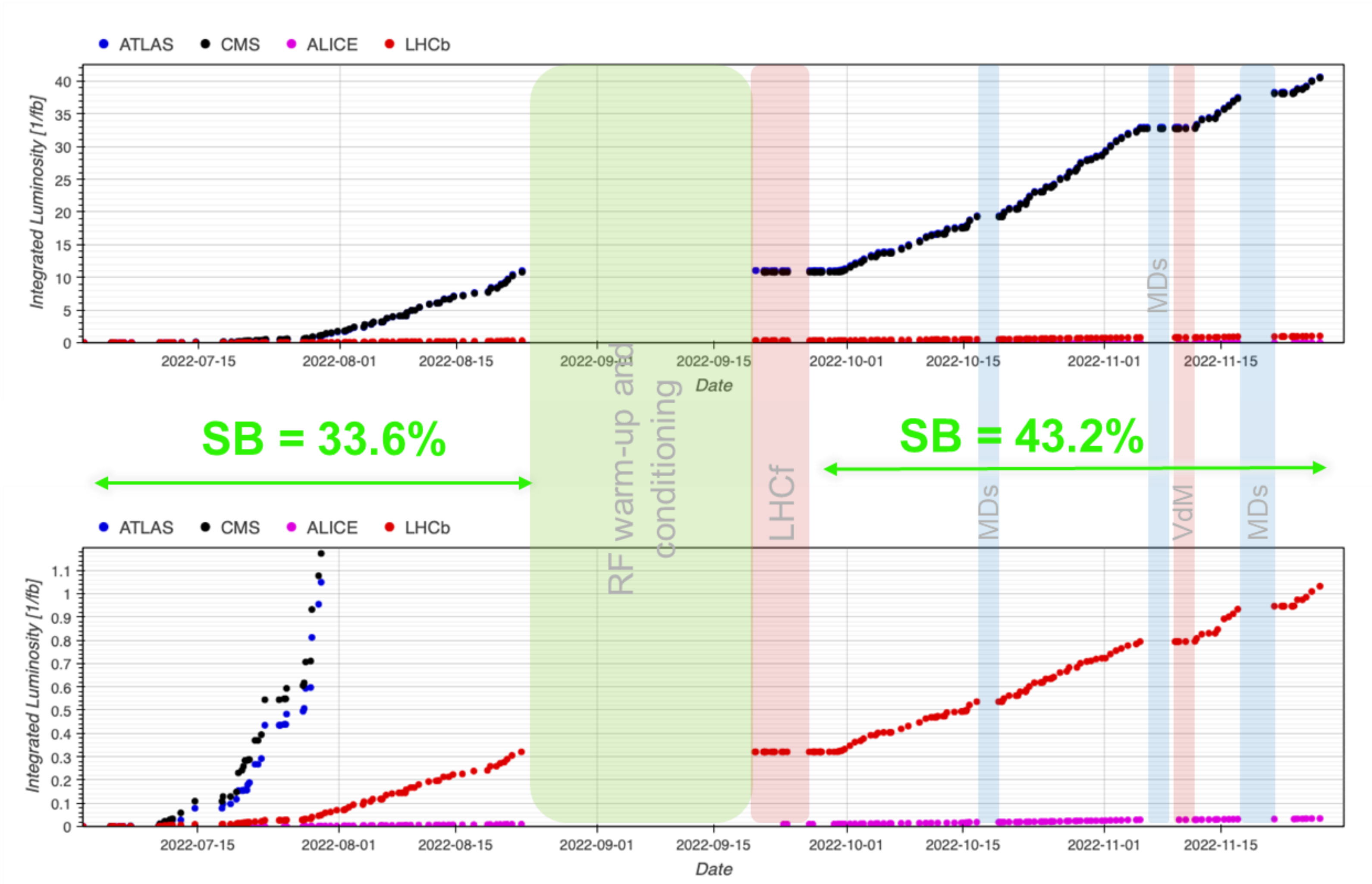
Status of the LHC

Dr. Rhodri Jones

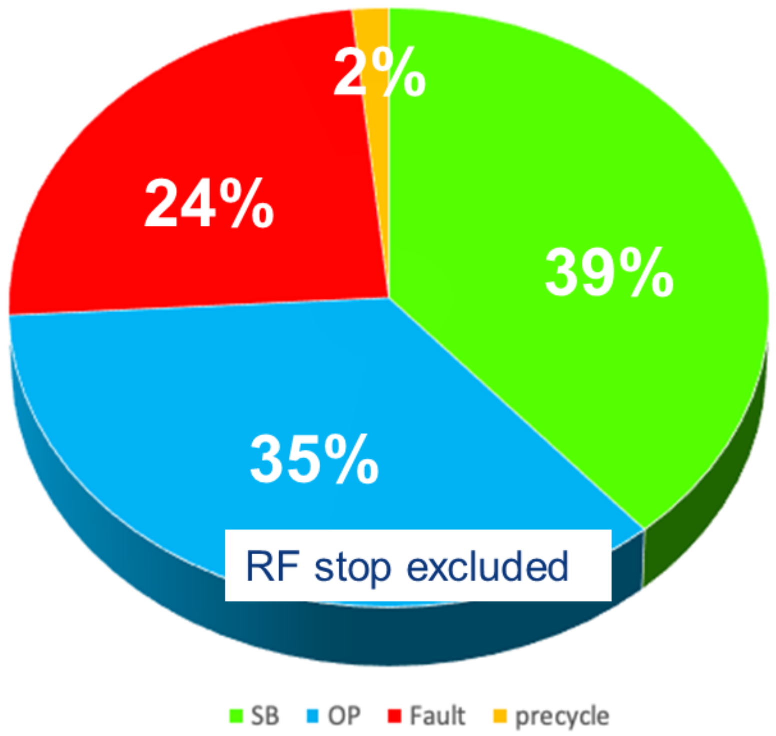
Head of the CERN BEAMS Department

22/05/2023

Recap of LHC Performance in 2022



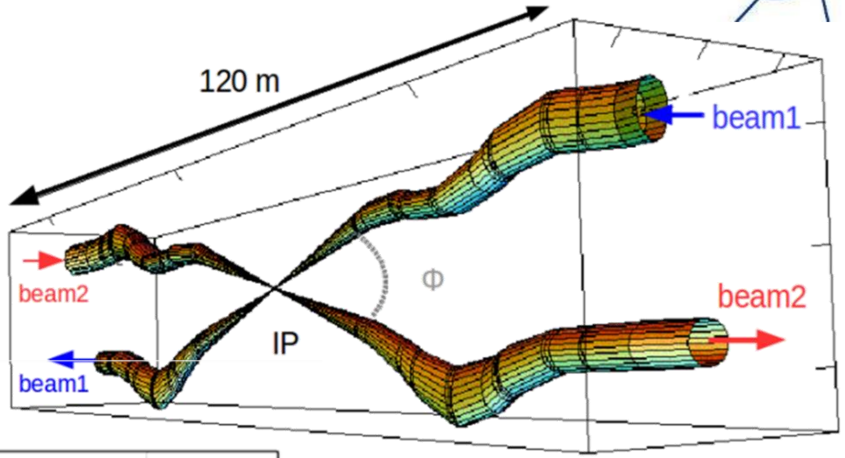
Machine availability = 76%

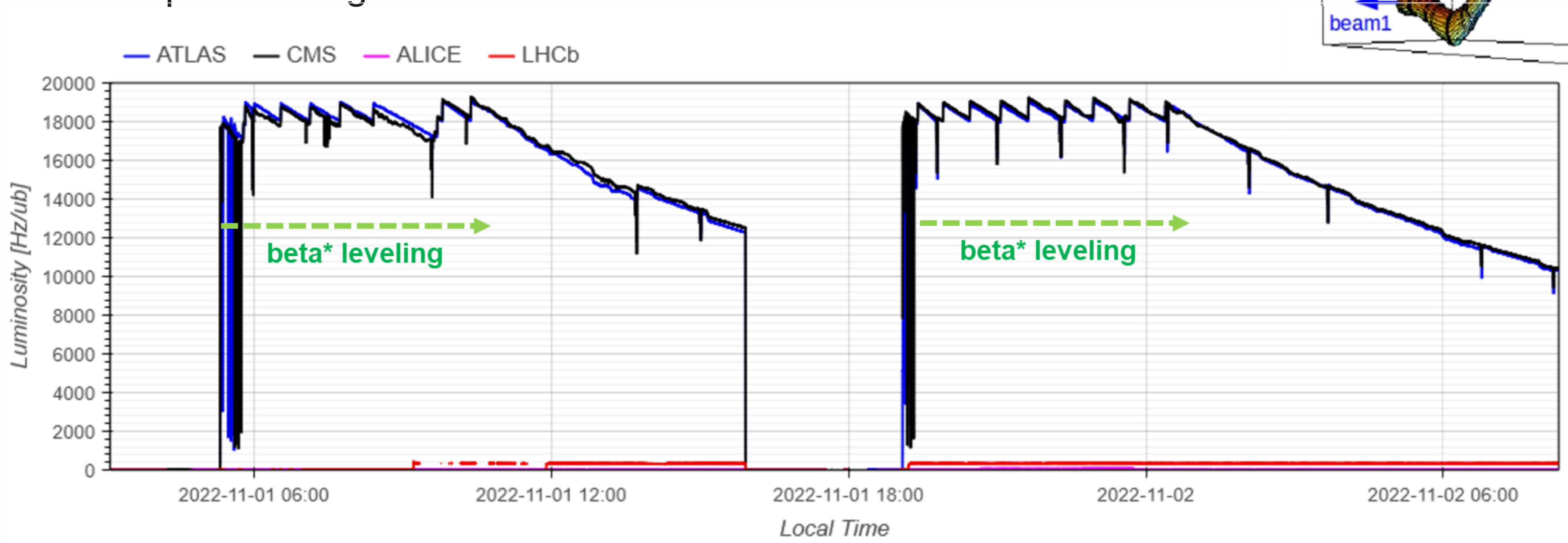


- **Striking performance** for first year after LS
- > 40 fb^{-1} to ATLAS/CMS
- ~1 fb^{-1} to LHCb
- 0.03 fb^{-1} to ALICE

