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LHC Status and Outlook

EPS-HEP 2017 conference

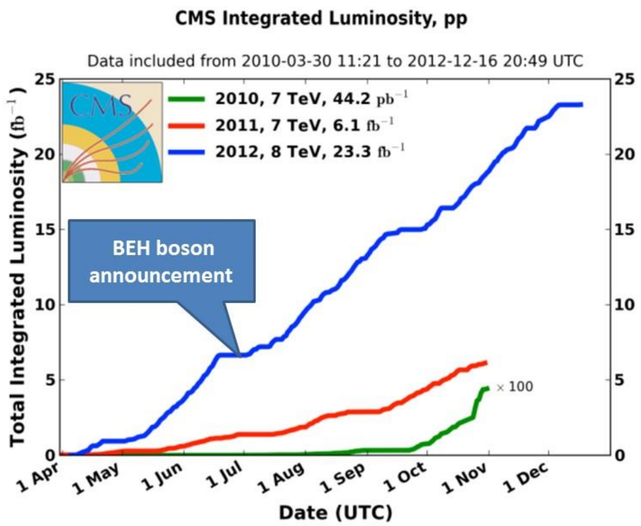
Frédérick Bordry

Venice, Italy, 10th July 2017

LHC Run 2

The LHC was operated between 2010 and 2013 at 7 TeV and 8 TeV: **Run 1**.

Run 1 was followed by a ~2 year long shutdown to prepare the LHC for high energy operation.



Goals of the 4 year long Run 2 that extends from 2015 to 2018:

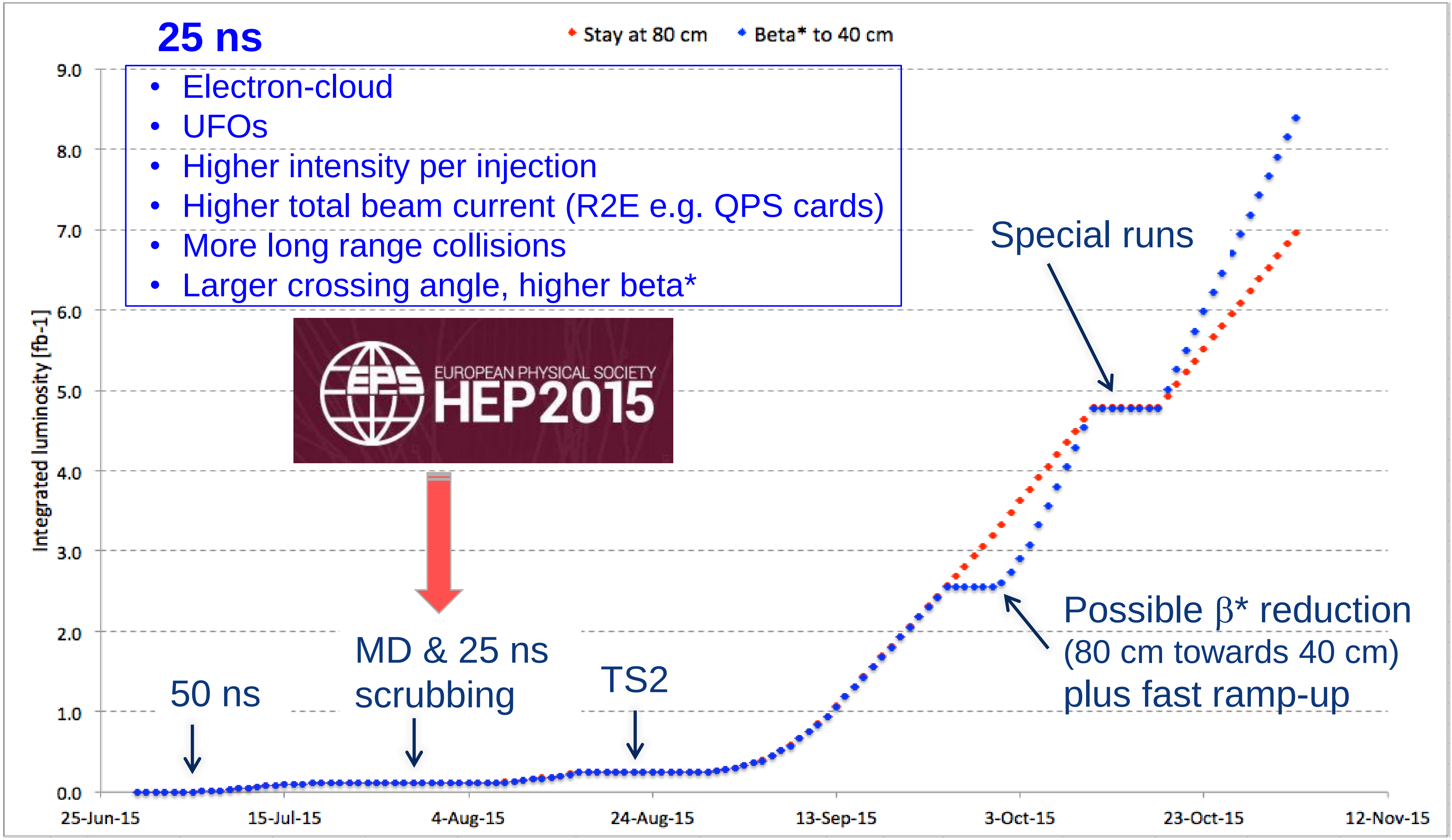
- ✓ Operate the LHC at 13 TeV.
- ✓ Operate with a bunch spacing of 25 ns.
  - *During Run 1 LHC was operated with 50 ns spacing (e-cloud).*
- ✓ Deliver ≥ 120 fb^{-1} of integrated luminosity.

2015: recovery and learning year

2016: 1st production year and to push the machine towards design performance.

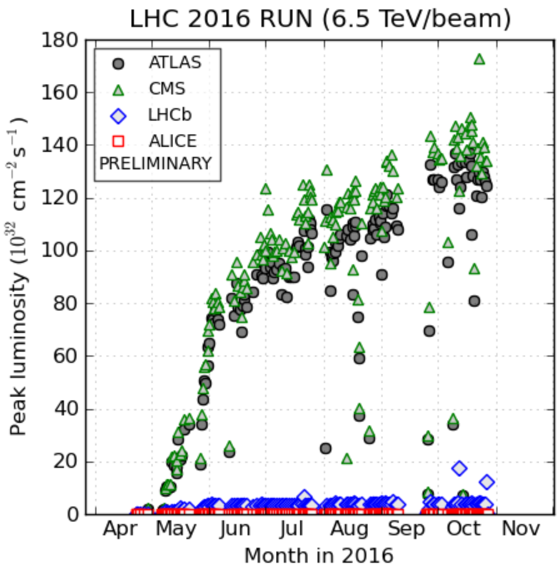
LHC 2015: projection

"Prediction is very difficult, especially if it's about the future." --Nils Bohr



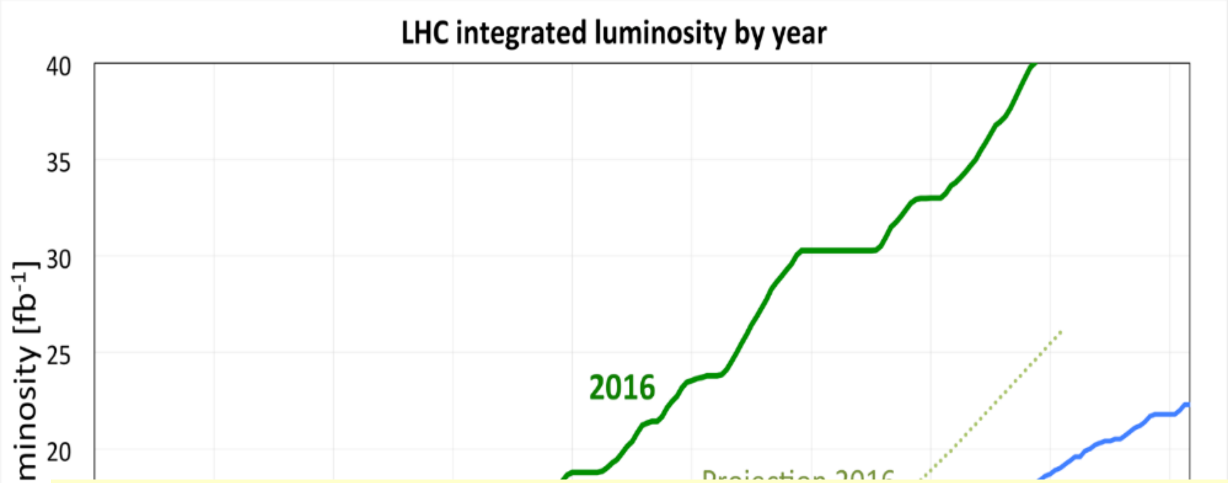
2016 LHC

a rich harvest of collisions



Peak luminosity > 1.4 x 10^{34} $cm^{-2}s^{-1}$

OVER 25 fb^{-1} in both ATLAS and CMS ☺



LHCb

Ingredients for the excellent results in 2016:

- **Building on 2015 as the year to commission the machine at this energy**
- **High machine availability ~ 50 % (many HW issues fixed)**
- **High luminosity lifetime (improved knowledge of machine parameters for operation)**
- **High peak luminosity (small beam size from injectors and stronger focussing)**

Still room for improvement in 2017 & 18

- **More bunches, higher bunch intensity, stronger focussing**

2016: LHC Limitations

SPS beam-dump

Nb of bunches per injection limited to 96

Total number of bunches: 2200

LHC Injection kickers

Outgassing from ceramic

Bunch population limited to around 1.1 x 10^{11}

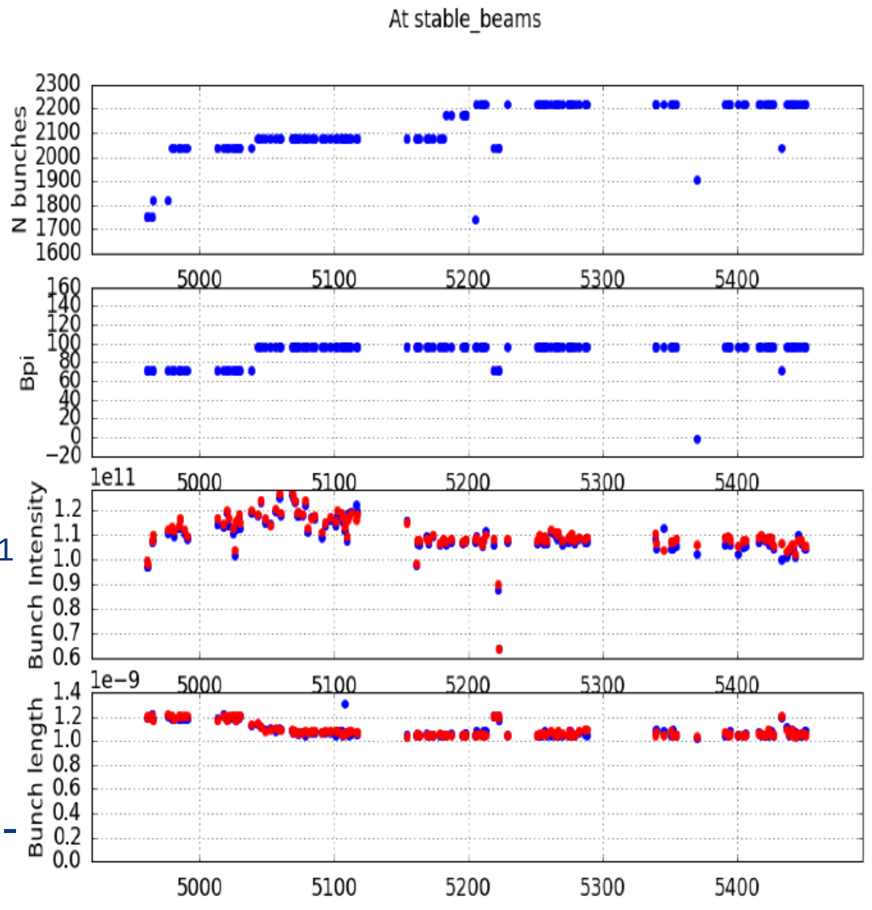
Electron cloud

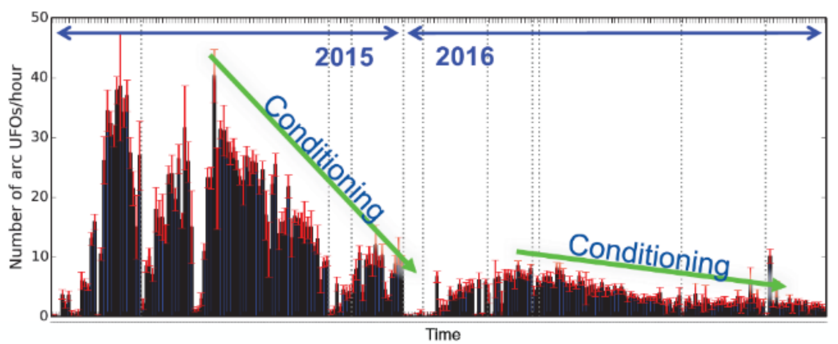
Still significant heat-load within cryogenic limits

Dynamics – well handled by cryogenics feed-forward – no impact on operations in the present conditions

