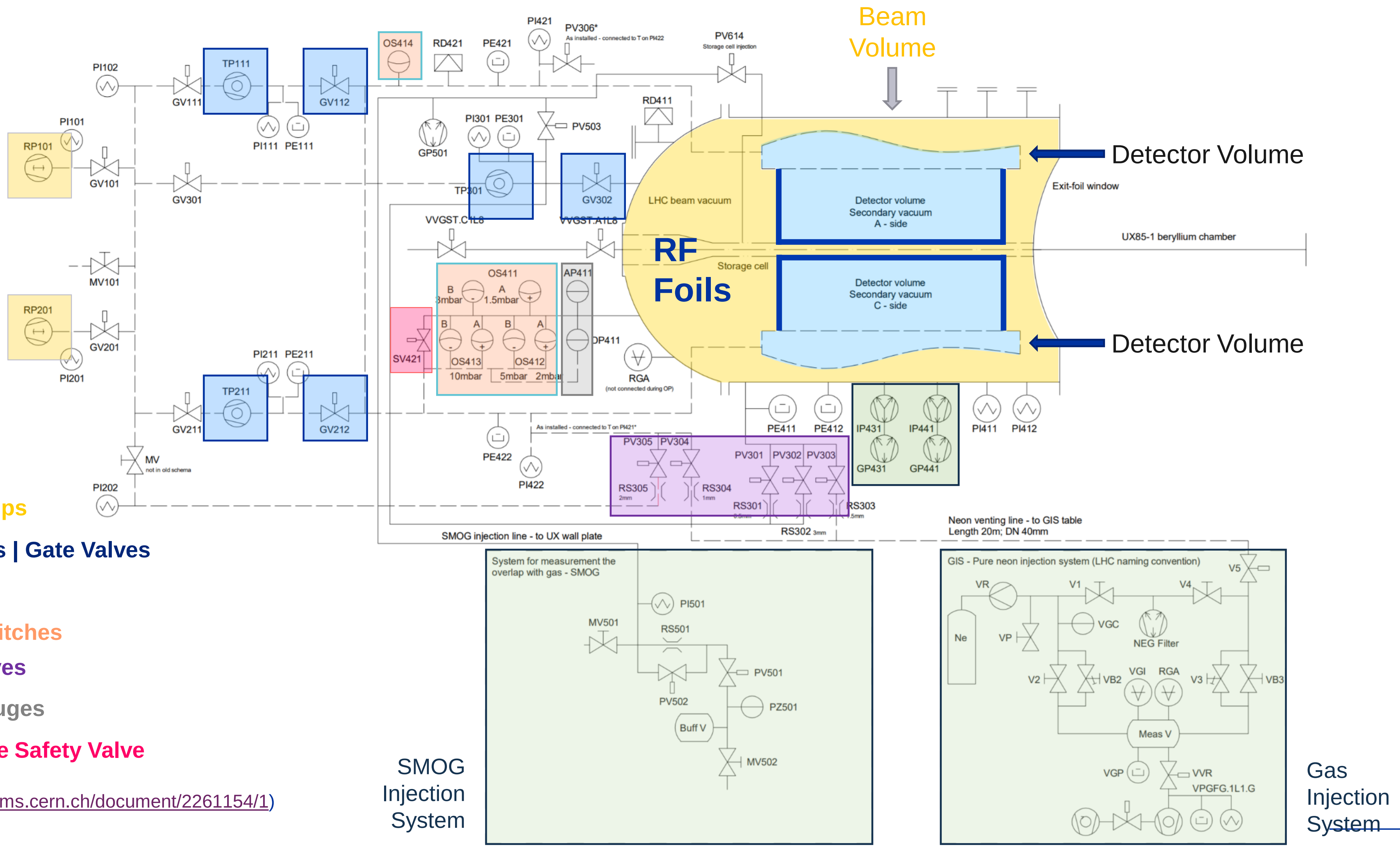
Leak found on a TCTPV edge welded bellow (A4L8.X)

MKB Consolidation

Where	Sector	Activity	NEG activation
LSS6	MKB	Upgrade with NEG cartridges	N
LSS4	E5R4.B	BWS Maintenance	Y
	E5R4.R	BSRTM mirror exchange	Y
	E5L4.R	Pressure spikes (tbc)	Y
	C5L4.B	BGC installation	N
LSS7	A4L7.B	TCPCH.A4L7.B1 Exchange	Y
	A5R7.R	TCPCH.A5R7.B2 Exchange	Y
	A4R7.R	Sector valve exchange	Y
LSS8	E5R8.R-B	MKI Cool Installation	Y
	G5R8.R-B	MKI Cool Installation	Y
	A4L8.C	Leak on a TCTPV	Y
-	-	Sector valve consolidation in high radiation area	N

