LHC machine: status and prospects

CHIPP Annual Plenary Meeting 2015

Frédérick Bordry

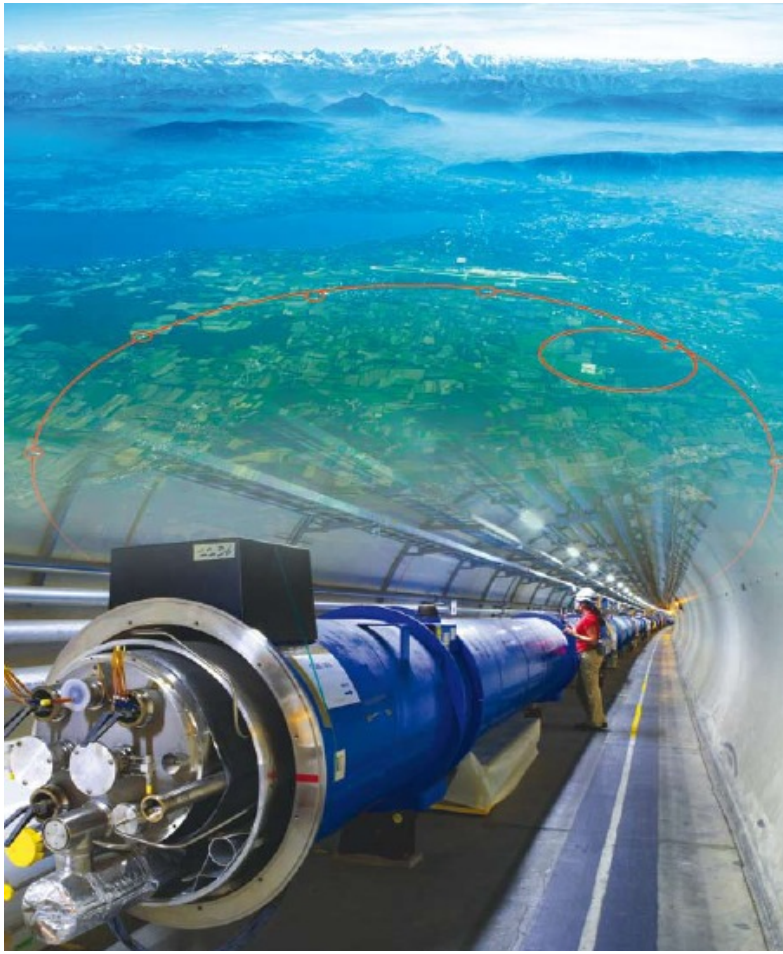
29th June 2015

LHC (Large Hadron Collider)

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

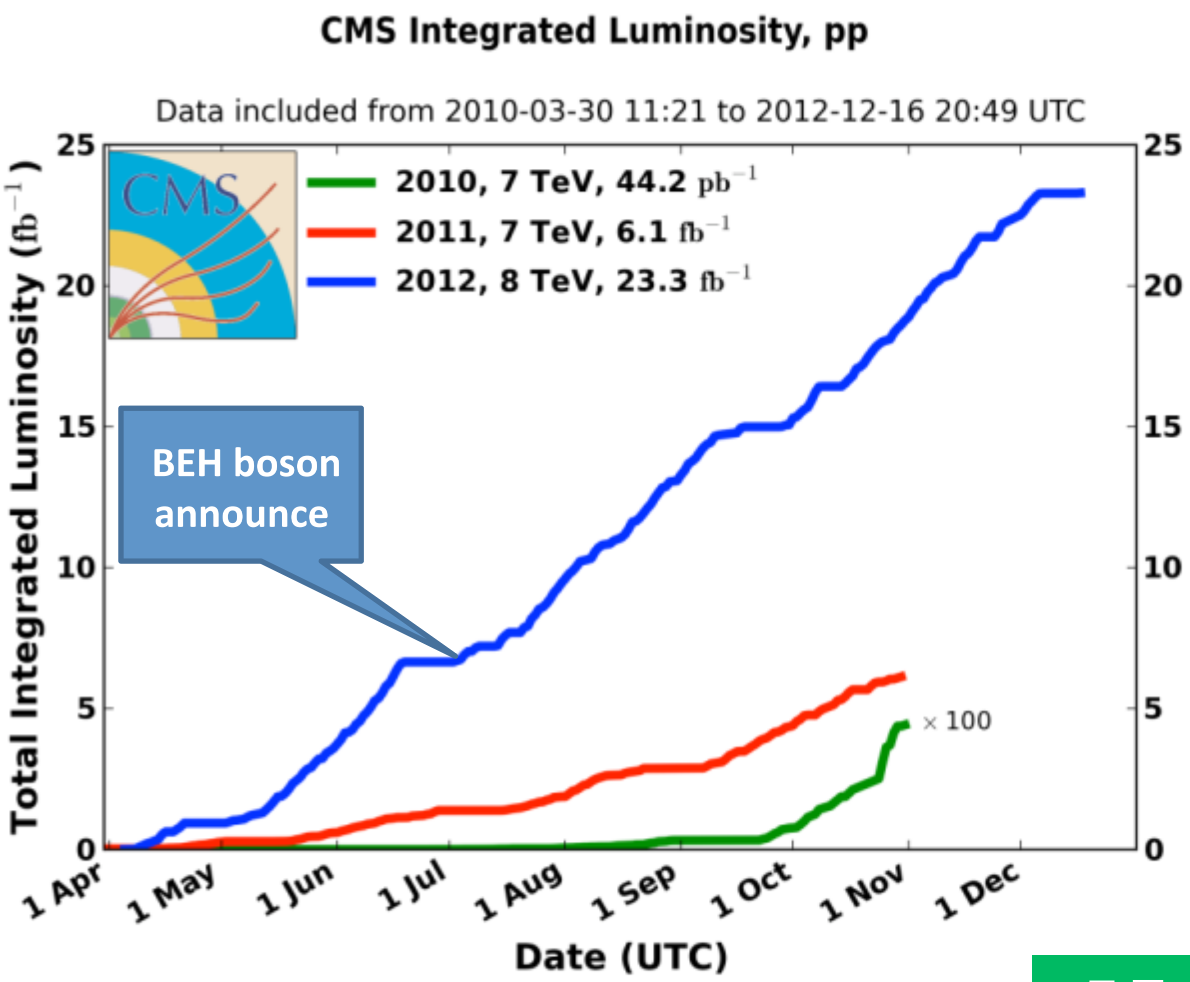
Lead-Lead (Lead-proton) collisions

1983	:	**First studies for the LHC project**
1988	:	**First magnet model (feasibility)**
1994	:	**Approval by the CERN Council**
1996-1999	:	**Series production industrialisation**
1998	:	**Declaration of Public Utility & Start of 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

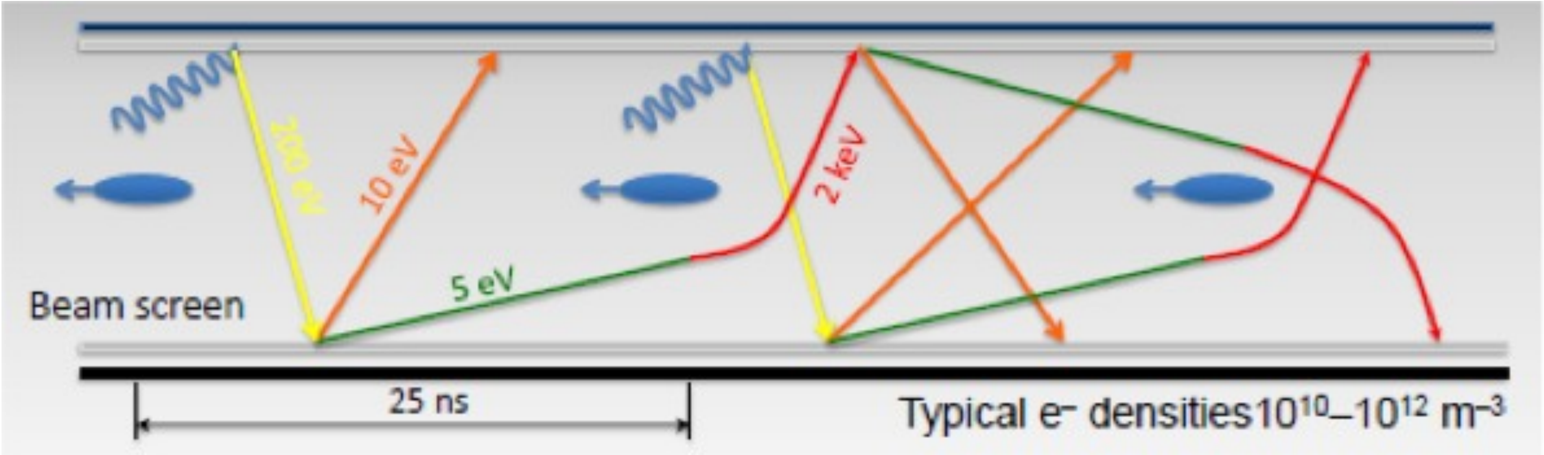
7 TeV and 8 TeV in 2012

2012: Some Main Beam Parameters

	25 ns (design)	50 ns (2012)	25 ns (2012)#
Energy per beam [TeV]	7	**4**	4
Intensity per bunch [x10^{11}]	1.15	**1.7**	1.2
Norm. Emittance H&V [μm]	3.75	**1.8**	2.7
Number of bunches	2808	**1380**	N.A. #
β* [m]	0.55	**0.6**	N.A. #
Peak luminosity [cm^{-2}s^{-1}]	1×10^{34}	$\mathbf{7.7 \times 10^{33}}$	N.A. #

The 25 ns was only used for scrubbing and tests in 2012

Some Limitations: e-cloud

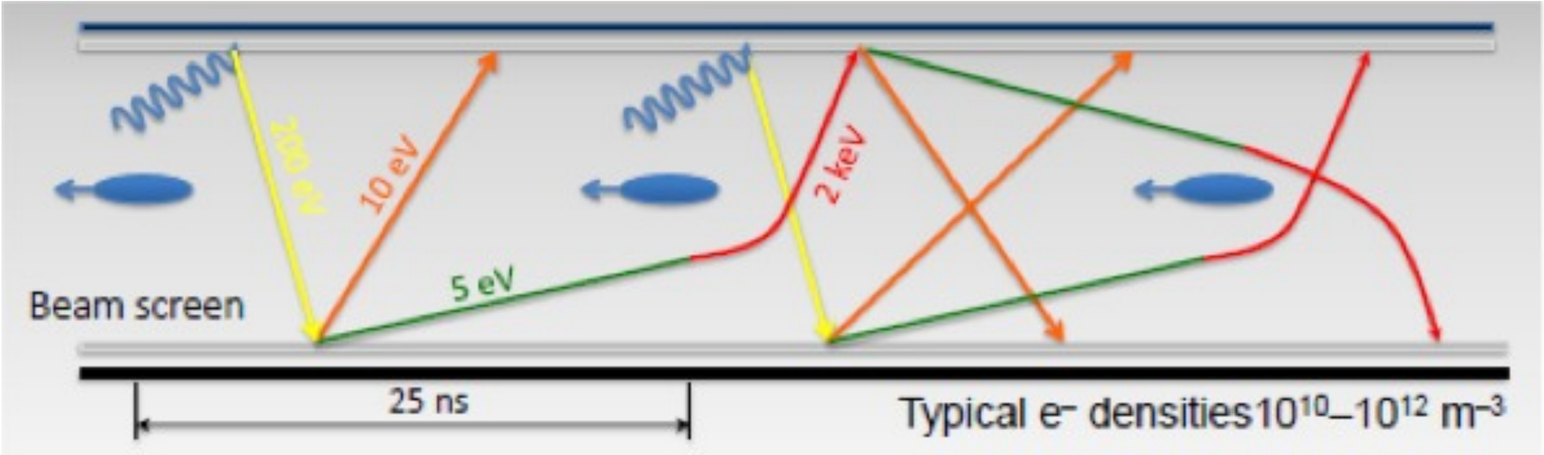


Synchrotron radiation from proton bunches creates photoelectrons at the beam screen wall. These photoelectrons are pulled toward the positively charged proton bunch. When they hit the opposite wall, they generate secondary electrons which can in turn be accelerated by the next bunch. Depending on surface reflectivity, photoelectron and secondary electron yield, this mechanism can lead to the fast build-up of an electron cloud.

Possible consequences:

- instabilities, emittance growth, desorption – bad vacuum
- excessive energy deposition in the cold sectors

Some Limitations: e-cloud



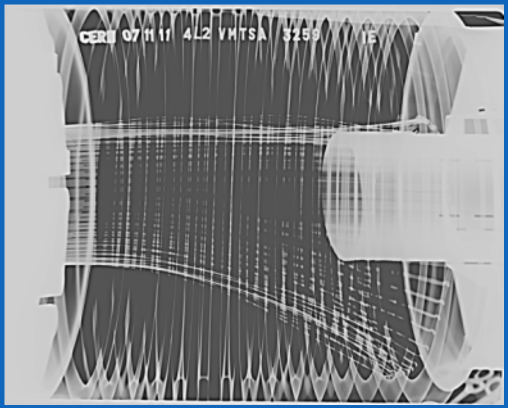
Electron bombardment of a surface has been proven to reduce drastically the **secondary electron yield (SEY)** of a material. This technique, known as **scrubbing**, provides a mean to suppress electron cloud build-up.

Electron cloud significantly worse with 25 ns

Some Limitations: cont'd

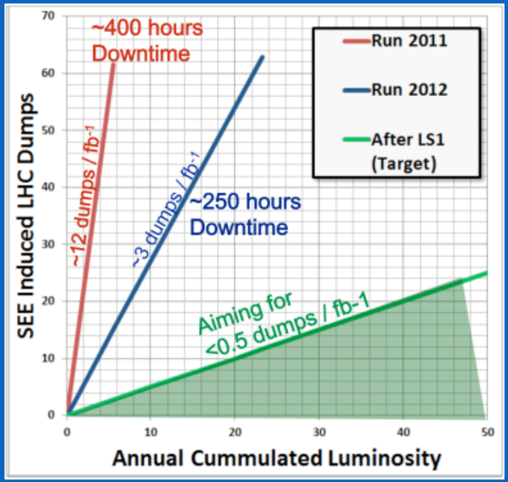
Beam induced heating

- Local non-conformities (design, installation)
  - Injection protection devices
  - Sync. Light mirrors
  - Vacuum assemblies



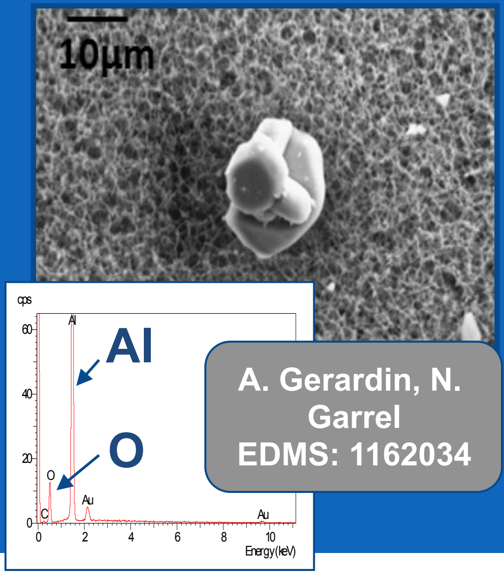
Radiation to electronics

- Concerted program of mitigation measures (shielding, relocation…)
- Premature dump rate down from 12/fb^{-1} in 2011 to 3/fb^{-1} in 2012



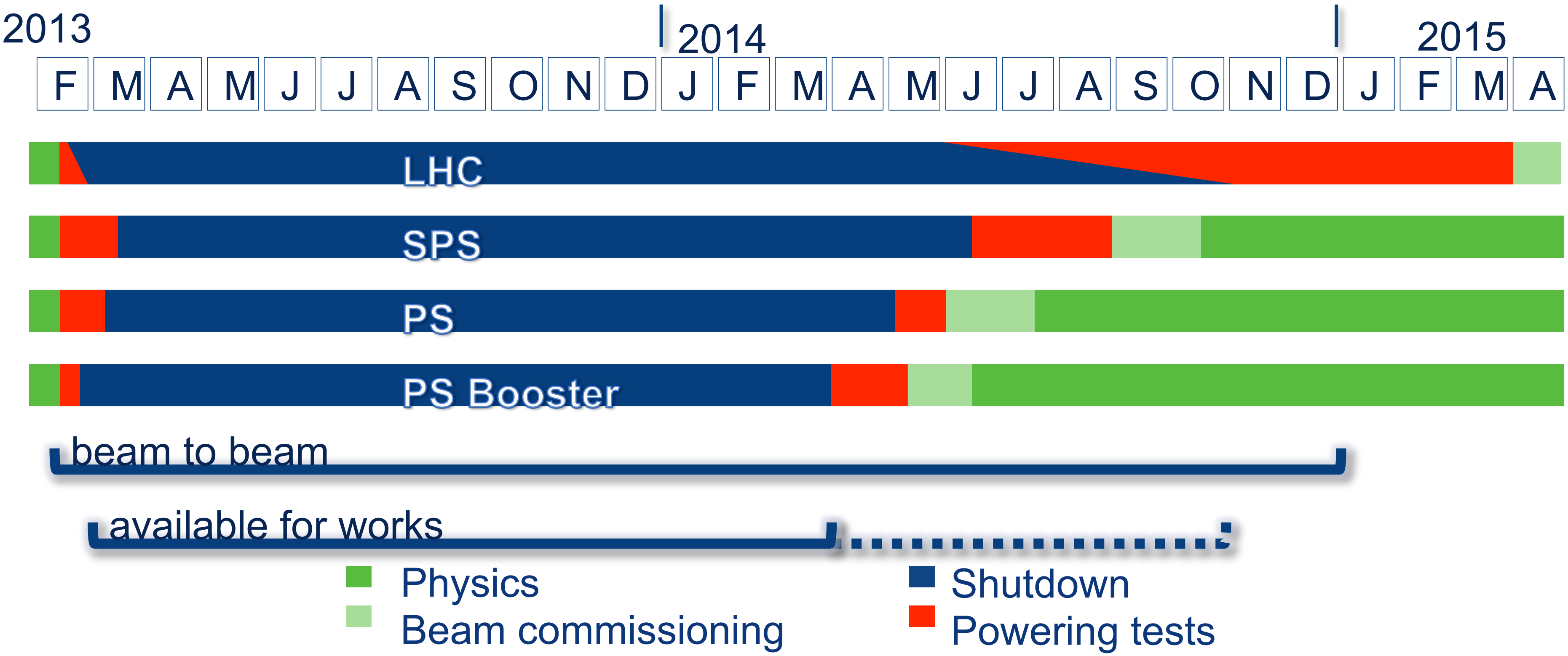
UFOs

- 20 dumps in 2012
- Timescale 50-200 μs
- Conditioning observed
- Worry about 6.5 TeV



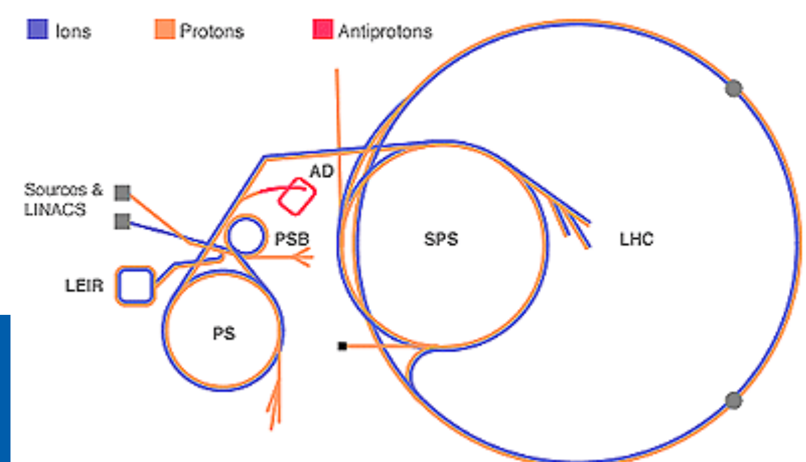
A. Gerardin, N. Garrel
EDMS: 1162034

LS 1 from 16th Feb. 2013 to Mar. 2015



Over 1 Million Hours Worked in the LHC Tunnel

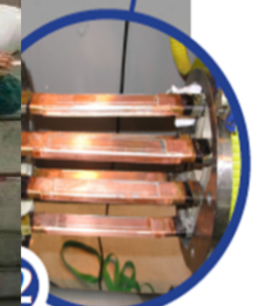
Safety First,
Quality Second,
Schedule Third.



