LHC Upgrade Plans: Options and Strategy

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Highlights

- LHC: a long story and even a longest future?
- LHC upgrade : the 2001-2010 studies
- LHC present perfomance: impact on upgrade
- Lumi upgrade: scope, baseline and variants
- The HL-LHC technical program and FP7-HiLumi LHC design study
- Energy upgrade: the HE-LHC parameters space, the challanges and the roadmap.

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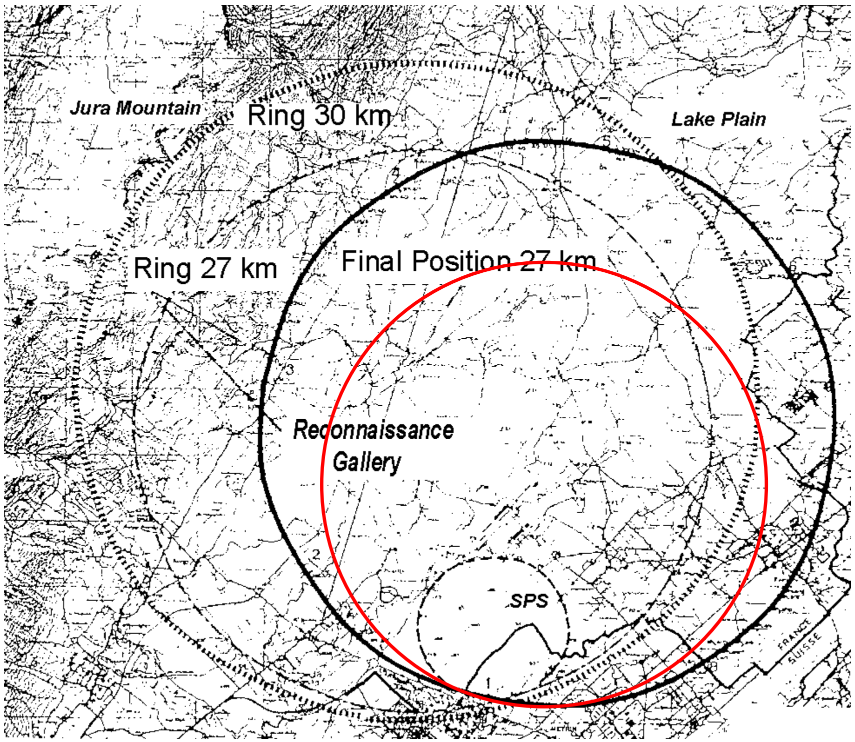
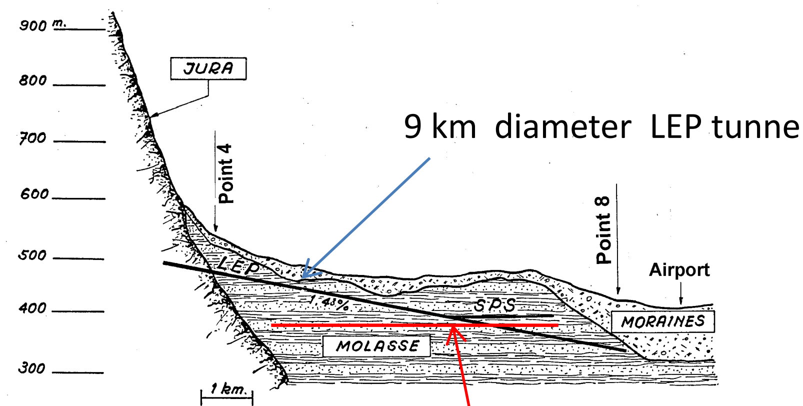
LEP and LEP II 1980-1989: the tunnel, for LEP/LHC



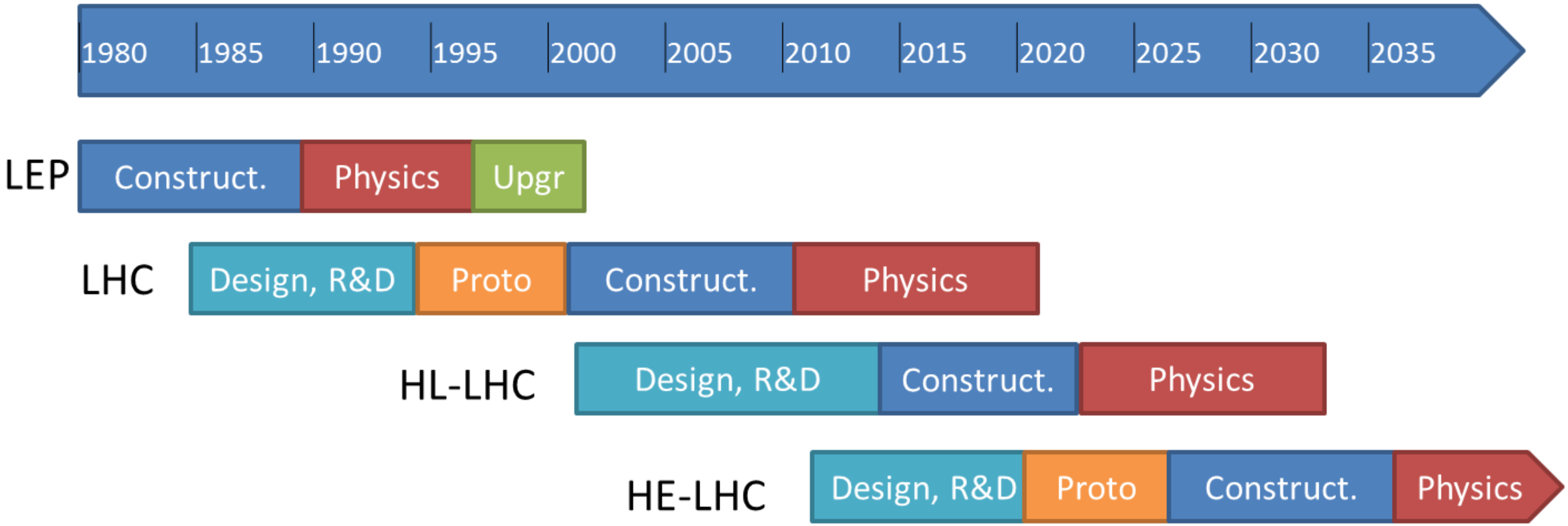


6-7 km diameter and cheap LEP tunnel,
as advocated by many people

The tunnel size was decided, by H. Schopper , CERN DG and E. Picasso, LEP P.L., **in view of the LHC**

LEP/LHC : the best use of the (renovated) existing infrastructure

The super-exploitation of the CERN compelx: Injectors, LEP/LHC tunnel, infrastructures



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Luminosity: main ingredients

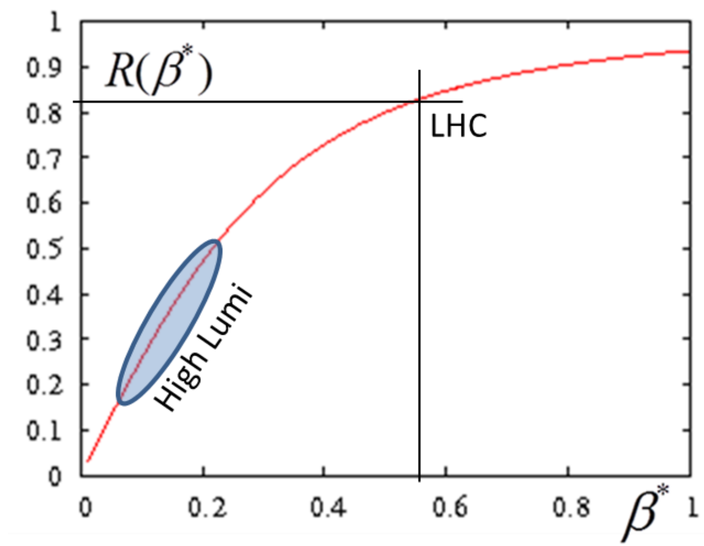
Beam current

$$L = \gamma \frac{f_{rev}\, n_b\, N_b^{\,2}}{4\pi \varepsilon_n \beta^*} R$$

energy

Beam size

$$R = \frac{1}{\sqrt{1 + \left(\frac{\theta_c \sigma_s}{2\varepsilon_n \beta^*}\gamma\right)^2}}$$



Beam current and emittance: involve Inj chain and whole ring
β* involve only 2 IRs, 600 m.

$$L_0 = 1 \cdot 10^{34}\ cm^{-2}s^{-1}$$

Unit of lumi through the talk

Table from the task force 2001

Parameter	Nom. 25 ns	Ultim. 25 ns	Upgr. base	Upgr. Piw.	Upgr. s-bun
N_b [10^{11}]	1.1	1.7	**1.7**	2.6	5600
n_b	2808	2808	**2808**	2808	1
I [A]	0.56	0.86	**0.86**	1.32	1
θc [μrad]	300	315	**445**	485	1000
β^* [m]	0.5*	0.5 →	**0.25**	0.25	0.25
ε_n [μm]	3.75	3.75	**3.75**	3.75	3.75
ε_s [eV s]	2.5	2.5 →	**1.78**	2.5	15000
f_{RF} (MHz)	400.8	400.8 →	**1202.4**	400.8	10
$V_{p\ RF}$(MV)	16	16	**43**	16	3.4
σ_s [cm]	7.55	7.55	**3.78**	7.55	7500
IBS h [h]	111	72	**42**	46	63
IBS l[h]	65	42	**50**	28	856
Piwinski	0.71	0.75	**0.75**	1.63	=
F red.fact.	0.81	0.80	**0.80**	0.53	=
L $10^{34}cm^{-2}s^{-1}$	**1**	**2.3**	**4.6**	**7.2**	**9.0**
Pile up	19	44	**87**	137	=

Double bunch #, 12.5 ns, L ~9 L_0,short bunches

Main alternative, large Piw, Hi N_b

Comments

- **Based on ΔQ_{bb} max of 0.01 in design condition (nominal)**
  - ΔQ_{bb} max of 0.015 in ultimate condition
    ultimate: N_p=1.7 10^{11} p (1.1 nom), I_b=0.86 A (0.56)
- **Main ingredients for the upgrade**
  - lower β^* (0.5 $\rightarrow$ 0.25 m) inner triplet quads (LHC designed with double b3 correction strenght)
  - Shorter bunches: 2.5 $\rightarrow$ 1.78 cm to -fully- compensate the geometric reduction
  - Doubling bunch number, spacing 12.5 ns to reach $\sim$ 9 L_0
- **Other routes were proposed:**
  large Pw with very high bunch popolation
  Super-bunches
  other variants

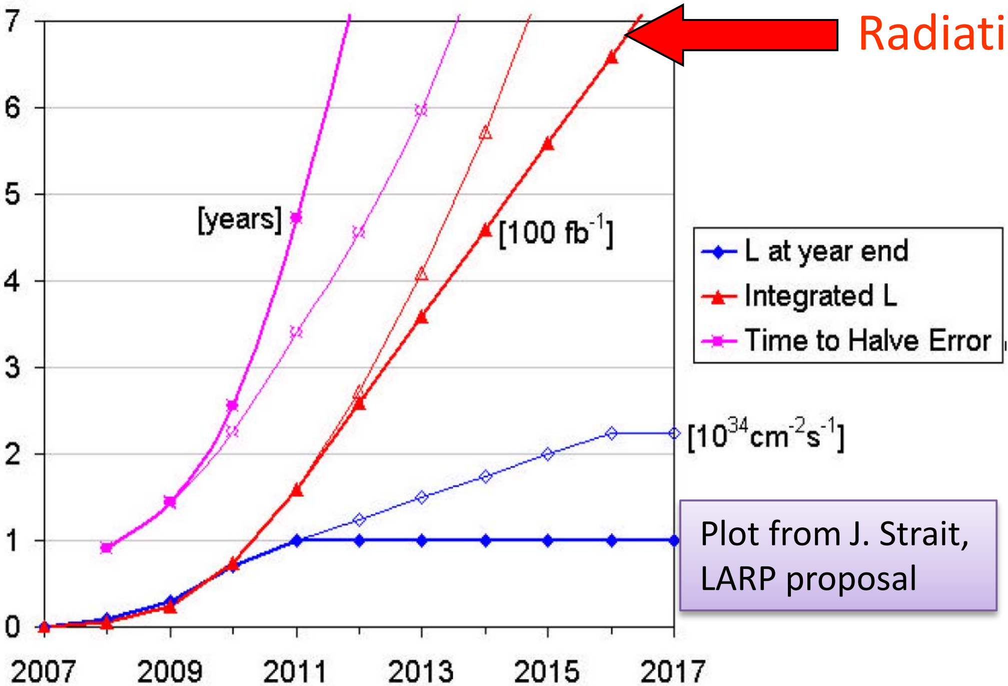
Comments - conts

- **Peak lumi was main concern**
- **Integrated lumi was considered 60-80% of the increase of L_{peak}**
- **Levelling was not discussed**
- **Crab cavities were just mentioned**

2003-2007: CARE-HHH and LARP

- **Lhc Accelerator Research Programme, LARP**
  - J. Strait, et al., “Towards A New LHC Interaction Region Design for a Luminosity Upgrade”, Proceedings of PAC03
  - LARP has given fundamental contribution to the hardware development and to the conceptual study for High Lumi
- **High energy High intensity Hadron collider HHH**
  - HHH, a newtwork inside FP6-CARE
  - Task on accelerator physics
  - Task on magnets design
  - Task on beam diagnostics upgrade

Necessity of upgrade and of immediate R&D



Plot from J. Strait, LARP proposal

Radiation damage limit ~700 fb^{-1}

Plan luminosity upgrade by 2014.

New low-β quads with high gradient and larger aperture based on Nb_3Sn SC require 9-10 years for short model R&D and component development, prototyping, and final production.

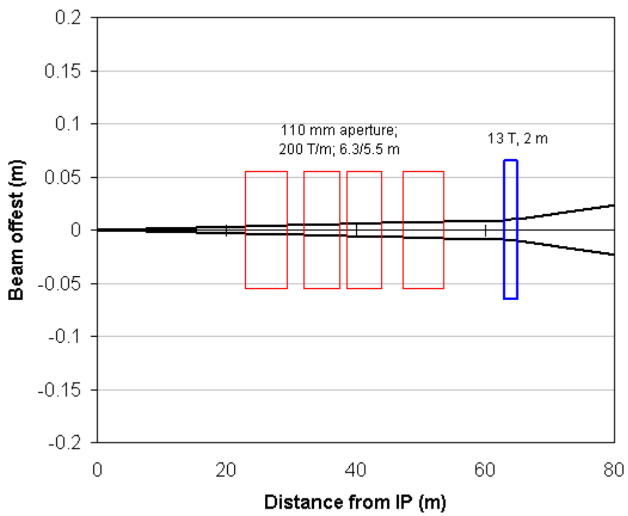
CERN task force on LHC machine upgrade -> LHC PR 626+666

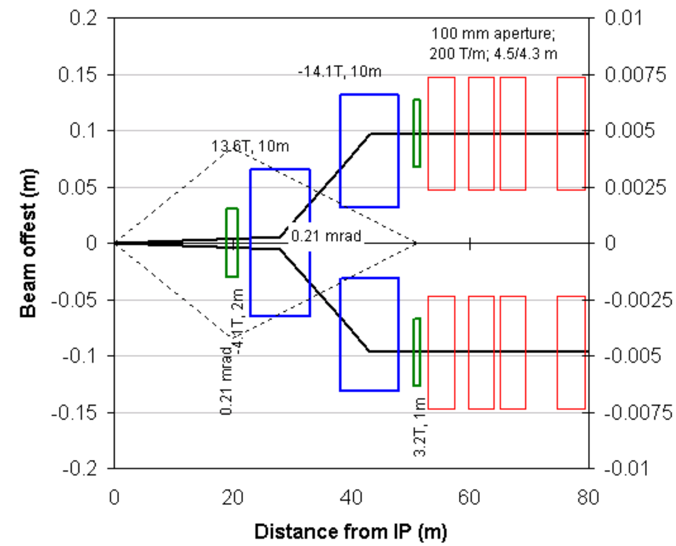
Luminosity: $L_{nom}=10^{34}$ -> 10^{35}, Energy: E_{cm}=14 TeV -> 25 TeV

Slide from F. Ruggiero , 2004

SC magnet R&D for lumi upgrade also useful for energy upgrade: can be integrated with LHC magnet consolidation. Beam dynamics R&D for LHC commissioning also useful for LHC upgrade: needed to guide new IR design.

