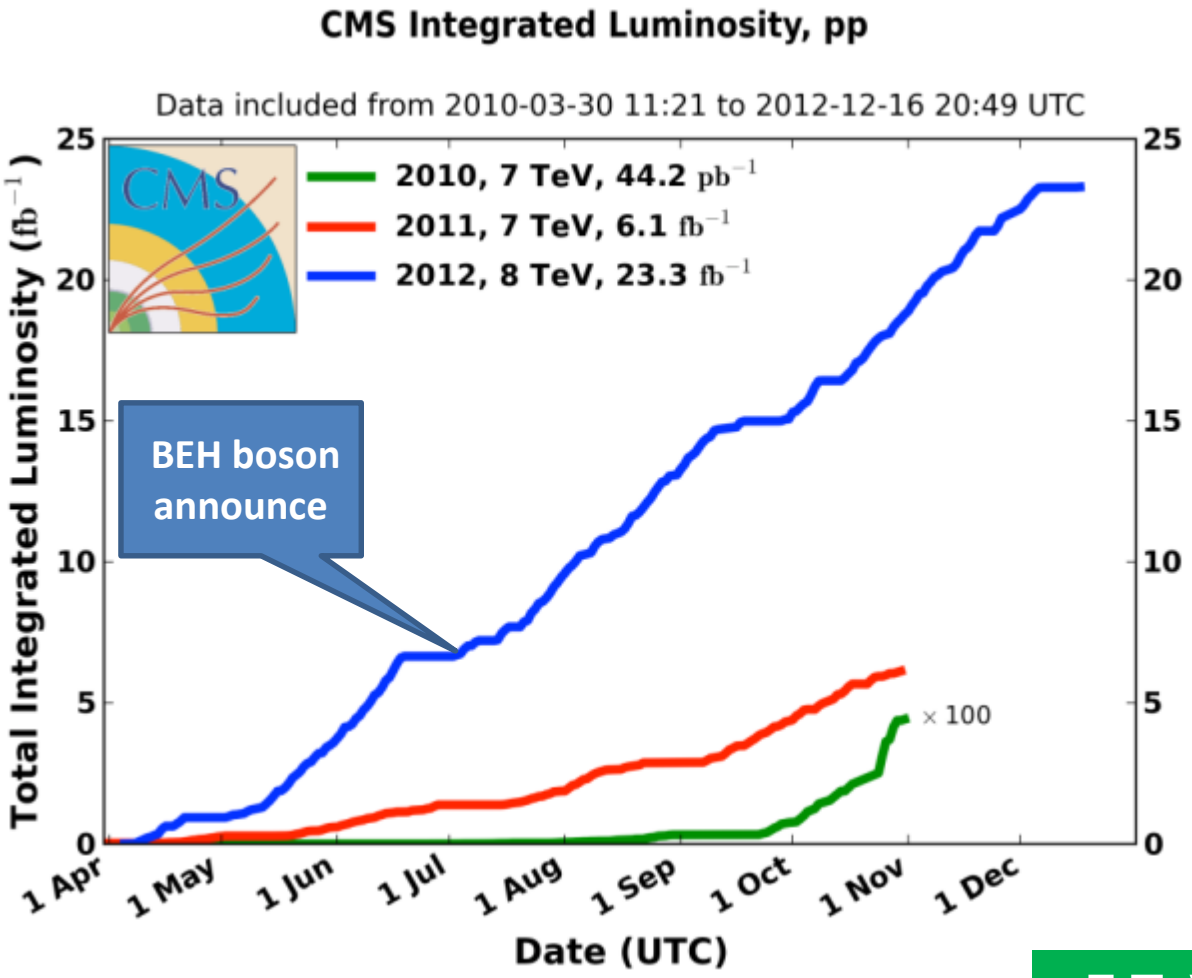
www.cern.ch

Status of LHC and HL-LHC

Frédérick Bordry
27th July 2015

EUROPEAN PHYSICAL SOCIETY HEP2015

LHC Run 1 (2010-2012): a rich harvest of collisions



Σ ~30 fb^{-1}

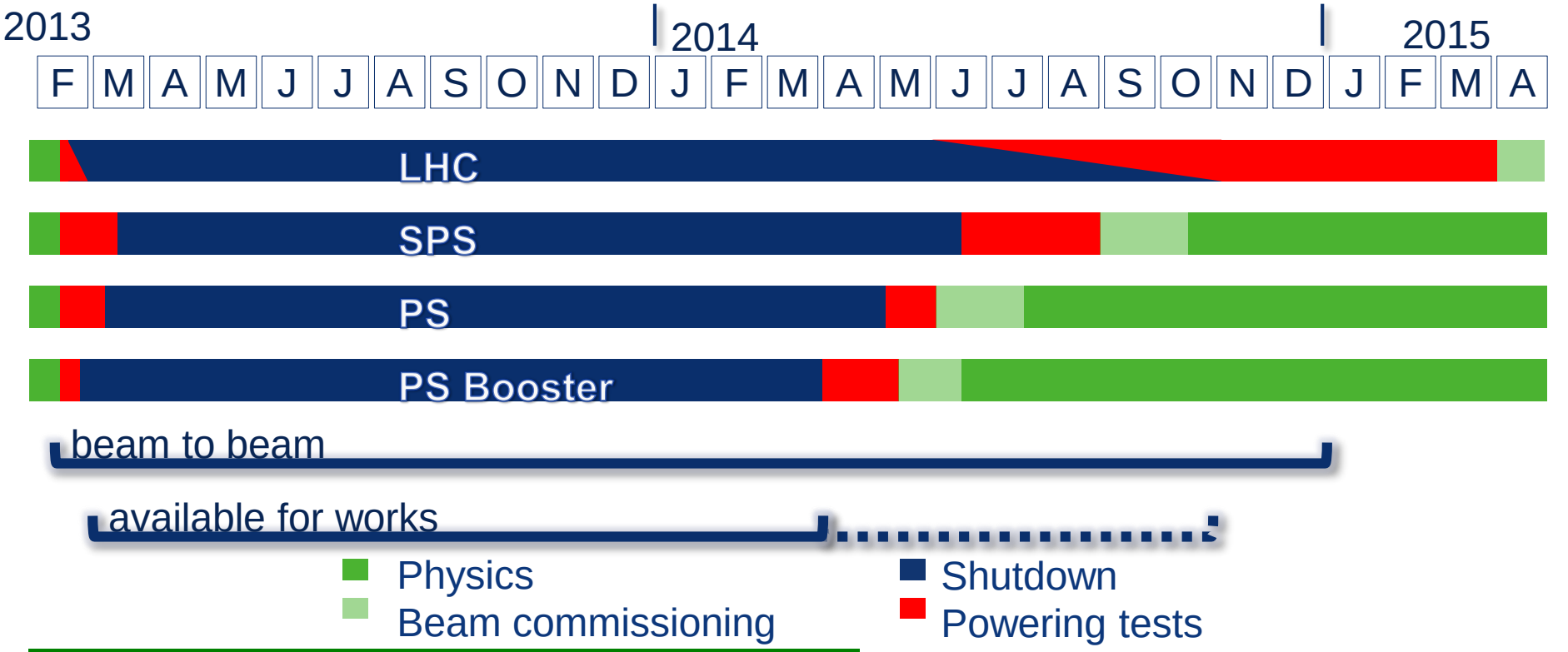
2010: **0.04 fb^{-1}**
- 7 TeV CoM
- Commissioning

2011: **6.1 fb^{-1}**
- 7 TeV CoM
- … exploring limits

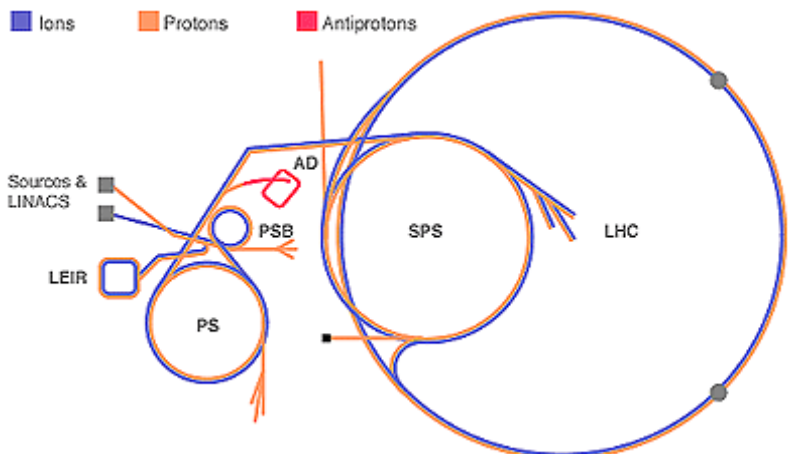
2012: **23.3 fb^{-1}**
- 8 TeV CoM
- … production

7 TeV and 8 TeV in 2012

Long Shutdown LS1 from Feb. 2013 to Mar. 2015

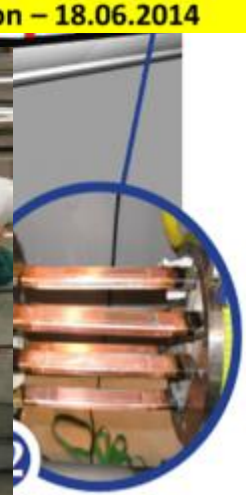


- **Prepare the LHC for operation at nominal energy 14 TeV**
- **Consolidate, Upgrade the LHC and Injector performance**
- **Major maintenance programme**



The main 2013-14 LHC consolidations

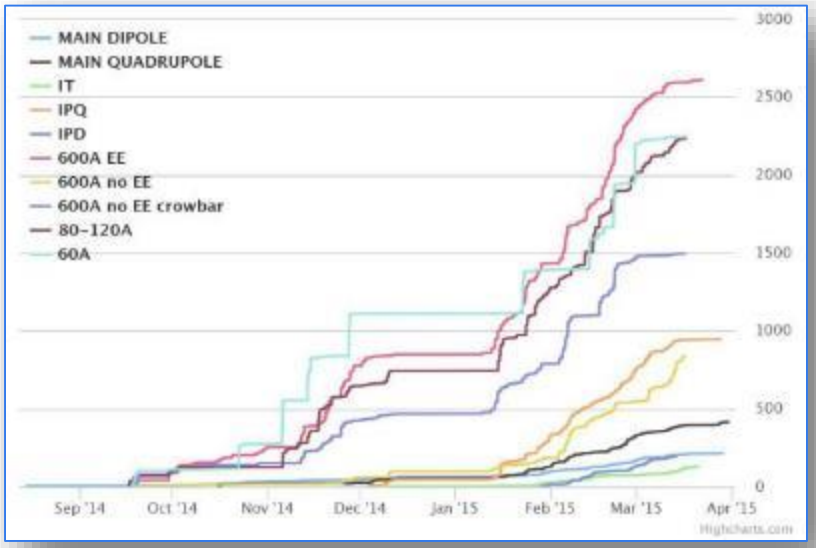
SMACC project : Closure of the last interconnection – 18.06.2014



