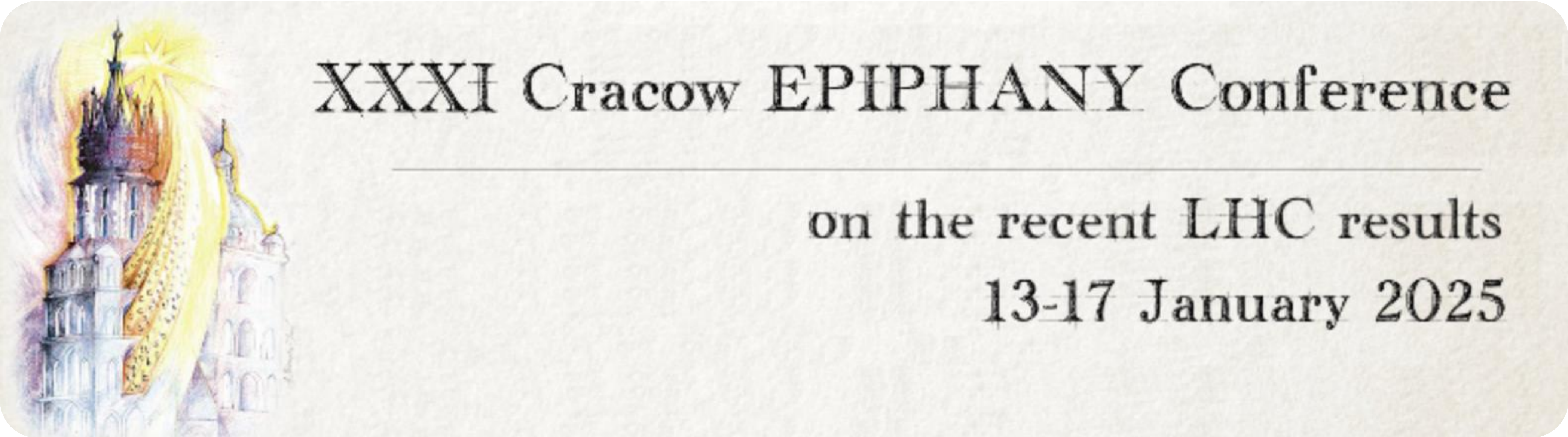


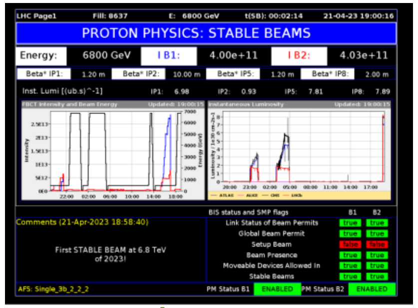
Overview of the LHC performance in Run 3

- Major LHC events and performance in 2023 and 2024
- Prospects for 2025 & 2026
- Status of HL-LHC preparation

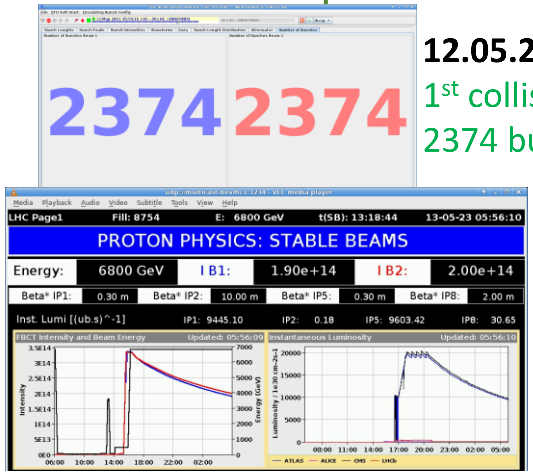
Reyes Alemany Fernandez, CERN
Beams department – Accelerator and Beam Physics group

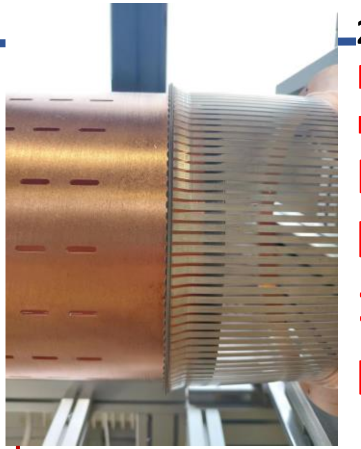
LHC in 2023

21.04.2023
1st stable beam of 2023



12.05.2023
1st collisions
2374 bunches

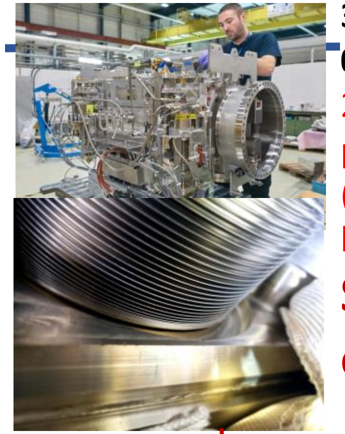




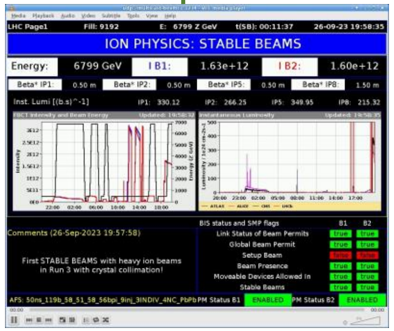
25.05.2023
RF finger module issue.
Intensity limited to $1.6x10^{11}$ p+/b

~4 days downtime

17.07.2023
Fallen tree in VD causing power glitch, magnet quench, and leaking bellow between cold mass and insulation vacuum
~50 days of downtime

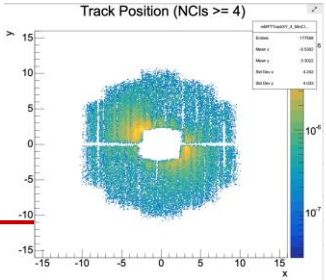


31.08.2023 (B)
08.09.2023 (A)
2 x injection protection device (TDIS) vacuum leak.
Stop p+ operation!

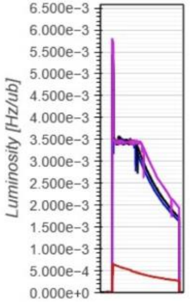


26.09.2023:
1st stable Pb ion beam

End Sep – Early Oct
ALICE background issue followed by studies and solution



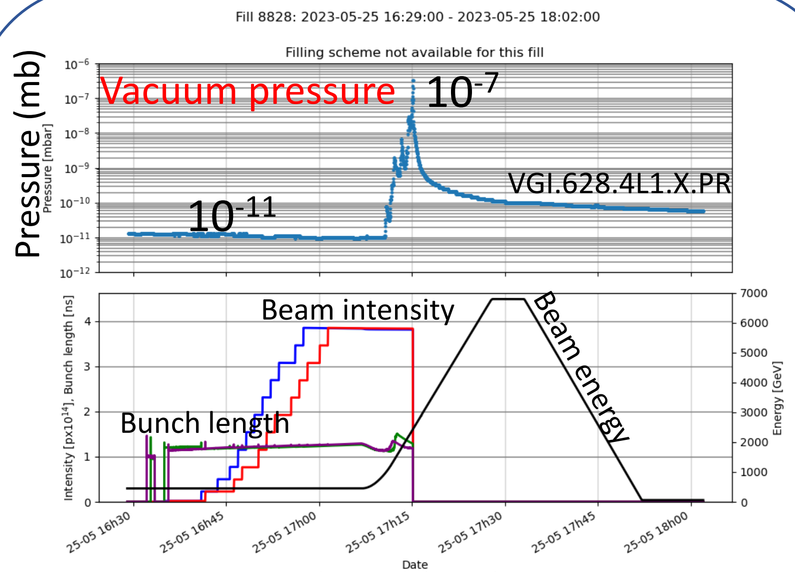
October
Beam loss induced SEU causing trips, quenches, etc.
Studies, Lumi levelling



Mar-Apr | May | Jun-Jul | Aug-Sep | Oct-Nov

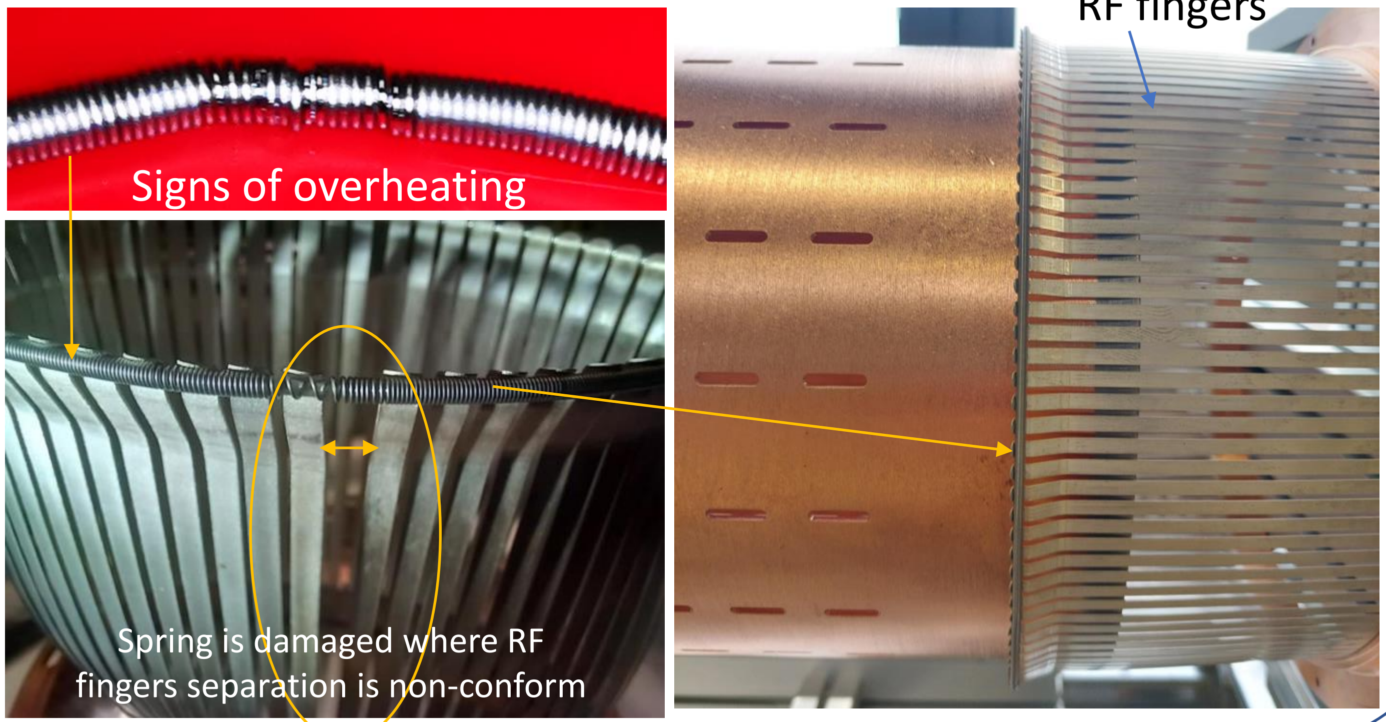
LHC RF Finger Module Issue

25.05.2023



2023: Pressure spikes within the vacuum sector A4L1 during the fill ID 8828 ($1.63 \cdot 10^{11}$ p/b – 2358 bunches) ➔ beam dumped during the ramp (BLM)

Visual inspection ➔ annealed/plasticized spring on the 212 mm vacuum module due to localized temperature increase to more than 500°C



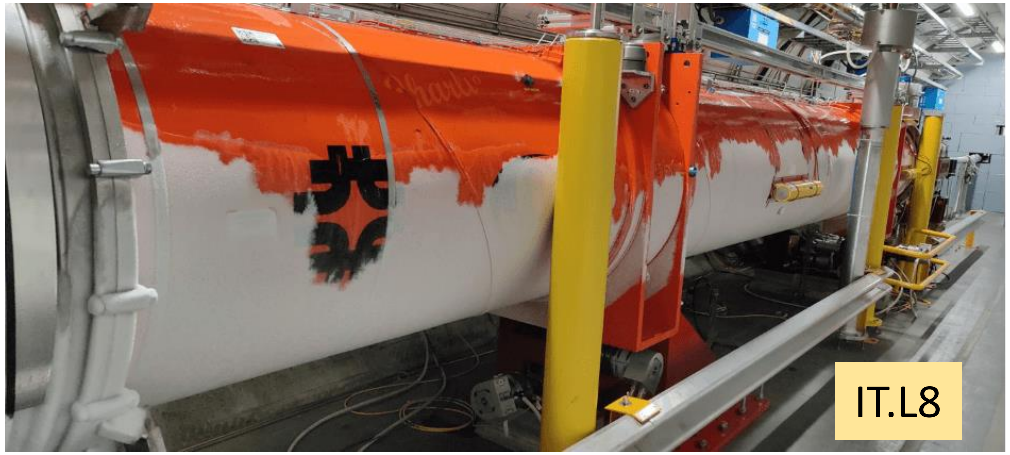
- ~ 4 days of downtime for repair
- Total number of modules present in LHC = 1819
- Inspections in 2023 of 212 mm type revealed 8 degraded modules
- Full replacement in 2023 not possible
- **Replacement strategy staged in YETS23-24 (47/71) and YETS24-25**

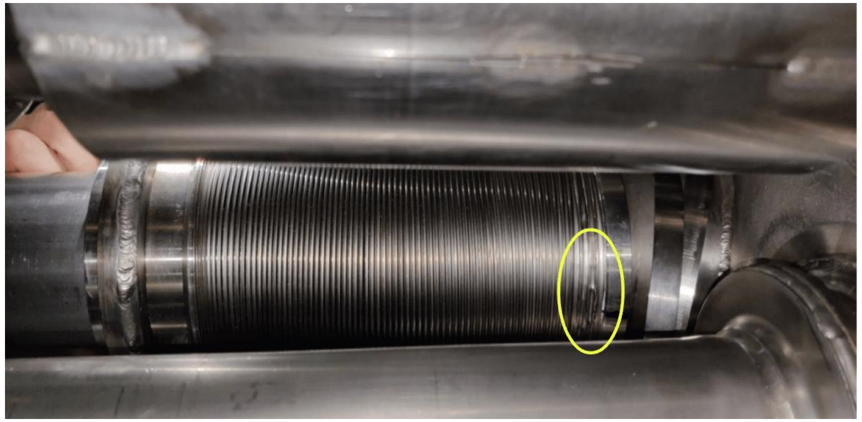
Mitigation for 2023 & 2024:
Bunch intensity limited to **$1.6 \cdot 10^{11}$** p+
Bunch length kept above 1.2 ns

YETS: Year End Technical Stop

LHC Inner Triplet (IT) Bellow Leak

17.07.2023





- Magnet Quench due to electrical perturbation

  'Normal' high pressures in the He lines during the magnet quench created a small hole (1 mm^2) in an edge welded bellow (non-conform) with major consequences (vacuum vessel pressure degraded and below reparation)
- Quick repair in-situ with partial cryogenic warm-up
- **~50 days of downtime**
- **Similar events possible** on triplets and mainly in Q1-Q2 interconnection **until LS3**
- Inspection not possible without warm-up
- But warm-up poses a significant risk due to a thermal cycle of irradiated triplets

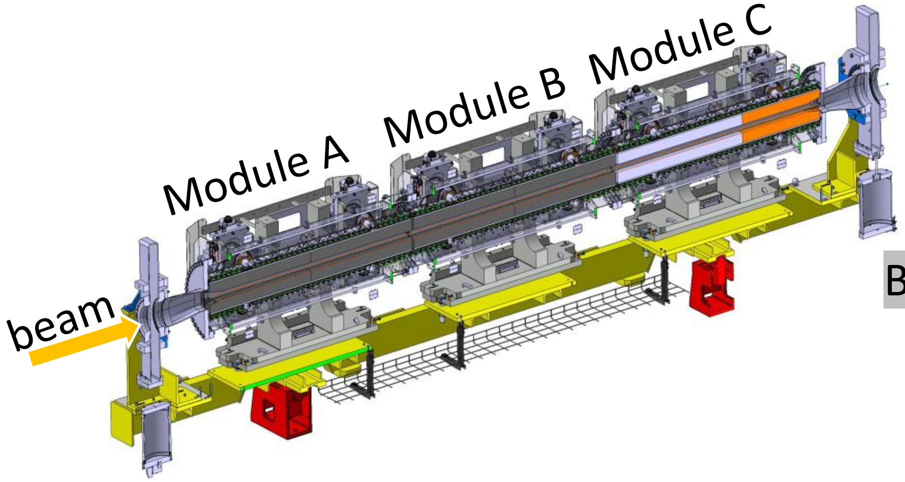
Consolidation of IP2 and IP8 IT proposed in LS3
(IP1 and IP5 replaced by HL-LHC upgrade)