LHC team

The VELO Vacuum System



Primary Pumps

Turbo Pumps | Gate Valves

Ion Pumps

Pressure Switches

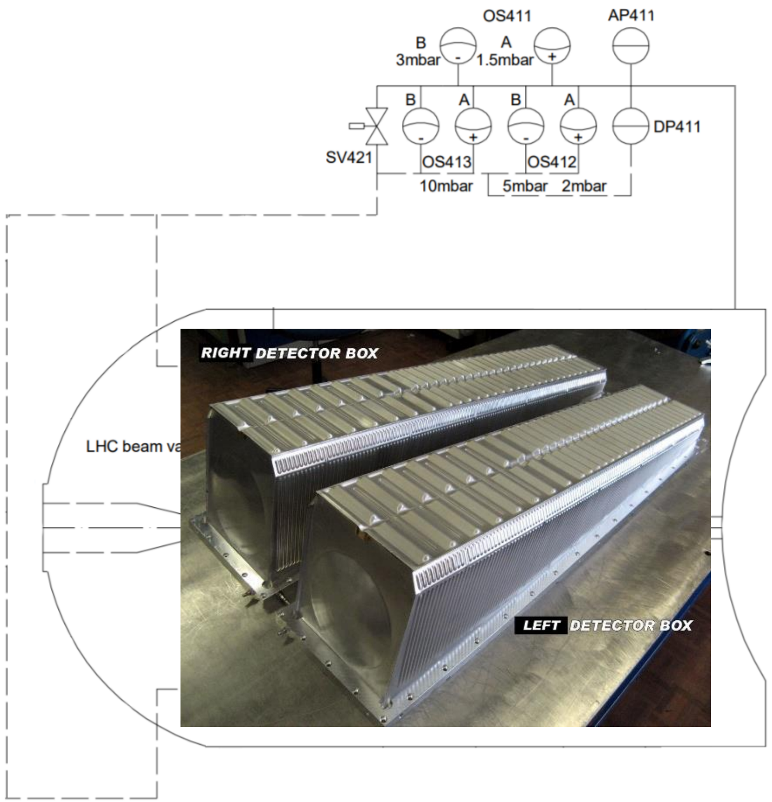
Process Valves

Baratron Gauges

Overpressure Safety Valve

J. Sestak (https://edms.cern.ch/document/2261154/1)

The RF Foils



The Beam and Detector volumes are separated by two extremely delicate aluminum foils, NEG coated on the Beam side.

Finite-element simulations have shown that the foils will become irreversibly deformed if the differential pressure between Beam and Detector volumes reaches ≈ 20 mbar and that even below this value they might touch the detectors. They will eventually rupture if the pressure value reaches a few hundred mbar [1].

[1] - Technical Design of the LHCb VELO Vacuum System (https://edms.cern.ch/document/901534/1)

Damaging the foils will effectively render the LHCb experiment inoperable, so it is of the utmost importance that we keep the differential pressure under control – below 10 mbar - at all times.

R.Ferreira – TE-VCS Seminar

Chronological events on the VELO vacuum system

- **Night 09-10 of January 2023:**
  - Both detector and beam vacuum at the same pressure of ultra pure Neon of ≈ 920 mbar
  - LHCb VELO team – warm up of the detector prior the AUG test
  - **23h11min - warm up of the detector starts**
    - Differential pressure on the detector side starts to increase (initial value -3.4mbar).
  - **23h25min – First balancing cycle DP between detector as beam vacuum reaches -5mbar**
    - Detector volume is overpressure compared to the beam vacuum volume. Vacuum Control System compensates by standard balancing cycles (+2/-5mbar).
  - **23h41min – Differential pressure reaches -6.8mbar (exceeded limit of -5mbar)**
    - VELO team stops the warming cycle and contact TE-VSC.
    - It was found that the exceeding of the DP is caused by low pressure of the neon in the gas injection system. This requires manual re-adjustment of the manometer at the UX85.
    - Also, as this is a first YETS warm-up we also need to understand pre-warm-up pressure in the beam vacuum in order to not overpressure the whole system with respect to the atmosphere.
    - Decision to stop the warm-up, revert the temperature and wait morning 10/01/2023.

Chronological events on the VELO vacuum system

- **Morning 10 of January 2023**
  - State over night was stable DP -2.4mbar without any balancing cycles.
  - **6h22min Pressure increase on the detector volume side**
    - Dry air stopped, Cooling plant stopped, uncontrolled warm-up of the detector.
  - **6h23min DP between detector as beam vacuum volume reaches -5mbar**
    - Balancing system tries to compensate the DP by injection, increase on the detector side continues quickly in non-controlled way.
  - **6h24min DP between detector as beam vacuum volume reaches -8.8mbar**
    - Vacuum control system receives signal from pressure switches referring to change of pressure being now >+2mbar on **beam volume** side AND both beam and detector volumes are >ATM pressure.
    - Standard reaction of balancing system in this case is to pump-down of the beam volume which system does using opening of PV301 process valve and TP301 turbo-molecular pump. Pressure on the beam vacuum side measured by absolute Baratron gauge 822mbar.