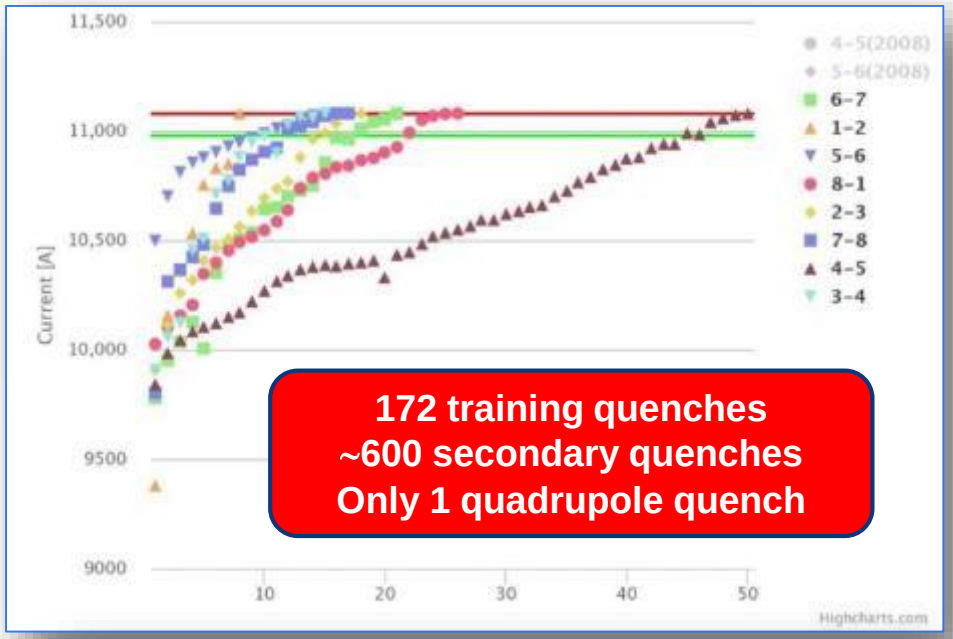
18 000 electrical
Quality Assurance tests

nsolidation of the
kA circuits in the 16
in electrical feed-
boxes

The LHC powering tests overview



Powering tests were completed at 8 am on Friday 3rd April 2015



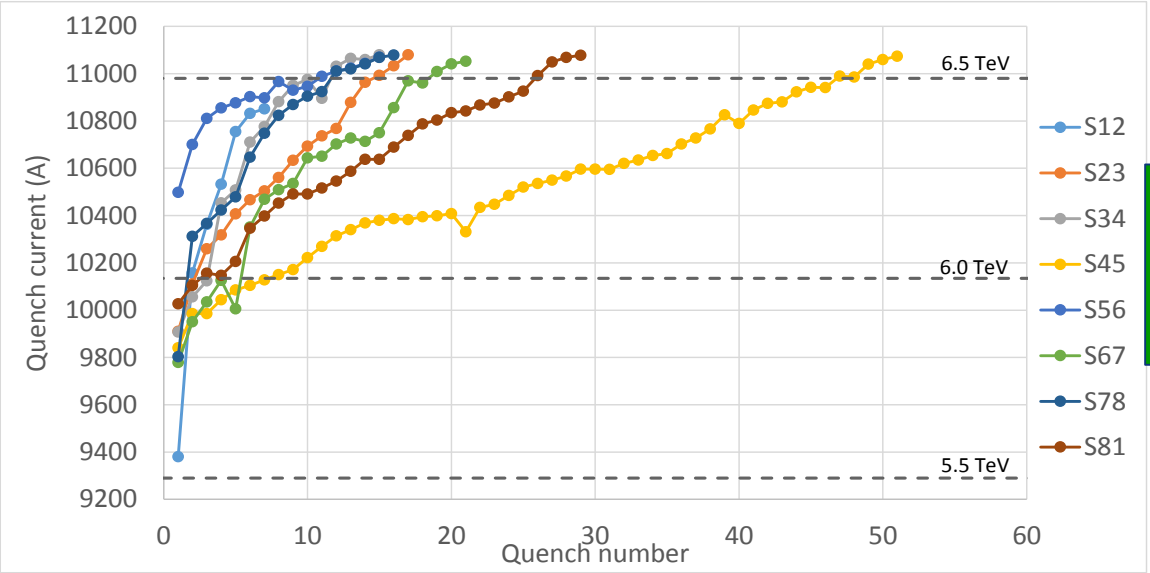
172 training quenches
~600 secondary quenches
Only 1 quadrupole quench

Since September 15th 2014:

1566 superconducting circuits commissioned through execution and analysis of **more than 10.000 test steps** (~13.800 test steps including re-execution)

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

Dipole Training Campaign



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

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

Detailed Analysis in Progress!

Maximum beam energy : **13 TeV c.m. in 2015**

Decision to run at a **maximum** energy of 13 TeV c.m. during the powering tests and during 2015.

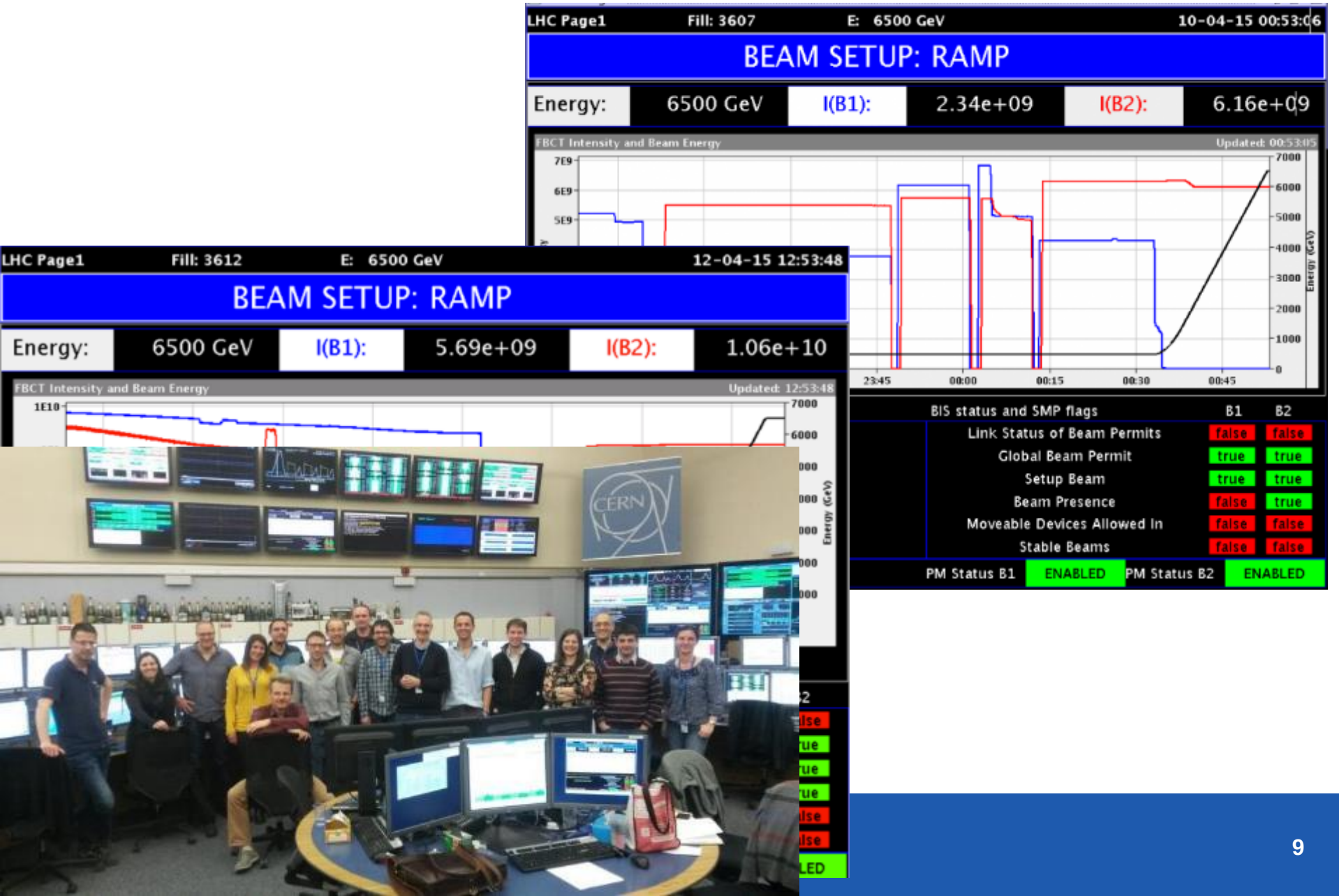
NO change of beam energy in 2015.

A decision regarding the possibility of increasing the energy will be taken after 2015 operation, based on data analysis of the powering tests and on the experience gained in all eight sectors at 6.5 TeV with beams.

First circulating beams in LHC on Easter Sunday

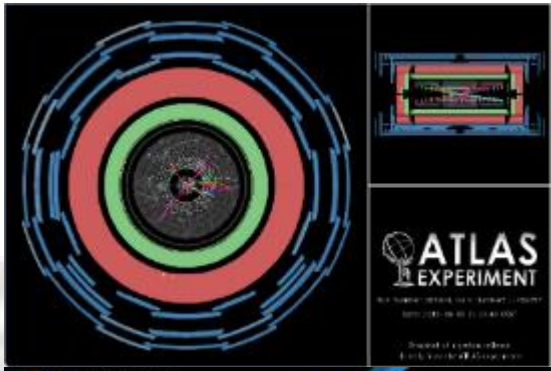
5th April 2015

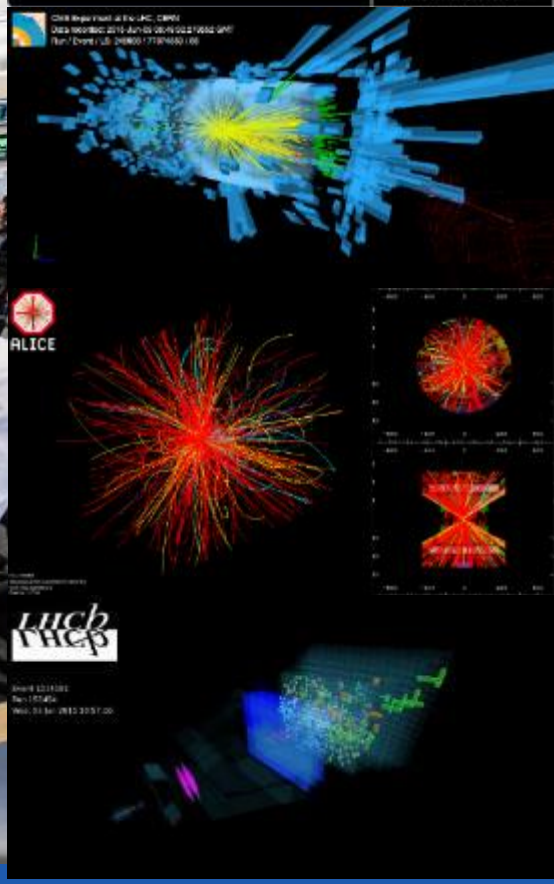
First beamS at 6.5 TeV! (12th April)



LHC experiments are back in business at a new record energy 13 TeV

3rd June 2015



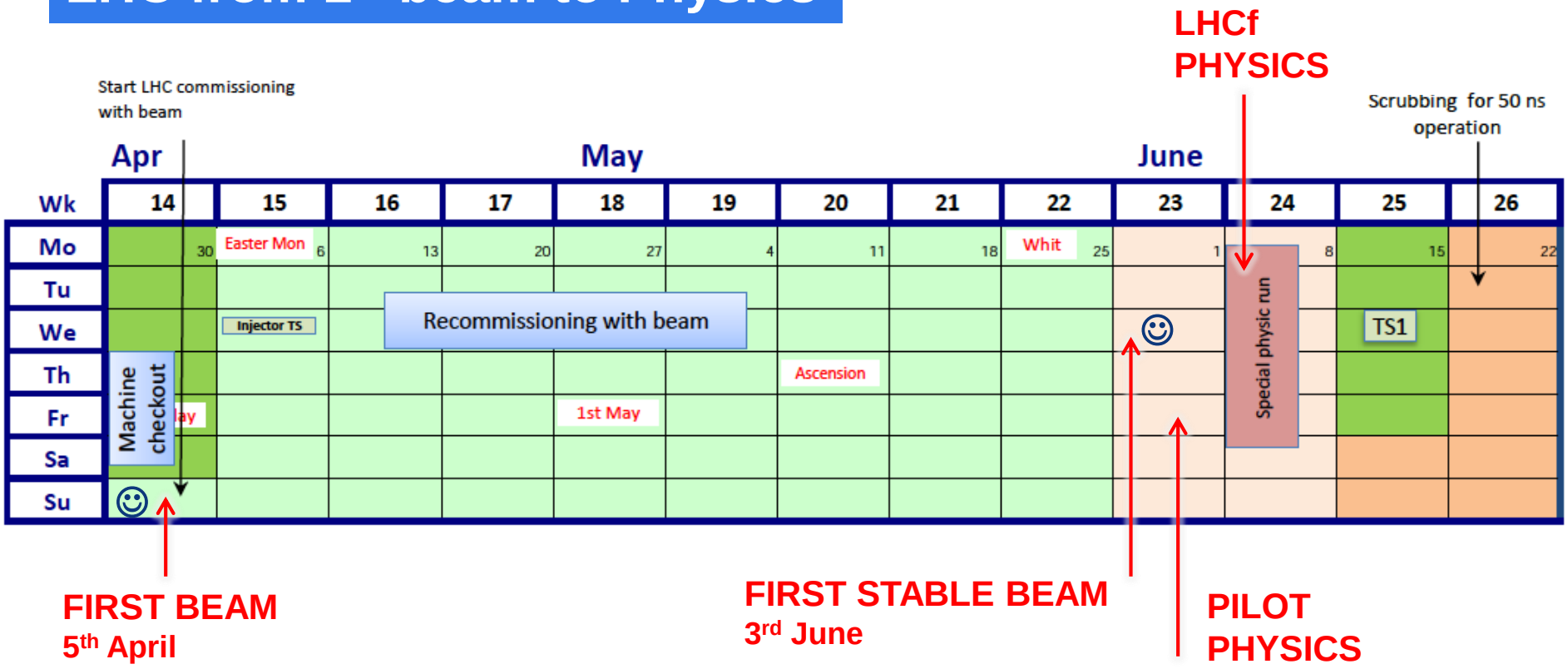


Beam commissioning in two months ☺

13 TeV

- **A lot of lessons learnt and experience from Run 1**
- Excellent and improved system performance **(LS1)**
  - Beam Instrumentation
  - Transverse feedback
  - RF
  - Collimation
  - Injection and beam dump systems
  - Vacuum
  - Machine protection
- Improved software & analysis tools **(LS1)**
- Magnetically reproducibility
- Optically good, corrected to excellent
- Behaving well at 6.5 TeV
  - One additional training quench so far
- Operationally well under control
  - Injection, ramp, squeeze, de-squeeze