LHC luminosity upgrade: some IR options with β*=0.25 m





Quadrupole-first IR: baseline

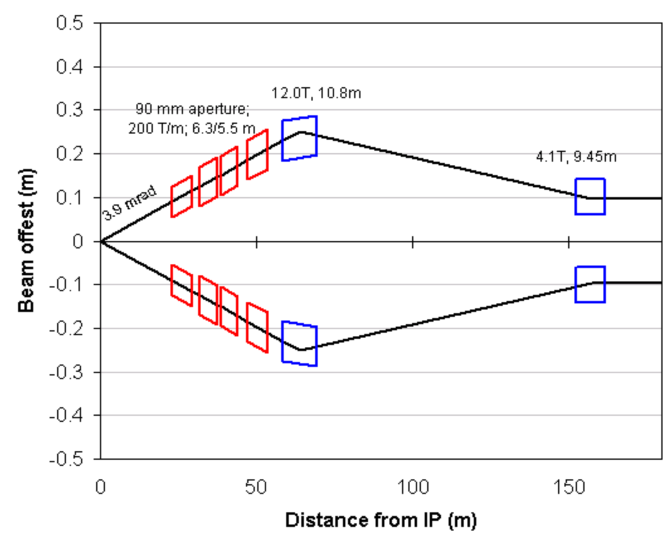
Dipoles-first IR: less parasitic bb

Baseline: θ_c=445 μrad, I_{ultim}=0.86 A,
1.2GHz RF -> halve σ_z -> **L=4.6x10^{34}**
bunch spacing 12.5 ns -> L=9.2x10^{34}
Excluded by e-cloud and parasitic bb?

High intensity option with large θ_c:

- θ_c=485 μrad, I~1.3 A -> **L=7.2x10^{34}**
- super-bunches, I~1 A -> **L=9x10^{34}**

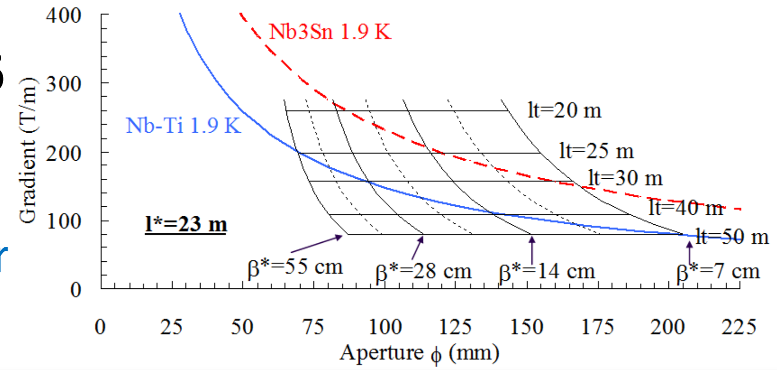
Quadrupole-first IR with large θ_c:
requires long super-bunches



Slide from F. Ruggiero , 2004

A few new inputs

- **HHH lumi workshop in Valencia Oct.2006**
  - 12.5 ns, 5600 bunches, options ruled out! (cryoconsumption in the beam screen)
  - Scaling laws, solutions possible with larger aperture, lower gradient low-β quads Intermediate solution wiht Nb-Ti as envisaged in F. Ruggiero et al. @EPAC04 (Nb_3Sn not ready before 2016)

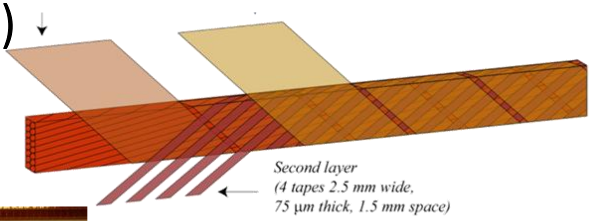


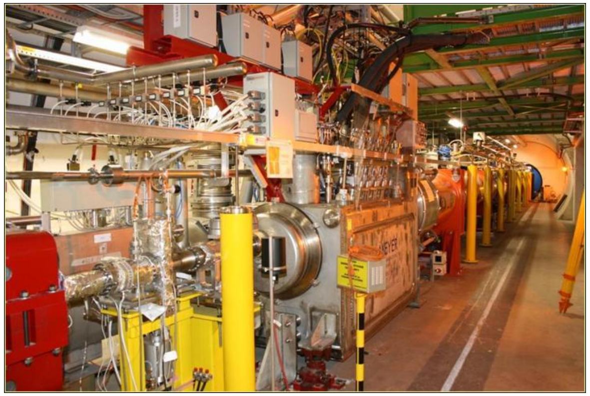
Plot from E. Todesco, see also Bruning-DeMaria

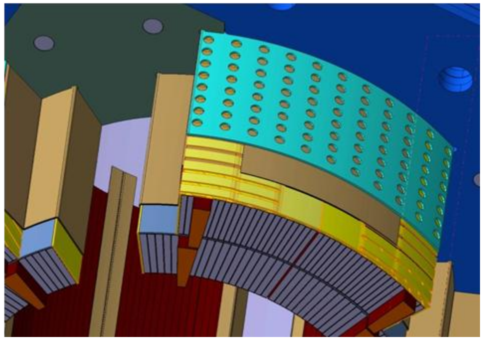
- **Last dipole delivered on time: 7 Nov 2006**
  ⇒ beam commissioning in 2007; early saturation?
  ⇒ launch an «early» upgrade by 2013: Phase I
- **2007-08: Lumi Levelling as important tool**
  proposed for the early separation scheme(abandoned)
  now a vital ingredient
- **2007-08: Crab Cavities for LHC (cancel geometric reduction, so favoring low β* and also ideal levelling tool)**

Luminosity upgrade Phase I

- **Set up in 2007**
  - Installing new triplets (ATLAS-CMS) by 2013, not modification outside Interaction Regions. *A way to cope with early rad damage (350 fb^{-1})*
  - Phase 2 foreseen around 2018-20. High Field program establishes at CERN
  - Adding modification of IRs (D1, shielding, DFXs)
  - Aug 2008: quads ∅=120 mm G= 125 T/m (LHC 70 mm, 205 T/m): new quad models







June 2010 Phase I regrouped in HL-LHC (High Luminosity LHC)

- **LHC incident 19 Sept 2008 (+ delays)**
  - 3-4 years delays in installing phase 1
  - Rediscussion of the program
  - Fragility of the machine and changes
  - Difficulty of integrations with strict boundary conditions; longer time to install.
  - Longer time to reach saturation in lumi 3-400 fb^{-1} not before 2020.
  - Difficulties in increasing performance ($30<\beta^*<40$ cm). Matching and b3 Corrections difficulties if changes limited to the IRs (despite that b3 circuit was designed for β^* of 25 cm
  - **Decision to stop Phase 1 and regroup it into a general HL-LHC**

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The first good suprise!

W. Herr, Oral WEODA01 poster TUPZ029 and invited talk by M. Lamont

Beam-Beam tune shift

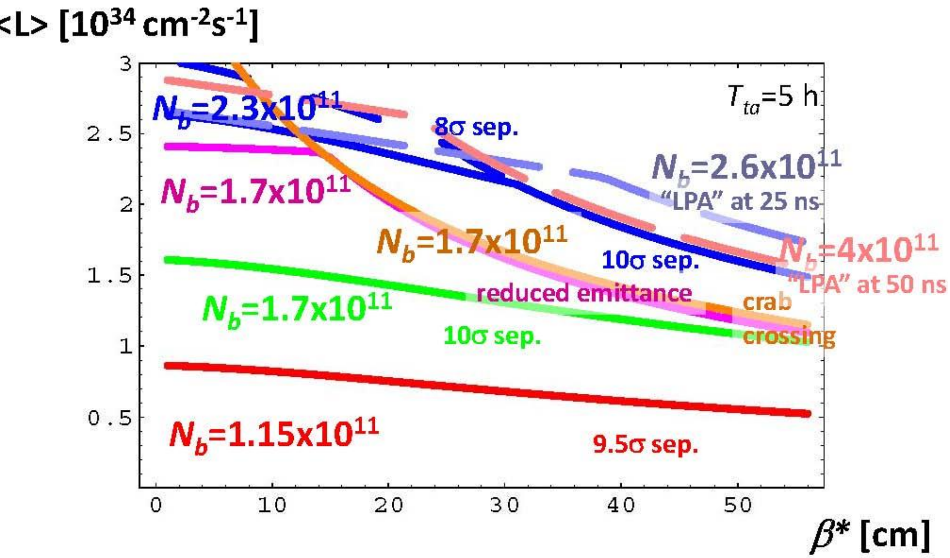
- **LHC is much less sensitive than foreseen**
- **ΔQ_{bb} 3 (5) times design has been run without τ_{lumi} reduction !**
- **Field fluctuation 100-1000 times less? (inductance SC magnets, better EPC)**
  others?
- **50 ns becomes a competitor of 25 ns**
  - Less beam current
  - Less e-cloud (which is there!)
  - (pile up)

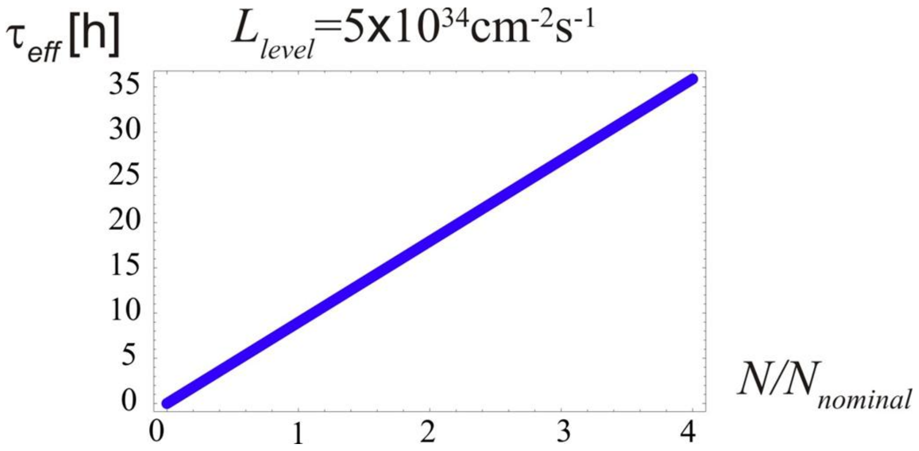
Much more…

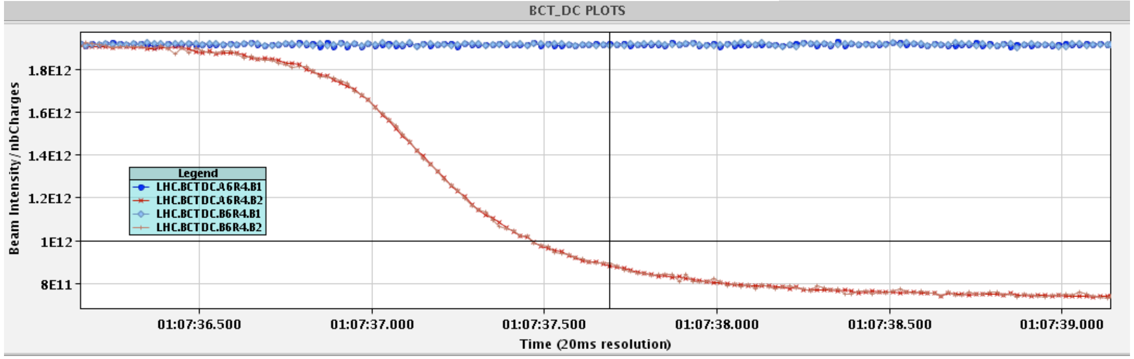
- **Separation of 4 down to 0 σ is not detrimental!**
  Used continously to level lumi for LHC-b
- **The emittance better than expected**
  - From injector ! Preserved between chain
  - the LHC preserves emittance better : we run at 2 (60%of nominal 3.75 μm)
- **τ_{beam} is long (and so the τ_{lumi})**

Robustness to beam current

Integrated lumi strongly favor I_{beam}







Present collimation system is robust

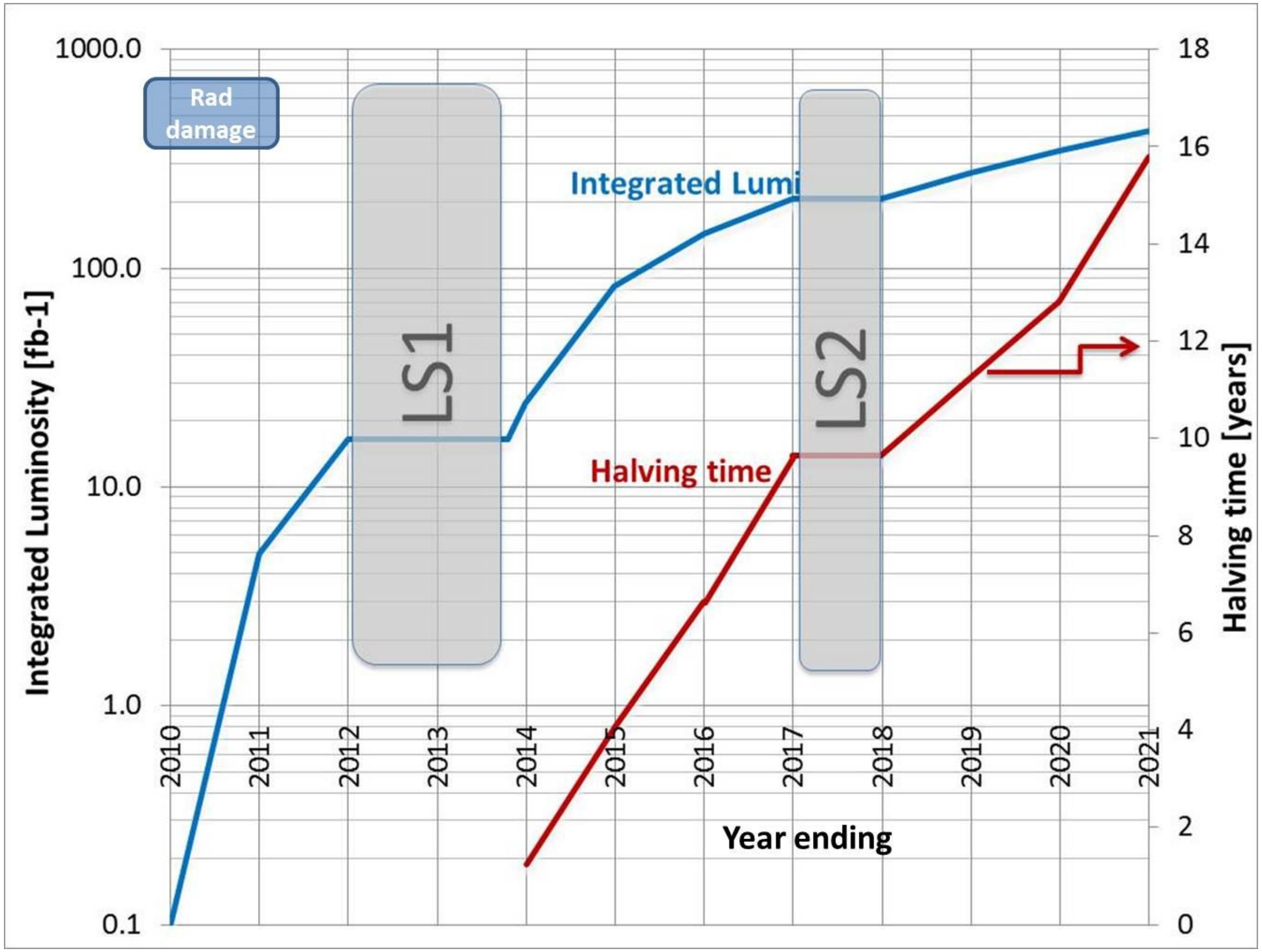
Test Loss rate:

9e11 p/s @ 3.5 TeV

505 kW for2 s

No quench of Sc magnets!

