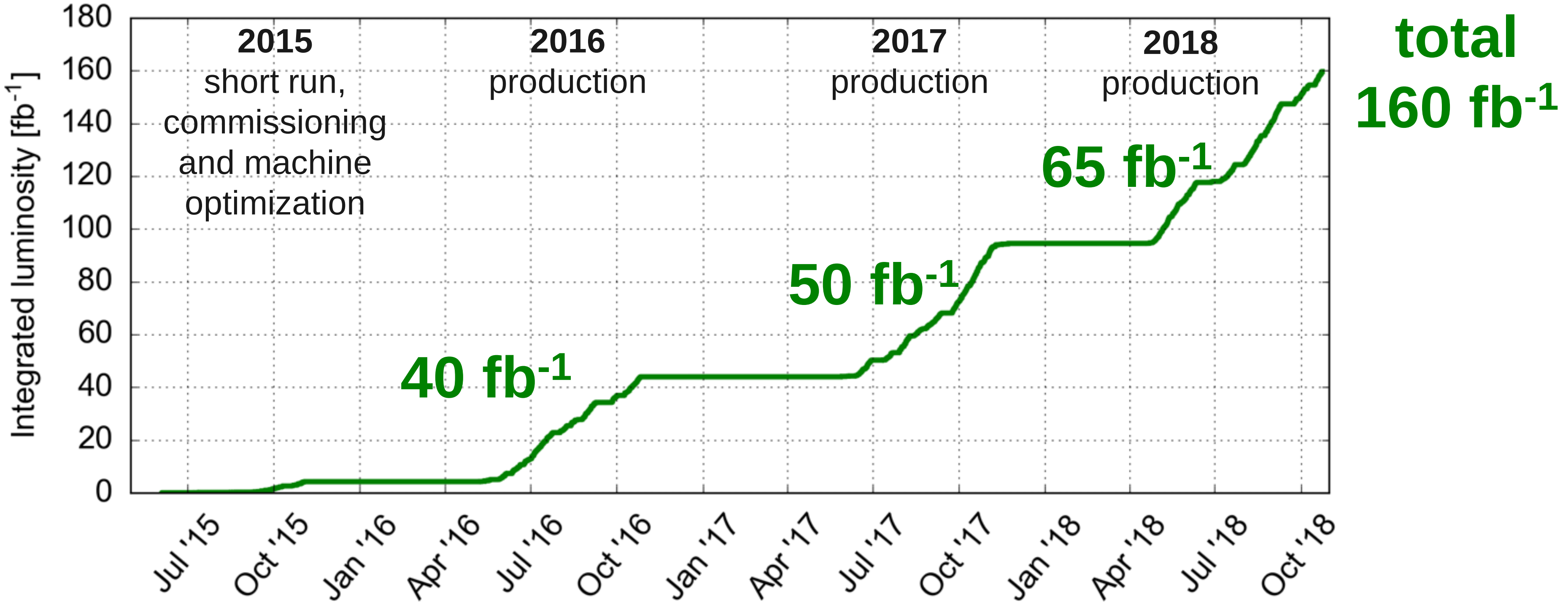
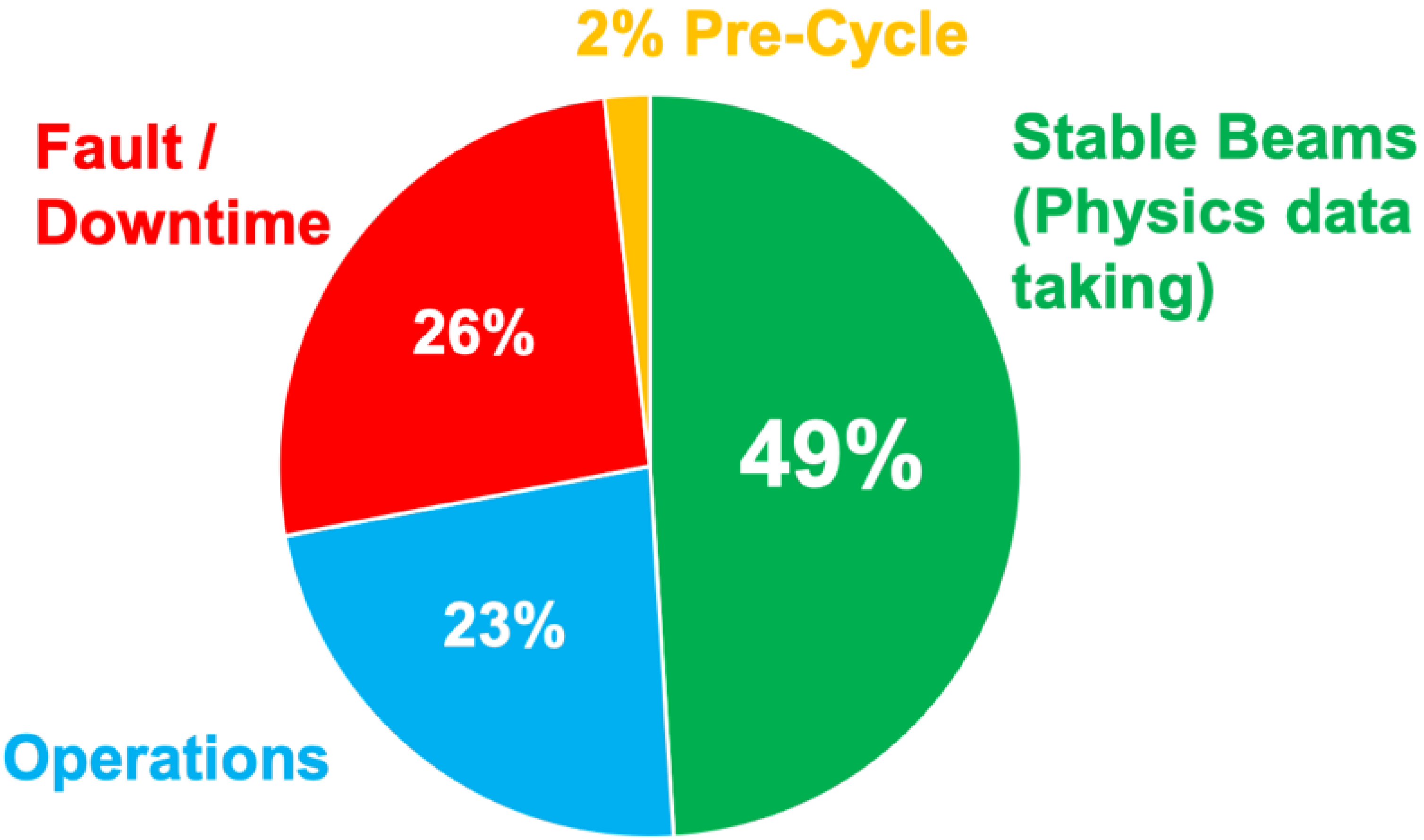
The LHC future: from Run 3 to the ultimate performance

Run 2: p-p operation

- **During Run 2:**
  - Demonstrated reliable operation with **6.5 TeV beams**
  - Exploited **25 ns** bunch spacing to operate with **>2500 bunches**
  - Reached **design luminosity** $L_{IP1/5} = 10^{34}\ cm^{-2}s^{-1}$ … **and doubled it!**
  - Delivered **160 fb^{-1} to ATLAS and CMS**



