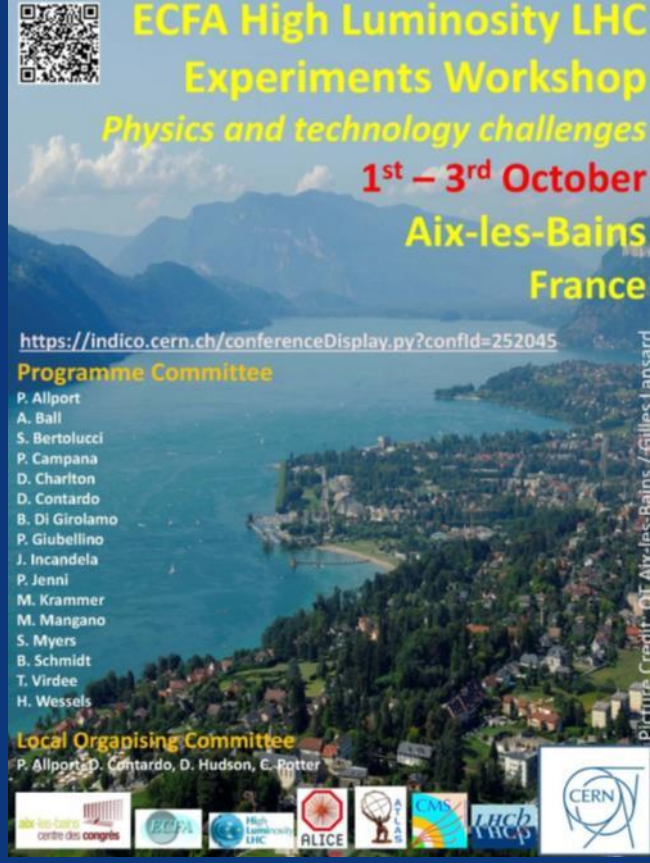

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The High Luminosity LHC

Frédérick Bordry

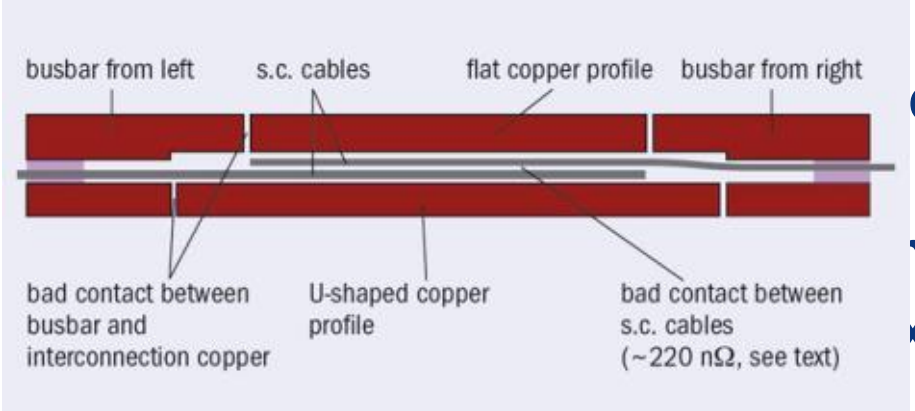
ECFA High Luminosity LHC Experiments Workshop – 1st October 2013

Outline

- **LS1 status (few slides) and 2012 last performance**
- **Run 2 (from LS1 to LS2), LS2 and Run 3**
- **HL-LHC project**
- **Conclusion**

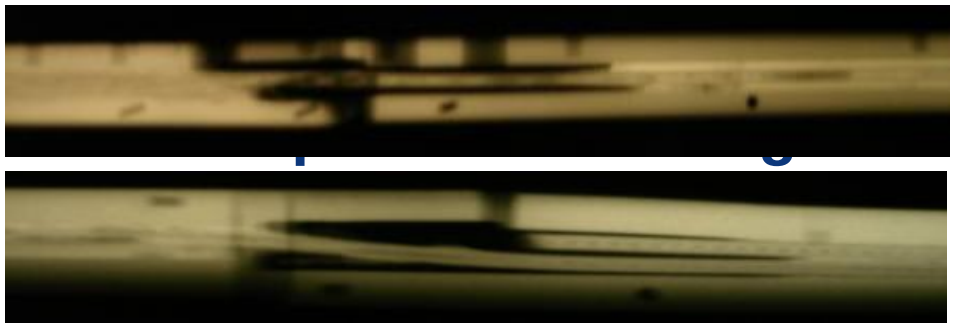
Long Shutdown 1

LS1 starts as the shutdown to repair the magnet interconnects to allow nominal current in the dipole and lattice quadrupole circuits of the LHC.

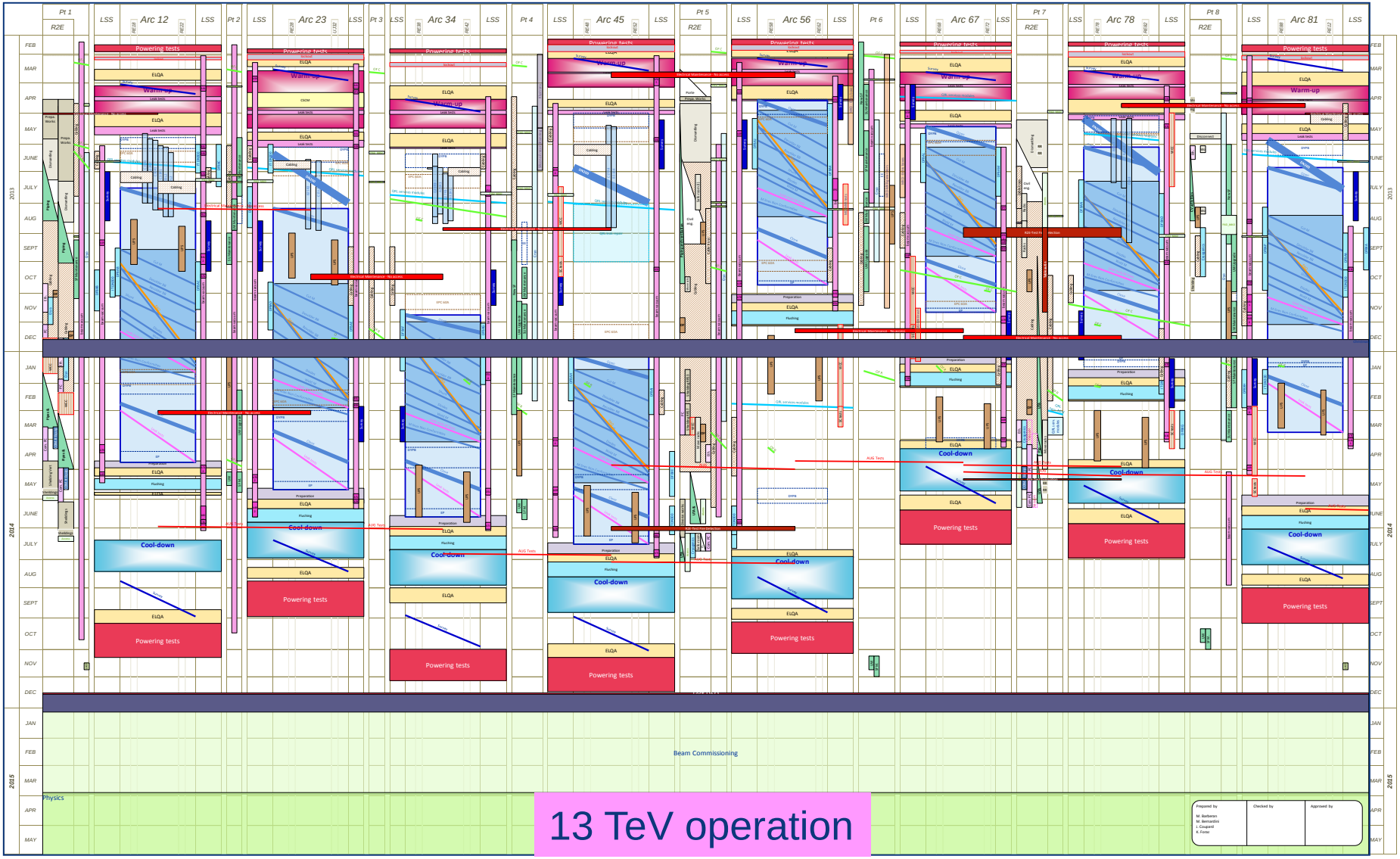


or shutdown which, in repairs, maintenance, nd cabling across the x and the associated experimental facilities.

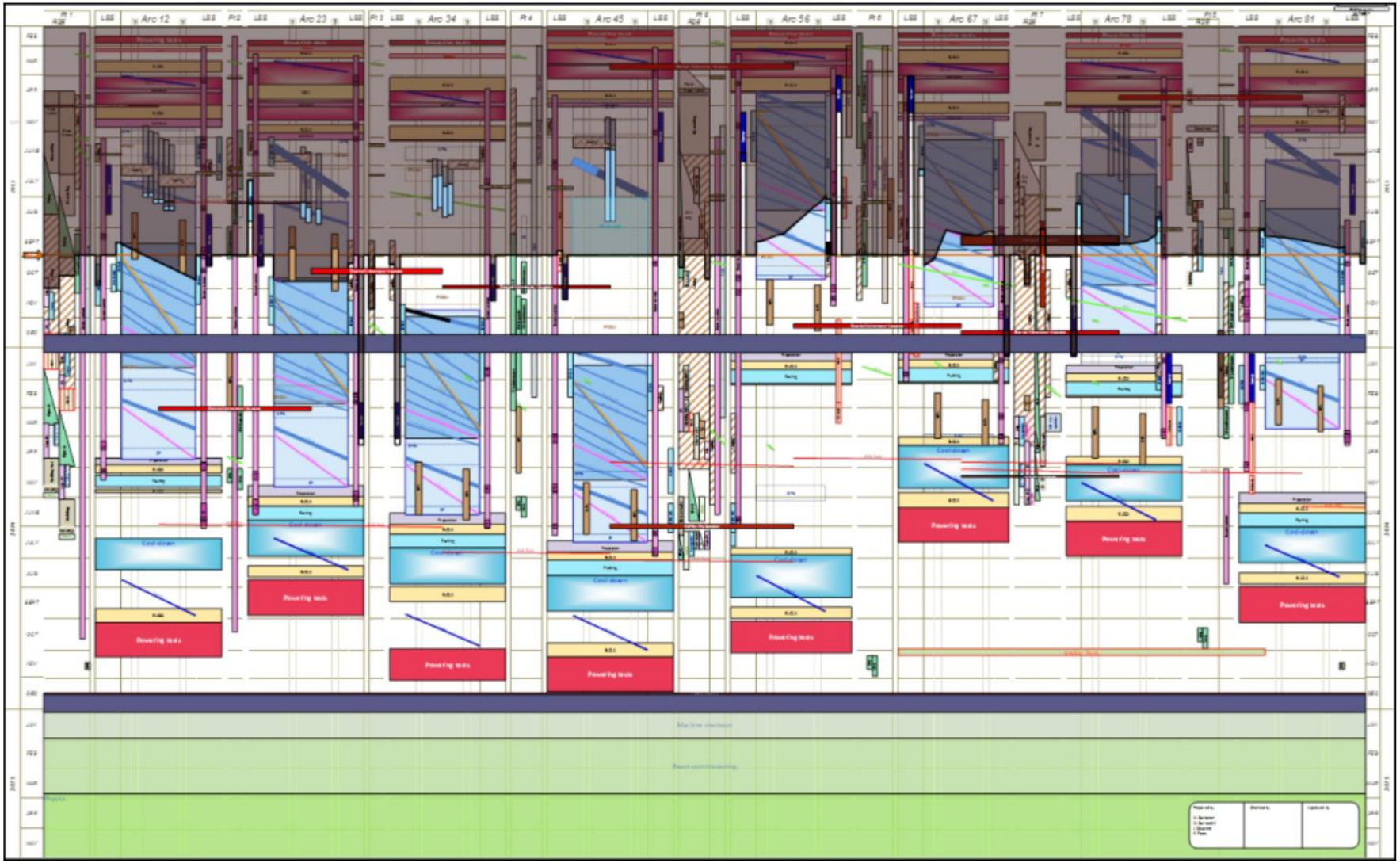
All this in the shadow interconnects.