What is the possible reach of LHC in the next decade?



Invited Talk
M. Lamont
on LHC first
perfomance

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Scope of HL-LHC project

- **Challenge by the experiments in 2010: 3000 fb^{-1} in 10-12 years after the upgrade**
- **With no excessive pile up (max 200?) $\Rightarrow$ 5 L_0 (5 10^{34} $cm^{-2}s^{-1}$) as peak luminosity : fundamental for designing detector upgrade**
- **Necessity to run at constant luminosity, i.e. to use levelling.**
- **L_{peak} of $5L_0$ with levelling, 250 fb^{-1}/year $\Rightarrow$ 3000 fb^{-1}**
- It means to make sure LHC works till 2035… in the HL-LHC conditions
- Rely on the LIU - LHC Injector Upgrades *(Talk M. Vretenar on L4, gneral poster on LIU WEPS017 by S. Gilardoni et al.)*

What we will receive from the LHC Injectors (after upgrade)

What we need as minimum in operative condition

Parameter	nominal	25ns	50ns
N	1.15E+11	**2.0E+11**	**3.3E+11**
n_b	2808	2808	1404
beam current [A]	0.58	1.02	0.84
x-ing angle [μrad]	300	475	520
beam separation [σ]	10	10	10
β^* [m]	0.55	0.15	0.15
ε_n [μm]	3.75	**2.5**	**3.0**
ε_L [eVs]	2.51	2.5	2.5
energy spread	1.00E-04	1.00E-04	1.00E-04
bunch length [m]	7.50E-02	7.50E-02	7.50E-02
IBS horizontal [h]	80 -> 106	25	17
IBS longitudinal [h]	61 -> 60	21	16
Piwinski parameter	0.68	2.5	2.5
geom. reduction	0.83	0.37	0.37
beam-beam / IP	3.10E-03	3.9E-03	5.0E-03
Peak Luminosity	$1\ 10^{34}$	**$7.4\ 10^{34}$**	**$8.4\ 10^{34}$**

What LIU is aiming to: L4, PSB 2GeV, SPS up e-cloud suppression + …

Parameter	nominal	25ns	50ns
N	1.15E+11	**1.7E+11**	**2.5E+11**
n_b	2808	2808	1404
beam current [A]	0.58	0.86	0.64
x-ing angle [μrad]	300	480	430
beam separation [σ]	10	10	10
β^* [m]	0.55	0.15	0.15
ε_n [μm]	3.75	**2.5**	**2.0**
ε_L [eVs]	2.51	2.5	2.5
energy spread	1.00E-04	1.00E-04	1.00E-04
bunch length [m]	7.50E-02	7.50E-02	7.50E-02
IBS horizontal [h]	80 -> 106	25	10
IBS longitudinal [h]	61 -> 60	21	13
Piwinski parameter	0.68	2.56	2.56
geom. reduction	0.83	0.37	0.36
beam-beam / IP	3.10E-03	3.0E-03	5.6E-03
Peak Luminosity	$1\ 10^{34}$	**$5.3\ 10^{34}$**	**$7.2\ 10^{34}$**

25 ns: not that far: 15% more bunch population: but probably 30% needed
50 ns: is far, HL-LHC brightness request may be out of reach, but….

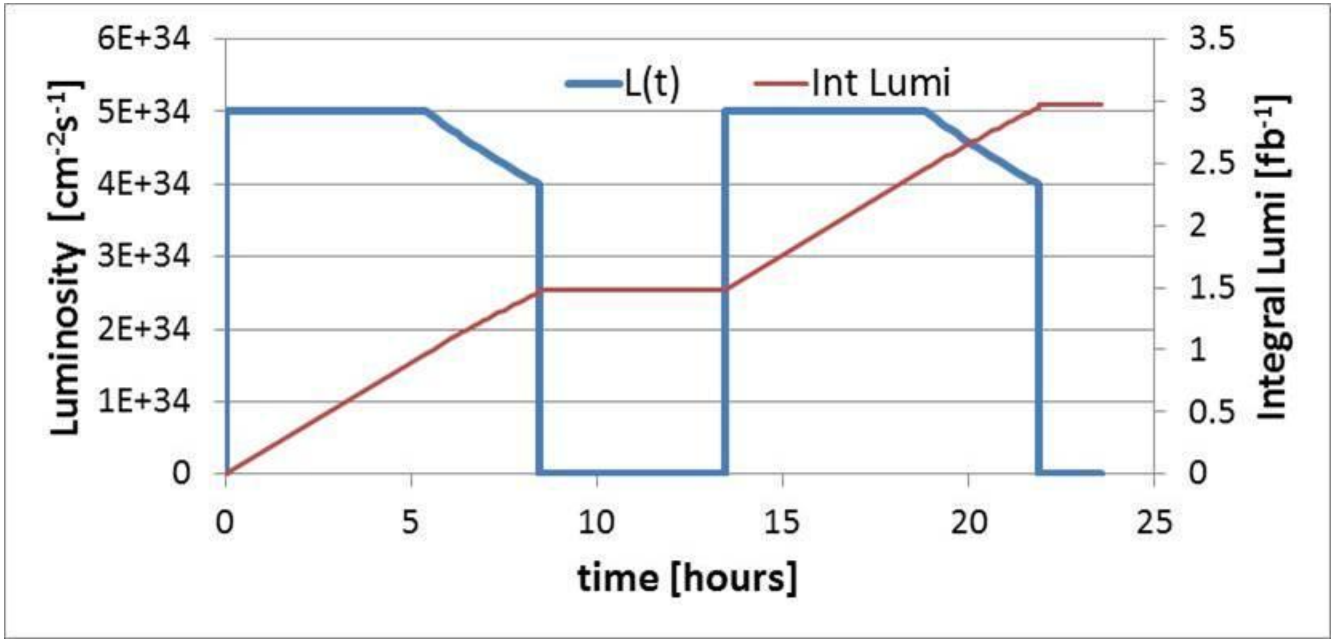
Scenarii for HL-LHC 25 and 50 ns

Efficiency is defined as the ratio between the annual luminosity target of 250 fb^{-1} over the potential luminosity that can be reached with an ideal cycle run time with no stop for 150 days: $t_{run} = t_{lev} + t_{dec} + t_{turn}$. The turnaround time after a beam dump is taken as 5 hours, t_{decay} is 3 h while t_{lev} depends on the total beam current

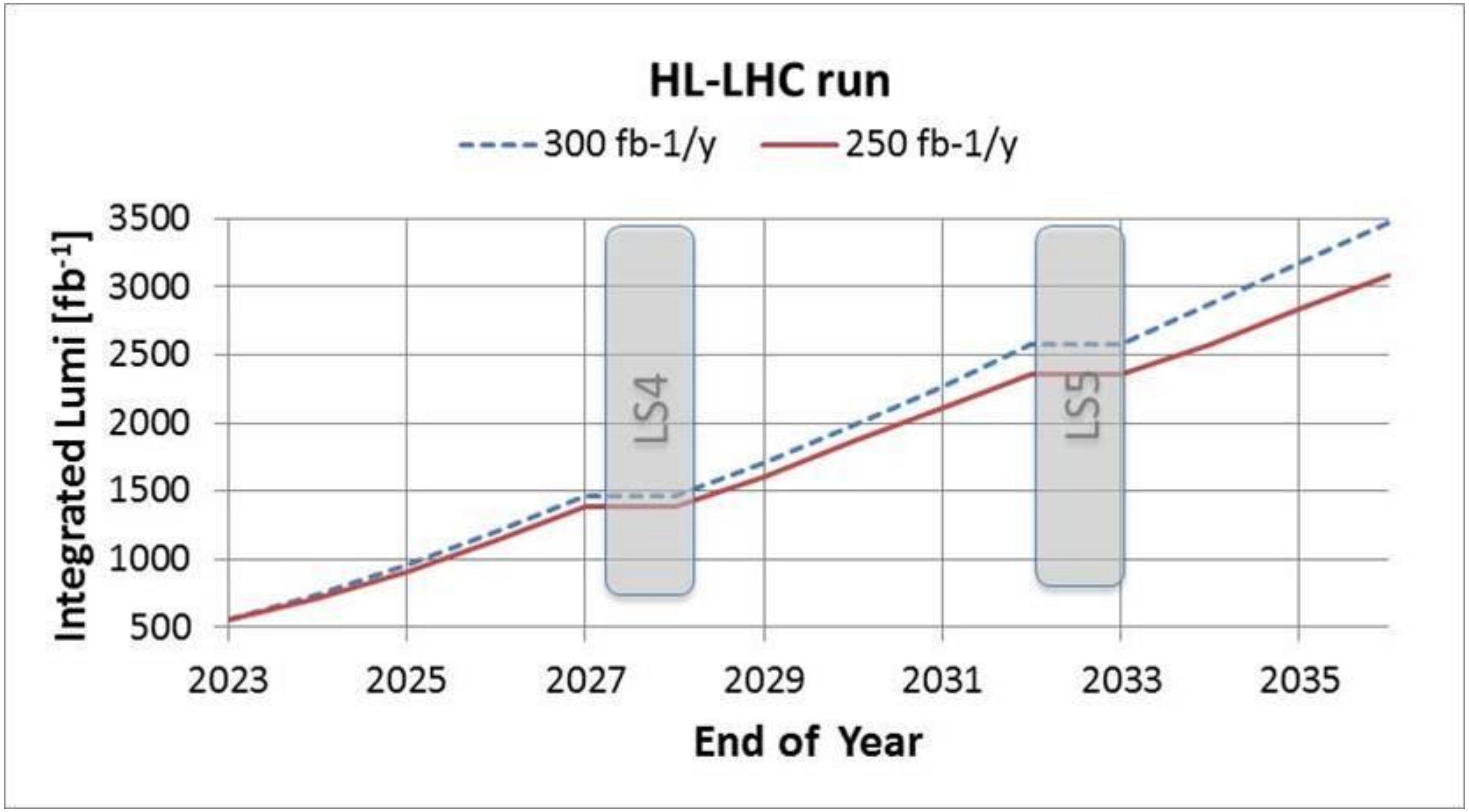
Parameter	Nom. 25 ns	Target 25 ns	Target 50 ns	LIU 25 ns	LIU 50 ns
N_b [10^{11}]	1.15	2.0	**3.3**	1.7	2.5
n_b	2808	2808	1404	2808	1404
I [A]	0.56	**1.02**	0.84	0.86	0.64
θc [μrad]	300	475	445	480	430
β* [m]	0.55	**0.15**	**0.15**	**0.15**	**0.15**
ε_n [μm]	3.75	**2.5**	**2.0**	**2.5**	**2.0**
ε_s [eV s]	2.5	2.5	2.5	2.5	2.5
IBS h [h]	111	25	**17**	25	**10**
IBS l[h]	65	21	**16**	21	**13**
Piwinski	0.68	2.5	2.5	2.56	2.56
F red.fact.	0.81	0.37	0.37	0.37	0.36
b-b/IP[10^{-3}]	3.1	3.9	**5**	3	**5.6**
L_{peak}	1	7.4	8.4	5.3	**7.2**
Crabbing	no	**yes**	**yes**	**yes**	**yes**
$L_{peak\ virtual}$	1	20	22.7	14.3	19.5
Pileup $L_{lev}=5L_0$	19	141	257	137	274
Eff.†150 days	=	0.62	0.61	0.66	0.67

HL-LHC cycle (as exemple)

for example in second column "Target 25 ns" t_{lev}=5.4 h. If we would run with the cycle for 150 days we would get about 400 fb^{-1}: an efficiency of 62% would yield 250 fb^{-1}/y. Today is 40%



Target of HL-LHC



To make this a reality improving downtime, reliability, robustness, and safety is important as luminosity performance

Comments and variant

- **High I_{beam}, but low β^* as well**
  - **Achromatic Telescopic Squeezing** (*ATS, see poster **S. Fartouk**, R. De Maria*), **novel scheme, fruit of optics difficulties of Phase 1.**
    - Allows β^*as low as 15 (10-12?) cm round beams
    - Allows solution of 7.5/30 cm with flat beams (alternative to CC)
- **If CC does not work**

$$R = \frac{1}{\sqrt{1 + (\frac{\theta_c \sigma_s}{2\varepsilon_n \beta^*}\gamma)^2}}$$

  - Flat beam, Large Pw, very short σ_s .
  - Long range b-b compensation even more necessary!
  - Levelling by varying θ_c, beam separation or β^*
  - Resume of Early Separation Scheme (invasive small dipole in the detectors)? Very difficult but…
- **We have many solutions at hand: the critical point is to develop the hardware!**

See papers by ;R. De Maria; O.Brunings, F. Zimmermann and others

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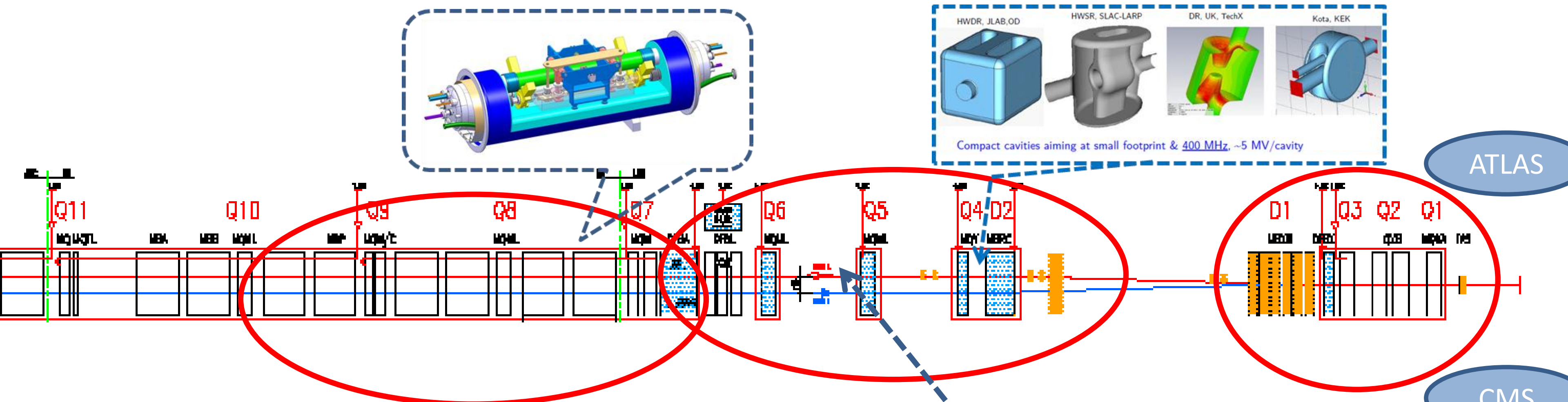
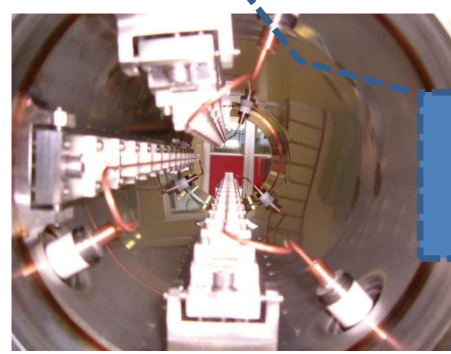
LSS (IR+MS+DS) is critical zone a lot of magnet changes +CC+ wire