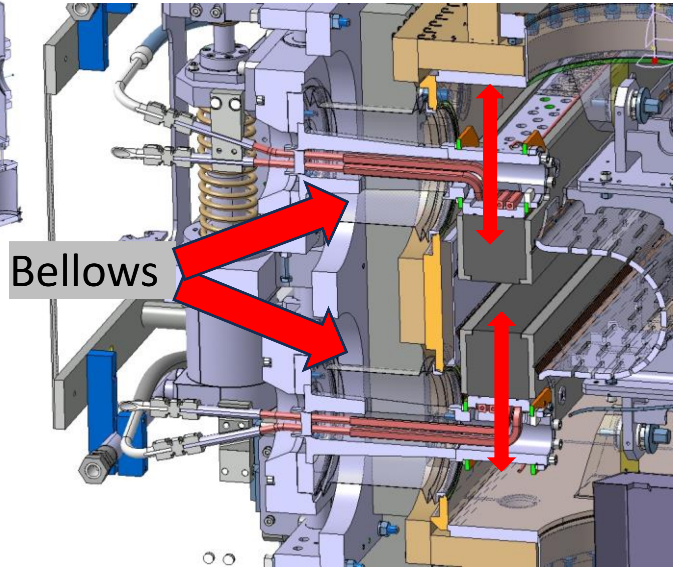
LHC TDIS (Target Dump Injection Segment)

- Machine protection devices used during injection – regularly moving in and out
  - Located in front of IP2 (ALICE) for beam 1 and IP8 (LHCb) for beam 2
  - Each TDIS contains 3 modules with 12 edge welded bellows per TDIS
- Two leaks appeared on separate bellows of the same TDIS (IP8) within 1 week
  - Both varnished and blocked in out position

- Root cause: misspecification of the bellow, causing wear-out after 2-3 years
- Intensity per injection severely limited
  ➔ **End of high-intensity p+ physics**
  Ion run extended
  p-p reference run moved to 2024

31.08.2023 (B)
08.09.2023 (A)





Mitigation:
- Both TDIS replaced by (non-conform) spares during YETS23-24 (expected life-cycle covers the year of operation)
- YETS24-25 replace by conform spares (based on refurbished TDIS with new bellows)

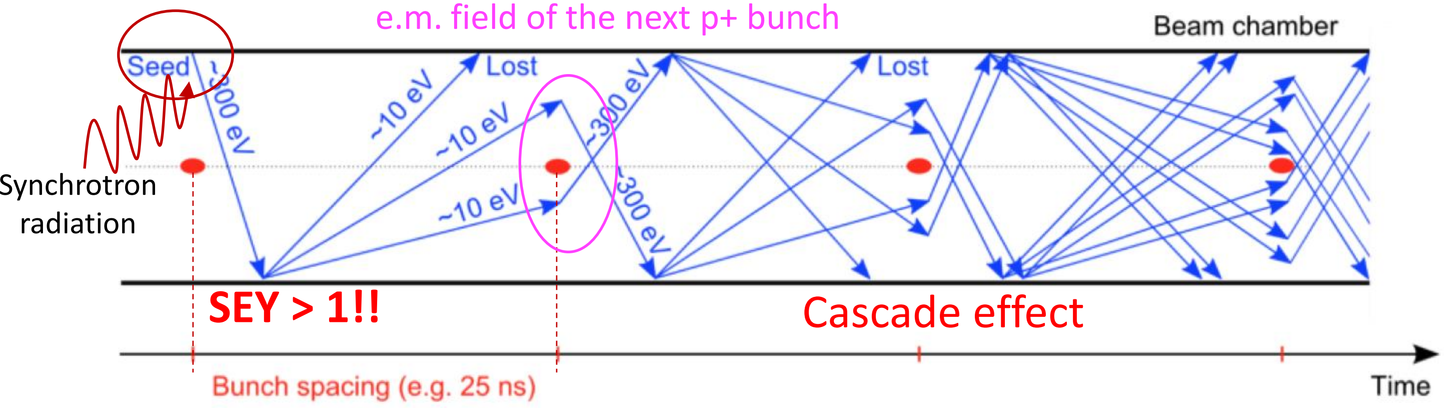
(E)YETS: (Extended) Year End Technical Stop

Other limitations in Run 3 that require LHC parameters and configuration optimization

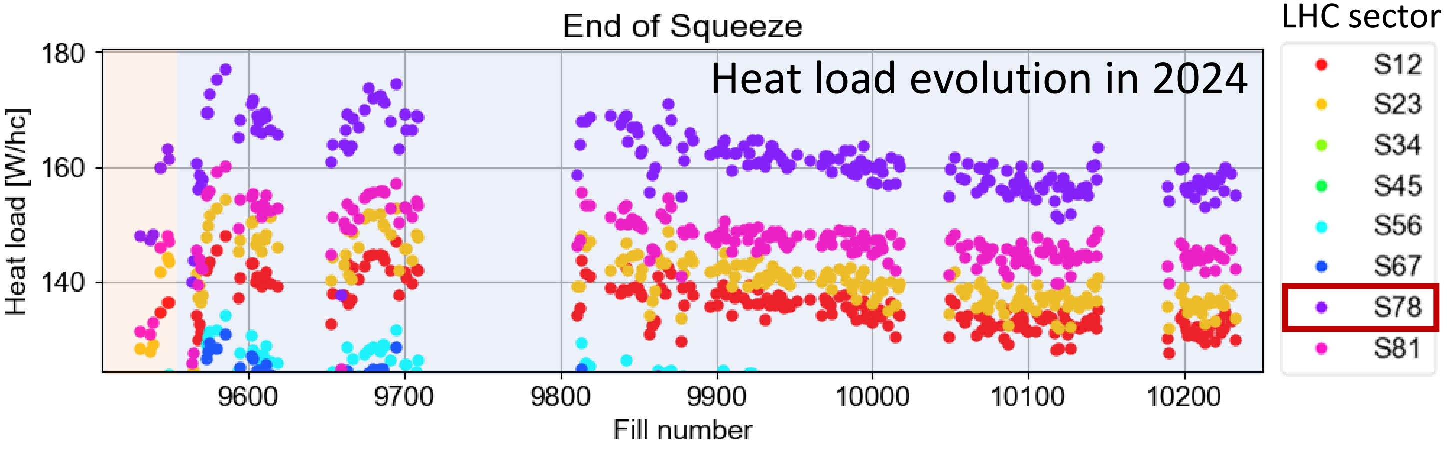
- Electron cloud and cryogenics load
  → limits bunch pattern

- Radiation to inner triplets
  → change of optics

Electron cloud and cryogenics load



- **Heat load** ➔ at the limit of cryogenic system
- Pressure rise
- Beam instabilities
- Emittance growth



~10% heat load reduction between Apr & Sep!

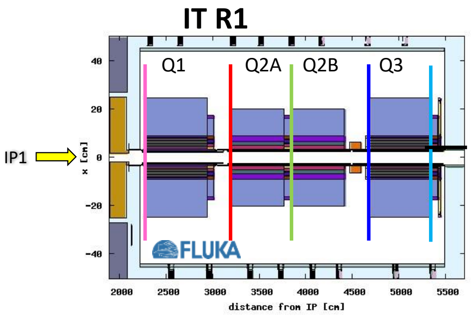
The additional 10% scrubbing leaves room to increase the number of bunches and bunch intensity:

- 2400 bunches with 1.8e11 p+/b with trains of 4-5x36b in reach

SEY: Secondary Electron Yield
hc: LHC half-cell ~53 m

Under the effect of the cloud itself, conditioning of the copper surface of the LHC beam pipes is expected, decreasing thus the SEY of the surface. Such a process seems therefore to be hindered in some parts of the LHC ring.

Ensuring the Longevity of the IT until LS3



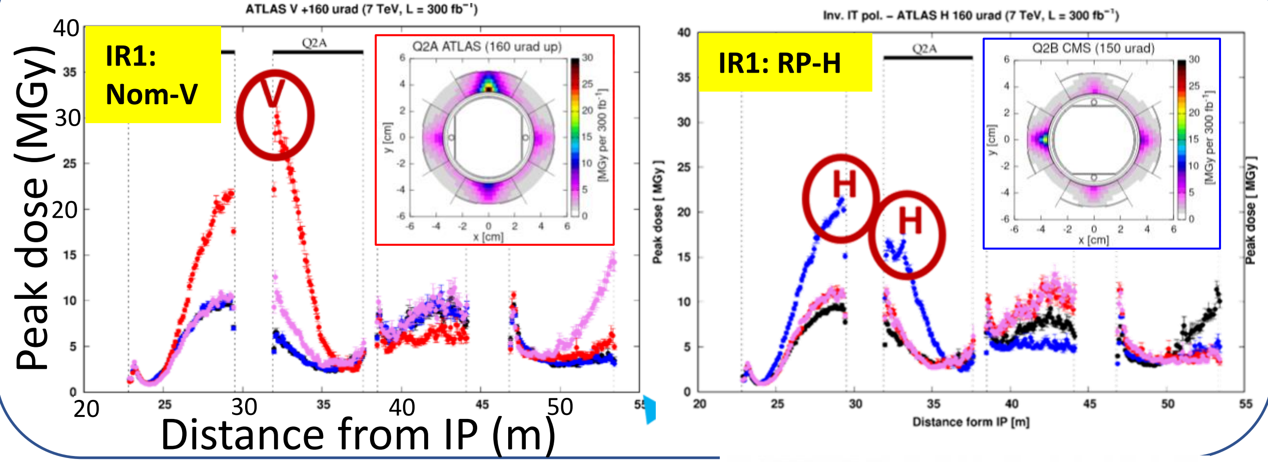
The problem: collision debris (mainly pions) capture in the IT

The consequence: reduced lifetime of magnets ➔ change needed before LS3

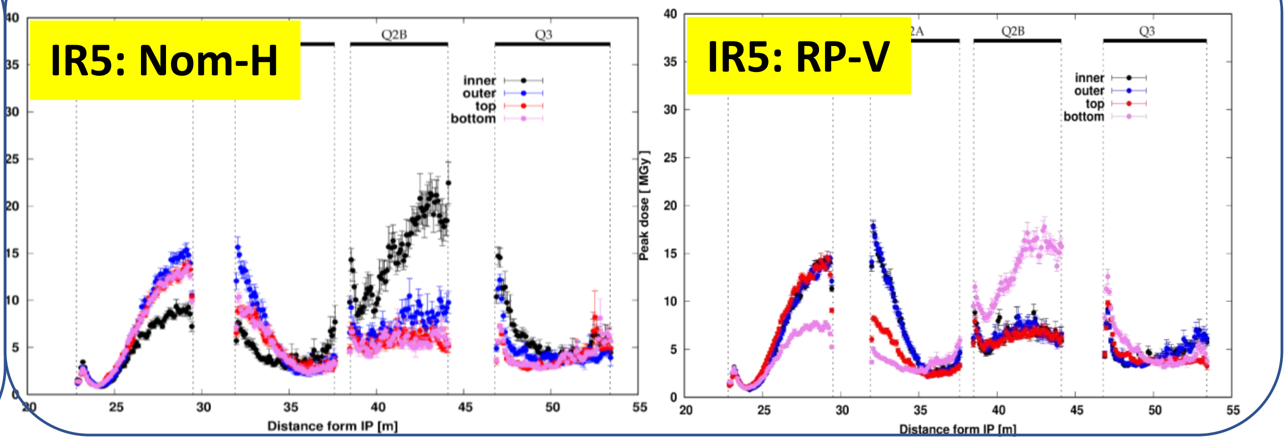
The mitigation: from nominal (FDF) to **R**everse **P**olarity (DFD) optics

p-p @√s=14 TeV
85 mb inel xs

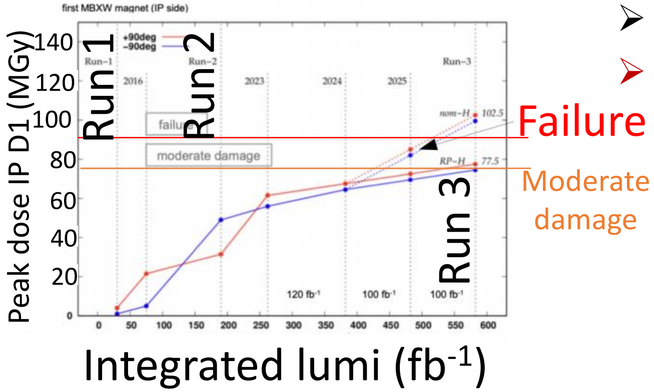
Mitigation applied in **2024** in IP1



Mitigation in **2025**: IP5 RP-V, IP1 Nom-V, Xang rot IP1&5)



Main drawback: risk of radiation damage for the first module of D1 of both sides of IP1



- ➢ Exchange with spare should be considered for the YETS25-26
- ➢ **Moderate risk for 2025:**

Replacement of a spare →7 weeks of work in the tunnel

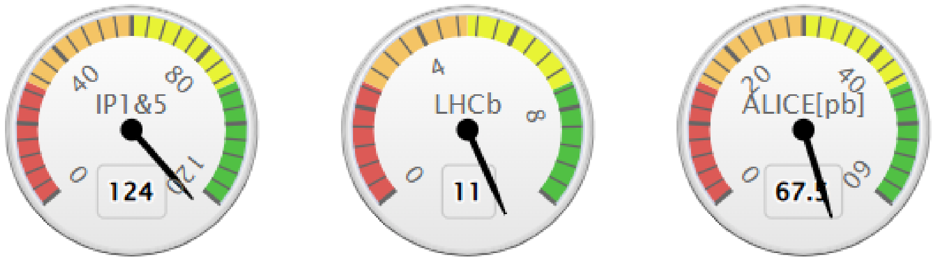
Possibility to run with the first D1 module disconnected (~1 shift of work in the tunnel), increasing the strength of the remaining 5 modules (per IP side) and the MCBHX3

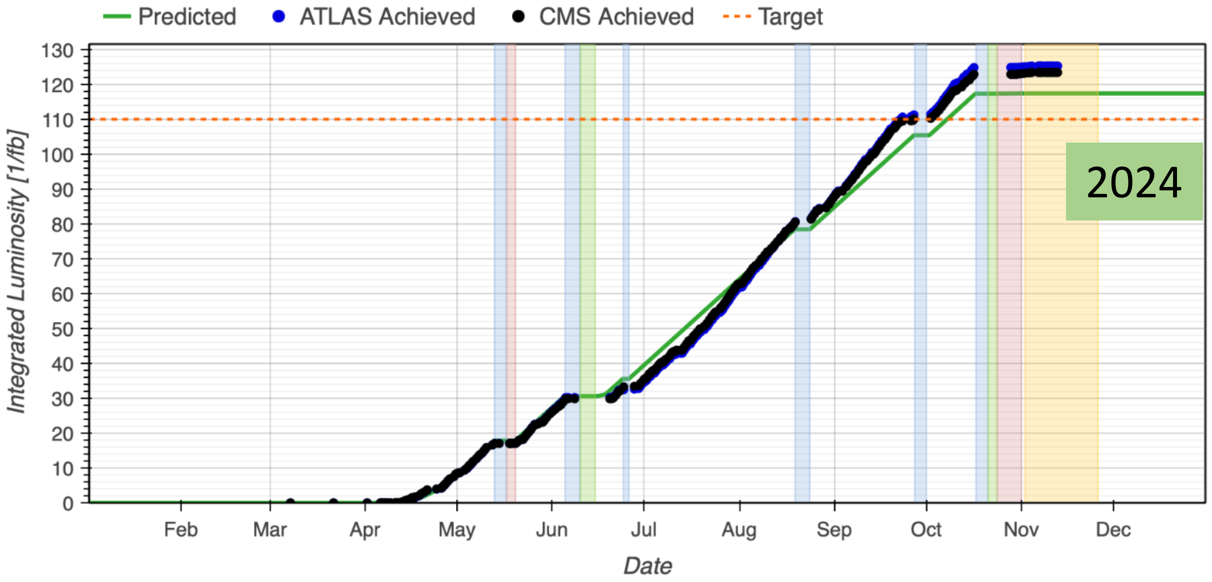
IT: Inner Triplet
IR: Insertion Region, IP: Interaction Point
RP: Reverted Polarity

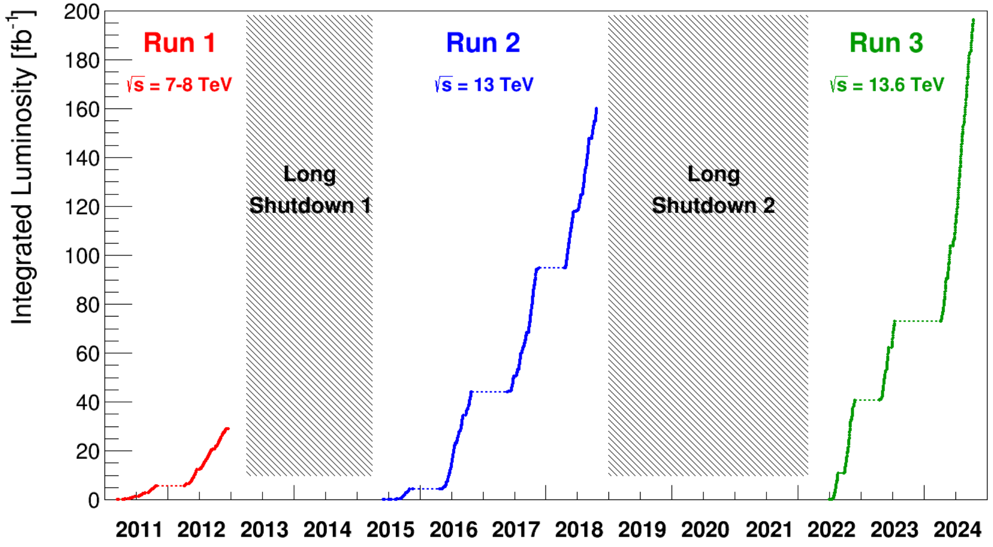
D1: separation dipole
FDF: Focusing Defocusing Focusing
DFD: Defocusing Focusing Defocusing

