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LHC accelerator status and prospects

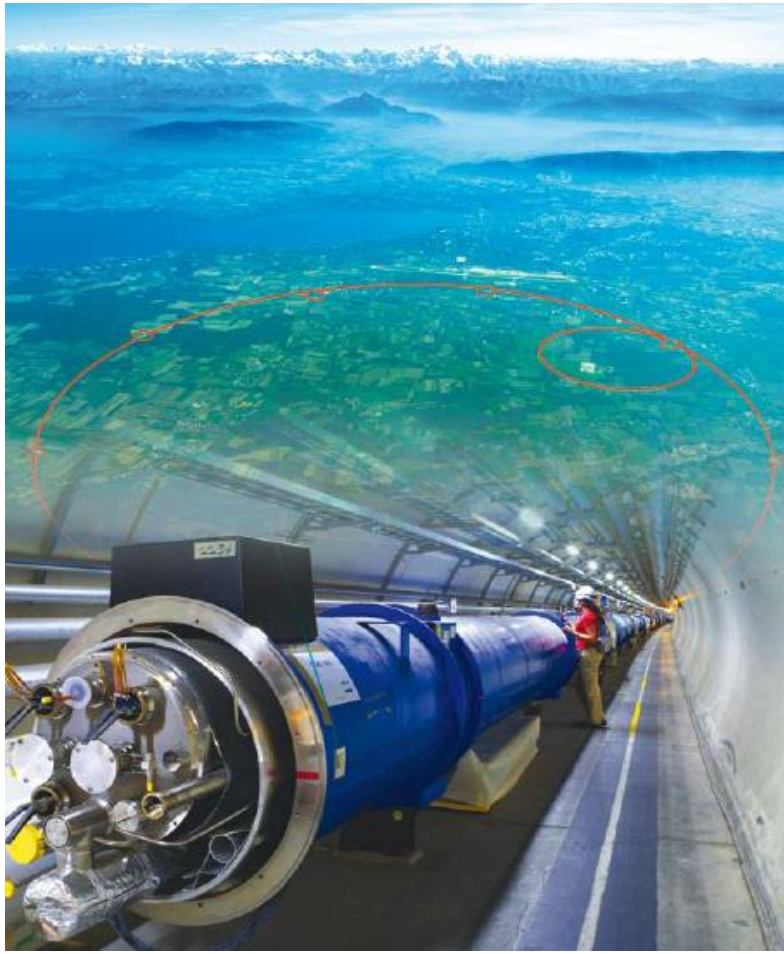
Frédérick Bordry

LHC (Large Hadron Collider)

14 TeV proton-proton accelerator-collider built in the LEP tunnel

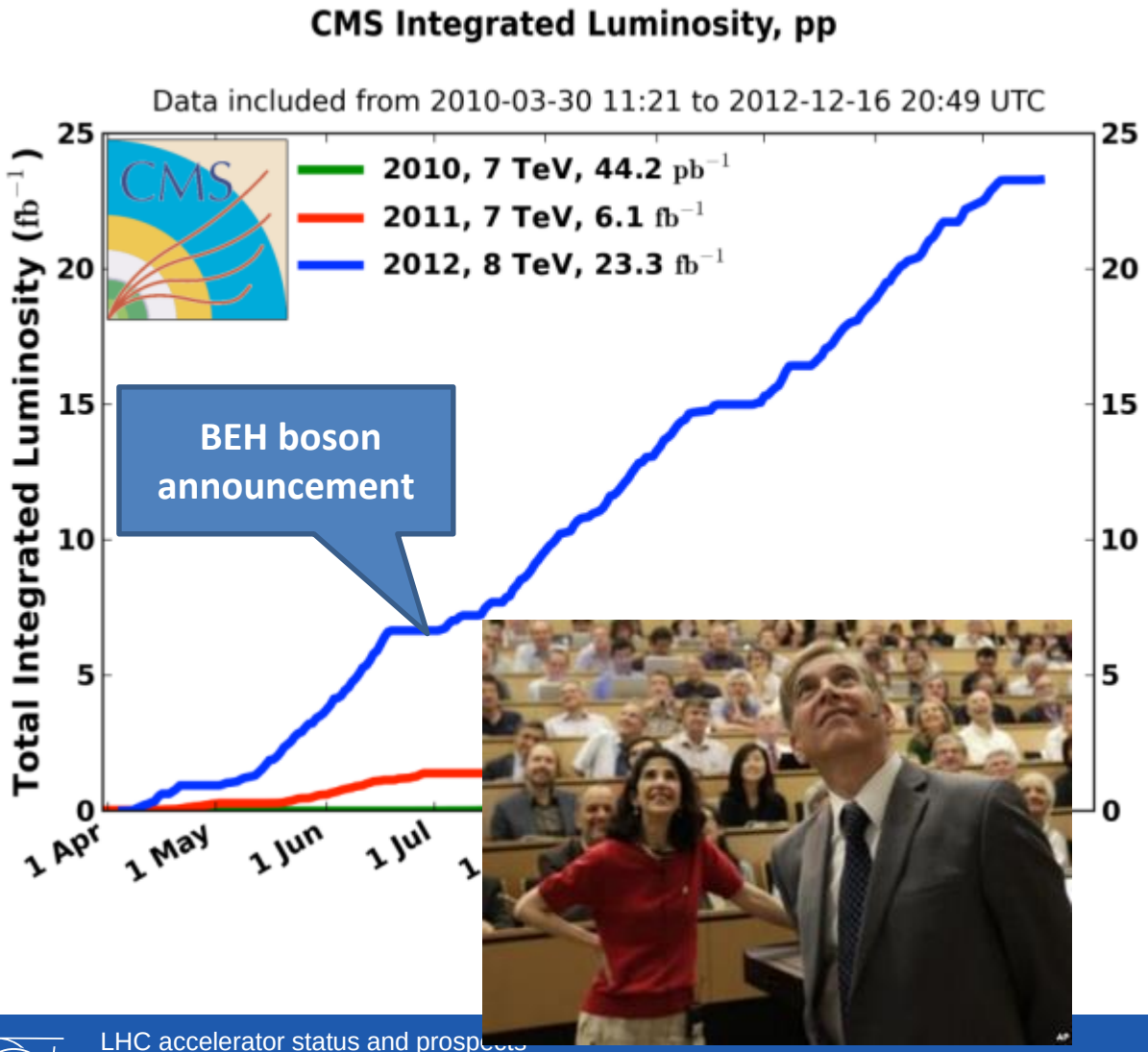
Lead-Lead (Lead-proton) collisions

1983 : First studies for the LHC project
1988 : First magnet model (feasibility)
1994 : Approval of the LHC by the CERN Council
1996-1999: Series production industrialisation
1998 : Declaration of Public Utility & Start of civil engineering
1998-2000: Placement of the main production contracts
2004 : Start of the LHC installation
2005-2007: Magnets Installation in the tunnel
2006-2008: Hardware commissioning
2008-2009: Beam commissioning and repair
2010-2035: Physics exploitation



A 27 km circumference collider…

LHC 2010-2012: a rich harvest of collisions



Σ ~30 fb^{-1}

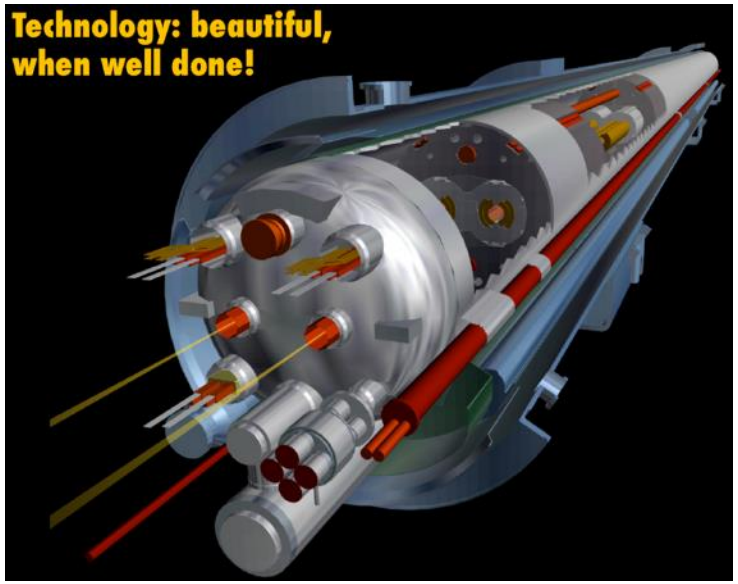
2010: **0.04 fb^{-1}**
7 TeV CoM
Commissioning
2011: **6.1 fb^{-1}**
7 TeV CoM
… exploring limits
2012: **23.3 fb^{-1}**
8 TeV CoM
… production

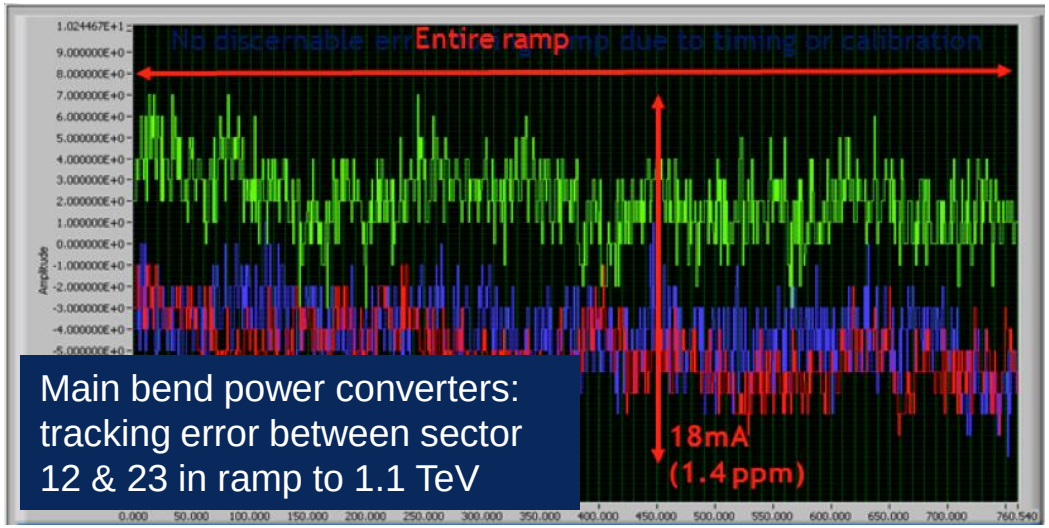
7 TeV and 8 TeV in 2012
Up to 1380 bunches
With 1.5 10^{11} protons

Run 1

Run 1 (2010 – 2012)

- Foundations well proven at 8 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