Availability

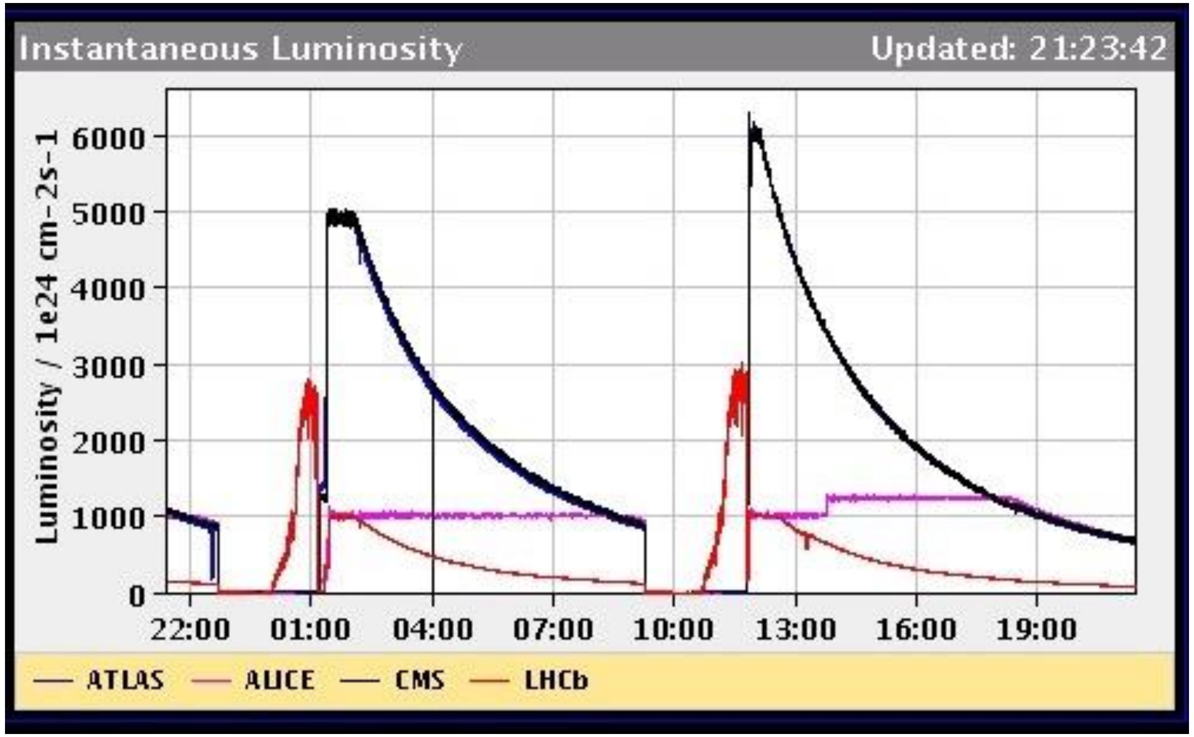


2018 data

Heavy ion operation

HL-LHC instantaneous luminosity (~$6x10^{27}$ $cm^{-2}s^{-1}$) i.e. 6 times the LHC design value was already demonstrated in IP1 and IP5

Pb-Pb luminosity record in 2018



Further improvements incoming in 2022

HL-LHC - goals

Prepare machine for operation beyond 2025 and up to ~2040

Operation scenarios for:

- Total integrated luminosity of 3000 fb^{-1} in around 10-12 years
- An integrated luminosity of ~250 fb^{-1} per year
- **Nominal:** levelled luminosity of 5 x 10^{34} $cm^{-2}s^{-1}$ (events/crossing ~130)
- **Ultimate:** levelled luminosity of 7.5 x10^{34} $cm^{-2}s^{-1}$ (events/crossing ~200)

Higher Intensity

Increase bunch population

$$\mathcal{L} = \frac{N^2 f_{rev} k_c}{4\pi\beta^* \epsilon_{xy}} F$$

Increase F

Crossing angle reduction factor

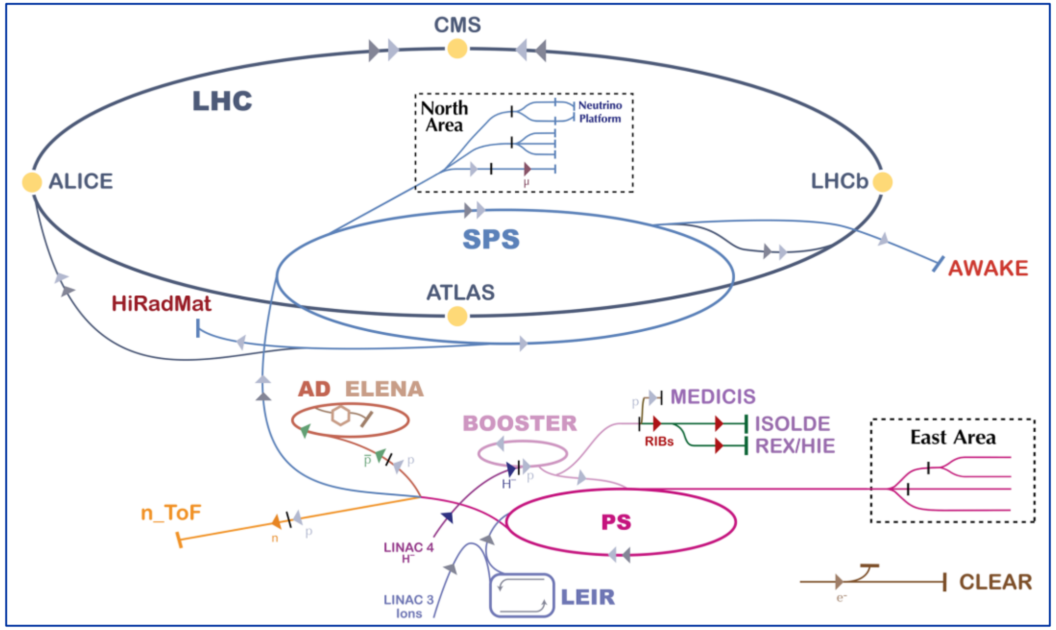
$$\frac{1}{\sqrt{1 + (\frac{\sigma_s}{\sigma_x}\frac{\phi}{2})^2}}$$

