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Upgrade projects of the LHC

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XXI Cracow Epiphany Conference

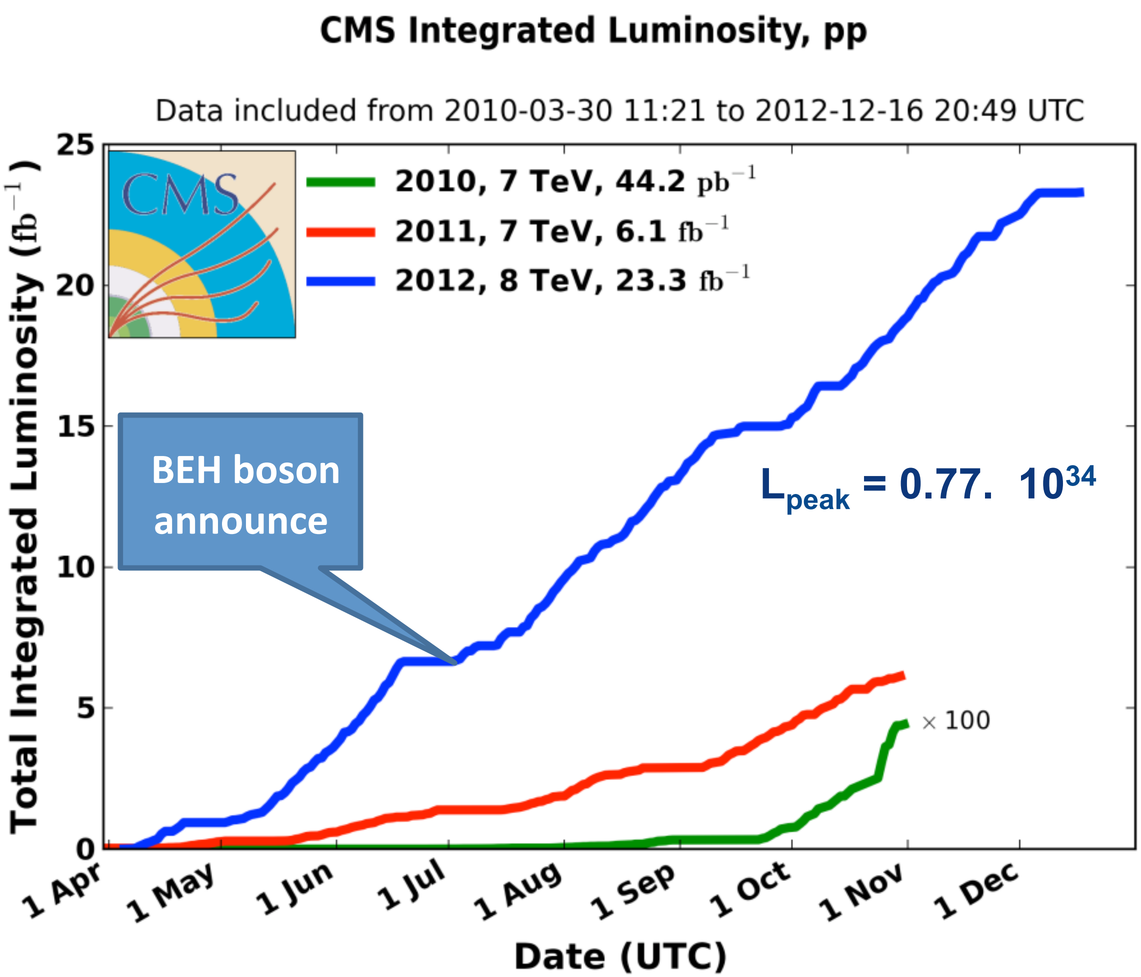
8th January 2015

Outline

- **LHC recall**
  - **Run 1**
  - **LS1 status**
  - **Run 2 (from LS1 to LS2) ⇒ *13 TeV***
  - **LS2 and Run 3 ⇒ 300 fb^{-1}**

- **LHC Injectors Upgrade project (LIU)**
- **High Luminosity LHC project**

2010-2012 (Run 1): LHC integrated luminosity



Σ ~30 fb^{-1}

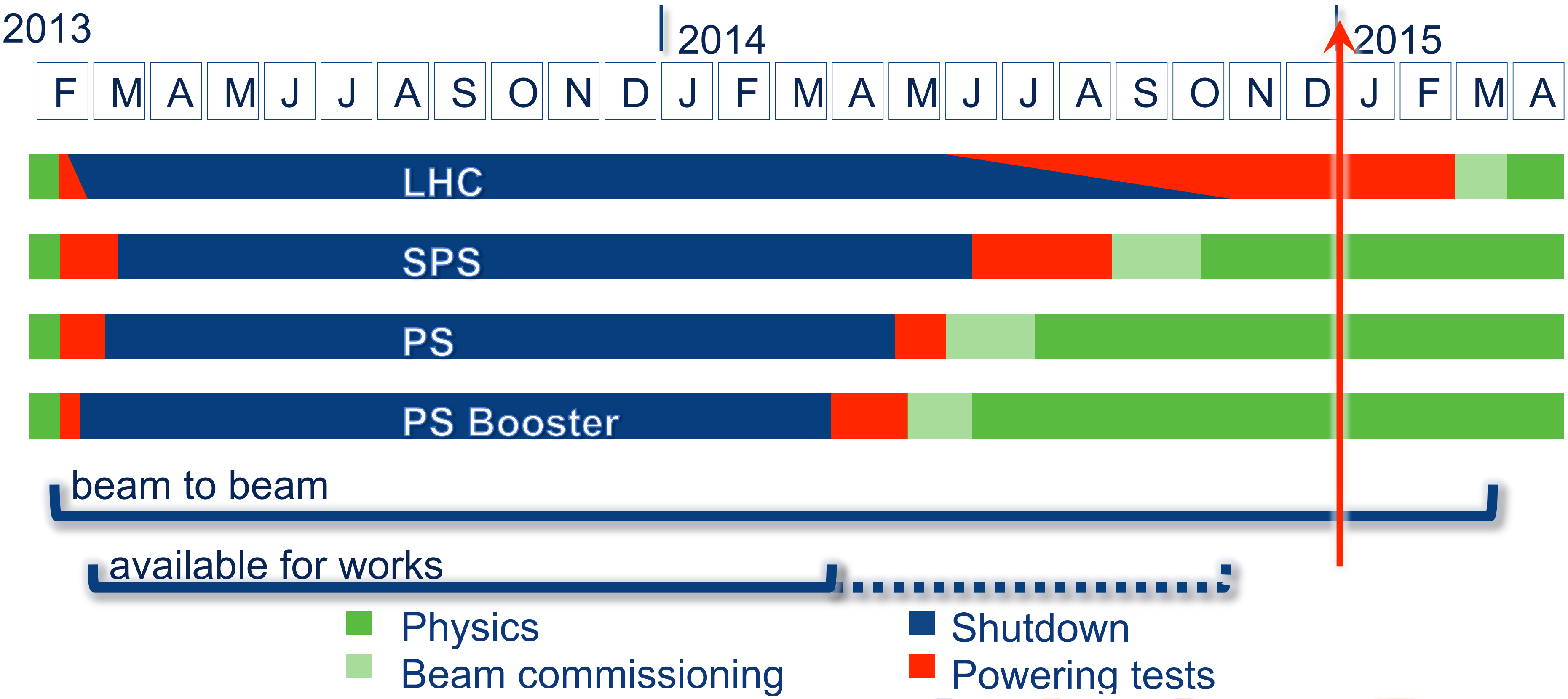
2010: **0.04 fb^{-1}**
7 TeV CoM
Commissioning

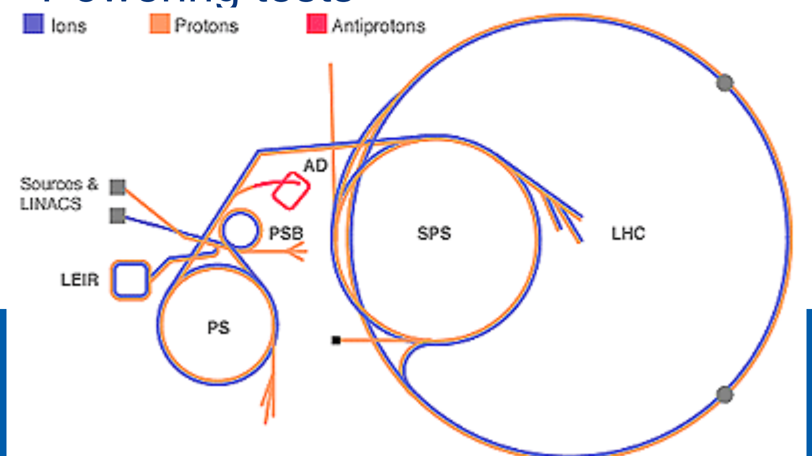
2011: **6.1 fb^{-1}**
7 TeV CoM
… exploring limits

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

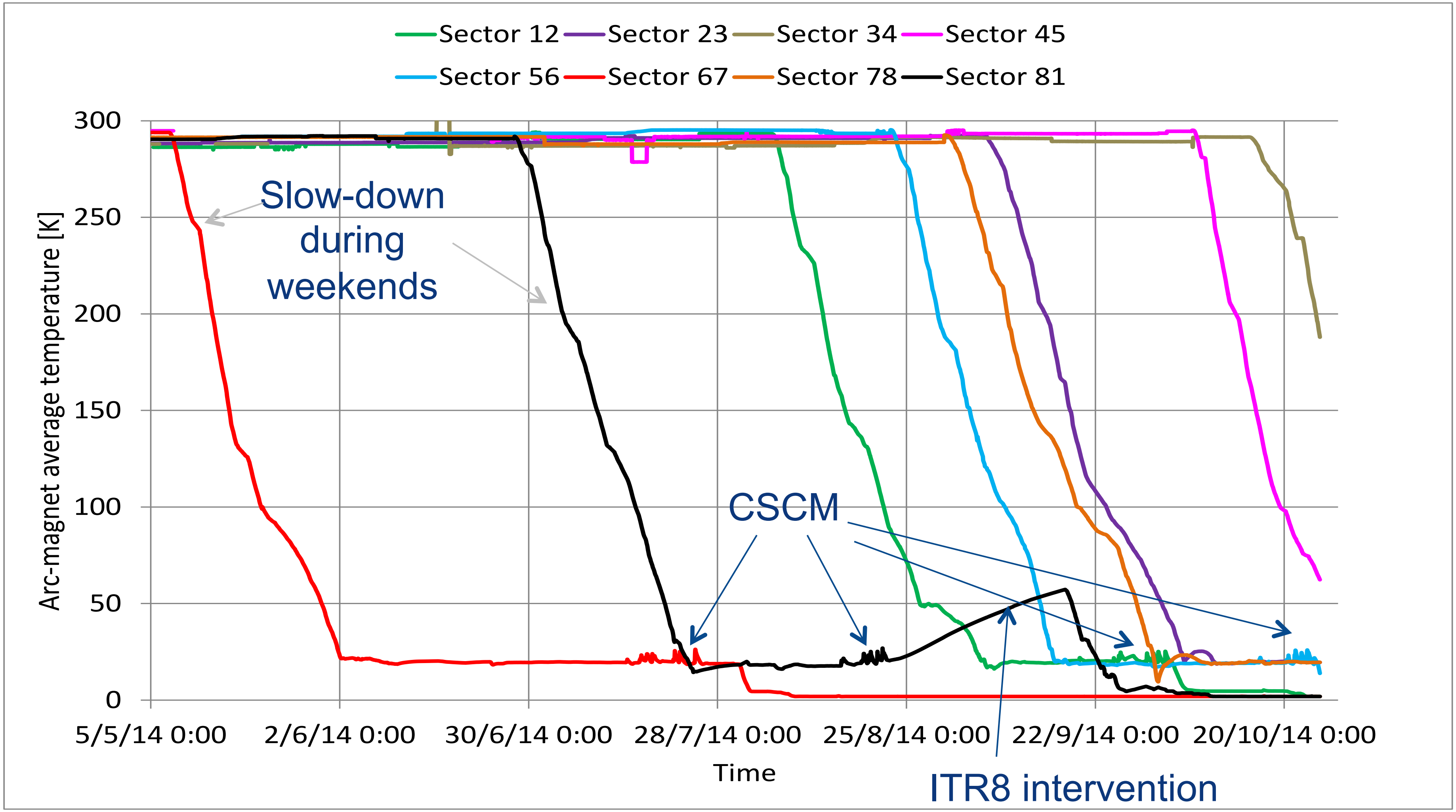
7 TeV and 8 TeV in 2012
Up to 1380 bunches
with1.5 10^{11} protons

LS 1 from 16th Feb. 2013 to Dec. 2014





Cool-down of LHC sectors



Courtesy of Laurent Tavian

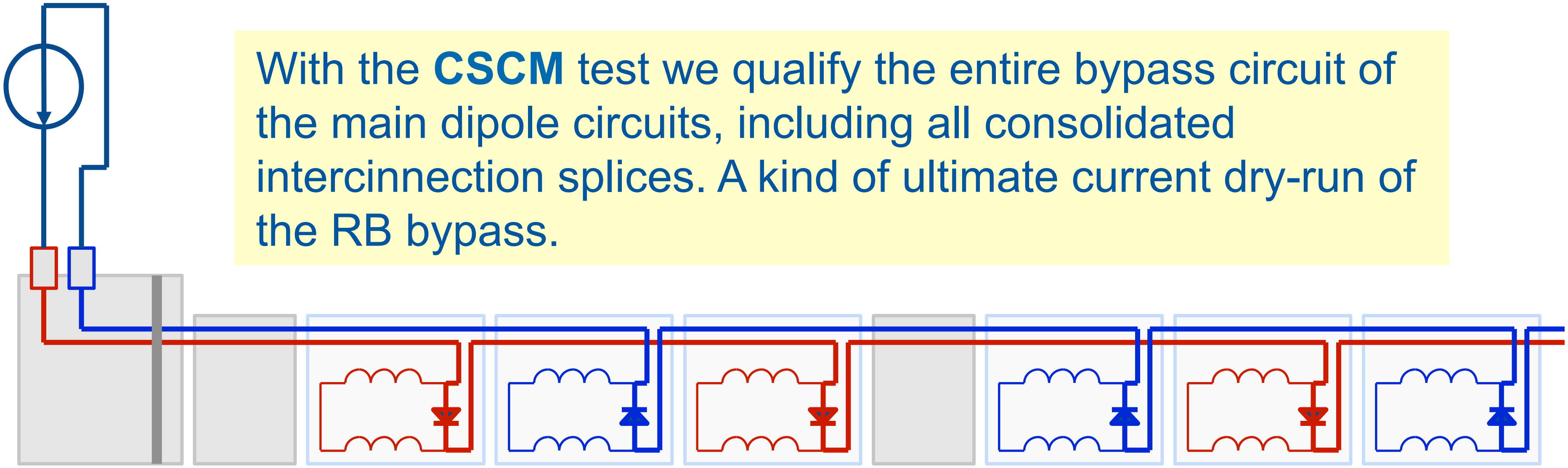
LHC schedule V4.1

Safety First,
Quality Second,
Schedule Third

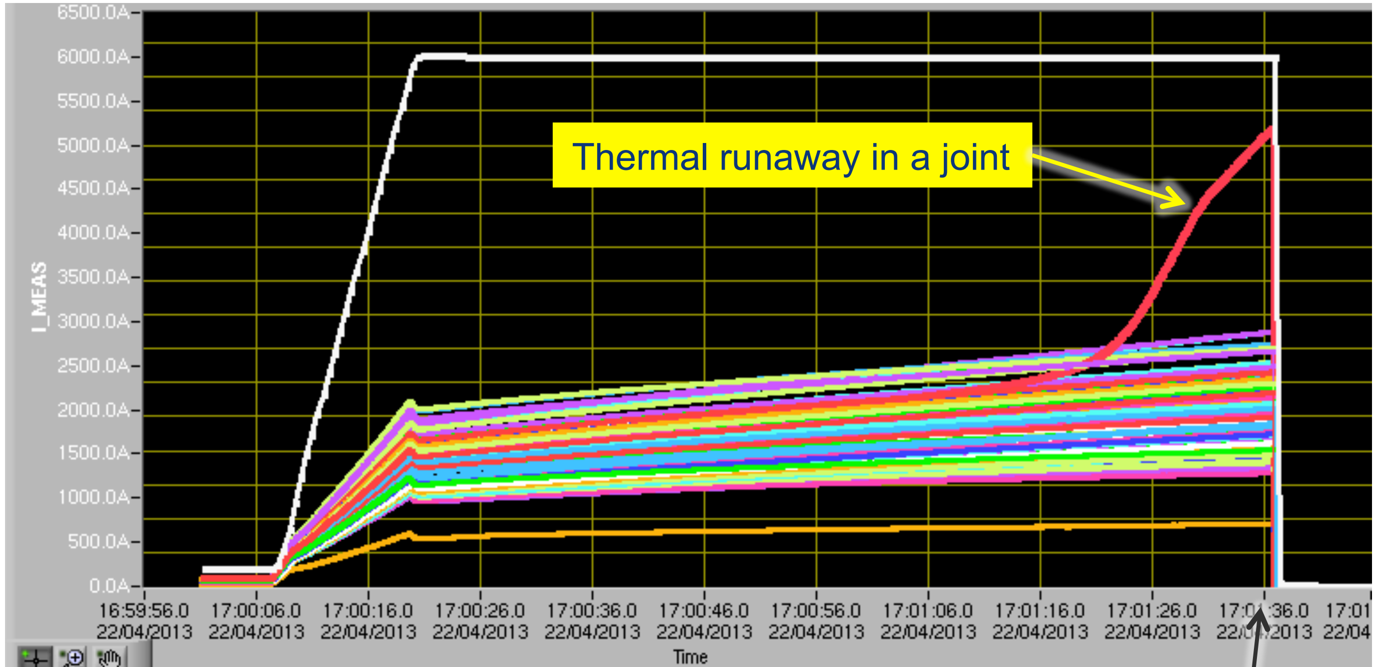
1st beam (March 2015)

CSCM: Copper Stabilizer Continuity Measurement Validation of the main LS1 splice consolidation campaign

With the **CSCM** test we qualify the entire bypass circuit of the main dipole circuits, including all consolidated intercinnection splices. A kind of ultimate current dry-run of the RB bypass.