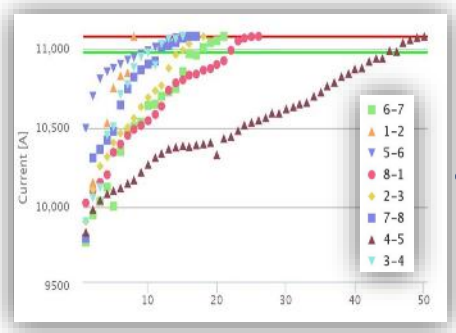
April ‘13 to Sep. ‘14

5th April

3rd June
First Stable Beams

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

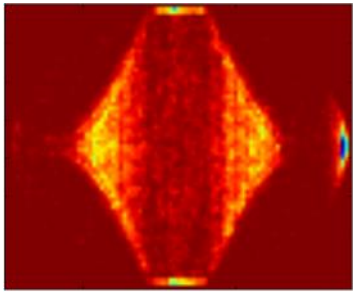
13-14 | Aug 14-Apr | 2015



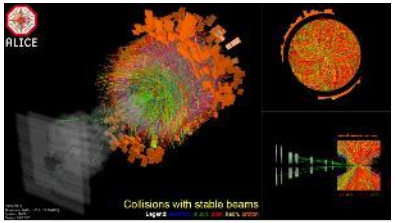
Dipole training campaign

10th April
Beam at 6.5 TeV

Struggle



IONS



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

2015 LHC Luminosity at 13 TeV

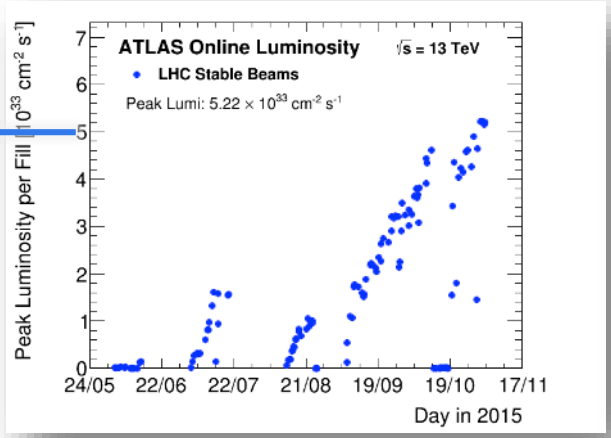
ATLAS

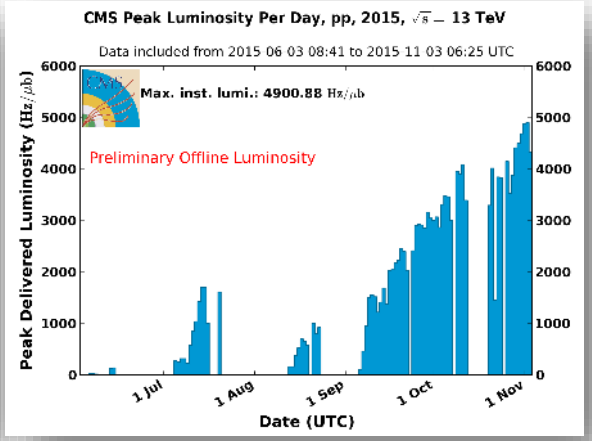
CMS

Peak

5 x 10^{33} cm^{-1} s^{-1}

Design 10^{34} cm^{-1} s^{-1}

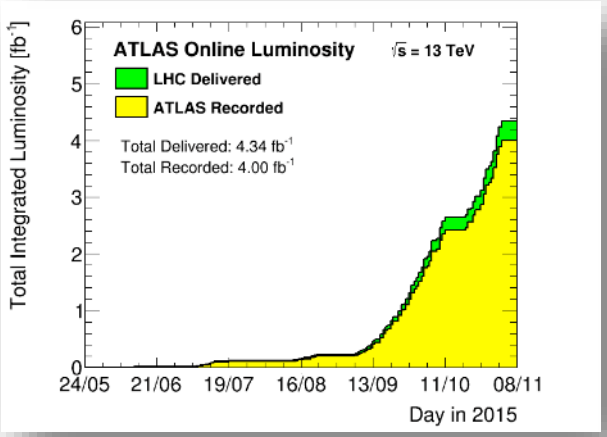


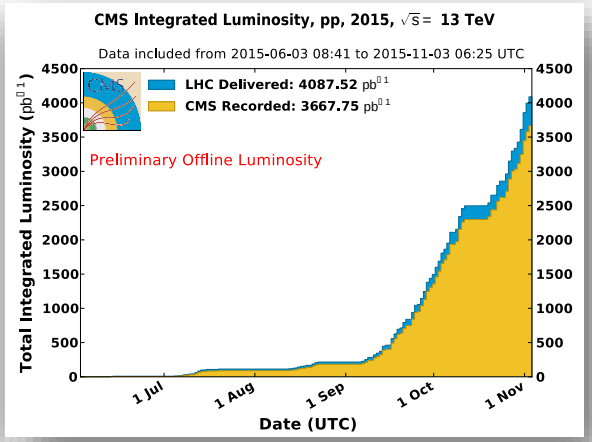


Integrated

Achieved ~ 4.3 fb^{-1}

Last week of operation > 1 fb^{-1}

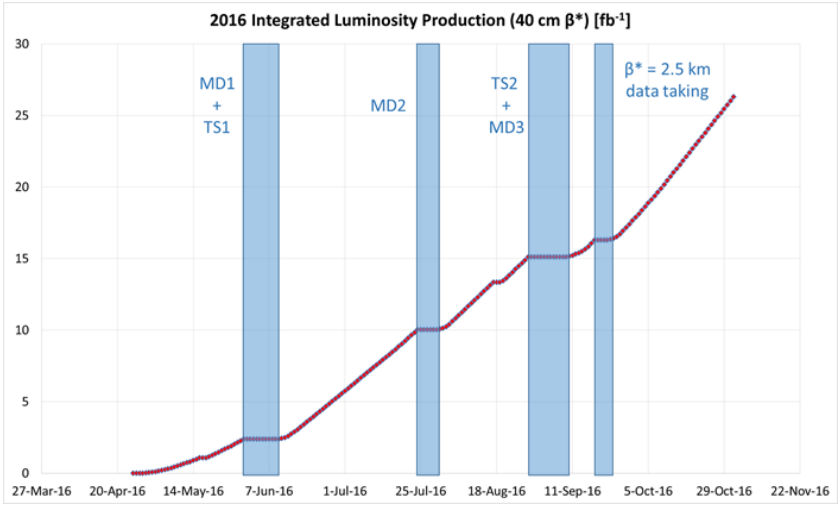


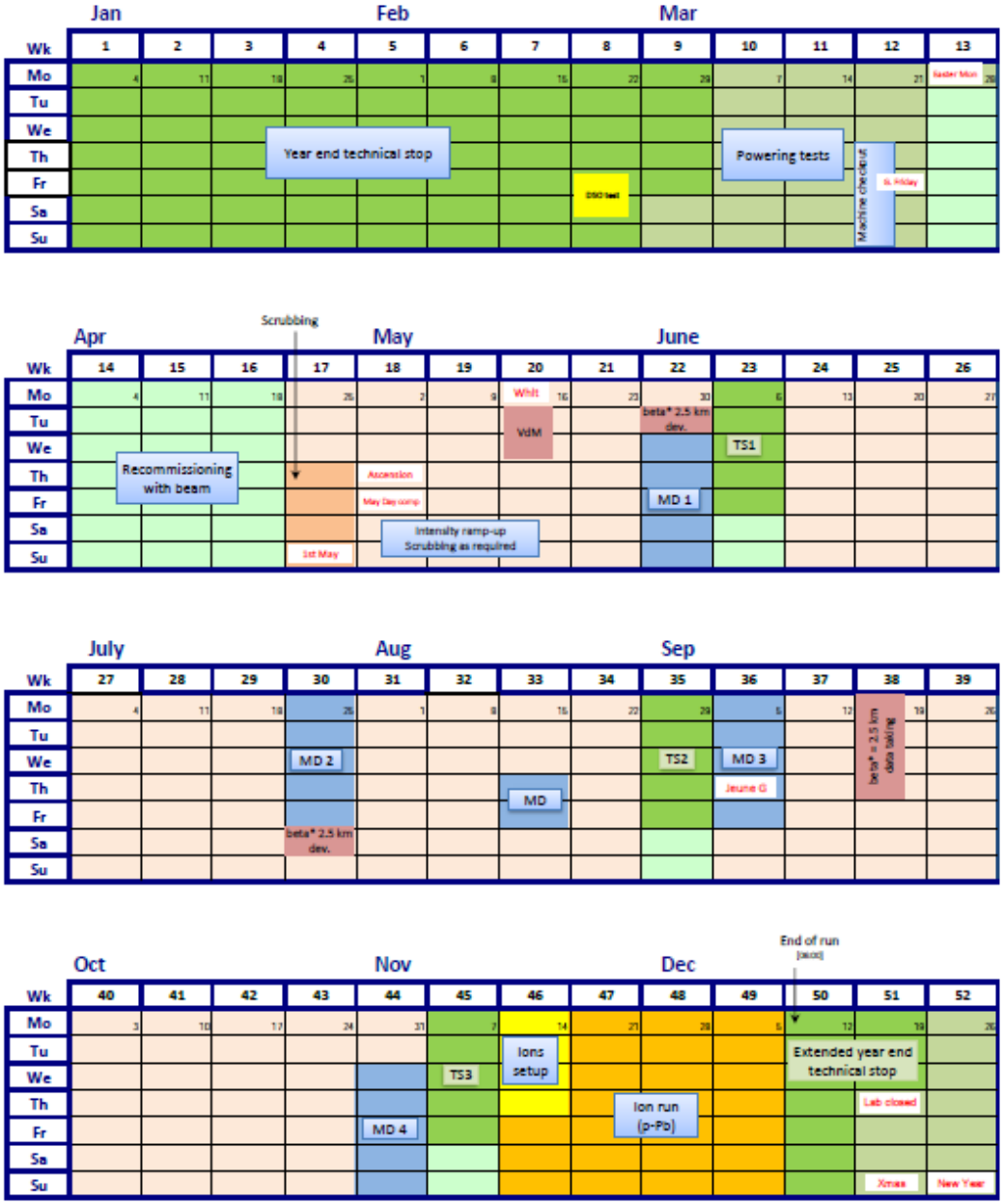


LHC schedule 2016

2016: a production year

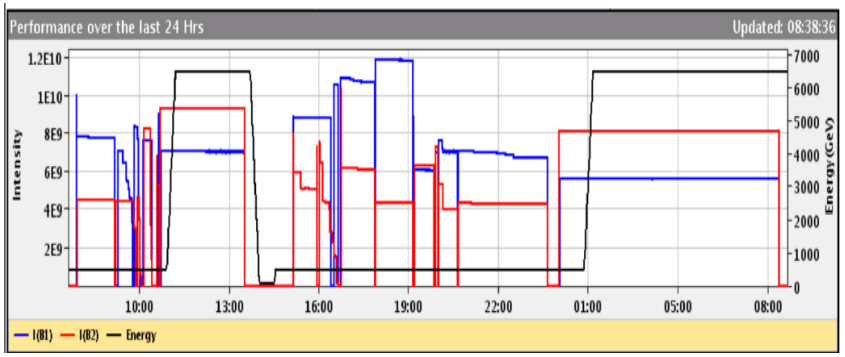
Integrated luminosity goal:
2016 : ~ 25 fb^{-1} at 13 TeV c.m





First circulating beams in LHC in 2016 on Easter Friday 25th March 2016

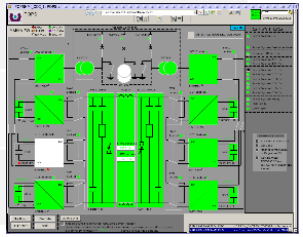
LHC Start-up 2016



Friday 25th March	First circulating beam
Saturday 26th March	First ramp to 6.5 TeV
Sunday 27th March	Squeeze to 0.4 m and optics measurements
Thursday 31st March	Optics correction at 6.5 TeV (flat-top+squeeze)
Wednesday 6th April	Nominal bunch to flat-top
Friday 8th April	Nominal bunches into collisions
Tuesday 12th April	Quiet beams
Sunday 17th April	Aperture measurement (collision)
Thursday 21st April	72 bunch injection to 444 bunches/beam
Friday 22nd April	First Stable Beams – 3 bunches/beam

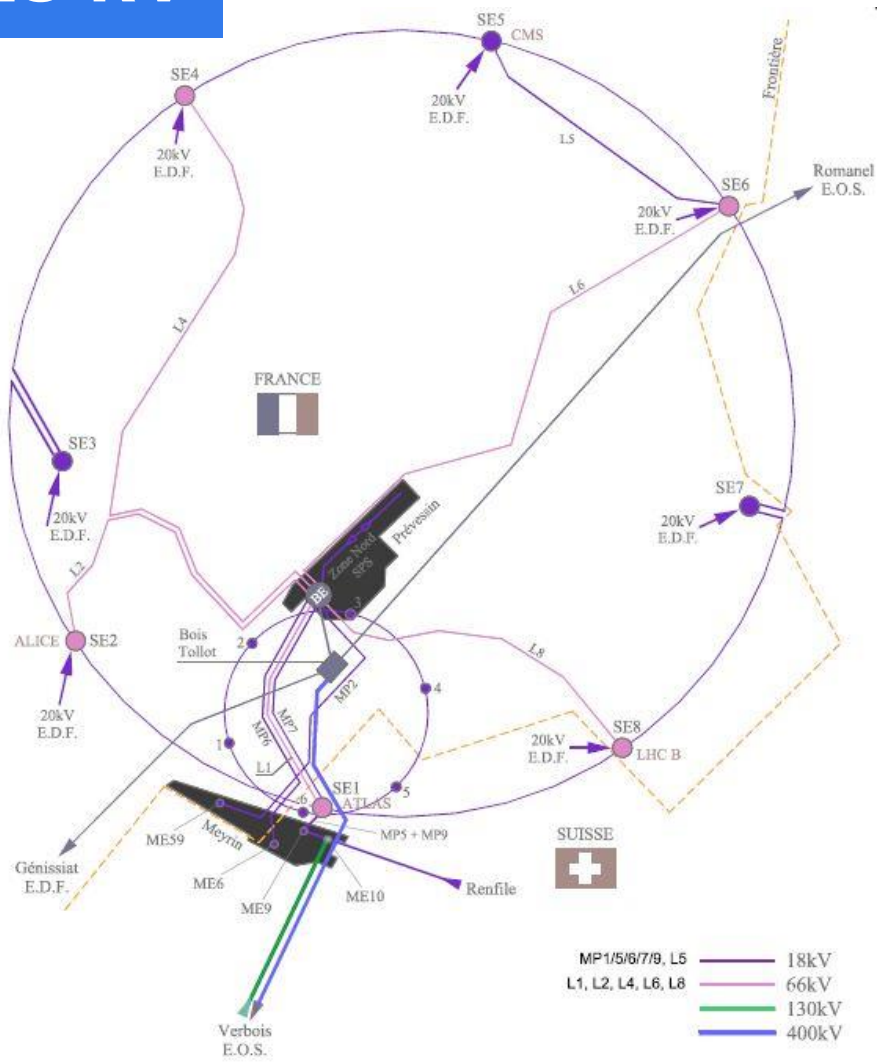
LHC April – May 2016

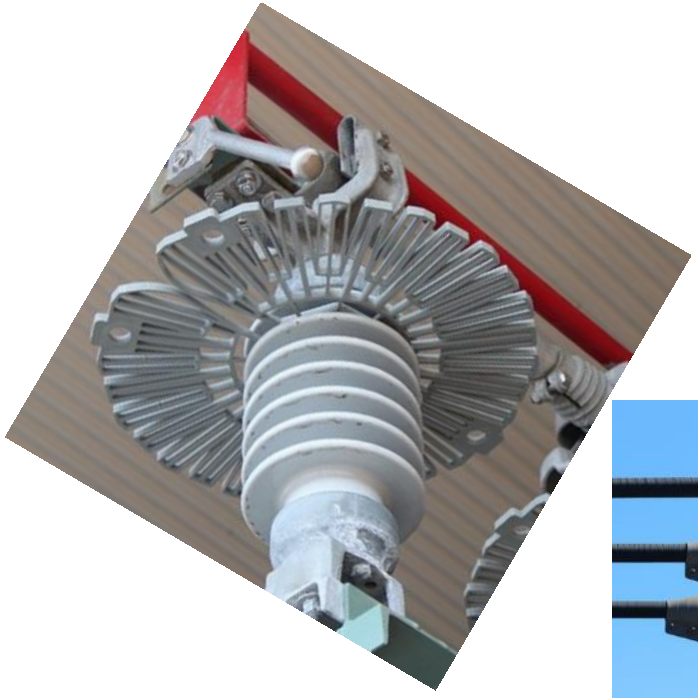
Mon 25th April	Start scrubbing	
Tues 26th April	1668+1884 bunches	**Vacuum leak on SPS dump**
Weds 27th April	Stable Beams 12 bunches.	**POPS – capacitor bank**
Thu 28th April	Beam back (PS on rotating machine)	
Fri 29th April	Stable Beams 49 bunches	**Weasel Transformer Pt8**
Thu 5th May	Beam back	
Fri 20th May	Stable Beams 1177 bunches	**Rotating machine down**
Sat 21st May	Fill 4947 lost after 35.5 hours	
Thu 26th May	POPS back in action	