UFOs

Frequency has happily conditioned down





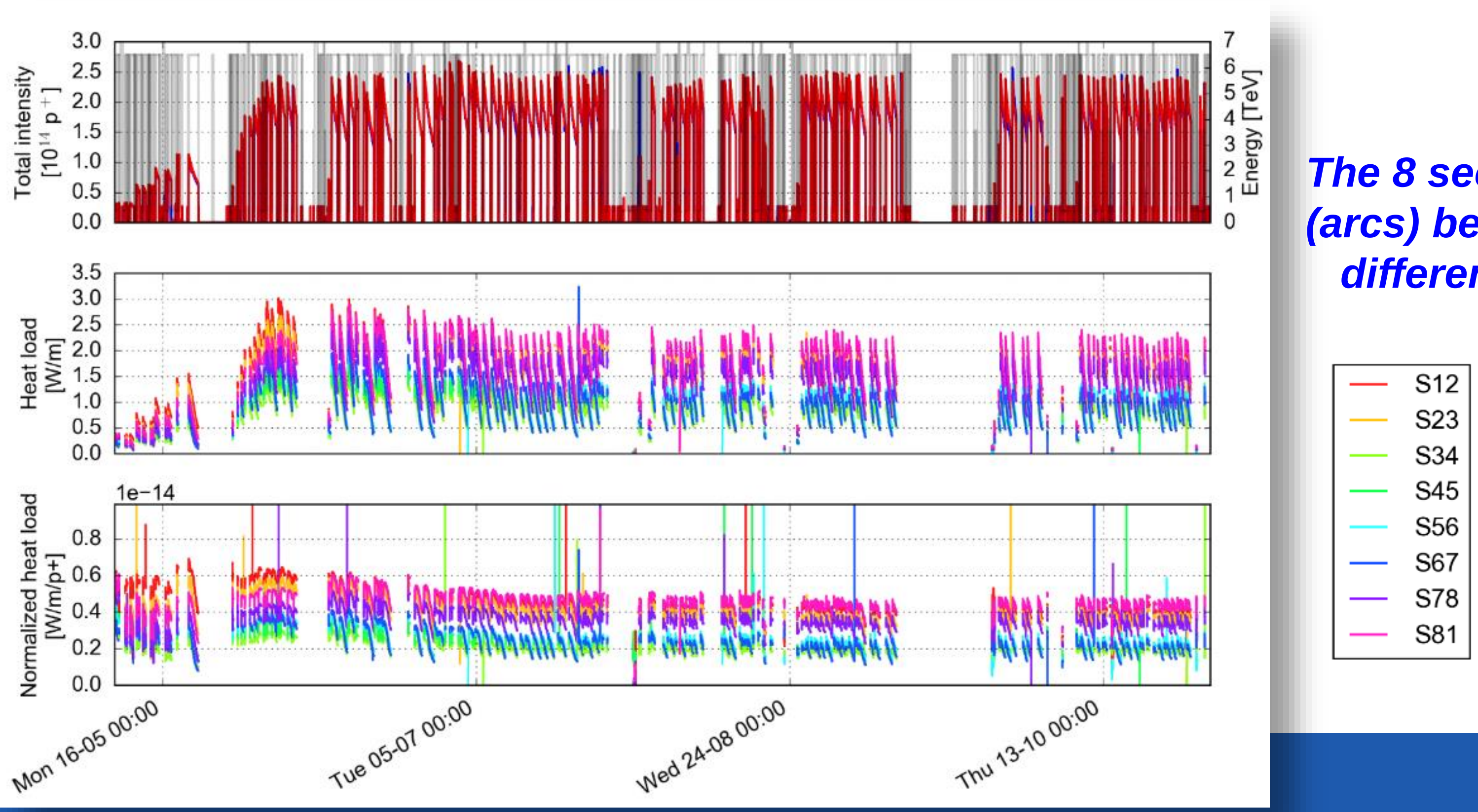
2016 LHC: Electron clouds

- At high intensity the LHC is operated in the **presence of electron clouds**.
- There is a slightly decreasing trend of electron cloud heat-loads in 2016 with **~20% gained** over the year (gain of 2015 40%).
  - *Most electron could 'scrubbing' is performed parasitically to physics operation.*
  - *The beams are stabilized with a transverse feedback, octupoles and head-on beam-beam (Landau damping).*

Beam intensity

Heat load (W/m)

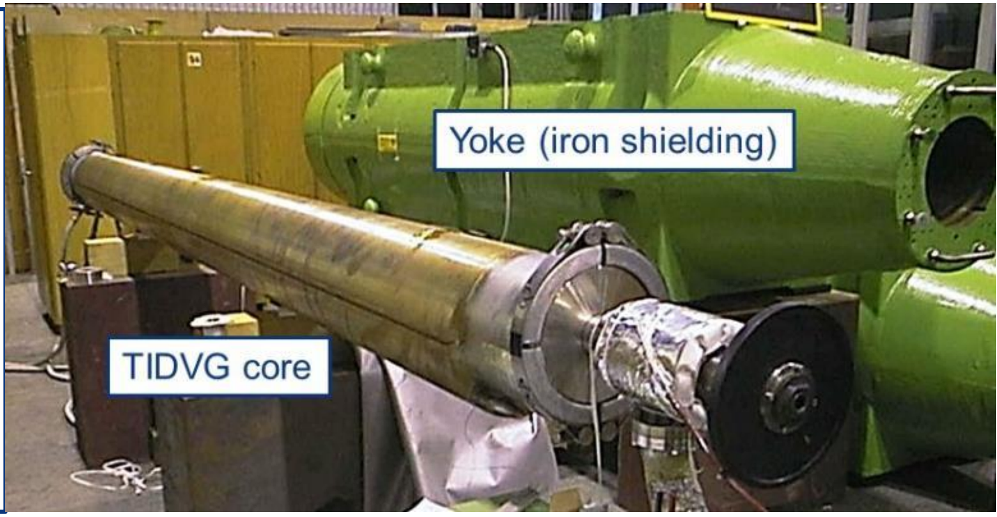
Heat load per proton (W/m/p)



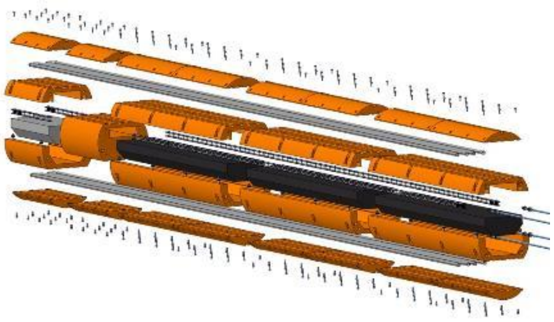
The 8 sectors (arcs) behave differently

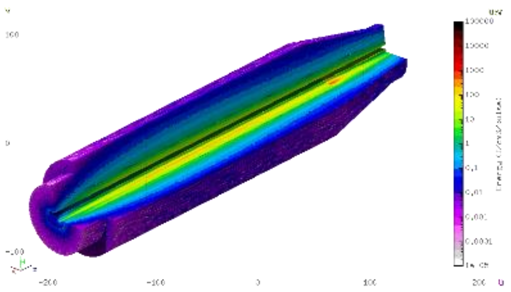
SPS tunnel: internal beam dump

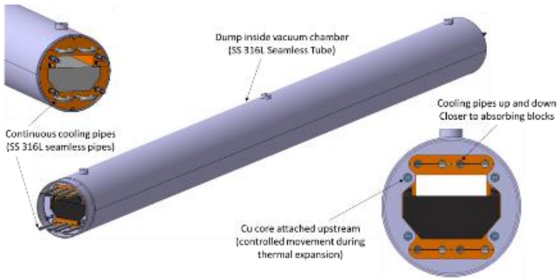
- Device essential for the operation of the accelerator complex
- New SPS internal dump (innovative design) constructed in ~8 months following failure of 2016
- Completely new design – “prototype” for new dump for LS2 (LIU)

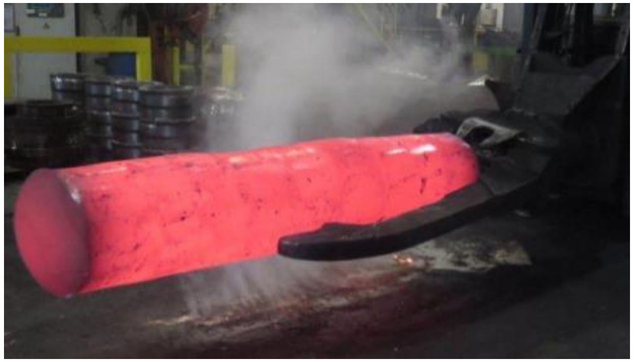


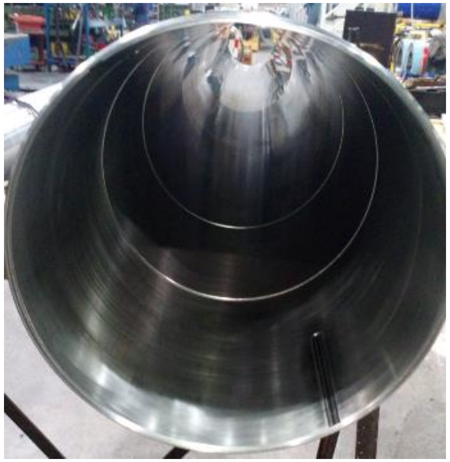
SPS: from paper to reality in 8 months







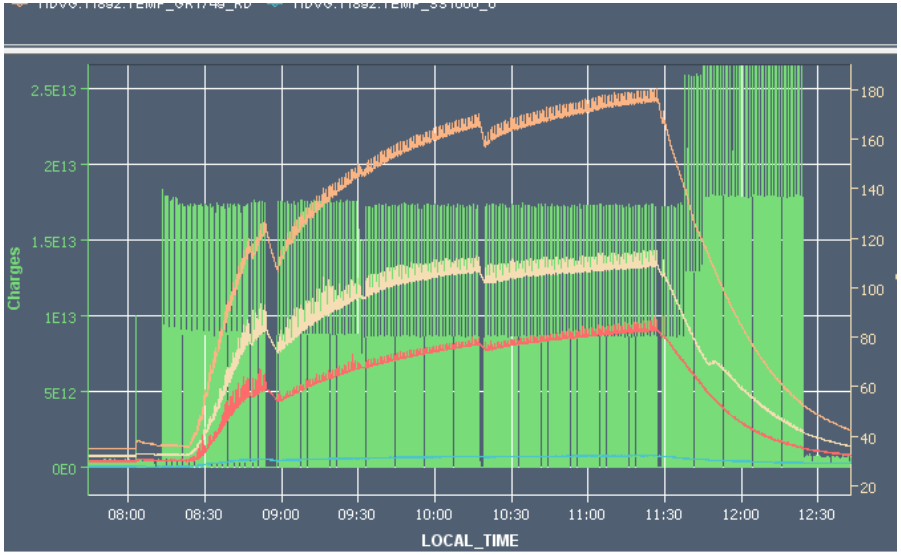




Courtesy of Marco Calviani and Simone Gilardoni

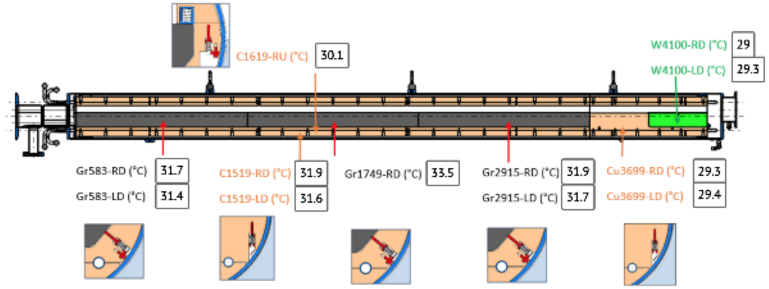
SPS: Dump commissioning – first operation

~Steady state at **144** bunches (25 kW deposited)

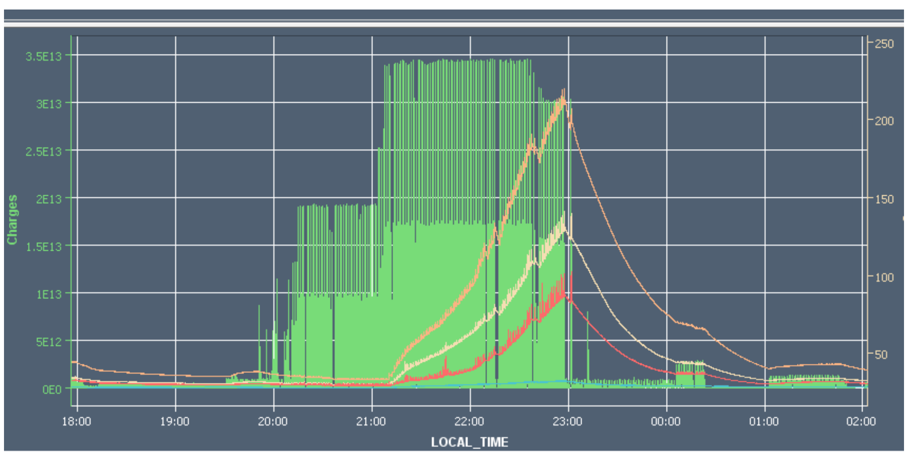


Temp. (°C)

Temperature probes



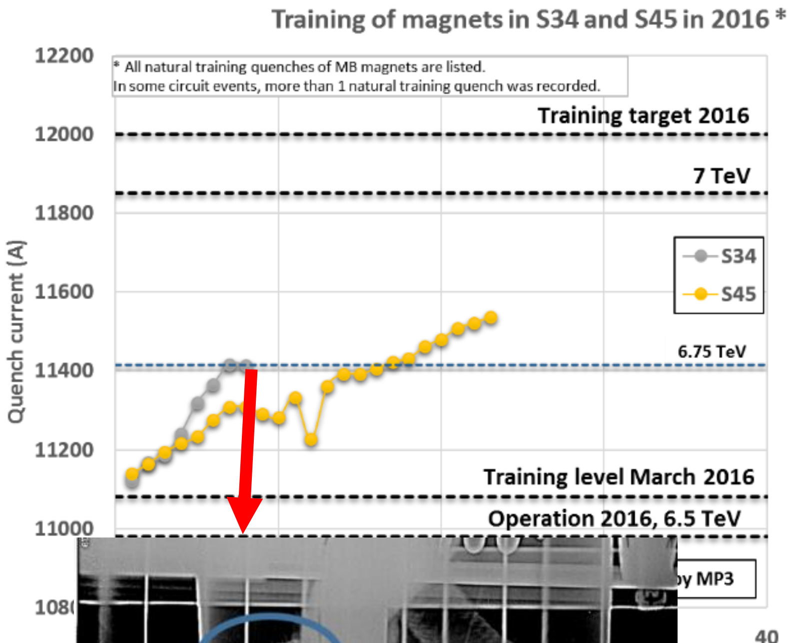
288 bunches (1h30 hours at full power – 55 kW deposited)

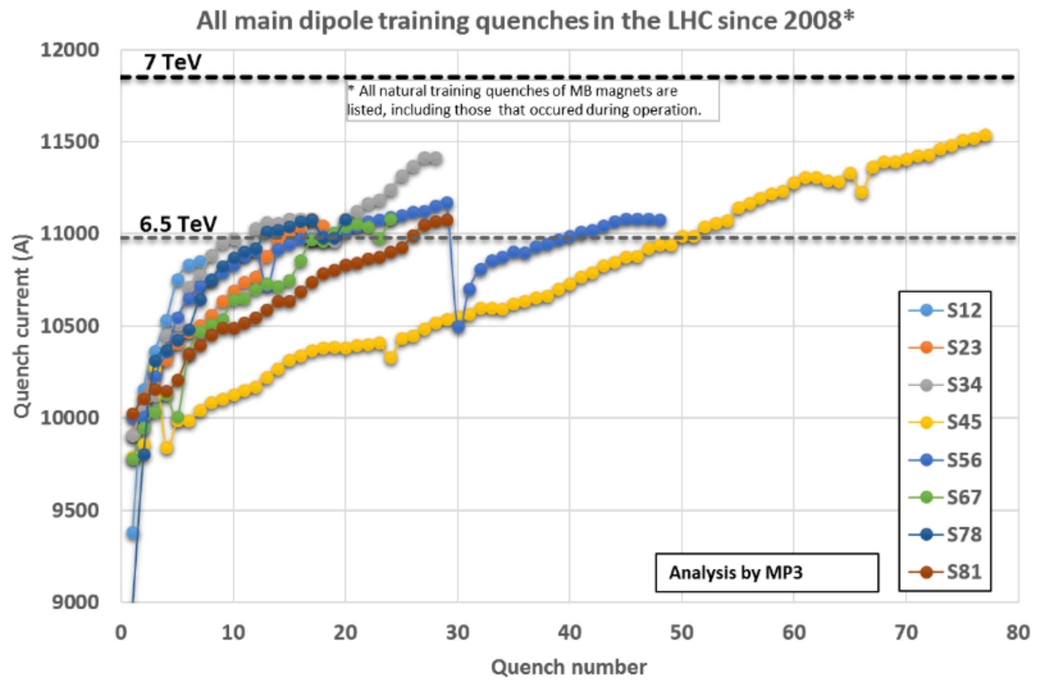


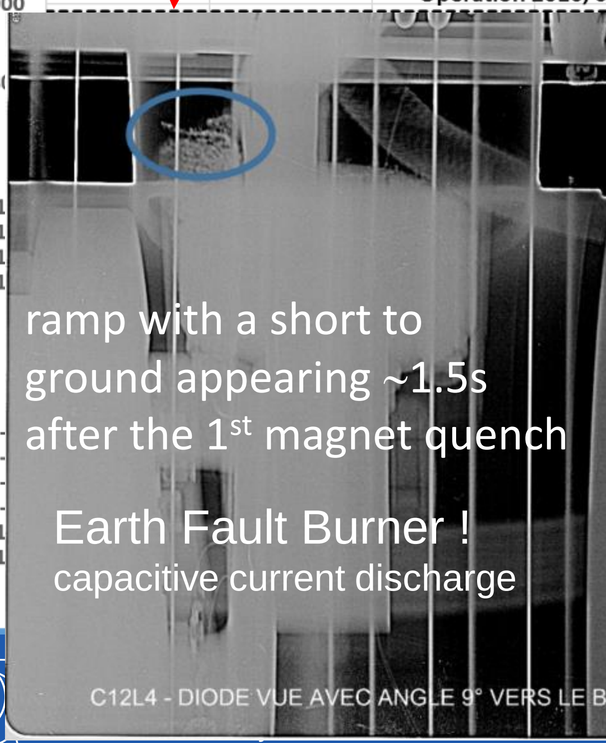
Temp. (°C)