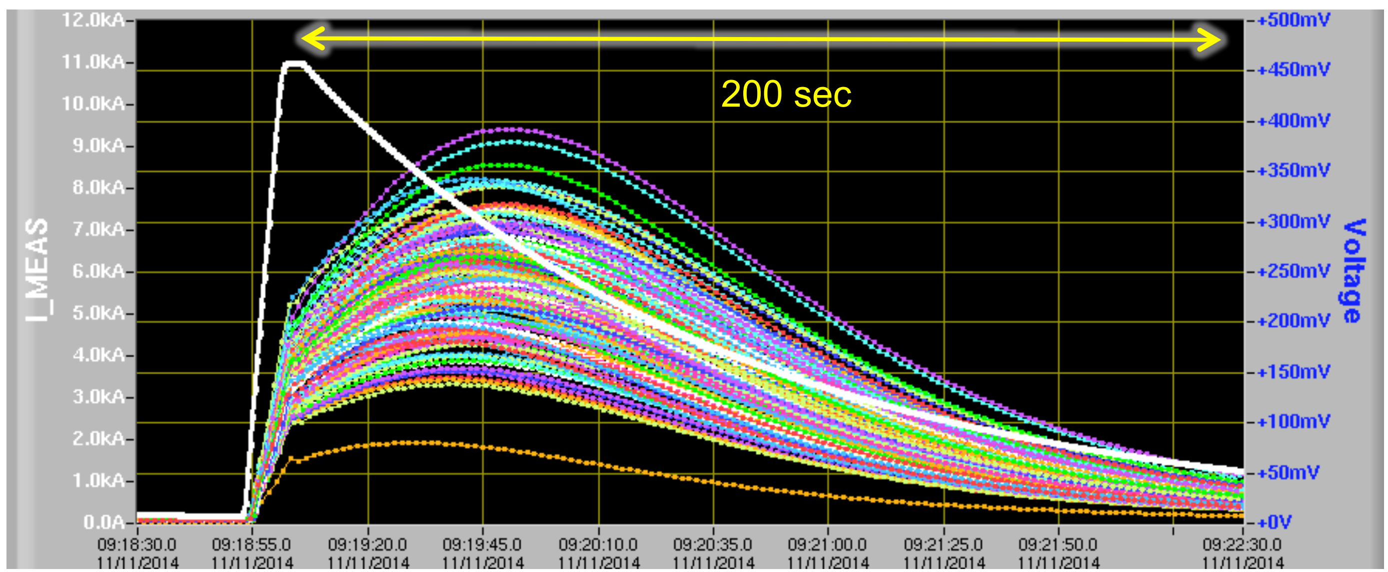


CSCM at 9 kA in S-23 **BEFORE** consolidation of the 13 kA joints, clearly showing a runaway after a few seconds at 9 kA.



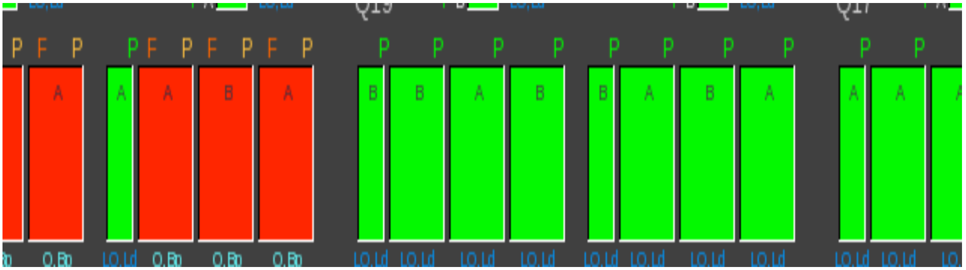
Trip and fast current decay

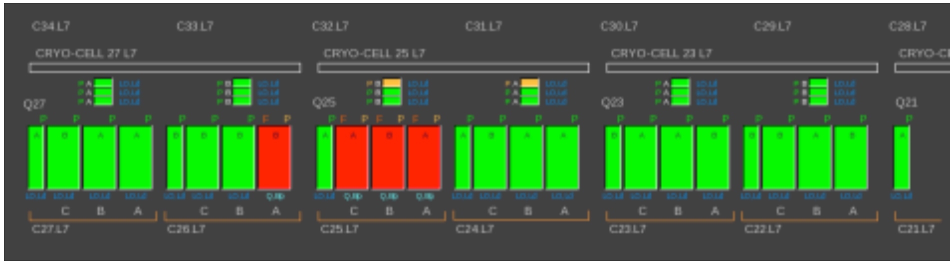
CSCM at 11.1 kA in S-23 **AFTER** LS1, clearly showing stable voltage behaviour.



All main RB circuits were validated by the end of 2014

Main dipole quench campaign is ongoing





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6290
4347
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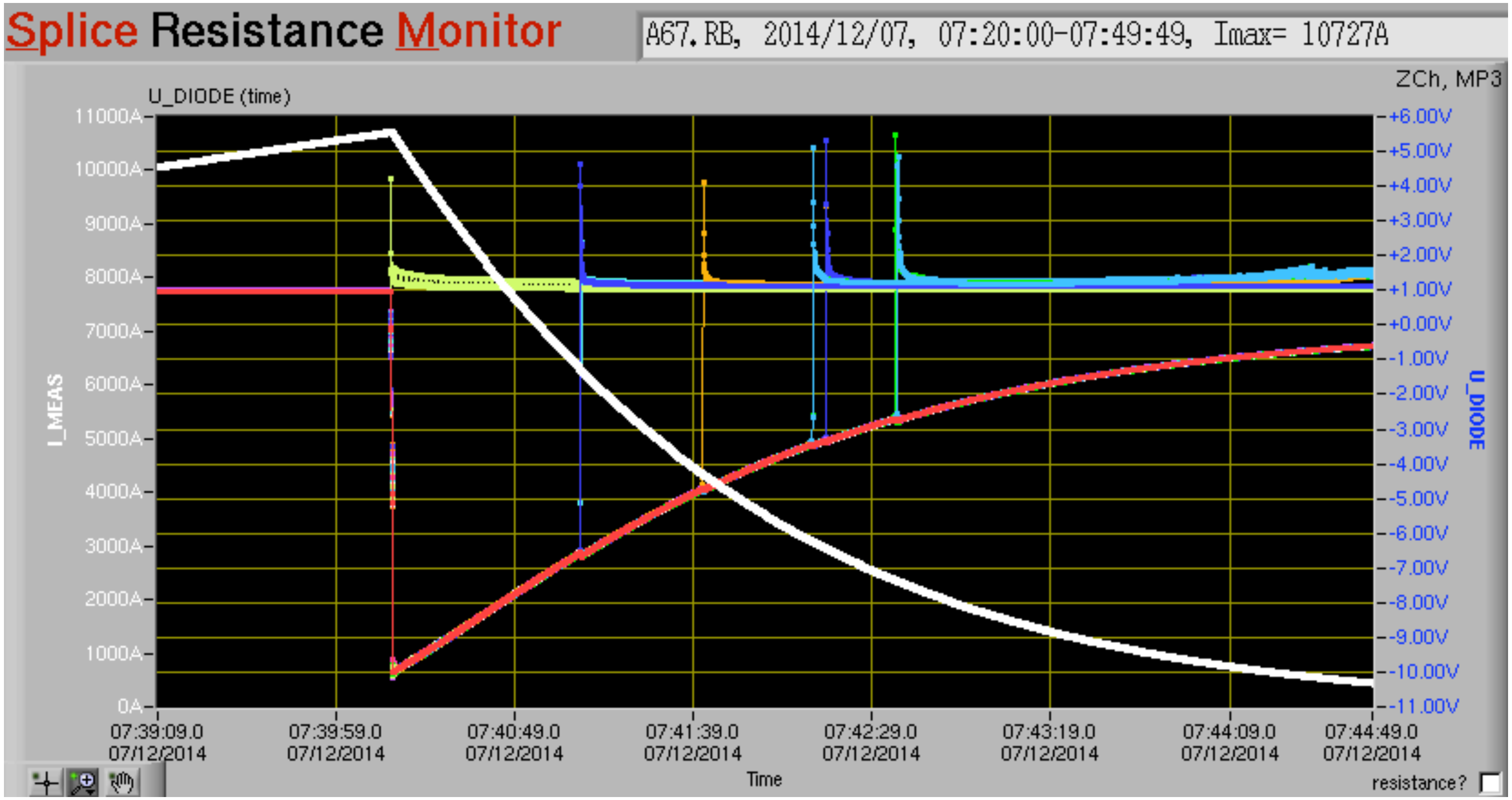
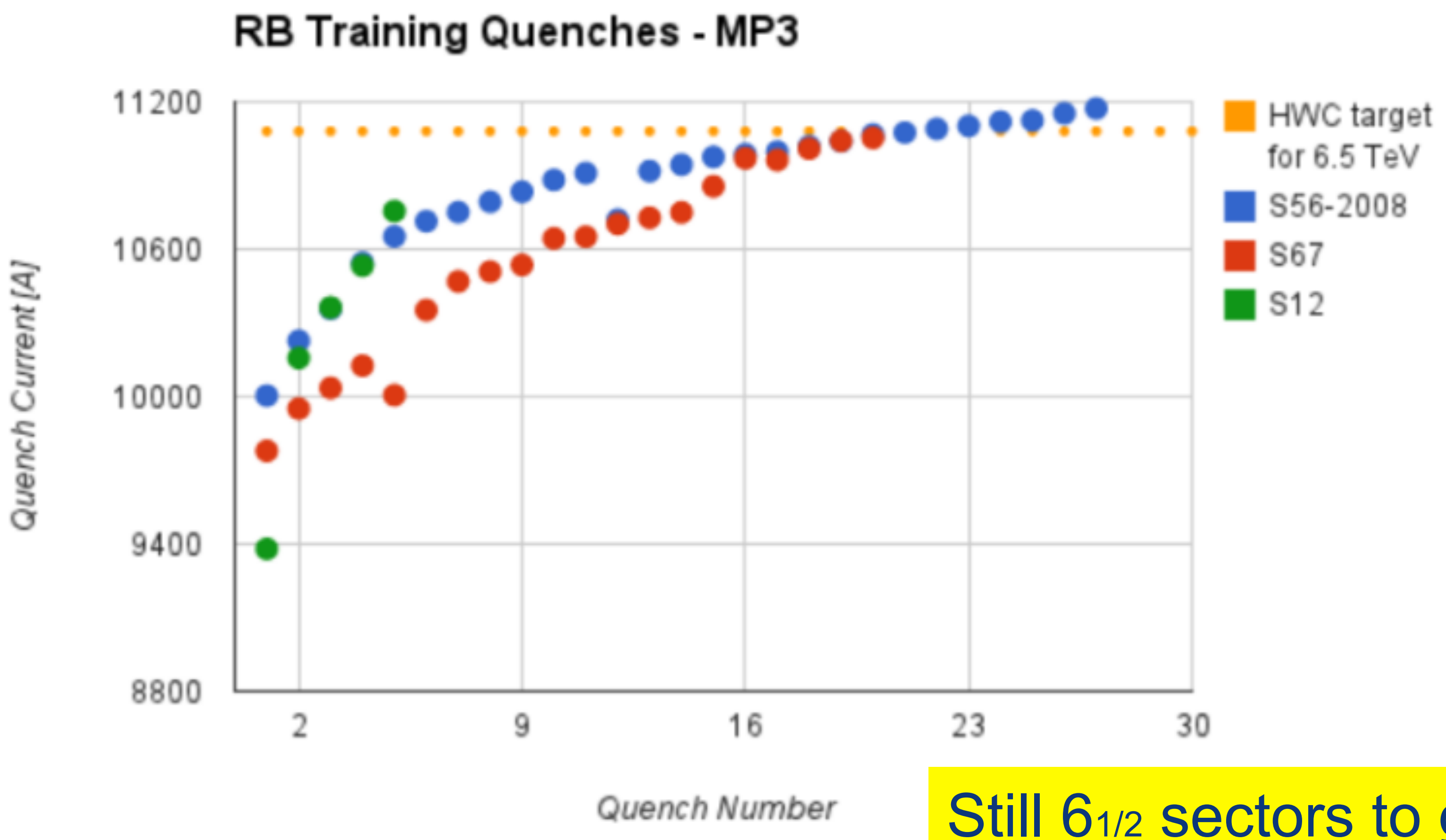
2371
2355



S-67 is at 6.5 TeV, S-12 is at 6.37 TeV

Each quench requires extensive analysis to see if all systems (converter, magnets, current leads, quench detection, quench heaters, bypass diodes, energy extraction system, PM-files) work as expected.



Still 6 1/2 sectors to go…

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

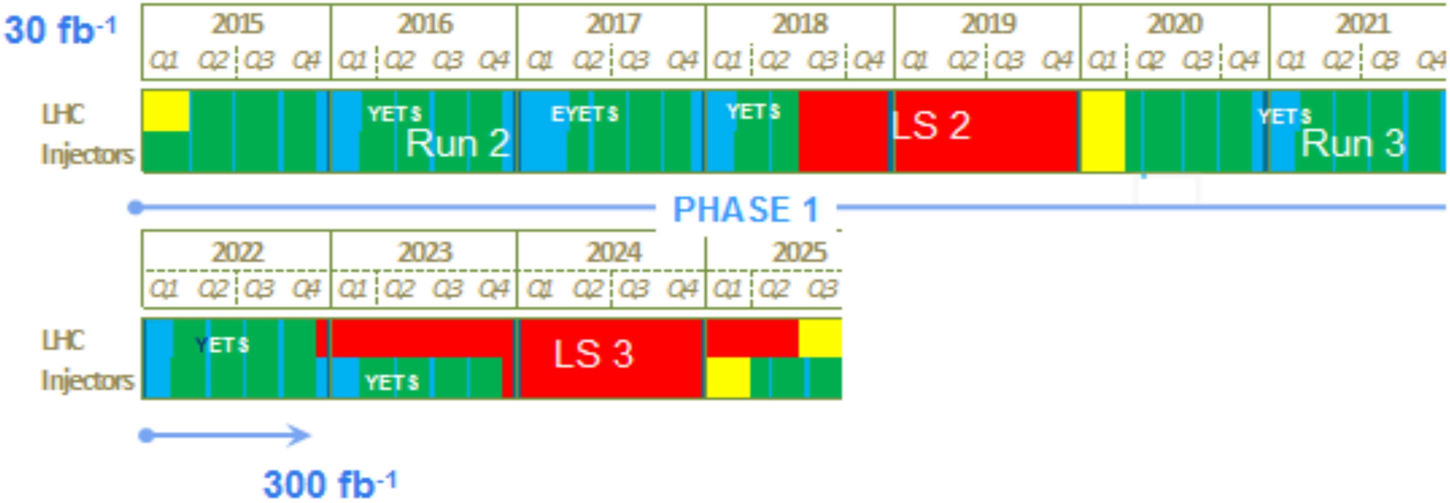
Integrated luminosity goal:

2015 : 10 fb^{-1}

Run2: ~100-120 fb^{-1}

(better estimation by end of 2015)

RUN3: total ~300 fb^{-1} before LS3



European Strategy for Particle Physics

The European Strategy for Particle Physics
Update 2013

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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} → 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 ~2036) closely related to consolidation program

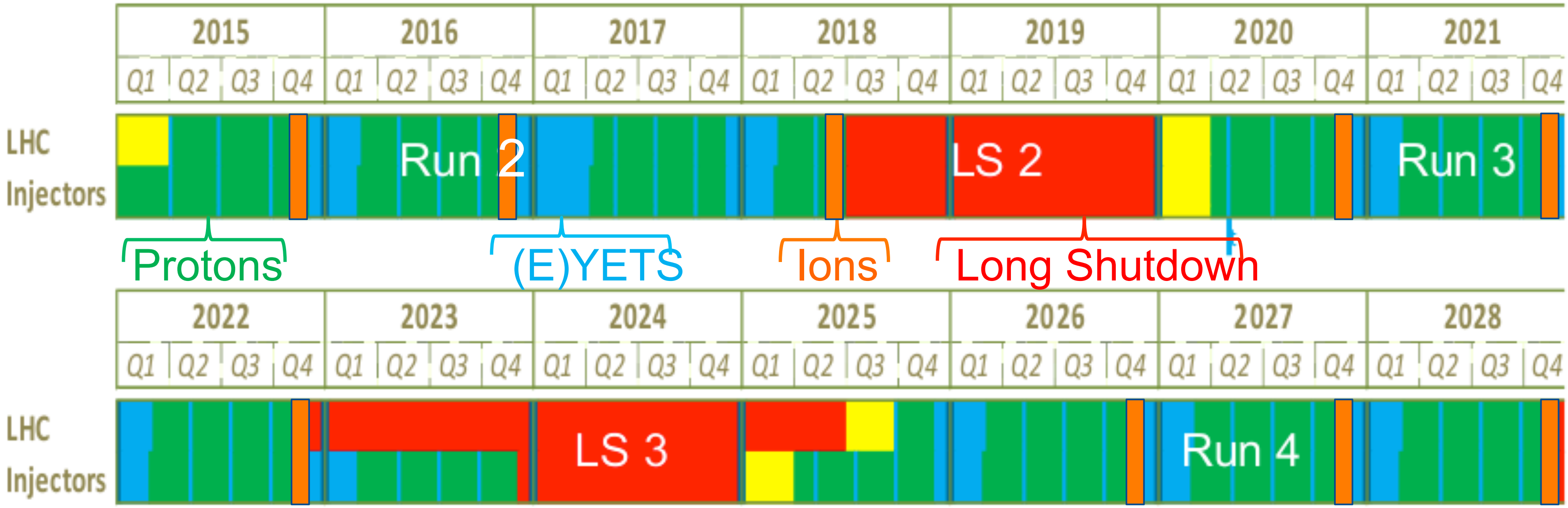
⇒ Upgrade/replace ageing equipment (power supplies, magnets, RF…)

⇒ Improve radioprotection measures (shielding, ventilation…)

Courtesy of Malika Meddahi

Timelines of the LIU project

- LIU (machine and simulation) studies during **Run 2** until **LS2**
  - Key dates for pending decisions until 2016
- LIU installations and hardware works mainly during **LS2**
- Beam commissioning of LIU beams
  - **Pb ion beams** need to be ready by **2020 ion run**
  - **Proton beams** during **Run 3** to be ready after **LS3**



LIU-IONS target: 7x nominal peak luminosity!