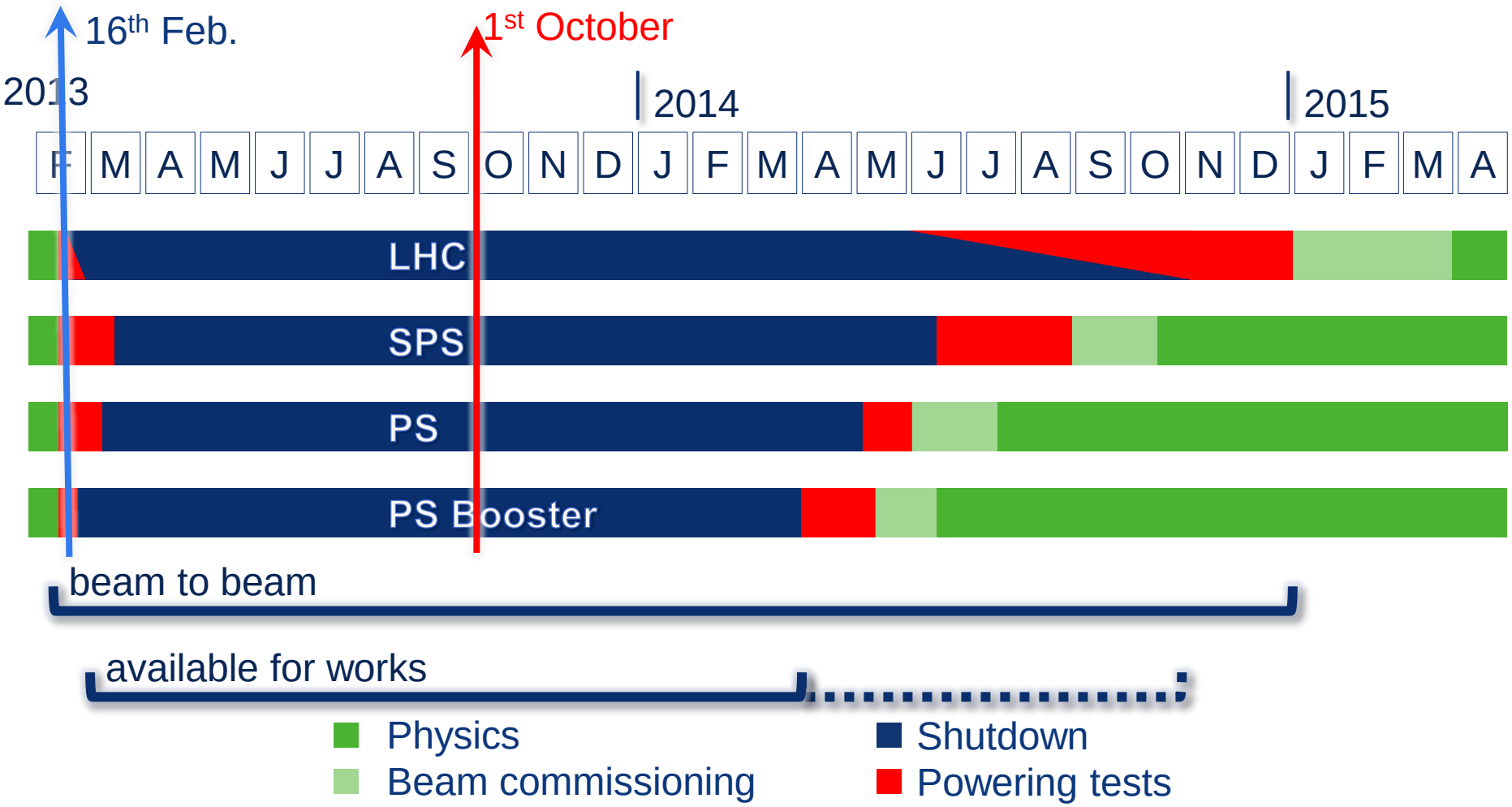
LS1: LHC schedule



So far, LS1 is on schedule for beams in January 2015 for LHC



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



2012: Some Main Beam Parameters

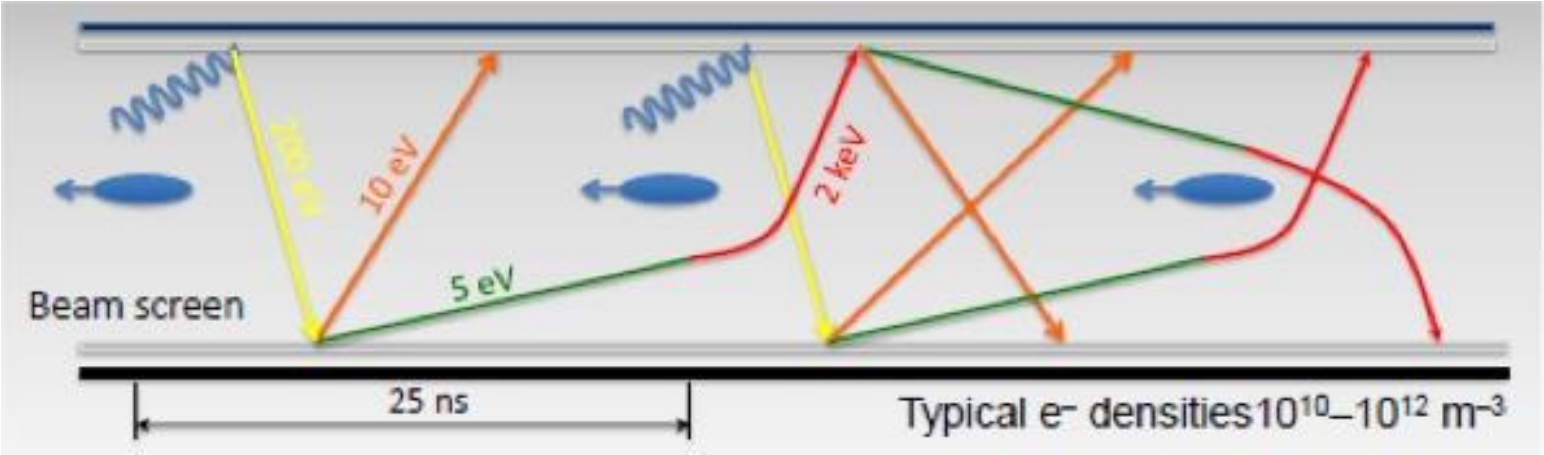
	25 ns (design)	50 ns (2012)	25 ns (2012)#
Energy per beam [TeV]	7	**4**	4
Intensity per bunch [x10^{11}]	1.15	**1.7**	1.2
Norm. Emittance H&V [µm]	3.75	**1.8**	2.7
Number of bunches	2808	**1380**	N.A. #
β* [m]	0.55	**0.6**	N.A. #
Peak luminosity [$cm^{-2}s^{-1}$]	1×10^{34}	**7.7×10^{33}**	N.A. #

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

Some Limitations:

Electron cloud

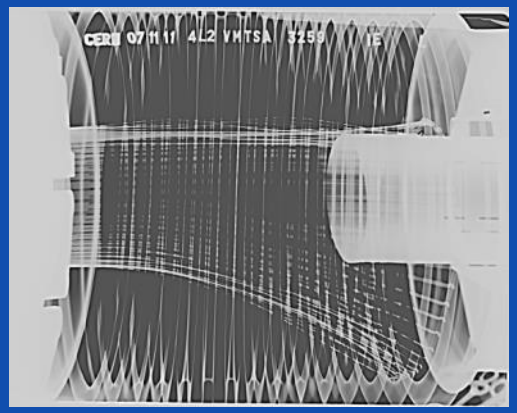
- Reason for running with 50 ns
- Scrubbing to suppress electron cloud build up by reducing the secondary electron yield (SEY)
- Remains still worrisome in the arcs for 25 ns bunch spacing



Some Limitations: cont'd

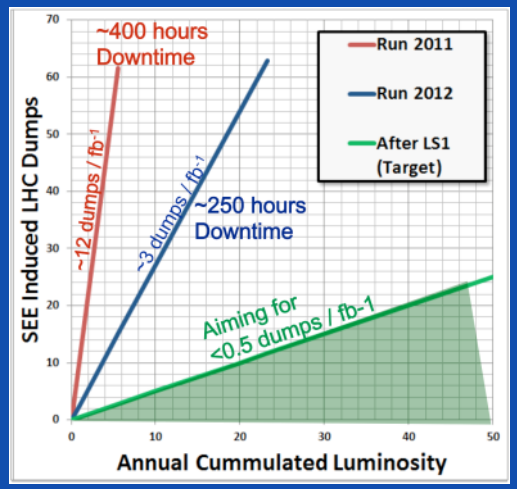
Beam induced heating

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



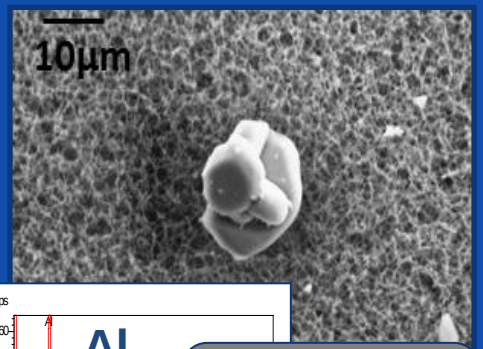
Radiation to electronics

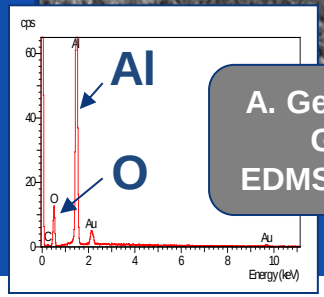
- Concerted program of mitigation measures (shielding, relocation…)
- Premature dump rate down from 12/fb^{-1} in 2011 to 3/fb^{-1} in 2012



UFOs

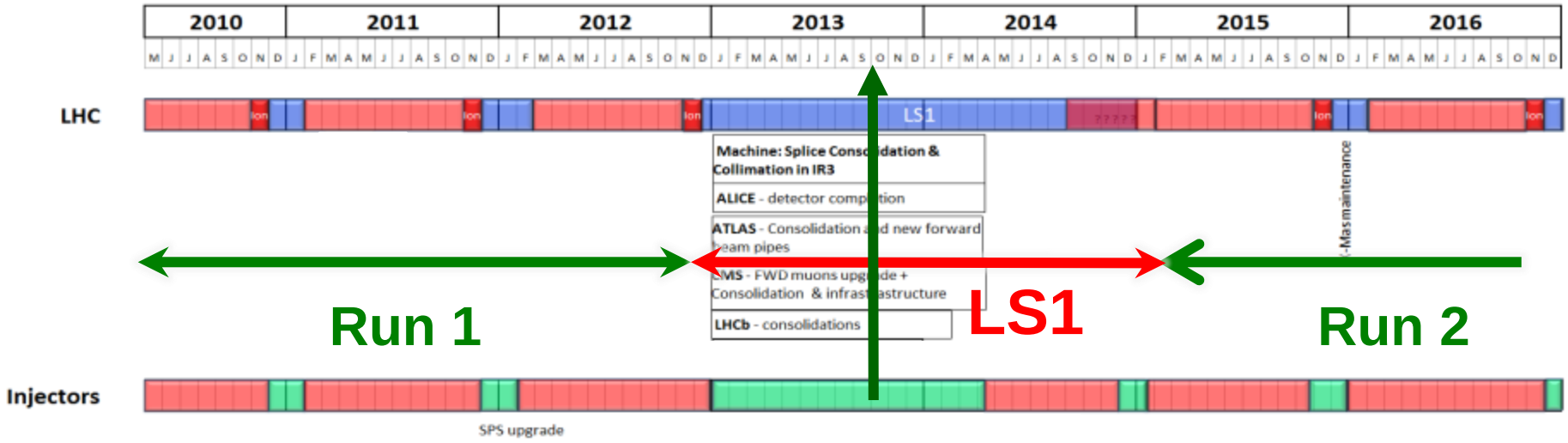
- 20 dumps in 2012
- Timescale 50-200 µs
- Conditioning observed
- Worry about 6.5 TeV

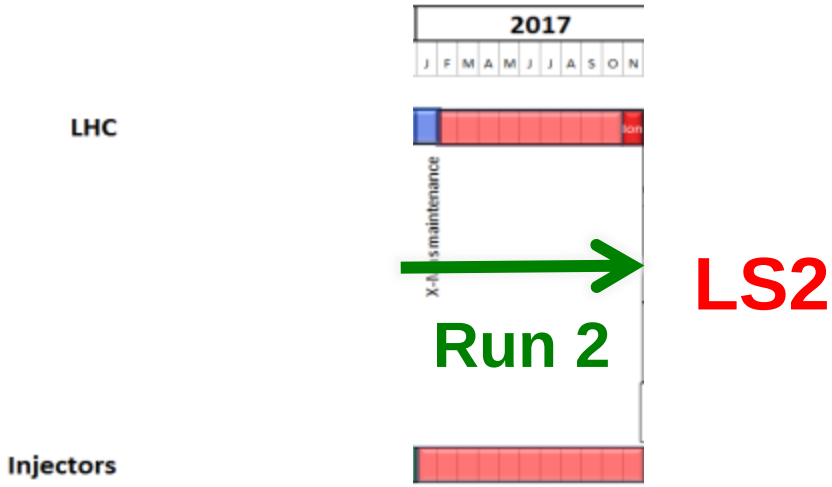




A. Gerardin, N. Garrel
EDMS: 1162034

Run2: 3 years Operation Run after LS1





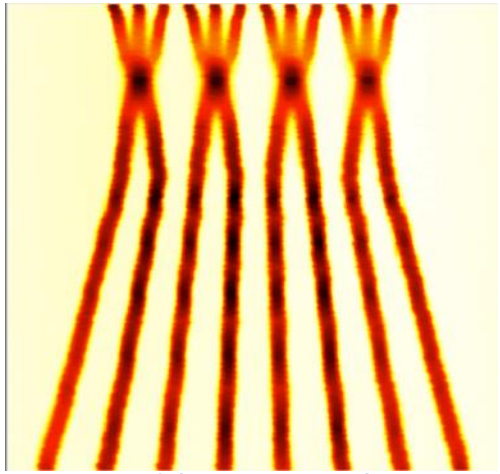
Run 2:
Start with 6.5 TeV and later decision towards 7 TeV according to magnet training

Expectations after Long Shutdown 1 (2015)

- Collisions at least at **13 TeV** c.m.
- **25 ns** bunch spacing

  Using new injector beam production scheme (BCMS), resulting in brighter beams.

