High Luminosity LHC Upgrade

Tatsushi NAKAMOTO

KEK

Acknowledgement

- CERN: L. Bottura, M. Lamont, G. de Rijk, L. Rossi, E. Todesco
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Information and slides are available at;
http://hilumilhc.web.cern.ch/HiLumiLHC/index.html
https://espace.cern.ch/HiLumi/2012/SitePages/Home.aspx

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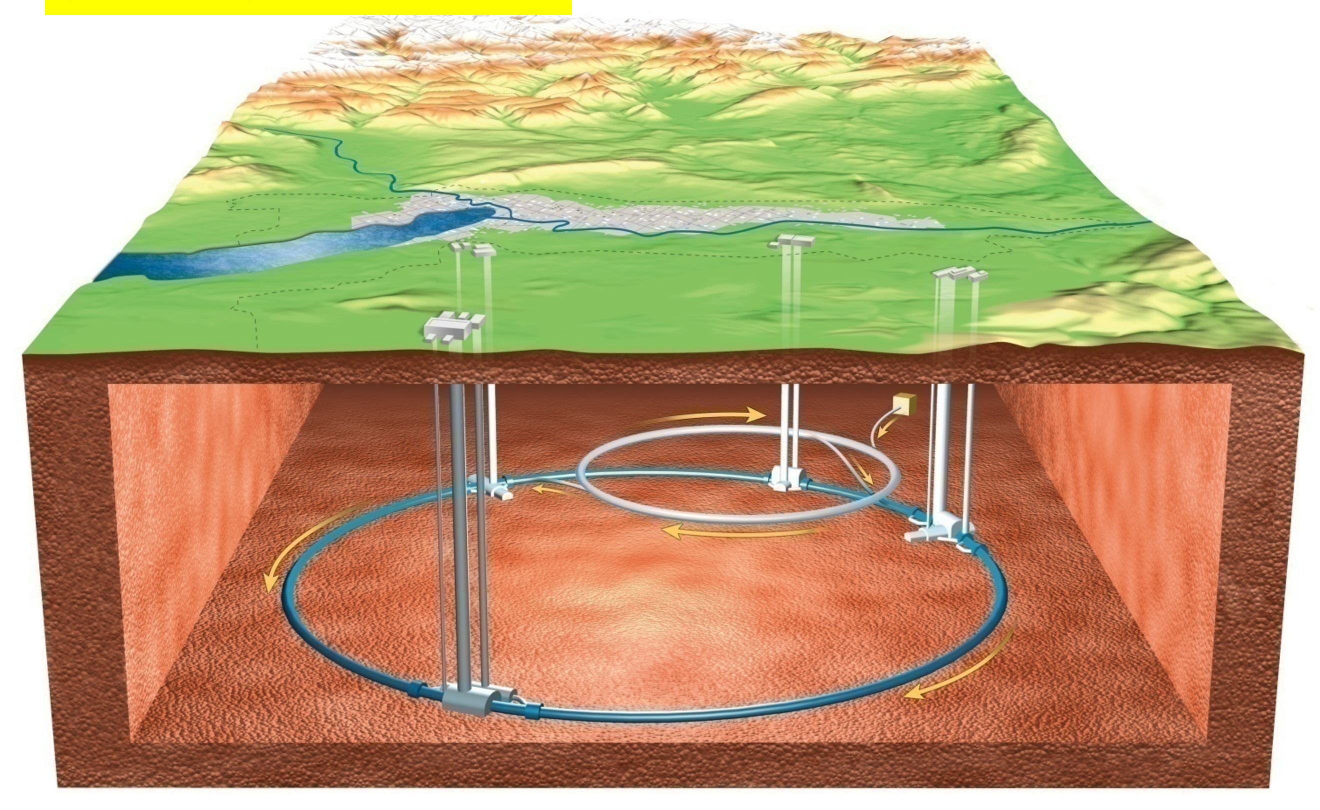
LHC (Large Hadron Collider)

proton + proton collision



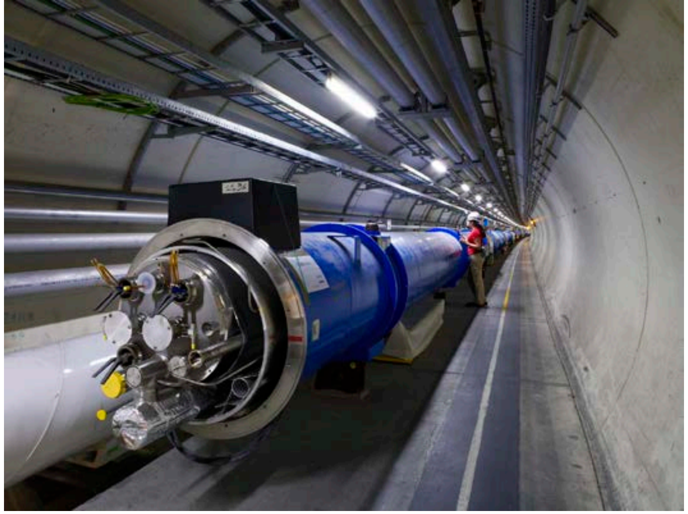
Circumference of
27 km

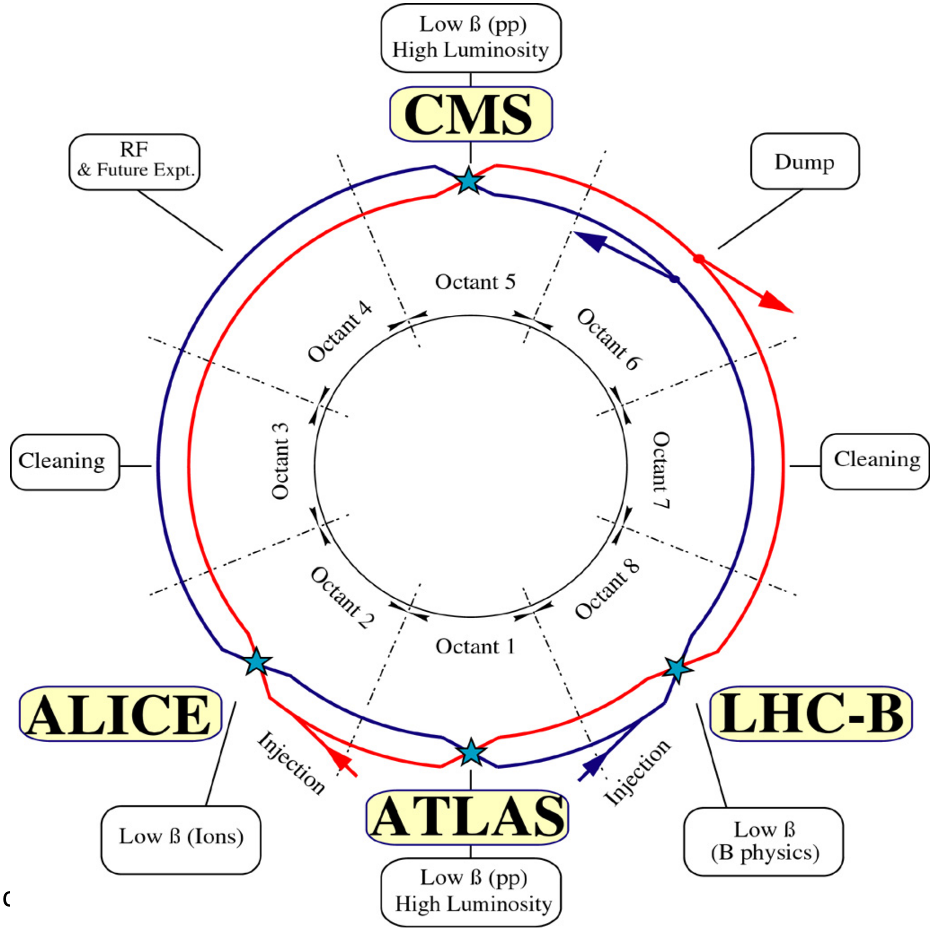
Origin of mass ?
What is dark matter, dark energy?

Overview: LHC

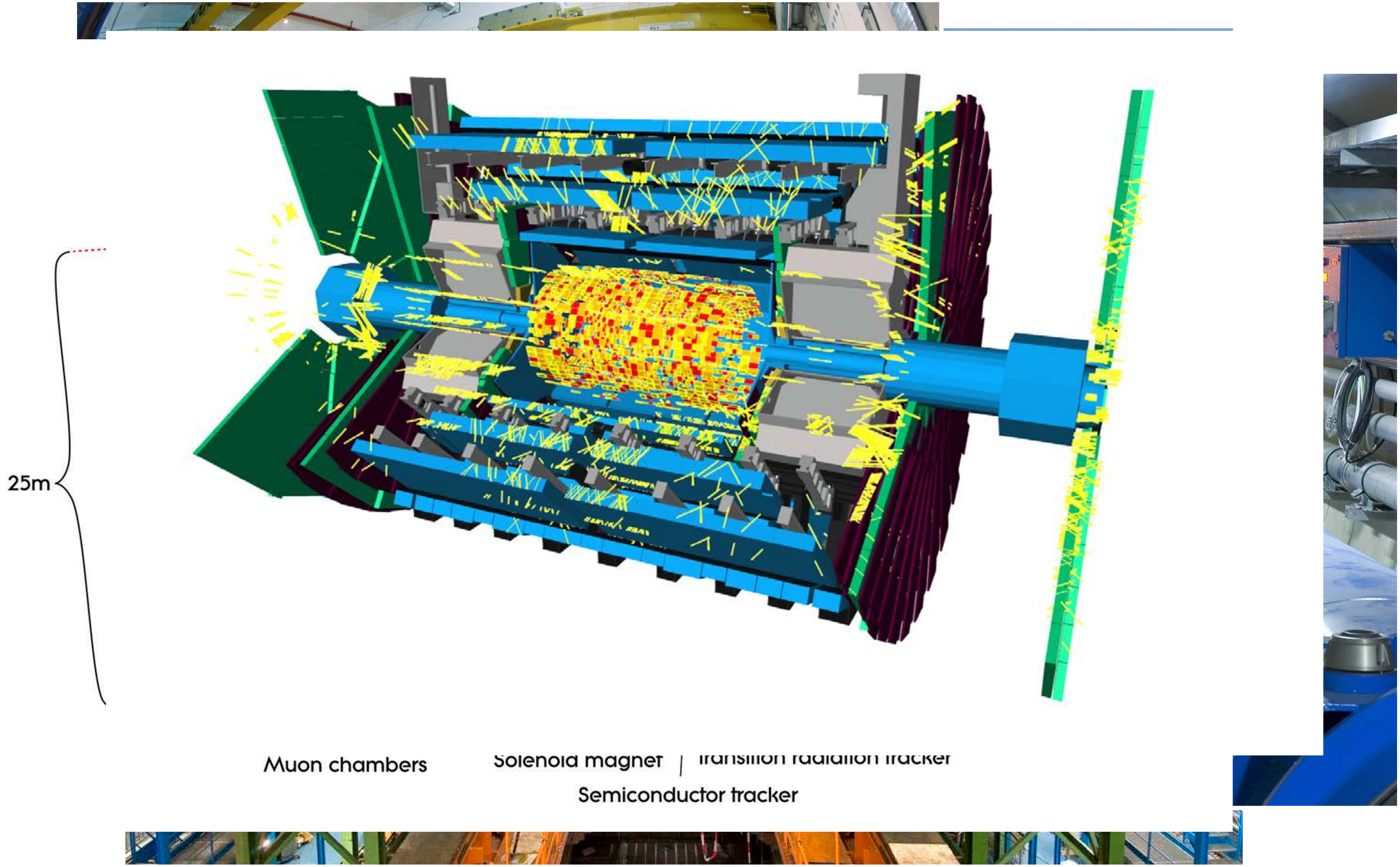
- Large Hadron Collider
- Circumference: 26.7 km
- Proton Beam Injection Energy: 450 GeV
- p + p Collision Energy:
  - 4 + 4 TeV (2012)
  - 7 + 7 TeV (design)

    Splice consolidation work in LS1 (2013-2014)
- Nominal Luminosity: 1 x 10 ^{34} cm^{-2} sec^{-1}
- Superconducting Technology and Cryogenics
  - 2 in 1 main dipole at 8.3T: 1232 magnets
  - Cooled at 1.9 K by 100 tons of superfluid helium
  - Total weight of cold mass: 35,000 ton
  - Electrical power of 40 MW for cryogenics plant
- Construction budget: > 5000 MCHF



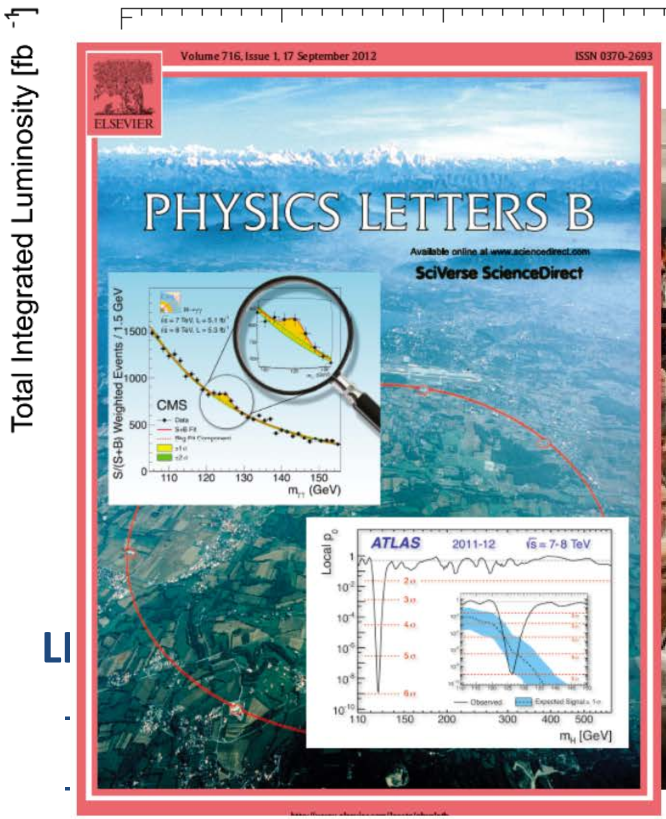


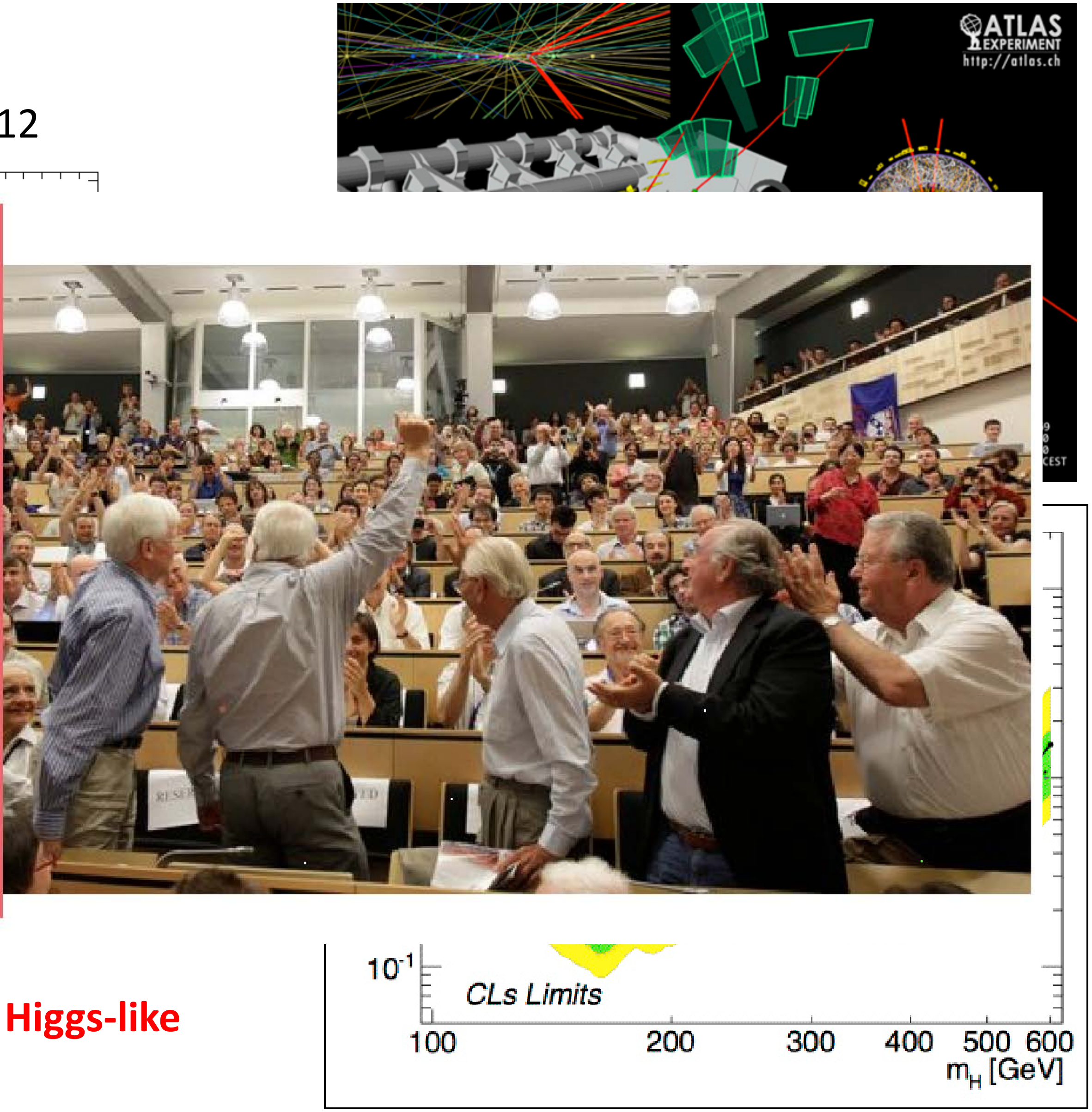
LHC “Accelerator” and “Detector”



Results So Far

Integrated luminosity in 2012





- LI
  - – 23.3 fb^{-1} (2012)
- July 4th, 2012: Indication of SM Higgs-like particle around 126 GeV

http://www.atlas.ch/
http://www.atlas.ch/news/2012/latest-results-from-higgs-search.html
http://atlas.kek.jp/index.html

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  - Performance so far
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- Summary

Superconducting Technology

Only possible way to realize an "energy frontier" collider…

$$E \cong 0.3 \times B \times R$$

E: particle energy in TeV, B: magnetic field in T, R: radius of circumference in km.

- The LEP tunnel is given, which means "R" is fixed. If you want higher particle energy, bending field must be increased.
- Available (achievable) magnetic field for accelerators:
  - Conventional magnet (copper, water cooling, iron dominated) < 1.9 T
  - SC magnet (NbTi, iron yoke, LHe at 4.2 K, Tevatron, HERA, RHIC) 4 ~ 5 T
  - **SC magnet (NbTi, iron yoke, HeII at 1.9 K) ~8 T**

The choice was really challenging and realization was not trivial…

- R = 4.3 km, B = 5.5 T (averaging over the circumference including straight sections),

$$E \cong 7 \text{ TeV}$$

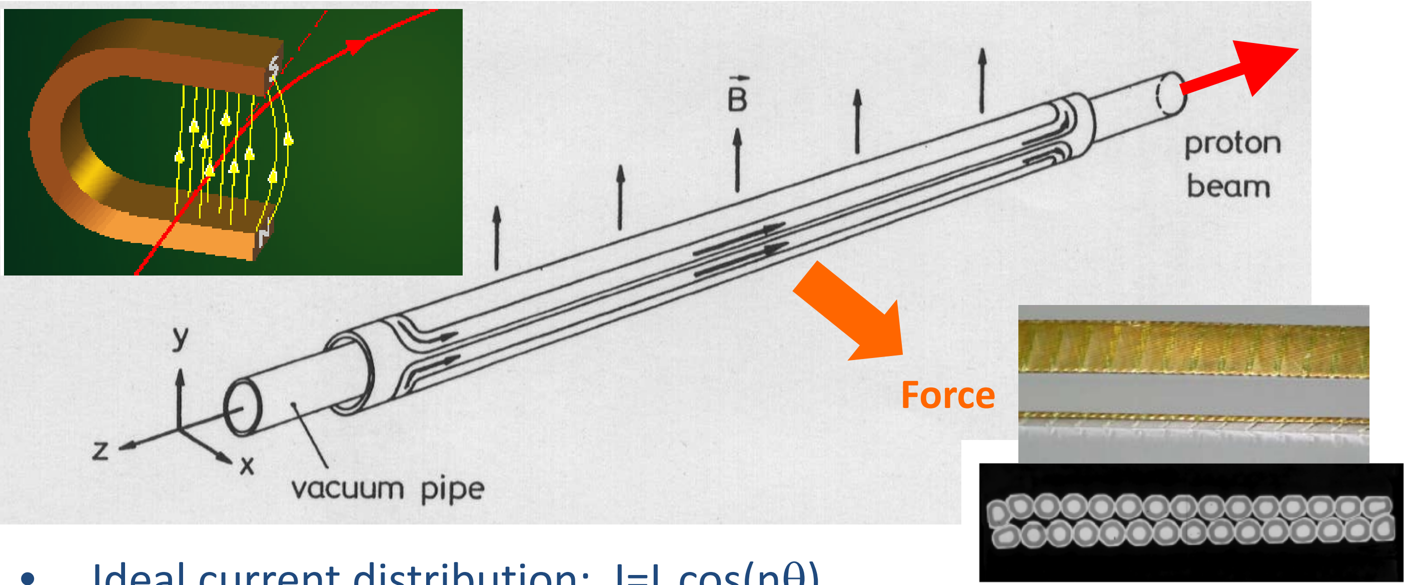
P + P collision energies of 7 + 7 TeV

* Energy loss of proton due to synchrotron radiation is about 7 keV per turn.

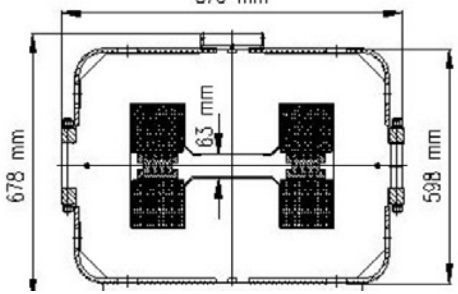
$$P_{loss} \propto \frac{E^4}{m_0{}^4 \bullet R^2}$$

SC magnets & cryogenics are key technologies for the LHC.

SC Accelerator Magnets

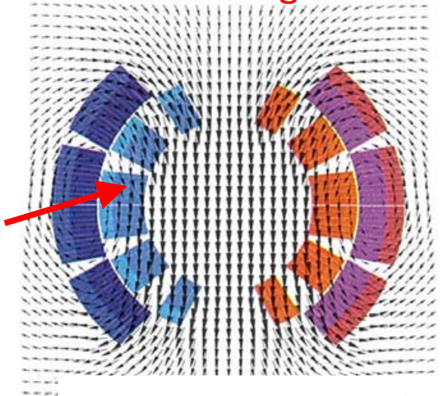


SC Rutherford Cable



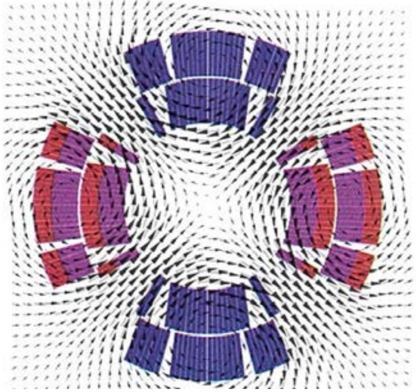
Warm Dipole Magnet

Bending



SC Dipole Coil (cosθ)

Focusing



SC Quadrupole Coil（cos2θ）

- Ideal current distribution: $I = I_0 \cos(n\theta)$
  - n=1 Dipole, n=2 Quadrupole, n=3 Sextupole,…
  - Represented by sector coil blocks
- Field magnitude and distribution: “cable currents” and “coil position”
- Requirement of field quality for accelerator $< 10^{-4}$
  - dimensional error of the coil: ~20 μm
- Current density of SC accelerator coils: ~500 A/mm^2
- Magnetic stress (magnetic energy density): $P = B^2/2\mu_0$
  - If B = 8 T, P = 25 MPa or MJ/m3
  - Very rigid mechanical support structure needed

SC Accelerator Magnets

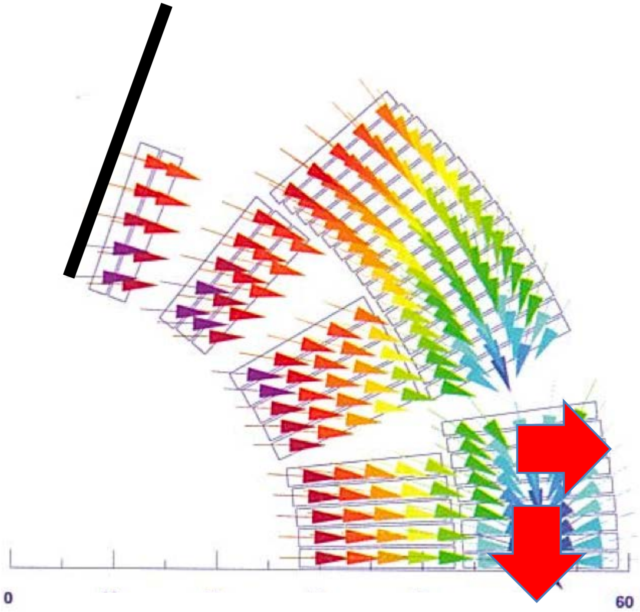
Field quality, training quench performance

↓

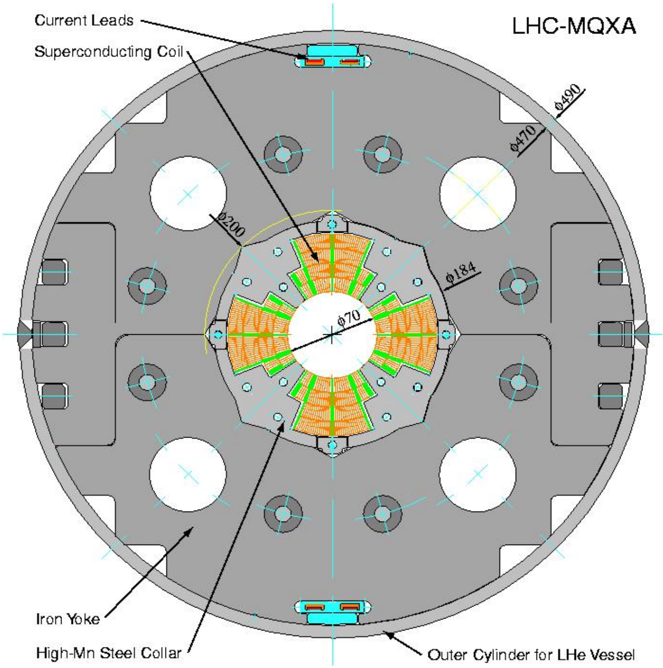
Coil must stay at "pole".

↓

Pre-load on the coil at assembly, even after cool-down.

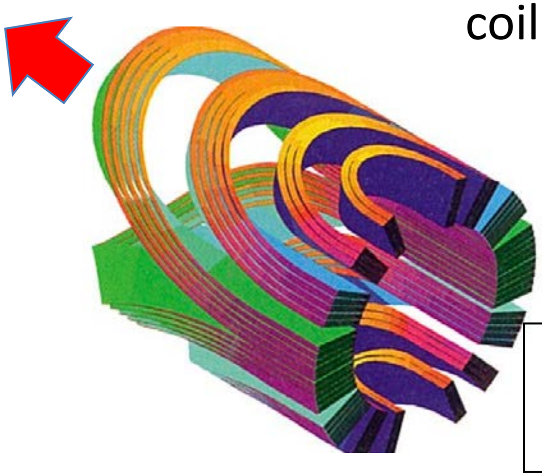


E.M. force in dipole coil cross section.



