Highlights from the LHC

• The most recent results and future developments •

Helga Timko, CERN

EPS-HEP Conference, Marseille, France, 10th July 2025

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Setting the scene

LHC design

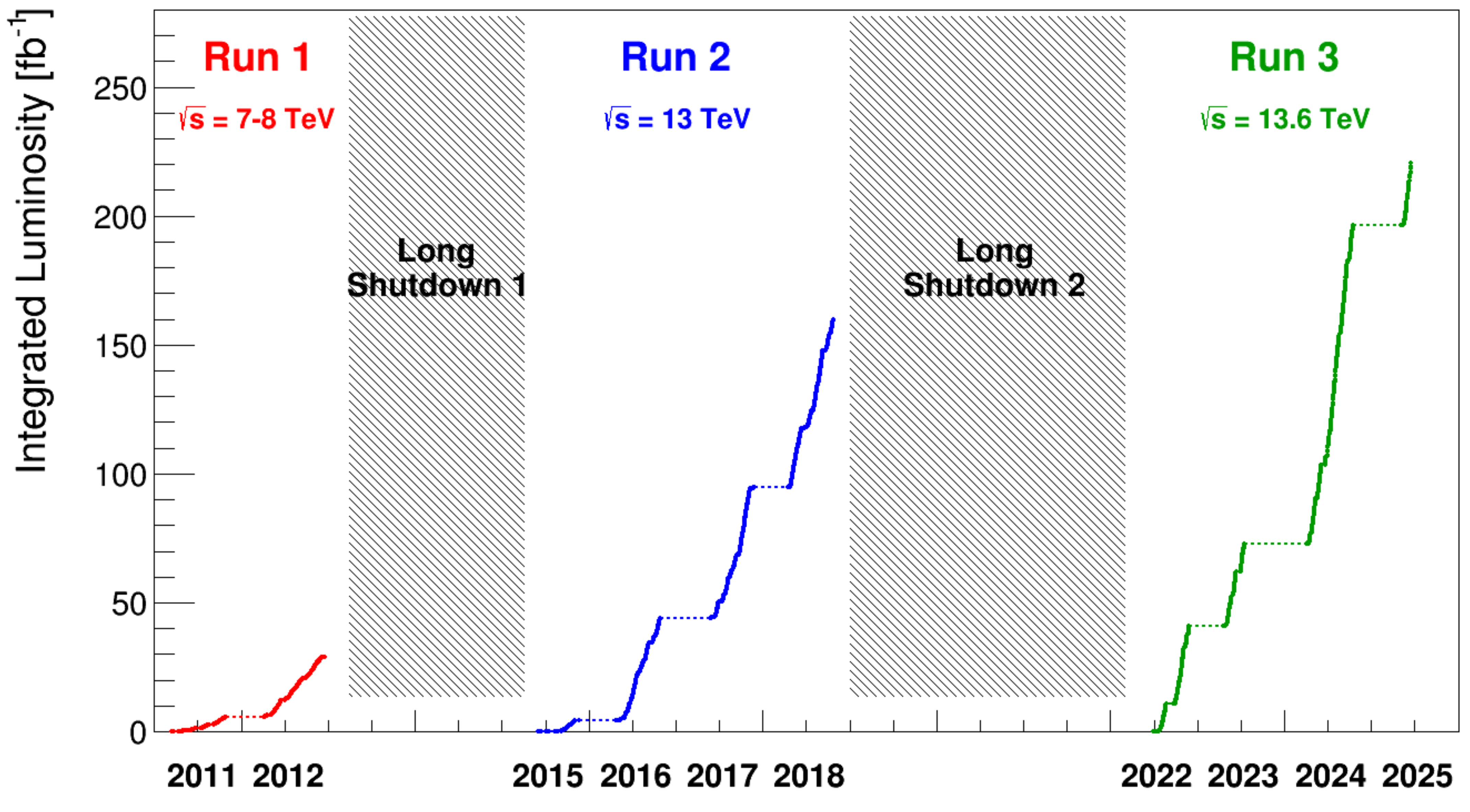
- 1.15×10^{11} p/b, β* = 55 cm
- 30 fb^{-1}/year

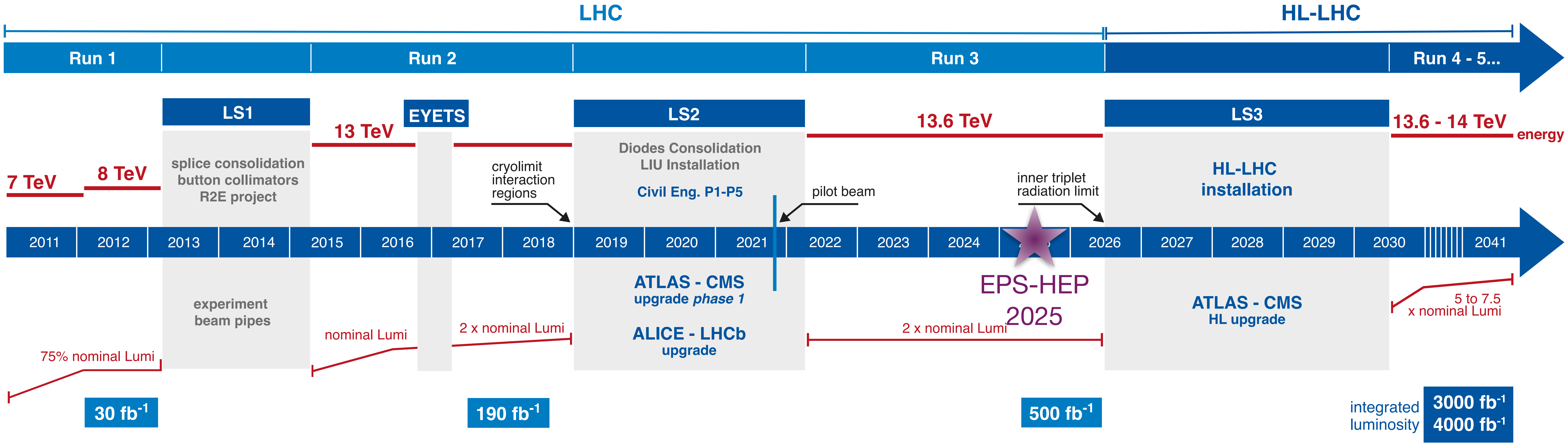
LHC today

- 1.6×10^{11} p/b, β* = 60/18 cm
- 110-120 fb^{-1}/year

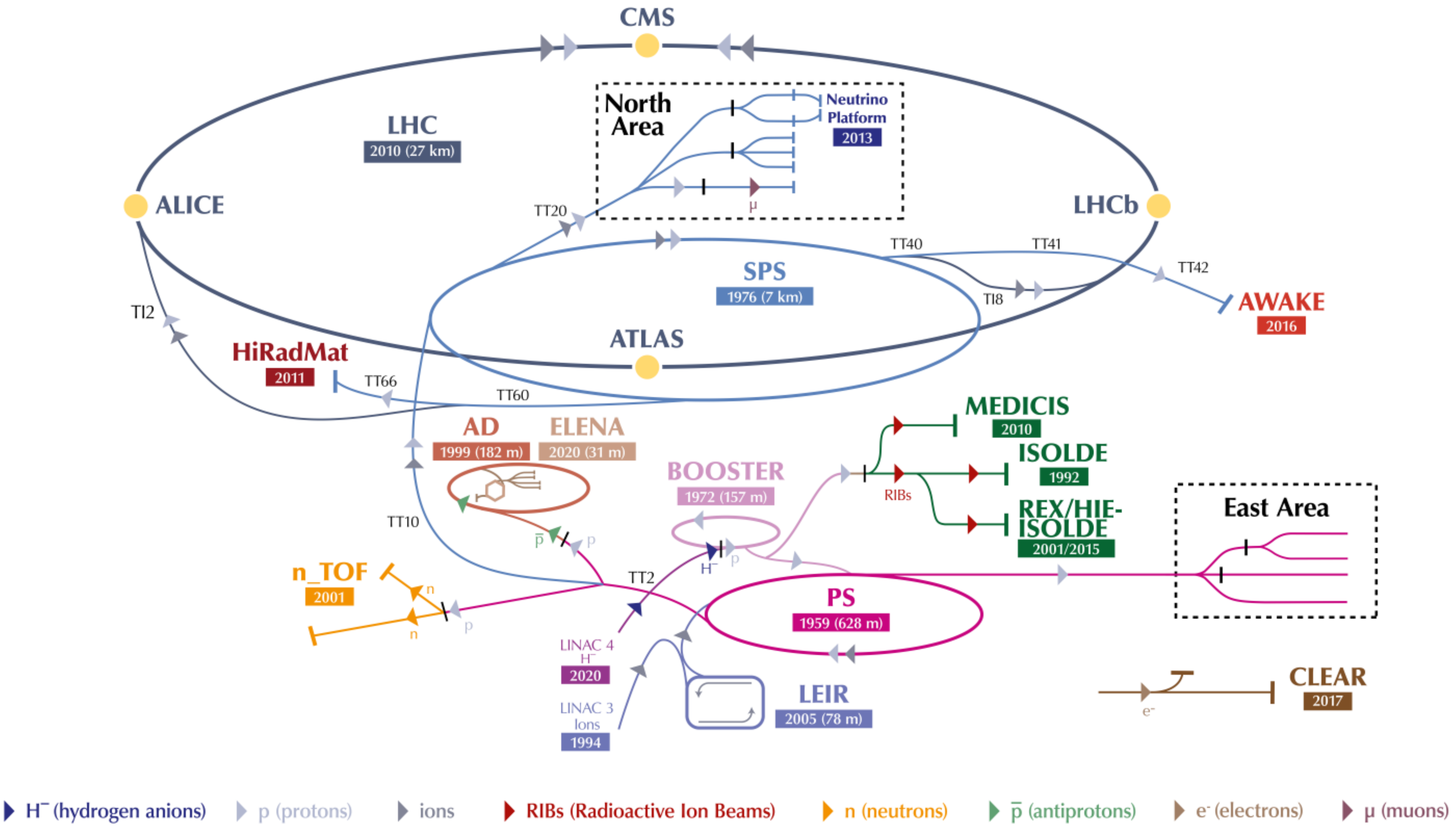
HL-LHC

- 2.2×10^{11} p/b, β* = 15 cm
- 300 fb^{-1}/year





The CERN accelerator chain



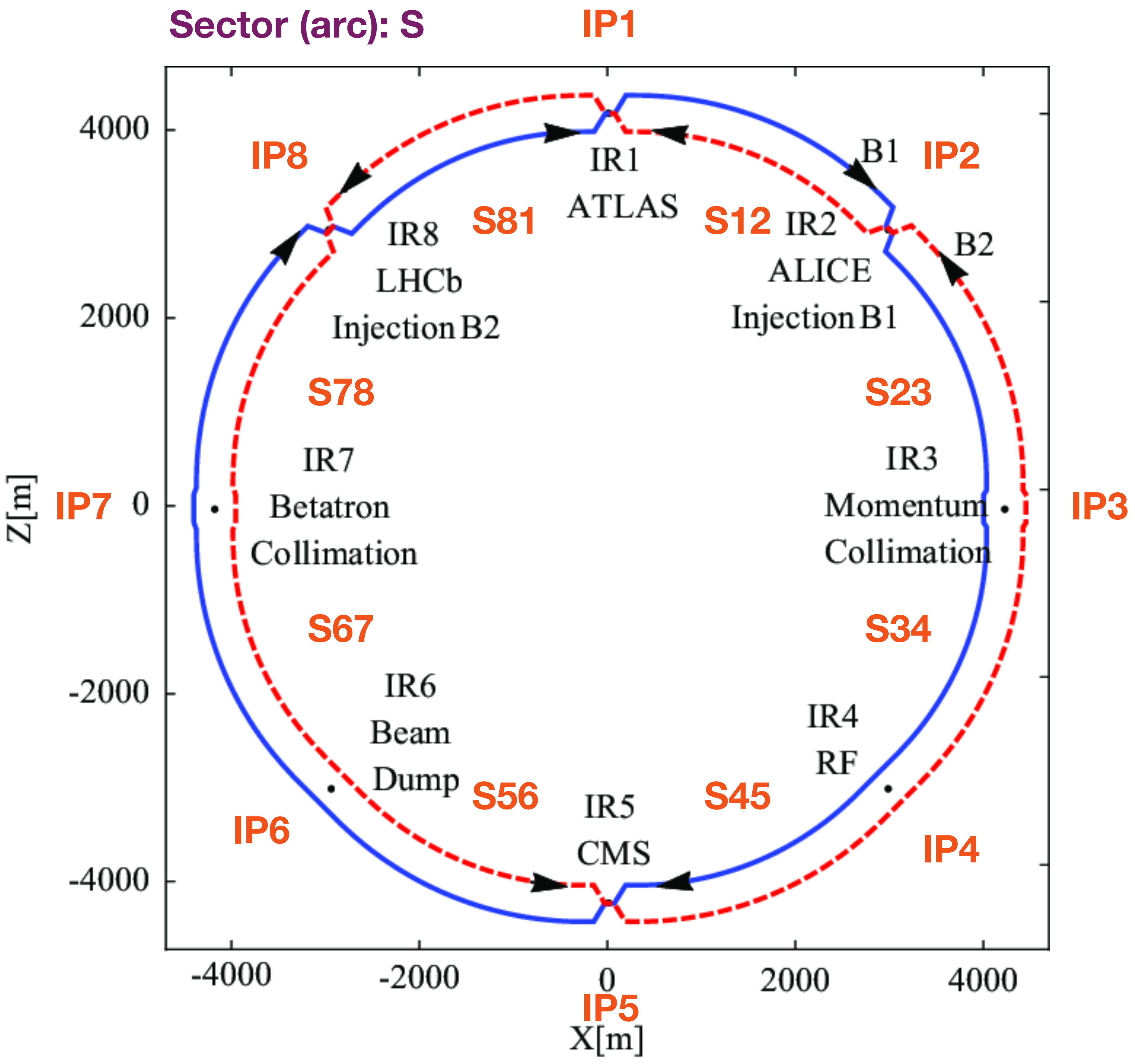
LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

LHC layout

Interaction region: IR

Interaction point: IP

Sector (arc): S



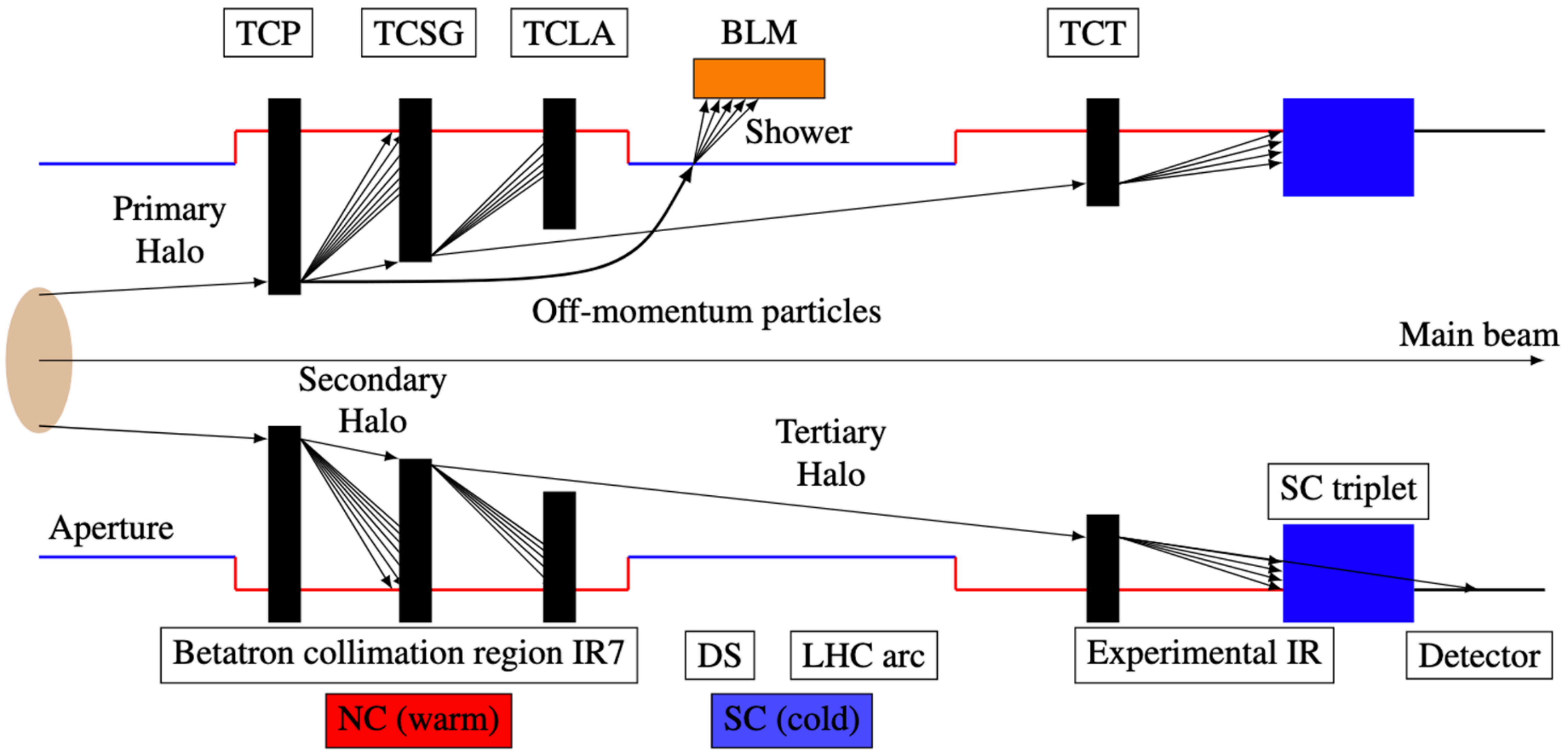
LHC rings for beam 1 (blue) and beam 2 (red)