	$\mathcal{L}_{peak}$	Beam energy
Achieved in 2011	$5x10^{26}$ Hz/cm^2	3.5 *Z* TeV
LIU-IONS	**$7x10^{27}$ Hz/cm^2**	7 *Z* TeV

IBS & space-charge already at the limit on SPS flat bottom …

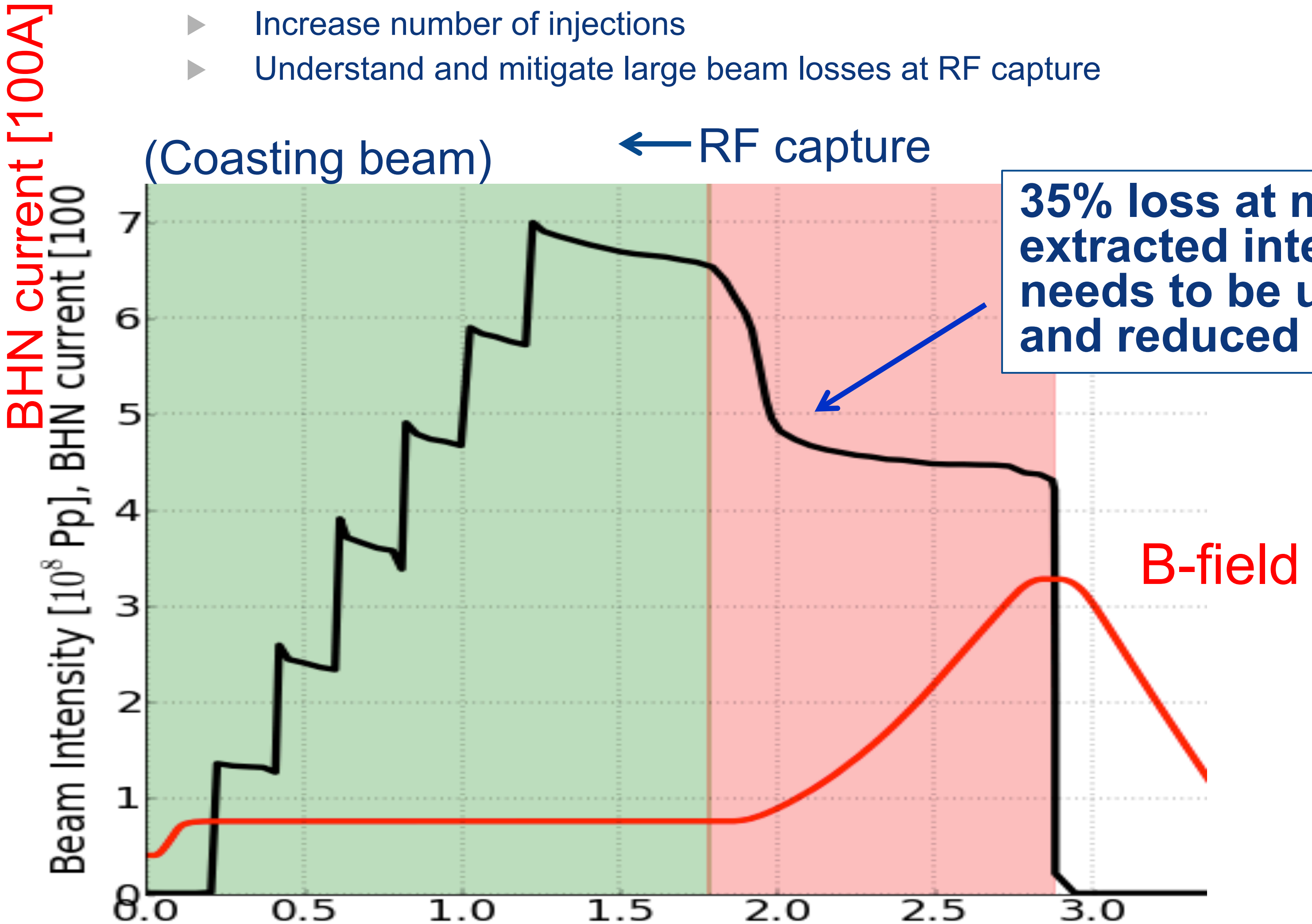
We need to pack **a larger number** of only **slightly less intense (compared to 2013)** bunches in LHC

Means to achieve target luminosity

- Source & Linac3:
  - Increase beam current by improving Low Energy Beam Transport (LEBT)
  - Injection rate: 5 Hz → 10 Hz
- LEIR:
  - Increase number of injections
  - Understand and mitigate large beam losses at RF capture
- PS:
  - Bunch splitting to produce 4 bunches with 100 ns bunch spacing
- SPS:
  - Mitigate beam degradation at flat bottom
  - Upgrade SPS injection system with 100 ns rise time
  - Longitudinal slip-stacking → 50 ns bunch spacing

LEIR challenges

- LEIR:
  - Increase number of injections
  - Understand and mitigate large beam losses at RF capture



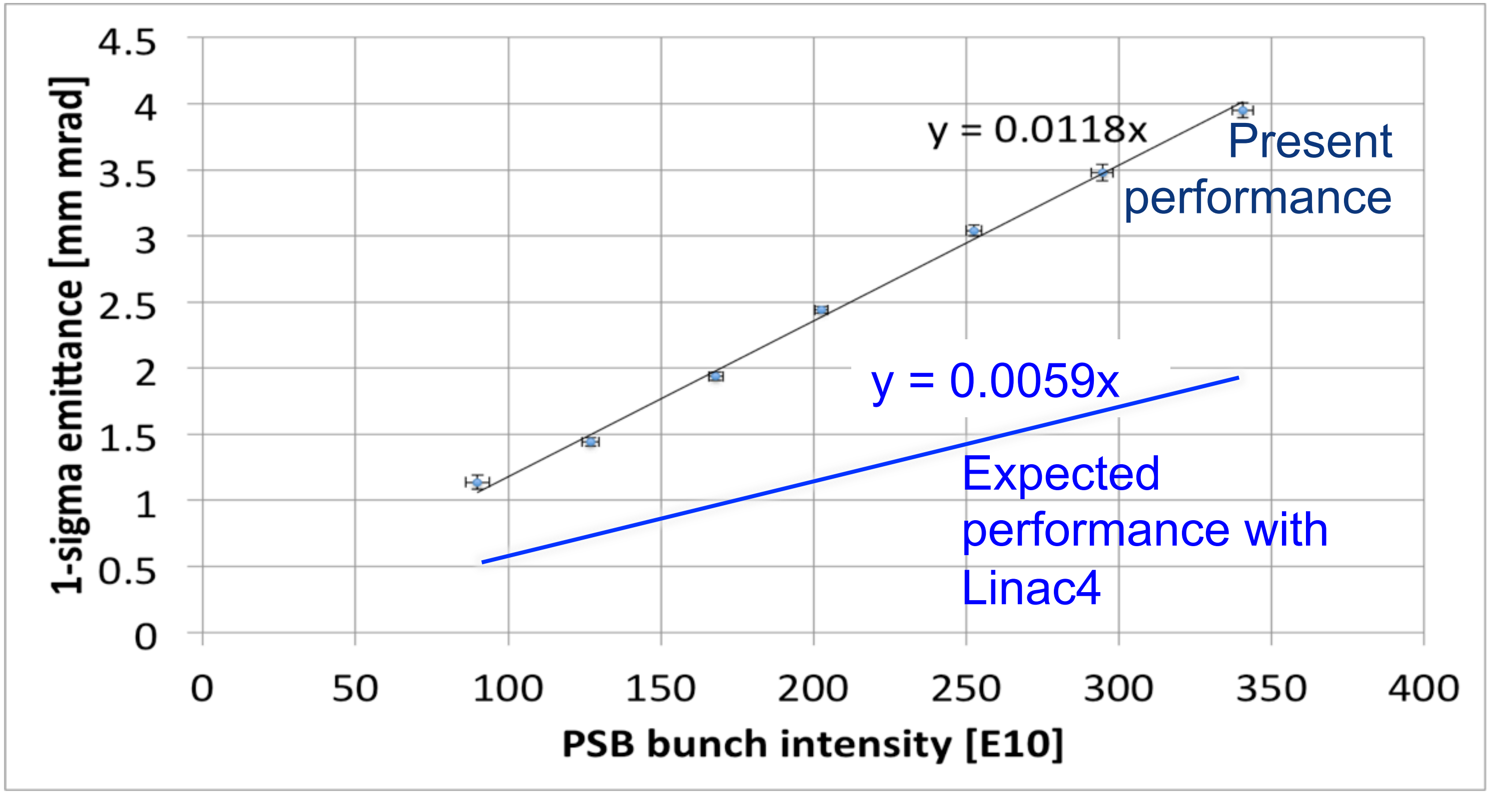
LIU Proton target → HL-LHC beam parameters

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

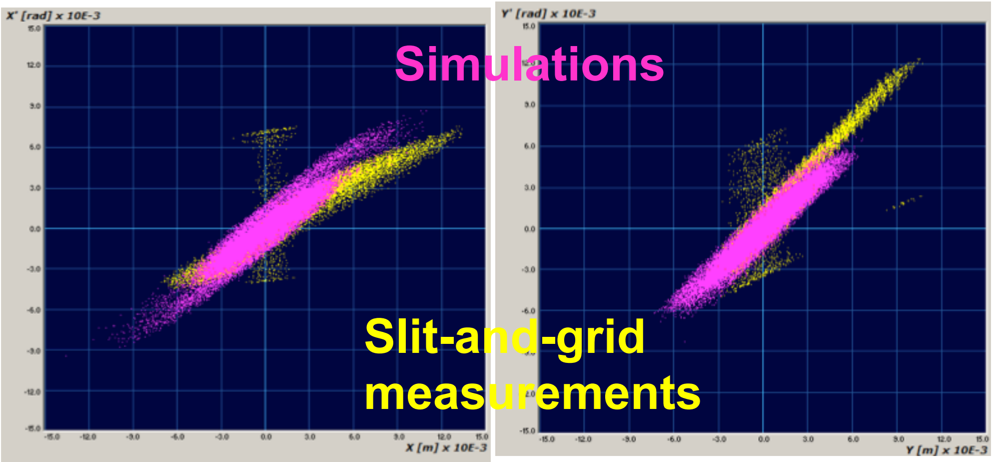
Linac2 → Linac4

- Linac4 will replace Linac2
  - H^- injection into PSB at 160 MeV
  - Expected double brightness for LHC beams out of the PSB



Linac2 → Linac4

- Linac4 is being commissioned stage by stage with a temporary source
  - Acceleration to 12 MeV is validated
    - RFQ and chopper behave correctly
    - DTL tank1 accelerates the beam without losses
  - Emittance measurements agree with code predictions (PARMTEQ, PATH, TRACEWIN)
    - Reconstruction methods for transverse and longitudinal emittances are also validated!



Linac2 → Linac4

- New caesiated source ready for use
  - Will provide 40 mA within 0.35 μm
    - > 20 turns injection for future LHC beams → simulations ongoing to establish future emittance vs. intensity curve

- Half-sector test planned for June 2016 to “simulate” injection into PSB with the real equipment

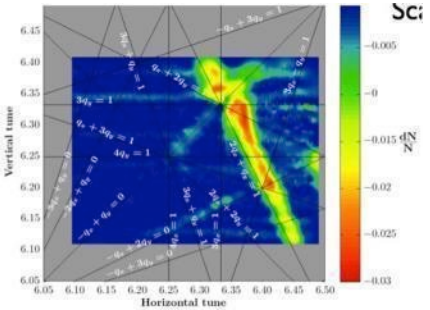
LS2 : (2018-2019), LHC Injector Upgrades (LIU)