Batch Compression and Merging and splitting (BCMS)



Courtesy of the LIU-PS project team

- **$\beta^* \leq 0.5$m** (was 0.6 m in 2012)
- Other conditions:
  - Similar turn around time
  - Similar machine availability
- Expected maximum luminosity: **1.6×10^{34} cm^{-2} s^{-1}** ± 20%
  - Limited by inner triplet heat load limit, due to collisions debris

	Number of bunches	Intensity per bunch	Transverse emittance	Peak luminosity	Pile up	Int. yearly luminosity
25 ns BCMS	**2508**	**1.15×10^{11}**	**1.9 µm**	**1.6×10^{34} cm^{-2}s^{-1}**	**~43**	**~42 fb^{-1}**

Potential performance

	Number of bunches	Ib LHC [1e11]	Collimator scenario	Emit LHC (SPS) [um]	Peak Lumi [cm^{-2}s^{-1}]	~Pile-up	Int. Lumi [fb^{-1}]
25 ns	2760	1.15	S1	3.5 (2.8)	9.2e33	21	24
25 ns low emit	***2508***	***1.15***	***S4***	***1.9 (1.4)***	***1.6e34***	***43***	***42***
50 ns	1380	1.6	S1	2.3 (1.7)	1.7e34 levelling 0.9e34	76 levelling 40	~45*
50 ns low emit	1260	1.6	S4	1.6 (1.2)	2.2e34	108	…

- **6.5 TeV**
- **1.1 ns bunch length**
- **150 days proton physics, HF = 0.2**

All numbers approximate

* different operational model – caveat - unproven

“Baseline”

	J	F	M	A	M	J	J	A	S	O	N	D
2011		1	2	3	4	5	6	7	8	9	IONS	
2012			1	2	3	4	5	6	7	8	9	
2013	IONS	IONS	LS1 - SPLICE CONSOLIDATION									
2014												
2015	CHECK-OUT	RECOM	RECOM	RAMP-UP	2	3	4	5	6	7	IONS	
2016		RAMP-UP	1	2	3	4	5	6	7	8	IONS	
2017		RAMP-UP	1	2	3	4	5	6	7	8	IONS	
2018	LS2 (LIU UPGRADE: LINAC4, BOOSTER, PS, SPS…)											
2019	RECOM	RECOM	RAMP-UP	1	2	3	4	5	6	7	IONS	
2020		RAMP-UP	1	2	3	4	5	6	7	8	IONS	
2021		RAMP-UP	1	2	3	4	5	6	7	8	IONS	
2022	HL-LHC UPGRADE											

Technical stop or shutdown
Proton physics
Ion Physics
Recommissioning
Intensity ramp-up

Courtesy Mike Lamont

“Baseline” luminosity

Review of LHC & Injector Upgrade Plans Workshop (RLIUP)

29-31 October 2013
Centre de Convention, Archamps
Europe/Zurich timezone

Search

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Support

Acc-Tec-Director.Offi…

*** **Invitation Only*****

The workshop will focus on:

Review of the parameters of the LIU and HL-LHC projects following the experience and changes in the beam parameters experienced in the past two years

Produce a staged plan(beam parameters, technical work, all machines) of how we proceed from the performance at the end of 2012 to the required performance for the HL-LHC. In order to do this we need to know at what level of integrated luminosity will necessitate replacement of the inner detectors and the insertions. Also to see the importance of 3000fb-1 and what level of minimum integrated luminosity would be tolerated.

- Chairman : Steve Myers
- Co-Chairman : Frédérick Bordry
- Deputy Chairman : Mike Lamont
- Scientific Secretary: Frank Zimmermann
- Deputy Scientific Secretary: Brennan Goddard
- Technical Support Pierre Charrue

Editor of proceedings: Frank Zimmermann and Brennan Goddard

DRAFT timetable and session information

Deadline for registration:** Friday 27 September 2013

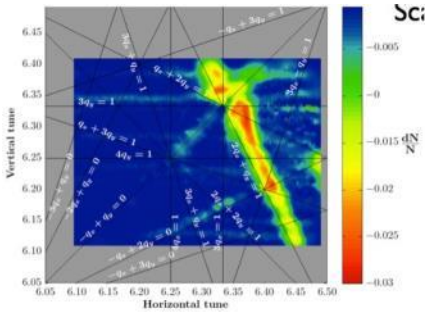
LS2 : (2018), LHC Injector Upgrades (LIU)

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



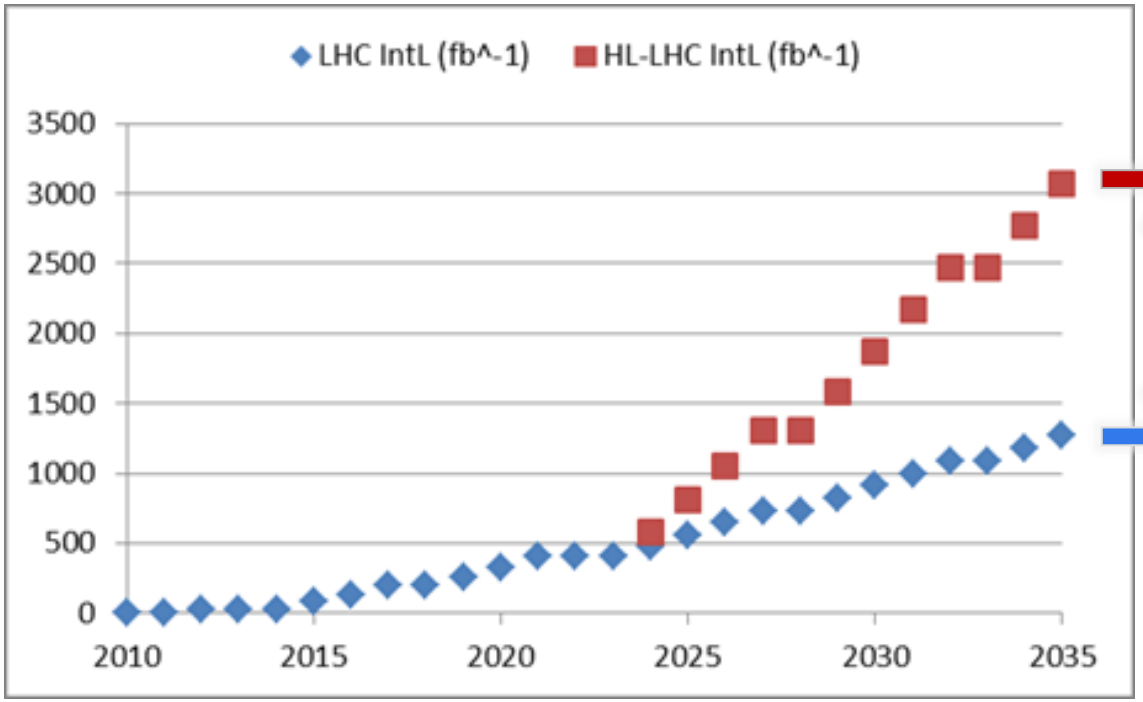
SPS

- 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

Project leadership: R. Garoby and M. Meddahi

Why High-Luminosity LHC ? (LS3)



By implementing HL-LHC

Almost a factor 3

By continuous performance improvement and consolidation

Goal of HL-LHC project:

- 250 – 300 fb^{-1} per year
- 3000 fb^{-1} in about 10 years

High Luminosity LHC

Initial Milestones of High Luminosity LHC

July 2010: Start of the Design and target R&D, preparation of FP7-HiLumi Design Study application

Nov 2010: application FP7-Hilumi LHC

Dec 2010: Official launch of the design study at CERN

Mar 2011: Approval FP7 HiLumi LHC by EC: 15/15 score, full request granted: 3.9 M€ (1.2 CERN)

Nov 2011: Start FP7 HiLumi LHC design study

July 2012: paper HiLumi for EU strategy
(CERN ATS-2012-236)

MTP High Luminosity LHC split into:

- **PIC (Performance Improving Consolidation)** **1000 fb^{-1}**
- **Full Upgrade** **3000 fb^{-1}**

The European Strategy for Particle Physics
Update 2013

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

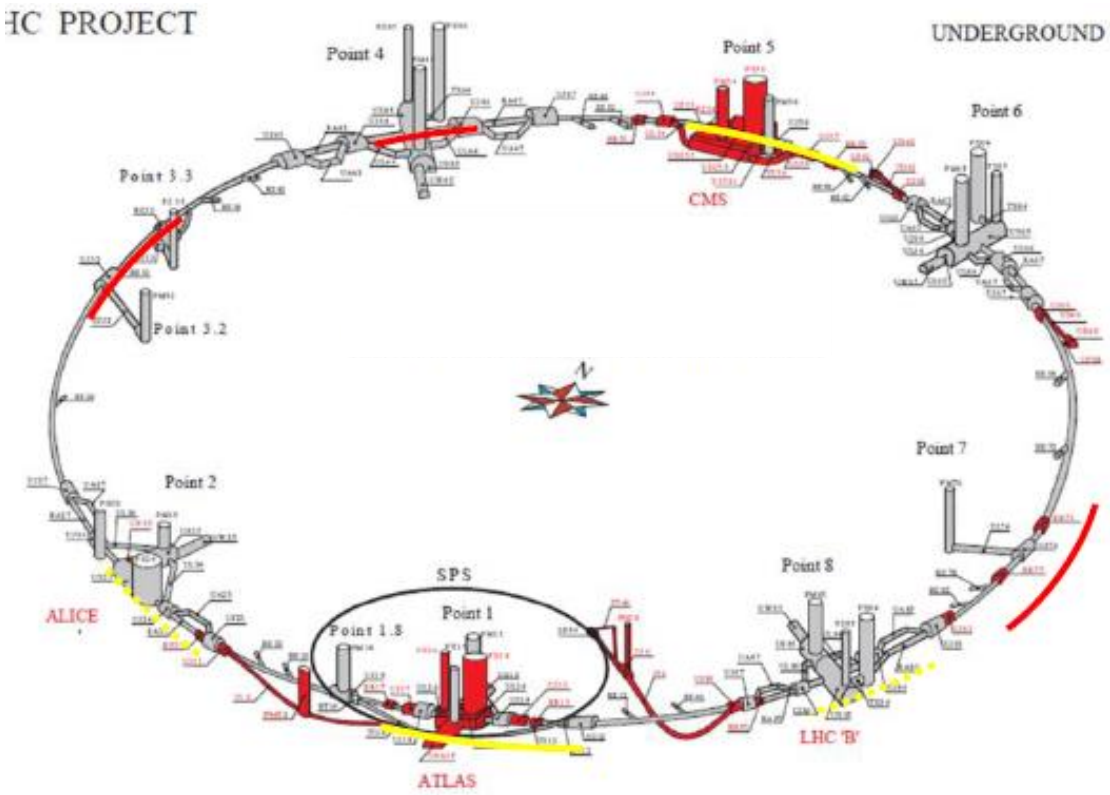
HL-LHC from a study to a PROJECT

300 fb^{-1} → 3000 fb^{-1}

including LHC injectors upgrade **LIU**

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

The HL-LHC Project



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

Major intervention on more than 1.2 km of the LHC

Project leadership: L. Rossi and O. Brüning

Squeezing the beams: High Field SC Magnets

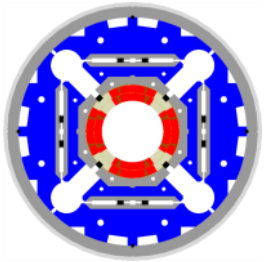
Quads for the inner triplet

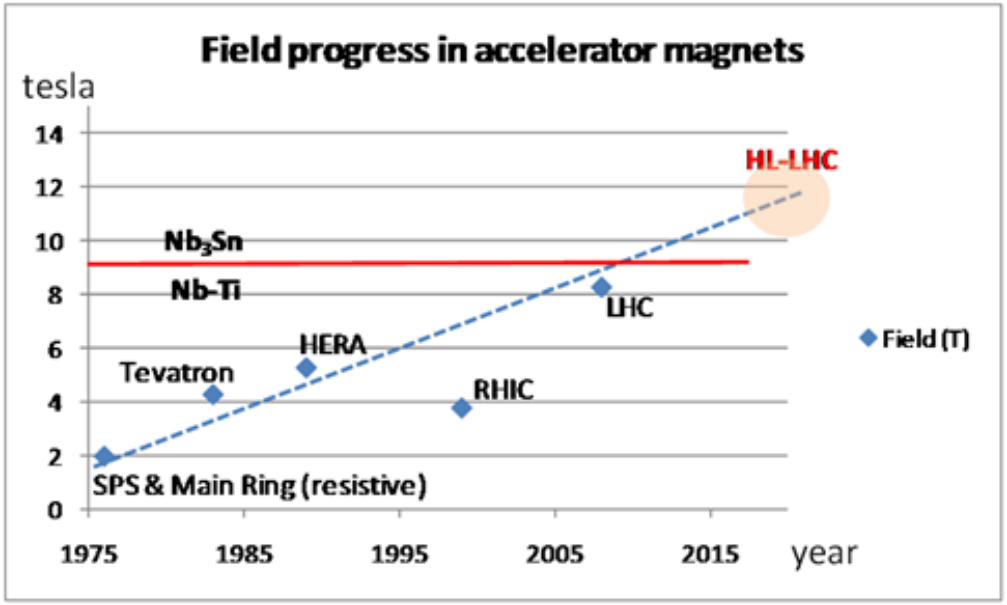
Decision 2012 for low-β quads

Aperture ∅ 150 mm – 140 T/m

(B_{peak} ≈12.3 T)