- Non-magnetic stainless steel collar: good field quality
- Iron yoke: flux return
- Stainless steel shell: helium outer vessel

Mechanical support structure

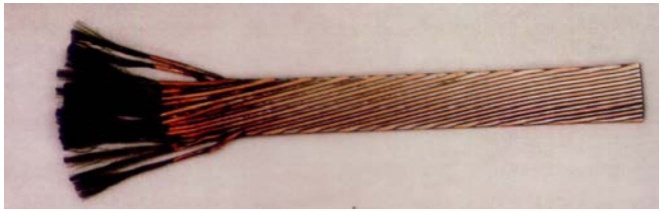


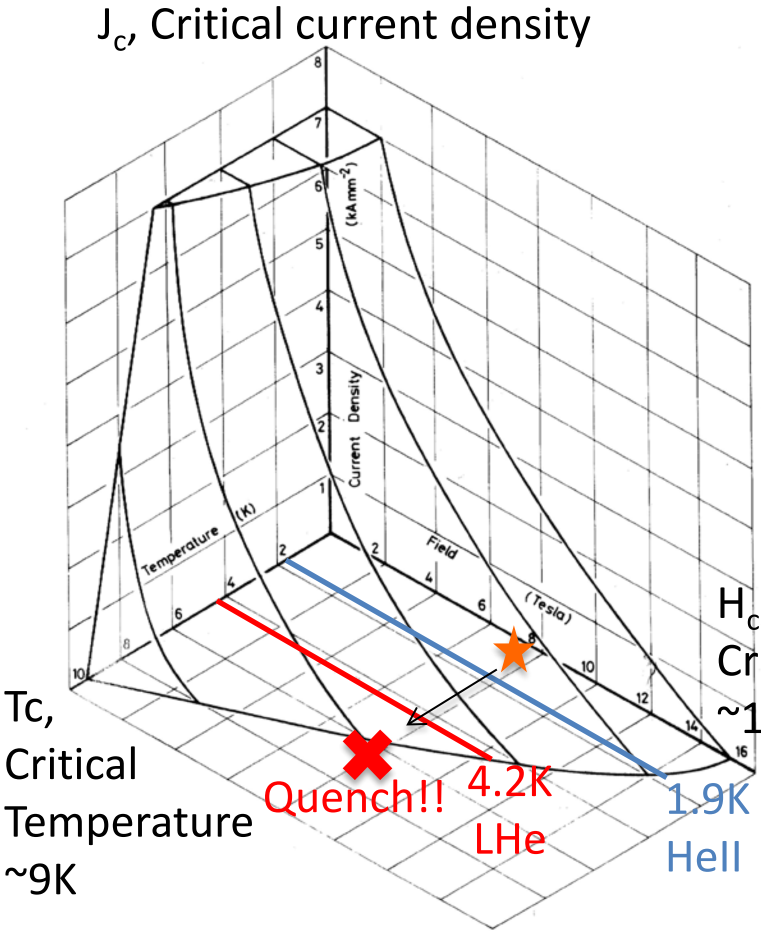
Dipole coil end

Coil end support for hoop stress.

Why operated at 1.9 K by Superfluid Helium?

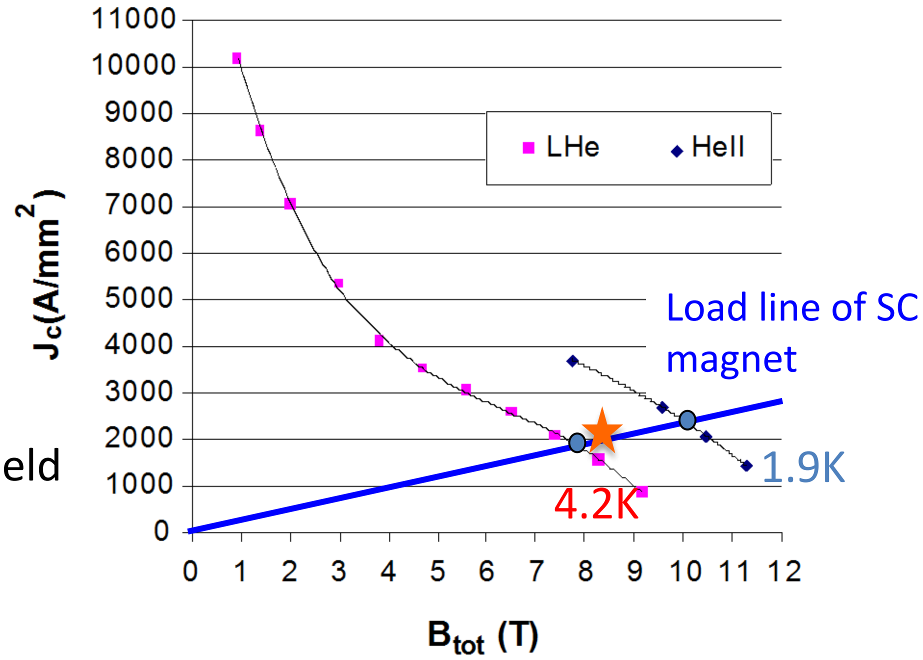
Superconductor: NbTi, workhorse!!





H_c,
Critical Field
~15T

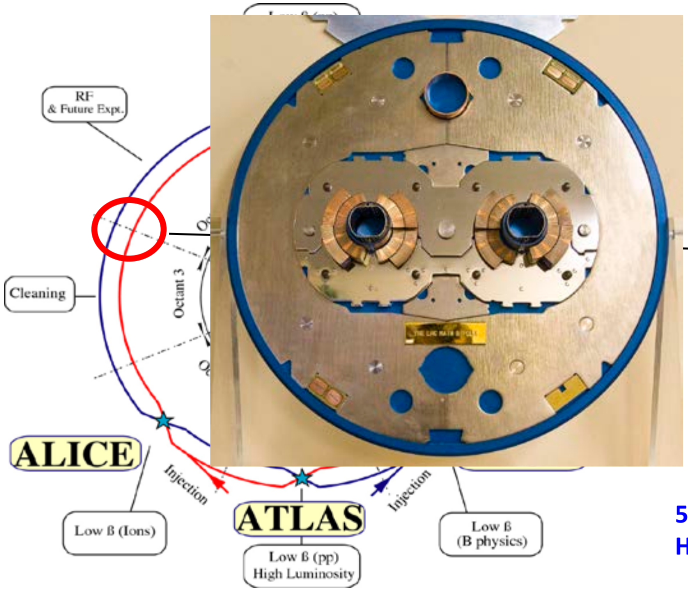
Critical surface of NbTi
(from Wilson textbook)

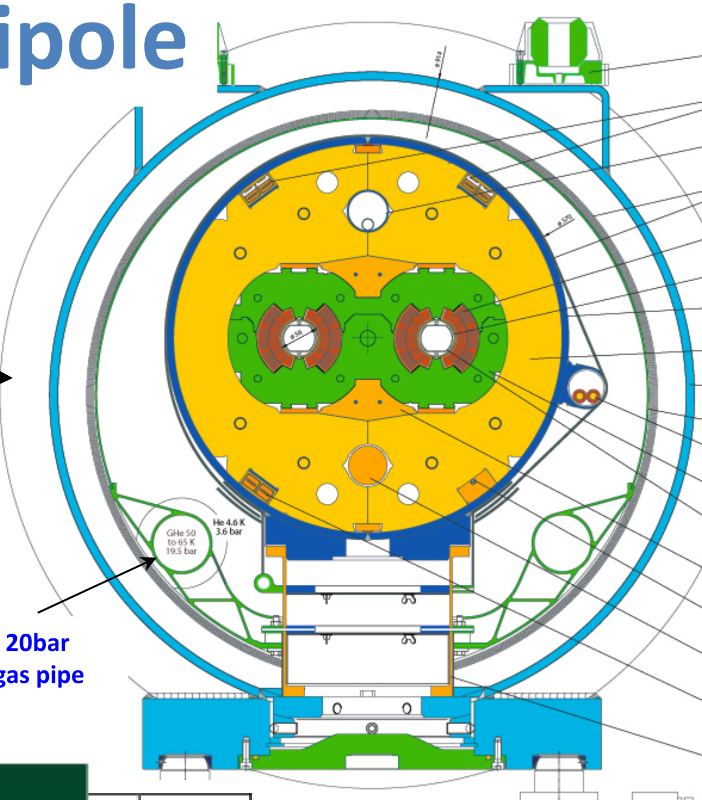


Critical current of best Cu/NbTi with typical **3 T field shift at superfluid helium** (INFN-LASA lab, february 2000)

HeII: enabling “higher field SC magnet” → Need: state of the art, complicated cryogenics

“2 in 1” LHC Main Dipole





50K 20bar
He gas pipe

Alignment Target

SC Bus for Main Quads

Saturated HeII HX Pipe

Super-insulation (MLI)

SC Coil

Beam pipe (< 10^-7 Pa)

Helium vessel SEL

Iron Yoke

Vacuum Vessel (< 10^-4 Pa)

Radiation shield

AUXILIARY BUS-BARS

Non-magnetic steel collar

BEAM SCREEN

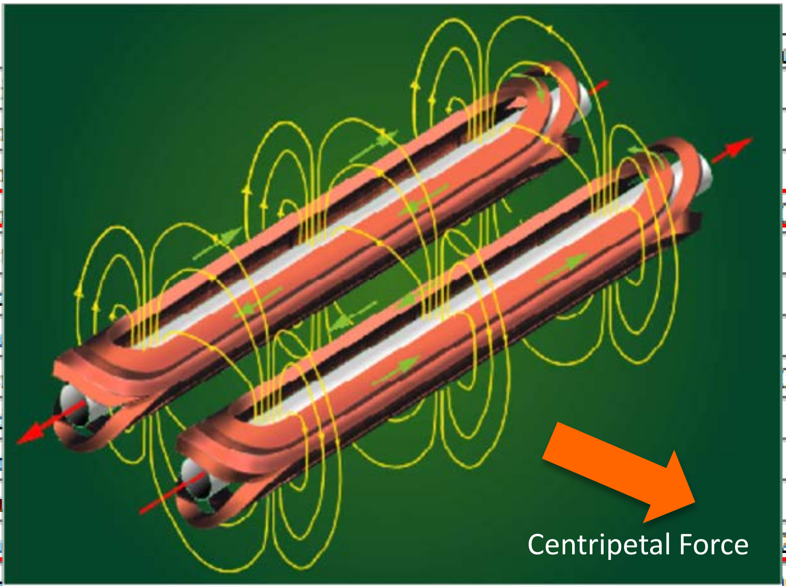
IRON INSERT

INSTRUMENTATION WIRES

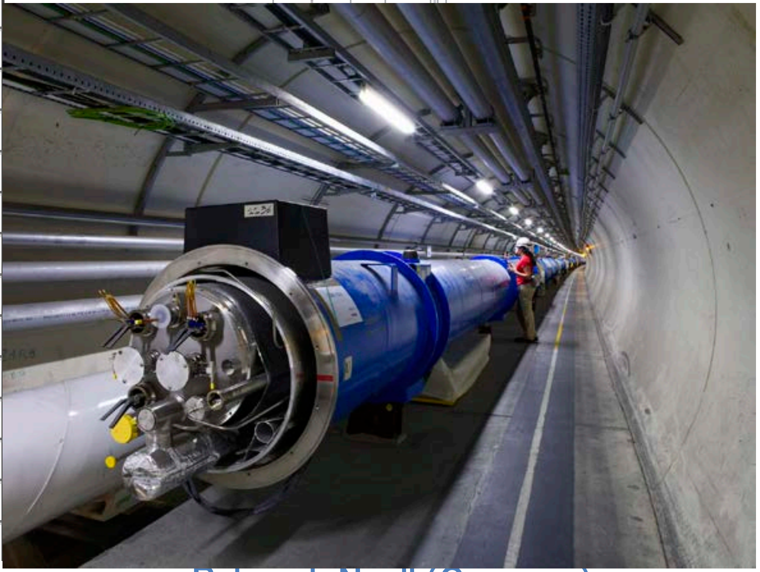
FILLER PIECE

SC bus for Main Dipoles

Support post



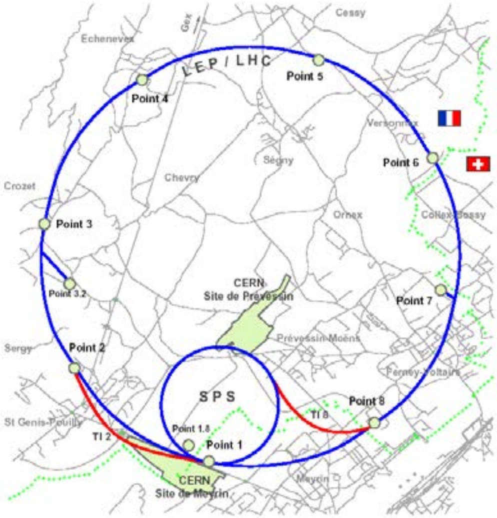
	e	Unit
Inject		T
Curre		A
Nomi		T
Curre	0	A
Induc		mH
Storec		MJ
Ultim		T
Curre	0	A
Storec		MJ
Maxi		T
Opera		K
Magn	2	mm
Distance between aperture axes at 1.9 K	194.00	mm

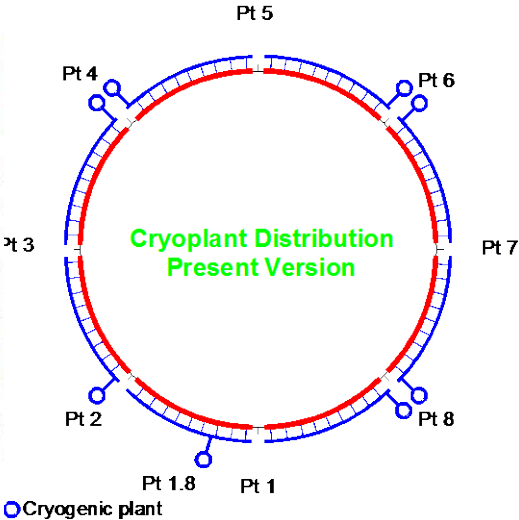


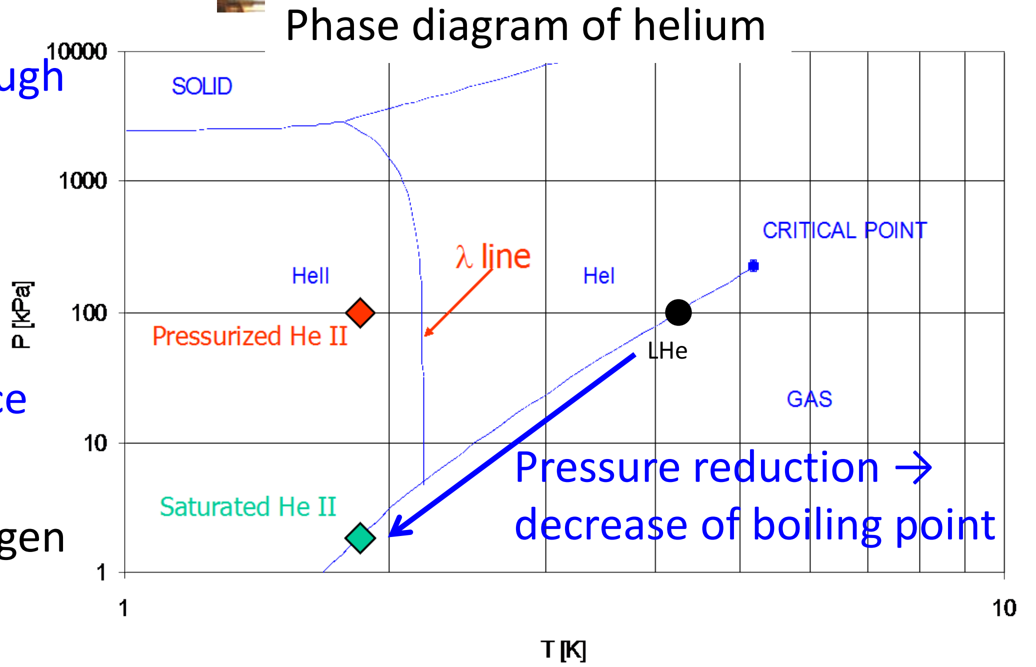
– Babcock Noell (Germany)

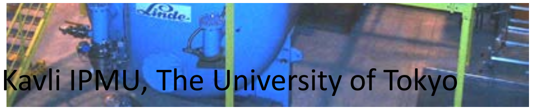
Cryogenics

- Cold mass of 37000 tons in 27km tunnel
- Cool-down to 1.9 K within 2 weeks
  - 18 kW@ 4.5 K refrigerator × 8
  - 2.4 kW@ 1.8 K refrigerator × 8
- GHe&LHe 4.2K: Pre-cooling, immersion
- Superfluid helium (HeII）1.9K: magnet coolant
  - Very low viscosity
    - “Super-fluidity”: penetrating through very small holes
  - Very high specific heat
    - more than 1000 times that of SC conductor
    - robustness for thermal disturbance
  - Very high thermal conductance
    - More than 1000 times that of oxygen free copper
    - heat absorption capability

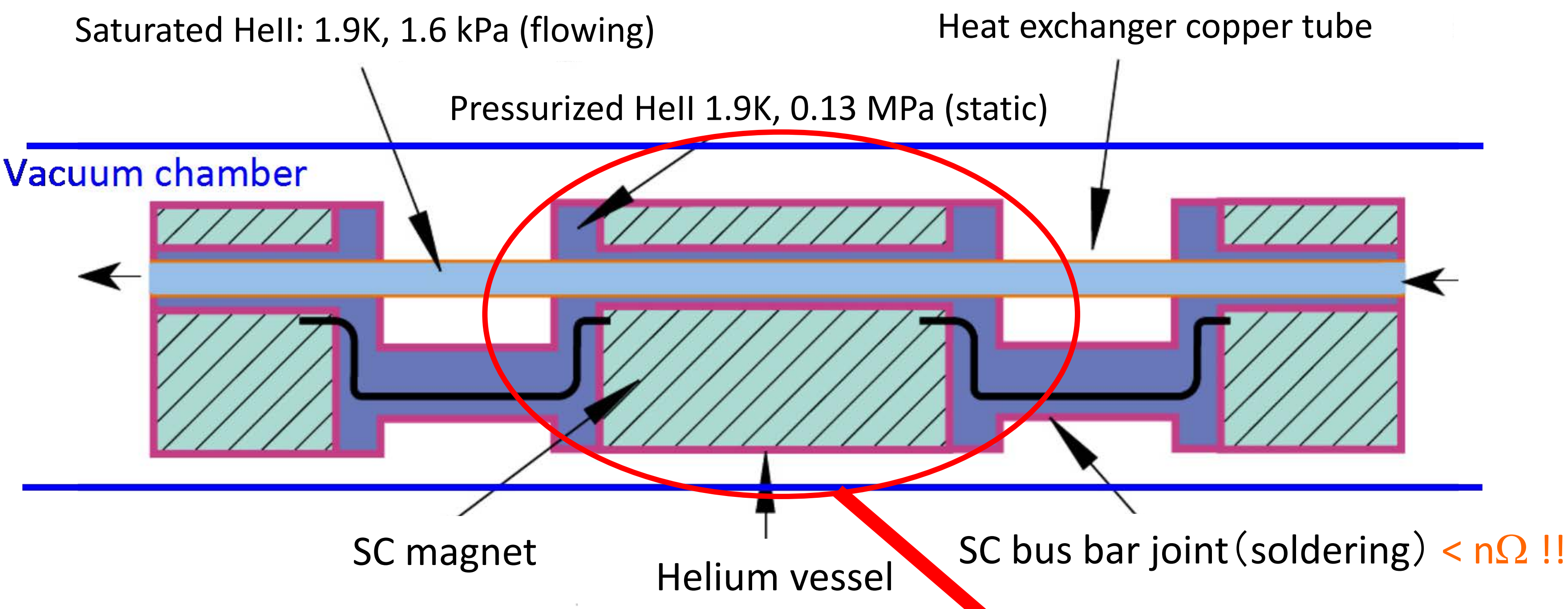





Phase diagram of helium



Cryogenics



Saturated HeII: 1.9K, 1.6 kPa (flowing)

Heat exchanger copper tube

Pressurized HeII 1.9K, 0.13 MPa (static)

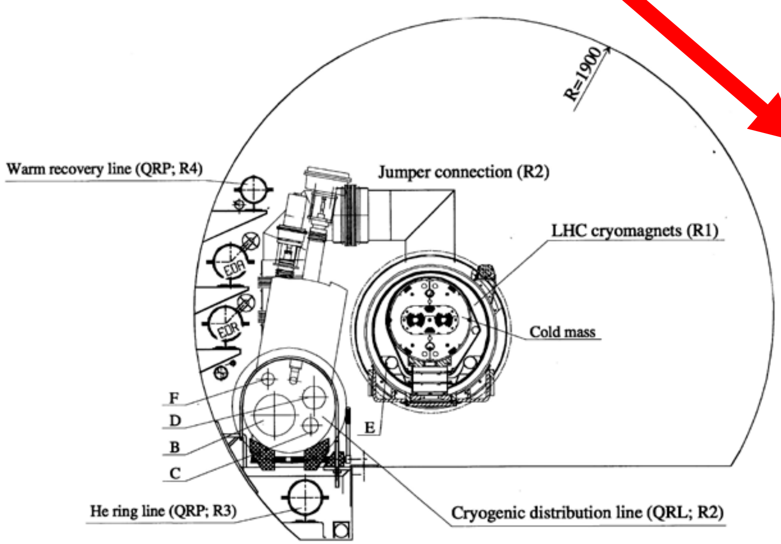
Vacuum chamber

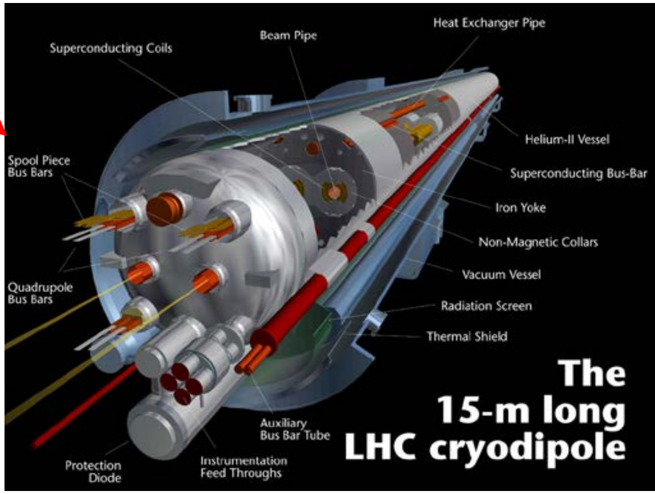
SC magnet

Helium vessel

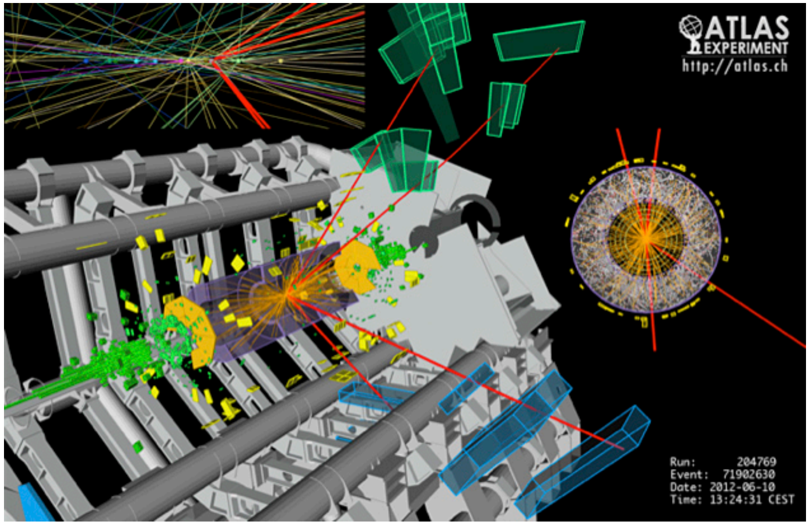
SC bus bar joint（soldering） < nΩ !!

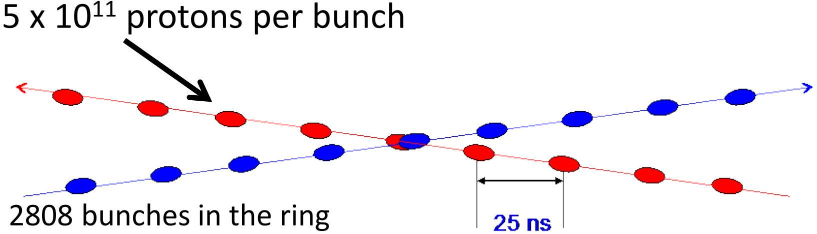
- Huge, complicated cryogenics system at ground and in the tunnel.
- Number of welding…
  - Suffering of “cold leak” at commissioning

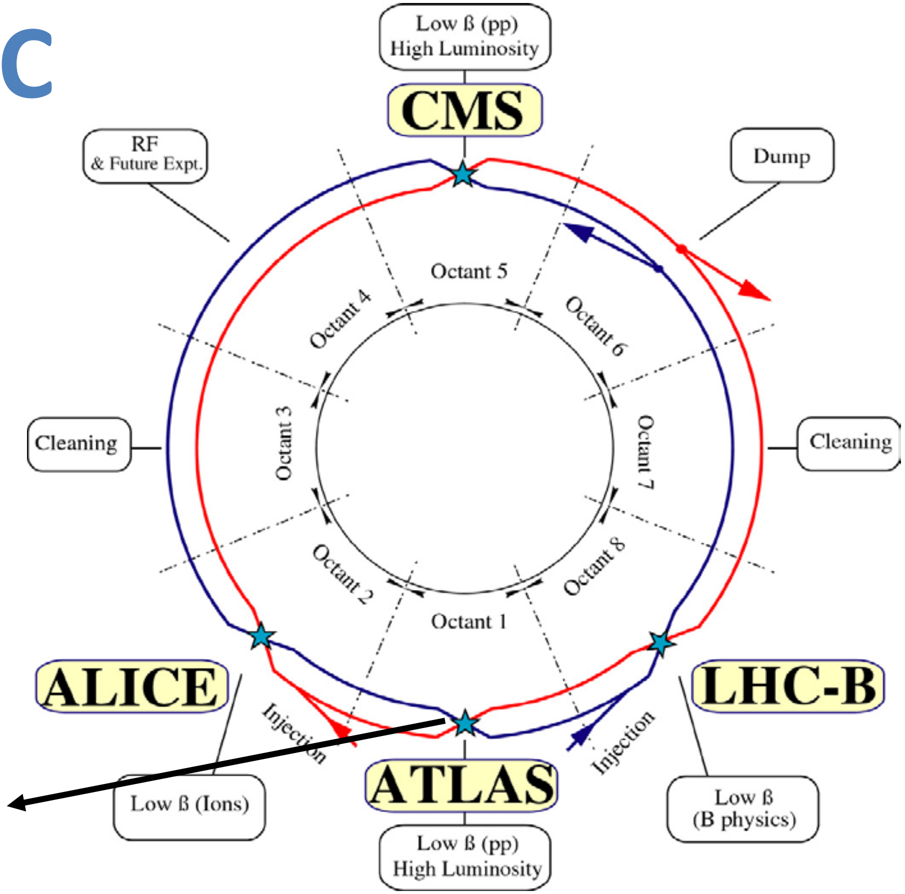




Review: Nominal LHC







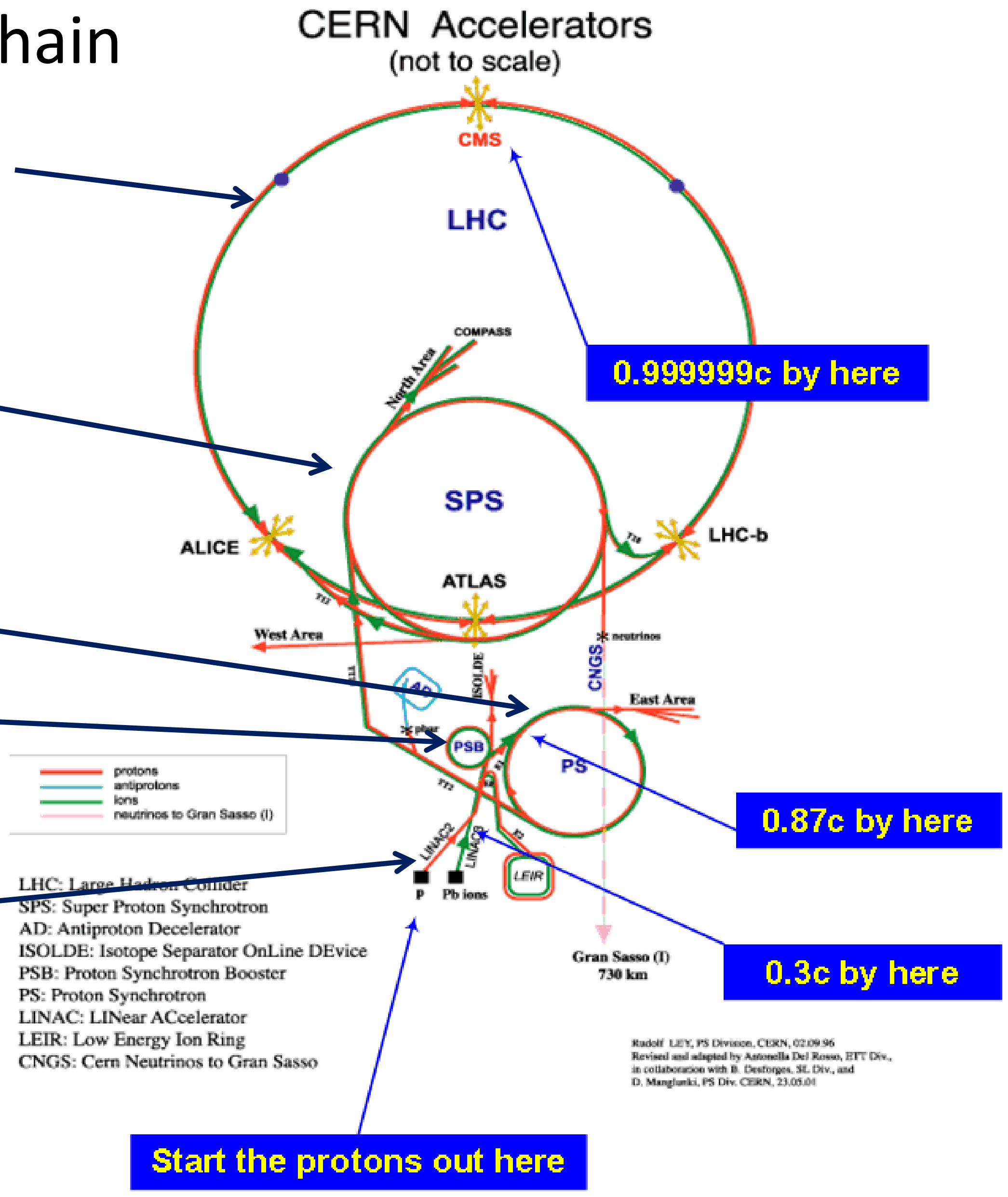
- LHC is a circulator collider with the world highest collision energy (7 +7 TeV).
  - SC magnets and cryogenics are key technologies.
- LHC is one of the world largest SC magnet system.
  - LHC consists of 1232 main dipole magnets (15m, 8.33T, 11850A) and more than 6000 other SC magnets operated at 1.9 K by HeII.
- 2 proton beams repeatedly circulate in the ring and number of collision events(~1,000,000,000 Hz) take place at luminosity of 1×10^{34} $cm^{-2}sec^{-1}$.