TCP: primary collimator

TCSG: secondary collimator

TCLA: active absorber

TCT: tertiary collimator



LHC staged collimation system

LHC injectors

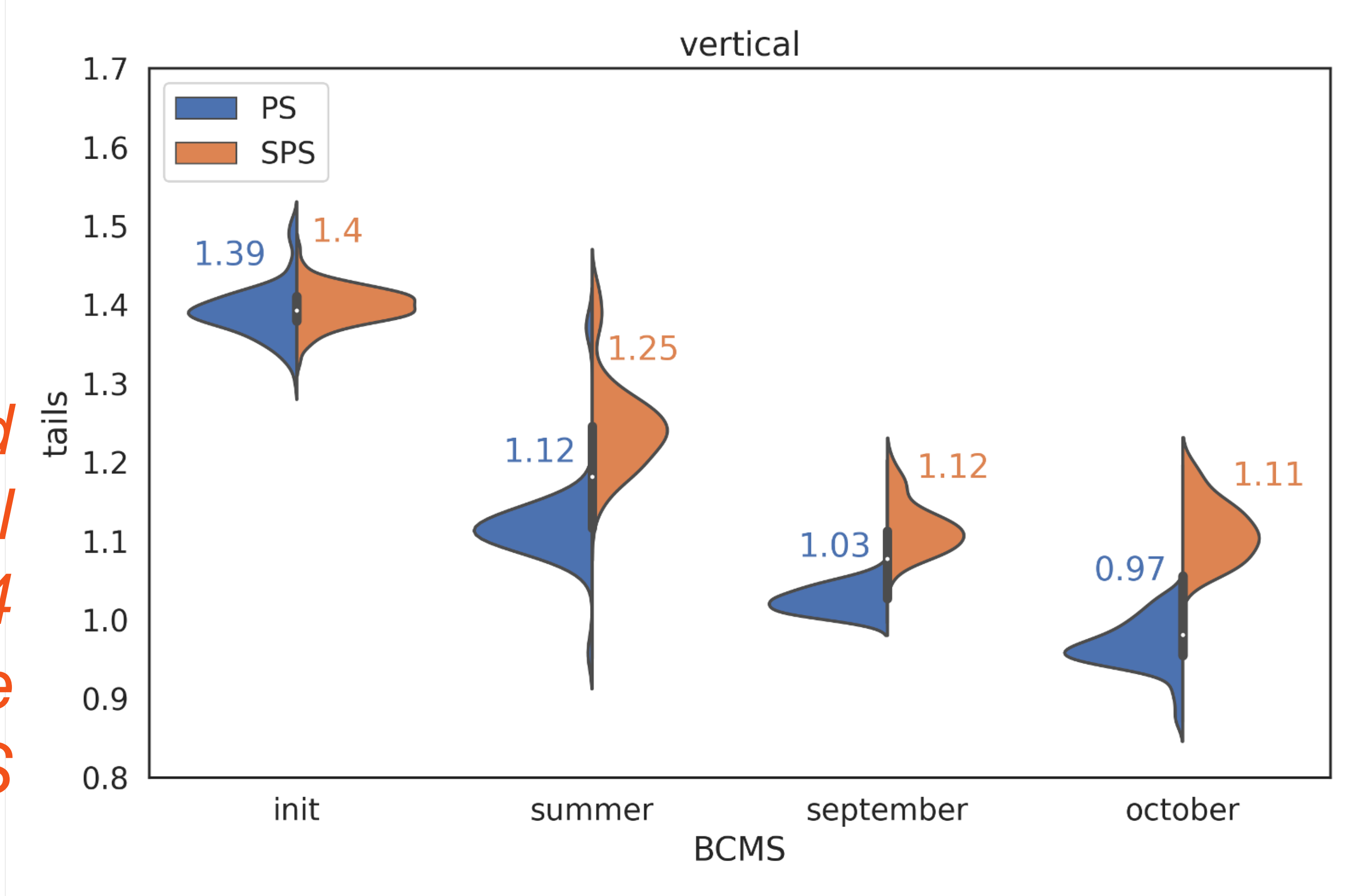
Performance and highlights

Beams from the injectors

Hybrid beam: used in 2023

- Interleaving "8 bunches 4 empty slots" (8b4e) beam with standard 25 ns beam
- As a mitigation of e-cloud and cryo heat load
  - Difficult to produce homogeneous intensity and emittance

Reduced transverse tail content over 2024 in the PS and the SPS



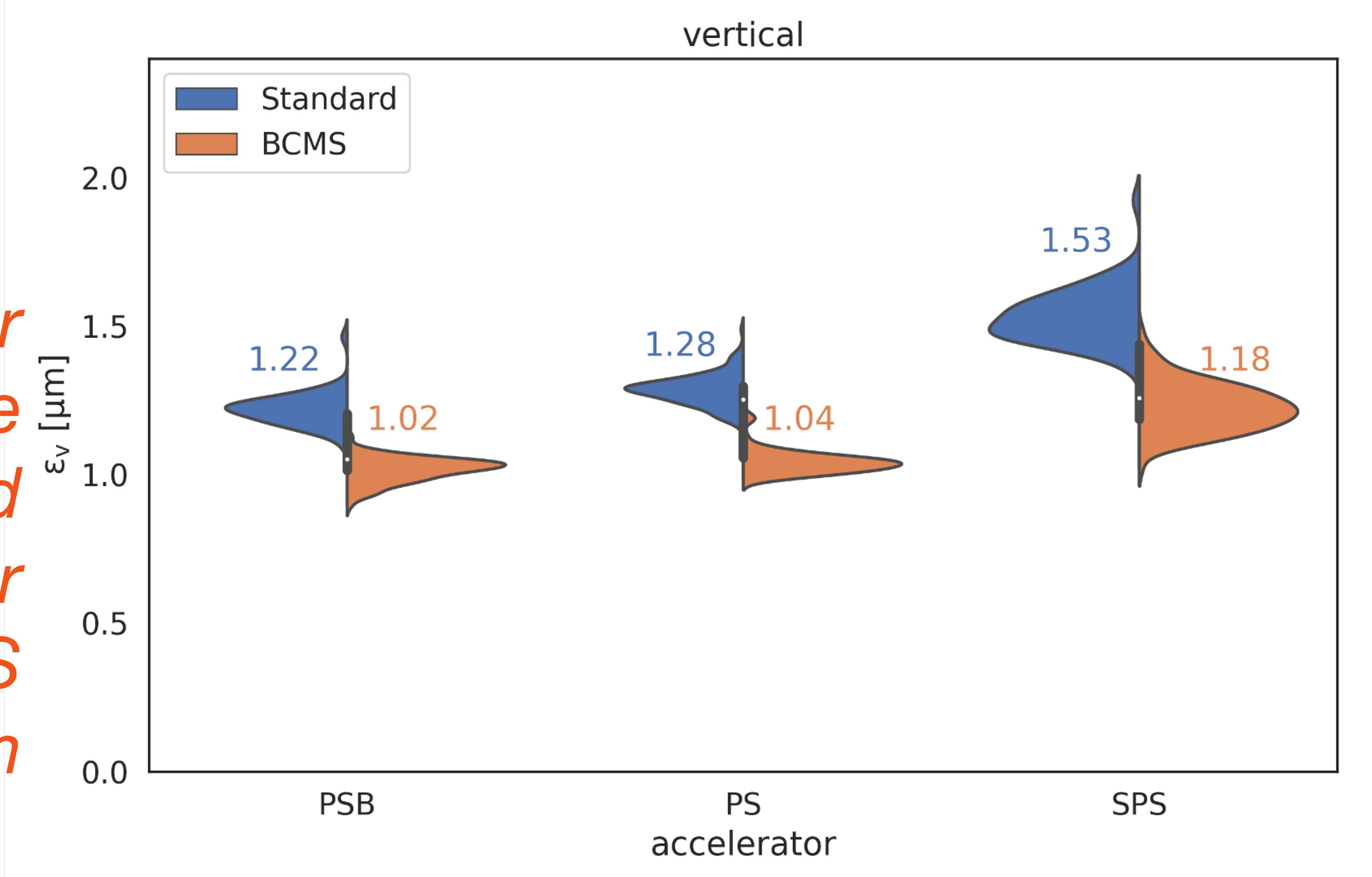
Standard 25 ns beam: used early 2024

- Used for beam commissioning with 3x36b trains
- Intensity: (1.6-1.65)x10^{11} p/b at injection

BCMS beam: used since mid-2024

- PS producing this high brightness beam using the "batch compression, merging, and splitting" scheme
- Intensity: (1.6-1.65)x10^{11} p/b at injection
- Longest batches: 3x36b (2024) and 4x36b (2025)
- Significant work on reducing tails and emittance blow-up

Smaller transverse emittance and thus brighter beam for BCMS beam



Achievements of LHC injectors

LIU: LHC Injectors Upgrade

LHC Injectors Upgrade

Intensity ramp-up of HL-LHC beams in 2023

- PSB delivering beams **beyond** the LIU targets
- PS **reaching** the LIU targets
- SPS accelerating **2.2×10^{11} p/b** with **4x72** bunches to 450 GeV

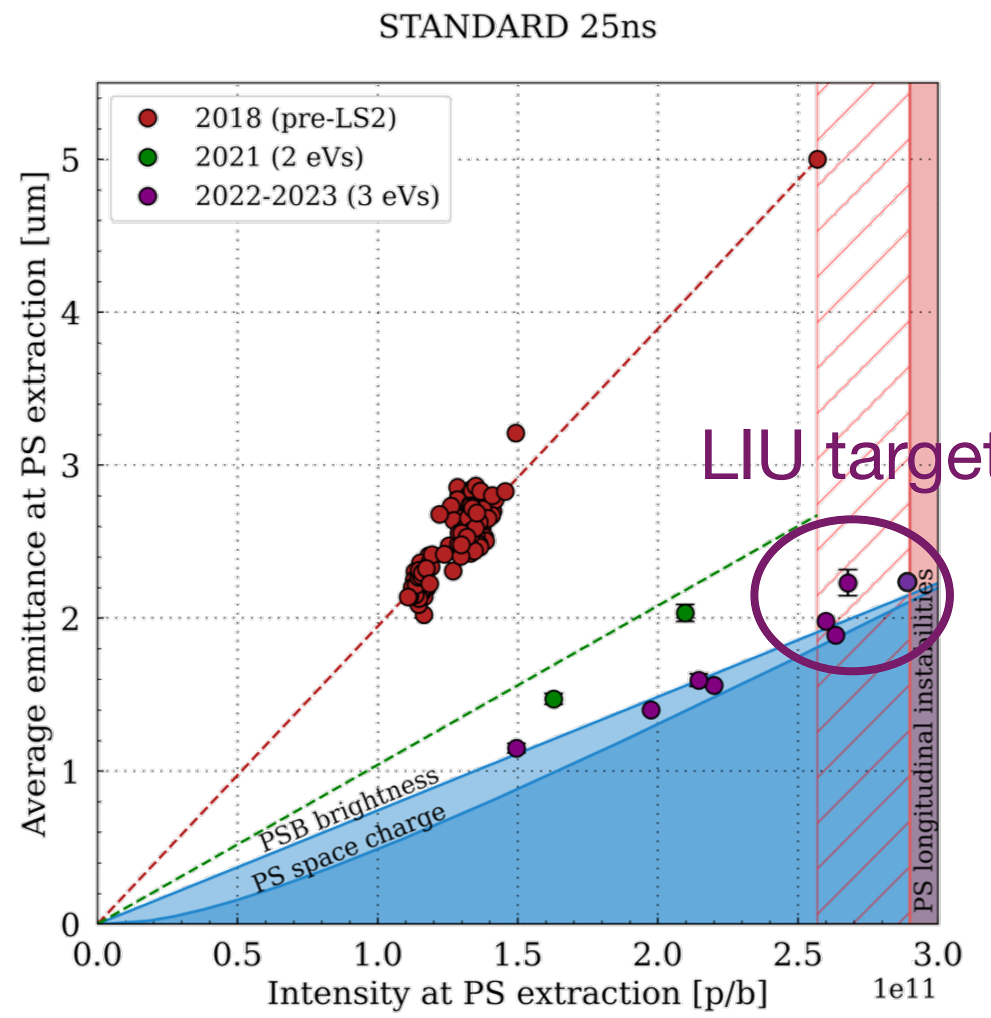
Reaching LIU targets in 2024

- Scrubbing in SPS was effective
- Established LIU parameters repeatedly
  - With standard 25 ns beam, 4x72b trains (HL-LHC baseline)
    - With baseline mean 2.3×10^{11} p/b and 1.65 ns bunch intensity and length
  - With BCMS beam, 5x48b trains (HL-LHC alternative)

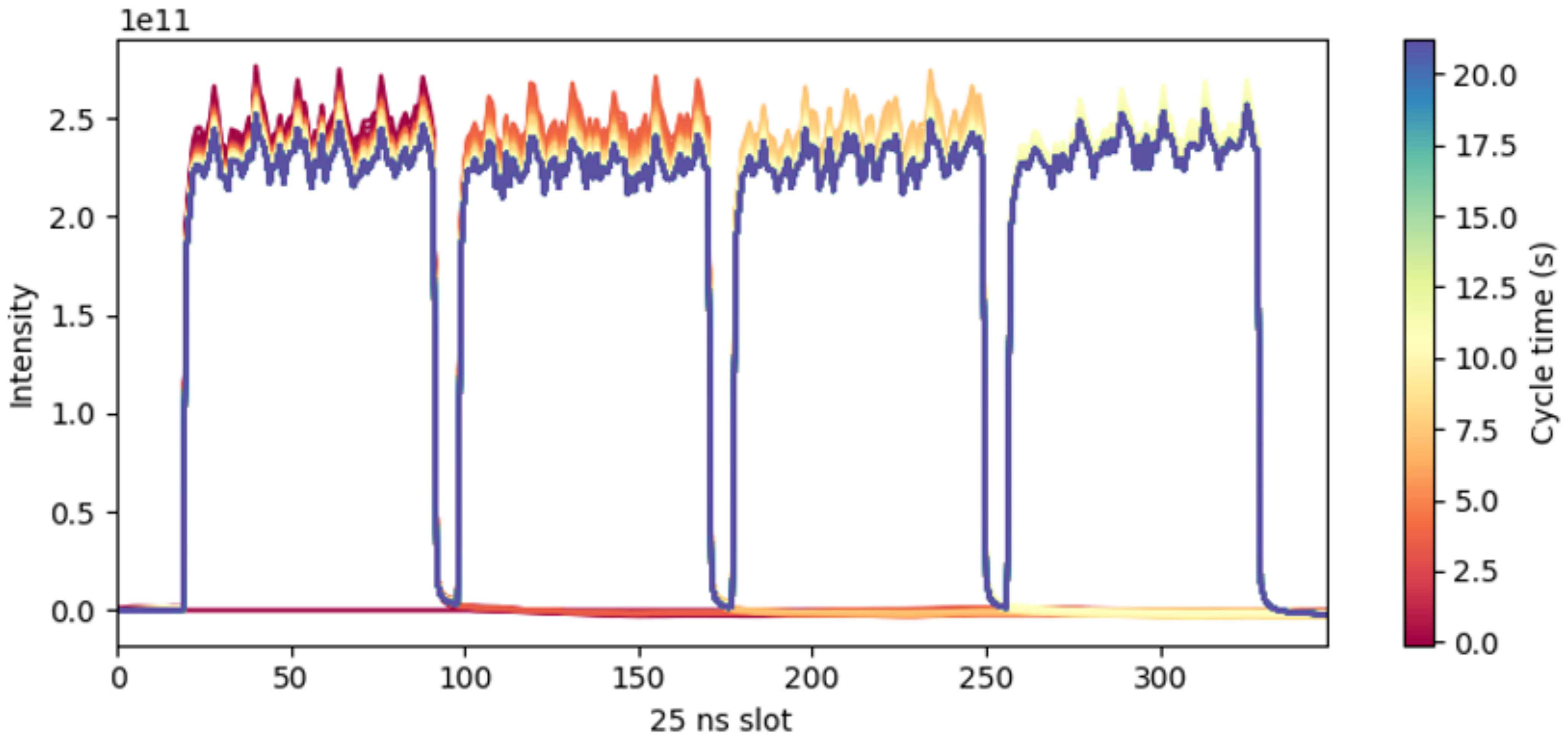
Preparation for proton/time sharing in Run 4

- Increased demands from LHC and fixed-target experiments
  - Extensive use of automation and optimisers