Chronological events on the VELO vacuum system

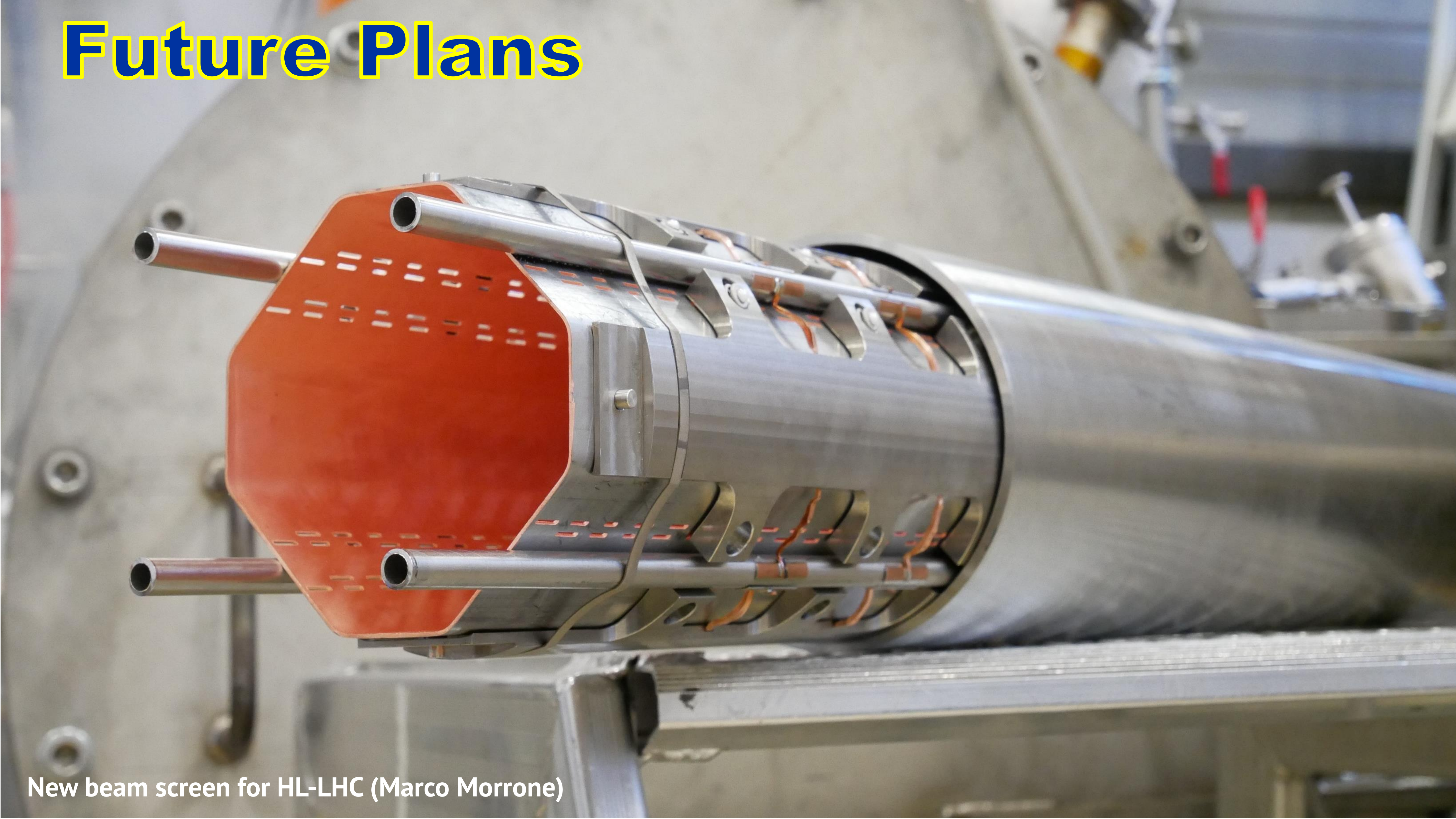
- **6h24min DP between detector as beam vacuum volume reaches -8.8mbar,**
- **6h25min DP between detector as beam vacuum volume reaches -9.8mbar and stabilizes.**

- **9h43min PV301 process valve manually disabled by TE-VSC**

- Pressure readout of absolute Baratron gauge on the beam vacuum at 9h43min 659mbar.
- P reduced by pump-down ≈ 160 mbar on the beam vacuum side
- P Increase on the detector volume due to warm-up ≈ 40 mbar