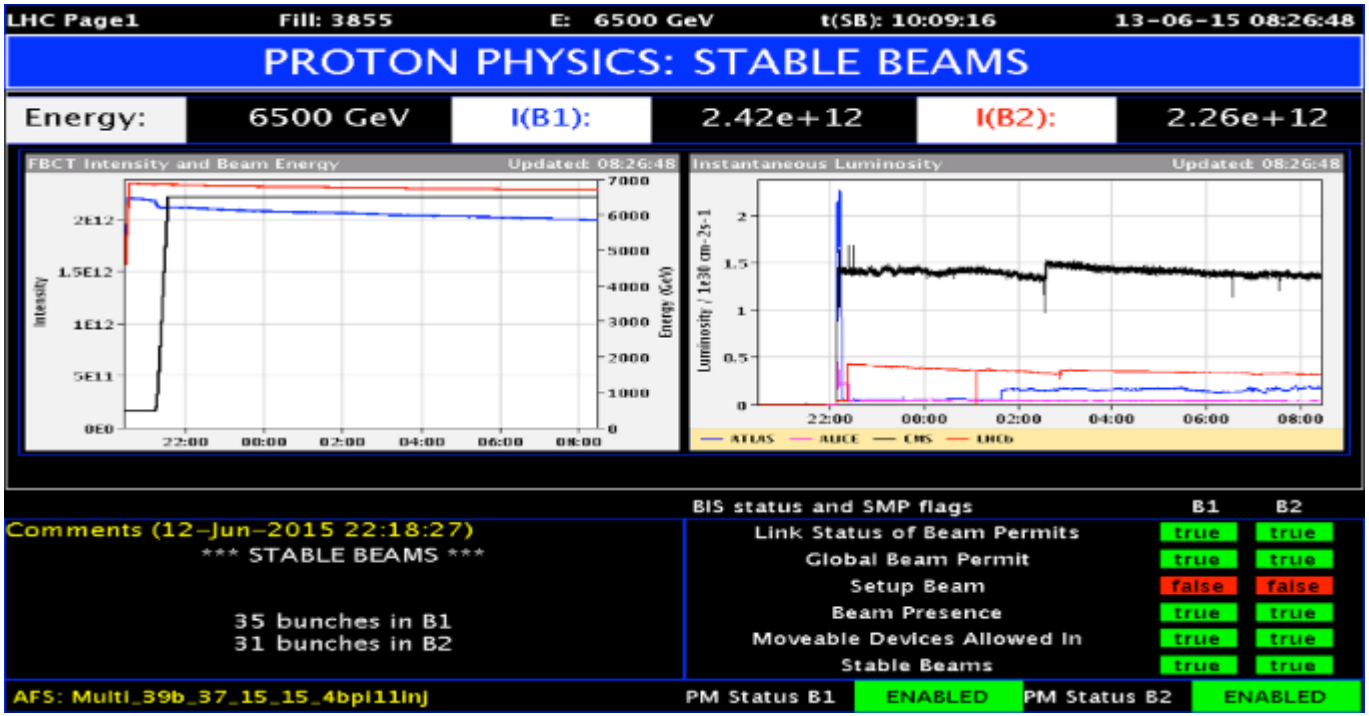
LHC from 1st beam to Physics



- 8 weeks beam commissioning
- Pilot physics – up to ~40 bunches per beam
- 5 days special physics at beta* = 19 m for LHCf, (VdM, TOTEM & ALFA - postponed)
- Technical stop as foreseen – 15th-19th June

LHCf physics

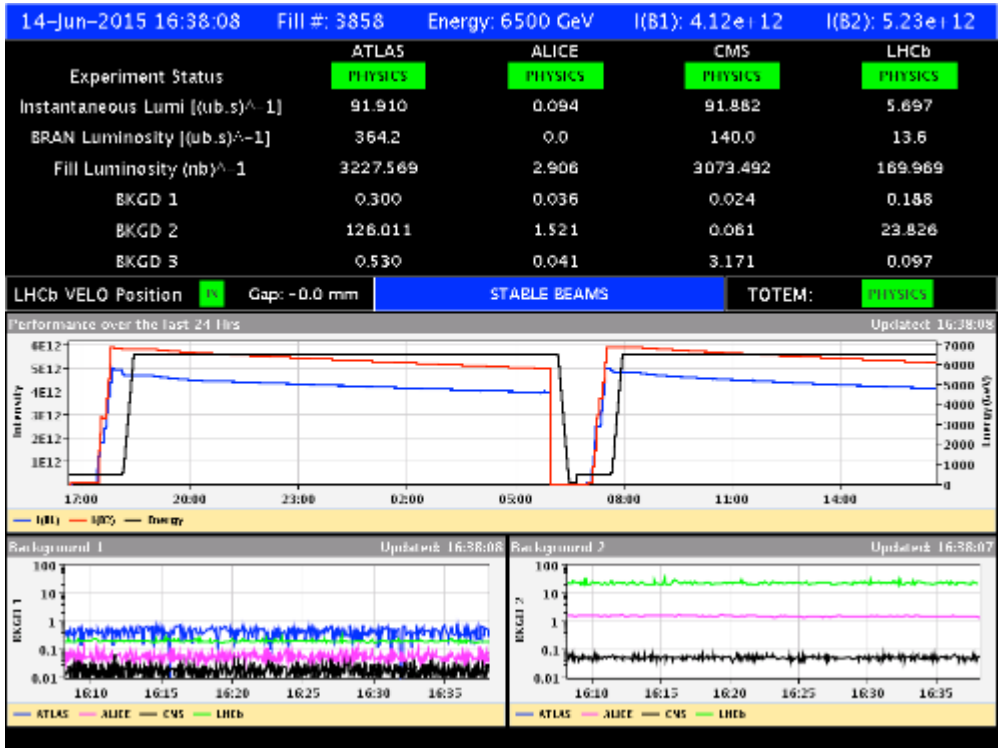
Request: 10 nb^{-1}



Σ > 16 nb^{-1}

fill	Stable beams	nb^{-1}	bunches
3846	1h55m	0.1	39 pilots
3847	2h16m	0.28	39 pilots
3848	2h42m	0.91	12 nominal
3850	2h49m	1.95	39 nominal
3851	11h13m	6.81	39 nominal
3855	14h15m	6.49	39 nominal

Weekend 13th-14th: June: start of intensity ramp-up 50 bunches

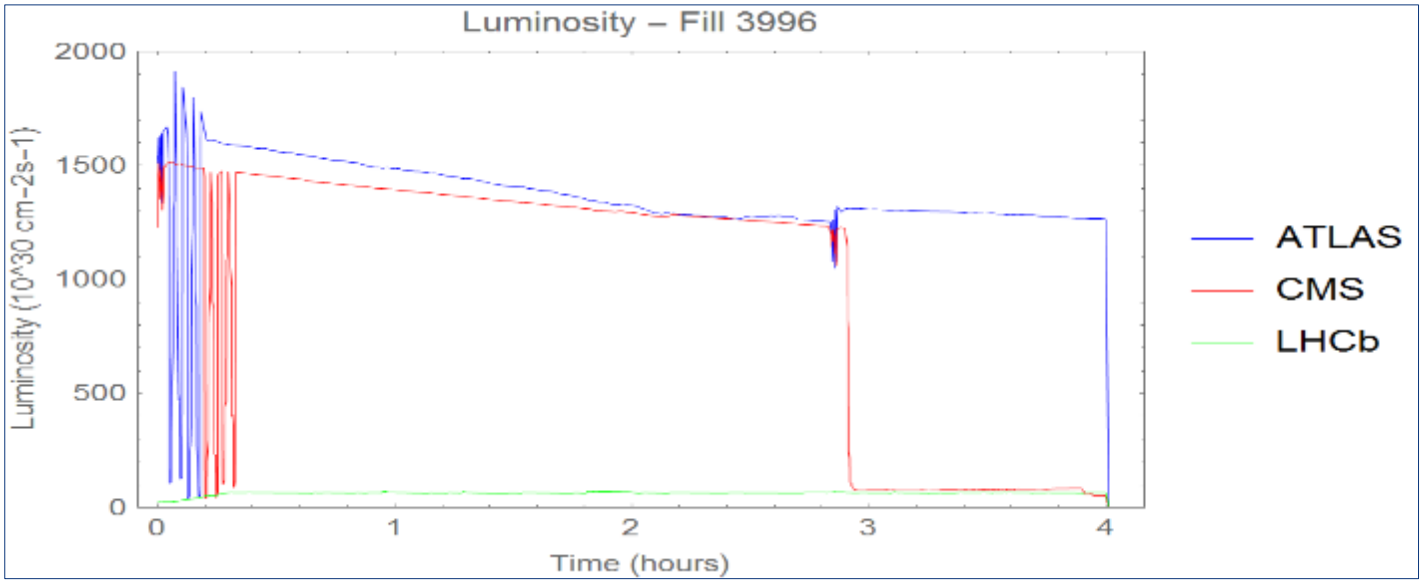


Number of bunches	**50**
Number of colliding bunches (ATLAS/CMS)	**38**
Peak luminosity	**1.45 x 10^{32} $cm^{-2}s^{-1}$**
Integrated luminosity	**3.8 + 3.5 pb^{-1}**
Peak <Events>/BX	**~27**

50 ns intensity ramp-up: up to 476 nominal bunches

	Fill	Stable Beams	Peak lumi [$cm^{-2}s^{-1}$]	Int. lumi pb^{-1}	Nc	Ibunch	emittance [micron]
July 13th	3392	5h18	$1.32\ 10^{33}$	20.6	414	$1.10\ 10^{11}$	2.1
July 14th	3396	4h40	**$1.60\ 10^{33}$**	18.9	414	$1.12\ 10^{11}$	1.8

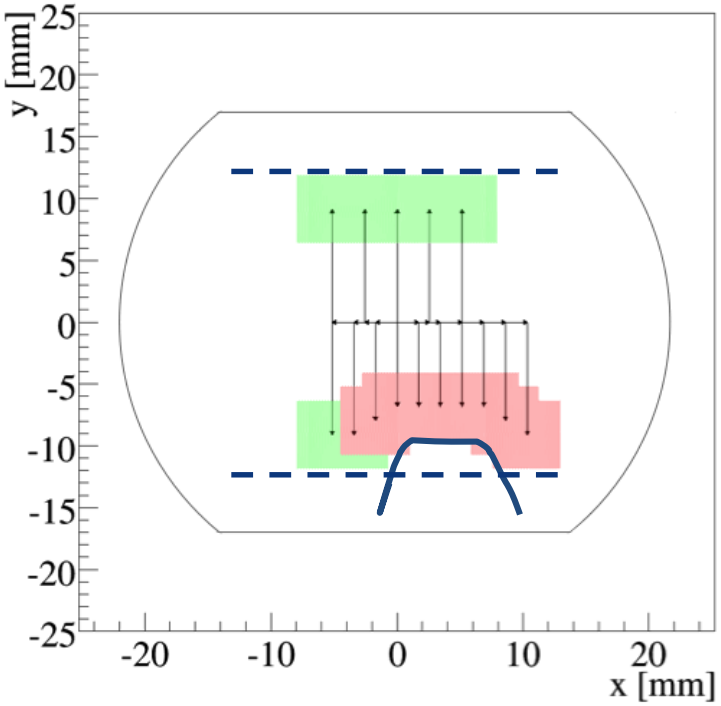
- 50 ns – injecting around nominal bunch intensity with low emittance (not BCMS)
- Instabilities at injection under control, low blow-up through the cycle



Not everything is plain sailing! *e.g. examples…*

Aperture restriction in one sector:

- Measured at injection and 6.5 TeV
- UFO stopped after 2nd beam screen warm-up
- Reference orbit is bumped by +1mm in V and -3mm in H at 15R8.
- Probably not a limiting aperture for operation
- But stability of the object remains a concern