- **Lost around 2 weeks to technical faults**
- **Limitation number of injected bunches to avoid stressing SPS beam dump**

P8 Transformer 66 kV/18 kV





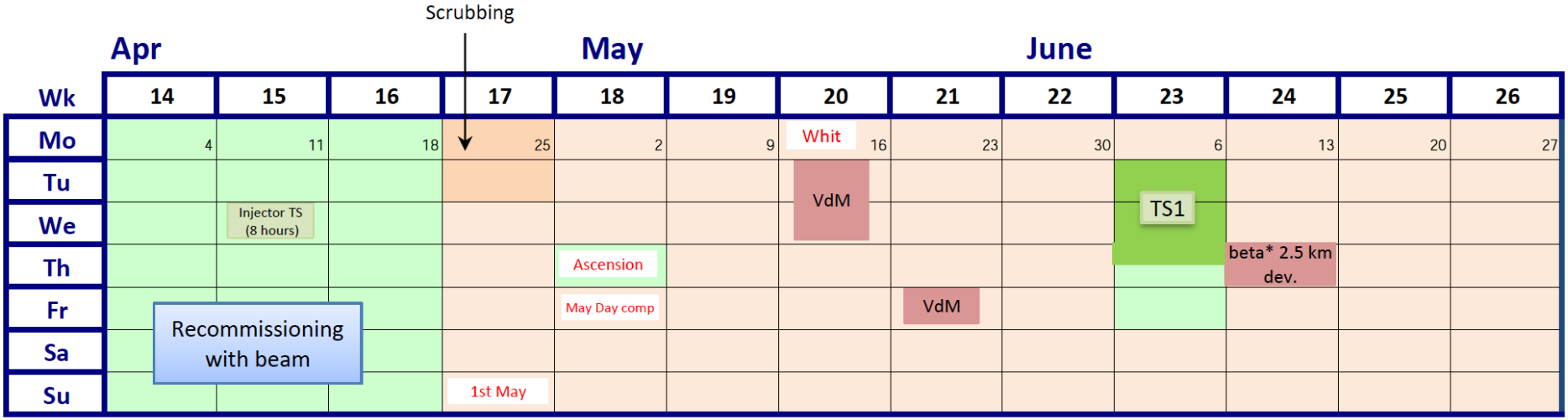
Tests divers

Eviter les dégâts de fouines

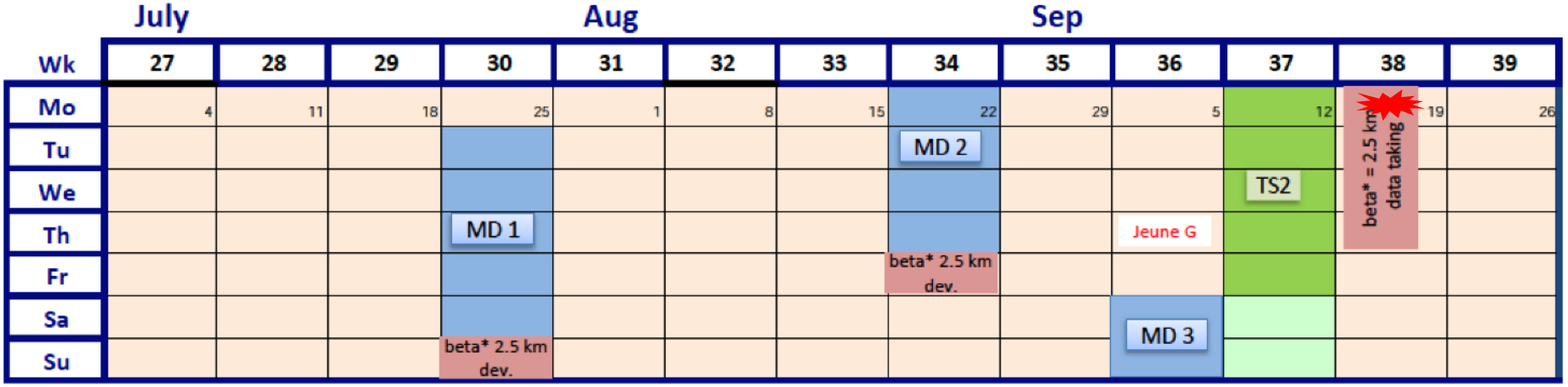
Contre les fouines avides de ronger, toute une panoplie de méthodes, plus ou moins efficaces, sont mises en oeuvre. Aucun moyen ne garantit une protection totale. Néanmoins, diverses recommandations vous montrent comment éloigner les fouines par des procédés simples.

Les assurances sont mises à contribution
Certes, le nombre de cas annoncés diminue, mais pour les assurances, les frais demeurent, c'est-à-dire que le coût moyen par cas est toujours plus élevé. Chaque année, les compagnies d'assurances suisses doivent débourser des dizaines de millions de francs à cause de dégâts

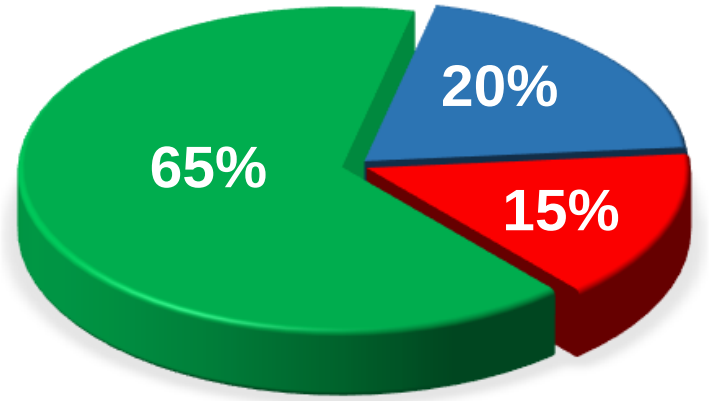
LHC : new schedule



- MD1 period postponed (5 days)
- TS1 shortened to 2.5 days – considerable amount done during extended stops for technical issues



2016 Overall machine efficiency



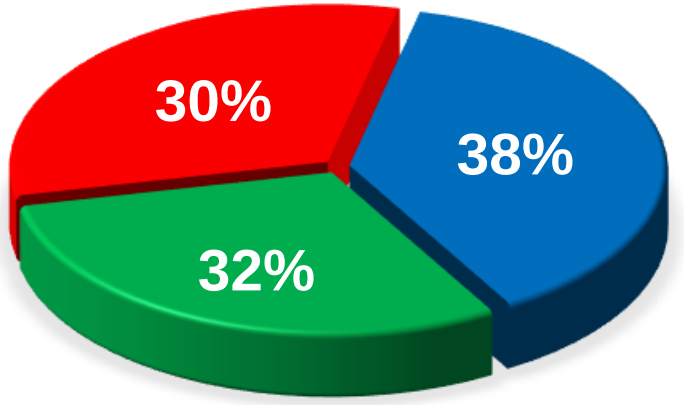
STABLE BEAMS

FAULTS

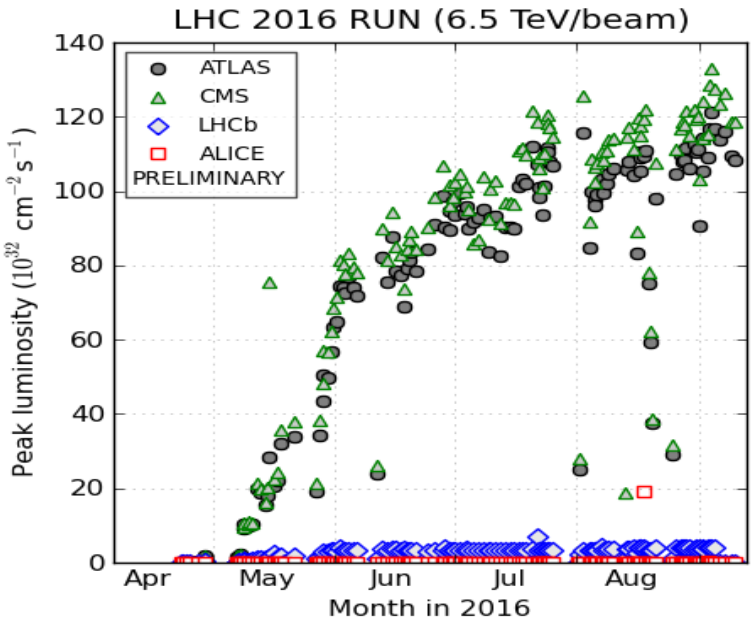
Setting Up
(Ramp down, Injection, Ramp up, Squeeze, Adjust)

Performance of data production
(no commissioning, MD, …)

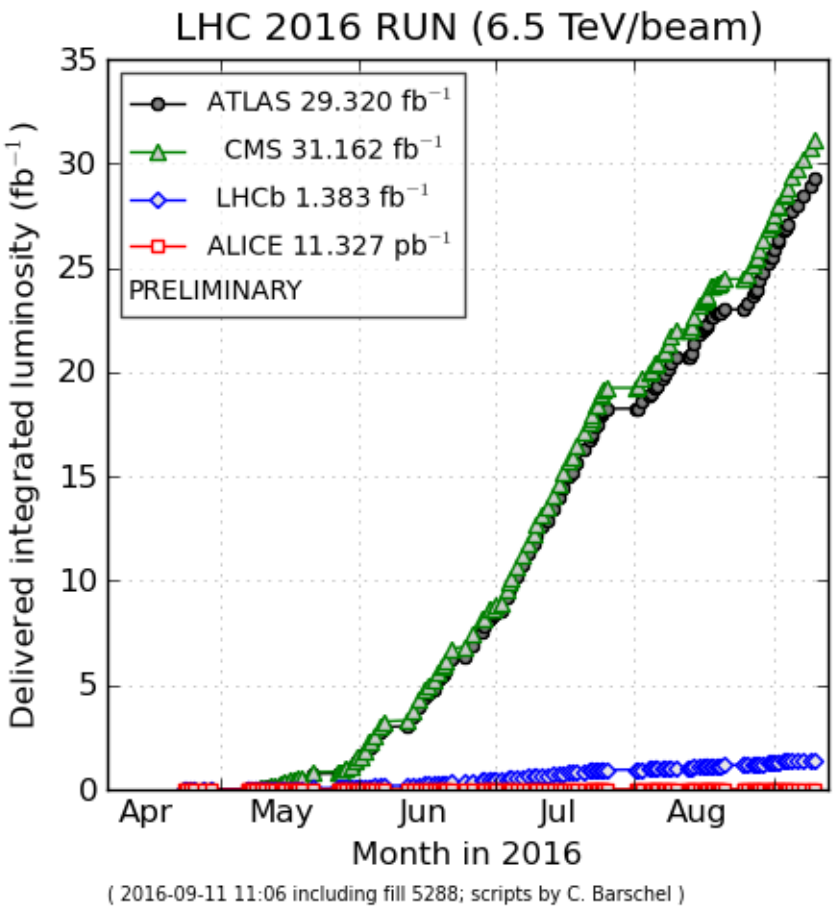
2015 efficiency



Peak and Integrated luminosity overview



Design luminosity
> 10^{34} cm^{-2} s^{-1}



(2016-09-11 11:06 including fill 5288; scripts by C. Barschel)

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}

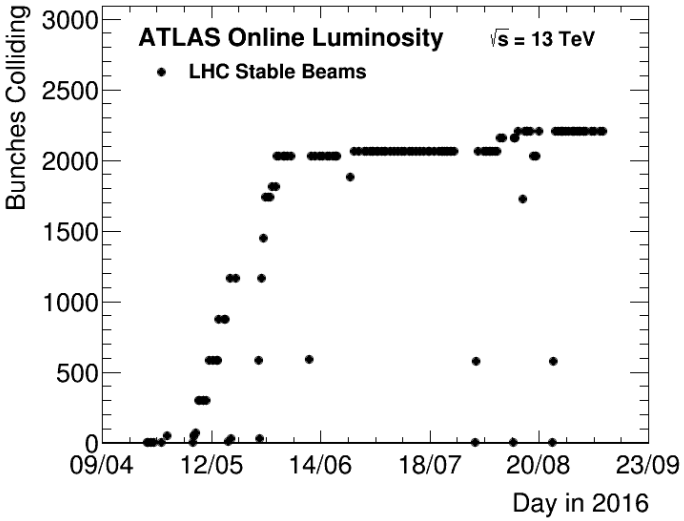
Electron cloud

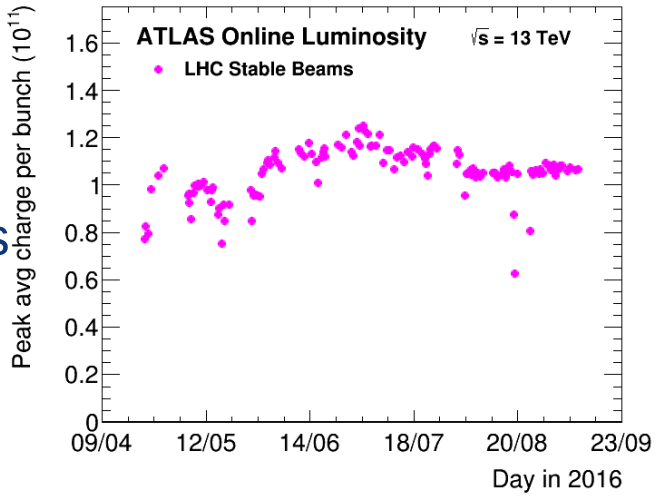
Still significant heat-load within cryogenic limits

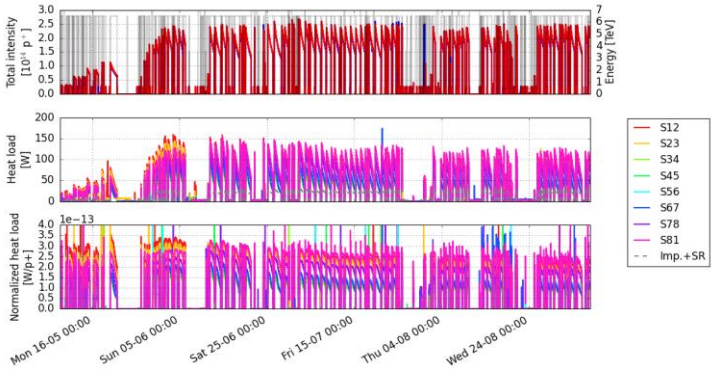
Dynamics – well handled by cryogenics feed-forward – no impact on operations in the present conditions