The main 2013-14 LHC consolidations

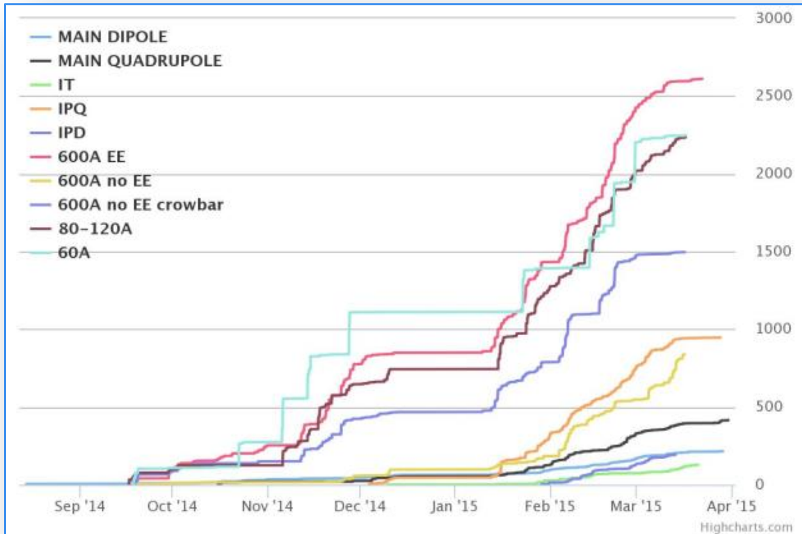
SMACC project : Closure of the last interconnection – 18.06.2014

18 000 electrical
Quality Assurance tests

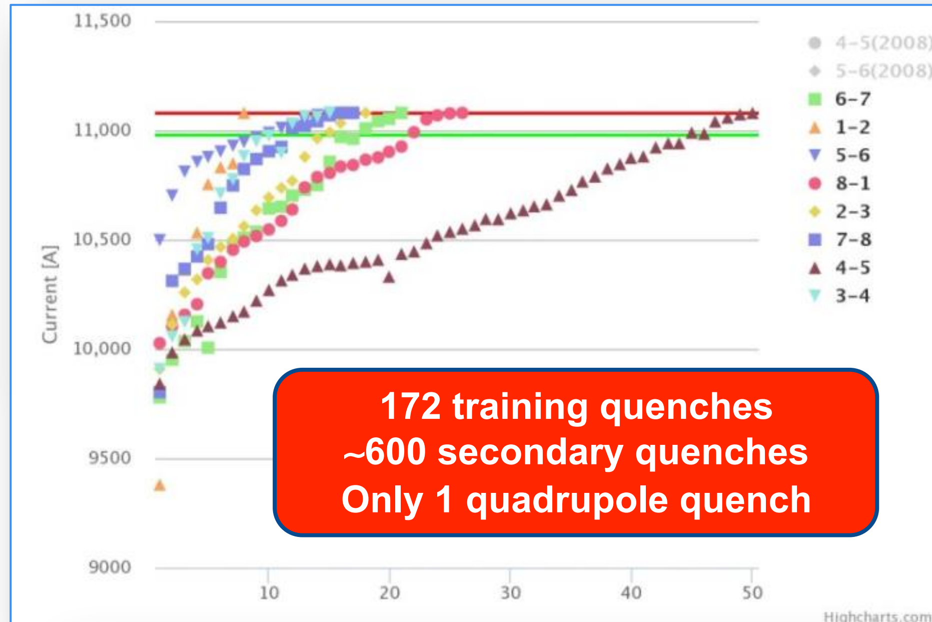


nsolidation of the
kA circuits in the 16
in electrical feed-
oxes

The LHC powering tests overview



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



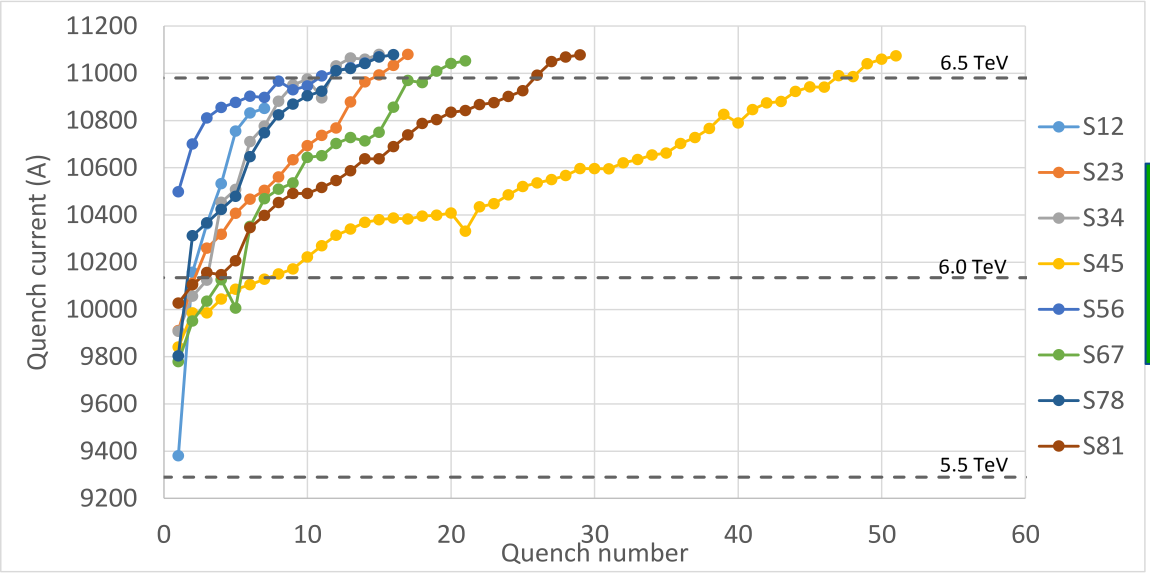
172 training quenches
~600 secondary quenches
Only 1 quadrupole quench

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!

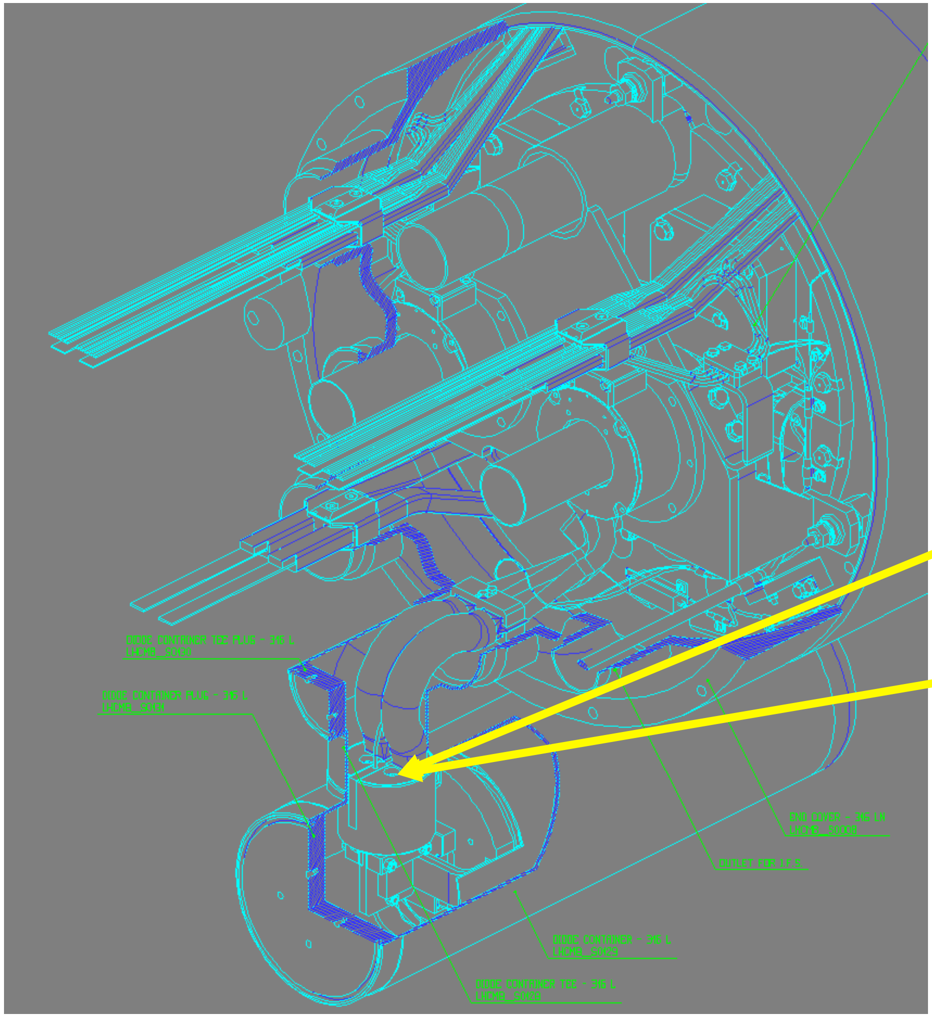
Maximum beam energy : **13 TeV c.m. in 2015**

Decision to run at a **maximum** energy of 6.5 TeV per beam during the powering tests and during 2015.

NO change of beam energy in 2015.

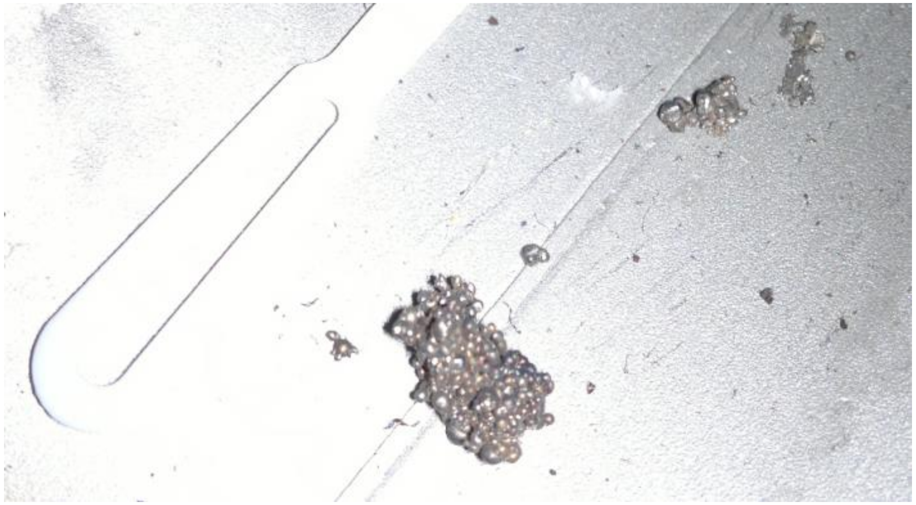
A decision regarding the possibility of increasing the energy will be taken after 2015 operation, based on the experience gained in all eight sectors at 6.5 TeV per beam during powering tests and operation with beams.

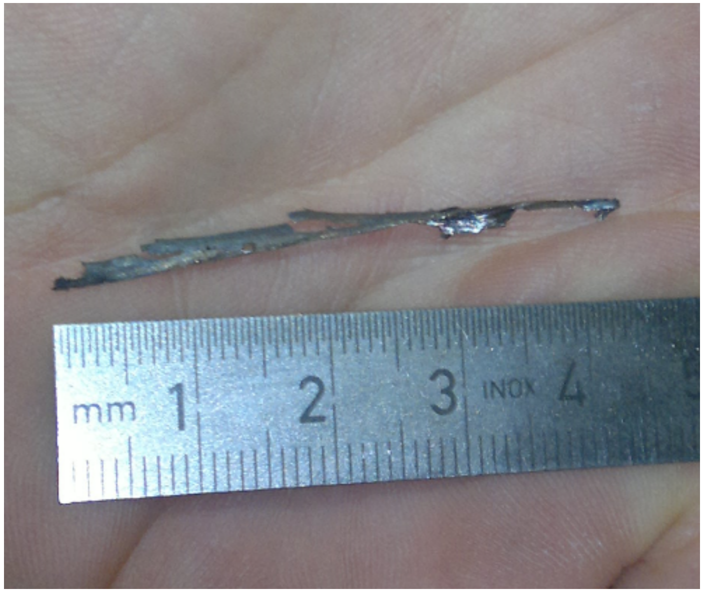
Not everything is plain sailing! *One example… sector 3-4*



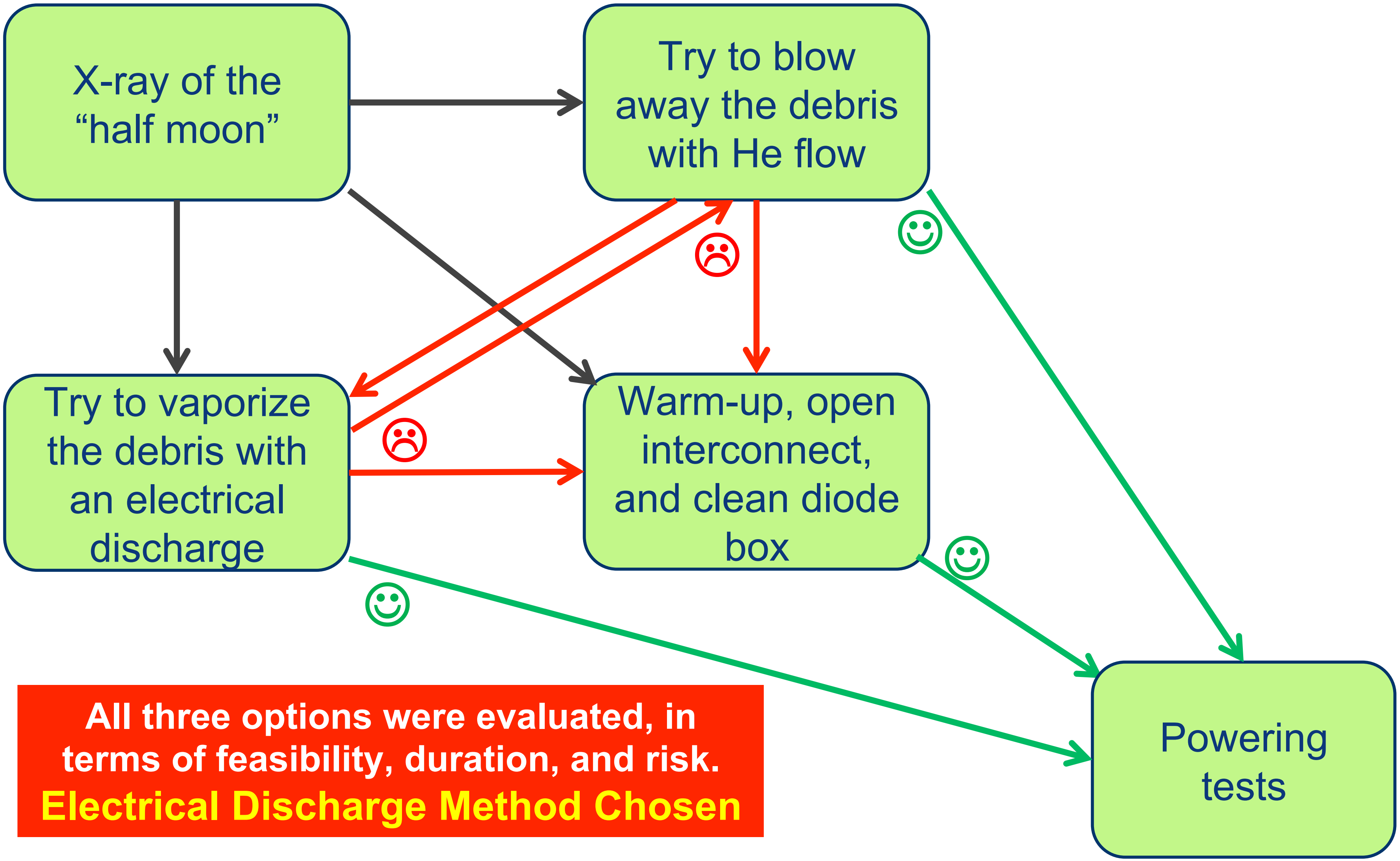
Unfortunately can not see the debris in the affected magnet

Metal chips and pieces found in the past





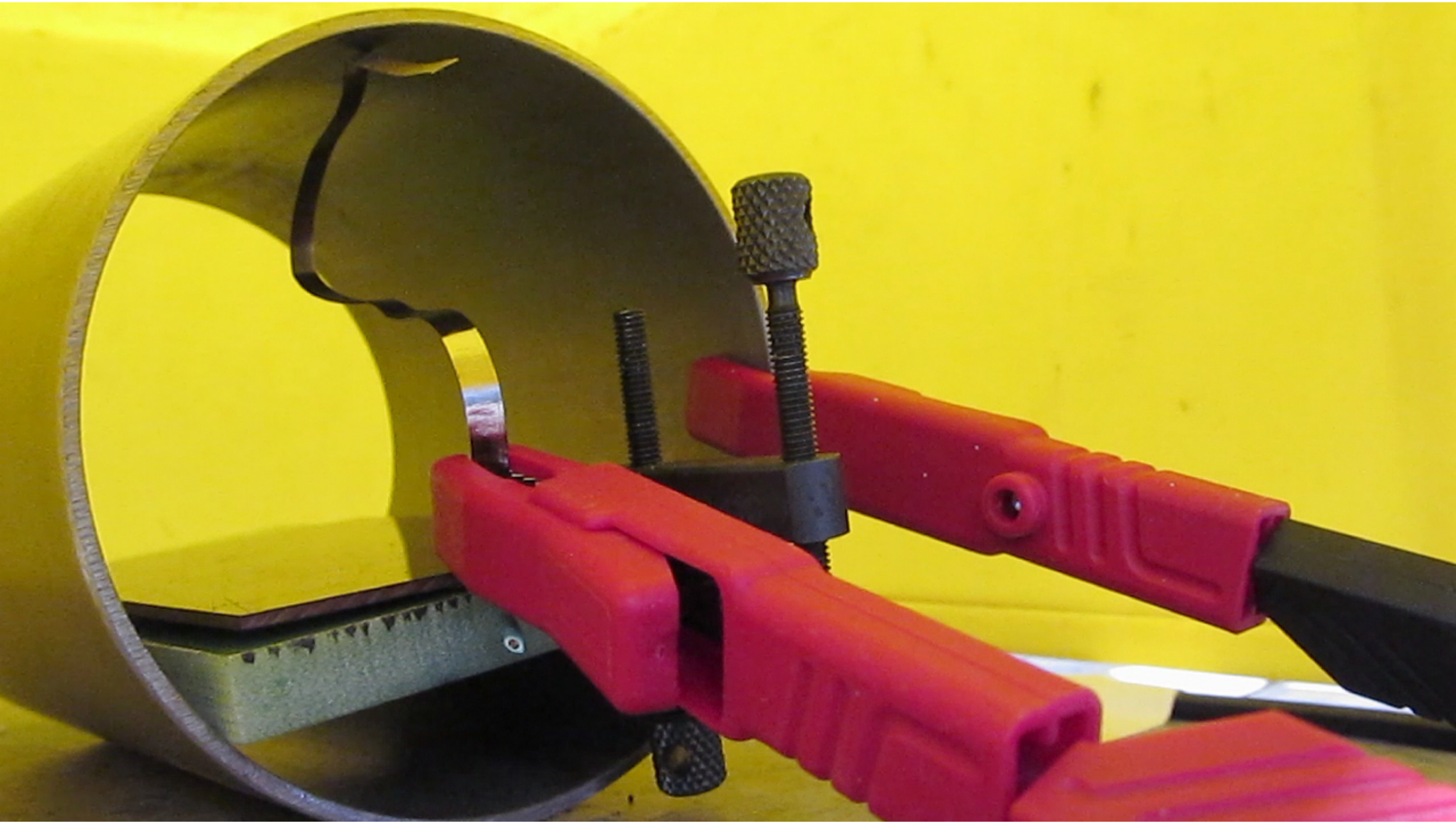
Three options were evaluated



All three options were evaluated, in terms of feasibility, duration, and risk.