PS performance for LIU proton beams →



SPS performance for LIU proton beams ↓



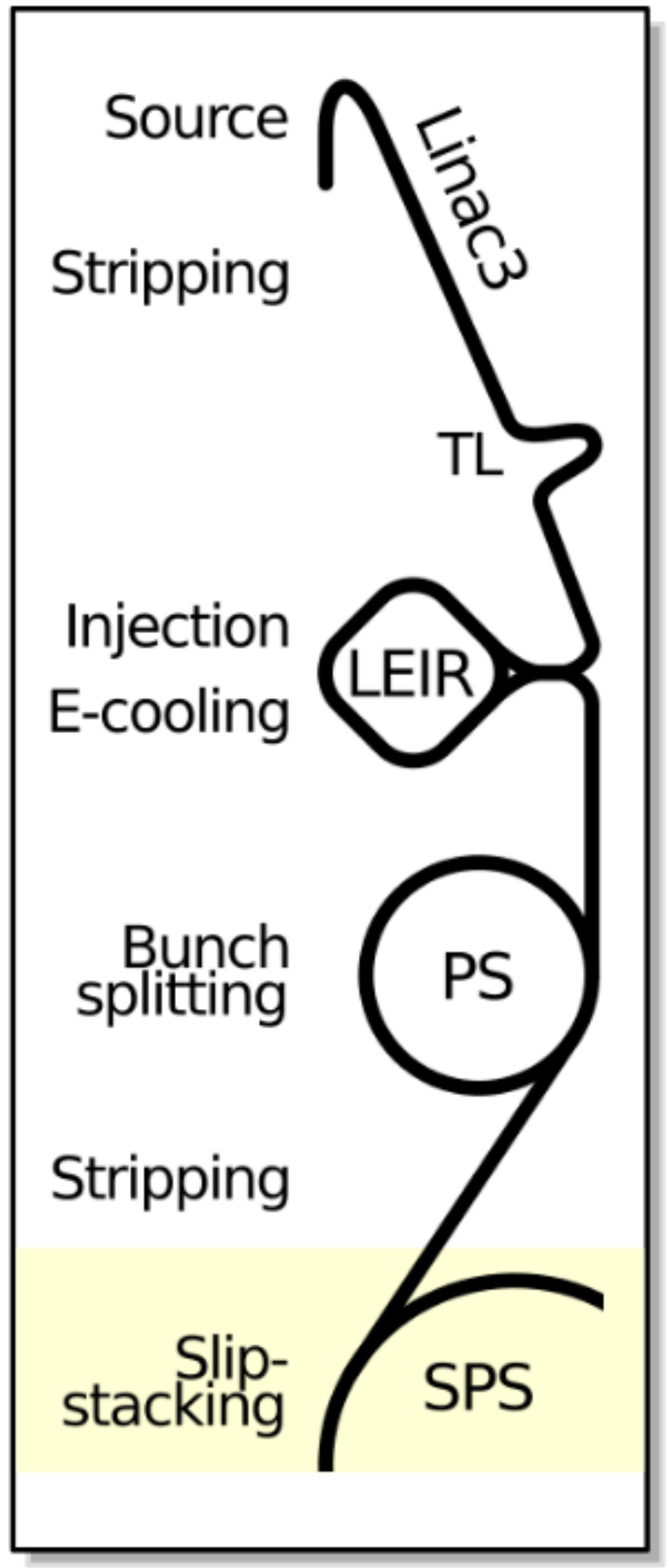
For ions, the best performance ever

In 2023, first-time operation with slip-stacked ions

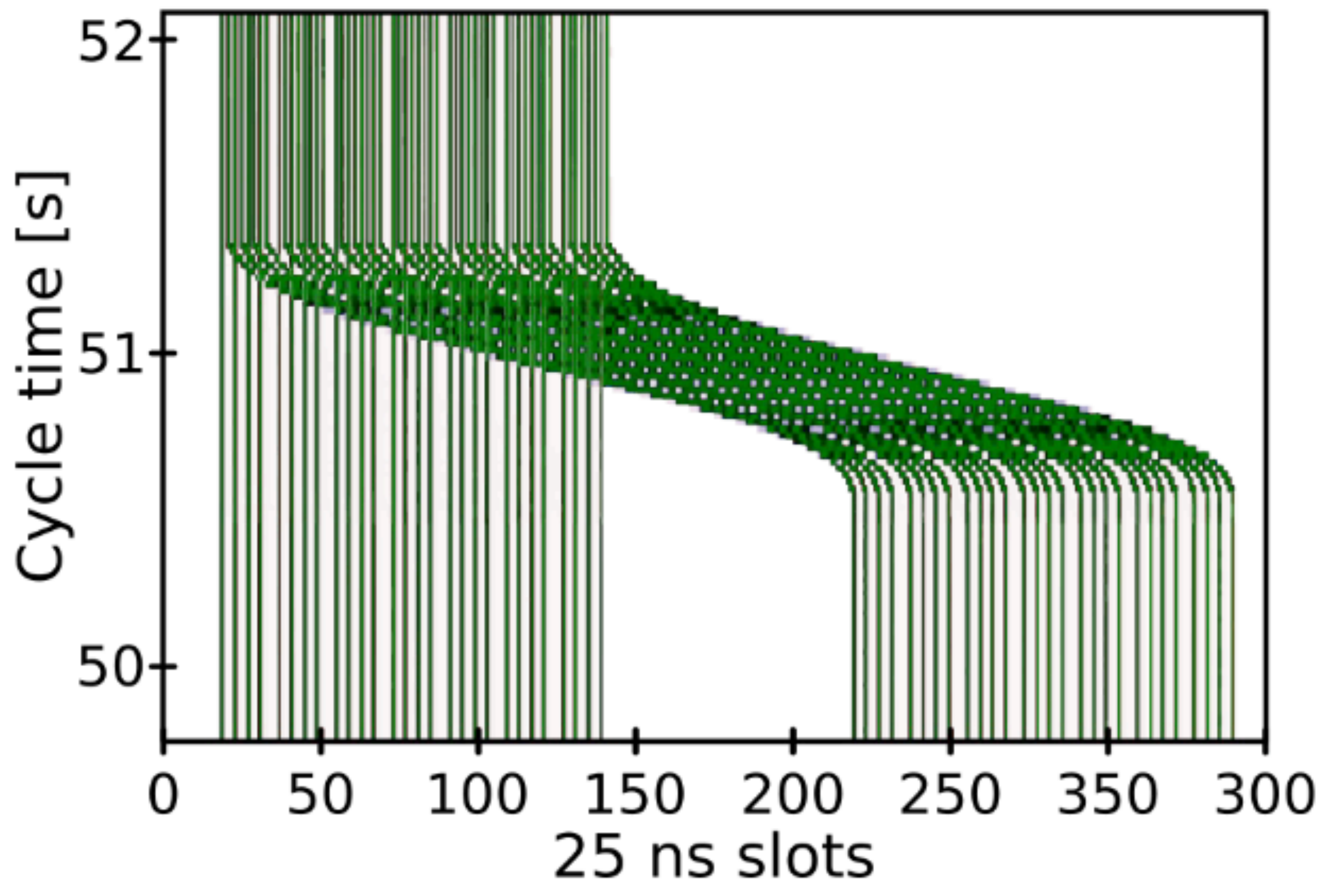
- 50 ns slip stacked beam with LIU intensity demonstrated
  - Good, stable transmission over time
  - Extracted intensity not yet stable in 2023

In 2024, exceeded the LIU intensity target

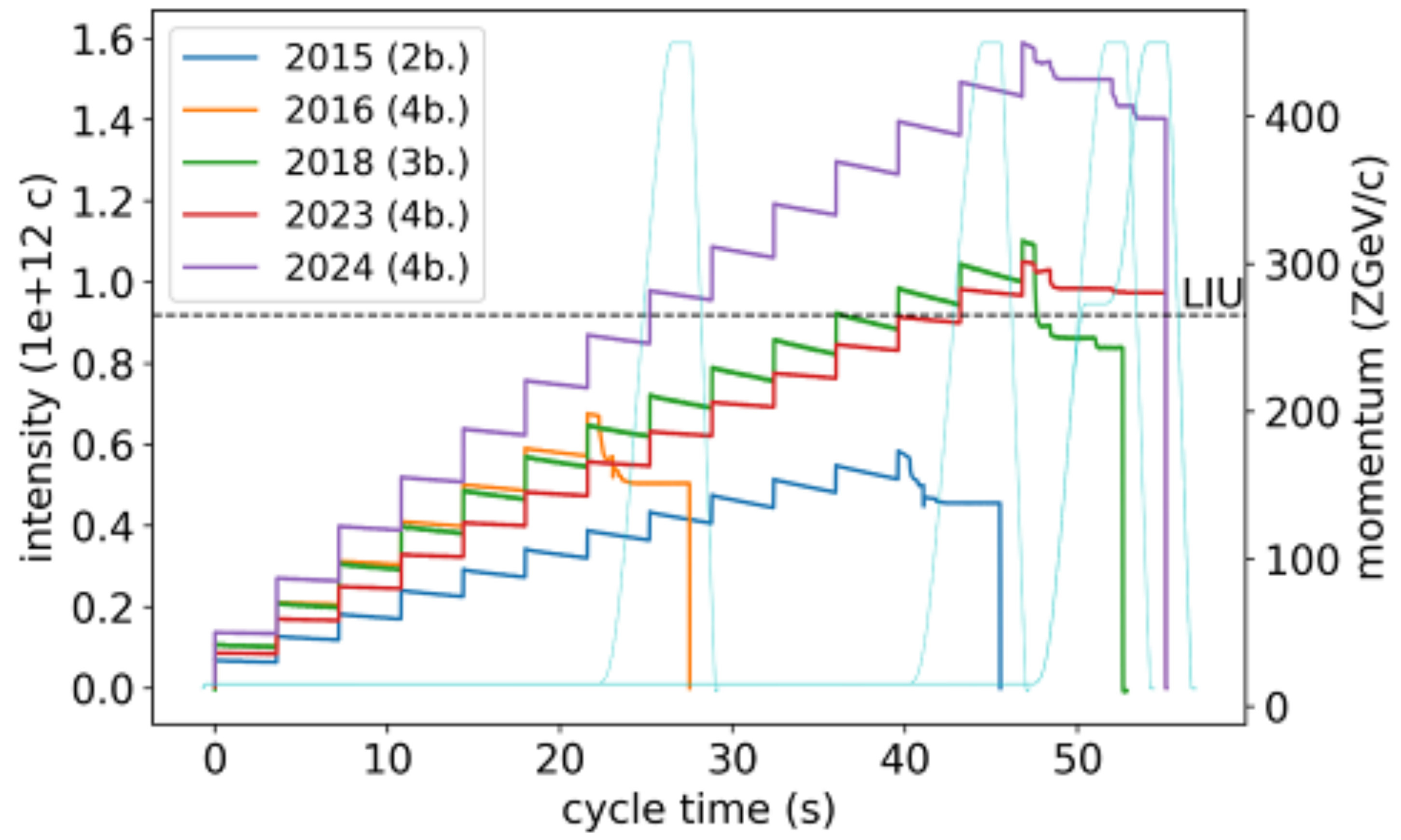
- SPS
  - Around **30 %** higher intensity injected to LHC
  - More bunches: 5x8b and 7x8b injections to LHC
  - Improved transmission in SPS
    - Compensation of 50 Hz power supply ripple
    - Working point optimisation
- LEIR
  - Highest intensity ever, using optimisers
- LINAC3
  - Beam current above LIU 30 μm target



CERN ion injector complex



SPS slip stacking: Interleaving bunches



Ion intensity during SPS cycle

Proton operation

Performance and highlights

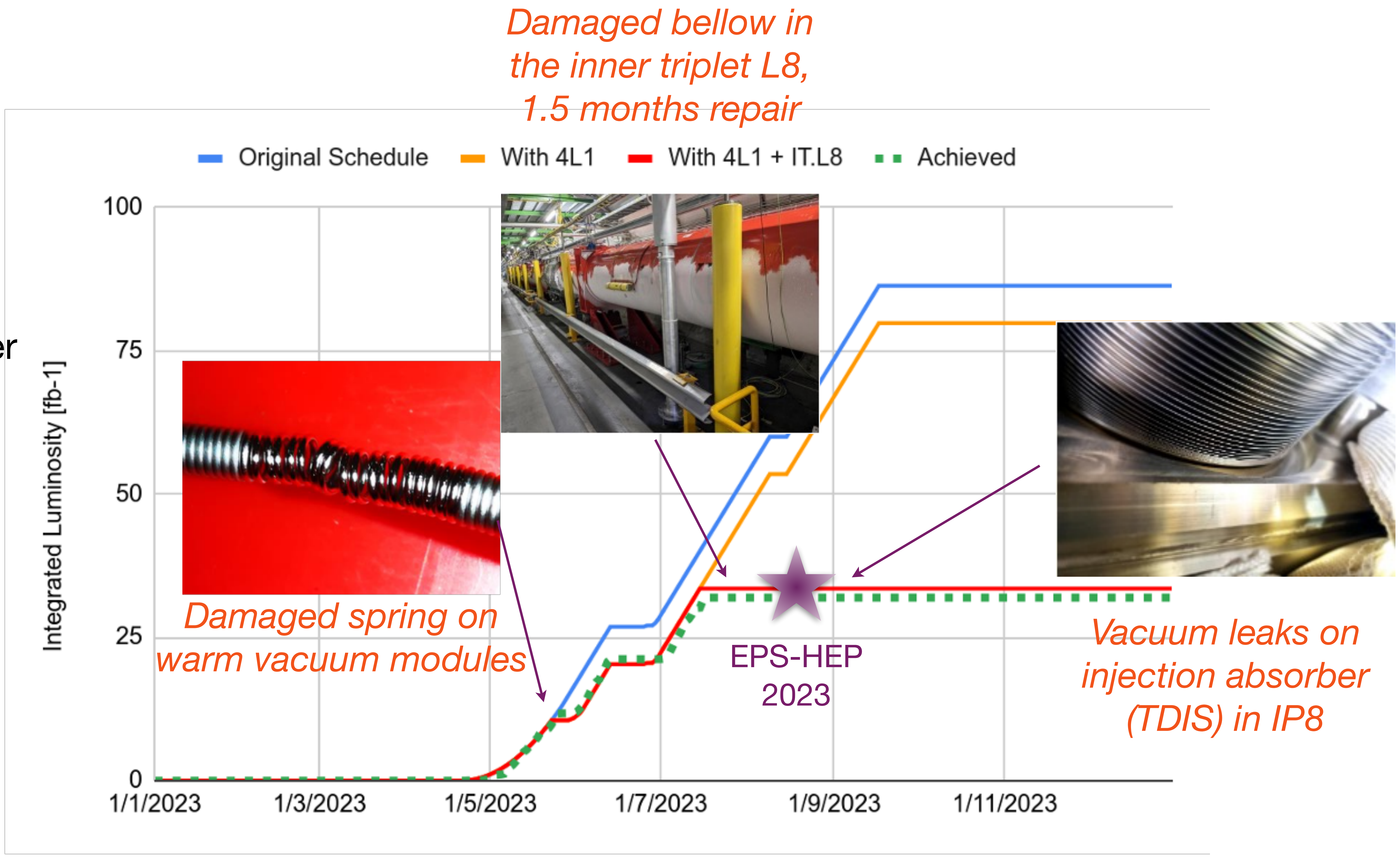
Proton luminosity production 2023

Two events limiting performance

- Damaged spring on warm vacuum modules (region 4L1)
  - Limits bunch intensity to **1.6×10^{11} p/b**
- Damaged bellow in IT (region L8)
  - End of 2023 proton run
- Vacuum leaks on IP8 injection absorber
  - Preventing p operation, but Pb ion operation possible
- Delivered **32 fb^{-1}** (expected **75 fb^{-1}**)

Key components

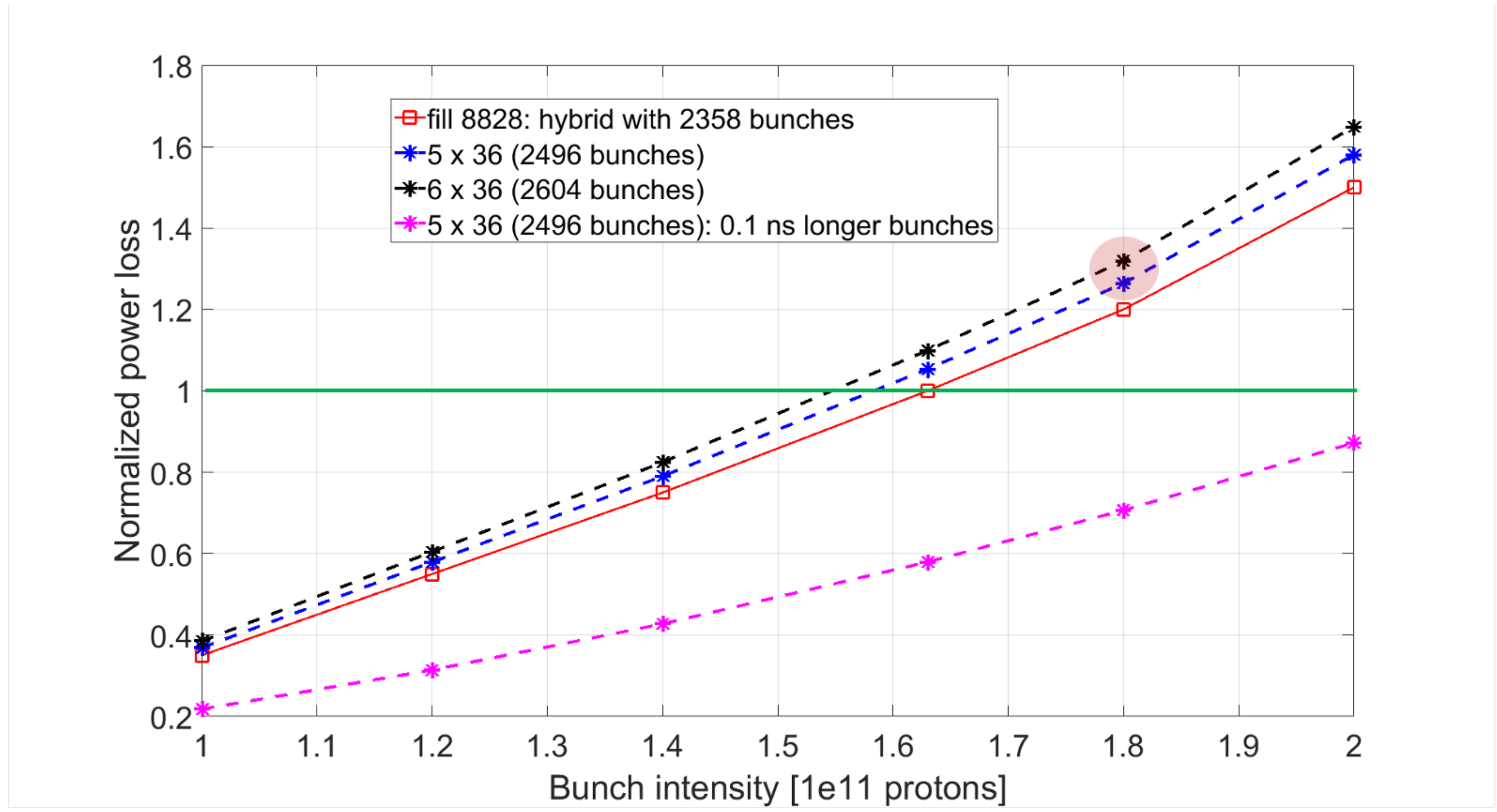
- Operated with hybrid **8b4e + Nx36b** bunch trains
- Production of **~0.8 fb^{-1}/day**
- Beta* levelling **120 → 30 cm**
- **Completed** the Run 3 high-beta run



Mitigations put in place for 2024

Annual shutdown 2023/2024

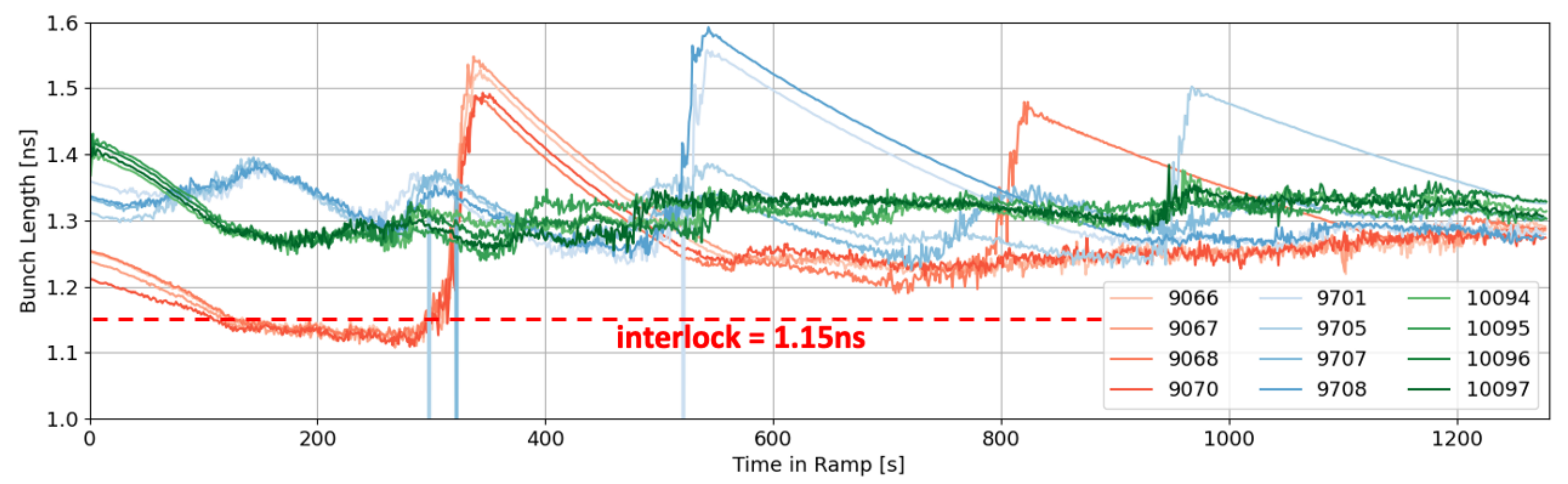
- Injection absorbers replaced with spares having the same non-conformities
  - No limitation for operation though
- Partial consolidation of spring non-conformities in warm vacuum modules



Safe operation region: below the green line, based on beam-induced power loss

Proton operation

- Limit beam-induced heating in remaining non-conform warm modules
  - Bunch length interlocking
  - Bunch intensity so far at **$1.6x10^{11}$ p/b**
  - Foreseen increase to **$1.8x10^{11}$ p/b** this Autumn (Run 3 target)
- Improved bunch length control in the ramp, during controlled longitudinal emittance blow-up
  - Mitigating bottleneck at the start of ramp



