LHC: Present Status and Future Projects

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Thanks to F. Bordry, L. Bottura, R. Garoby, L. Rossi

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- The present: LHC in the 10’s
  - Luminosity equations
  - Consolidation to 7 TeV
  - Physics phenomena limitating LHC and injectors
  - What was planned and what has been reached
- The 20’s: HL-LHC
  - How to improve luminosity
  - Magnets
  - Crab cavities
  - Injectors
- Plans for the 30’s
  - Aiming at 30-100 TeV centre of mass

LHC in the 10's: Luminosity equation

- Equation for the luminosity

$$L = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \varepsilon_n \beta^*} F = \frac{c}{4\pi} \frac{\gamma}{l} N_b^2 n_b \frac{1}{\varepsilon_n \beta^*} F$$

Accelerator features

Energy of the machine 7 TeV

Length of the machine 27 km

Beam intensity features

N_b Number of particles per bunch 1.15×10^{11}

n_b Number of bunches ~2808

Beam geometry features

ε_n Size of the beam from injectors: 3.75 mm mrad

β^* Squeeze of the beam in IP (LHC optics): 55 cm

F: geometry reduction factor: 0.84

Nominal luminosity: 10^{34} cm^{-2} s^{-1}

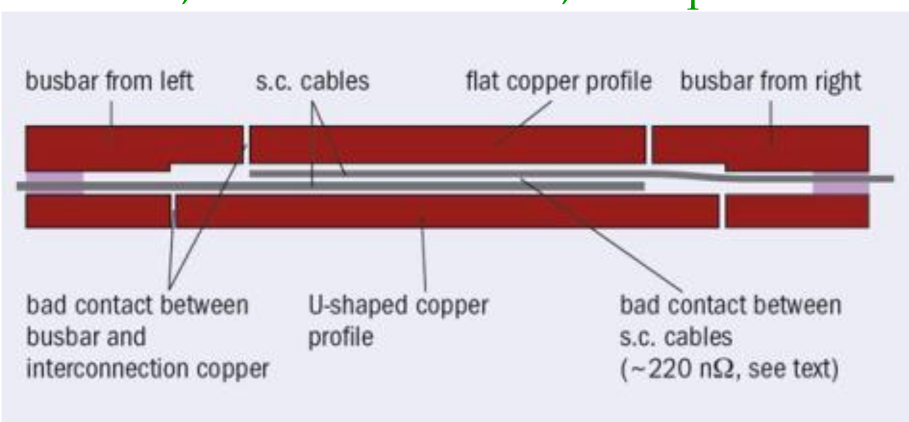
(considered very challenging in the 90's, pushed up to compete with SSC)

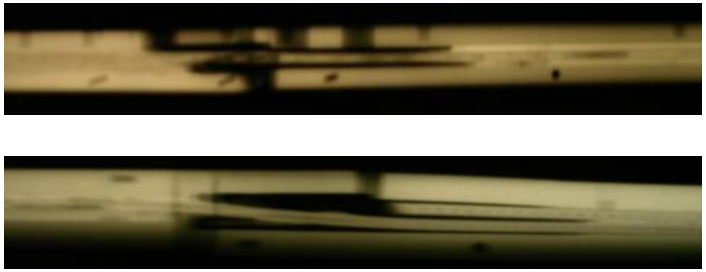
LHC in the 10's: towards 7 TeV

- Luminosity proportional to energy

$$L = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \varepsilon_n \beta^*} F = \frac{c}{4\pi} \frac{\gamma}{l} N_b^2 n_b \frac{1}{\varepsilon_n \beta^*} F$$

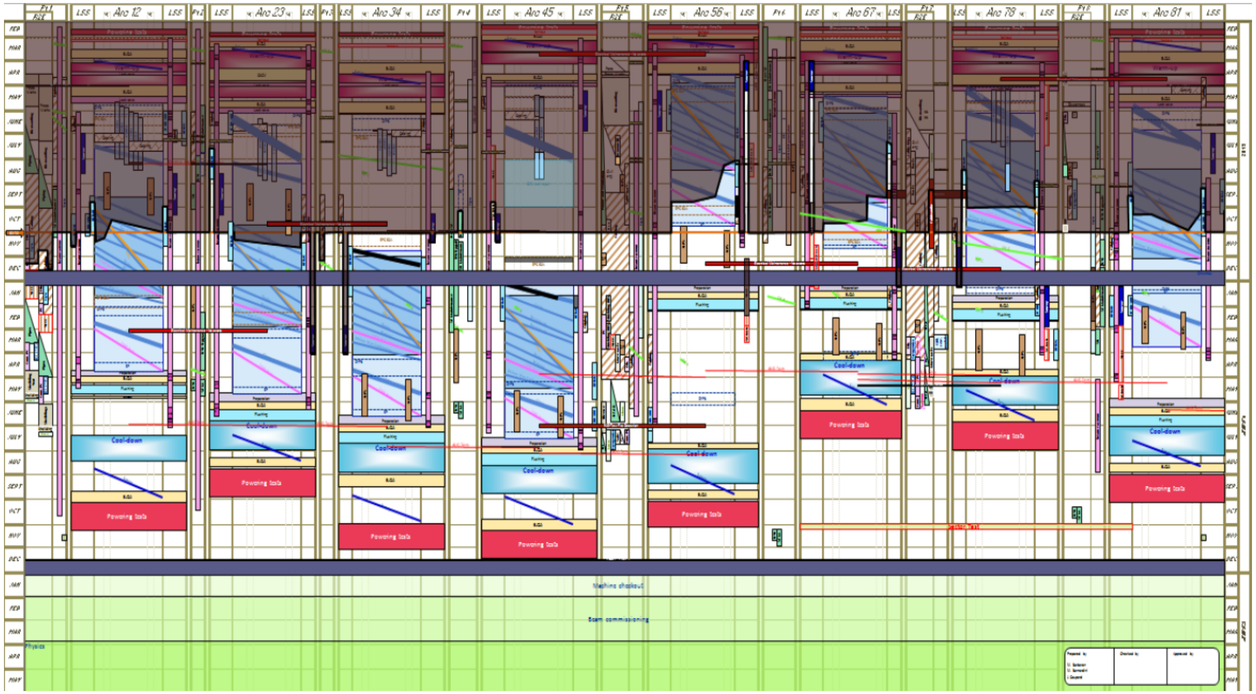
  - So running at 4 TeV instead of 7 TeV we lose nearly a factor two
- Reason for lower energy: weakness in the interconnections
  - This caused the 2008 incident – operation limited at 4 TeV in 1st run
  - Shunt being added to cure the problem 2013-2014 [J. P. Tock, F. Bordry, et al., EUCAS conference, to be published on IEEE Trans. Appl. Supercond.]





Cross-section of the intreconnection and radiography showing missing continuity [F. Bordry, J. P. Tock and LS1 team]

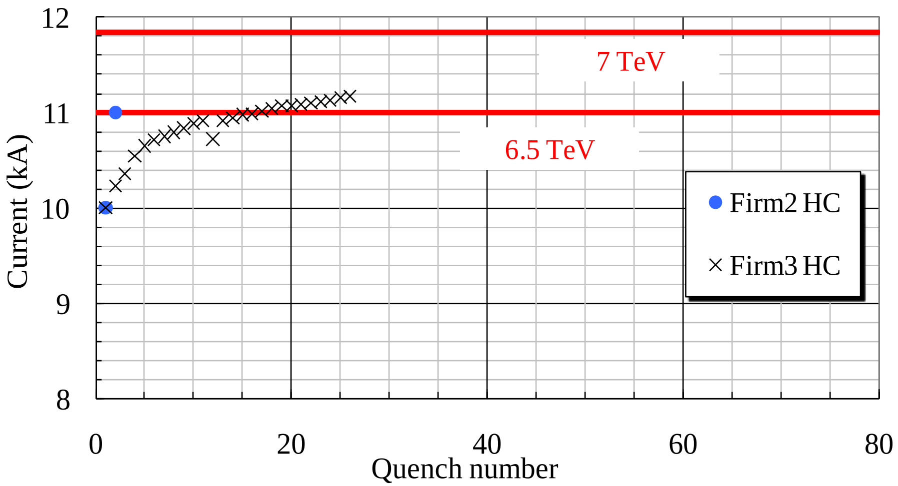
- Consolidation project is on schedule www.cern.ch/ls1dashboard
  - Some delays have been recovered – others are not critical
  - First powering in June (indications on operational energy in the 6 to 7 TeV range, most probably 6.5 TeV)