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

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

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



4. LR BB compensation wires

Plan

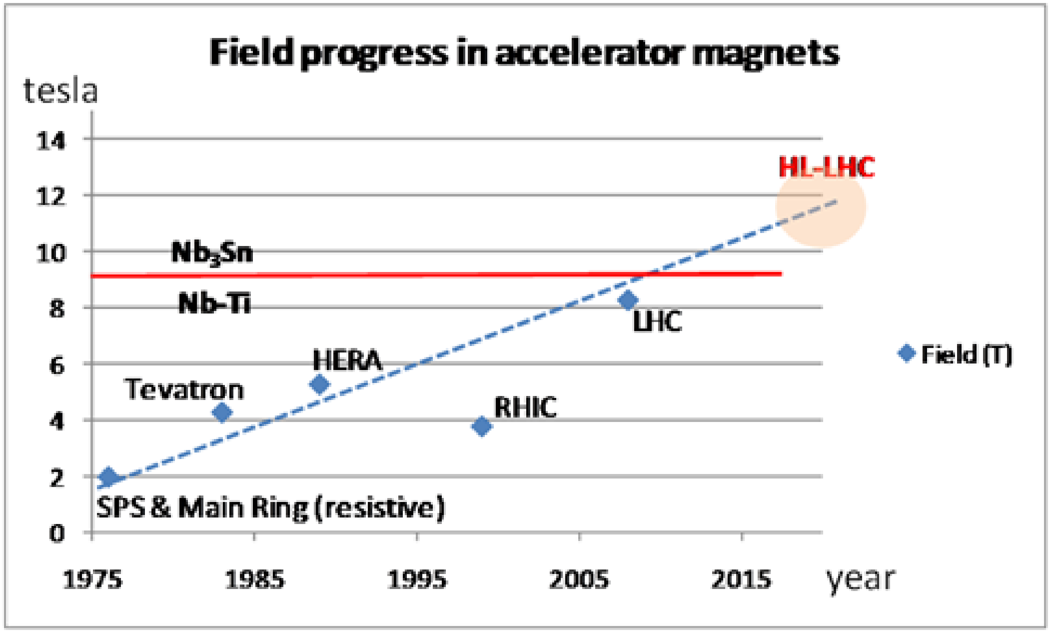
- **LS1 2013-14: driven by splice consolidation (energy LHC) preparation relocation of MS (Match. section) EPC in surface + relocation of EPC in P7**
- **LS2 2018: driven by Injector upgrade and Intensity LHC**
  - Relocation of MS EPC to surface, preparation for IRs EPC
    - 4 Sc links 200 kA, DFBs in surface
    - Eliminate SEU fin EPC
  - New cryoplant in P4 (**to decouple RF from Magnets and restore P5 -Left capacity**)
  - Intall Crab Cavity in P4, to test it in LHC
  - Install New collimation system with 11 T new LHC dipole in P3, P2, P7?

Plan - cont

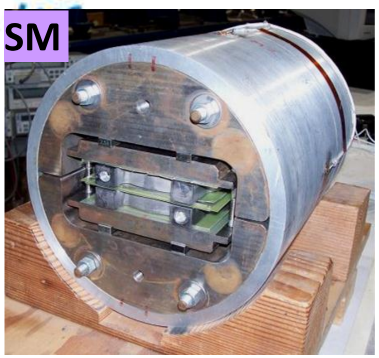
- LS3 **2022-23: HL-LHC installation**
  - 2 new low β^* triplets (16 large SC quads)
  - 4 D1, 4 D2 Separation/Recombination dipoles
  - 8 new MS quadrupoles, larger apertures
  - 8 compact SCRF Crab Cavities
  - Two new large Cryoplants for the IRs (cryopower but also **decoupling arc and IRs**)
  - New collimators for the triplets
  - New shielding and detector interfaces
  - New Cold powerign based on Sc link for the IRs magnets

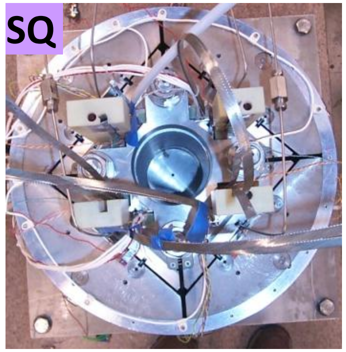
Squeezing the beam
High Field SC Magnets

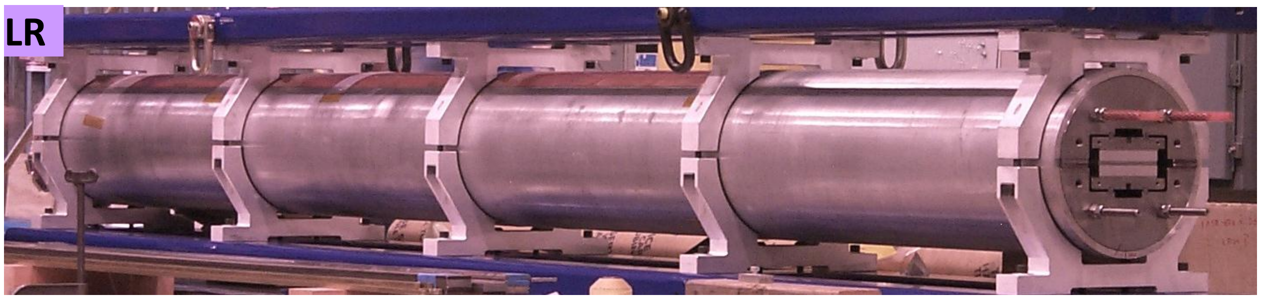
- **13 T, 120-150 mm aperture Quads for the inner triplet**
  - LHC: 8 T, 70 mm.
- **More focus strength, β* as low as 15 cm, vs. 55 cm in LHC. In some scheme even β* down to 7.5 cm are considered**
- **Dipoles for beam recombination/separation capable of 6-8 T with 150-180 mm aperture (LHC: 1.8 T, 70 mm)**

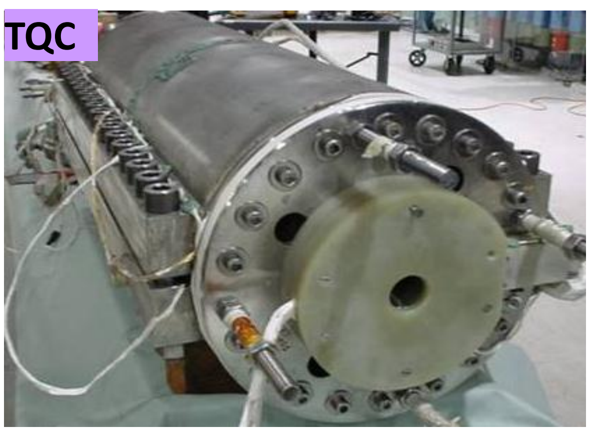


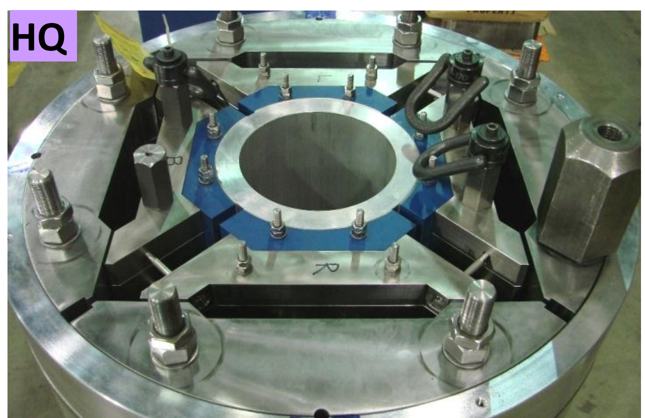
LARP (US LHC program) Magnets



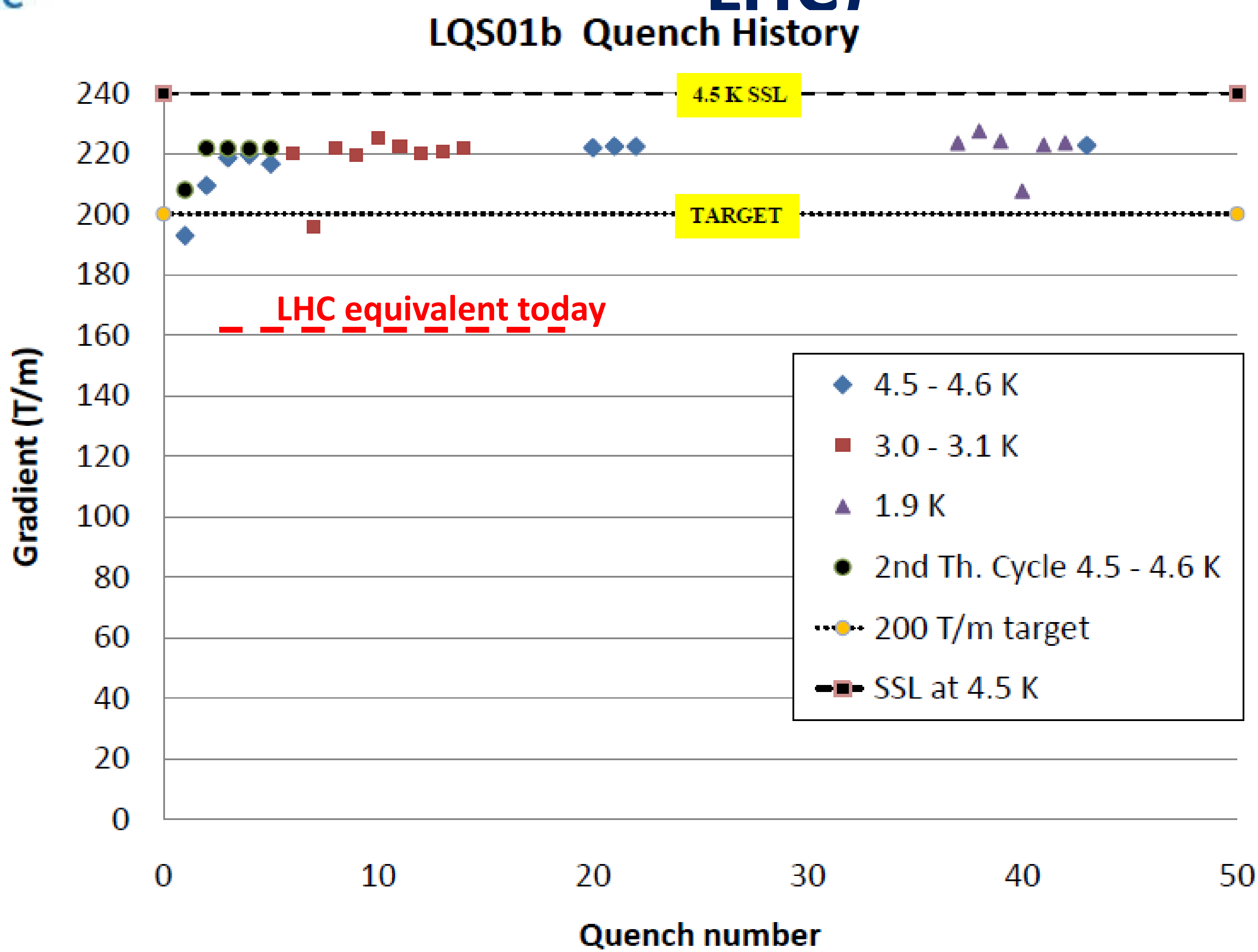




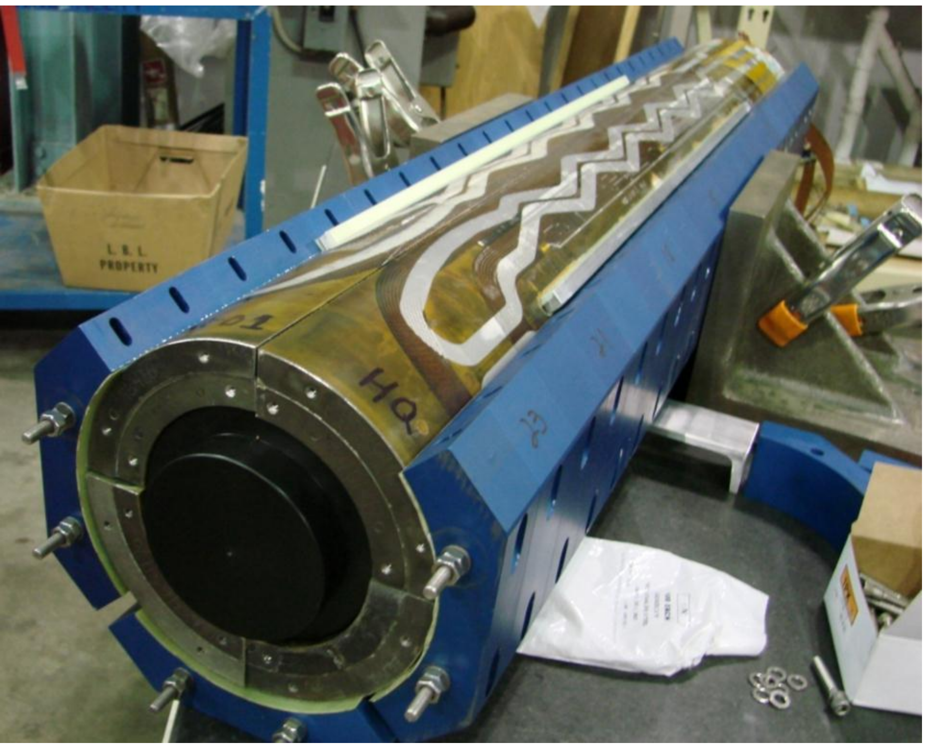


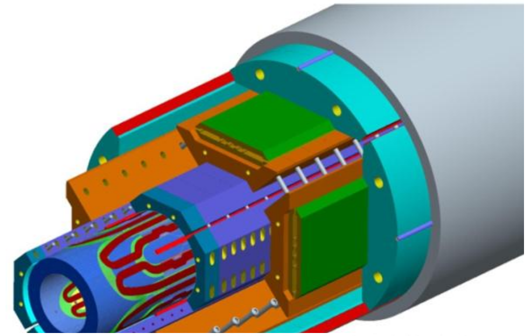


Results LARP LQ (90 mm vs 70 mm LHC)