(LHC: 8 T, 70 mm)





More focus strength,

β* as low as 15 cm (55 cm in LHC)

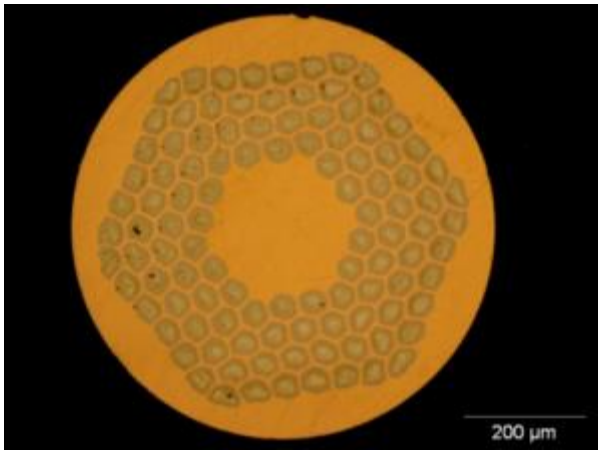
thanks to ATS** (Achromatic Telescopic Squeeze) **optics

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

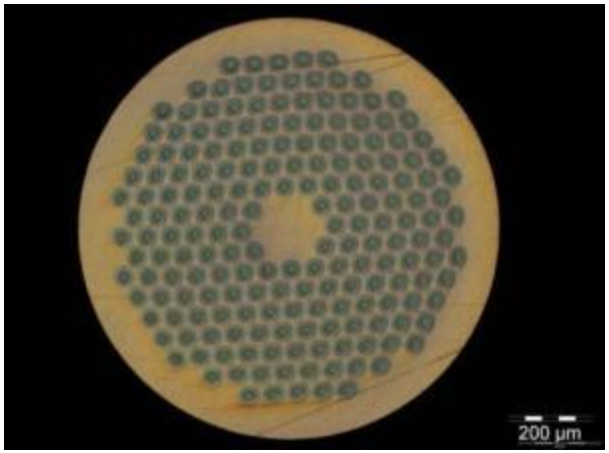
- Dipoles for beam recombination/separation capable of 6-8 T with 150-180 mm aperture (LHC: 1.8 T, 70 mm)
- Dipoles 11 T for LS2 (see later)

The « new » material : Nb_3Sn

- Recent 23.4 T (1 GHz) NMR Magnet for spectroscopy in Nb_3Sn (and Nb-Ti).
- 15-20 tons/year for NMR and HF solenoids. Experimental MRI is taking off
- ITER: 500 tons in 2010-2015!
  It is comparable to LHC *(1200 tons of Nb-Ti but HL-LHC will require only 20 tons of Nb_3Sn)*
- HEP ITD (Internal Tin Diffusion):
  - High Jc., 3xJc ITER
  - Large filament (50 μm), large coupling current...
  - Cost is 5 times LHC Nb-Ti

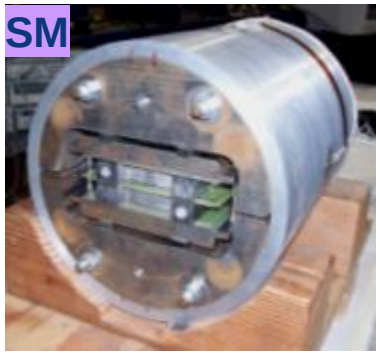


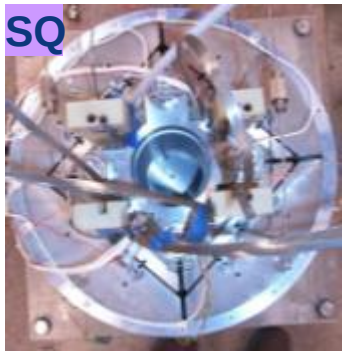
0.7 mm, 108/127 stack RRP from **Oxford OST**

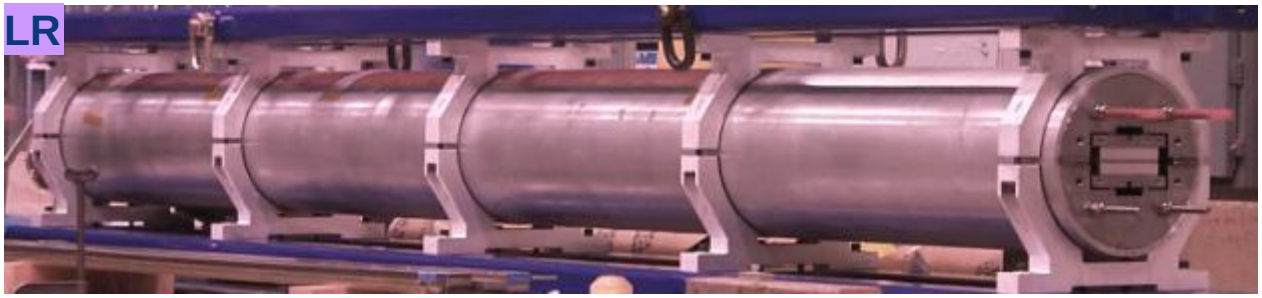


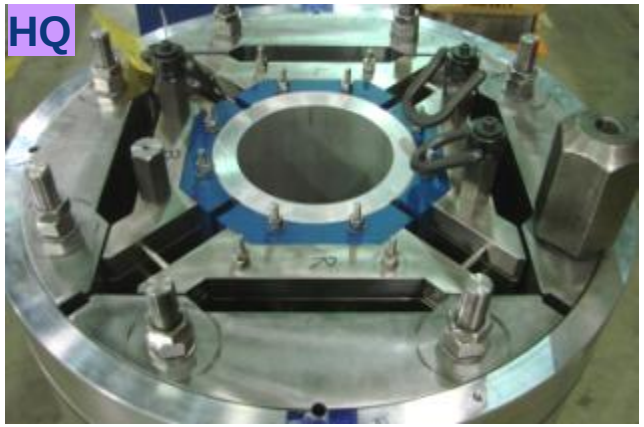
1 mm, 192 tubes PIT from **Bruker EAS**

LARP (US LHC program) Magnets





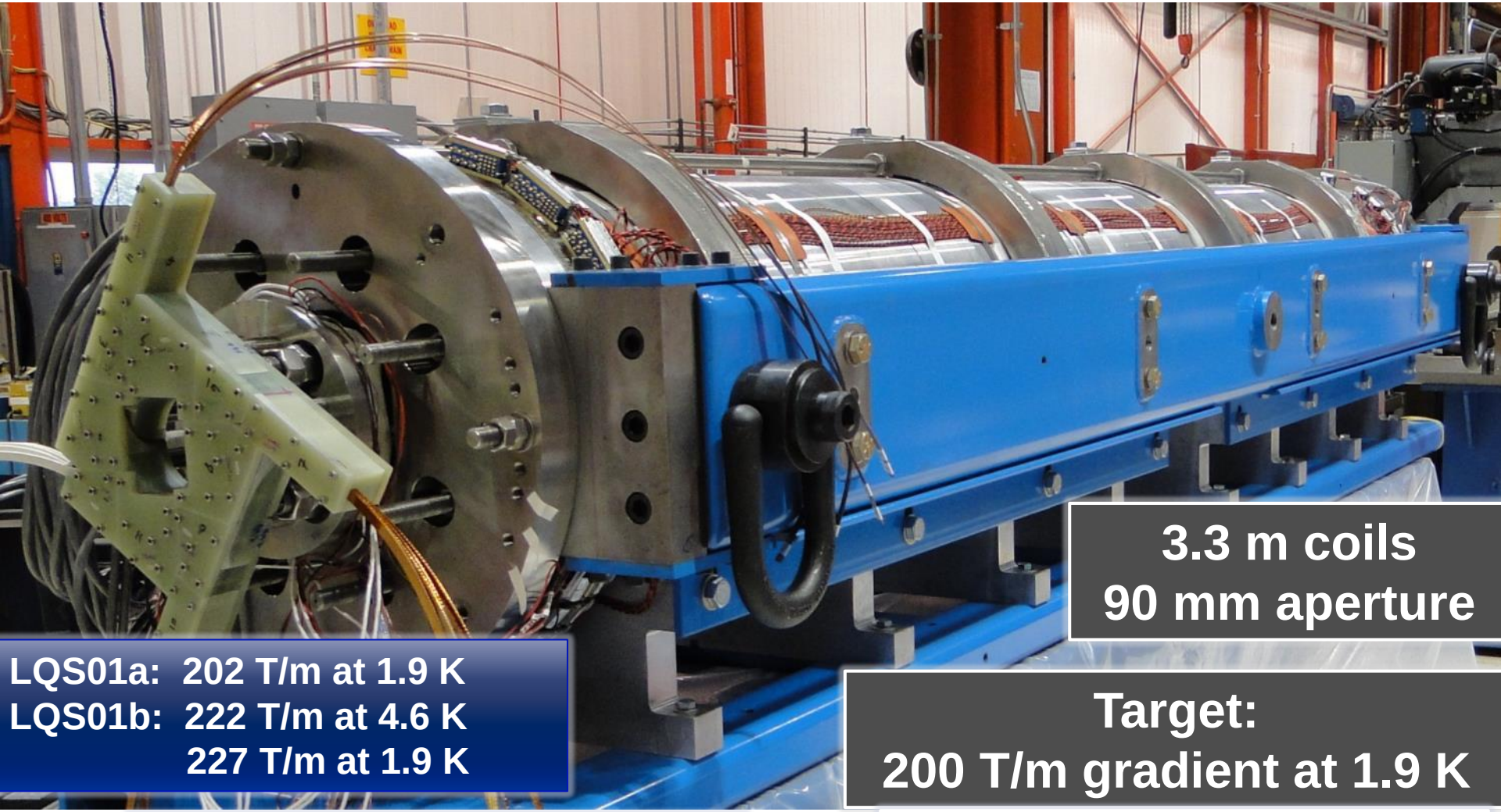




LQS of LARP

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

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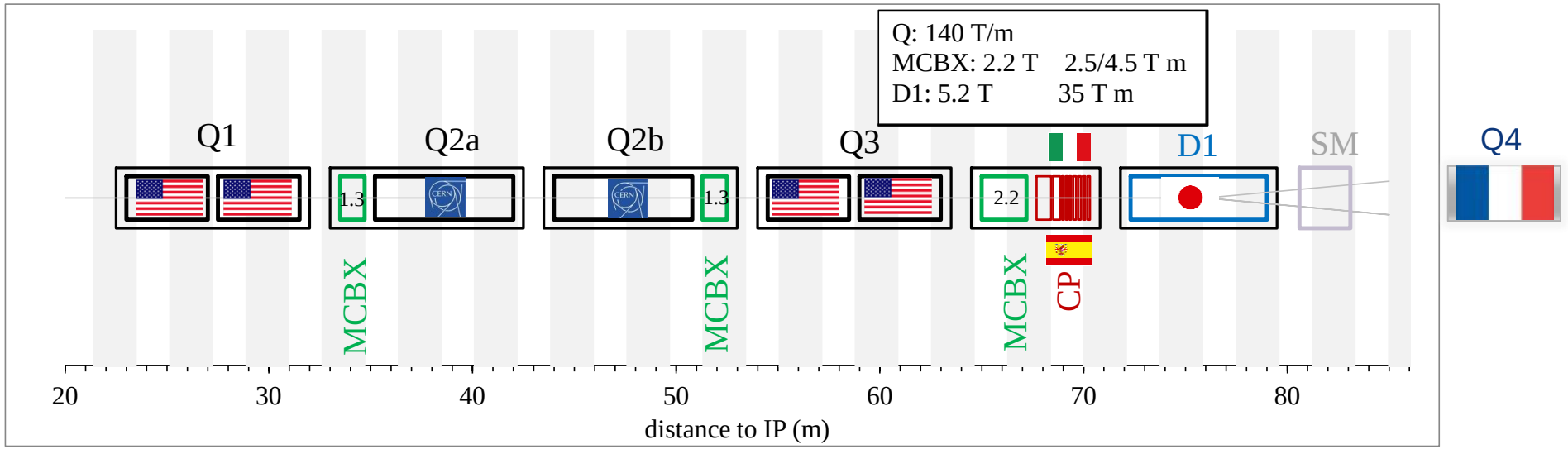
Setting up International collaboration