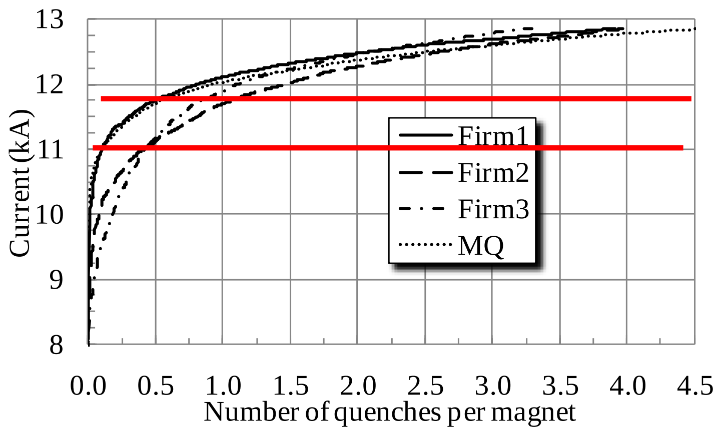
Plan of the works foreseen for Long Shutdown 1
[K. Foraz and LS1 team]

LHC in the 10's: towards 7 TeV

- What will be the final energy of the LHC?
  - This is a feature of the training magnets (main dipoles)
  - LHC dipoles are designed for 7 TeV (8.3 T, which is 86% of the 9.7 T maximum performance)
- All dipoles rapidly reached this value individually
  - But detraining observed in 2008 (only 1/8 of the dipoles tested)
  - 6.5 TeV looks reasonable, 7 TeV challenging



Training of sector 5-6 (154 dipoles) during 2008
[HC team]



Quenches per magnet to reach 6.5 and 7 TeV during the LHC dipole production

LHC in the 10's: Luminosity equation

- Equation for the luminosity

$$L = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \varepsilon_n \beta^*} F = \frac{c}{4\pi} \frac{\gamma}{l} N_b^2 n_b \frac{1}{\varepsilon_n \beta^*} F$$

- Now we will outline some of the luminosity limits
  - Beam beam (limit on N_b/ε_n)
  - Electron cloud (limit on n_b)
  - Squeeze (limit on $\beta^* \varepsilon_n$)
  - Injectors (limit on N_b, n_b, ε_n)

LHC in the 10's: Luminosity limits in the LHC

- The beam-beam limit (Coulomb)

$$\xi = n_{IP} \frac{r_p}{4\pi} \frac{N_b}{\varepsilon_n} < 0.01?$$

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

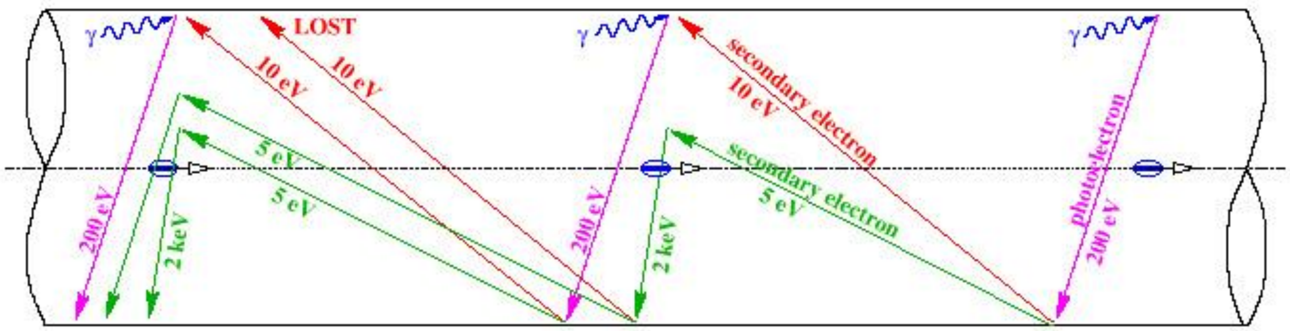
  - N_b Number of particles per bunch ε_n transverse size of beam
  - One cannot put too many particles in a "small space" (brightness)
    - Otherwise the Coulomb interaction seen by a single particle when collides against the other bunch creates instabilities (tune-shift)
  - This is an empirical limit, also related to nonlinearities in the lattice
    - Very low nonlinearities → larger limits
    - LHC behaves better than expected – boost to 50 ns

		Nominal	Ultimate	September 2012	2012 MD*
N_b	(adim)	1.15E+11	1.70E+11	1.55E+11	2.20E+11
ε_n	(m rad)	3.75E-06	3.75E-06	2.50E-06	1.70E-06
ξ_{IP}	(adim)	0.0034	0.0050	0.0068	0.0142
N_{IP}	(adim)	2	2	2	2
ξ	(adim)	0.007	0.010	0.014	0.028

* No long range interactions, W. Herr et al, CERN-ATS-Note-2011-029-MD

- The electron cloud

$$L = \frac{N_b^2 n_b f_{rev}\gamma}{4\pi\varepsilon_n \beta^*} F = \frac{c}{4\pi}\gamma \frac{1}{L} N_b^2 n_b \frac{1}{\varepsilon_n \beta^*} F$$



Mechanism of electron cloud formation [F. Ruggiero]

- This is related to the extraction of electrons in the vacuum chamber from the beam
- A critical parameter is the spacing of the bunches: smaller spacing larger electron cloud – threshold effect
  - So this effect pushes for 50 ns w.r.t. 25 ns
- Spacing (length) ↔ spacing (time) ↔ number of bunches n_b

  7.5 m ↔ 25 ns ↔ 3560 free bunches (2808 used)

LHC in the 10's: Luminosity limits in the LHC

- The electron cloud

$$L = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \varepsilon_n \beta^*} F = \frac{c}{4\pi} \gamma \frac{1}{L} N_b^2 n_b \frac{1}{\varepsilon_n \beta^*} F$$

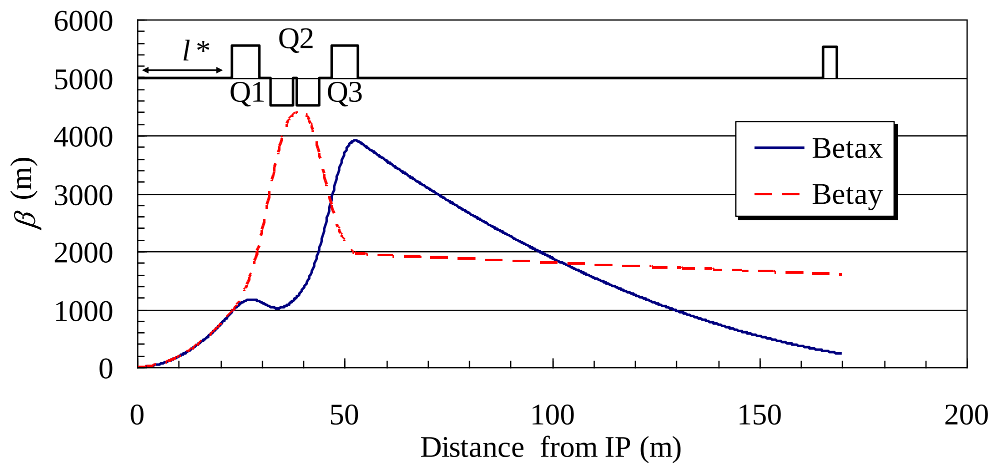
  - Electron cloud has been observed close to what expected from models, in 2010 when n_b>500 (from 150 ns to 75 ns bunch spacing)
  - Was cured by scrubbing of surface with intense beam as from baseline – operation at 50 ns stable without electron cloud with limited scrubbing (a few days in 2011)
- (i) no visible tune shift limit, (ii) electron cloud as expected (iii) injector performance giving large N_b for 50 ns pushed operation to stay at 50 ns spacing in 2011-12
  - The drawback: pile up ☹