Shorter bunches, smaller crossing angle, crab cavities

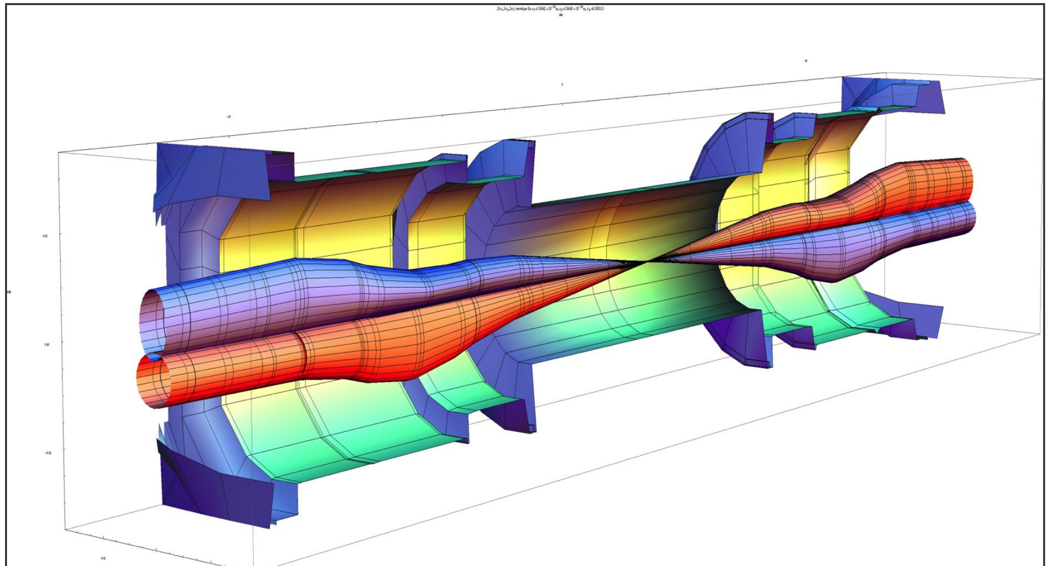
Smaller β^*

Reduced emittance

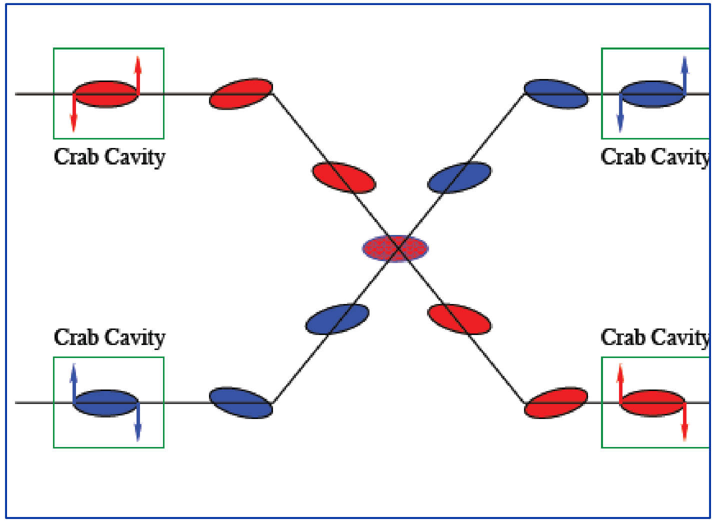
Smaller beam size at IP



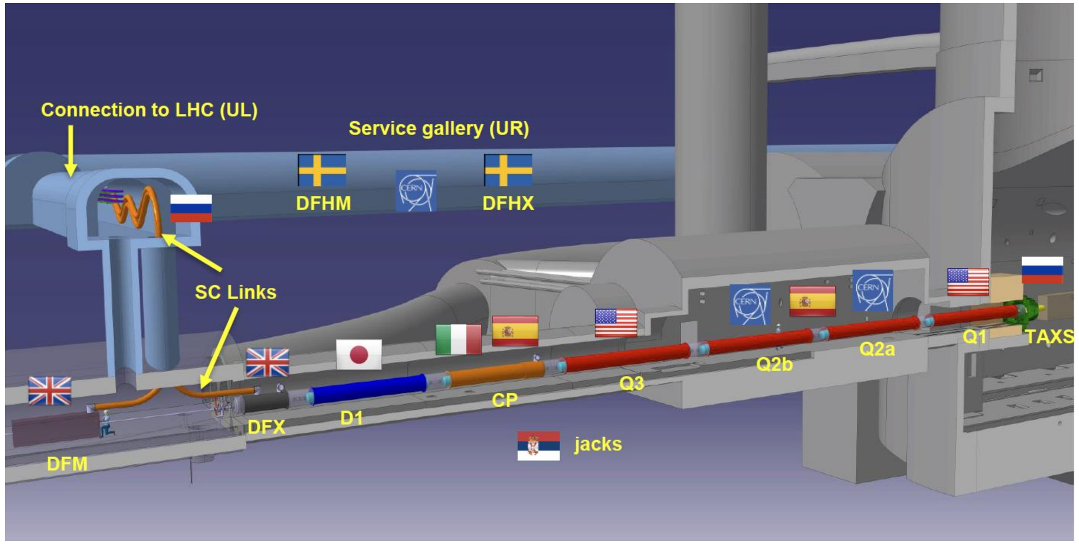
Injector upgrade (bunch population, emittance)



Interaction region upgrade (beta*)



Crossing angle compensation (crabs)

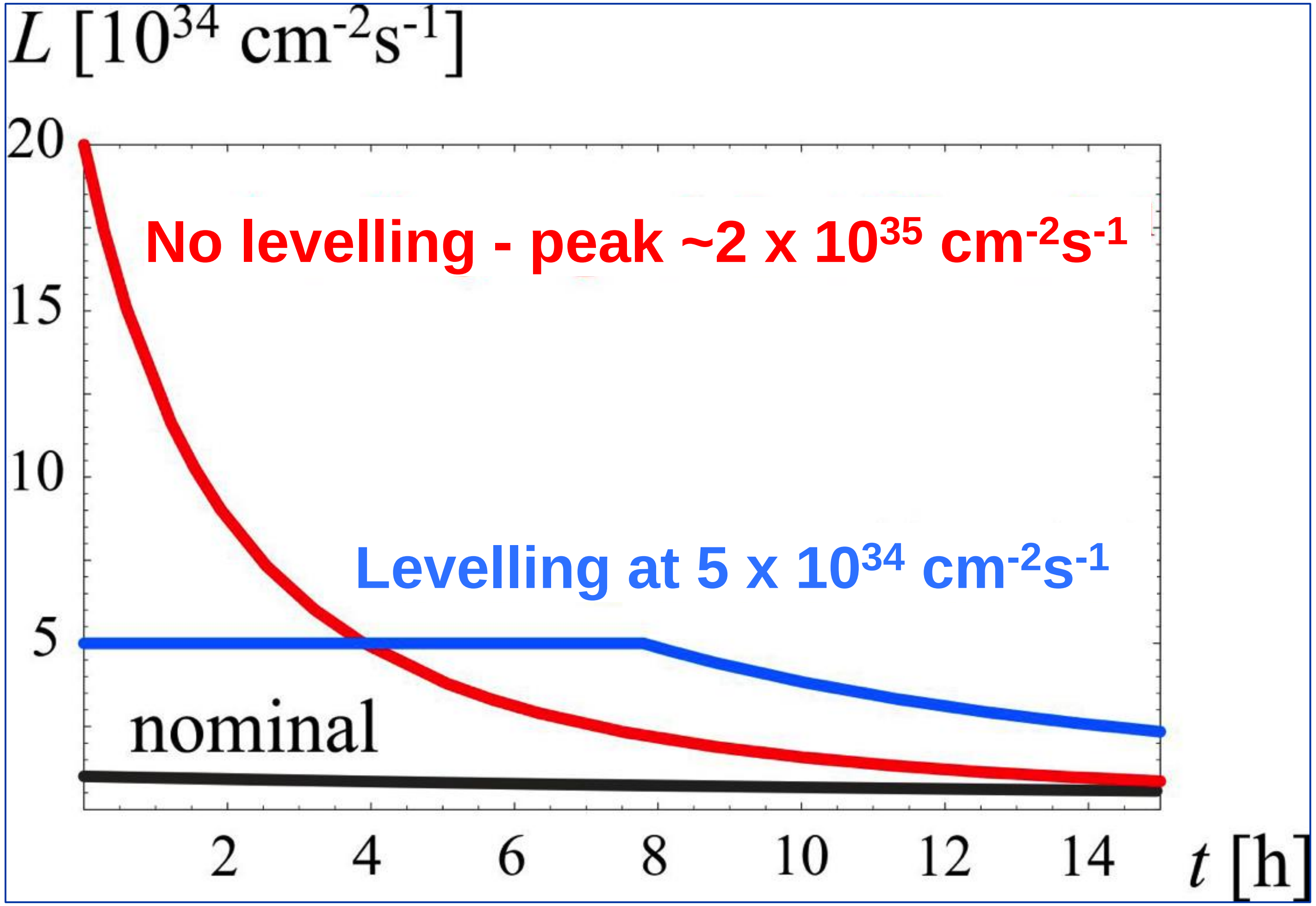


Operate in a high luminosity regime

HL-LHC: key nominal 25 ns parameters (GPDs)

Beam energy	7 TeV
Protons per bunch	2.2×10^{11}
Number of bunches	2760
Normalized emittance	2.5 μm
Beta*	15 cm
Crossing angle	500 μrad
Geometric reduction factor (F)	0.342
"Virtual" luminosity (with crabs)	1.7×10^{35} cm^{-2}s^{-1}
Levelled luminosity	5×10^{34} cm^{-2}s^{-1}
Levelled <pile-up>	~130