What was new in 2022

- **Beta* levelling routinely used for first 5-6 hours of every fill**
  - Fully automated levelling for IP1 / IP5 (μ = 54 ± 2.5%)
  - Luminosity jumps below ~5% (as requested by Experiments)
  - Inner Triplet cooling for collision debris limited to ~2×10^{34} cm^{-2} s^{-1}

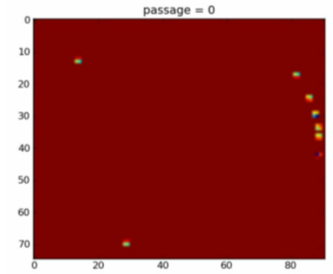


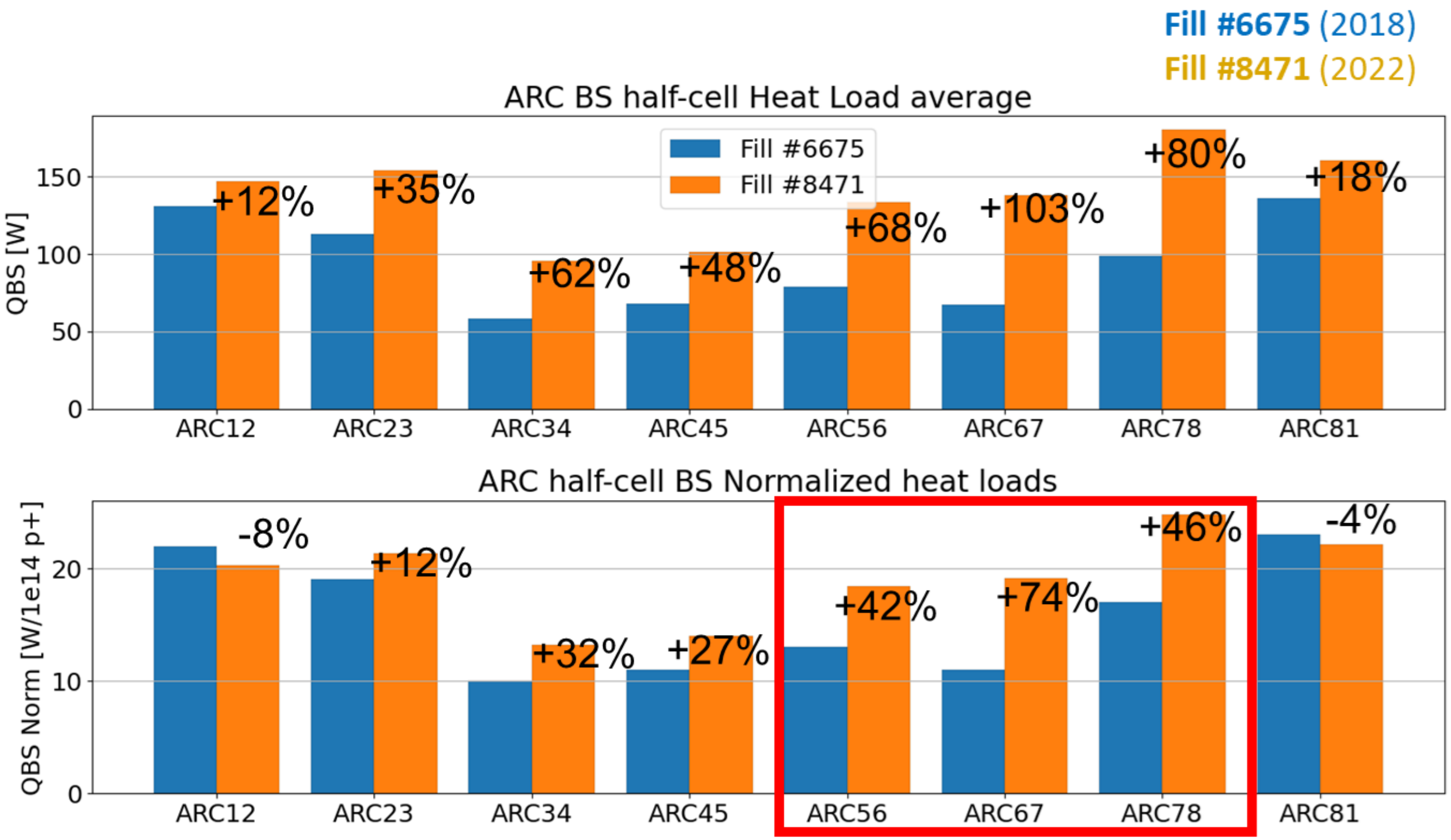


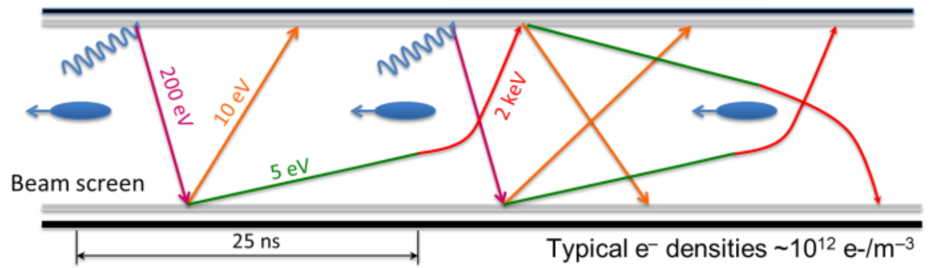
- **Crystal collimators demonstrate that machine is ready for Run 3 HL-LHC ion operation**
- **Quench test results underline that collimation system is ready for HL-LHC proton operation**

What we Learnt in 2022

- **Dealing with electron cloud**
  - Sector 7-8 emerged degraded from LS2, determining heat load limitation of LHC







Long Shutdown 1 (2013-2015)

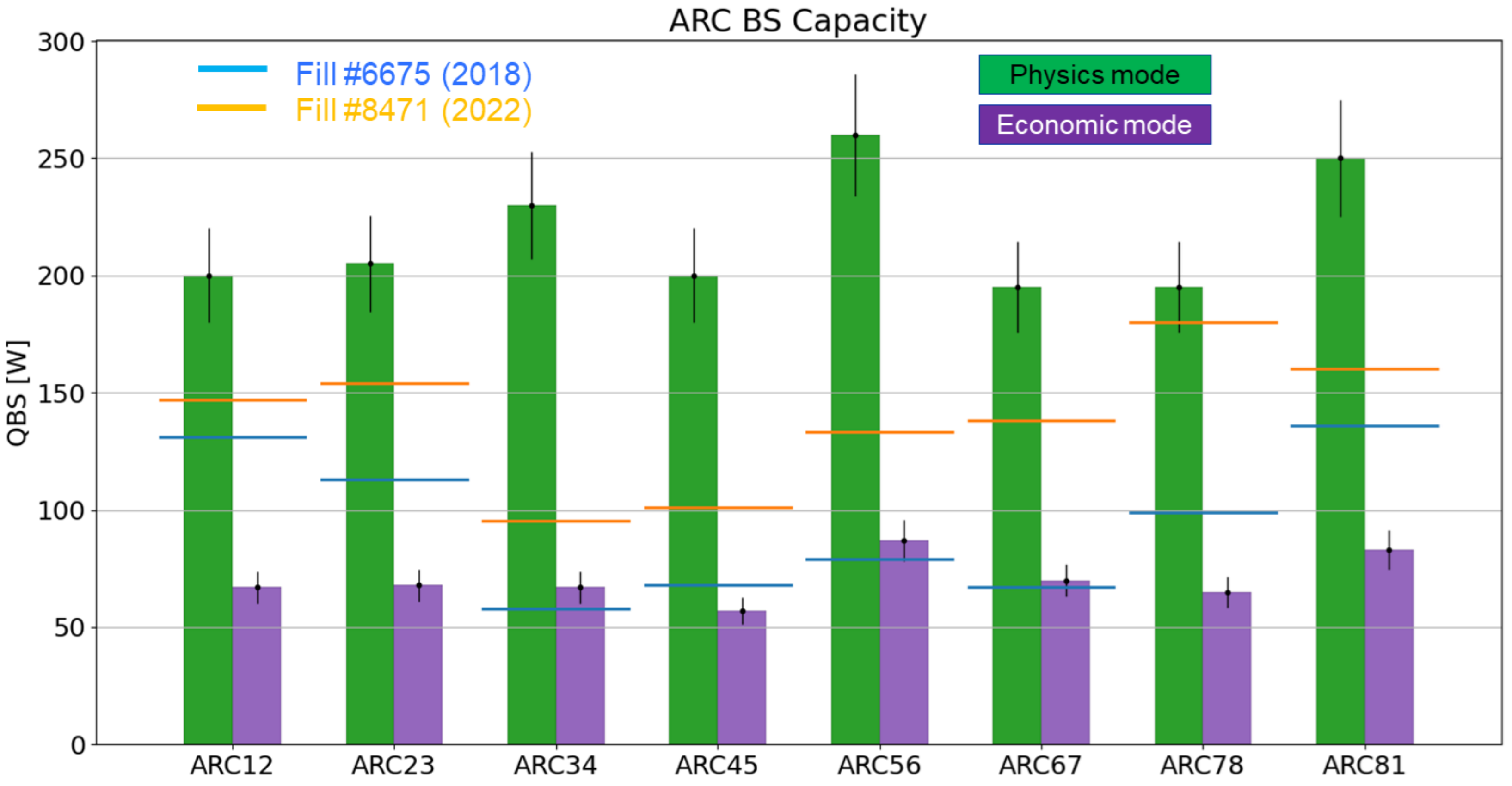
- Provoked significant degradation of heat loads in S12 & S23 & S78 & S81