		Nominal	September 2012	Gain L
N_b	(adim)	1.15E+11	1.55E+11	1.82
ε_n	(m rad)	3.75E-06	2.50E-06	1.50
n_b	(adim)	2808	1380	0.49
				1.34
Pile-up*	(adim)	25	36	

LHC in the 10's: Luminosity limits in the LHC

- Optics: squeezing the beam $L = \frac{N_b^2 n_b f_{rev}\gamma}{4\pi\varepsilon_n \beta^*} F = \frac{c}{4\pi}\gamma \frac{1}{L} N_b^2 n_b \frac{1}{\varepsilon_n \beta^*} F$
  - Size of the beam in a magnetic lattice $|x(s)| = \sqrt{\frac{\varepsilon\beta(s)}{\gamma_r}}$
  - Luminosity is inverse prop to ε and β*
- In the free path (no accelerator magnets) around the experiment, the *β** has a nasty dependence with *s* distance to IP

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*} \approx \frac{s^2}{\beta^*}$$



- The limit to the squeeze is the magnet aperture
  - Key word for magnets in HL LHC: not stronger but larger

LHC in the 10's: Luminosity limits in the LHC

- Optics: squeezing the beam

$$L = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \varepsilon_n \beta^*} F = \frac{c}{4\pi} \gamma \frac{1}{L} N_b^2 n_b \frac{1}{\varepsilon_n \beta^*} F$$

  - Size of the beam in a magnetic lattice

$$|x(s)| = \sqrt{\frac{\varepsilon \beta(s)}{\gamma_r}}$$

- LHC was designed to reach β^* = 50 cm with 70 mm aperture IR quads
  - This aperture had no margin - when beam screen was added, one had to lower the target β^* = 55 cm (and recover L=10^{34} by slightly increasing bunch intensity from 10^{11} to 1.15×10^{11})

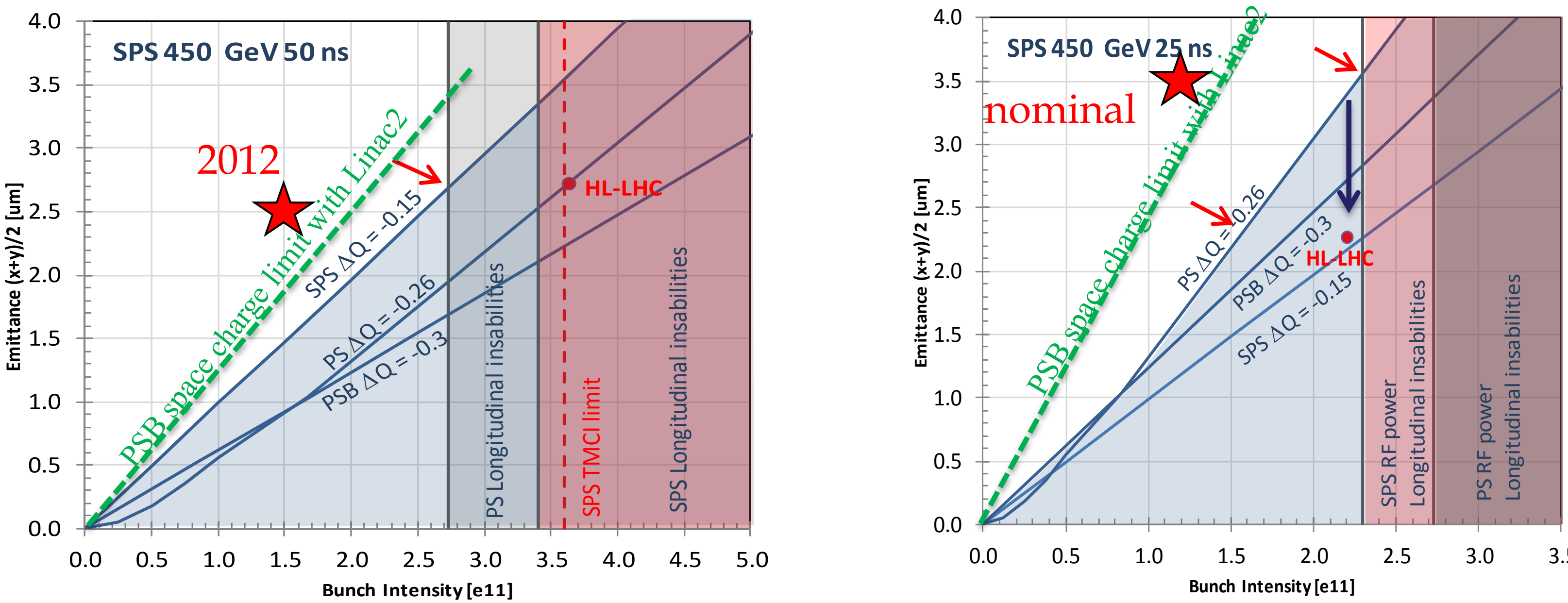
- Today, less energy → larger beam → higher β^*
  - But lower emittance
  - So at the end we are already at 60 cm

		Nominal	2012	Gain β^*
E	(TeV)	7.0	4.0	0.57
ε_n	(m rad)	3.75E-06	2.50E-06	1.50
				0.86

LHC in the 10's: Luminosity limits in the injectors

- The injector chain limits
  - Emittance ε_n vs intensity N_b
  - This relation also depends on the bunch spacing n_b

$$L = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \varepsilon_n \beta^*} F = \frac{c}{4\pi} \gamma \frac{1}{L} N_b^2 n_b \frac{1}{\varepsilon_n \beta^*} F$$



Limits imposed by the injectors to the LHC beam [R. Garoby, IPAC 2012]

  - Surprise: very low emittance with high intensities at 50 ns
- Pushing up these limits is the aim of the injector upgrade

UNKNOWNS & SURPRISES

- The hump (2011)
  - A spurious frequency in the beam endangering stability
  - Disappeared later

M. Feldman in the famous scene of Frankenstein Junior (what hump ?) [M. Brooks, 1974]

- UFO (Unidentified Falling Objects)
  - Particles in the beam vacuum creating showers of secondaries and stopping operation
  - Not a problem at 4 TeV
  - Will they be a problem at 7 TeV?

UFO conceptual design

- Octupoles and instabilities
  - Stability of beam at collision
  - Do we have enough force at 7 TeV?

CONTENTS

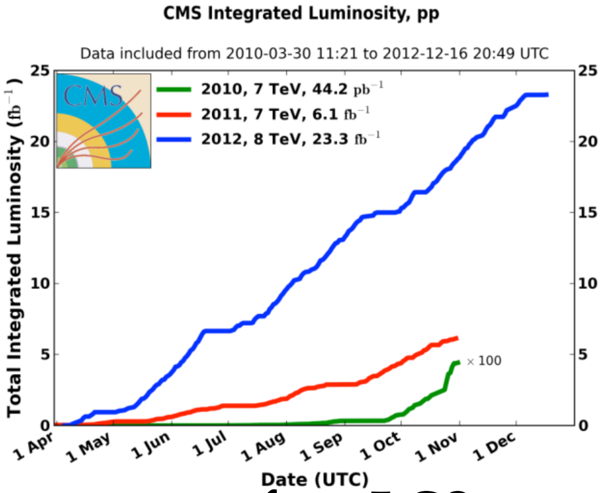
- The present

		Nominal	September 2012	Gain L	Ultimate	Gain L
N_b	(adim)	1.15E+11	1.55E+11	1.82	1.7E+11	2.2
ε_n	(m rad)	3.75E-06	2.5E-06	1.50	3.75E-06	1.0
n_b	(adim)	2808	1380	0.49	2808	1.0
β^*	(m)	0.55	0.60	0.92	0.55	1.0
E	(TeV)	7.0	4.0	0.57	7.0	1.0
L	(cm^{-2} s^{-1})	1.0E+34	7.0E+33	0.70	2.2E+34	2.2
Pile-up*	(adim)	25	36		55	