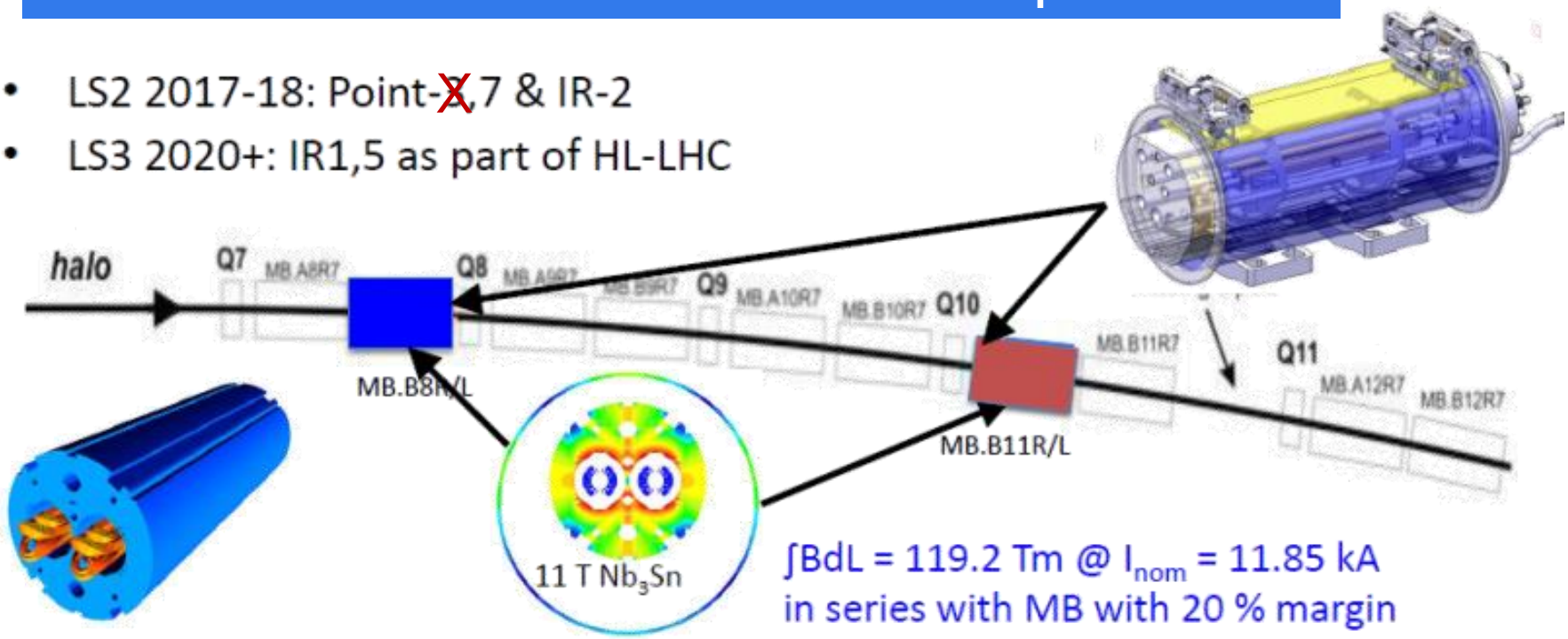
with national laboratories but also involving industrial firms



Baseline layout of HL-LHC IR region

LS2 : collimators and 11T Dipole

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



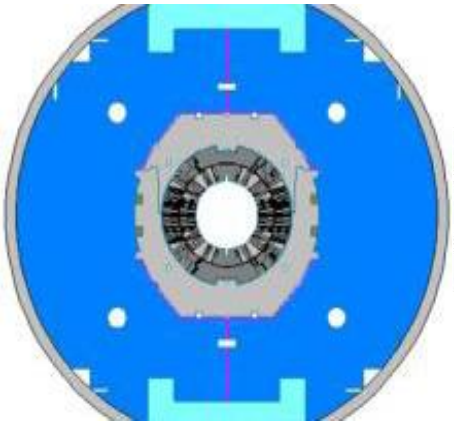
$\int BdL = 119.2$ Tm @ $I_{nom} = 11.85$ kA
in series with MB with 20 % margin

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

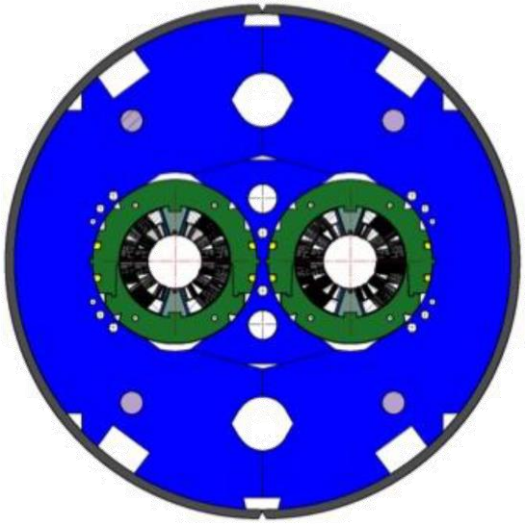
LS2: 24 coldmass + 4 spares = 28 CM
LS3: 16 coldmass + 4 spares = 20 CM
Total 48 CM

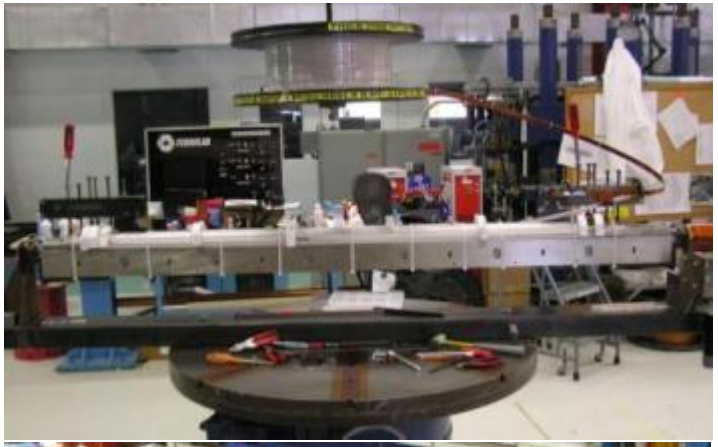
Nb_3Sn 11T Dipole R&D

Single aperture model



Twin aperture model



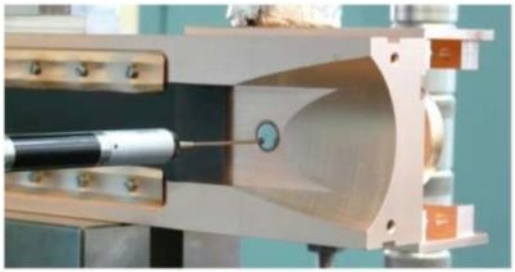


Fermilab

IR Collimation Upgrade

Update of present collimation system during LS1:

- Replace existing collimators
- Reduce setup time (gain of factor ~100)
- Improved monitoring



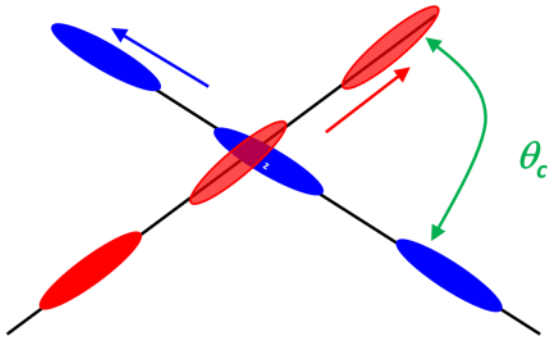
For HL-LHC add dispersion suppressor collimation

- Eliminate off-momentum particles in a region with high dispersion
- Technology of choice for the DS collimators is warm with by-pass cryostat
- **low impedance collimators: coating with Molybdenum**
- Design completed with 4.5 m integration length.
- Prototyping on-going

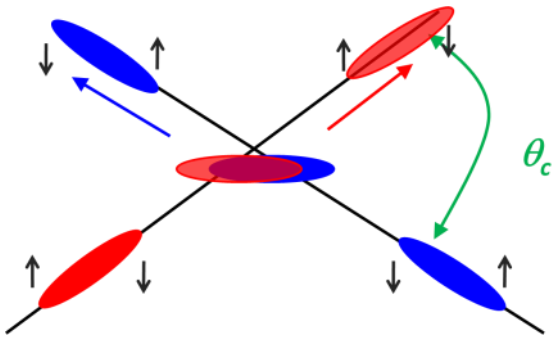
Crab Cavities, Increase "Head on"

Aim: reduce the effect of the crossing angle

Without crabbing

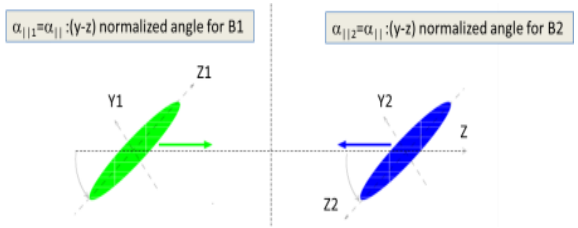


Without crabbing

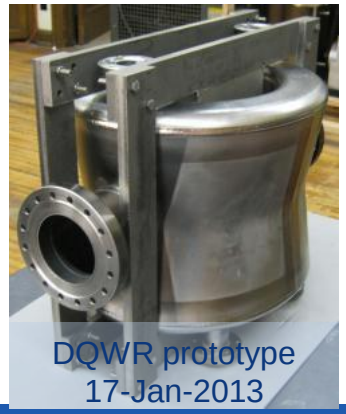



RF-Dipole Nb prototype

New crossing strategy under study to soften the pile-up density:
some new schemas have interesting potential as "crab-kissing", to be discussed with all experiments
("Pile-up at HL-LHC and possible mitigation" Stephane Fartoukh on Wed. 2nd Oct.)

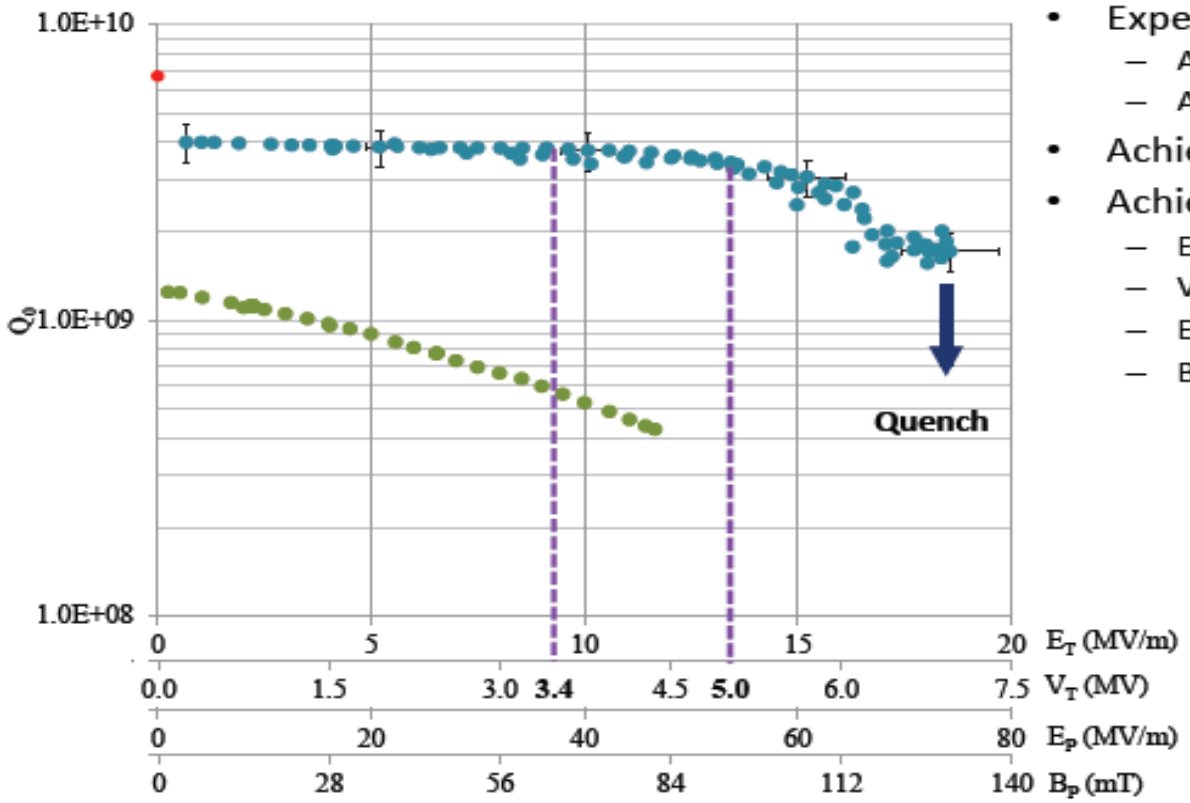


- 3 proto types available
- Cavity tests are on-going
- Test with beam in SPS foreseen in 2015-2016
- Beam test in LHC foreseen in 2017