Long Shutdown 2 (2019-2022)

- Provoked significant degradation of heat loads in S56 & S67 & S78

What we learnt in 2022

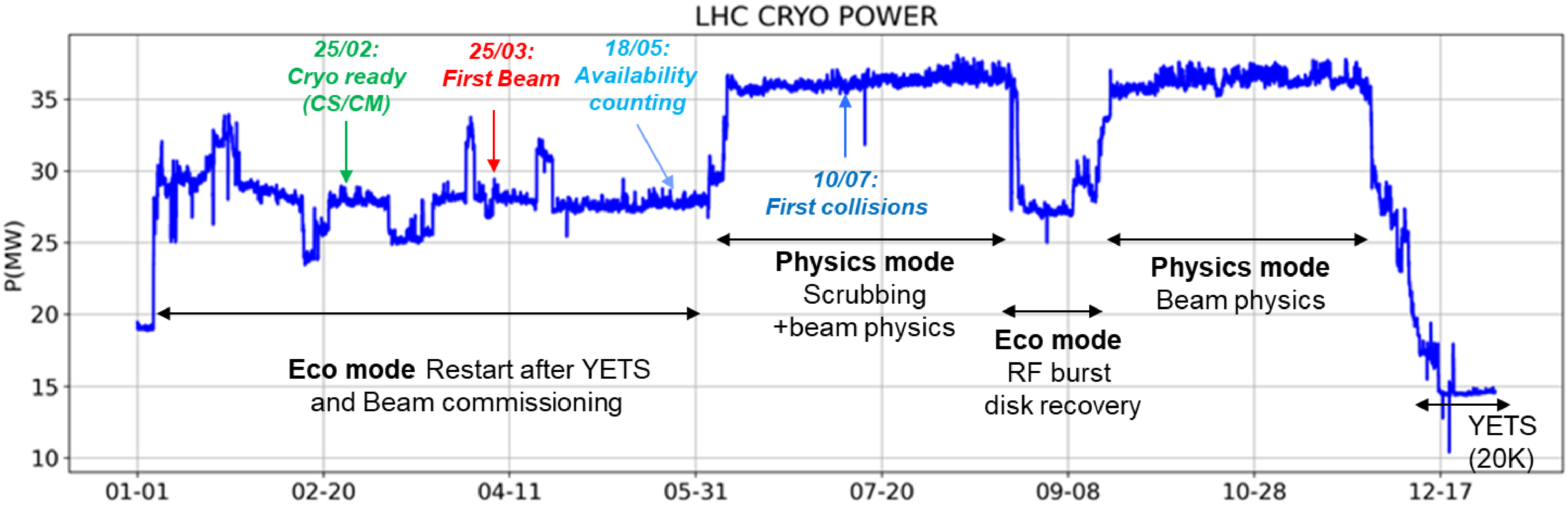
- **Available Cryo power**
  - Standard 25ns fill pattern adjusted to run at electron cloud limit in Sector 7-8
  - Bunch intensity increased slowly up to 1.5×10^{11} p/b as machine conditioned



NB: the capacities given for the "eco mode" are calculations, special measurements would be needed to better assess these numbers

What we learnt in 2022

- **Energy Management**
  - Cryogenics accounts for over half of LHC machine energy consumption (271 GWh out of 537 GWh)
  - Eco mode implemented & used for all compatible periods (Commissioning, Ion Run, Long stops, ...)
  - ~20 GWh saved by using the Eco mode in 2022

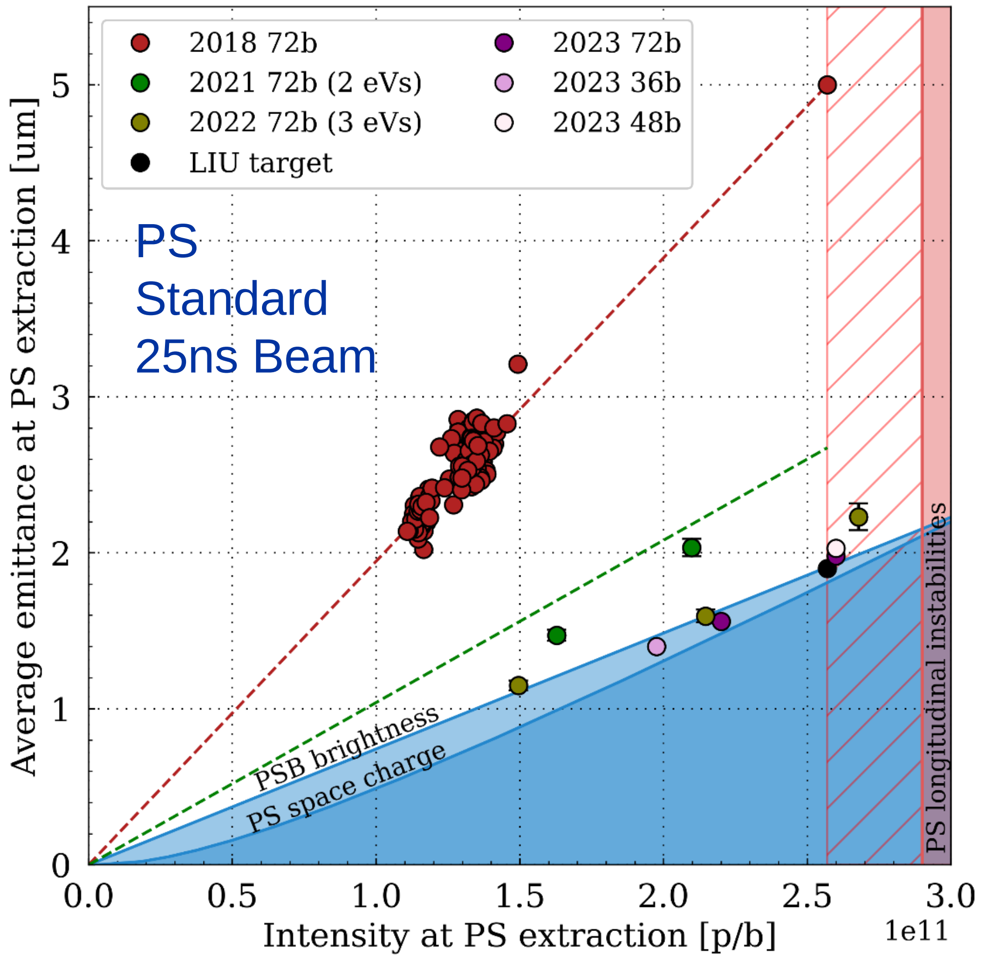


Progress in 2023
&
Looking Towards the Rest of Run 3

Injector Performance

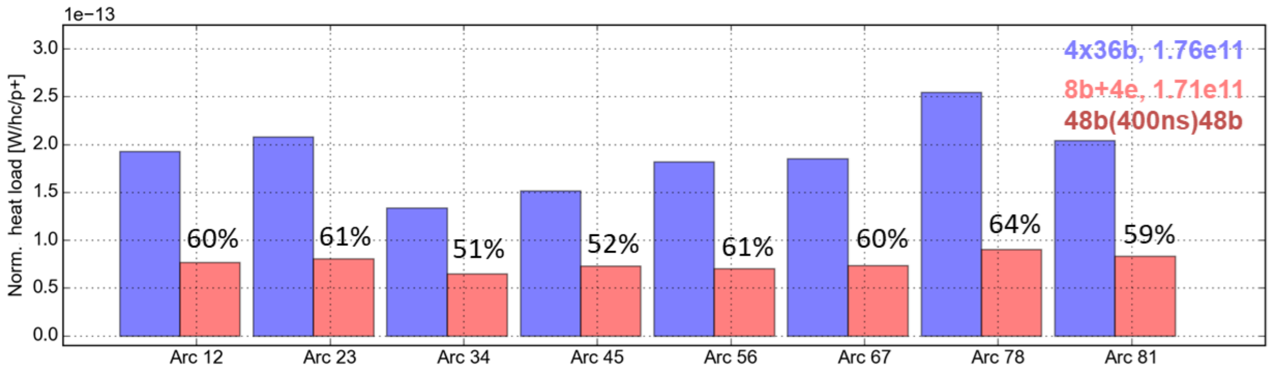
- **Injector Performance**
  - Excellent progress in performance ramp-up for protons
  - **PSB and PS reached LIU intensity & brightness with sufficient operational margin**
  - SPS intensity target at extraction in 2023 is 1.8×10^{11} p/b
    - Reached with full trains
    - Tuning still ongoing to ensure long term stability and homogeneity of intensity and emittance

