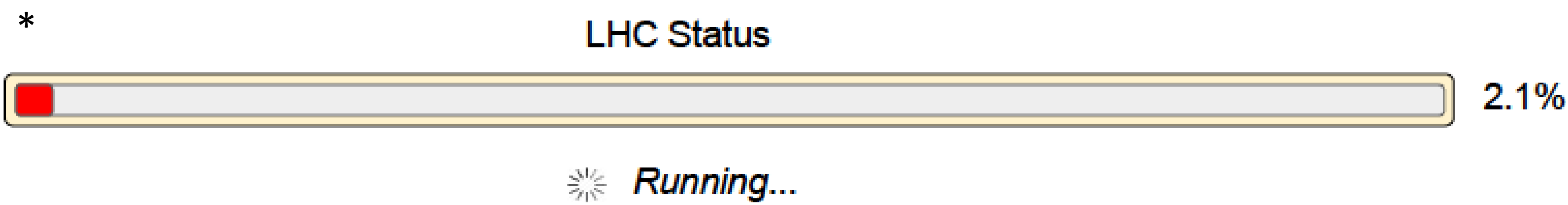
# The LHC
# and preparations for HL-LHC

Mike Lamont for the LHC team

Annual meeting of the Institute of Physics
Particle Accelerators and Beams Group

7th April 2017

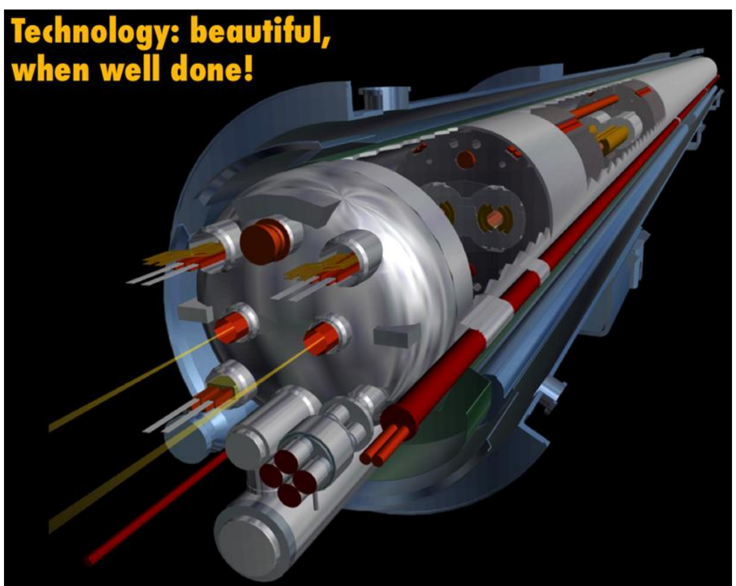
*

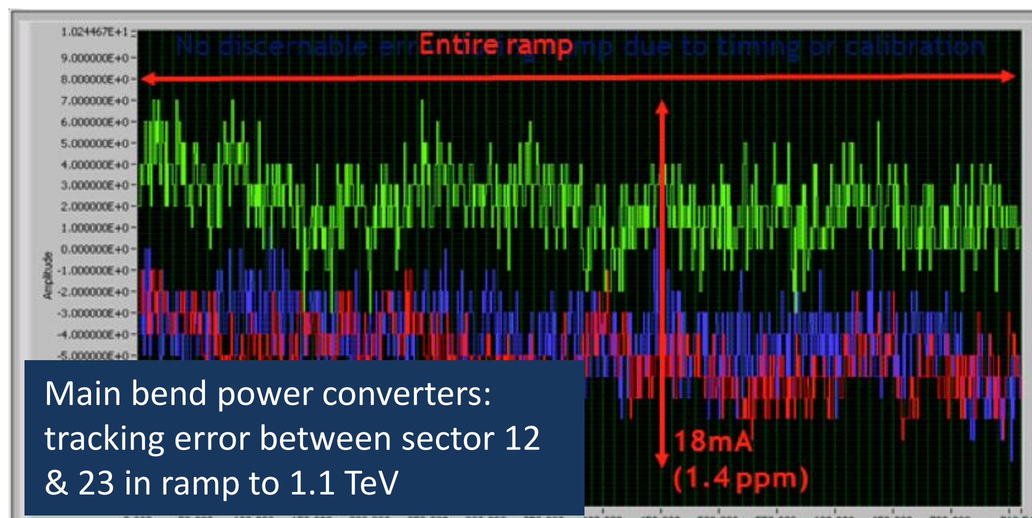



*c/o Joel Butler Aspen March 17

# Exit Run 1(2010 – 2012)

- Foundations well proven at 4 TeV
  - Magnets, vacuum, cryogenics, RF, powering, instrumentation, collimation, beam dumps etc.
- Huge amount of experience gained
  - Operations, optics, collimation…
- Healthy respect for machine protection




Main bend power converters: tracking error between sector 12 & 23 in ramp to 1.1 TeV

# 2013 - 2015

April ‘13 to Sep. ‘14

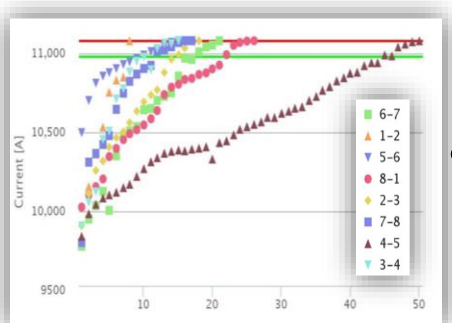

5th April


3rd June
First Stable Beams

28th October
Physics with record number of bunches
Peak luminosity 5 x $10^{33}$ $cm^{-2}s^{-1}$



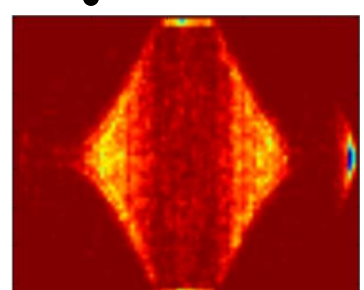
| 13-14 | Aug 14-Apr 15 | 2015 |
|---|---|---|



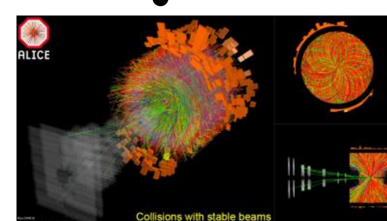

Dipole training campaign

10th April
Beam at 6.5 TeV

Struggle



IONS




**Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV**

# LHC 2016

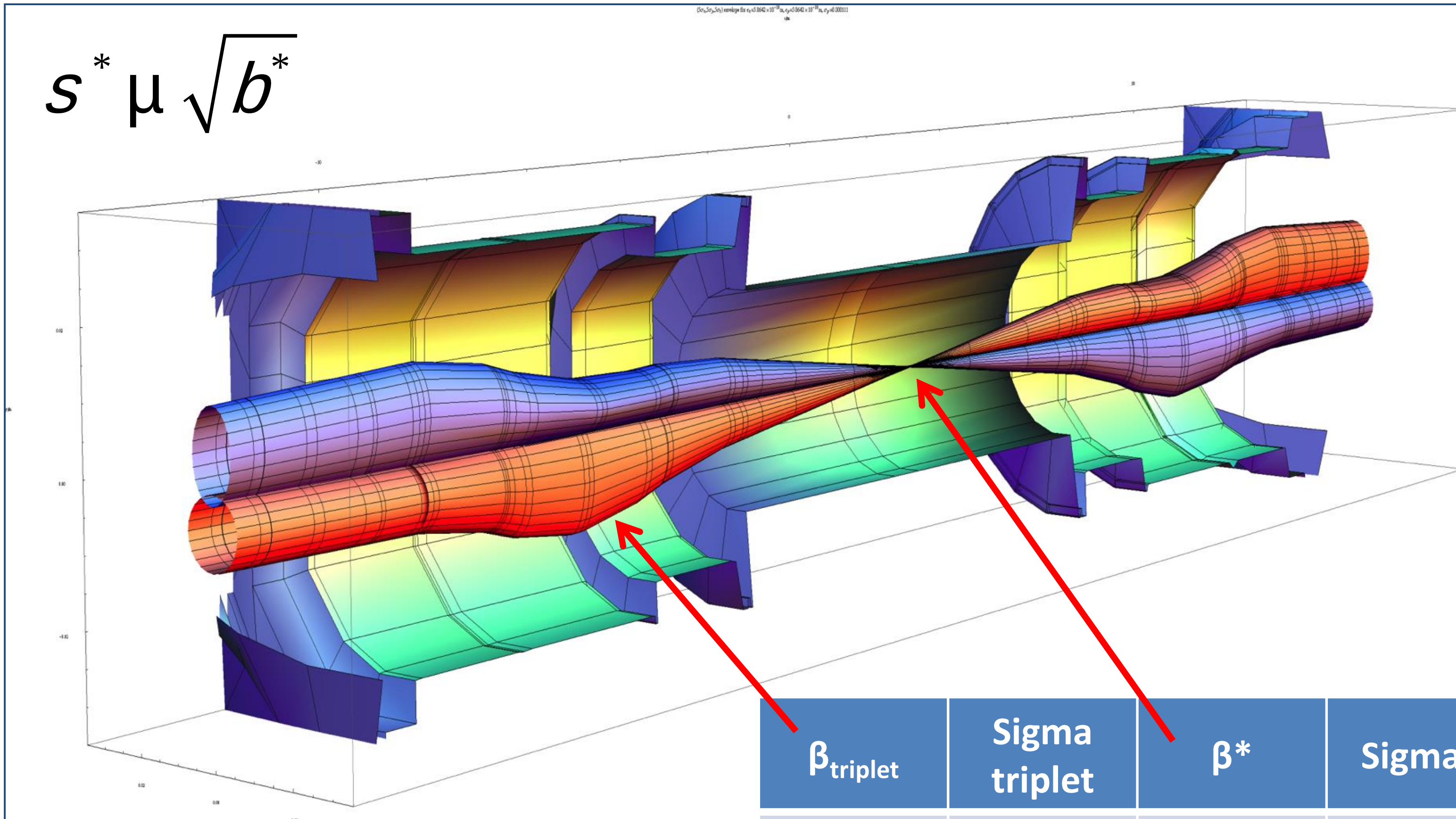
**Choose a relatively bold set of operational parameters based on past experience**