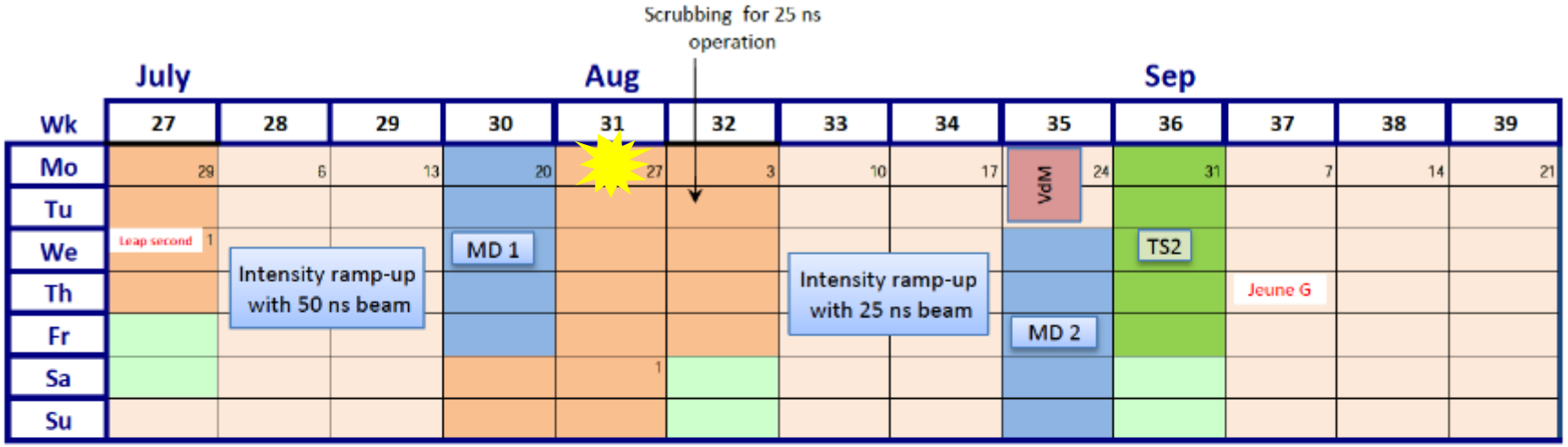
…to come

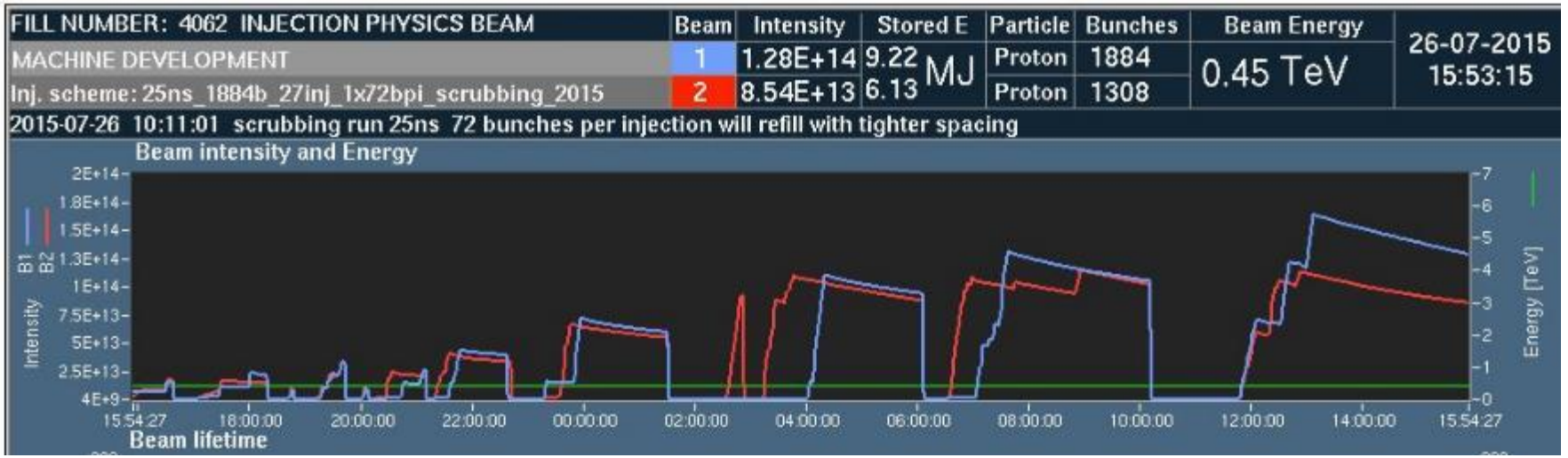
- How does it behave with higher intensities? bunch trains? …

Still have to face the intensity ramp-up

- UFOs, e-cloud, beam induced heating, instabilities,… especially 25 ns
- R2E : QPS electronics cards
- ULO (Unidentified Laying Object)

LHC 2015 – Q3/Q4 (V1.6)





LHC goal for **2015**

Priorities for the 2015 run :

- **Establish proton-proton collision at 13 TeV with 25ns and *low* β* to prepare production run in 2016 and 2017-2018.**

  Optimisation of physics-to-physics duration

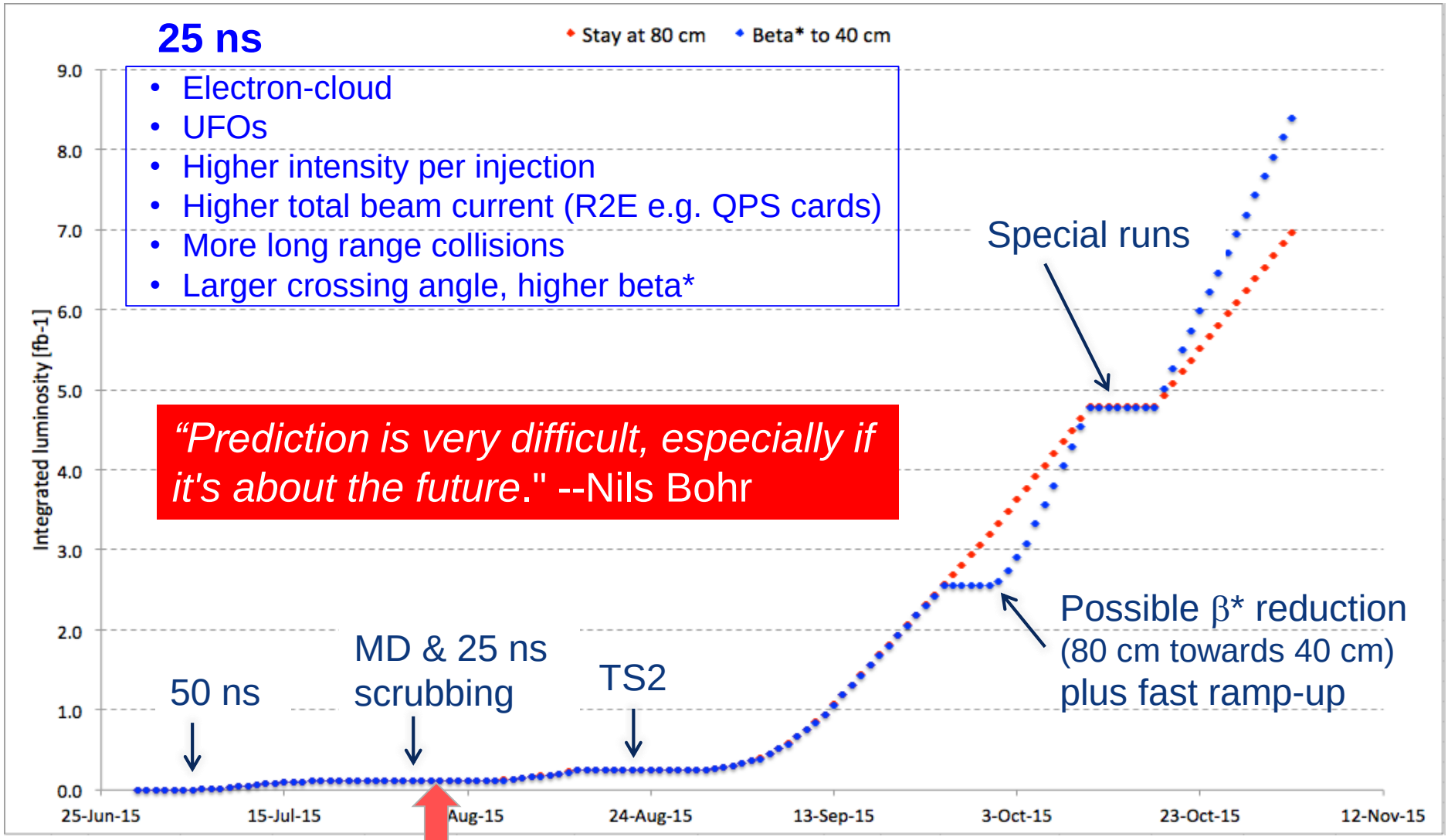
- **Pb-Pb run at the end of 2015**

The goal for Run 2 luminosity is 1.3 x 10^{34} cm^{-2} s^{-1} and operation with 25 ns bunch spacing (2800 bunches), giving an estimated pile-up of 40 events per bunch crossing.

"A maximum pileup of ~50 is considered to be acceptable for ATLAS and CMS"

LHC 2015: projection

Including intensity ramp-ups and steadily increasing physics efficiency



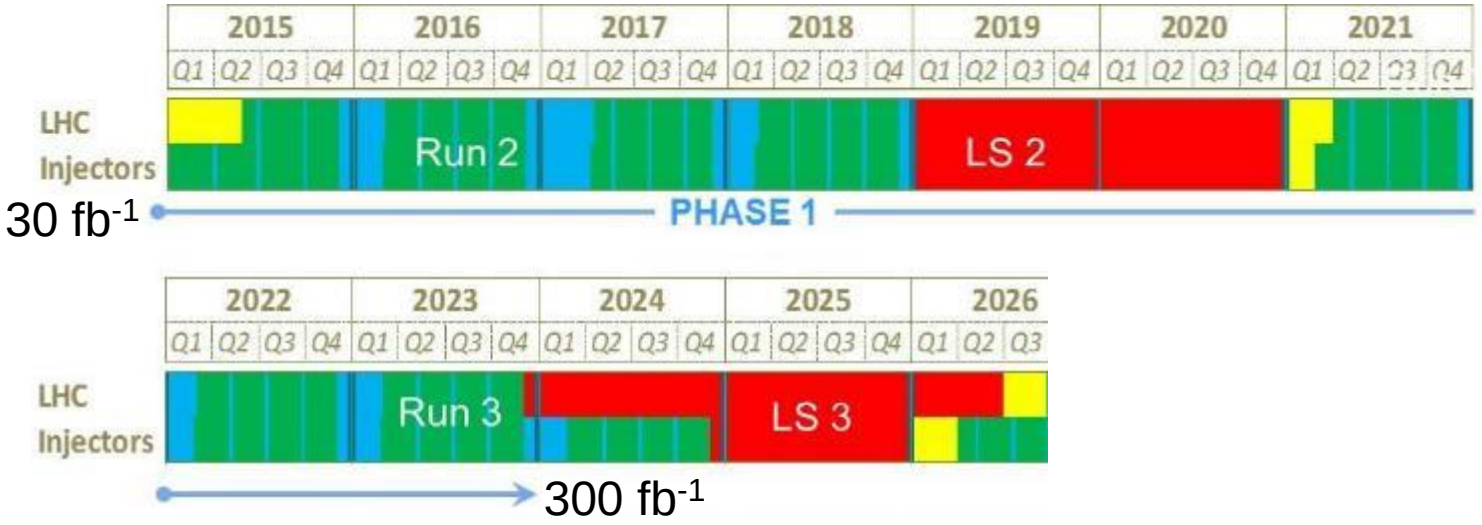
LHC goals **for Run 2 and 3**

Integrated luminosity goals:

2015 : 5-8 fb^{-1}

Run2: ~120-140 fb^{-1} (better estimation by end of 2015)

300 fb^{-1} before LS3



2015 Priority : Establish Production running with 25ns bunch spacing

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*

Fully in line with the P5 recommendations, May 2014

Near-term & Mid-term High-energy Colliders

LARGE HADRON COLLIDER

- **The HL-LHC is strongly supported and is the first high-priority large-category project in our recommended program. It should move forward without significant delay to ensure that accelerator and experiments can continue to function effectively beyond the end of this decade and meet the project schedule.**
- *Recommendation 10:* ***Complete the LHC phase-1 upgrades, and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project.***