Improved bunch length control during the ramp

Proton luminosity production 2024 & 2025

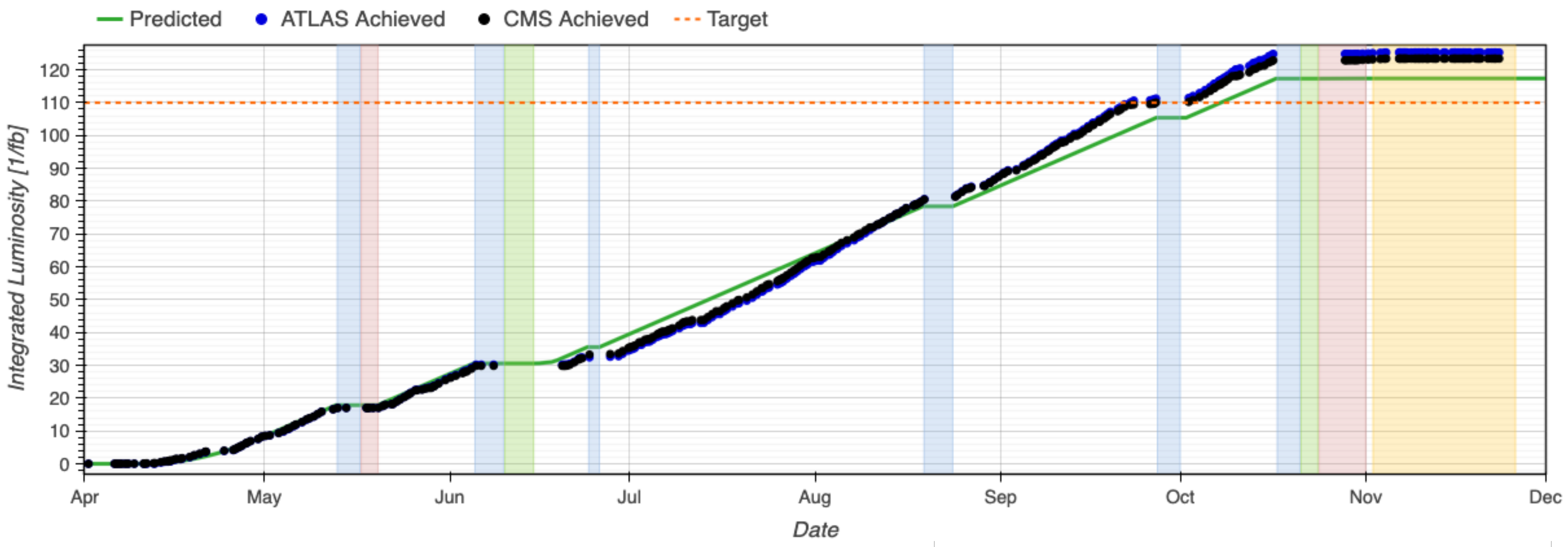
2024: the most productive year to date!

- ATLAS, CMS: **124 fb^{-1}**
- LHCb: **11 fb^{-1}**
- ALICE: **67.5 pb^{-1}**

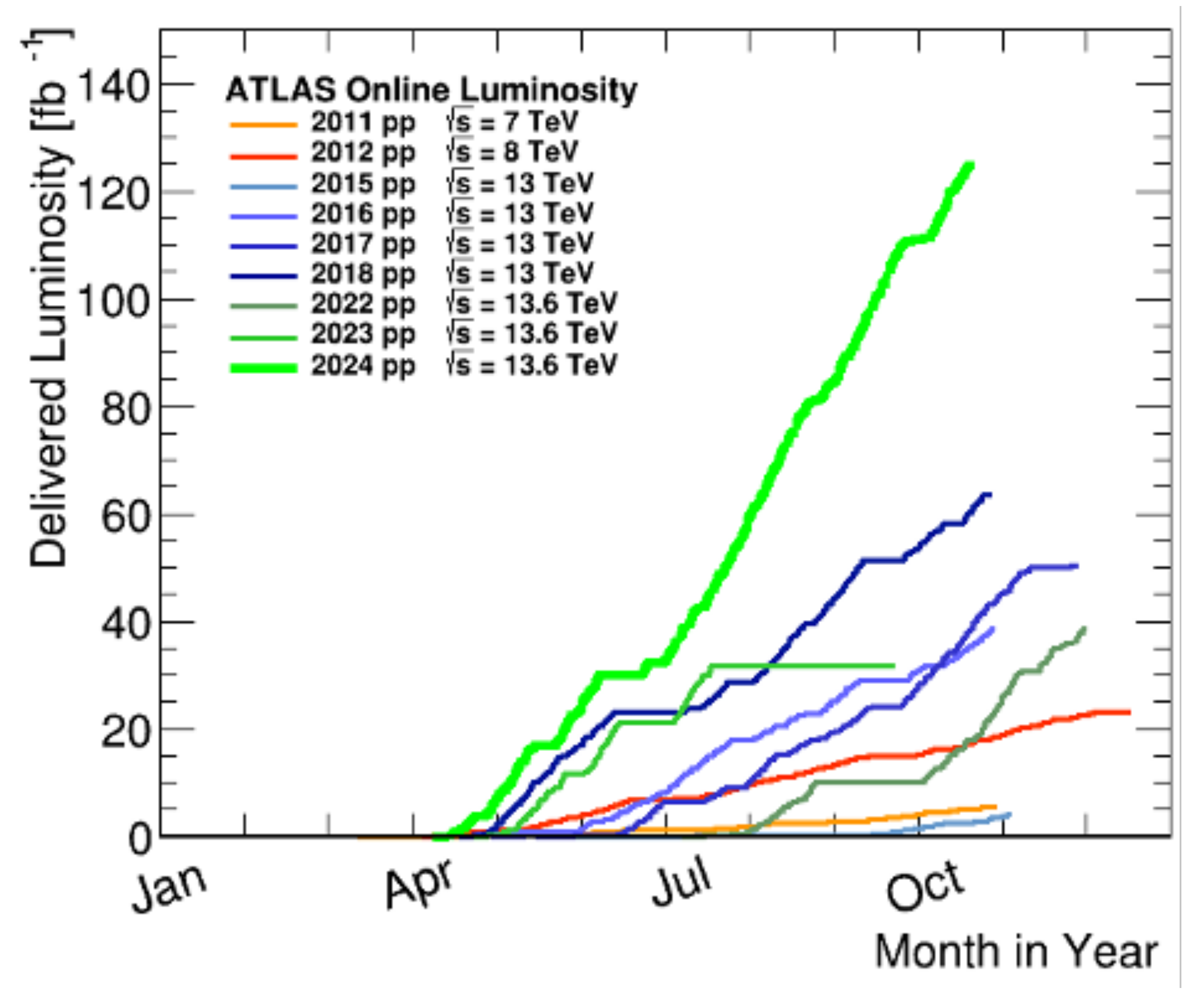
Breaking records

- Average production rate of **0.83 fb^{-1}** in 24 h
- Peak production rate of **1.5 fb^{-1}** in 24 h

Integrated luminosity in 2024: beyond the target of 110 fb^{-1}

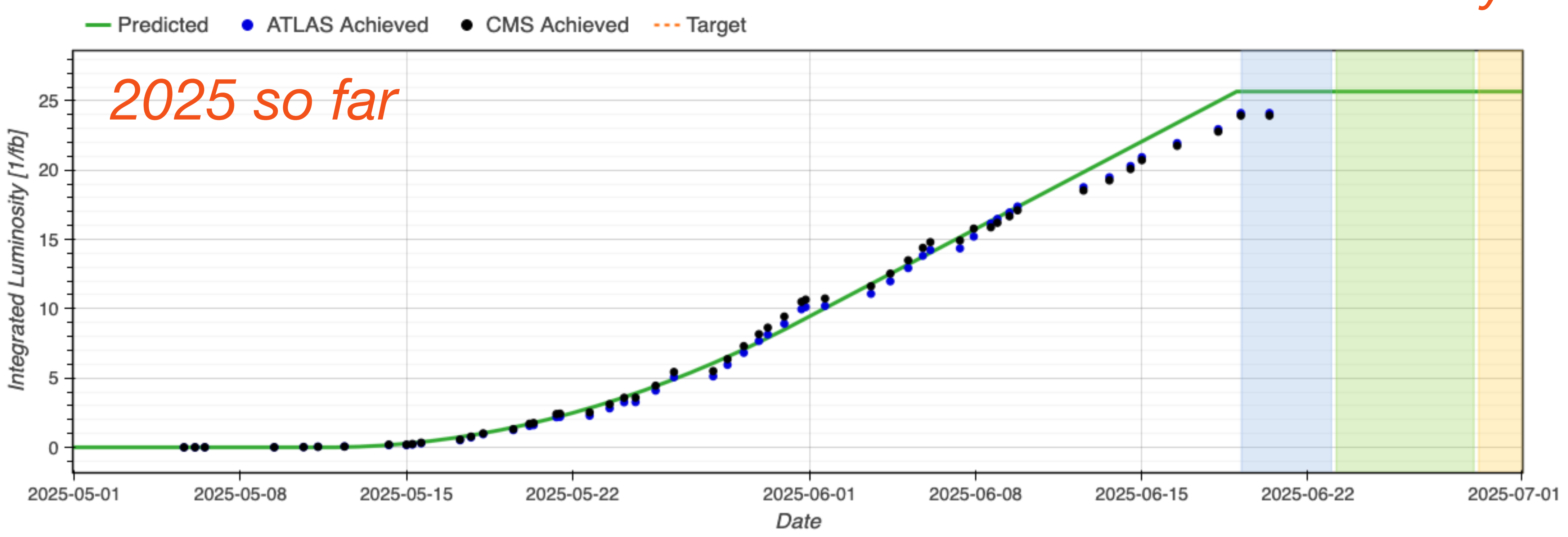


Increase in production rate over the years →



2025: on track so far

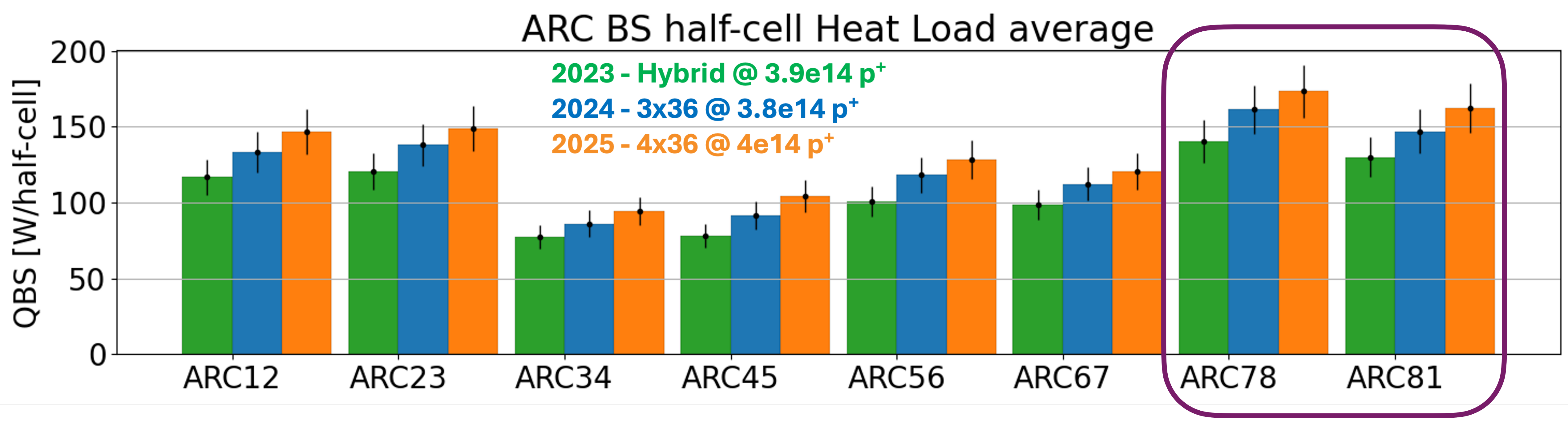
- ATLAS/CMS: **24 fb^{-1}**
- LHCb: **2.6 fb^{-1}**
- ALICE: **14.3 pb^{-1}**



Cryogenics and heat load limitations

Maximum operational heat load: 170 W/hc in S78

- Regulation margin: **10 W/hc**
  - LHC design was **85 W/hc**
- Highest heat load sectors: S78 and S81

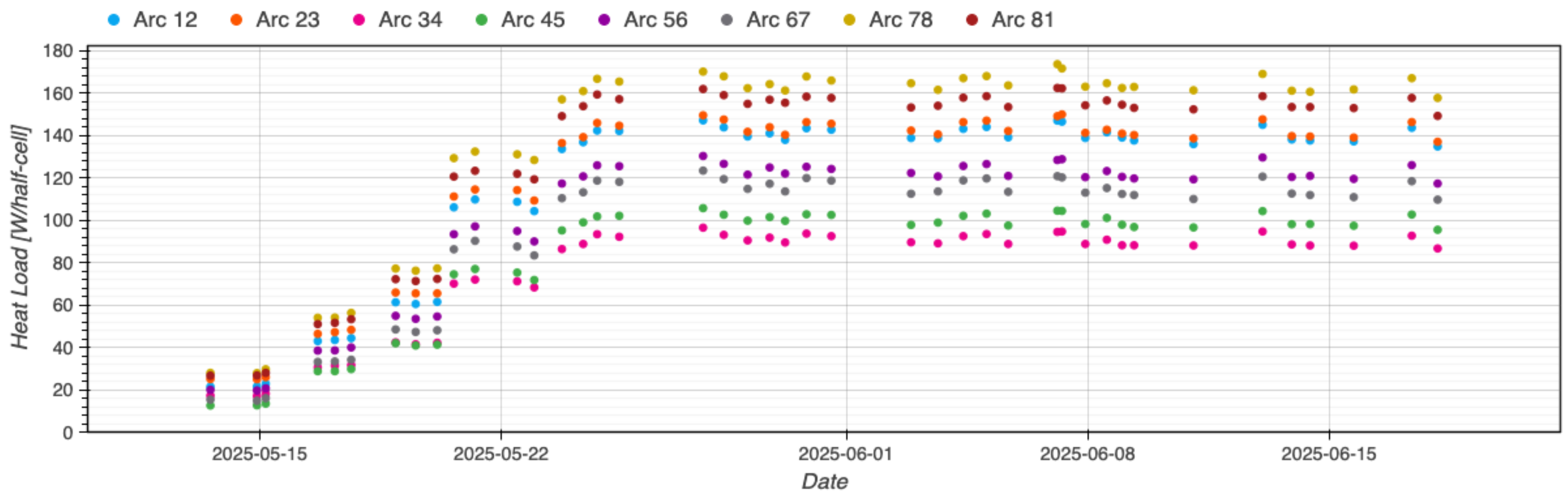


Heat loads for different beam types

Uneven distribution along the machine

Heat load over the past two years

- With hybrid beam of 2023, heat load **<150 W/hc**
  - Re-balancing of refrigerators for enough cooling capacity in critical sectors
- With BCMS beam of 2024, peak at **177 W/hc**
  - 2352 b and 1.6×10^{11} p/b
  - Conditioned down to 160 W/hc over the year
  - Further optimisation of configuration end of 2024
- With BCMS beam of 2025, peak at **174 W/hc**
  - 2460 b and 1.6×10^{11} p/b
  - Working **close to the limit**



Heat loads evolution in 2025

The LHC cycle

ENERGY

450 GeV

INJECTION PROBE BEAM → INJECTION PHYSICS BEAM

Adjust settings with a low-intensity bunch

Tune, orbit, injection phase/energy, etc.

Fill both rings with bunches of operational intensity

May take up to 1 hour

Filling schemes designed to give an agreed amount of collisions in each IP

RAMP

Ramp the magnets and the RF frequency

Controlled longitudinal emittance blow-up, etc.

6.8 TeV

FLATTOP → SQUEEZE → ADJUST → STABLE BEAMS

Arrival to flattop

Orbit bumps keep the beams separated at the IP

Beam size reduction in IP

Achieved by reducing the β^* in the IP

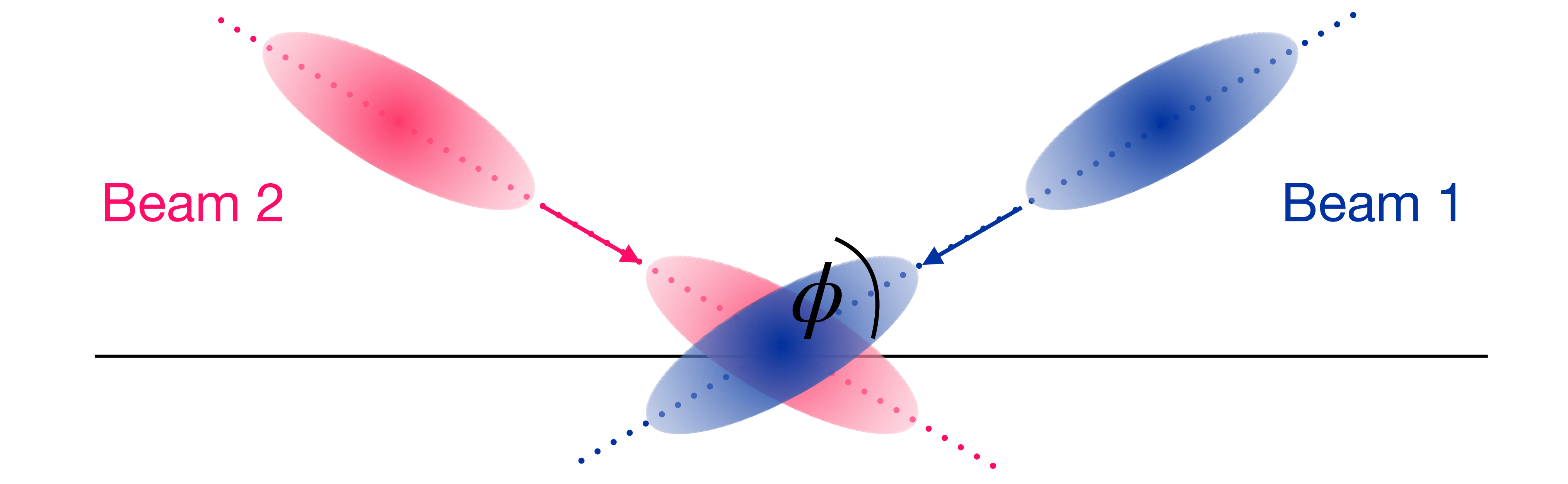
Close in IP separation

Optimisation of luminosity using orbit scans

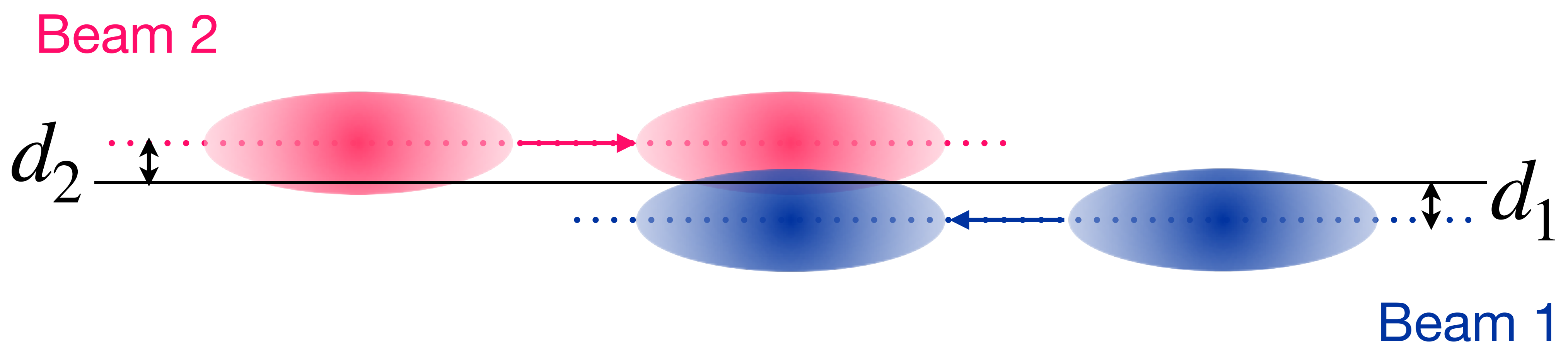
Luminosity production

Start of levelling

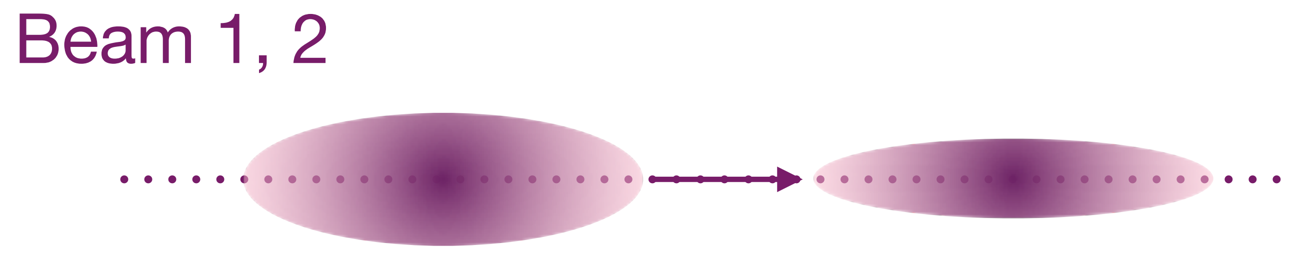
How is it done?