- Energy: 6.5 TeV
- 25 ns beam - nominal bunch population (~1.2e11)
- Low emittance from injectors – variations possible
- Squeeze harder in ATLAS and CMS
  - **beta* = 40 cm**
  - cf. 80 cm in 2015
  - cf. 55 cm design

$$\mathcal{L} \propto \frac{1}{\beta^*}$$

# Squeeze in ATLAS/CMS

- Lower beta* implies larger beams in the triplet magnets
- Larger beams implies a larger crossing angle
- Aperture concerns dictate caution – experience counts

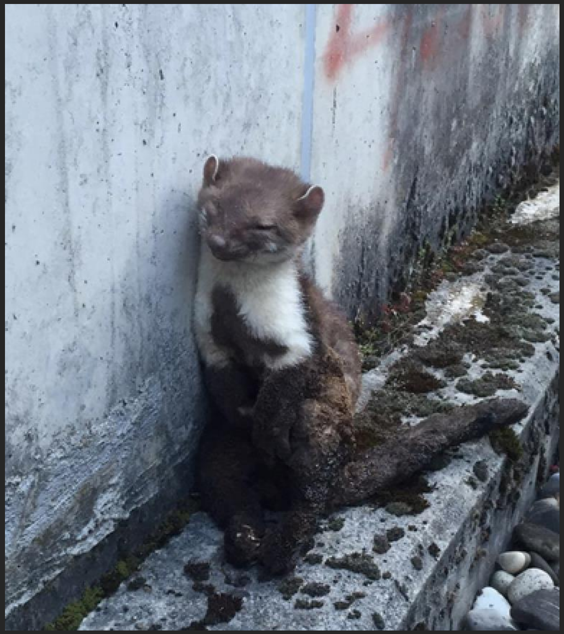



| $\beta_{triplet}$ | Sigma triplet | β* | Sigma* |
|---|---|---|---|
| ~4.5 km | 1.5 mm | 40 cm | 13 um |

Image courtesy John Jowett

# 2016 - overcome a few problems

**WEASEL**



**PS MAIN POWER SUPPLY**

**SPS BEAM DUMP**

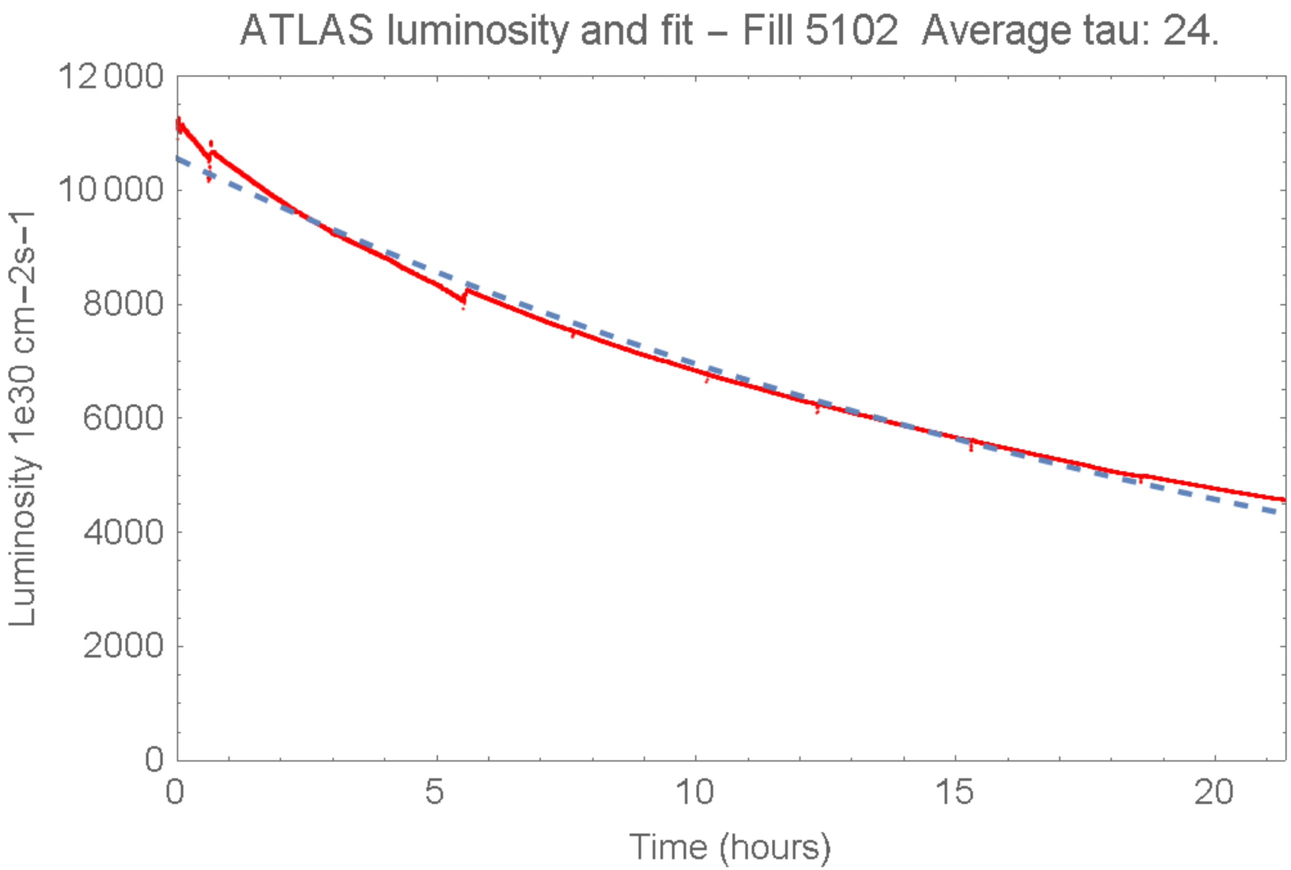
- **Limited to 96 bunches per injection in 2016**
- **2220 bunches per beam cf. 2750**

# Design luminosity reached



Reduced beta* and lower transverse beam sizes from the injectors compensating the lower number of bunches

# Luminosity lifetime

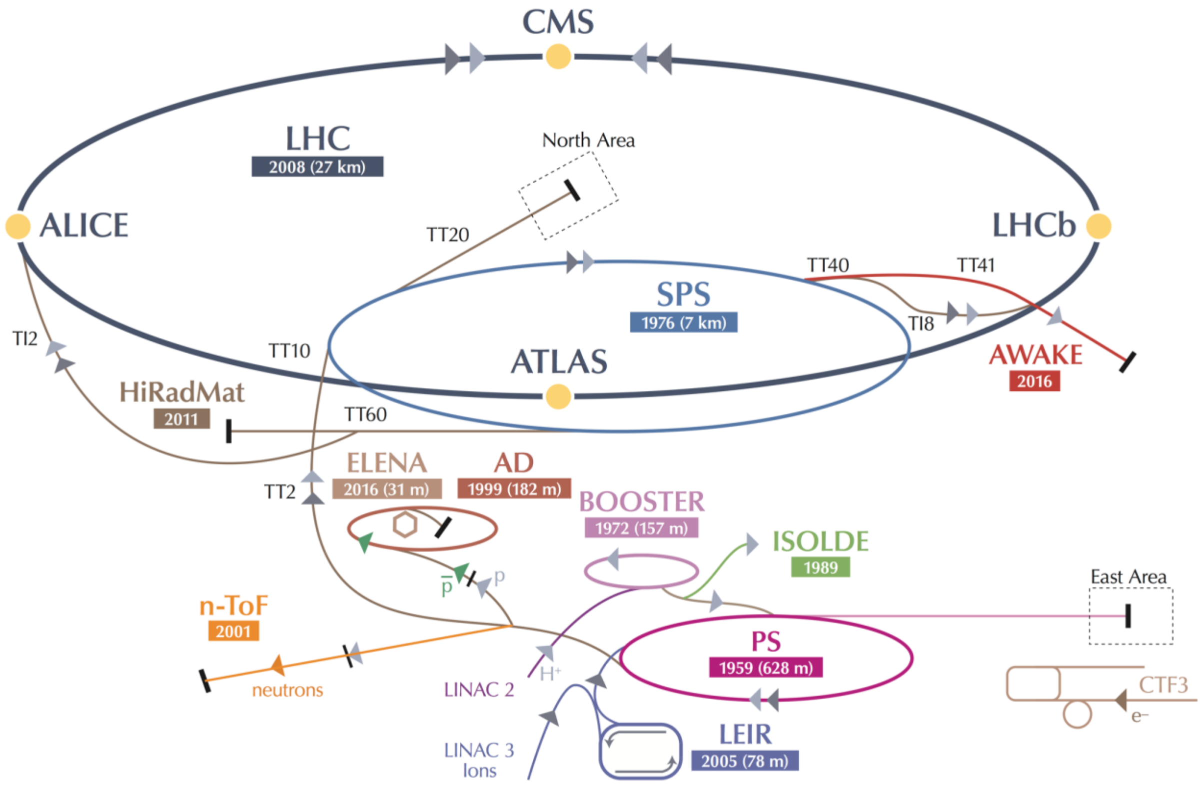



Excellent luminosity lifetime – main component - proton loss to inelastic collisions in ATLAS, CMS and LHCb

# An extra boost from the injectors

The LHC performance fully relies on the **performance of its injector complex**

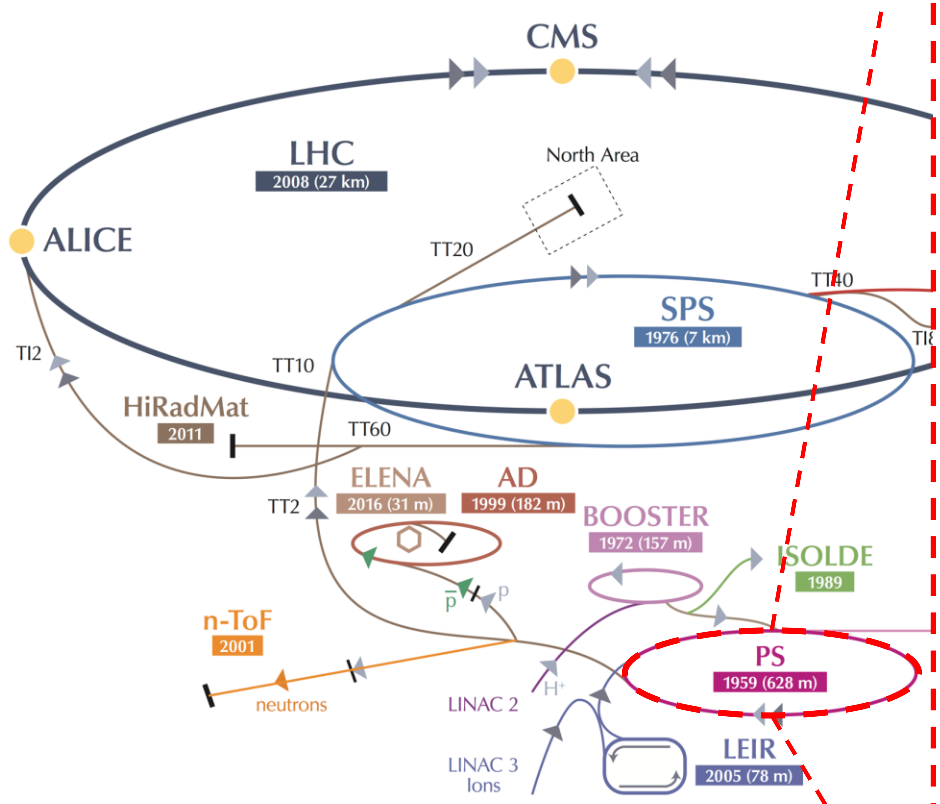
- By itself **one of the largest accelerator facilities in the world** with its own diverse and, for many aspects, unique physics program