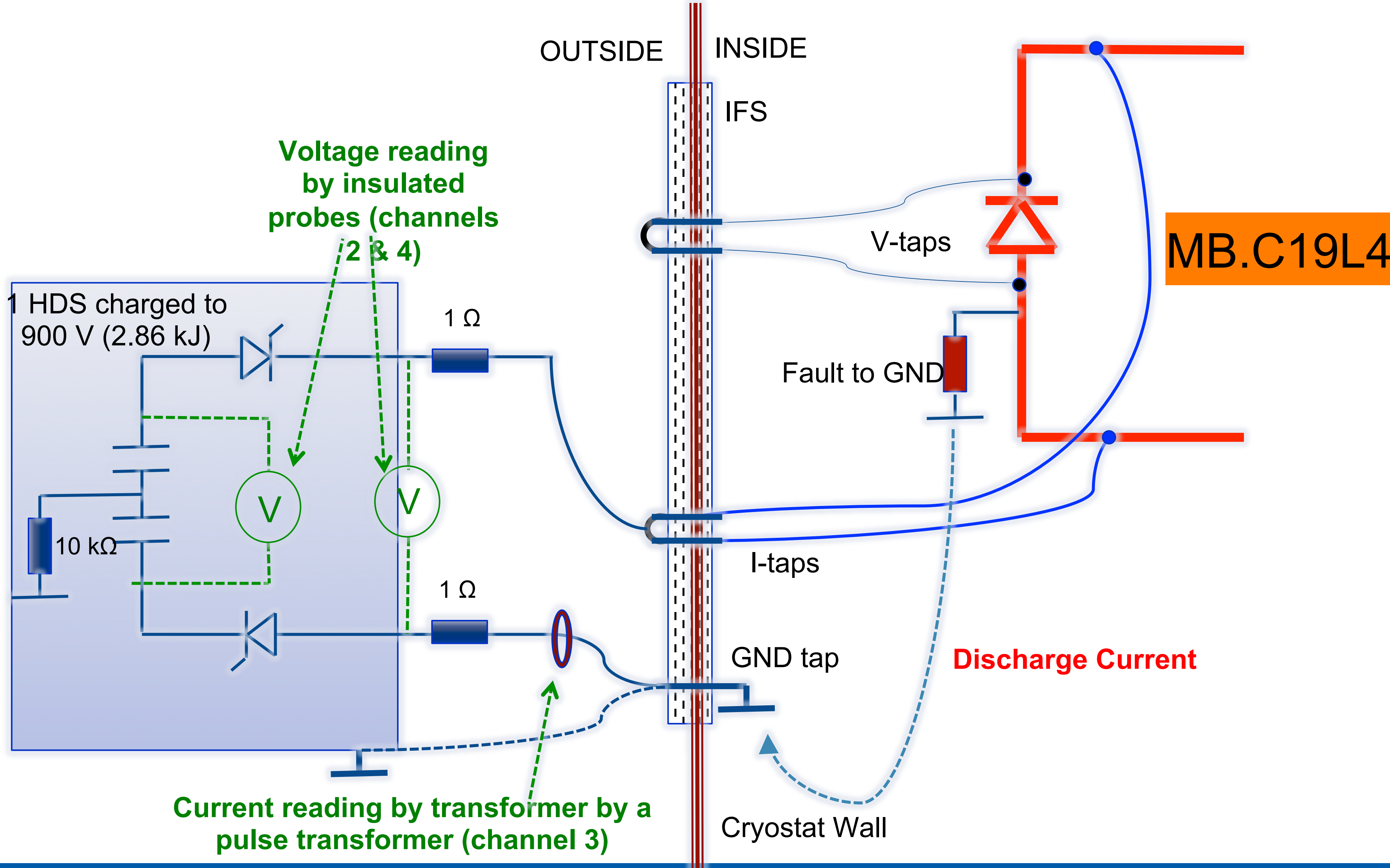
Electrical Discharge Method Chosen

One week of intense preparation



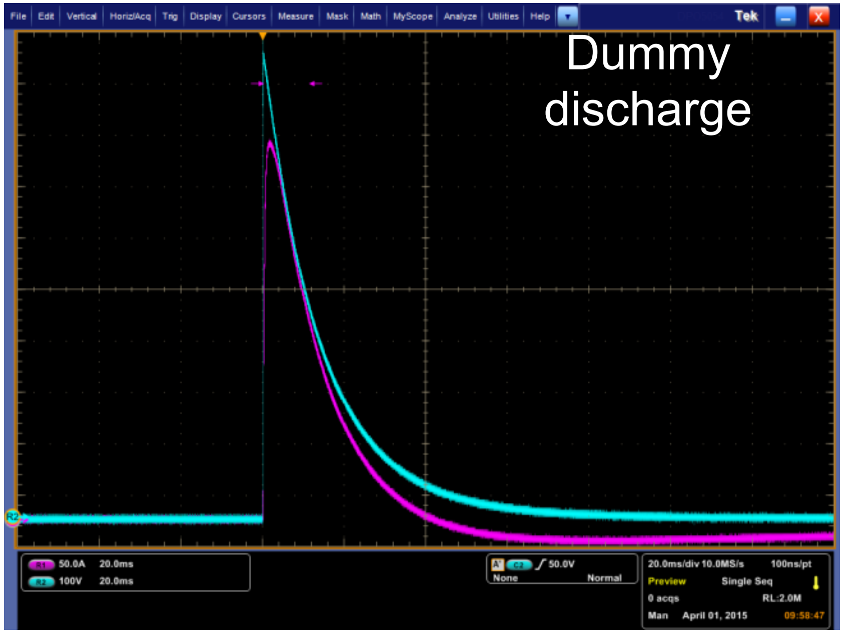
Courtesy Andrzej Siemko

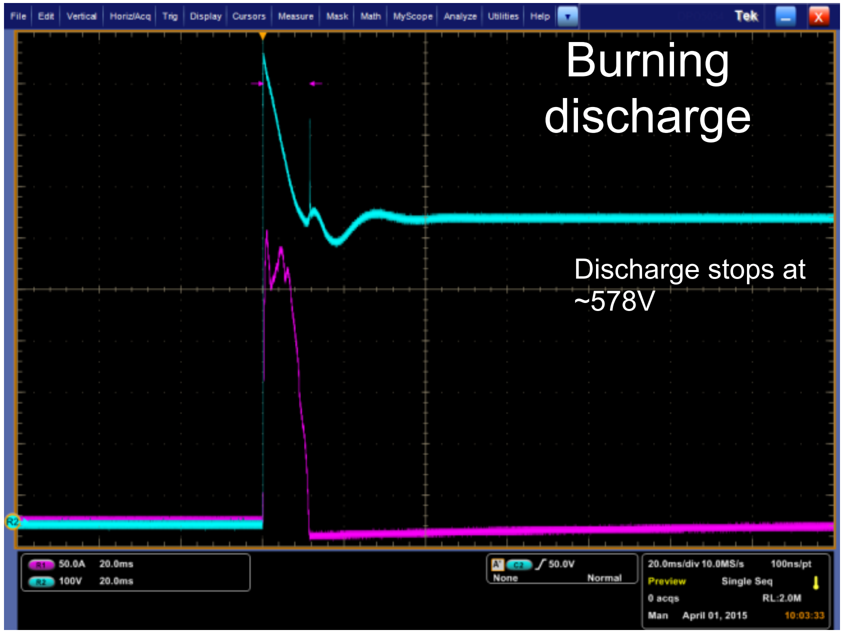
Discharge Set-Up

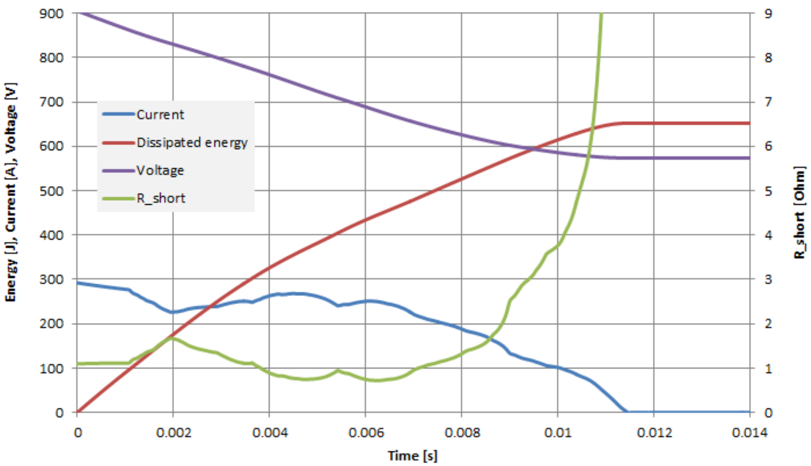


How it worked ?

and 11ms instead of 2 month
(10 days of thinking and preparation)





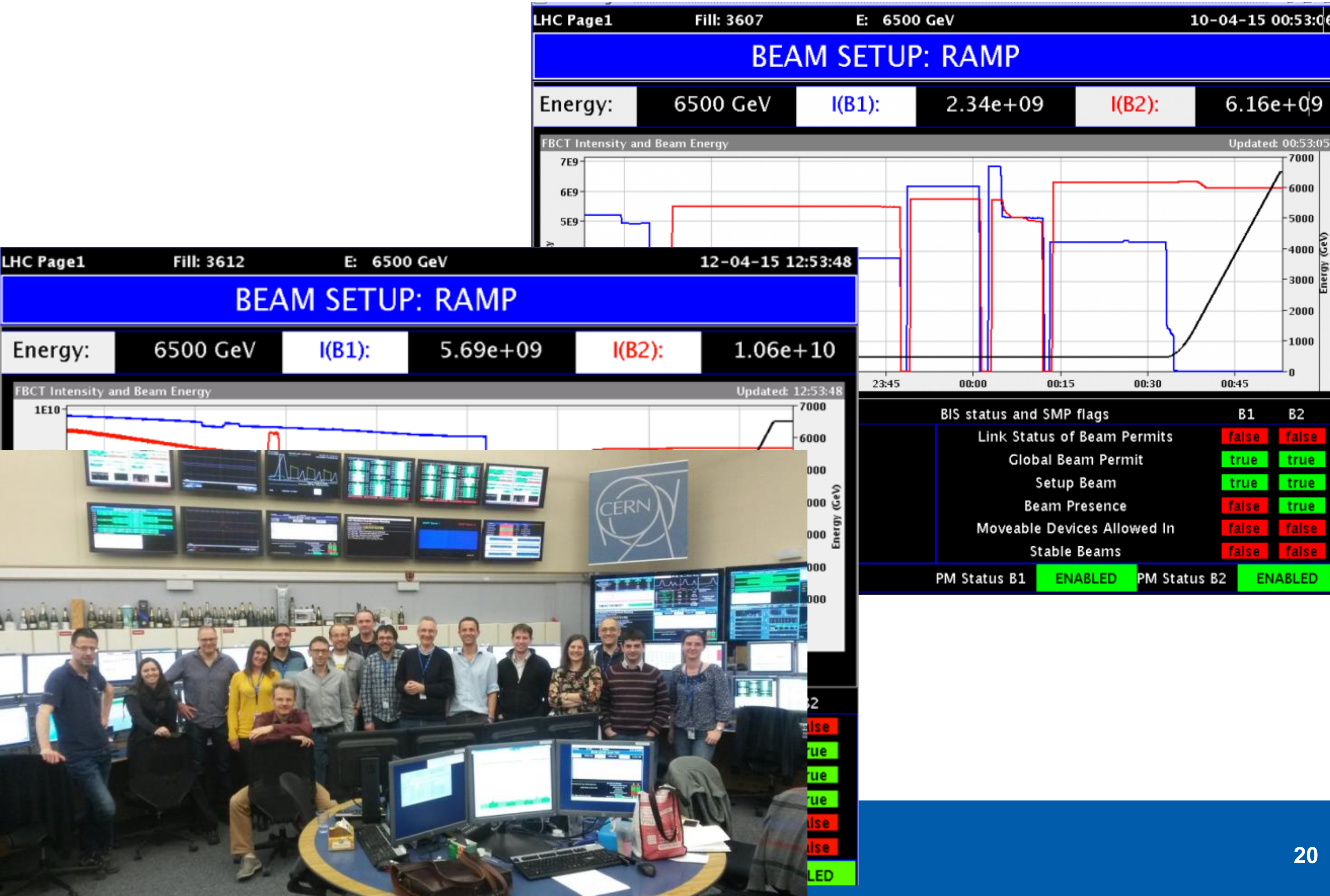


Discharge time:	~11.5ms
Discharge voltage:	906V to 578V
Dissipated energy:	~1.5kJ
Balancing resistors:	2x1Ohm
Short resistance:	~1 Ohm
Energy dissipated in short:	~500J

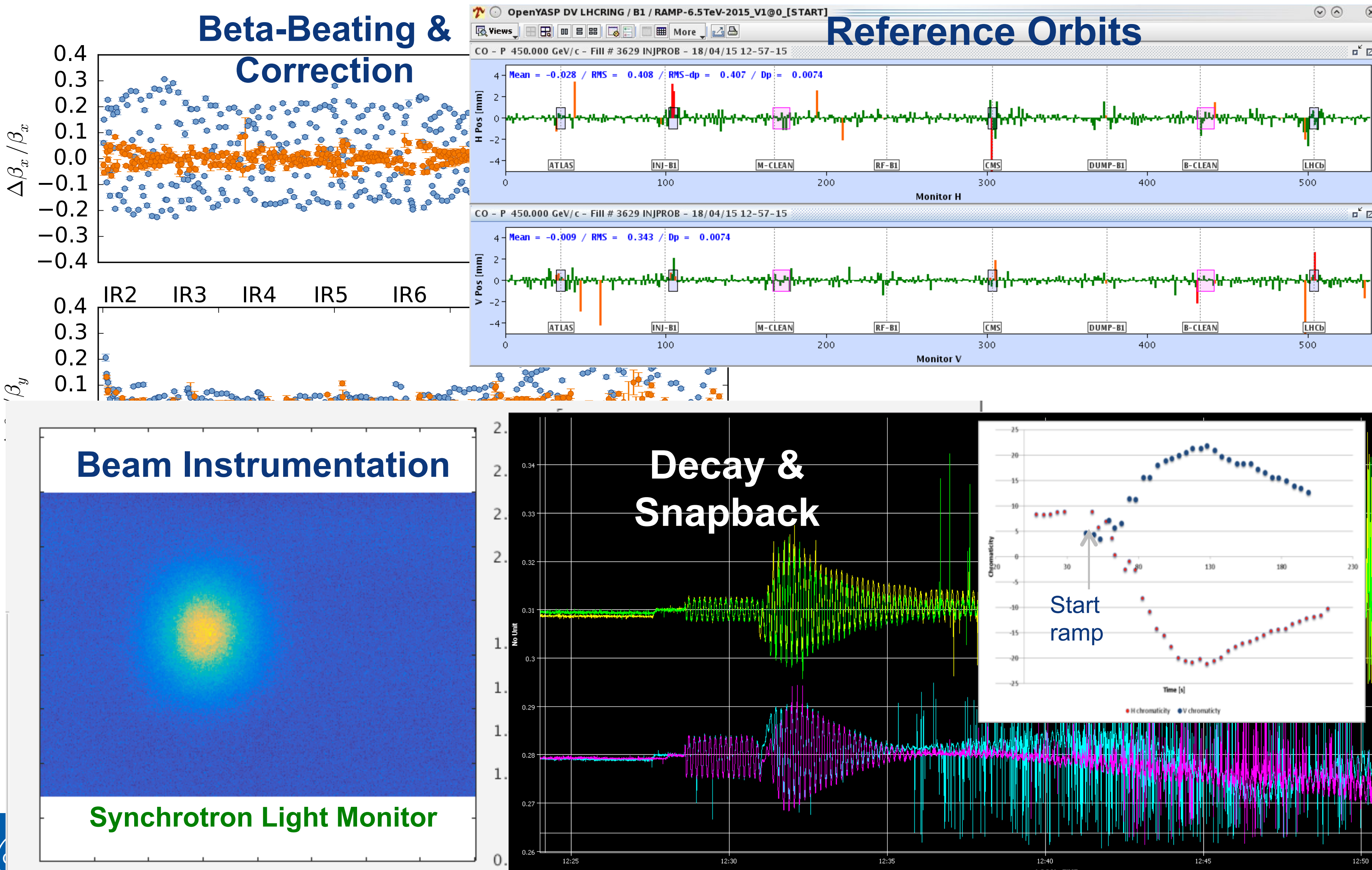
Courtesy of J. Steckert, M. Dominguez and A. Verweij

First circulating beams in LHC on Easter Sunday
5th April 2015

First beamS at 6.5 TeV! (12th April)



Beam Commissioning



Beam Commissioning Roadmap

- **System commissioning with beam**
  - Collimation
  - Beam dump
  - Feedbacks
  - Beam instrumentation
  - Machine protection
  - RF
  - Transverse damper
  - Injection
- **Machine characterization**
  - Optics measurement and correction
  - Magnetic machine
- **Operations**
  - High intensity injection
  - Ramp to 6.5 TeV
  - First squeeze tests
  - Debugging
  - Squeeze
  - Collision