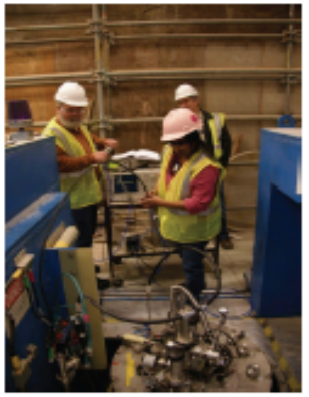

DQWR prototype
17-Jan-2013

First test of RF dipole (April 2013) (ODU-SLAC at J-LAB)

PoP RF Dipole 4.2 K and 2 K Test Results



- Expected $Q_0 = 6.7 \times 10^9$
  - At $R_S = 22$ nΩ
  - And $R_{res} = 20$ nΩ
- Achieved $Q_0 = 4.0 \times 10^9$
- Achieved fields
  - $E_T = 18.6$ MV/m
  - $V_T = 7.0$ MV
  - $E_P = 75$ MV/m
  - $B_P = 131$ mT



Courtesy A. Ratti, LBL

Thinking to cryomodule…

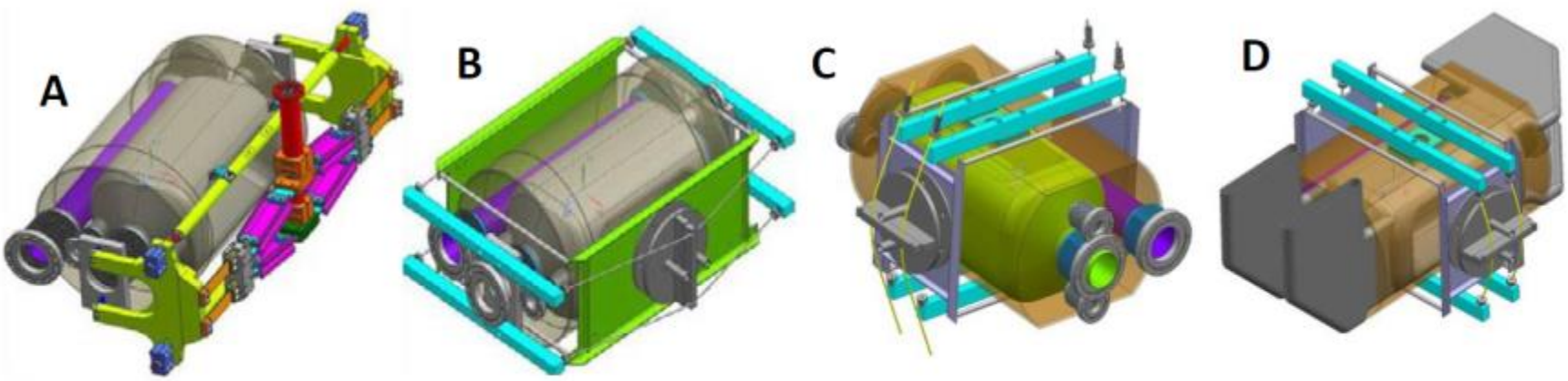
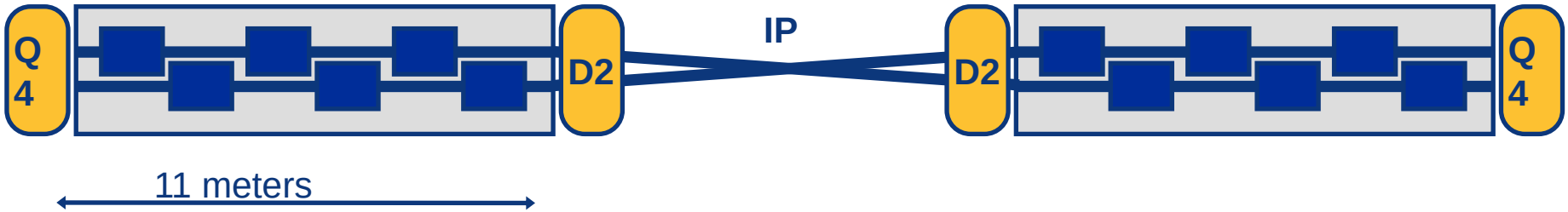
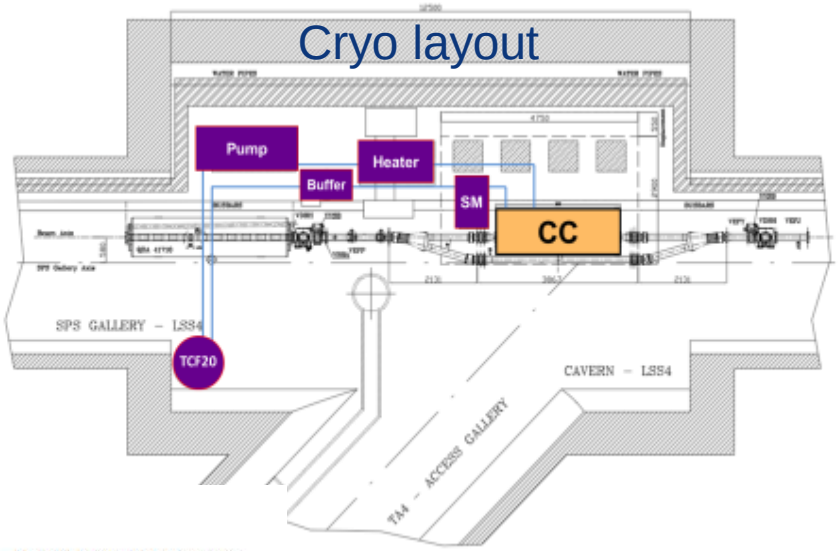
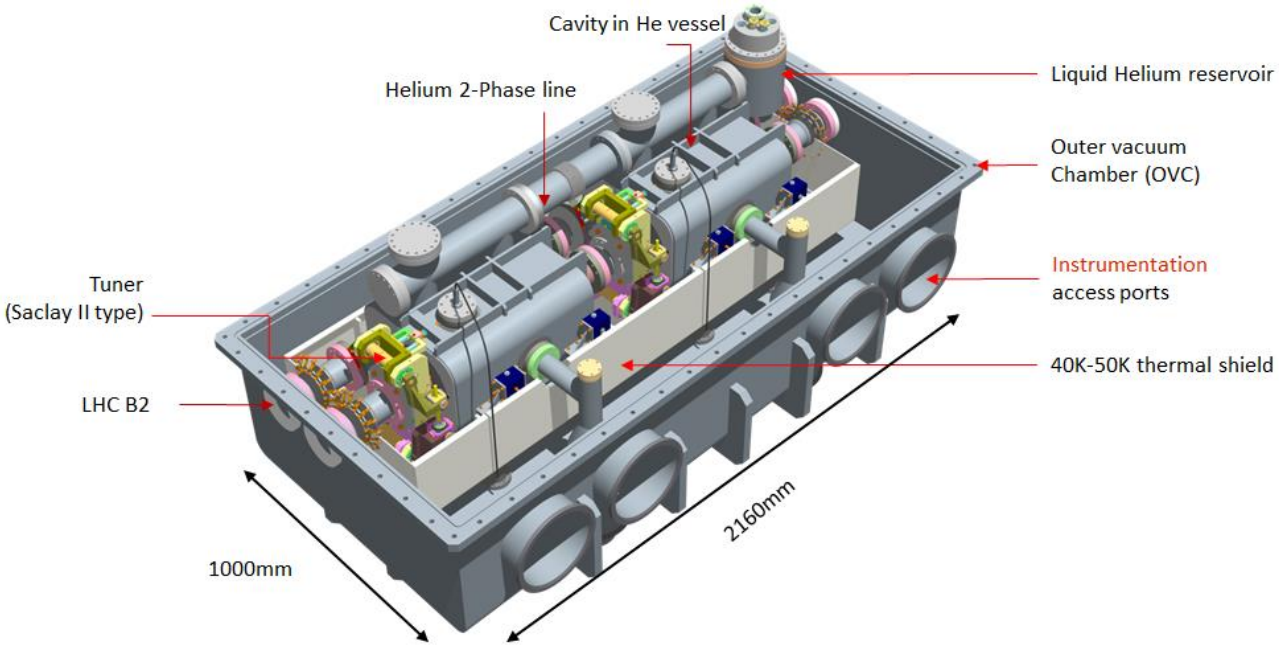


Figure 1: LHC crab cavity cryostat concept – A) JLab design, B) ANL design (helium pressure actuates bellows), C) ANL design (tuner deforms cavity outer surfaces), D) Waveguide

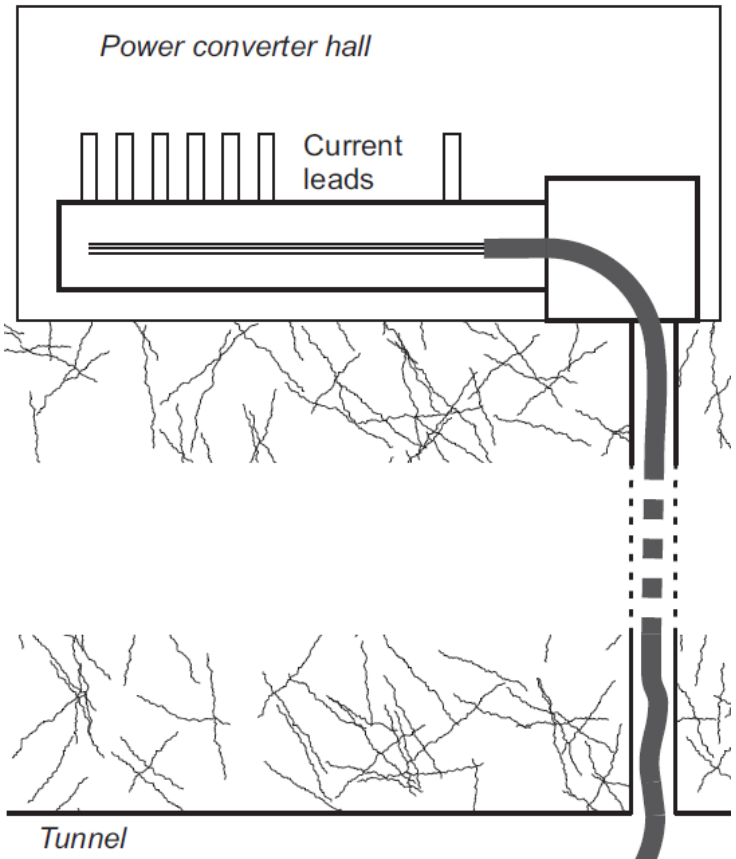


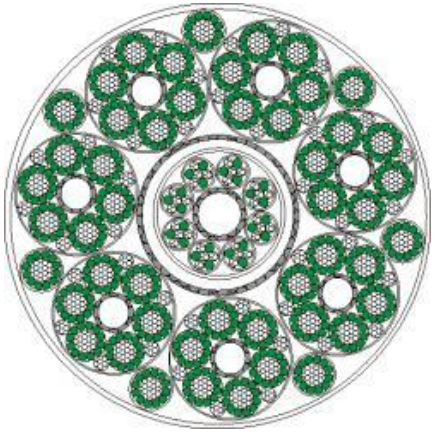
…and to test with beam in the CERN SPS (2016-2017)