- Operation of the dump successfully so far
- Reached up to almost nominal power at **~55 kW** average deposited beam power
- Long irradiation periods at beginning of the run necessary for graphite conditioning – now reached (required for safe operation at 288 bunches)

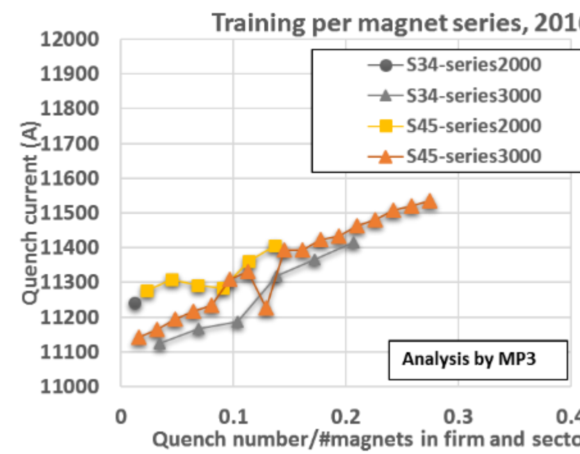
MB Training campaign 2016, December 5 - 14







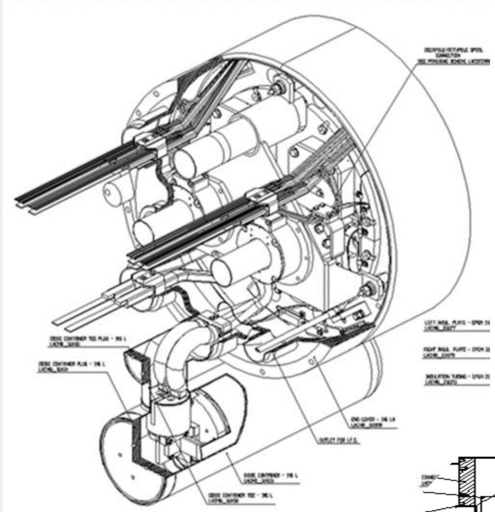
	Training quenches December 2016		
	Series 1000	Series 2000	Series 3000
RB.A34	1	1	6
RB.A45	0	6	17
total	1	7	23



Beam energy : **Run 2 @ 13 TeV c.m.**

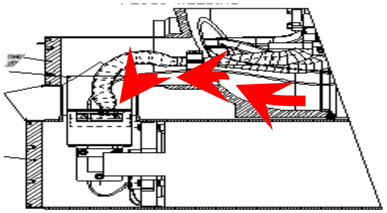
NO change of beam energy in 2017 and 2018

Goal is to prepare the LHC to run at 14 TeV during Run 3.



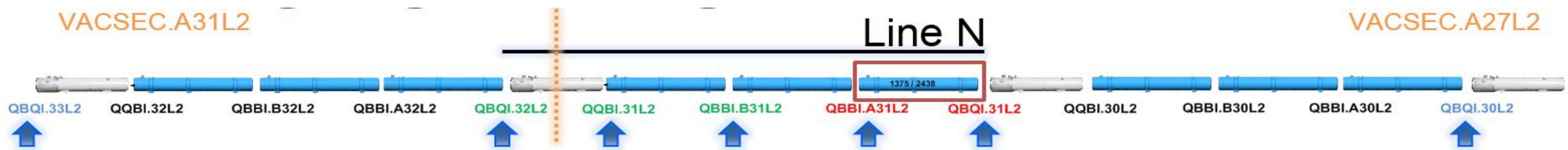
Study how to reinforce the insulation (and to clean) during LS2 the electrical part connecting the dipole bypass diode. **DONE**

Powering tests before and during LS2 should be defined:
S1-2 to 7 TeV at end of Run 2 ?



Work will be done during LS2

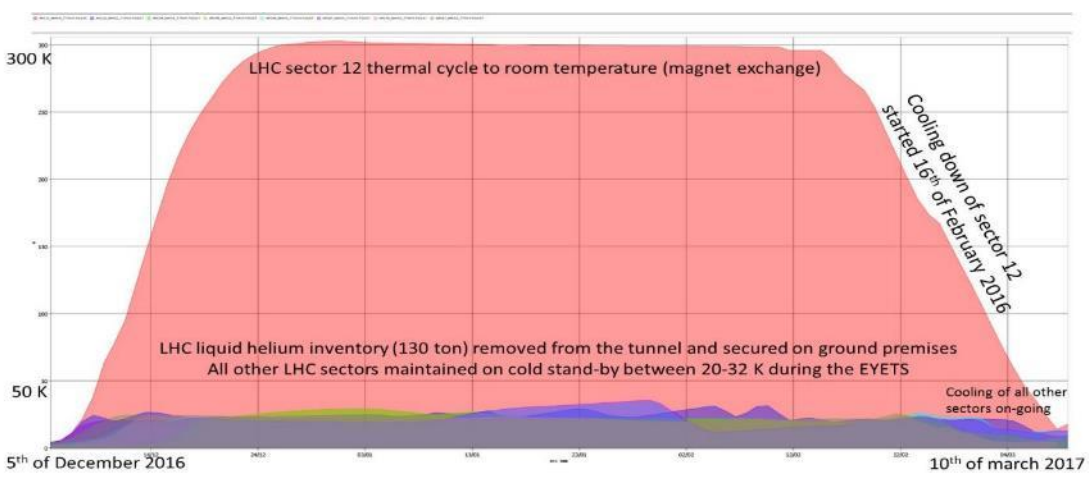
LHC : Magnet Exchange during eYETS (extended Year-End Technical Stop)



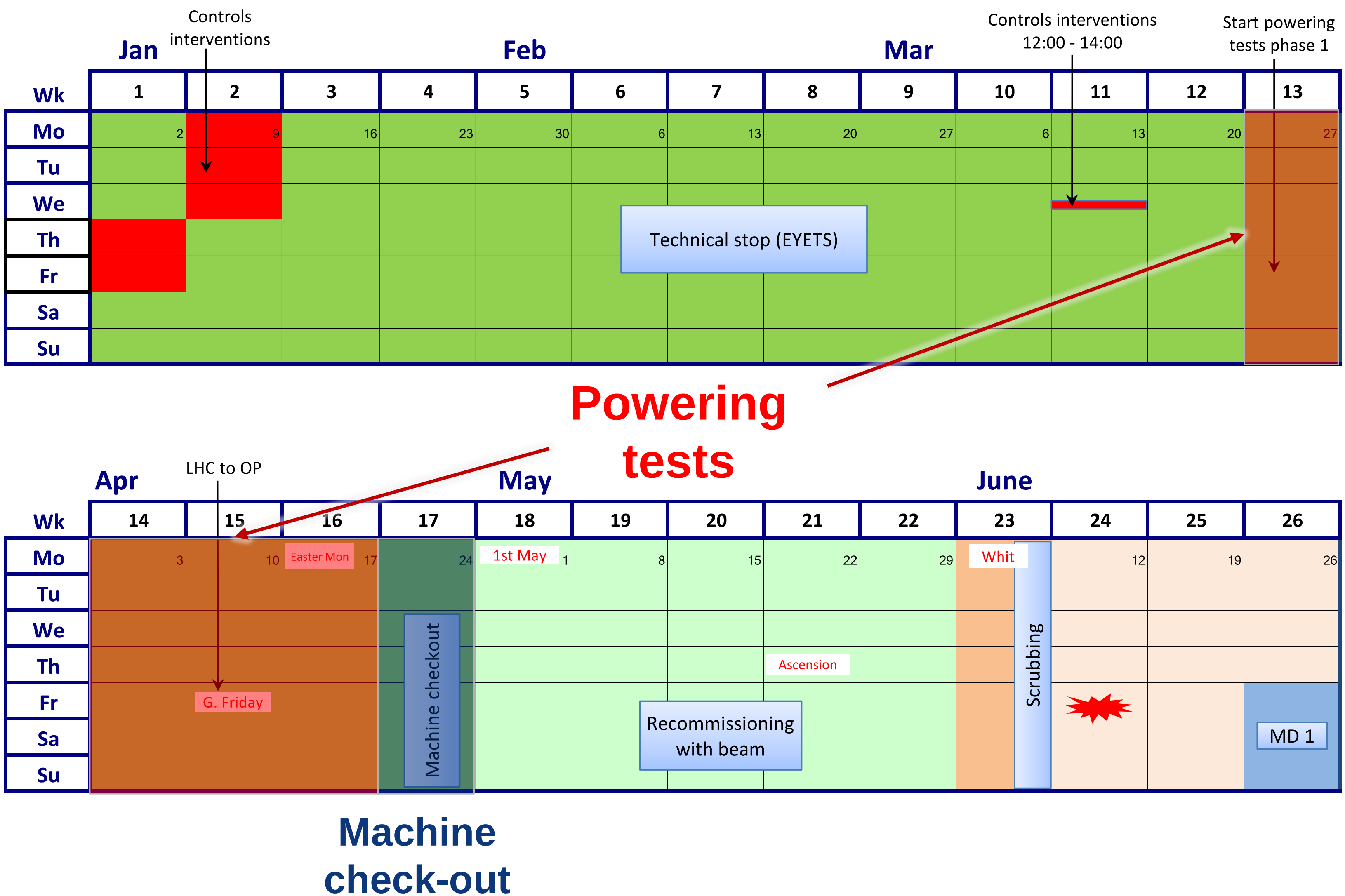
7 interconnections must be opened for the re-connection and the validation of the auxiliary circuits (correctors)

21 weeks required for the warm-up, exchange of the magnet, cool-down and the re-commissioning of the sector

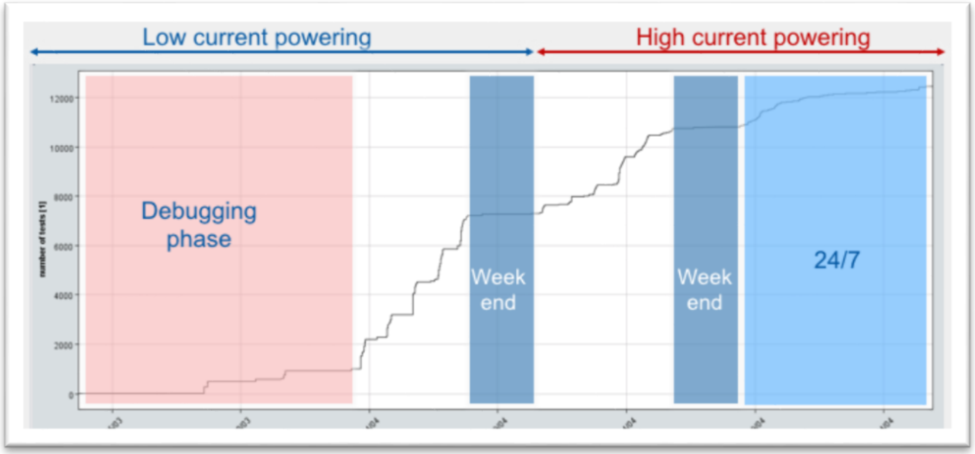
4 ½ weeks (7days/7) will be necessary to disconnect and re-connect the dipole



LHC schedule : Q1 and Q2



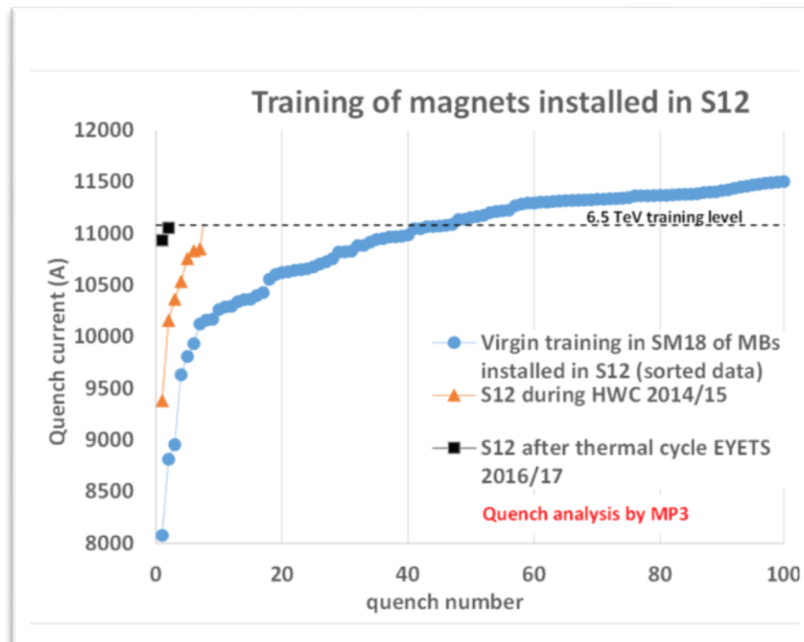
LHC powering tests



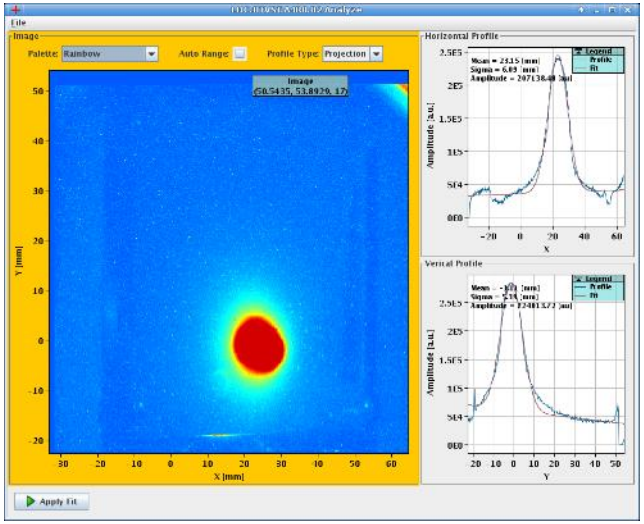
1572 superconducting circuits commissioned!