Contents

LHC is not alone…

CERN Proton Accelerator Chain

- LHC : 2x(0.45 – 7) TeV
- SPS : 26 – 450 GeV
- PS : 1.4 - 26 GeV
- PSB : 0.05 -1.4 GeV
- Linac: 0-50 MeV



0.999999c by here

0.87c by here

0.3c by here

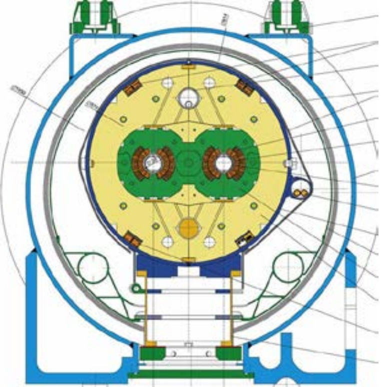
Start the protons out here

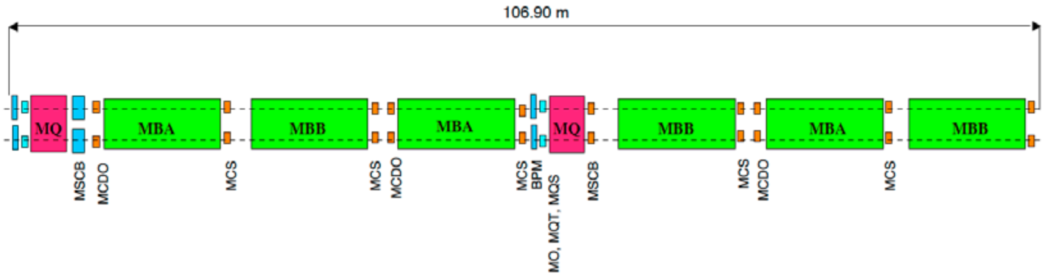
LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

Rudolf LEY, PS Division, CERN, 02.09.96
Revised and adapted by Antonella Del Rosso, ETT Div.,
in collaboration with B. Desforges, SL Div., and
D. Manglunki, PS Div. CERN, 23.05.01

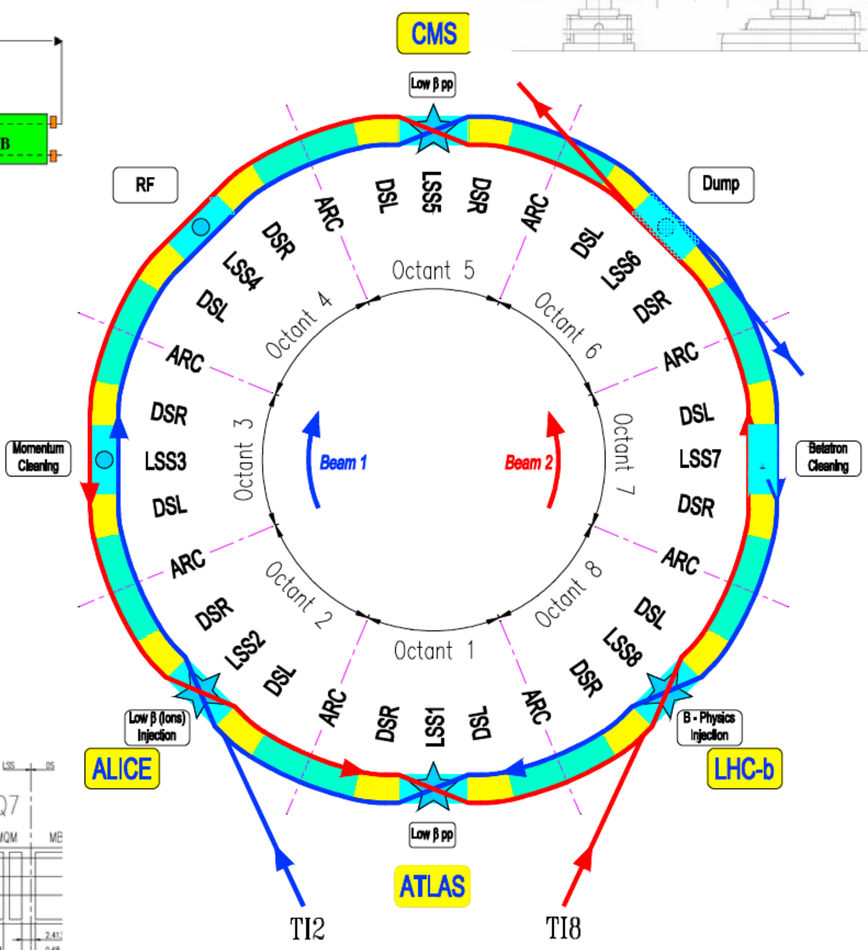
LHC: Arcs & Insertions

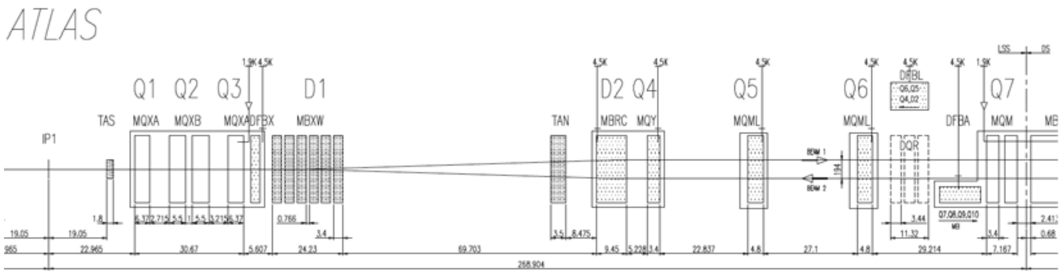
- 8 Arcs
  - 23 * a single cell: a FODO lattice (90° phase advance)
  - Two beams separated by 194 mm.
    - Concept of “2 in 1” dipole and quadrupole magnets





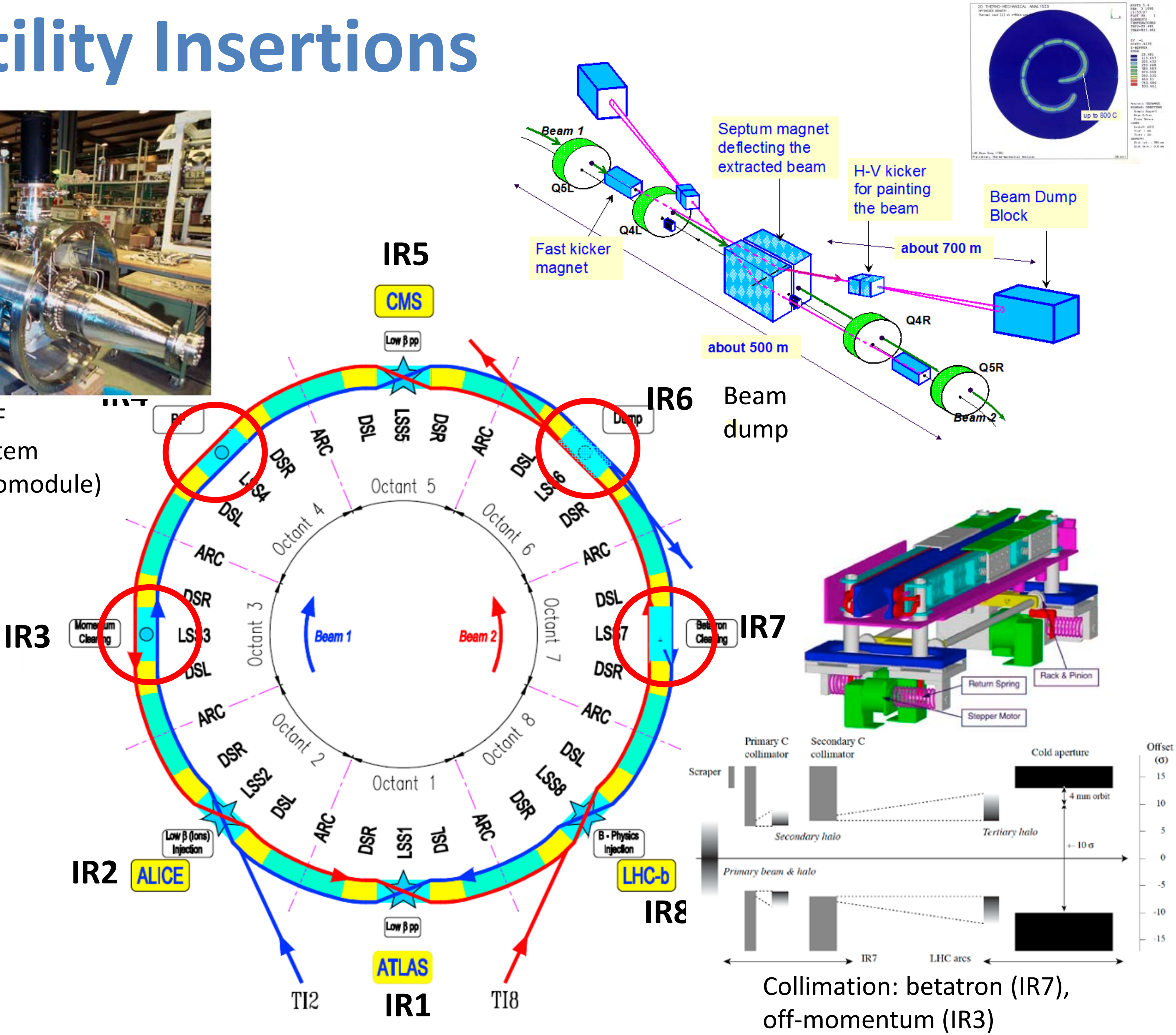
- Dispersion Suppressor
- 8 LSS (~530 m)
  - 4 experimental insertions
  - 1 for beam accelerations (RF)
  - 2 for beam collimation
  - 1 for beam dump





LHC: Utility Insertions

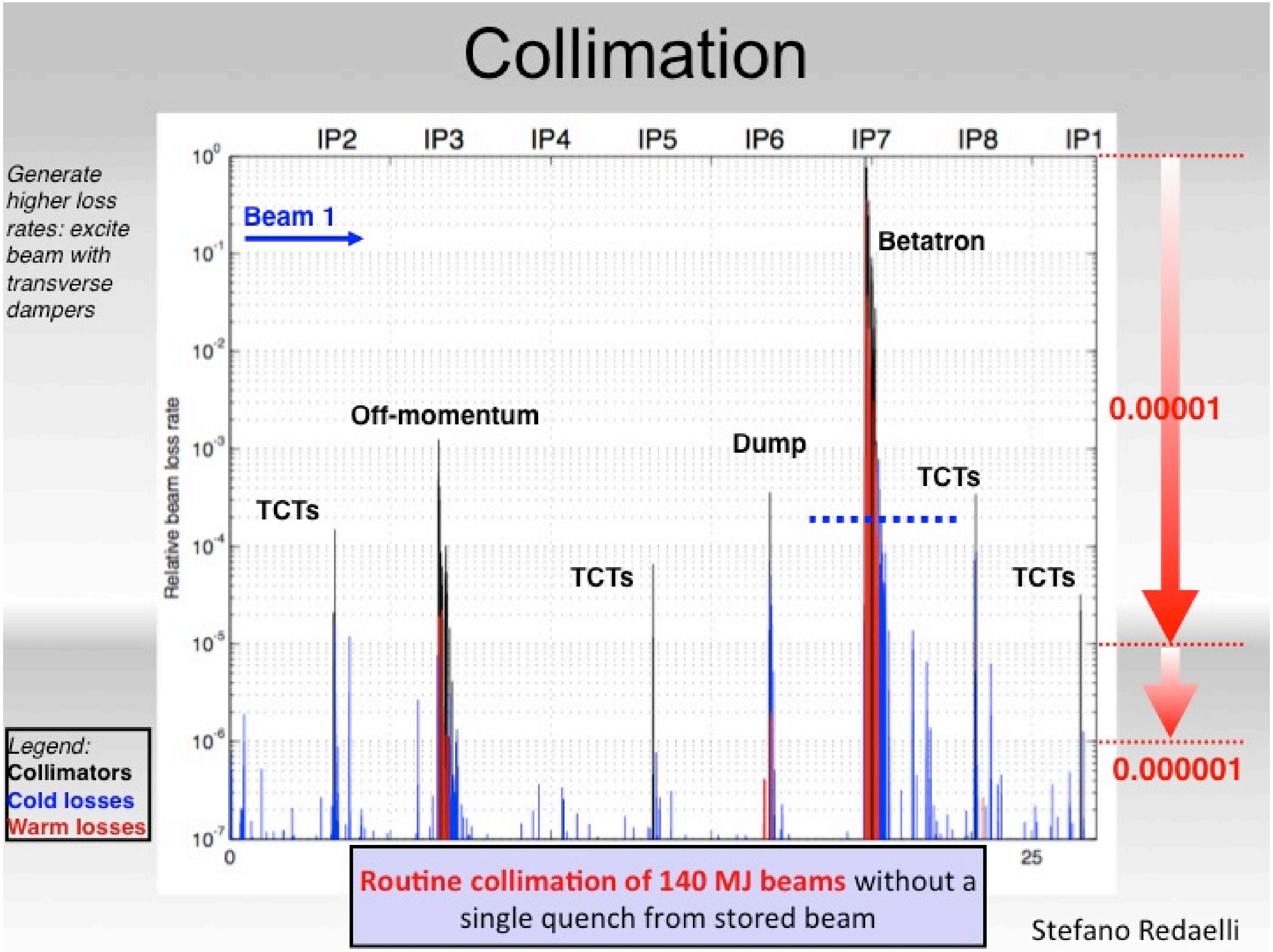
Main 400MHz RF Accelerating System (Four-Cavity Cryomodule)



Beam dump

Collimation: betatron (IR7), off-momentum (IR3)

Collimation



Collimation

Generate higher loss rates: excite beam with transverse dampers

Legend:
Collimators
Cold losses
Warm losses

Routine collimation of 140 MJ beams without a single quench from stored beam

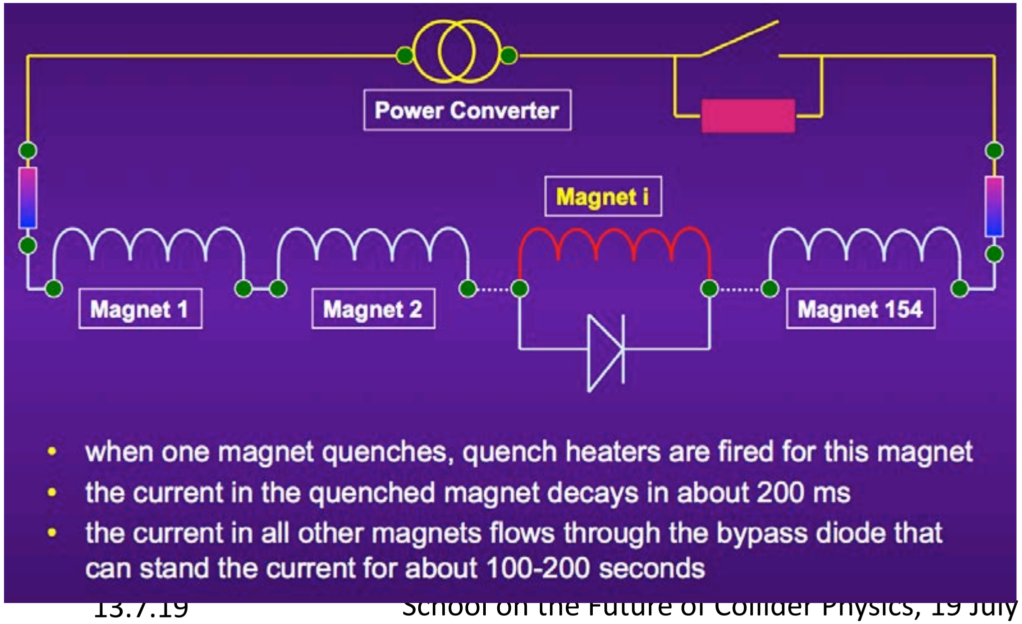
Stefano Redaelli

Safety, Protection

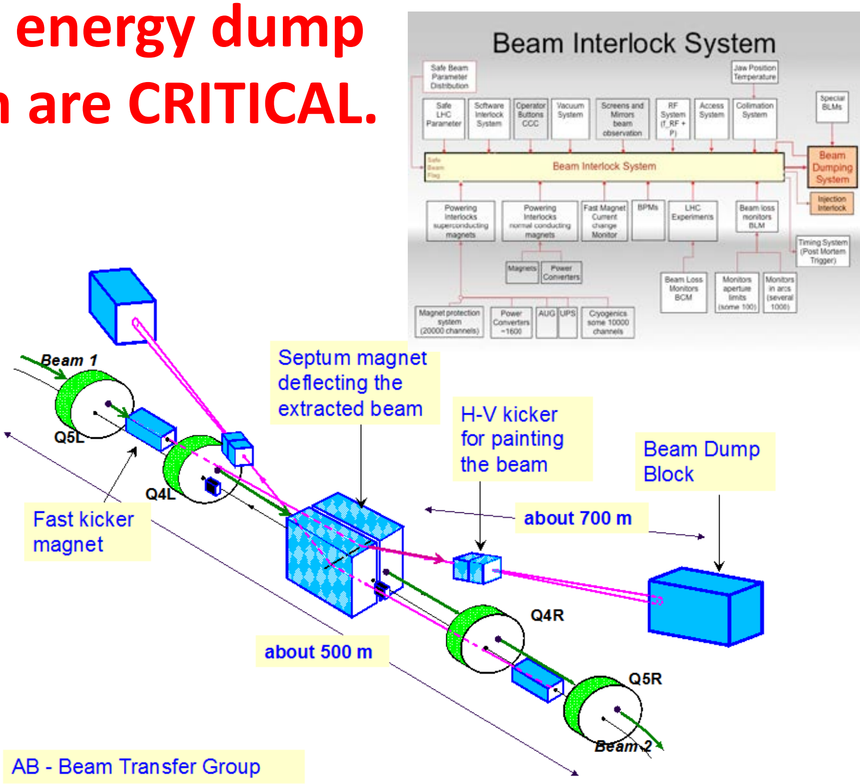
Are you aware of …

- total stored energy of the SC magnets in the LHC?
  - 10 GJ
    - equivalent to the energy of 2400 kg TNT explosive…
- total proton beam energy in the LHC ring?
  - 720 MJ
    - which can melt 1 ton of copper…

Detection of failure and quick & safe energy dump system for the magnet and the beam are CRITICAL.



- when one magnet quenches, quench heaters are fired for this magnet
- the current in the quenched magnet decays in about 200 ms
- the current in all other magnets flows through the bypass diode that can stand the current for about 100-200 seconds



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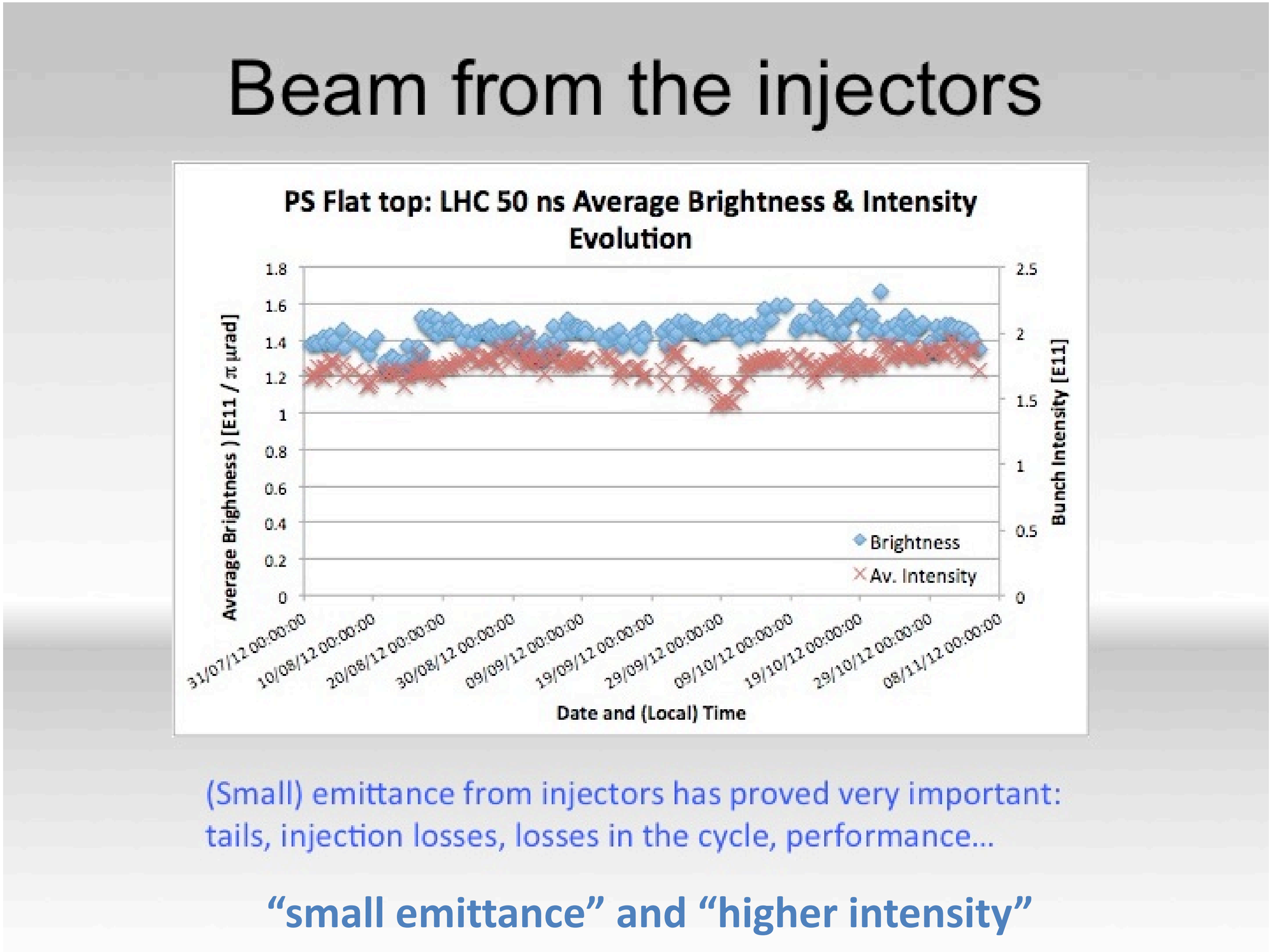
LHC Performance: Injector

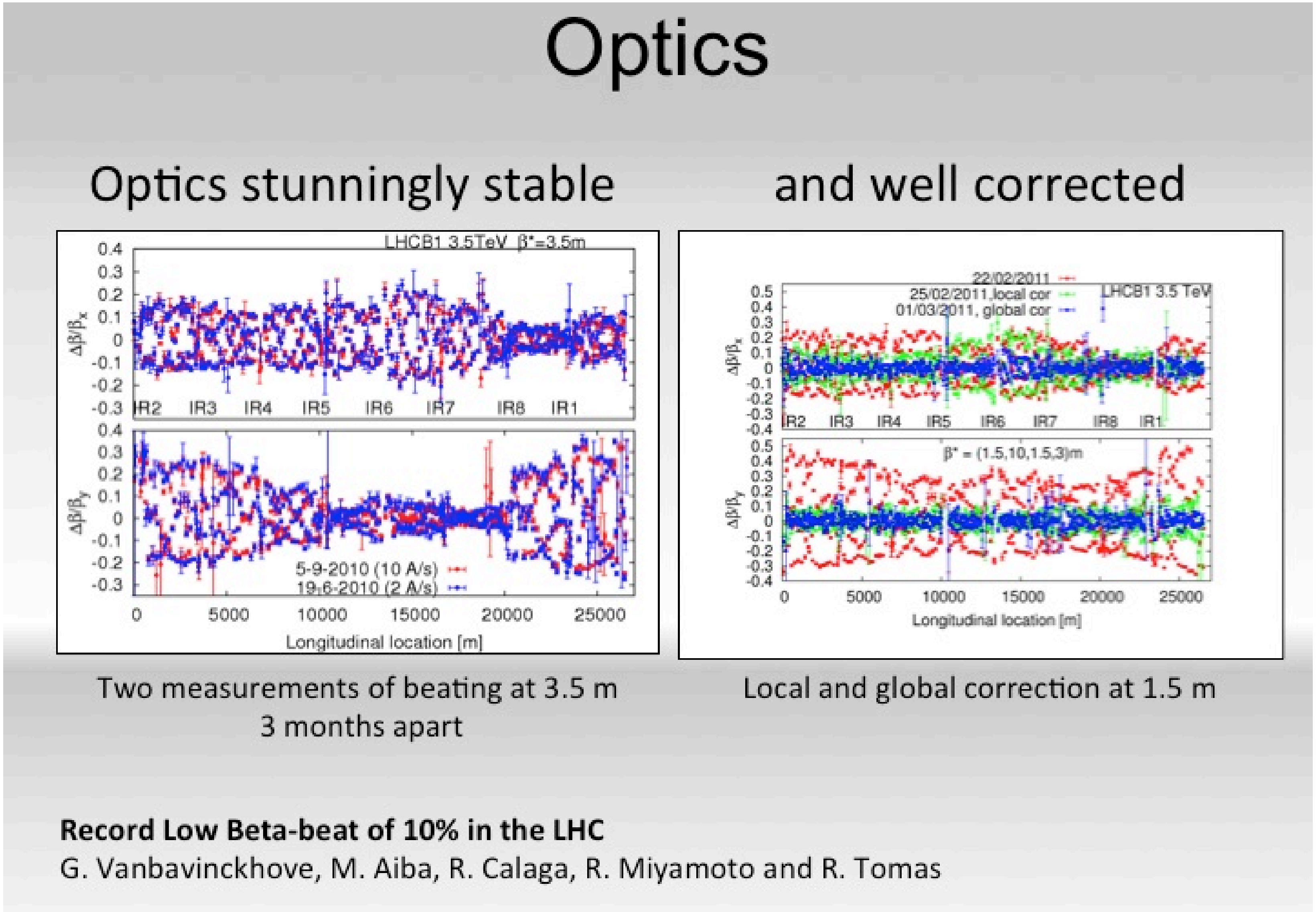


Beam from the injectors

(Small) emittance from injectors has proved very important: tails, injection losses, losses in the cycle, performance…

"small emittance" and "higher intensity"

LHC Performance: Optics



Optics

Optics stunningly stable

and well corrected

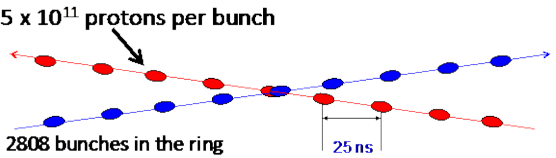
Two measurements of beating at 3.5 m
3 months apart

Local and global correction at 1.5 m

Record Low Beta-beat of 10% in the LHC
G. Vanbavinckhove, M. Aiba, R. Calaga, R. Miyamoto and R. Tomas

β^* close to the model: field quality, correction, collimation, alignment…

Present LHC Performance



Beam current

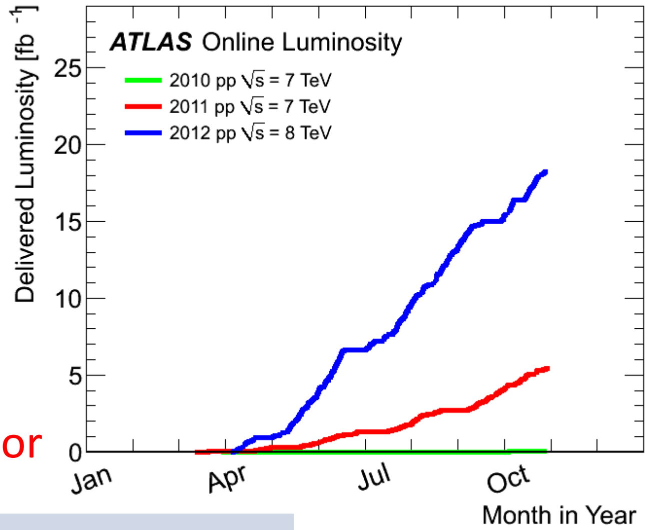
$$L = \gamma_r \frac{N_b^2 n_b f_{rev}}{4\pi\varepsilon_n\beta^*} F$$

Energy

Beam Size

$$F = 1/\sqrt{1+\frac{(\theta_c\sigma_z)^2}{4\varepsilon_n\beta^*}\gamma_r}$$

Geometric reduction factor



	Best by 2012	Nominal
Energy [TeV]		7.0
β^* [m] IP 1,5		0.55
Bunch spacing [ns]		25
ε_n, Normalized emittance [mm.mrad]		3.75
N_b, Bunch intensity		1.15e11
n_b, Number of bunches		2808
Stored energy [MJ]		362/beam
Peak luminosity [$cm^{-2}s^{-1}$]		1.0e34

Close to design

Pile up

67% of nominal !!