Operational scenario



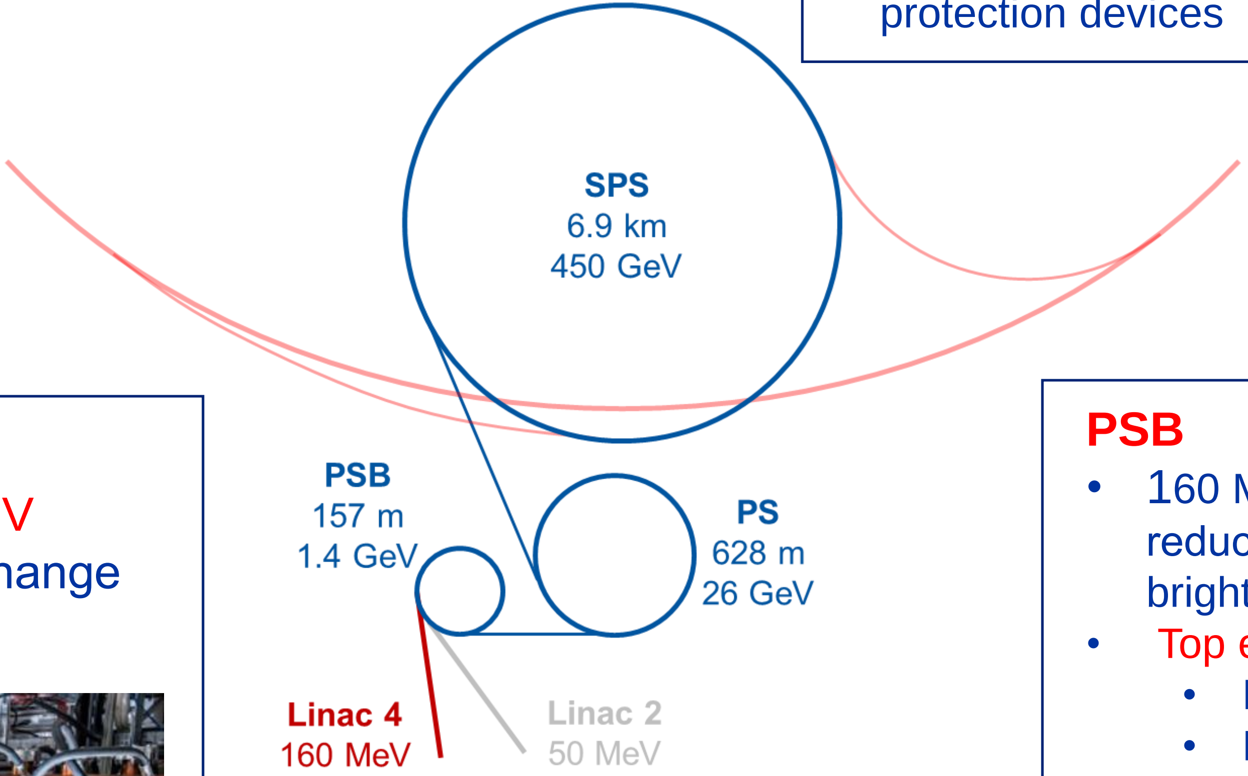
Nominal levelling time ~7 hours

LHC Injectors Upgrade

Deployed in LS2 (2019-20)

SPS

- RF system upgrade → solid state power amplifiers
- Impedance mitigation
- Robust beam dump and protection devices



Linac 4

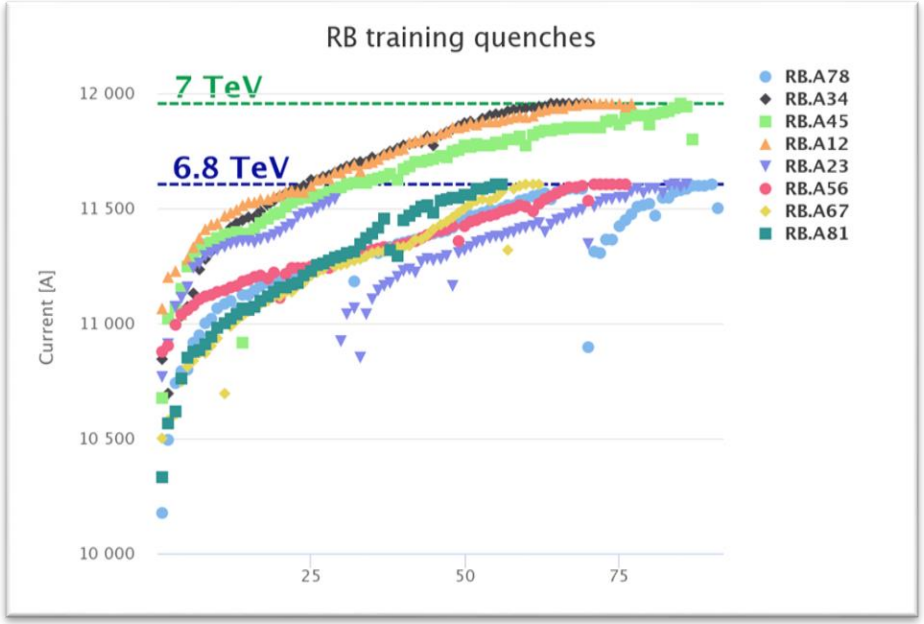
- Higher energy 160 MeV
- H- ions → charge exchange injection into the PSB

PSB

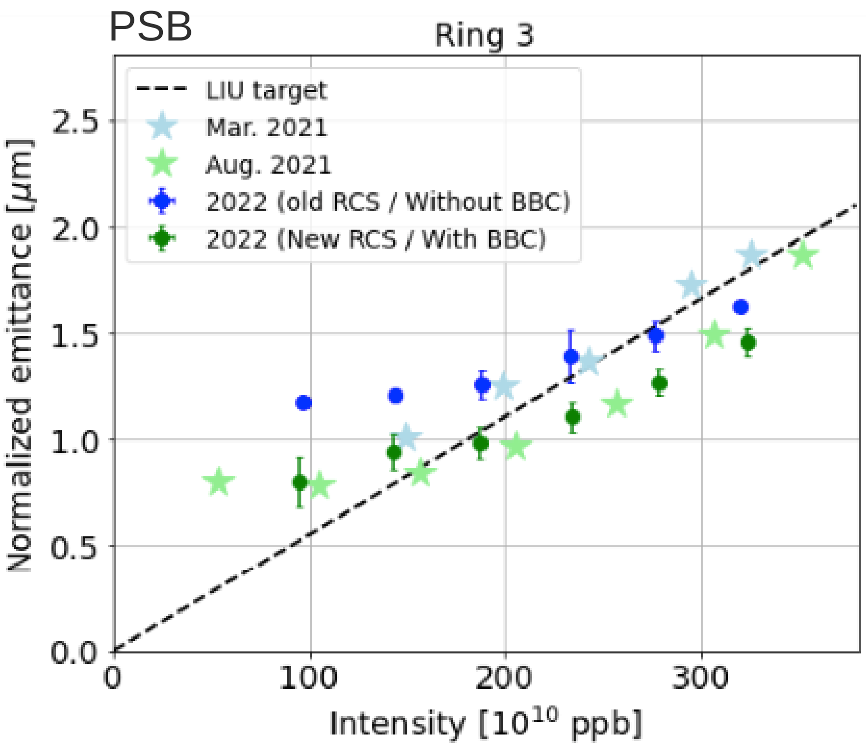
- 160 MeV, charge exchange injection, reduced space charge → improved brightness
- Top energy : 1.4 GeV to 2 GeV
  - New main power supply
  - New RF systems

Run 3 at 6.8 TeV

Targeted consolidation and upgrades during LS2 followed by a long training campaign