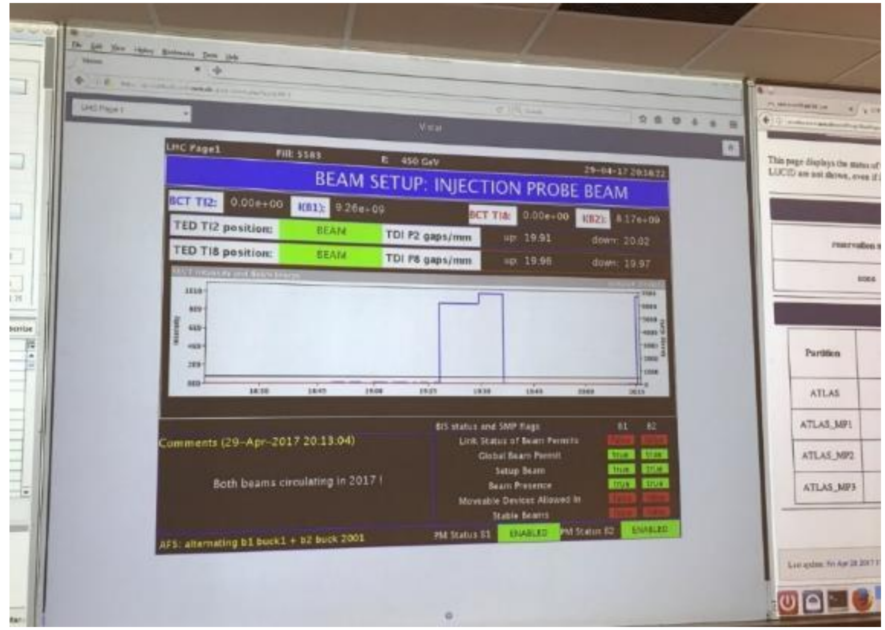
- **More than 10.000 tests** executed and analyzed in about 1 month
- Early debugging and increased automation proved to be the **key elements for the success**

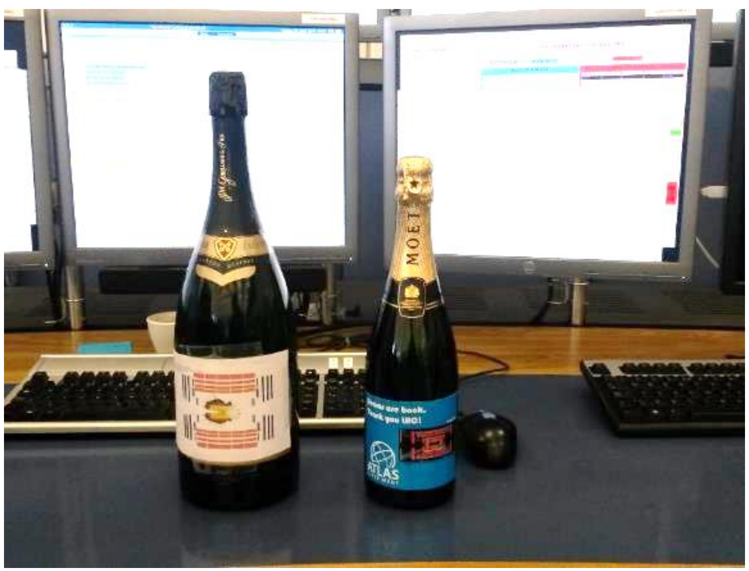
- **Dipole magnets in S12 needed 2 training quenches to reach the current level required for 6.5 TeV operation (11080 A)**
- **7 quenches** were needed after LS1
- The quenches occurred on **different magnets** wrt after LS1 campaign



2017: beams back in LHC from Friday 28th April

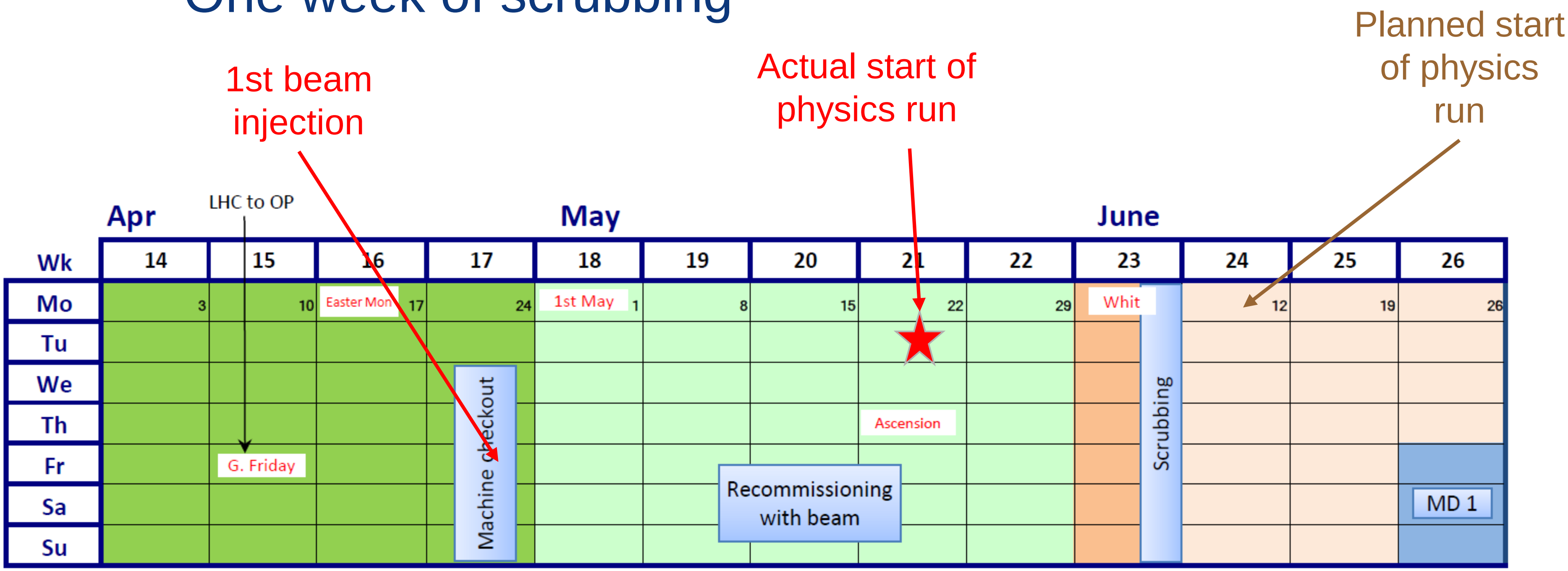




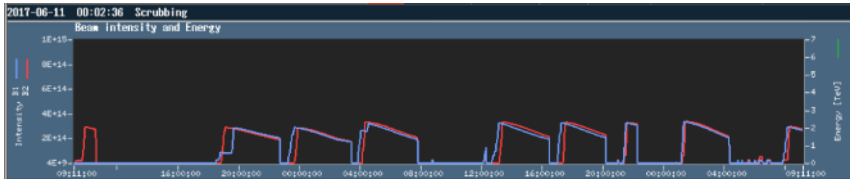


LHC beam commissioning

- Planned LHC start-up after EYETS: 5 weeks
- Actual LHC start-up:
  - 1st beam injection 2 days ahead of schedule (28th April)
  - 3.5 weeks to first physics (23rd May)
  - Very well tuned start-up sequence (new ATS optics)
  - One week of scrubbing

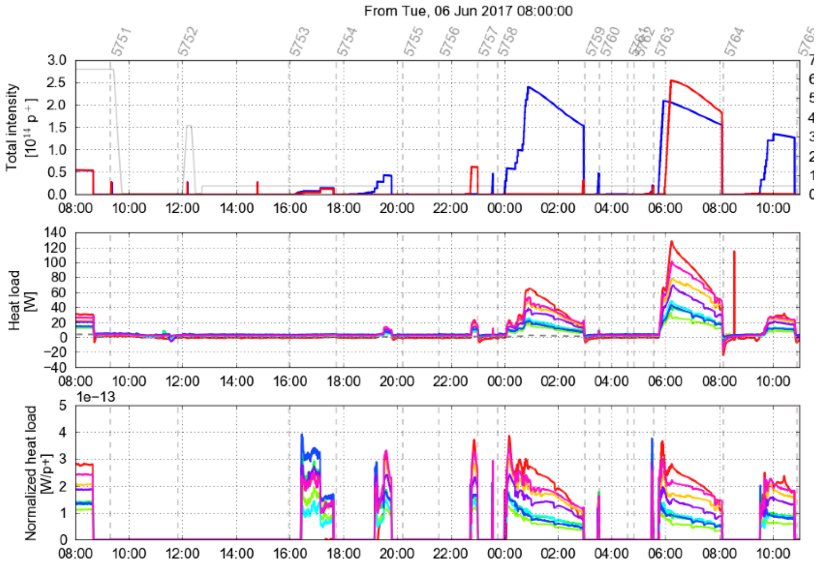


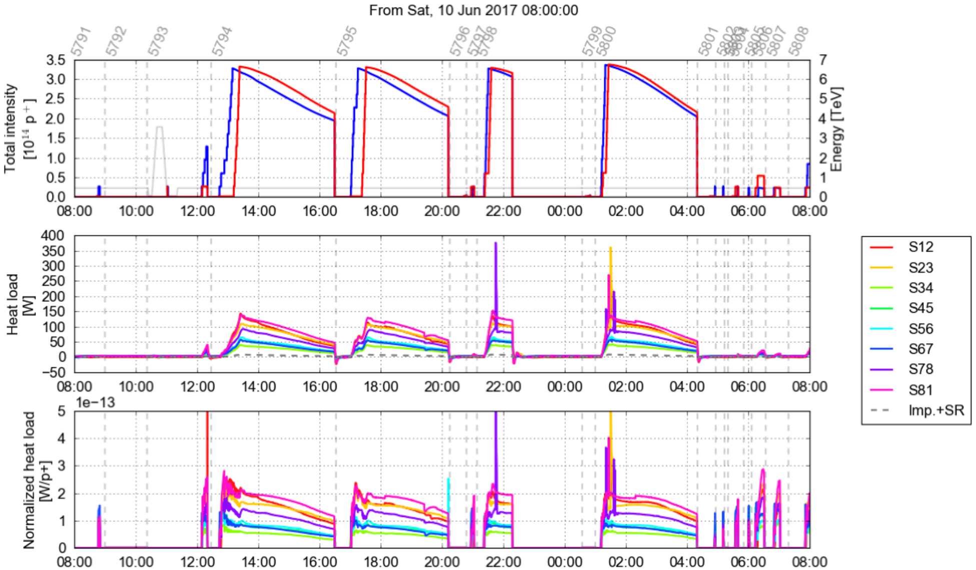
LHC: Electron Cloud Scrubbing



First e-cloud observations in 2017

- Heat load in S12 found much higher (as expected due to warm-up and venting), but fast conditioning.
- Heat load "ranking" of the other sectors stayed unchanged.
- Up to now no more issues with vacuum in injection regions (upgrade of pumping).





Conditioning evident on Sector 1-2,
less so on the others

Up to 2820b/beam

LHC 2017 : Parameters and Plans

Parameter	Design	2015	2016	2017
Bunch population N_b [10^{11} p]	1.15	~1.2	~1.1	**~1.2**
No. bunches k	2780	2244	2220	**2556**
Emittance ε [mm mrad]	3.5	~3.5	~2.2	**~2.2**
β^* [cm]	55	80	40	**40 (33)**
Full crossing angle [μrad]	285	290	370 / 280	**300 (340)**
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	0.51	1.4	**~1.7 (1.9)**
Integrated luminosity [fb^{-1}]		**4.5**	**40**	**~ 45**

Push LHC performance

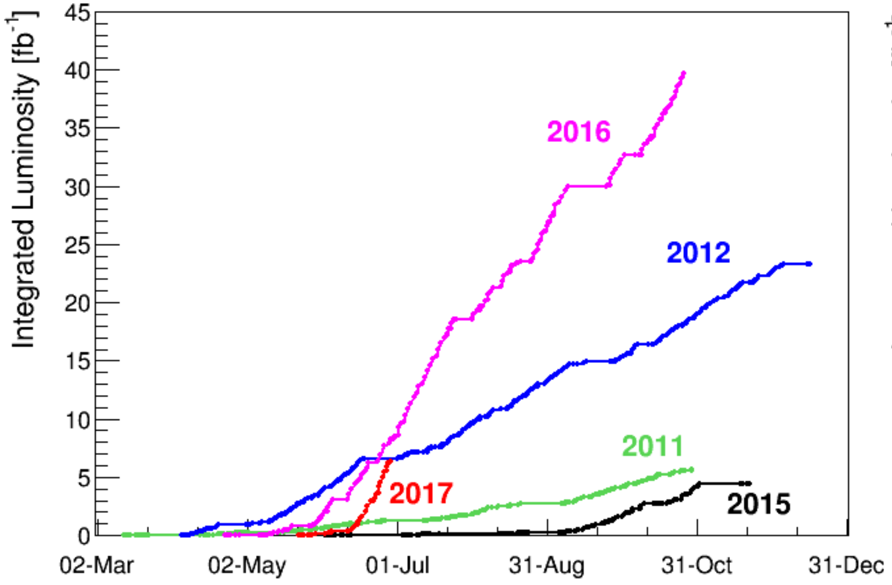
- **Mitigate e-cloud by scrubbing with longer trains**
- **Increase the number of bunches => 2556**
- **Increase the bunch intensity**
- **Possibly decrease the β* from 40cm to 33 cm**

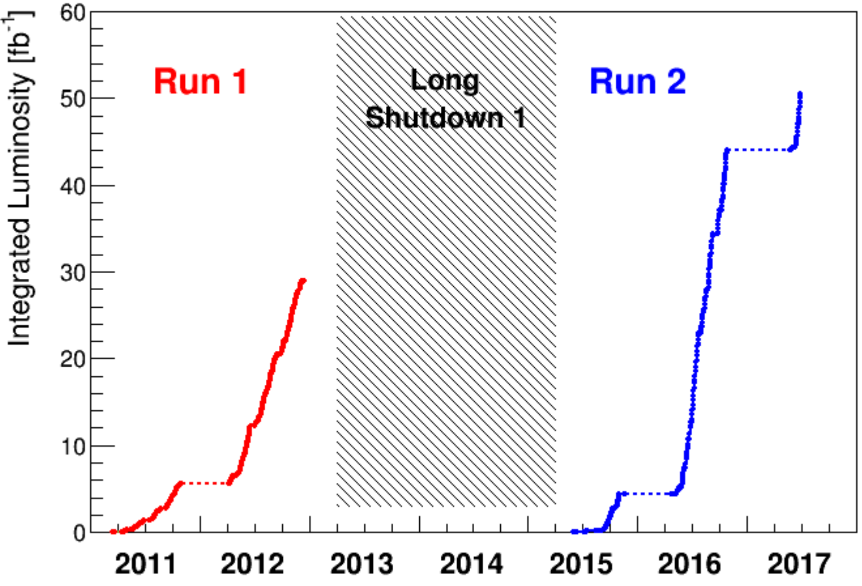
Prepare for HL-LHC

- **Run with ATS optics (Achromatic Telescopic squeeze)**
- **Test levelling schemes (crossing angle, β*)**
- **Use full RF detuning**