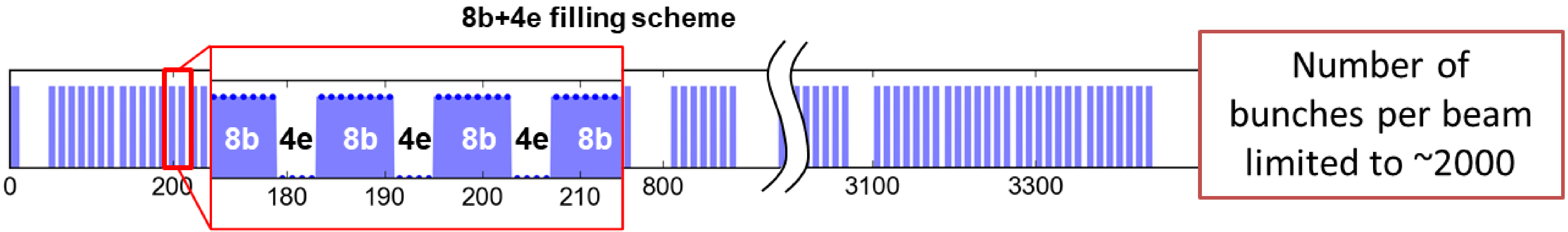
STANDARD 25ns



Running in 2023

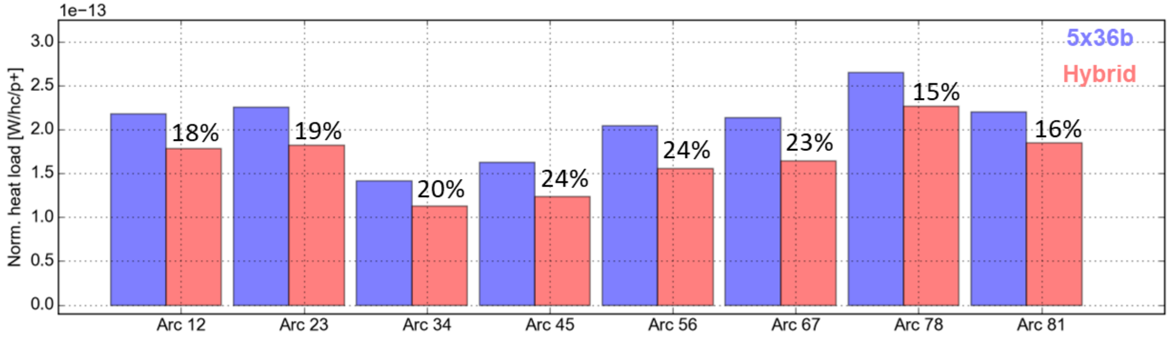
- **Dealing with Electron cloud in the LHC**
  - Alternative filling schemes – **8b4e**
    - Introduces gaps on rising slope of the e-cloud build-up so that the cloud never reaches full saturation
    - Strong e-cloud reduction confirmed up to 1.7×10^{11} p/b in 2022 test
      - ~50-65% reduction of total heat load per sector
    - Could run cryo in Eco-mode up to ~1.8×10^{11} p/b



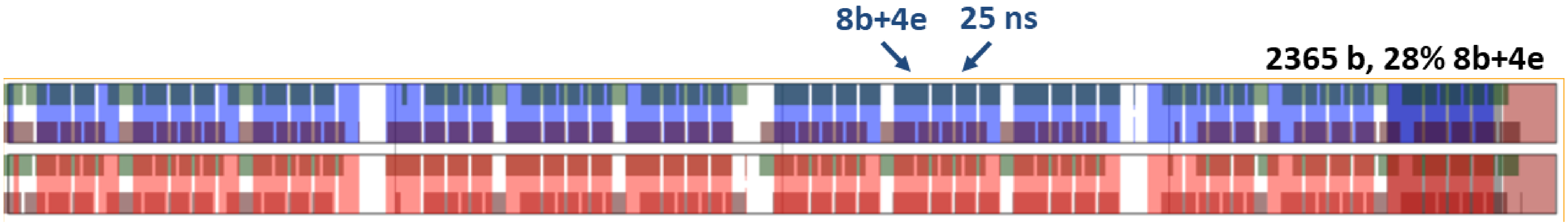


Running in 2023

- **Dealing with Electron cloud in the LHC**
  - Alternative filling schemes – **Hybrid 8b4e**
    - Best compromise for maximising performance while keeping heat loads within acceptable limits obtained with hybrid schemes, mixing 25 ns & 8b+4e beams
    - Fraction of 8b+4e beam tuned to adapt to the cooling capacity, to maximize the achievable number of bunches



Test in 2022 demonstrated 15% reduction of heat load in S78 with hybrid scheme



Intensity Reach for 2023 and Beyond

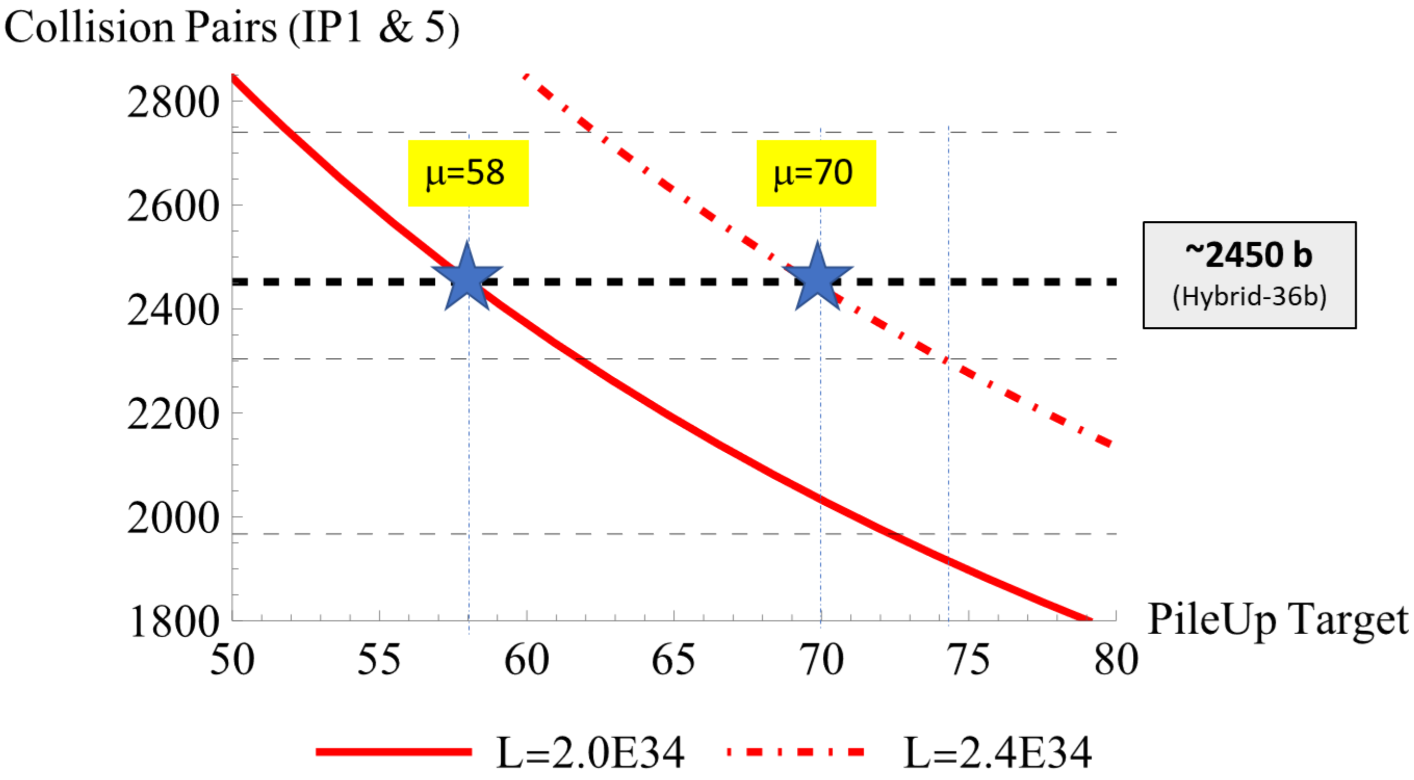
- **The intensity reach for different filling schemes is determined by the limitation in S78**

	4x72b	5x48b	5x36b	hyb-48b	hyb-36b	8b+4e
N bunches	2760	2748	2496	2452	2464	1972
Intensity	1.1e11	1.2e11	1.5e11	1.75e11	2e11	-
Int. lumi/day [fb^{-1}]	0.80 -27%	0.93 -15%	1.10 ref.	1.19 +8%	1.24 +13%	1.09 -1%

Lumi estimates (LPC calculator) with μ=54, L_{lev}< 2e34 cm^{-2} s^{-1}

- **Hybrid 56b(8b4e)+5×36b the most promising option**
  - Use of hybrid scheme in 2023 confirms heat-load benefit with intensity of 1.5E11 p/b reached to date
  - Run 3 bunch intensity limited to 1.8e11 p/b by LHC beam extraction system until HL-LHC upgrade

Matching Pile-up Limit and Triplet Cryo-Capacity



μ = 60

Positive evaluation from both ATLAS & CMS, with no expected negative impact on physics performance or detector readout and trigger