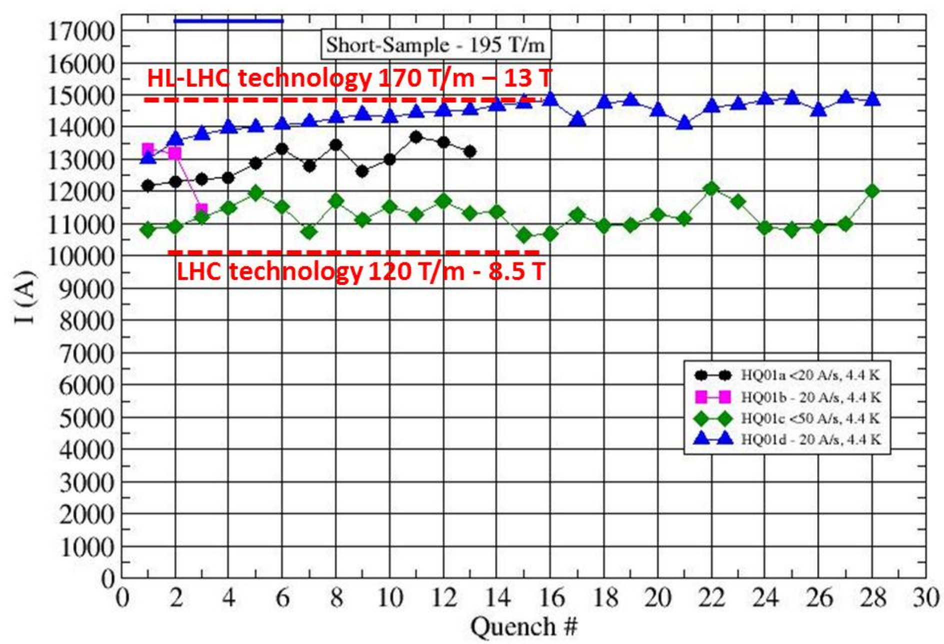


LARP HQ (120 mm- 13 T)



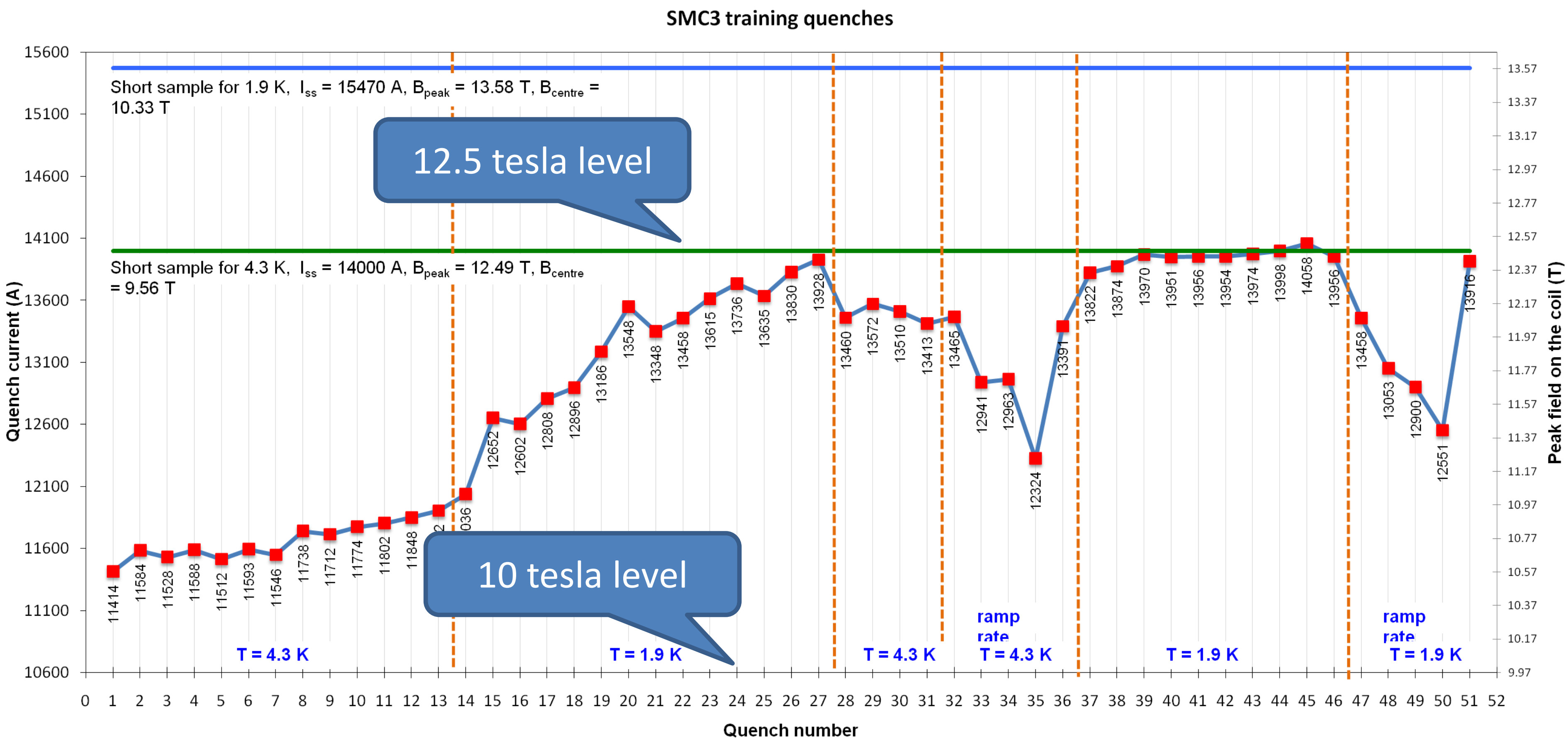


HQ01a-b-c-d 4.4K Training



Tue Apr 26 09:45:58 2011

CERN: recent success 12.5 T at 4.2 K, first 400 mm Nb_3Sn coil!

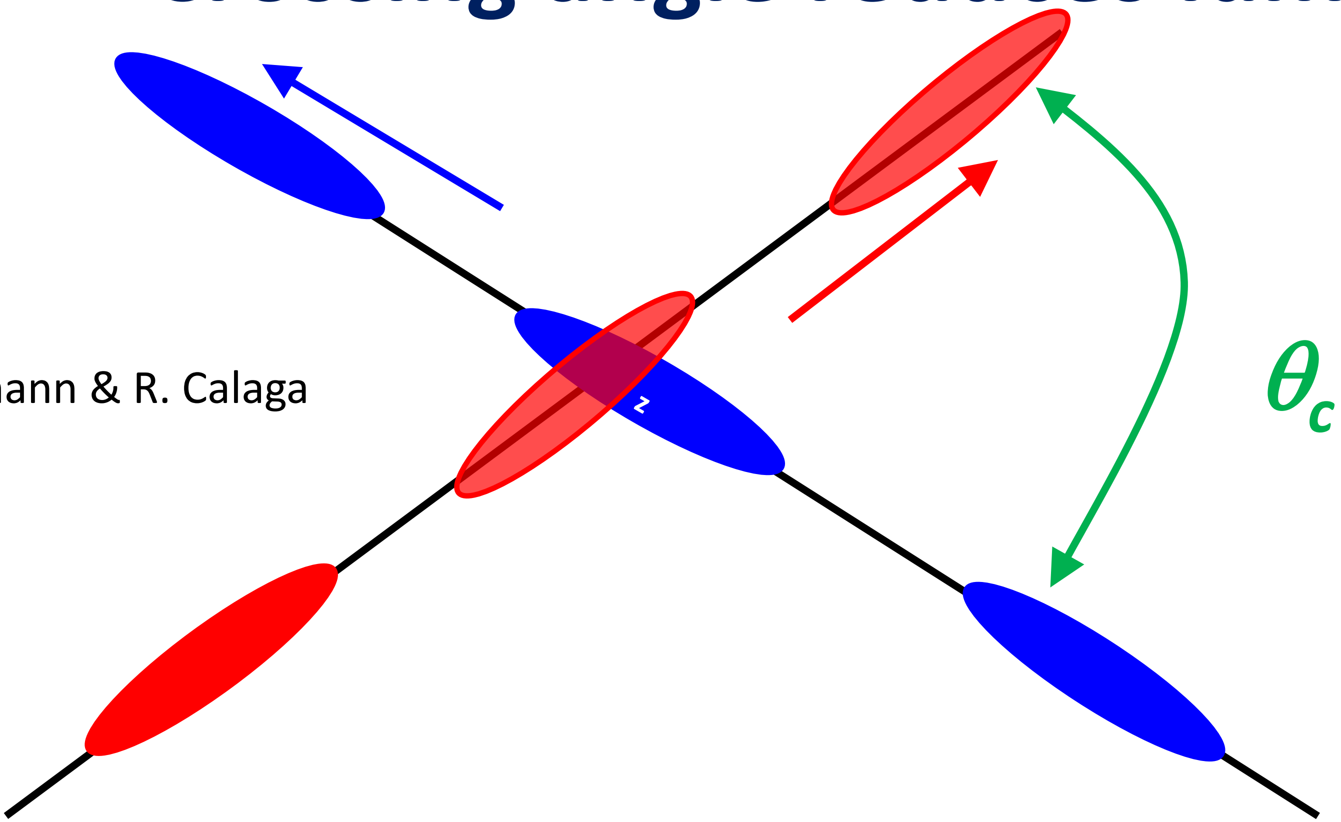


Picture of the 12.5 T coil

A coil like that is like testing a single cell cavity: the route to real Accelerator Magnet is very long, but it shows that performance is at hand

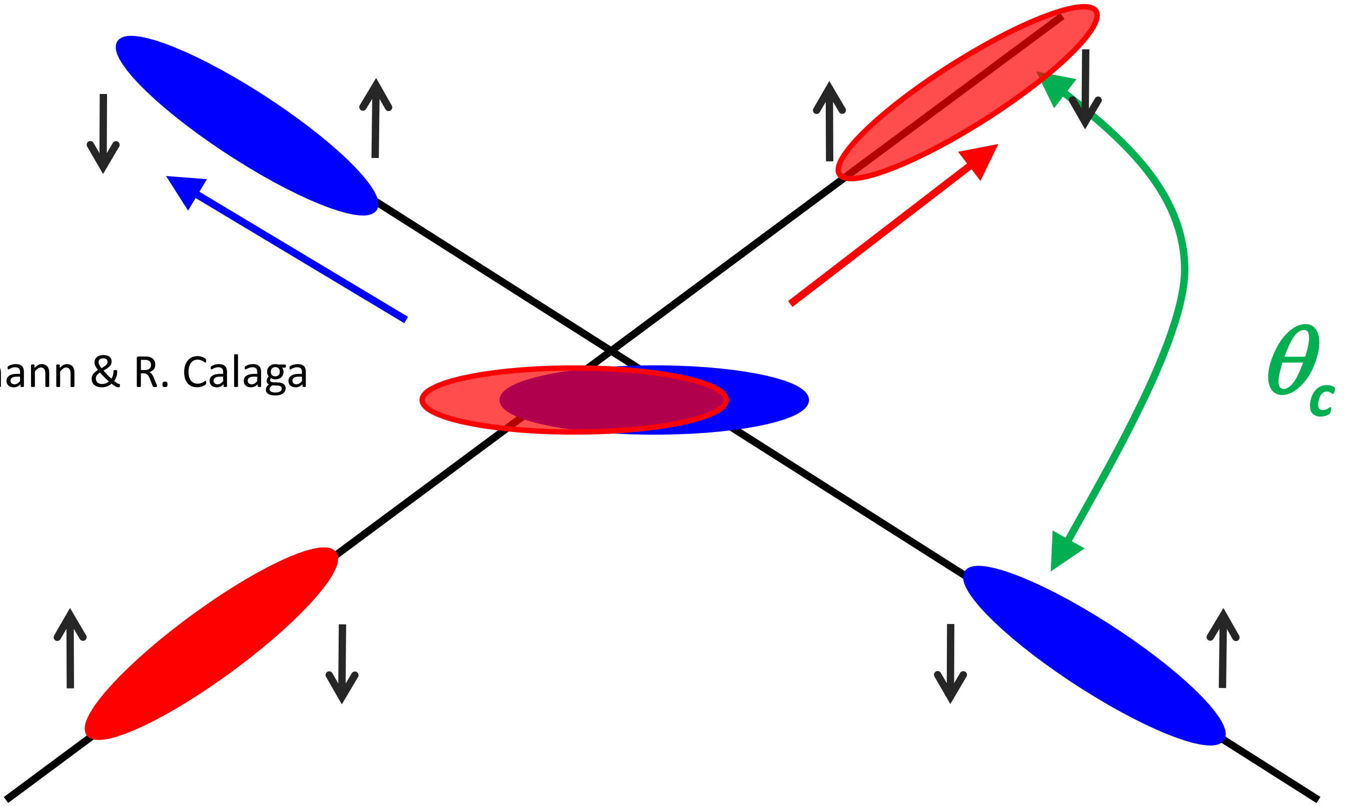
Crossing angle reduces lumi

F. Zimmermann & R. Calaga



- **luminosity loss comes from imperfect geometric overlap**
- **it becomes significant if $\sigma_z\theta_c/2>\sigma_x^*$ or $\phi_{piw}>1$ with $\phi_{piw}=\sigma_z\theta_c/(2\sigma_x^*)$ the "Piwinski angle": for HL-LHC we will be at $\phi_{piw}=2.5$!**

Beam rotation (crab) recovers it



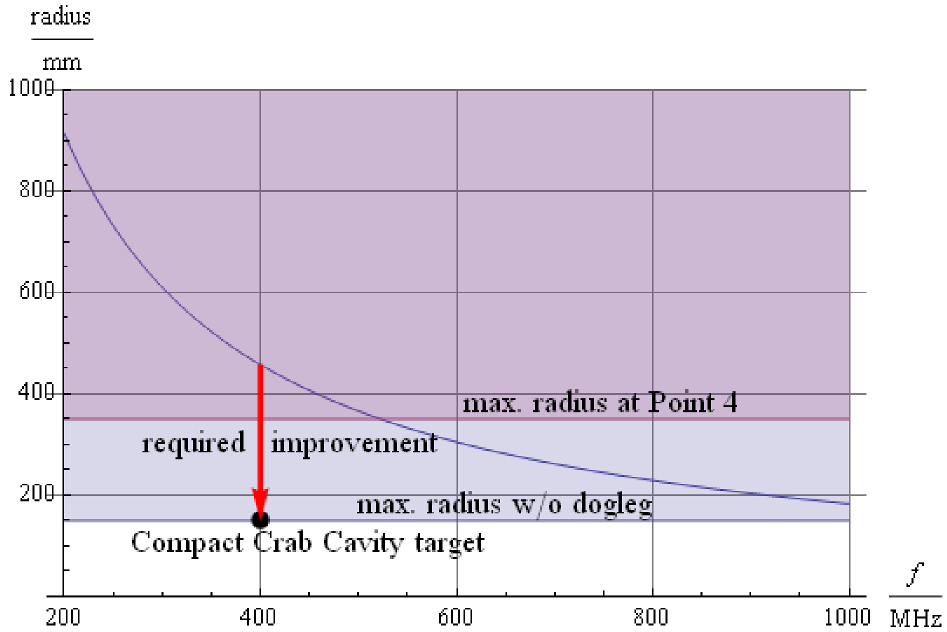
F. Zimmermann & R. Calaga

- **RF crab cavity deflects head and tail in opposite direction so that collision is effectively "head on" for luminosity and tune shift**
- **bunch centroids still cross at an angle (easy separation)**
- **1st proposed in 1988, in operation at KEKB since 2007**