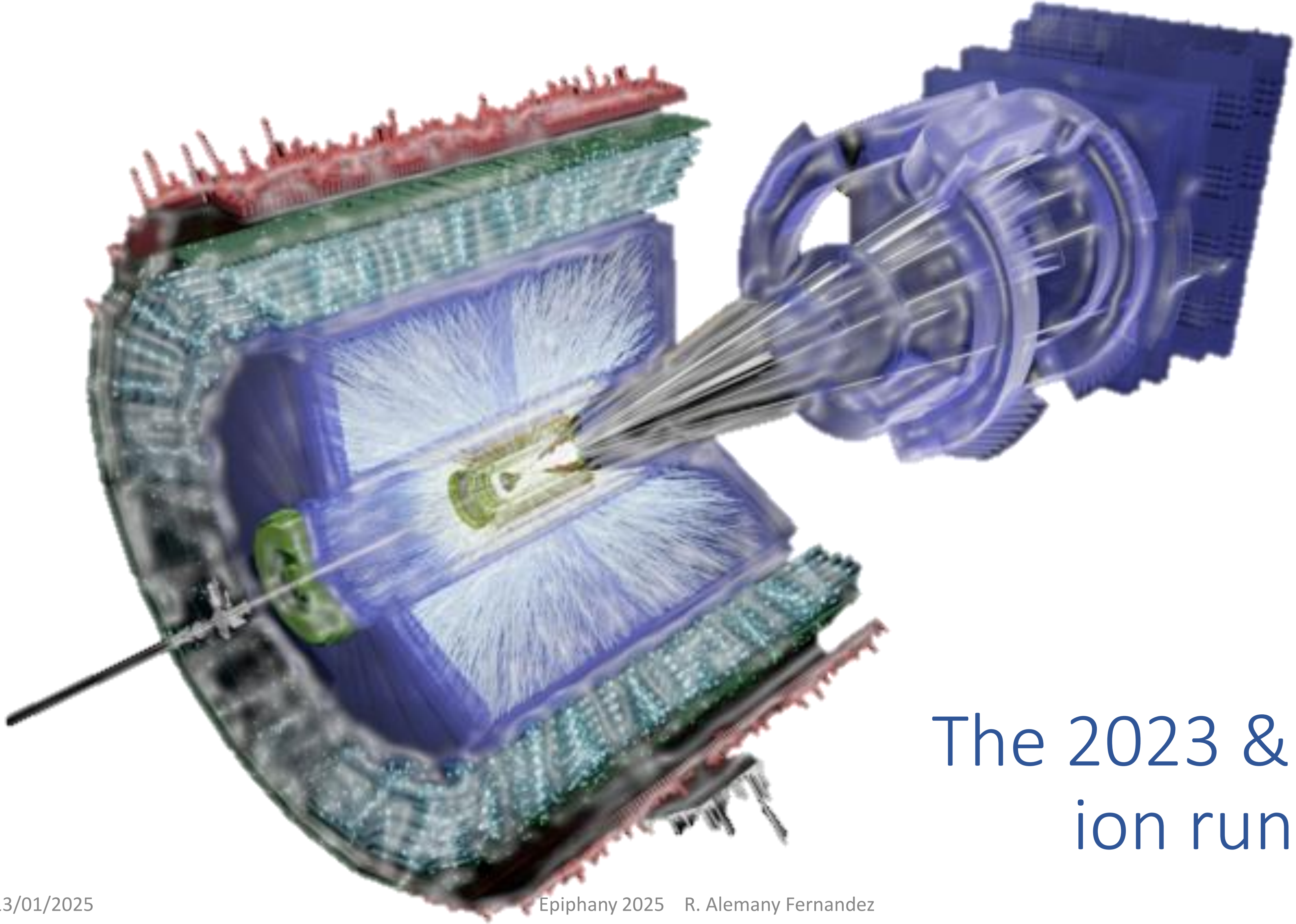
2023 & 2024 LHC Performance

- 2023 summary:
  - p+ period best availability 76%, stable beams for physics 52%
  - Many long-term faults ➔ target 75 fb^{-1}/exp not reached
- 2024 summary:
  - Highest production rate ever - up to **1.5 fb^{-1}/24h**
  - Peak luminosity at **~2.1×10^{34} $cm^{-1}s^{-1}$**
    - Limited by cryogenic cooling capacity in the IT





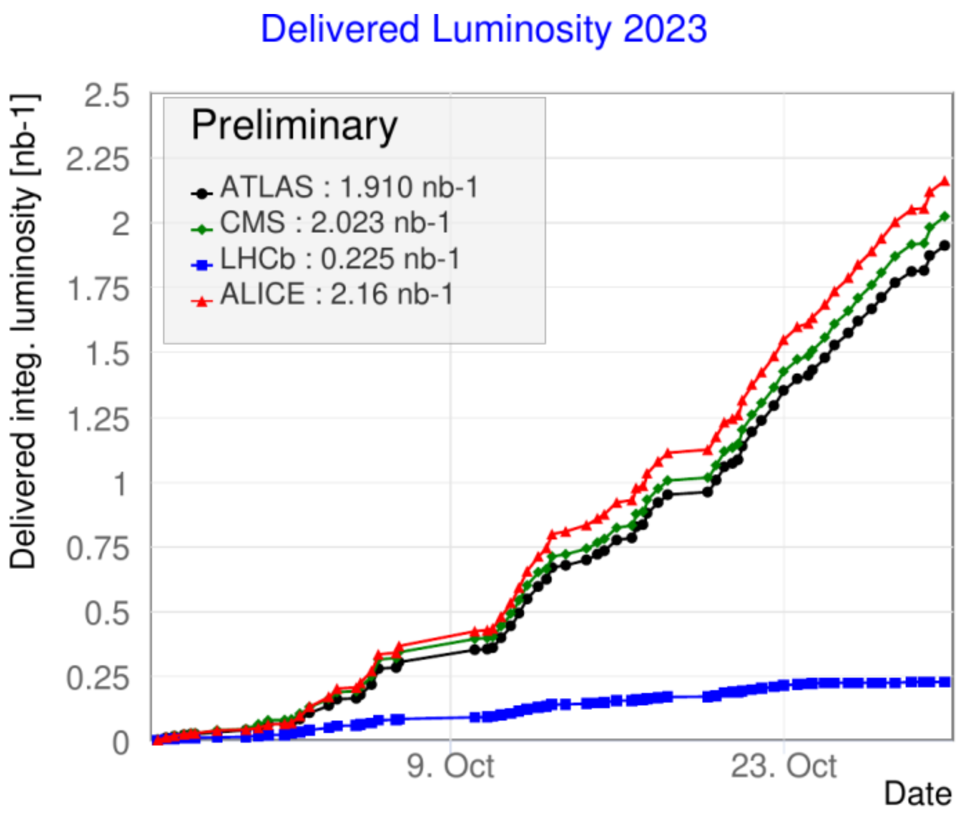




The 2023 & 2024 ion runs

2023 LHC Lead Ion Run Performance

- Ion run relied on several new concepts all successfully used in operation
  - Slip-stacked 50 ns beams from injectors to provide higher intensity
  - Crystal collimation to handle higher intensity without quenches
  - TCLD collimators (HL-LHC equipment) & BFPP bump in IR2 to allow full luminosity for ALICE
  - BFPP bump in IR8 to allow higher LHCb luminosity



- Several problems encountered
  - Background in ALICE experiment – mitigated in 2023
  - High beam losses in the ramp – mitigated in 2024
  - Beam losses due to 10 Hz orbit oscillation – culprit found and fixed!
  - Single-event upsets on quench protection system – mitigated in 2024

TCLD: Target Collimator Long Dispersion suppressor in IR7
BFPP: Bunch Free Pair Production
IR: Insertion Region

2024 LHC Ion Run Performance

2024 Production

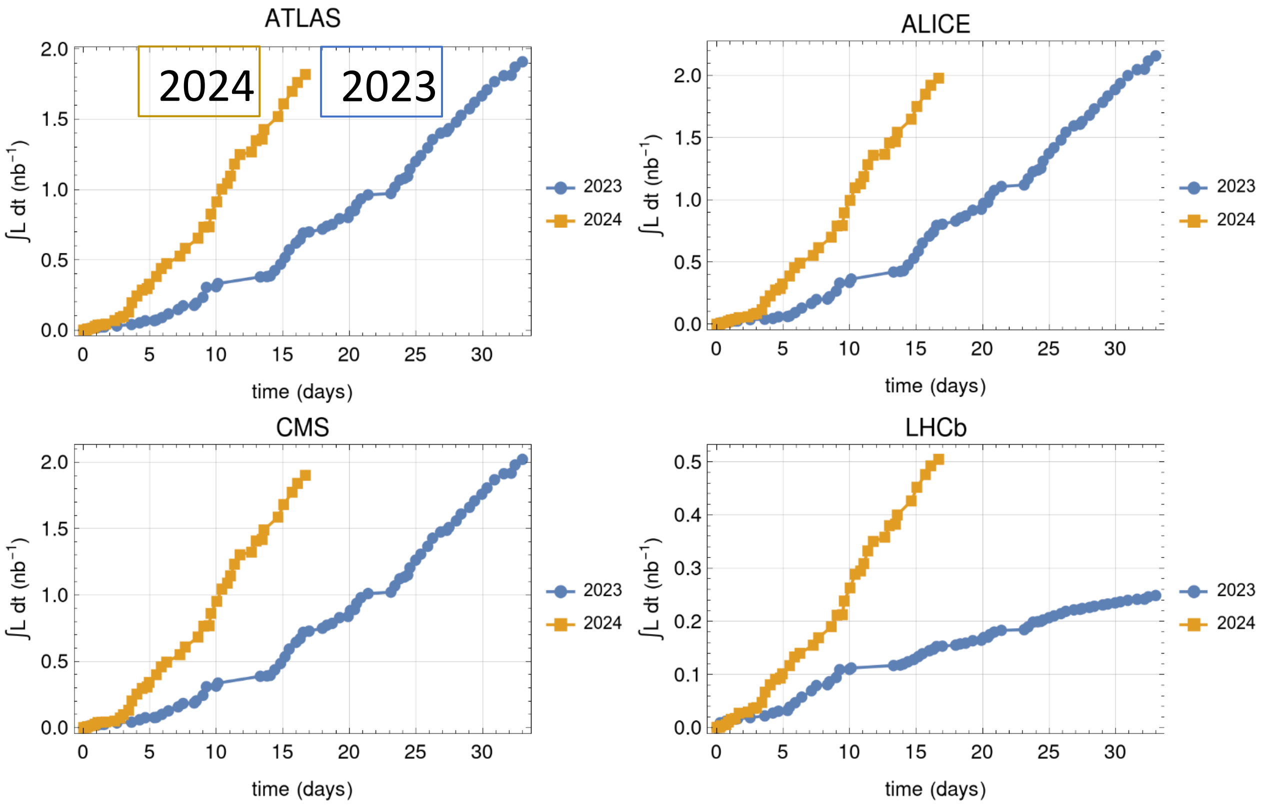
- ALICE, ATLAS, CMS: average **1.9 nb^{-1}**
- LHCb: doubled 2023 production in half the time ➔ achieved!

Excellent injectors performance:

- Higher bunch intensities than LIU target
- Higher transmission efficiencies than before

Experiments' expectations for the full Run 3

- ATLAS/CMS/ALICE
  5.35 nb^{-1} for full Run3
- LHCb
  1 nb^{-1} but strong request for higher target (x2)

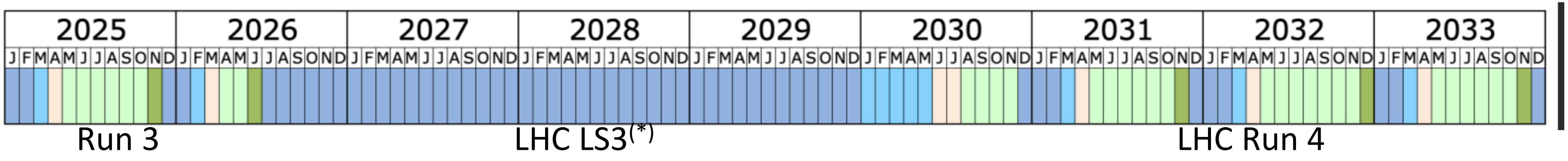


IP1,2,5: Remains 1.45 nb^{-1} to be collected in 2025&2026

LIU: LHC Injectors Upgrade

2025 & 2026 schedules

- 18.09.2024 Research Board approved the update of Run3/LS3/Run4 schedule:
  - Short YETS25-26 (08.12.2025 to 23.02.2026)
  - Run LHC until end of June 2026 with Heavy Ion run taking place in June
  - End of LHC Run 3 date on Monday 29th June 2026 (SPS North Area physics continues)



2025 scheduled (approved)

- 138 days of p+ physics
- 2 days of Vdm
- 25 days Pb run end of 2025
- NO pp ref run
- O-O and p-O collisions last week of June

2026 scheduled (info)

- 66 days of p+ physics
- 2 days of Vdm
- 25 days Pb run in June (PbPb or pPb)
- NO pp ref run

(*) LS3 Injectors is shorter

YETS: Year End Technical Stop
Vdm: Van der Meer scan for luminosity calibration

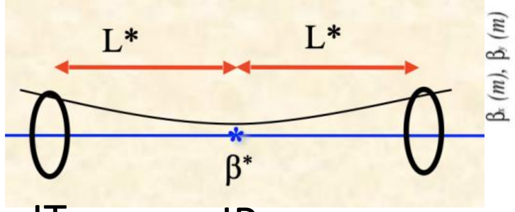
Status of HL-LHC preparation

HL-LHC parameters

- $2.3 \cdot 10^{11}$ p+/bunch
- 2.1 µm ε^{n}x,y

LHC Injectors Upgrade

- 25 ns bunch spacing
- β*= 0.15 m (β*= 0.5 m @LHC)
- Virtual peak lumi with crab $1.7 \cdot 10^{35}$ cm^{-2}s^{-1}
- LHC p+ Lumi Levelled @ $5 \cdot 10^{34}$ cm^{-2}s^{-1}
- Pile up = 131

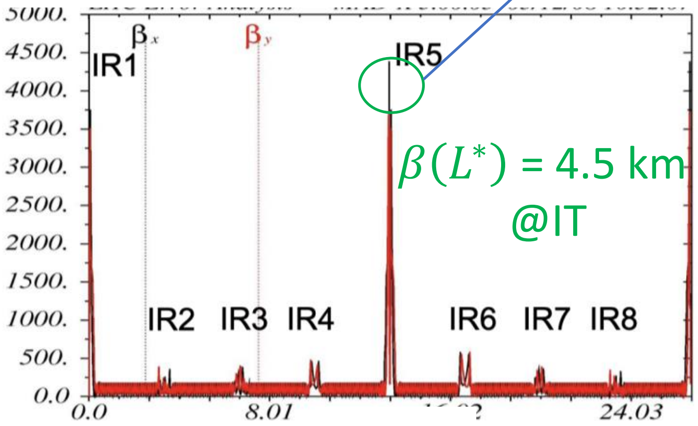


IT IP

$$\beta(L^*) = \beta^* + \frac{L^{*2}}{\beta^*}$$

$$\sigma_{x,y} = \sqrt{\varepsilon_{x,y} \cdot \beta_{x,y}}$$

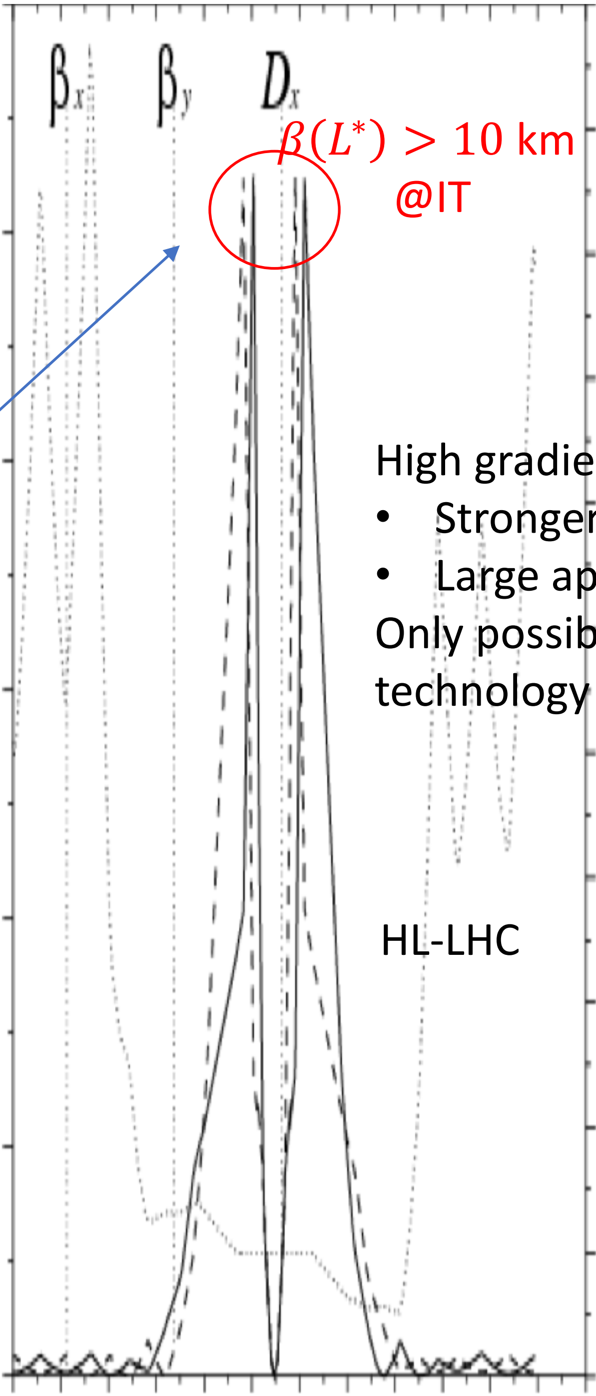
LHC



27 km

10 km

5 km



High gradient magnets:
- Stronger focusing
- Large aperture

Only possible with new technology

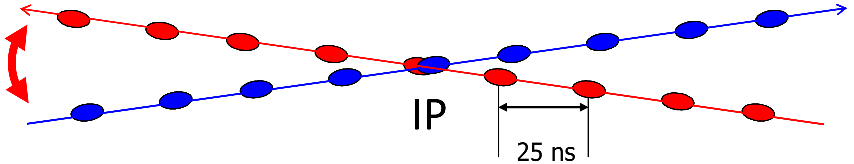
HL-LHC

IT: Inner Triplet
IP: Interaction Point

HL-LHC parameters

- But, larger beam size at the IT ➔ larger crossing angle to avoid beam-beam interactions (need of large aperture)