Under study the possible damage and future action

Future Plans



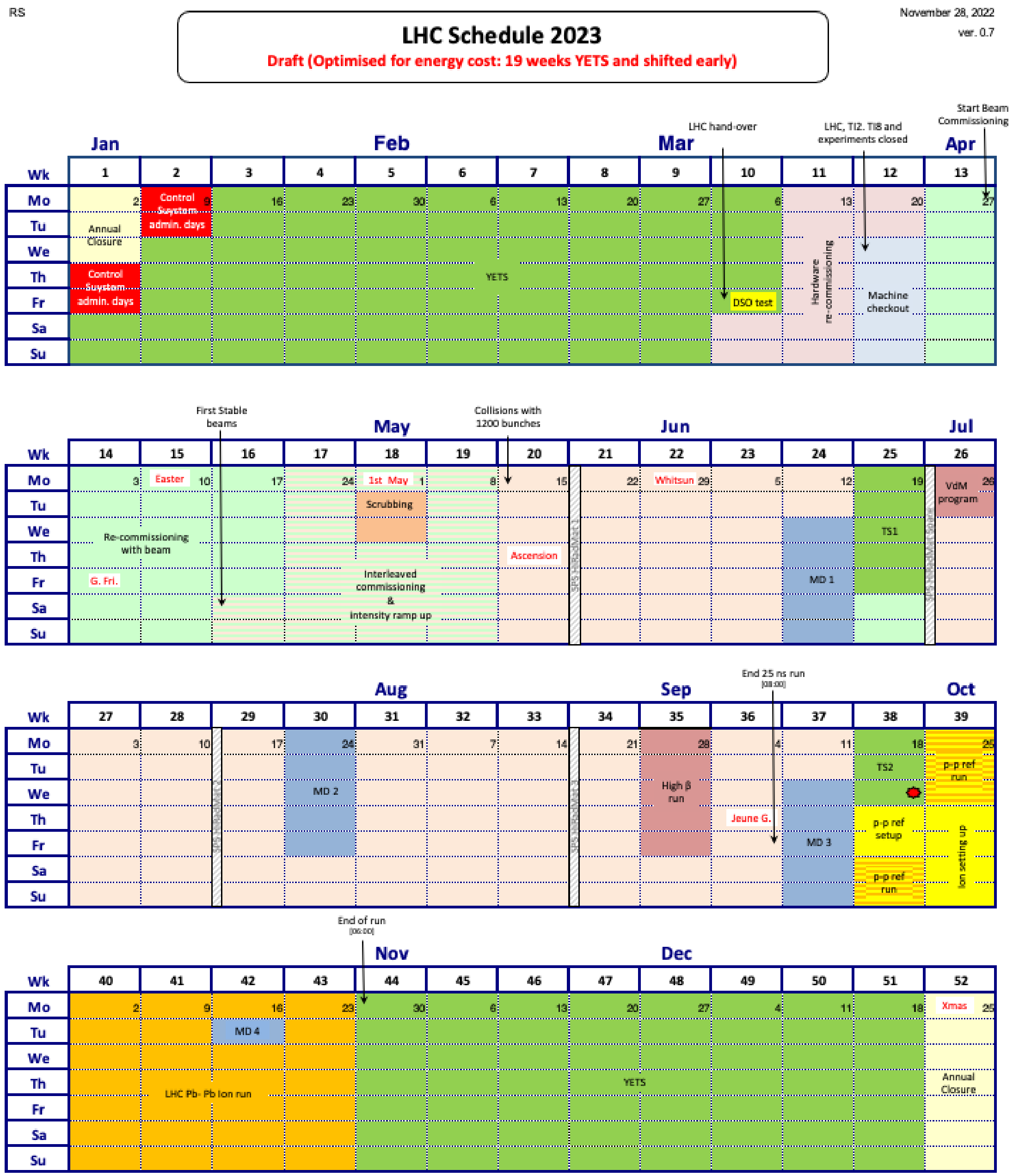
New beam screen for HL-LHC (Marco Morrone)