→ *world record luminosity!*

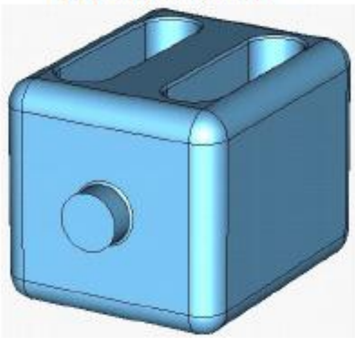
Improve beam overlap SC RF Crab cavities

- **Crab cavities to rotate the beam and colliding with good overlap**
- **Providing « easy » way for levelling**
- **Necessary to fully profit of the low β***
- **Very demanding phase control (better than 0.001°) and protection**
- **Very compact design**
- **40-80 MV (16 MV in LHC)**

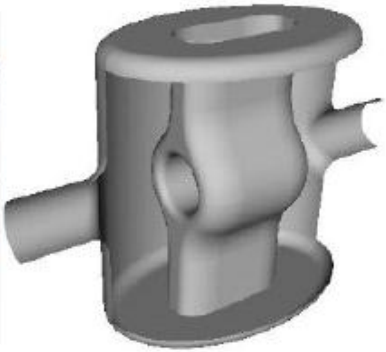


Compact 400 MHz Completely new domain

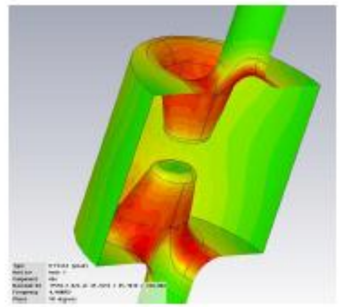
HWDR, JLAB,OD



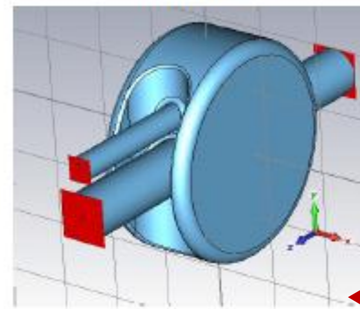
HWSR, SLAC-LARP



DR, UK, TechX



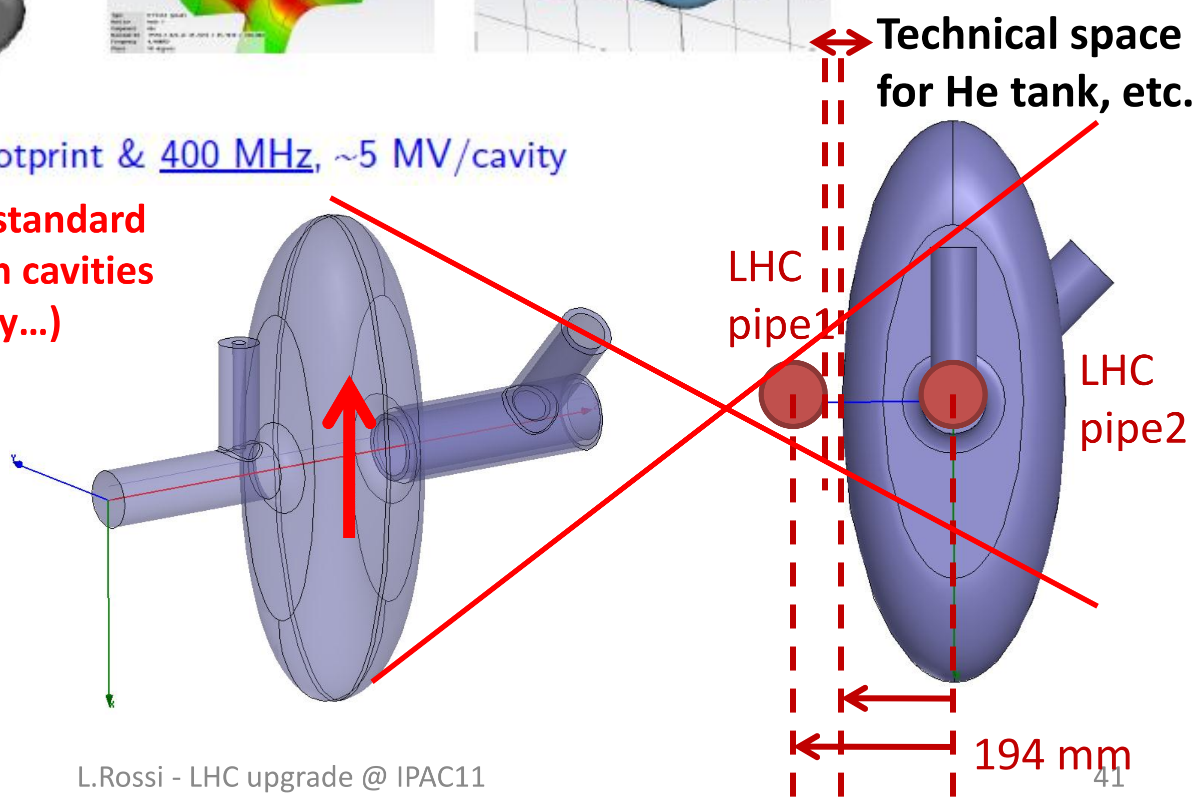
Kota, KEK



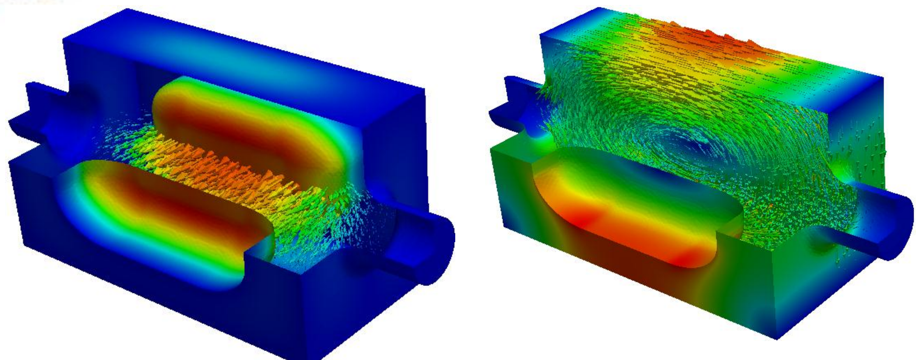
Compact cavities aiming at small footprint & 400 MHz, ~5 MV/cavity

All these 400 MHz can fit into the standard 194 mm LHC beam separation with cavities in a common cryostat (but not easy…)

New idea for a very compact elliptical 800 MHz

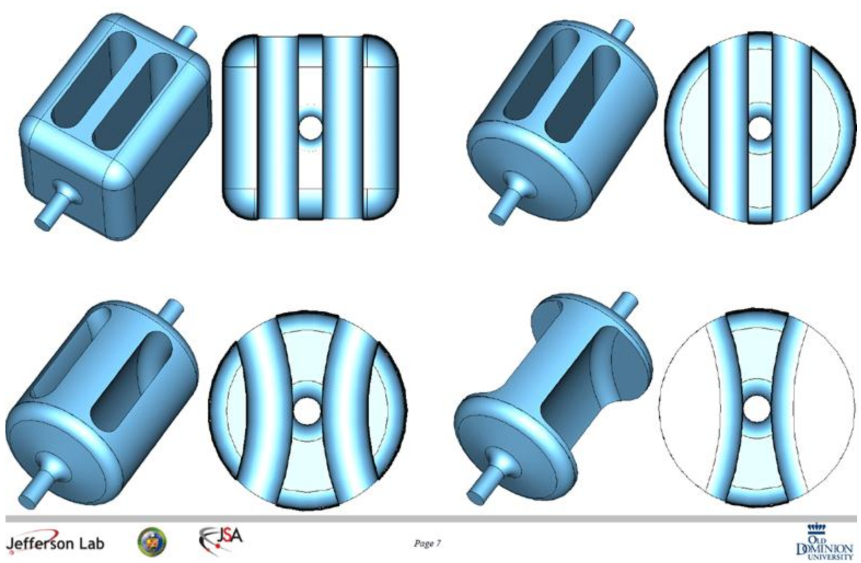


New Ridged waveguide deflector (Z. Li, SLAC) and design parallel bar J. Delayen, ODU Jlab



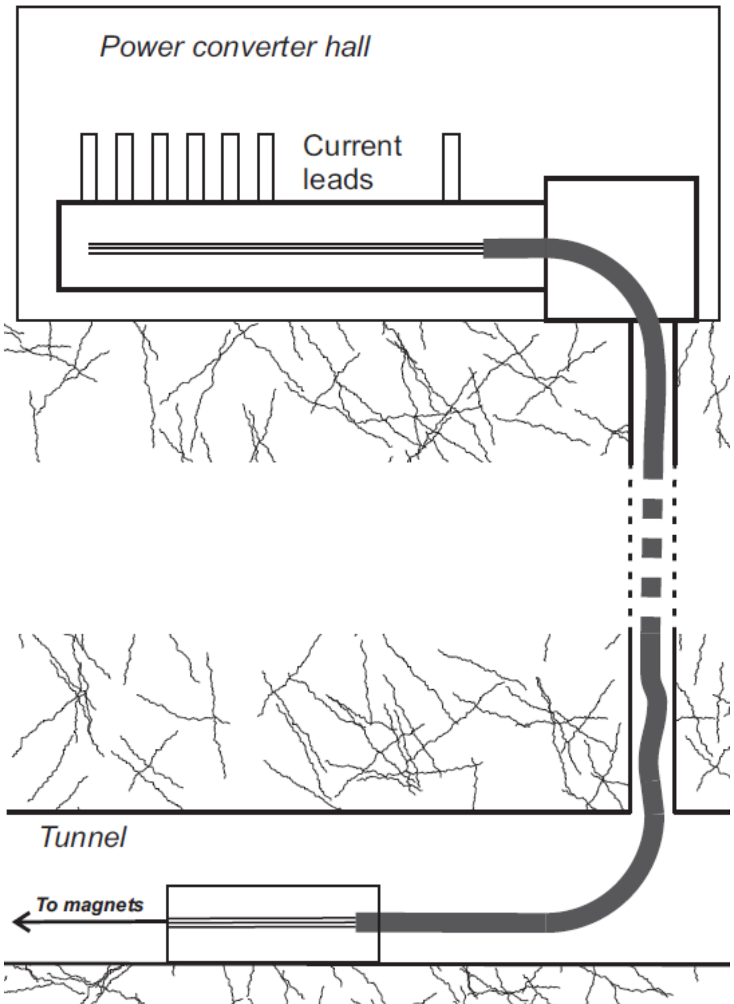
- Transverse dimension: 250mmX270mm
- Fit both H and V crabbing schemes

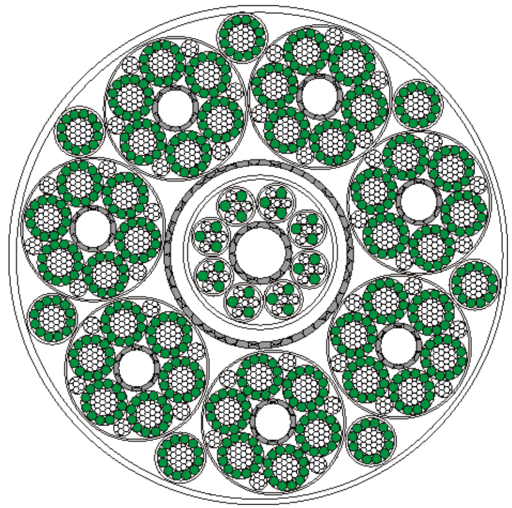
Operating mode Frequency	400 MHz
Operating Mode	TE11 like mode
Lowest acc mode Frequency	671 MHz
Lowest vertical HOM Frequency	617 MHz
Lowest horizontal HOM Frequency	698 MHz
Iris aperture (diameter)	84 mm
Transverse dimension	250 mm
Vertical dimension	270 mm
Longitudinal dimension	525 mm
Transverse Shunt Impedance	330 ohm/cavity
Required deflecting voltage per cavity	5 MV
Peak surface magnetic field	94 mT
Peak surface electric field	45 MV/m



- **The two designs by Zenghai Li (SLAC) and Jean Delayen (ODU) are now similar and it was agreed in Montauk (US-LARP meeting, May '11) that they will join forces to work on a single design!**

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





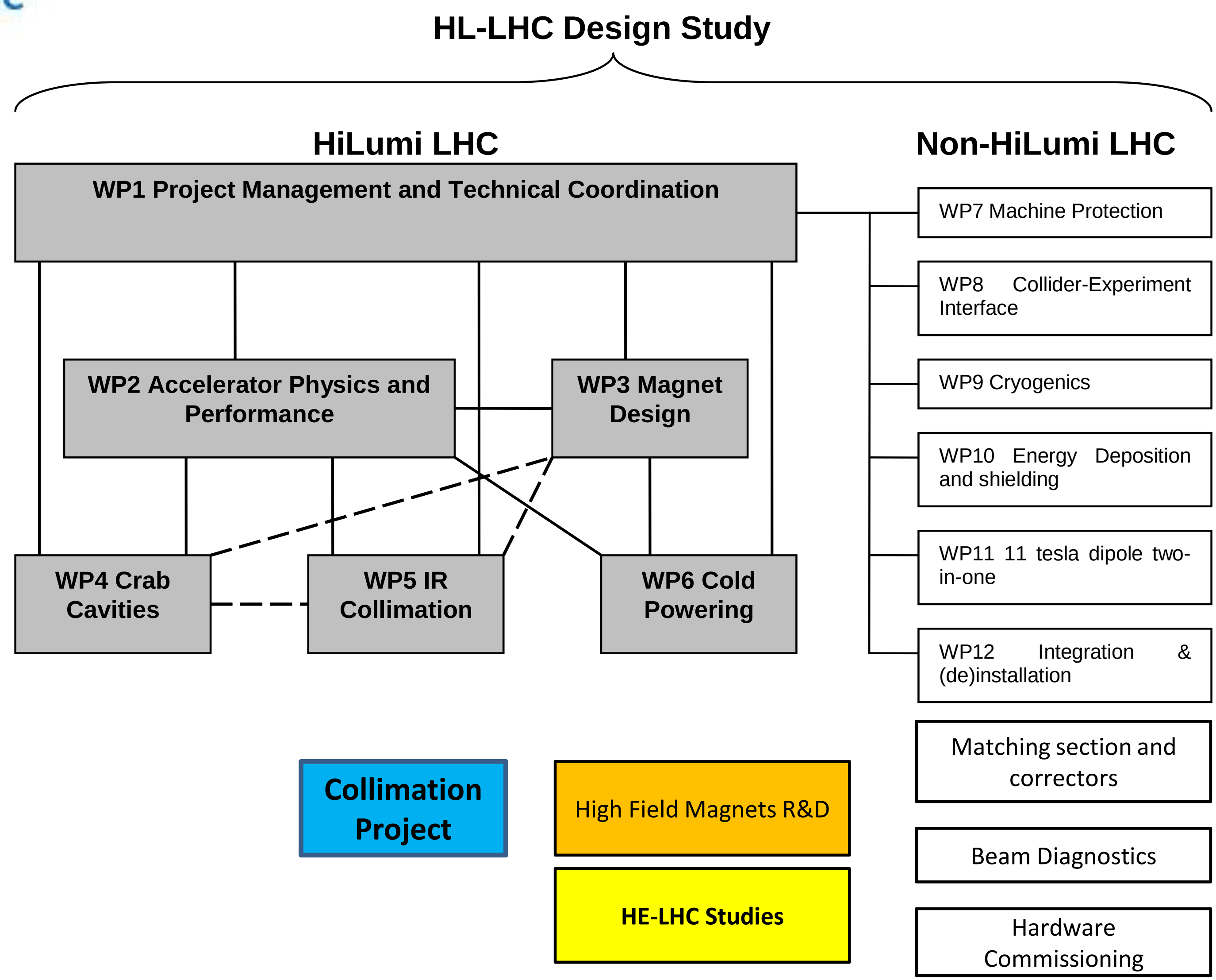
Φ = 62 mm

MgB2
(or other HTS)