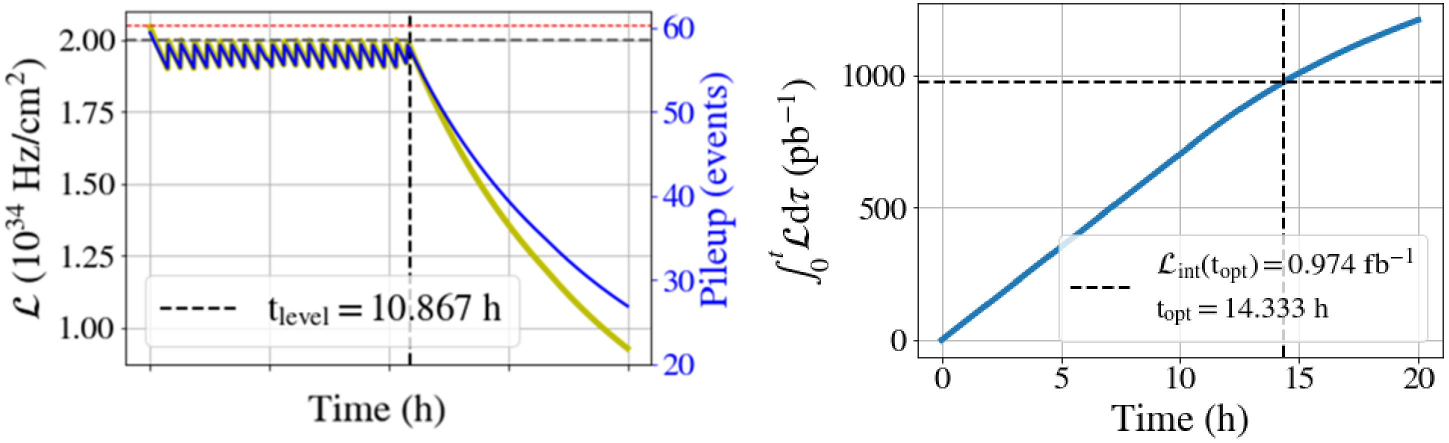
- μ = 60 **(Lpeak = 2 x 10^{34} $cm^{-2}s^{-1}$)** positive evaluation
- μ = 65 **(Lpeak = 2.2 x 10^{34} $cm^{-2}s^{-1}$)** under consideration
- μ = 70 **(Lpeak = 2.4 x 10^{34} $cm^{-2}s^{-1}$)** strongly disfavoured

2023 Performance Estimate

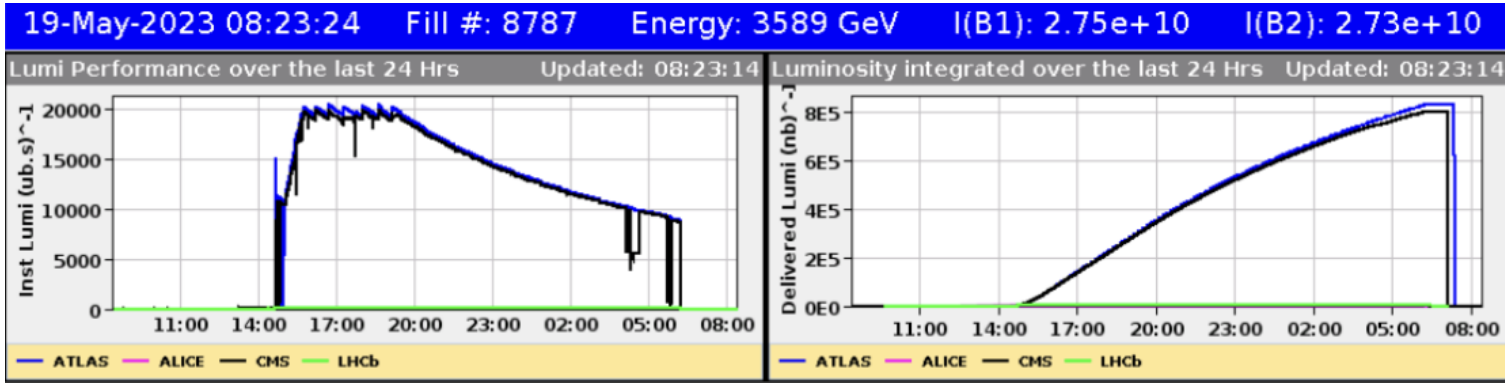
A typical 2023 fill:

- **Evolution of beam parameters**
  - Impact from IBS, SR, burn-off & extra emittance blowup
- **Optics**
  - Discrete β* steps from 1.2 m to 30 cm
  - Accompanied by appropriate increase in crossing angle
- **Levelling on pile-up**
  - 60 ± 2.5% (target for 2023)
- **Luminosity levelling**
  - 2×10^{34} cm^{-2} s^{-1} cryo-cooling limit