Crossing angle = ϕ

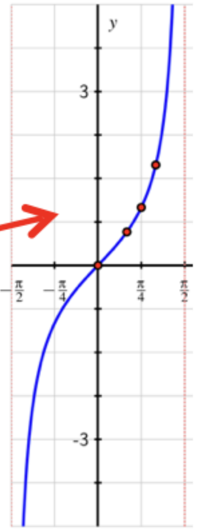


Lumi = Lumi_{ideal} * Spaghetti-Loss Factor

$\text{Lumi}_{ideal} = f(N_b\uparrow, I_b\uparrow, \varepsilon\downarrow, \beta^*\downarrow)$

$$F = \frac{1}{\sqrt{1 + 2\dfrac{\sigma_s^2}{\sigma_{1x}^2 + \sigma_{2x}^2}\tan^2\dfrac{\phi}{2}}}$$

F = Spaghetti-Loss Factor



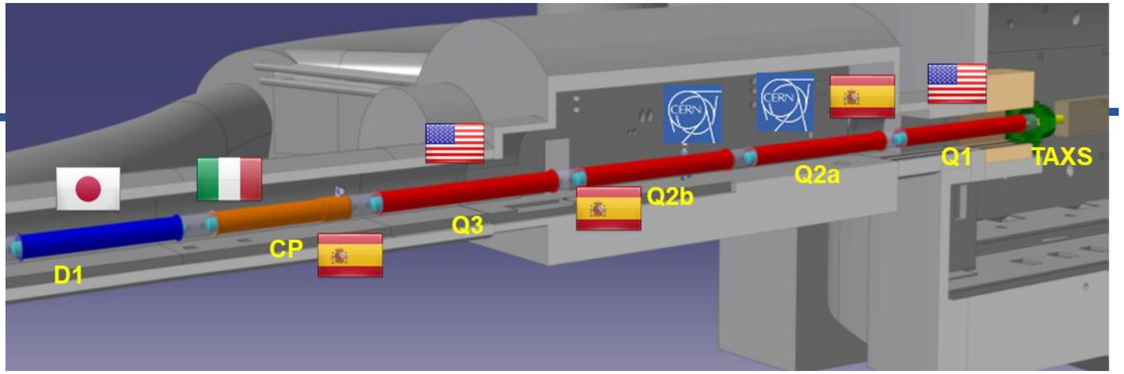
If Spaghetti-Loss Factor is not cured ➔

LHC ➔ $\phi/2$ = 285 µrad ➔ F ~ 85%

HL-LHC ➔ $\phi/2$ = 590 µrad ➔ F ~ 30%

Crab-cavities are the solution

Magnets Nb_3Sn

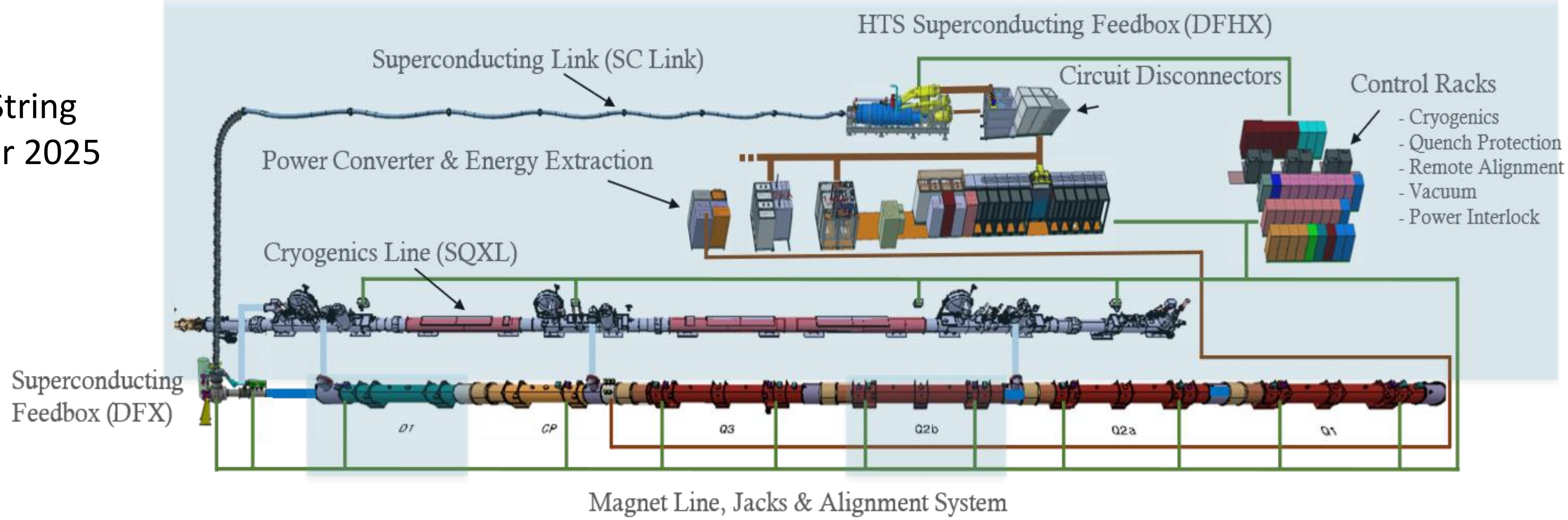


- Good progress across all key technologies
- US and CERN magnet production well underway
- Inner Triplet String testbed taking shape
  - Infrastructure in place and magnets starting to be installed

LHC NbTi → 12 kA
HL-LHC Nb_3Sn → 16.5 kA (ultimate 17.5 kA)

The IT String will deliver the first complete experience of installing and operating the IT zone

The Inner Triplet String Testbed – focus for 2025

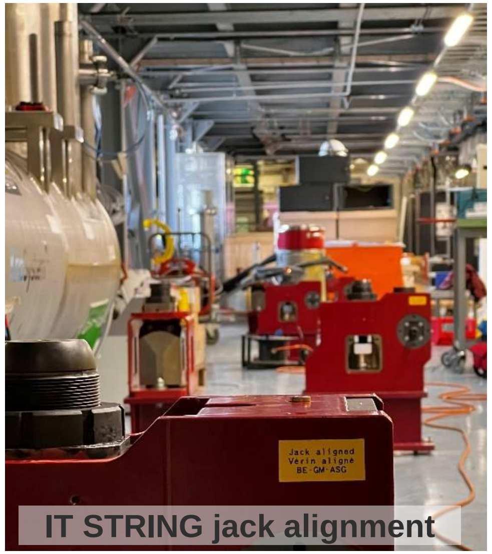


Preparing for the Inner Triplet String Test

- Tracing on the floor:
  - Beamlines, pillars, jumpers, beam pts, jacks, anchors, …
  - Robotic solutions for tracing to reduce time
- Magnet support jacks - installation and alignment
- First magnets aligned
  - Q2a and D1 in place and aligned in Nov 2024

IT STRING tracing

Tracing robotic solutions testing



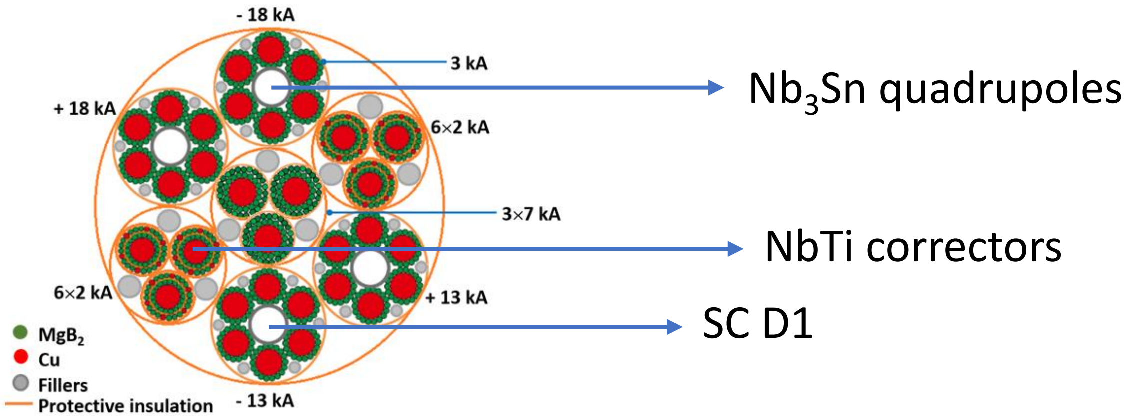
IT STRING jack alignment

IT STRING – D1 placed and aligned

MgB_2 superconducting link

The flexible, double-wall, corrugated cryostat:

- **19 MgB_2 SC cables** in a single assembly, twisted together to form a compact bundle
- Can transfer altogether a DC current of about **120 kA at ~20 K**

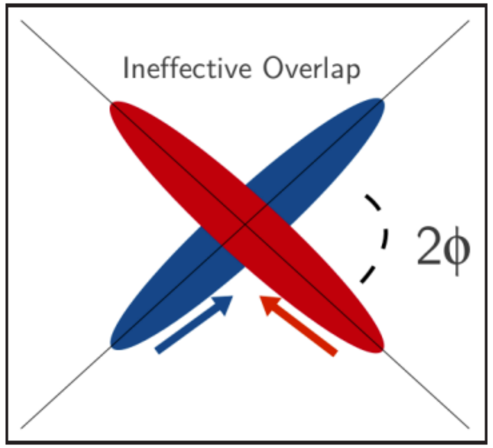


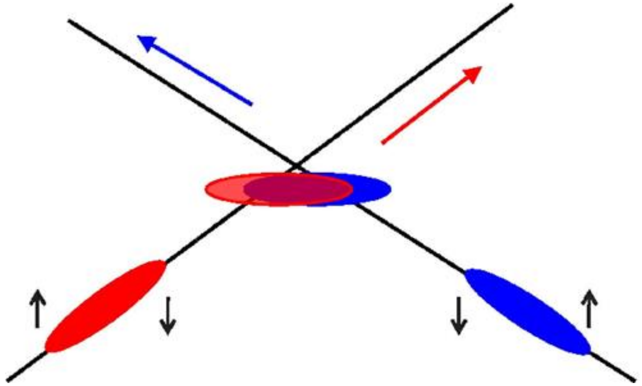
The first Cold Powering System for the HL-LHC Triplets has been successfully validated: cryogenic, electrical and mechanical performance all met design parameters

Today in an advanced phase of series production

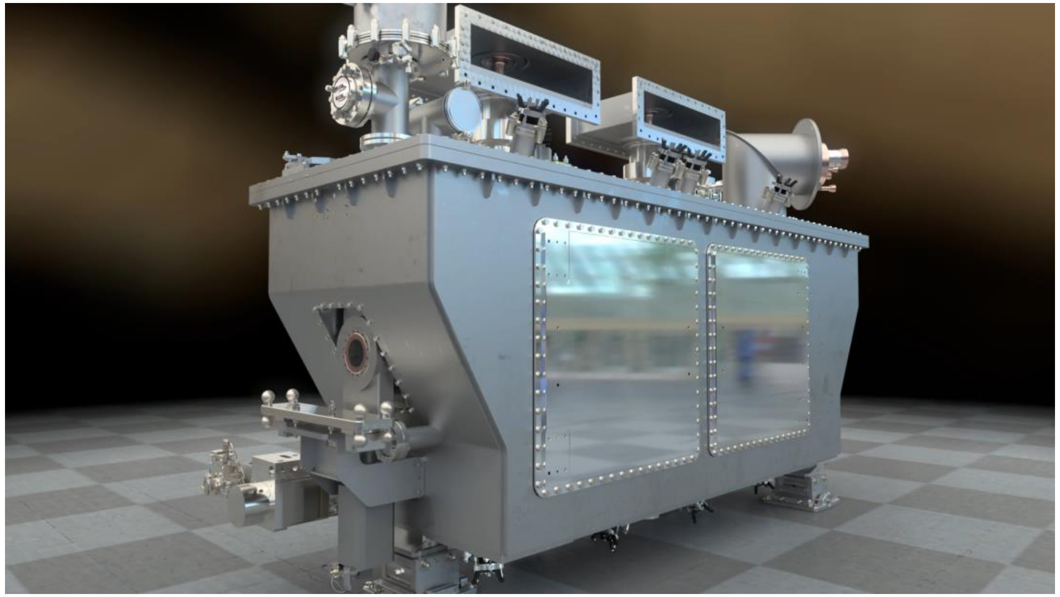
SC: Super Conducting
D1: separation dipole

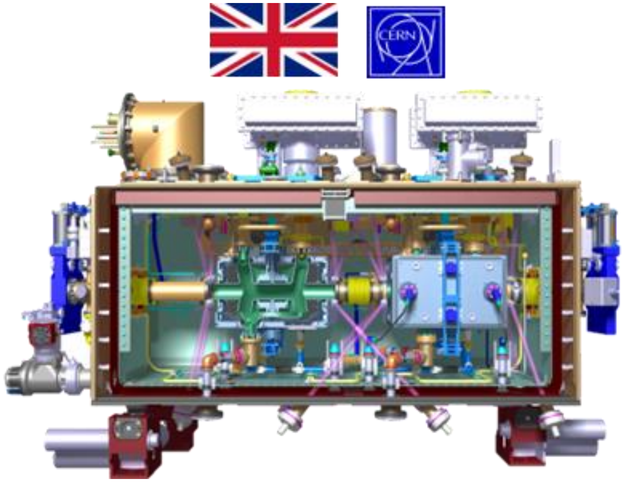
Crab Cavities



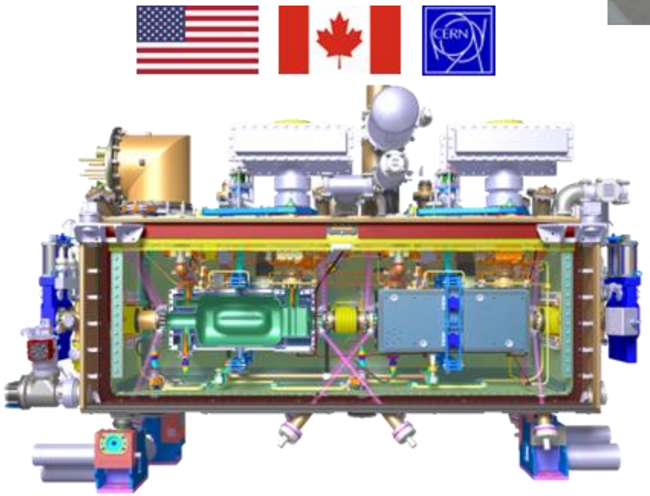


Increasing the number of collisions in the HL-LHC





5 DQW cryomodules (Europe)

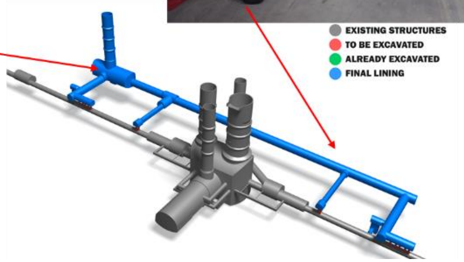


5 RFD cryomodules (North America)

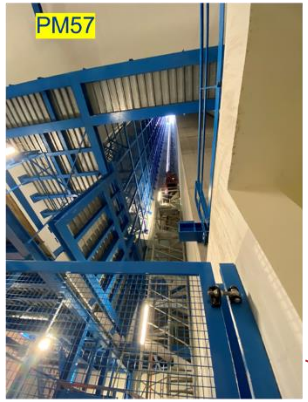
Delays in RFD cavities jeopardizes completion of RFD cryomodules in-time for LS3 installation