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

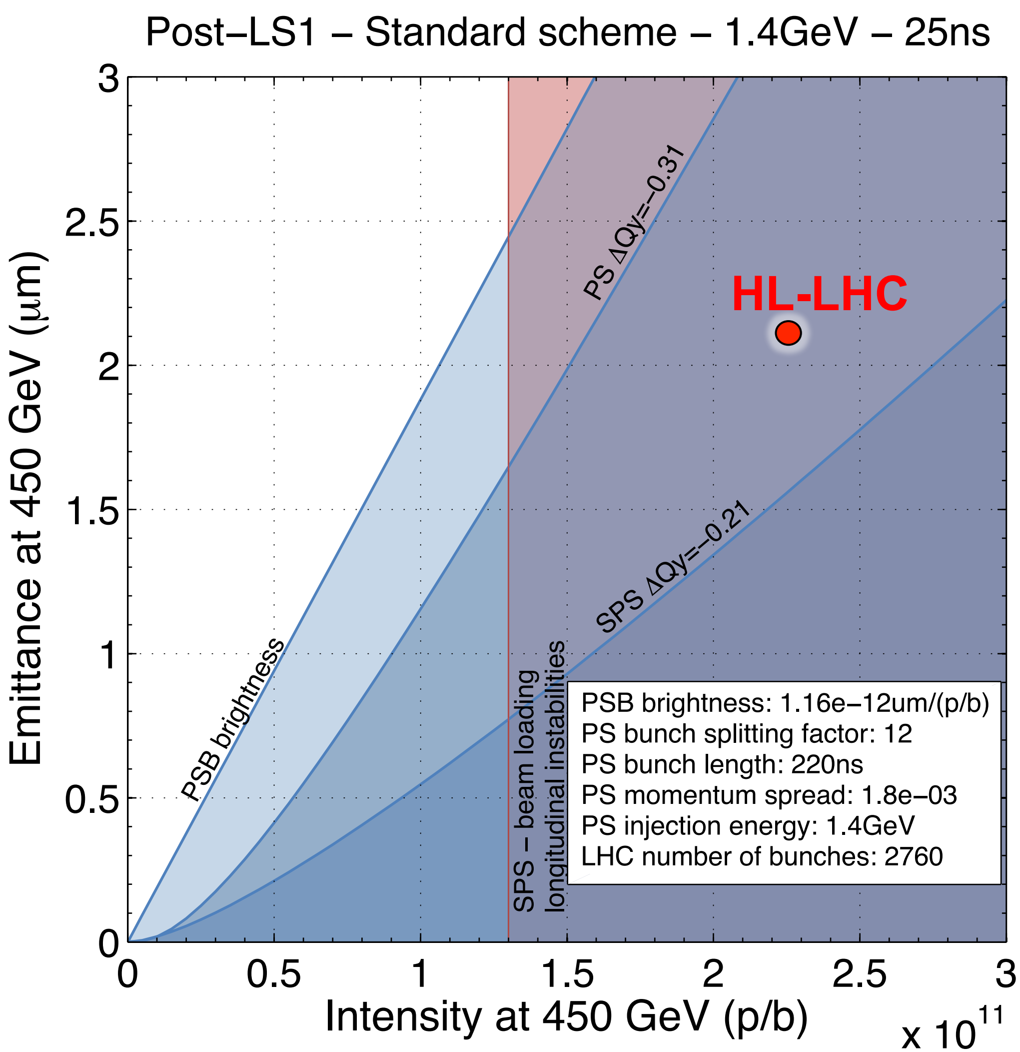


SPS

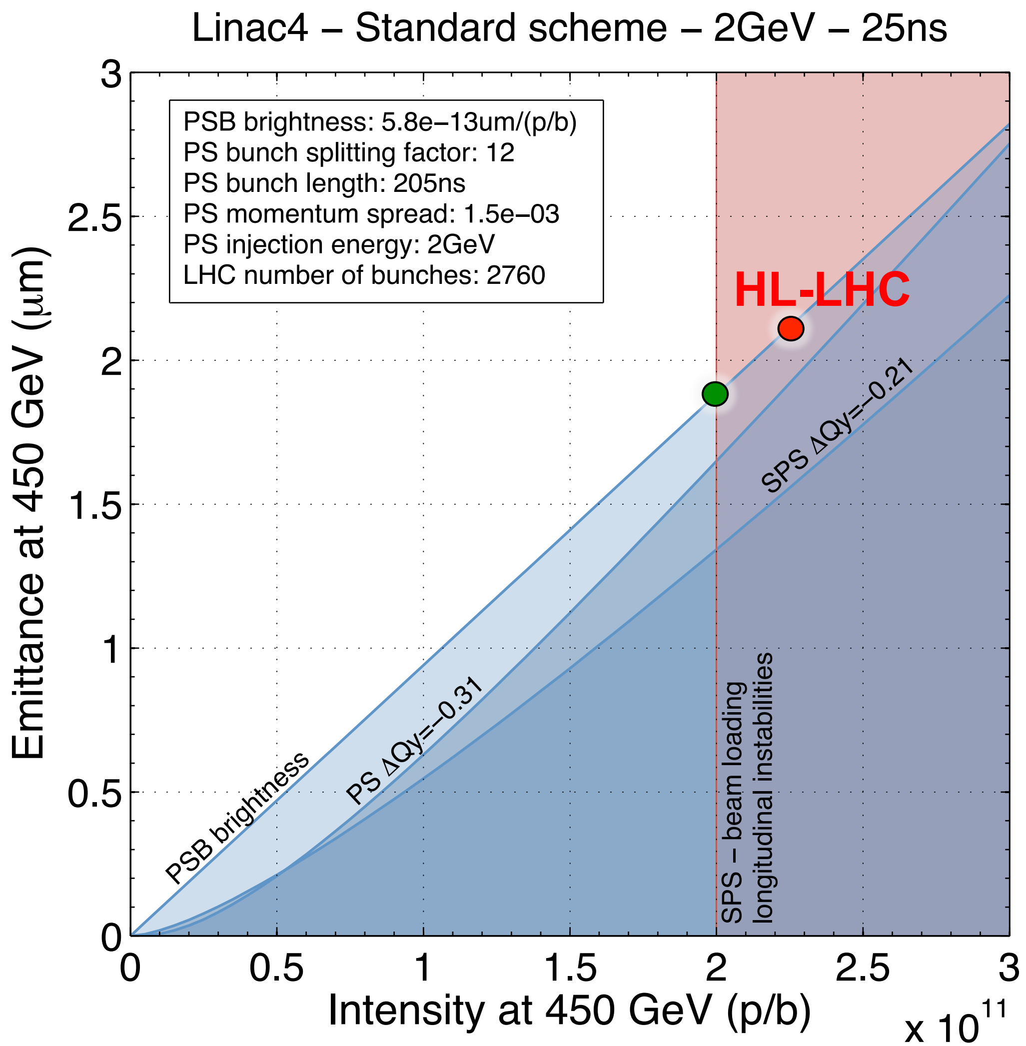
- Electron Cloud mitigation – scrubbing, strong feedback system, or coating of the vacuum system
- Impedance reduction, improved feedbacks
- Large-scale modification to the main RF system

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

Standard scheme (72b trains) presently



Standard scheme (72b trains) after LIU



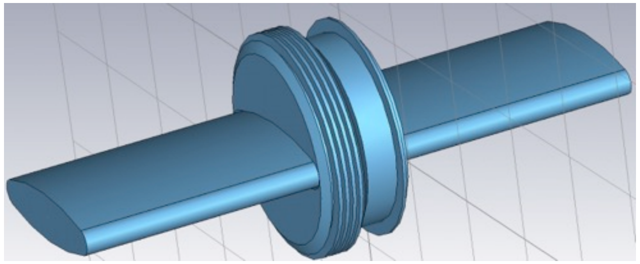
- With Linac 4
- LIU upgrades
  - SPS 200 MHz upgrade
  - SPS e-cloud mitigation
  - PSB-PS transfer at 2 GeV
- Limitations standard scheme
  - SPS: longitudinal instabilities + beam loading
  - PSB: brightness
- Performance reach
  - 2.0x10^{11}p/b in 1.9μm (@ 450GeV)
  - 1.9x10^{11}p/b in 2.3μm (in collision)

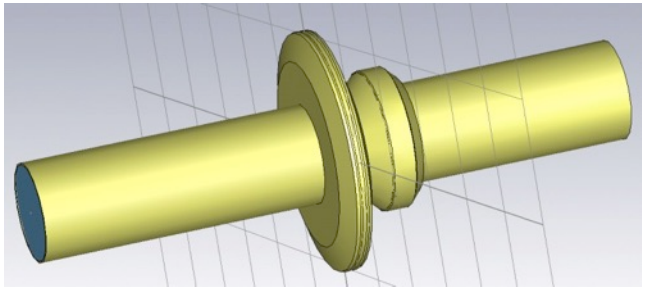
Can we do it better for HL-LHC?

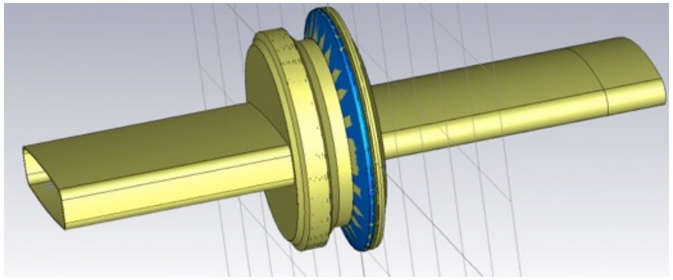
- Higher bunch current from the SPS (larger longitudinal emittance at flat top)
  - Intermediate optics (Q22) → trade off between margin in TMCI threshold and constraint on RF power
  - Reduced ramp rate & bunch rotation at 450 GeV
  - Impedance identification and reduction
- Higher number of bunches into LHC
  - Inject trains of 80 bunches into the SPS
    - Based on injecting 7 bunches from the PSB into PS
    - One out of 21 bunches is kicked out with transverse damper before acceleration
- Higher brightness from injectors
  - BCMS beams
    - Trains of 48 bunches into SPS
    - High damage potential for beam intercepting devices in the SPS, transfer lines and LHC

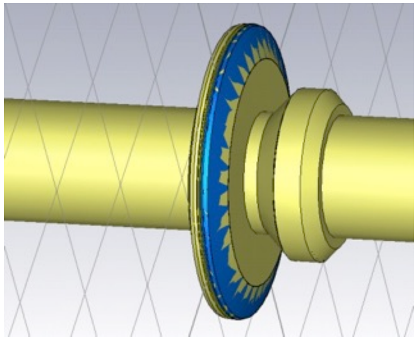
SPS impedance identification and reduction

- Vacuum flanges (≈550) are the likeliest candidate
  - **Particle tracking simulations** show that intensity threshold **increases by a factor of 2** without the impedance of vacuum flanges

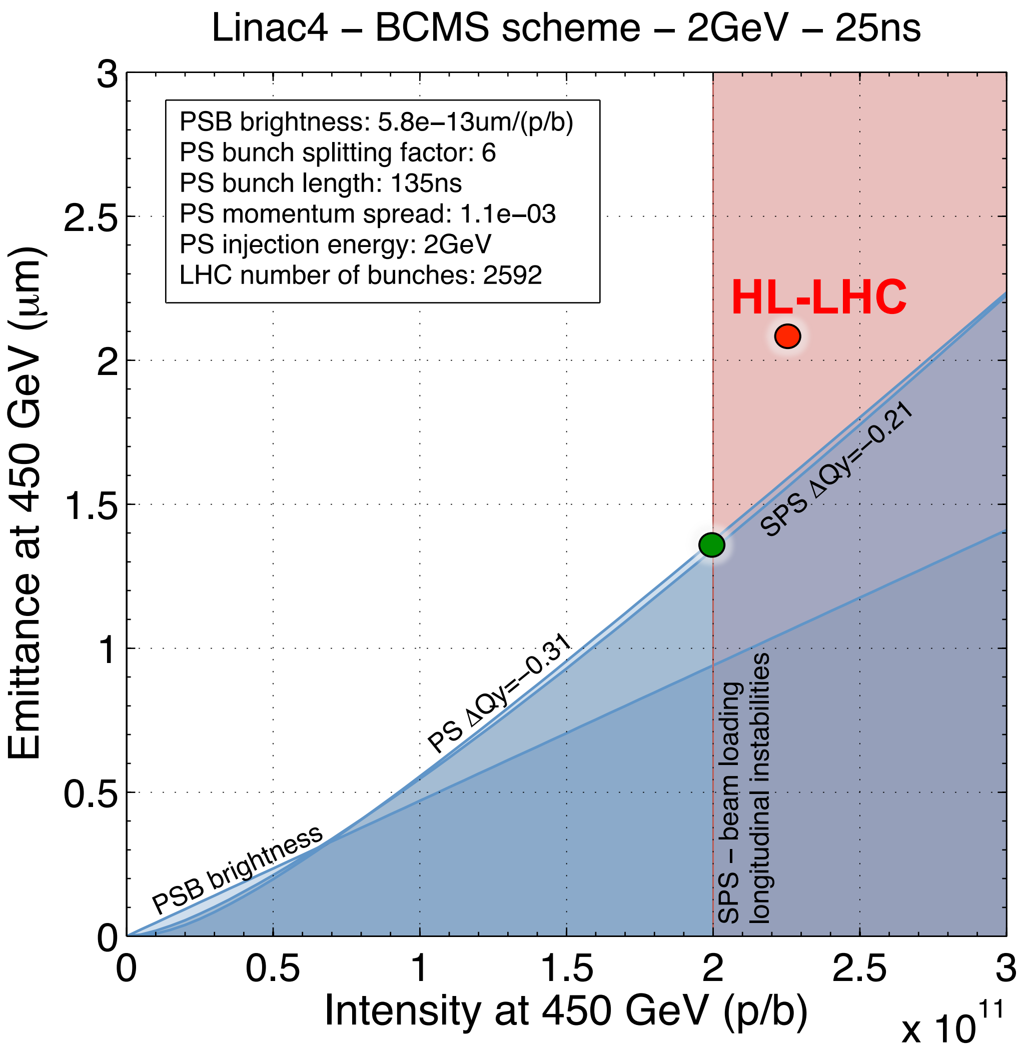








BCMS scheme (48b high brightness trains)



- With Linac 4
- LIU upgrades
  - SPS 200 MHz upgrade
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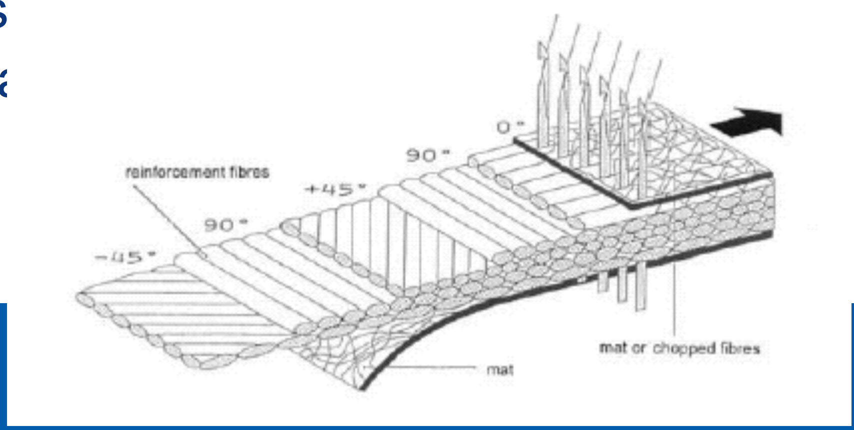
  - PSB-PS transfer at 2 GeV
- Limitations BCMS scheme
  - SPS: longitudinal instabilities + beam loading
  - PS: space charge
  - SPS: space charge
- Performance reach
  - 2.0×10^{11}p/b in 1.37µm (@ 450GeV)
  - 1.9×10^{11}p/b in 1.65µm (in collision)

Dangers of high brightness

- Choice of material is challenging
  - Stresses in case of impact of high brightness beams are estimated to be beyond the strength of materials presently used in passive protection absorbers (even standard HL-LHC can pose problems)
  - R&D needed to possibly find suitable materials for new absorbers post LS2.

- HiRadMat facility will use SPS beam at 450 GeV to test
  - Material properties (used as input for simulations)
  - Robustness against "s
  - New promising materi



Progress of the LIU project

- Protons:
  - **LIU baseline program established** to ensure production of LHC proton beams with parameters close to HL-LHC request
    - Right brightness, ~15% lower intensity per bunch
    - Very dense machine and simulation study program until 2016 to
      - Take decisions latest 2015 for few remaining pending items
  - **Promising options identified and under study** to increase intensity and/or brightness of LIU beams delivered to LHC
    - Need additional studies & define action planning/cost estimates
    - Brightness may clash with safety of machine protection devices
- Ions:
  - **List of actions defined** to achieve the target ion beam parameters at LHC injection to fulfil the luminosity goals
    - However, big challenges ahead
      - Increase beam current into and out of LEIR
      - Reduce beam degradation along chain (e.g. SPS flat bottom)
      - ⇨ First in line to require beam after LS2 …

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:

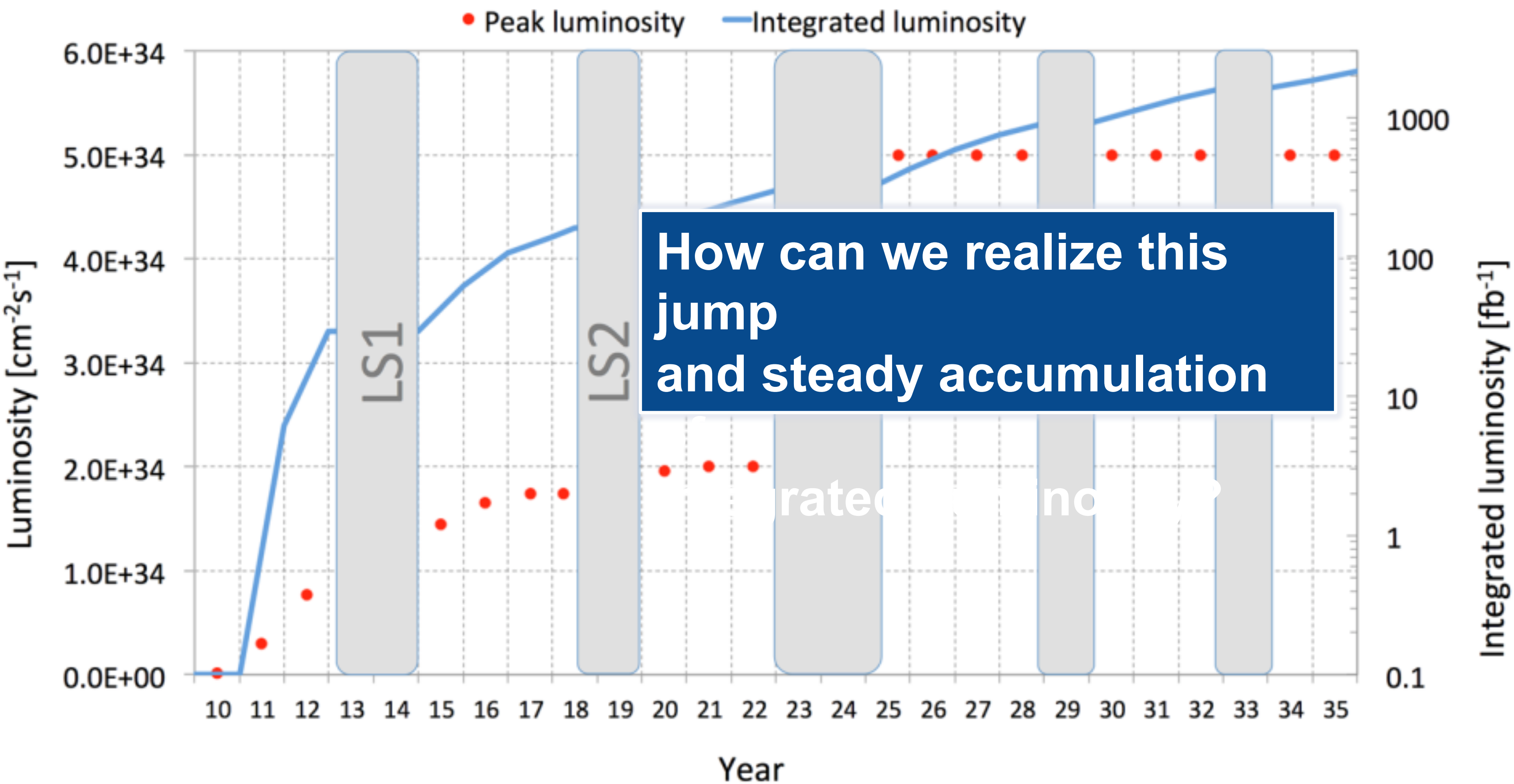
Prepare machine for operation **beyond 2025 and up to ~2036**

Devise beam parameters and operation scenarios for:

- # enabling a total nominal integrated luminosity of **3000 fb^{-1}**
- # implying an integrated luminosity of **250-300 fb^{-1} per year**,
- # design for μ ~ **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