Benefiting from the Injector upgrade



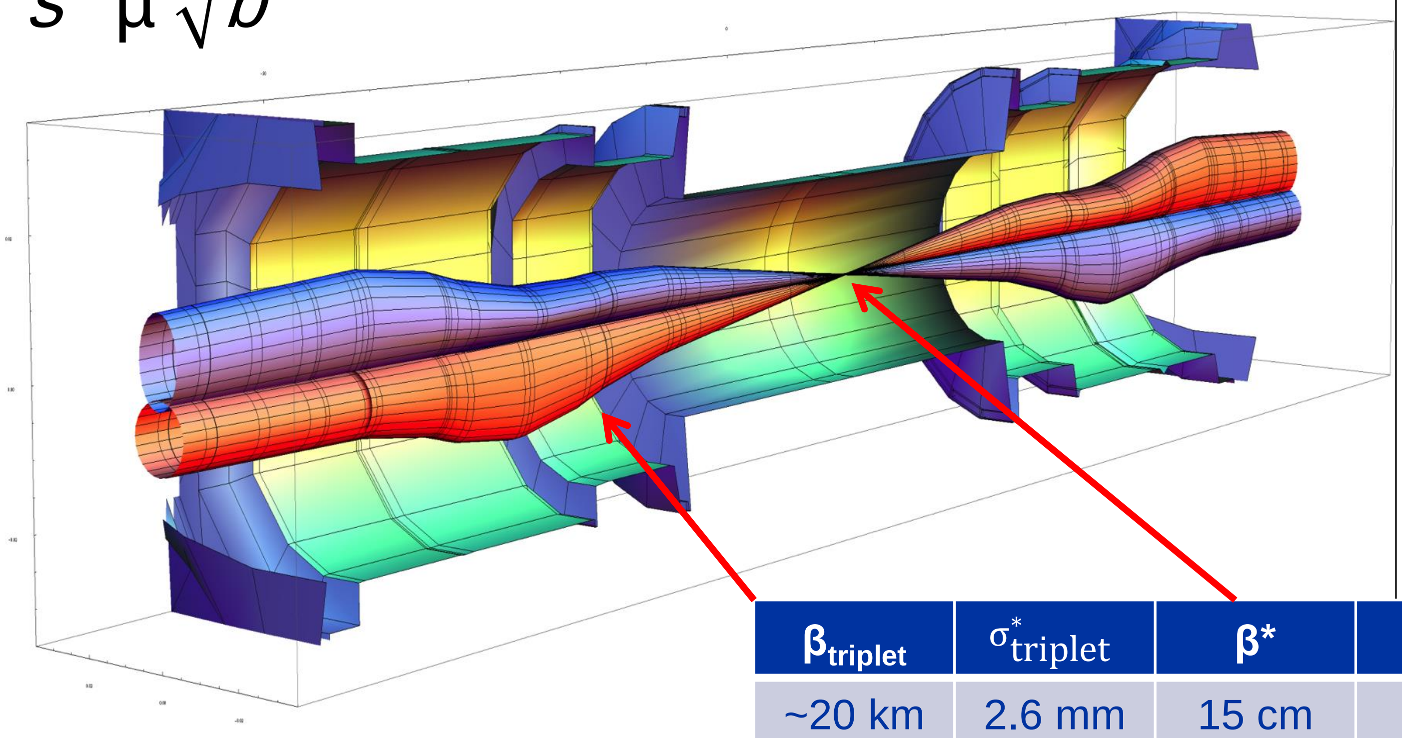
Proton-proton

- Levelled to a maximum luminosity 2.05×10^{34} $cm^{-2}s^{-1}$ in ATLAS and CMS
- Levelled to a target of ~1.4×10^{31} $cm^{-2}s^{-1}$ and 2×10^{33} $cm^{-2}s^{-1}$ in ALICE and LHCb respectively
- **~1.8×10^{11} proton/bunch in 2023 – 2025 - long levelling times!**

Squeeze

- Small beam size at interaction point implies larger beams in the triplet magnets
- Larger beams implies a larger crossing angle
- For the LHC, aperture concerns dictates caution
- For the HL-LHC → **new wide aperture magnets**

$$s^* \mu \sqrt{b^*}$$



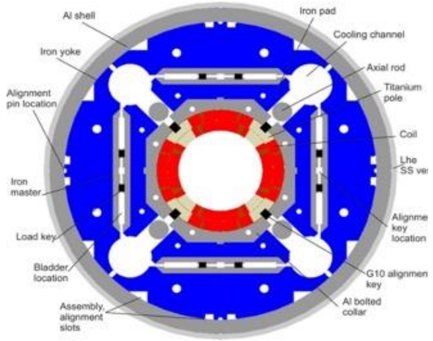
$\beta_{triplet}$	$\sigma^*_{triplet}$	β^*	σ^*
~20 km	2.6 mm	15 cm	7 um

Image courtesy John Jowett

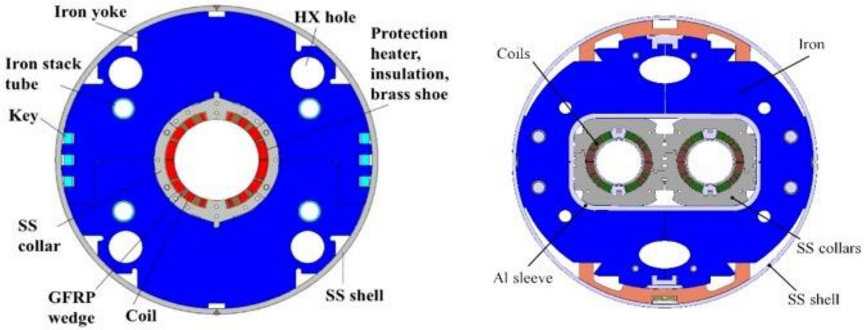
HL-LHC: IR magnets

New wide-aperture **superconducting magnets for the interaction regions**

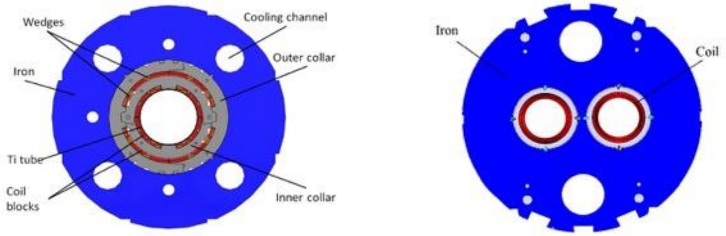
Final focus quadrupole (MQXF)