UFOs

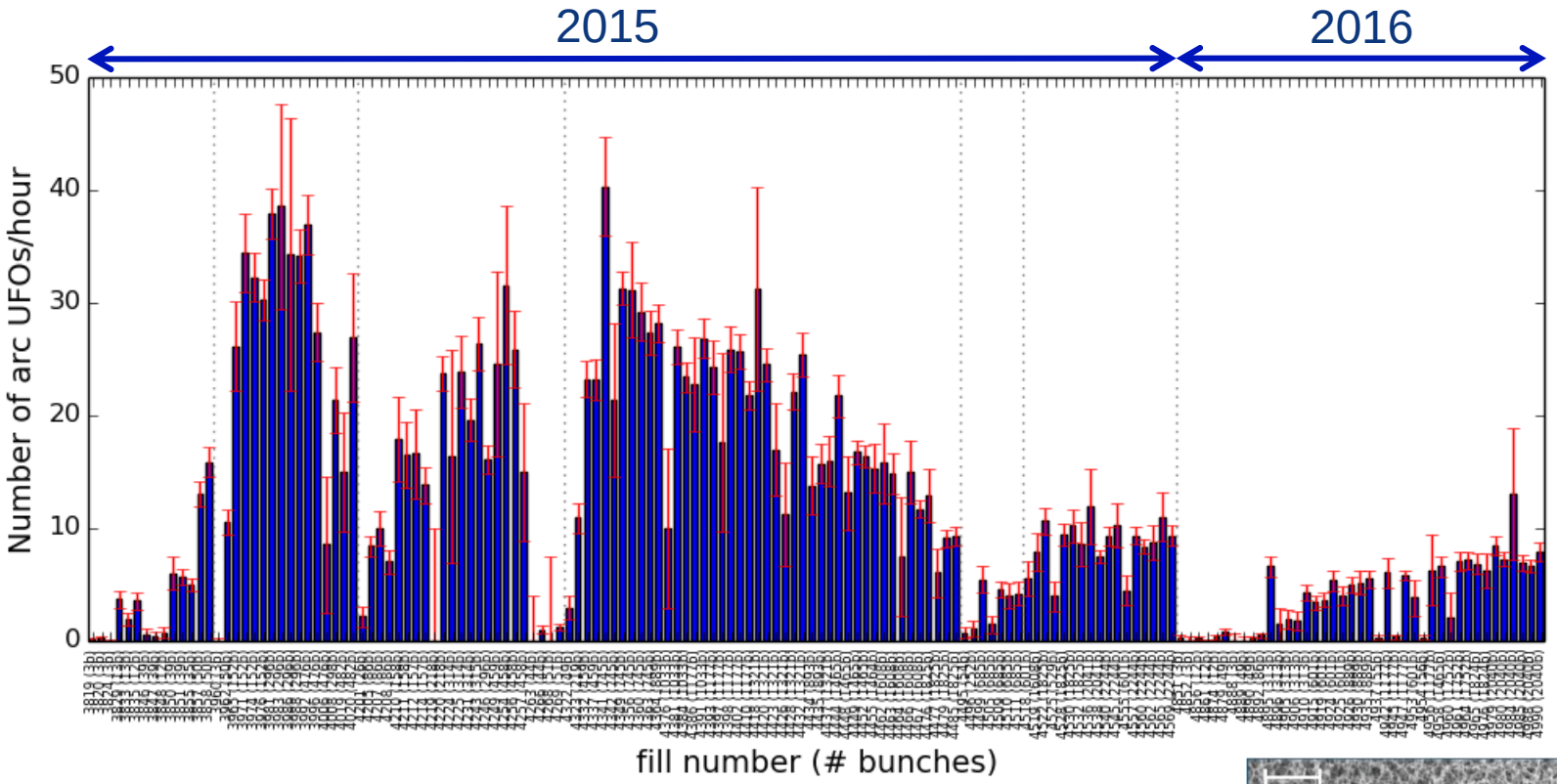
Frequency has happily conditioned down

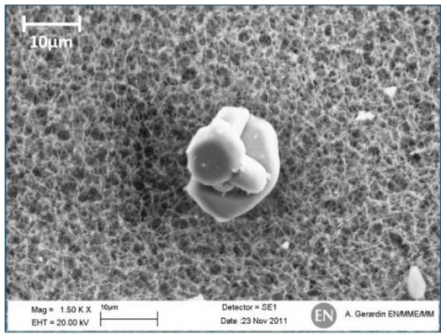






UFOs – 2015 and beginning 2016

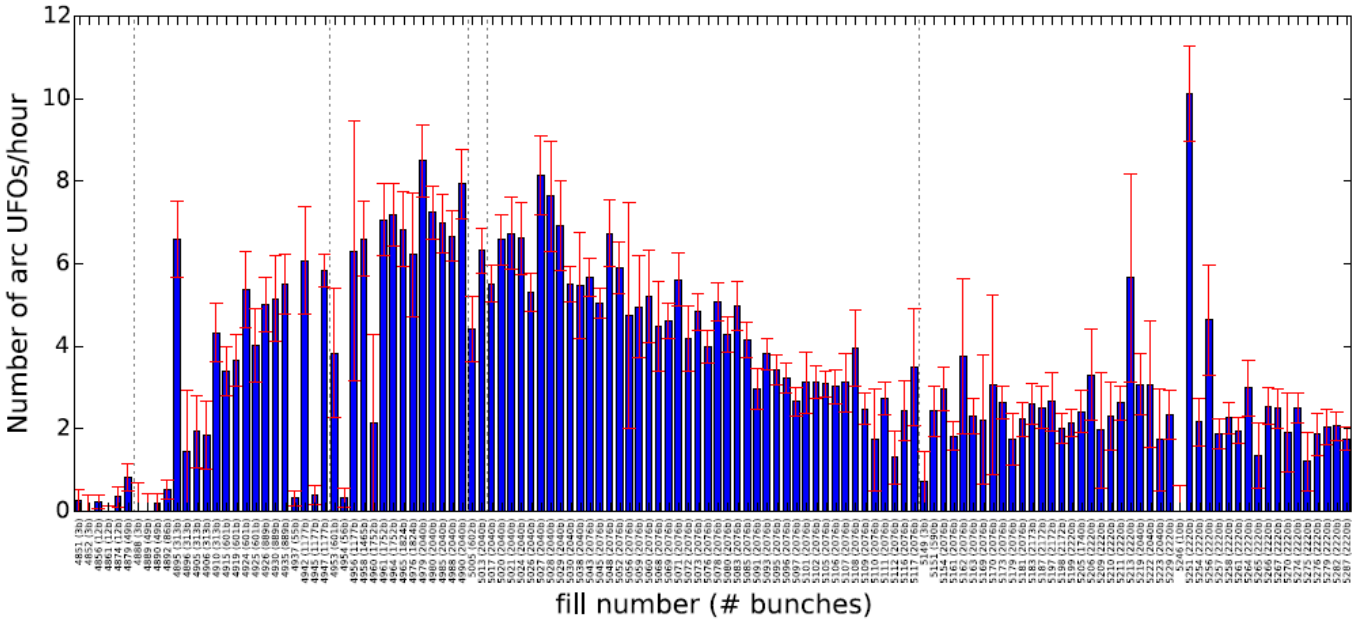




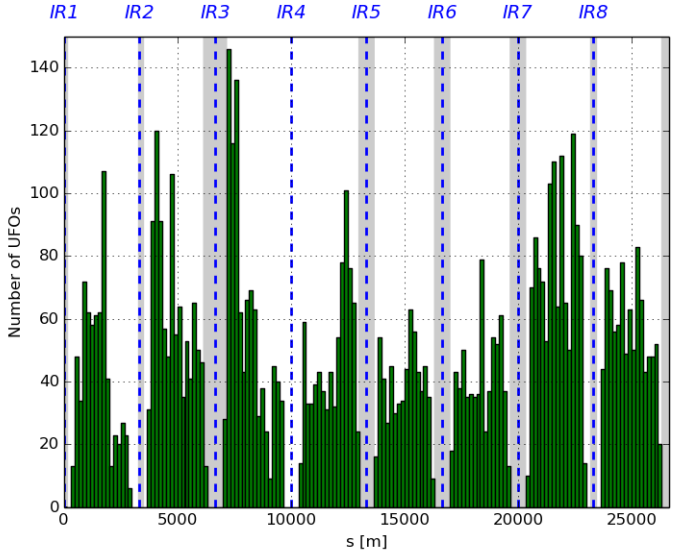
Arc UFOs : rates similar to end of 2015

- did not lose conditioning over the YETS stop

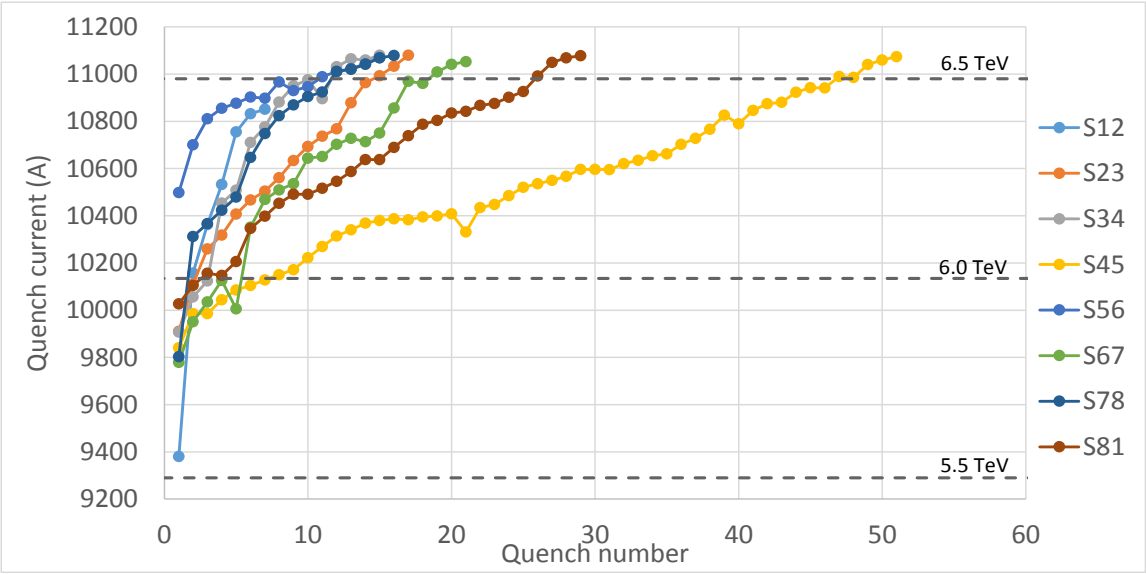
UFOs - 2016



longitudinal locations (whole 2016)



Recall: Dipole Training Campaign after LS1 (2015)



Each Sector Trained to 6.55TeV (11080A)
(100 A above the operational field)

172 training quenches
~600 secondary quenches
Only 1 quadrupole quench

Cryogenics recovery time: 8 – 10 hours

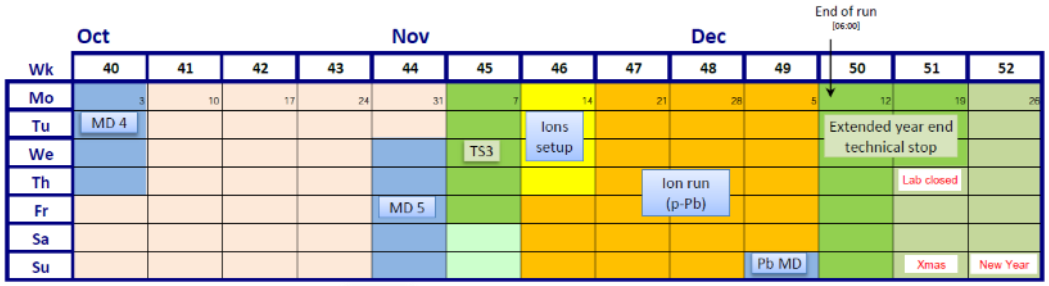
Sector	# Training quench	Flattop quenches
S12	7	0
S23	17	0
S34	15	1
S45	51	0
S56	18	3
S67	22	1
S78	19	3
S81	29	0
Total	171	8

Large variation in number of training quenches per sector

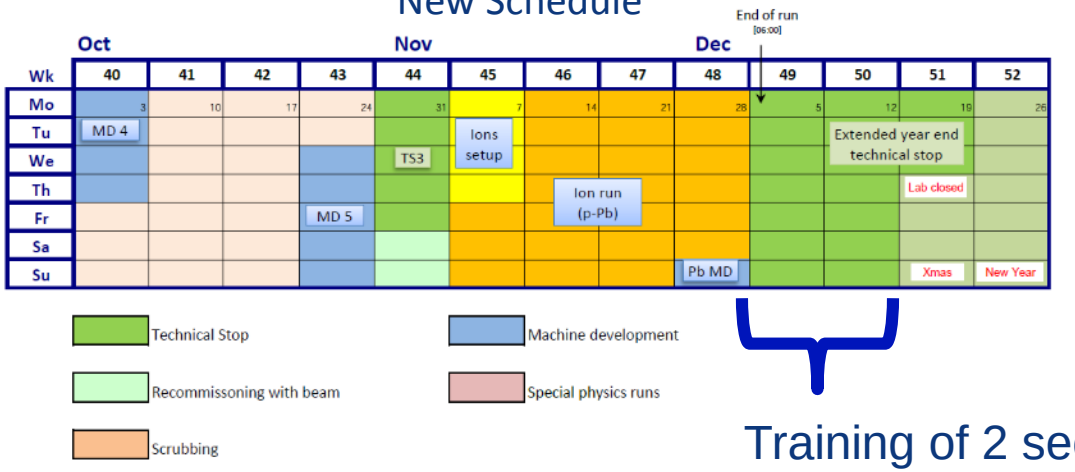
Circuit	Status	#M Firm 1	#M Firm 2	#M Firm 3	#MQ Firm 1	#MQ Firm 2	#MQ Firm 3	#MQ total	#CQ total
RB.A12	11080 A reached	50	95	9	2	1	4	7	7
RB.A23	11080 A reached	56	58	40	0	2	15	17	17
RB.A34	11080 A reached	44	81	29	1	7	8	16	16
RB.A45	11080 A reached	48	44	62	-	3	48	51	49
RB.A56	11080 A reached	28	42	84	0	0	18	18	17
RB.A67	11080 A reached	57	36	61	0	1	21	22	21
RB.A78	11080 A reached	53	40	61	2	10	7	19	19
RB.A81	11080 A reached	64	24	66	0	3	26	29	26