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

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

HL-LHC composition

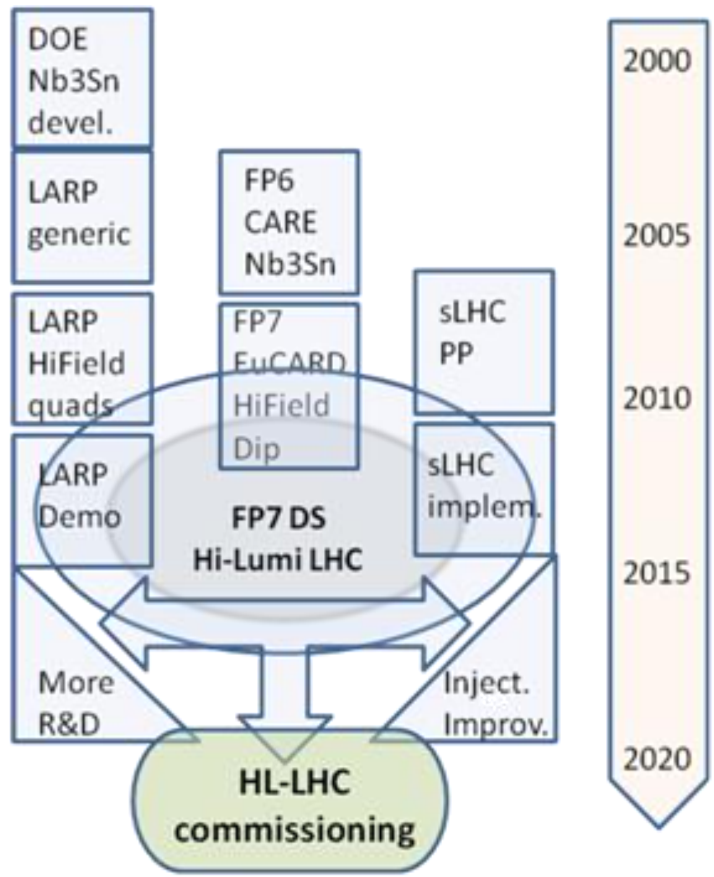


Large participation FP7 HiLumi application 25 Nov 2010

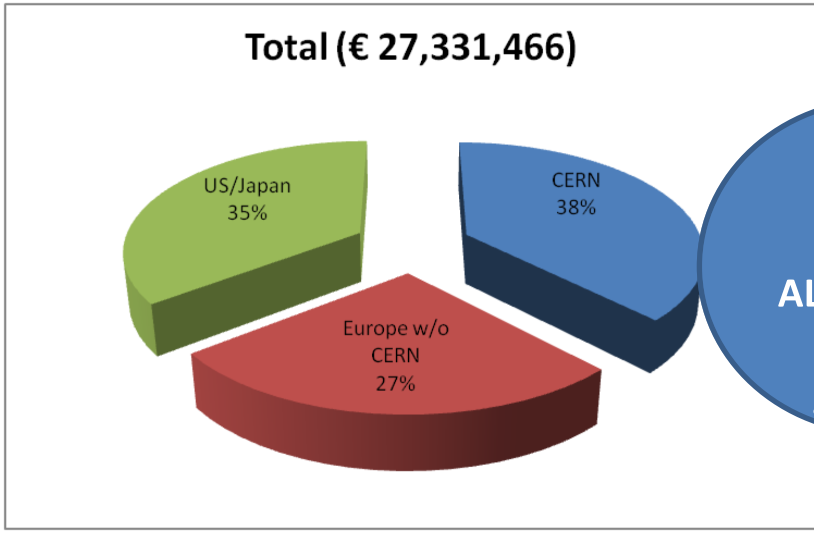
Participant no.	Participant organisation name	Short name	Country
1 (Coord-inator)	European Organization for Nuclear Research	CERN	IEIO[1]
2	Commissariat à l'Énergie Atomique et aux énergies alternatives	CEA	France
3	Centre National de la Recherche Scientifique	CNRS	France
4	Stiftung Deutsches Elektronen-Synchrotron	DESY	Germany
5	Istituto Nazionale di Fisica Nucleare	INFN	Italy
6	Budker Institute of Nuclear Physics	BINP	Russia
7	Consejo Superior de Investigaciones Cientificas	CSIC	Spain
8	École Polytechnique Fédérale de Lausanne	EPFL	Switzerland
9	Royal Holloway, University of London	RHUL	UK
10	University of Southampton	SOTON	UK
11	Science & Technology Facilities Council	STFC	UK
12	University of Lancaster	ULANC	UK
13	University of Liverpool	UNILIV	UK
14	University of Manchester	UNIMAN	UK
15	High Energy Accelerator Research Organization	KEK	Japan
16	Brookhaven National Laboratory	BNL	USA
17	Fermi National Accelerator Laboratory (Fermilab)	FNAL	USA
18	Lawrence Berkeley National Laboratory	LBNL	USA
19	Old Dominion University	ODU	USA
20	SLAC National Accelerator Laboratory	SLAC	USA

HiLumi is the focal point of 20 years of converging International collaboration

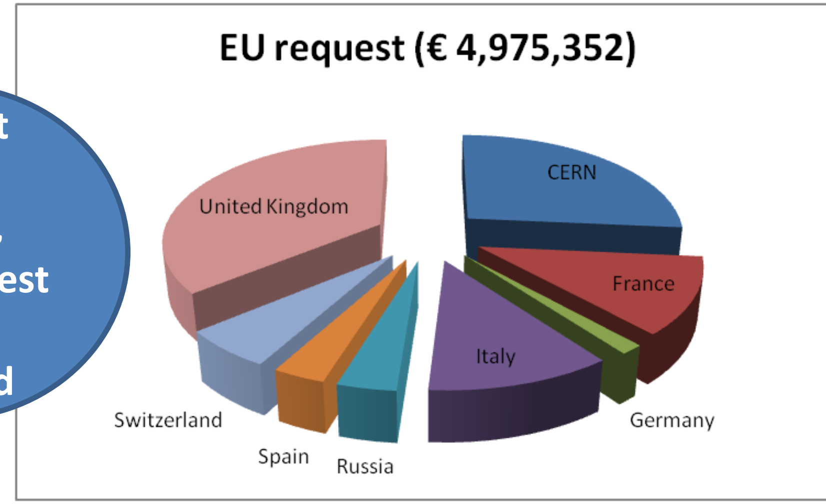
- The collaboration wiht US on LHC upgrade started during the construction of LHC
- EU programs have been instrumental in federating all EU efforts
- With Hi-Lumi the coordination makes a step further: from coordinated R&D to a common project
- CERN is not anymore the unique owner, rather is the motor and cathalizer of a wider effort.
- Managed like a large detector collaboration (with CERN in special position as operator of LHC)



Budget FP7 HiLumi and HL-LHC



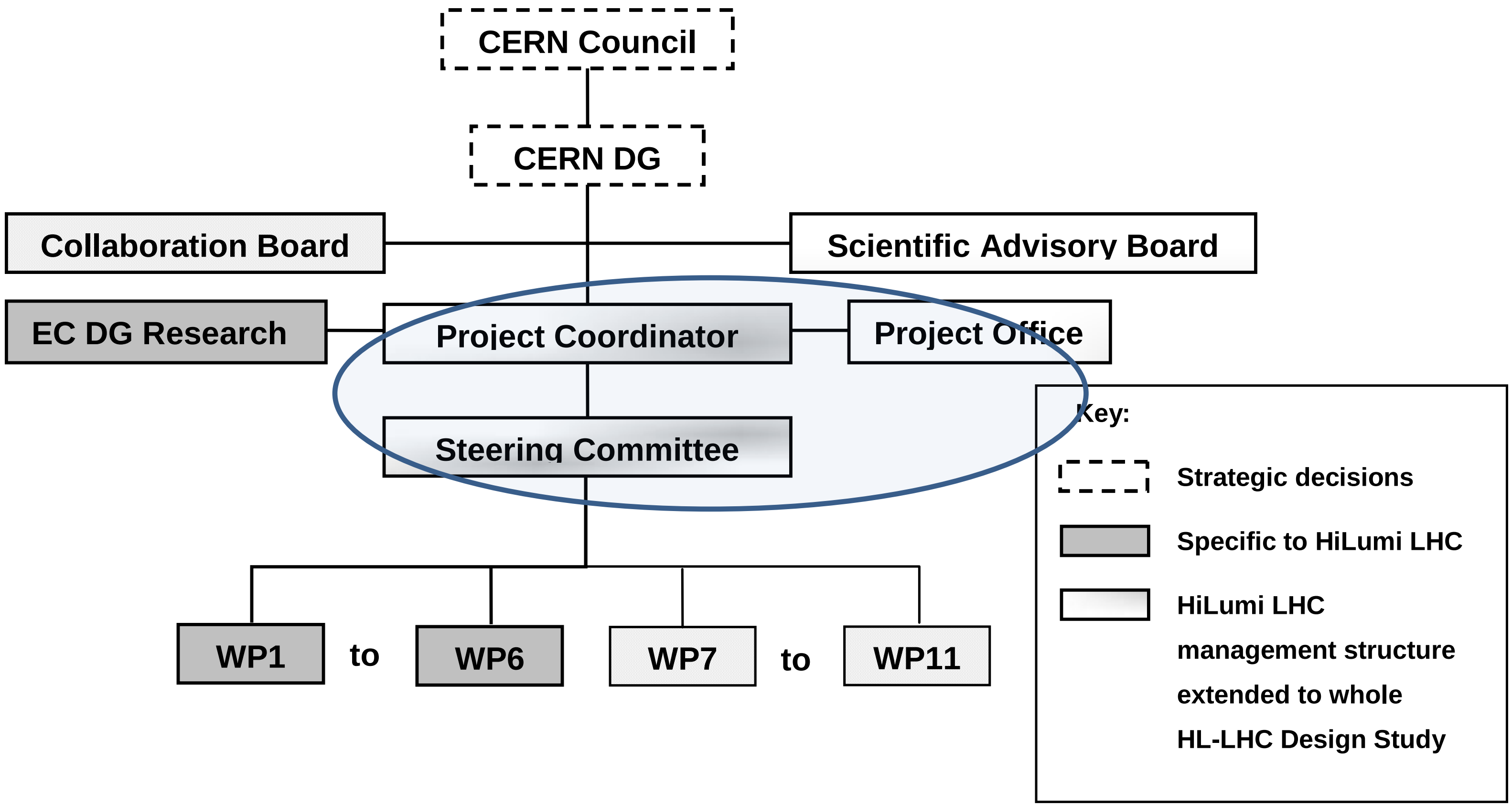
Perfect score 15/15, ALL request to EU granted



Estimated cost for the the whole HL-LHC over **10 years in M€**

	Design in FP7 HiLumi	Extra effort for Design	R&D and proto	Industrialization & Construction	TOT	Industry
W1-WP6	27	10	50	200	287	160
WP7-12	0	15	30	100	145	80
Other	0	5	10	50	65	40
TOT	27	30	90	350	497	280

HL-LHC management



Highlights

- LHC: a long story and even a longest future?
- LHC upgrade : the 2001-2010 studies
- LHC present perfomance: impact on upgrade
- Lumi upgrade: scope, baseline and variants
- The HL-LHC technical program and FP7-HiLumi LHC design study
- **Energy upgrade: the HE-LHC parameters space, the challanges and the roadmap.**

Is it worth ?

- **Physics: apparently yes, only LHC at 14 TeV will say for sure…**
- **Technically**
  - **The LHC complex will have 25 y of operation in 2035**
  - **The LHC INJ will have 50-75 y ! But it will be largely renovated**
  - However the advantage of having an infrastructure –well maintained – is immense
  - The first action for the Energy upgrade is happening: **25 y consolidation project @ CERN**
  - **The project can grow in the shadow of HL-LHC…**
- **WG led by S. Myers in 2010:** CERN-ATS-2010-177 (2010) **Workshop in Malta October 2010: see** CERN–2011–003
- Cost is 6-7 B CHF range (80% B for Cryo-Magnets) **for 33 TeV c.o.m.**
  - New tunnel with LHC technology is no cheaper
  - Solution at **25 TeV** is more at hand and $\leq$ 5 Billions

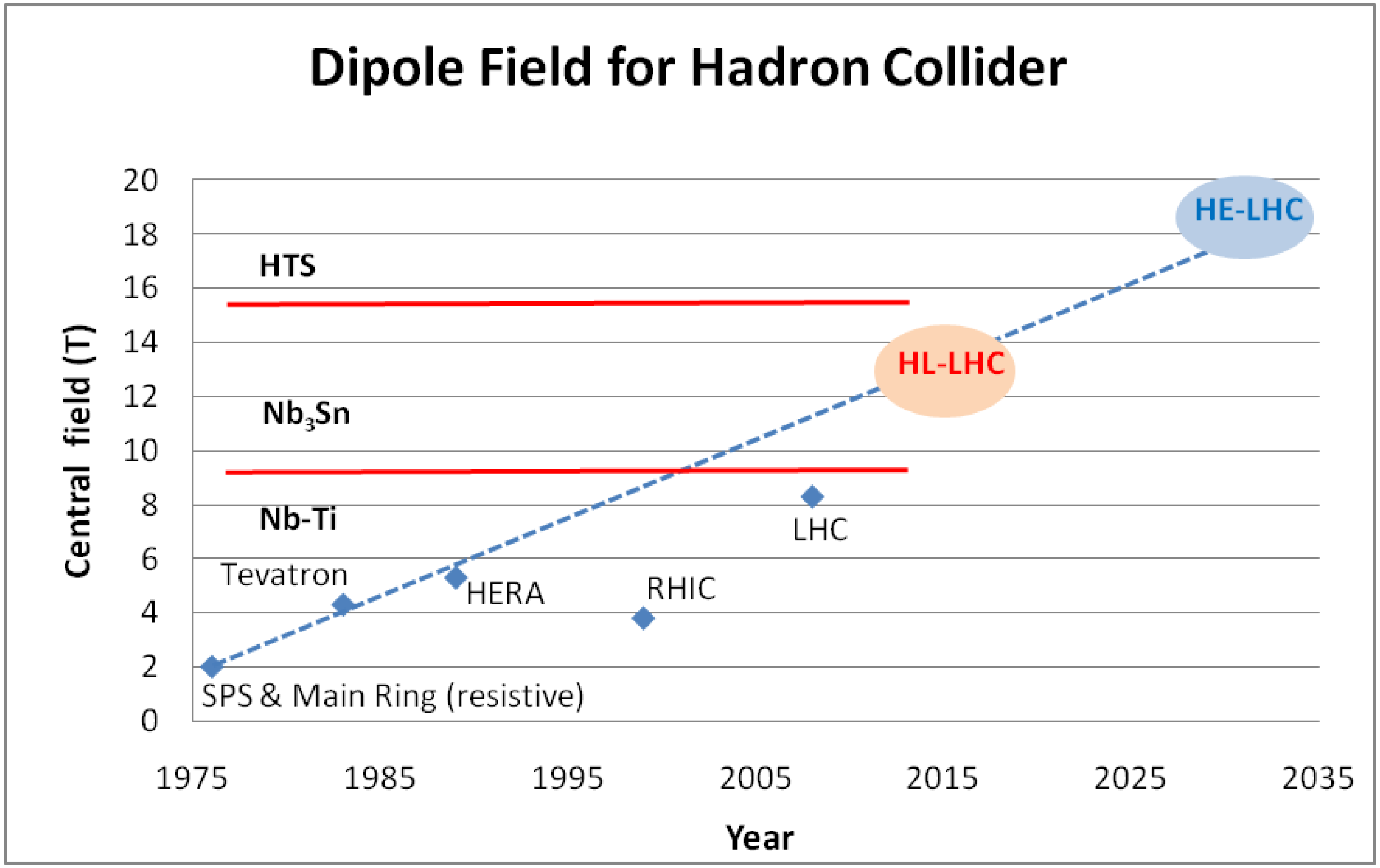
Possible list of parameters

	nominal LHC	HE-LHC	
beam energy [TeV]	7	16.5	
dipole field [T]	8.33	20	
dipole coil aperture [mm]	56	40	
beam half aperture [cm]	2.2 (x), 1.8 (y)	1.3	
injection energy [TeV]	0.45	>1.0	
#bunches	2808	1404	
bunch population [10^{11}]	1.15	1.29	1.30
initial transverse normalized emittance [μm]	3.75	3.75 (x), 1.84 (y)	2.59 (x & y)
initial longitudinal emittance [eVs]	2.5	4.0	
number of IPs contributing to tune shift	3	2	
initial total beam-beam tune shift	0.01	0.01 (x & y)	
maximum total beam-beam tune shift	0.01	0.01	
beam circulating current [A]	0.584	0.328	
RF voltage [MV]	16	32	
rms bunch length [cm]	7.55	6.5	
rms momentum spread [10^{-4}]	1.13	0.9	
IP beta function [m]	0.55	1 (x), 0.43 (y)	0.6 (x & y)
initial rms IP spot size [μm]	16.7	14.6 (x), 6.3 (y)	9.4 (x & y)
full crossing angle [μrad]	285 (9.5 $\sigma_{x,y}$)	175 (12 σ_{x0})	188.1 (12 $\sigma_{x,y0}$)
Piwinski angle	0.65	0.39	0.65
geometric luminosity loss from crossing	0.84	0.93	0.84