Double batch from booster

77 % design Lumi., even at 4/7 energy!!

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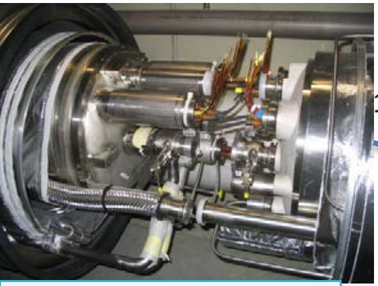
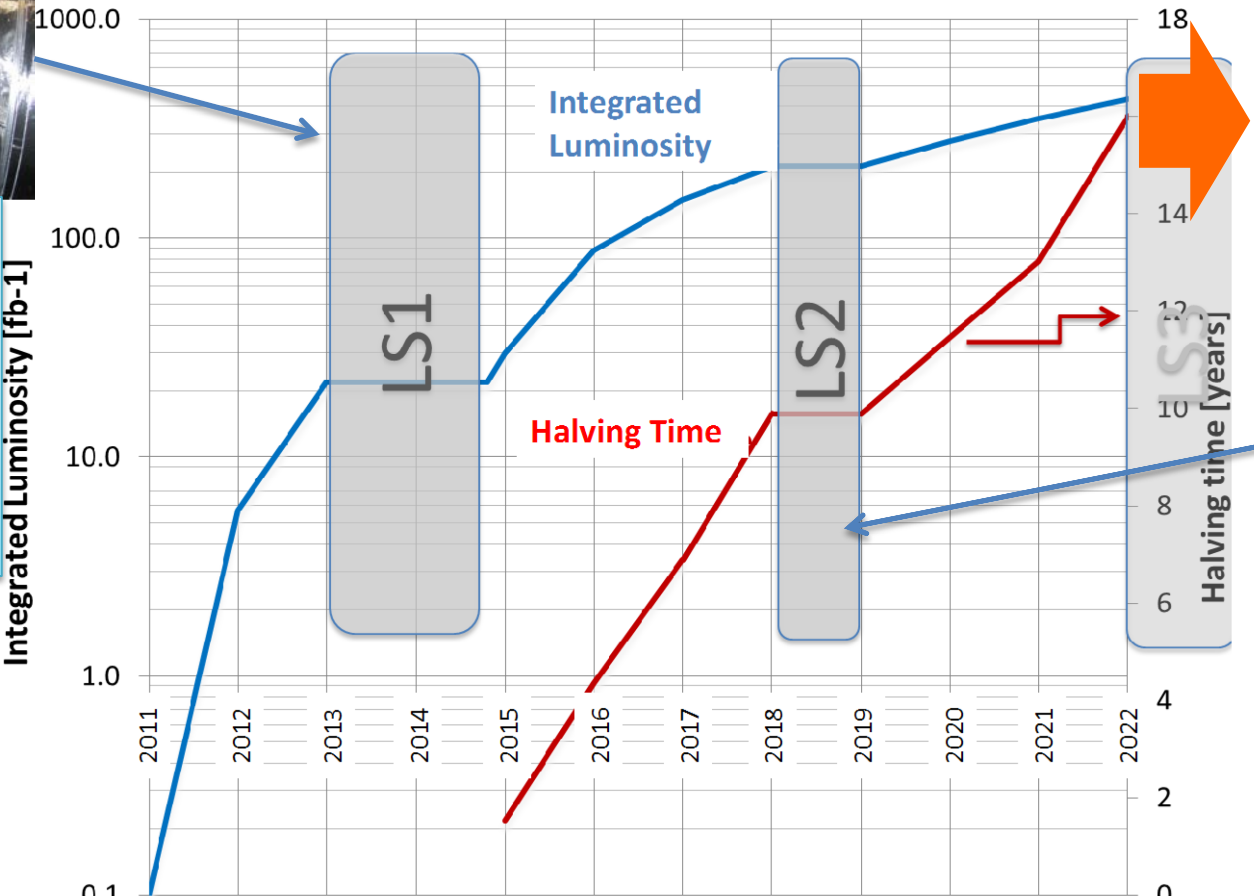
High Luminosity LHC Upgrade (HL-LHC)

Target: 3000fb^{-1}, 5x10^{34} cm^{-2} sec^{-1}

(Nominal LHC 300fb^{-1}, 1x10^{34} cm^{-2} sec^{-1})



Shut down to fix interconnects and overcome energy limitation (LHC incident of Sept 2008) and R2E



2022 Installation HL-LHC (plan)

Shut down to overcome beam intensity limitation (Injectors, collimation and more…)

Time evolution of “Integrated Luminosity” & “Halving time of

Upgrading Scenario

Beam current

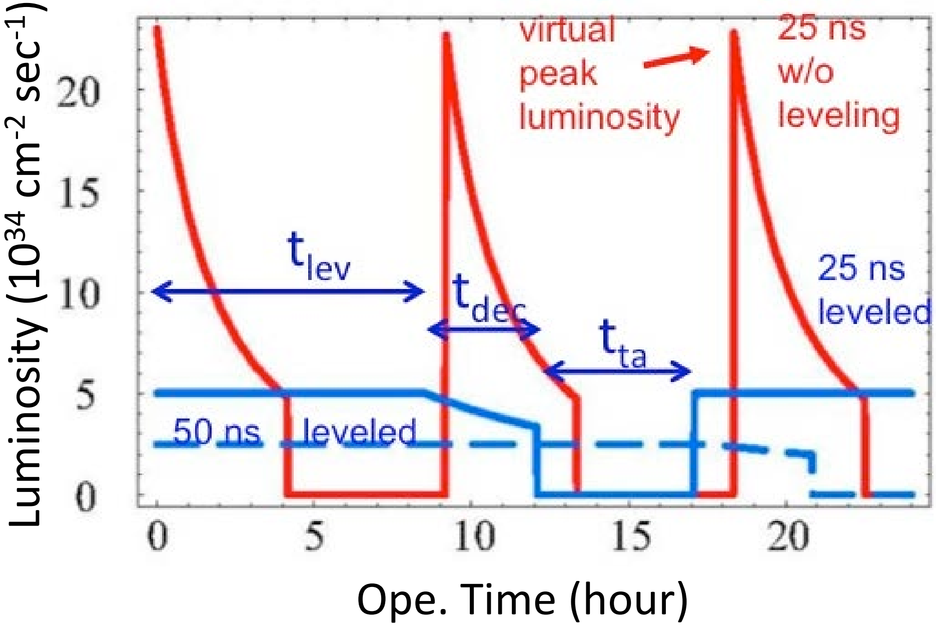
$$L = \gamma_r \frac{N_b^2 n_b f_{rev}}{4\pi\varepsilon_n\beta^*} F$$

Energy

Beam Size

$$F = 1 / \sqrt{1 + \frac{(\theta_c \sigma_z)^2}{4\varepsilon_n \beta^*} \gamma_r}$$

Geometric reduction factor



Attaining Higher Peak Luminosity

- Increasing beam current
  - LHC Injectors Upgrade (LIU)
    - * while keeping small emittance…
- Small β^*
  - New optics & Layout
    - Achromatic Telescopic Squeeze
    - New crossing angle
  - New IR magnets
    - Large aperture Quads and beam separation dipole
    - strong corrector
- Enhancement of collision efficiency
  - Crab-Cavities for IR
- Suppression of Pile-Up events
  - Leveled by detuning of optics, CC.

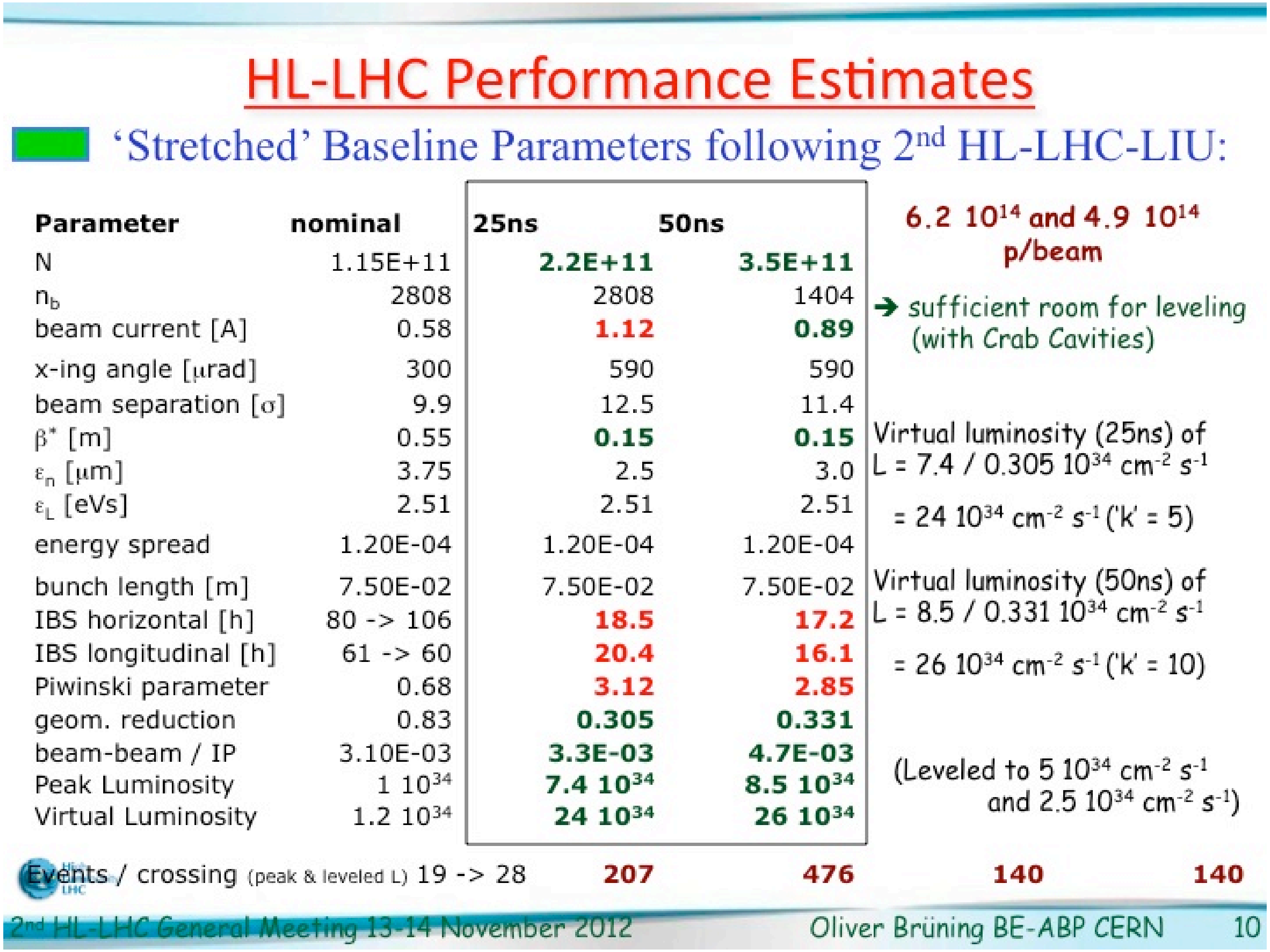
Additional Price

Measures associated with high beam power, radiation, heat load…

- Collimation upgrade
  - New collimator, e-Lens
  - 11T Nb_3Sn dipole for DS at IR 3/7
- Protection for electronics in the tunnel
  - SC Link & relocation of P/C to the surface
  - R2E (Radiation to Electronics)
- Heat deposition into the IR magnets
  - Reinforcement of new cryo-plants (!!)
  - Tungsten shield in beam pipe

Substantial efforts must be taken for the machine protection and the improvement of performance.

HL-LHC: Baseline Parameters at 2^{nd} CM 2012



HL-LHC Performance Estimates

🟩 'Stretched' Baseline Parameters following 2^{nd} HL-LHC-LIU:

Parameter	**nominal**	**25ns**	**50ns**
N	1.15E+11	**2.2E+11**	**3.5E+11**
n_b	2808	2808	1404
beam current [A]	0.58	**1.12**	**0.89**
x-ing angle [μrad]	300	590	590
beam separation [σ]	9.9	12.5	11.4
β^* [m]	0.55	**0.15**	**0.15**
ε_n [μm]	3.75	2.5	3.0
ε_L [eVs]	2.51	2.51	2.51
energy spread	1.20E-04	1.20E-04	1.20E-04
bunch length [m]	7.50E-02	7.50E-02	7.50E-02
IBS horizontal [h]	80 -> 106	**18.5**	**17.2**
IBS longitudinal [h]	61 -> 60	**20.4**	**16.1**
Piwinski parameter	0.68	**3.12**	**2.85**
geom. reduction	0.83	**0.305**	**0.331**
beam-beam / IP	3.10E-03	**3.3E-03**	**4.7E-03**
Peak Luminosity	$1\ 10^{34}$	**$7.4\ 10^{34}$**	**$8.5\ 10^{34}$**
Virtual Luminosity	$1.2\ 10^{34}$	**$24\ 10^{34}$**	**$26\ 10^{34}$**

Events / crossing (peak & leveled L) 19 -> 28 **207** **476** **140** **140**

$6.2\ 10^{14}$ and $4.9\ 10^{14}$ p/beam

→ sufficient room for leveling (with Crab Cavities)

Virtual luminosity (25ns) of $L = 7.4 / 0.305\ 10^{34}\ cm^{-2}\ s^{-1}$

$= 24\ 10^{34}\ cm^{-2}\ s^{-1}$ ('k' = 5)

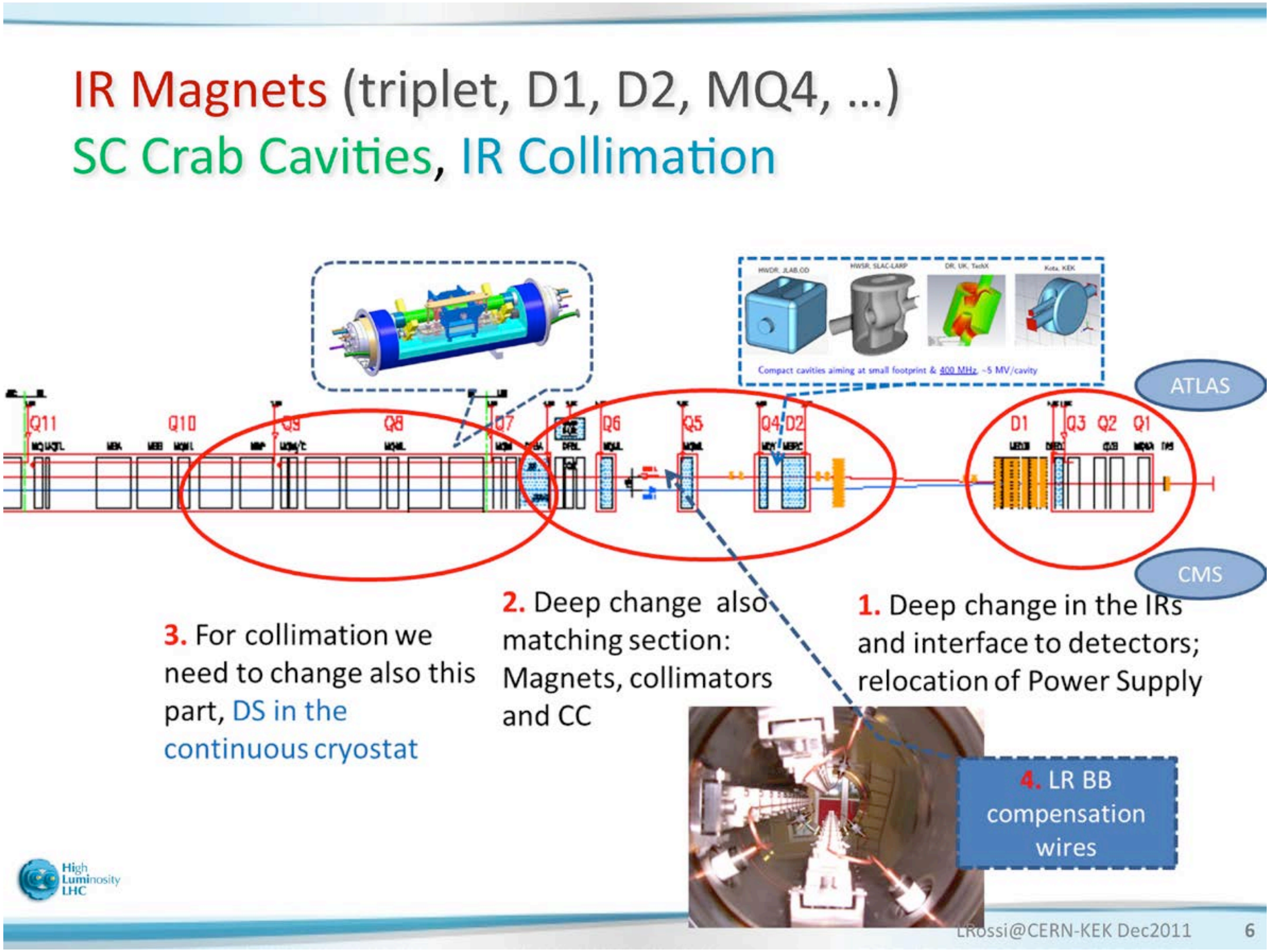
Virtual luminosity (50ns) of $L = 8.5 / 0.331\ 10^{34}\ cm^{-2}\ s^{-1}$

$= 26\ 10^{34}\ cm^{-2}\ s^{-1}$ ('k' = 10)

(Leveled to $5\ 10^{34}\ cm^{-2}\ s^{-1}$ and $2.5\ 10^{34}\ cm^{-2}\ s^{-1}$)

2^{nd} HL-LHC General Meeting 13-14 November 2012 Oliver Brüning BE-ABP CERN 10

HL-LHC: R&D Items



IR Magnets (triplet, D1, D2, MQ4, …)

SC Crab Cavities, IR Collimation

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

1. Deep change in the IRs and interface to detectors; relocation of Power Supply

2. Deep change also matching section: Magnets, collimators and CC

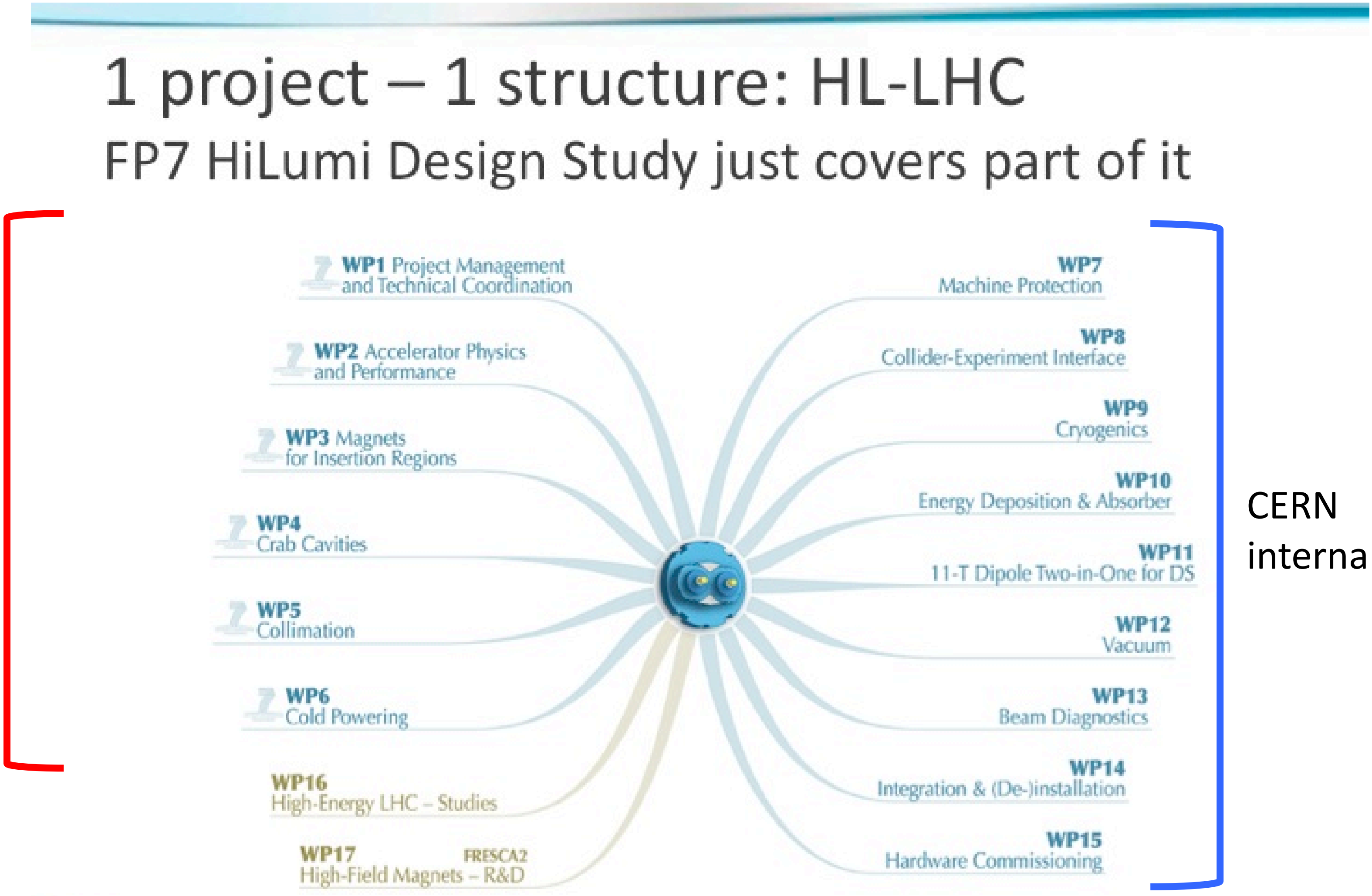
3. For collimation we need to change also this part, DS in the continuous cryostat

4. LR BB compensation wires

LRossi@CERN-KEK Dec2011 6

HL-LHC Project: Work Packages

HiLumi-LHC in EC-FP7



1 project – 1 structure: HL-LHC

FP7 HiLumi Design Study just covers part of it

WP1 Project Management and Technical Coordination

WP2 Accelerator Physics and Performance

WP3 Magnets for Insertion Regions

WP4 Crab Cavities

WP5 Collimation

WP6 Cold Powering

WP16 High-Energy LHC – Studies

WP17 High-Field Magnets – R&D FRESCA2

WP7 Machine Protection

WP8 Collider-Experiment Interface

WP9 Cryogenics

WP10 Energy Deposition & Absorber

WP11 11-T Dipole Two-in-One for DS

WP12 Vacuum

WP13 Beam Diagnostics

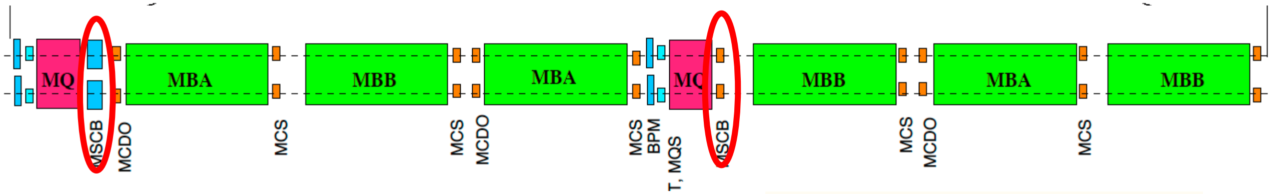
WP14 Integration & (De-)installation

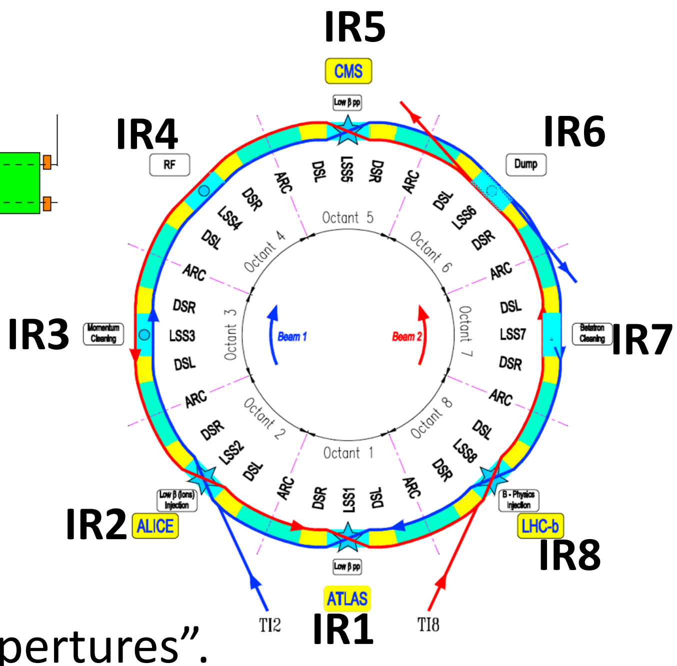
WP15 Hardware Commissioning

CERN internal

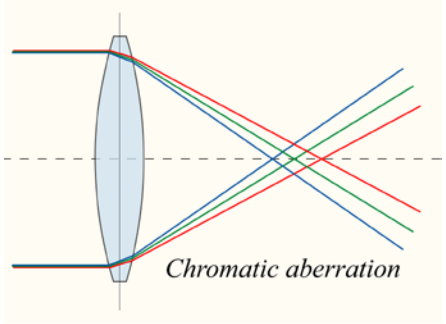
- Conceptual design study and model R&D started at 2011
- International collaboration by CERN, European institute, US-LARP, Japan
- Another ongoing project "LIU": LHC Injectors Upgrade project https://espace.cern.ch/liu-project/default.aspx

WP2: Accelerator Physics





- Motivation: having small β*
- Constraint:
  - Modification only at IR.
  - Preserve “arc” as is.