# An extra boost from the injectors

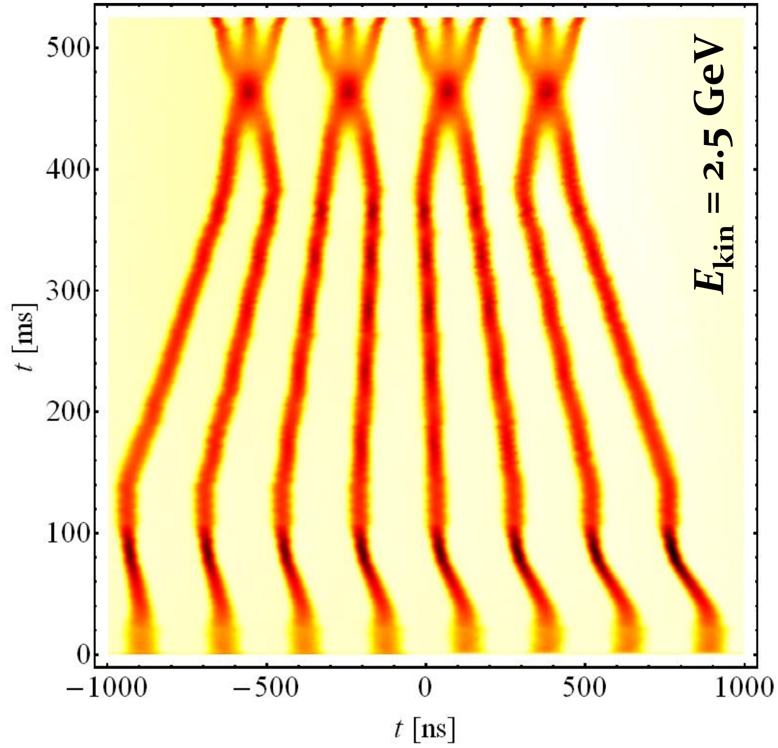
The LHC performance fully relies on the p

- By itself **one of the largest accelera** diverse and, for many aspects, uniqu

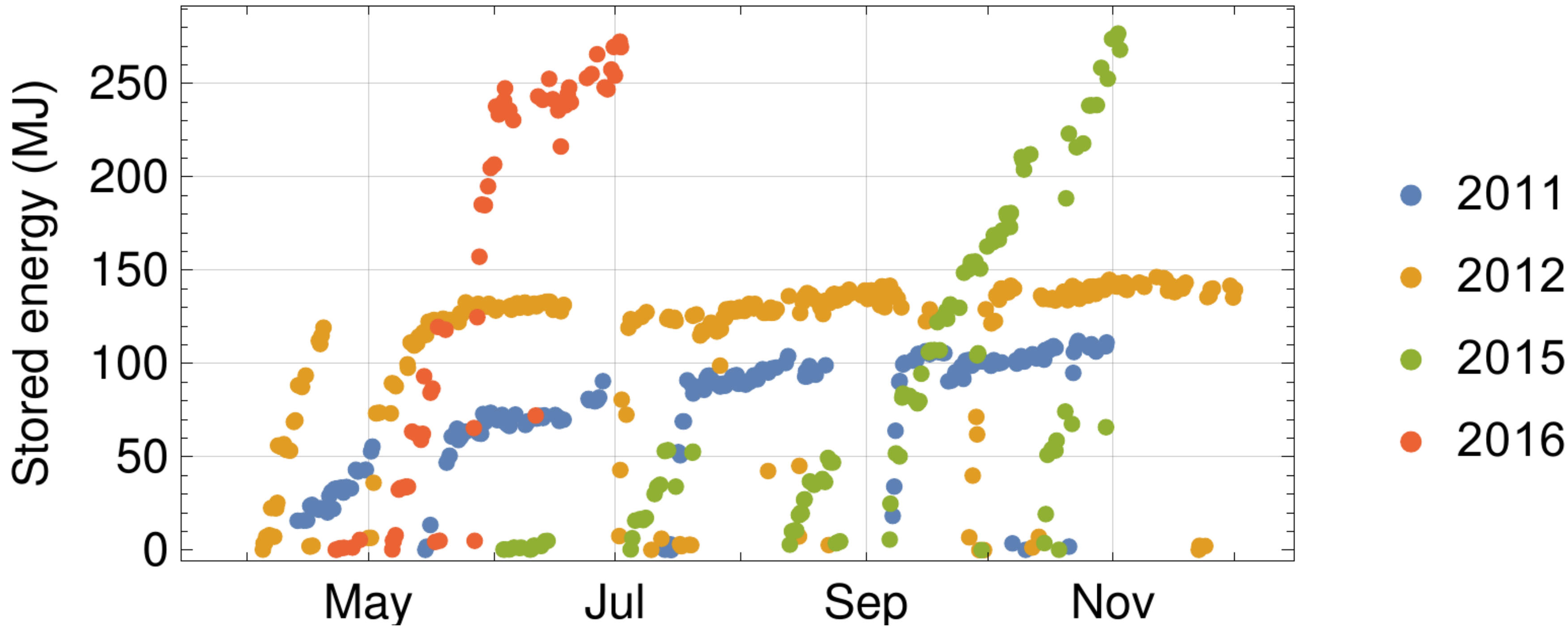



An **advanced production scheme** – the **"BCMS"** - was put in place in the PS

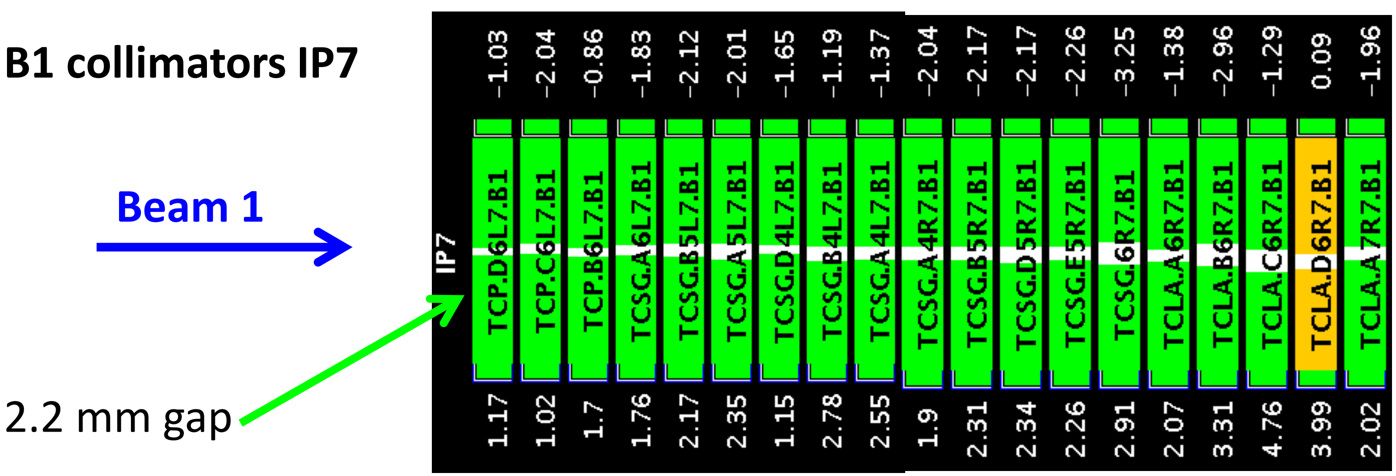
- RF cavities tuned at different frequencies play together to **compress, merge and split proton bunches**
- Beams **~30% brighter** than standard scheme



# Stored energy per beam



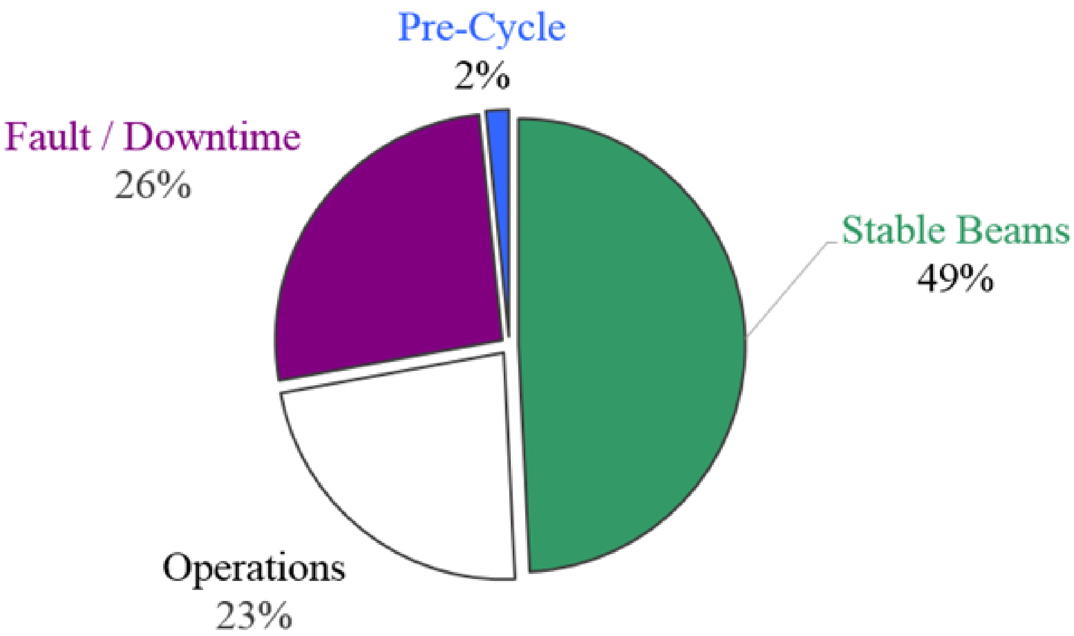

**B1 collimators IP7**



# p-p physics – machine availability

2016 was characterized by **unprecedented machine availability**:

- The machine was **available for operation 72% of the time** scheduled for physics
- Overall **Stable Beam efficiency of 49%** (to be compared to 36% in 2012, and 30% for the short production period in 2015)



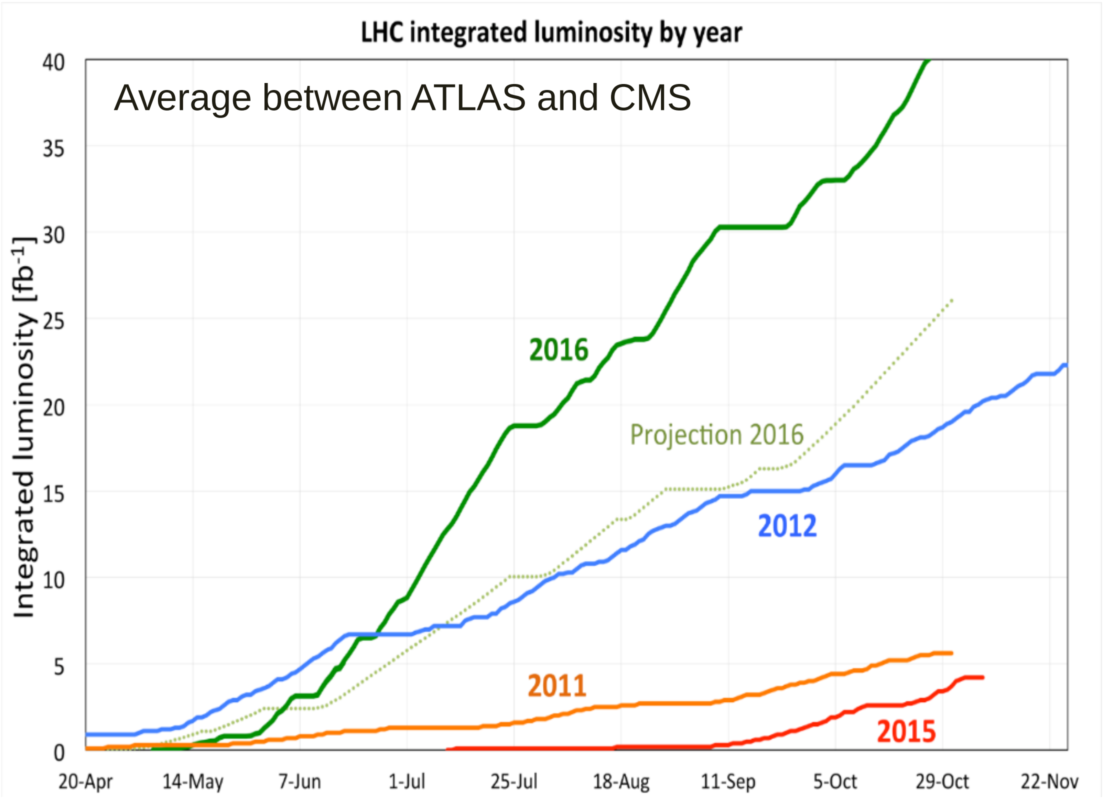

Possible thanks to:

- **Professionalism**, **commitment** and **attention to the details** from all the different **equipment groups**
- **Solid understanding** of the machine and beam behaviour
- Continuous effort in **fault and availability tracking**

# p-p physics – summing all up

Combination of high **peak performance** and excellent **machine availability**

→ quite impressive progression of the **integrated luminosity**



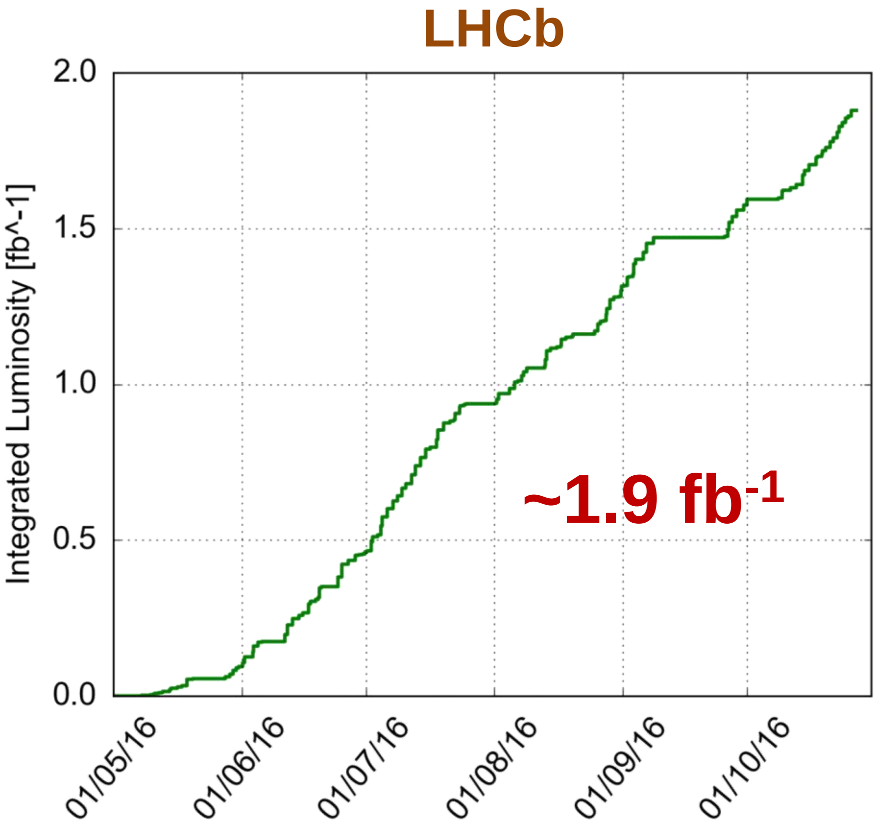

**~40 $fb^{-1}$**

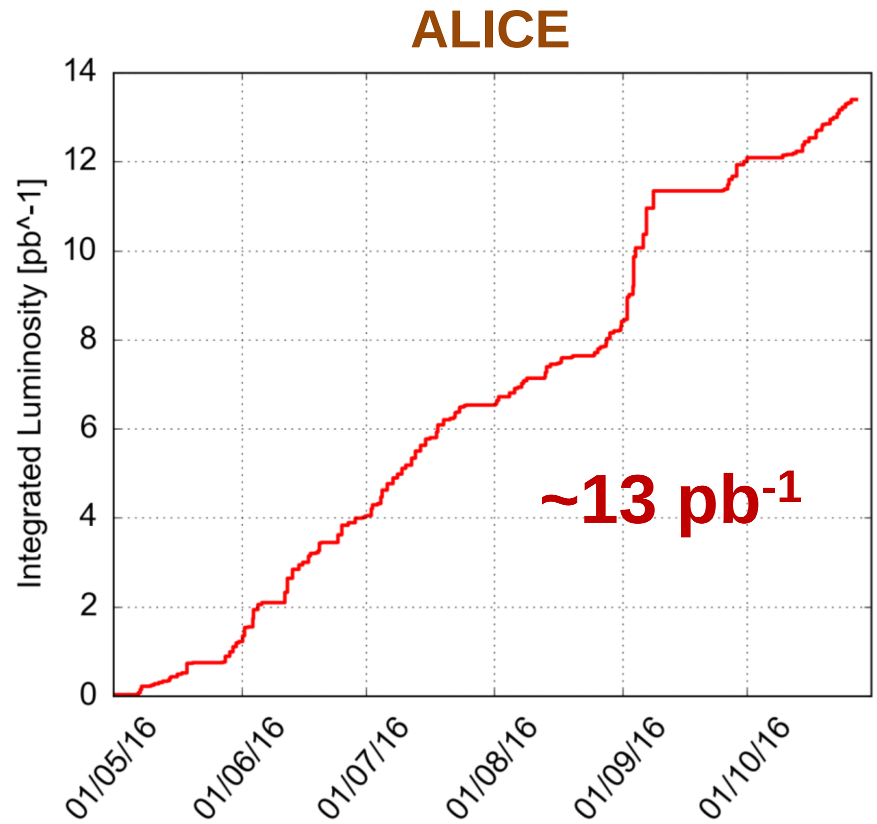
**for ATLAS and CMS**

(2016 target was 25 $fb^{-1}$!)