Crossing angle



Beam separation — orthogonal to crossing plane



Beam size at IP

What can we act on?

$$\mathscr{L} = \frac{kN_1N_2f_{\text{rev}}}{4\pi\sigma_x\sigma_y}\frac{e^{-\frac{1}{4\sigma_y^2}(d_2-d_1)^2}}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\tan\frac{\phi}{2}\right)^2}}$$

Separation

Beam size at the IP

↕

Optics (strong focussing magnets)

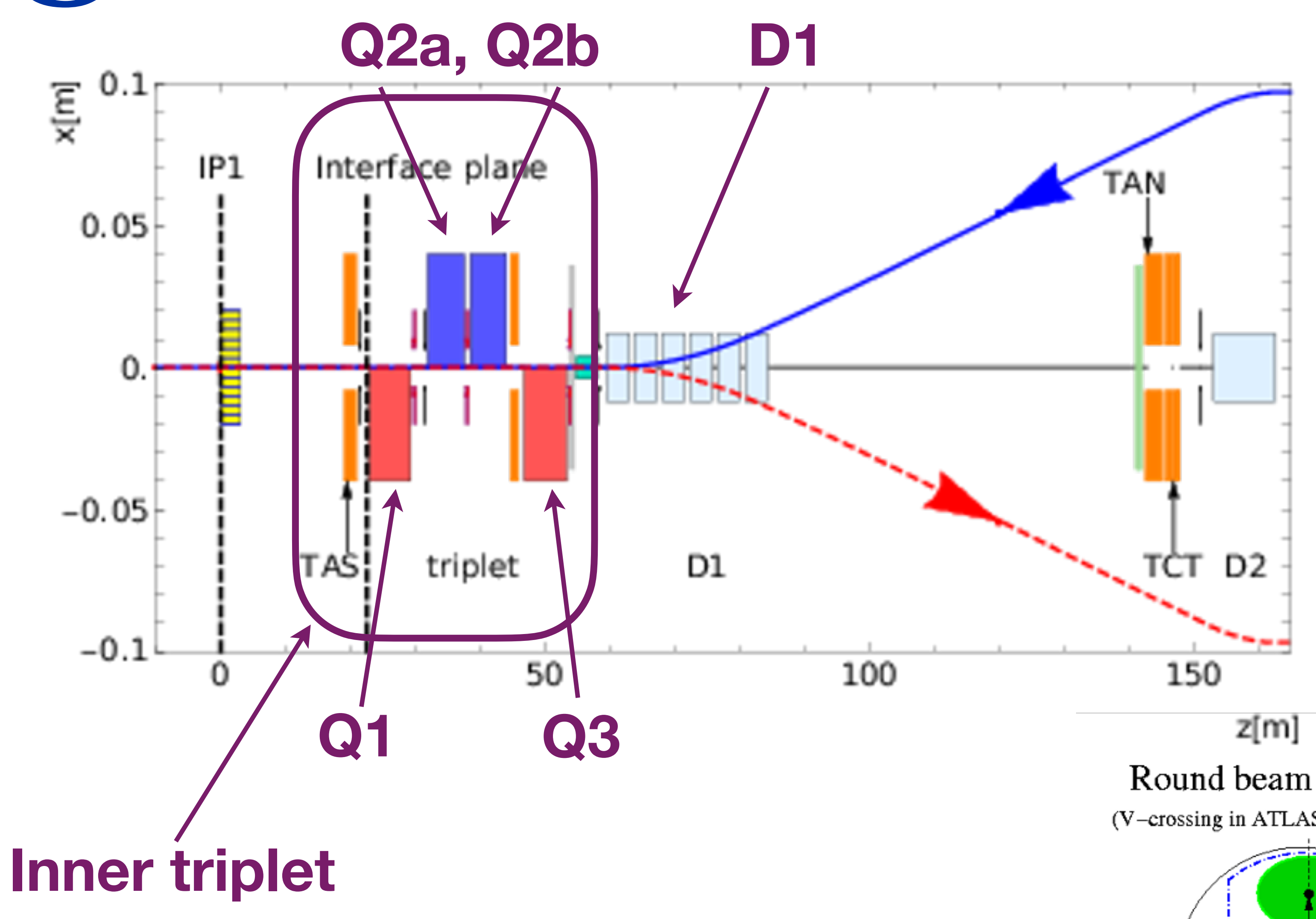
Crossing angle

f_{rev}	revolution frequency
k	number of bunches
N_i	bunch population (beam i)
ϕ	crossing angle
σ_x, σ_y	transverse beam size
σ_s	longitudinal beam size

Optics configurations

Irradiation of inner triplets (IT) through proton collisions

- With optics, the dose can be distributed over different coils
  - Thus, the lifetime of the magnets can be better preserved
- Recommended dose limit: **30 MGy** in IT, **75 MGy** in D1
- Target integrated luminosity of **300 fb^{-1}** in Run 3
  - Achieved by pushed beam parameters and crossing angle
- Dose projections exceed limit in nominal optics (FDF)

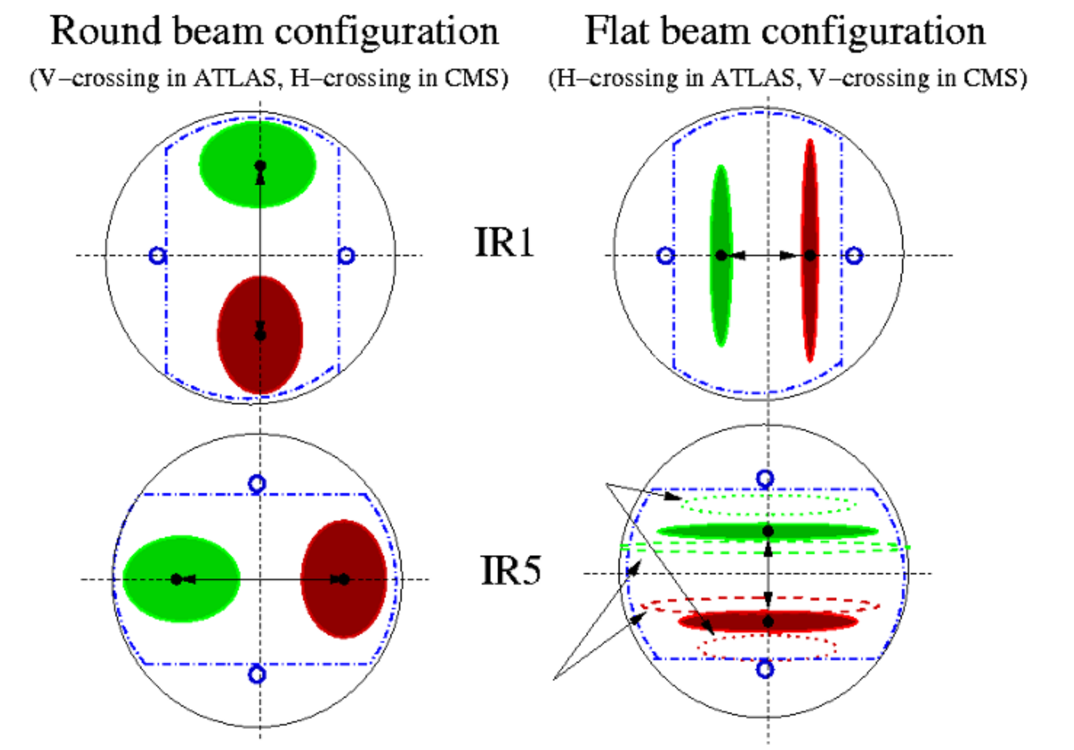


Layout around the IP with inner triplet and D1

Reverse polarity (DFD) optics in 2024

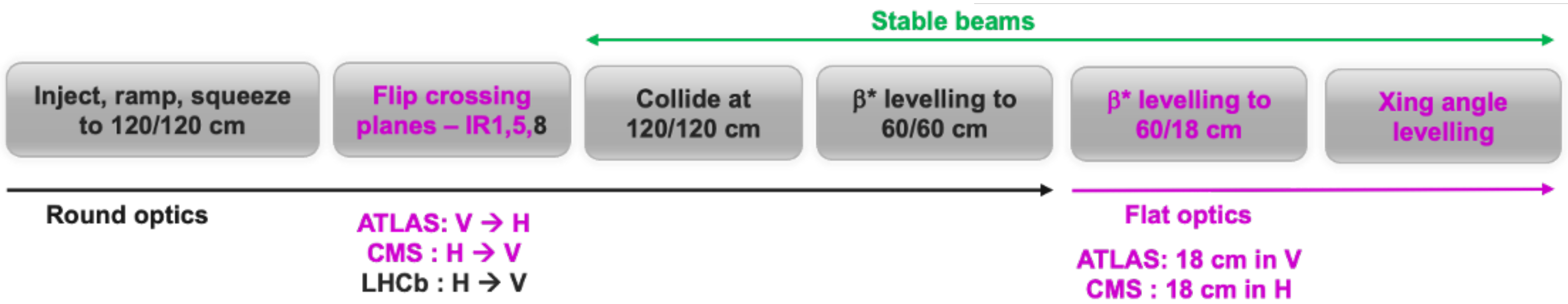
- Reverted polarity and crossing angle in IR1 only
  - Spreads the dose more evenly and reduced the overall dose
- Drawback: increased background at FASER/SND

2025 configuration: inverted crossing planes and flat optics



Flat optics in 2025

- Reverse polarity in IP5, nominal in IP1
- Best performance with inverted crossing planes
  - Possible with flat optics in asymmetric aperture



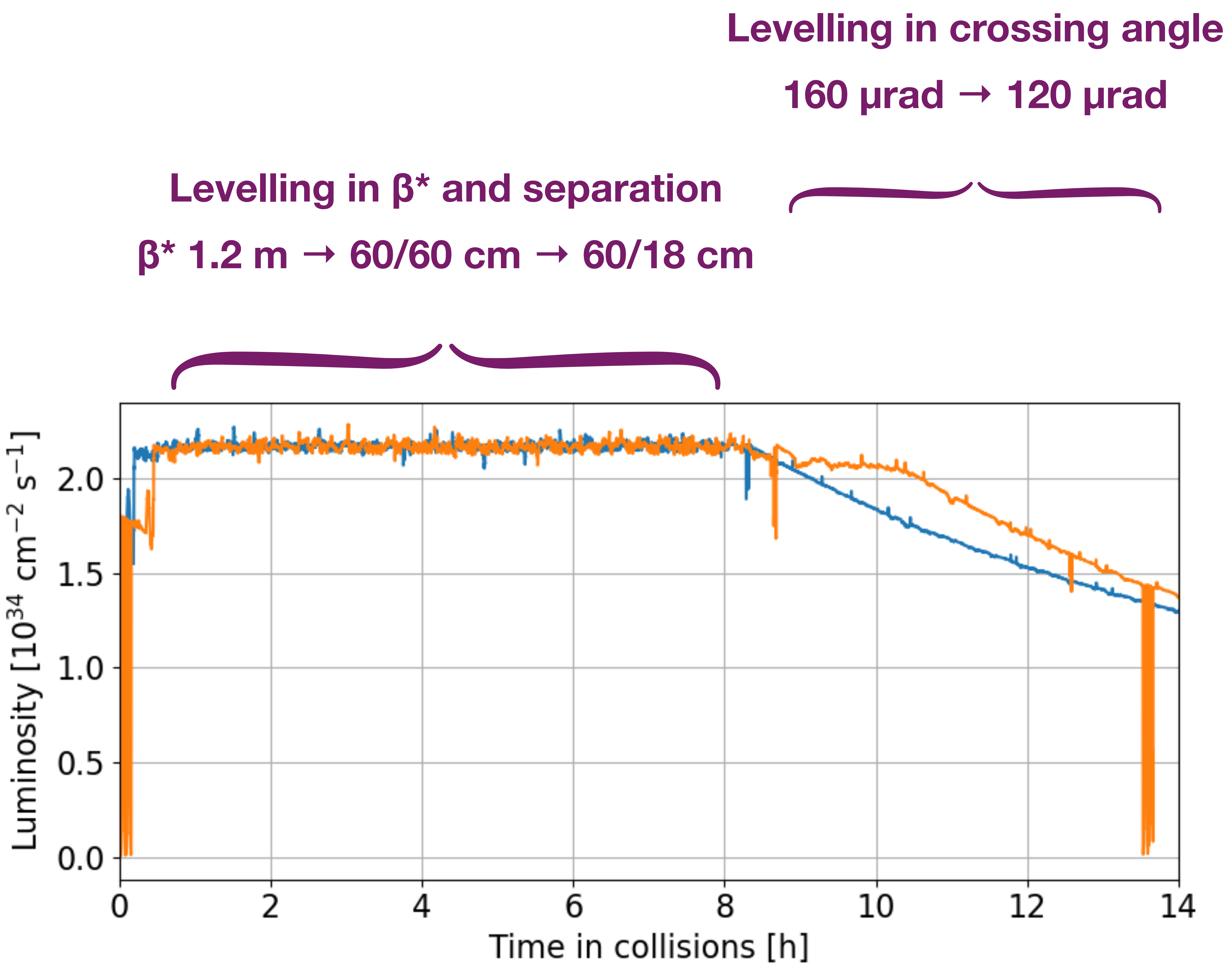
Luminosity levelling

Required by cooling limitations in IT magnets and pile-up in the detector

- LHCb levelled at all times
- ATLAS and CMS levelled till sufficient burn-off is reached
- Luminosity control better than **2.5 %**

Levelling technique

- Combining β* (beam size) and beam offset levelling
  - BCMS beams extend levelling time by 1-2 h → **6-7 h** total
  - Levelling time is extended with increased bunch intensity increase
- As of 2025, added quasi-continuous crossing-angle levelling
  - Extends levelling time by another **~1.5 h**
  - Gain in integrated luminosity: **~1-2 %**
  - Preparing also the ground for the HL-LHC alternative flat optics scenario

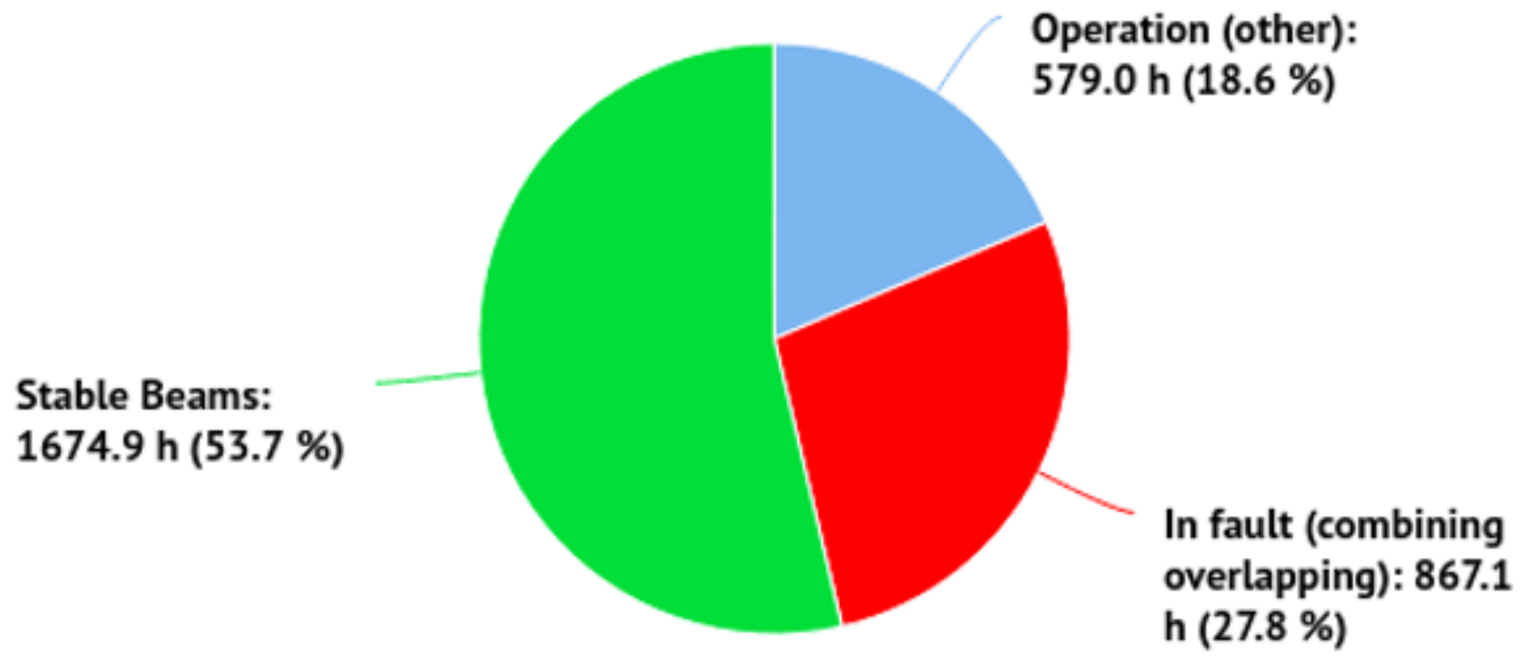


Typical luminosity evolution with (orange) and without (blue) crossing-angle levelling