HL-LHC goal could be reached in 2036



How can we realize this jump
and steady accumulation

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 ultimate (virtual) luminosity:

$$L > 7.5 \times 10^{34}\ cm^{-2}\ s^{-1}$$

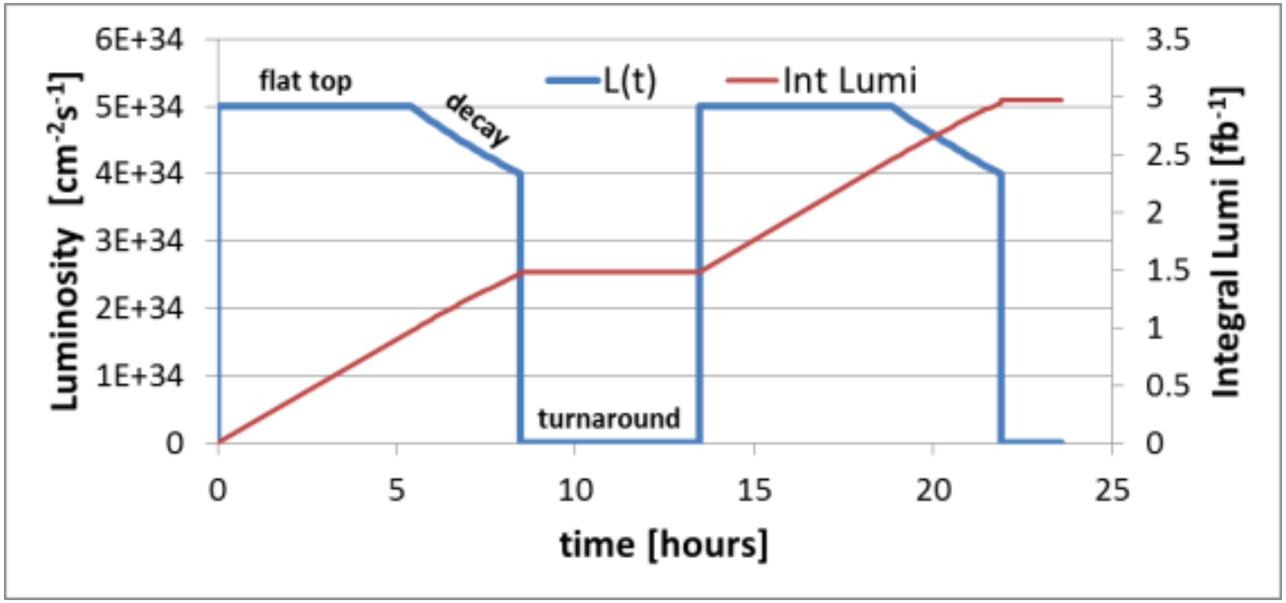
- Peak Luminosity limitation(s):
  - Event Pileup in detectors
  - Debris leaving the experiments and impacting in the machine (magnet quench protection @ heat load)

Operate with Leveled peak luminosity:

$$L = 5 \times 10^{34}\ cm^{-2}\ s^{-1}$$

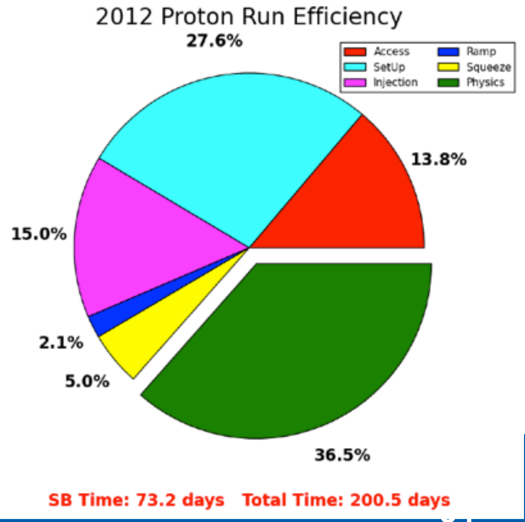
LHC Upgrade Goals: Performance optimization

- Levelling:

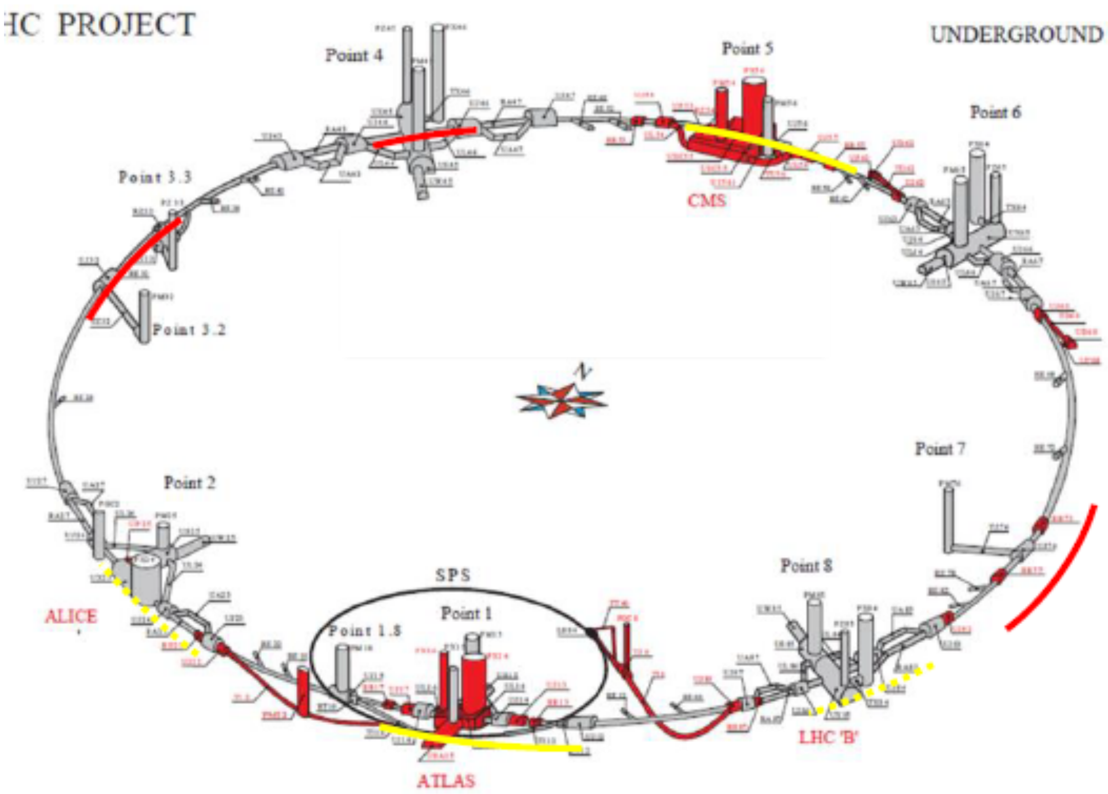


- Integrated Luminosity limitation(s):
  - Average Fill length (must be larger then levelling time)
  - Average Tournaround time (must be small wrt fill length)
  - Number of operation days
  - Overall machine efficiency

    (fraction of physics over scheduled time)



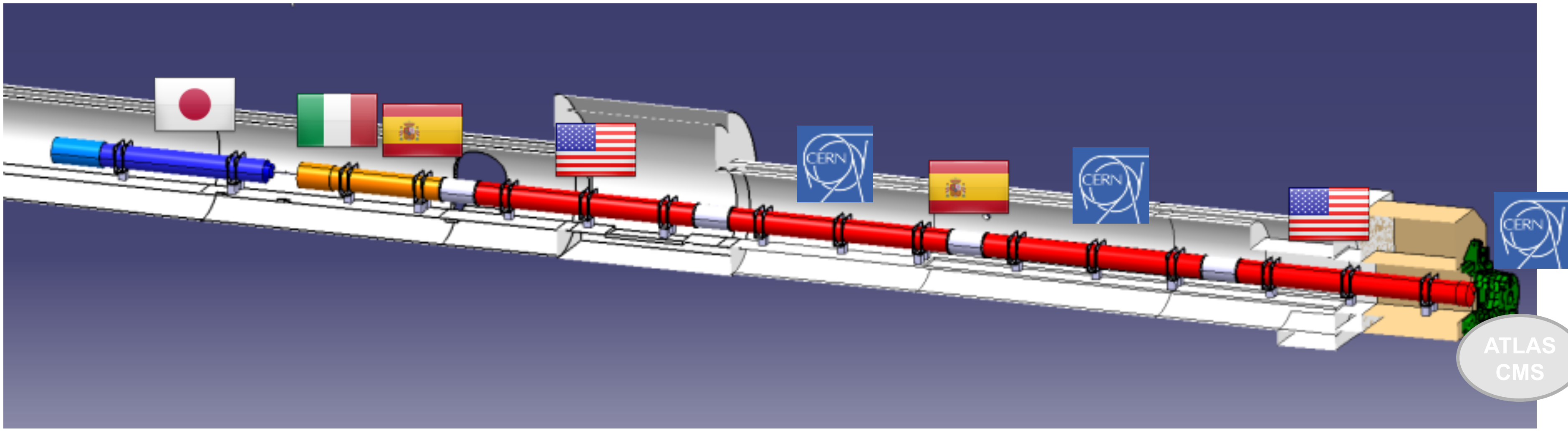
The HL-LHC Project

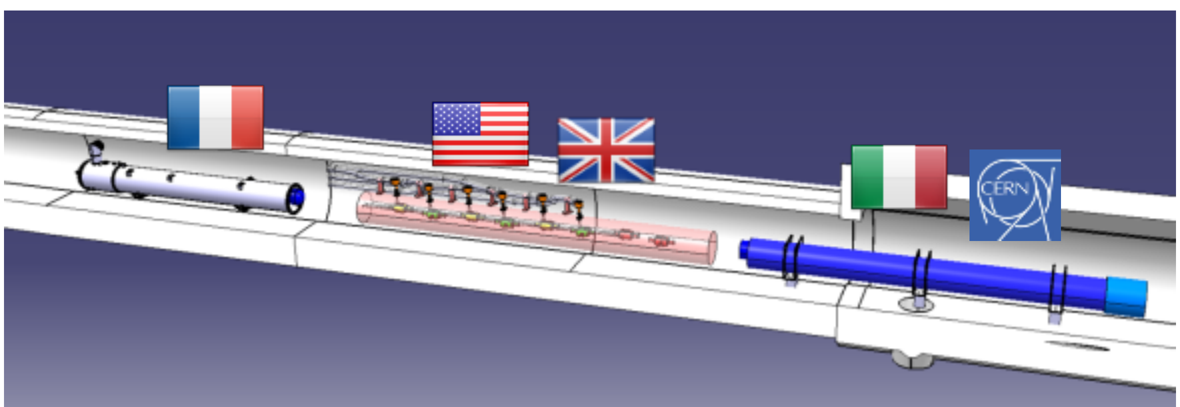


- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention on more than 1.2 km of the LHC

In-kind contribution and Collaboration for HW design and prototypes





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

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

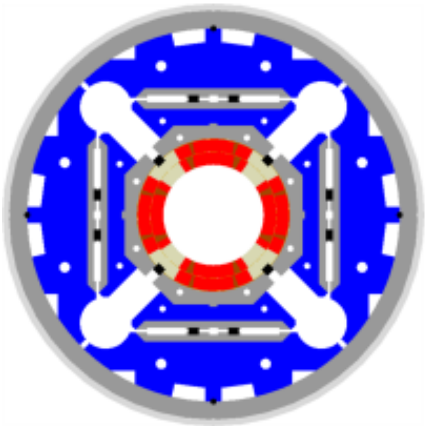
Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

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

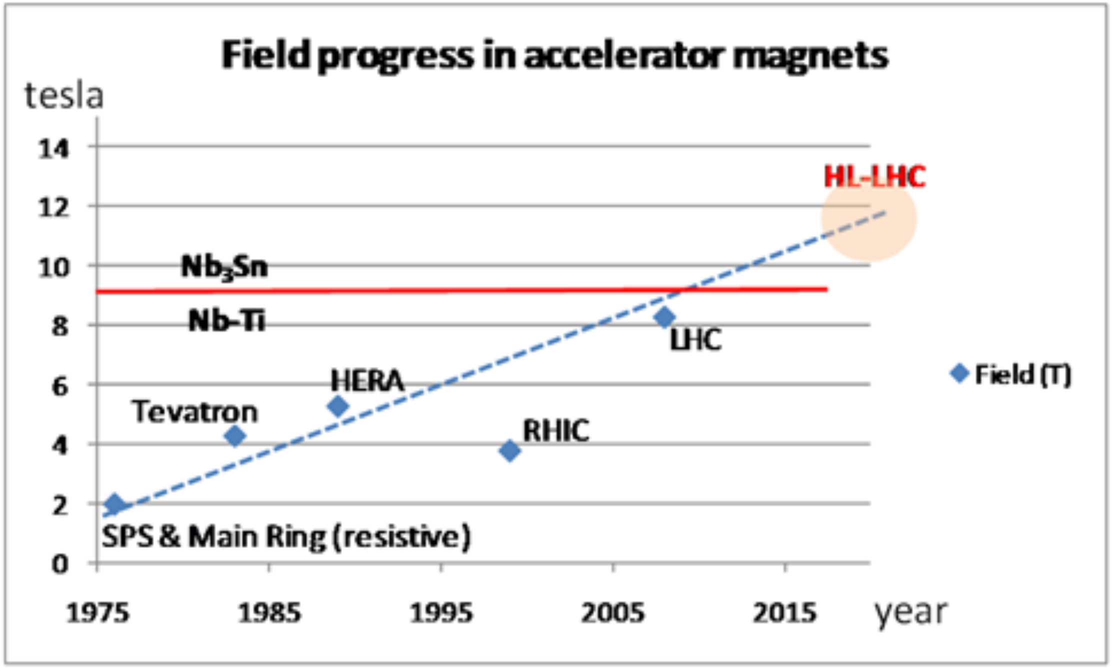
=> Nb_3Sn technology



(LHC: 8 T, 70 mm)

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

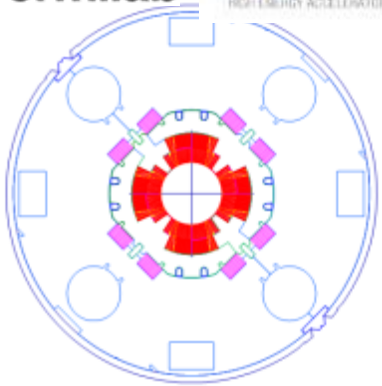
thanks to ATS** (Achromatic Telescopic Squeeze) **optics
In some scheme even β down to 7.5 cm are considered*

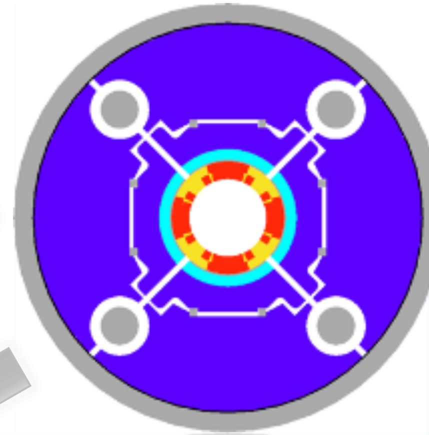


LHC low-β quads: steps in magnet technology from LHC toward HL-LHC (Nb_3Sn)

Fermilab KEK

LHC (USA & JP, 5-6 m)
∅70 mm, B_{peak}~ 8 T
1992-2005





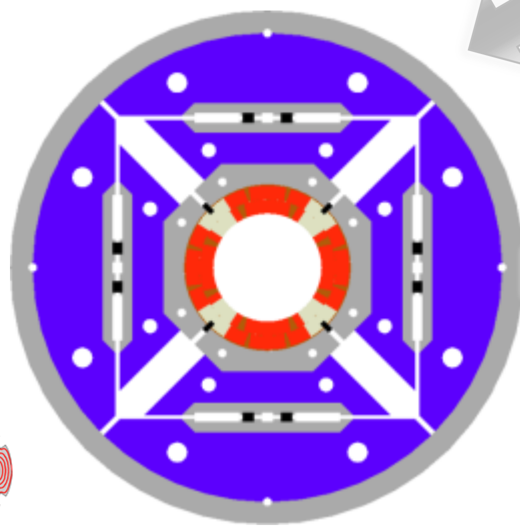
LARP

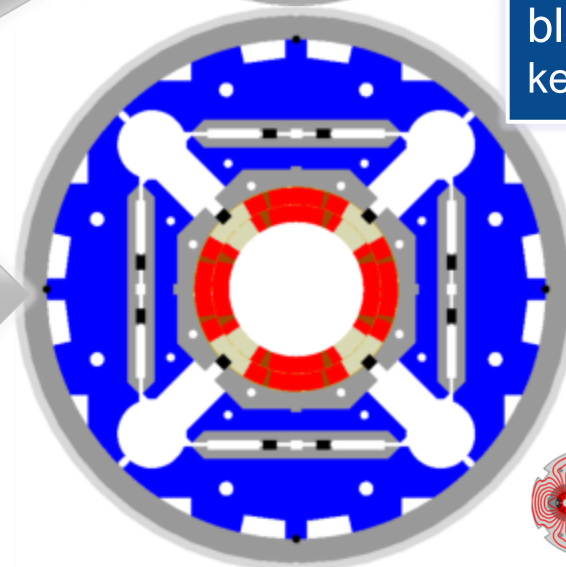
LARP TQS & LQ (4m)
∅90 mm, B_{peak}~ 11 T
2004-2010

New structure based on bladders and keys (LBNL, LARP)