The 2023 Draft LHC Schedule in Numbers

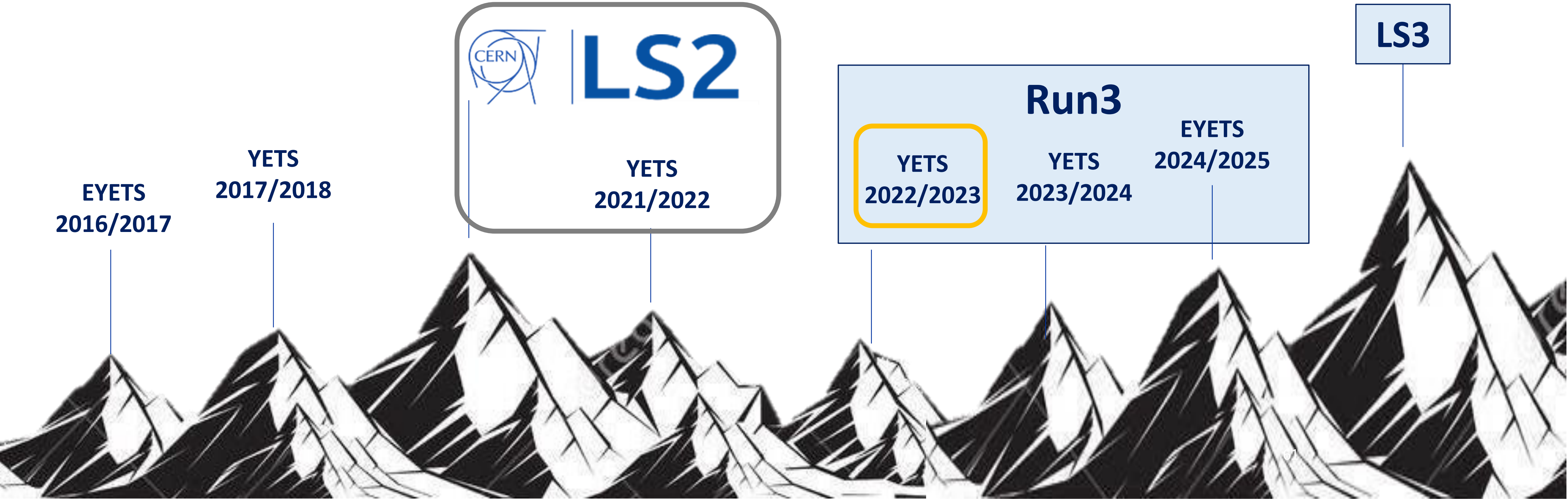
Activity	Duration [days]	Ratio [%]
Beam Commissioning & Intensity ramp-up	47	21.7
Scrubbing	2	0.9
25 ns physics (>1200 bunches)	**97**	**44.7**
Special physics runs (incl. setting-up)	**7**	**3.2**
Pb-Pb ions & p-p ref. setting-up	6	2.8
Pb-Pb ions physics & p-p ref. run	**32**	**14.7**
Technical stop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

If the beam commissioning goes faster than scheduled, the time gained will be to the benefit of physics time.