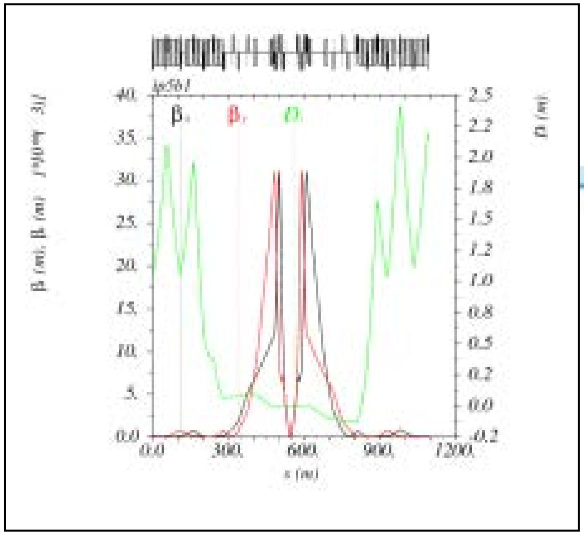


- IR magnets, anyway, must be renewed with “large apertures”.

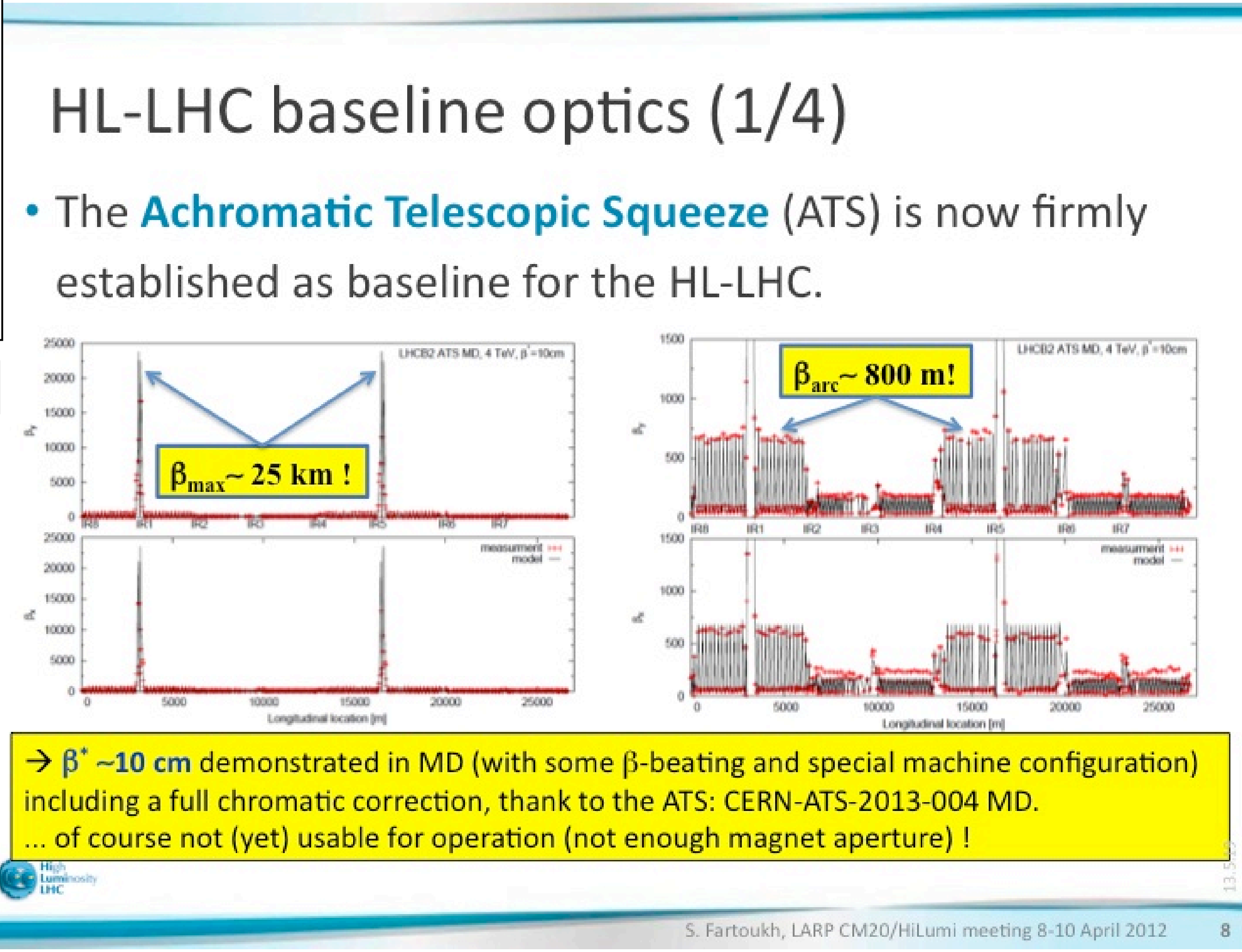
$$\beta_{\max} \sim \frac{\ell^{*2}}{\beta^{*}} \ , \ \sigma_{IRbeam} = \sqrt{\varepsilon \beta_{\max}}$$

- Problematic huge chromatic aberration induced by the final focusing quads (Q1-Q3) must be corrected: Achromatic Telescopic Squeezing (ATS)
  - Pre-squeeze: using the quads at IR1(ATLAS) and IR5(CMS) as usual.
  - Squeeze: also acting on the insertions at IR8/2 for IR1 and IR4/6 for IR5 to gain a factor of 4 to 8.
    - Sizable β-beating bumps induced in the 4 sectors (81, 12, 45, 56) are necessary to enhance the chromaticity correction at the existing “lattice sextupole correctors”.

WP2: Accelerator Physics



ATLAS & CMS: β^*=10 cm (…”ultimately”)



HL-LHC baseline optics (1/4)

- The **Achromatic Telescopic Squeeze** (ATS) is now firmly established as baseline for the HL-LHC.

β_{max}~ 25 km !

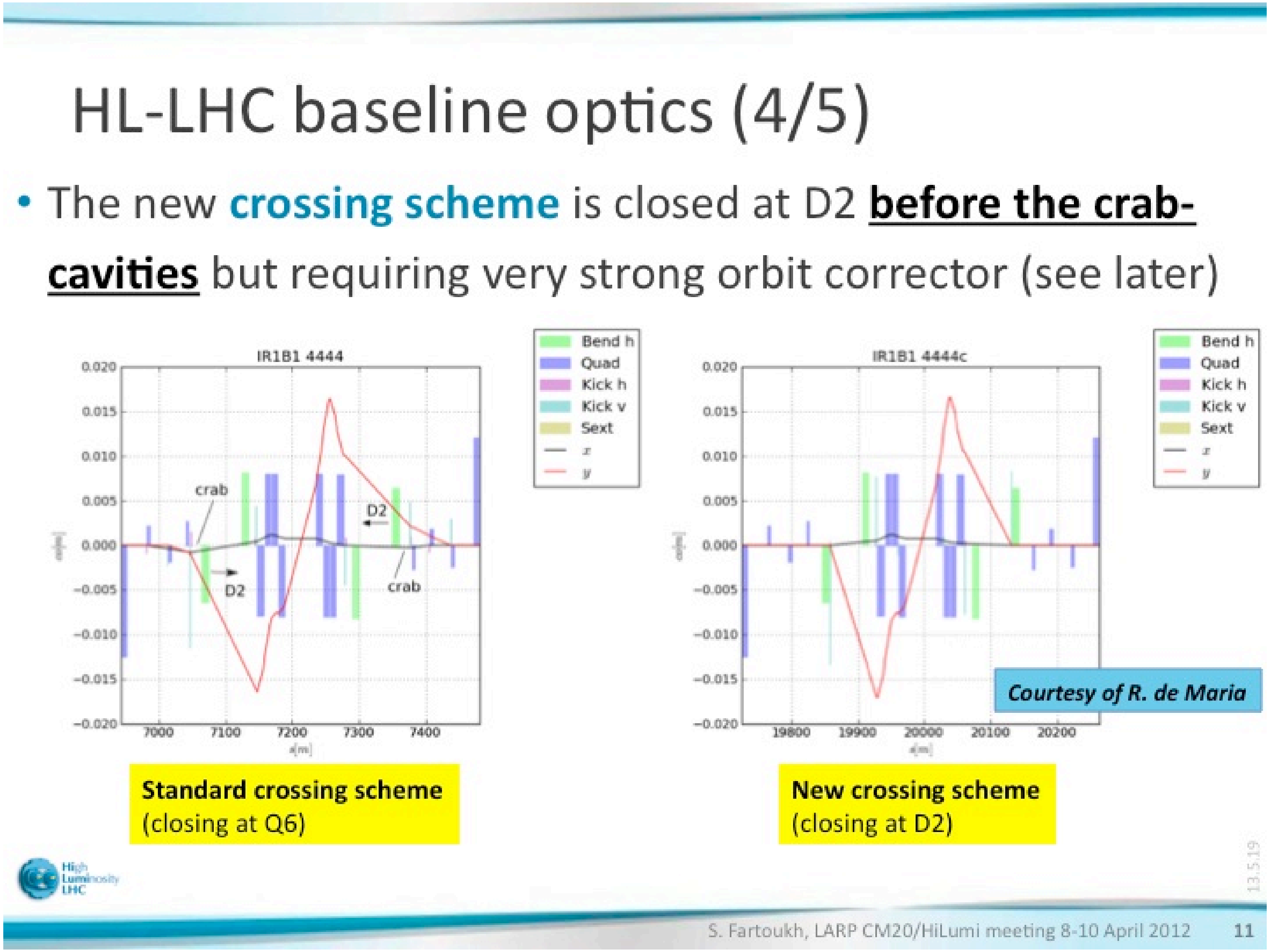
β_{arc}~ 800 m!

→ β^* ~10 cm demonstrated in MD (with some β-beating and special machine configuration) including a full chromatic correction, thanks to the ATS: CERN-ATS-2013-004 MD.
… of course not (yet) usable for operation (not enough magnet aperture) !

High Luminosity LHC

S. Fartoukh, LARP CM20/HiLumi meeting 8-10 April 2012 8

WP2: Accelerator Physics



HL-LHC baseline optics (4/5)

- The new **crossing scheme** is closed at D2 **before the crab-cavities** but requiring very strong orbit corrector (see later)

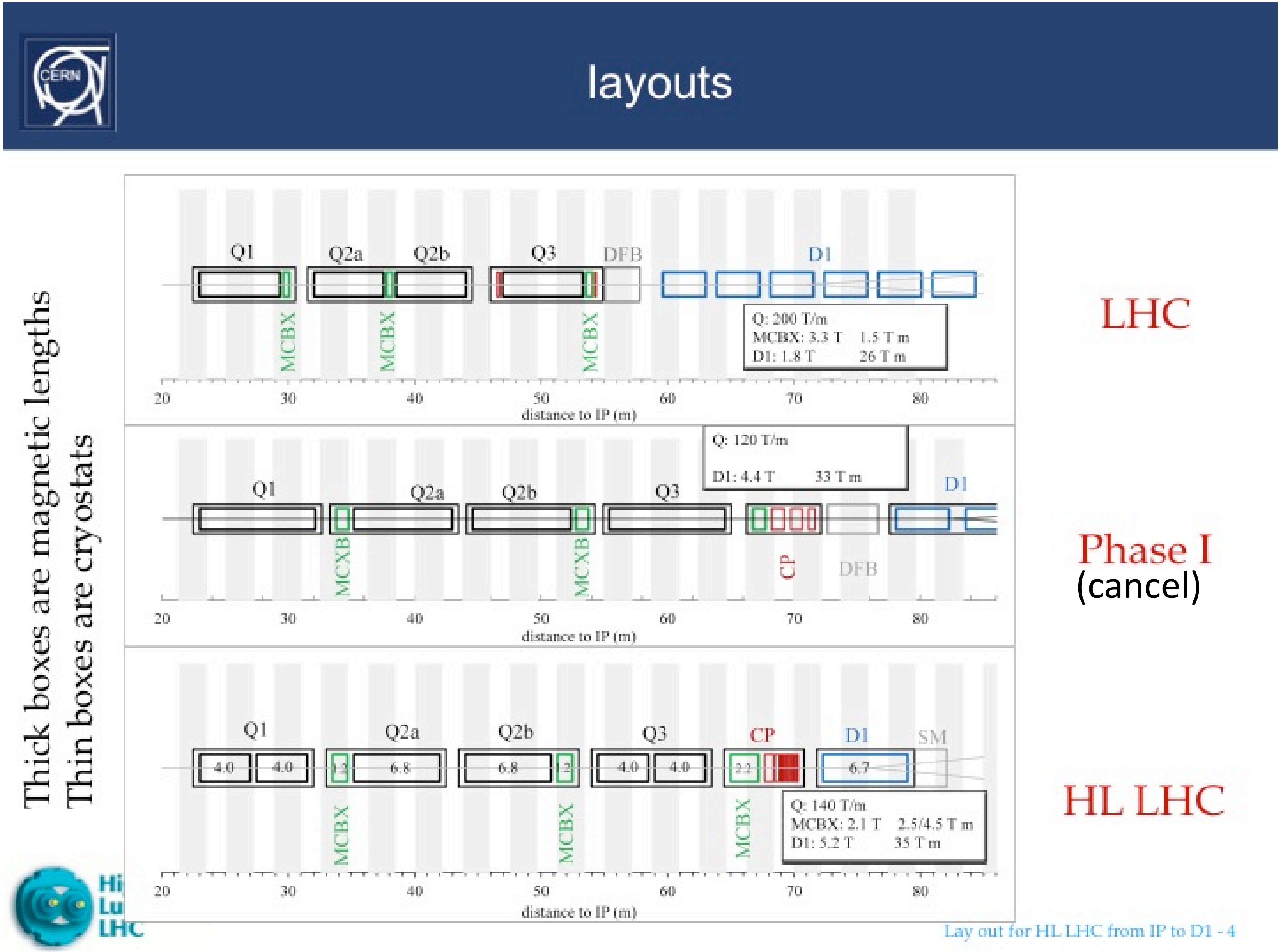
Standard crossing scheme
(closing at Q6)

New crossing scheme
(closing at D2)

Courtesy of R. de Maria

S. Fartoukh, LARP CM20/HiLumi meeting 8-10 April 2012 11

WP3: IR Magnets, Layout



layouts

Thick boxes are magnetic lengths
Thin boxes are cryostats

Q: 200 T/m
MCBX: 3.3 T 1.5 T m
D1: 1.8 T 26 T m

LHC

Q: 120 T/m
D1: 4.4 T 33 T m

Phase I
(cancel)

Q: 140 T/m
MCBX: 2.1 T 2.5/4.5 T m
D1: 5.2 T 35 T m

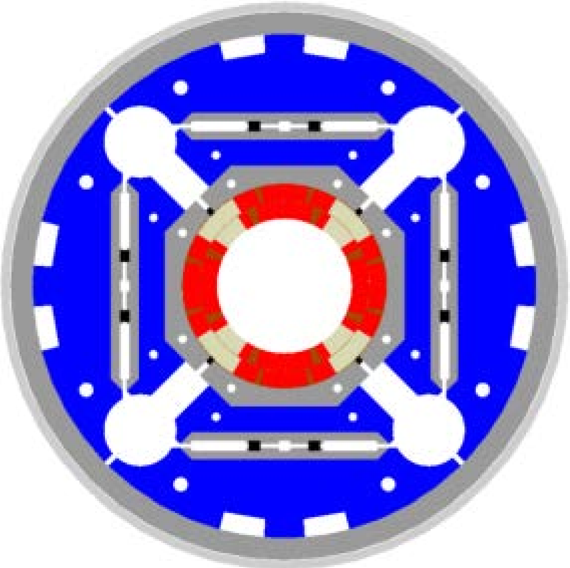
HL LHC

Hi Lu LHC

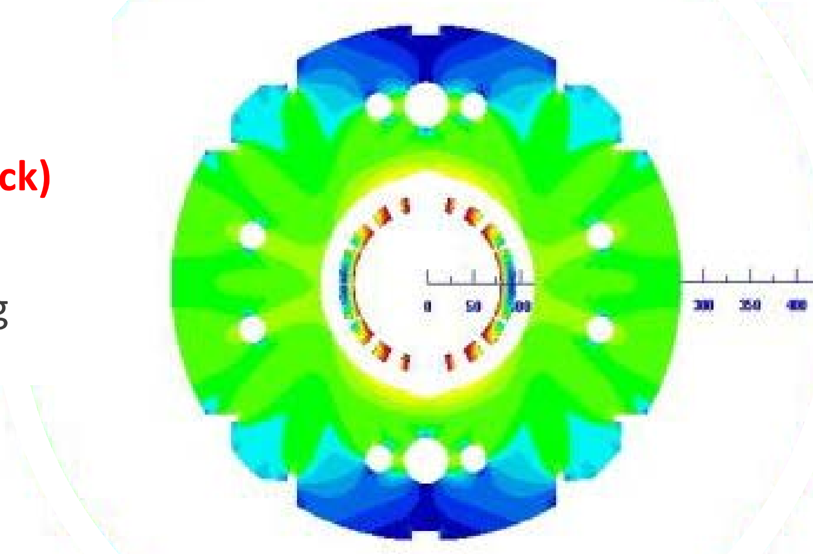
Lay out for HL LHC from IP to D1 - 4

WP3: IR Magnets

- Aperture selection: **Q1-Q3 150 mm**, **D1: 160 mm**, **Q4: 90 mm**
- Energy deposition and heat load targets
  - Targets for peak values: **40 MGy - 4 mW/cm^3**
  - Achieved with large shieding with beam screen and W
  - Higher temperature in the coil: 1.9+0.75 K (midplane)
- Most critical triplet features, priorities for 2013
  - Performance: 80% on the loadline tight but achieved in LARP quads – instabilities are still an issue
  - **Conductor: smaller filament size, but where to stop ?**
  - Coil fabrication, electrical integrity
  - **Protection critical (HQ affected/protected by quenchback)**
- D1 tentative choice: 1 layer LHC cable, 5.2 T, 7.6 m long
- Q4 tentative choice: 1 layer LHC cable, 120 T/m, 4.5 m long



IT-Quad MQXF (Nb3Sn, 150 mm, G=140 T/m, B_{peak}= 12 T)

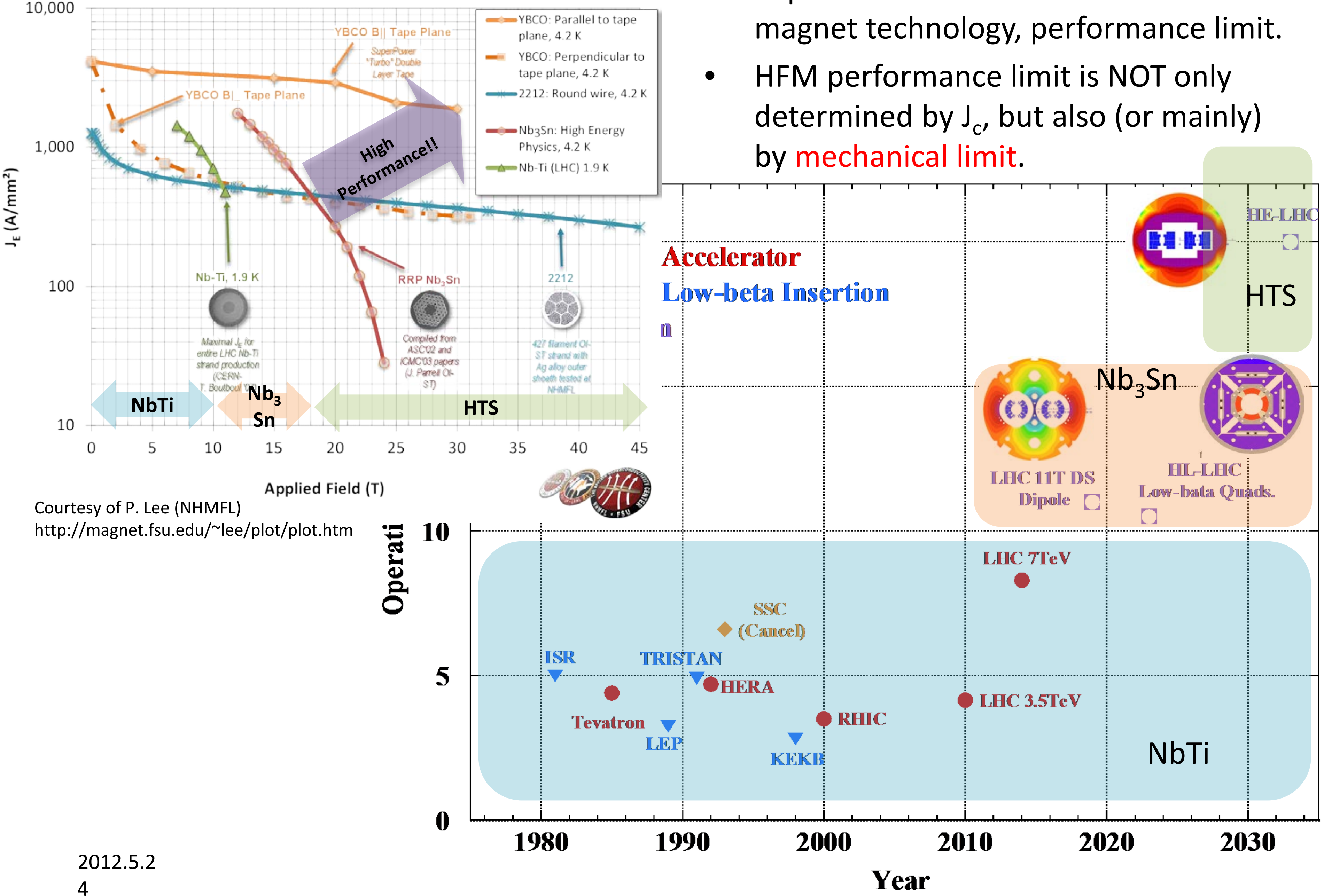


Beam separation Dipole (NbTi, 160 mm, B=5.2 T, B_{peak}= 6 T)

SC Magnets in Accelerators

Muon Collider 40T ???★

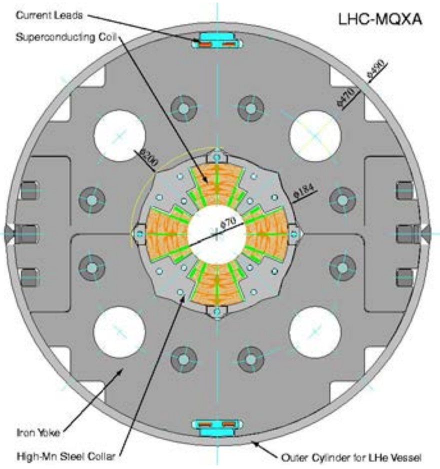
- Superconductor determines the magnet technology, performance limit.
- HFM performance limit is NOT only determined by J_c, but also (or mainly) by mechanical limit.

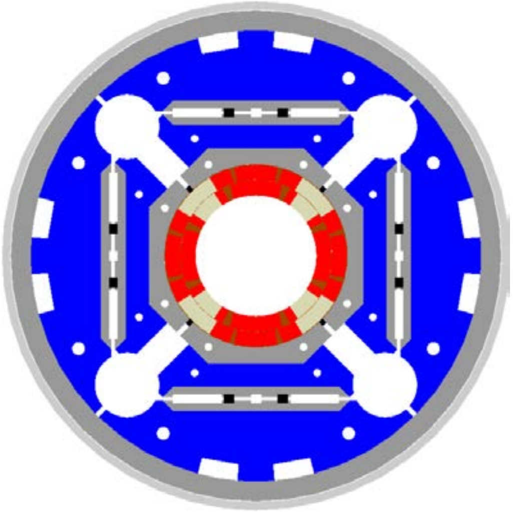


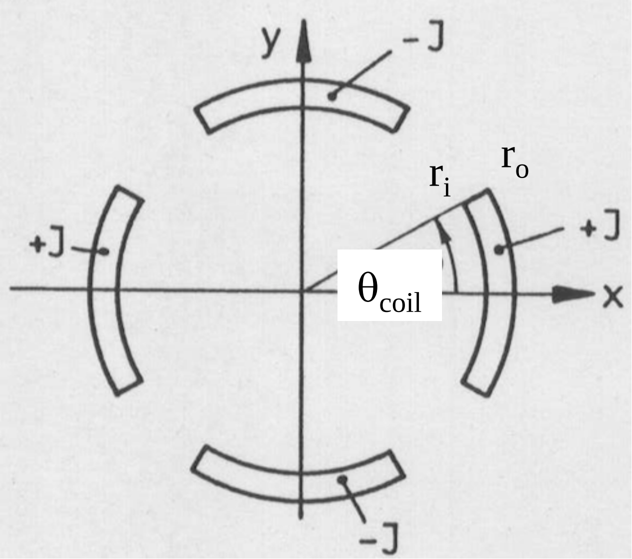
Courtesy of P. Lee (NHMFL)
http://magnet.fsu.edu/~lee/plot/plot.htm

70 mm NbTi vs 150 mm Nb_3Sn

- Coil aperture of IR Quads. (Q1-Q3)
  - LHC: 70 mm (MQXA, MQXB)
  - HL-LHC: 150 mm (MQXF)
- The larger, the better?
  - Yes: acceptable for larger beam, better field quality, lower heat deposition.
  - Price: stored energy, quench protection.