* 80 mbarn cross section assumed

- The 20’s: HL-LHC
  - Magnets
  - Crab cavities
  - Injectors
- Plans for the 30’s
  - Aiming at 30-100 TeV centre of mass

HL-LHC
THREE REASONS FOR THE UPGRADE



- 2011: 6 fb^{-1}
- 2012: 23 fb^{-1}
  - peak lumi of 7×10^{33} cm^{-2} s^{-1}
- Ultimate: 60 fb^{-1} per year?
  - peak lumi of 2.4×10^{34} cm^{-2} s^{-1}

- Assuming 40 fb^{-1} after LS1 and 60 fb^{-1} per year after LS2, we got to 30+40*3+60*3= 330 fb^{-1} for the LHC
  - Magnets (triplet, correctors, around ATLAS and CMS are designed to resist to 300-500 fb^{-1}) [L. Bottura, RLIUP meeting, https://indico.cern.ch/conferenceTimeTable.py?confId=260492#20131029]
  - Experiments as well have components to be replaced for radiation damage
  - Moreover as statistics is $\propto \sqrt{N}$, little interest to run for many years with constant luminosity

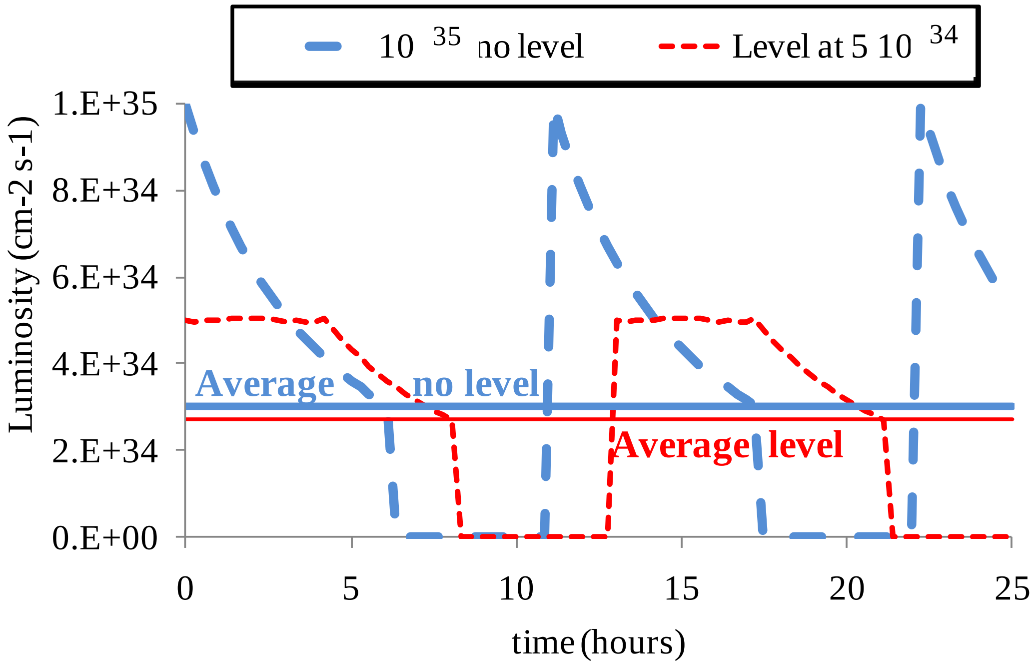
HL-LHC
THE PATH TOWARDS 3000 FB^{-1}

- CERN Project, EU funds for the design study, DR in 2014
  www.cern.ch/hilumi [L. Rossi]
  - The target:after reaching 300 fb^{-1} in the 10's, we need 3000 fb^{-1} in the 20's
- We need to gain a factor four-five (250-300 fb^{-1} per year, from the beginning of HL-LHC)
  - Peak lumi 10^{35} cm^{-2} s^{-1} is not acceptable for the experiments (pile up)
- A levelling is proposed at 5×10^{34} cm^{-2} s^{-1}
  - To have this the LHC must be able to reach a peak lumi 2×10^{35}cm^{-2} s^{-1}
- 20 larger than nominal:
  - Factor 5 from the beam
  - Factor 4 from optics (reducing β^*)

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

HL-LHC
LUMINOSITY LEVELLING

- The luminosity levelling aims at compensating the faster decay in luminosity induced by higher peak lumi
  - That's why we need a factor 20 but we use only a factor 5
  - How to do leveling
    - With crossing angle ?
    - With separation ?
    - With β^* ?



Luminosity levelling principle (with a factor 10 shown)

- Main result: similar integrated lumi but lower pile up
  - That's the desiderata of experiments

HL-LHC: LOWER BETA*

- How to get a factor four from the optics ?

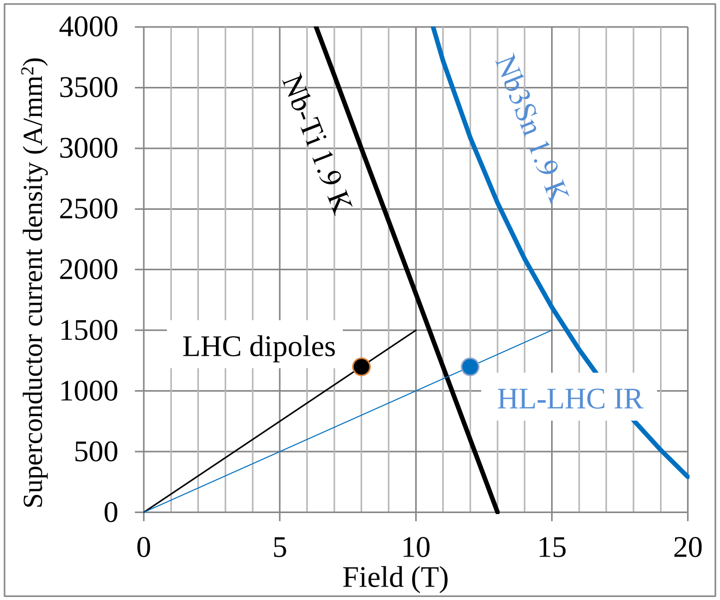
- To reduce β^* to 15 cm (factor four from 55 cm nominal) one needs larger aperture quadrupoles
  - β in the quads is $\propto 1/\beta^*$
  - Scaling with square root: a factor two in aperture, i.e. 150 mm aperture quadrupoles
    - First upgrades aimed β^*=25 cm [F. Ruggiero, et al, LHC PR 626 (2002)]

$$|x(s)| = \sqrt{\frac{\varepsilon\beta(s)}{\gamma_r}}$$

  - Other optics constraints: chromaticity
    - Cured by ATS (Achromatic Telescopic Squeeze) optics – first successful tries in MD [S. Fartoukh, sLHC PR 53 (2011)]

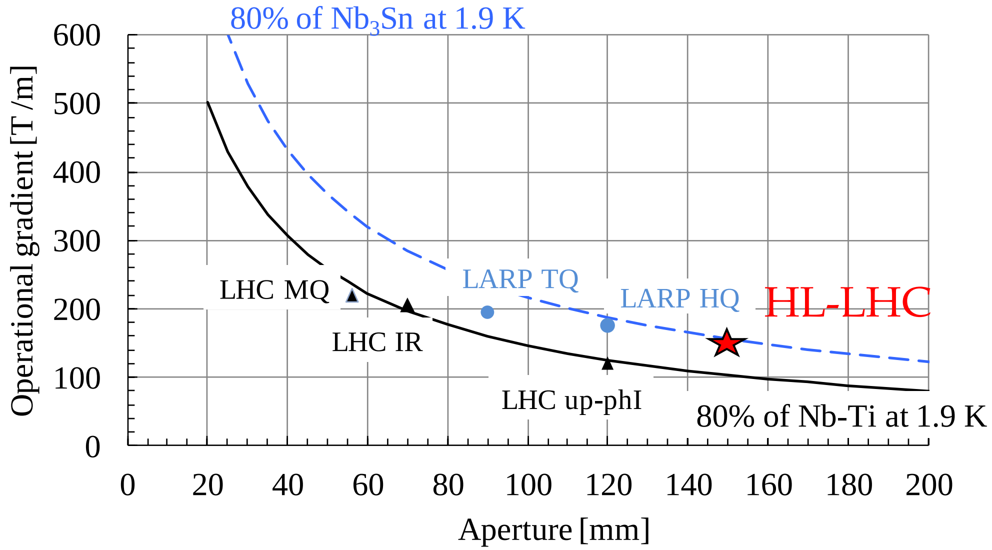
HL-LHC: Magnet technology for lower beta*