# p-p physics – ALICE and LHCb

… acquiring data with **luminosity levelled at their desired values** all along the p-p fills



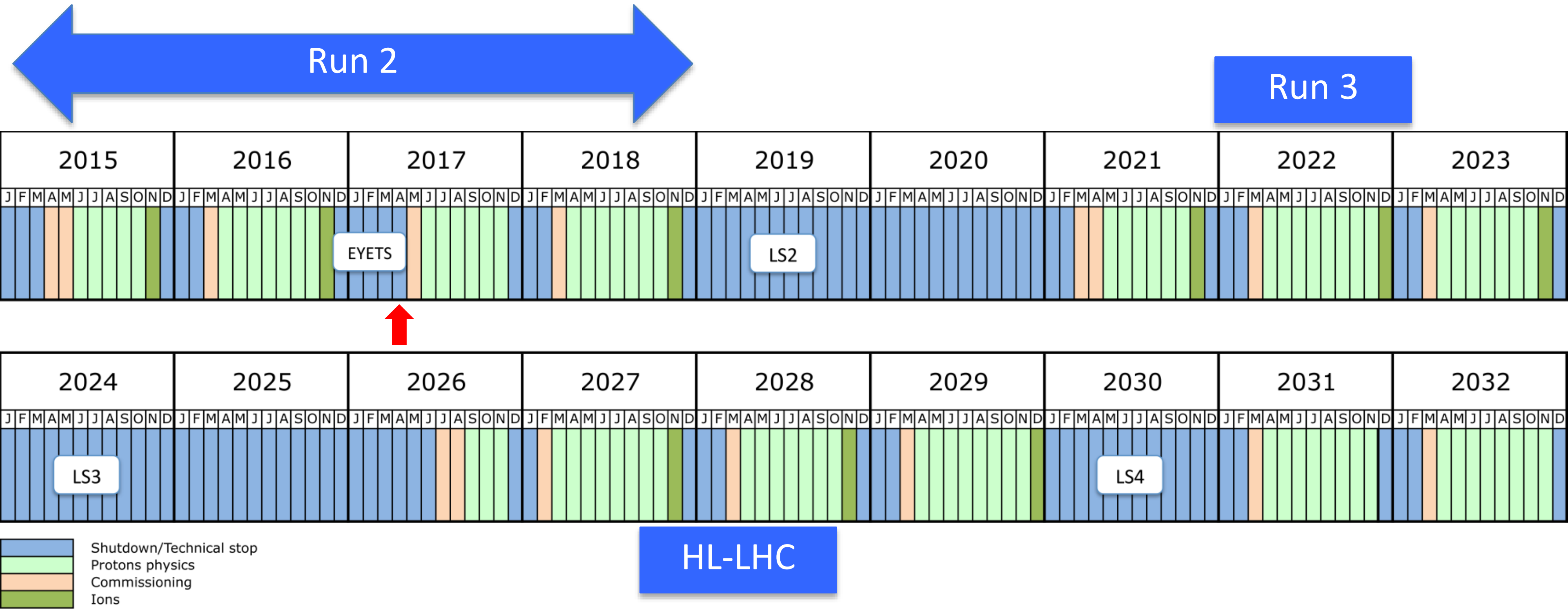
# Where are we? 1/2

- Mature performance of injectors
- Good operational efficiency and flexibility
- Remarkable reproducibility
- Good beam behaviour (with these intensities)
  - Stability
  - Transmission through the cycle
  - Luminosity lifetime
  - Emittance growth
- Continue to worry about electron cloud

# Where are we? 2/2

- Excellent availability in 2016 – it can be done
- Mature system performance
  - Quench protection, RF, Cryogenics, transverse damper, Power converters, Collimation, instrumentation, Controls, beam dump system, injection….
  - Improved functionality, diagnostics, understanding
- Premature dumps significantly reduced
  - UFOs, Radiation to electronics
- Machine protection
  - excellent as always

# Schedule




- EYETS – Extended Year End Technical Stop – CMS pixel upgrade
- Pb-Pb end 2018
- Considerable special physics runs to be slotted in (90 m, 5 TeV pp, low energy high beta*…)

# Run 2 - objectives

- Deliver 100-120 $fb^{-1}$ to GPDs, keep ALICE, LHCb, TOTEM, ALFA, AFP happy
- Keep pushing performance and availability
- Look forward to HL-LHC without compromising present performance:
  - Optics (ATS), beta* levelling, LRBB compensation, RF full de-tuning, electron cloud…
- Look forward to the post-LS2 LIU era and how to exploit the potential
- Prepare for 7 TeV operation (but don't go there)

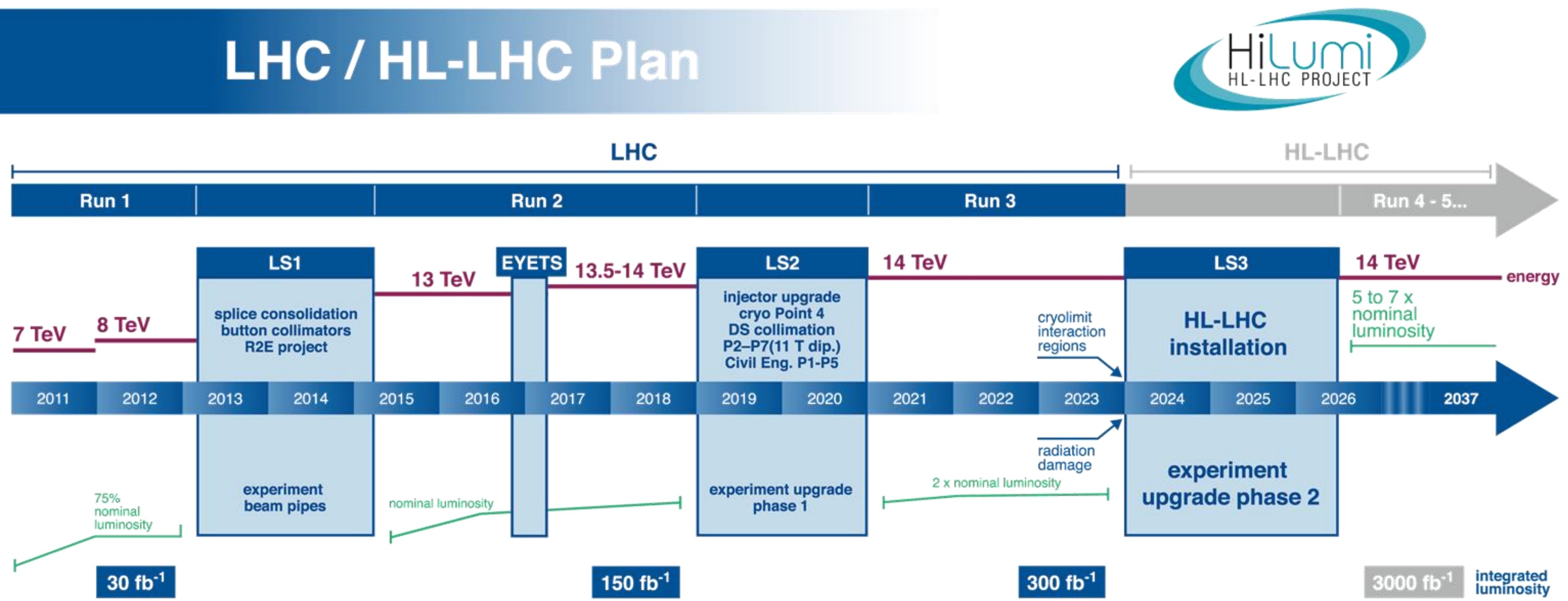
# 2017

- Another production year
  - Late start – no ions
  - **Target 45 $fb^{-1}$** to ATLAS & CMS at 6.5 TeV
- Machine configuration
  - Deploy HL-LHC optics
  - Start with beta* = 40 cm, maybe 33 cm later
  - 25 ns BCMS nominal bunch intensity
  - 2016 hardware issues resolved
  - Max. luminosity ~1.75 x $10^{34}$ $cm^{-2}s^{-1}$ – limit cooling capacity of inner triplets

**Continue to wrestle with electron cloud**

# HL-LHC - goals

- Prepare machine for operation beyond 2025 and up to ~2035
- Operation scenarios for:
  - total integrated luminosity of 3000 $fb^{-1}$ in around 10-12 years
  - an integrated luminosity of ~250 $fb^{-1}$ per year
  - mu ≤ 140 (peak luminosity of $\sim 5 \times 10^{34}\ cm^{-2}s^{-1}$)



# HL-LHC - how?

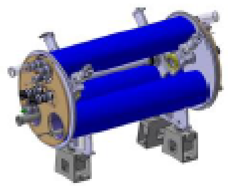
- **Lower beta* (~20 cm)**
  - New inner triplet magnets - wide aperture $Nb_3Sn$
  - Large aperture NbTi separator magnets
  - Novel optics solutions
- **Crossing angle compensation**
  - Crab cavities, long-range beam-beam compensation
- **Dealing with the regime**
  - Collision debris, high radiation
- **Beam from injectors**
  - High bunch population, low emittance, 25 ns beam

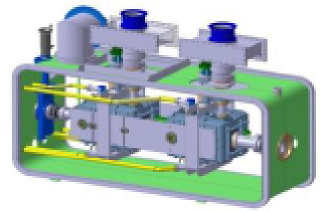
# HL-LHC: key 25 ns parameters

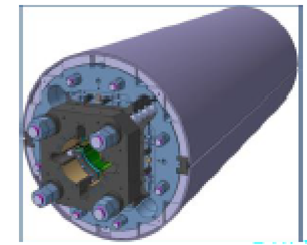
| | |
|---|---|
| Protons per bunch | $2.2 \times 10^{11}$ |
| Number of bunches | 2748 |
| Normalized emittance | 2.5 micron |
| Beta* | 20 cm |
| Crossing angle | 510 microrad |
| Geometric reduction factor | 0.369 |
| Levelled luminosity | $5.32 \times 10^{34}$ $cm^{-2}s^{-1}$ |
| Levelled <pile-up> | 140 |

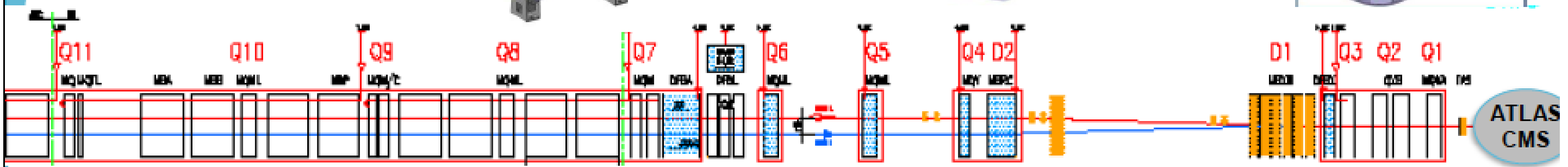
Other variations are considered (BCMS, 8b+4e)

# The largest HEP accelerator in construction










**Dispersion Suppressor (DS) in P7** | **Matching Section (MS)** | **Interaction Region (ITR)**

Modifications
1. In IP2: new DS collim. in C.Cryost.
2. In IP7 new DS collimation with 11 T