Field strength in the sector coil at r_{ref}

Dipole $$B_1 = -\frac{2\mu_0 J}{\pi}\sin(\theta_{coil})\underline{(r_o - r_i)}$$

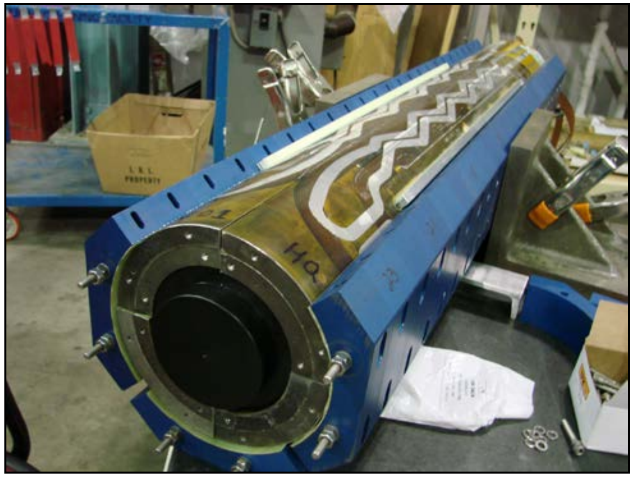
Quadrupole $$B_2 = -\frac{2\mu_0 \boxed{J} r_{ref}}{\pi}\sin(2\theta_{coil})\underline{\ln(\frac{r_o}{r_i})}$$

- If NbTi in larger coil aperture, field gradient ($G=B_2/r_{ref}$) will be reduced.
- Higher field Quads need “high J_c”: **Nb_3Sn**

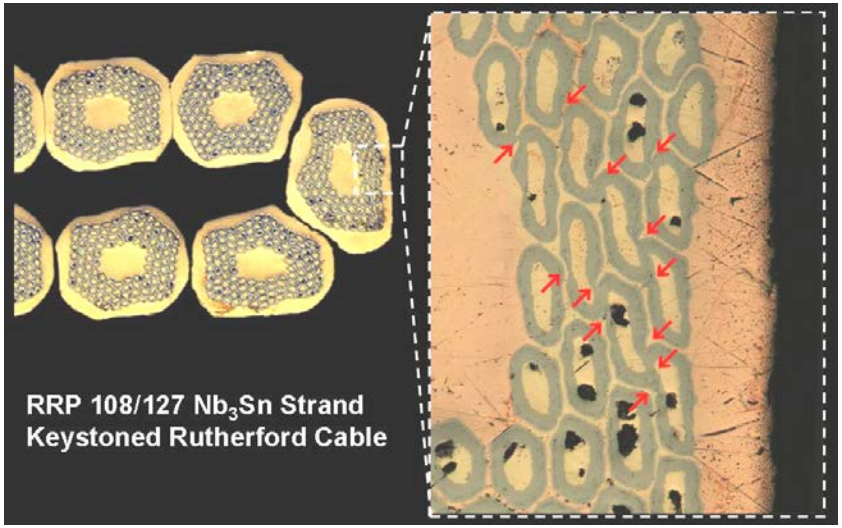
Nb_3Sn Magnet Technology

Superconductor	NbTi	Nb_3Sn	Remarks
Field Limit	~10 T @ 1.9 K	~17 T @ 4.2 K	
Fabrication	Winding (ductile)	Winding & React	very brittle
Heat treatment	~150 ° C for Cure	~650 ° C	thermal contraction, anisotropic transformation
Insulation	Polyimide, epoxy prepreg.	S/E glass, ceramic	not robust
Coil Parts	GFRP (G10)	Stainless steel, Ti alloy	need of ground insulation
Axial strain limit	-	~0.3 %	J_c degradation, damage
Lateral stress limit	-	~200 MPa	J_c degradation, damage

- Heat Reaction at ~650 ° C after coil winding
  - dedicated mechanical design and analysis for brittle Nb_3Sn coil: strain, stress.
  - inorganic insulation.
  - vacuum impregnation: essential for electrical insulation, mechanical reinforcement.



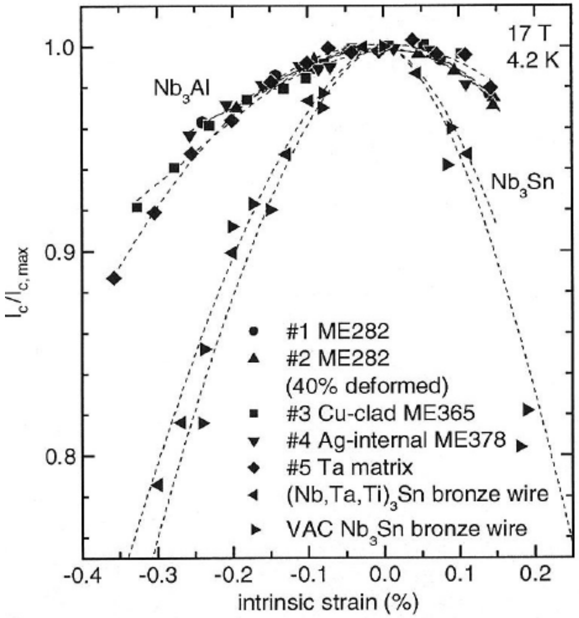
Difficulty



Courtesy of E. Barzi (Fermilab)

Strain sensitivity of J_c

A15 compounds (Nb_3Sn, Nb_3Al)

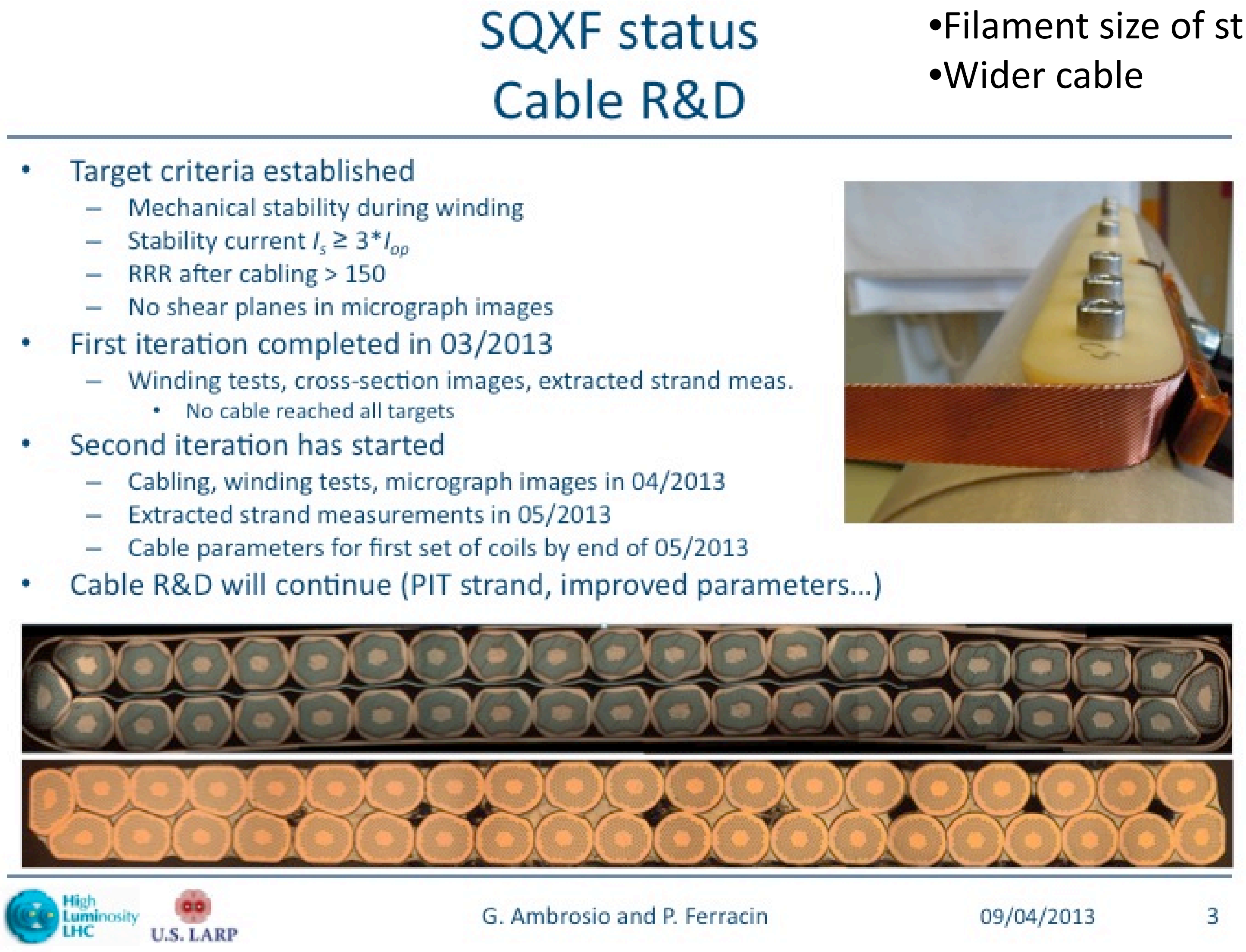


Supercond. Sci. Technol. 18 (2005) p. 284.
by N. Banno et al.

- Deformation, damage in cabling (Nb_3Sn, Nb_3Al)
  - Sub-elements: elongation, merger, breakage.
  - Tin leak at HT (Nb_3Sn).
- Strain dependence of Jc.
- Cracking of filament.
  - irreversible degradation.
  - stress history

Handling of stress issues is crucial in HFM.
For Nb_3Sn HFM, coil stress designed below the target limit of 200 MPa.

WP3: Nb_3Sn SC Cable for IT Quad. (150mm)



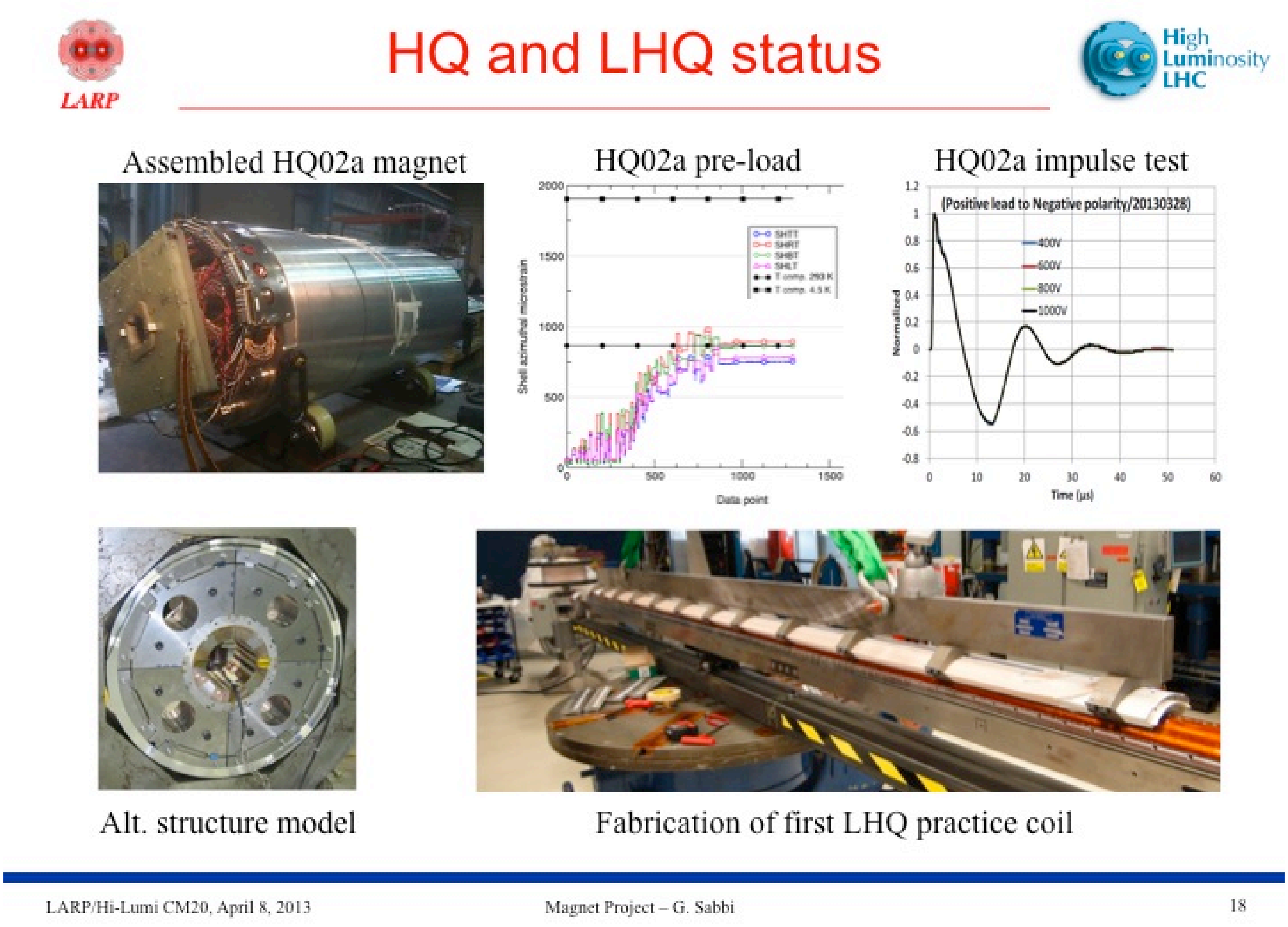
SQXF status
Cable R&D

- Target criteria established
  - Mechanical stability during winding
  - Stability current $I_s \geq 3^* I_{op}$
  - RRR after cabling > 150
  - No shear planes in micrograph images
- First iteration completed in 03/2013
  - Winding tests, cross-section images, extracted strand meas.
    - No cable reached all targets
- Second iteration has started
  - Cabling, winding tests, micrograph images in 04/2013
  - Extracted strand measurements in 05/2013
  - Cable parameters for first set of coils by end of 05/2013
- Cable R&D will continue (PIT strand, improved parameters…)

High Luminosity LHC U.S. LARP G. Ambrosio and P. Ferracin 09/04/2013 3

- Filament size of strand
- Wider cable

WP3: HQ (120 mm) Model Study



LARP

HQ and LHQ status

High Luminosity LHC

Assembled HQ02a magnet

HQ02a pre-load

HQ02a impulse test

Alt. structure model

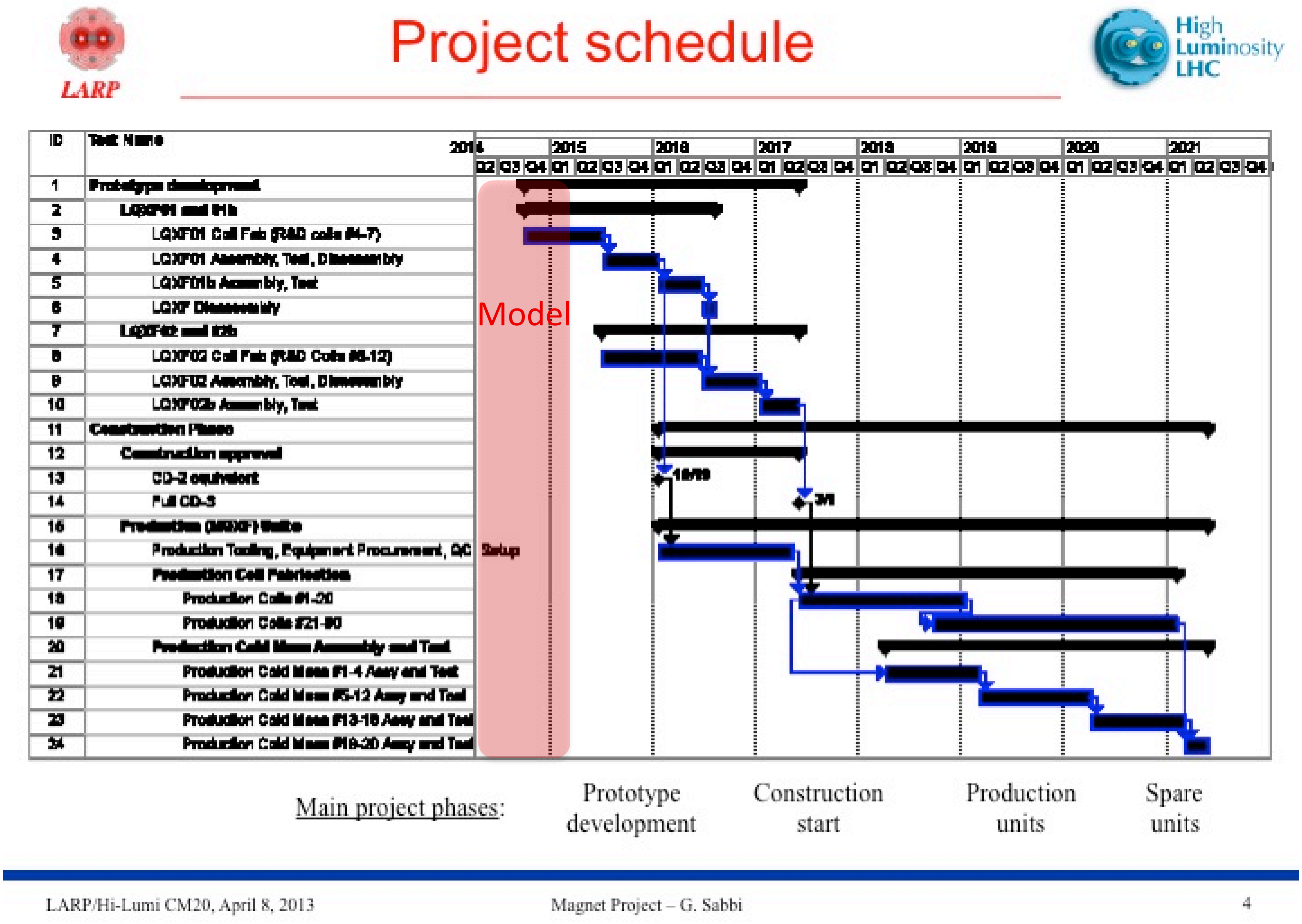
Fabrication of first LHQ practice coil

LARP/Hi-Lumi CM20, April 8, 2013

Magnet Project – G. Sabbi

18

WP3: Schedule of IT Quad.



Project schedule

LARP

High Luminosity LHC

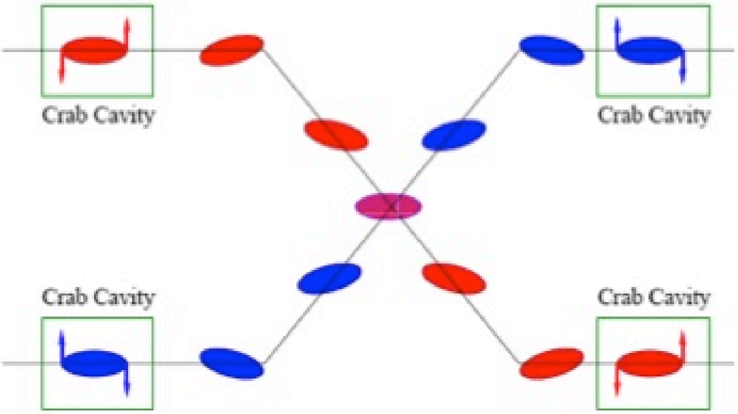
ID	Task Name
1	Prototype development
2	LQXF01 and 01b
3	LQXF01 Coil Fab (R&D coils #4-7)
4	LQXF01 Assembly, Test, Disassembly
5	LQXF01b Assembly, Test
6	LQXF Disassembly
7	LQXF02 and 02b
8	LQXF02 Coil Fab (R&D Coils #8-12)
9	LQXF02 Assembly, Test, Disassembly
10	LQXF02b Assembly, Test
11	Construction Phase
12	Construction approval
13	CD-2 equivalent
14	Full CD-3
15	Production (MQXF) Units
16	Production Tooling, Equipment Procurement, QC Setup
17	Production Coil Fabrication
18	Production Coils #1-20
19	Production Coils #21-40
20	Production Cold Mass Assembly and Test
21	Production Cold Mass #1-4 Assy and Test
22	Production Cold Mass #5-12 Assy and Test
23	Production Cold Mass #13-18 Assy and Tes
24	Production Cold Mass #19-20 Assy and Tes

Main project phases: Prototype development | Construction start | Production units | Spare units

LARP/Hi-Lumi CM20, April 8, 2013   Magnet Project – G. Sabbi   4

WP4: Crab Cavities

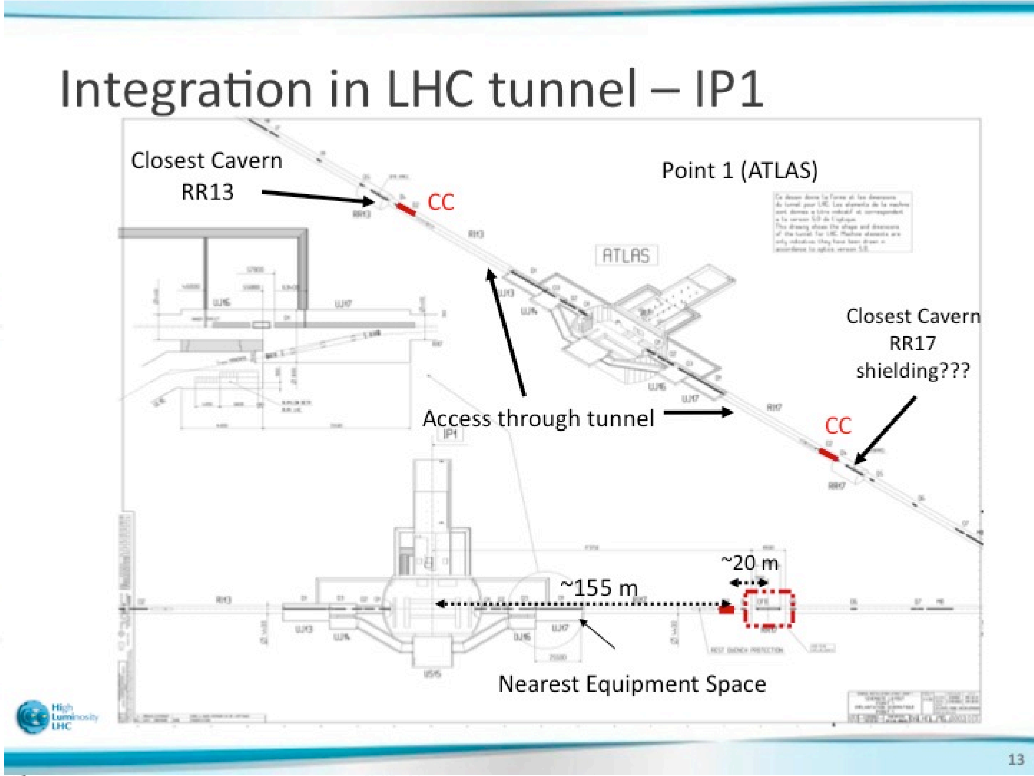
Crab Cavities

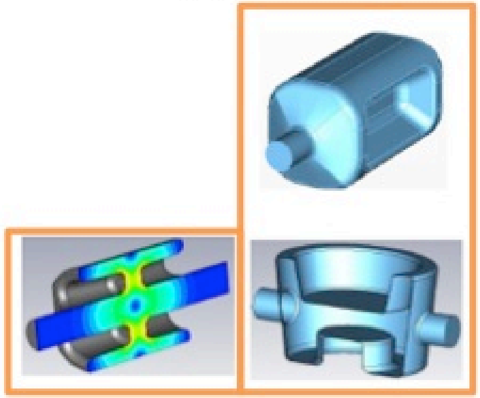


- Technical Challenges
  - Crab cavities have only *barely* been shown to work.
    - Never in hadron machines
  - LHC bunch length ➔ low frequency (400 MHz)
  - 19.4 cm beam separation ➔ “compact” (exotic) design
- Additional benefit
  - Crab cavities are an easy way to level luminosity!
- Currently aiming for:
  - Down-select -next year
  - SPS test in 2015

Increasing effectiveness with larger crossing angles

Integration in LHC tunnel – IP1

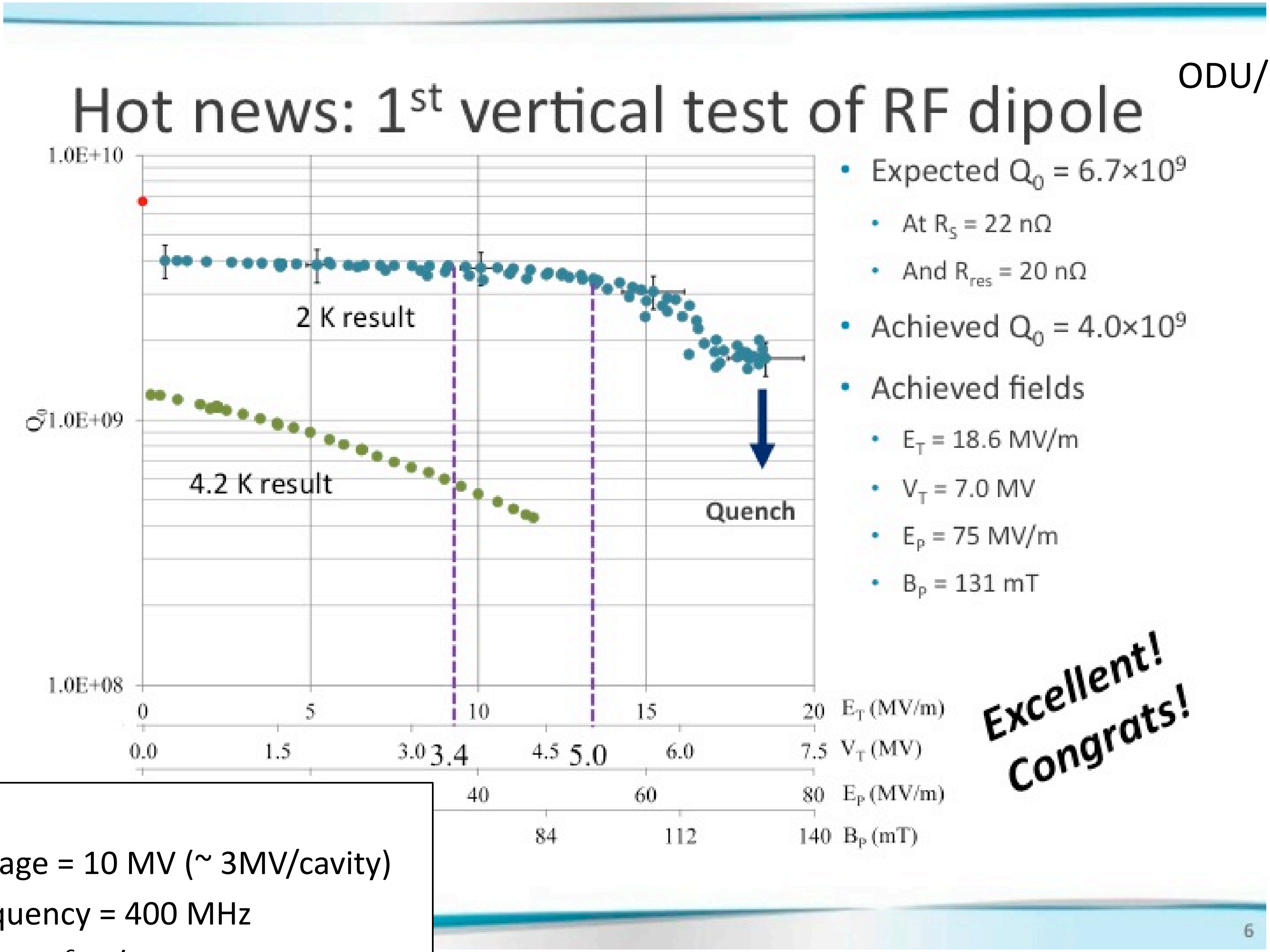




- 3 different versions being developed.
- Planning beam tests at SPS by LS2.

WP4: Crab Cavities

ODU/SLAC



Hot news: 1st vertical test of RF dipole

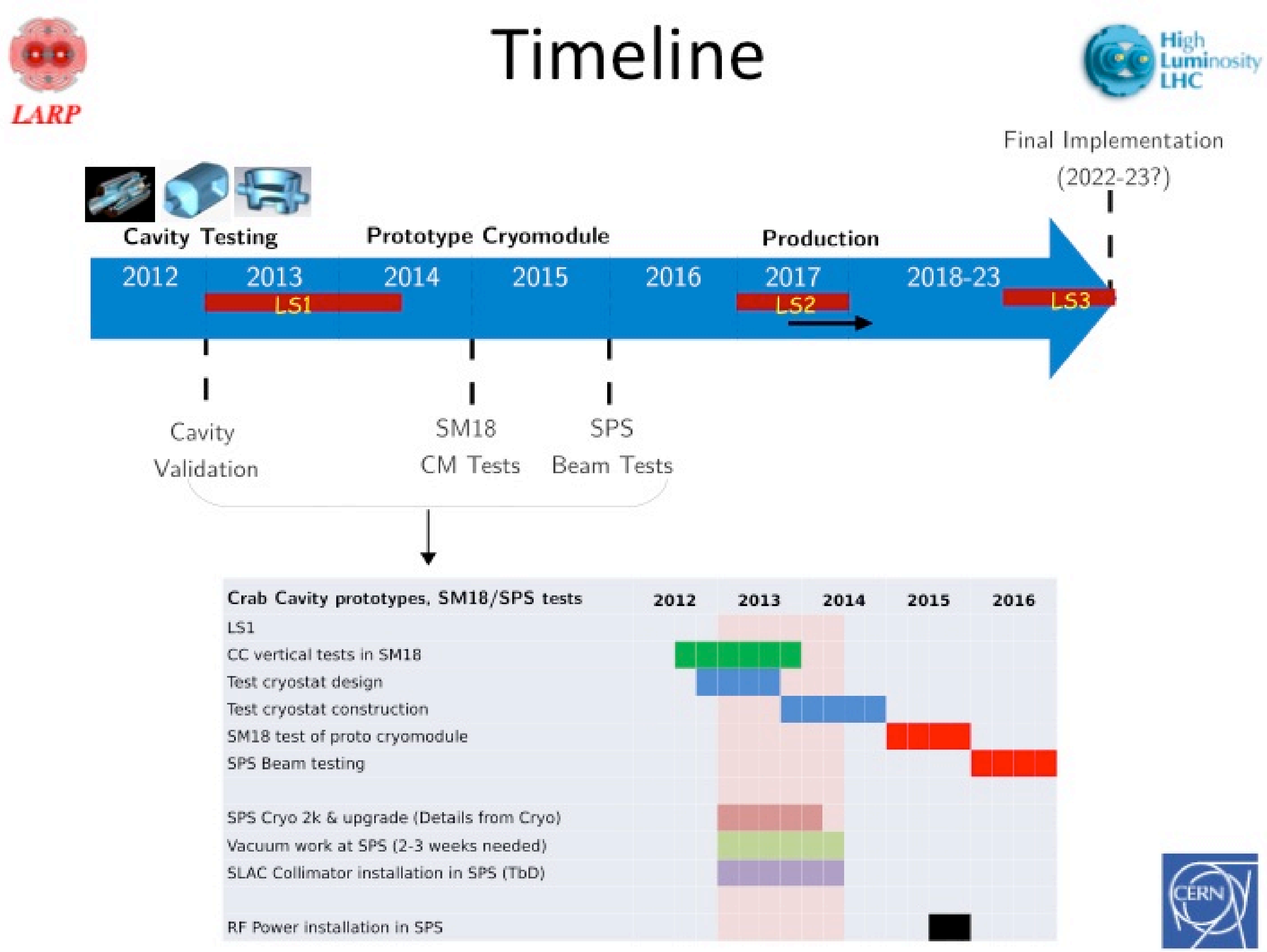
- Expected $Q_0 = 6.7\times10^9$
  - At R_S = 22 nΩ
  - And R_{res} = 20 nΩ
- Achieved $Q_0 = 4.0\times10^9$
- Achieved fields
  - E_T = 18.6 MV/m
  - V_T = 7.0 MV
  - E_P = 75 MV/m
  - B_P = 131 mT

Excellent! Congrats!