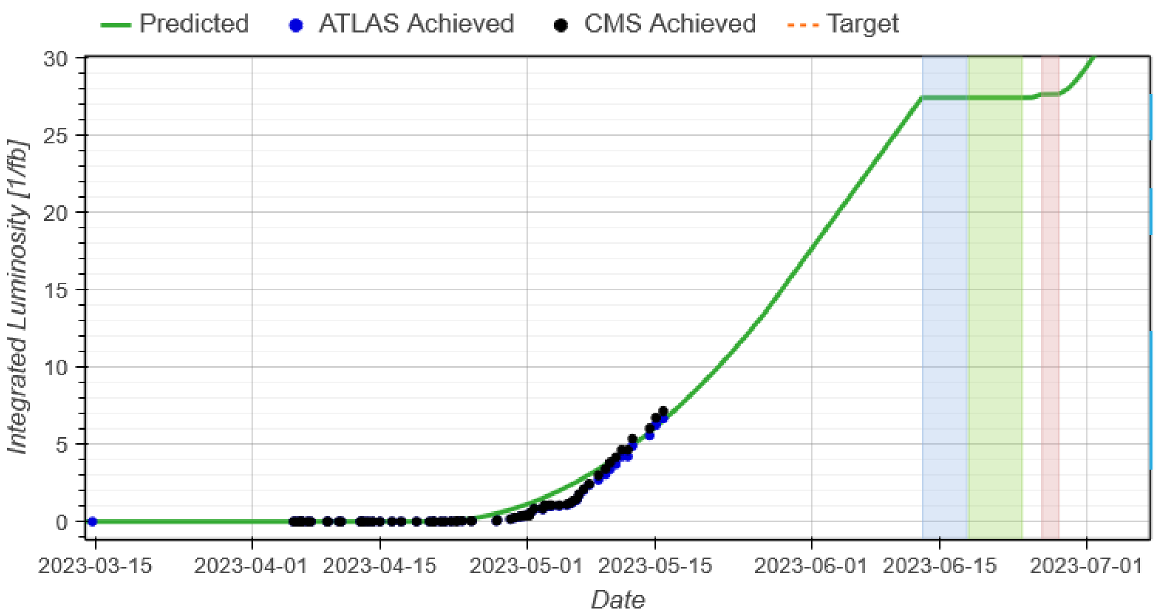
2022 Simulation

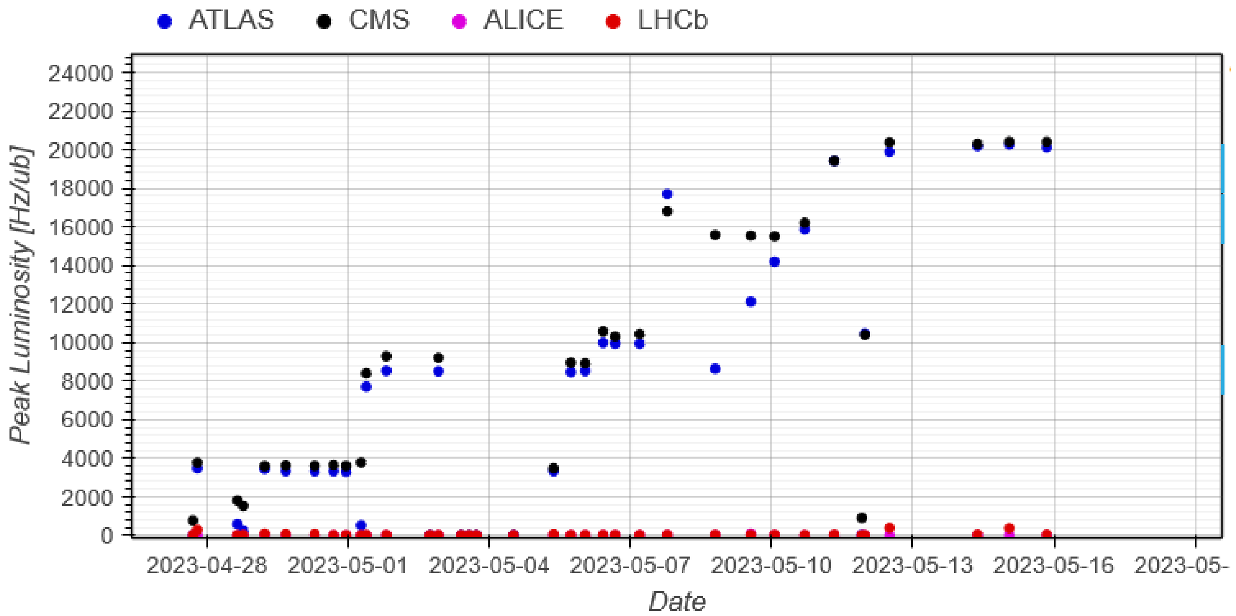


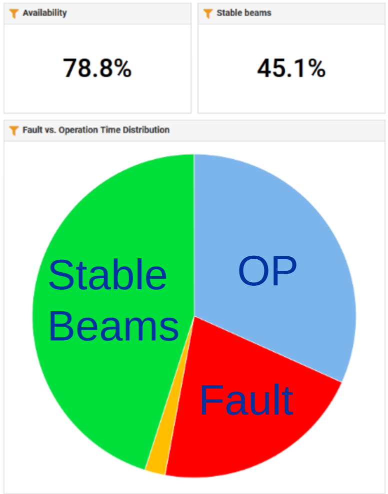
Fill from last week

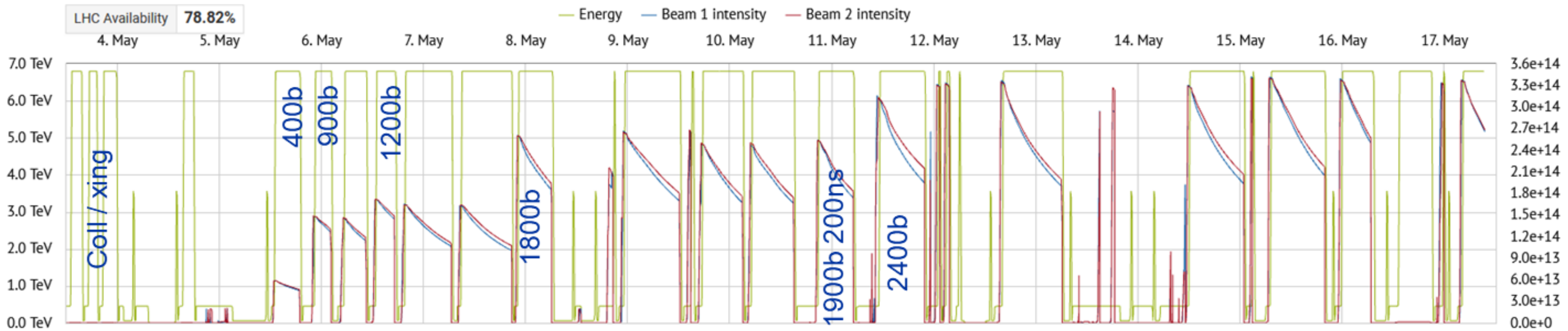


2023 Current Status

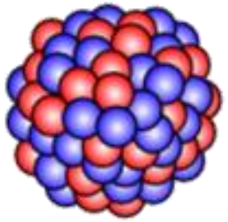




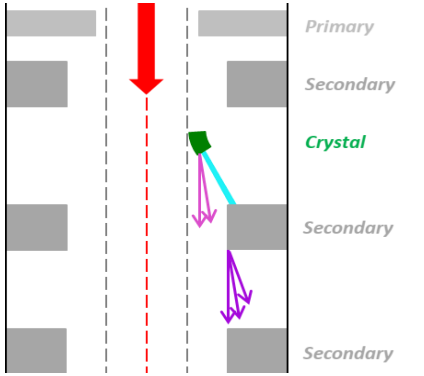




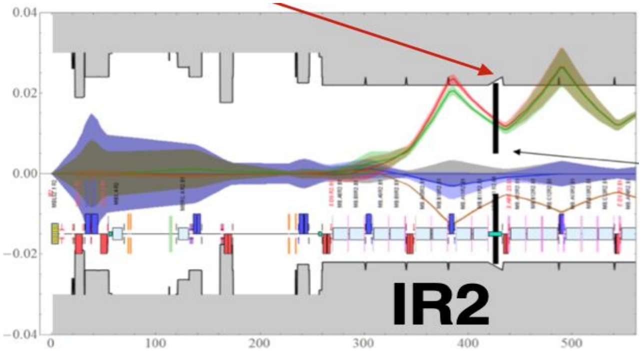
Ion Operation in 2023



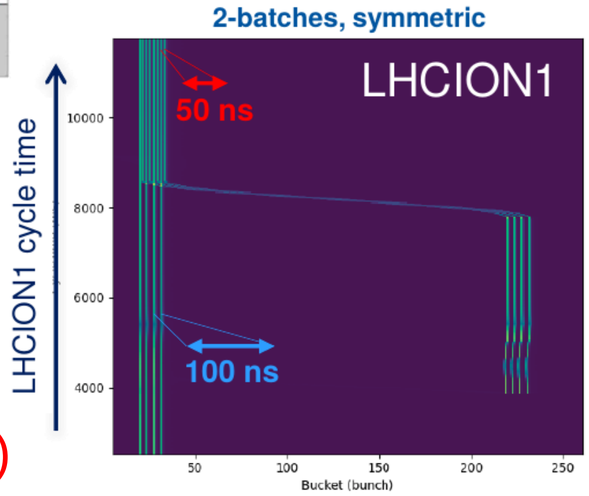
- **Crystal Collimation**
  - Good performance demonstrated during 2022 Pb test
  - Faulty crystal unit to be re-installed during the first technical stop (June)



- **Alleviation of collision losses**
  - IR1/5: Orbit bumps successfully deployed in Run 2
  - IR2: new dispersion suppressor collimator (TCLD)



- **Slip-stacked beams from the SPS**
  - 8-bunch trains successfully used in 2022 Pb test
  - 56-bunch trains to be commissioned during 2023



- **First ion optics commissioning already successfully completed**
  - Measurement and correction throughout the cycle using protons

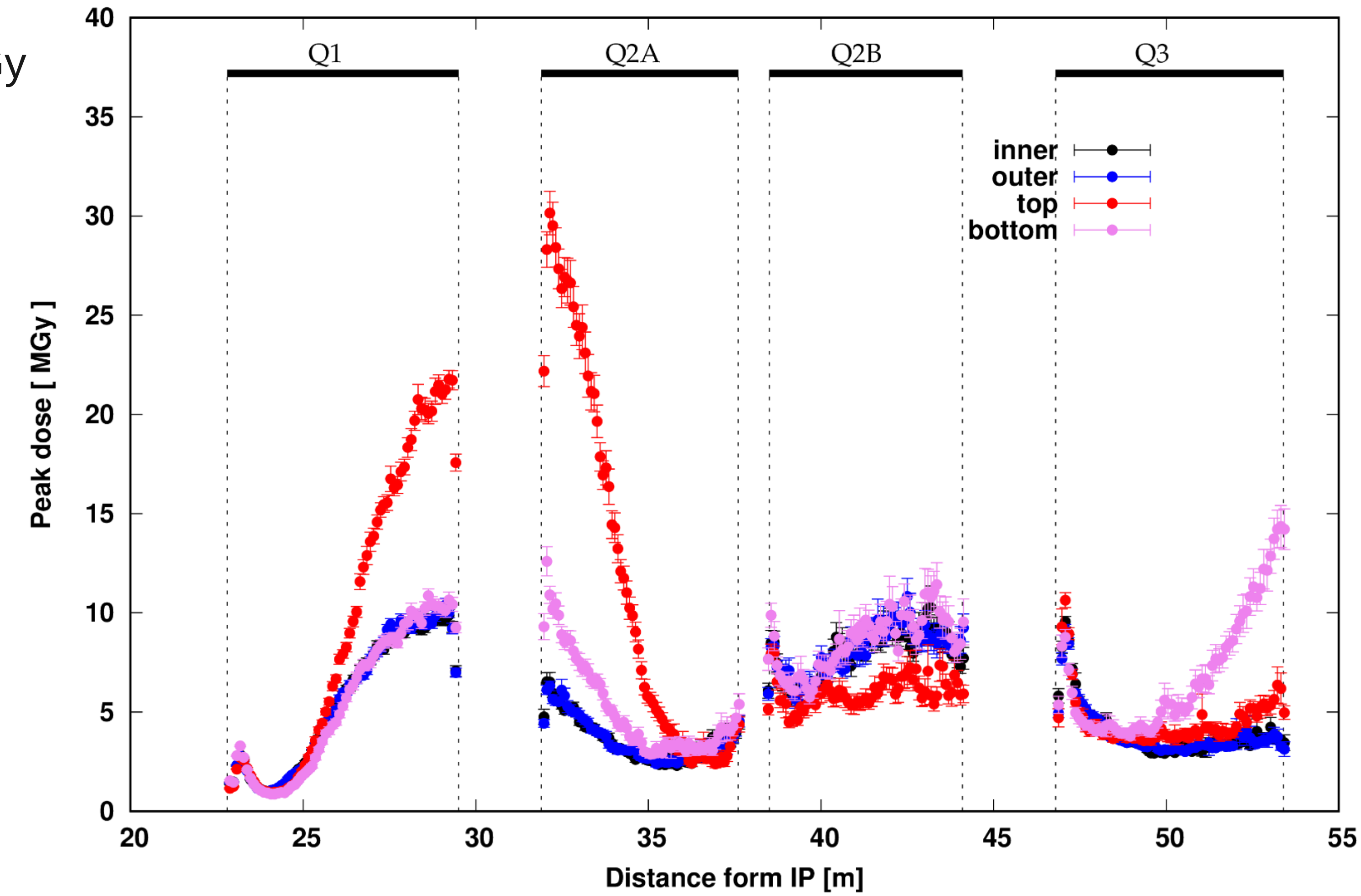
Ion energy choice for Run 3: 5.36 TeV per nucleon-nucleon collision (6.8 Z TeV)

Survival of the Interaction Region Focusing Magnets (Triplets) in Run 3

Triplet ageing due to Irradiation

- **Design Criteria**
  - Main quadrupoles to withstand > 30 MGy
  - Correctors to withstand > 7 MGy
  - Actual limits not known

- **Dose distribution affected by:**
  - Luminosity & Beam energy
  - Crossing angle orientation, sign and amplitude
    - Regular inversion of ATLAS crossing angle polarity to minimize integrated radiation dose
  - Beam screen orientation
  - IP transverse position wrt triplet
  - Triplet quadrupole polarity