- Superconductivity takes place in some materials below thresholds values for magnetic field, current density and temperature
  - Thresholds called critical surface
  - Phenomena known since 100 years, applications since more than 50 years
    - Related to quantum mechanics
  - In a SC electromagnet, the coil must tolerate field and current density to produce that field
  - This sets a limit of ~8 T for Nb-Ti
    - LHC is built on this limit
  - Nb_3Sn has a wider critical surface, with possibility of increasing to 12-15 T



HL-LHC: Magnet technology for lower beta*

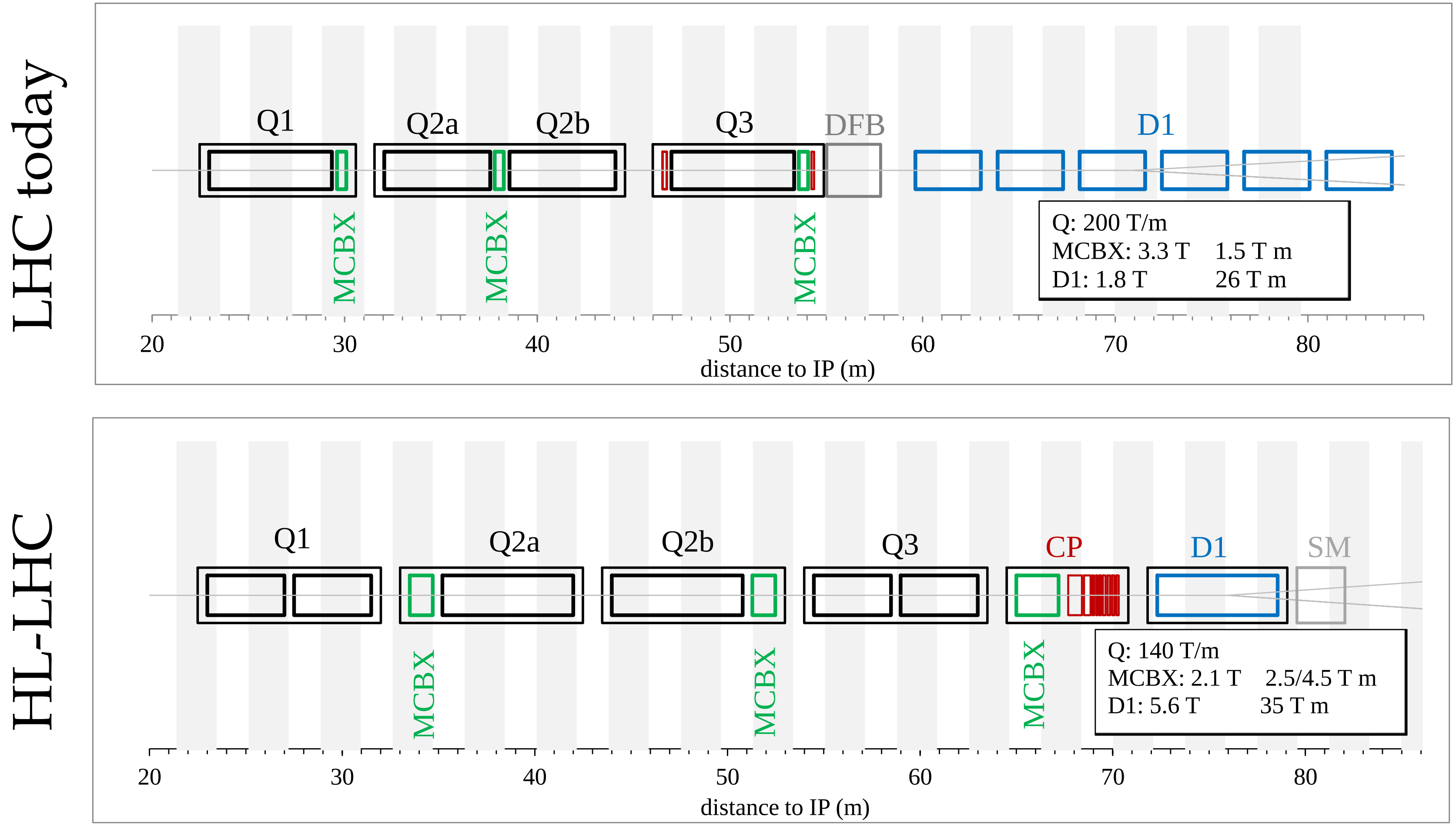
- In a superconducting quadrupole gradient*aperture is limited by maximum operational field (field on the coil)
  - Present Nb-Ti triplet: 70/2 (mm) * 200 (T/m) +10% ~ 8 T
  - With Nb_3Sn one can get 50% more: 140/2 (mm) * 150 T/m + 10% ~ 12 T
- Larger aperture can be obtained with lower gradients but
  - Nb_3Sn gives ~50% more gradient for the same aperture, ~25% more luminosity



Aperture versus gradient relation [L. Rossi, E. Todesco, Phys. Rev. STAB 9 (2006) 102401]

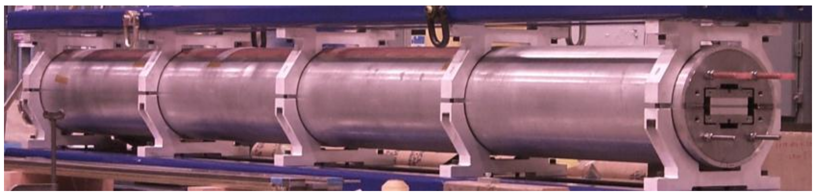
HL-LHC: Larger apertures for lower beta*

- First baseline around CMS and ATLAS for the upgrade

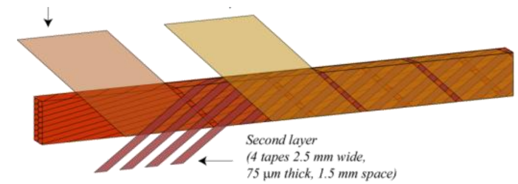


HL-LHC: Larger apertures for lower beta*

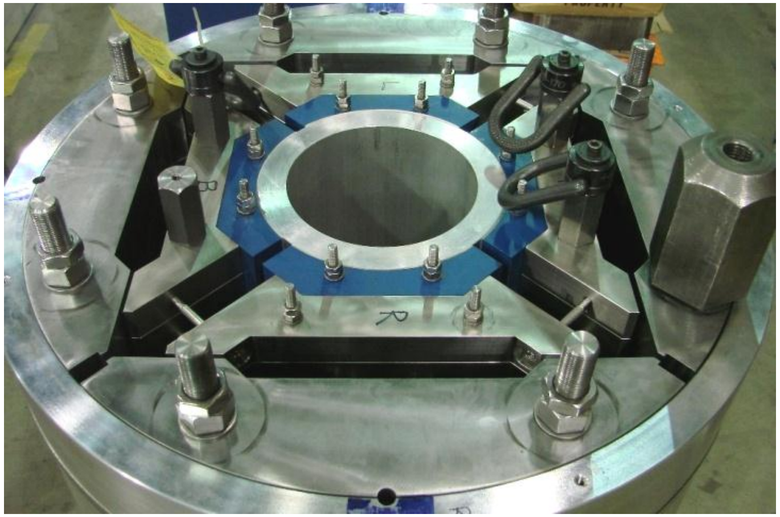
- Some hardware (1-m long models) already built
  - 90 mm, 120 mm aperture Nb_3Sn quads (US LARP collaboration)
  - 120 mm aperture Nb-Ti quadrupole (CERN, ex phase I)



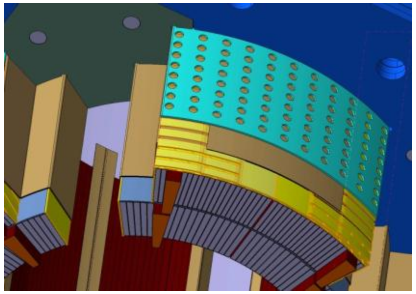
LR (first long Nb_3Sn racetrack, LARP) [G. Ambrosio, et al.]