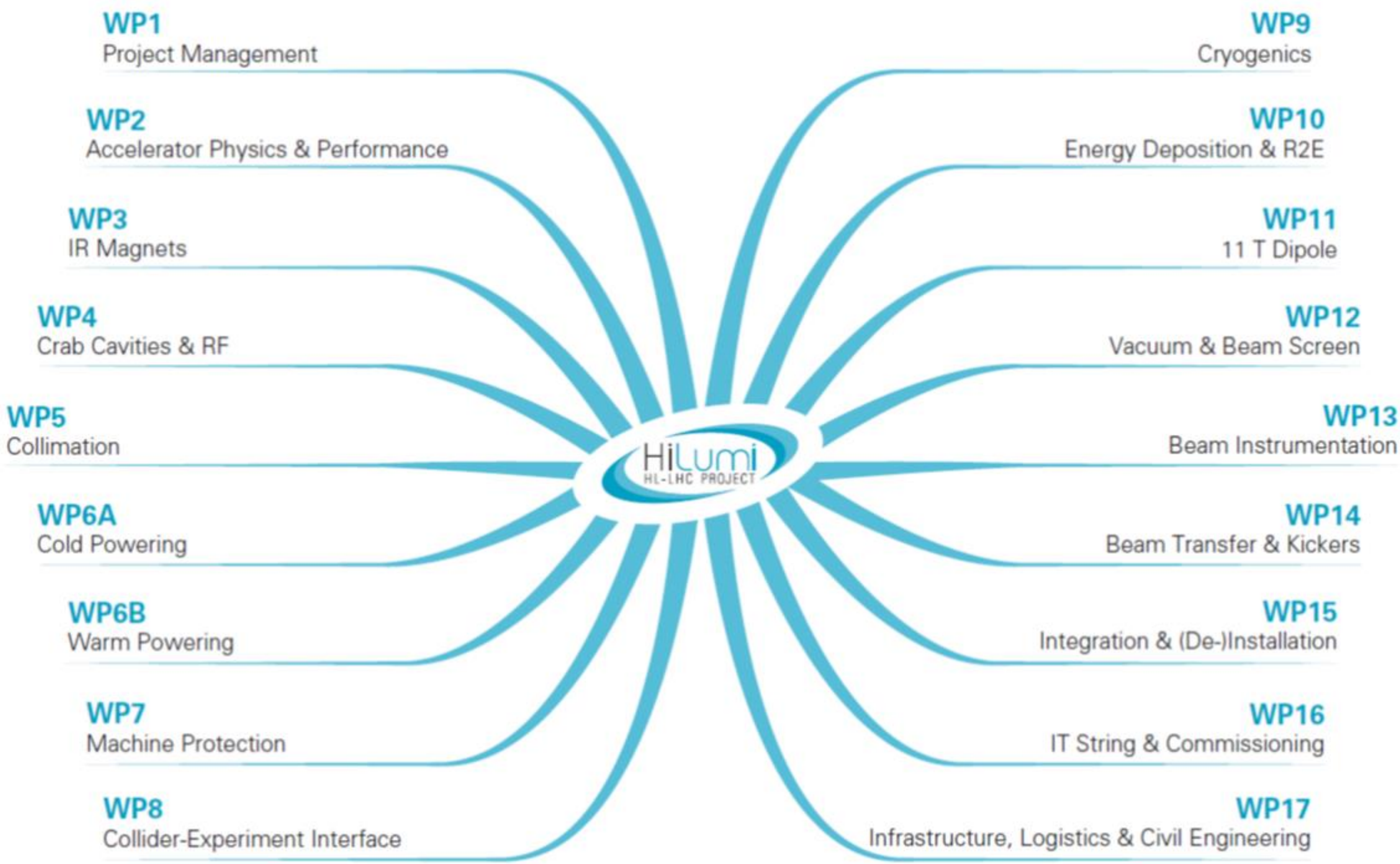
Cryogenics, Protection, Interface, Vacuum, Diagnostics, Inj/Extr, Controls, new UG and surface infrastr.

Change/new lay-out
1. TAXN
2. D2
3. CC
4. Q4
5. Correctors
6. Q5
7. Q5@1.9K in P6
8. New collimators

Complete change and new lay-out
1. TAXS
2. Q1-Q2a-Q2b-Q3
3. D1
4. All correctors
5. Heavy shielding (W)

**> 1.2 km of LHC !!**

# Project structure

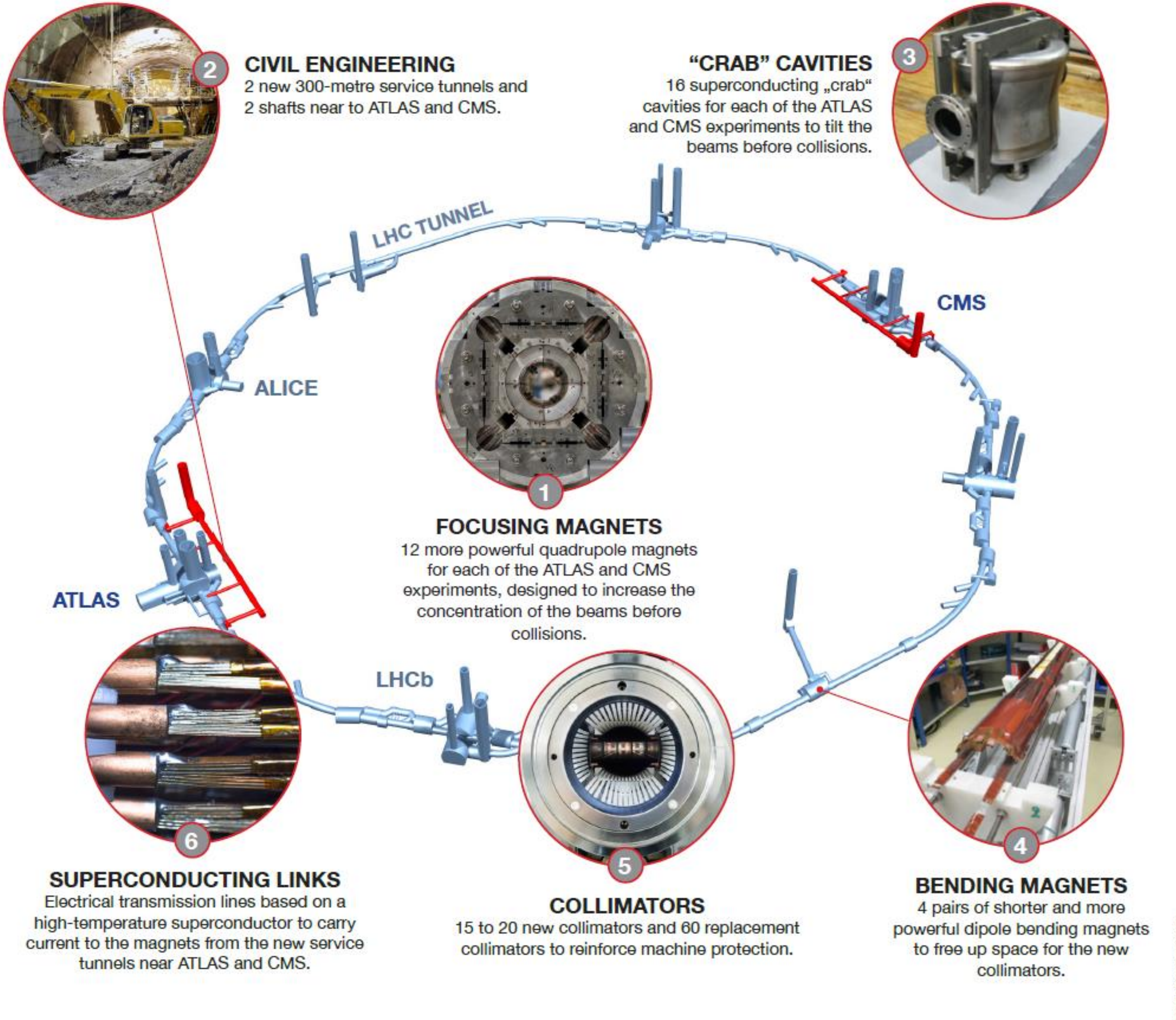


# Project status

- 2016 (June Council): formal approval of the entire HL-LHC project
- 2016 June-August: re-baseline of the project
- 2016 2nd Cost & Schedule Review with full endorsement of new baseline cost

Re-baseline:

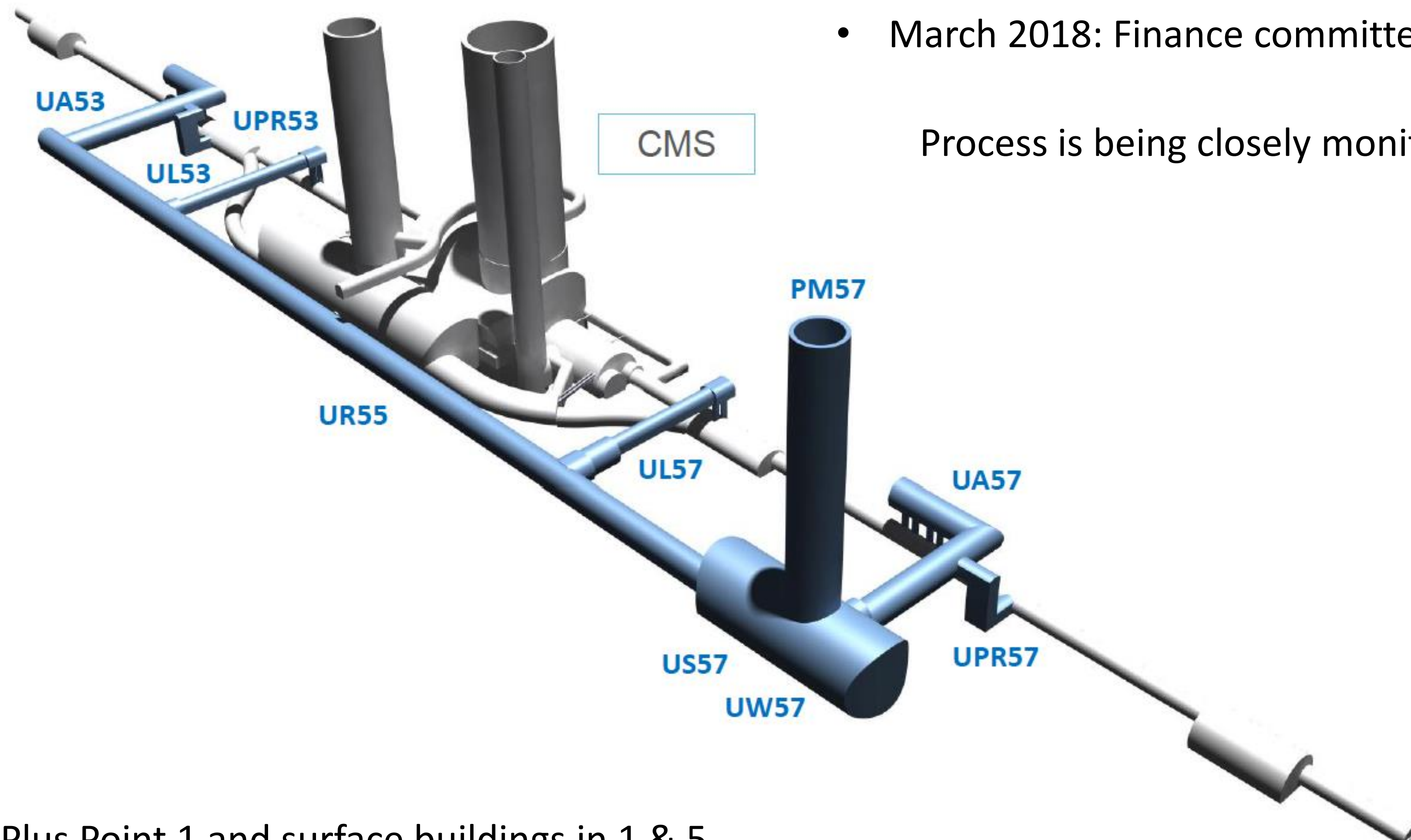
- Identification of the all possible savings, with reasonable impact on performance and availability, reducing the levels of redundancy/mitigations
- Keep reversibility (possibility to recovery the missed hardware later on)


CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near to ATLAS and CMS.
"CRAB" CAVITIES
16 superconducting „crab“ cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.
LHC TUNNEL
CMS
ALICE
FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.
ATLAS
LHCb
SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS.
COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.
BENDING MAGNETS
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.
1
2
3
4
5
6
CERN Novembre 2015

# One focus of attention at the moment: civil engineering contract

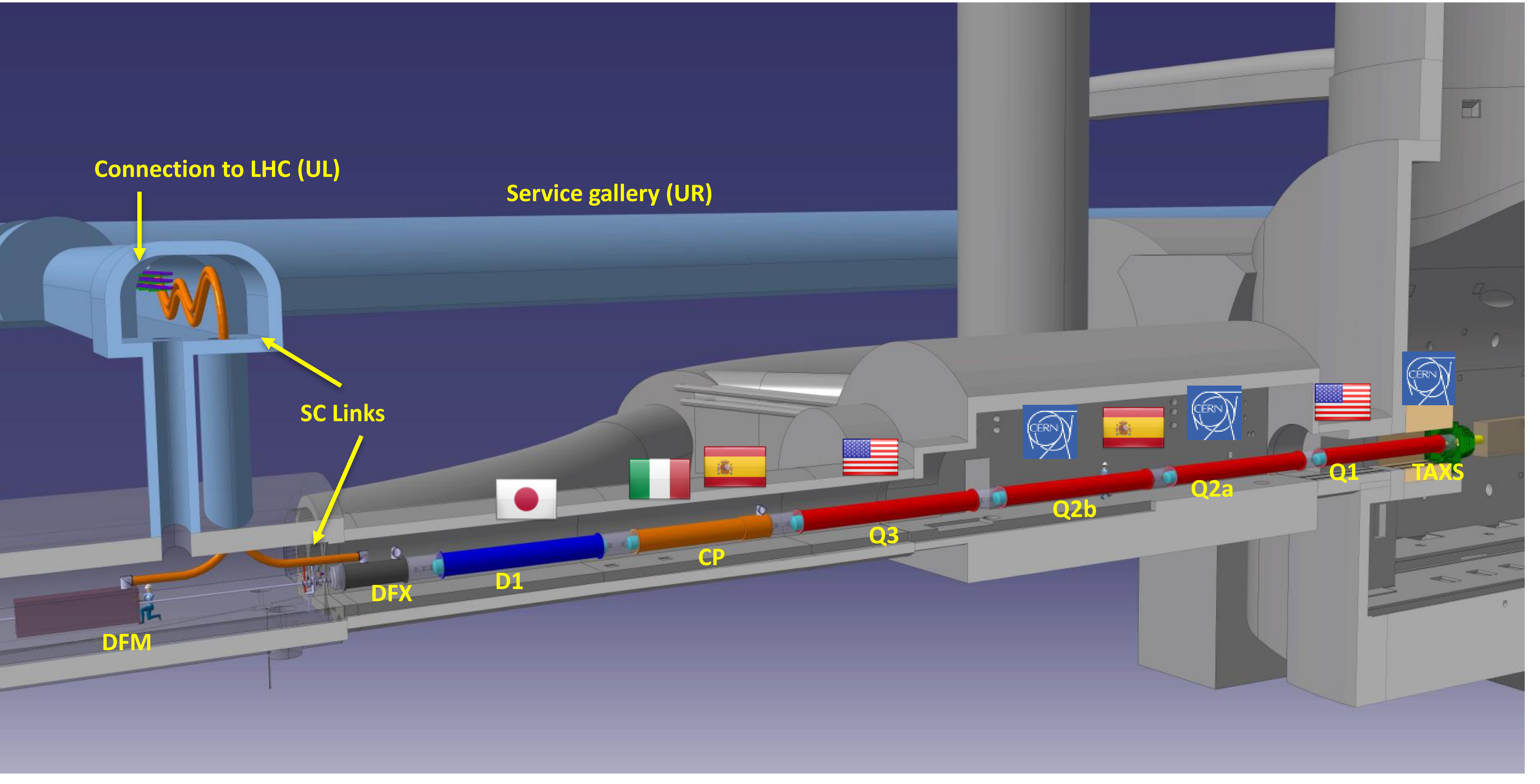
- 19 April: Market survey short list
- 30 June: Issue Invitation to tender
- March 2018: Finance committee

Process is being closely monitored!