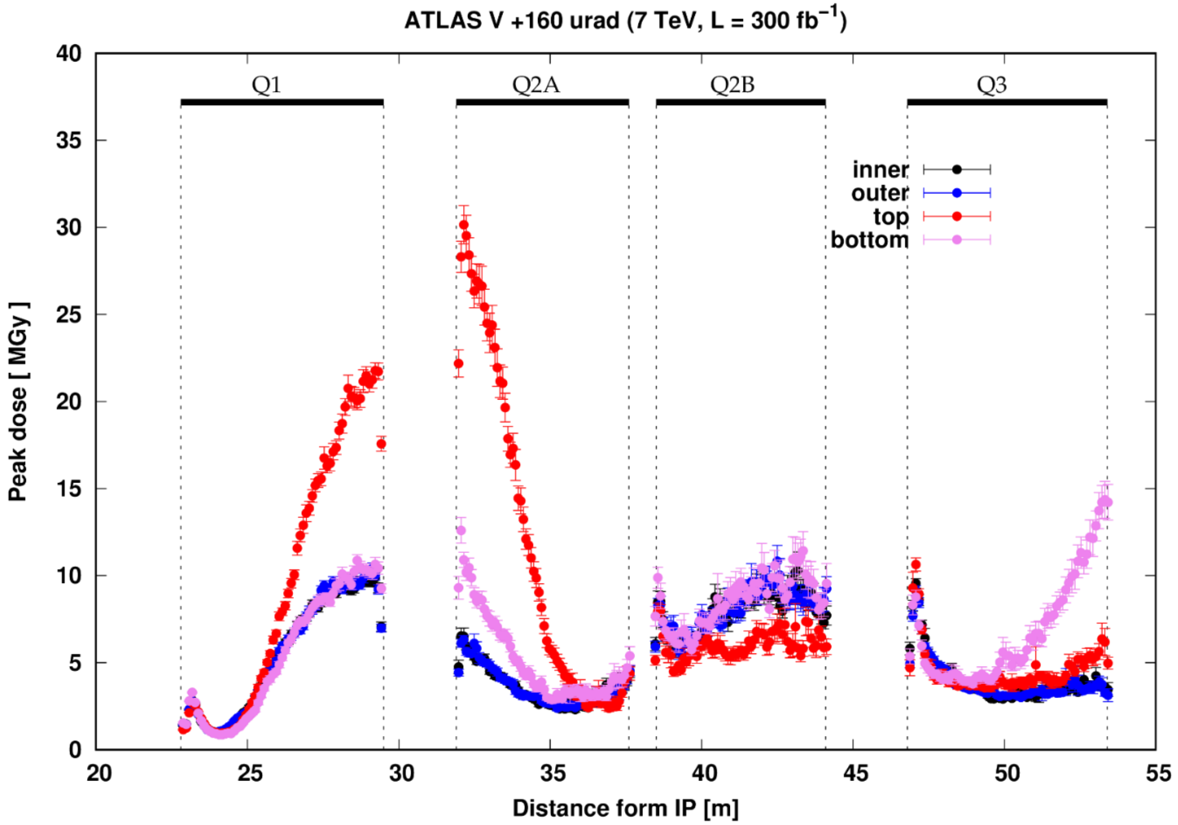


IR1 – 300 fb^{-1} – 7TeV

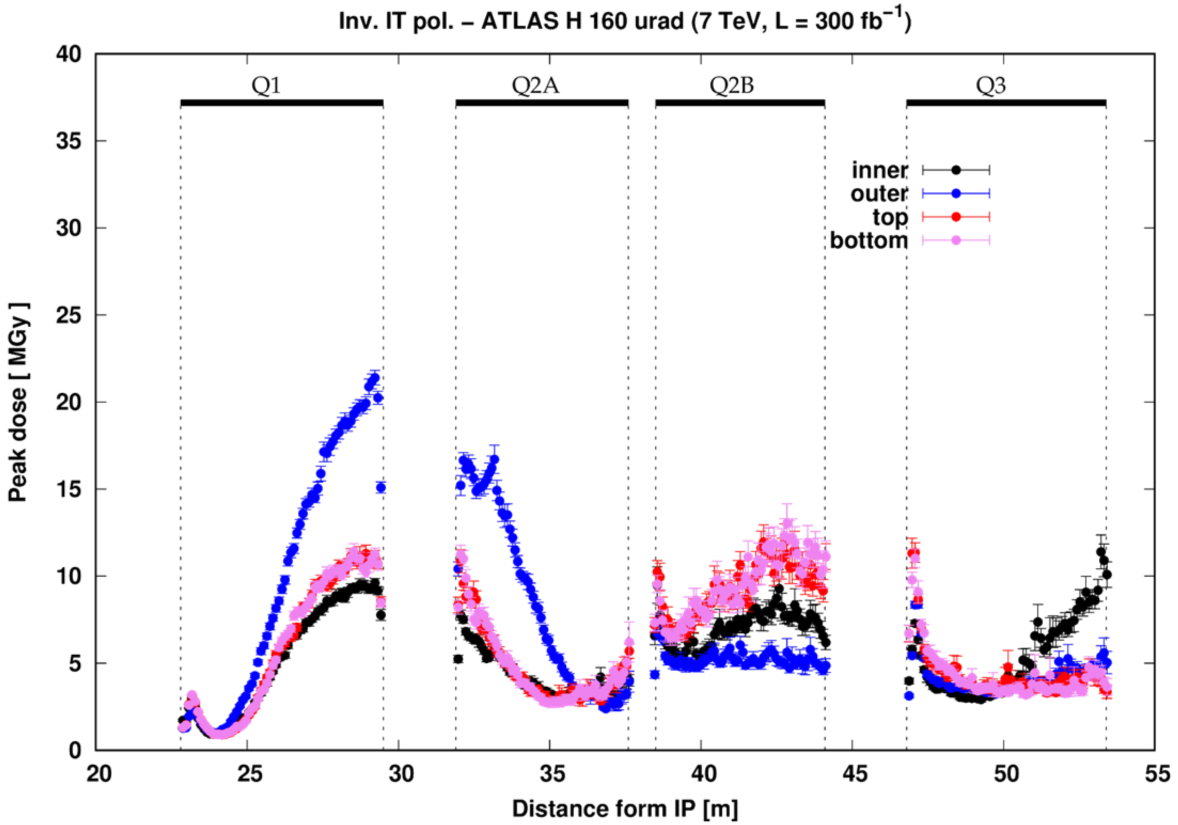
Triplet Task Force - Possible Mitigation

- **Radiation dose distribution significantly affected by triplet quadrupole polarity and crossing angle orientation**

IR1 – 300 fb^{-1} – 7TeV



Present polarity – FDF and crossing angle orientation (V)

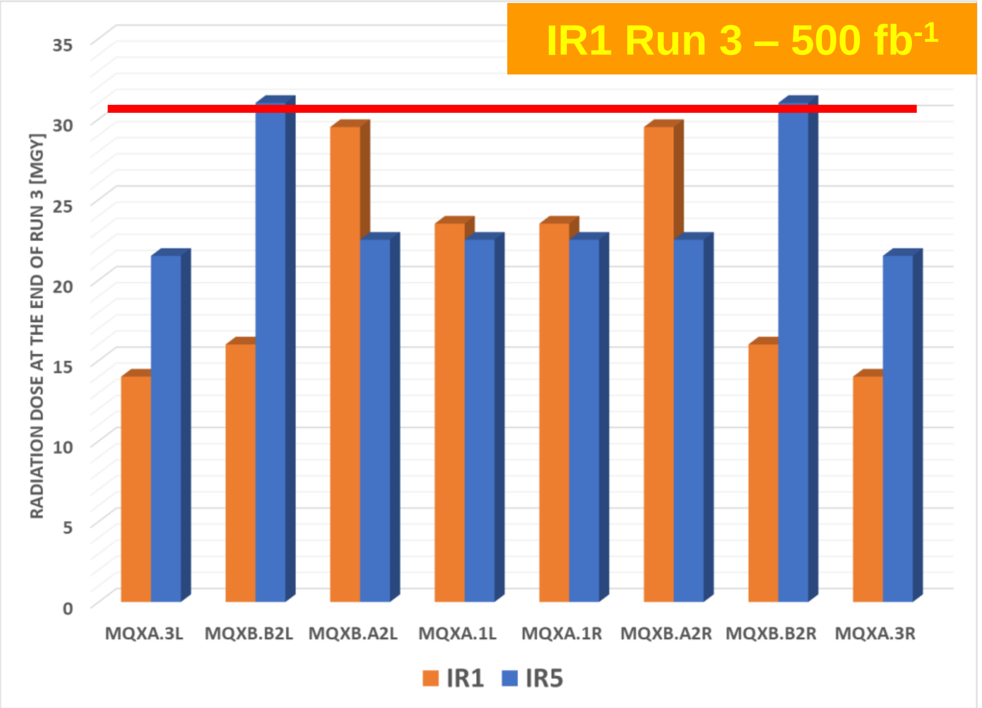


Inverted polarity – DFD and swapped crossing angle orientation (H)

Triplet Task Force – Summary & Outlook

- **Quite some uncertainty on the radiation resistance of insulators in particular for the correctors**