Spec.

- Voltage = 10 MV (~ 3MV/cavity)
- Frequency = 400 MHz
- $Q_{ext} = 10^6$, R/Q ~300 W

WP4: Crab Cavities



Timeline

Final Implementation (2022-23?)

Cavity Testing | Prototype Cryomodule | Production

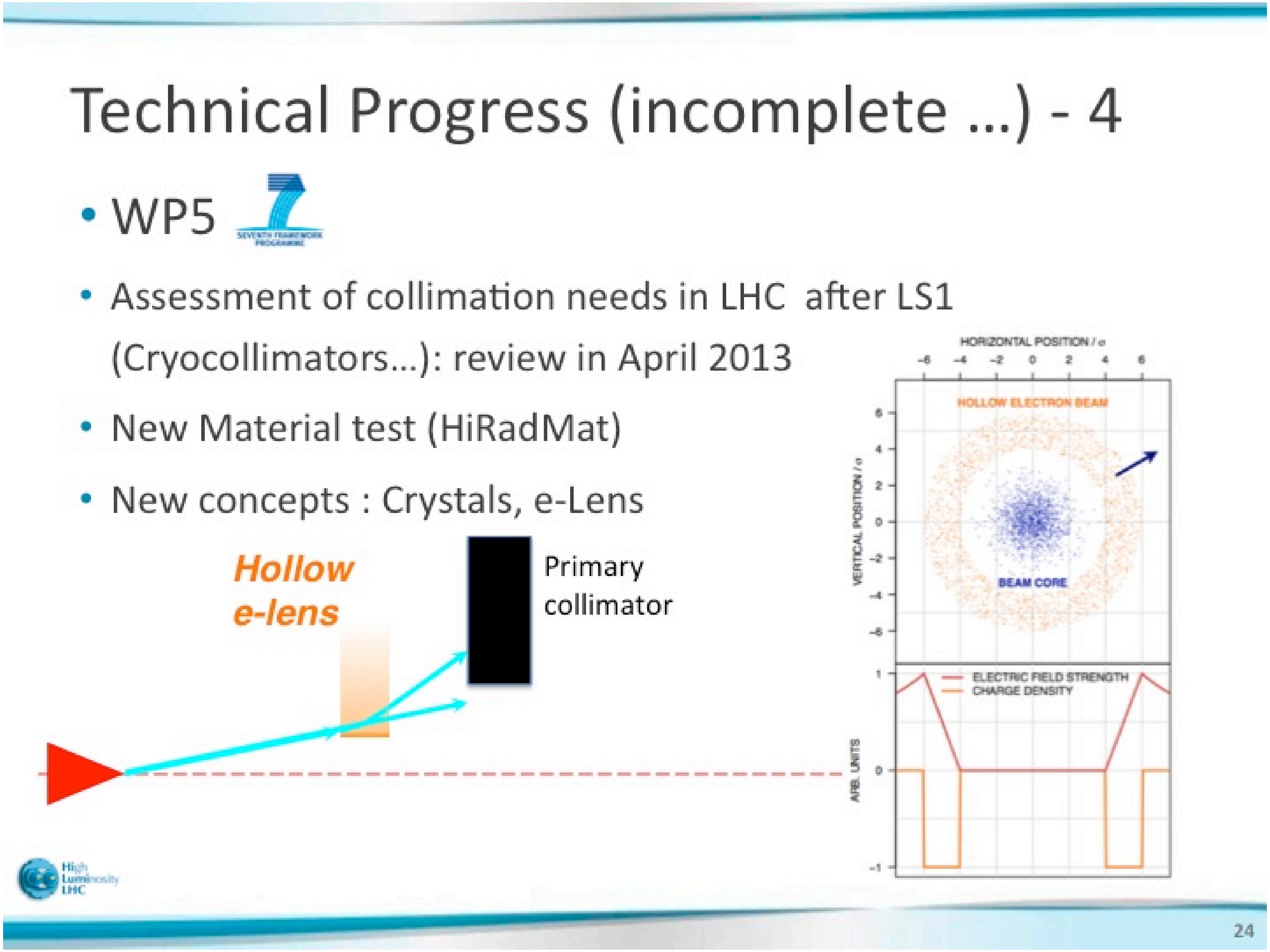
2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018-23

LS1 | LS2 | LS3

Cavity Validation | SM18 CM Tests | SPS Beam Tests

Crab Cavity prototypes, SM18/SPS tests	**2012**	**2013**	**2014**	**2015**	**2016**
LS1					
CC vertical tests in SM18	🟩🟩	🟩🟩🟩🟩			
Test cryostat design	🟦	🟦🟦🟦			
Test cryostat construction		🟦	🟦🟦🟦🟦		
SM18 test of proto cryomodule				🟥🟥🟥🟥	
SPS Beam testing					🟥🟥🟥🟥
SPS Cryo 2k & upgrade (Details from Cryo)		🟥🟥🟥🟥	🟥		
Vacuum work at SPS (2-3 weeks needed)		🟩🟩🟩🟩	🟩🟩		
SLAC Collimator installation in SPS (TbD)		🟪🟪🟪🟪	🟪🟪		
RF Power installation in SPS				⬛⬛	

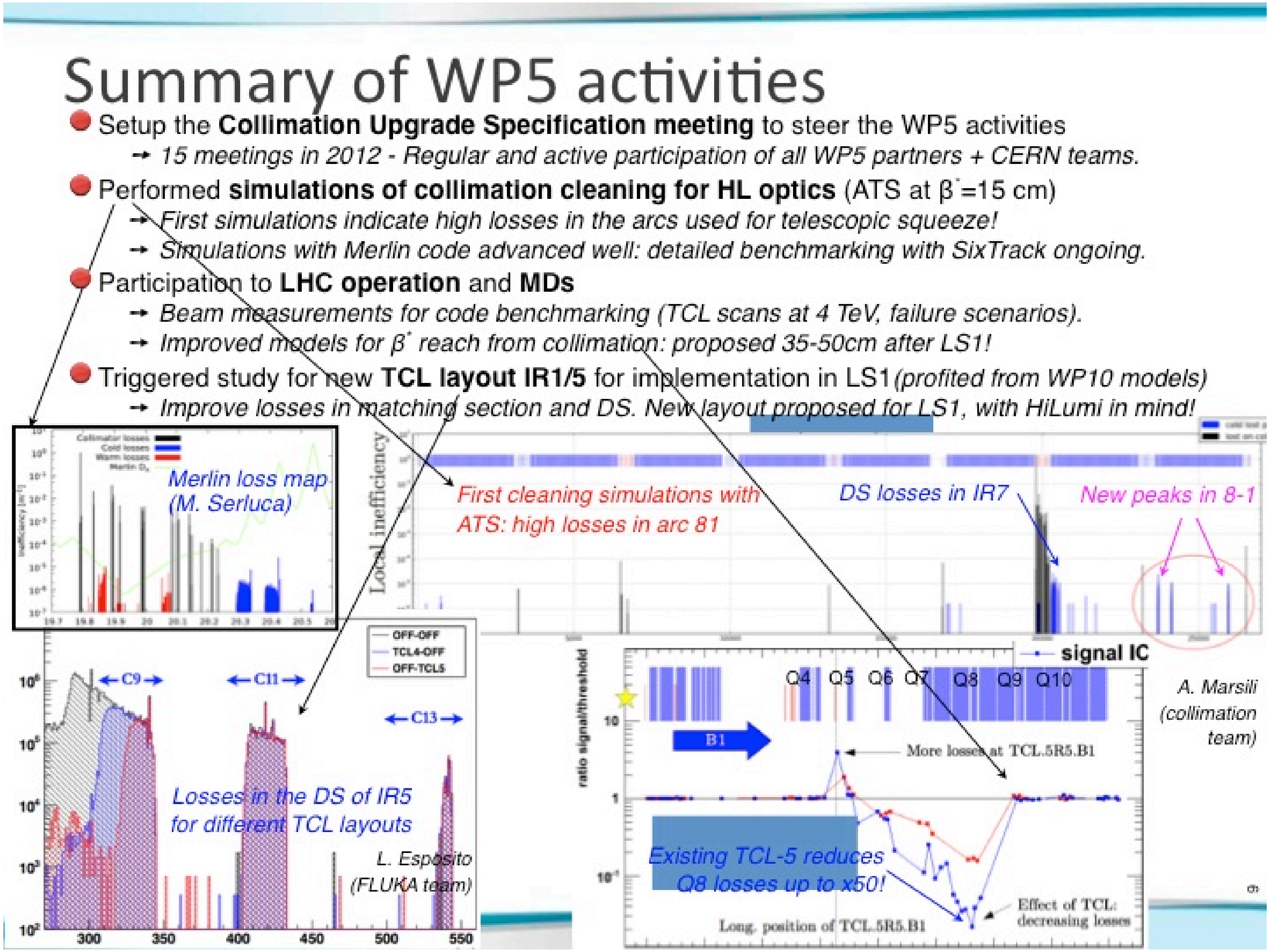
WP5: Collimation



Technical Progress (incomplete ...) - 4

- WP5
- Assessment of collimation needs in LHC after LS1 (Cryocollimators...): review in April 2013
- New Material test (HiRadMat)
- New concepts : Crystals, e-Lens

WP5: Collimation



Summary of WP5 activities

- Setup the **Collimation Upgrade Specification meeting** to steer the WP5 activities
  - → *15 meetings in 2012 - Regular and active participation of all WP5 partners + CERN teams.*
- Performed **simulations of collimation cleaning for HL optics** (ATS at β*=15 cm)
  - → *First simulations indicate high losses in the arcs used for telescopic squeeze!*
  - → *Simulations with Merlin code advanced well: detailed benchmarking with SixTrack ongoing.*
- Participation to **LHC operation** and **MDs**
  - → *Beam measurements for code benchmarking (TCL scans at 4 TeV, failure scenarios).*
  - → *Improved models for β* reach from collimation: proposed 35-50cm after LS1!*
- Triggered study for new **TCL layout IR1/5** for implementation in LS1 *(profited from WP10 models)*
  - → *Improve losses in matching section and DS. New layout proposed for LS1, with HiLumi in mind!*

Merlin loss map (M. Serluca)

First cleaning simulations with ATS: high losses in arc 81

DS losses in IR7

New peaks in 8-1

Losses in the DS of IR5 for different TCL layouts

L. Esposito (FLUKA team)

Existing TCL-5 reduces Q8 losses up to x50!

A. Marsili (collimation team)

More losses at TCL.5R5.B1

Effect of TCL: decreasing losses

Long. position of TCL.5R5.B1

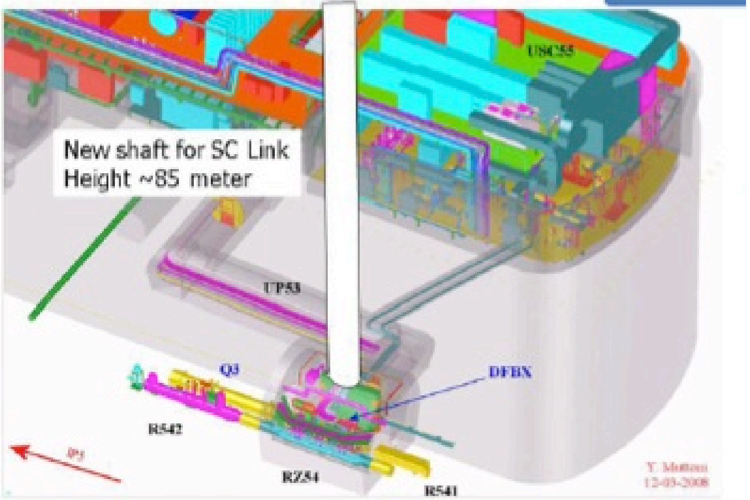
WP6: Cold Powering

This would be a first large scale application using advanced superconductors: MgB_2, HTS.

WP6

SC Link at CERN: 20 m length, up to 20 kA

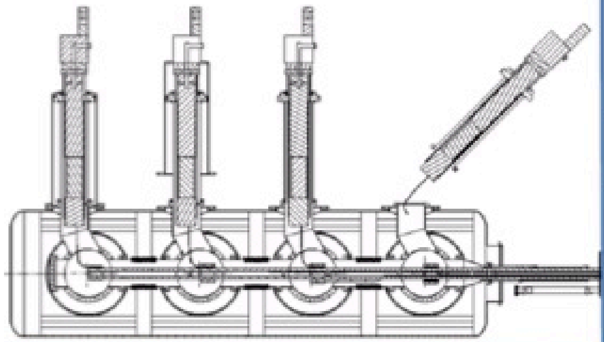
Integration studies : P5 L



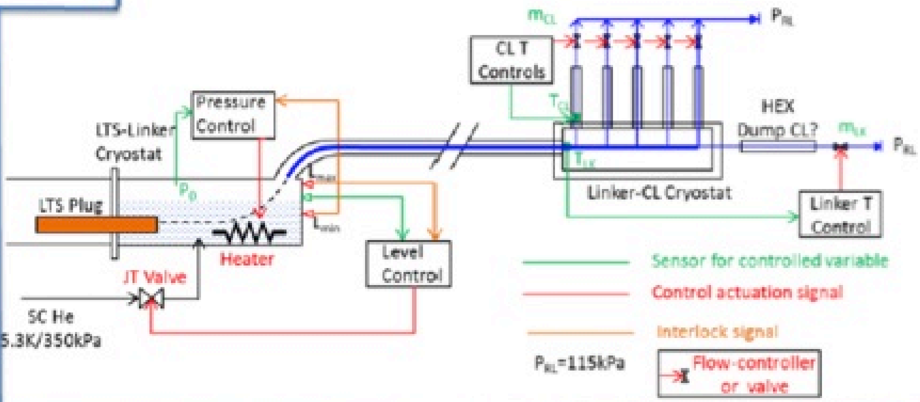
New shaft for SC Link
Height ~85 meter

Evaluation of beam effect on MgB_2 with ^{10}B, ^{11}B and ^{nat}B

LHC distribution feed-box

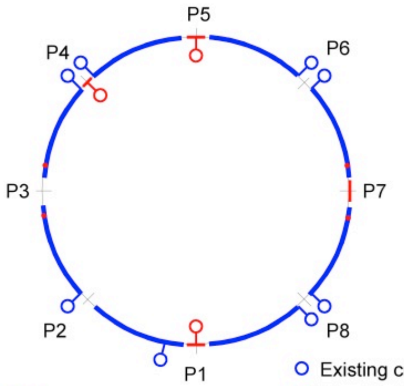


Baseline cryogenic flow-scheme for LHC SC links



WP9: Cryogenics

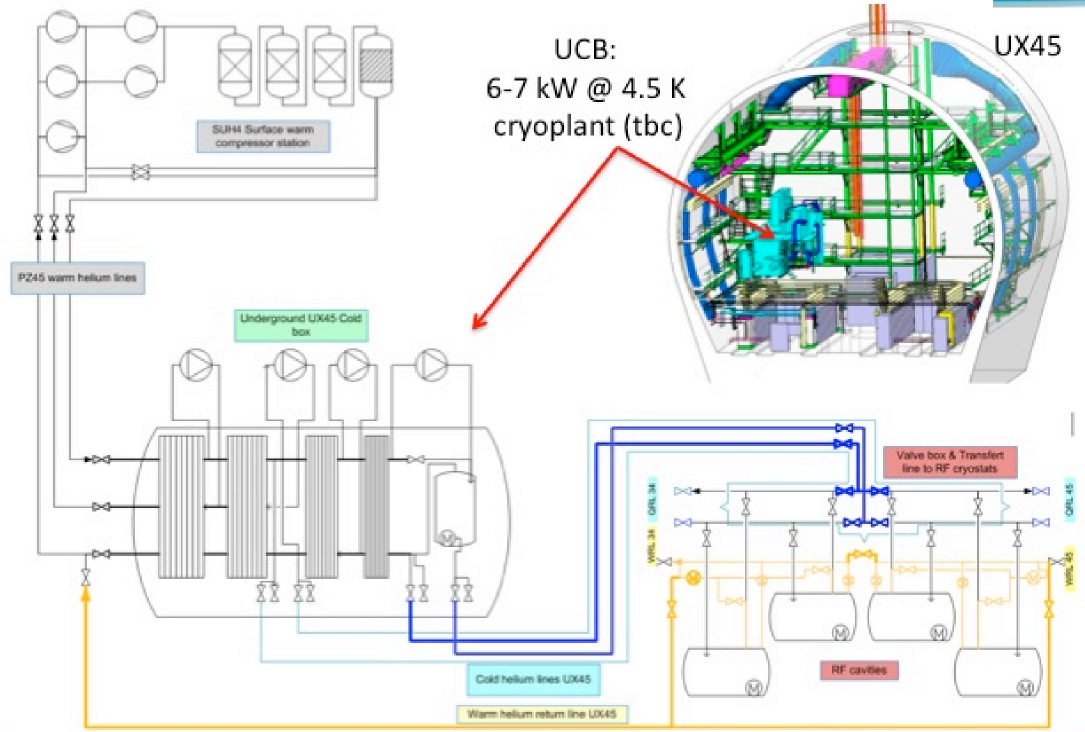
Overall HL-LHC layout



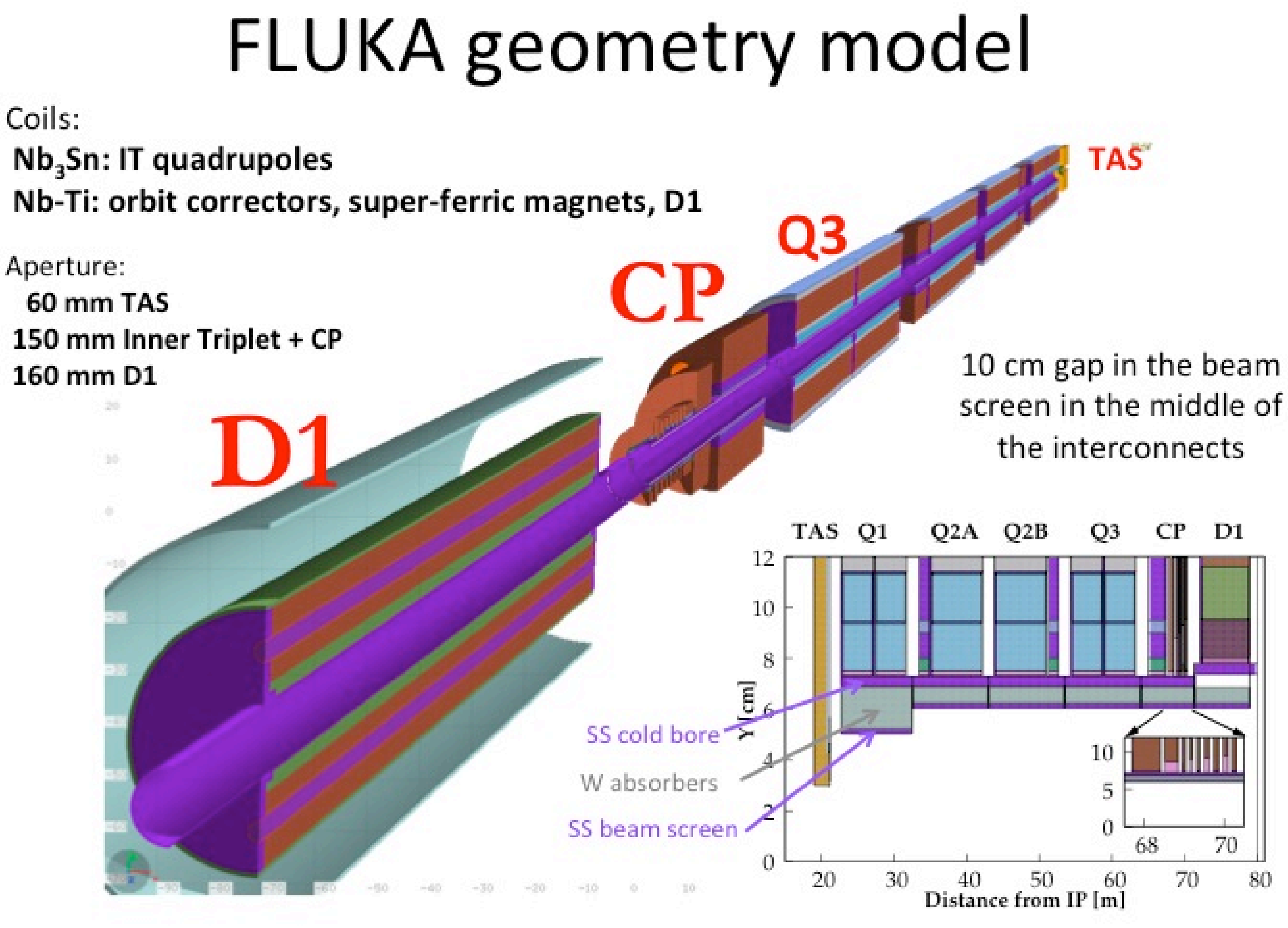
- HL-LHC cryo-upgrade:
  - 2 new cryoplants at P1 and P5 for high luminosity insertions
  - 1 new cryoplant at P4 for SRF cryomodules
  - New cooling circuits at P7 for SC links and deported current feed boxes
  - Cryogenic design support for cryo-collimators and 11 T dipoles at P3 and P7

○ Existing cryoplant
○ New HL-LHC cryoplant

P4 cryogenic process & flow diagram



WP10: Energy Dep.



FLUKA geometry model

Coils:

Nb$_3$Sn: IT quadrupoles

Nb-Ti: orbit correctors, super-ferric magnets, D1

Aperture:

60 mm TAS

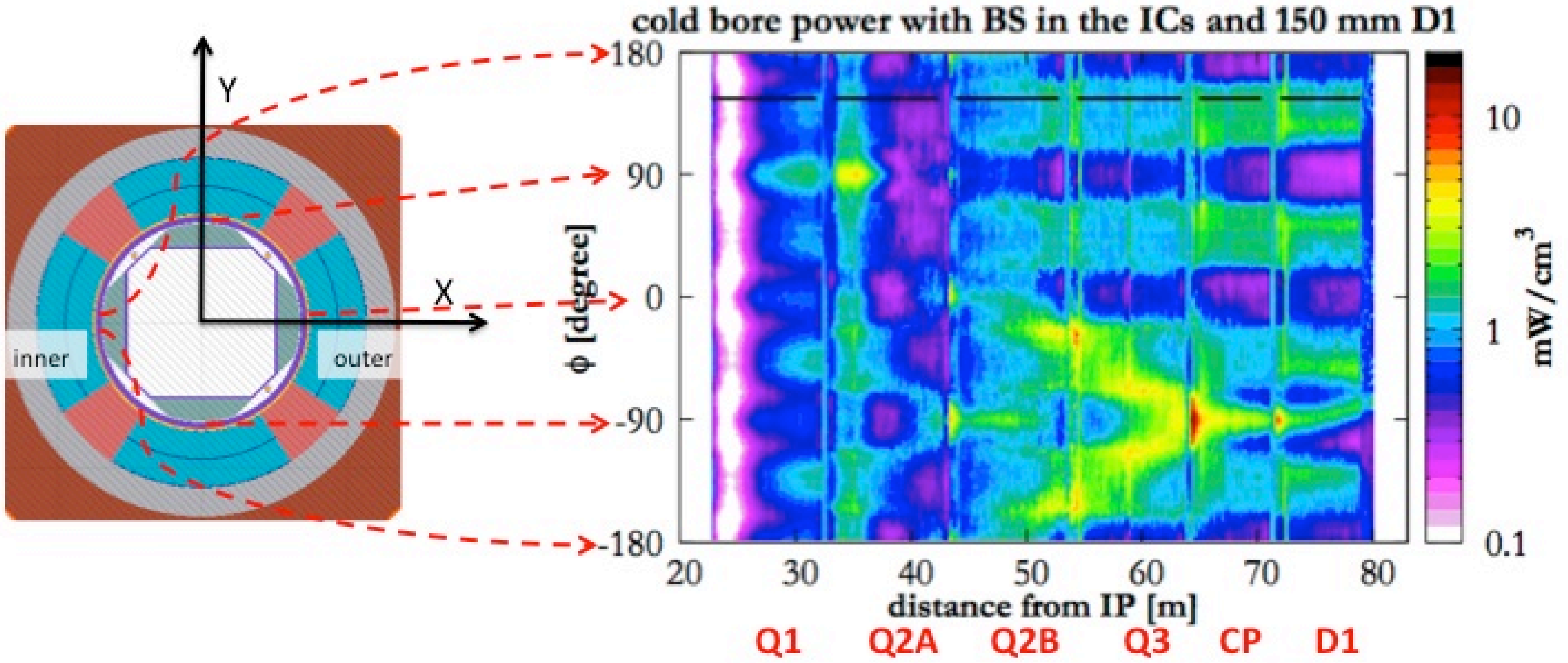
150 mm Inner Triplet + CP

160 mm D1

10 cm gap in the beam screen in the middle of the interconnects

WP10: Energy Dep.