Goals and means of the LIU project

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

Increase injector reliability and lifetime to cover HL-LHC run (until ~2035) closely related to consolidation program

⇒ Upgrade/replace ageing equipment (power supplies, magnets, RF…)

⇒ Improve radioprotection measures (shielding, ventilation…)

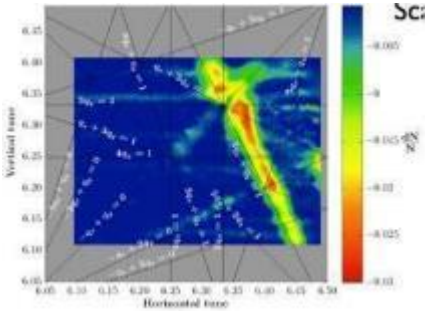
LS2 : (mid 2018-2019), LHC Injector Upgrades (LIU)

LINAC4 – PS Booster:

- H^- injection and increase of PSB injection energy from 50 MeV to 160 MeV, to increase PSB space charge threshold
- New RF cavity system, new main power converters
- Increase of extraction energy from 1.4 GeV to 2 GeV

PS:

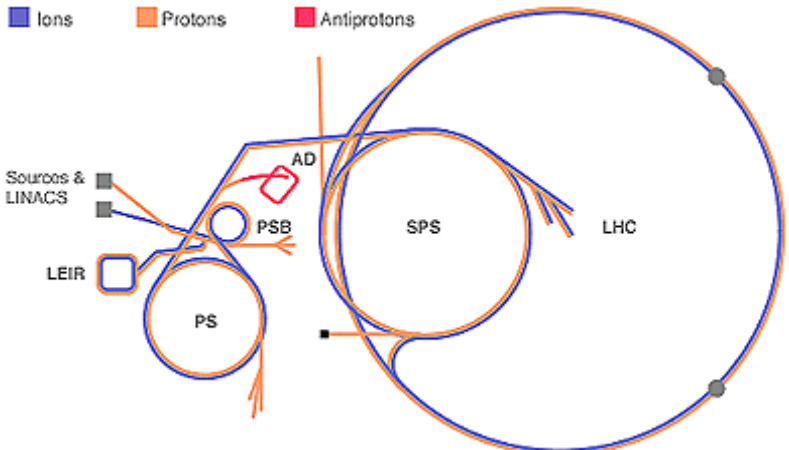
- Increase of injection energy from 1.4 GeV to 2 GeV to increase PS space charge threshold
- Transverse resonance compensation
- New RF Longitudinal feedback system
- New RF beam manipulation scheme to increase beam brightness



SPS

- Electron Cloud mitigation – strong feedback system, or coating of the vacuum system
- Impedance reduction, improved feedbacks
- Large-scale modification to the main RF system

These are only the main modifications and this list is far from exhaustive



Goal of High Luminosity LHC (HL-LHC):

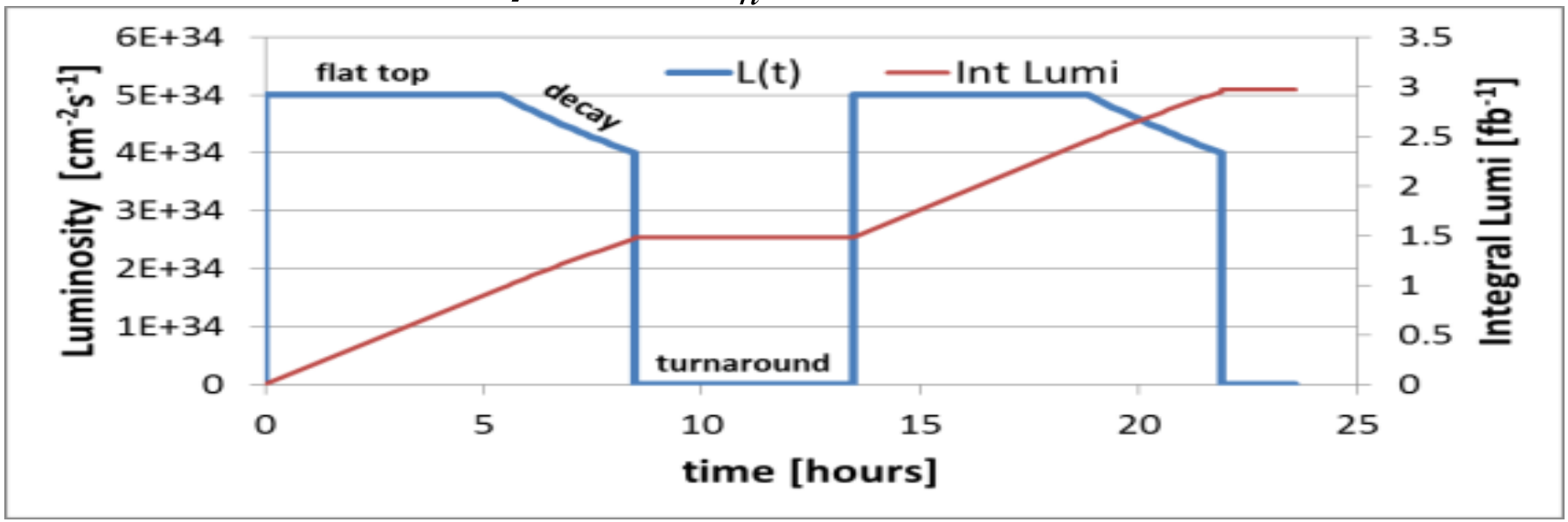
The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

- 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

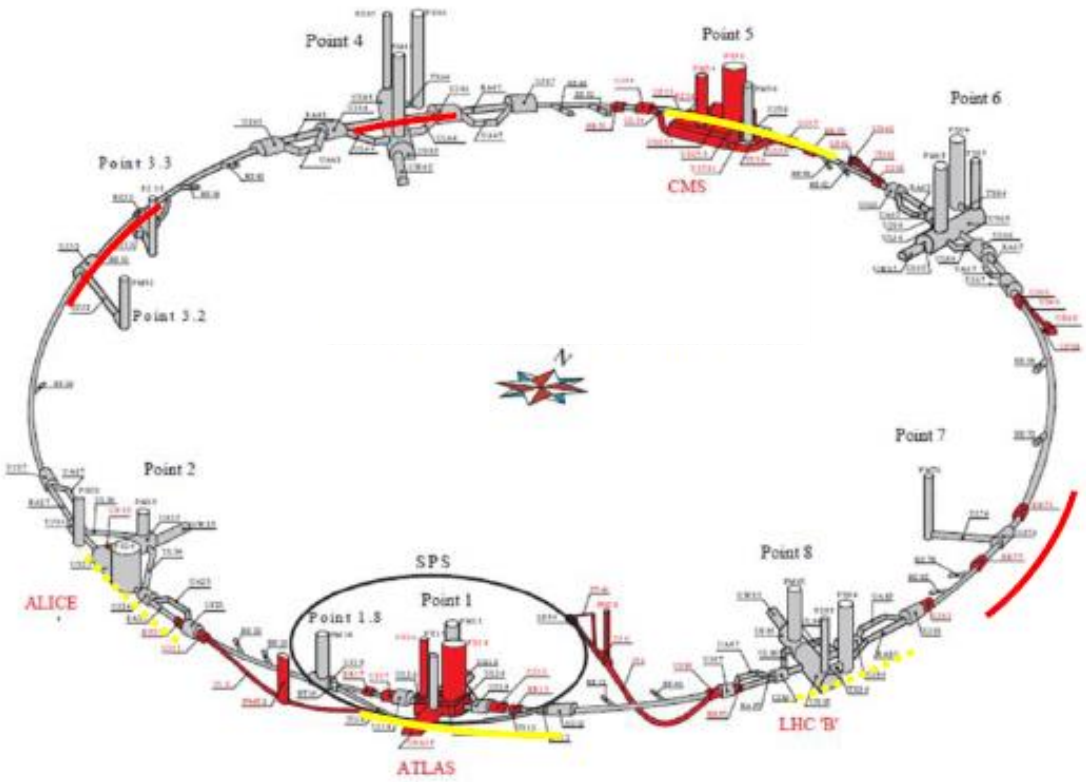
LHC Upgrade Goals: Performance optimization

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



- ✧ **Use F & β* to level the luminosity avoiding too high a pile up in the experiments** ➔ **Levelling**
- ✧ **Improve machine efficiency** ➔ **minimize number of unscheduled beam aborts**

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

Squeezing the beams: High Field SC Magnets

Quads for the inner triplet

Decision 2012 for low-β quads

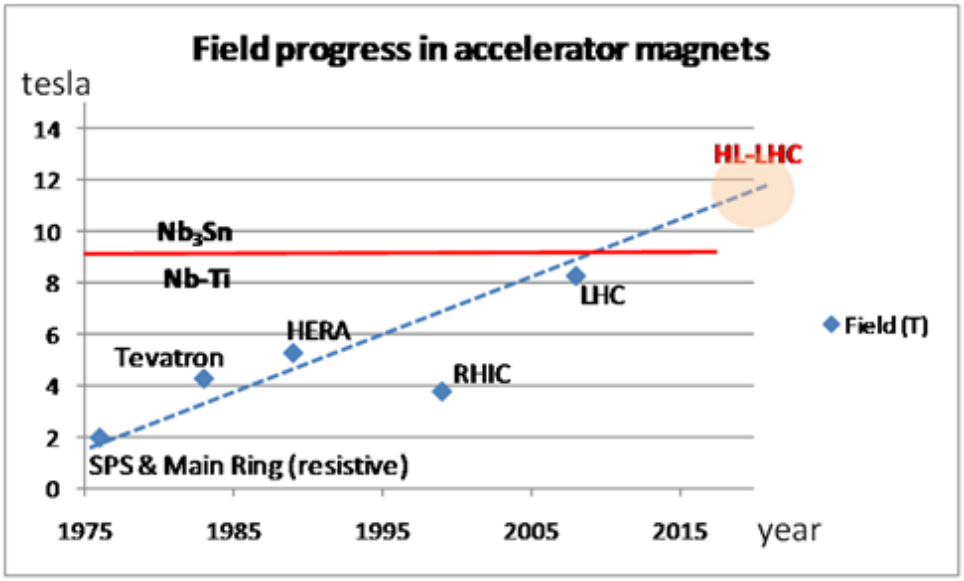
Aperture ∅ 150 mm – 140 T/m

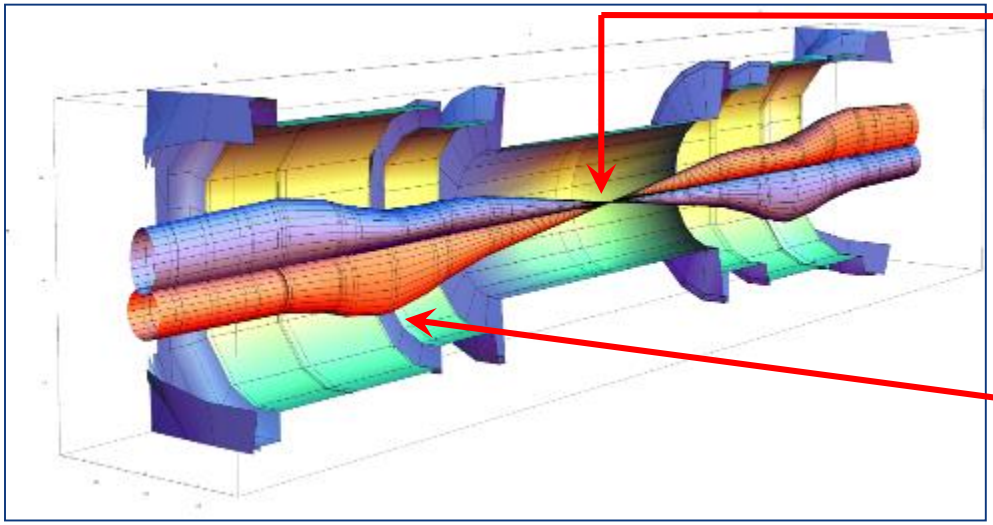
(B_{peak} ≈12.3 T)

operational field, designed for 13.5 T

=> Nb_3Sn technology

(LHC: 8 T, 70 mm)