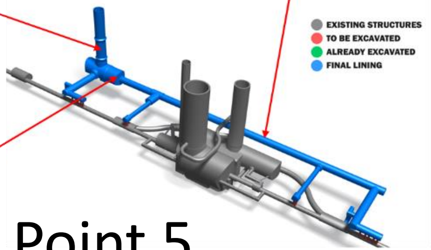
- Mitigation strategy being worked on

Civil Engineering Complete



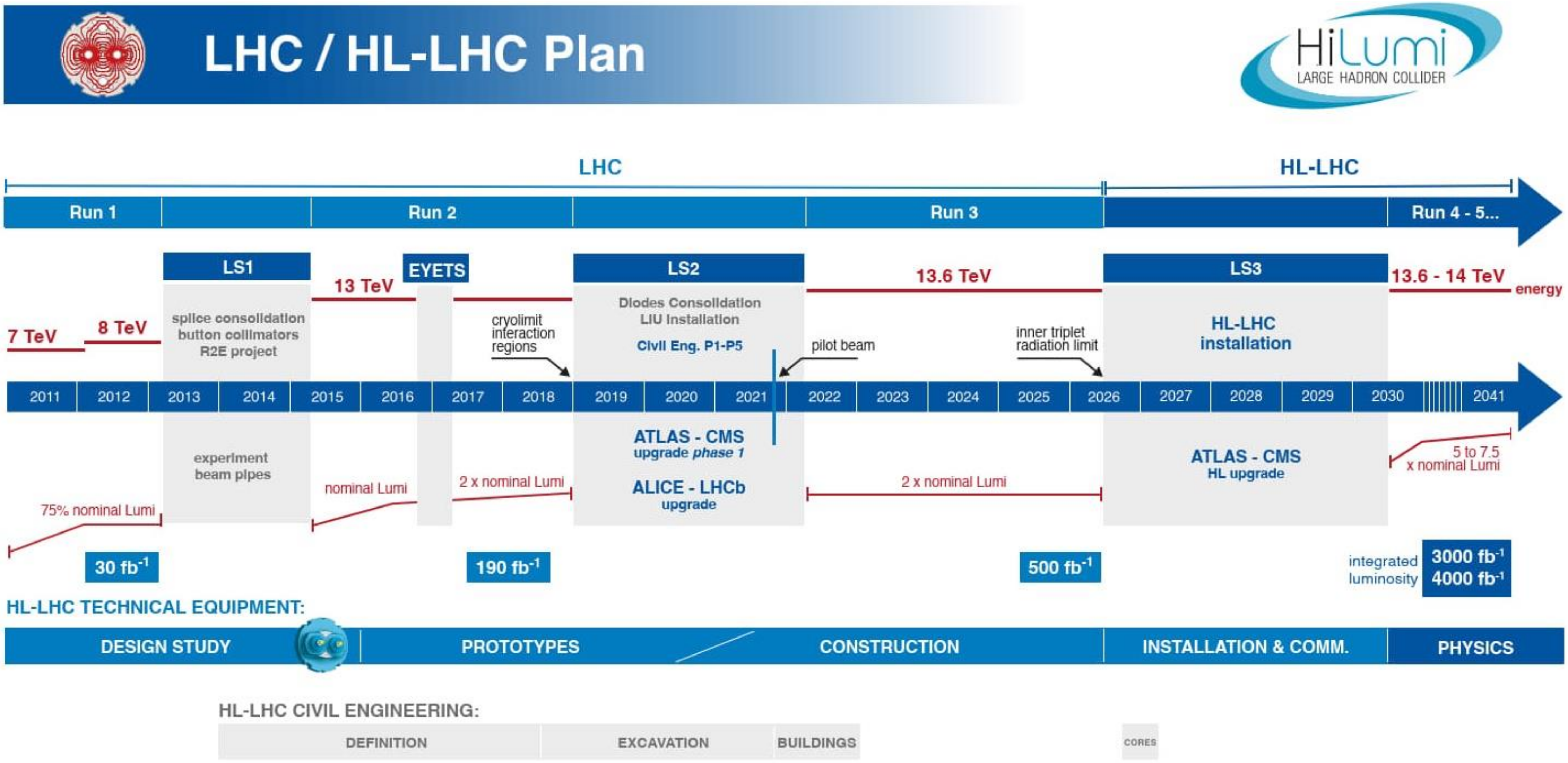
Point 1



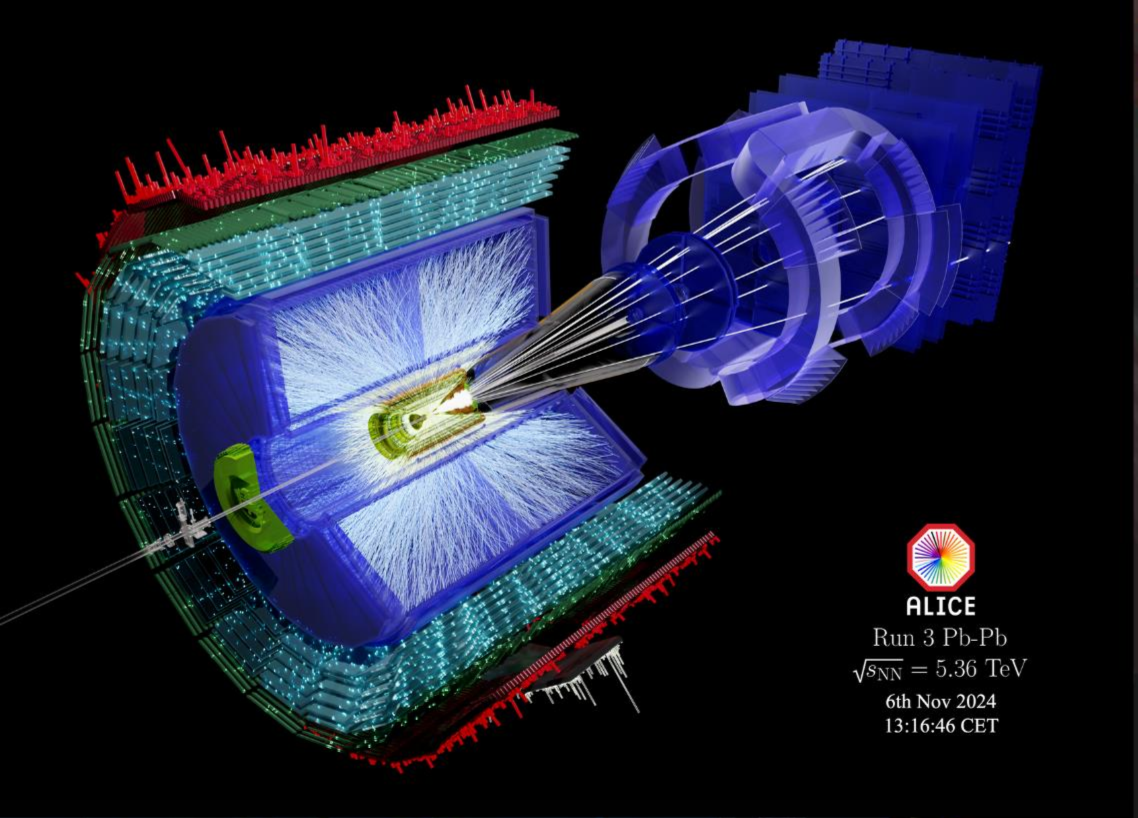


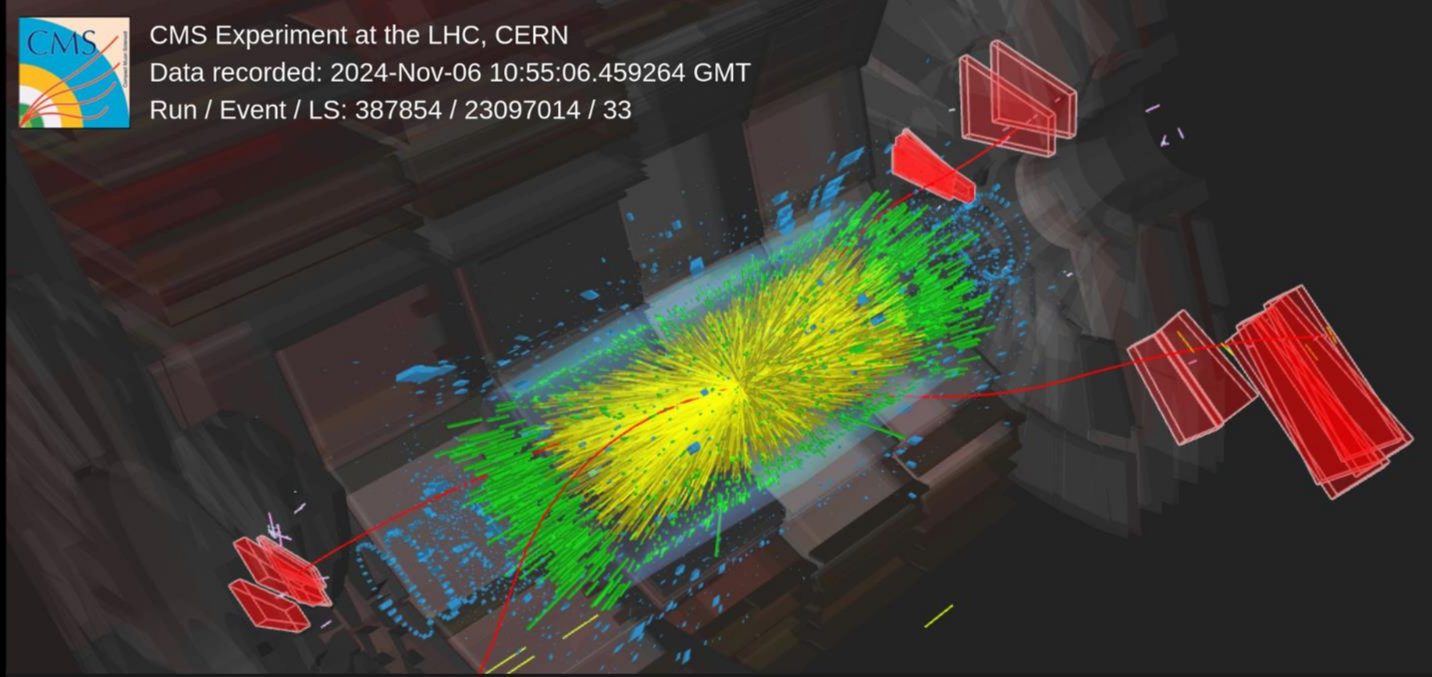
Point 5

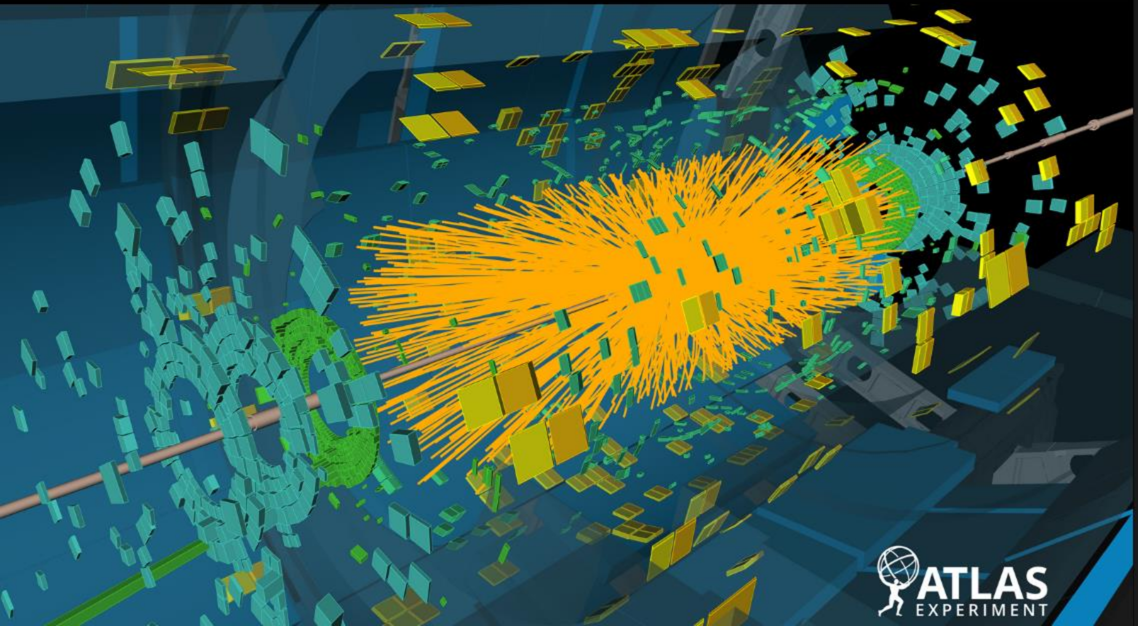
Updated Schedule for HL-LHC

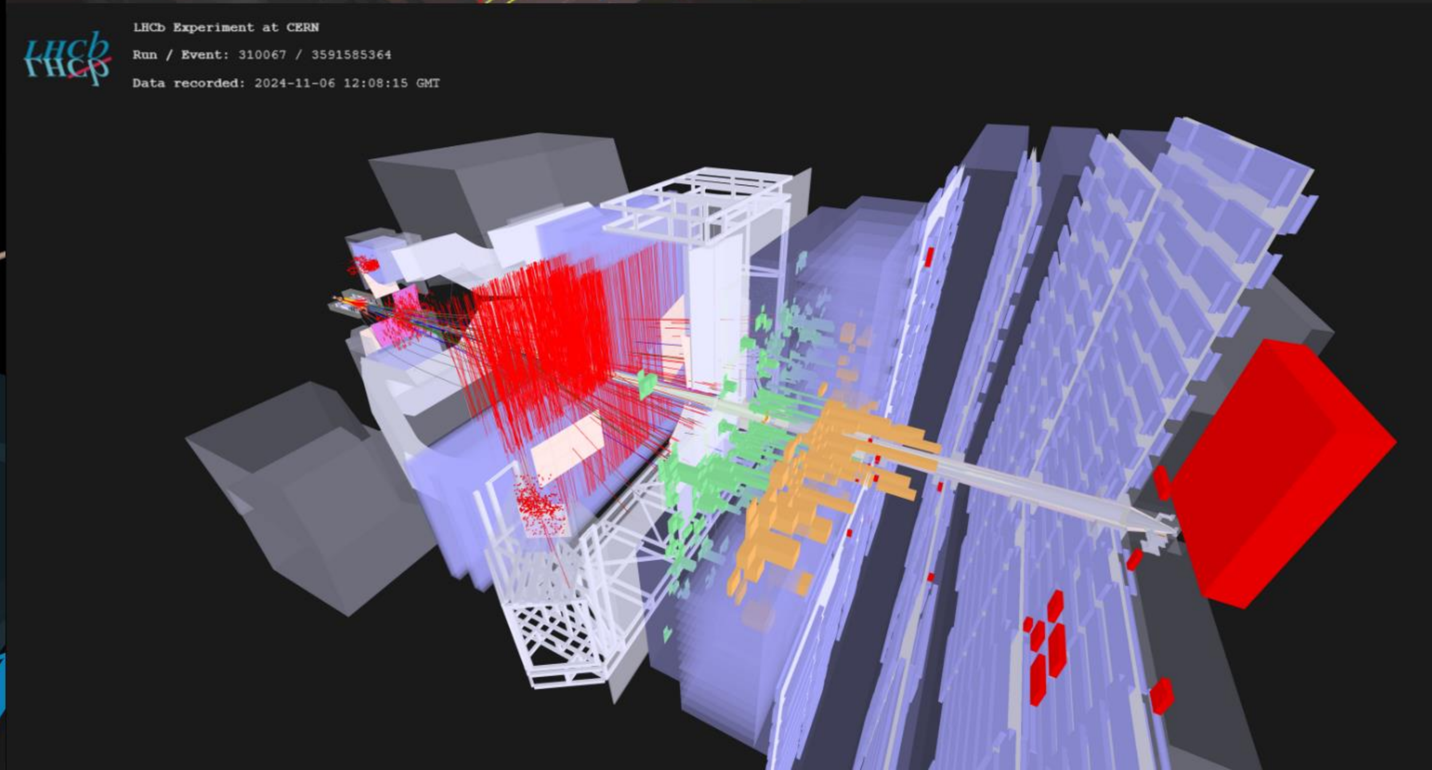


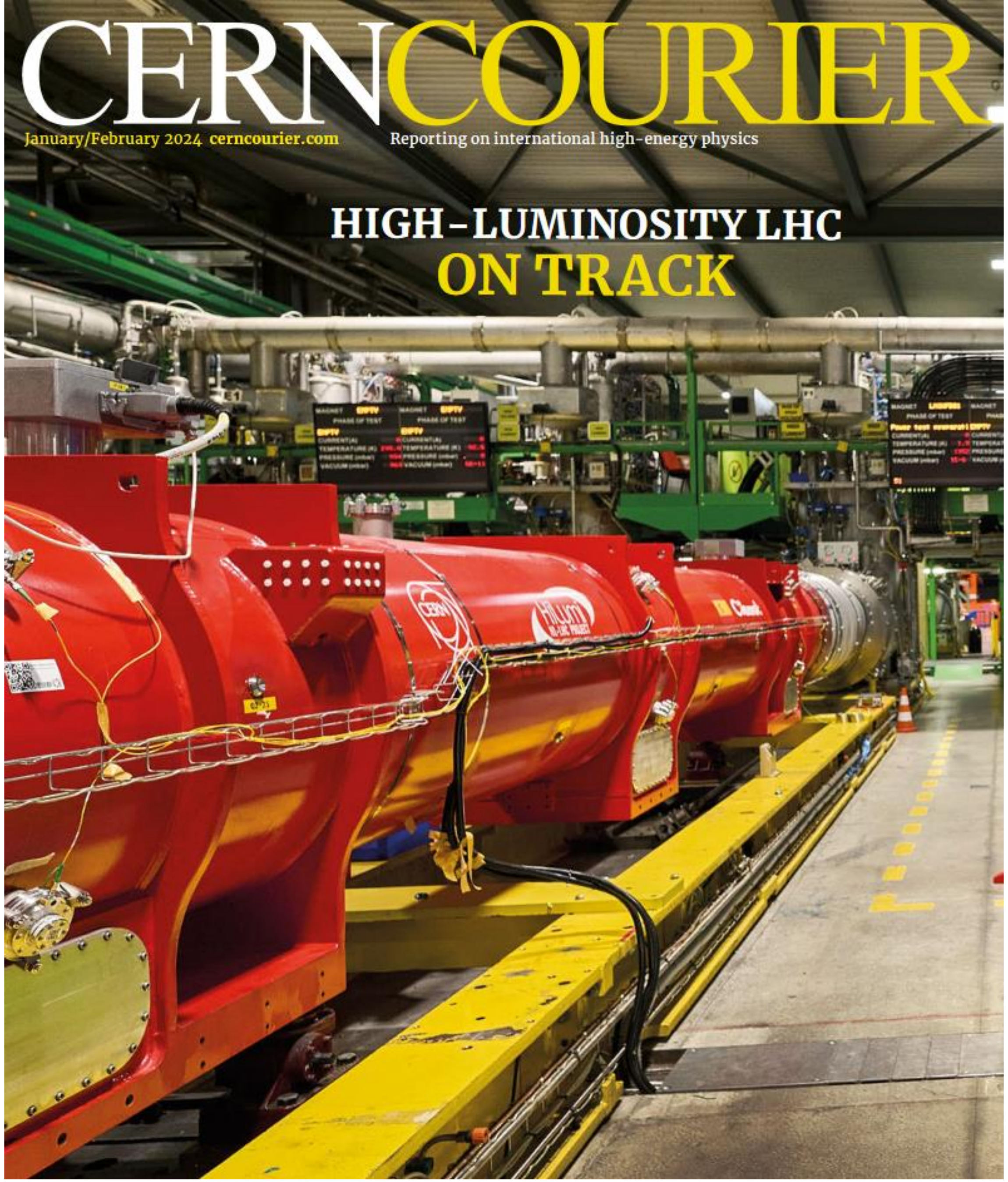
Conclusions


ALICE
Run 3 Pb-Pb
$\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV
6th Nov 2024
13:16:46 CET


CMS Experiment at the LHC, CERN
Data recorded: 2024-Nov-06 10:55:06.459264 GMT
Run / Event / LS: 387854 / 23097014 / 33


ATLAS
EXPERIMENT


LHCb
LHCb Experiment at CERN
Run / Event: 310067 / 3591585364
Data recorded: 2024-11-06 12:08:15 GMT


CERN COURIER
January/February 2024 cerncourier.com
Reporting on international high-energy physics
HIGH-LUMINOSITY LHC
ON TRACK

Spares

Setting the scene

2015 - 2018		2021 - 2026		≥ 2030
RUN 2	LS2	RUN 3	LS3	RUN 4

Injectors RUN 2 achieved parameters $^{\text{SPS ejection}}$:

- **$1.2 \cdot 10^{11}$ p+/bunch**
- 2.6 μm $\varepsilon^{n}_{x,y}$
- 25 ns bunch spacing

Integrated LHC luminosity **~140 nb^{-1}** @6.5 TeV (per high lumi experiment)

LIU & 1^{st} phase of HL-LHC

- New Linac 4 @160 MeV H-
- Booster injection @160 MeV and extraction @2 GeV
- PS injection @2GeV, RF system upgrade, etc
- SPS RF system upgrade, etc

Injectors LIU targets $^{\text{SPS ejection}}$

- **$2.3 \cdot 10^{11}$ p+/bunch**
- 2.1 μm ε^{n}x,y
- 25 ns bunch spacing

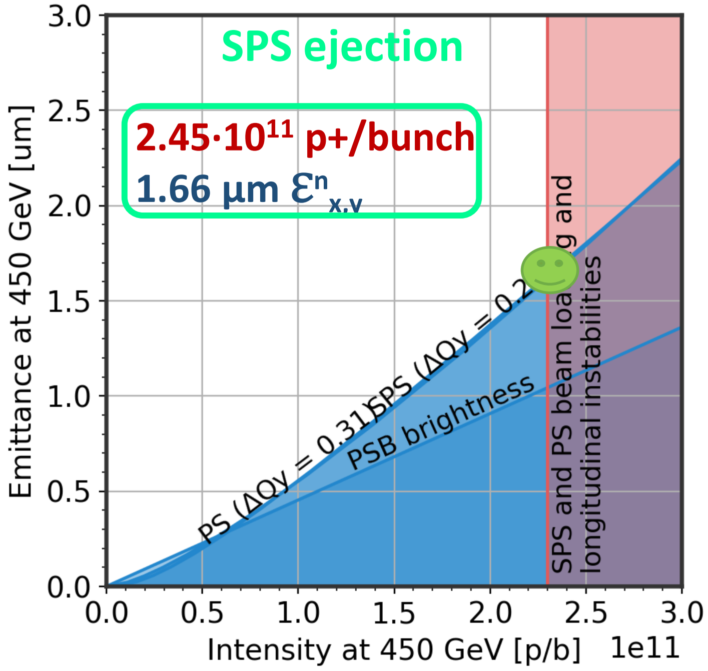
LHC p+ Lumi Levelled @ **$5 \cdot 10^{34}$ $cm^{-2}s^{-1}$**

LIU & 1^{st} phase of HL-LHC commissioning and exploitation

HL-LHC upgrades installation

HL-LHC commissioning and exploitation

BCMS 25ns - H



Achieved in MD, not yet operational

LHC 2024 operation

- 3 x 36 bunches BCMS
- **$1.6 \cdot 10^{11}$ p+/bunch**
- Integrated lumi **~125 nb^{-1} @6.8 TeV** (per high lumi experiment)

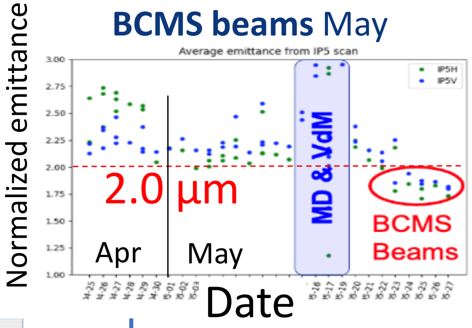
$\varepsilon^{n}_{x,y}$: normalized transverse emittance
LIU: LHC Injectors Upgrade

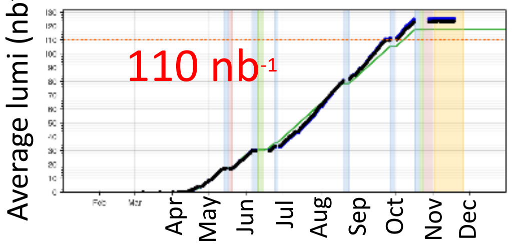
LHC in 2024

First injection: 8th March (3 days early)

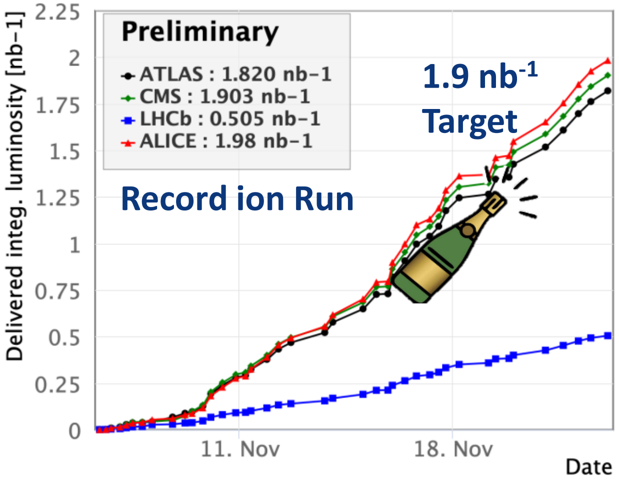
Beam position around the 27 km

1200 bunches on 14th April (10 days early)



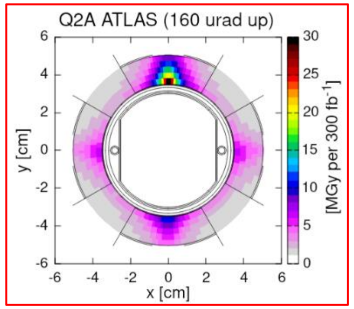


Beyond the 110 fb^{-1} target