Injection - probe

Ramp - probe

Flat-top - probe

Squeeze - probe

Injection - nominal

Ramp - nominal

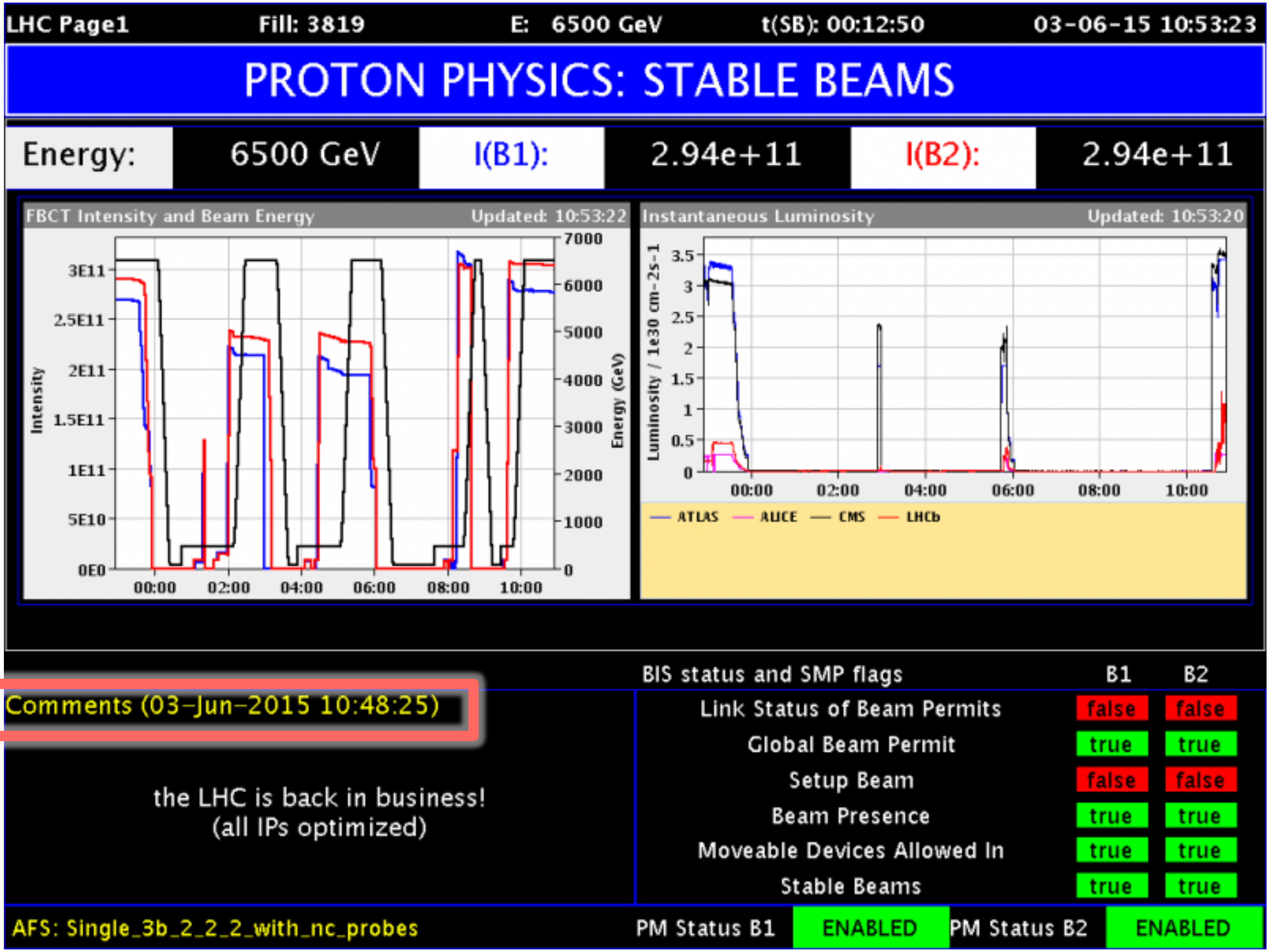
Flat-top - nominal

Squeeze - nominal

Collide & validation

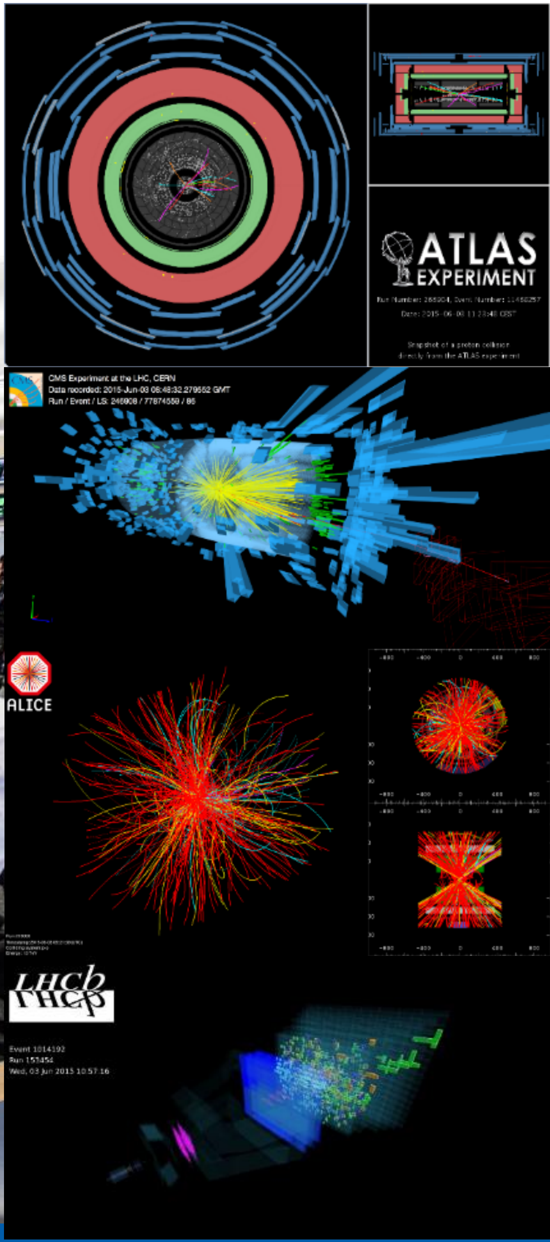
Courtesy Mike Lamont

First stable beams in LHC: 3rd June 2015



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

3rd June 2015



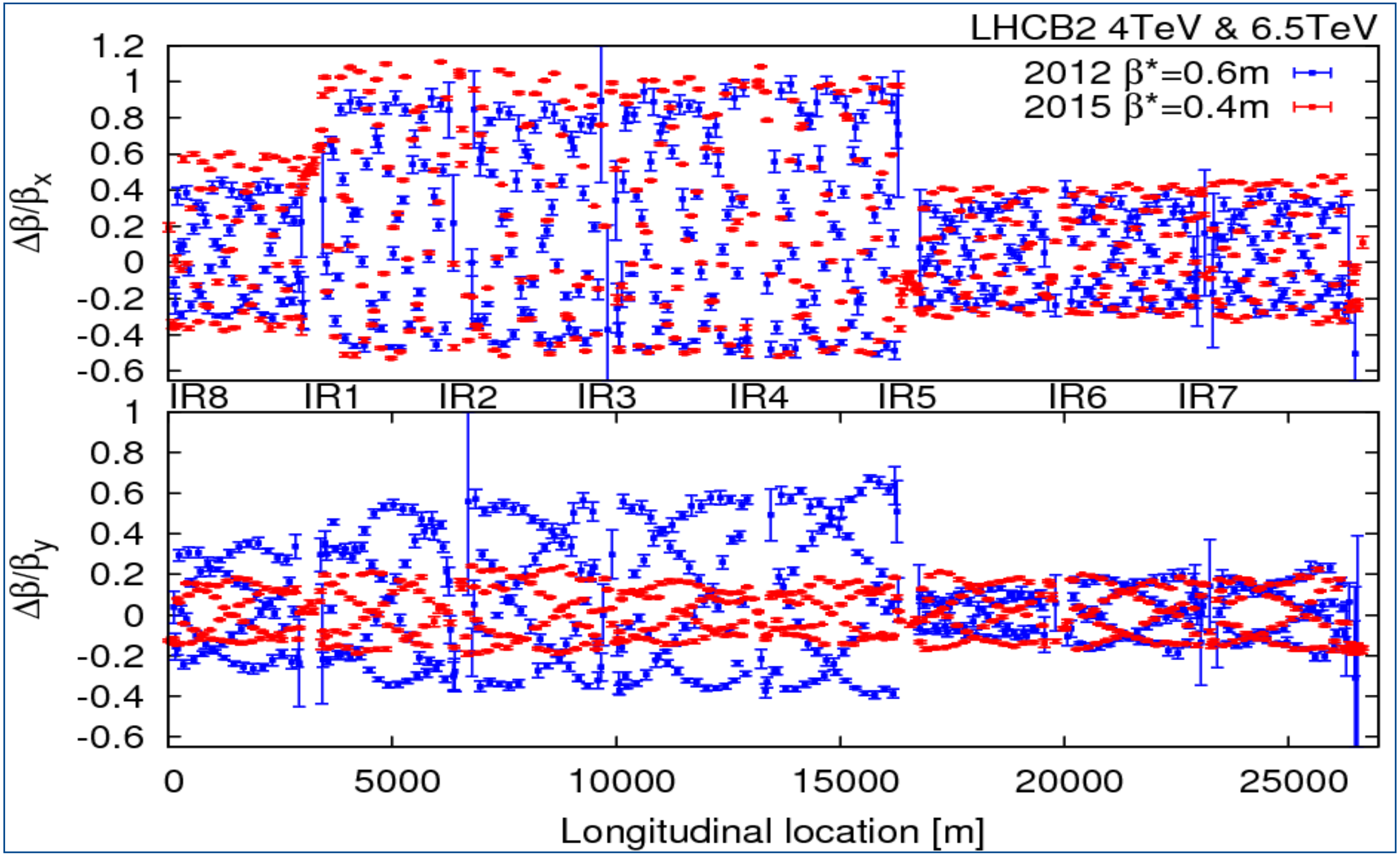
Beam commissioning in two months ☺

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

Terrific team work

Optics: Squeeze down to β* 40 cm

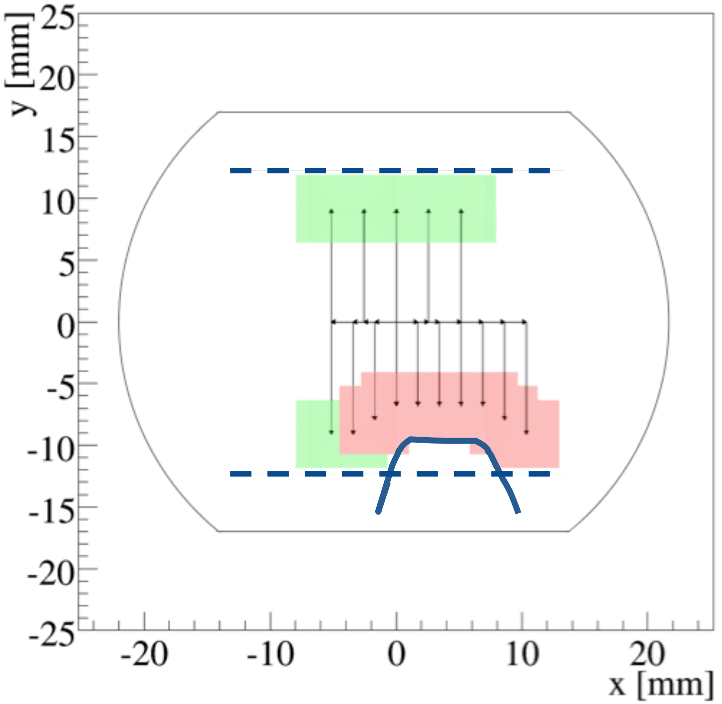


Courtesy of Rogelio Tomas and
OMC (Optics Measurement and Corrections) team

Aperture in 15R8 : MUFO => ULO

Aperture restriction:

- 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



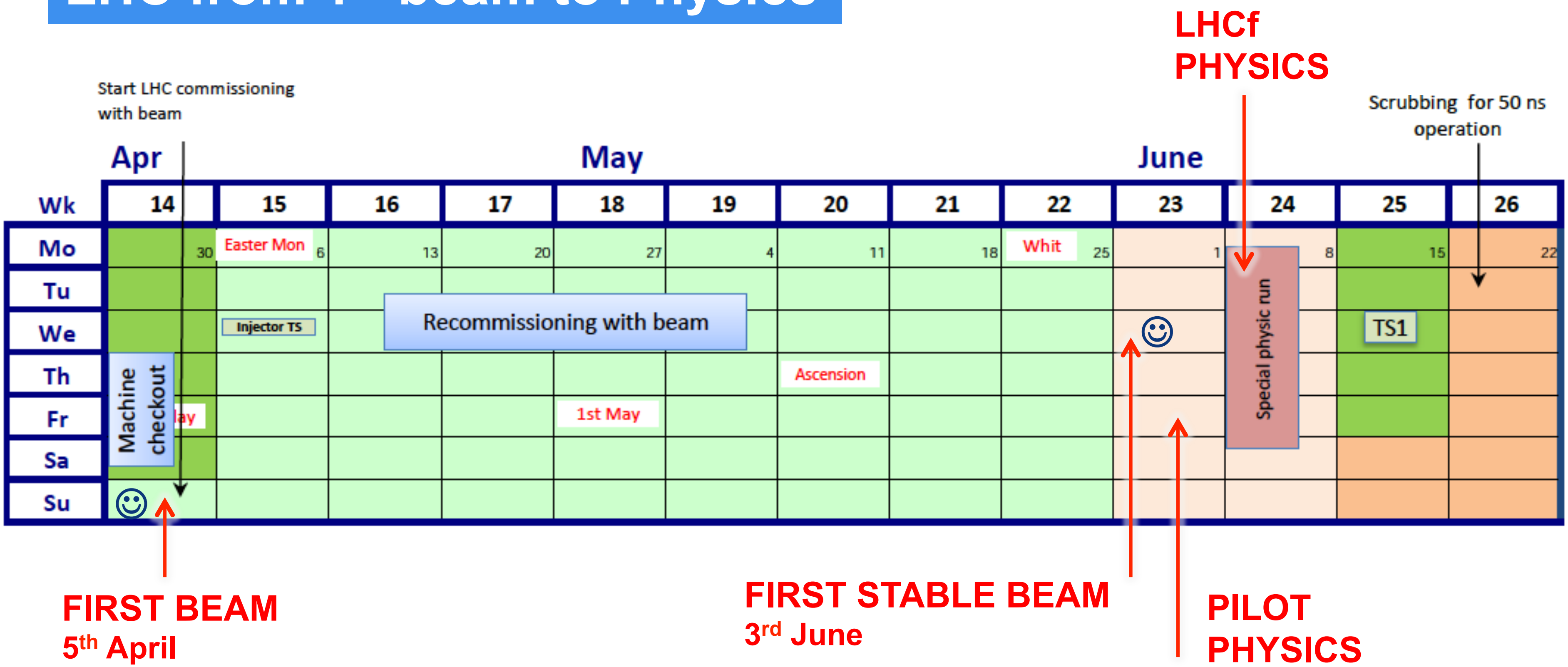
…to come

- 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
- **ULO (Unidentified Laying Objects)**

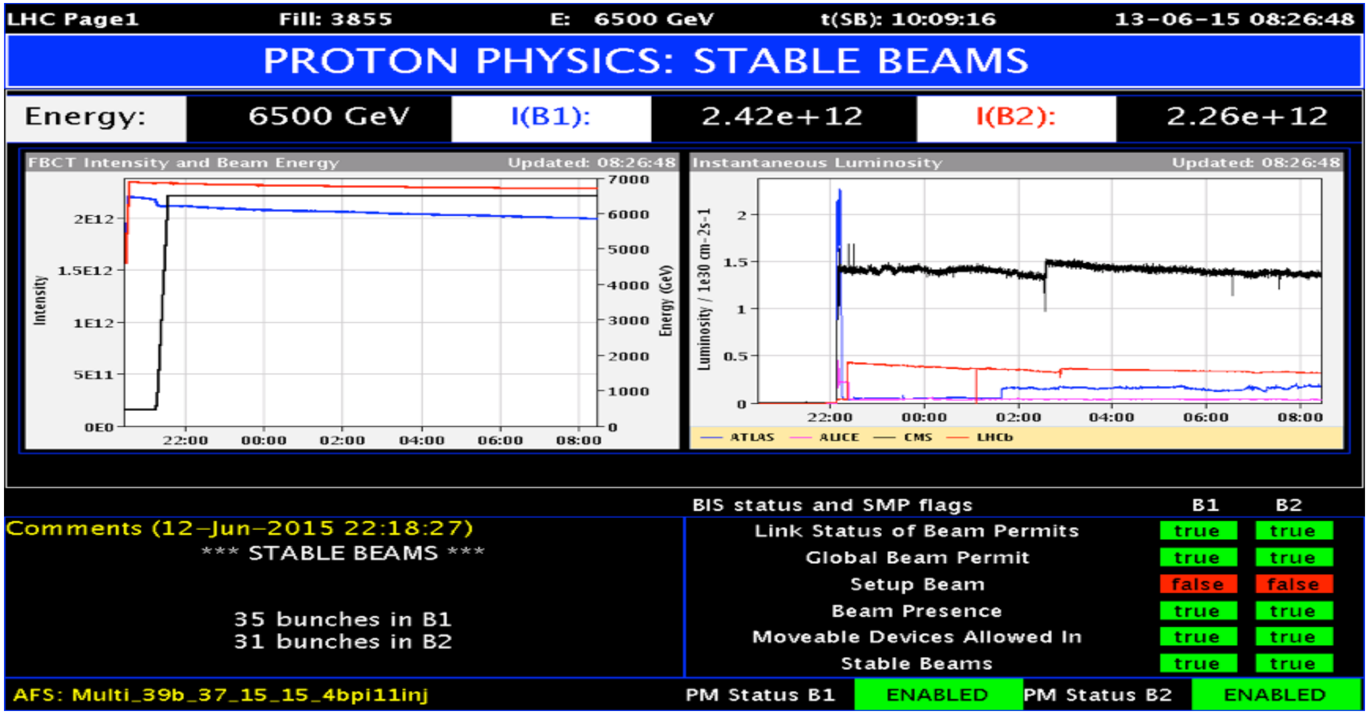
LHC from 1st beam to Physics



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

LHCf physics

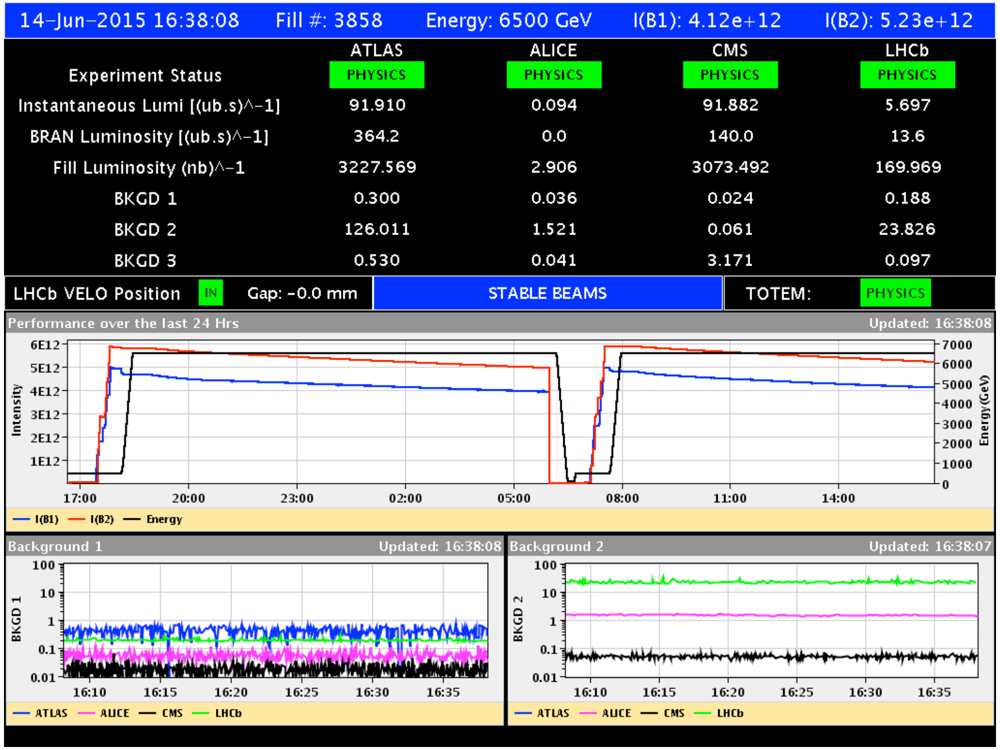
Request: 10 nb^{-1}



$\Sigma > 16\ nb^{-1}$

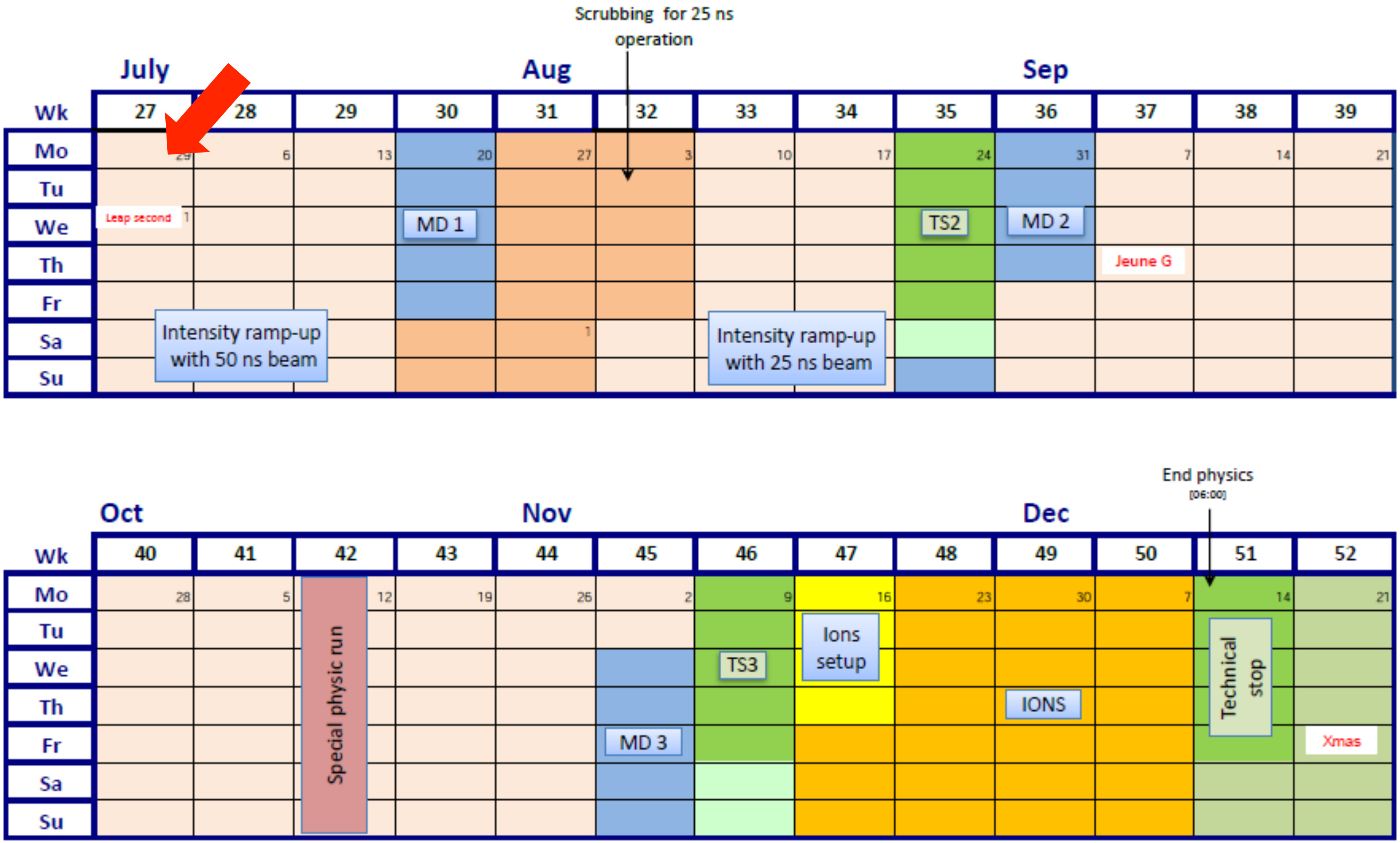
fill	Stable beams	nb^{-1}	bunches
3846	1h55m	0.1	39 pilots
3847	2h16m	0.28	39 pilots
3848	2h42m	0.91	12 nominal
3850	2h49m	1.95	39 nominal
3851	11h13m	6.81	39 nominal
3855	14h15m	6.49	39 nominal