Permeable insulation
[D. Tommasini, et al,
IEEE Trans. Appl. Supercond.
20 (2010) 168]



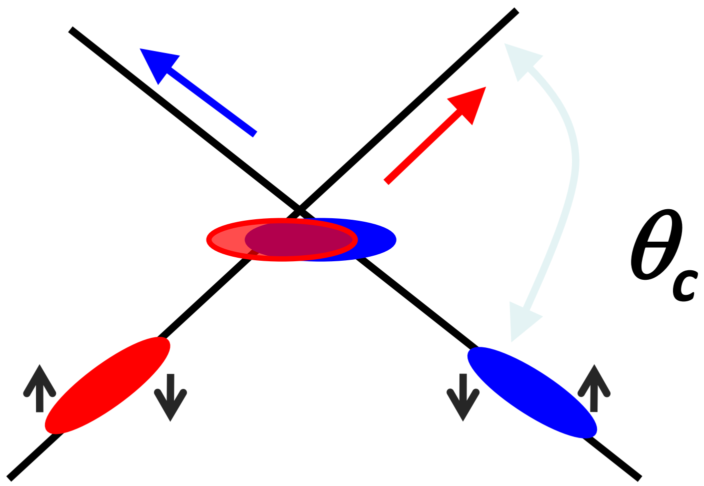
HQ (Nb_3Sn LARP 120 mm magnet) [G. Sabbi, S. Caspi, et al.]



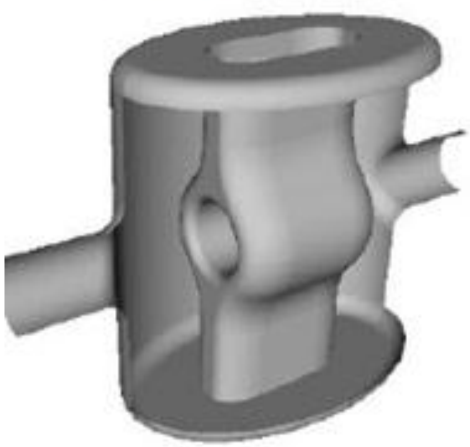
MQXC (Nb-Ti CERN ex phase I upgrade) [G. Kirby, et al.]

HL-LHC: CRAB CAVITIES

- When going to very low β^*, (below 25 cm) the geometric factor considerably reduces the gain
  - Crab cavity allows to set this factor to one by turning the bunches in the longitudinal space [R. Calaga, Chamonix 2012]



Crab crossing

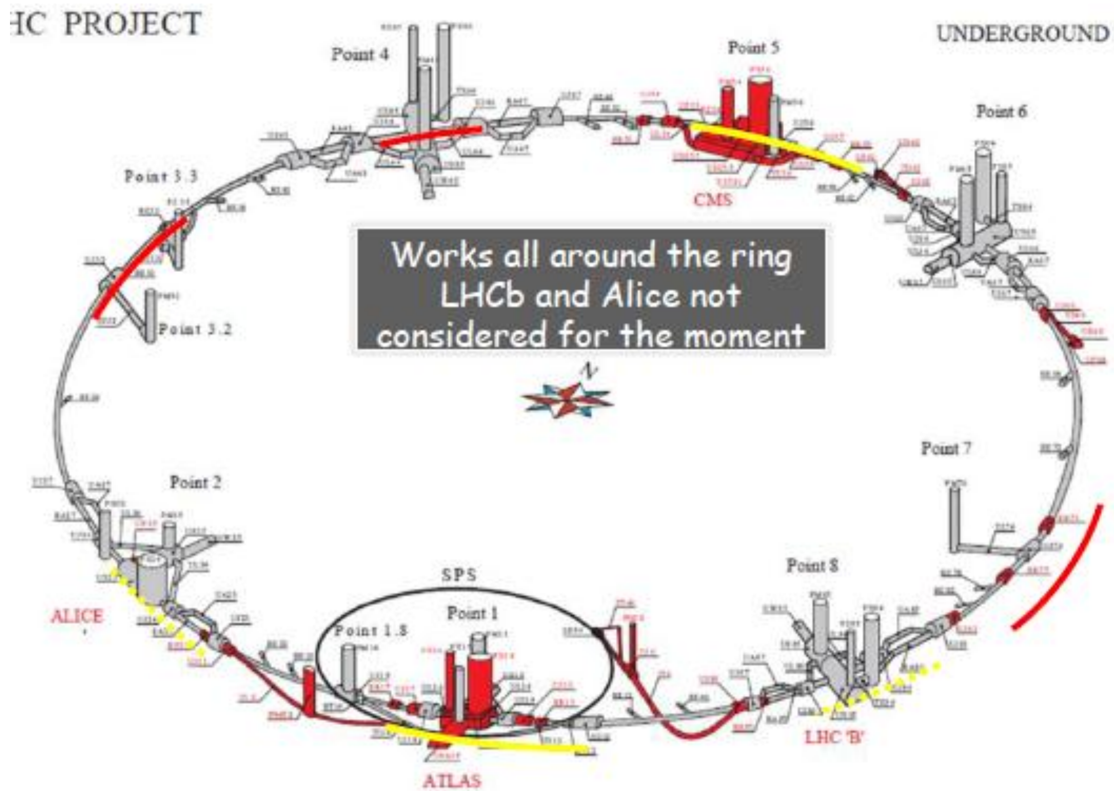


One possible option for the design of crab cavity

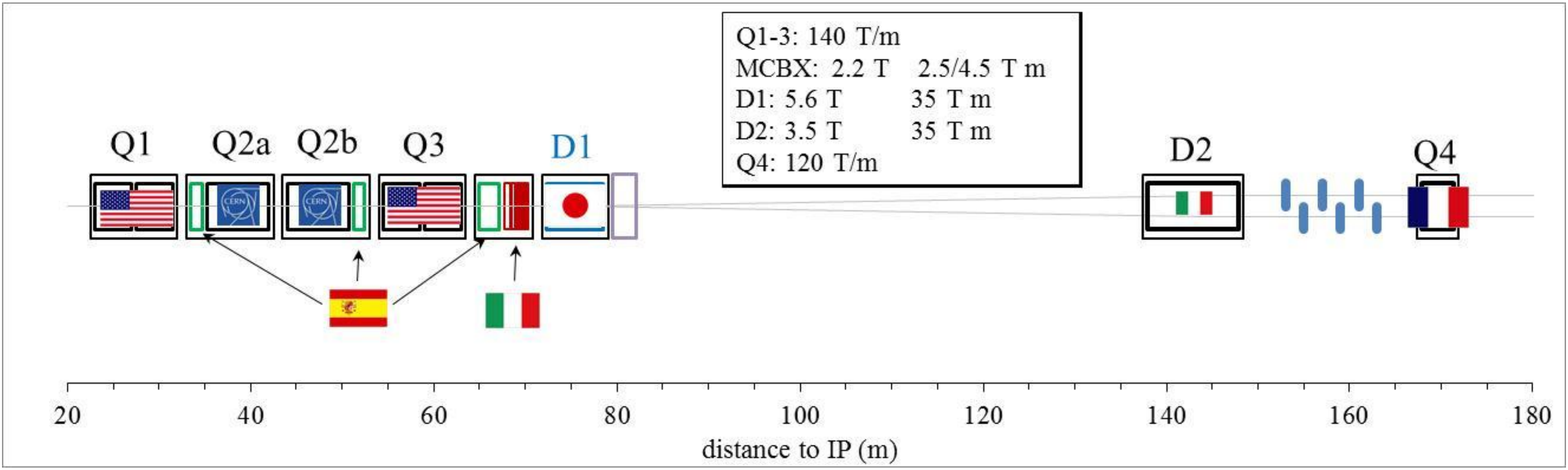
  - Hardware being built, successful test in some electron machines [WP4, E. Jensen, collaboration with many institutes]
  - First compact crab cavities with good performance have been built