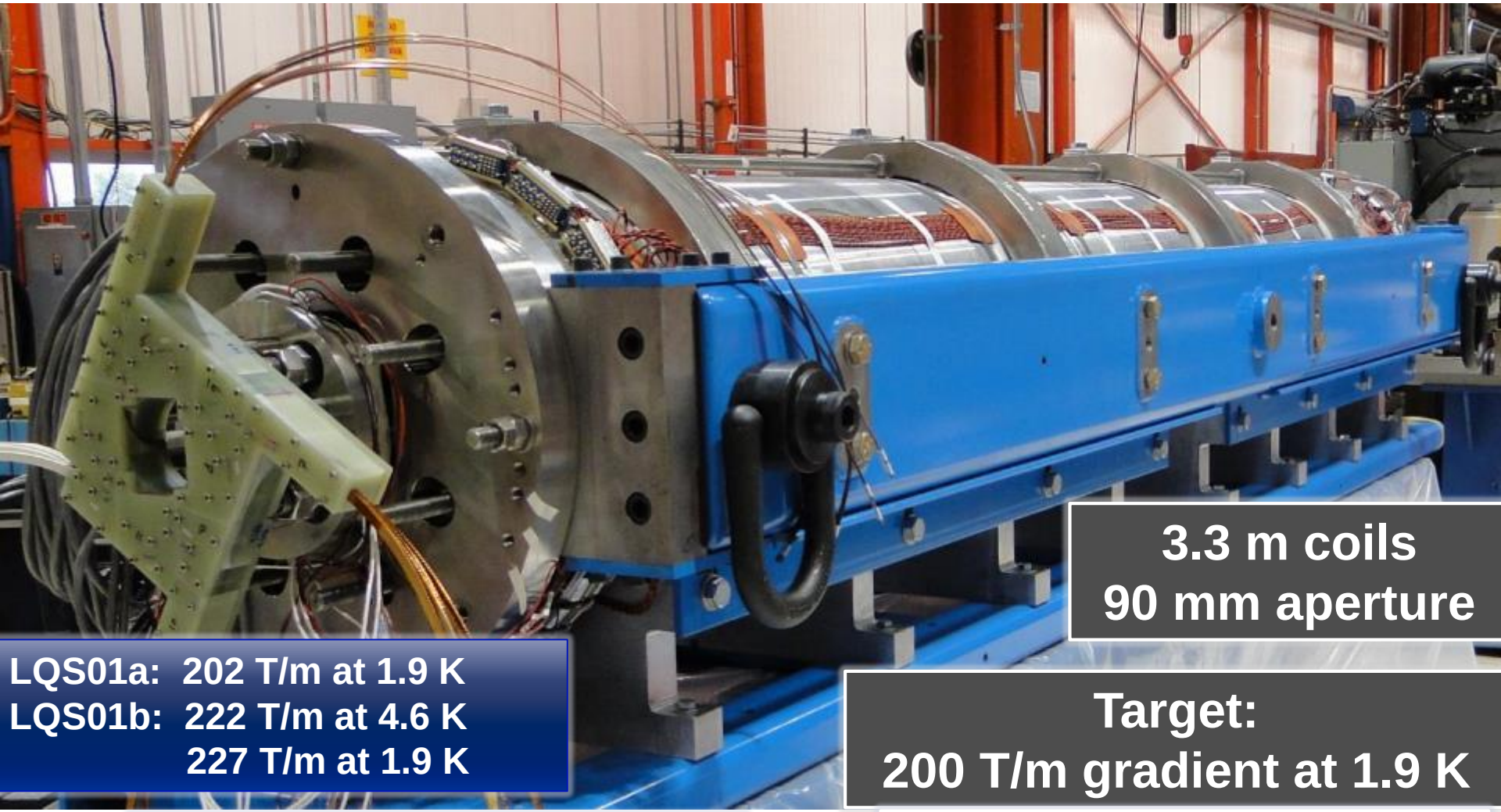


	$\beta_{triplet}$	Sigma triplet	β*	Sigma*
Nominal	~4.5 km	1.5 mm	55 cm	17 um
HL-LHC	~20 km	2.6 mm	15 cm	7 um

Quadrupoles of LARP

Courtesy: G. Ambrosio FNAL and G. Sabbi , LBNL

LARP



3.3 m coils
90 mm aperture

LQS01a: 202 T/m at 1.9 K
LQS01b: 222 T/m at 4.6 K
227 T/m at 1.9 K

Target:
200 T/m gradient at 1.9 K

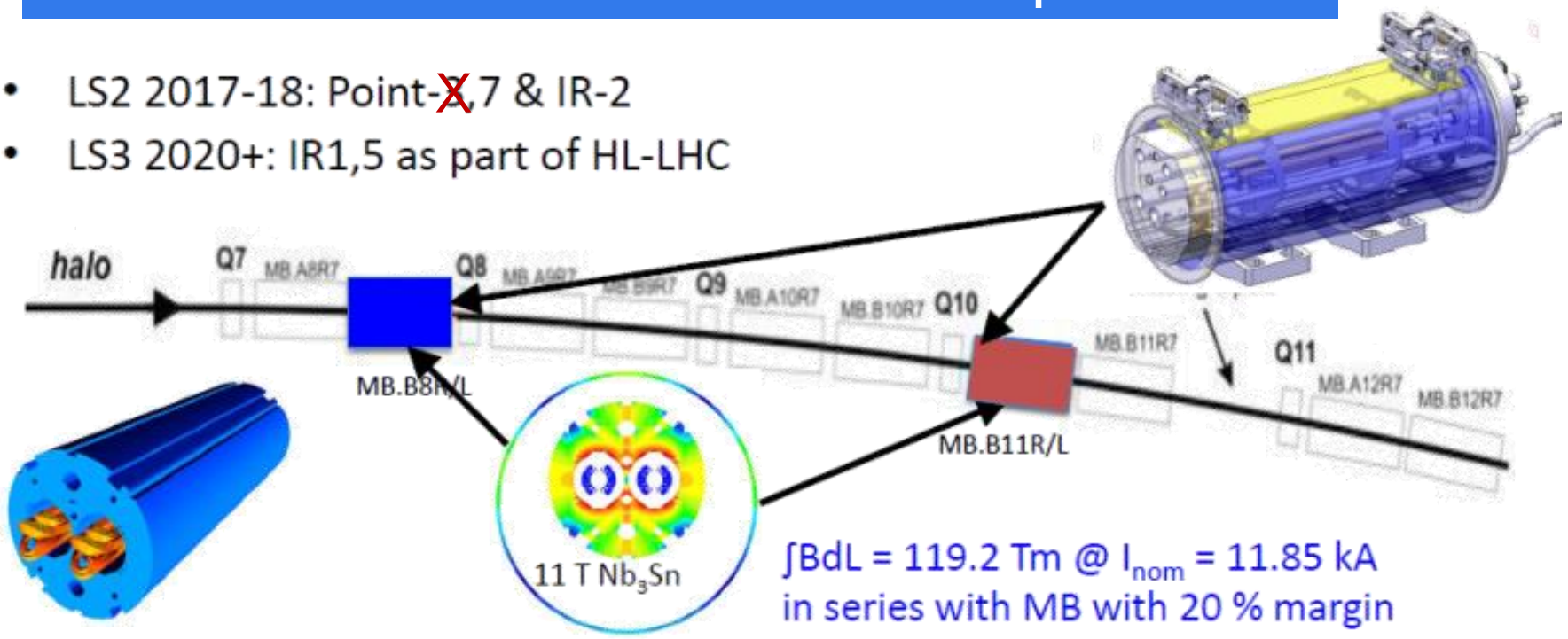
LQS02: 198 T/m at 4.6 K 150 A/s
208 T/m at 1.9 K 150 A/s
limited by one coil

LQS03: 208 T/m at 4.6 K
210 T/m at 1.9 K
1st quench: 86% s.s. limit

CERN

LS2 : collimators and 11T Dipole

- LS2 2017-18: Point-~~2~~,7 & IR-2
- LS3 2020+: IR1,5 as part of HL-LHC

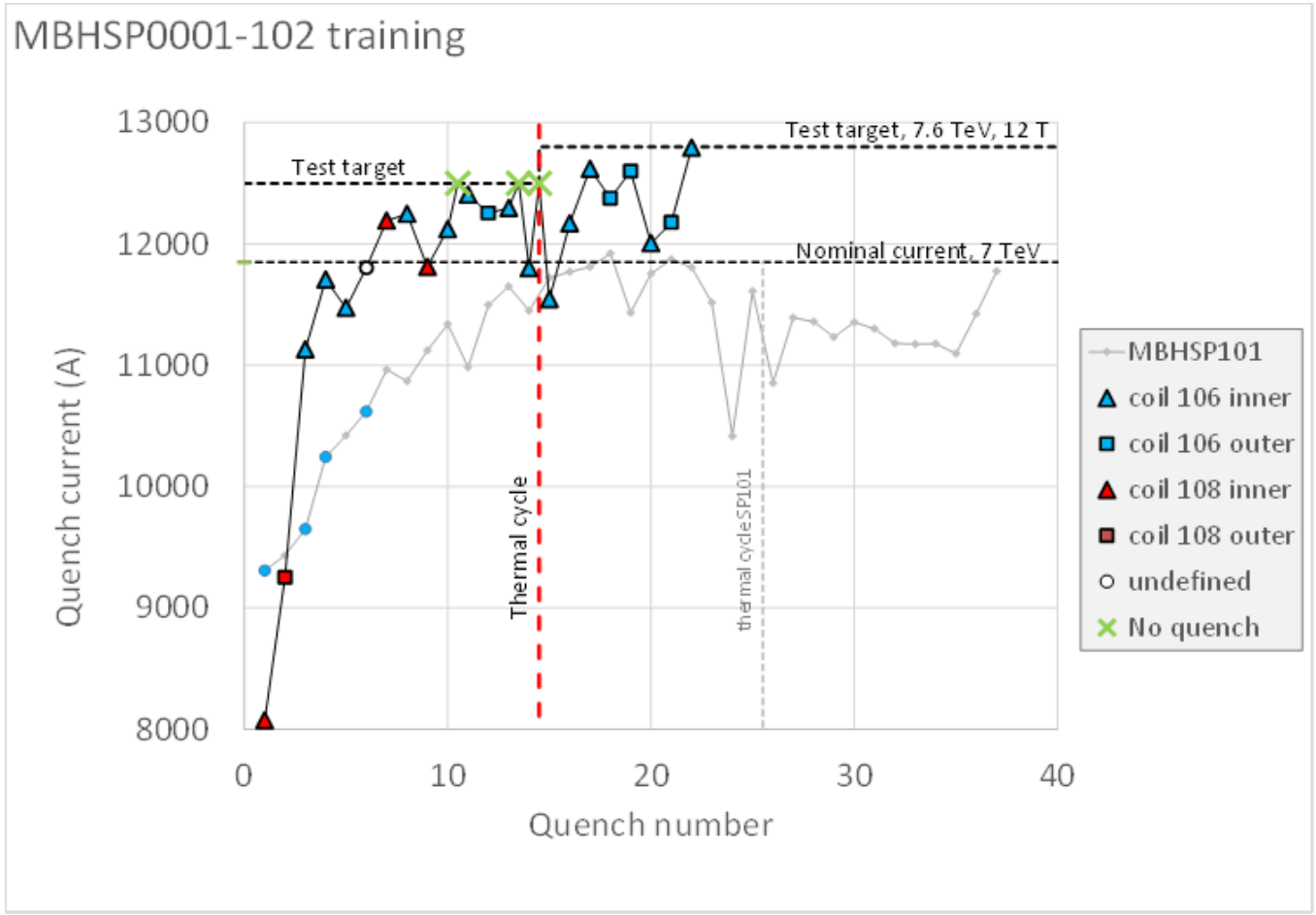


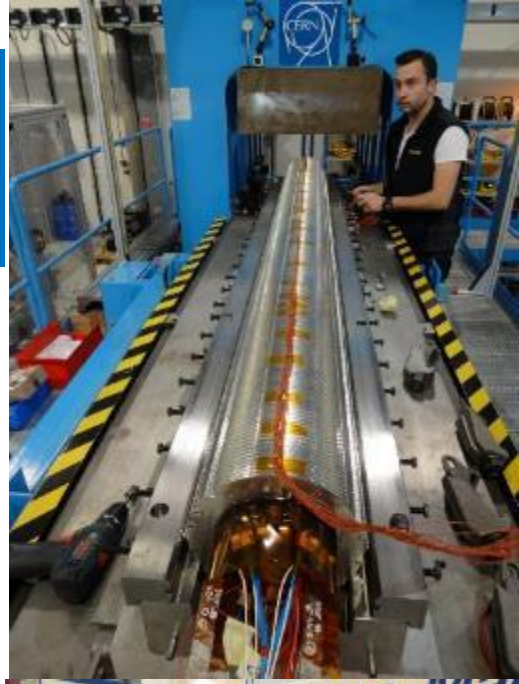
$\int BdL = 119.2$ Tm @ $I_{nom} = 11.85$ kA
in series with MB with 20 % margin