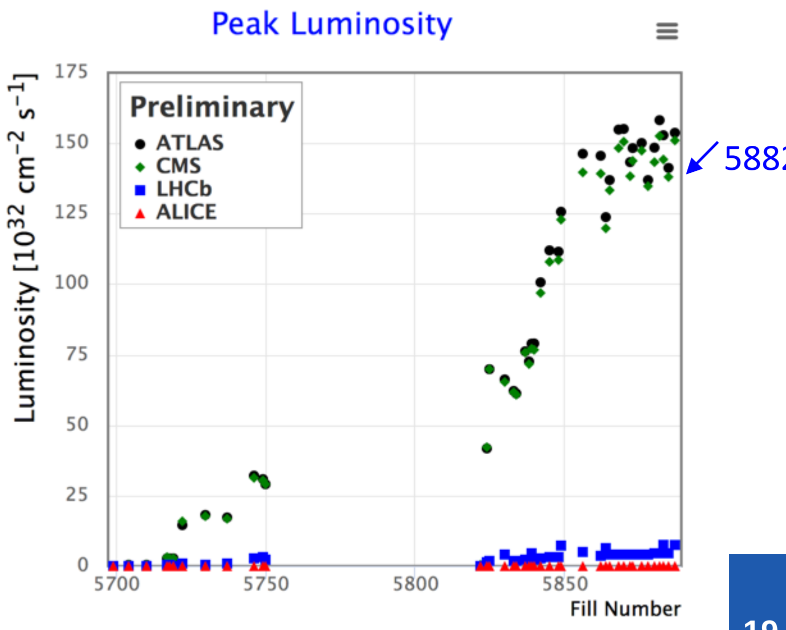
Continue to increase performance and to maintain availability ~50%

2017 LHC: a good start !

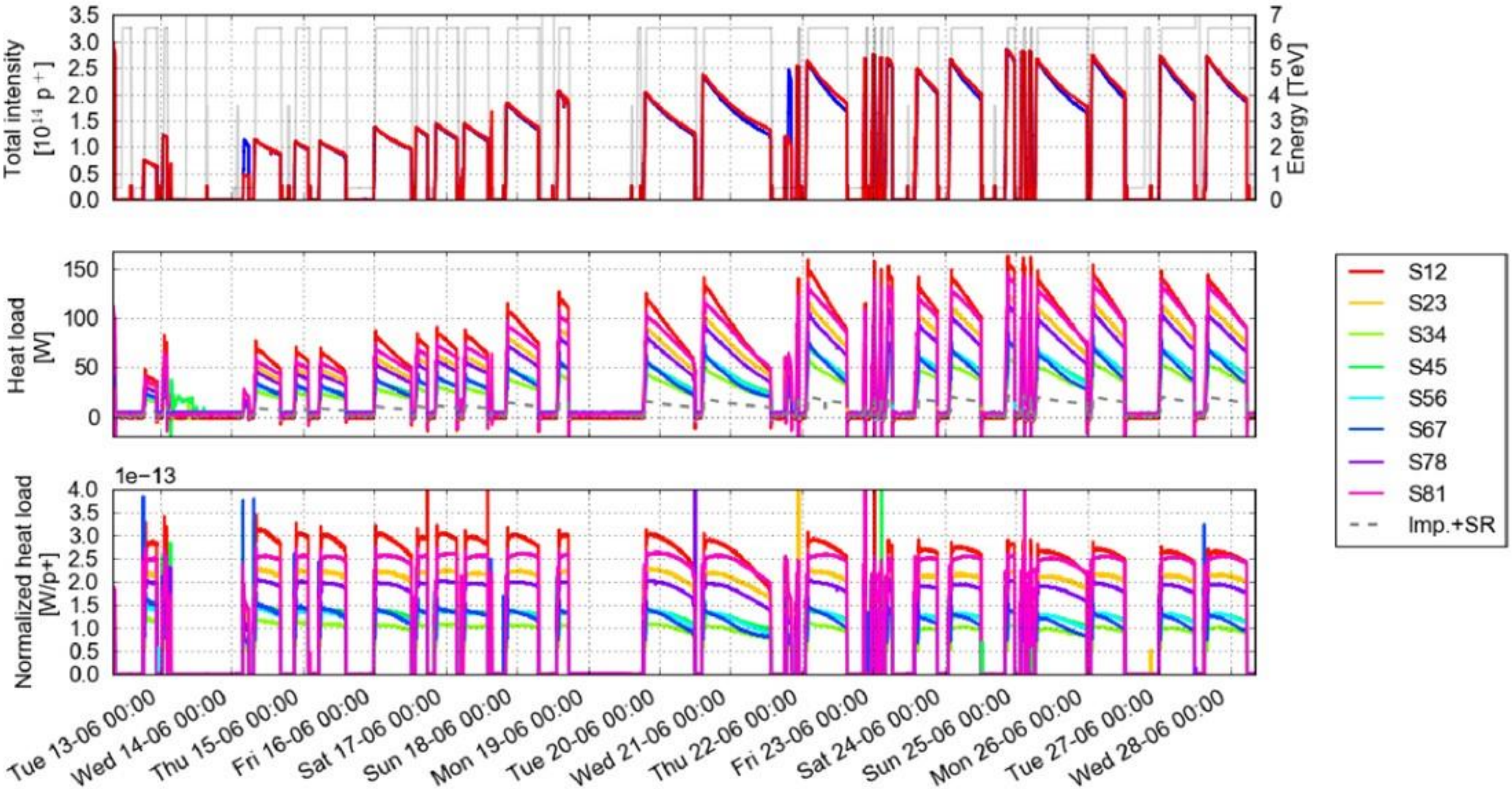




- **Very steep performance ramp up**
- **2556 bunches**
- **Peak Luminosity 1.58 $10^{34} cm^{-2}s^{-1}$**
  (fill #5882)
- **Integrated luminosity : 6.4 fb^{-1}**

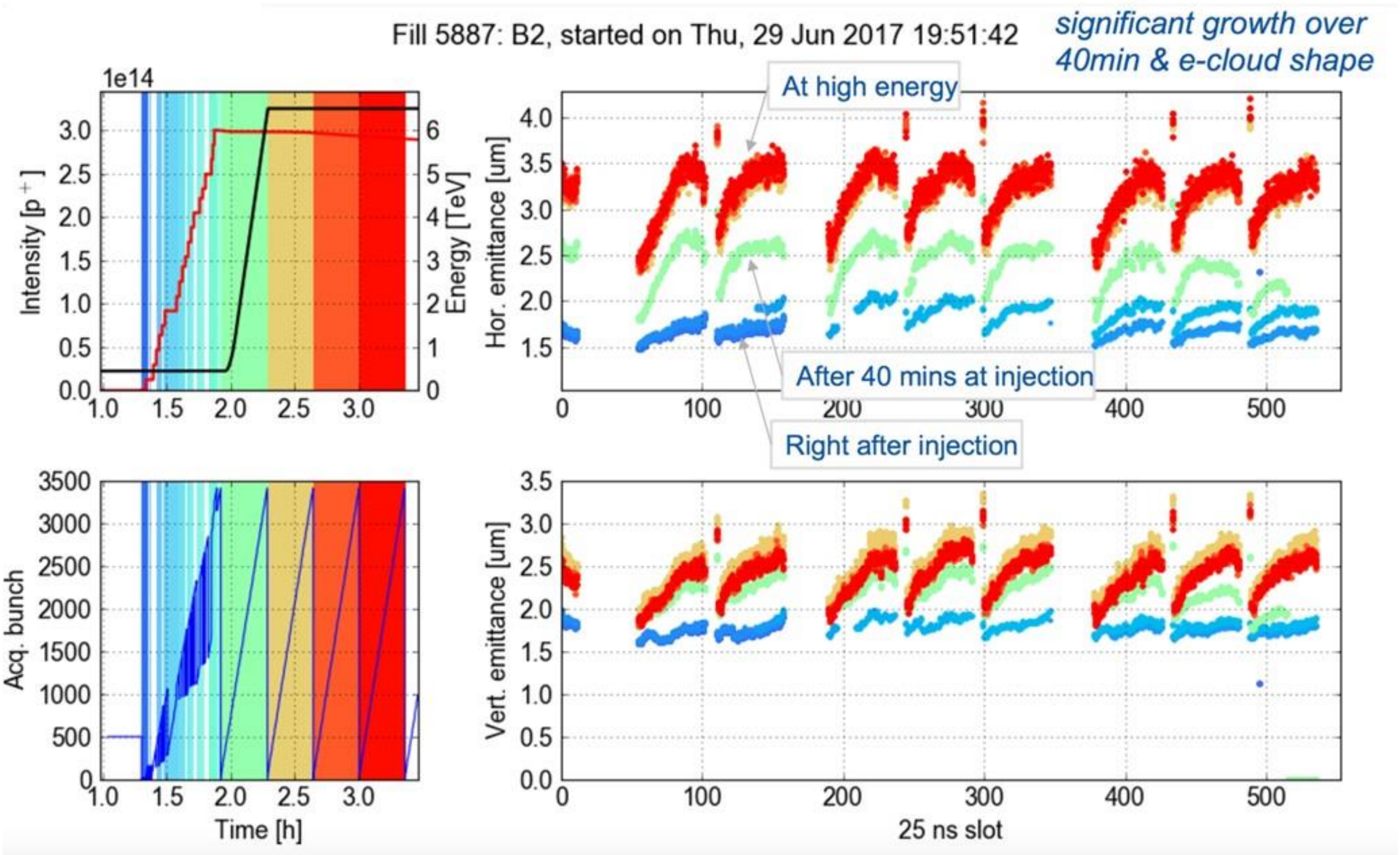


2017 LHC: Electron clouds



Very smooth during intensity ramp-up (nb of bunches)

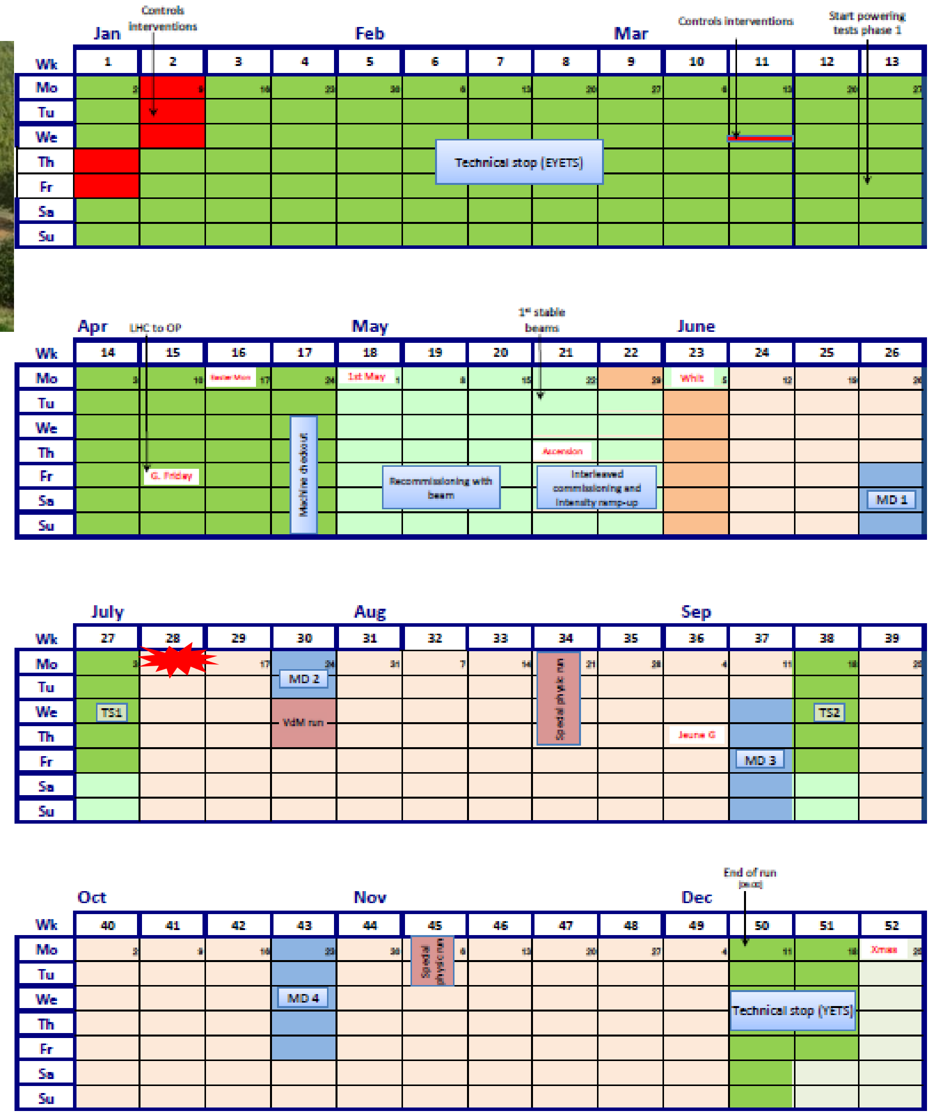
2017 LHC: Emittance evolution from Injection to stable beam



Potential improvement

LHC schedule 2017

a new production year at 13 TeV



Goal 45fb^{-1}

(145 days of physics)

keeping the LHC availability

close to 50% (stable beams)

15 days of MD;

+ 3 days, later during 2017 according integrated luminosity

Special runs: VdM scans,…

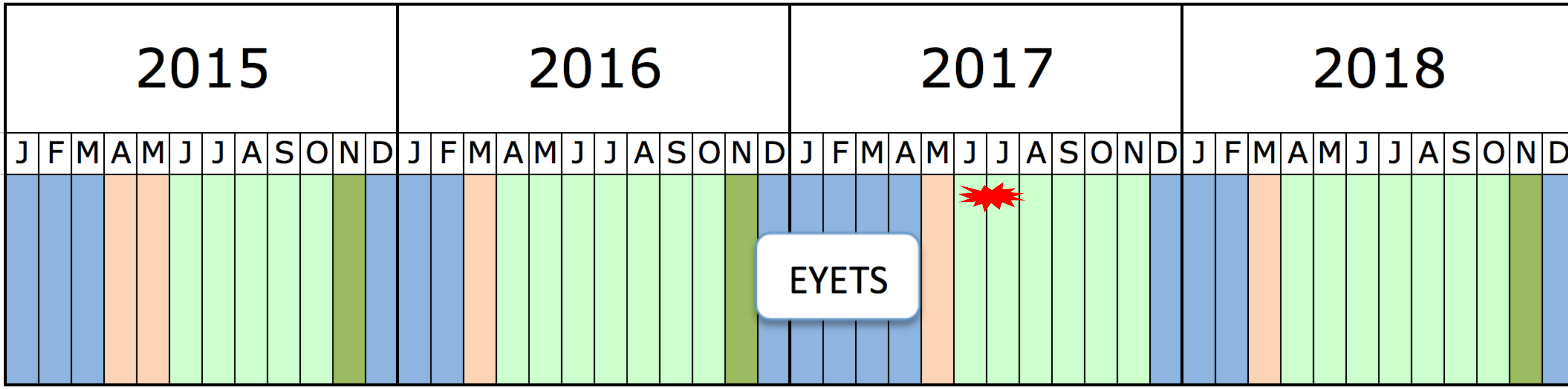
and … 5 TeV pp reference run

(for Pb-Pb and p-Pb physics analysis)