HL-LHC

- HL LHC is not only new magnets in ~1 km of the the main ring, but also
  - Cryogenics upgrade
  - Collimation upgrade
  - “Cold” powering



- As LHC, also HL LHC is an international collaboration



First baseline from Q1 to Q4, and tentative contributions

HL-LHC: INTENSITY

- How to get the factor five from the beam ?
  - Increase current … and reduce emittance
  - Preferred option is 25 ns

		Nominal	HL LHC 50 ns	Gain	HL LHC 25 ns	Gain
N_b	(adim)	1.15E+11	3.4E+11	8.7	2.2E+11	3.7
ε_n	(m rad)	3.75E-06	3.0E-06	1.3	2.5E-06	1.5
n_b	(adim)	2808	1404	0.5	2808	1.0
β^*	(m)	0.55	0.15	3.7	0.15	3.7
L_{max}	(cm^{-2} s^{-1})	1.0E+34	2.0E+35	20	2.0E+35	20
L_{lev}	(cm^{-2} s^{-1})	1.0E+34	5.0E+34		5.0E+34	
Pile-up*	(adim)	25	254		127	

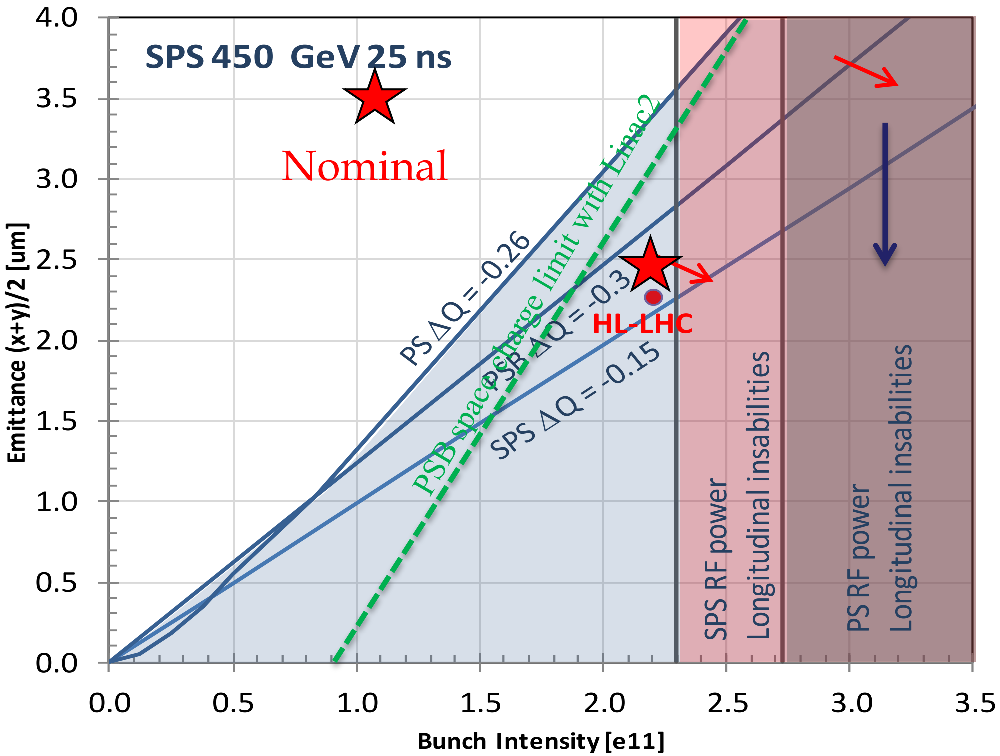
* 80 mbarn cross section assumed

Please note: parameters for beam intensity are evolving, this is a possible option

HL-LHC: INTENSITY

- How to get the factor five from the beam ?
  - 25 ns option

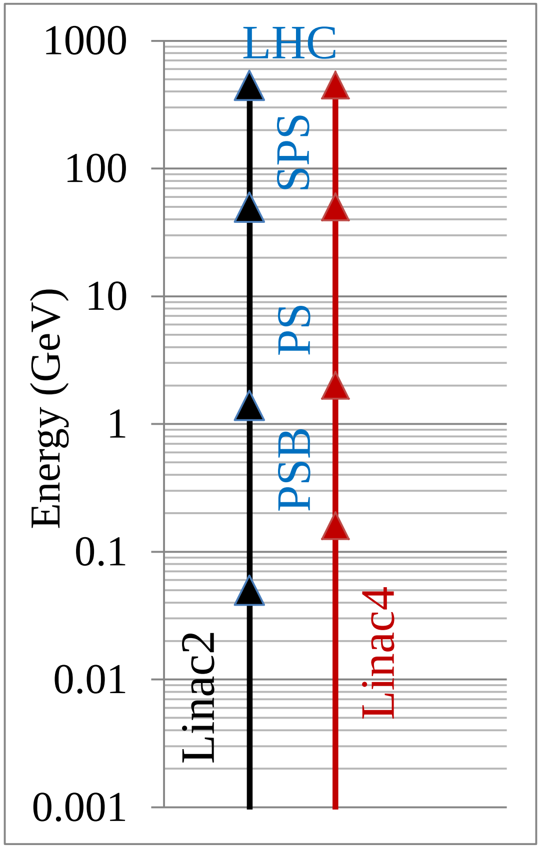
		Nominal	HL LHC 50 ns	HL LHC 25 ns
N_b	(adim)	1.15E+11	3.40E+11	2.20E+11
ε_n	(m rad)	3.75E-06	3.00E-06	2.50E-06
n_b	(adim)	2808	1404	2808
β^*	(m)	0.55	0.15	0.15
L	(cm^{-2} s^{-1})	1.0E+34	2.0E+35	2.0E+35



Emittance vs intensity at 25 ns [R. Garoby, IPAC 2012]

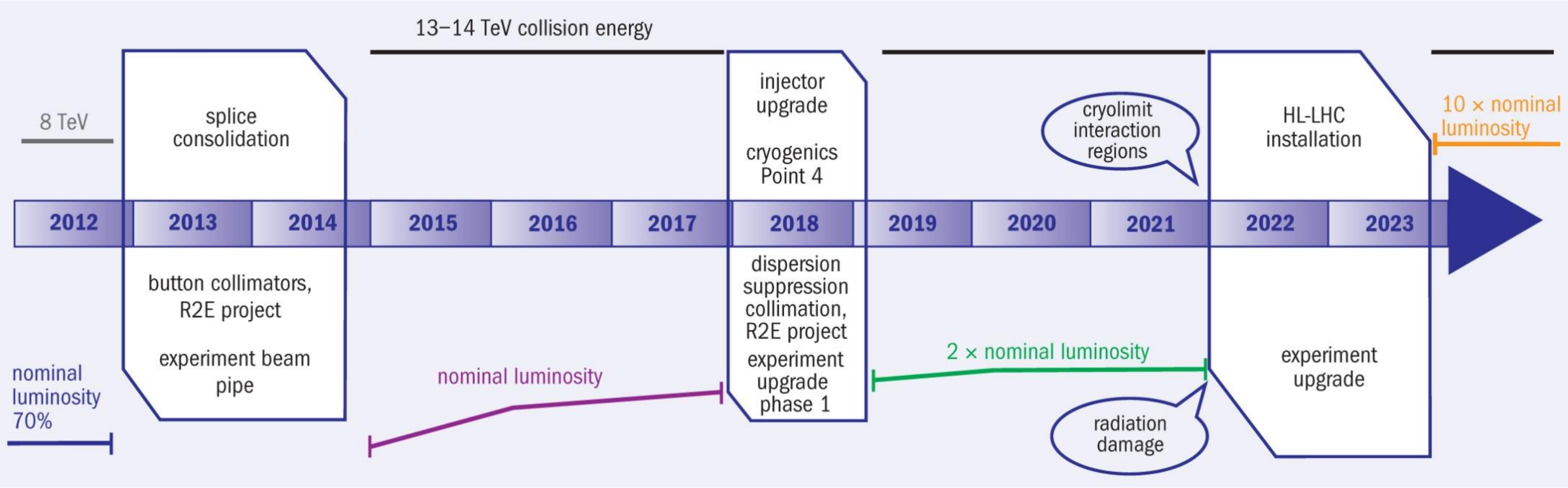
HL-LHC: INJECTOR UPGRADE

- Injector upgrade steps:
  - Higher brighteness:
    - Increase PSB energy from 1.4 to 2 GeV, replacing power supply and changing transfer equipment (space charge in PS)
    - Increase injection energy in the PSB from 50 to 160 MeV, Linac4 (160 MeV H-) to replace Linac2 (50 MeV H+)
    - Upgrade the PSB , PS and SPS to make them capable to accelerate and manipulate a higher brightness beam
  - Reliability
- Timeline: 2018 (LS2)
    - Linac4 alone does not give additional performance
- Injector upgrade project LIU [R. Garoby]