LARP HQ
∅120 mm,
B_{peak}~ 12 T
2008-2014

LARP





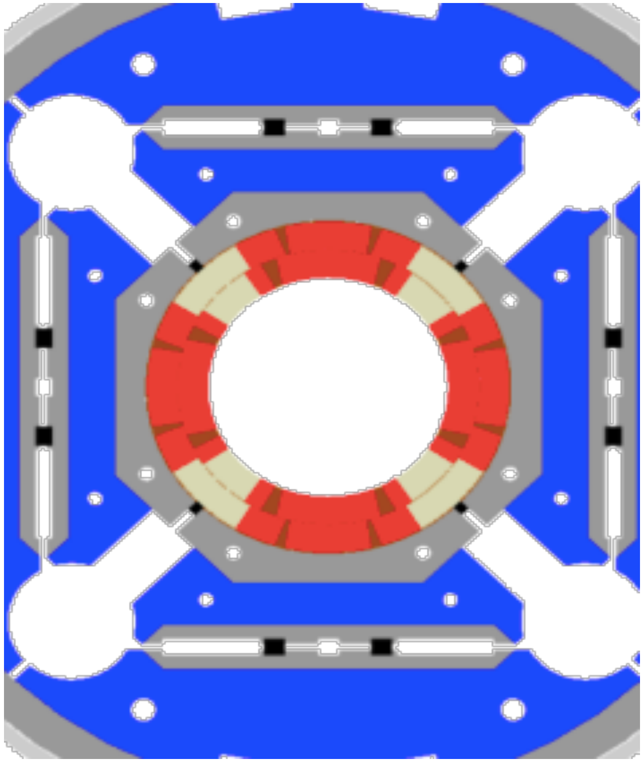
LARP & CERN MQXF
∅150 mm,
B_{peak}~ 12.1 T
2013-2020

LARP CERN

IR-quads program (Nb_3Sn)

Aperture	(mm)	150
Gradient	(T/m)	140
Current	(A)	17500
Temperature	(K)	1.9
Peak field	(T)	12.3

- Q1/Q3 (by US-LARP) 4.0 m long
- Q2 (by CERN), 6.8 m long
  - **2014-2016**: Short models
  - **2015-2017**: Long models
  - **2017-2021**: Production

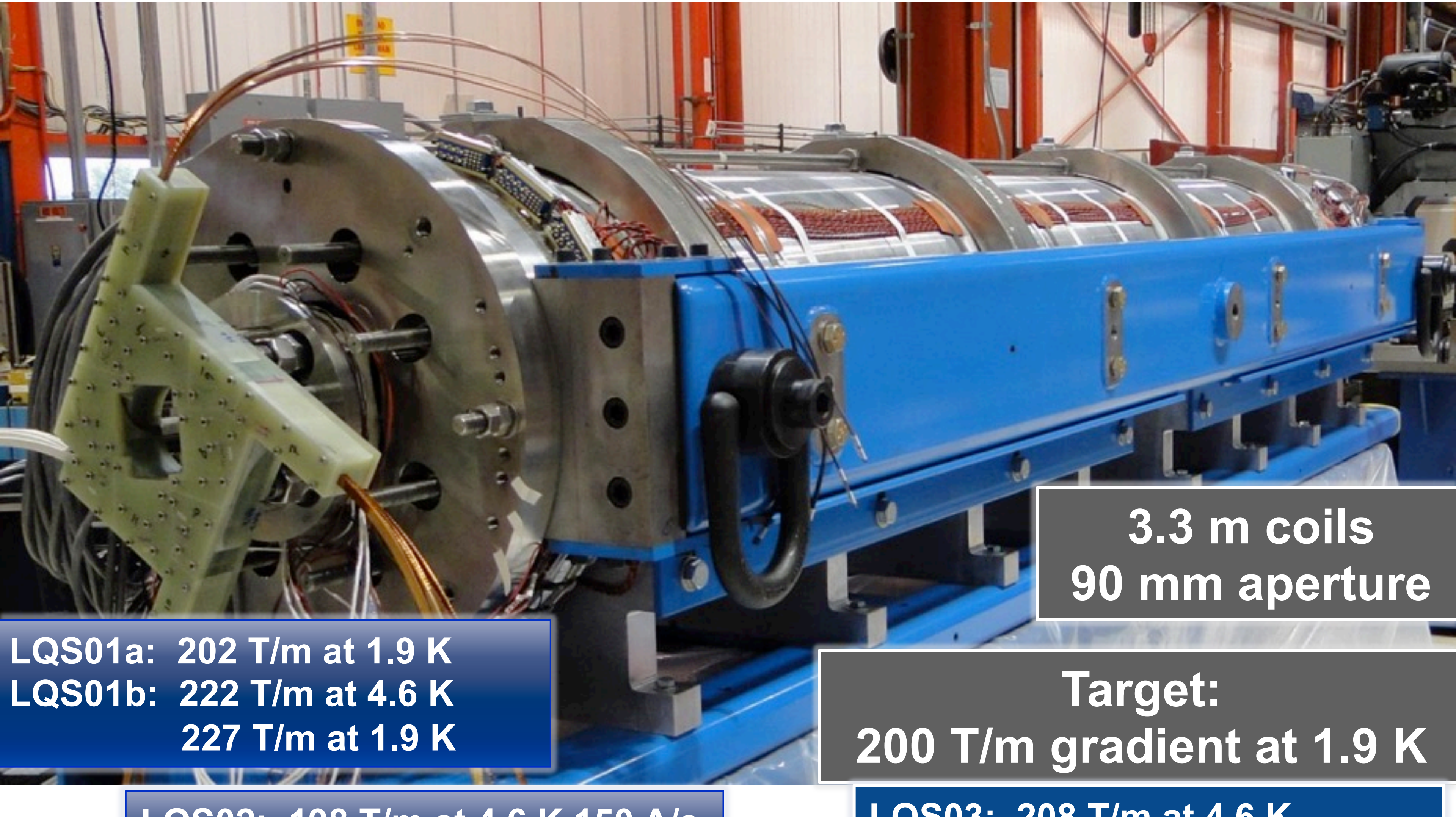


Shell-based support structure (aka *bladder-and-keys*) developed at LBNL for strain sensitive material

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

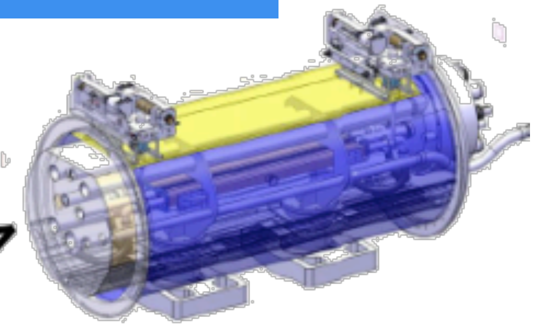
LQS02: 198 T/m at 4.6 K 150 A/s
208 T/m at 1.9 K 150 A/s
limited by one coil

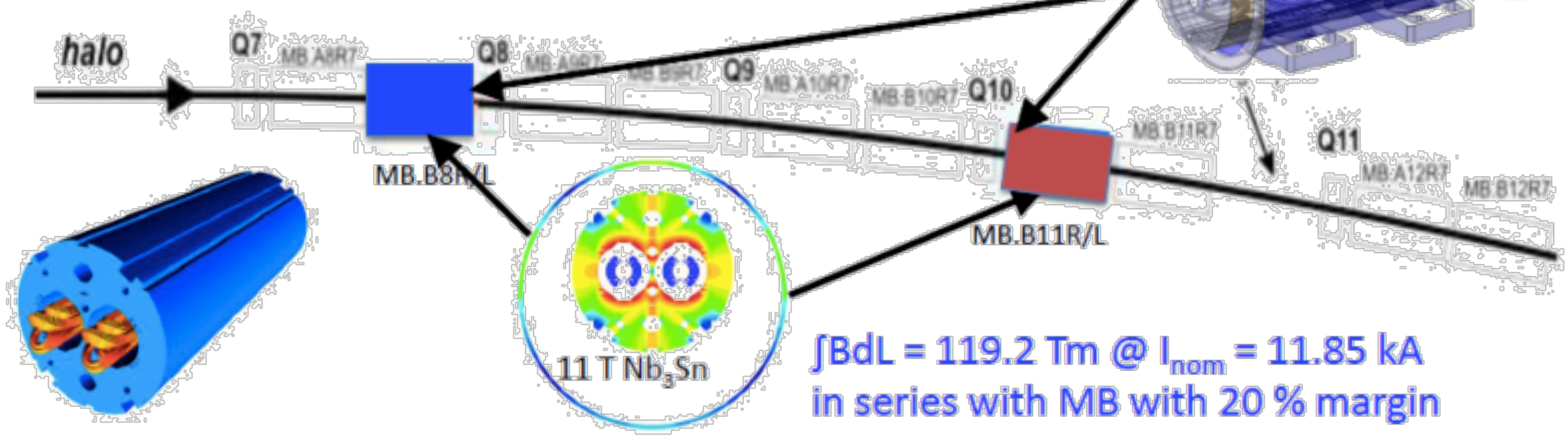
LQS03: 208 T/m at 4.6 K
210 T/m at 1.9 K
1st quench: 86% s.s. limit

CERN

LS2 : collimators and 11T Dipole

- LS2 2017-18: Point-~~3~~,7 & IR-2
- LS3 2020+: IR1,5 as part of HL-LHC





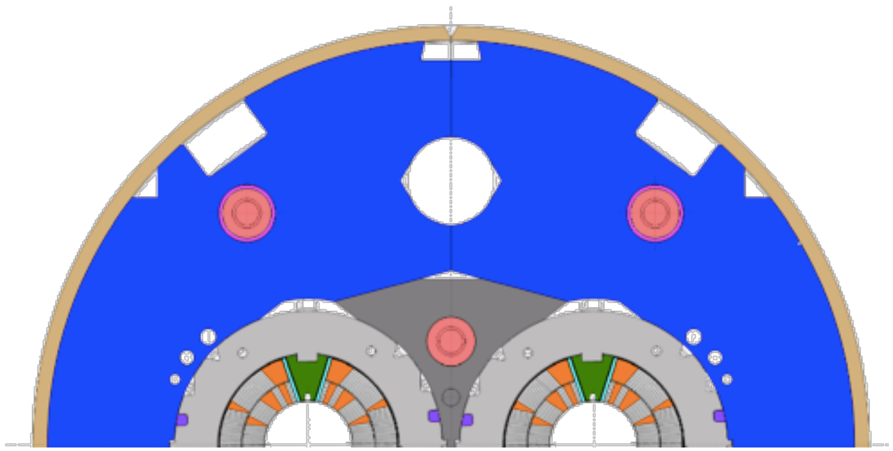
$\int BdL$ = 119.2 Tm @ I_{nom} = 11.85 kA
in series with MB with 20 % margin

11 m Nb_3Sn	3 m Collim	
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

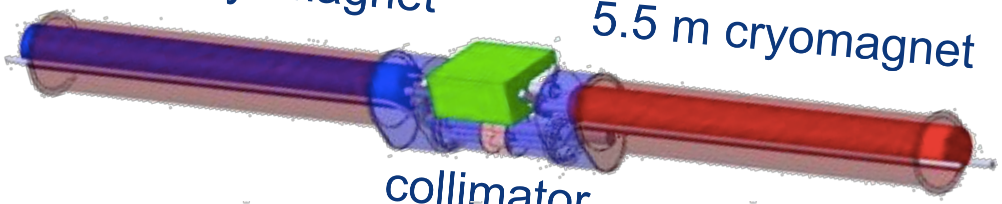
LS2: 12 coldmass + 2 spares = 14 CM
LS3: 8 coldmass + 2 spares = 10 CM
Total 24 CM

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

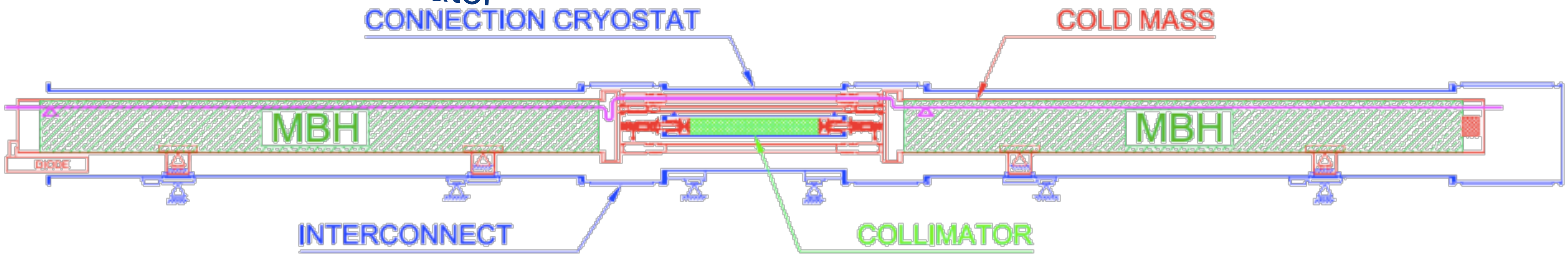
11 T dipole program (Nb_3Sn)



Aperture	(mm)	60
Field	(T)	10.8
Current	(A)	11850
Temperature	(K)	1.9
Peak field	(T)	11.35

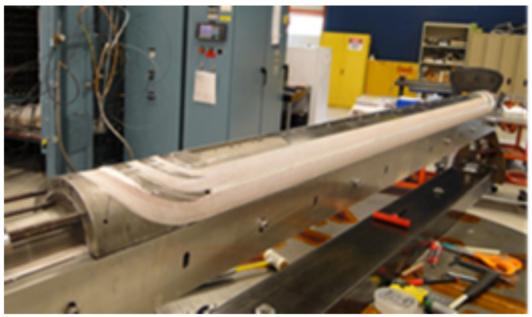


Cryo-unit design with integrated collimator



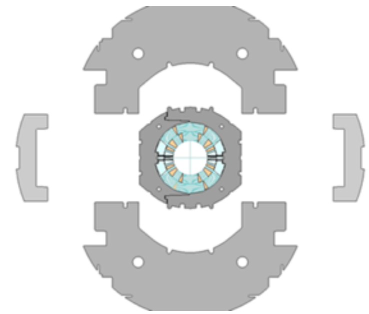
FNAL: MBHSP01 – 1-in-1 Demonstrator (2 m)

40-strand cable fabricated using FNAL cabling machine

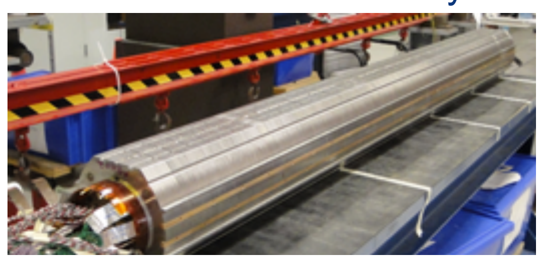


Coil fabrication

Collared coil assembly



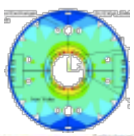
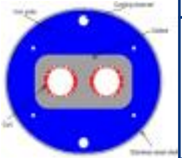
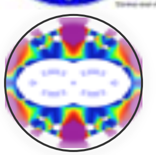
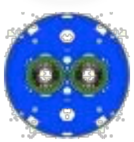
Cold mass assembly