LHC: new schedule approved on 31st August

Initial LHC SCHEDULE



New Schedule

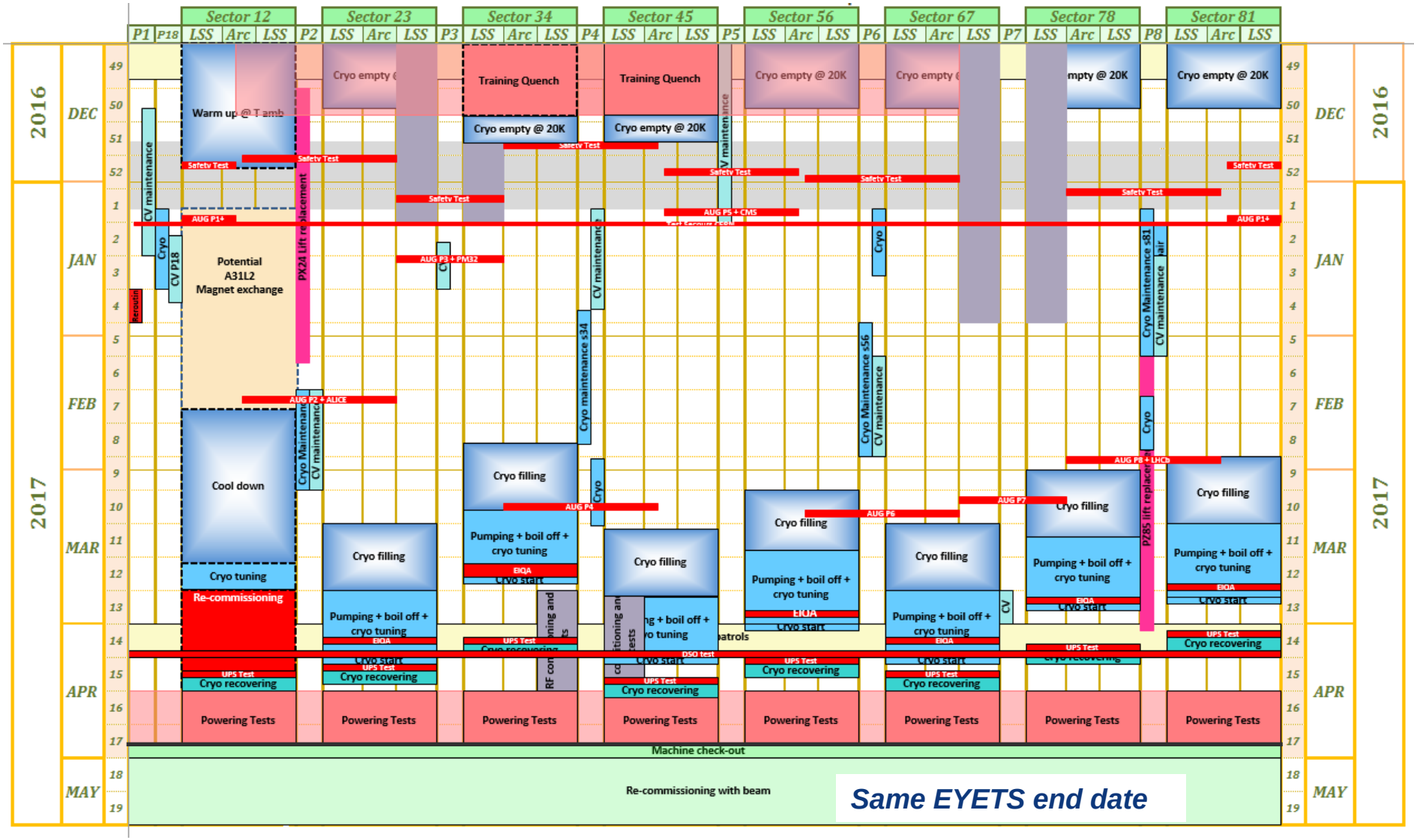


LHC Proton Run 2016 is reduced by one week: one week investment for energy increase

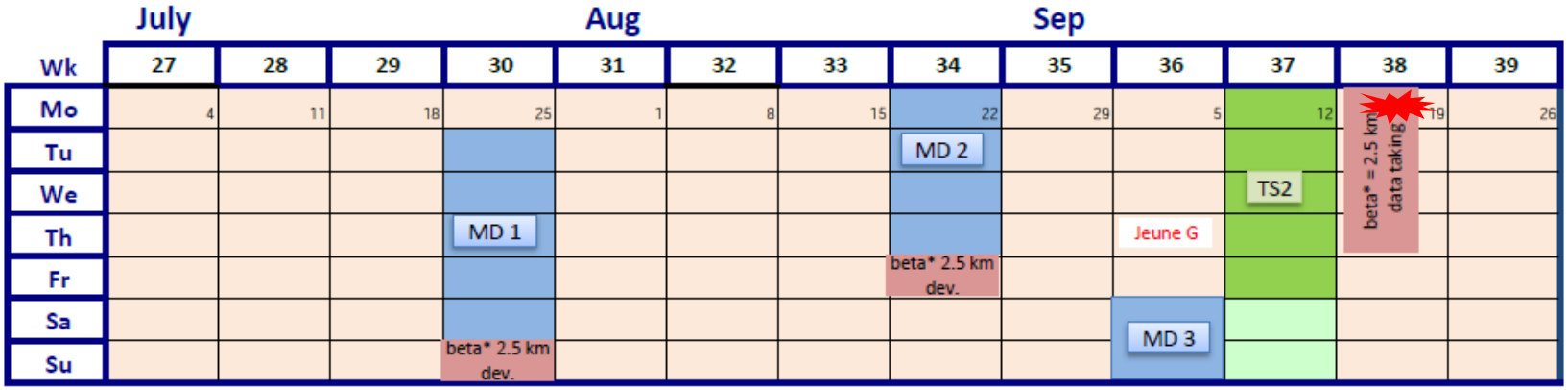
The restart date in 2017 is unchanged

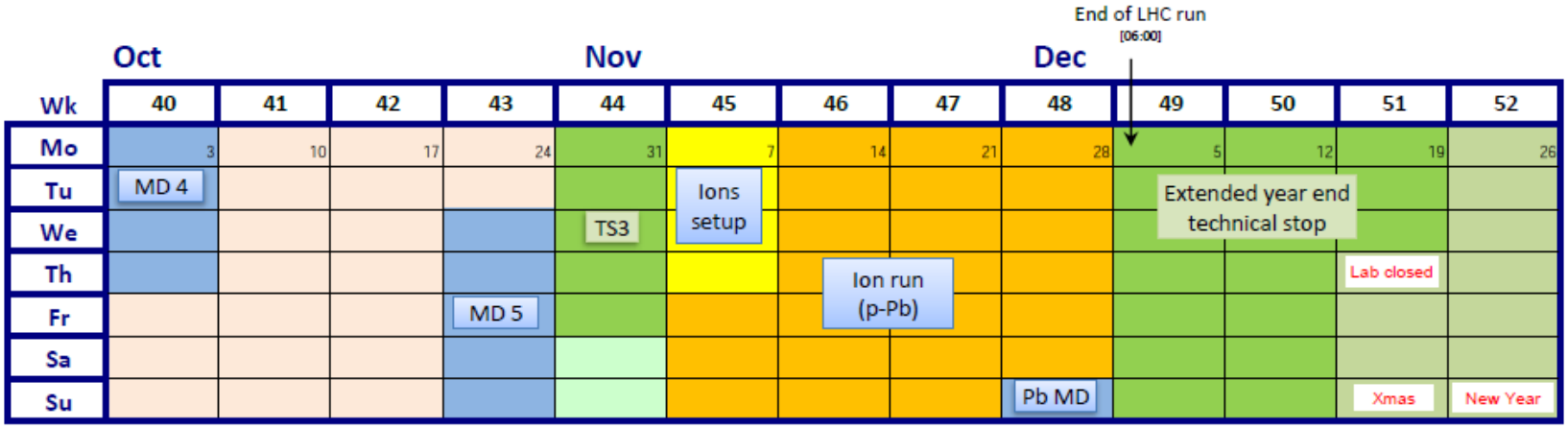
Training of 2 sectors towards 7 TeV (max 2 weeks)

LHC EYETS approved on 31st August 2016



LHC: Incoming 2016

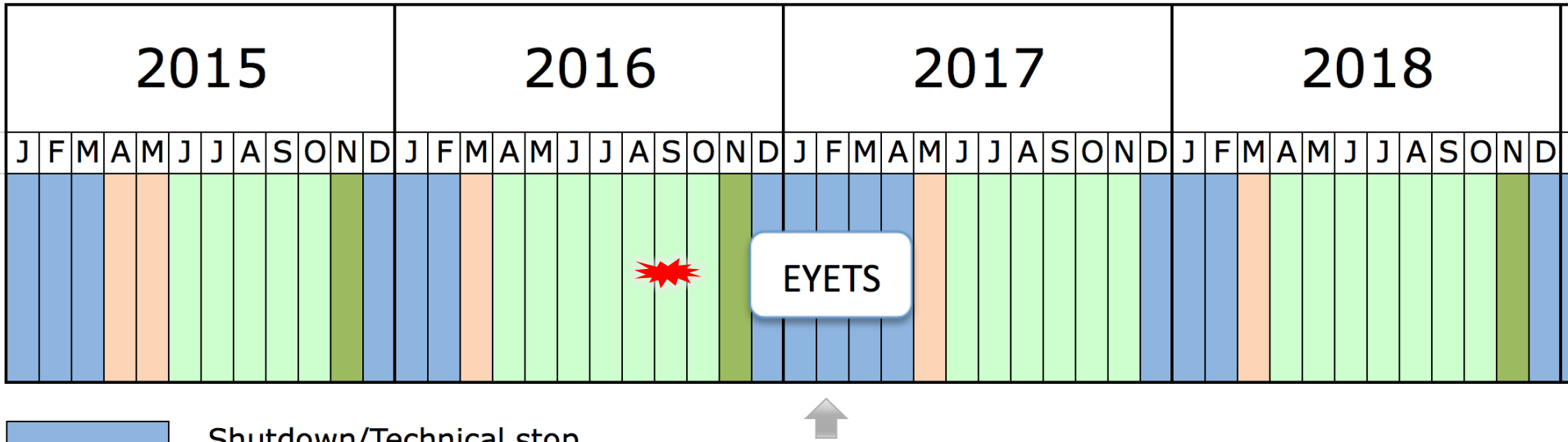




- **Beta* 2.5 km physics (4 days and long preparation)**
- **29 days of proton physics left**
- **Proton-lead run at $\sqrt{s_{NN}}$ of 5 and 8 TeV**
- **2 weeks dipole training before Christmas**

Run 2

Ion runs in 2016 (p-Pb) and 2018 (Pb-Pb)



Shutdown/Technical stop
Protons physics
Commissioning
Ions

Push 2 sectors towards 7 TeV
Extended Year End Technical Stop – 20 weeks
General maintenance: LHC and injectors
and CMS pixel upgrade;

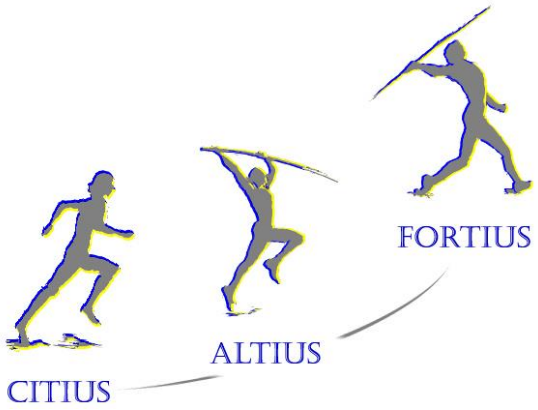
- **Peak luminosity to ~1.7 10^{34} (limited by inner triplets)**
- **~ 40-45 fb^{-1}/year in 2017 and 2018 (goals will be fixed at Chamonix 2017)**