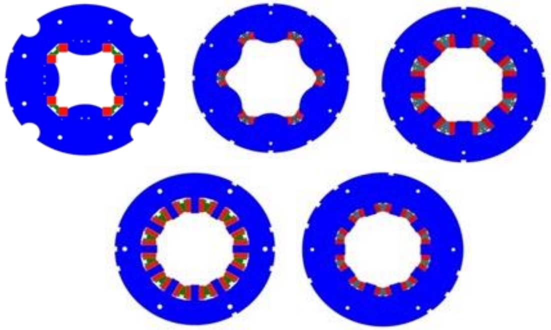
Separation/recombination dipoles



Dipole correctors

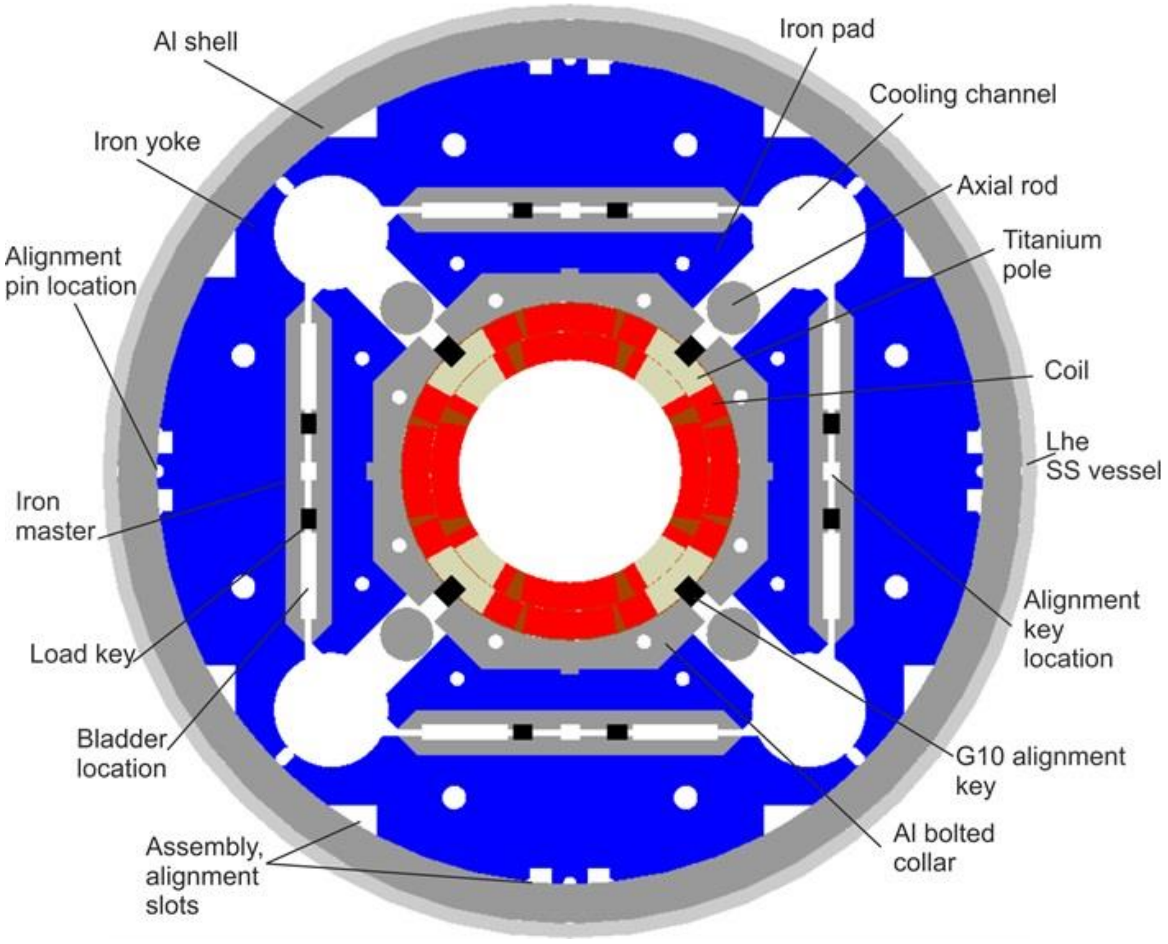


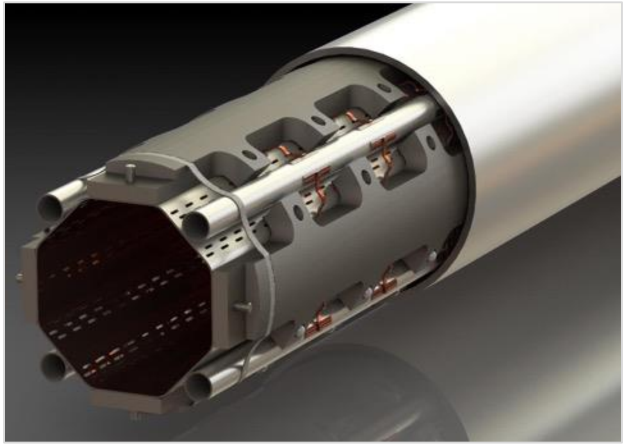
Higher order correctors



MQXF

- **Large aperture**: 150 mm
  → Allows for **smaller beam size** at the interaction points
  → Allows introduction of **tungsten shielding** to protect the magnet from luminosity debris
- **Nb_3Sn technology** → Larger operational peak fields (11.4 T)