Automation and availability

Availability and turnaround are key factors in luminosity production

- An immense effort is continuously being invested in ensuring that failure don't repeat or don't occur at all



Availability during the 2024 proton operation

Automation is the key to limit human errors and optimise time in operation

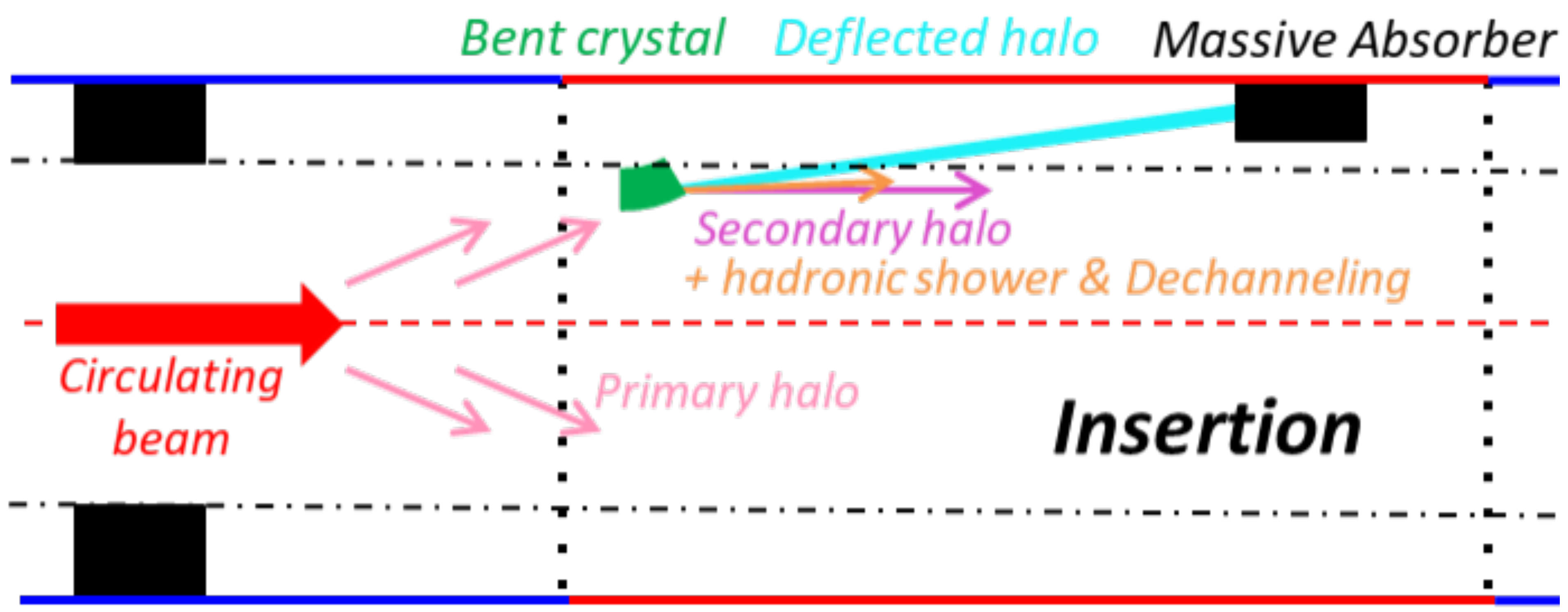
- A large fraction of the LHC operational processes is automised
- Some examples are:
  - The levelling logic, controllable by the experiments through their requests
  - Bunch length control in ramp and in stable beams
  - Orbit feedback
  - Minimisation of RF power at injection
  - … and many others


CERN
Ion operation
Performance and highlights

HL-LHC ion upgrade

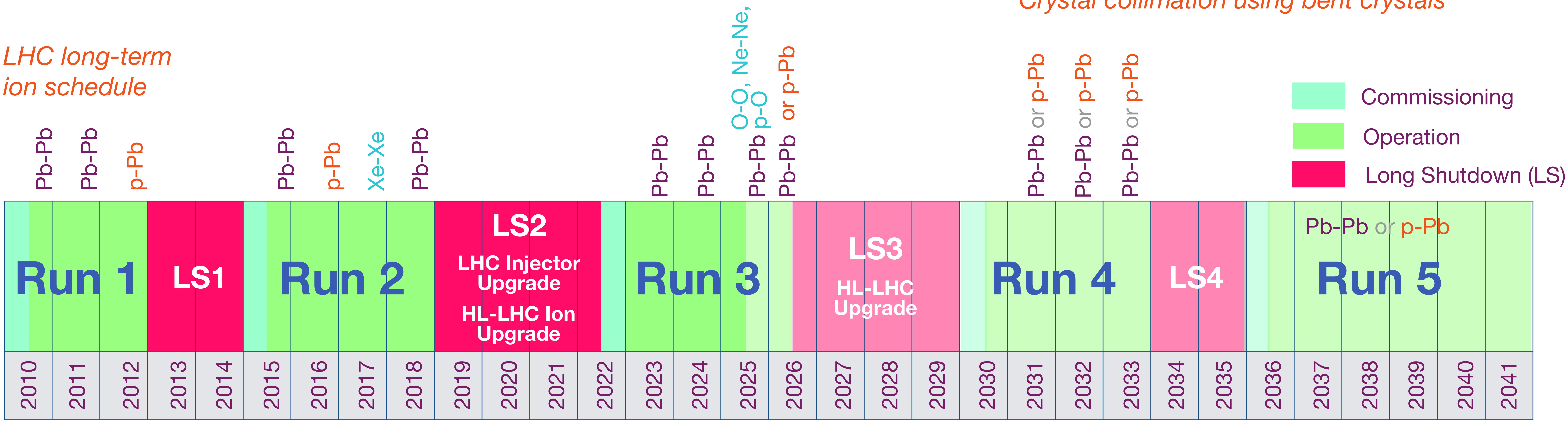
Improvements already implemented in Long Shutdown 2

- Slip stacking: ~70 % more bunches
- Crystal collimators: handling higher beam losses
- Orbit bumps and new collimators around ALICE: sustaining higher collisional losses
- Upgraded ALICE detector: handling higher event rate



Crystal collimation using bent crystals

LHC long-term ion schedule



Ion luminosity production 2023

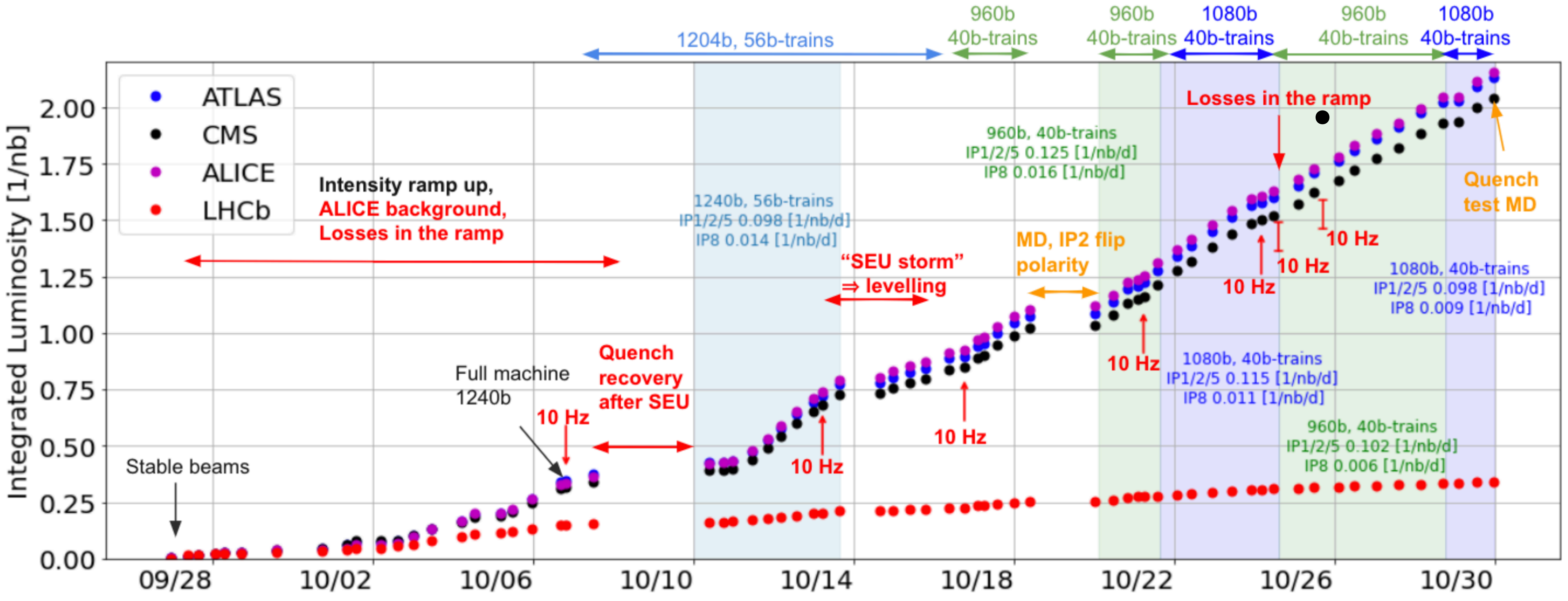
Successfully entered in the HL-LHC ion operation

Leaning how to operate with slip-stacked beams

- Ion bunch parameters below expectations
  - Ions/bunch: **< 1.8x10^8 Pb/b**, emittances: **> 2 μm**

Luminosity

- Average daily production (full machine) of **80 μb^{-1}**
  - Integrated luminosity: only ~**2/3** of initial goal (due to problems see next slide), but still higher than in 2018
- For ALICE
  - Record peak luminosity of **6.4x10^{27} $cm^{-2}s$**
  - Integrated **2.16 nb^{-1}** > Run 1 & Run 2 combined!
    - Partially high background data



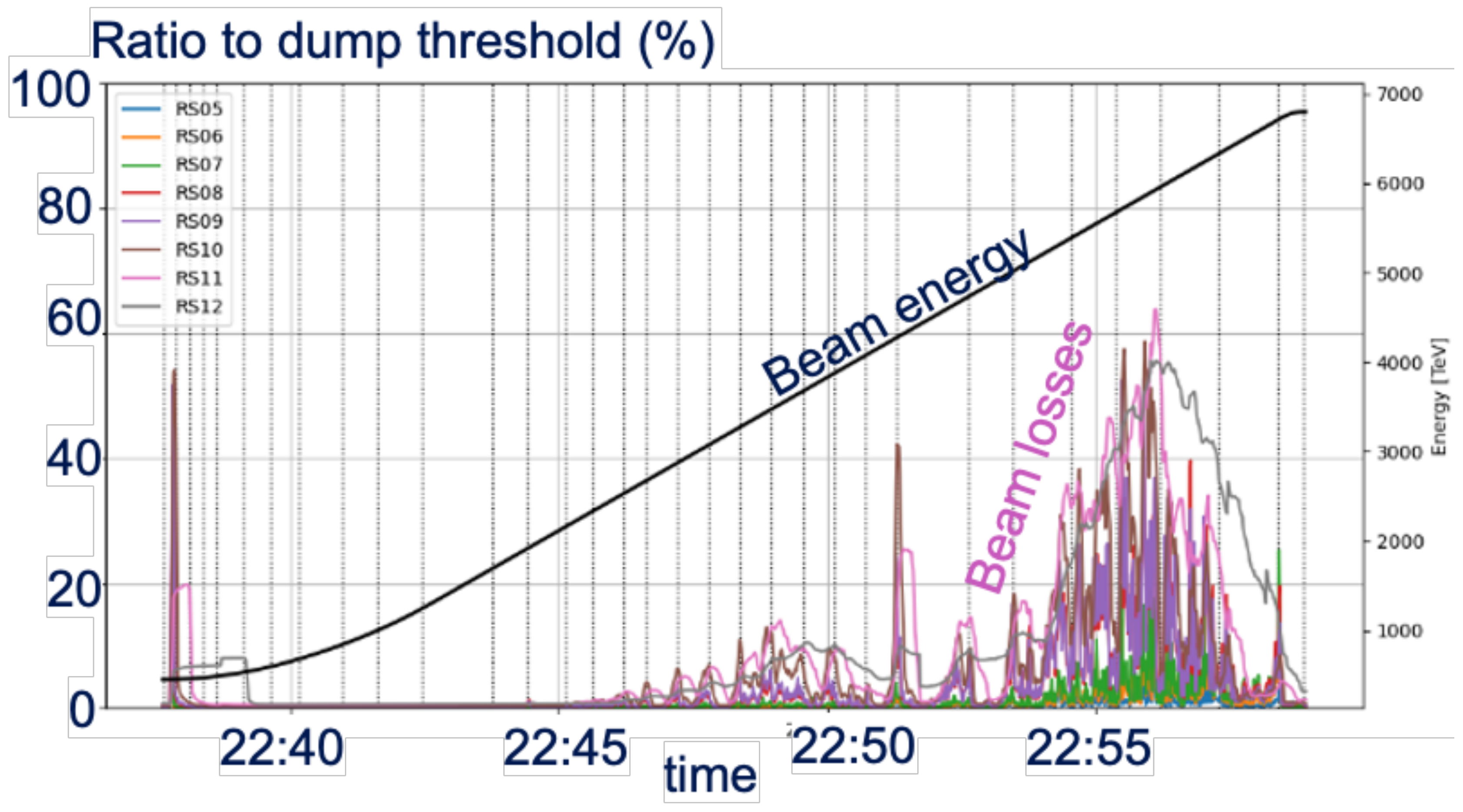
Integrated luminosity for ions in 2023 for the four LHC experiments

… and challenges encountered (in red)

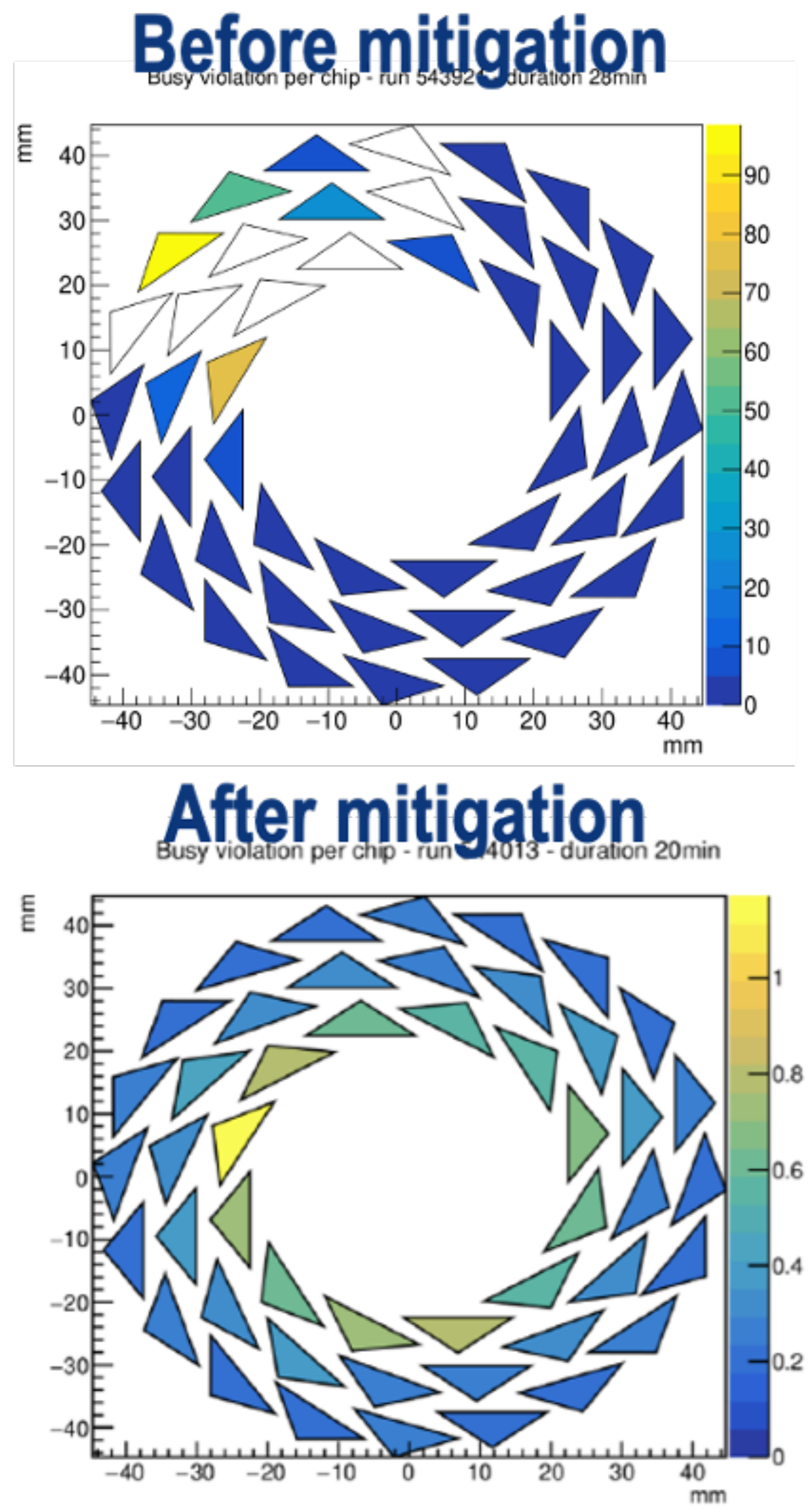
Challenges and Mitigations

Issues encountered during the 2023 ion run — and their mitigations for 2024

- Radiation-induced SEU in the quench protection system
  - Boards replaced by new radiation-hard ones
- Sudden losses and beam dump due to 10 Hz horizontal orbit oscillations
  - Tracked to the opening of a valve, now constrained to no-beam time
- Beam dumps due to transverse losses in the ramp
  - More open collimators
- High ALICE background
  - Dispersion correction in IP1
- Issues with crystal goniometer stability
  - Automatic channeling optimisation