LS2: 12 coldmass + 2 spares = 14 CM
LS3: 8 coldmass + 2 spares = 10 CM
Total 24 CM

LS2: 24 coldmass + 4 spares = 28 CM
LS3: 16 coldmass + 4 spares = 20 CM
Total 48 CM

11 T Magnet – **Nb3Sn** technology
Status on recent developments &tests at CERN





Courtesy of Frédéric Savary

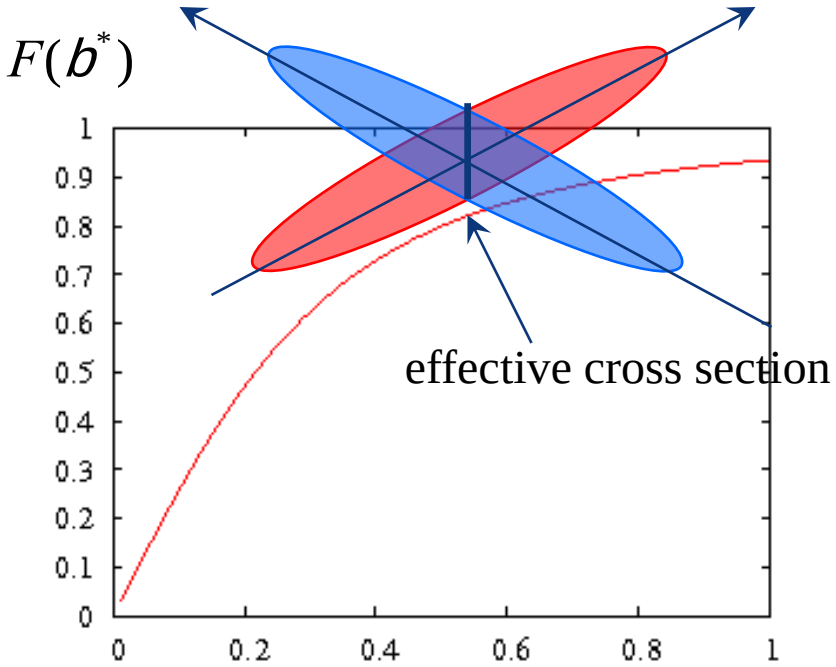
HL-LHC Upgrade Ingredients: Crab Cavities

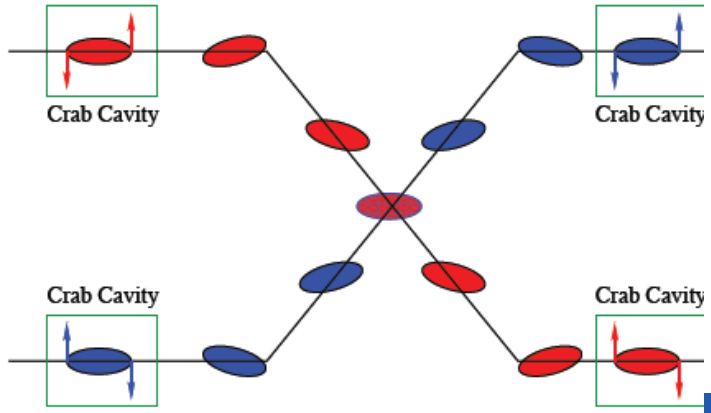
Crab Cavities:
Geometric Luminosity Reduction Factor:

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

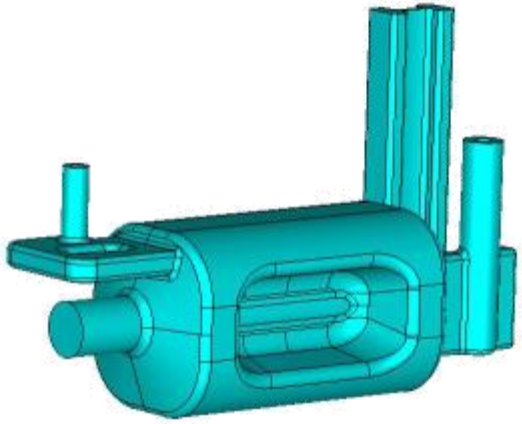
$$F = \frac{1}{\sqrt{1+Q^2}}; \quad Q^o \frac{q_c s_z}{2 s_x}$$

- Noise from cavities to beam ?
- Challenging space constraints



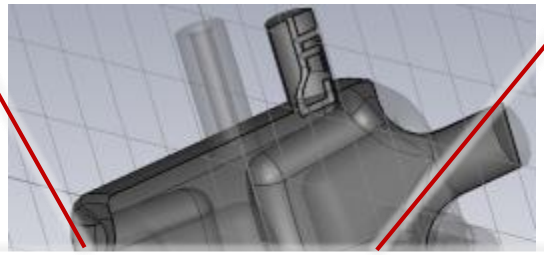


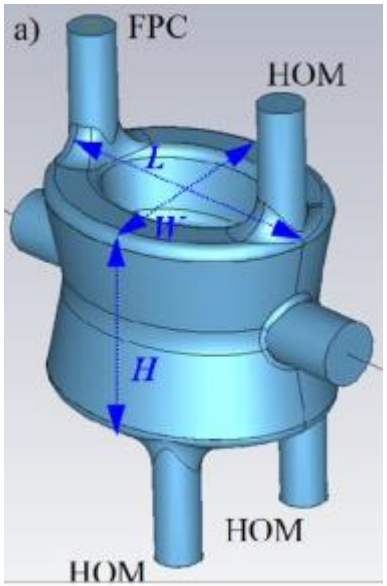
Latest cavity designs toward accelerator



RF Dipole: Waveguide or waveguide-coax couplers

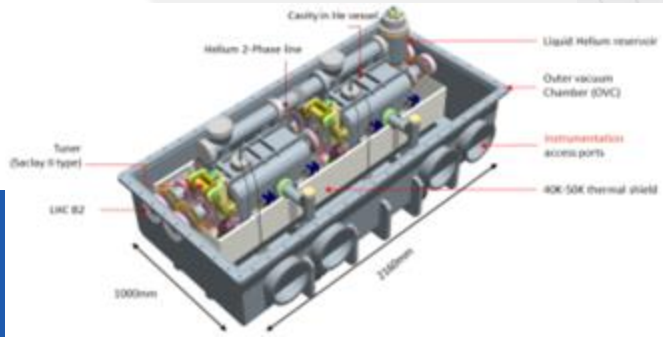
3 Advanced Design Studies with Different Coupler concepts





Double ¼-wave:

Concentrate on two designs in order to be ready for test installation in SPS in 2016/2017



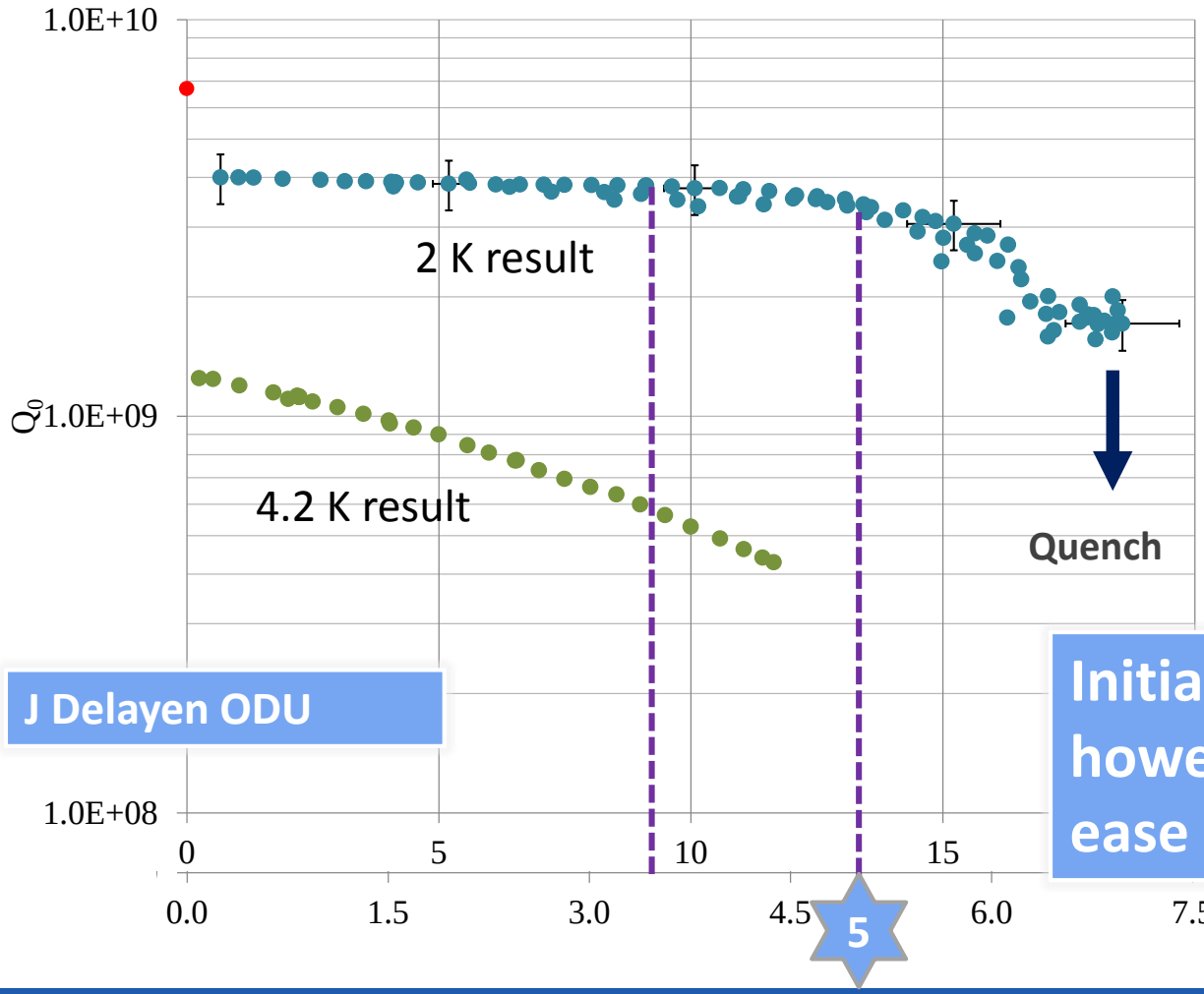
Coaxial couplers with

nt a

Present baseline: 4 cavity/cryomodule
TEST in SPS under preparation for 2017

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

¼ w and 4-rods also tested (1.5 MV)