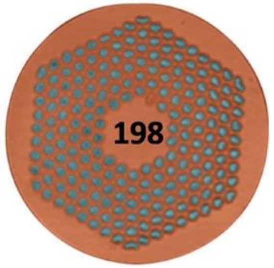


CERN

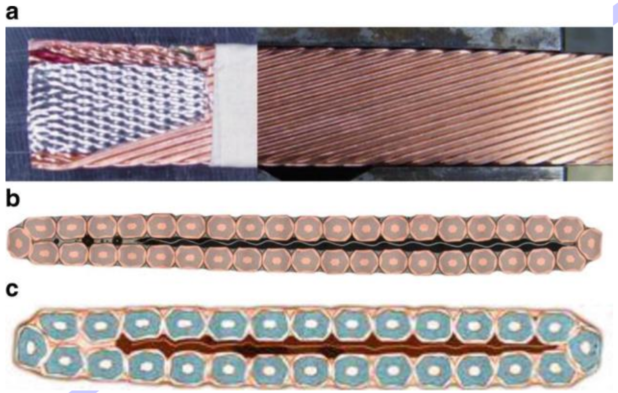
US HL-LHC AUP

HL-LHC Nb_3Sn magnets

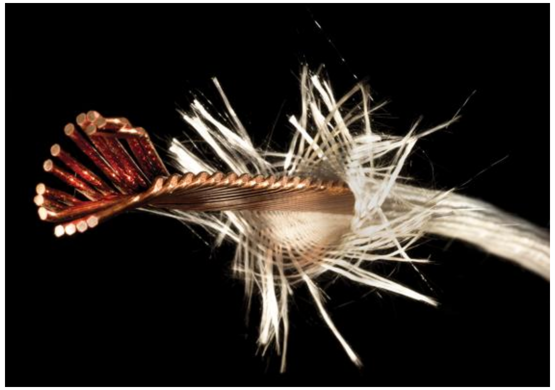
Wire reception tests



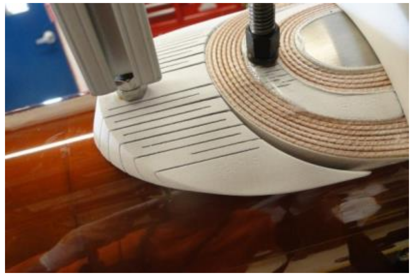
Cable manufacturing and reception tests



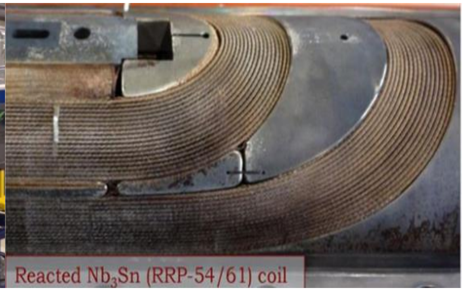
Cable insulation



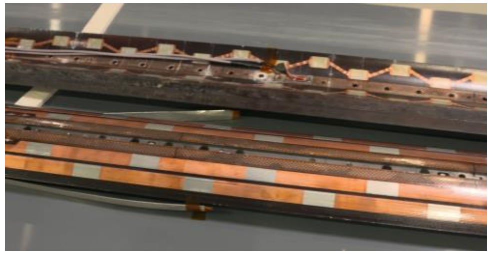
Coil winding



Coil reaction

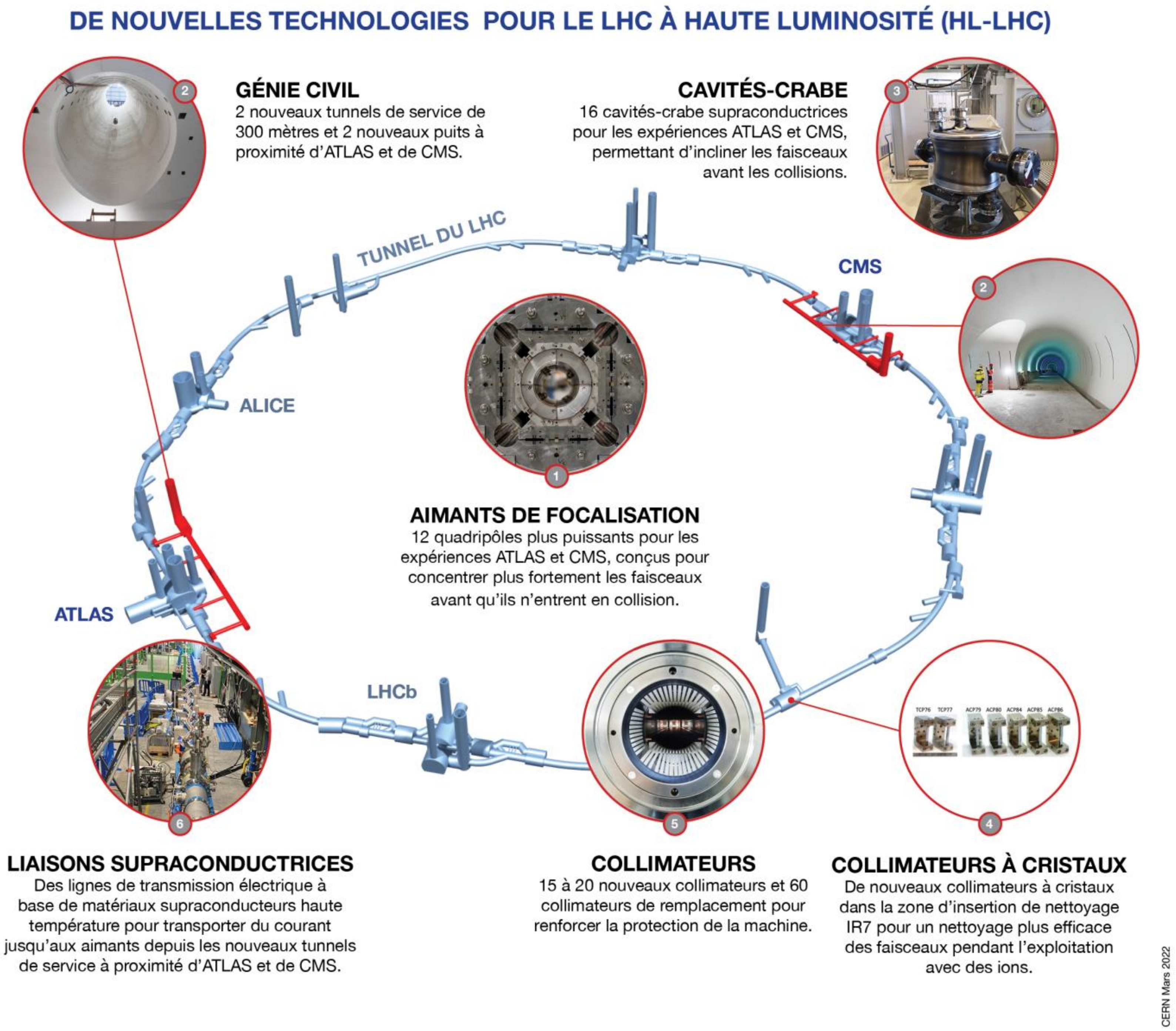


Impregnation



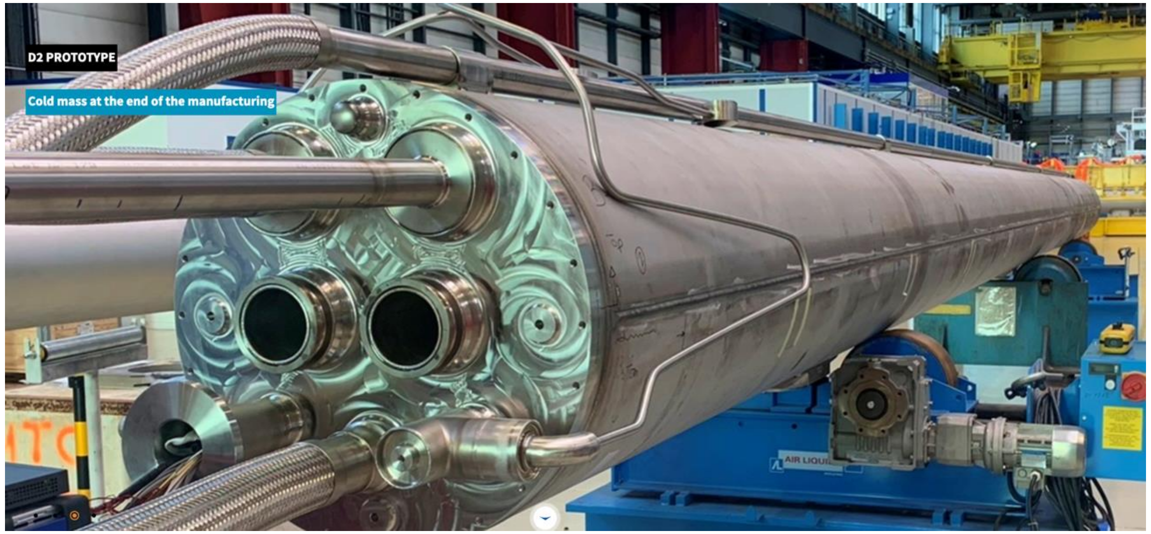
Collaring

Cold mass assembly

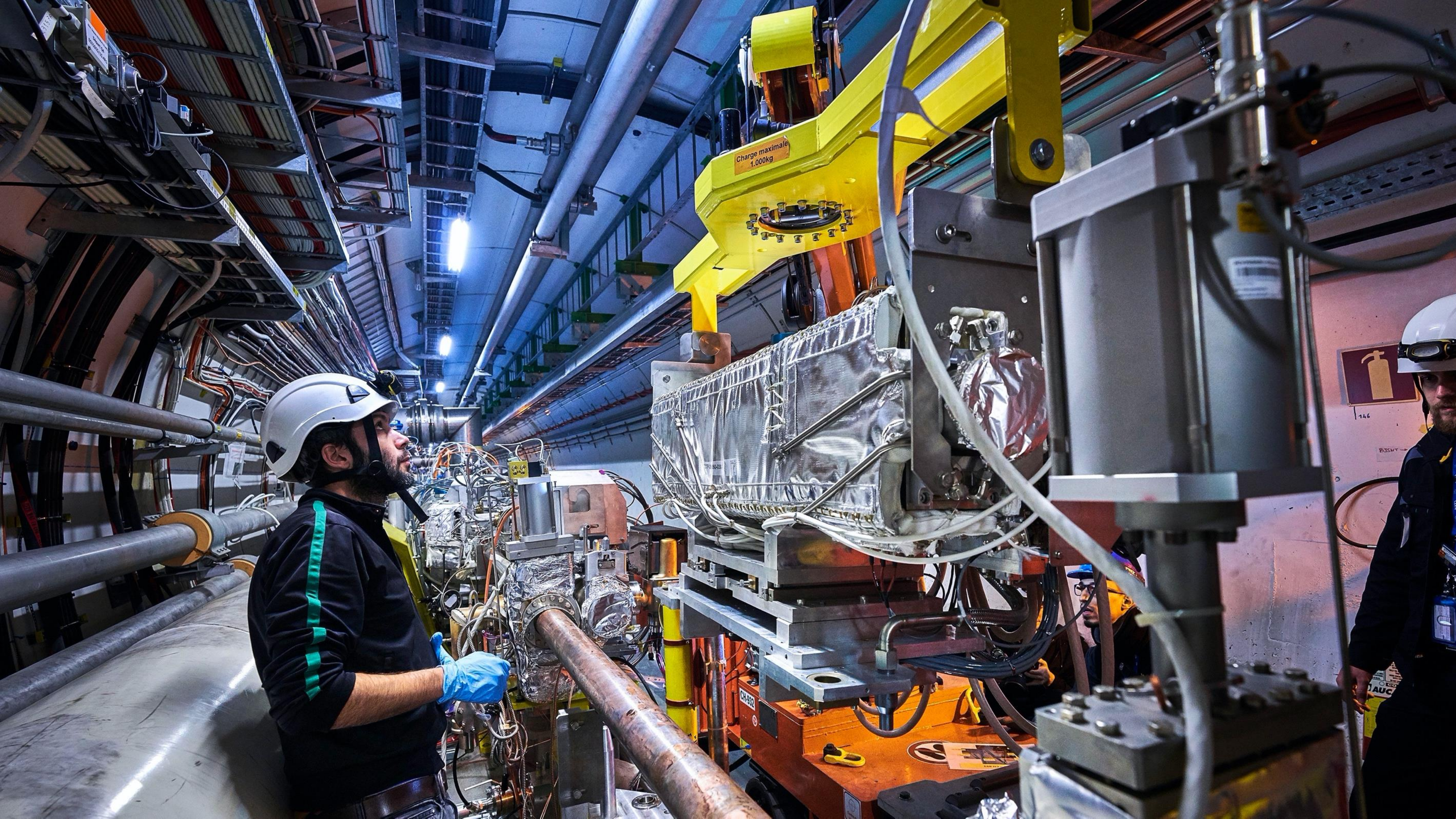

DE NOUVELLES TECHNOLOGIES POUR LE LHC À HAUTE LUMINOSITÉ (HL-LHC)
GÉNIE CIVIL
2 nouveaux tunnels de service de 300 mètres et 2 nouveaux puits à proximité d'ATLAS et de CMS.
CAVITÉS-CRABE
16 cavités-crabe supraconductrices pour les expériences ATLAS et CMS, permettant d'incliner les faisceaux avant les collisions.
TUNNEL DU LHC
CMS
ALICE
AIMANTS DE FOCALISATION
12 quadripôles plus puissants pour les expériences ATLAS et CMS, conçus pour concentrer plus fortement les faisceaux avant qu'ils n'entrent en collision.
ATLAS
LHCb
1
2
3
4
5
6
LIAISONS SUPRACONDUCTRICES
Des lignes de transmission électrique à base de matériaux supraconducteurs haute température pour transporter du courant jusqu'aux aimants depuis les nouveaux tunnels de service à proximité d'ATLAS et de CMS.
COLLIMATEURS
15 à 20 nouveaux collimateurs et 60 collimateurs de remplacement pour renforcer la protection de la machine.
COLLIMATEURS À CRISTAUX