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





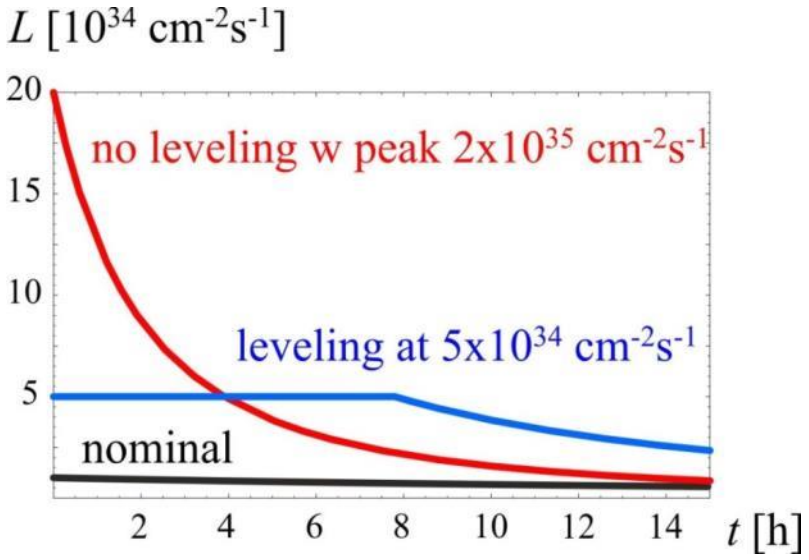
Φ = 62 mm

MgB_2
(or other HTS)

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

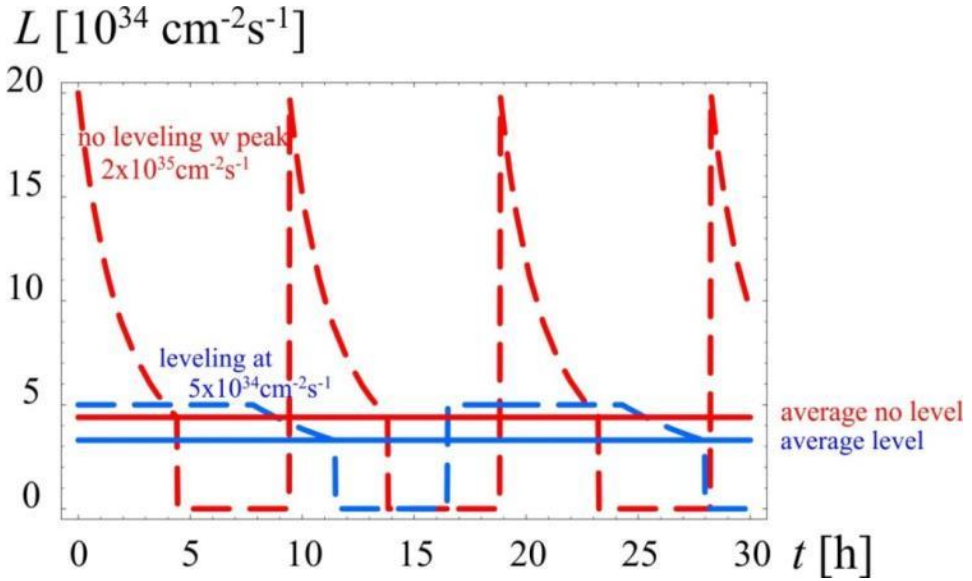
Also DFBs (current lead boxes) removed to surface
Final solution to R2E problem – in some points
Make room for shielding un-movable electronics
Make the maintenance and application of ALARA principle much easier and effective

Luminosity Levelling, a key to success



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

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



Baseline parameters of HL for reaching 250 -300 fb^{-1}/year

25 ns is the option

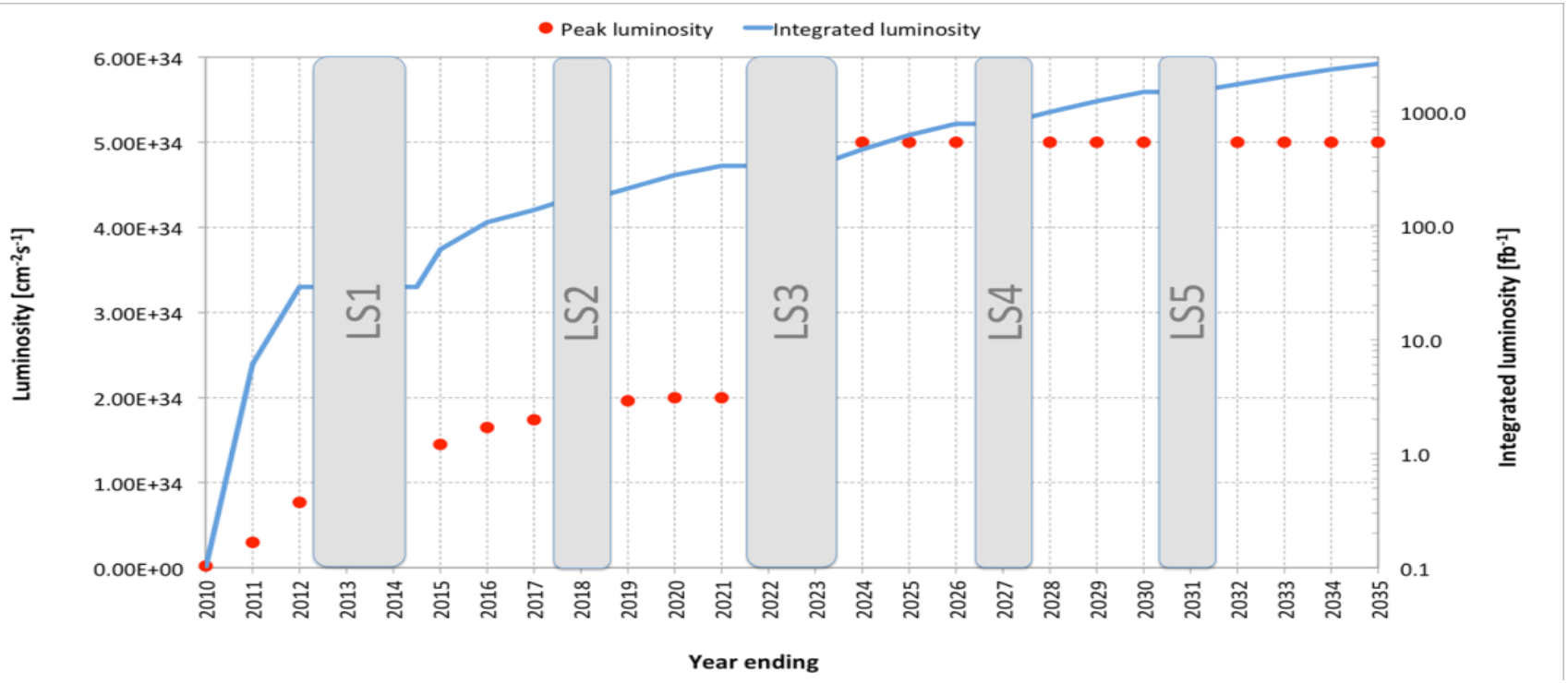
However:
50 ns should be kept as alive and possible because we DO NOT have enough experience on the actual limit *(e-clouds, I_{beam})*

Continuous global optimisation with LIU

	25 ns	50 ns
# Bunches	2808	1404
p/bunch [10^{11}]	**2.0 (1.01 A)**	**3.3 (0.83 A)**
ε_L [eV.s]	2.5	2.5
σ_z [cm]	7.5	7.5
$\sigma_{\delta p/p}$ [10^{-3}]	0.1	0.1
$\gamma\varepsilon_{x,y}$ [μm]	**2.5**	**3.0**
β^* [cm] (baseline)	15	15
X-angle [μrad]	**590 (12.5 σ)**	**590 (11.4 σ)**
Loss factor	0.30	0.33
Peak lumi [10^{34}]	6.0	7.4
Virtual lumi [10^{34}]	20.0	22.7
$T_{leveling}$ [h] @ 5E34	**7.8**	**6.8**
#Pile up @5E34	123	247

Courtesy Oliver Brüning

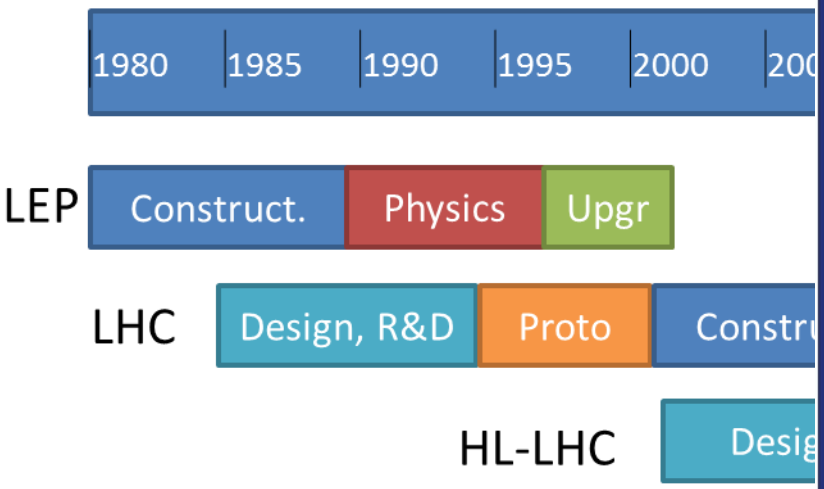
The plan of HL-LHC (baseline)



Levelling at 5 10^{34} cm^{-2} s^{-1}: 140 events/crossing in average, at 25 ns; several scenarios under study to limit to 1.0 → 1.3 event/mm
("Pile-up at HL-LHC and possible mitigation" Stephane Fartoukh on Wed. 2nd Oct.)

Total integrated luminosity of 3000 fb^{-1} for p-p by 2035, with LSs taken into account and 1 month for ion physics per year.

"…exploitation of the full pote
high-luminosity upgrade of th
=> High Lumi



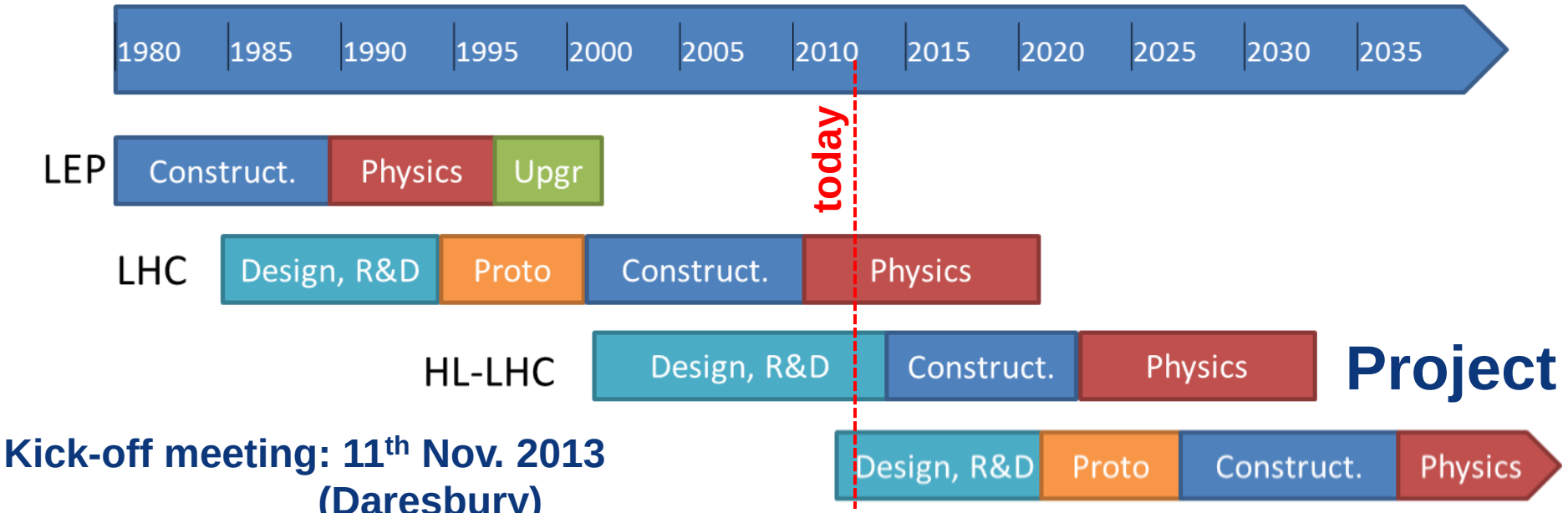
Kick-off meeting: 11th Nov. 2013
(Daresbury)

http://cern.ch/hilumilhc

Next Milestones: High Luminosity LHC

Jun. 2014:	PDR (Preliminary Design Report) and re-baseline (costing, time) of the project
Sep. 2015:	First short model QXF (inner triplet)
Nov. 2015:	TDR and end of FP7 Design Study
Sep. 2016:	First full size MQXF (long triplet Quad)
2016-17:	Test Crab Cavities in SPS
	Start Construction
LS2 (2018):	Installation in LS2 of Cryogenics P4, SC horizontal link P7, 11 T dipole and DS collimators in P2, first Molybdenum collimators
LS3 (2022-23) :	installation of all HL-LHC hardware synchronized with long detector shutdown

"CERN should undertake design studies for accelerator projects in a global context, with emphasis on ***proton-proton*** *and electron- positron* ***high-energy frontier machines.****"*



Kick-off meeting: 11th Nov. 2013 (Daresbury)

FCC Study : p-p towards 100 TeV

Kick-off meeting: mid-February 2014

FCC: Future Circular Colliders

Conclusion

- LS1 [2013-2014] : 1st beams in 2015
- Run 2 : 13 TeV – 25 ns – up to 1.7 10^{34} $cm^{-2}.s^{-1}$, 40-45 fb^{-1} per year
- LS2 (higher intensity - LIU) [2018 or 2019]
- Run 3 (up to ~2.0 10^{34} $cm^{-2}.s^{-1}$) ***300 fb^{-1} before LS3***

- HL-LHC : R&D => now an approved project with a kick-off meeting on 11th Nov.