Power deposition on the cold bore



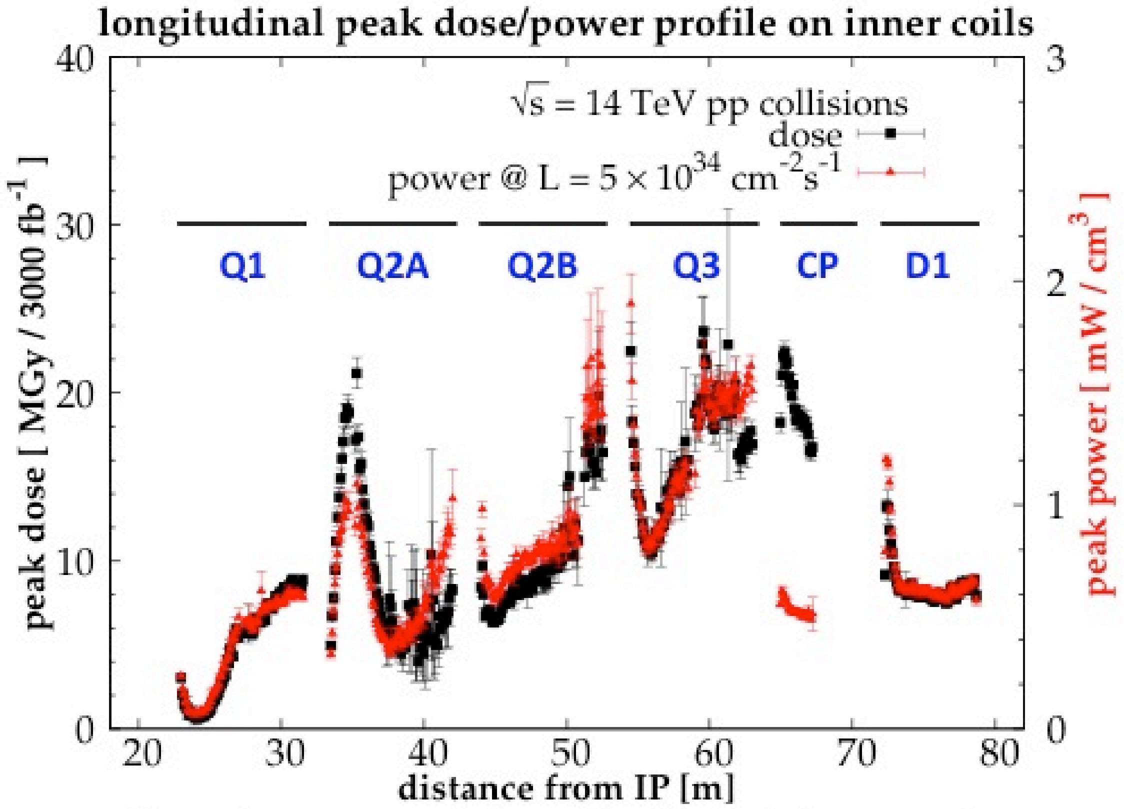
Energy deposition pattern in case of vertical crossing
To be noticed the inversion in the Inner Triplet and the bending in the D1

16 mm W absorbers in Q1, 6 mm elsewhere, 50 cm beam screen interruption in IC

WP10: Energy Dep.

If no W shield, 13 mW/cm^3, 200 MGy!!
Thanks to W shield, 2 mW/cm^3, < 30MGy

Dose and power estimates



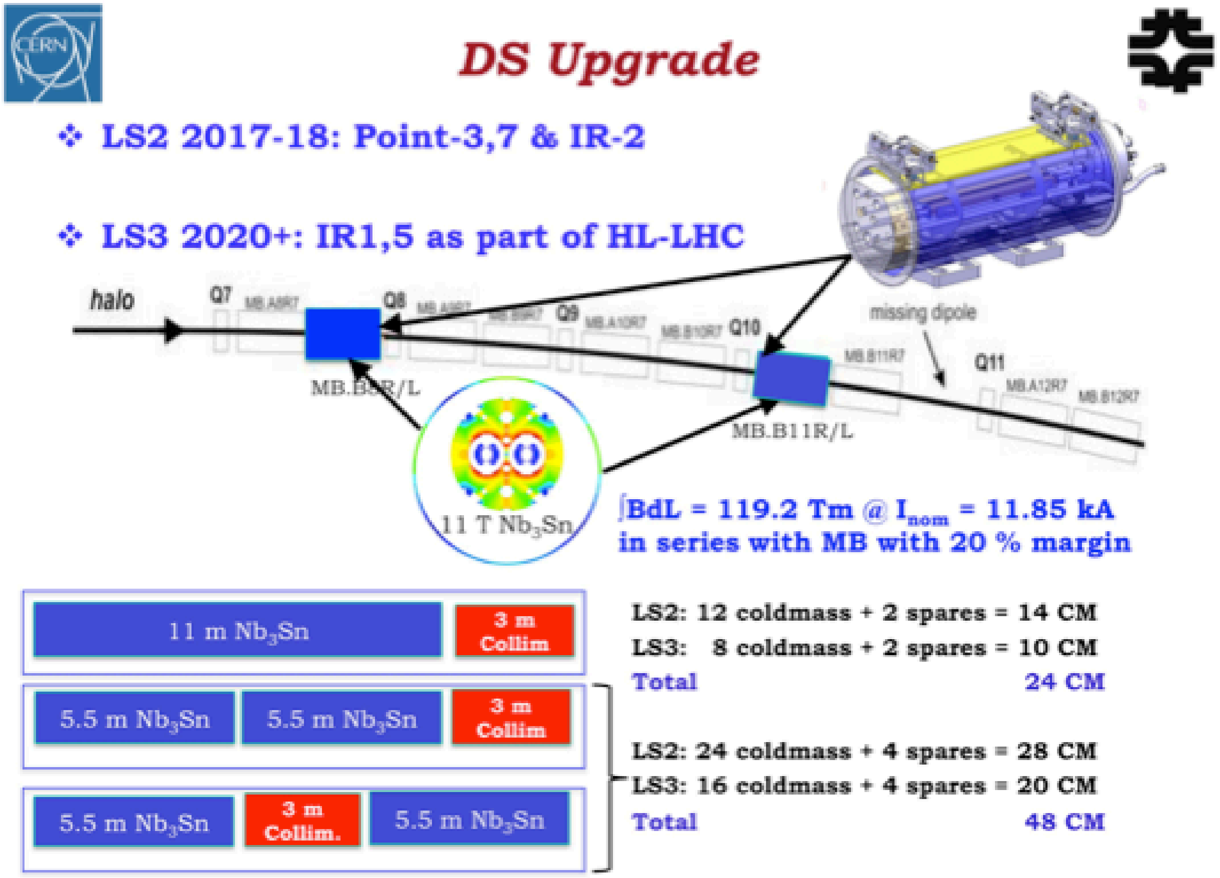
10 cm beam screen interruption in the interconnects
Power evaluated on the entire radial cable, dose on the innermost 3 mm

WP11: 11 T dipole for DS

- Fermilab-CERN
- Another Nb3Sn SC magnet development
- Rather tighter schedule (LS2)

Courtesy of A. Zlobin (Fermilab) and M. Karppinen (CERN)

- New collimators will be necessary to secure the main dipoles (MB) in the LHC DS regions.
  - Need the longitudinal space for the collimator.
  - Replacement of the current MB by new Nb_3Sn 11 T dipoles.
- Collaboration with CERN and Fermilab.



DS Upgrade

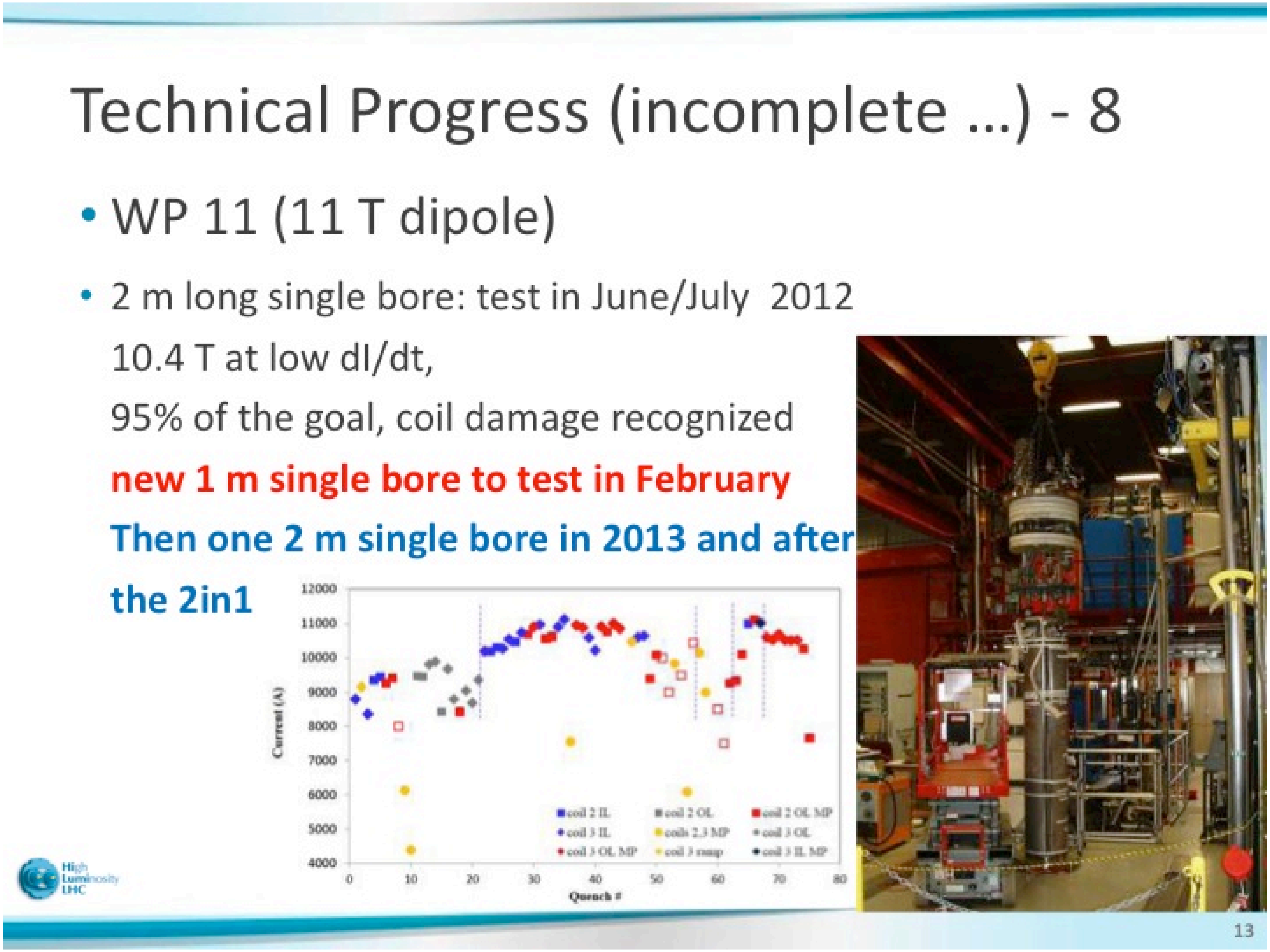
- LS2 2017-18: Point-3,7 & IR-2
- LS3 2020+: IR1,5 as part of HL-LHC

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

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

WP11: 11 T dipole for DS



Technical Progress (incomplete ...) - 8

- WP 11 (11 T dipole)
- 2 m long single bore: test in June/July 2012

  10.4 T at low dI/dt,

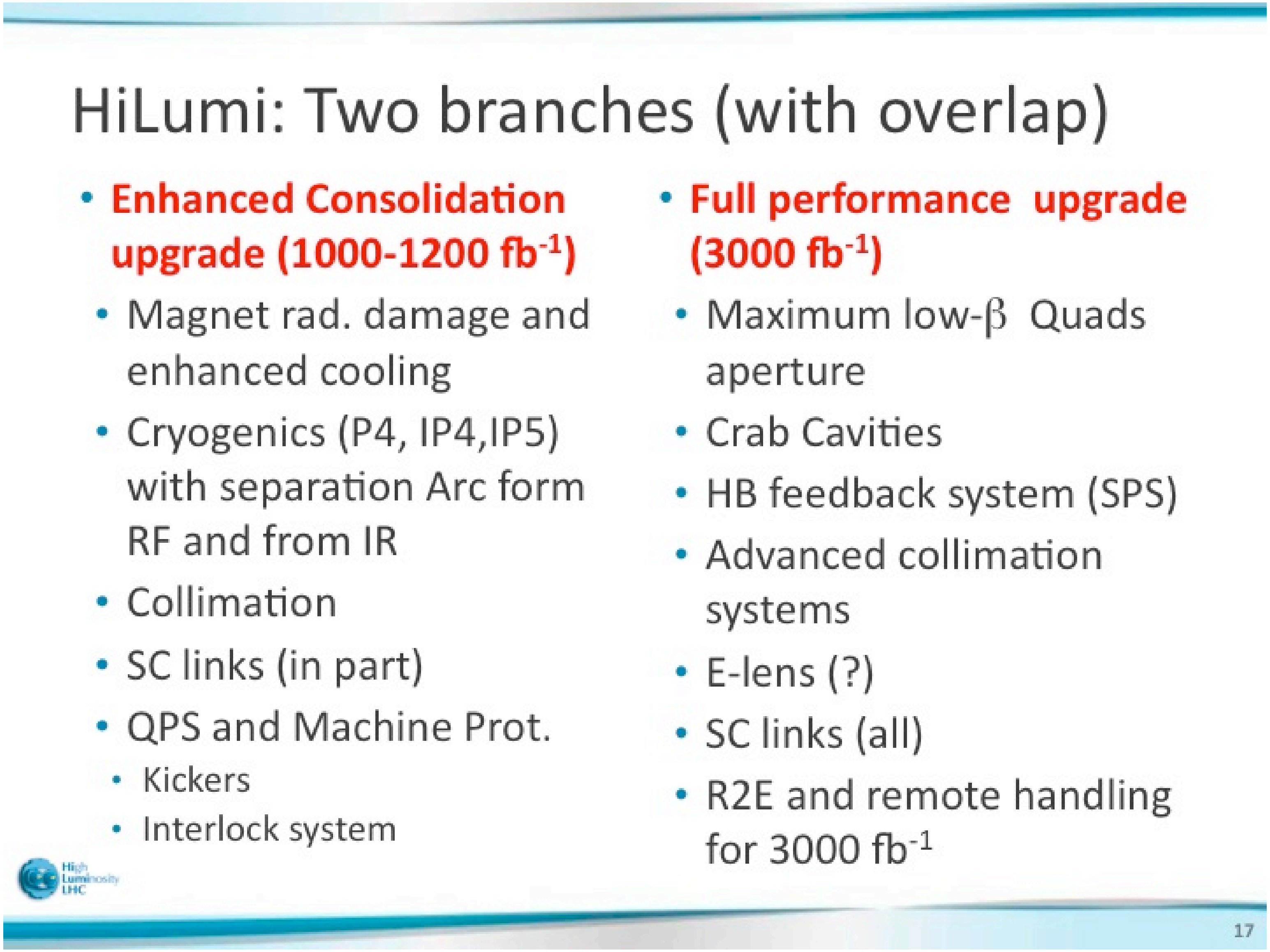
  95% of the goal, coil damage recognized

  new 1 m single bore to test in February

  Then one 2 m single bore in 2013 and after the 2in1

13

Upgrades: "Enhanced Consolidation" & "Full Performance"

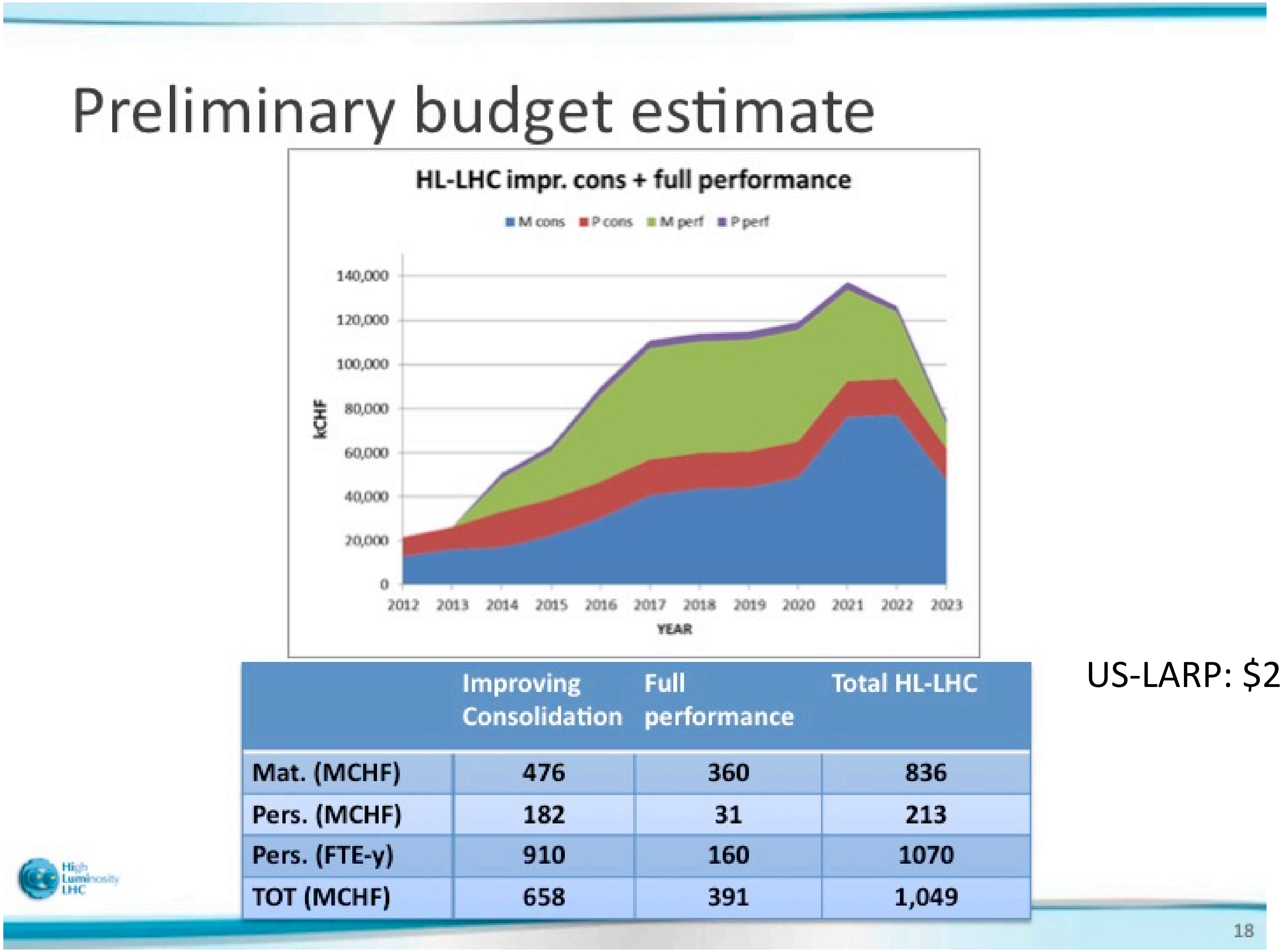


HiLumi: Two branches (with overlap)

- **Enhanced Consolidation upgrade (1000-1200 fb^{-1})**
  - Magnet rad. damage and enhanced cooling
  - Cryogenics (P4, IP4,IP5) with separation Arc form RF and from IR
  - Collimation
  - SC links (in part)
  - QPS and Machine Prot.
    - Kickers
    - Interlock system

- **Full performance upgrade (3000 fb^{-1})**
  - Maximum low-β Quads aperture
  - Crab Cavities
  - HB feedback system (SPS)
  - Advanced collimation systems
  - E-lens (?)
  - SC links (all)
  - R2E and remote handling for 3000 fb^{-1}

Budget Estimate (CERN)



Preliminary budget estimate

	Improving Consolidation	Full performance	Total HL-LHC
Mat. (MCHF)	476	360	836
Pers. (MCHF)	182	31	213
Pers. (FTE-y)	910	160	1070
TOT (MCHF)	658	391	1,049

US-LARP: $200M (Plan)

Contents

- Introduction
- Present (nominal) LHC
  - Key technologies
  - Overview
  - Performance so far
- HiLumi LHC Upgrade
- Summary

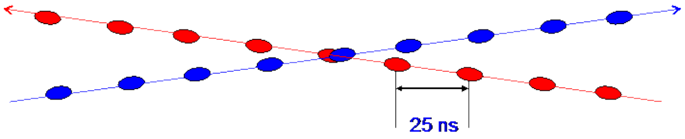
Summary

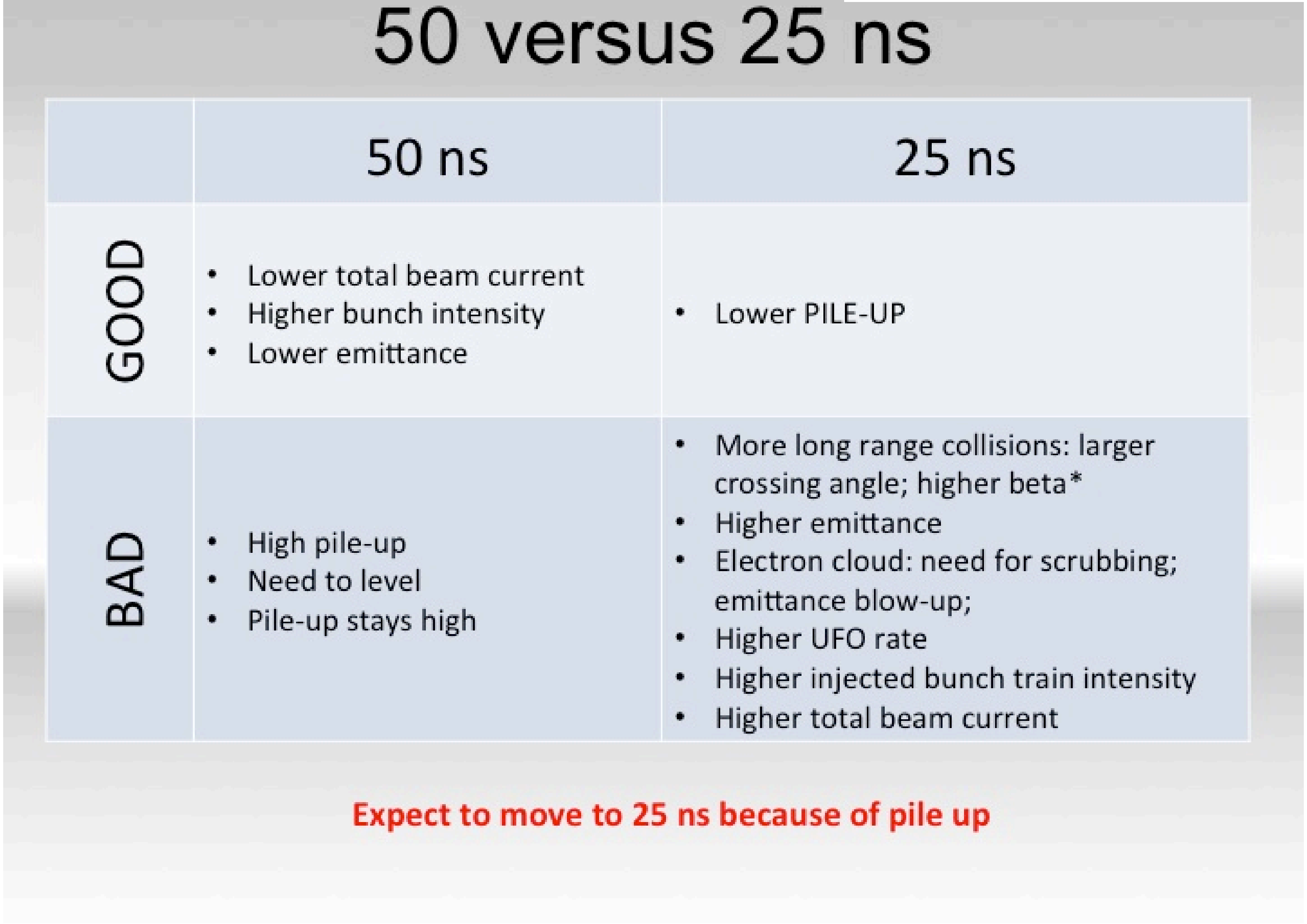
- Present LHC has been operated very successfully.
  - Delivery of 23.3 fb^{-1} in 2012
  - Harvest: discovery of Higgs-boson
  - Resume after LS1 with collision energy of 6.5 + 6.5 TeV

- High Luminosity LHC upgrade (HL-LHC) is planned to be started around 2023.
  - Target: 3000fb^{-1}, $5x10^{34}$ cm^{-2} sec^{-1}, for 10 years
  - Conceptual design study and R&D for various items.
    - New technologies, new facilities…
    - International collaboration by CERN, European labs, US-LARP, Japan.
  - Decision for construction is anticipated in 2015/2016.

We still keep busy….

Prospect: Bunch spacing



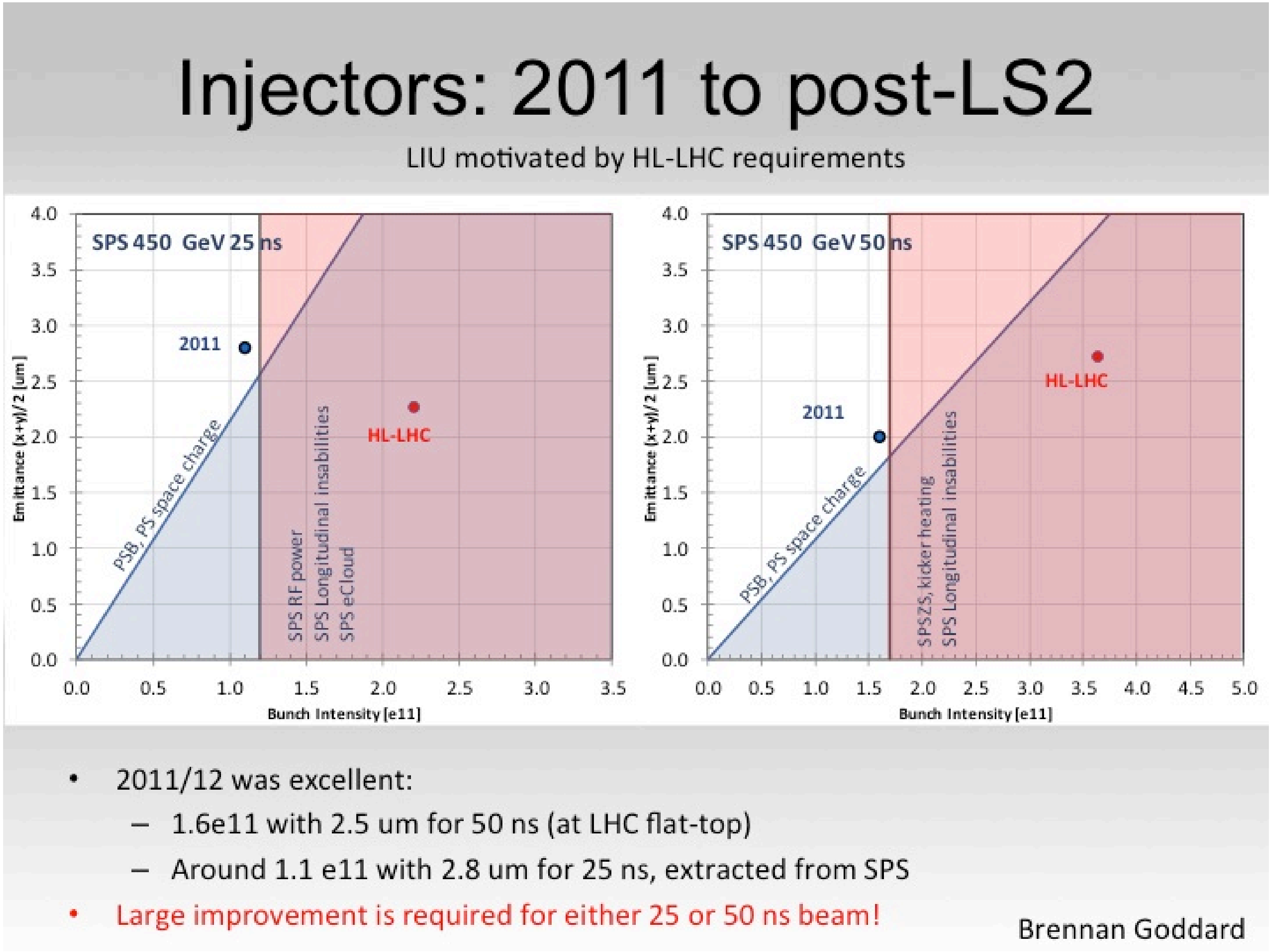


50 versus 25 ns

	50 ns	25 ns
GOOD	• Lower total beam current • Higher bunch intensity • Lower emittance	• Lower PILE-UP
BAD	• High pile-up • Need to level • Pile-up stays high	• More long range collisions: larger crossing angle; higher beta* • Higher emittance • Electron cloud: need for scrubbing; emittance blow-up; • Higher UFO rate • Higher injected bunch train intensity • Higher total beam current

Expect to move to 25 ns because of pile up

LHC Performance: Injectors



Injectors: 2011 to post-LS2

LIU motivated by HL-LHC requirements

- 2011/12 was excellent:
  - 1.6e11 with 2.5 um for 50 ns (at LHC flat-top)
  - Around 1.1 e11 with 2.8 um for 25 ns, extracted from SPS
- Large improvement is required for either 25 or 50 ns beam!

Brennan Goddard