De nouveaux collimateurs à cristaux dans la zone d'insertion de nettoyage IR7 pour un nettoyage plus efficace des faisceaux pendant l'exploitation avec des ions.
CERN Mars 2022

June 2022: MQXFBP2 and corrector MCBXFBP1 on the alignment bench

Separation/re-combination dipole (D2 - INFN) cold mass assembly – Large Magnet Facility



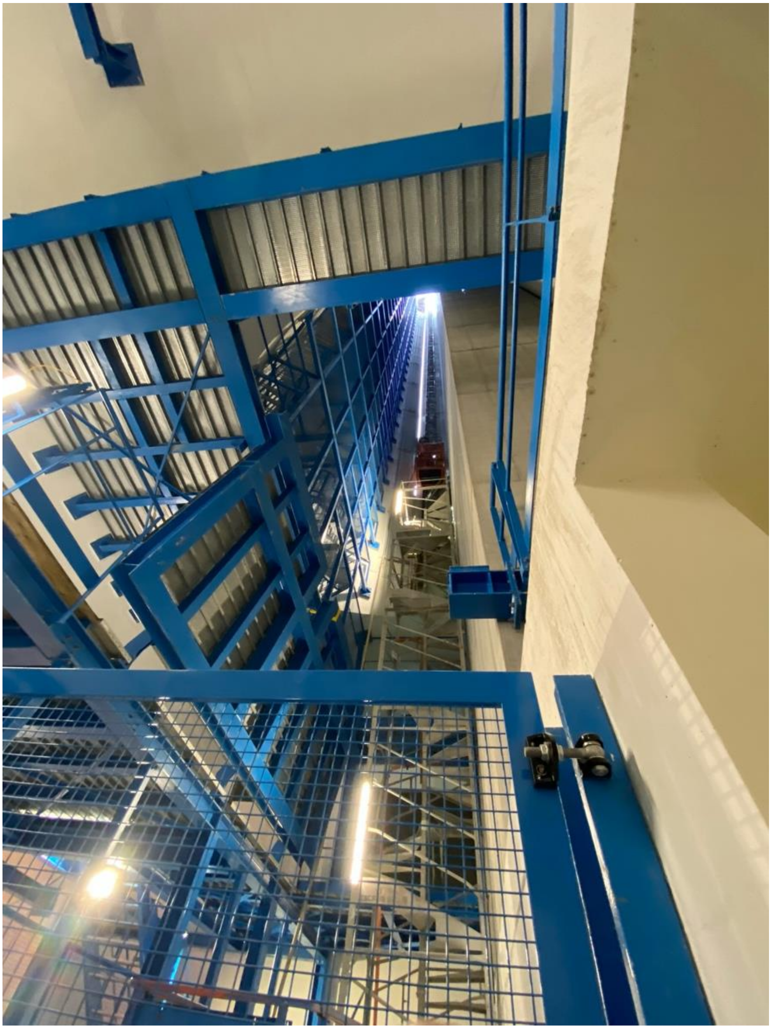

TRATOS
PROPERTY OF
Wooding


Charge maximale
1.000kg

CRANEbot will handle a VAX module without the need for human intervention.

Point 1 surface buildings

Underground works at P5



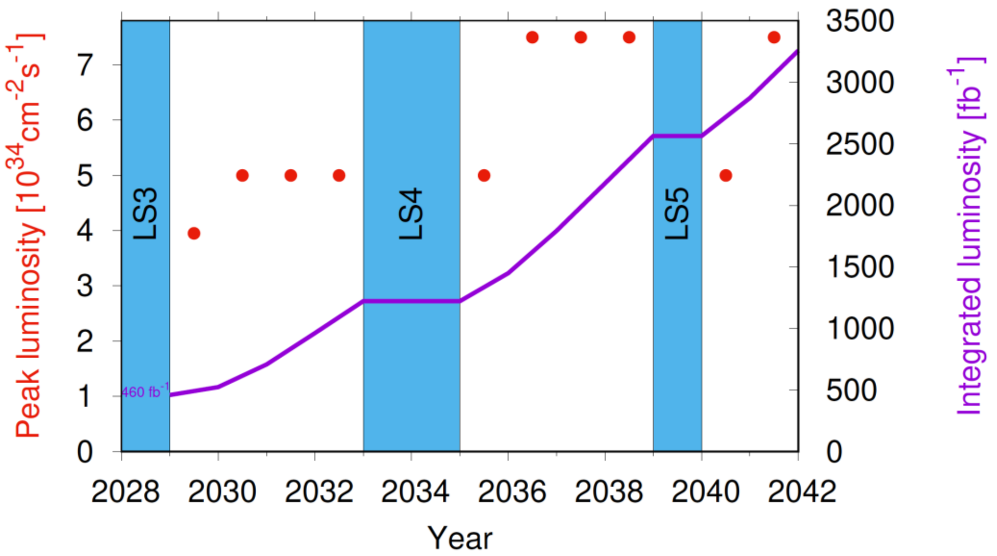
US57 cavern

PM57 shaft

UR55 gallery

Then another miracle happens…

Year	ppb [10^{11}]	Virtual lumi. [10^{34}cm^{-2}s^{-1}]	Days in physics	θ [μrad]	β^*_{start} [cm]	β^*_{end} [cm]	CC	Max. PU
2029	1.8	4.4	90	380	70	30	exp	116
2030	2.2	9.7	120	500	100	30	on	132
2031	2.2	11.3	160	500	100	25	on	132
2032	2.2	13.5	160	500	100	20	on	132
2033-34	Long shutdown 4							
2035	2.2	13.5	140	500	100	20	on	132
2036	2.2	16.9	170	500	100	15	on	132
2036	2.2	16.9	200	500	100	15	on	200



Conclusions

Run 1 & 2 legacy

- Complex operations well mastered
- Excellent system performance and availability

Run 3

- First Stable Beams at 16:00 tomorrow…

LHC Injectors Upgrade

- Successful deployment in LS2, essential for what follows

HL-LHC

- Paving the way from Run 3 to Ultimate performance
- Completion of prototypes and start of series production for many components – interesting times!

Acknowledgements and thanks to everyone in ATS, our colleagues from across the organization, and our international collaborators.


WE FOUND A NEW PARTICLE