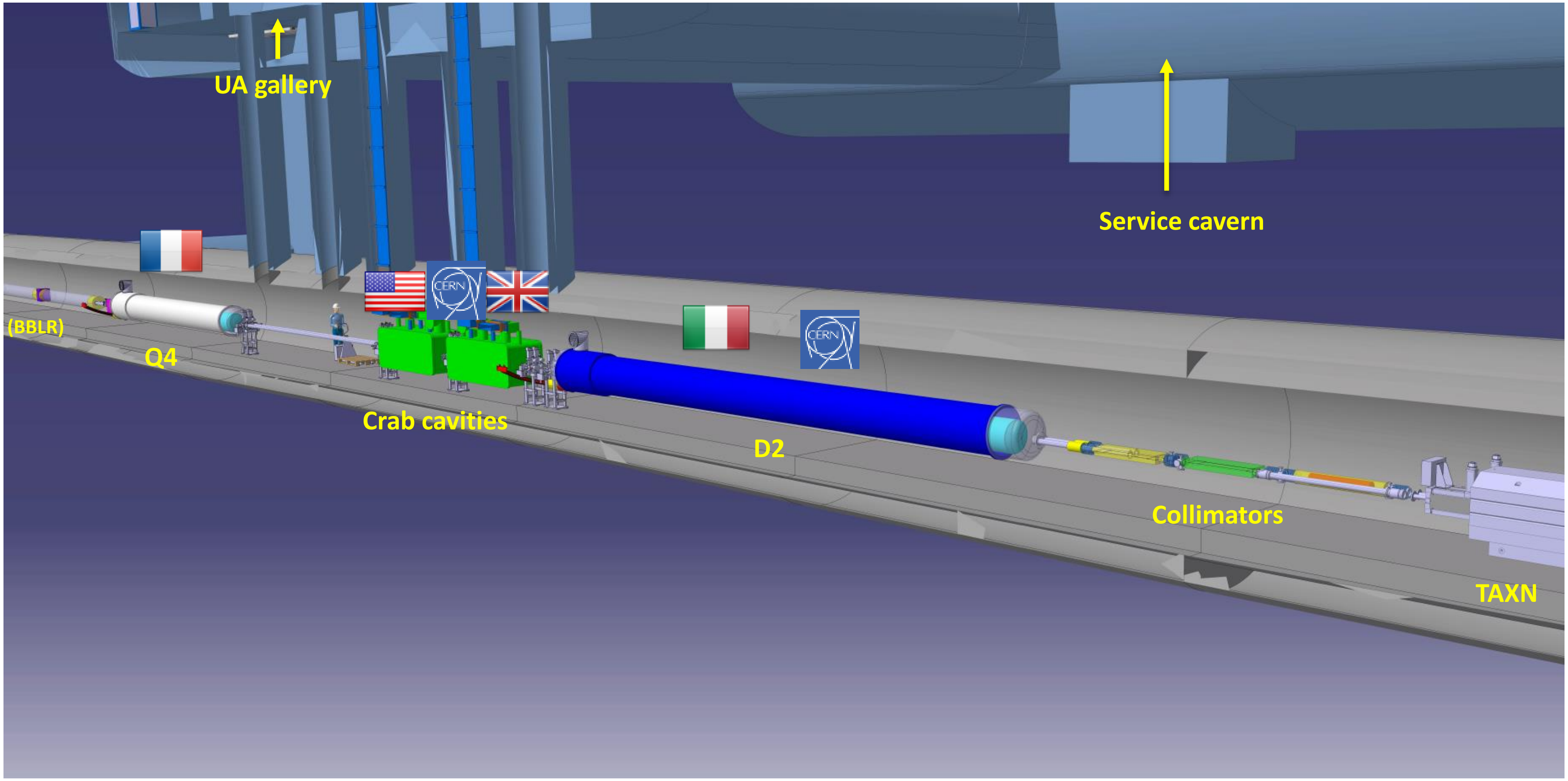



Plus Point 1 and surface buildings in 1 & 5

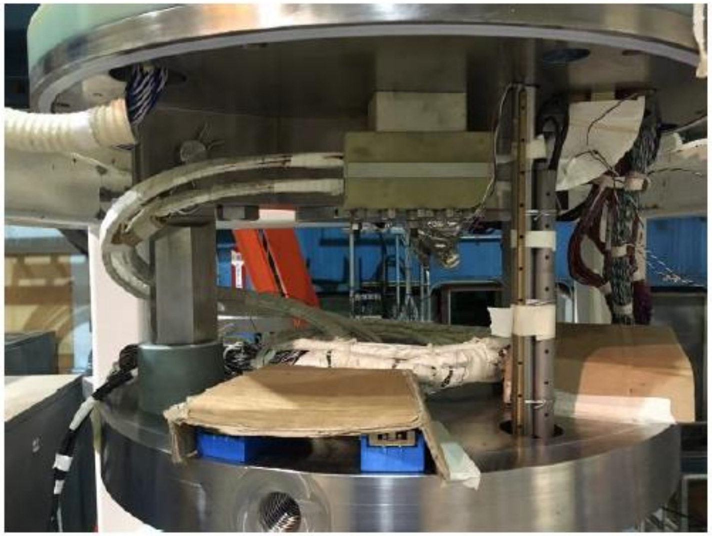
# The Inner Triplet region with in-kind



# The MS region with in-kinds

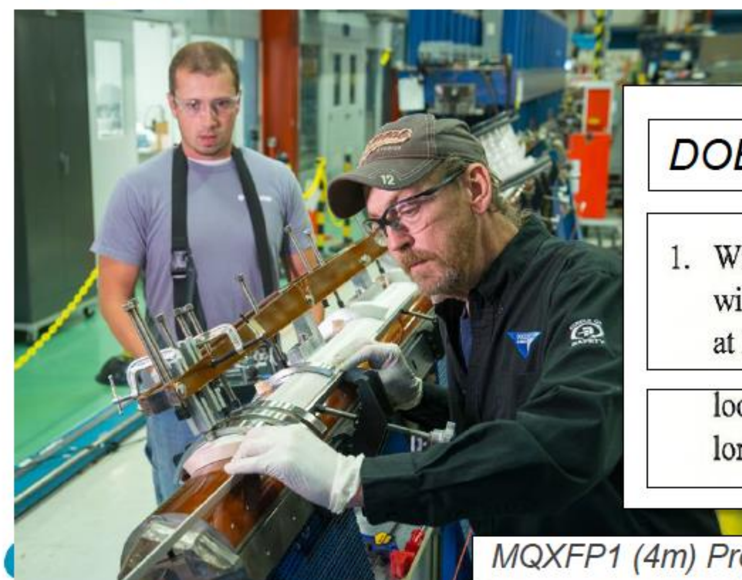


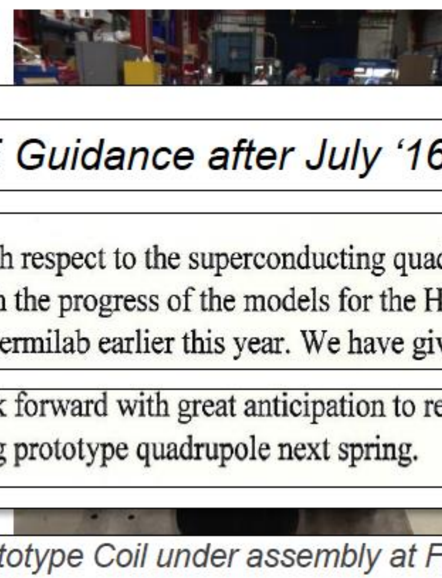
# Recent LARP Achievements – Magnets (2)

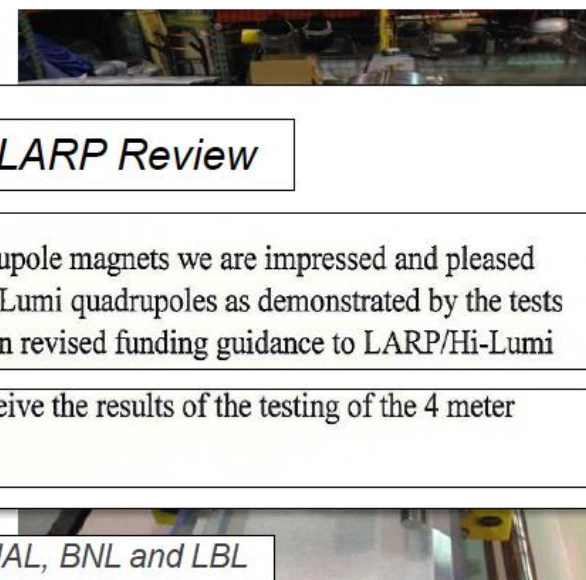



MQXFPM1 (4m) Coil in Mirror Configuration at BNL

- Two training quenches at 1.9K on Oct 31st 2016
  - Quench #1: 14.386 kA
  - Quench #2: 16.040 kA
    - Power supply failure at discharge of Quench #2.







*DOE Guidance after July '16 LARP Review*

1. With respect to the superconducting quadrupole magnets we are impressed and pleased with the progress of the models for the Hi-Lumi quadrupoles as demonstrated by the tests at Fermilab earlier this year. We have given revised funding guidance to LARP/Hi-Lumi

look forward with great anticipation to receive the results of the testing of the 4 meter long prototype quadrupole next spring.

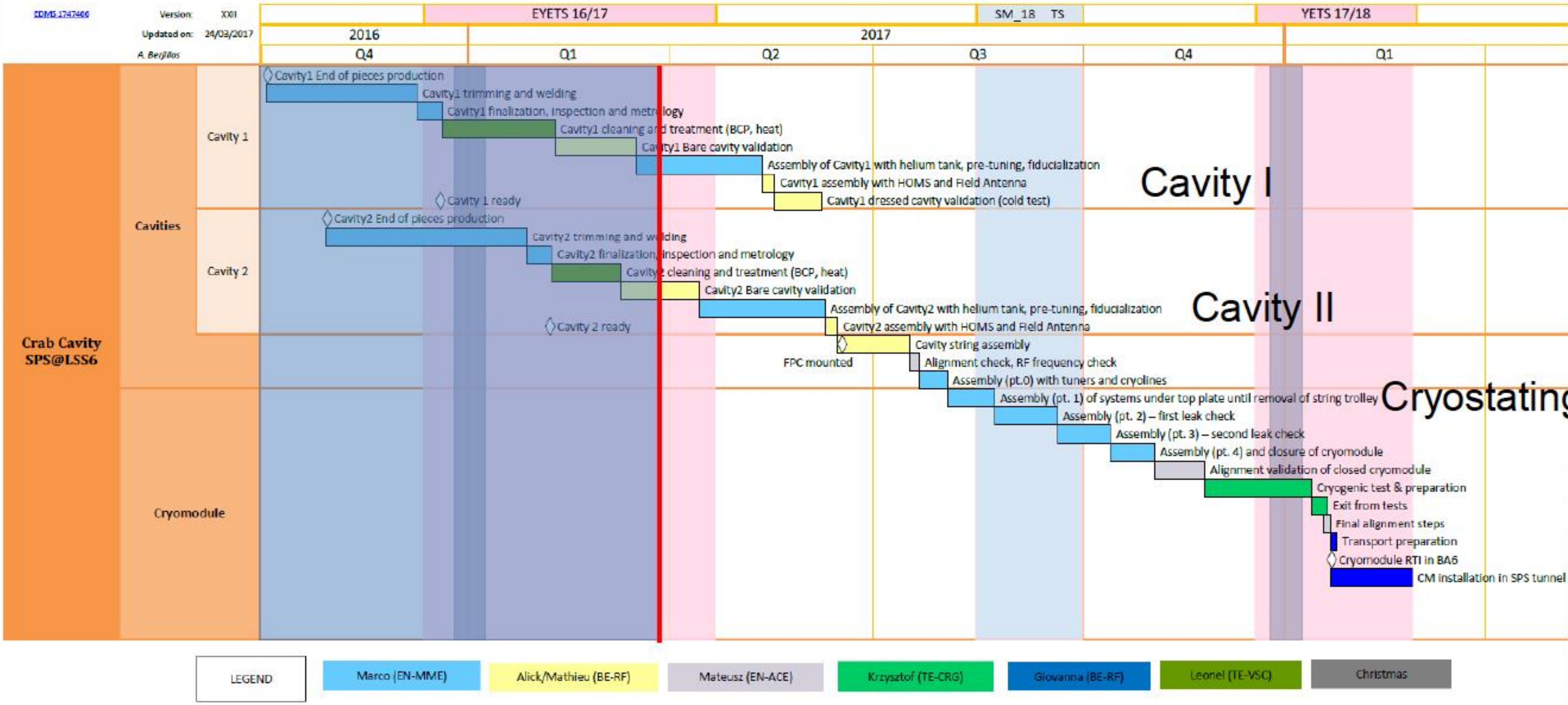
MQXFP1 (4m) Prototype Coil under assembly at FNAL, BNL and LBL

# Major Milestones in 2016/17

Several novel concepts designed/developed to meet HL-LHC needs, Prototyping of all critical items where possible


BROOKHAVEN NATIONAL LABORATORY | The Cockcroft Institute | Lancaster University | BERKELEY LAB | Science & Technology Facilities Council | OLD DOMINION UNIVERSITY | SLAC | Jefferson Lab

# SPS Tests Program – Weekly Schedule




Cryomodule delivered to SPS on 22nd Jan'18
Vacuum & cryo validation in SM18, RF tests insitu

# LHC Injector Upgrade (LIU)

**Main means to achieve the target HL-LHC proton beam parameters**

| | |
|---|---|
| Linac4 in for Linac2 | • **$H^-$ injection into PSB at 160 MeV**<br>• Expected double brightness for LHC beams out of the PSB |
| Booster | • **Increase energy to 2 GeV**<br>• New RF system<br>• New main power supply |
| PS | • **Injection at 2 GeV**<br>• **Beam production schemes**<br>• **Feedback systems**: new wide-band longitudinal feedback; transverse feedback against head-tail and e-cloud instabilities |
| SPS | • **Power upgrade of the main 200 MHz RF system**<br>• **Electron cloud mitigation** through a-C coating (baseline) or beam induced scrubbing |

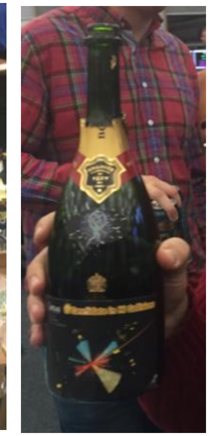
**Many other options plus a full ion upgrade program**

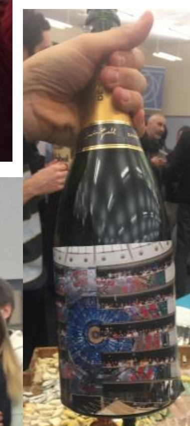
**Deployment: 2019 - 2020**

# LHC - conclusions

2016 - **memorable year** for CERN and the LHC

- **Reached design luminosity** and exceeded it by 40%!
- While maintaining **Stable Beams efficiency of ~50%!**
- …plus $\beta^*$=2.5 km, proton-ion, machine developments…




**Looking good for the next 2 years**
(usual caveats)

# HL-LHC Conclusions

- Fully approved and re-baselined
- Significant international technical effort on all fronts
- Critical civil engineering contract process is in progress…

***We are now heading for construction: All WPs are manufacturing models and prototypes. The boat is sailing…***