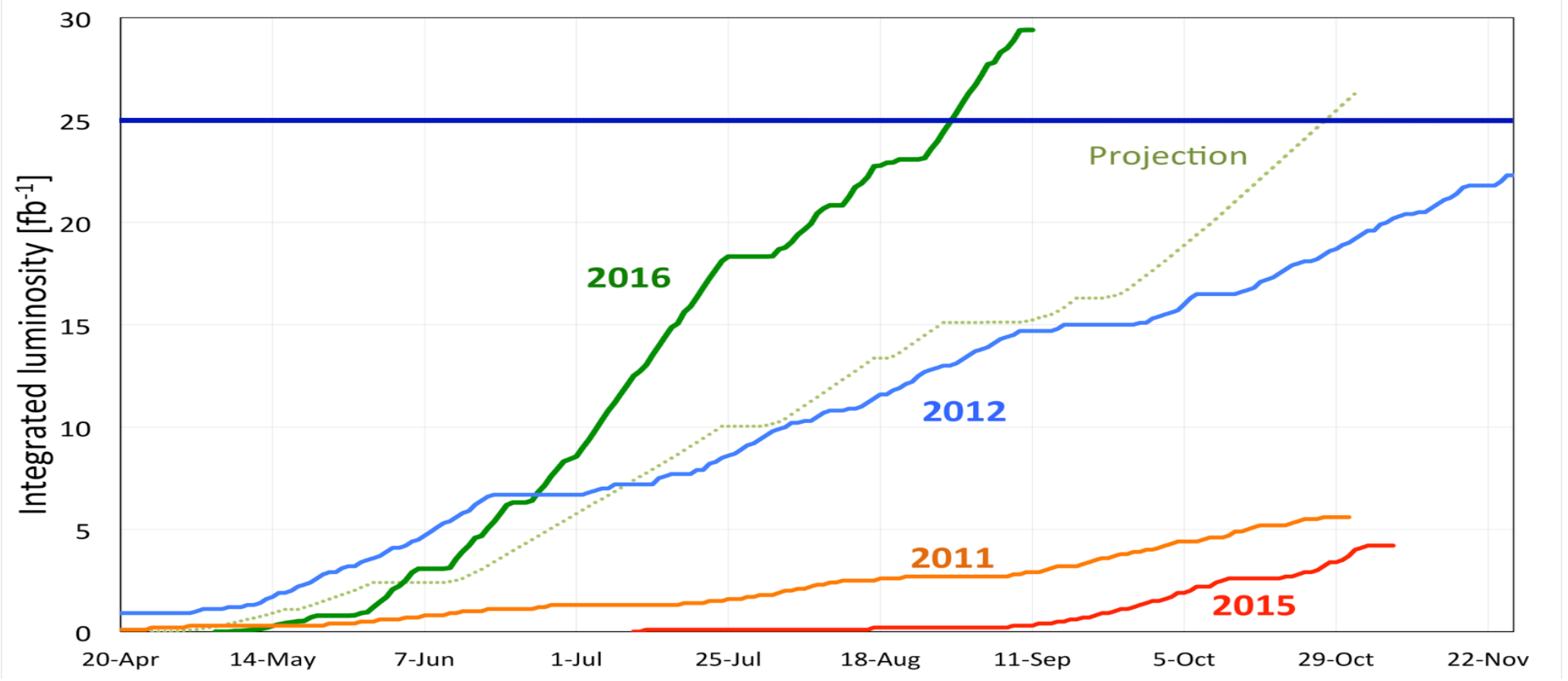
- **Prepare for HL-LHC and post-LS2 LIU era**
- **Prepare for 7 TeV operation**

Conclusion: 2016 goals

Peak luminosity > 1.2 x 10^{34} $cm^{-2}s^{-1}$

Over 25 fb-1 in both ATLAS and CMS ☺





Progress represents a phenomenal ongoing effort by all the teams involved

Peak luminosity > 1.2 x 10^{34} $cm^{-2}s^{-1}$

Integrated luminosity ~ 30 fb^{-1}

Peak luminosity > 1.2 x 10^{34} $cm^{-2}s^{-1}$
Integrated luminosity ~ 30 fb^{-1}

To reduce the crossing angle (test after TS2)
To keep the emittance growth through the cycle
To increase the number of bunches (2748, 288 per train) and bunch intensity
Reduction of β* (ATS optics could be an option)
Optimisation of the integrated luminosity (availability)
Prepare towards 14 TeV operation
…

The European Strategy for Particle Physics
Update 2013

*Europe's top priority should be the **exploitation of the full potential of the LHC**, including the high-luminosity upgrade of the machine and detectors with a view to collecting **ten times more data than in the initial design, by around 2030**. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

HL-LHC from a study to a PROJECT

300 fb^{-1} → 3000 fb^{-1}

including LHC injectors upgrade **LIU**

(Linac 4, Booster 2GeV, PS and SPS upgrade)

Goal of High Luminosity LHC (HL-LHC):

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

Prepare machine for operation **beyond 2025 and up to 2035-37**

Devise beam parameters and operation scenarios for:

- enabling a total integrated luminosity of **3000 fb^{-1}**
- implying an integrated luminosity of **250-300 fb^{-1} per year**,
- design for **$\mu \sim 140$ (~ 200)** (➔ peak luminosity of **5 (7) 10^{34} cm^{-2} s^{-1}**)
- design equipment for 'ultimate' performance of **7.5 10^{34} cm^{-2} s^{-1}** and **4000 fb^{-1}**

=> Ten times the luminosity reach of first 10 years of LHC operation

LHC Upgrade Goals: Performance optimization

Luminosity recipe :

$$L = \frac{n_b \times N_1 \times N_2 \times g \times f_{rev}}{4p \times b^* \times e_n} \times F(f, b^*, e, s_s)$$

➔1) maximize bunch intensities ➔Injector complex

➔2) minimize the beam emittance LIU ⇔ IBS

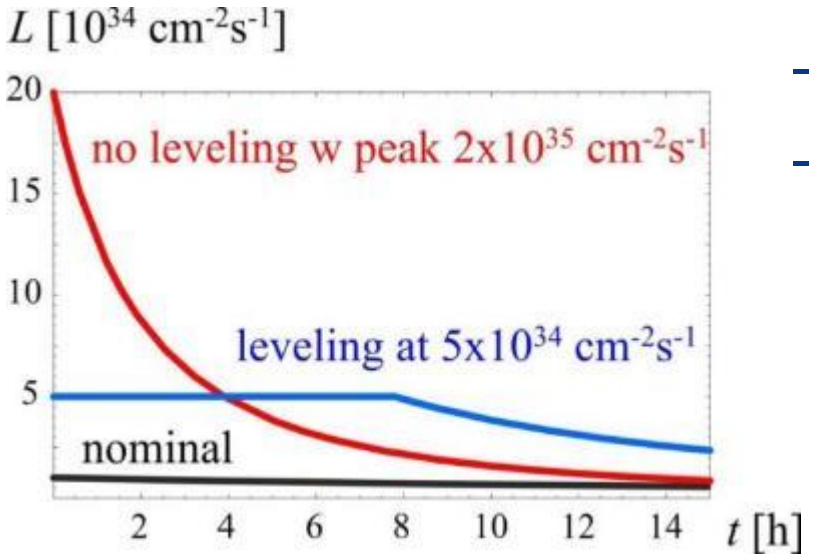
➔3) minimize beam size (constant beam power); ➔triplet aperture

➔4) maximize number of bunches (beam power); ➔25ns

➔5) compensate for 'F'; ➔Crab Cavities

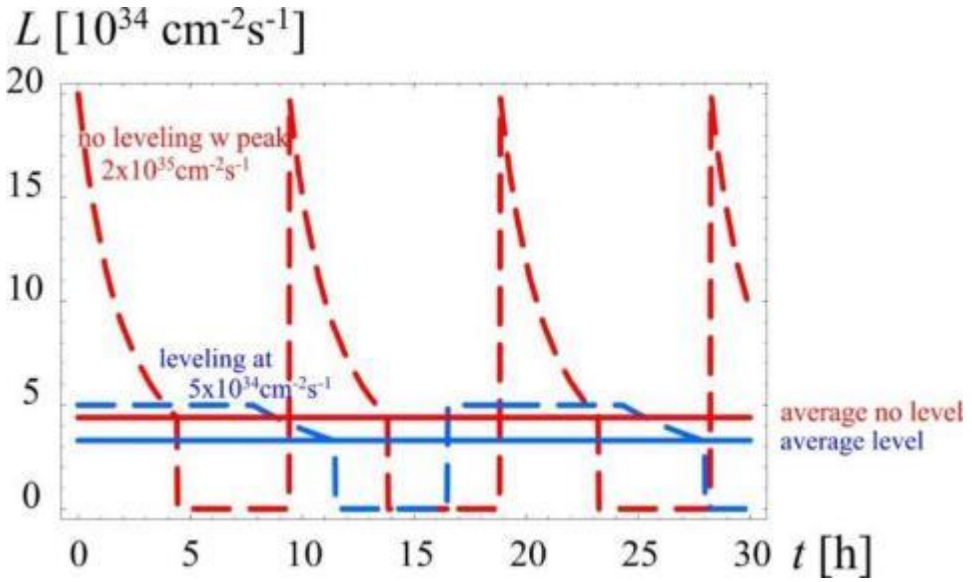
➔6) Improve machine 'Efficiency' ➔ **minimize number of unscheduled beam aborts**

Luminosity Levelling, a key to success

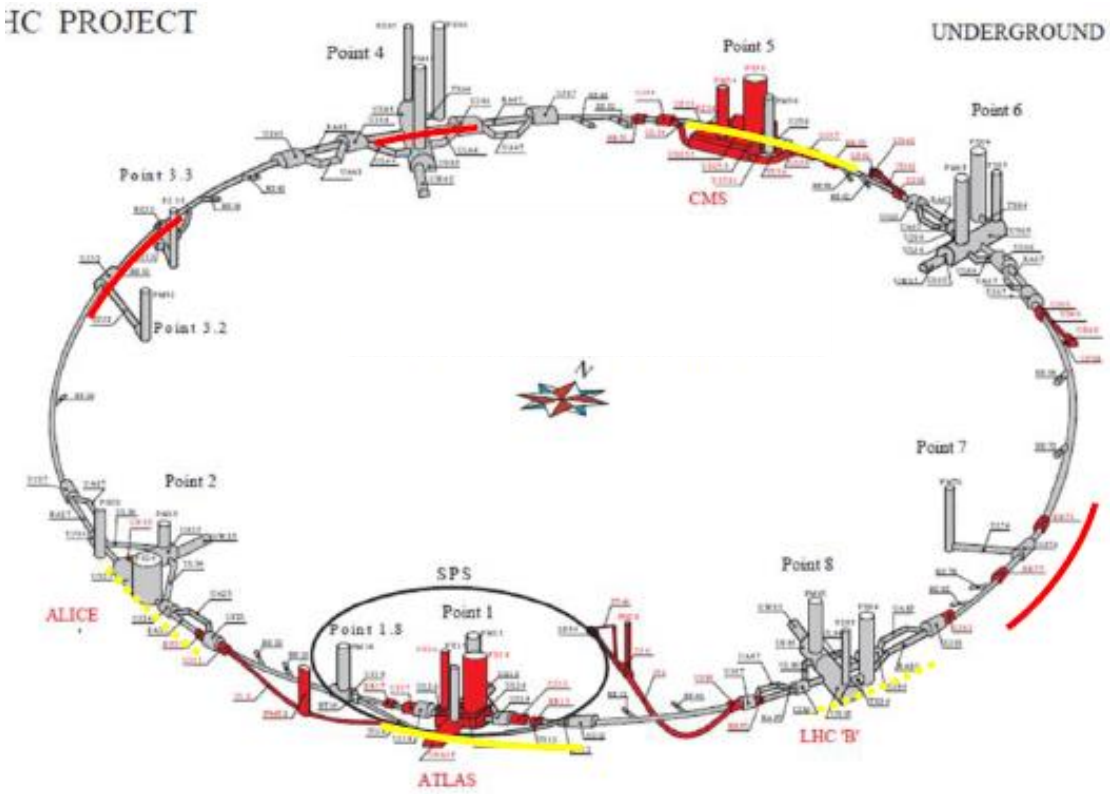


- High peak luminosity
- Minimize pile-up in experiments and provide “constant” luminosity

- Obtain about 3 - 4 fb^{-1}/day (40% stable beams)
- About 250 to 300 fb^{-1}/year