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



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

LHC 2015 – Q3/Q4



LHC schedule 2015: latest schedule

Phase	Days
Initial Commissioning	57
Scrubbing	23
Special physics run 1 (LHCf/VdM)	5
Proton physics 50 ns	**9 + 21**
Proton physics 25 ns	**70**
Special physics run 2 (TOTEM/VdM)	7
Machine development (MD)	15
Technical stops	15
Technical stop recovery	3
Ion setup/Ion run	4 + 24
Total	**253 (36 weeks)**

Four weeks delay from:
- Powering tests/quench training overrun
- Earth fault resolution (sector 3-4)

LHC goal for **2015 and for Run 2 and 3**

Priorities for the 2015 run :

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

  Optimisation of physics-to-physics duration

- **Later in 2015: decision on special runs "when and duration" (90m optics): not in the 1st part of the year. Waiting LHCC recommendation**

- **Pb-Pb run: one month 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"

2015: ATLAS and CMS performance

- Beta* = 80 cm, possible reduction later in year (4 days plus fast intensity ramp up)
- Nominal bunch population for 50 and 25 ns
- Reasonable emittance into collisions
- Assume slightly worse machine availability than in 2012
- TDI limit:144 bunches/injection – colliding bunches for 25 ns down to 2376
- If things go well… (recall 2012 – 1 fb^{-1}/week with ~7e33 $cm^{-2}s^{-1}$)

	Nc	β*	ppb	EmitN	Lumi [$cm^{-2}s^{-1}$]	Days (approx)	Int lumi	Pileup
50 ns	1300	80	1.2e11	2.5	4.8e33	21	< 1 fb^{-1}	25
2015.1	2376	80	1.2e11	3.1	7.0e33	35	~5 fb^{-1}	21
2015.2	2376	40	1.2e11	3.1	1.2e34	30	~4 fb^{-1}	35

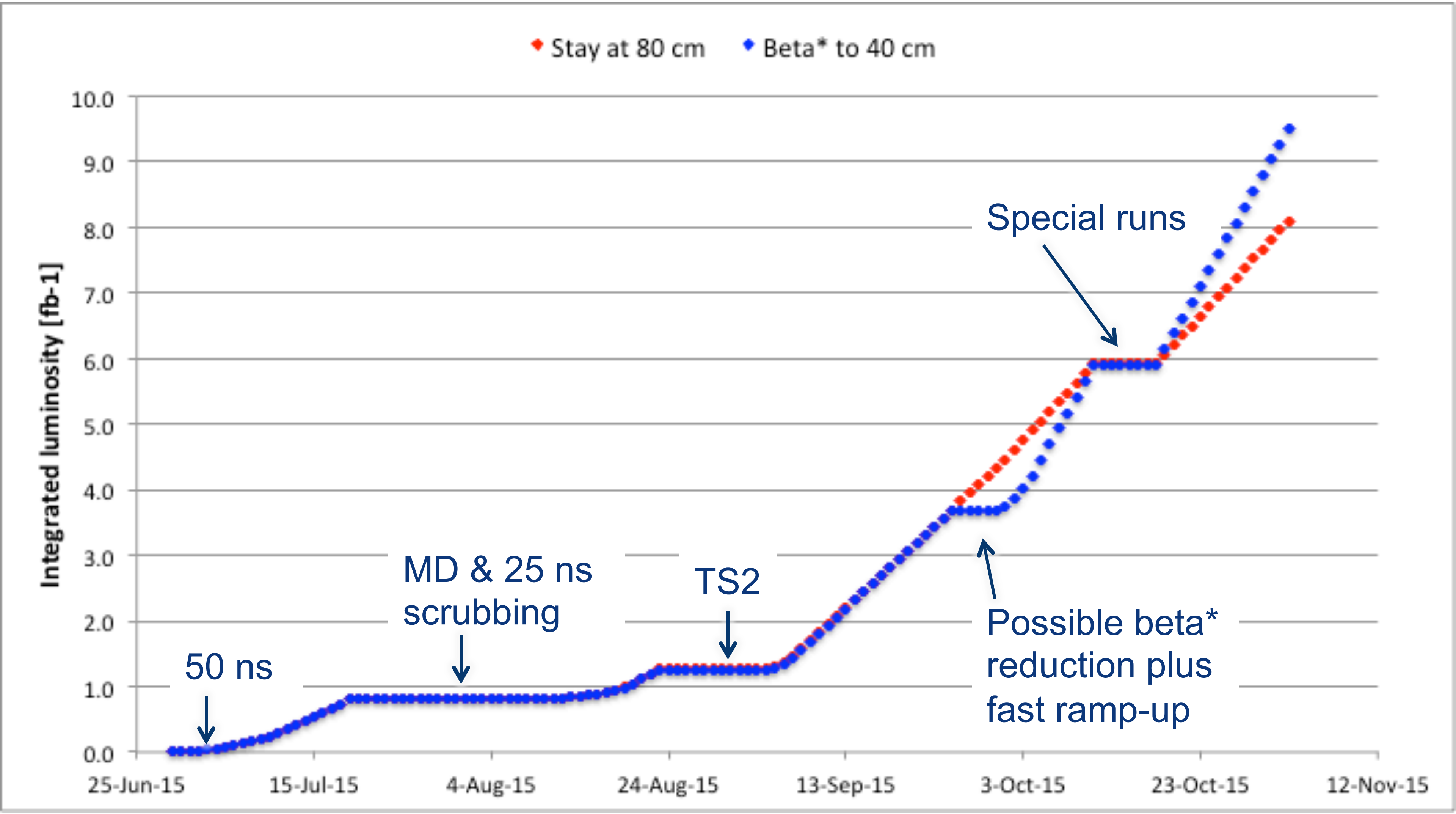
GPD Integrated luminosity target for the year was 10 fb^{-1}

(after Chamonix workshop Oct. 2014)

Now on the challenging side – 5 to 10 fb^{-1}

LHC 2015: projection

Including intensity ramp-ups and steadily increasing physics efficiency



Courtesy Mike Lamont

The European Strategy for Particle Physics
Update 2013

European Strategy
for Particle Physics

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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.***

HL-LHC from a study to a PROJECT

$300\ fb^{-1} \rightarrow 3000\ fb^{-1}$

including LHC injectors upgrade **LIU**

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

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…)

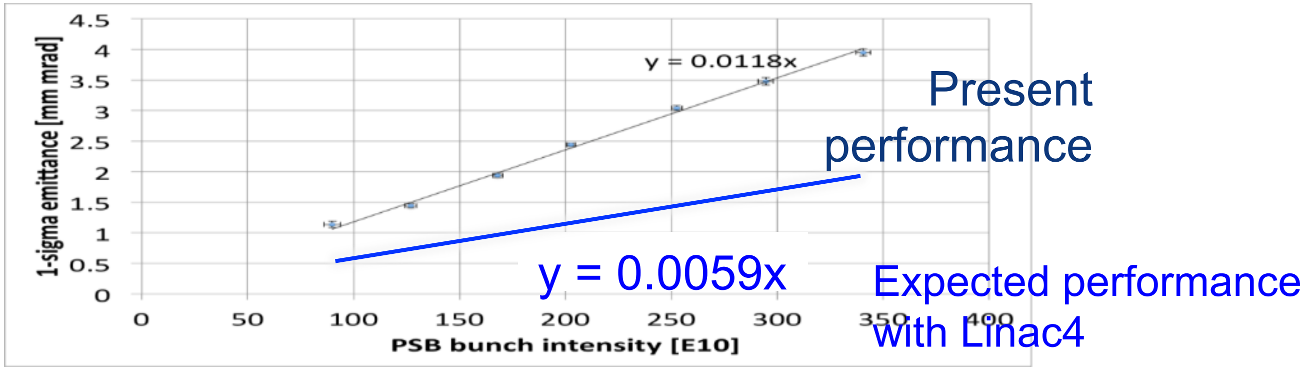
Courtesy of Malika Meddahi

LIU Proton target → HL-LHC beam parameters

25 ns	$\mathcal{N}$ (x 10^{11} p/b)	ε (μm)	B_l (ns)
Achieved in 2012	1.2	2.6 (std) 1.4 (BCMS)	1.5
HL-LHC	2.3	2.1	1.7

Injectors must produce 25 ns proton beams with about double intensity and higher brightness: A cascade of improvements is needed across the whole injector chain to reach this target

Ex: Linac4 will replace Linac2
12 MeV acceleration validated



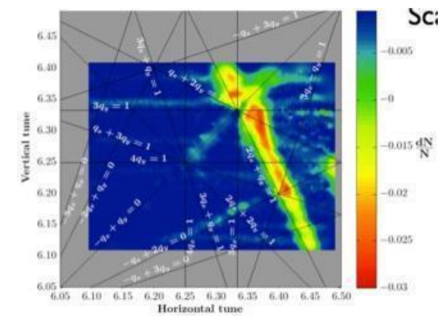
LS2 : (mid 2018-2019), LHC Injector Upgrades (LIU)

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:

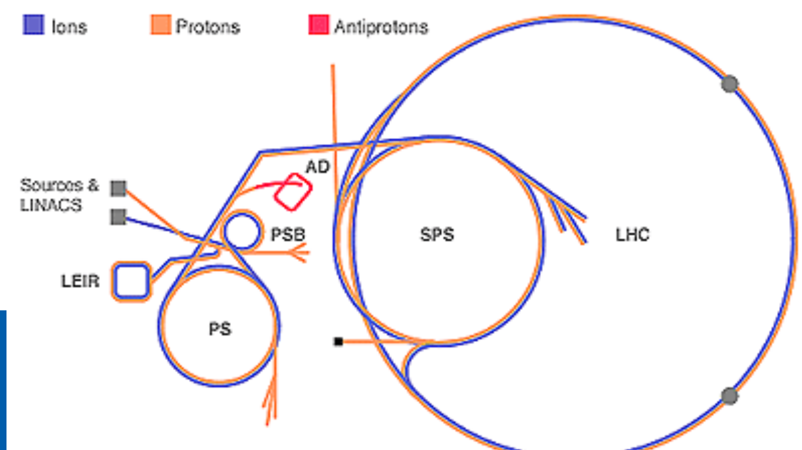
- Increase of injection energy from 1.4 GeV to 2 GeV to increase PS space charge threshold
- Transverse resonance compensation
- New RF Longitudinal feedback system
- New RF beam manipulation scheme to increase beam brightness



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 ($\sim$ 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 :

$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot \gamma \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot F(\phi, \beta^*, \varepsilon, \sigma_s)$$

- ➔ 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

HL-LHC Performance Goals

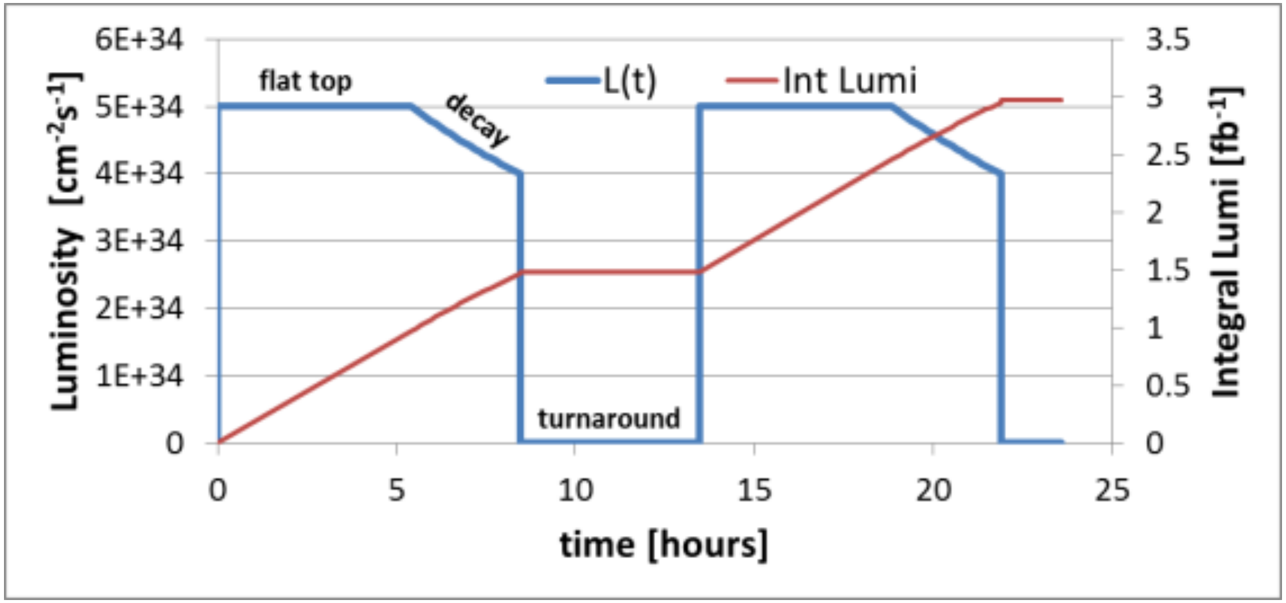
Design HL-LHC for Virtual luminosity:
$L > 10 \times 10^{34}$ cm^{-2} s^{-1}

- Peak Luminosity limitation(s):
  - Event Pileup in detectors
  - Debris leaving the experiments and impacting in the machine (magnet quench protection @ heat load)

Operate with Leveled peak luminosity:
$L = 5 \times 10^{34}$ cm^{-2} s^{-1}

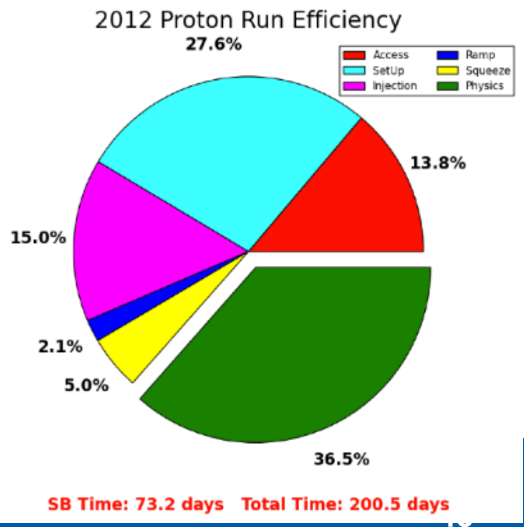
LHC Upgrade Goals: Performance optimization

- Levelling:

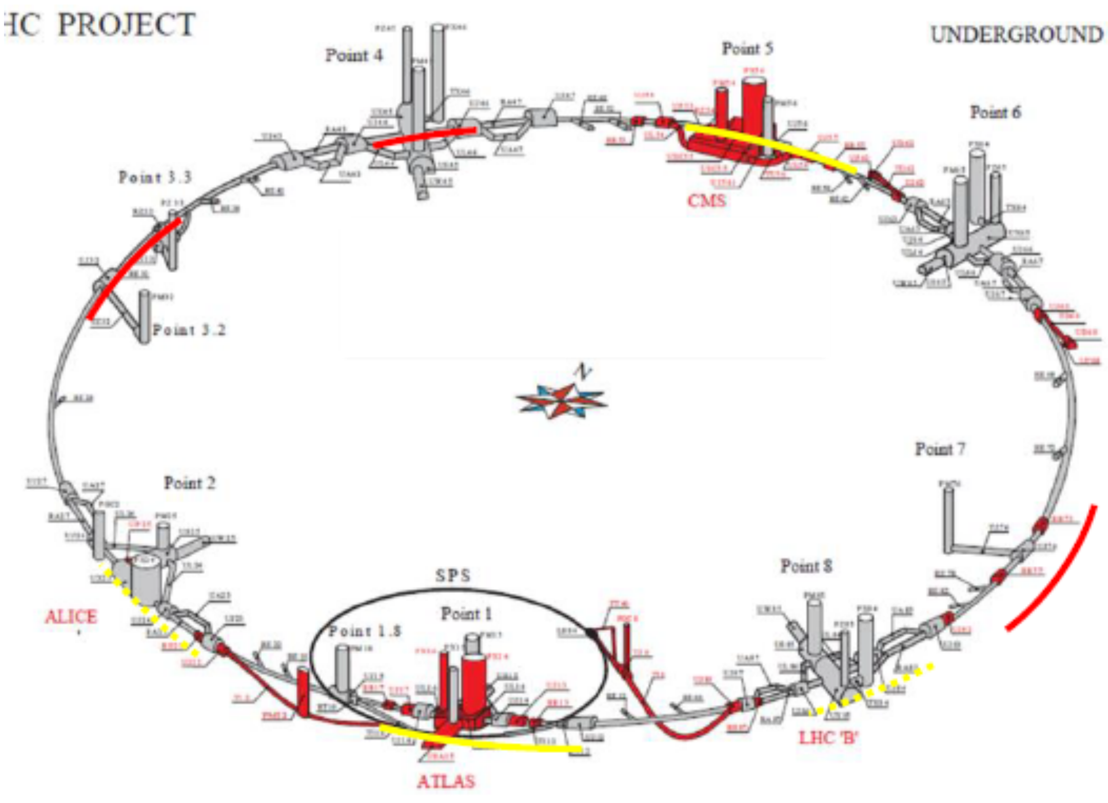


- Integrated Luminosity limitation(s):
  - Average Fill length (must be larger then levelling time)
  - Average Tournaround time (must be small wrt fill length)
  - Number of operation days
  - Overall machine efficiency

    (fraction of physics over scheduled time)



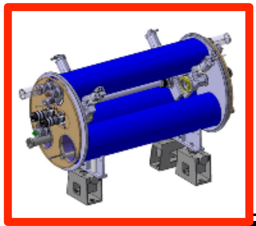
The HL-LHC Project

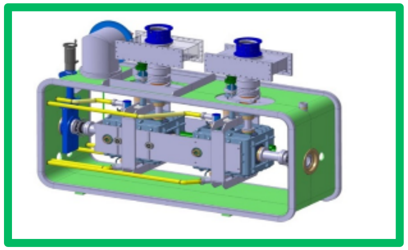


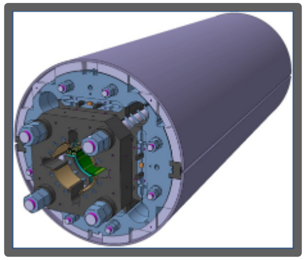
- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