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

Fermilab

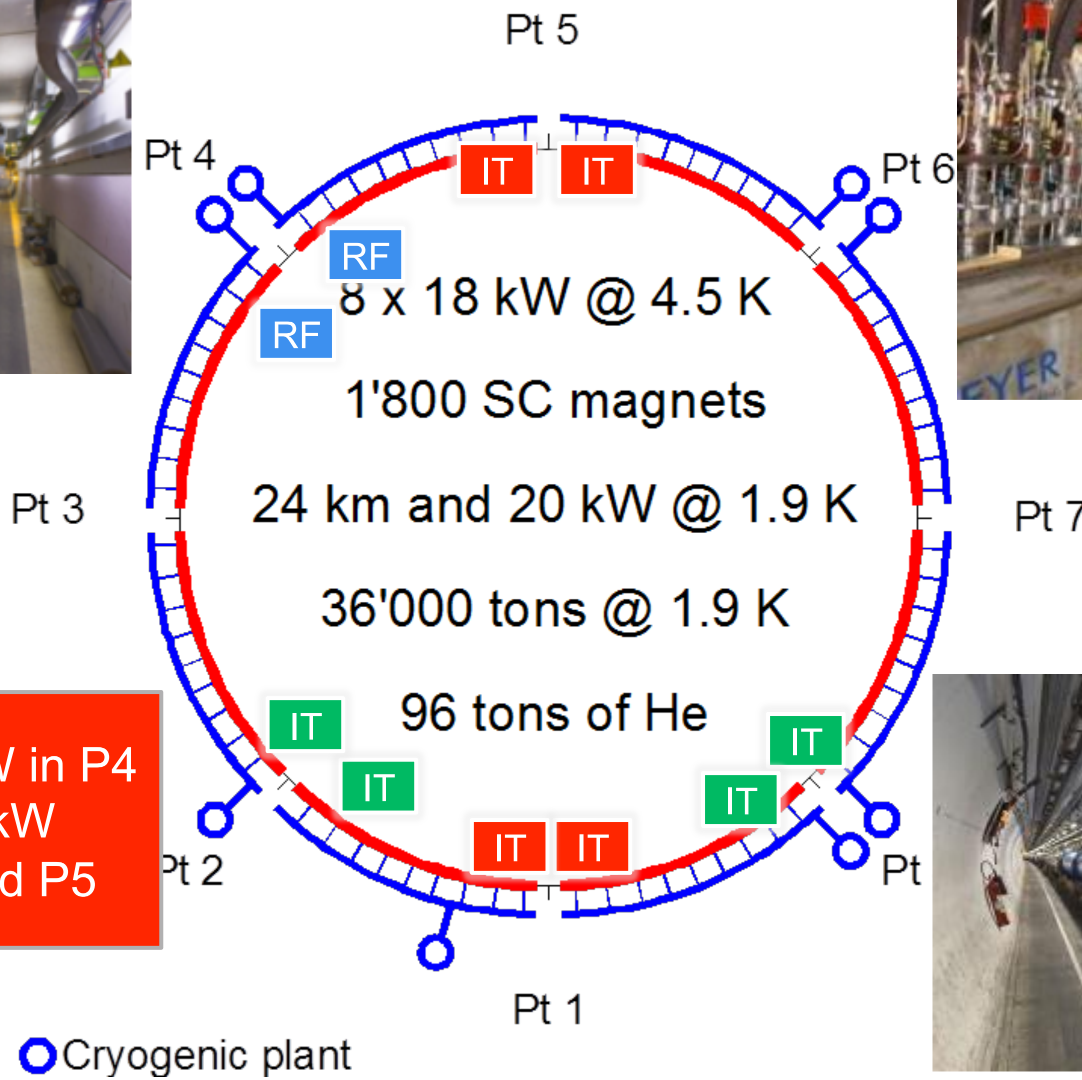
HL-LHC magnet specs

	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

Eliminating Technical Bottlenecks : Cryogenics P4 and P1-P5



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

HL-LHC Upgrade Ingredients: Crab Cavities

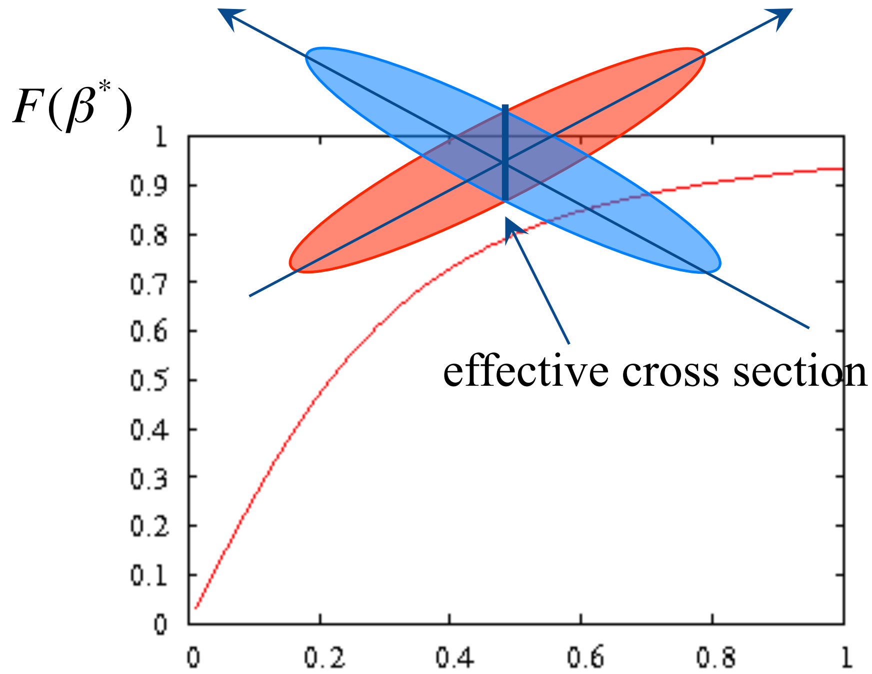
Crab Cavities:

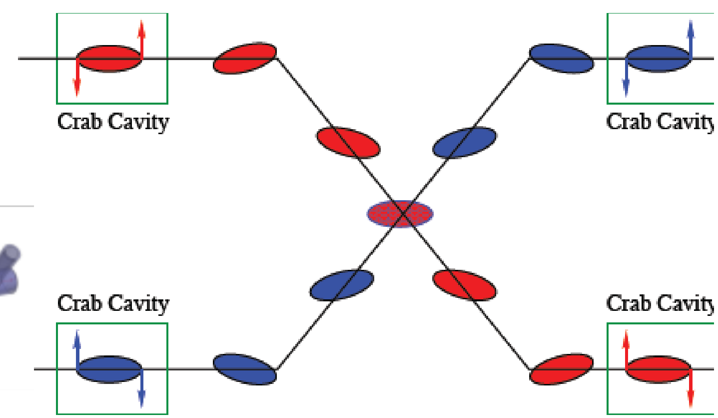
Geometric Luminosity Reduction Factor:

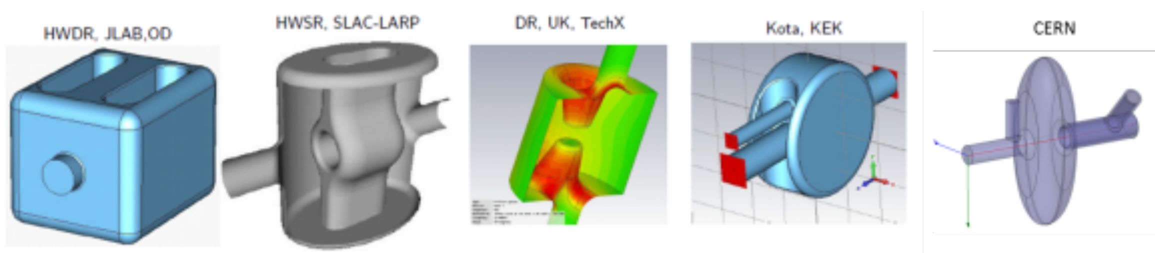
- Reduces the effect of geometrical reduction factor
- Independent for each IP

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

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

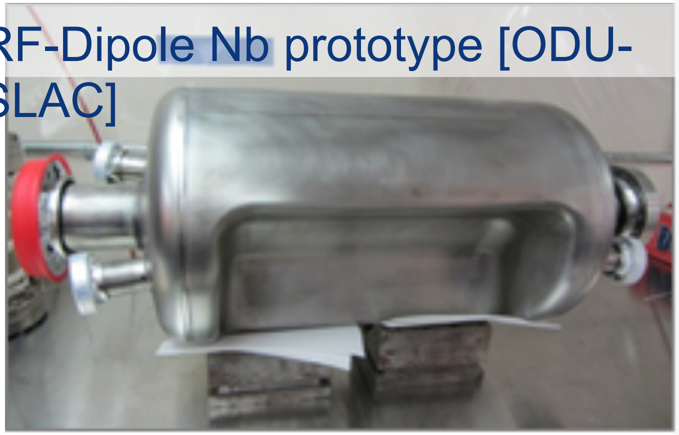






Compact cavities aiming at small footprint & 400 MHz, ~5 MV/cavity

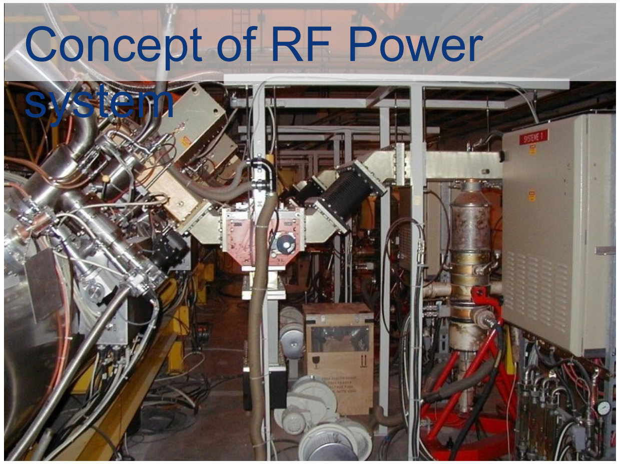
Development of 3 Crab Cavity prototypes


RF-Dipole Nb prototype [ODU-SLAC]

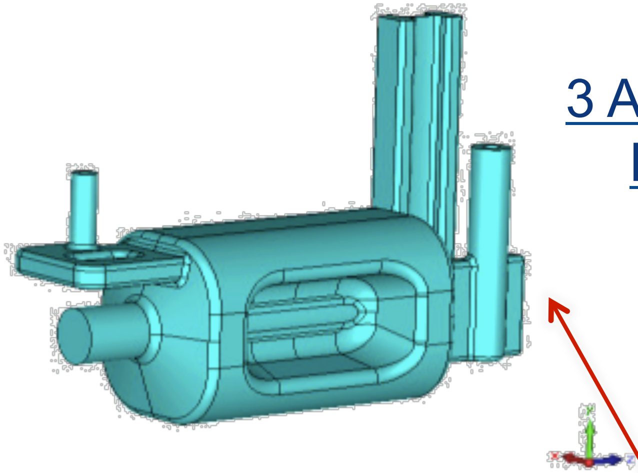

4-rod in SM18 for RF measurements [Lancaster UK]


4-rod prepared for rinsing @ CERN


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

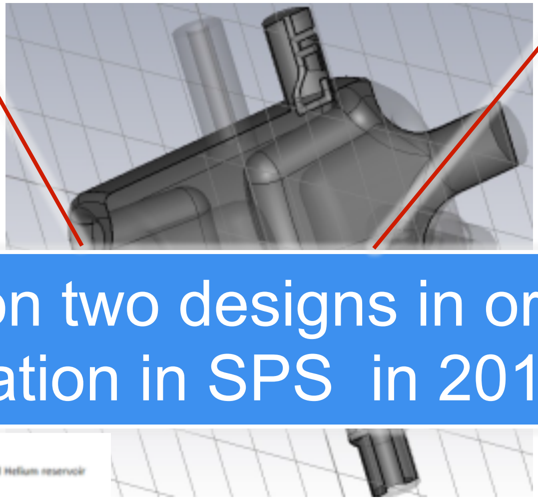

Concept of RF Power system

Latest cavity designs toward accelerator

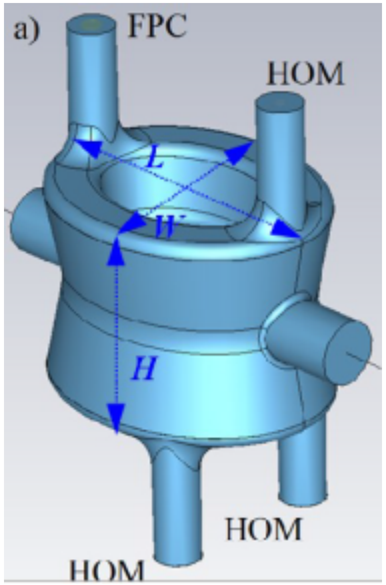


3 Advanced Design Studies with Different Coupler concepts

RF Dipole: Waveguide or waveguide-coax couplers

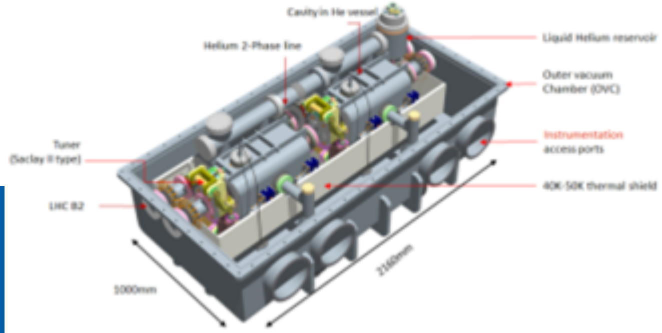


Coaxial couplers with
nt a



Double ¼-wave:
s
na

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



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

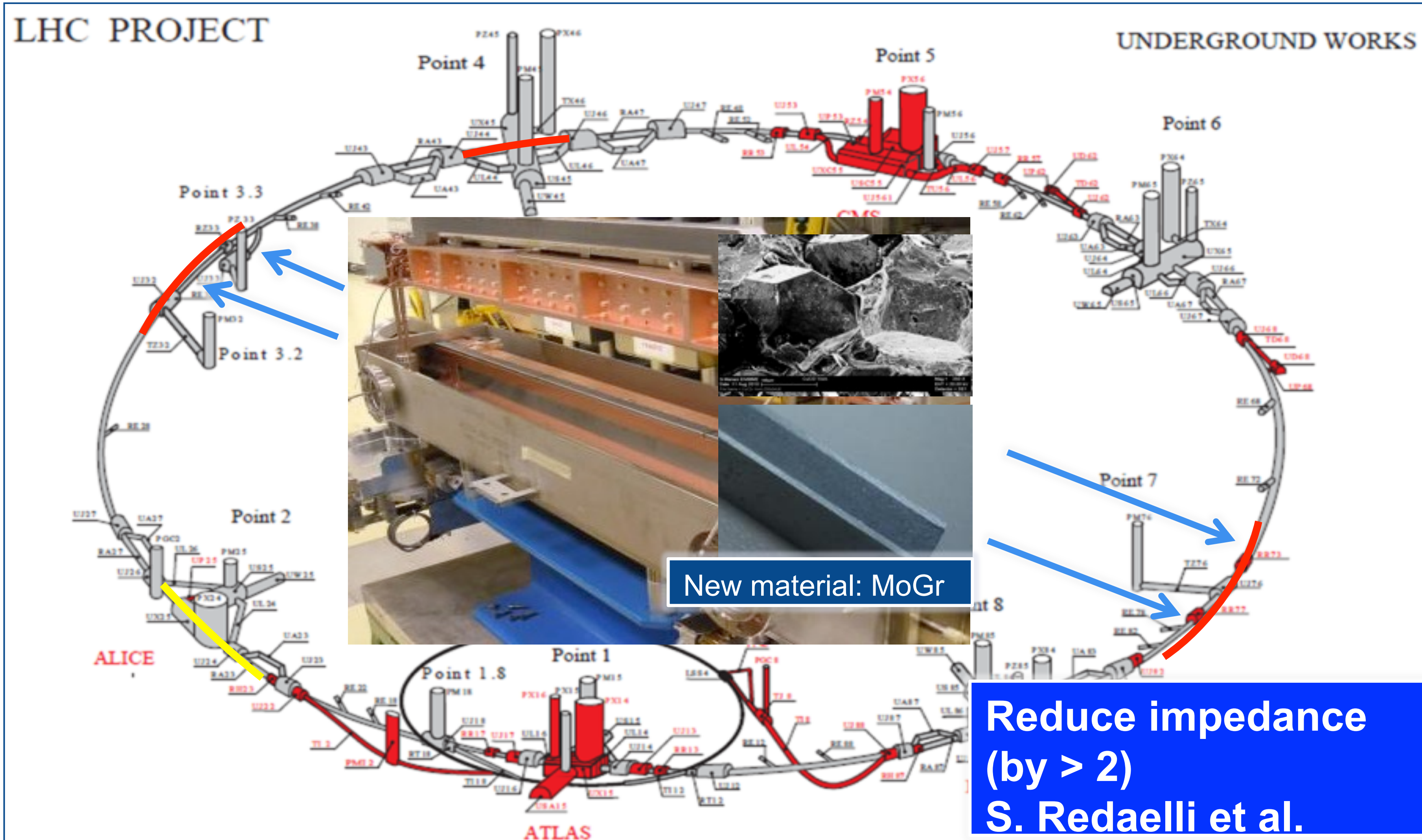
LHC Limitations

- Beam intensity and impedance (beam stability)
  ➔ low impedance collimator materials