Beam losses during the ramp



ALICE background

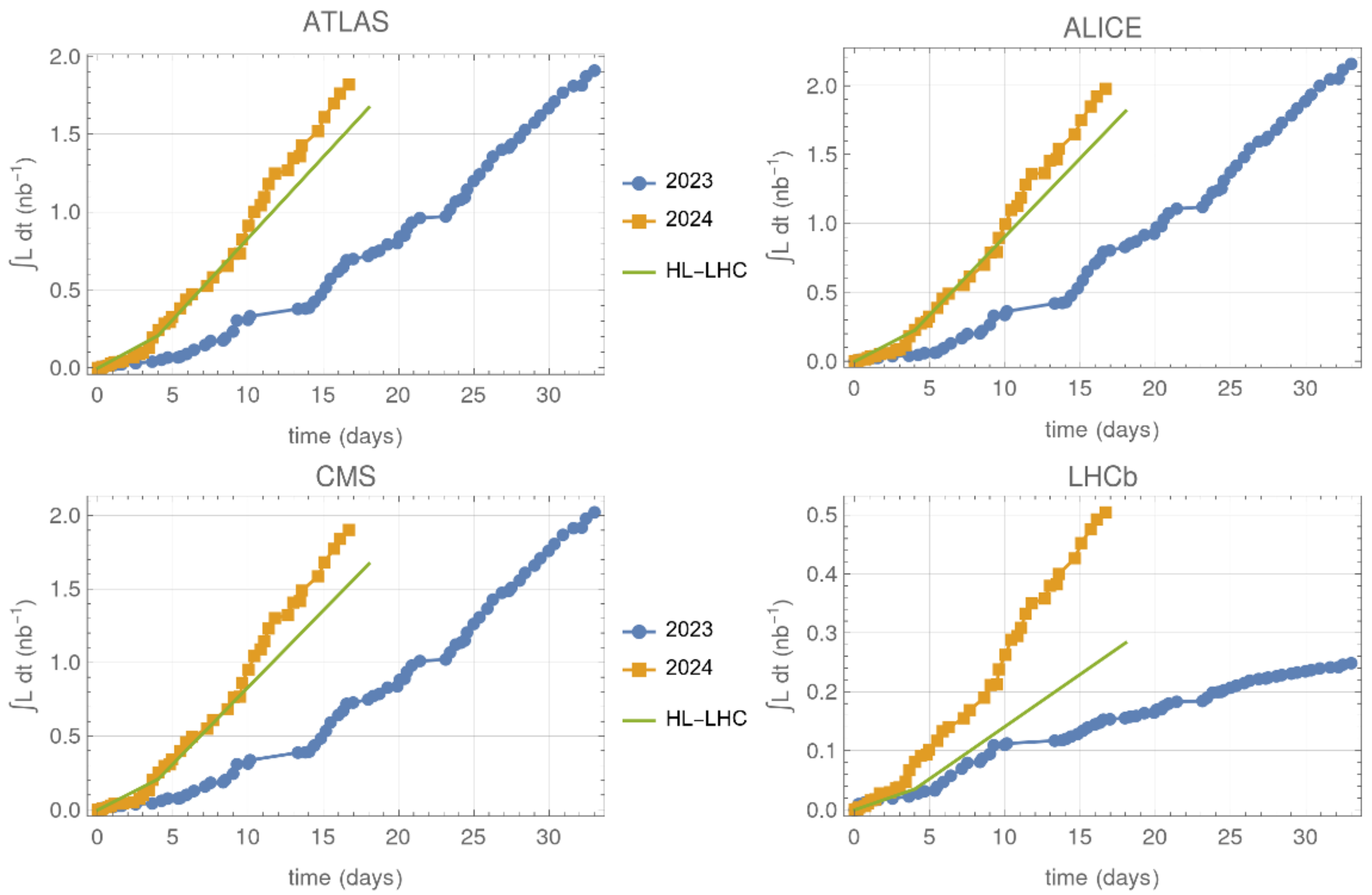
Ion luminosity production 2024

Operating beyond the HL-LHC target

	Bunch intensity	Max. stored beam energy
2023	1.6×10^{8} Pb/bunch	17.3 MJ
2024	2.3×10^{8} Pb/bunch	26.9 MJ
HL-LHC	1.8×10^{8} Pb/bunch	20.5 MJ

Luminosity production

- Proton-proton reference run (7 days) completed
- ALICE, ATLAS, CMS
  - Reached target of **1.9 nb^{-1}**, 2h levelling at **6.4×10^{27} cm^{-2} s^{-1}**
  - Almost same luminosity in 2024 as 2023, in half the time
  - Mean daily production: **142 μb^{-1}**
    - HL-LHC projection was: **118 μb^{-1}**
- LHCb
  - About double the luminosity in 2024 than in 2023, in half the time
  - Mean daily production: **37 μb^{-1}**
    - HL-LHC projection was: **20 μb^{-1}**



Luminosity production during the 2024 ion run in the four IPs

Special ion run 2025

Eight-day Oxygen and Neon run

- Tight schedule to commission and produce data with p-O, O-O, Ne-Ne
- Excellent availability and luminosity beyond expectations!
- p-O run
  - Produced beyond the targets for all experiments (>x10 in IP5/8)

	ATLAS/LHCf	ATLAS	ALICE	CMS	LHCb
Target	1.5 nb^{-1}	—	5 nb^{-1}	3 nb^{-1}	2 nb^{-1}
Achieved	**1.6 nb^{-1}**	**6.1 nb^{-1}**	**7.4 nb^{-1}**	**46.6 nb^{-1}**	**31.6 nb^{-1}**

- O-O run
  - Also exceeded the targets by >x10

	ATLAS	ALICE	CMS	LHCb
Target	0.8 nb^{-1}	0.5 nb^{-1}	0.8 nb^{-1}	0.5 nb^{-1}
Achieved	**8.2 nb^{-1}**	**5.1 nb^{-1}**	**9.0 nb^{-1}**	**5.5 nb^{-1}**

- Ne-Ne run
  - A brief 24 h run targeting 0.1-0.2 nb^{-1}

	ATLAS	ALICE	CMS	LHCb
Achieved	**1.3 nb^{-1}**	**0.9 nb^{-1}**	**0.9 nb^{-1}**	**0.56 nb^{-1}**

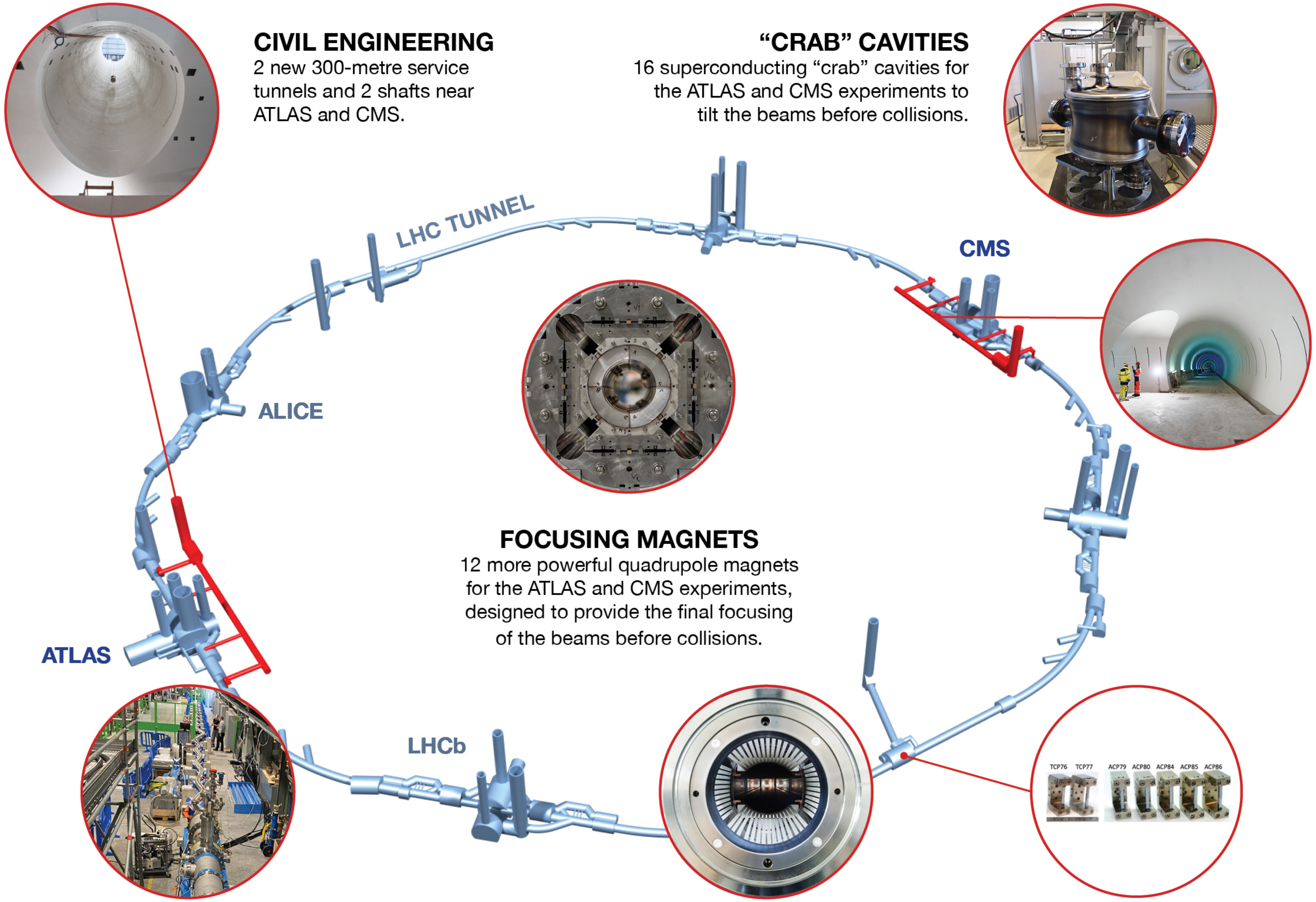
	Week 27	Week 28
Monday	pO setup	OO run
Tuesday	pO run	NeNe run
Wednesday	pO run	VdM setup
Thursday	OO setup	VdM run
Friday	OO run	VdM run
Saturday	OO run	pp setup
Sunday	OO run	pp run

LHC schedule for weeks 27 and 28


CERN
Towards HL-LHC
Tests in 2025-2026
Long Shutdown 3

New technologies for HL-LHC

HiLumi
HL-LHC PROJECT



CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near ATLAS and CMS.

“CRAB” CAVITIES
16 superconducting “crab” cavities for the ATLAS and CMS experiments to tilt the beams before collisions.

FOCUSING MAGNETS
12 more powerful quadrupole magnets for the ATLAS and CMS experiments, designed to provide the final focusing of the beams before collisions.

SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry the very high DC currents to the magnets from the powering systems installed in the new service tunnels near ATLAS and CMS.

COLLIMATORS
15 to 20 additional collimators and replacement of 60 collimators with improved performance to reinforce machine protection.

CRYSTAL COLLIMATORS
New crystal collimators in the IR7 cleaning insertion to improve cleaning efficiency during operation with ion beams.

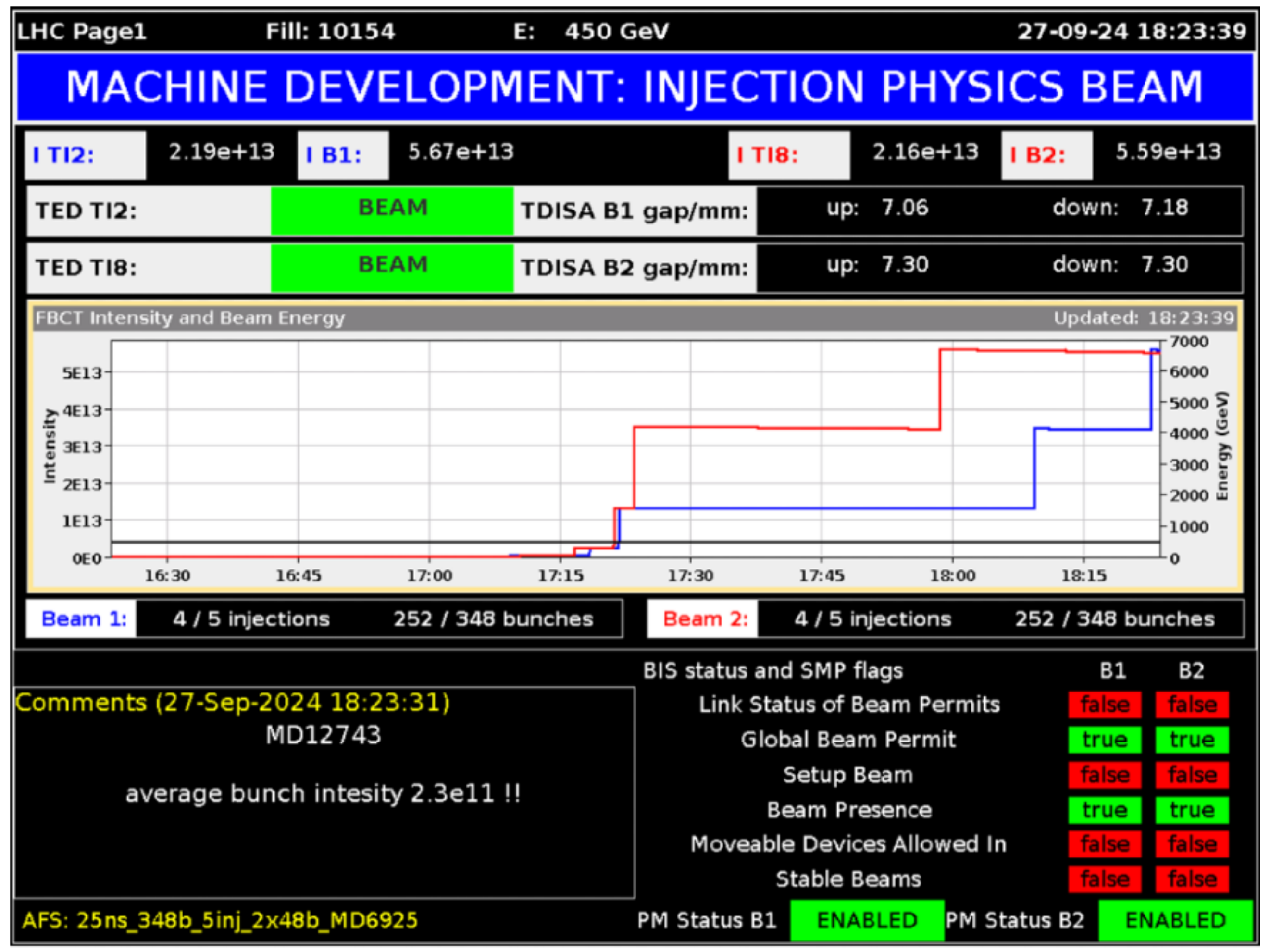
Plans for 2025/2026 to prepare for HL-LHC

Measurement programme 2025

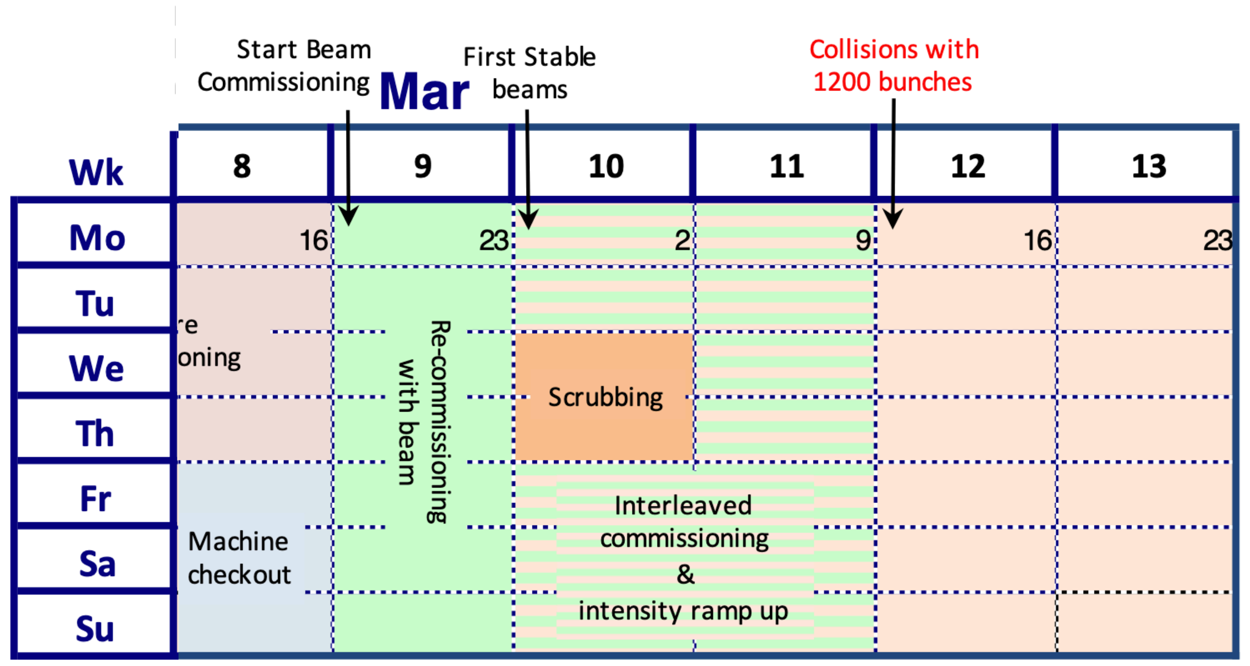
- **Beam dynamics tests** with injection and acceleration of bunch trains at **2.3×10^{11} p/b**
- During these tests, the RF heating power will not exceed the level in regular operation

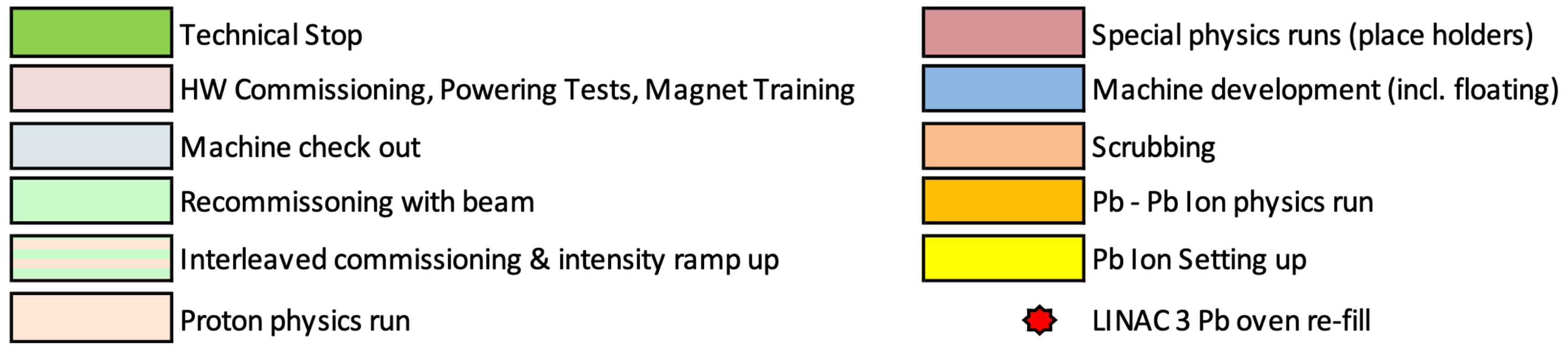
High-intensity test 2026

- Two-week **"preparatory run"** with HL-LHC beam being discussed for end of 2026 run
  - Critical investment for the success of HL-LHC!
- Aim at operating with **2.3×10^{11} p/b**
- No high-intensity collisions in this period



In September 2024, injected HL-LHC beams for the first time!