R. Steerenberg | LMC: Final Draft 2023 LHC Schedule

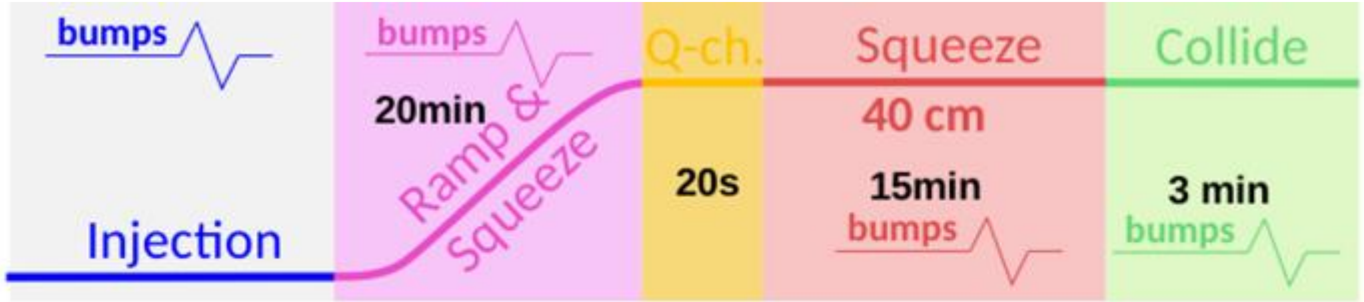


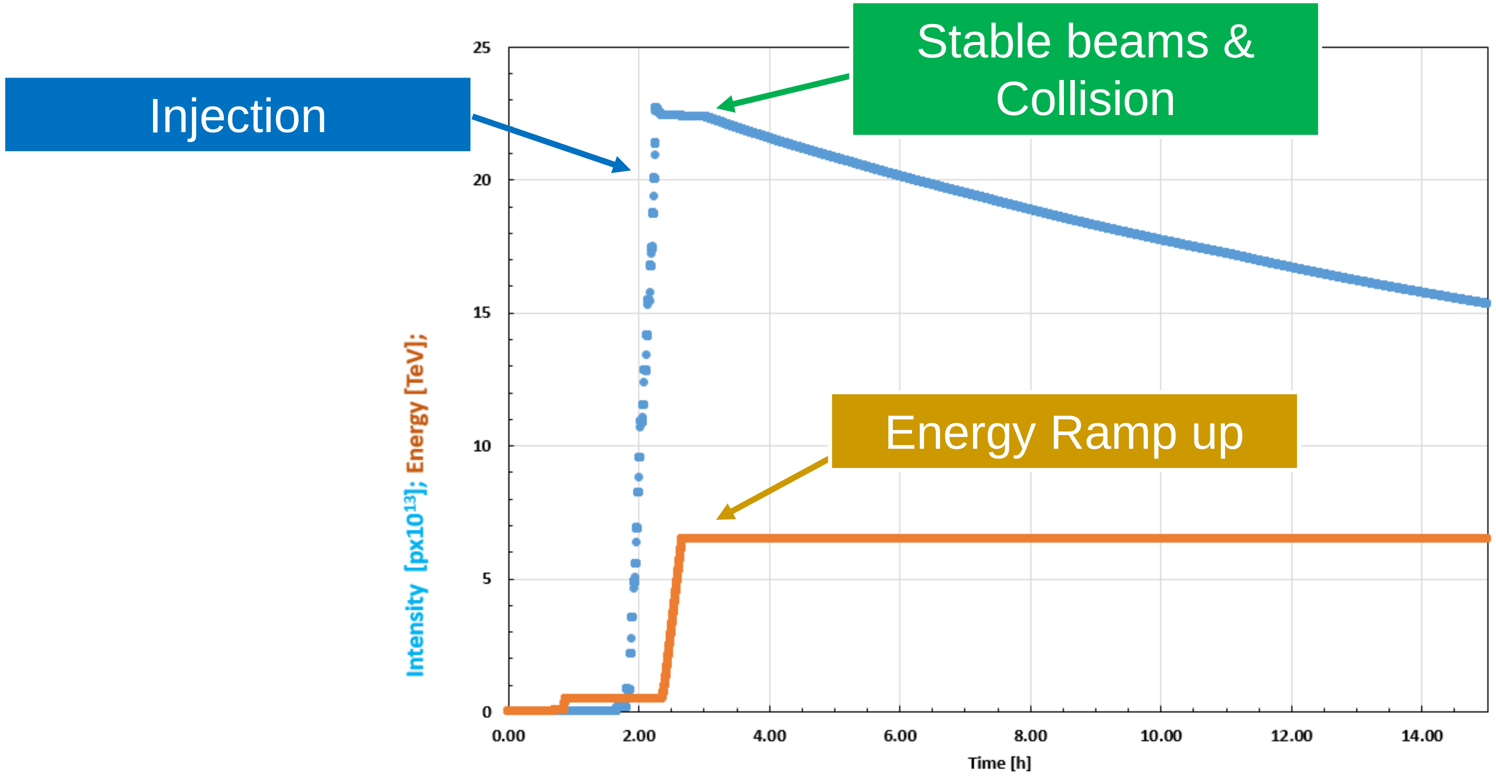
Conclusions



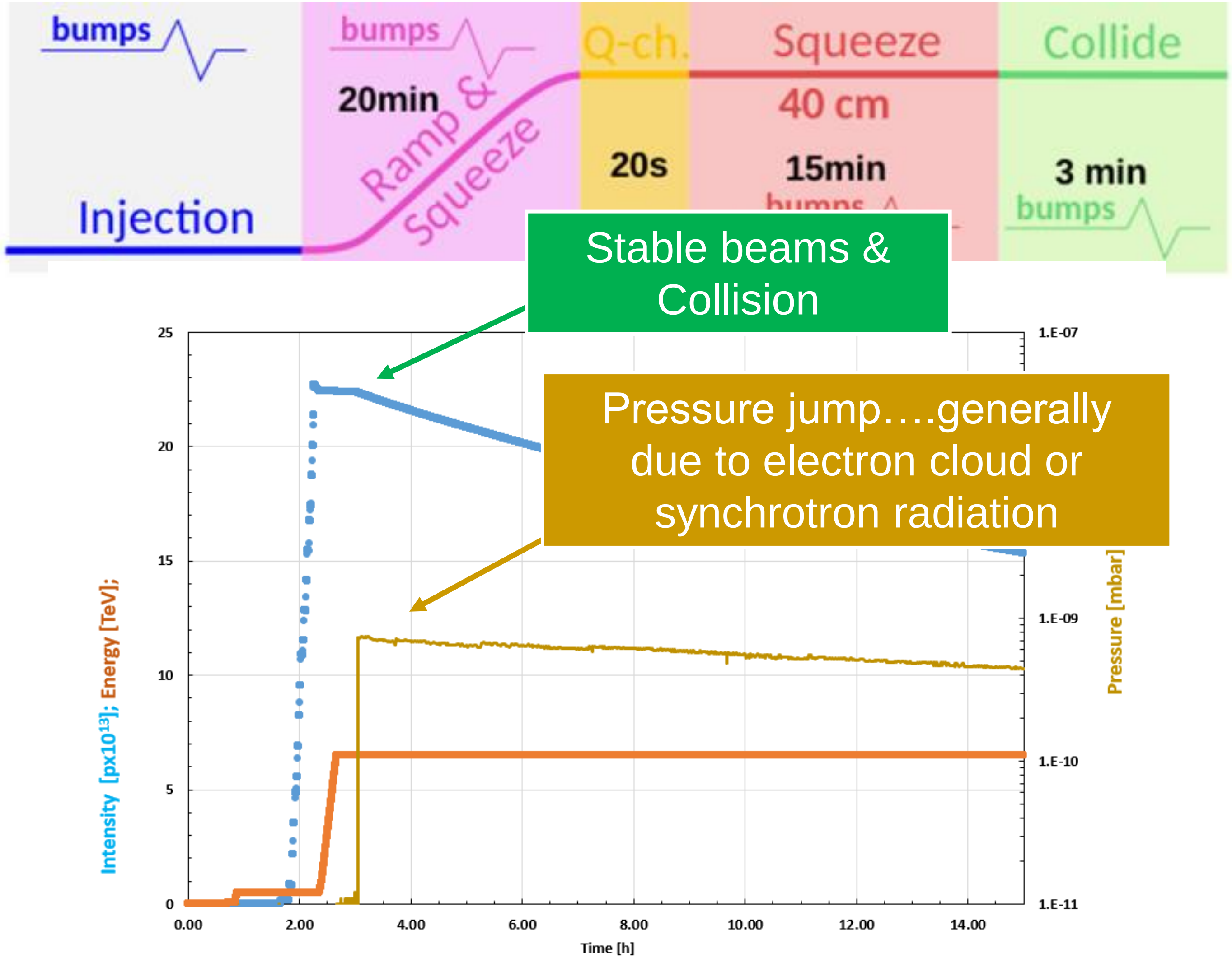
Thank you for your attention