LHCC recommendations in Sept.17

Run 2 and Run 3

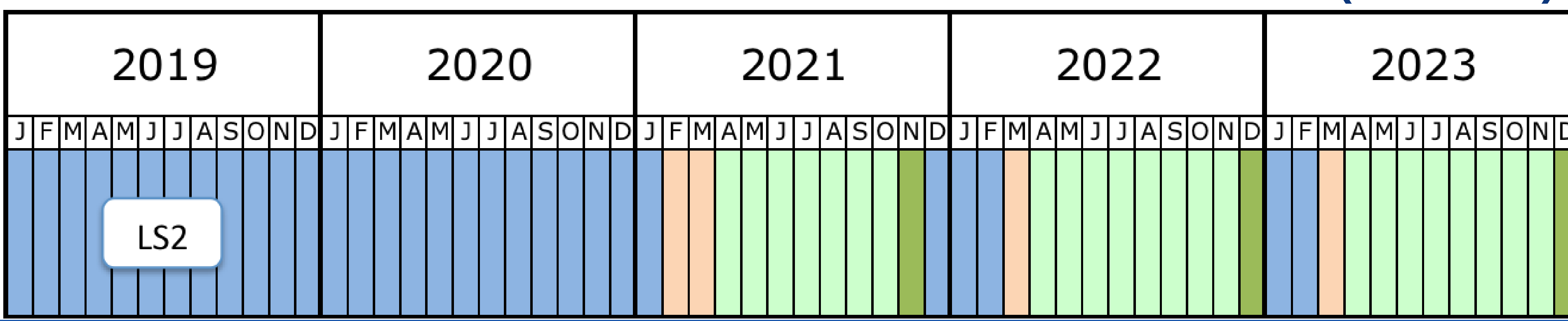
Ion runs end of 2018 (Pb-Pb)



Shutdown/Technical stop
Protons physics
Commissioning
Ions

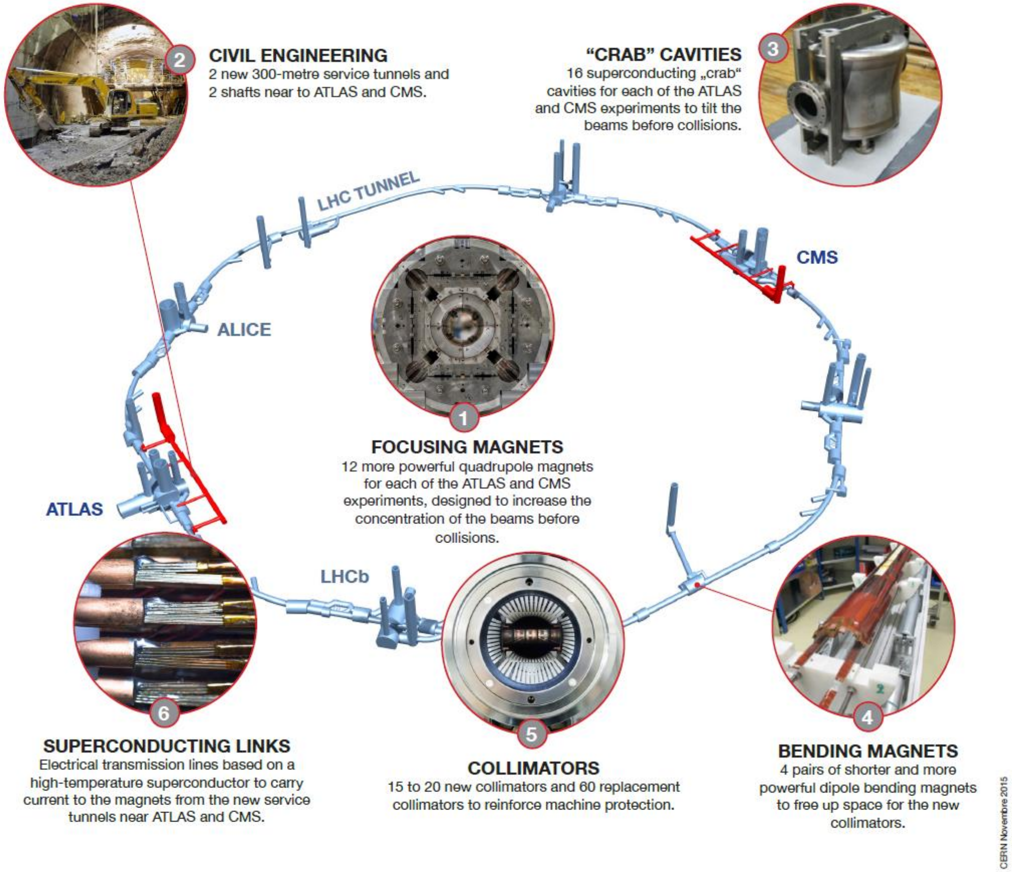
>120 fb^{-1} (13 TeV)

Σ 300 fb^{-1} (=>14 TeV)



The HL-LHC Project: 300 fb^{-1} → 3000 fb^{-1}

- **New IR-quads Nb_3Sn (inner triplets)**
- **New 11 T Nb_3Sn (5.5 m dipoles)**
- **Crab Cavities**
- Collimation upgrade
- Cryogenics upgrade
- Cold powering
- Machine protection
- …



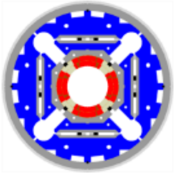
Major intervention on more than 1.2 km of the LHC

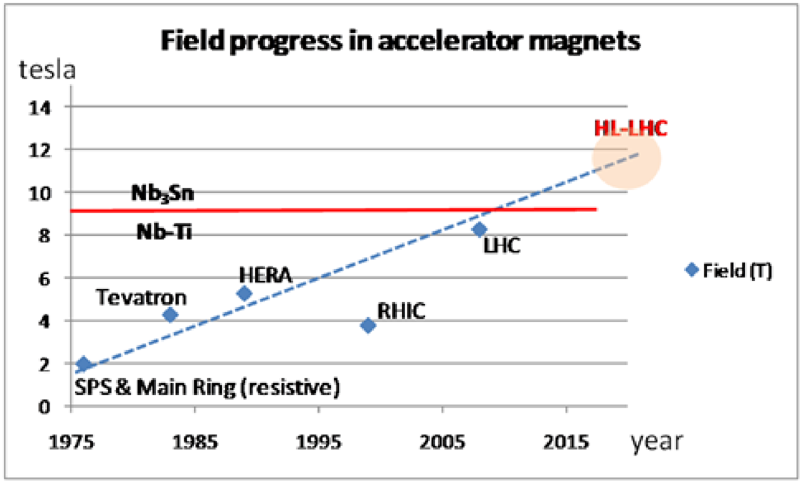
Squeezing the beams: High Field SC Magnets

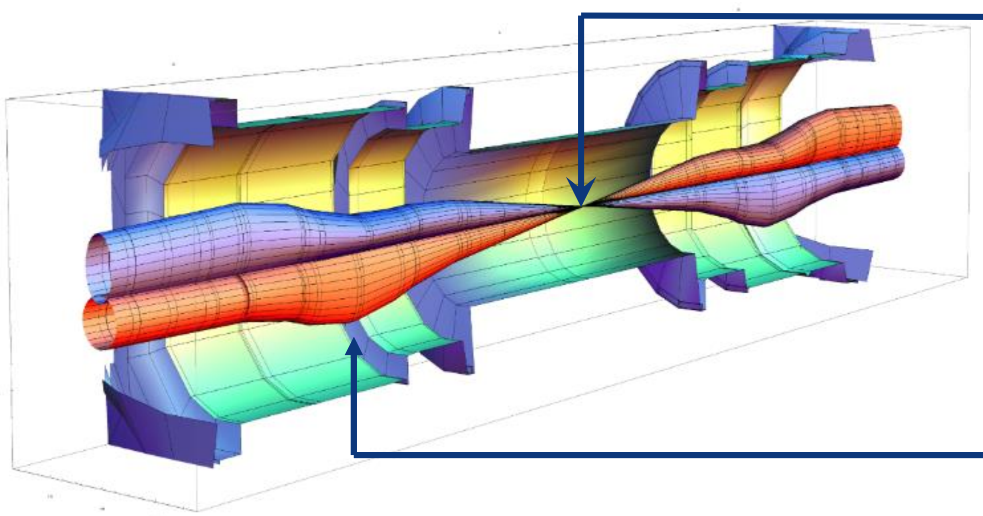
Quads for the inner triplet
Decision 2012 for low-β quads
Aperture ∅ 150 mm – 140 T/m
(B_{peak} ≈12.3 T)
operational field, designed for 13.5 T

=> Nb_3Sn technology

(LHC: 8 T, 70 mm)



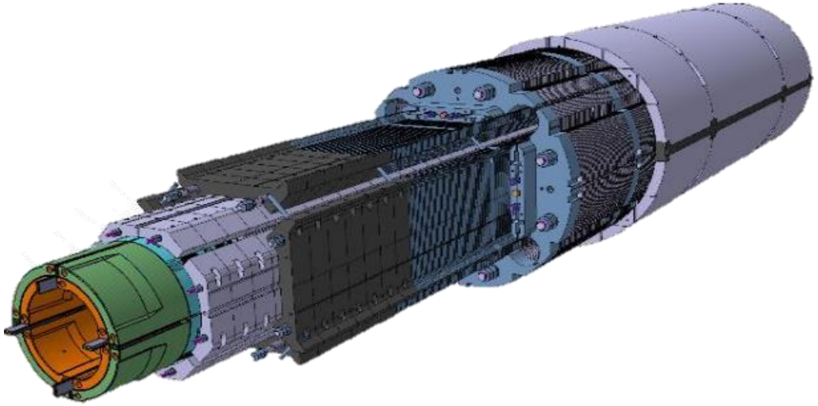




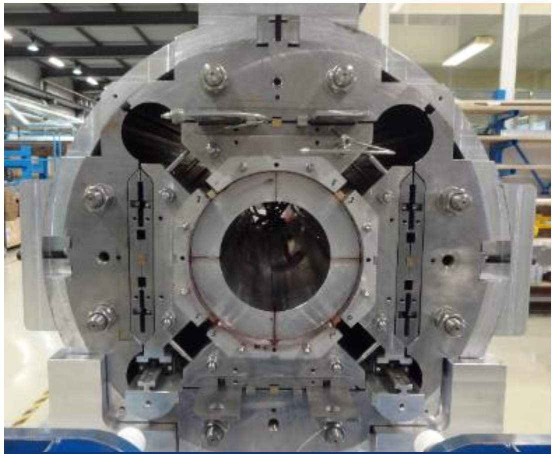
	$\beta_{triplet}$	Sigma triplet	β*	Sigma*
Nominal	~4.5 km	1.5 mm	55 cm	17 um
HL-LHC	~20 km	2.6 mm	15 cm	7 um

Nb_3Sn quadrupole: complexity increase vs Nb-Ti

Development of Nb3Sn Conductor with Jc almost 3 times of ITER



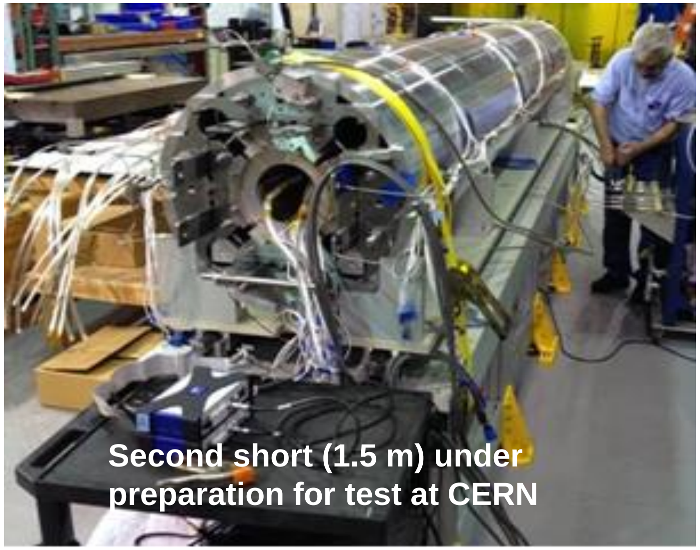
Laminated structure for series production



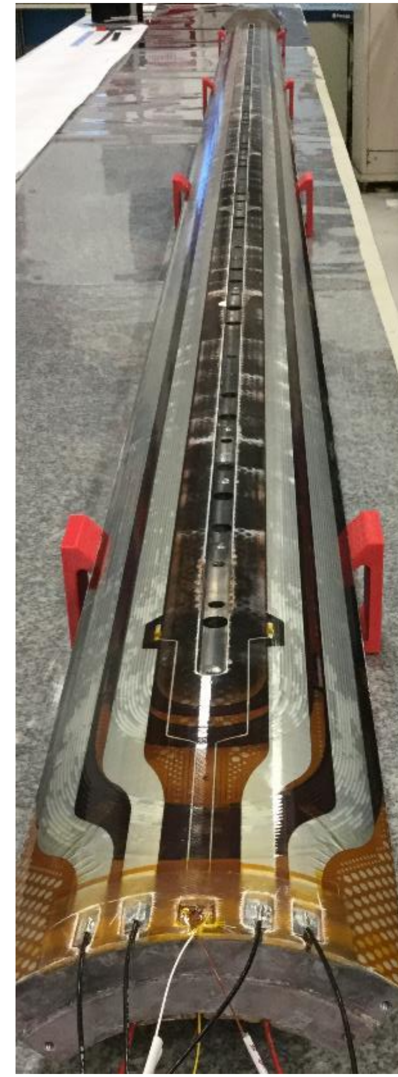
Section of MQXF mechanical model

Second long (4 m) Nb3Sn coil

Nb_3Sn quadrupole: 1st long prototype under construction



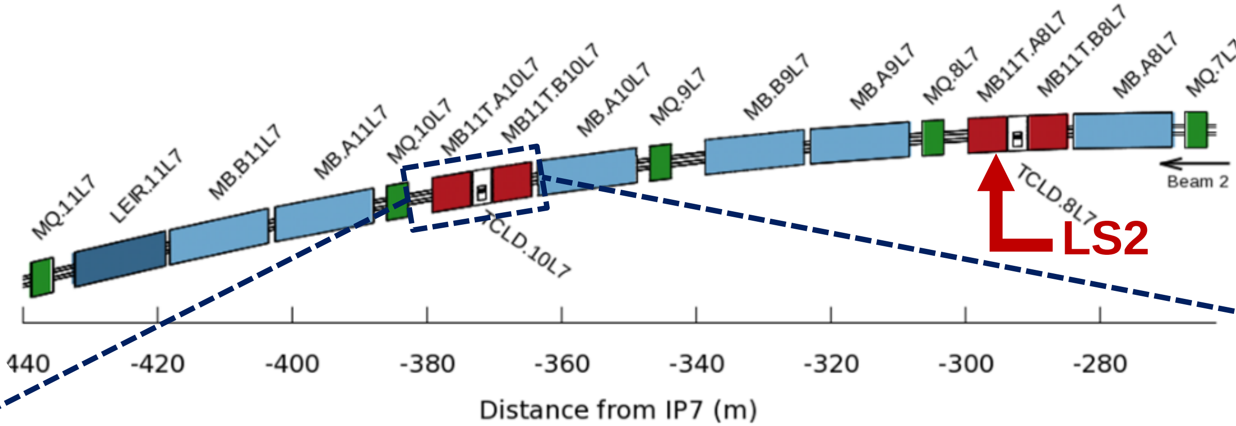
Second short (1.5 m) under preparation for test at CERN