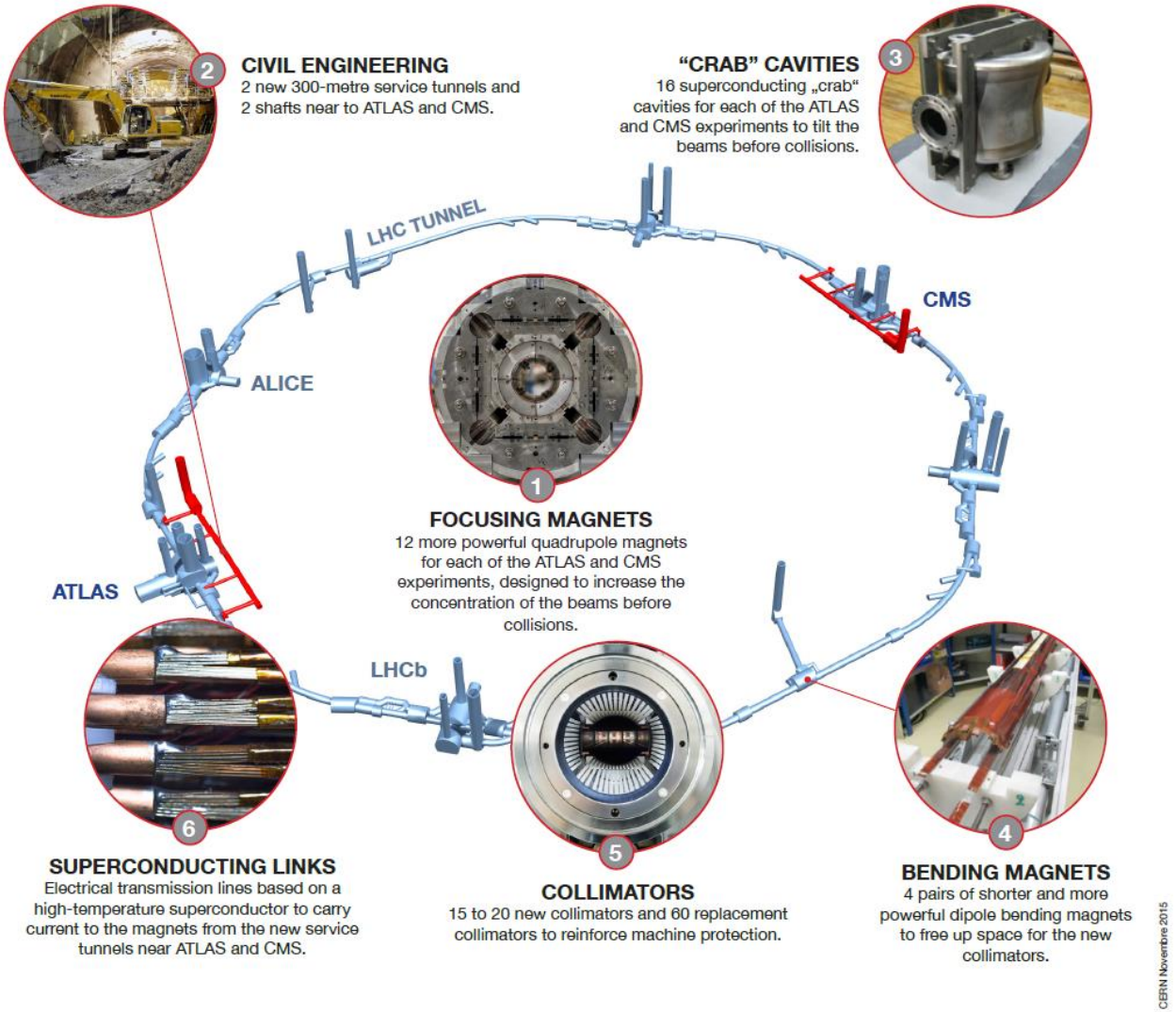
The HL-LHC Project



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

Major intervention on more than 1.2 km of the LHC

Project Landmarks



Squeezing the beams: High Field SC Magnets

Quads for the inner triplet

Decision 2012 for low-β quads

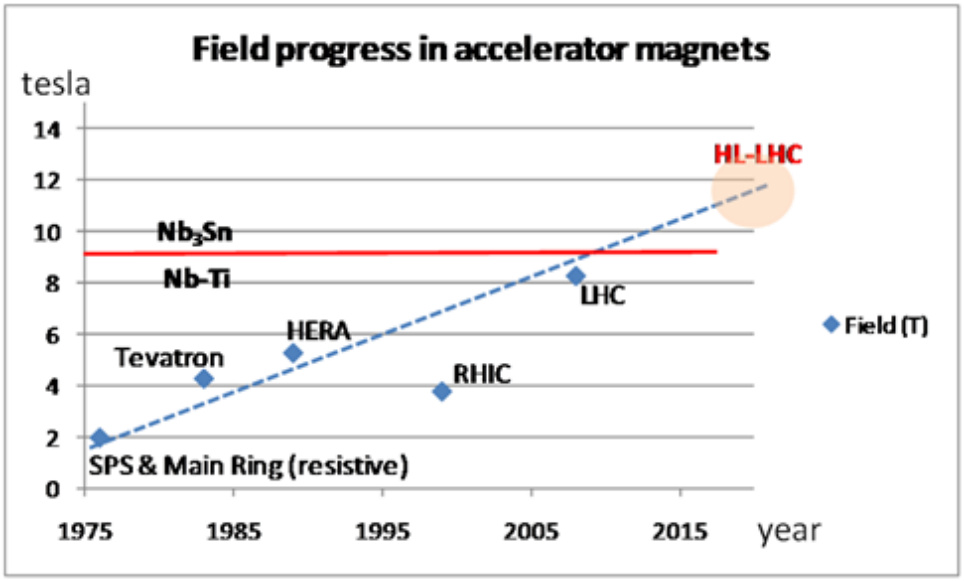
Aperture ∅ 150 mm – 140 T/m

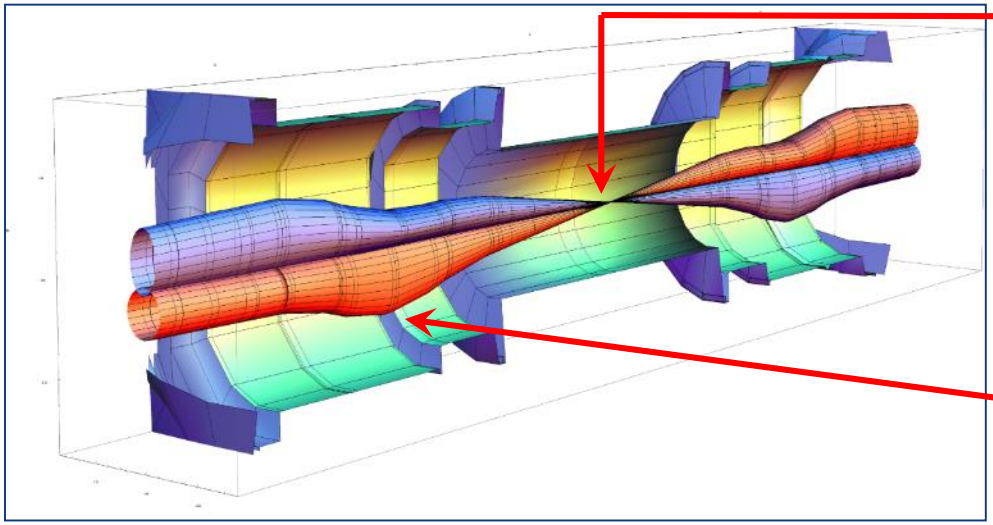
(B_{peak} ≈12.3 T)

operational field, designed for 13.5 T

=> Nb_3Sn technology

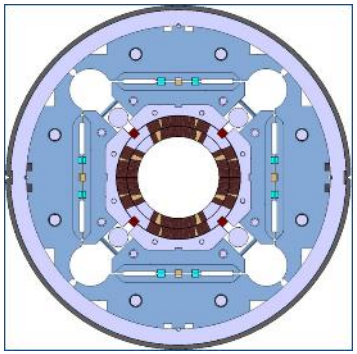
(LHC: 8 T, 70 mm)

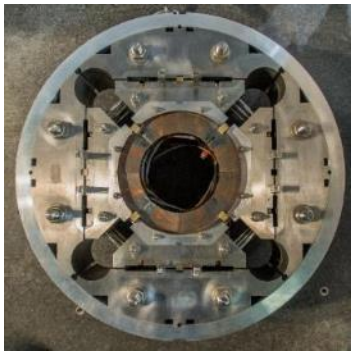




	$\beta_{triplet}$	Sigma triplet	β*	Sigma*
Nominal	~4.5 km	1.5 mm	55 cm	17 um
HL-LHC	~20 km	2.6 mm	15 cm	7 um

First short model magnet MQXFS1 (1.5 m)
Inner triplet Quad final cross section (∅ =150 mm)

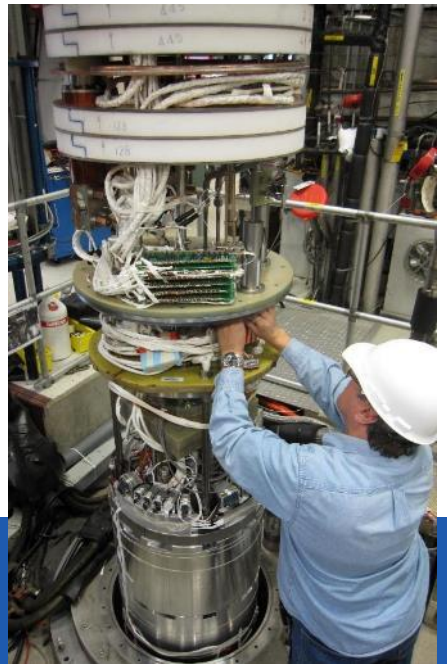




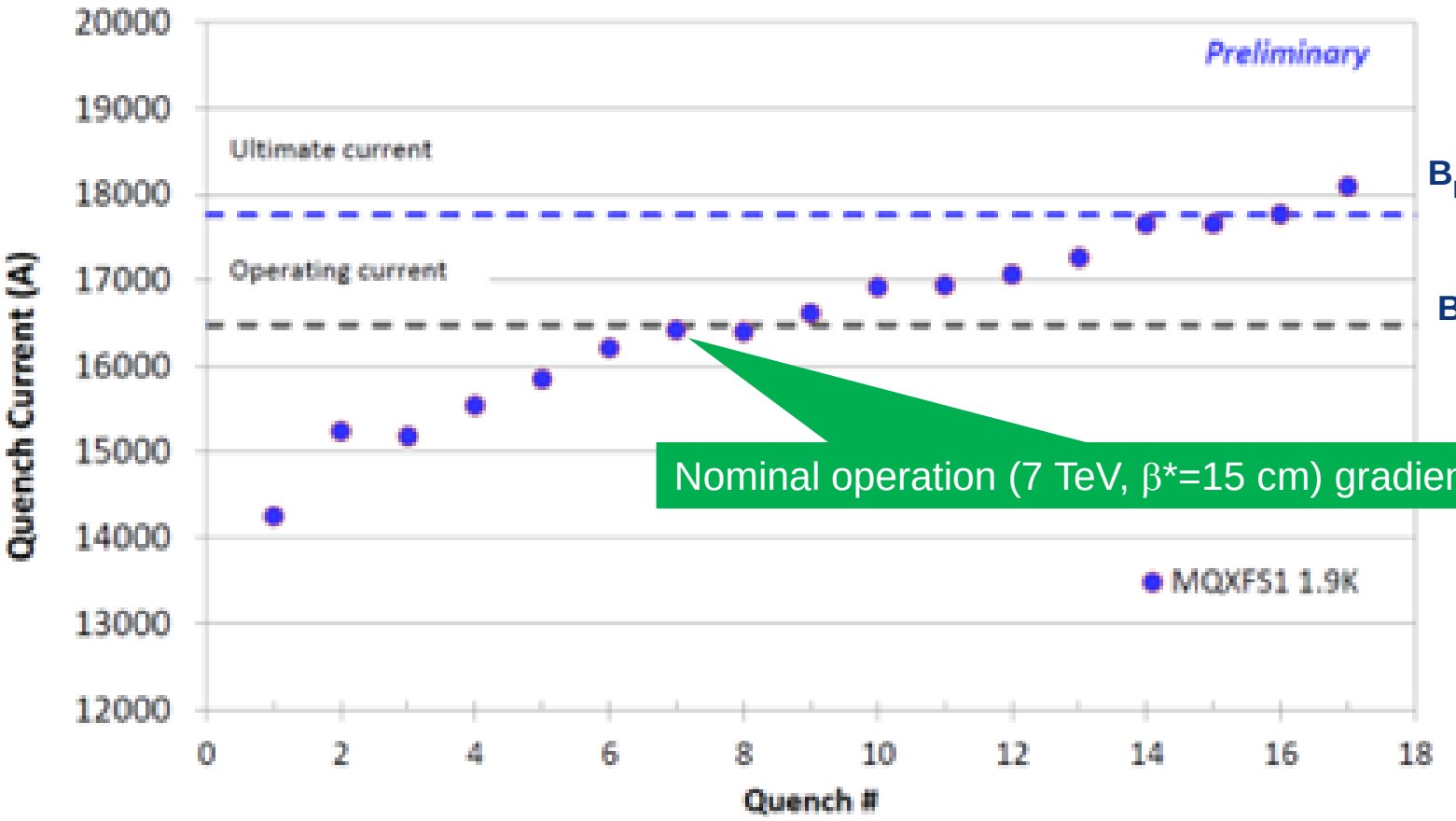
CERN - US LARP collaboration

Design and Nb_3Sn coils by CERN and LARP together (50%-50%)

Full collider characteristics.
Final length will be 3 to 5 times more



First short model magnet MQXFS1 (1.5 m)
Result of the first energization @ FNAL



B_{peak}> 12.5 T

B_{peak} = 11.4 T

Nominal operation (7 TeV, β*=15 cm) gradient : 133 T/m

Next: thermal cycle and memory test (and more…)

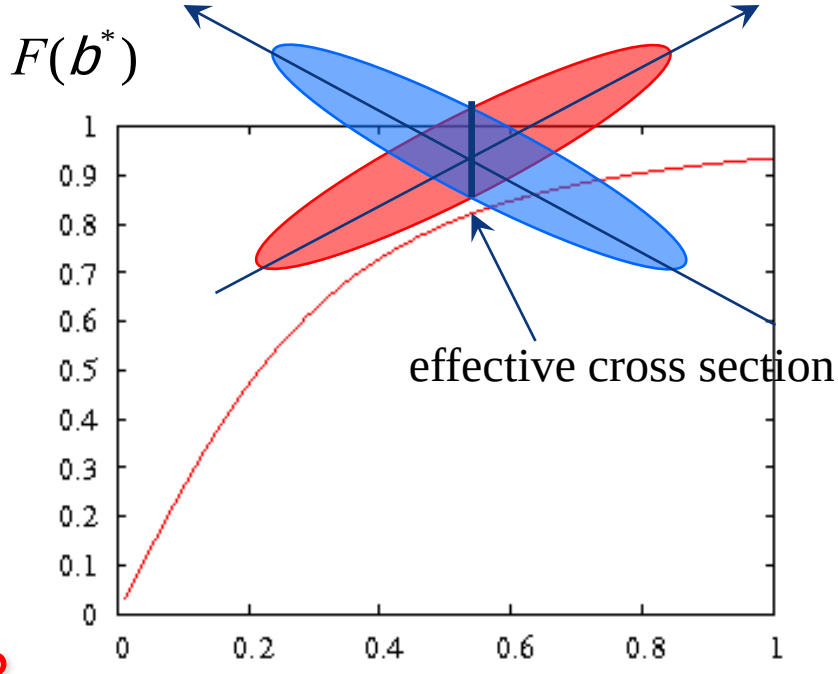
HL-LHC Upgrade Ingredients: Crab Cavities

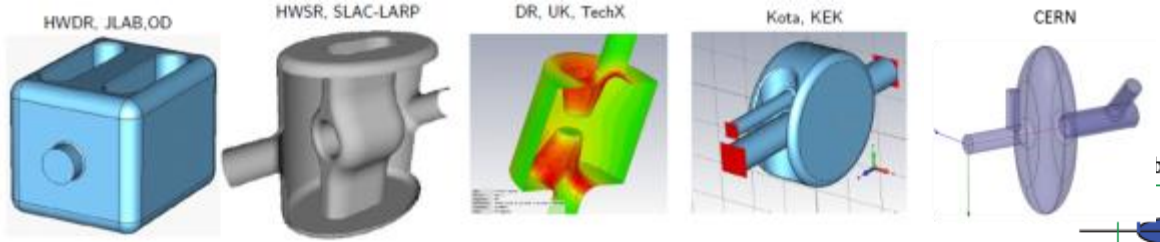
Crab Cavities: Luminosity Reduction Factor:

- Reduces the effect of geometrical reduction factor
- Independent for each IP

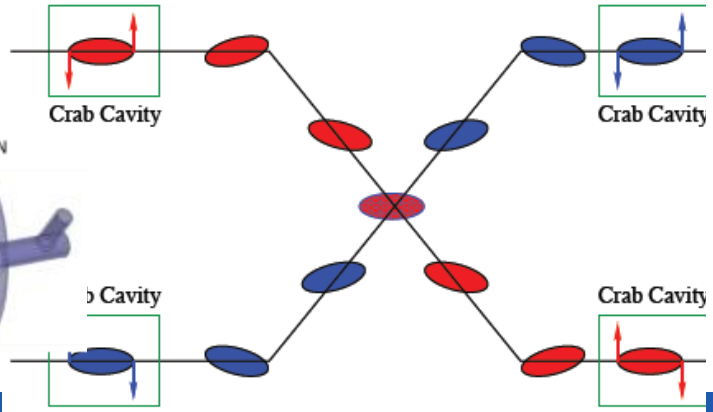
$$F = \frac{1}{\sqrt{1+Q^2}}; \quad Q^o \frac{q_c s_z}{2 s_x}$$

- Noise from cavities to beam?!?
- Challenging space constraints



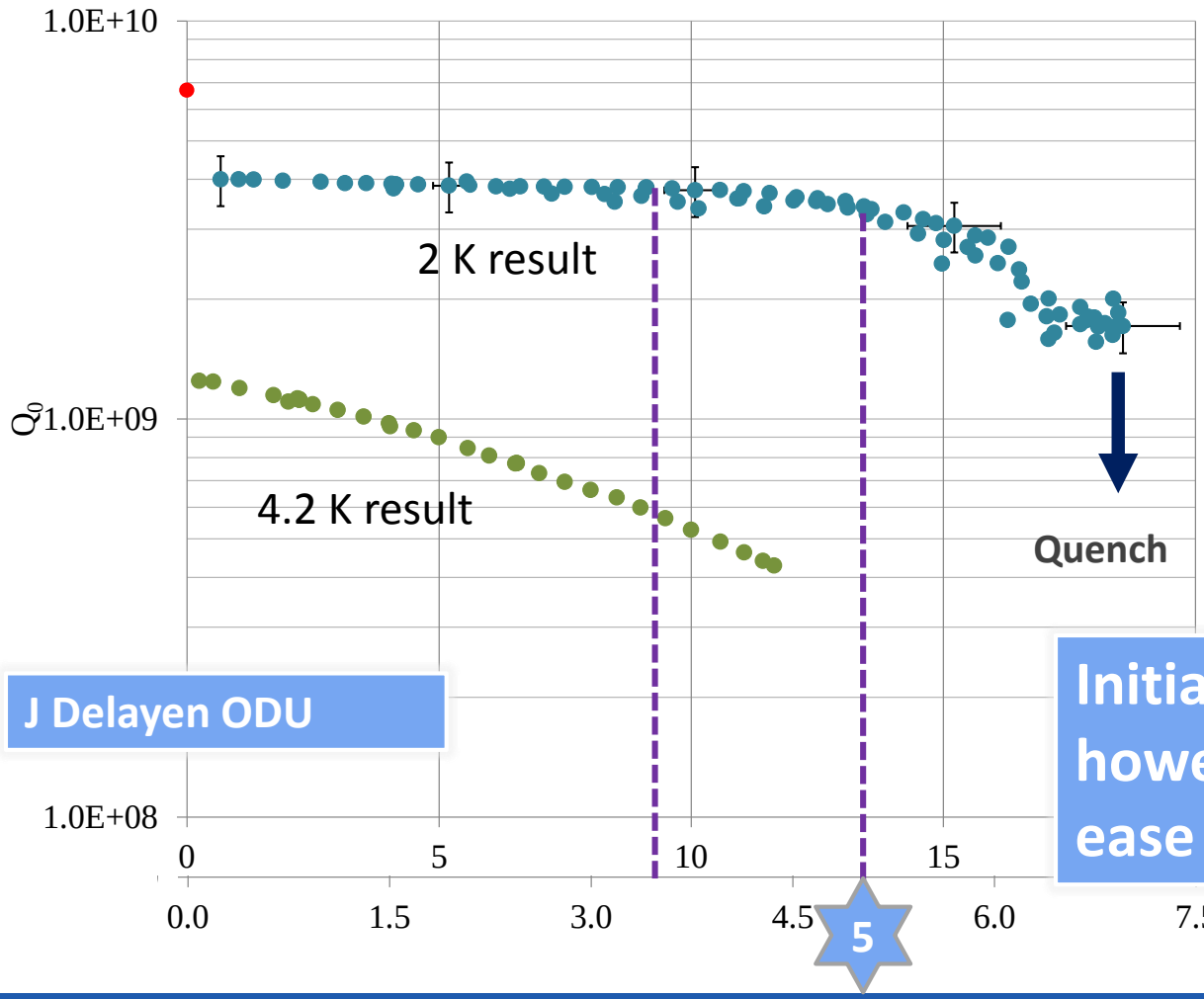


Compact cavities aiming at small footprint & 400 MHz, ~5 MV/cavity



Excellent first results: e.g. RF dipole > 5 MV

¼ w and 4-rods also tested (1.5 MV)

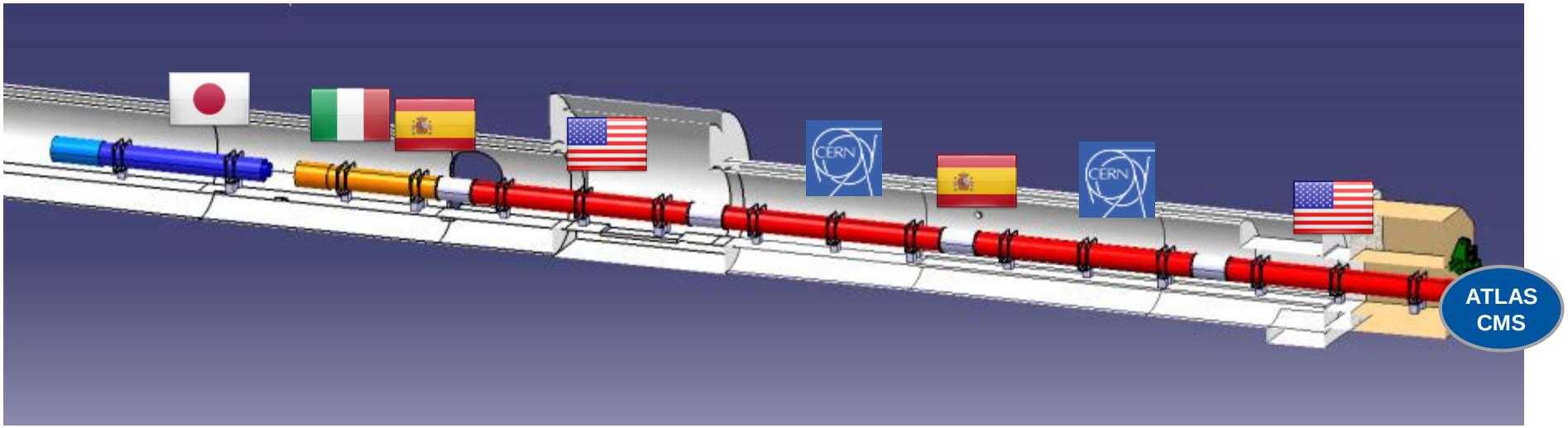


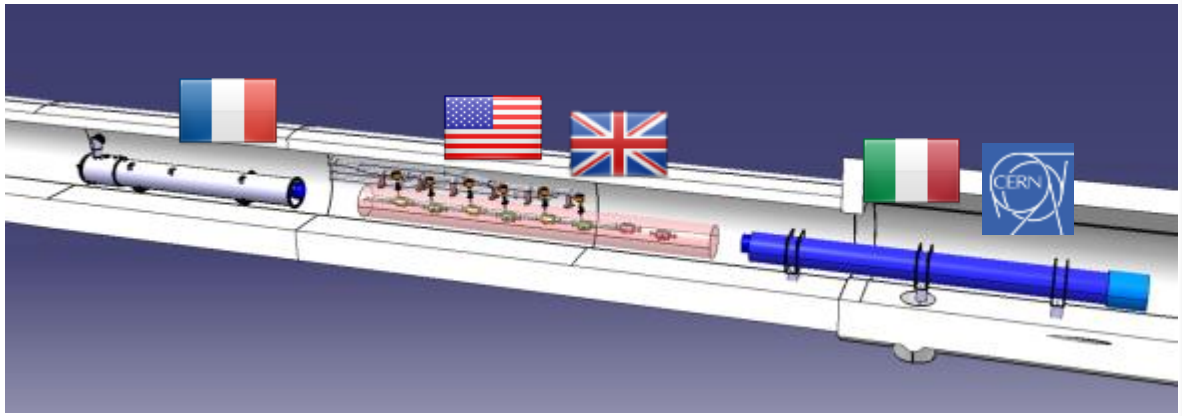
J Delayen ODU

Initial goal was 3.5 MV however ΔV > 5-6 MV would ease integration

In-kind contributions and collaborations for design, prototypes, production and tests

Discussions are ongoing with other countries, e.g Canada,…



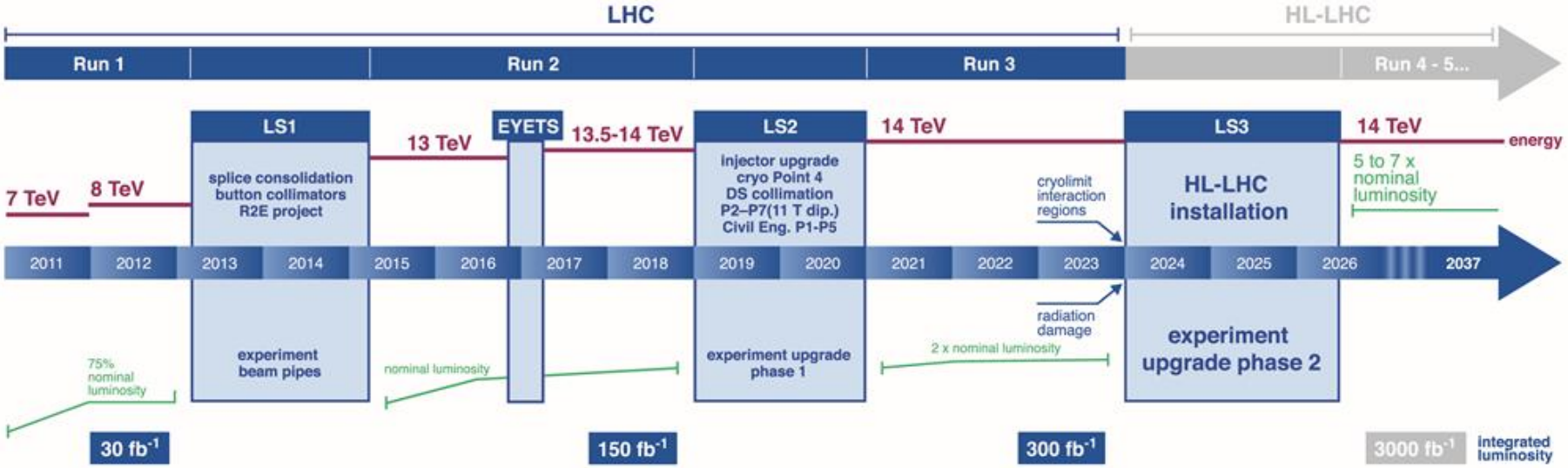


Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

CC : R&D, Design and in-kind **USA**

CC : R&D and Design **UK**

LHC / HL-LHC Plan



HL-LHC Plan

Conclusions

LHC is operational at 13 TeV c.m. and with 25ns beams

2016 : production mode at 13 TeV ; > 30 fb^{-1}

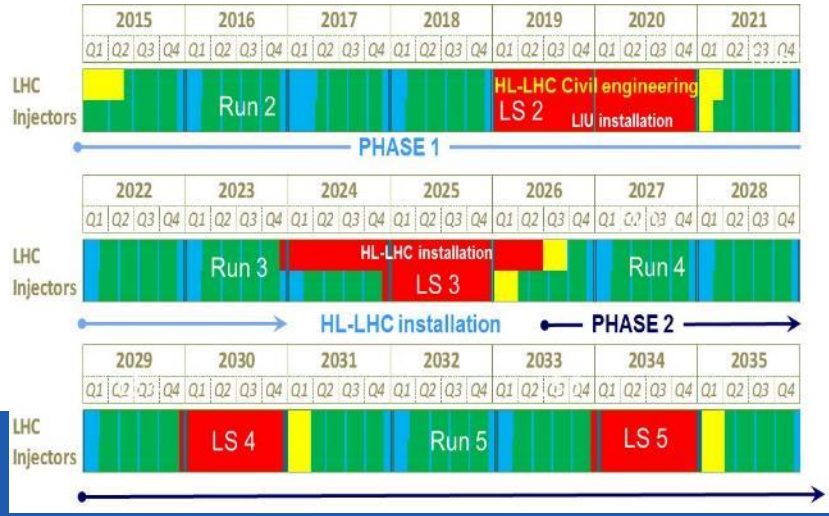
- **25 ns operation**
- **β^* = 40 cm in ATLAS and CMS ; 3m in LHCb ; 10m in ALICE**
- **Going towards combining ramp & squeeze**
- **Rapid intensity ramp up in spite several technical problems**

Nominal design luminosity 1x10^{34} cm^{-2} s^{-1} reached and exceeded (1.2 10^{34})

- **Optimisation of the integrated luminosity (availability ~ 65 %)**

RUN 2 goal : > 100 fb^{-1} and
to reach 300 fb^{-1} at the end of RUN 3

LHC Injector Upgrade (LIU => LS2)
and High Luminosity LHC (HL-LHC =>LS3)
well defined and now in construction phase



Hvala na pažnji

www.cern.ch