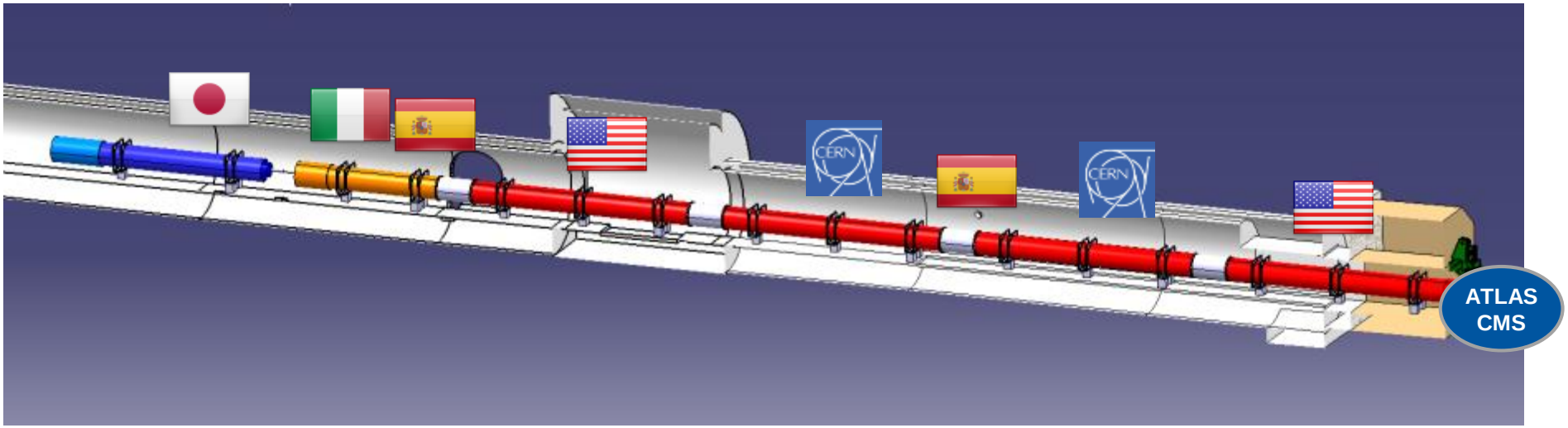


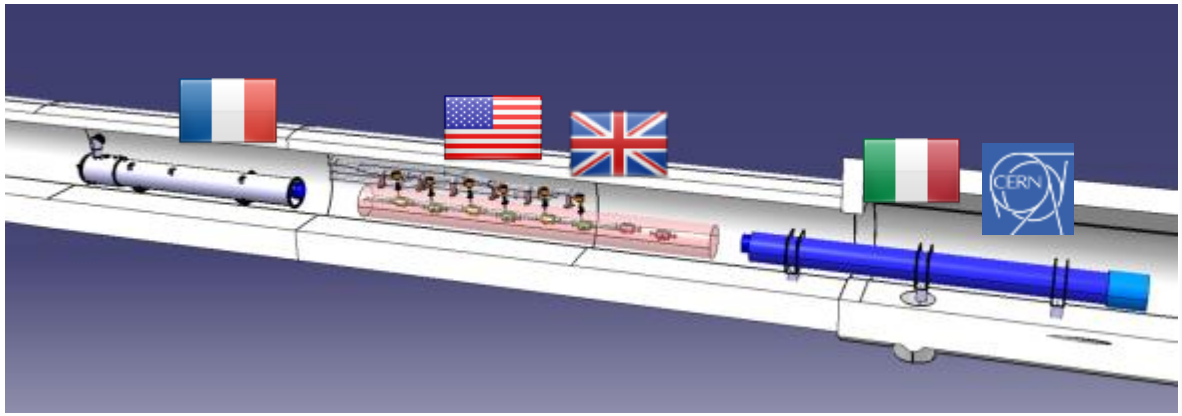
J Delayen ODU

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

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

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





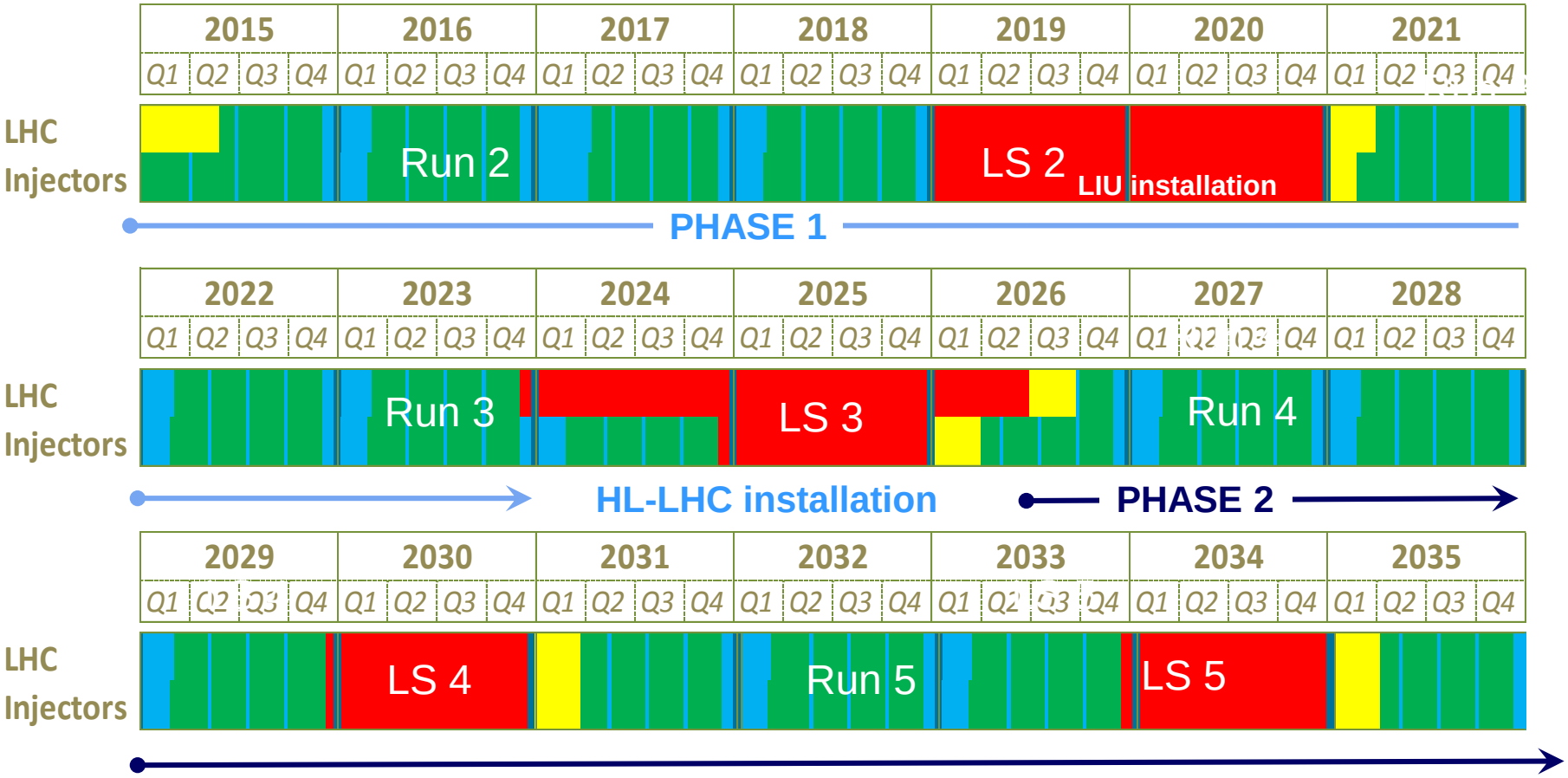
Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

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

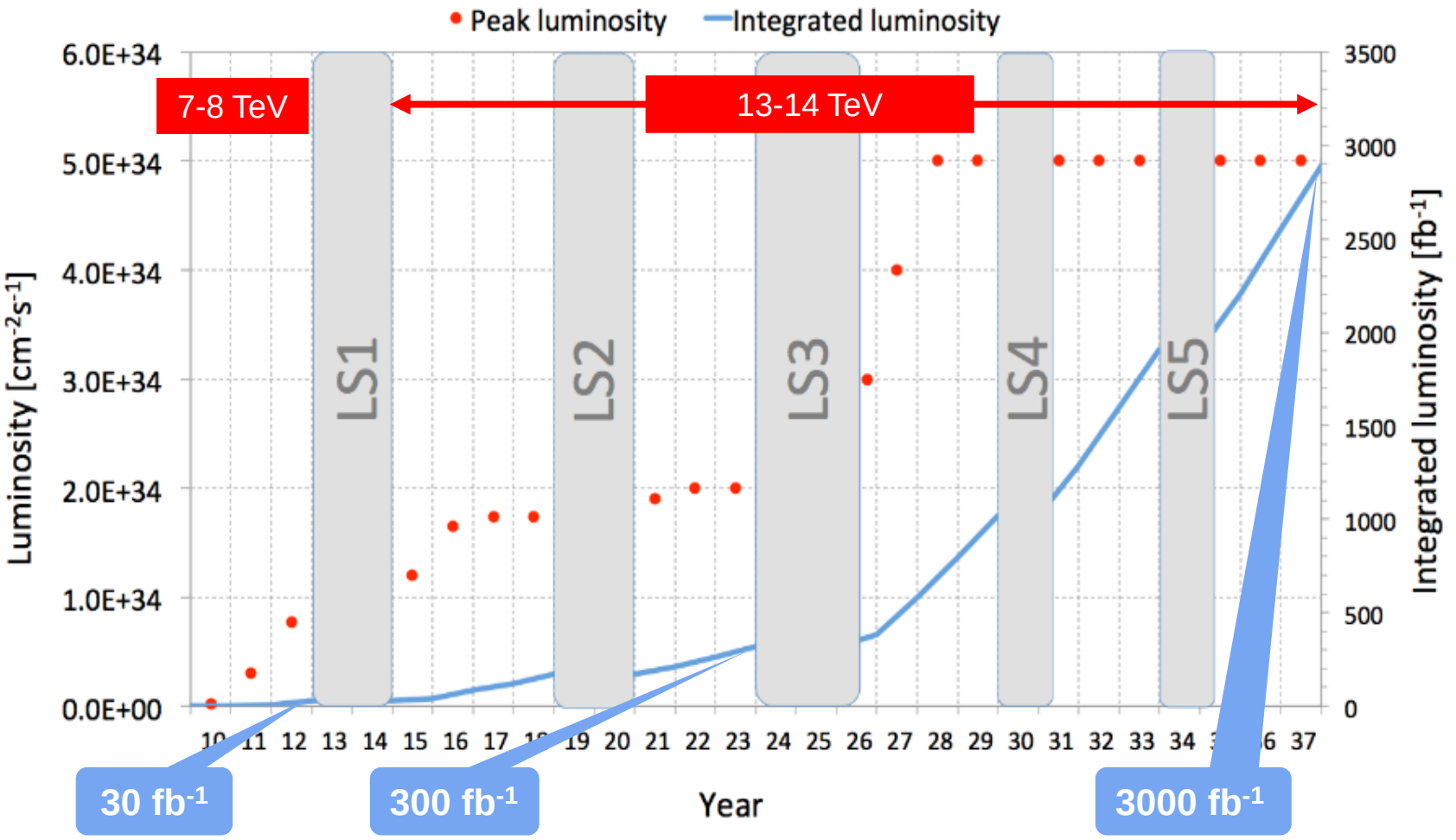
CC : R&D and Design **UK**

LHC roadmap

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC



LHC roadmap: Integrated luminosity



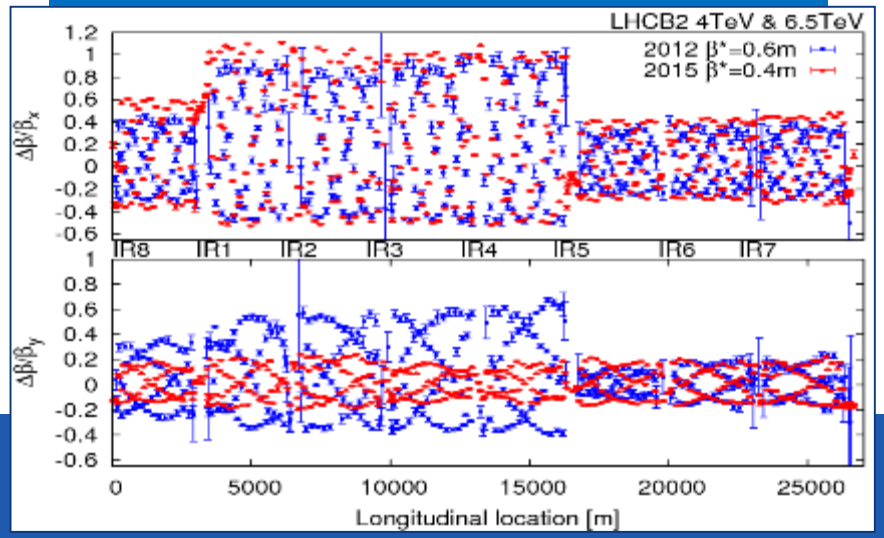
LS1 = consolidation for maximizing energy reach of the LHC (8 to 14 TeV)
LS2 = LIU for beam intensity upgrade
LS3 = HL-LHC for luminosity upgrade

Conclusions

- Lot of lessons learnt in Run 1 and tremendous works done in LS1
- Re-commissioning of the LHC superconducting circuits went well – even though some surprises ! (like earth faults)
- Magnet training roughly according to expectations
  (deeper analysis is now needed to understand their behaviour and decide upon energy increase after 2015 operation)
- Fantastic progress in beam commissioning and physics preparation
- The LHC looks good at 6.5 TeV
  with unsqueeze and squeeze optics
  - Magnetic reproducibility
  - Good optics

  (prepared squeezed optics up to β* 40cm)

Optics: Squeeze down to β* 40 cm



Conclusions

- **Next challenge: e-cloud (scrubbing campaign) and ramp-up in beam intensity (25 ns)**

- **Fundamentals look sound, no show stoppers for the moment**
  Some teething concerns (e.g. SEU on QPS electronics cards, ULO,…)

- **Priority for the 2015 run:**
  Establish proton-proton collisions at 13 TeV with 25ns and low β^* (~ 40cm) to prepare production run in 2016 and 2017-2018

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

- **Full exploitation of the LHC with optimised planning out to 2035.**

Thanks for your attention

The LHC is enjoying benefits of the decades long international design, construction, installation, LS1 upgrade effort and commissioning.
Progress with beam represents phenomenal effort by all the teams involved, injectors included.
Now preparation for the production of new collision data to see what nature has in store at these new ***unexplored energies*** (Terra Incognita)

Run 1

"It is much too early to expect any discovery, we will have to be patient" CERN DG