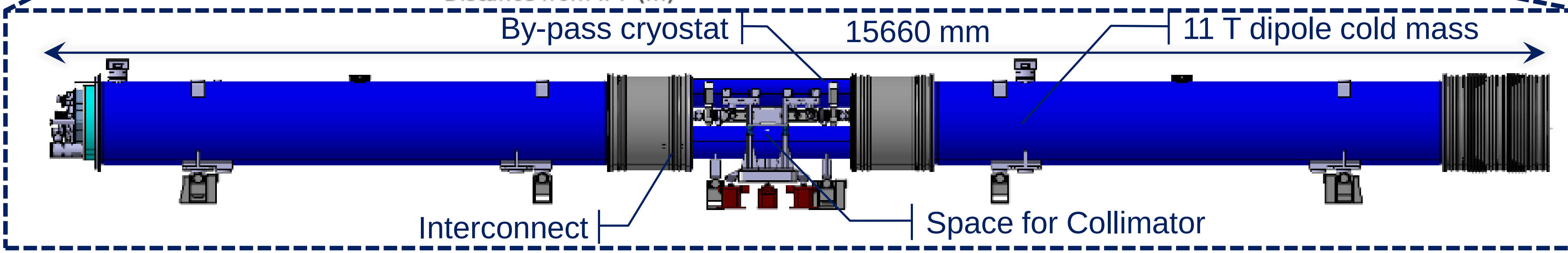


Insertion of coil package inside mechanical structure of the first IT quad prototypes (4.2 m long) in LBNL-USA

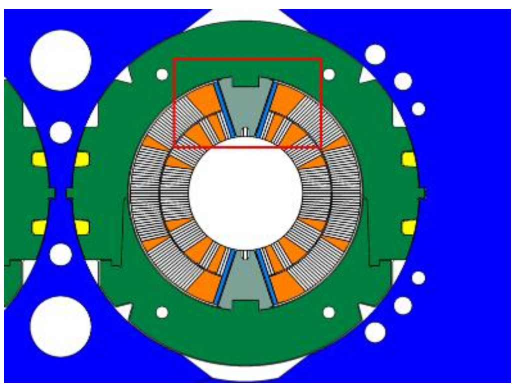
Courtesy of Frédéric Savary

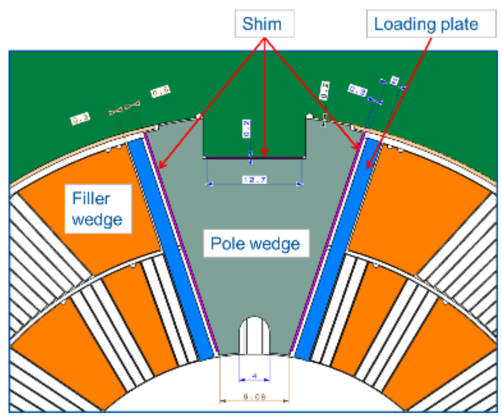
Nb_3Sn 11 T dipole: a lot of new features





Pole loading structure





Cable insulation with Mica (better coverage and rad-hard)

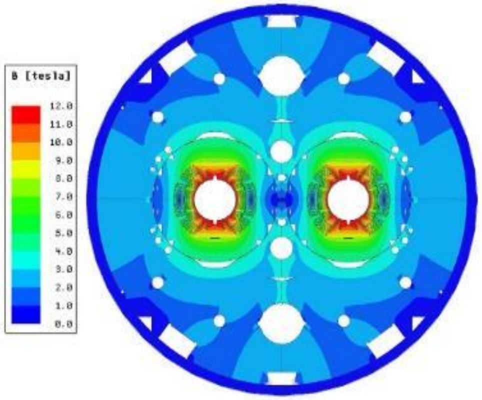
Courtesy of Lucio Rossi

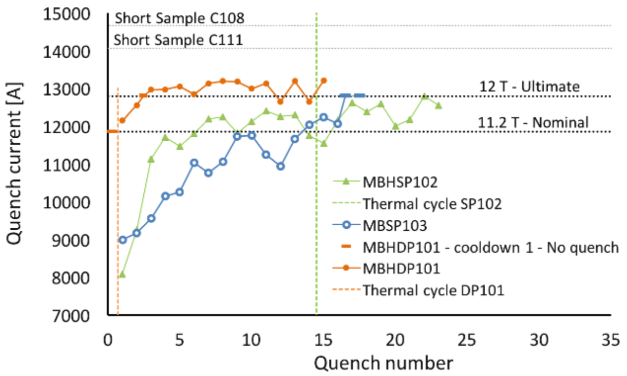
11T dipole (Nb_3Sn): constructing the first prototype at CERN

Milestone:
Magnet prototype (5.5m)
by December 2017

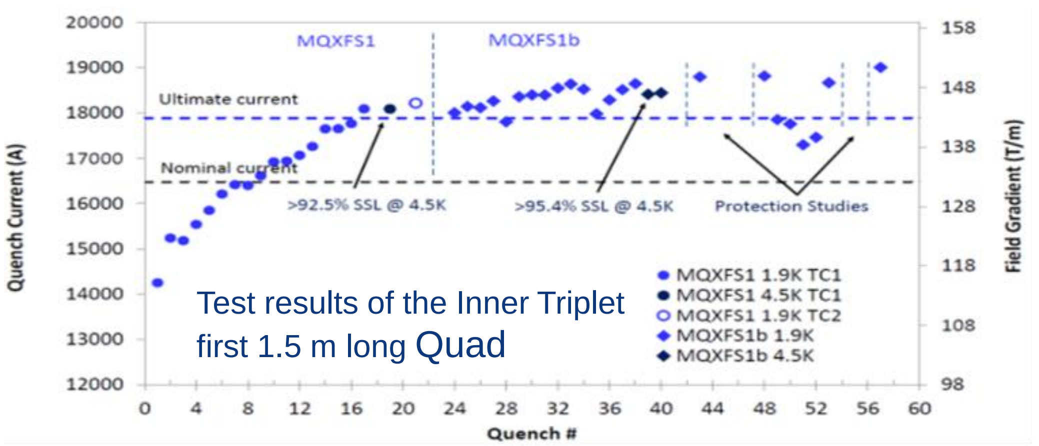
HL-LHC Main achievement 2016

The 11 T dipole 2 m long model reached a B_{max} of 12.5 T

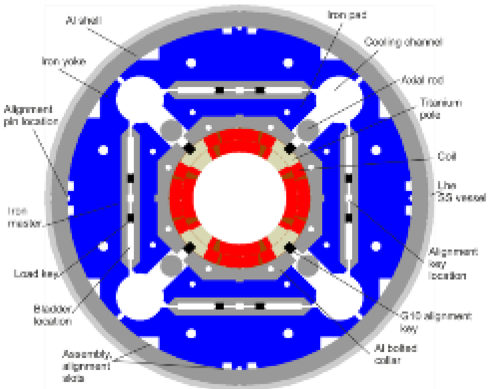




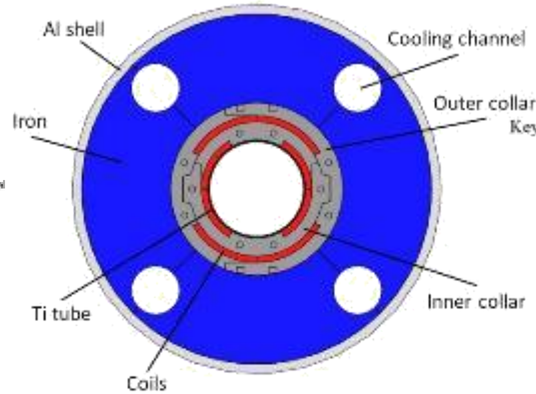
Test of the first full cross-section (150 mm aperture) Triplet Quadrupole, 1.5 m long, half CERN, half USA: it went beyond ultimate ($B_{max\ eq.}$ of 12.5 T)



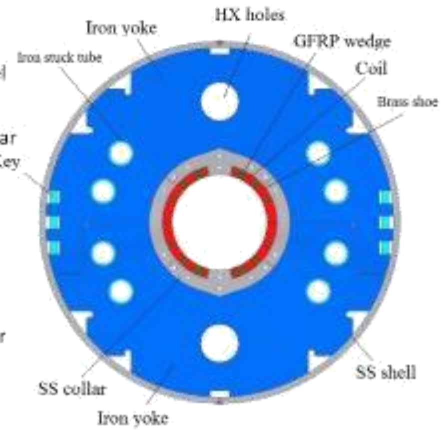
HL-LHC magnet “zoo” : global collaboration



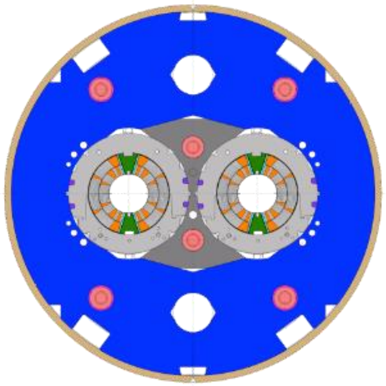
Triplet QXF (LARP and CERN)



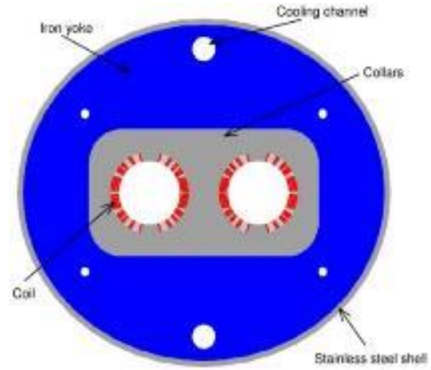
Orbit corrector (CIEMAT)



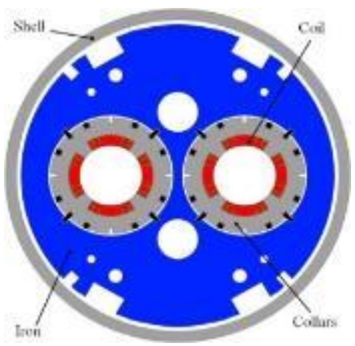
Separation dipole D1 (KEK)



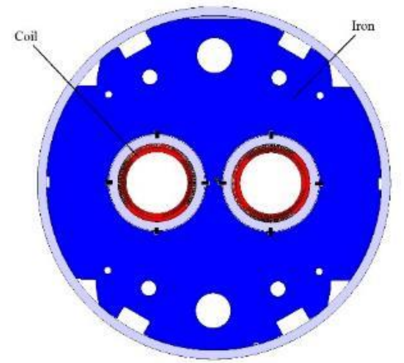
11 T dipole (CERN)



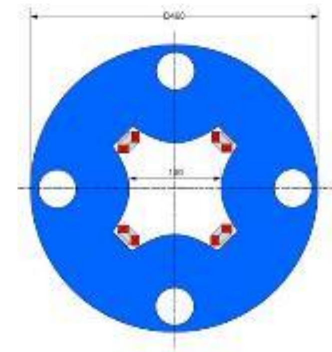
Recombination dipole D2 (INFN)



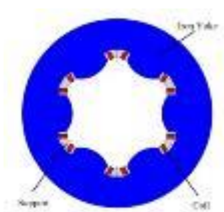
Q4 (CEA)



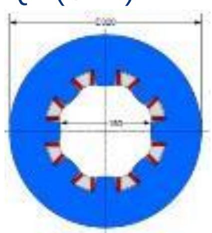
D2/Q4 orbit corrector (CERN)



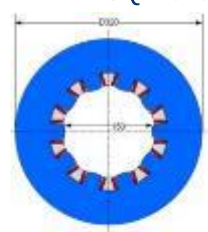
Skew quadrupole (INFN)



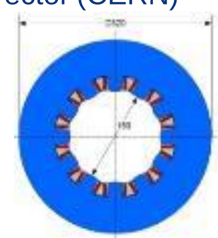
Sextupole (INFN)



Octupole (INFN)



Decapole (INFN)

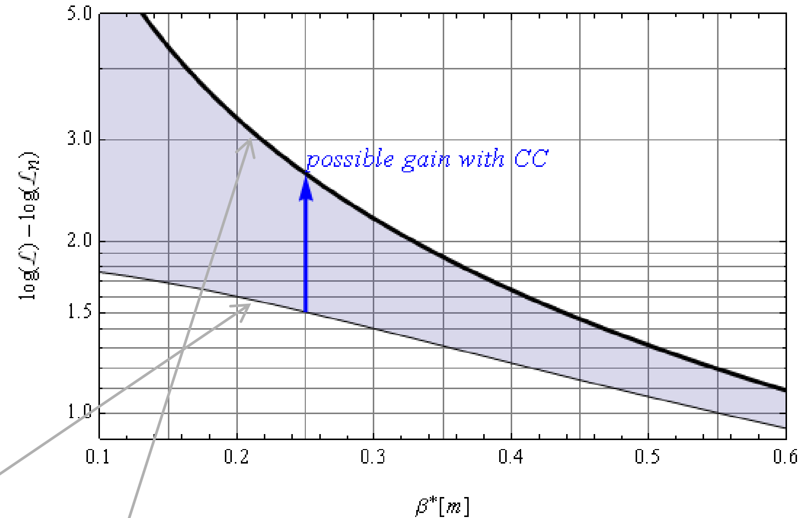


Dodecapole (INFN)

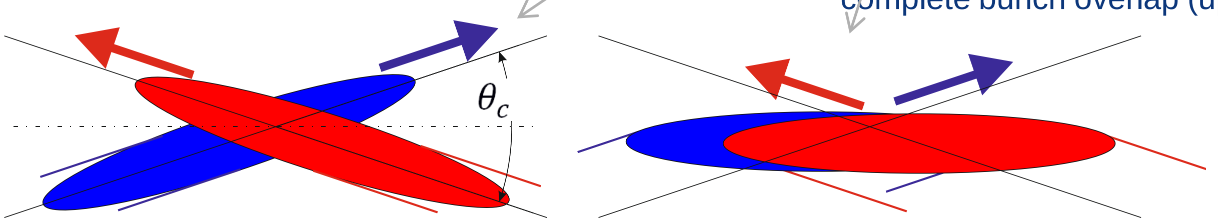
Approximately 150 single magnets and 50 cold masses for HL-LHC

Crab Cavity: Proton machine (HL-LHC)

- LHC Luminosity upgrade requires larger bunch charge and smaller β^*.
- To prevent parasitic bunch crossings, a larger crossing angle is needed.
- This leads to geometric luminosity loss at small β^*.
- A crab cavity is a deflecting cavity that kicks the head of each bunch one way, the tail the opposite way, such that the crossing angle is compensated for the bunch overlap in the collision point.