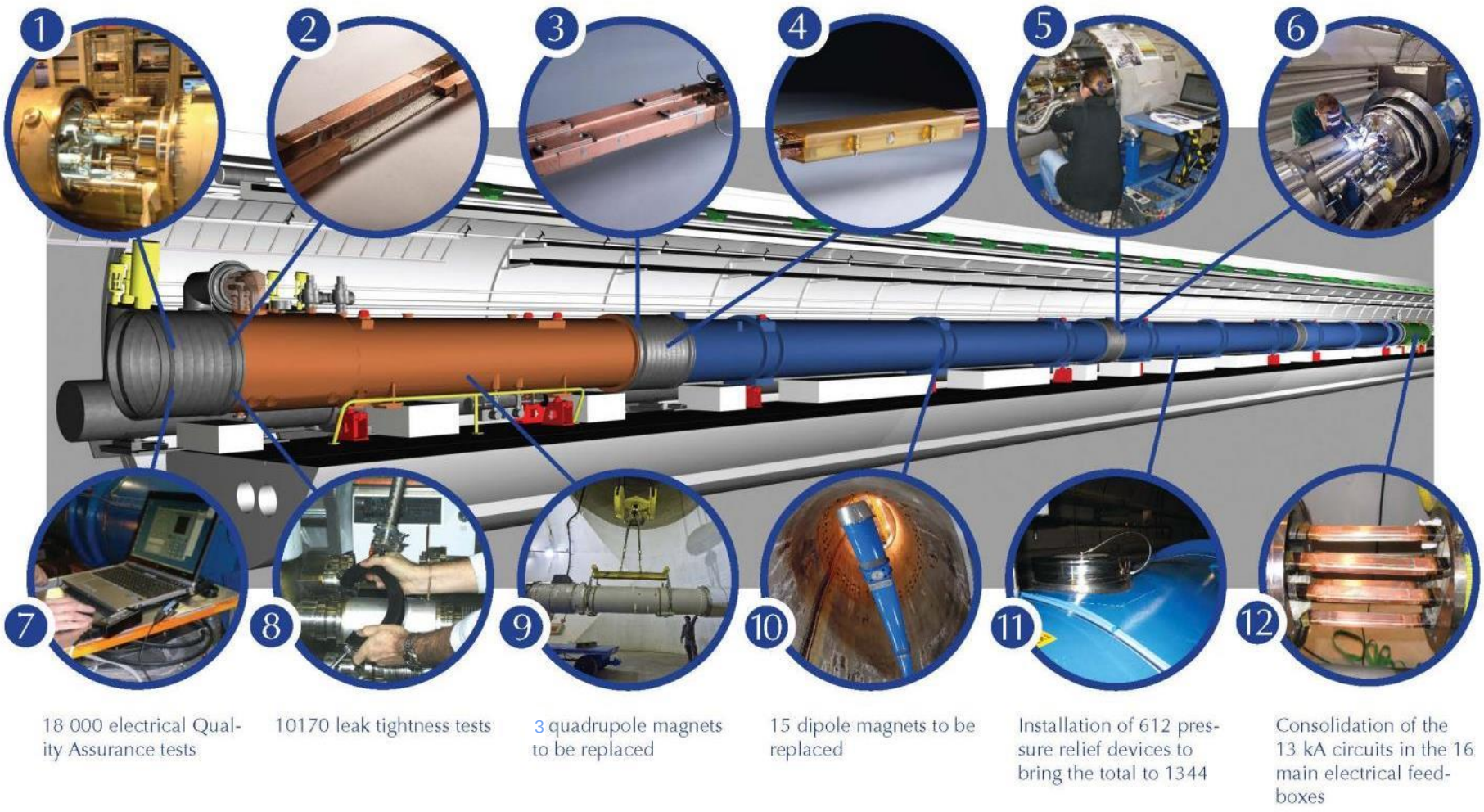
  A lot of technical and operation challenges :
  - Nb3Sn magnets (accelerator field quality) (HFM roadmap)
  - Collimators
  - Superconducting links
  - Crab cavities
  - Increased availability (machine protection,…)
  - …

  Accelerator-experiment interface are central:
  - Bunch spacing, pile-up density, crossing schemas, background, forward detectors, collimation,…

Thanks for your attention

www.cern.ch

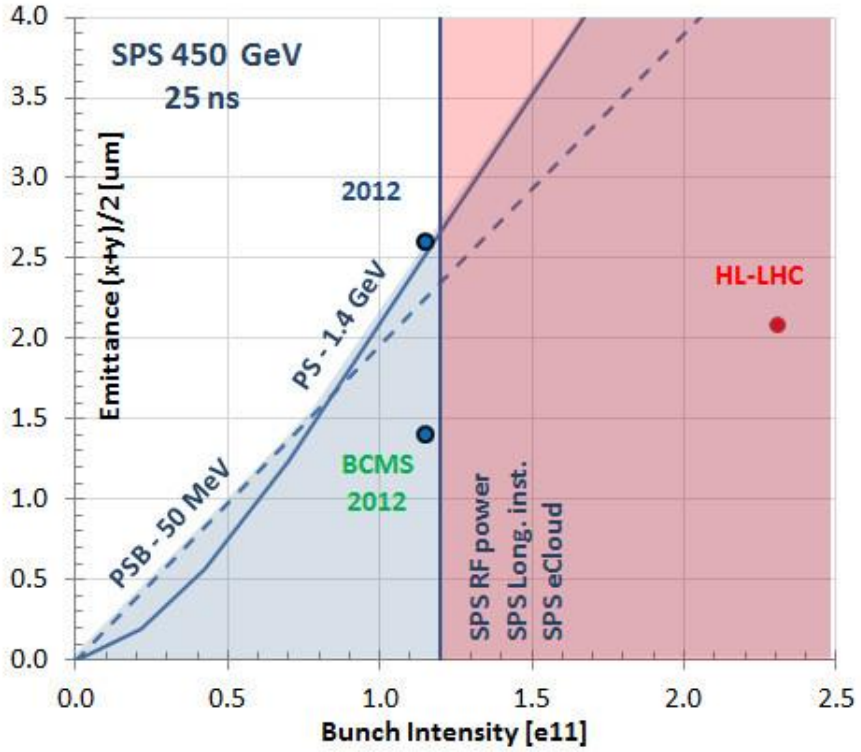
The main 2013-14 LHC consolidations



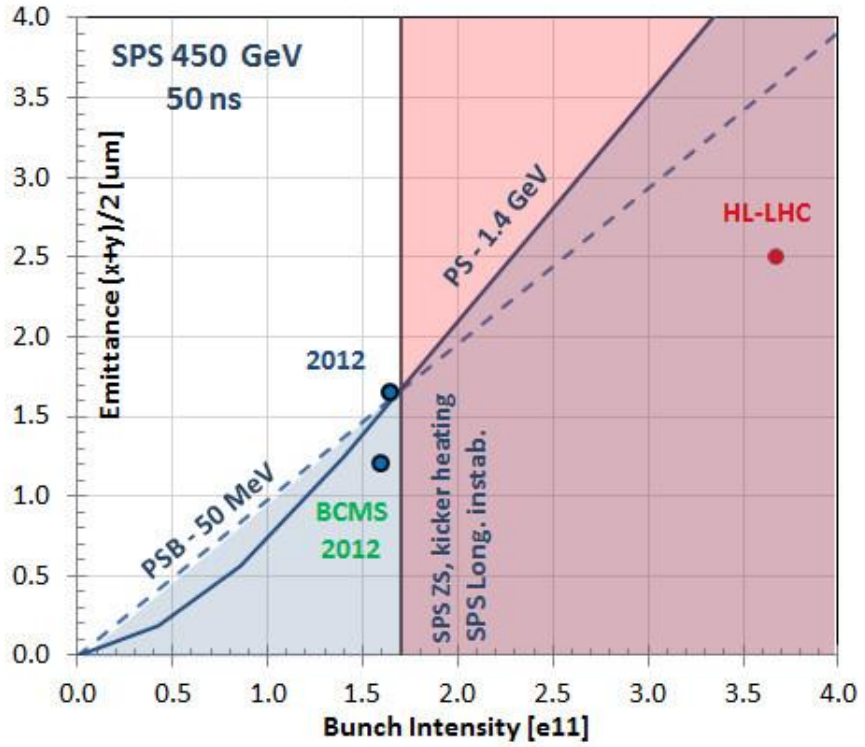
Proton beam characteristics at injection in LHC (1/2)

Performance at end of 2012

25 ns



50 ns

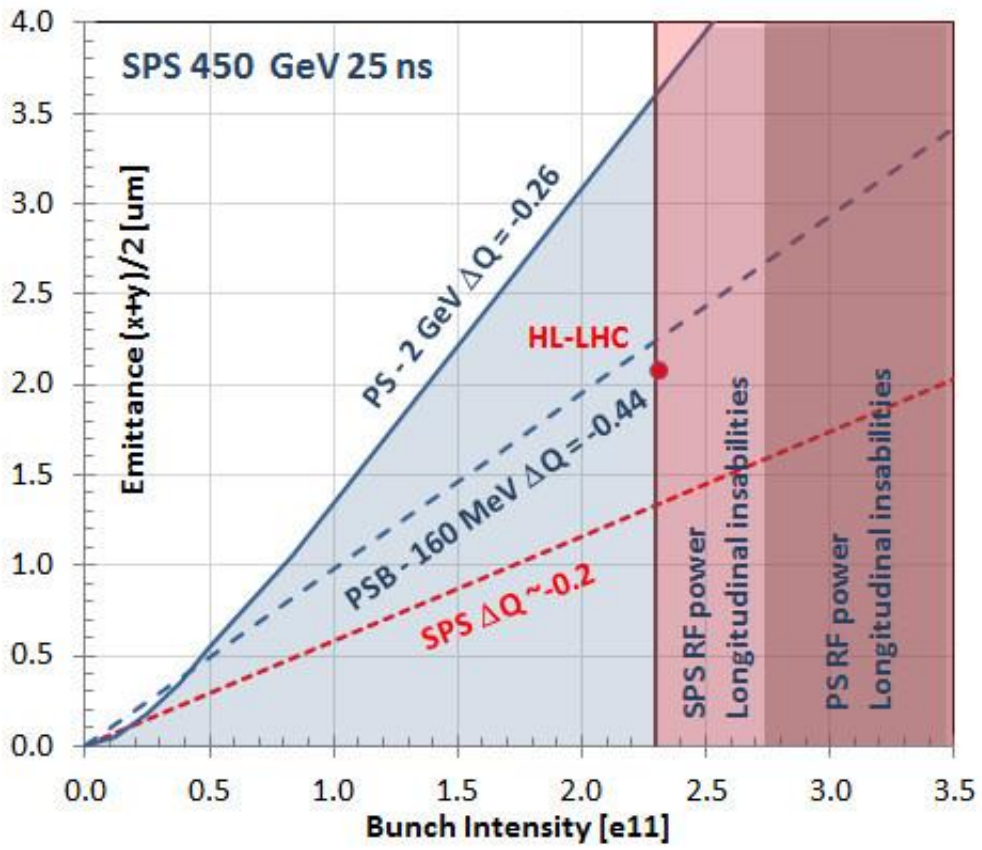


Warning!

10% less bunches in LHC with BCMS => need for 10% more protons/bunch

Proton beam characteristics at injection in LHC (2/2)

Performance after LIU (present guess: more accurate estimate at RLIUP workshop in October 2013)



~ OK except for
space charge-induced ΔQ in the PS

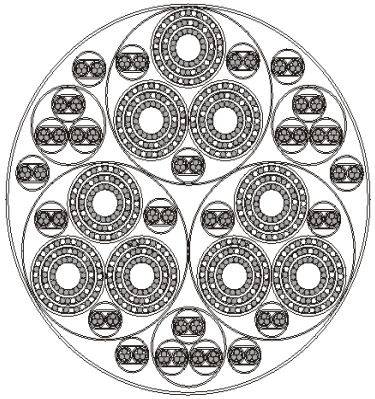
Alternatives (possibly in combination):

- Resonances compensation
- Better optimized working point
- «Moderate» batch compression
- ?

SC Link prototype test

New feed-box for supercritical helium (10 g/s) variable temperature (5 K … > 77K) and high current (13 kA)
Flexible cryostat to host various cable types and materials, up to 20 m length

27 cables 6000 A
48 cables 600 A
Itot = **190 kA** (~2 × 95 kA)



~7 kg/m
~ 900 m_{HTS}/m_{cable}