- Beam power & losses
  ➔ additional DS (cold region) collimators

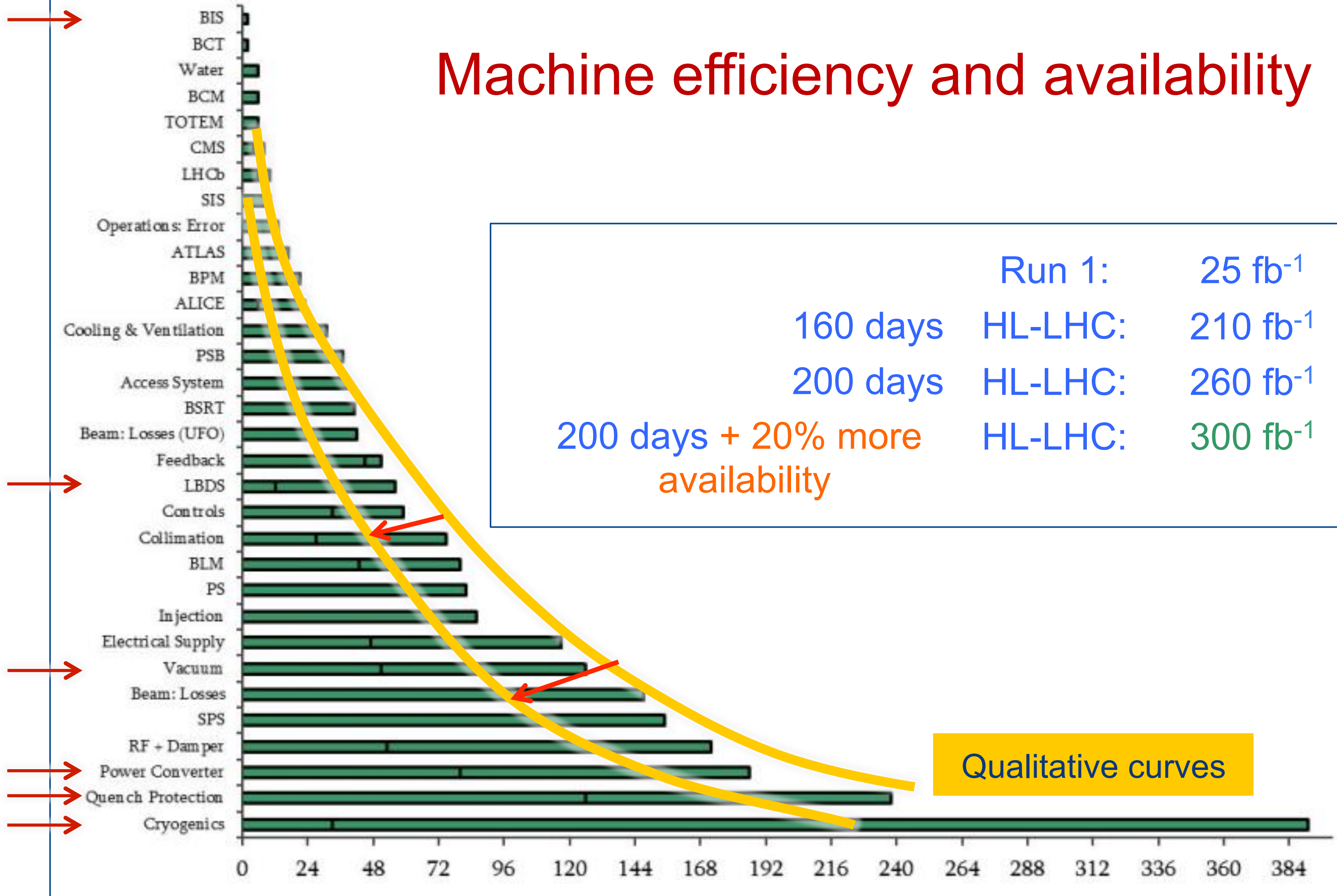
- Machine effciency and availability:
  # R2E ➔ removal of all electronics from tunnel region
  # e-cloud ➔ beam scrubbing (conditioning of surface)
  # UFOs ➔ beam scrubbing (conditioning of surface)

Low impedance collimators(LS2 & LS3)



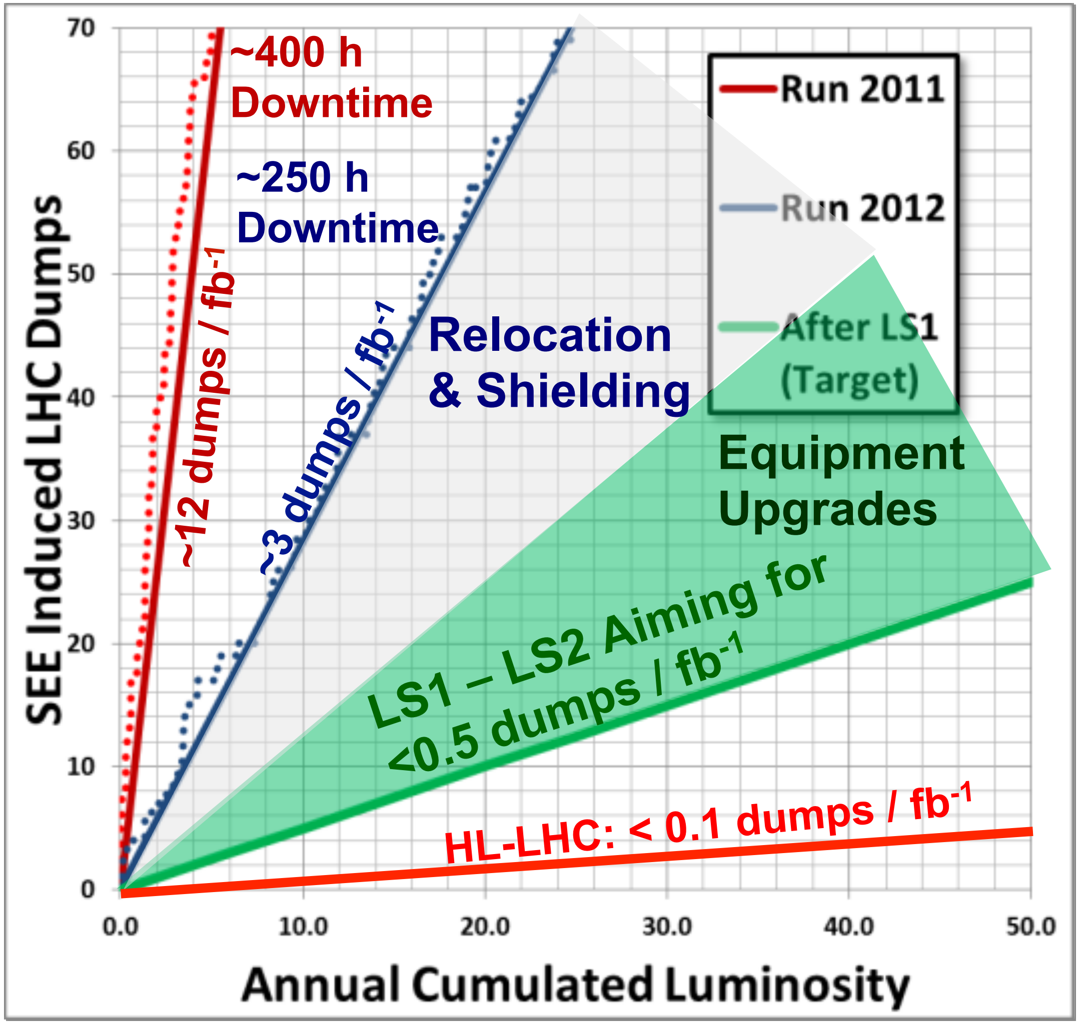
Reduce impedance (by > 2)
S. Redaelli et al.

Machine efficiency and availability



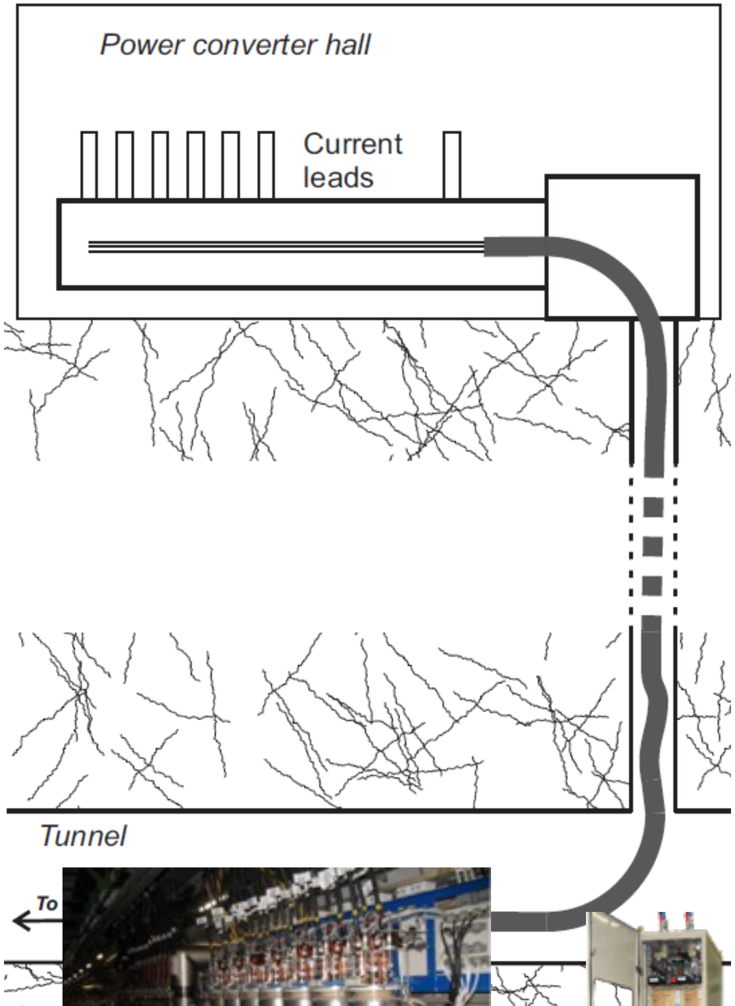
	Run 1:	25 fb^{-1}
160 days	HL-LHC:	210 fb^{-1}
200 days	HL-LHC:	260 fb^{-1}
200 days + 20% more availability	HL-LHC:	300 fb^{-1}

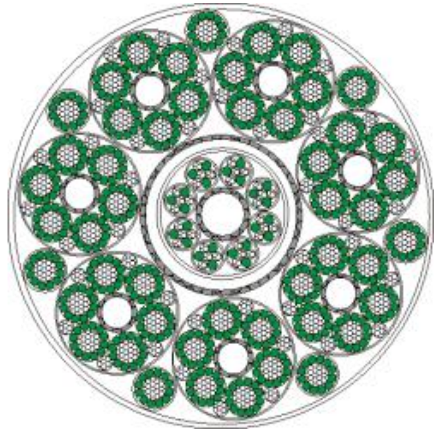
R2E SEE Failure Analysis - Actions



- **2008-2011**
  - Analyze and mitigate all safety relevant cases and limit global impact
- **2011-2012**
  - Focus on long downtimes and shielding
- **LS1 (2013/2014)**
  - Final relocation and shielding
- **LS1-LS2 (2015-2018)**
  - Tunnel equipment and power converters
- **-> LS3-HL-LHC**
  - **Tunnel Equipment (Injectors + LHC) + RRs**

R2E: Removal of Power Converter (200kA-5 kV SC cable, 100 m height)





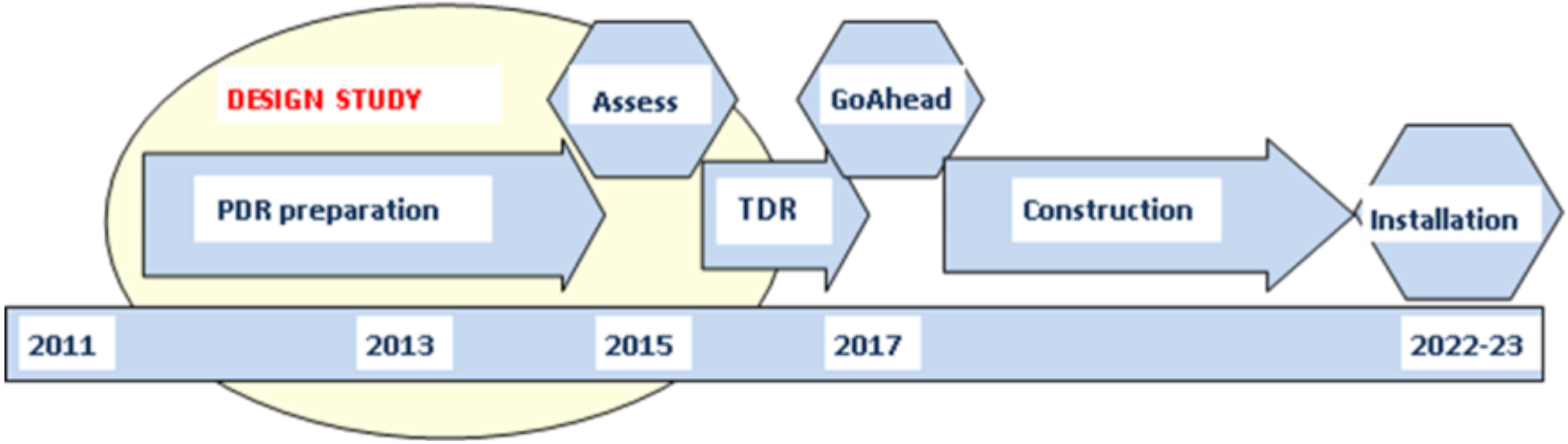
Φ = 62 mm

MgB_2
(or other HTS)

7 × 14 kA, 7 × 3 kA and 8 × 0.6 kA cables – Itot~120 kA @ 30 K

Also DFBs (current lead boxes) removed to surface
Final solution to R2E problem – in some points
Make room for shielding un-movable electronics
Make the maintenance and application of ALARA principle much easier and effective

Implementation plan



- PDR: Oct 2014 ; Ext. Cost & Schedule Review in March 2015;
- TDR: OCT 2015; TDR-v2 : 2017
- Cryo, SC links, Collimators, Diagnostics, etc. starts in LS2 (2018-2019)
- Proof of main hardware by 2016; Prototypes by 2017 (IT, CC)
- Start construction 2018 from: IT, CC, other main hardware
- IT String test (integration) in 2019-20; Main Installation 2023-24
- Tough but – based on LHC experience – feasible

High Luminosity LHC

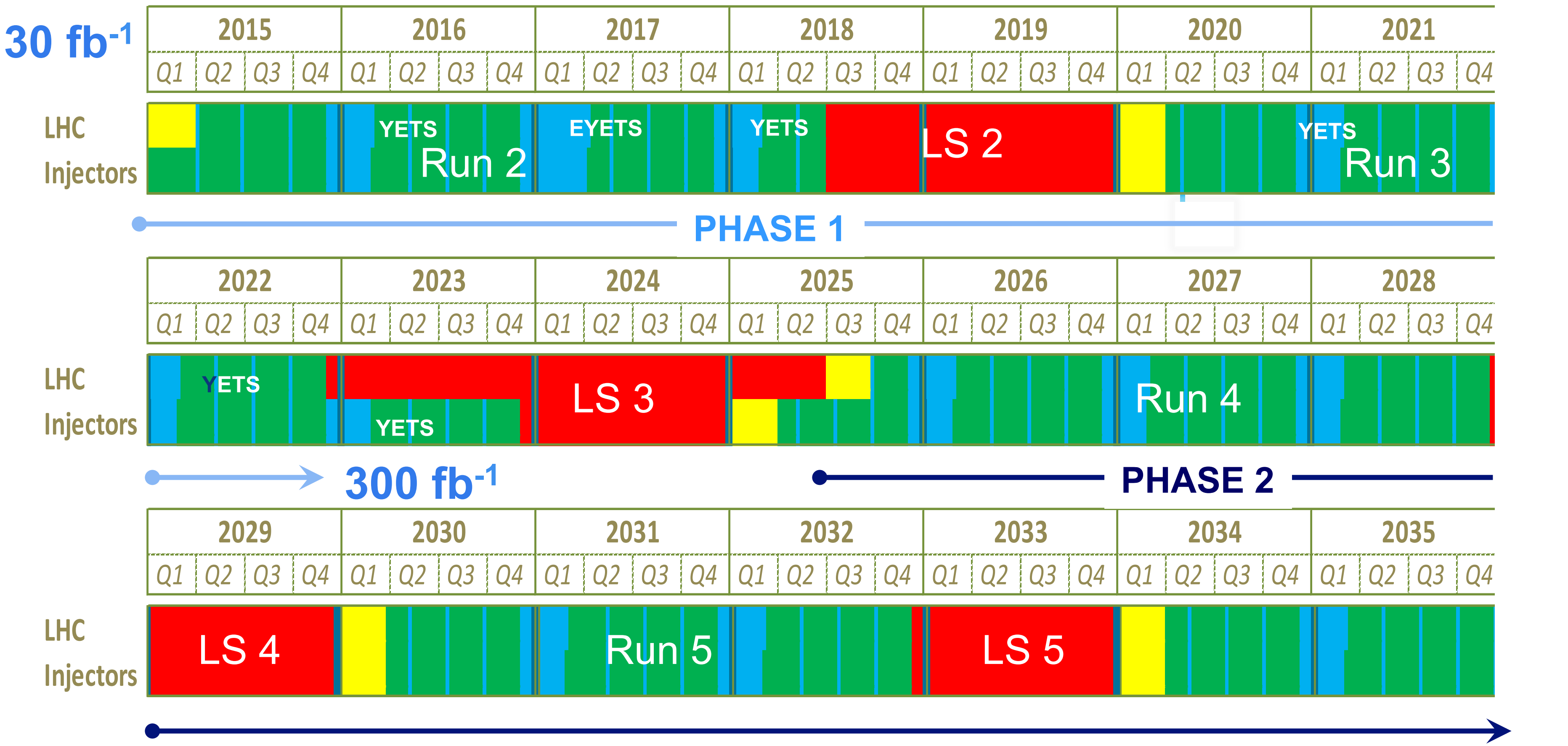
High Luminosity LHC Participants

LHC roadmap: schedule beyond LS1

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



Goal of 3’000 fb-1 by mid 2030ies

www.cern.ch

Thank you for your attention

Acknowledgements:

- **Thanks to all colleagues who made their slides available**
- **Special thanks to Frédérick Bordry (CERN Director for Accelerators), Malika Medahi (LIU Project Leader), Lucio Rossi (HL-LHC Project Leader) and Oliver Bruning (HL-LHC Deputy Project Leader)**

HL-LHC Baseline Summary

- New large aperture triplet magnets (Nb_3Sn)
- Tungsten shielding for triplet
- New Large aperture Insertion magnets (NbTi)
- Cryogenic system upgrade (IR4 and IR1&5)
- Crab Cavities for compensation of geom. Reduction
- Operation with Luminosity leveling
- Collimation upgrade (DS and impedance)
- R2E and superconducting link

HL-LHC Options

- Hollow electron lens (halo beam removal)
- Long Range Beam-Beam wire compensators (reduction of crossing angle)
- Flat beam operation (reduction of crossing angle)
- Crab Kissing Scheme
- Higher or lower harmonic RF system (bunch profile and beam stability)