LHC Filling scheme

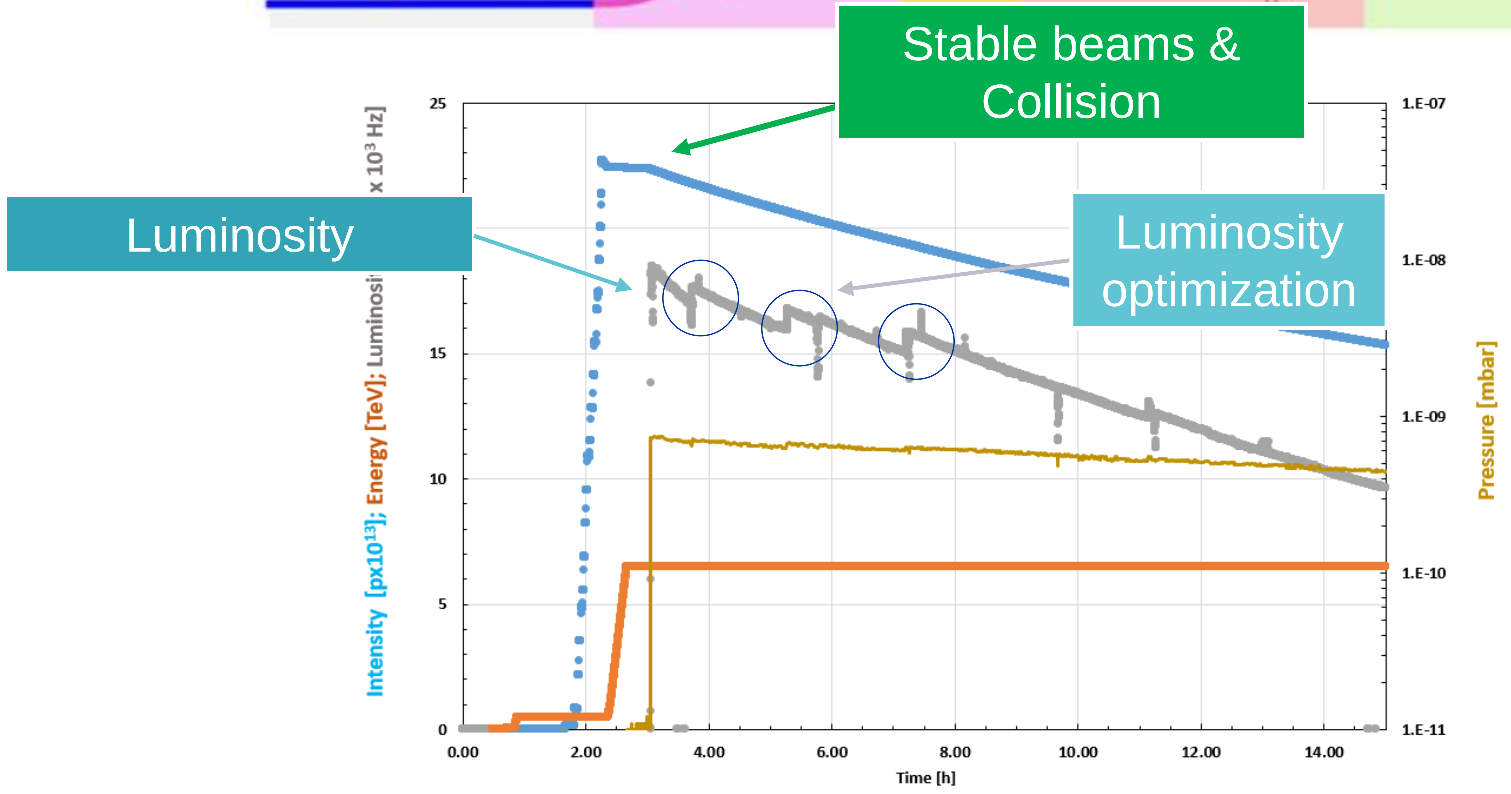




LHC Filling scheme

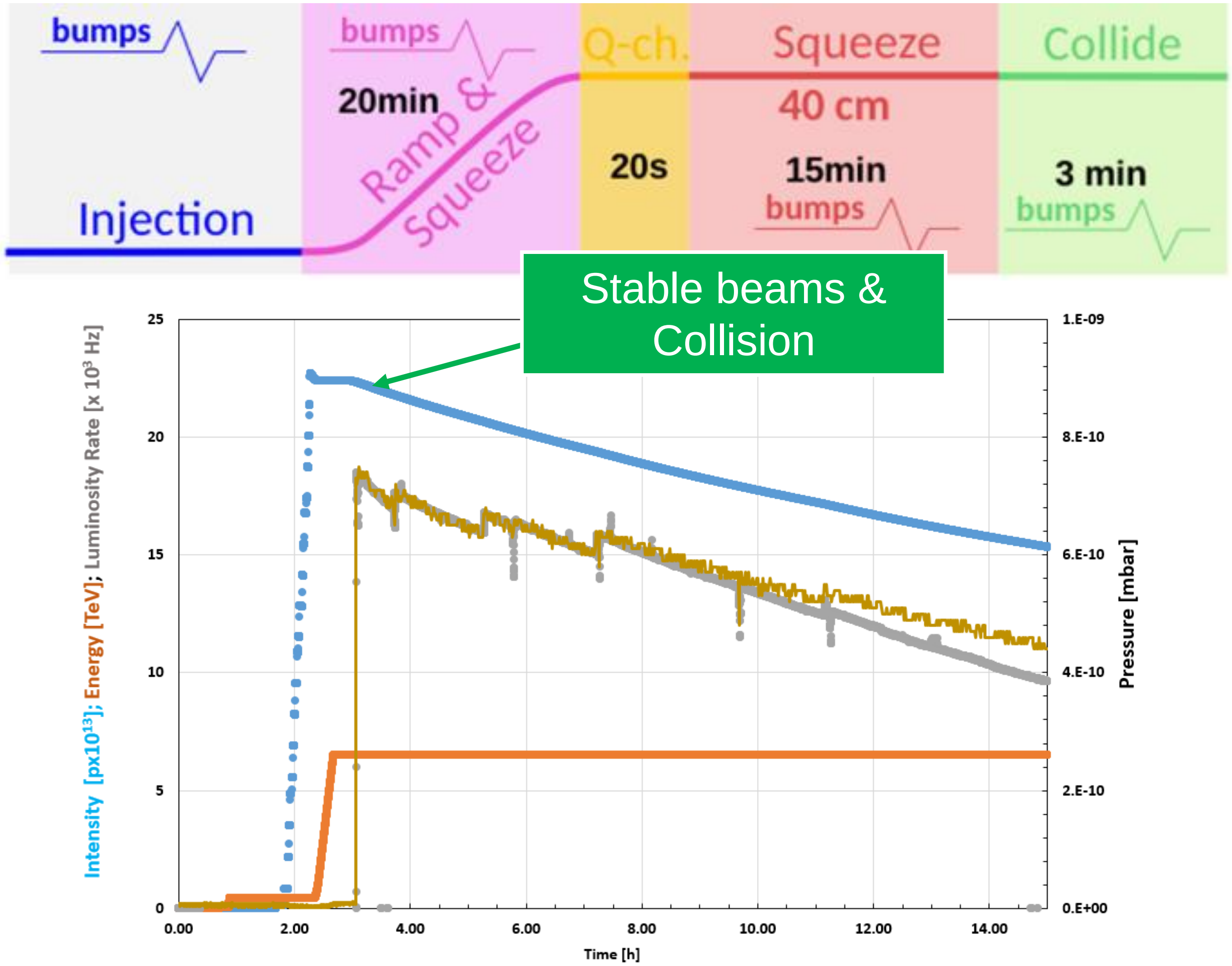


LHC Filling scheme



What if we fit the pressure in linear scale?

LHC Filling scheme



- Pressure reading in the high luminosity experiments is dominated by induced noise on the cables of the gauges
  - This phenomena is clearly visible up to ± 150 m from the

LHC / HL-LHC Plan