Very stable physics production

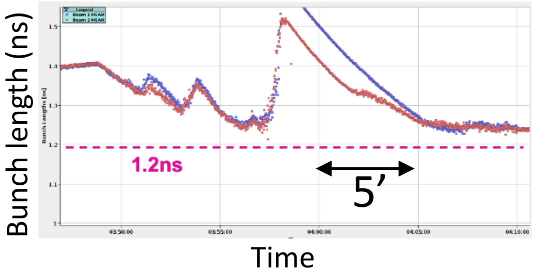
Reverse Polarity optics commissioned (~ +1 week)

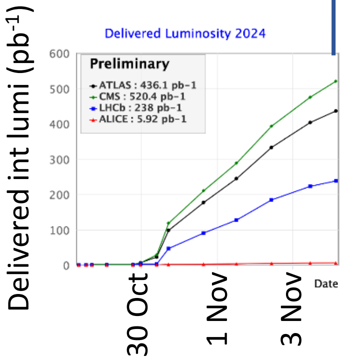


First Stable Beams @6.8 TeV 5th April (3 days early)

LHCb VELO closed for the 1st time

Operating with 1.6·10^{11} p+/bunch
Bunch length control/target
Limit RF module heating risk





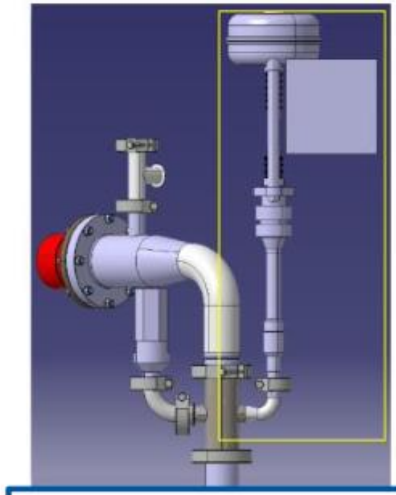
pp reference run
28th Oct – 2nd Nov
Integrated lumi over expectations

BCMS: **B**atch **C**ompression and (bunch) **M**erging and (bunch) **S**plitting

RF burst disk

02.04.2023

installed RF burst disk type



new depressuring valve

- Trigger event ➔ power cut in point 4 following a wrong manipulation after issue with compensator
- Afterwards: well-known chain of events:
  - the RF cavities are automatically isolated from the He input and output lines, consequently the cryomodule pressure increases due to the static heat loads the safety valves open and maintain the pressure around 1.9 bar
- Unfortunately, two of the new burst disks installed during YETS22-23 did not withstand the pressure and opened

- A test campaign on the spare disks confirmed that likely these two disks were outliers

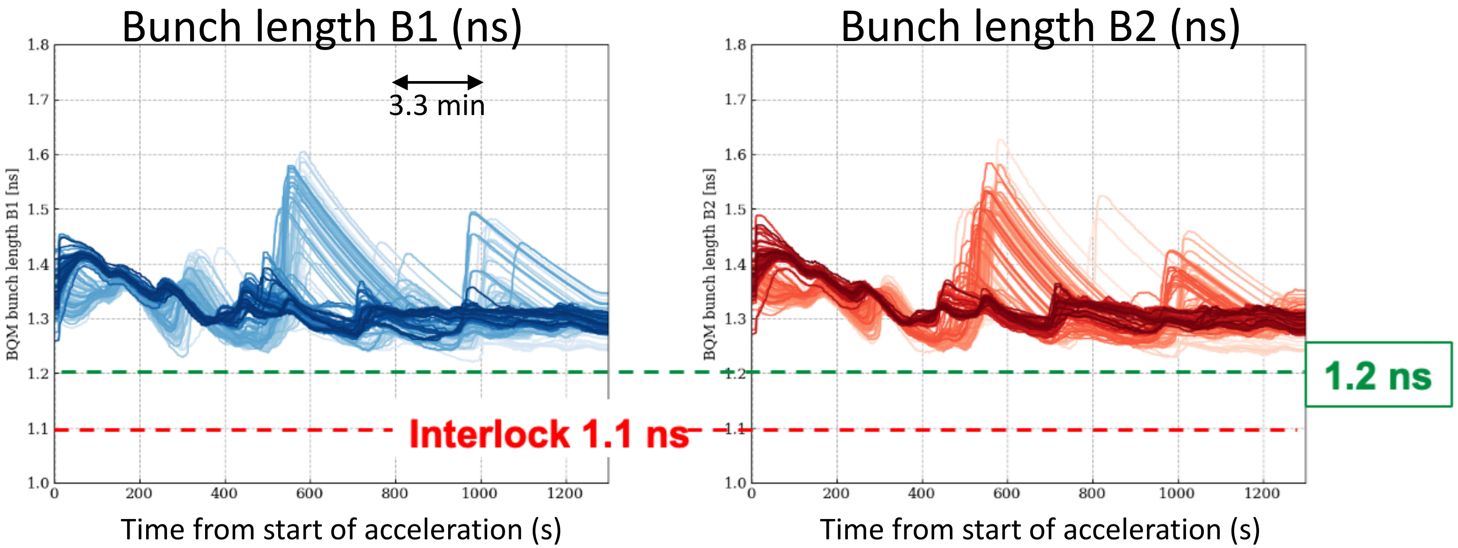
Mitigation to reduce the risk:

- Installation of fast depressurizing valves to back up the warm recovery line

- **Similar events may still happen** given small pressure margin between opening of safety valve and burst disk, which is necessary to able to protect the RF cavities against major events, for which the bust disks were foreseen

Dealing with Limitations – RF Finger Modules

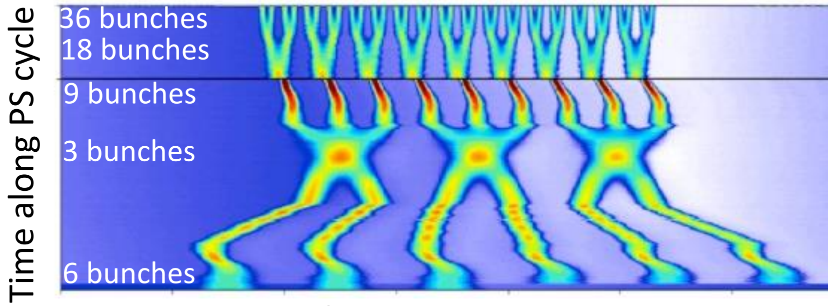
- Operating in 2024 with known weak modules
  - 47 of 71 replaced in YETS23-24
  - Remaining modules to be replaced YETS24-25
- Beam induced power depends on bunch intensity and bunch length
  - Bunch intensity limited to **$1.6 \cdot 10^{11}$ p+ in 2024**
    - **Run 3 max = $1.8 \cdot 10^{11}$ p+/b**
  - Bunch length control throughout the cycle



(E)YETS: (Extended) Year End Technical Stop

Performance optimization

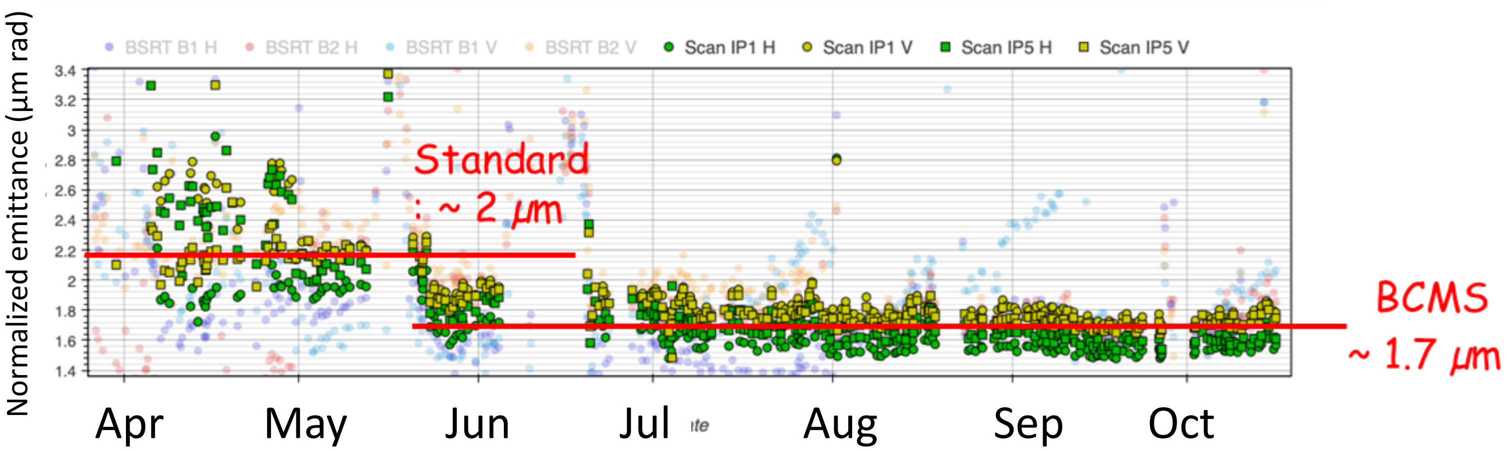
- Move to BCMS Beams
  - Filling scheme based on 3x36b patterns imposed by heat load limitation from electron cloud
  - Intensity limited to **$1.6 \cdot 10^{11}$ p+/bunch** by RF fingers
  - **Emittance: could be improved with BCMS**