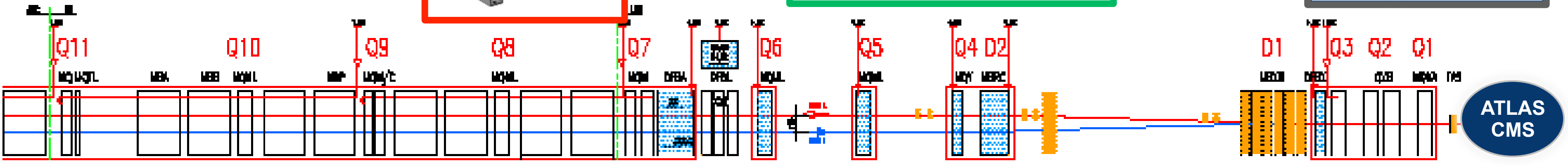
Major intervention on more than 1.2 km of the LHC

HL-LHC project: main upgrades









Dispersion Suppressor (DS)

Modifications
1. **In IP2: new DS collimation with 11 T**
2. **In IP7 new DS collimation with 11 T**

Cryogenics, Protection, Interface, Vacuum, Diagnostics, Inj/Extr… extension of infrastructure

Matching Section (MS)

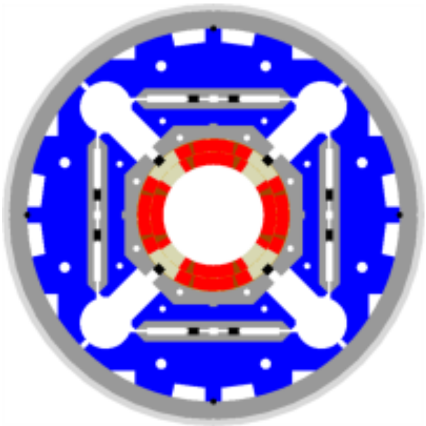
Complete change and new lay-out
1. **TAN**
2. **D2**
3. **Crab Cavities**
4. **Q4**
5. **All correctors**
6. **Q5 (Q6 @1.9 K?)**
7. **New MQ in P6**
8. **New collimators**

Interaction Region (ITR)

Complete change and new lay-out
1. **TAS**
2. **Q1-Q2-Q3** (inner triplet)
3. **D1**
4. **All correctors**
5. **Heavy shielding**

Courtesy of Lucio Rossi

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

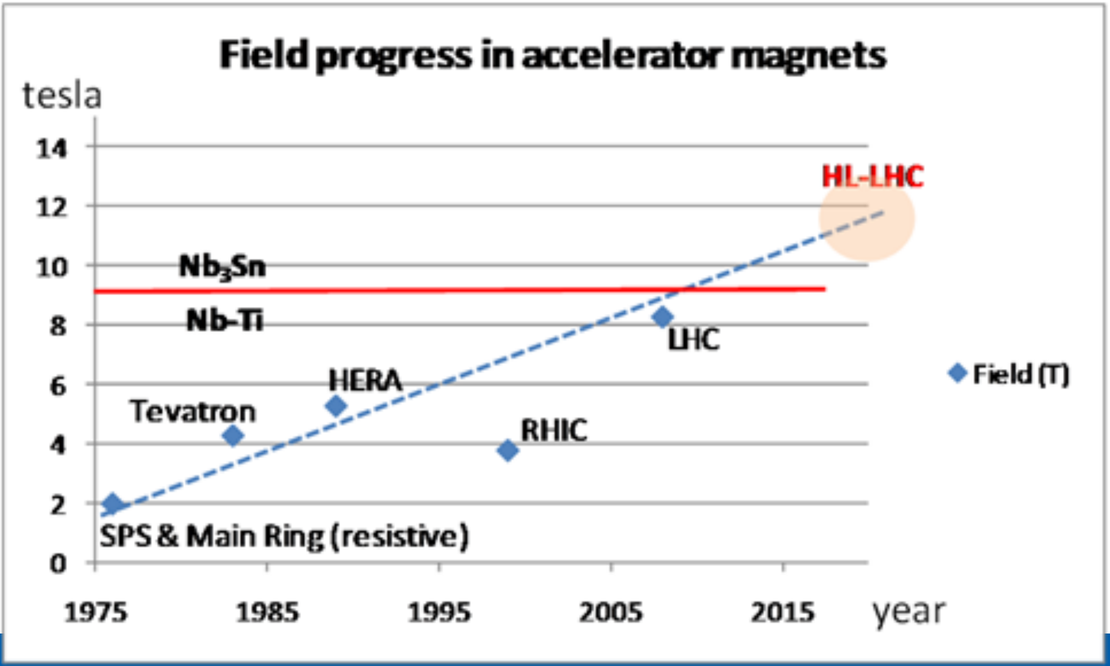
=> Nb_3Sn technology

(LHC: 8 T, 70 mm)

More focus strength,
β* as low as 15 cm (55 cm in LHC)

thanks to ATS** (Achromatic Telescopic Squeeze)* ***optics

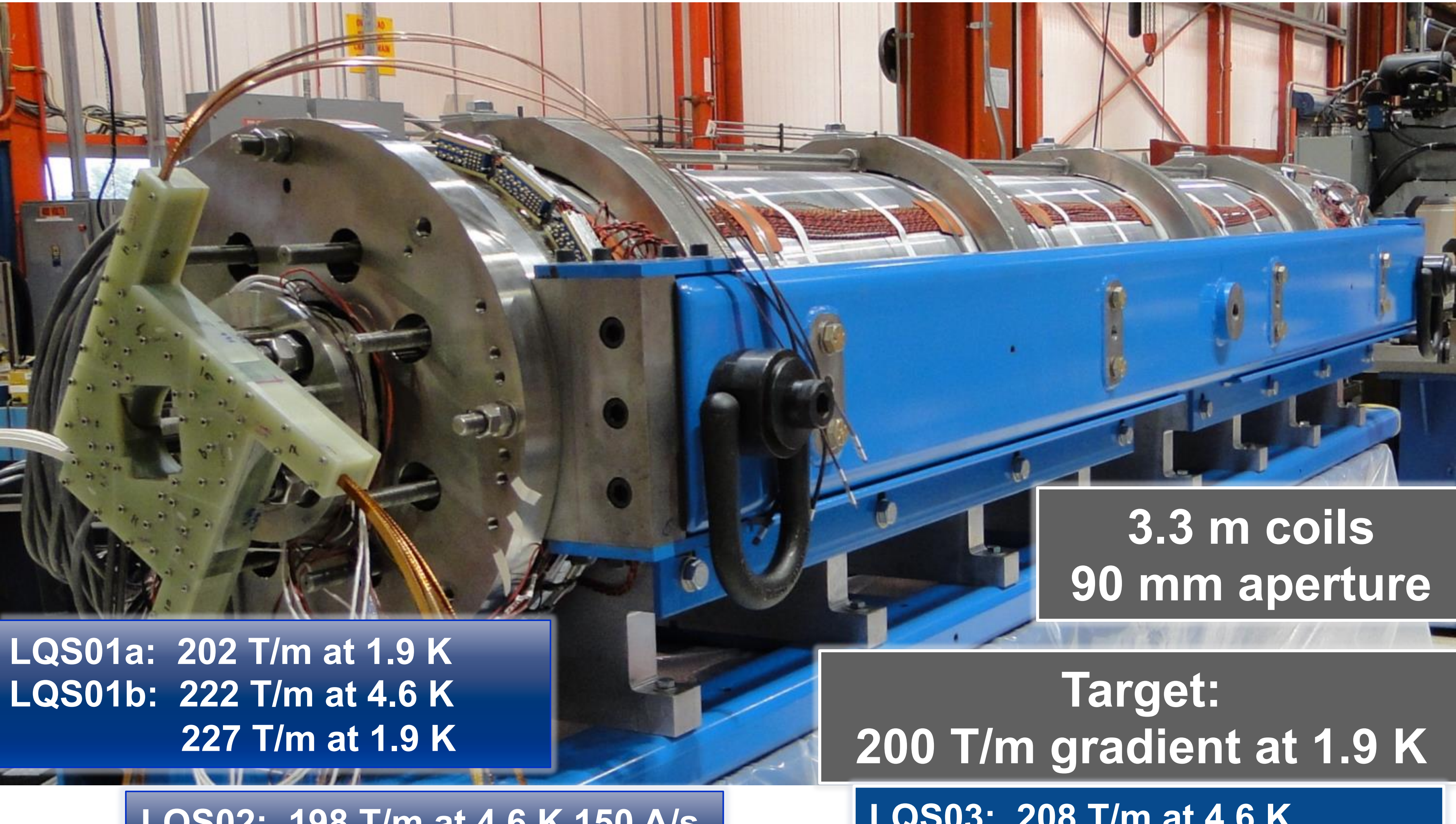
In some scheme even β down to 7.5 cm are considered*



LQS 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

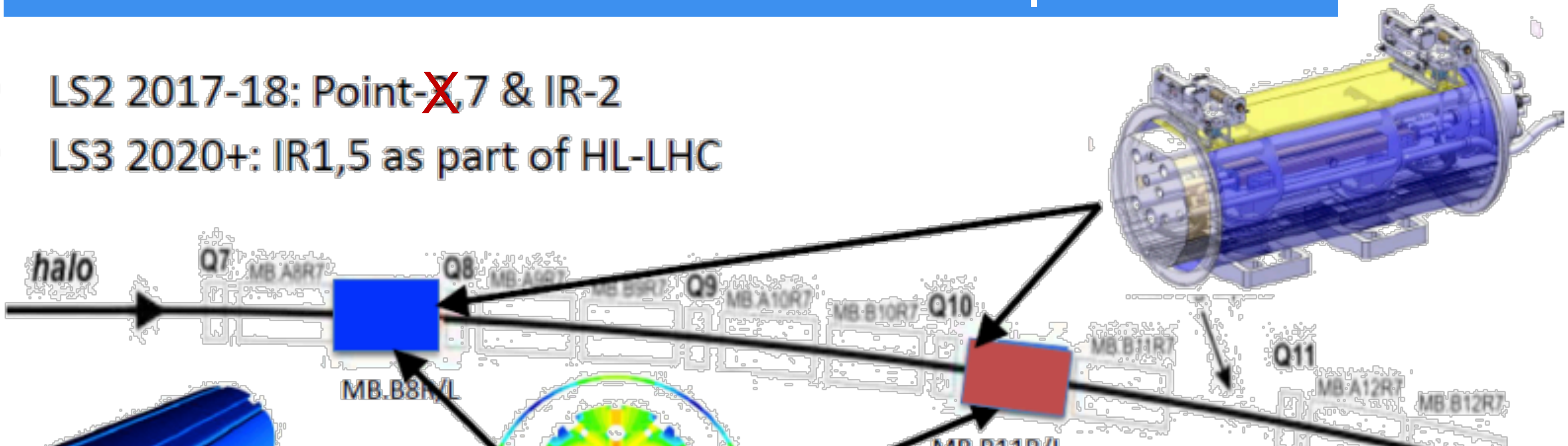
LQS02: 198 T/m at 4.6 K 150 A/s
208 T/m at 1.9 K 150 A/s
limited by one coil

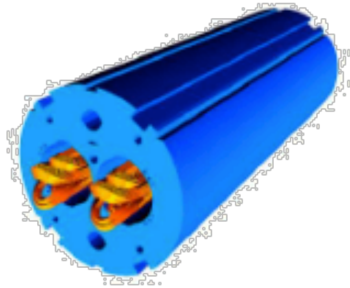
LQS03: 208 T/m at 4.6 K
210 T/m at 1.9 K
1st quench: 86% s.s. limit

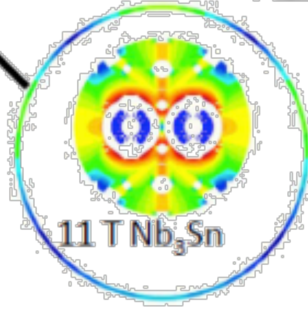
CERN

LS2 : collimators and 11T Dipole

- LS2 2017-18: Point-~~X~~,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

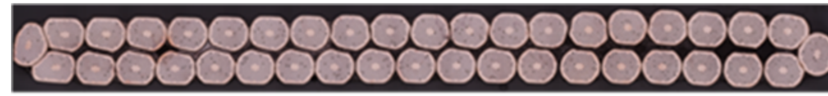
- 11 m Nb_3Sn | 3 m Collim

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

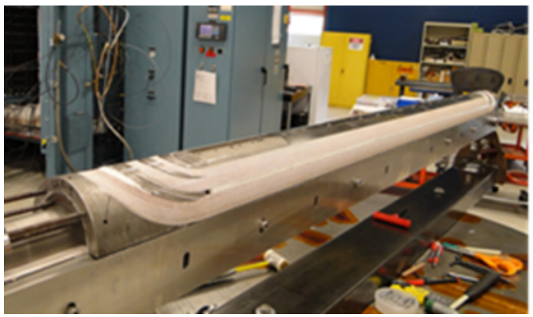
- 5.5 m Nb_3Sn | 5.5 m Nb_3Sn | 3 m Collim
- 5.5 m Nb_3Sn | 3 m Collim. | 5.5 m Nb_3Sn

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

FNAL: MBHSP01 – 1-in-1 Demonstrator (2 m)

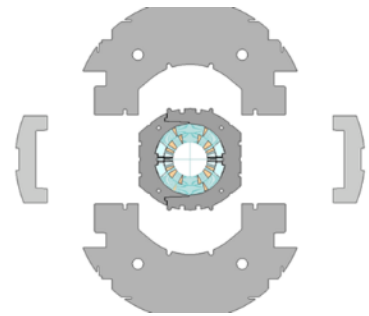


40-strand cable fabricated using FNAL cabling machine

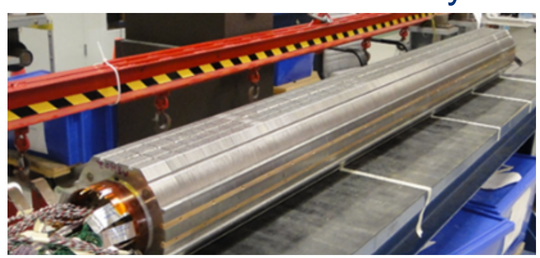


Coil fabrication

Collared coil assembly



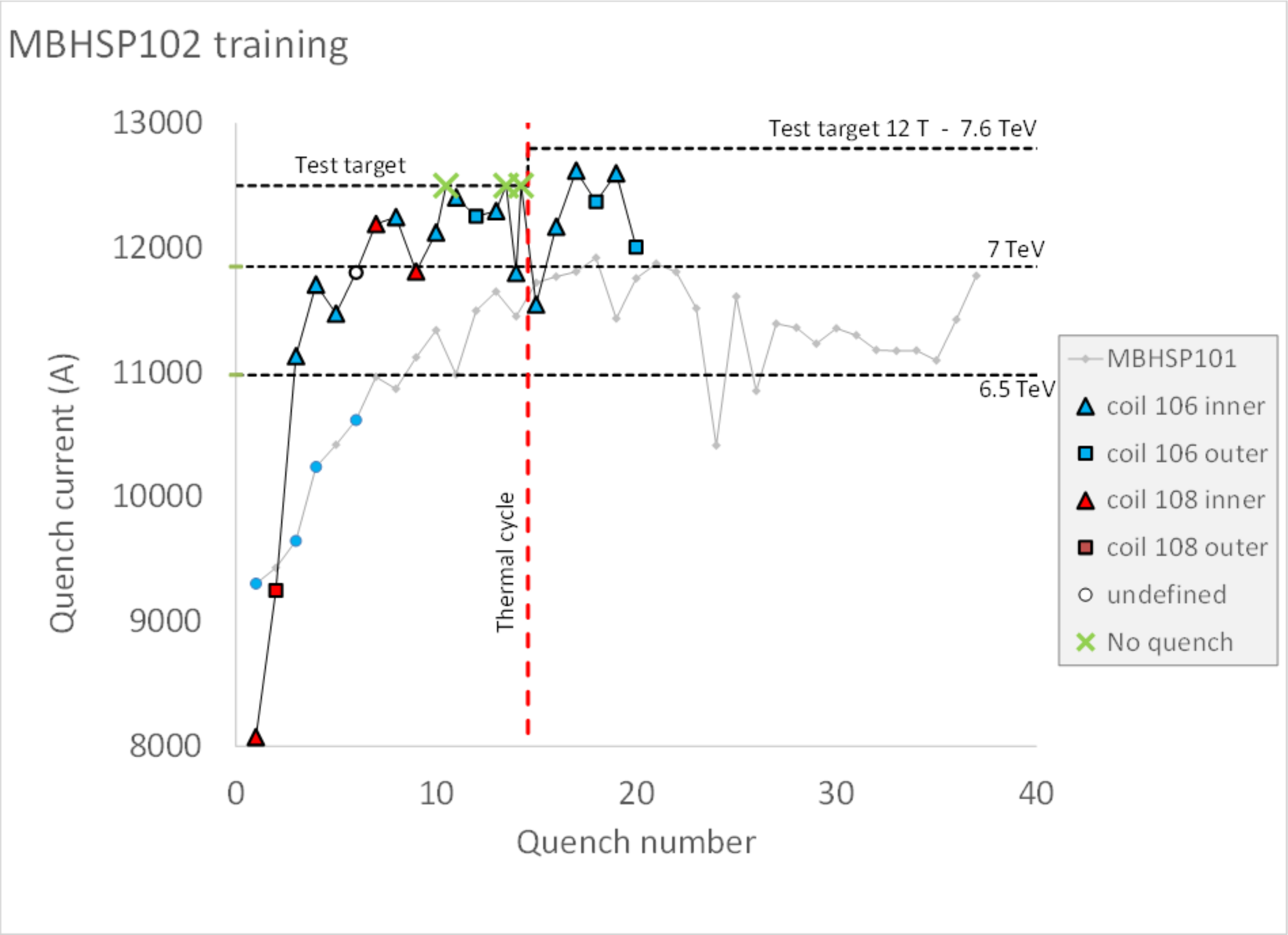
Cold mass assembly



MBHSP02 passed 11 T field during training at 1.9 K with I = 12080A on 5th March 2013!