Lisz parameters - cont.

stored beam energy [MJ]	362	478.5	480.7
SR power per ring [kW]	3.6	65.7	66.0
arc SR heat load dW/ds [W/m/aperture]	0.17	2.8	2.8
energy loss per turn [keV]	6.7	201.3	
critical photon energy [eV]	44	575	
photon flux [10^{17}/m/s]	1.0	1.3	
longitudinal SR emittance damping time [h]	12.9	0.98	
horizontal SR emittance damping time [h]	25.8	1.97	
initial longitudinal IBS emittance rise time [h]	61	64	~68
initial horizontal IBS emittance rise time [h]	80	~80	~60
initial vertical IBS emittance rise time [h]	~400	~400	~300
events per crossing	19	76	
initial luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	2.0	
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	2.0	
beam lifetime due to *p* consumption [h]	46	12.6	
optimum run time t_r [h]	15.2	10.4	
integrated luminosity after t_r [fb^{-1}]	0.41	0.50	0.51
opt. av. int. luminosity per day [fb^{-1}]	0.47	0.78	0.79

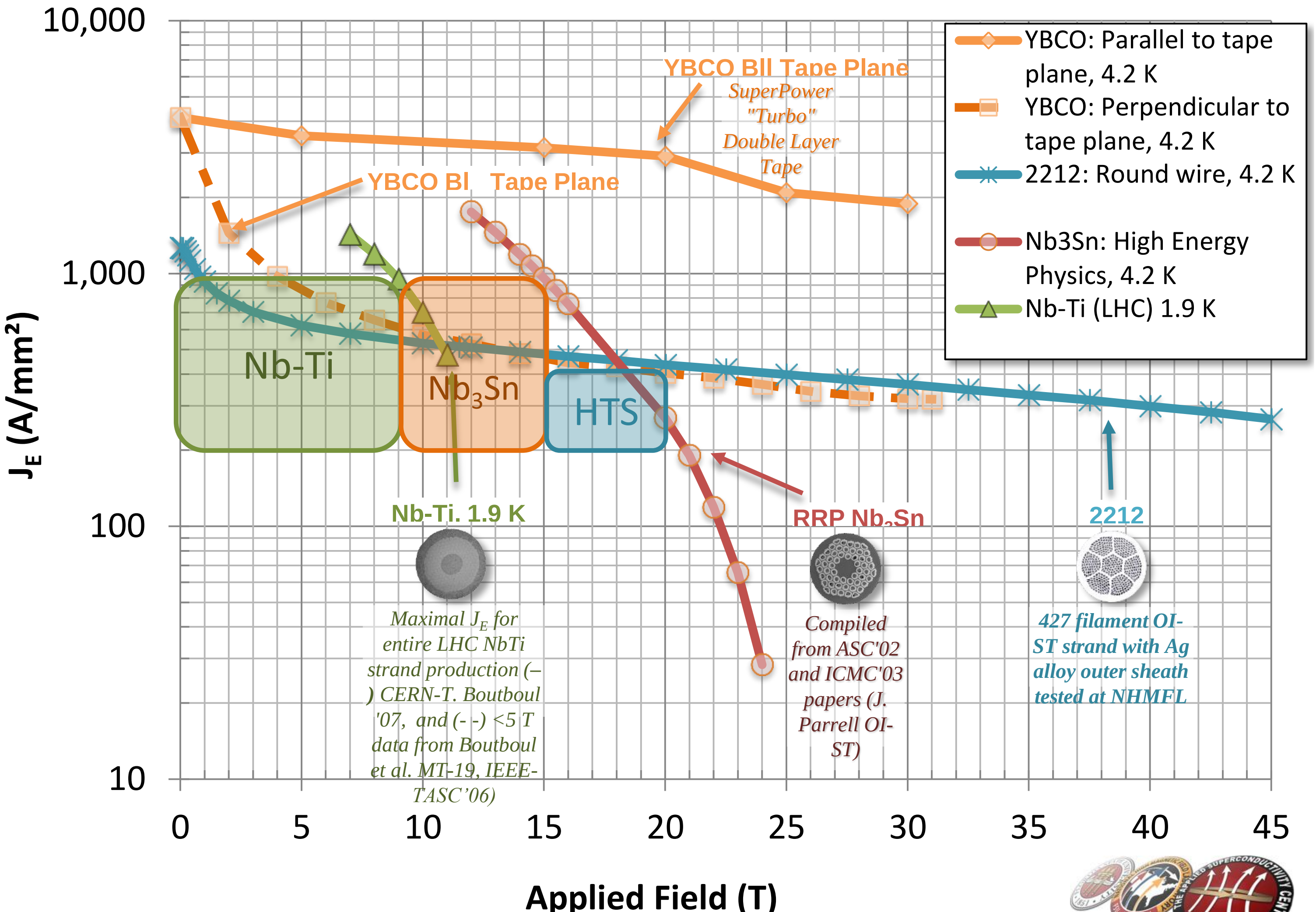
Main dipoles: is it possible ?



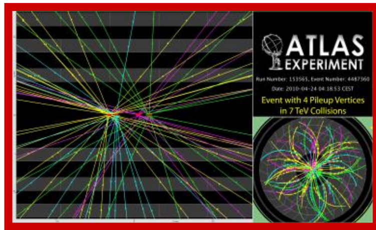
Looking at performance offered by practical SC, considering tunnel size and basic engineering (forces, stresses, energy) the practical limits is around 20 T. This could be compared to a 40 T solenoid!

We need to go faster than for LHC recovering the track on the straightline. But LHC « suffered » from LEP and LEP II endeavour.

The Superconductor « space »
We need to minimise HTS (cost)



LHC, the construction timeline: a 25 year old project



9 T - 1 m single bore

10 T-1m Nb3Sn dipole

9 T -10 m long protoype

9 T-15 m final protoype

Last LHC dipole

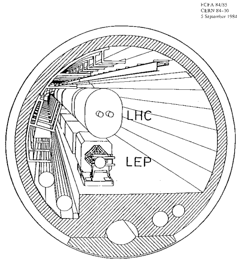
1985 1987 1990 1994 2000 2006 2010

LHC study

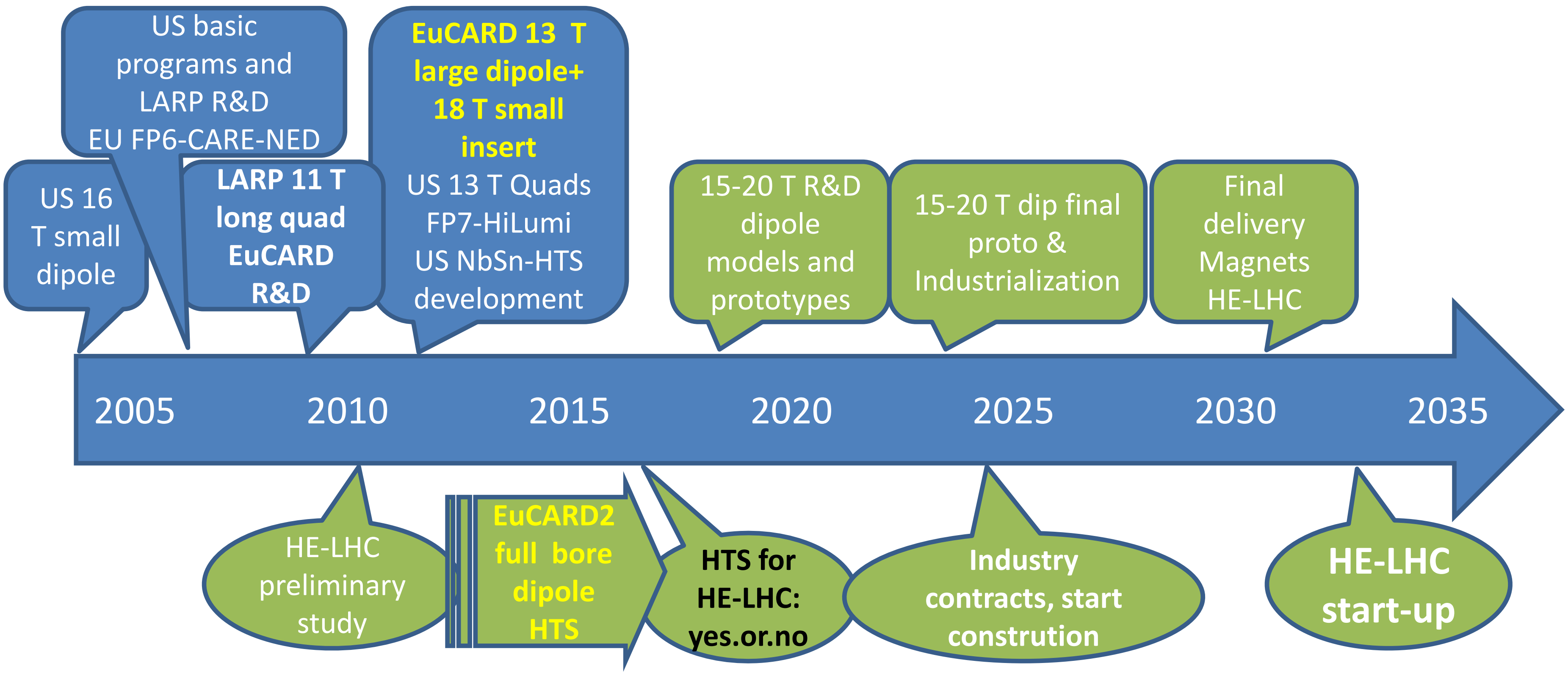
Decision for Nb-Ti

Industry contracts Nb-Ti

LHC start-up



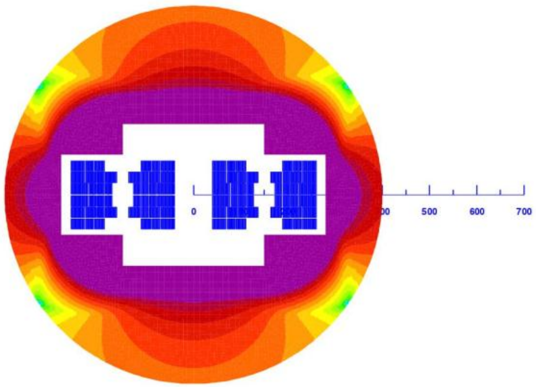
What is the possibile for HE-LHC?

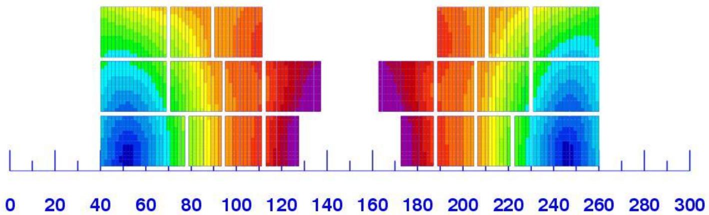


Malta Workshop14-16 October 2010

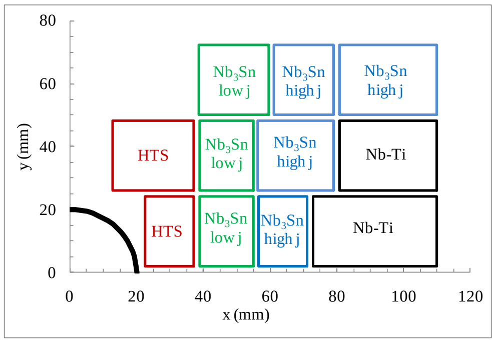
HE-LHC @ 33 TeV c.o.m

Magnet design: very challanging but not impossible.
300 mm inter-beam
Multiple powering in the same magnet (and more sectioning for energy)
Work for 4 years to assess HTS for 2X20T to open the way to 16.5 T/beam .
Otherwise limit field to 15.5 T for 2x13 TeV
Higher INJ energy is desirable (2xSPS)





Material	N. turns	Coil fraction	Peak field	$J_{overall}$ (A/mm^2)
Nb-Ti	41	27%	8	380
Nb3Sn (high Jc)	55	37%	13	380
Nb3Sn (Low Jc)	30	20%	15	190
HTS	24	16%	20.5	380



The synchrotron light is not a stopper by operating the beam screen at 60 K.
The beam stability looks « easier » than LHC thanks to dumping time.
Collimation is possibly not more difficult than HL-LHC. Reaching 2x10^{34} appears reasonable.
The big challenge, after main magnet technology, **is beam handling for INJ & beam dump**: new kicker technology is needed since we cannot make twice more room for LHC kickers.

Conclusions

- **HL-LHC project is starting, forming a large international collaboration**
- **HL-LHC aim to 3000 fb^{-1} by 2034-35: it has a flexible 10 year plan, however the development of the main hardware is – almost – traced**
- **HL-LHC builds on the strength and expertise of:**
  - CERN injectors (that will deliver the needed beam)
  - LHC operation and MD (for understanding the real limitation)
  - HL-LHC needs a long preparation, because it will use new hardware, beyond state-of-the-art and as such, in addition to the pyhsics goal**, it may pave the way toward a high energy LHC.**
- **HE-LHC might be the ultimate upgrade of the LHC: 25-33 TeV c.o.m. Project relies on the Very High Field Magnets: 15-20 tesla**
  - Injection, Beam Dump, Vacuum and Cryogenics, together with Collimation, are also a big challenge. Beam IN-OUT technology (Kickers) must be improved by a factor 1.5 to 2.
  - Doubling the energy in SPS is highly desirable
  - **Serious time scale can be for 2035 (2030 if HL is skipped and with more effort)**