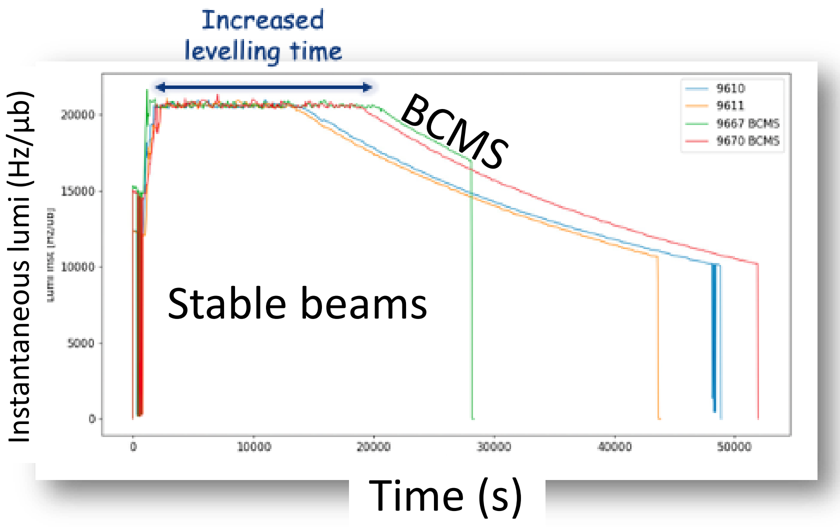


BCMS Beam for the LHC in the PS

BCMS: **B**atch **C**ompression and (bunch) **M**erging and (bunch) **S**plitting

- Optimised BCMS since May
  - Higher bunch brightness
    - Smaller emittance beneficial for reducing losses at injection





Outlook for the LHC in 2025

➢ 2025 Schedule

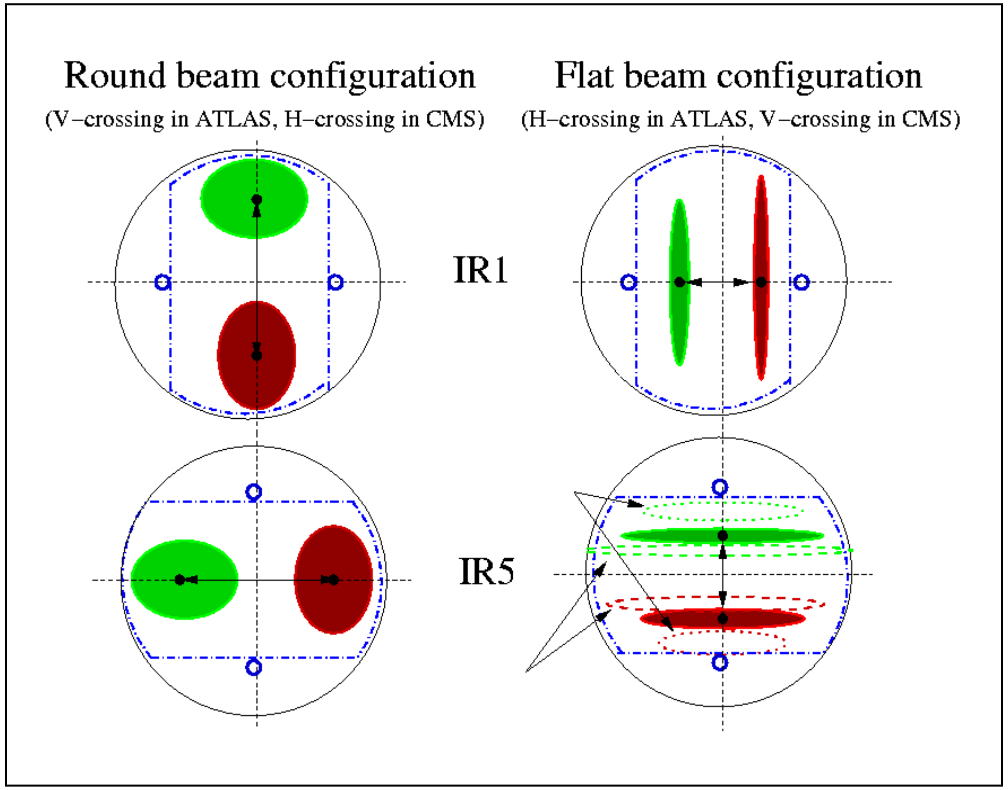
- 2025 luminosity target will be comparable to 2024 (target 110 nb^{-1})
- Short **Oxygen run** mid-year and **Pb Ion Run** to end the year

➢ Ensuring longevity of the IT Magnets

- Full reversed polarity gives best outlook but would stop any forward physics
- Compromise is flipping the crossing plane with nominal powering in IR1 and reversed polarity in IR5
  - Good background conditions for FASER and SND
  - PPS rotated to allow data taking to continue
- Several magnets still reach estimated limits if 2025 and 2026 are good production years

➢ Moving to Flat Optics

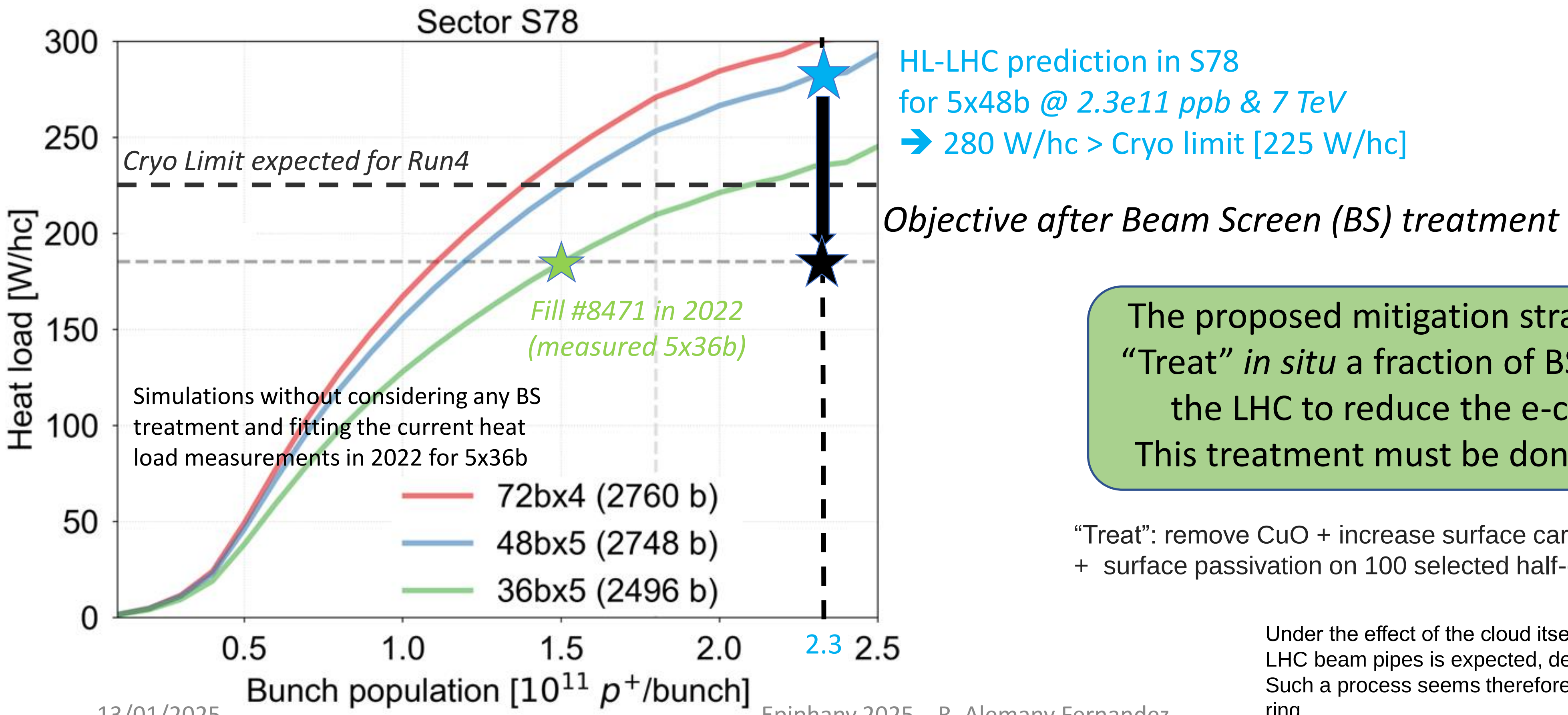
- Recovers luminosity loss due to limitation of aperture in triplet with flipped crossing plane



IT: Inner Triplet
FASER: Forward Search Experiment (close to IP1)
SND: Scattering and Neutrino Detector (close to IP1)
PPS: Precision Proton Spectrometer (close to IP5)

Beam screen heat load forecast @HL-LHC era

- The LHC **cryogenic capacity is limited** and cannot be easily increased
  Money, surface/underground available space, energy…
- From **Run 4, heat loads** applied to cryogenics will significantly **increase**
  LHC intensities ↑↑ ➔ Sync. Rad + Image Current + e-cloud ↑↑



The proposed mitigation strategy is :
"Treat" *in situ* a fraction of BS around the LHC to reduce the e-clouds
This treatment must be done in LS3

"Treat": remove CuO + increase surface carbon concentration
+ surface passivation on 100 selected half-cells

Under the effect of the cloud itself, conditioning of the copper surface of the LHC beam pipes is expected, decreasing thus the SEY of the surface. Such a process seems therefore to be hindered in some parts of the LHC ring.

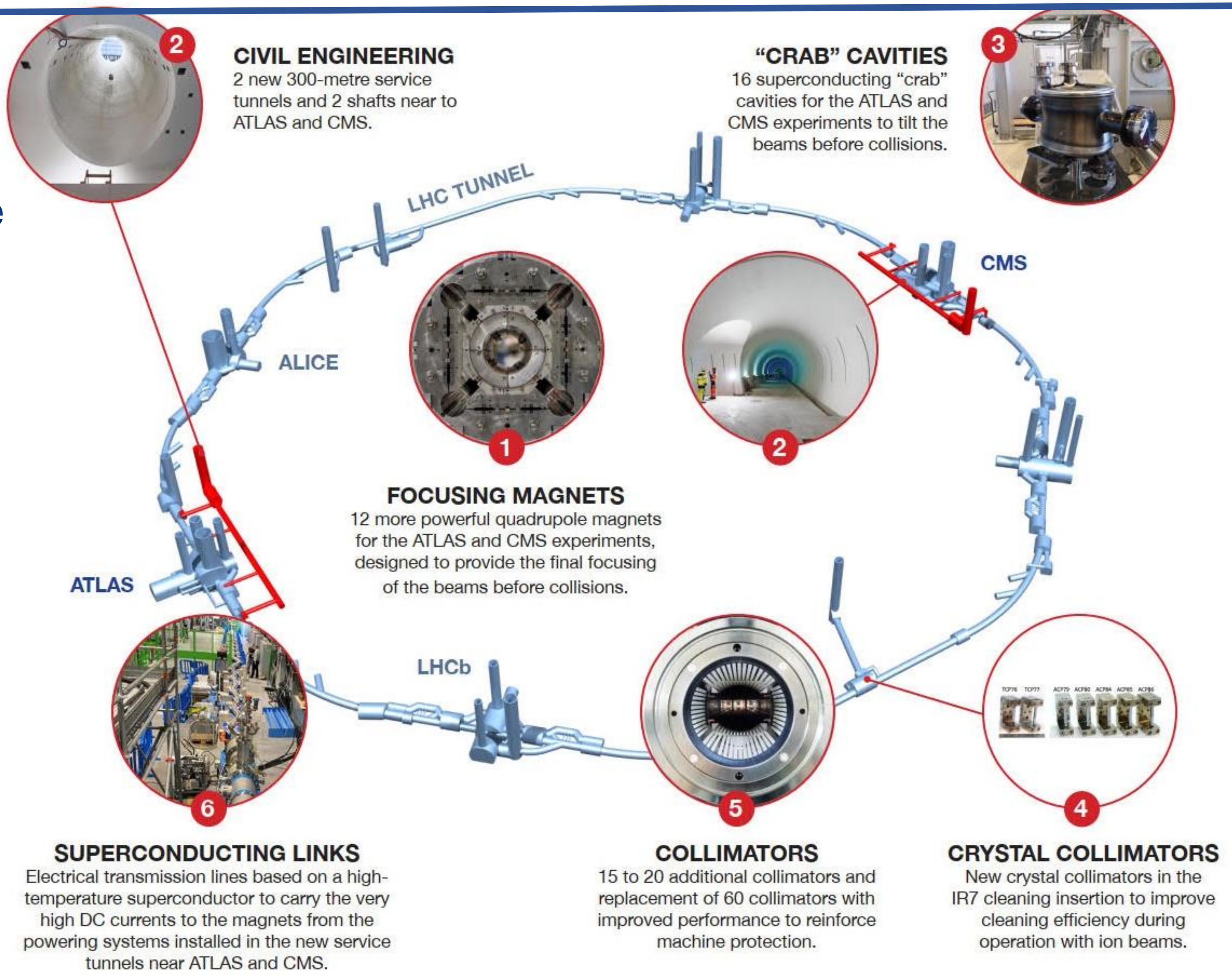
Key ingredients for the HL-LHC upgrade

A technologically “intense” upgrade project

1. New IT quadrupoles, Nb_3Sn
2. Civil engineering
3. Crab Cavities
4. Crystal collimation
5. Low impedance collimators
6. Superconducting links