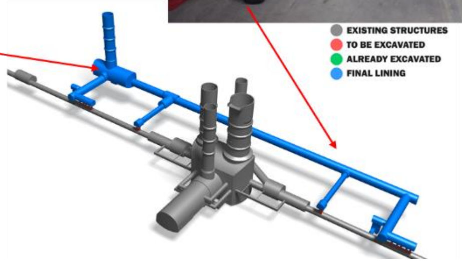
- **Triplet polarity inversion a promising option for reducing the peak integrated dose**
  - To be done in 2024 if we want to gain in lifetime
  - Feasibility of final solution being investigated
    - Report due by end of May 2023



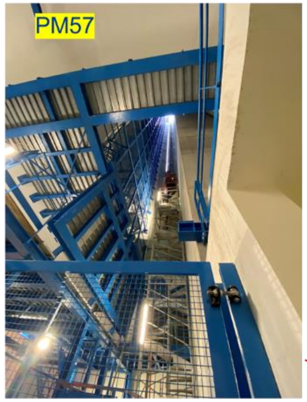
- **To be further addressed:**
  - Operational scenarios in case of equipment failure
  - Mitigation for other elements of concern - e.g. warm separation dipoles, correctors
  - Monitoring and results of irradiation tests

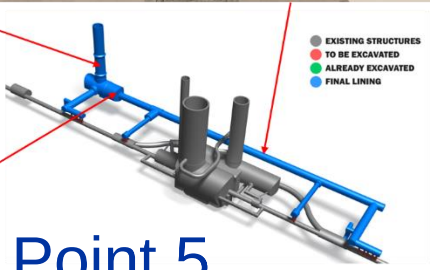
Advancement with High Luminosity LHC

HL-LHC Civil Engineering Completed



Point 1



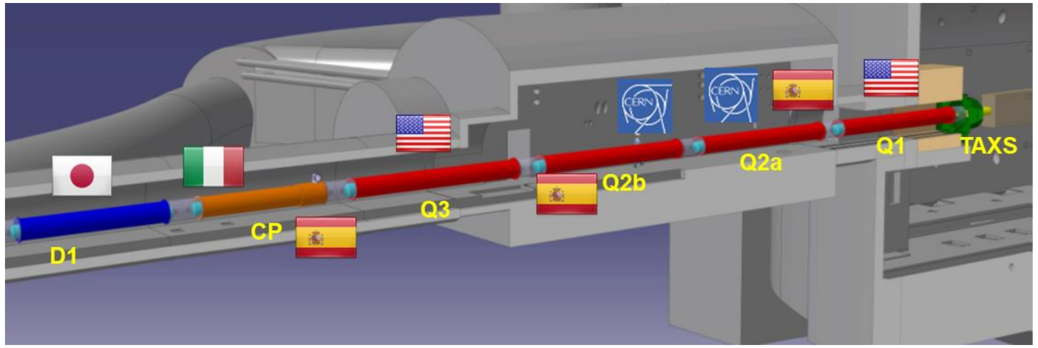


Point 5

Progress with the Nb_3Sn Interaction Region Magnets

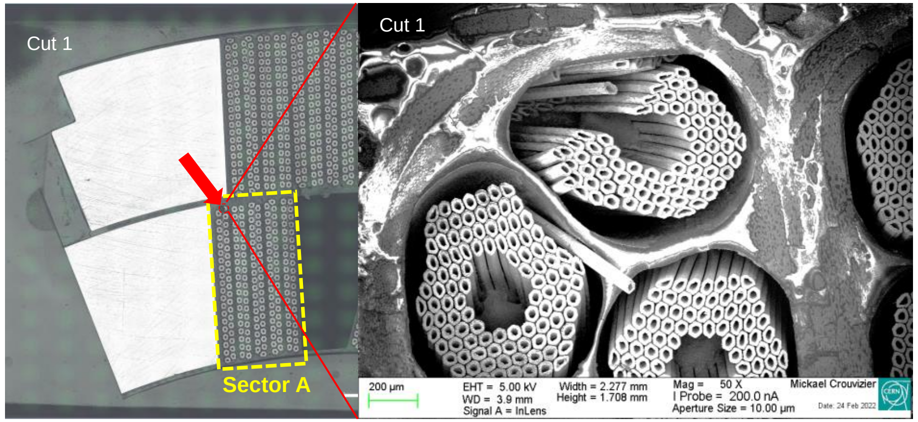
16 MQXFA (4.2m long US Magnets) to be installed

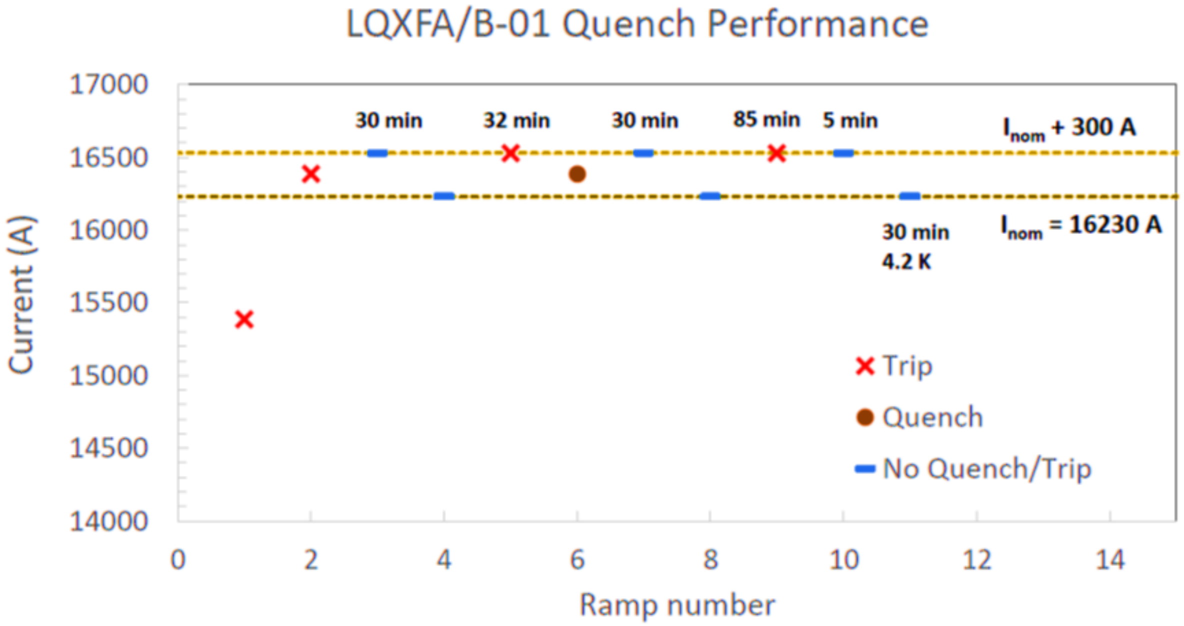
- Endurance test (50 quenches) of 4.2m long magnet successful
- 6 out of 8 magnets so far accepted after cold tests
- First 2 magnet cold-mass assembled & successfully tested



8 MQXFB (7.2m long CERN Magnets) to be installed

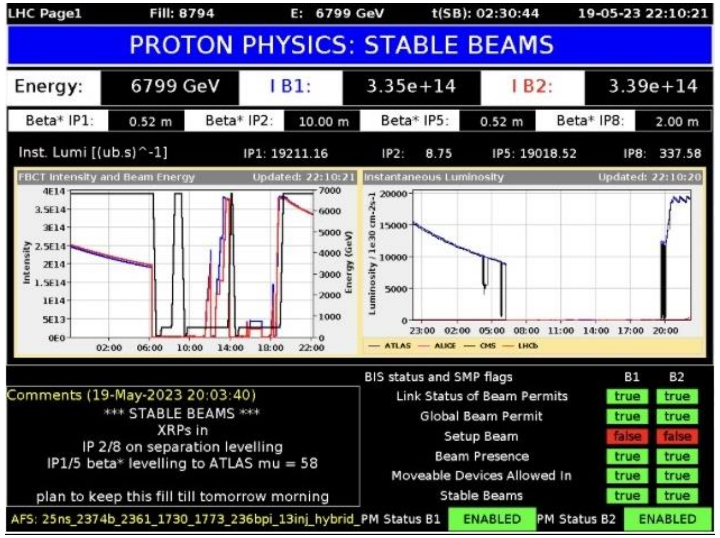
- Performance limitations identified in first 3 prototypes
- Studied in detail with 3 issues to be addressed
  - Revised welding procedure (successfully tested)
  - Revised assembly procedures (successfully tested)
  - New coil production procedure (underway)





Summary & Outlook

- **LHC Run in 2023**
  - Hybrid 56b (8b4e) + 5×36b the most promising option
  - Intensity up to 1.8×10^{11} protons per bunch
  - Extended beta* levelling range from 1.2 m to 30 cm
  - Levelling on pile-up up to $\mu = 60$
  - Aiming to integrate 1 fb^{-1} per 15h fill



- **Triplet Longevity**
  - Triplet Task Force has identified several mitigation measures to increase lifetime beyond 300 fb^{-1}
  - Most promising is inversion of triplet polarity to be considered for 2024

- **HL-LHC**
  - Significant progress with all main work packages
    - Encouraging news from both US and CERN Nb_3Sn magnet programmes
    - Built-up a good understanding of this new superconducting magnet technology
  - Main civil engineering completed with only vertical cores remaining to be excavated

Run 3 Schedule

- **Reduced operation in 2023 as part of energy saving measures**
- **Total for 2024/2025 remains unchanged for the moment**
- **Optimising the yearly running period to adapt to energy costs can bring significant savings without impacting overall physics time**

Baseline start of LS3 remains 17 November 2025