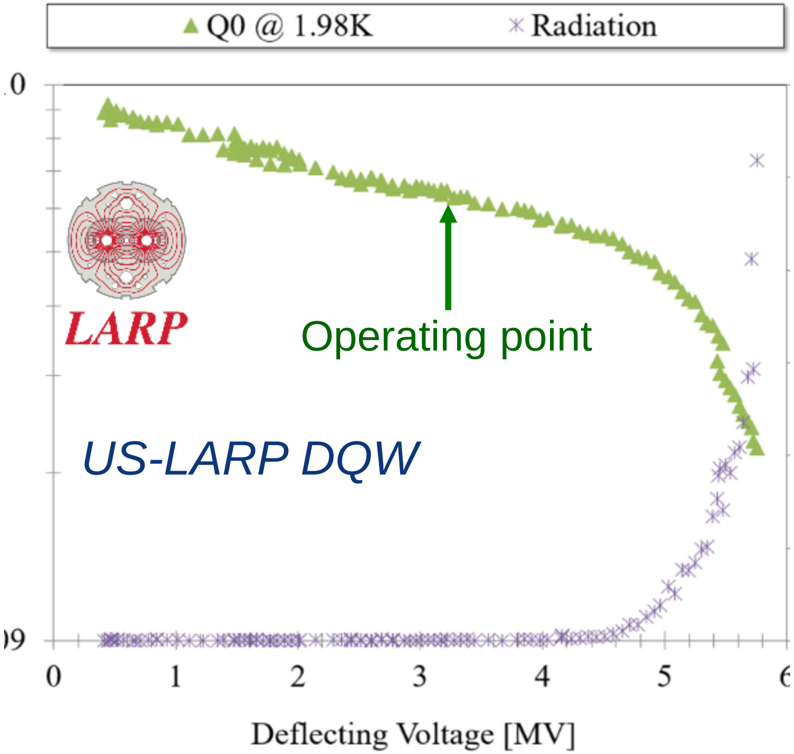


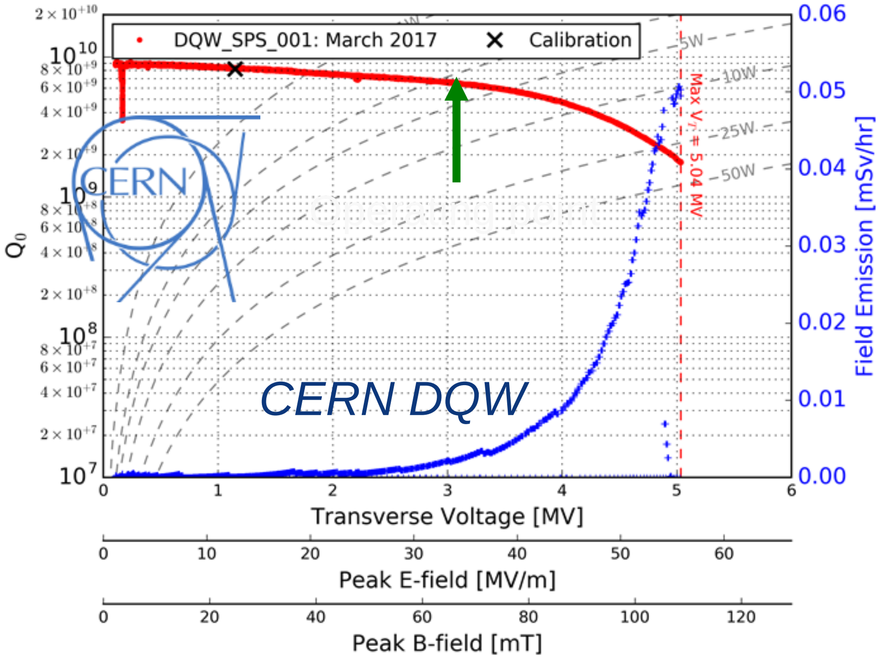
Luminosity vs. β^* for a non-zero crossing angle (lower curve) and possible luminosity for complete bunch overlap (upper curve)



Two bunches colliding with a non-zero crossing angle. Left: without crab cavity, right: with crab cavity

Superconducting RF Crab Cavity first prototypes



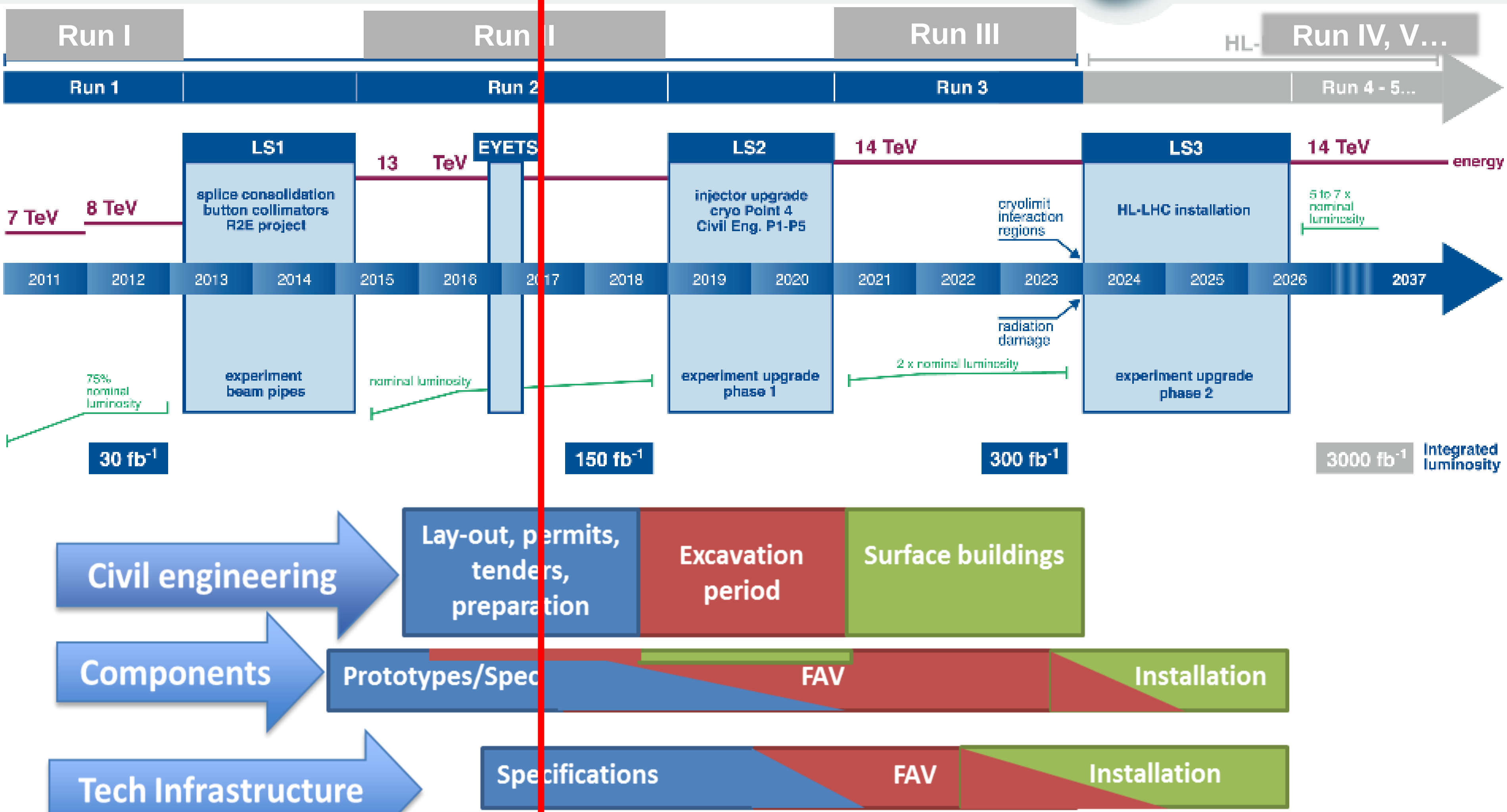


February 2017 three (naked) Crab Cavities were tested: all went well beyond the operating voltage of 3.4 MV

- **One US-LARP DQW (tested at JLab) went up to 5.4 MV**
- **One US-LARP RFD (tested at Jlab) reached 4.03 MV.**
- **One CERN DQW (test at SM18) went up to 5.04 MV**

Good results for the CC testing in the SPS in 2018

LHC / HL-LHC Plan



FAV = Fabrication, Assembly and Verification

Conclusions

- **Run 2 : LHC operates at 13 TeV with record performance**
  - **High availability ~ 50% and peak luminosity > 1.55 10^{34} cm^{-2} s^{-1}**
  - **2017 : a very good start; 6 fb^{-1} (29th June 2017)**
  - **2017 + 2018 : goal 90 fb^{-1} and to reach 1.8-2.0 10^{34} cm^{-2} s^{-1}**

- **LS2 preparation well advanced: mainly LIU, HL-LHC Civil Engineering and preparing to run at 14 TeV during Run 3**

- **(Run 1 + Run 2 + Run 3) => Goal 300 fb^{-1}**

- **The high luminosity project HL-LHC will allow to collect ten times more data (2026 - mid 2030ies) => Goal of 3'000 fb^{-1}**

- **The HL-LHC project is well established in terms of: beam parameters, technical requirements, needed technological developments.**
- **It is a "landmark project" in the ESFRI roadmap and formally approved by the CERN Council**
- **R&D work is well advanced and construction of some components started.**

HL-LHC is now a construction PROJECT

PALAIS DE TOKYO

During the performance Italian Artist Sven Sachsalber looked for a needle in haystack (November 2014)

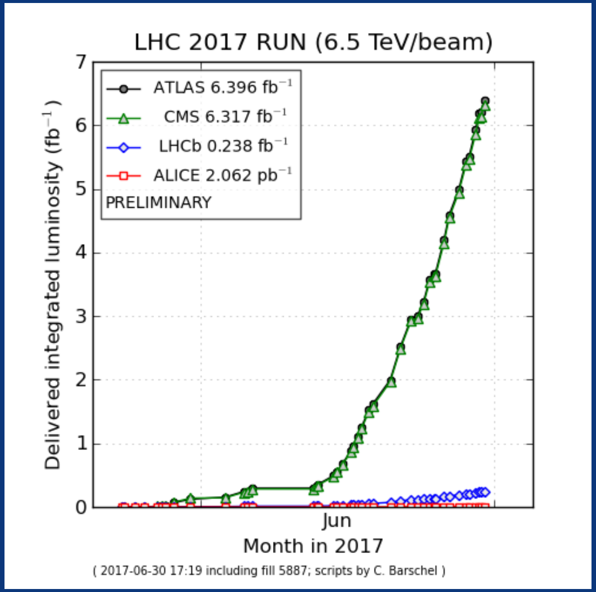


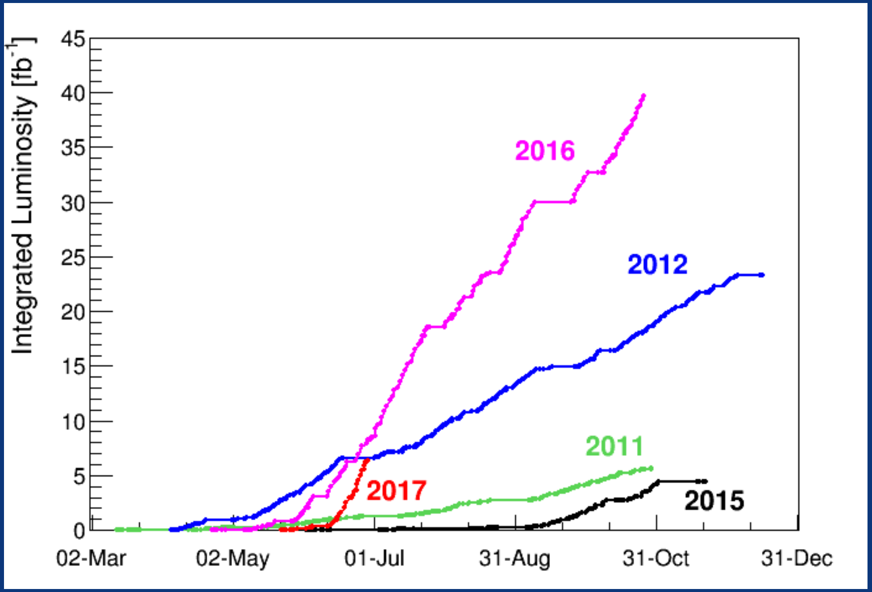

…he has gone through periods of doubt
and serious discouragement
… but after 2 days, he found it !


"Cercare un ago in un pagliaio"

A big thanks to all teams involved with LHC and injectors present and future operation

2017: a GOOD START, keep going !



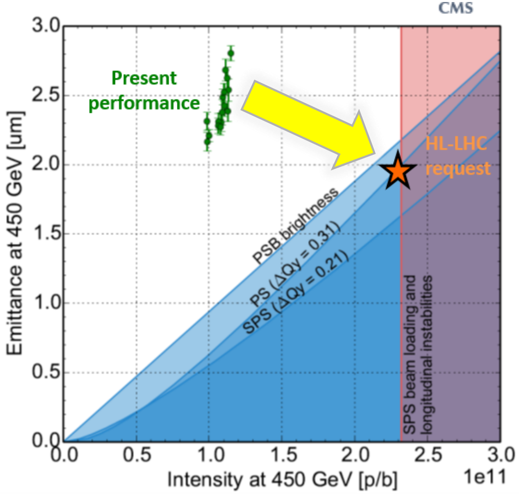


It is more difficult to stay on top than to get there

Mia Hamm

CERN

Goals and means of the LHC Injectors Upgrade: LIU project



	$\mathcal{N}$ (x 10^{11} p/b)	ε (μm)
LIU Baseline	2.3	2.2
HL-LHC	2.3	2.1

Increase injector reliability and lifetime to cover HL-LHC run (until ~2040) closely related to consolidation program

⇒ Upgrade/replace ageing equipment (power supplies, magnets, RF…)
⇒ Improve radioprotection measures (shielding, ventilation…)

Increase intensity/brightness in the injectors to match HL-LHC requirements

⇒ Enable Linac4/PSB/PS/SPS to accelerate and manipulate higher intensity beams (efficient production, space charge & electron cloud mitigation, impedance reduction, feedbacks, etc.)
⇒ Upgrade the injectors of the ion chain (Linac3, LEIR, PS, SPS) to produce beam parameters at the LHC injection that can meet the luminosity goal

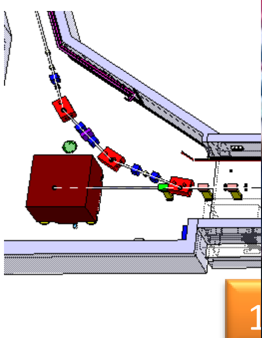
Linac4 reached its energy goal – Oct. 2016

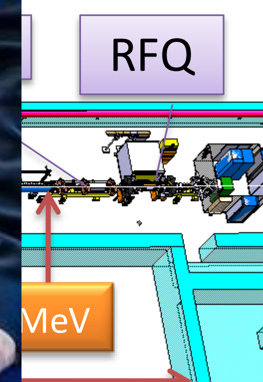
The PIMS s

September-November 2016: Commissioning with beam of 12 PIMS accelerating structures (built in collaboration CERN-NCBJ-FZJ).

he last beam
ugust 2016

ember 2017
50 MeV





LINAC4 Inauguration 9th May 2017