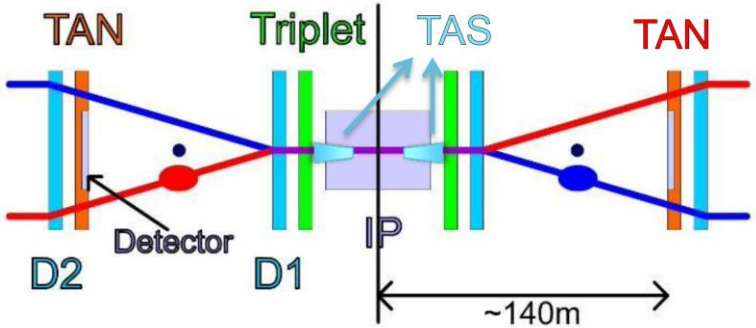
Injection and dump upgrades

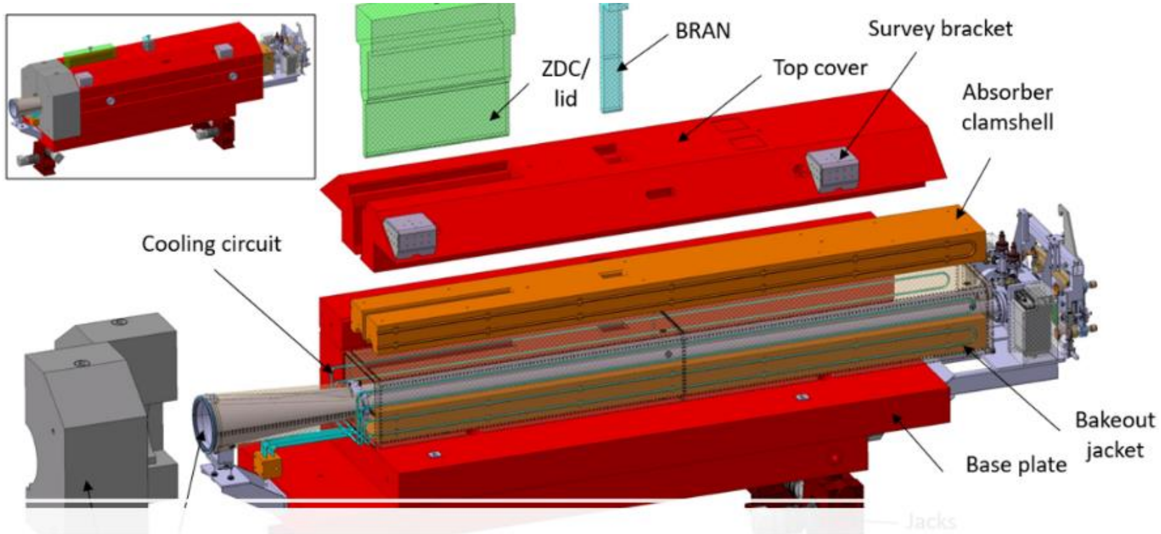
…



Preparing the Collider-Experiment Interface

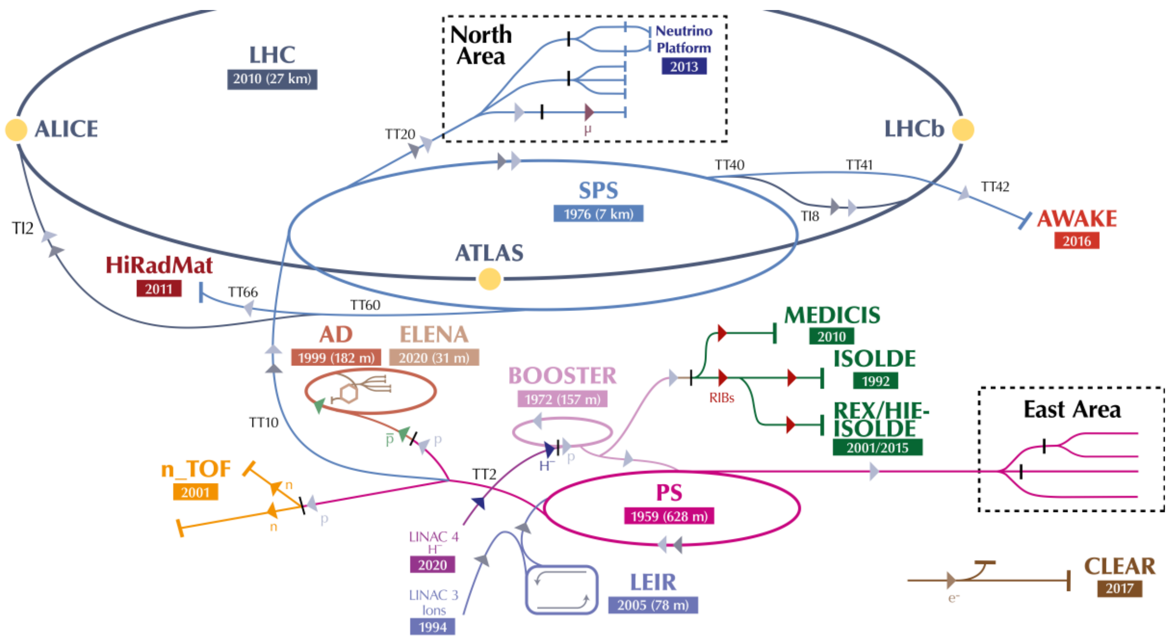
- Protecting the machine from collision debris
  - Moving into the production phase for both the **TAXS** (secondary particle absorber) the **TAXN** (neutral particle absorber)
  - Mock-up area heavily used to train and test
    - Very soon house full setups of both ATLAS and CMS

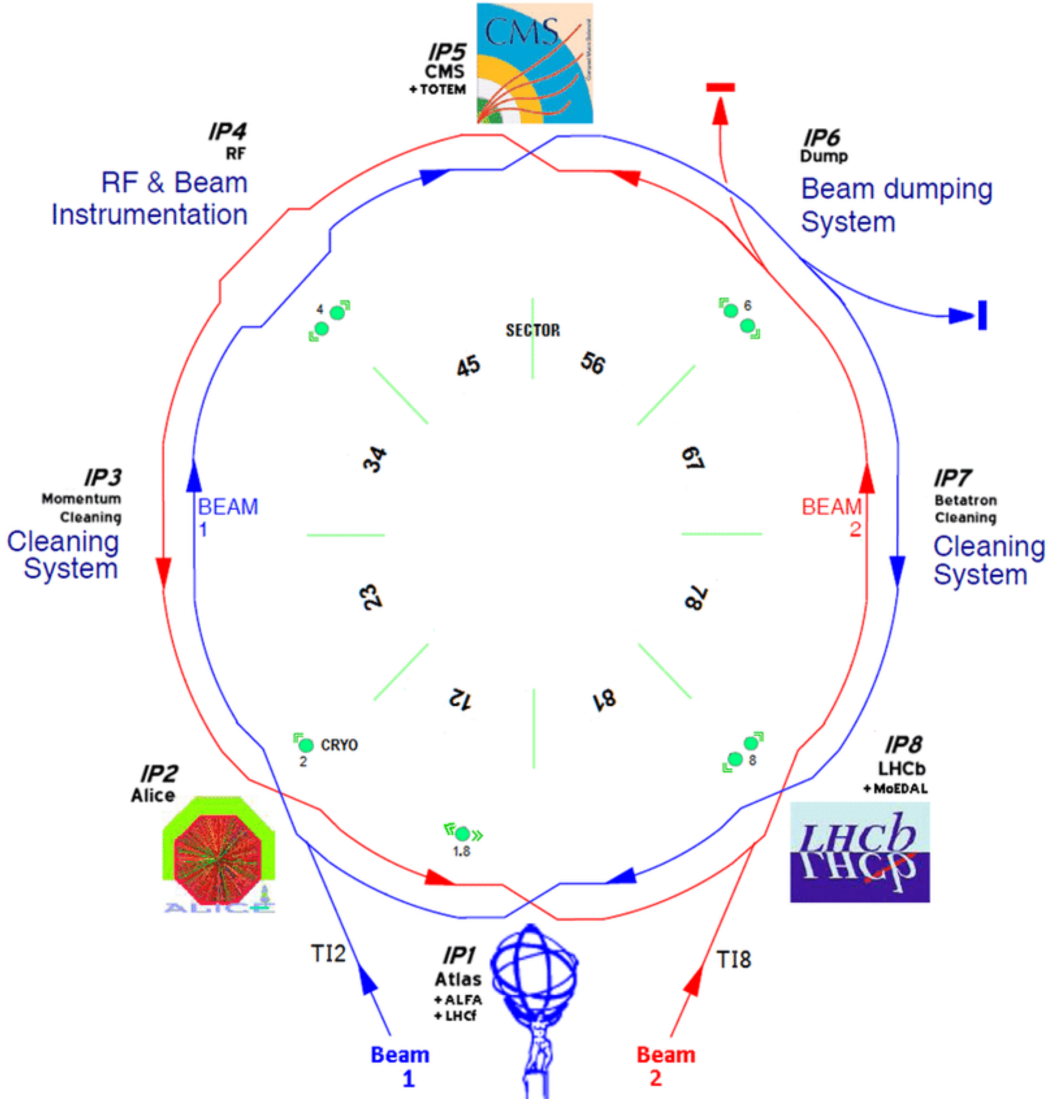




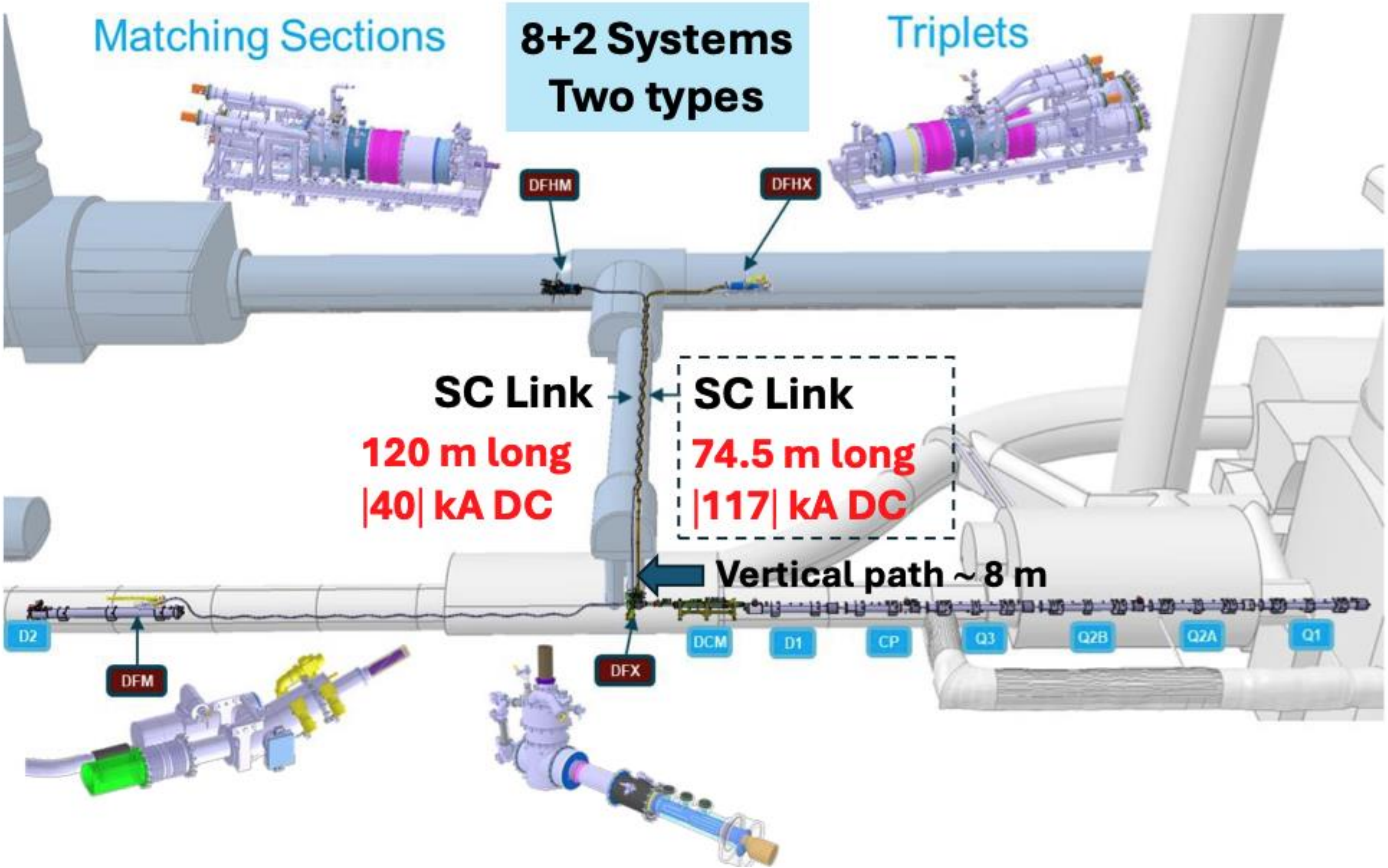
TAXN- Explosion view

LHC layout & beam production

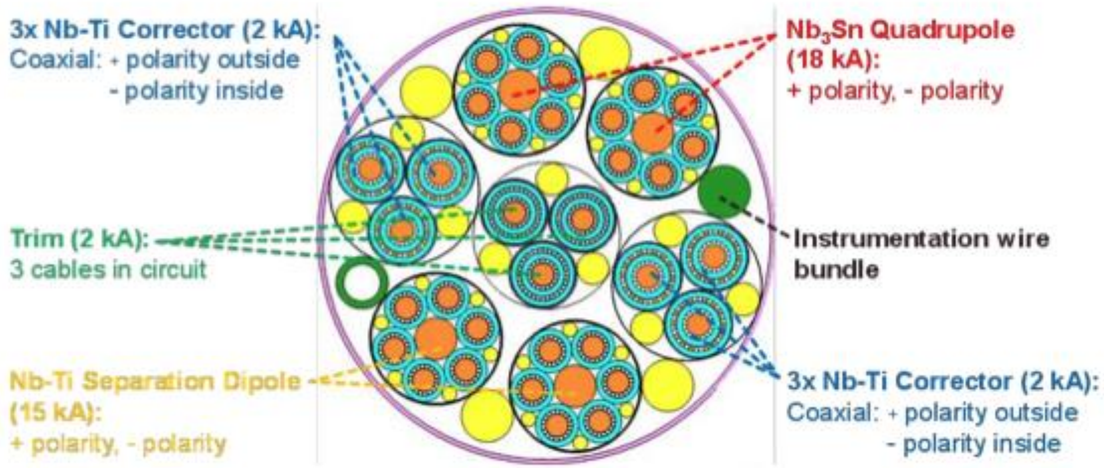




Powering the HL-LHC magnets

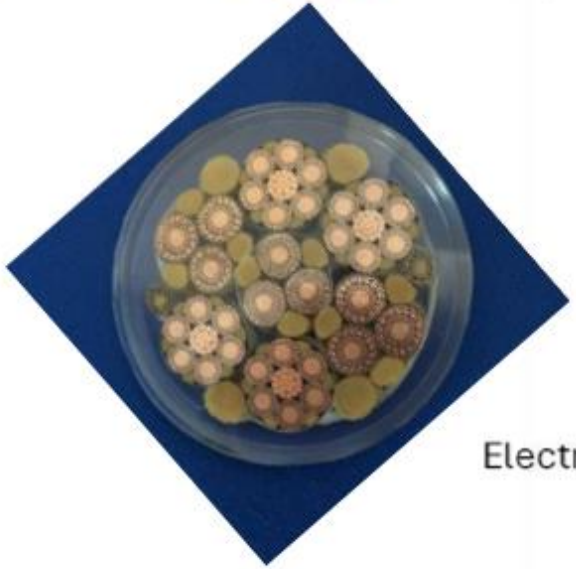


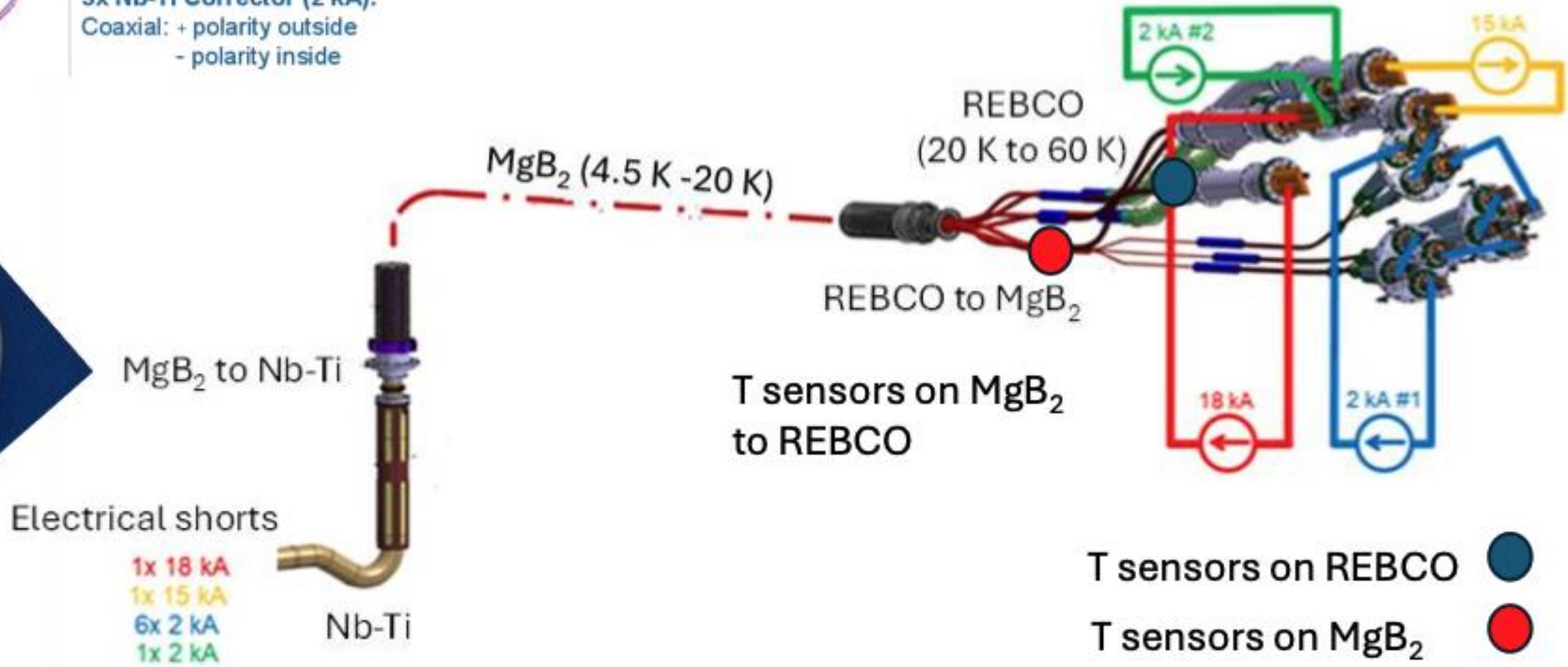
Powering Scheme



Four power converters:

18 kA – $I_{HL\text{-}LHC}$ = 16.23 kA (Nb$_3$Sn quadrupole)
15 kA – $I_{HL\text{-}LHC}$ = 12.11 kA (Separation dipole)
2 kA – $I_{HL\text{-}LHC}$ = 2 kA (Trim)
2 kA – $I_{HL\text{-}LHC}$ = 1.74 kA (Correctors)





Maximum current delivered by the power converters: **94 kA**

Other limitations in Run 3 that require LHC parameters and configuration optimization

- Besides: RF fingers modules
  - ➔ limits bunch intensity and bunch length

- Electron cloud and cryogenics load
  - ➔ limits bunch pattern

- Radiation to inner triplets
  - ➔ change of optics