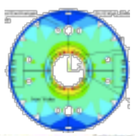
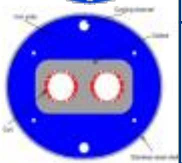
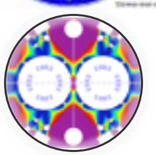
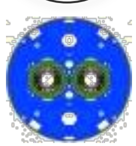
Fermilab

11 T Magnet – Status on recent tests



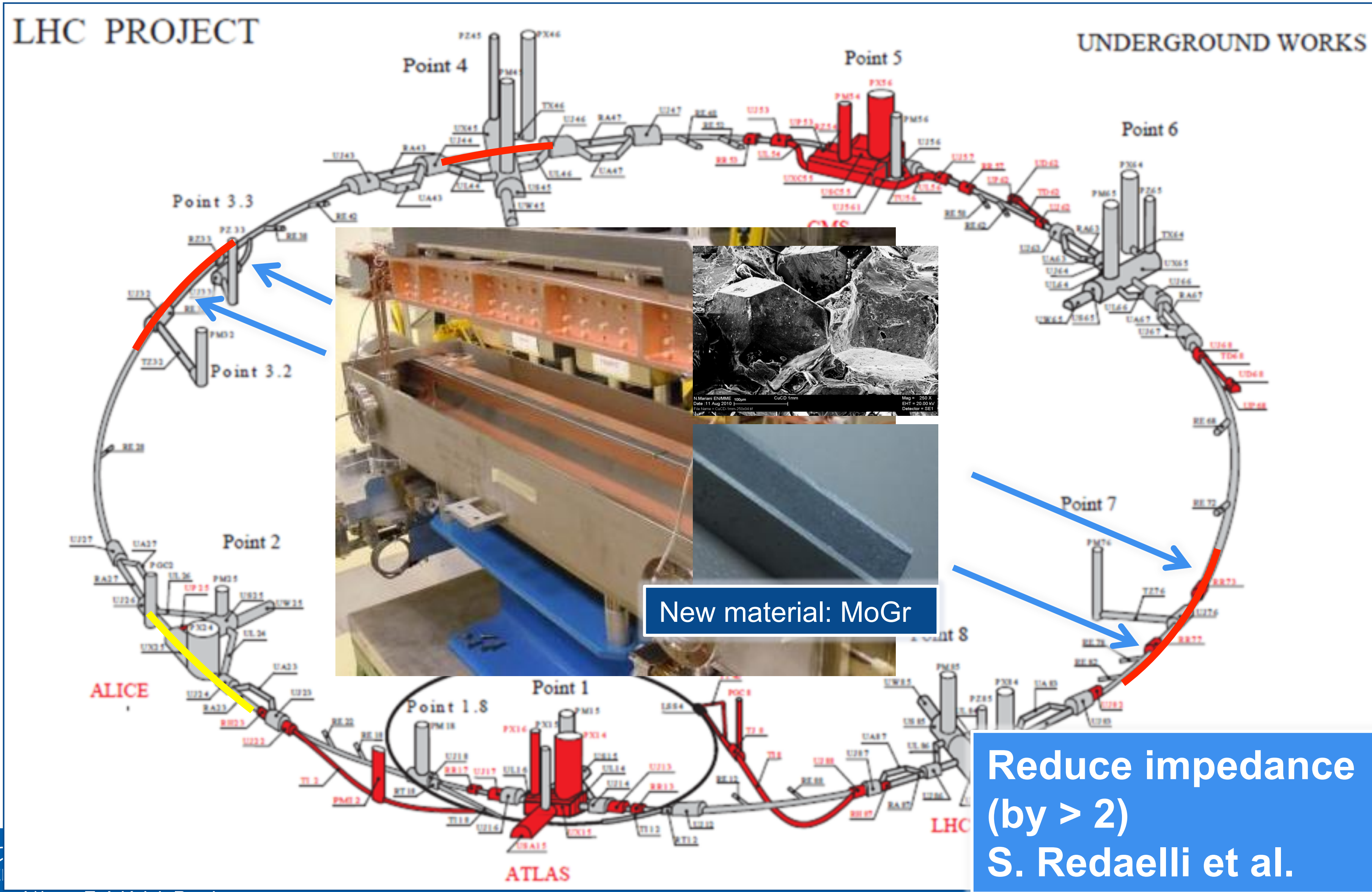
Courtesy of Frédéric Savary

HL-LHC magnet specs

		Type	Material	Field/Gradient (T)/(T/m)	Aperture (mm)	Length (m)	Units (-)
	Q1,Q3 Q2	Single aperture	Nb_3Sn	(12.1) 140	150	8 6.7	40
	D1	Single aperture	Nb-Ti	5.2	150	6.7	6
	D2	Twin aperture	Nb-Ti	3.5…5.0	95…105	7…10	6
	Q4	Twin aperture	Nb-Ti	(5.9) 120	90	4.2	6
	DS 11T	Twin aperture	Nb_3Sn	10.8	60	11	40

NOTE: a total of about **200 magnets** will be required, once correctors and other Nb-Ti magnets are included

Low impedance collimators(LS2 & LS3)



Reduce impedance (by > 2)
S. Redaelli et al.

HL-LHC Upgrade Ingredients: Crab Cavities

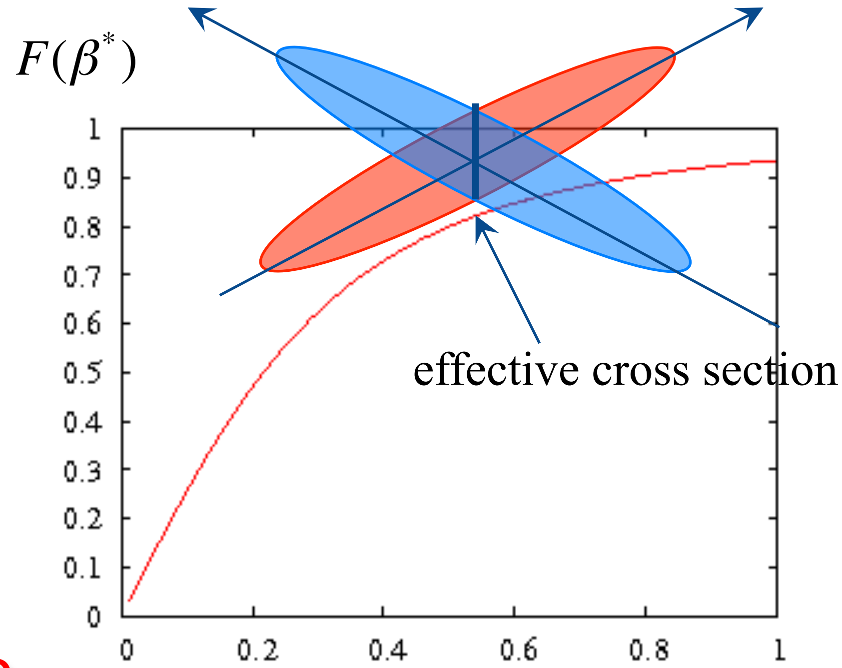
Crab Cavities:

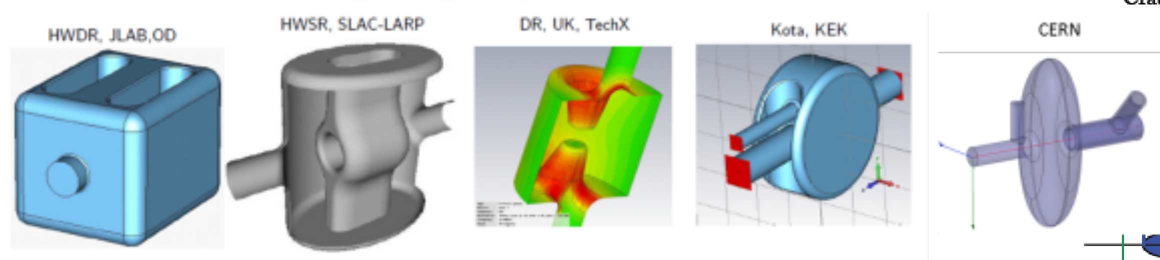
Geometric Luminosity Reduction Factor:

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

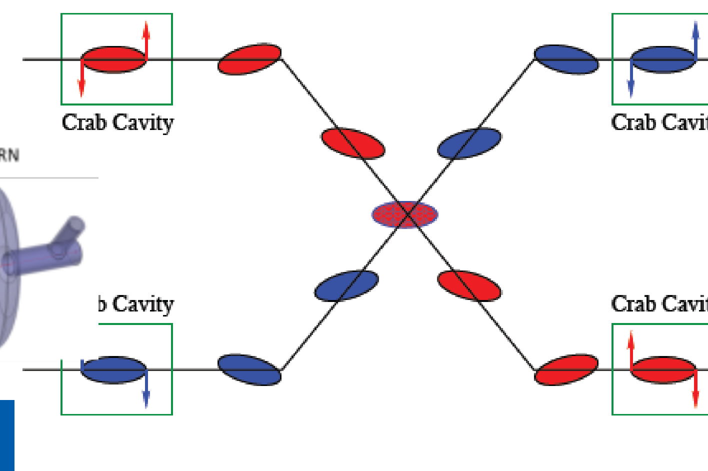
$$F = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

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

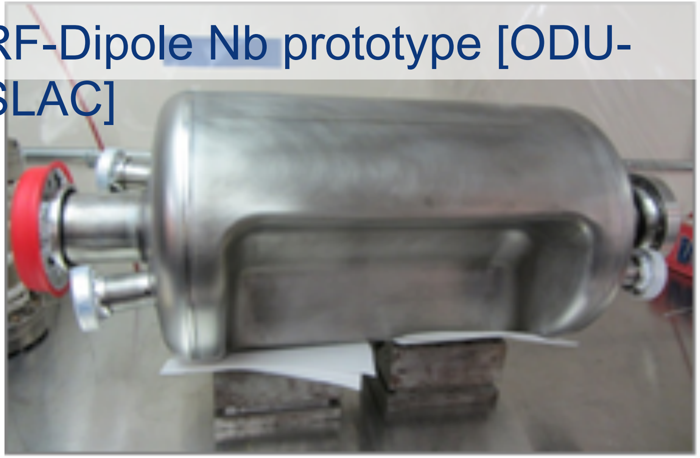




Compact cavities aiming at small footprint & 400 MHz, ~5 MV/cavity

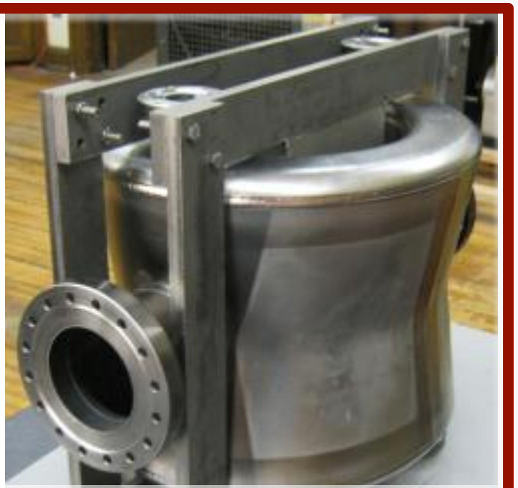


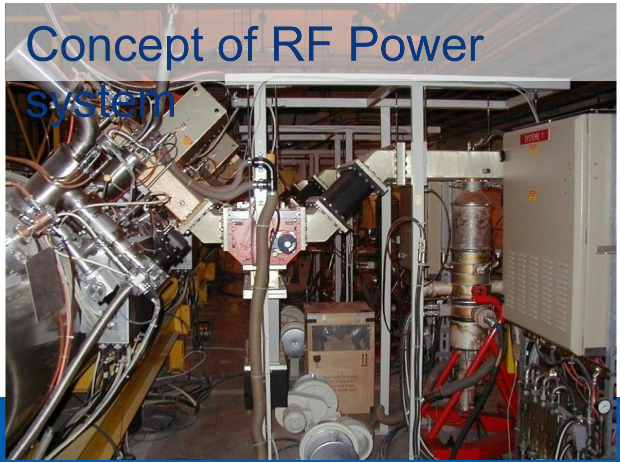
Development of 3 Crab Cavity prototypes


RF-Dipole Nb prototype [ODU-SLAC]


4-rod in SM18 for RF measurements [Lancaster UK]

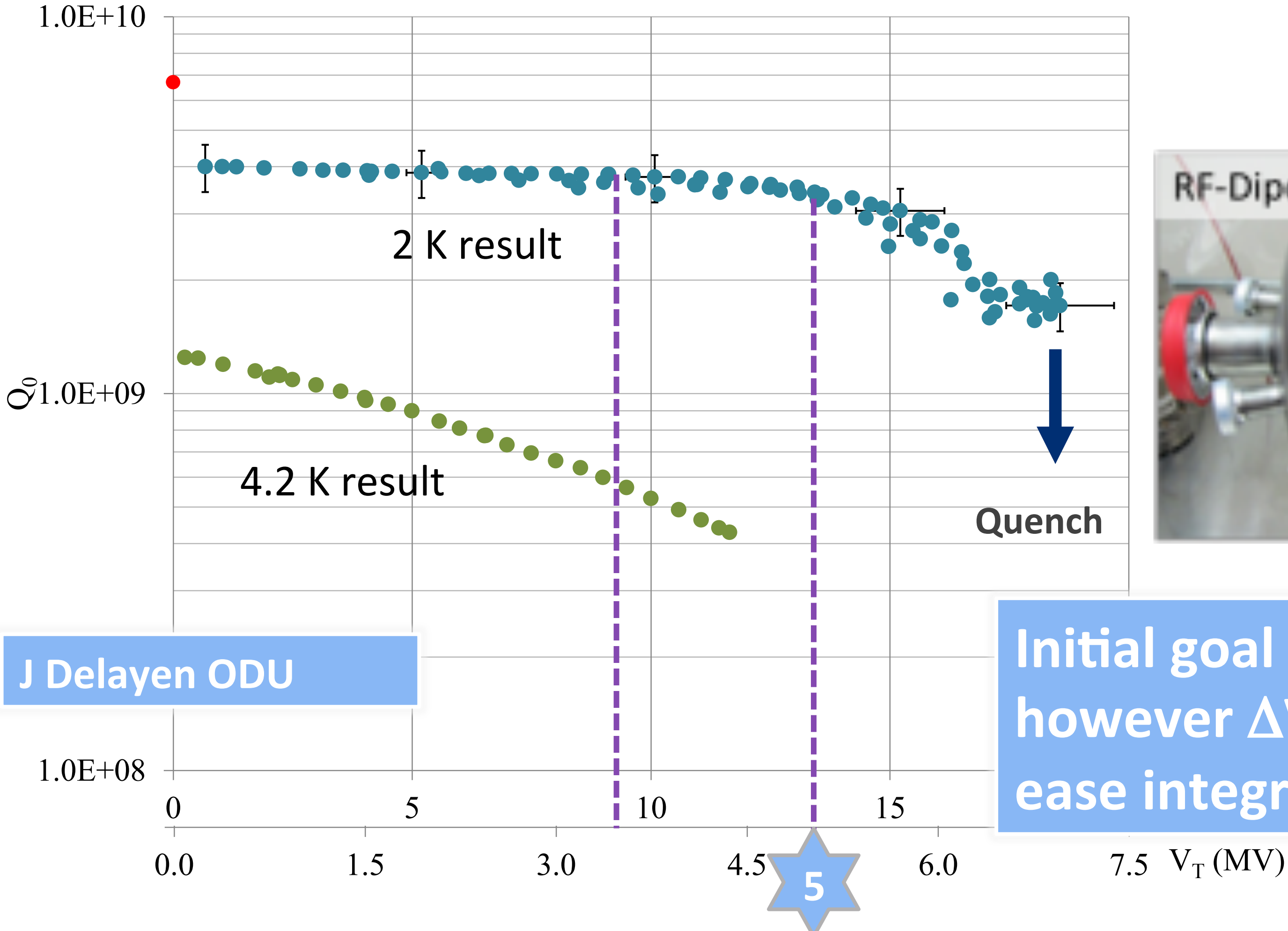

4-rod prepared for rinsing @ CERN


DQWR prototype (17-Jan-2013) [BNL]


Concept of RF Power system

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

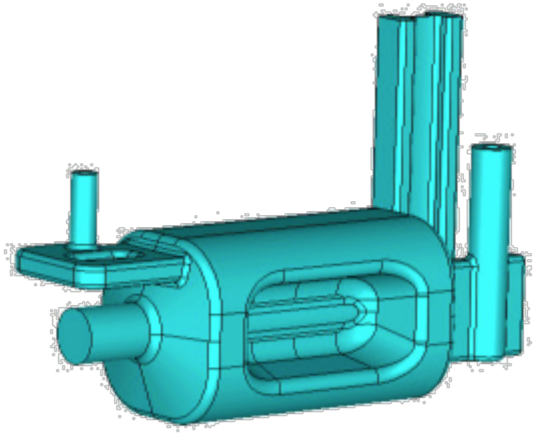
¼ w and 4-rods also tested (1.5 MV)



J Delayen ODU

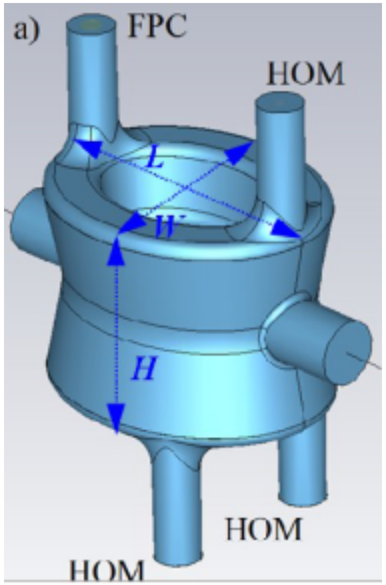
Initial goal was 3.5 MV however ΔV > 5-6 MV would ease integration

Latest cavity designs toward accelerator



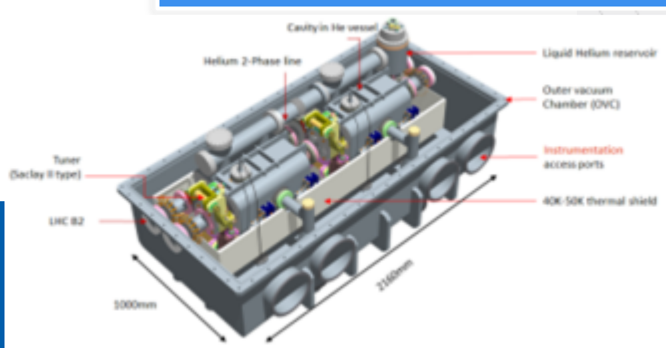
RF Dipole: Waveguide or waveguide-coax couplers

3 Advanced Design Studies with Different Coupler concepts



Double ¼-wave:
s
na

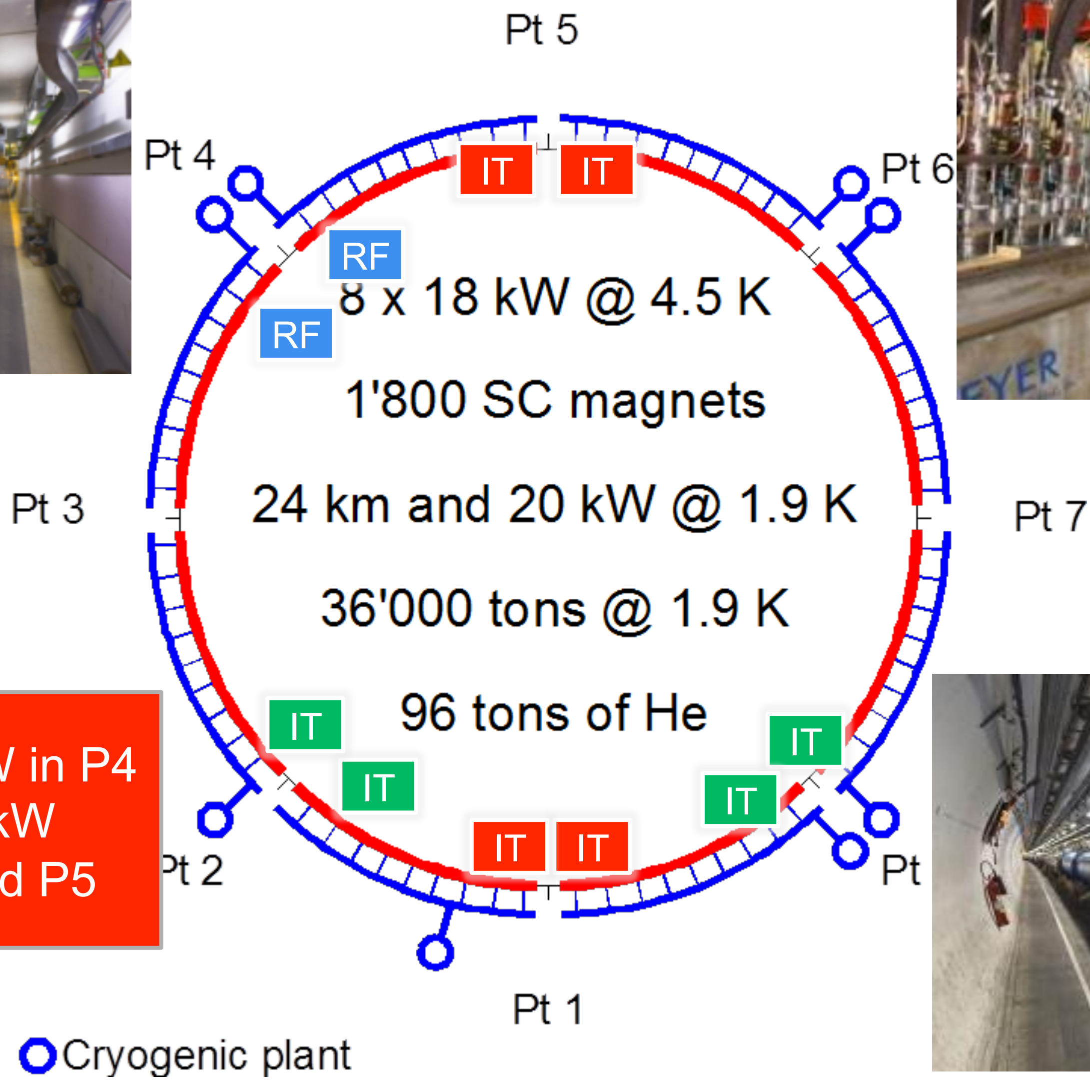
Concentrate on two designs in order to be ready for test installation in SPS in 2016/2017 TS