Draft LHC schedule for 2026

HL-LHC equipment going into production

Crab cavities for IP1 and IP5

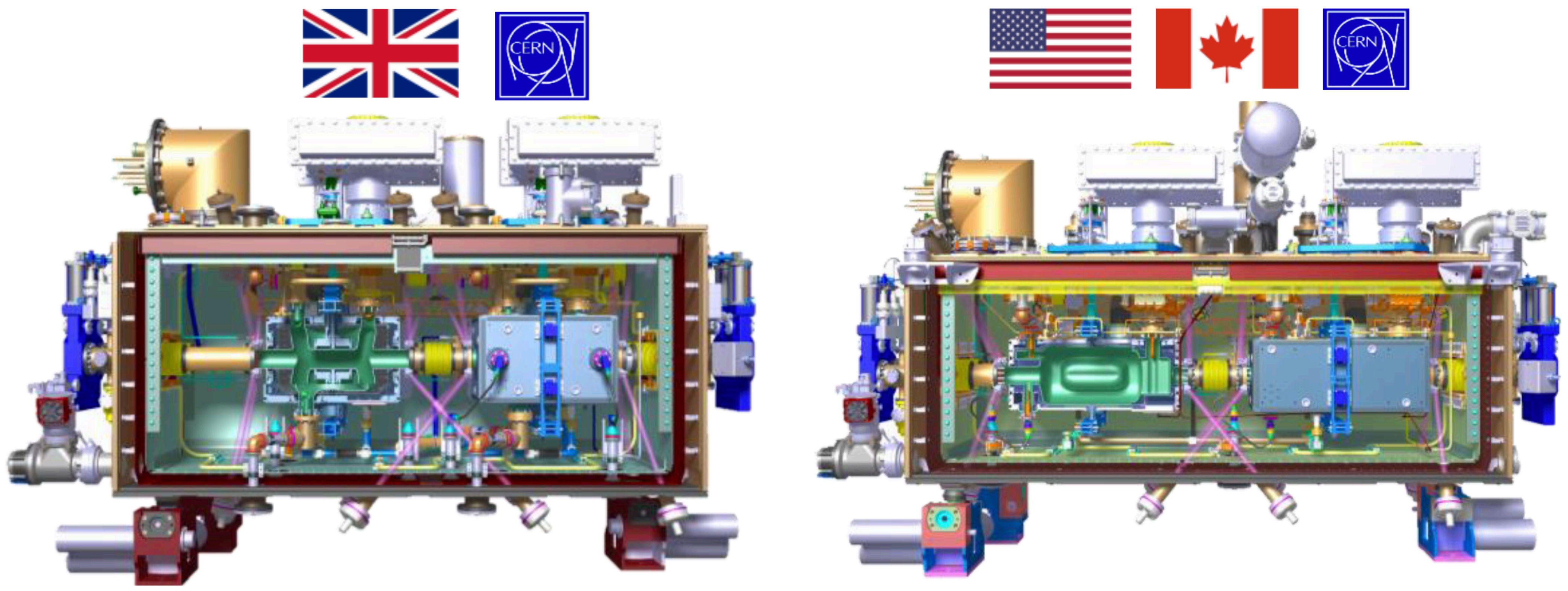
- Testing of DQW (2018-2023) and RFD cryomodules in SPS
  - Crabbing successfully demonstrated
- Series production of 10 cavities of each type and 20 power amplifiers has started

Inner triplet "string" assembly

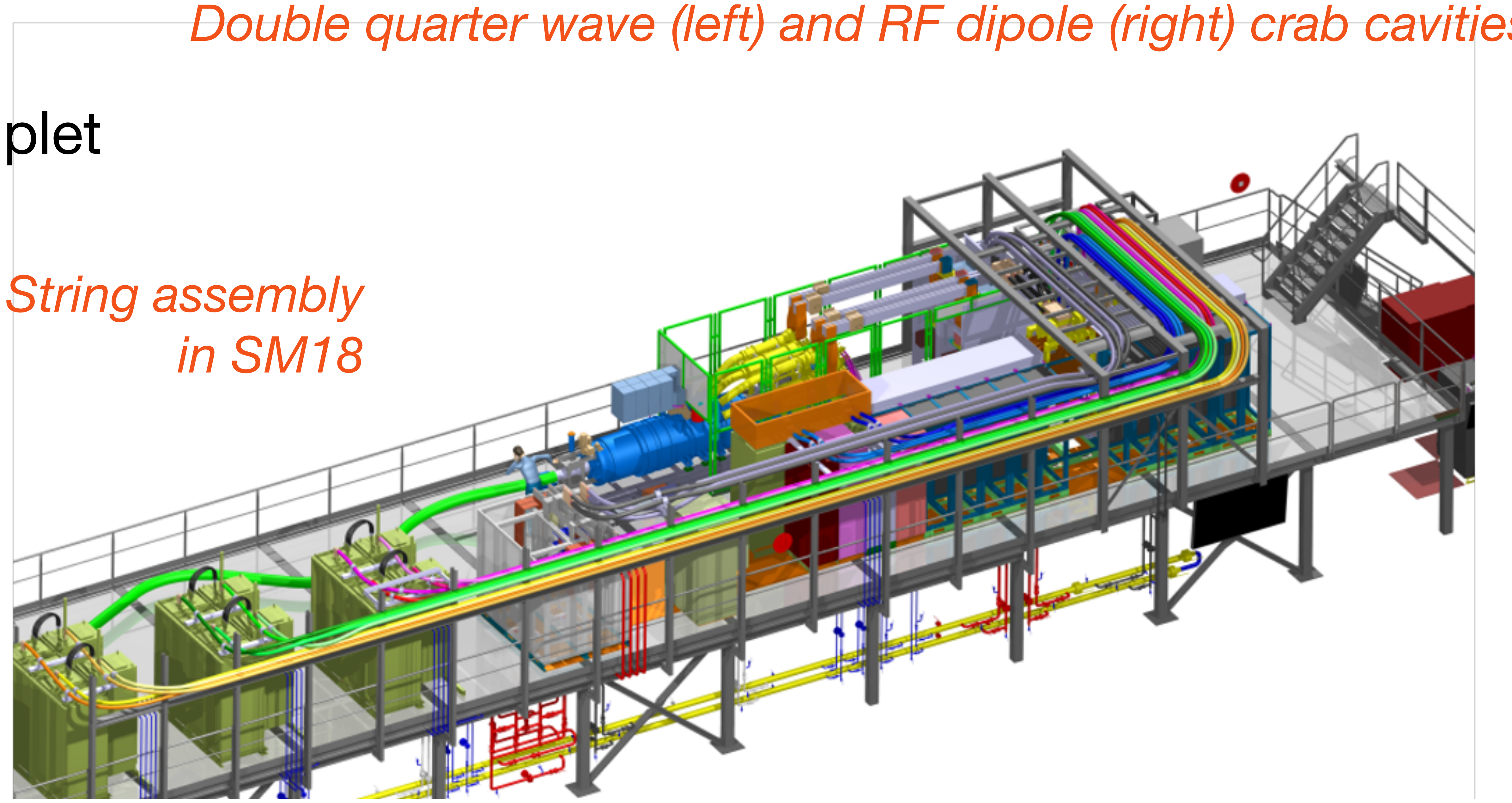
- Aim: study and validate on the surface the collective behaviour of different systems in the HL-LHC inner triplet
- Main equipment and systems installed
  - First powering tests expected Q4 2025

HL-LHC magnets for insertion regions 1 and 5

- Manufacturing, cryo-stating, and testing at full production speed
- A large variety of magnets
  - Material: NbTi and Nb_3Sn



Double quarter wave (left) and RF dipole (right) crab cavities



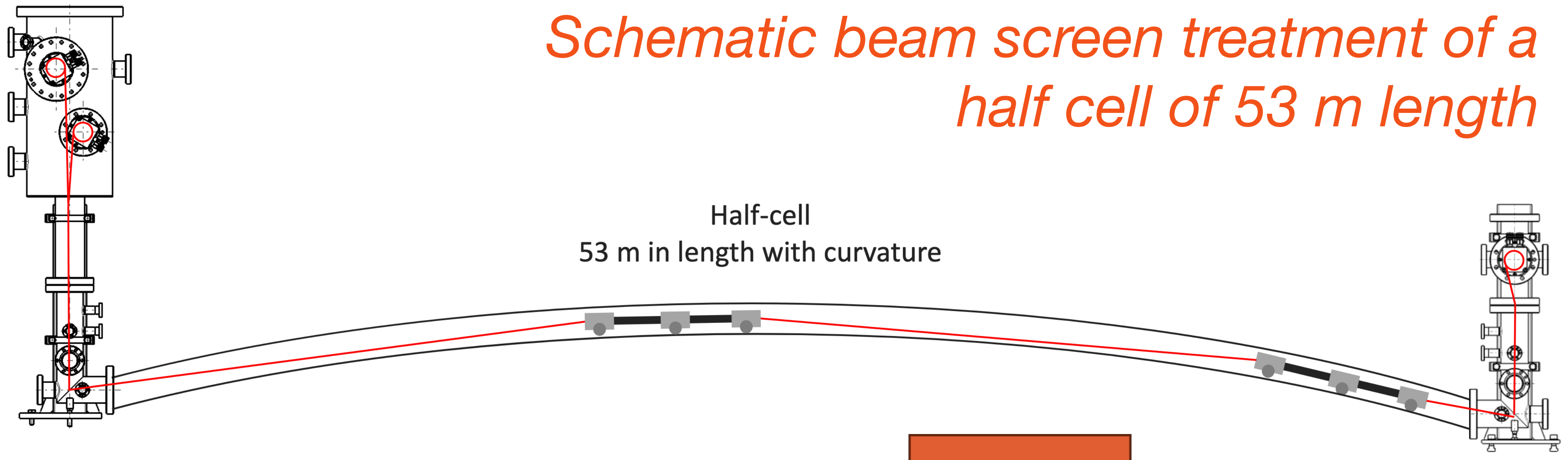
String assembly in SM18

Mitigations (not exhaustive)

Beam screen treatment to reduce SEY and e-cloud

- In-situ treatment in the arcs of 2x6 km (~1/3 of total length) with amorphous carbon coating
- Advancements on prototyping and full scale model
  - Validation ongoing for coating speed, mechanical design, etc.

Schematic beam screen treatment of a half cell of 53 m length



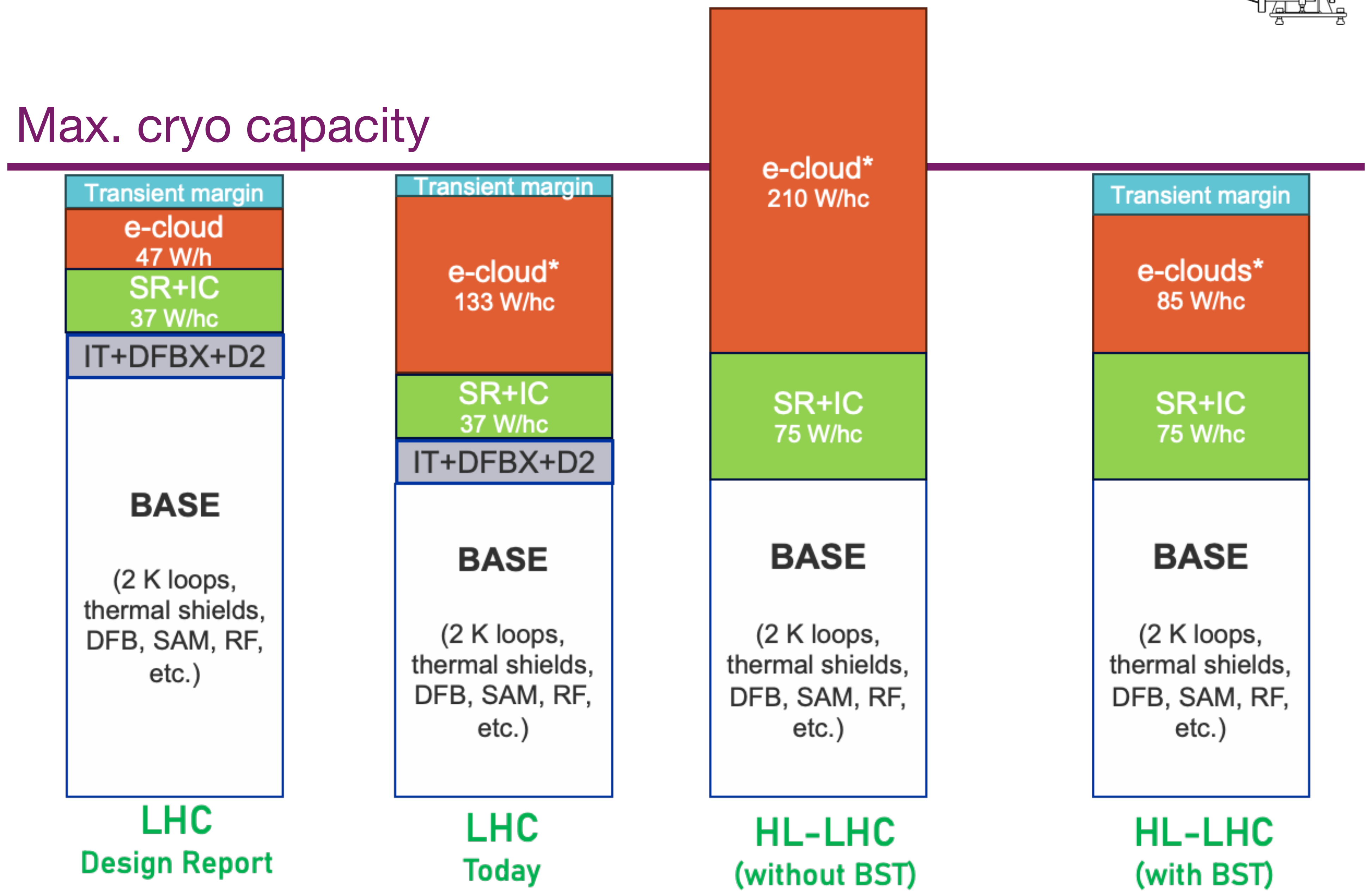
Cryogenics capacity for Run4

- New cryoplants only in IP1 and IP5
- Counting on beam screen treatment
- Yearly capacity tests to optimise operation

High-efficiency klystrons

- Start-of-ramp losses prevent accelerating a full machine at HL-LHC intensity
- Replacing existing klystrons with higher efficiency ones: **300 kW → 350 kW** output

Prototype high-efficiency klystron



Breakdown of cryo capacity usage

Restart after Long Shutdown 3

Long Shutdown 3 in LHC

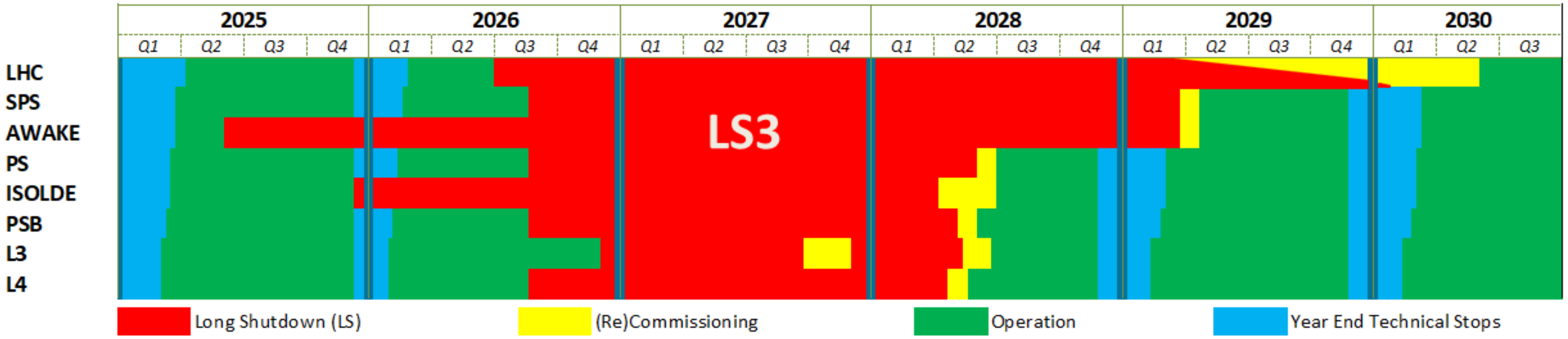
- Starting July 2026
  - Duration (beam to beam): **47 months**
- Opportunity for extensive consolidation, maintenance, and enhancements across the complex
- HL-LHC, beam screen treatment, upgrade and maintenance of LHC experiments, Hostlab
  - Putting it in the context of the CERN-wide LS3 activities

Restarting in the HL-LHC era (Run 4)

- 2030: “commissioning" year
  - Re-establish **2026 performance**
- 2031: ramp-up to HL-LHC intensities

Year	Beam Days Protons / Ions	Colliding Bunch intensity [1e11 ppb]	β^* [cm]	Crabbing	Maximum pile-up
2030	**175** (175 / 0)	1.4 ->1.8	30	off	101 (peak)
2031	**246** (217 / 29)	1.8 ->2.2	25	on	132 (levelling)
2032	**246** (217 / 29)	2.2	20	on	132 (levelling)
2033	**246** (217 / 29)	2.2	20	on	132 (levelling)

Preliminary plans for the LHC Run 4



Timeline for LS3 in the CERN accelerator complex

Starting in less than a year from now!

Conclusions

LHC breaking records in luminosity production

- On track for the overall accumulated **500 fb^{-1}** in Run 1 + Run 2 + Run 3
- 2024 proton physics produced an unprecedented **124 fb^{-1}**

For ions, the HL-LHC upgrade already took place

- Operation in 2024 exceeded the baseline specifications
- The pO, OO, NeNe special run performed beyond expectations

With HL-LHC beams, we have a bright future ahead of us!

Conclusions

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Thank you for your attention!

Backup slides

Preparing Long Shutdown 3

LS3 is the opportunity for extensive consolidation, maintenance, and enhancements across the complex

- HL-LHC, beam screen treatment, upgrade and maintenance of LHC experiments, Hostlab
  - Putting it in the context of the CERN-wide LS3 activities
- North Area consolidation + the upgrade and installation of the Beam Dump Facility for the future Search for Hidden Particles experiment in HI-ECN3
- The upgrade (to 2 GeV) and consolidation of the ISOLDE facility

Preparation activities on-going

- Top CERN objective for 2025
- Space management — intermediate storage for equipment to be installed or removed
- General and electrical safety
- Coordination of heavily-subscribed services
  - Cabling, vacuum, cooling and ventilation, transport, survey, etc.
- Readiness review and report published in 2024
  - Update at “Countdown to LS3” event, 3-4 Sept.

Timeline for LS3 in the CERN accelerator complex

Starting in less than a year from now!