Coaxial couplers with
nt a

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

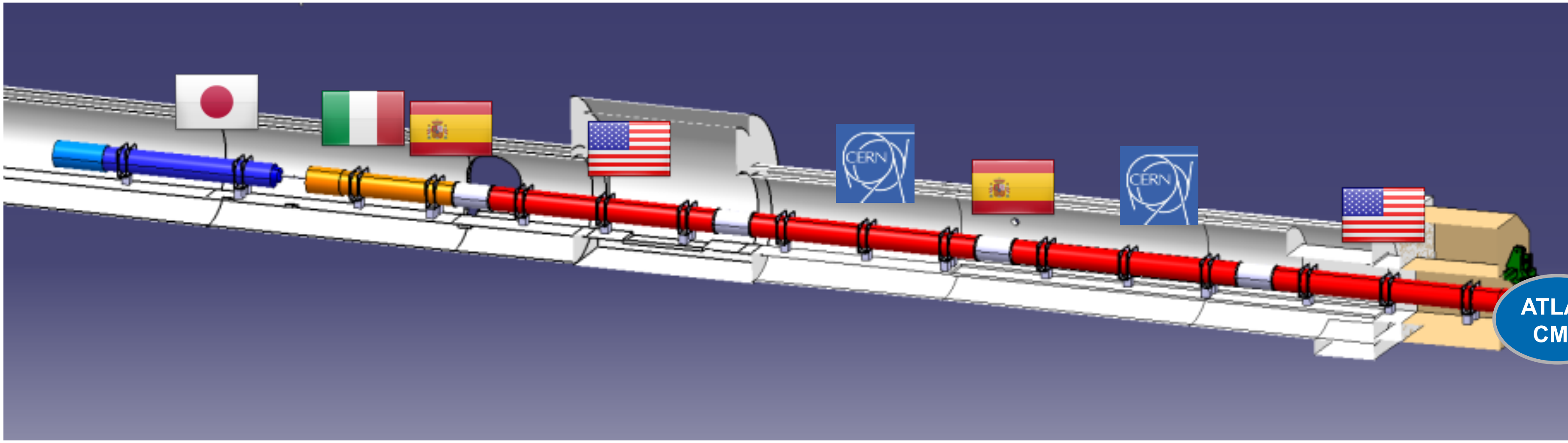
Eliminating Technical Bottlenecks : Cryogenics P4 and P1-P5

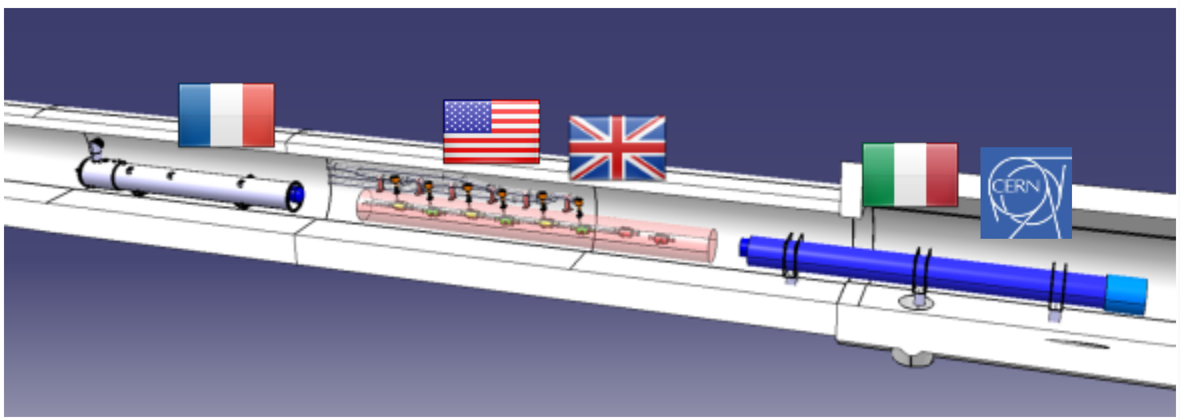


New Plant ≥ 6 kW in P4
Two new 18 kW
Plants in P1 and P5

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**

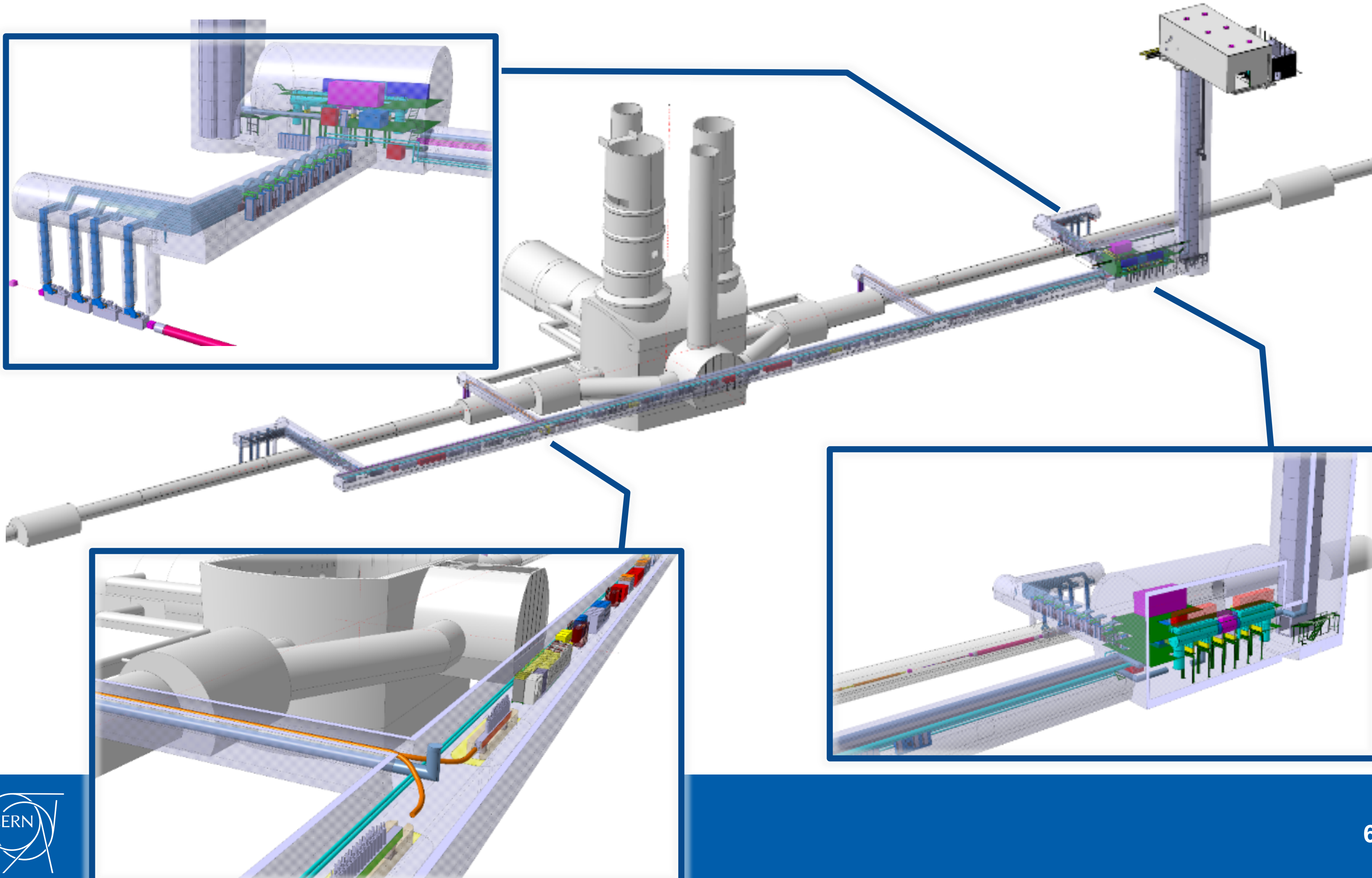
CC : R&D and Design **UK**

High Luminosity LHC

High Luminosity LHC Participants

HL-LHC civil engineering: main excavation during LS2

Civil Engineering - New baseline – e.g. P1

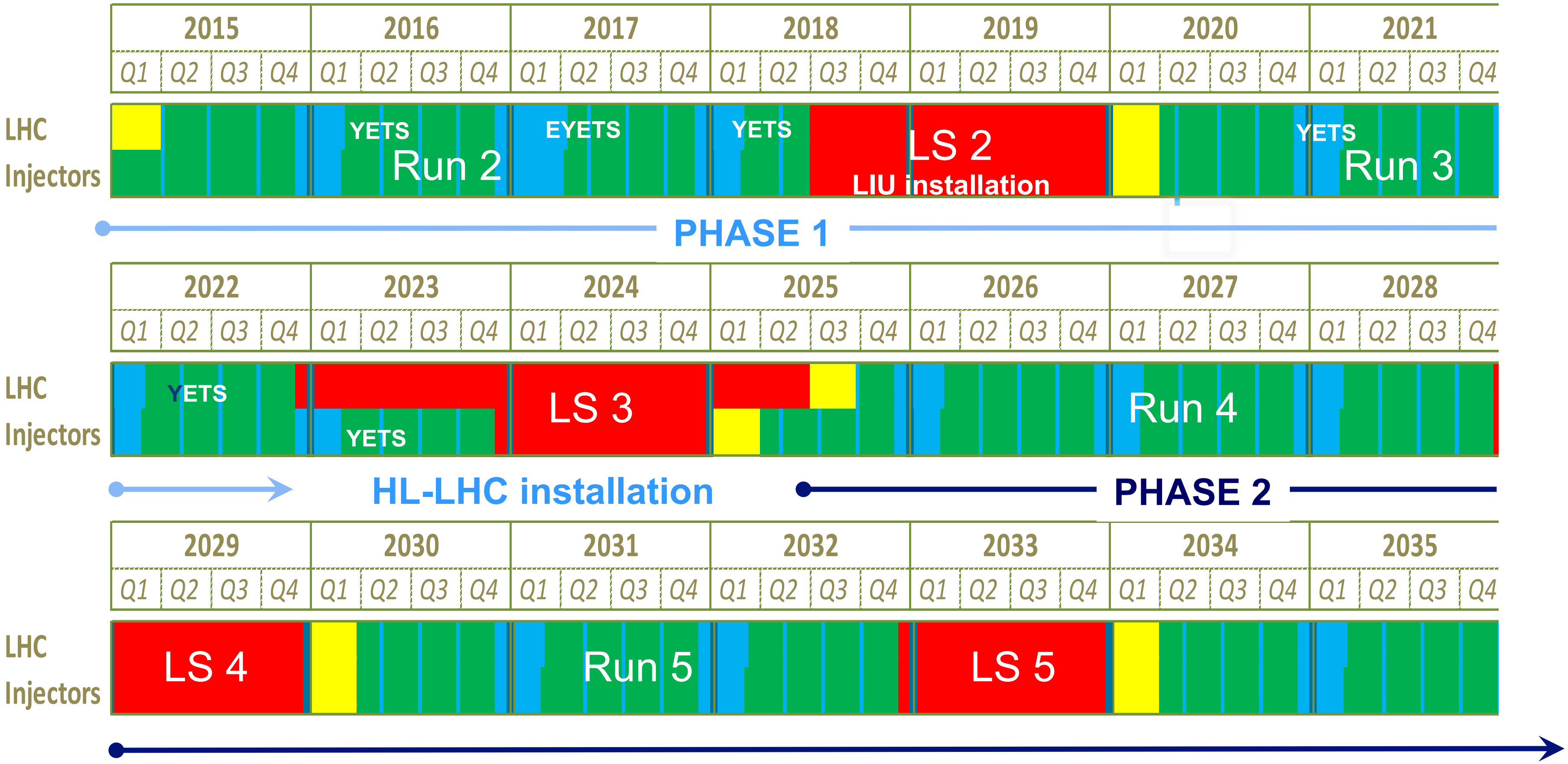


LHC roadmap: schedule beyond LS1 (MTP 2015-2019)

LS2 starting in 2018 (July) => 18 months + 3 months BC
LS3 LHC: starting in 2023 => 30 months + 3 months BC
Injectors: in 2024 => 13 months + 3 months BC

(Extended) Year End Technical Stop: (E)YETS

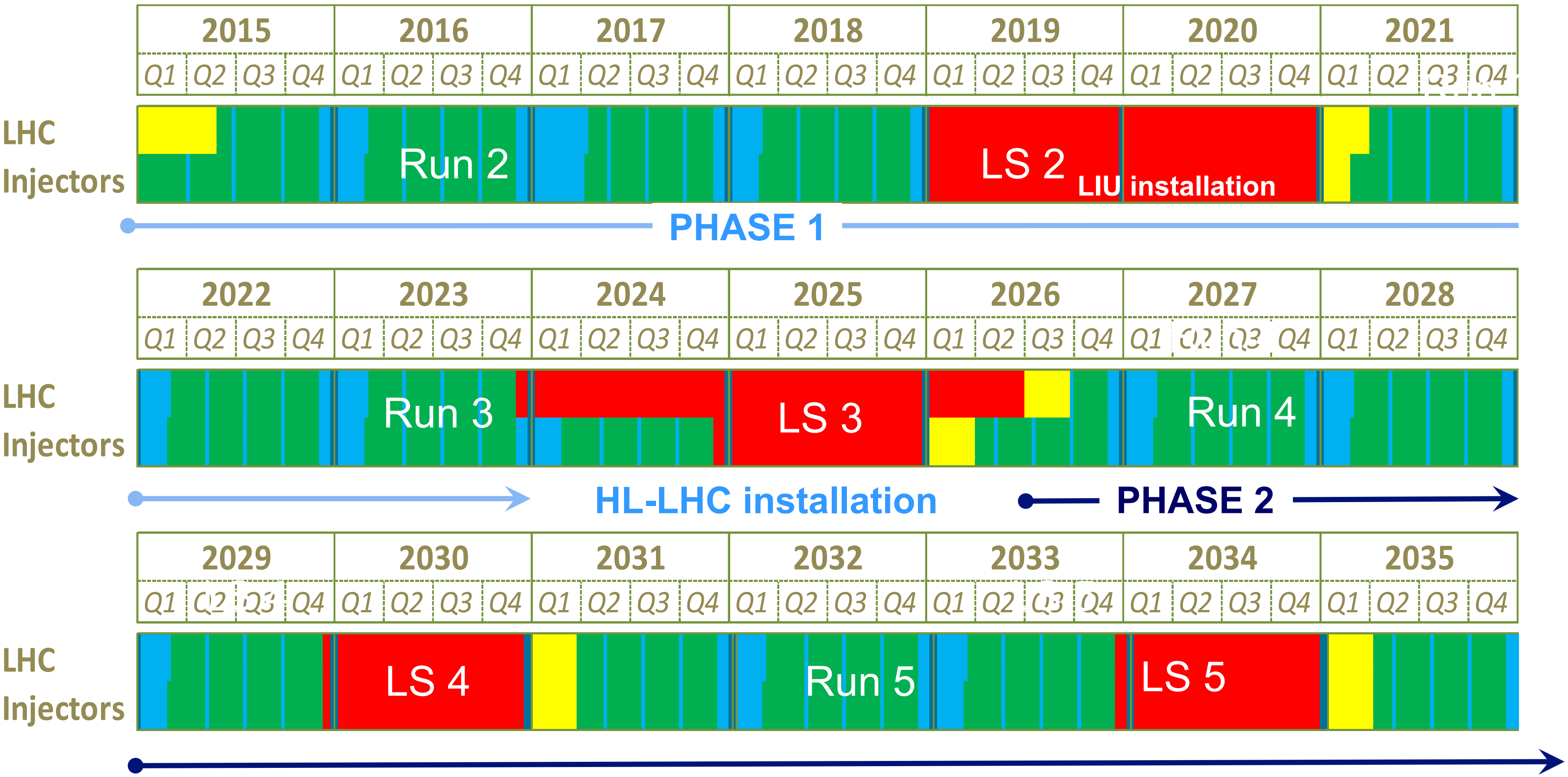
Physics
Shutdown
Beam commissioning
Technical stop



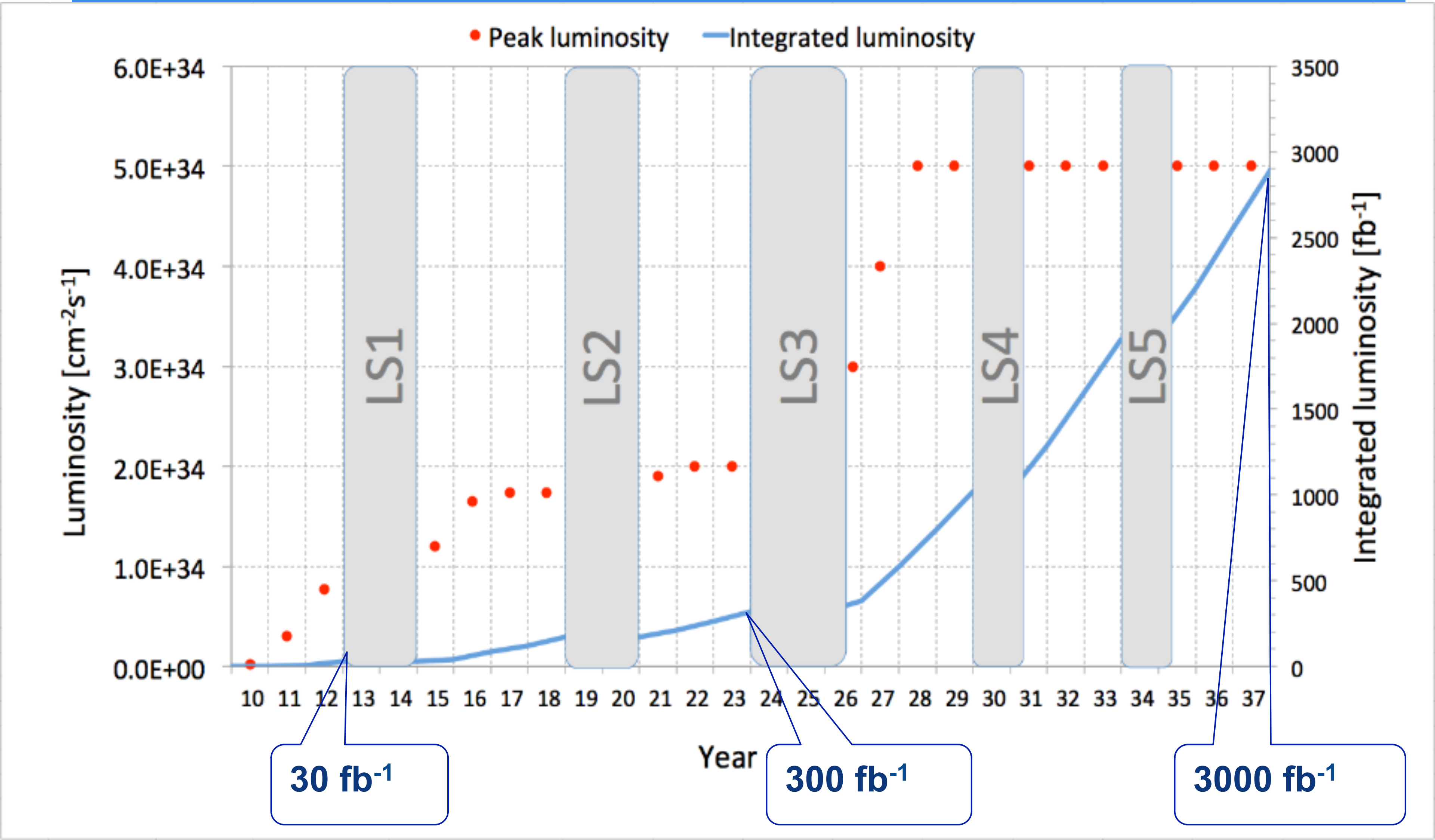
LHC roadmap: according to MTP 2016-2020

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

- Physics
- Shutdown
- Beam commissioning
- Technical stop



LHC roadmap: Integrated luminosity



Thanks for your attention