Upgrade of injector chain
[R. Garoby, IPAC 2012]

A TENTATIVE SCHEDULE FOR NEXT 10 (20) YEARS



A plan for the LHC in the next 10 years [L. Rossi, IPAC 2011]

Please note: we are a research lab, we must have a plan but we can change it

CONTENTS

- The present: LHC in the 10's
  - Luminosity equations
  - Limitations: LHC/injectors
  - What was planned and what has been reached
- The roaring 20's: HL-LHC
  - How to improve luminosity
  - Magnets
  - Crab cavities
  - Injectors
- Plans for the 30's
  - Aiming at 30-100 TeV centre of mass

The High Energy Frontier

- First ideas
  - Installing a 16.5+16.5 TeV proton accelerator in the LEP tunnel

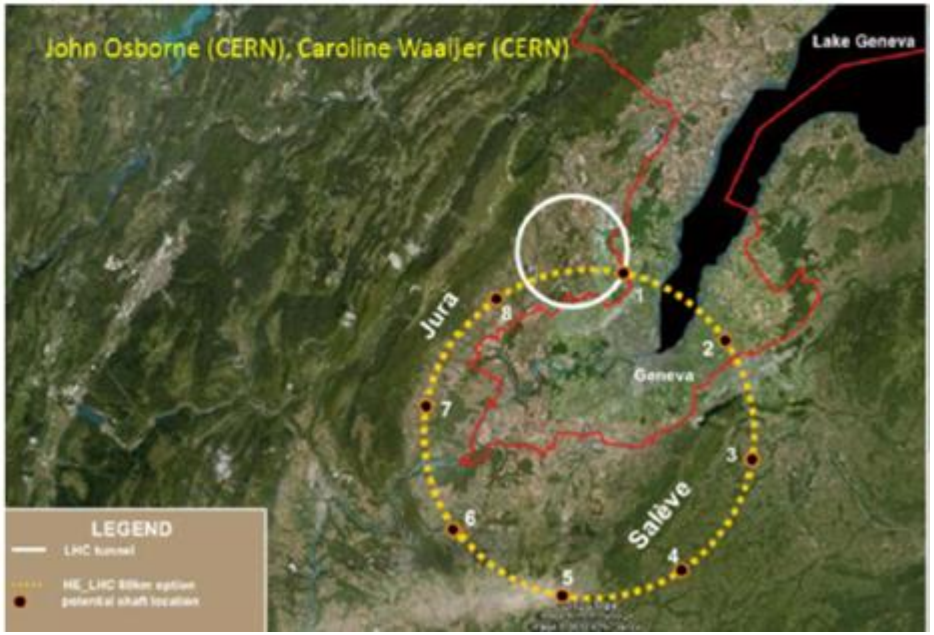
		LHC	HE LHC	ratio
Collision energy	(TeV)	7.0	16.5	2.4
Dipole field	(T)	8.3	20	2.4

  - Main ingredient: 20 T operational field dipoles
    - Proposal in 2005 for an LHC tripler, with 24 T magnets [P. McIntyre, A. Sattarov, "On the feasibility of a tripler upgrade for the LHC", PAC (2005) 634].
- CERN study: Working Group in 2010 www.cern.ch/he-lhc
  - R. Assmann, R. Bailey, O. Bruning, O. Dominguez Sanchez, G. De Rijk, M. Jimenez, S. Myers, L. Rossi, L. Tavian, E. Todesco, F. Zimmermann, « First thoughts on a Higher Energy LHC » CERN ATS-2010-177
  - E. Todesco, F. Zimmermann, Eds. « The High Energy LHC » CERN 2011-003 (Malta conference proceedings)
- Motivations [J. Wells, CERN 2011-3]

> "The results of the LHC will change everything, one way or another. There will be a new "theory of the day" at each major discovery, and the arguments will sharpen in some ways and become more divergent in other ways. Yet, the need to explore the high energy frontier will remain."

  - The energy frontier is always extremely interesting and for many processes cannot be traded with more luminosity at lower energy

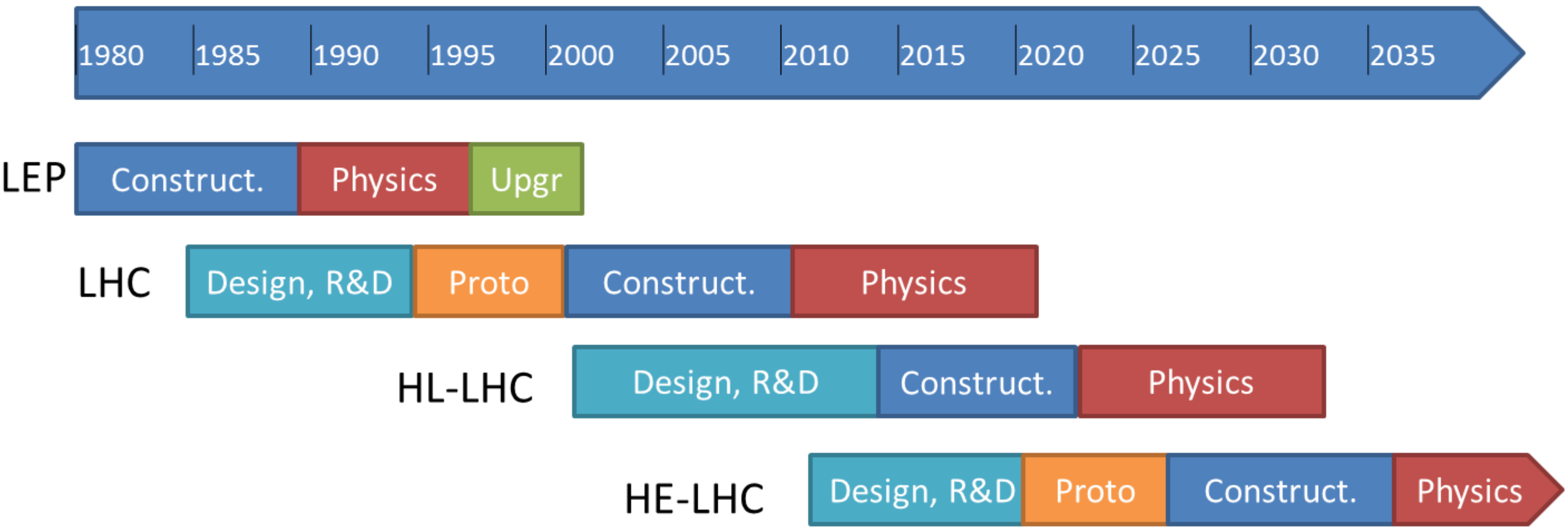
- More ideas
  - Having a new tunnel of 80-100 km with 16-20 T magnets to reach 50+50 TeV with proton collisions
- Study group Future Circular Collider (FCC) established in late 2013 [M. Benedikt, F. Zimmermann]



A new tunnel in the CERN area [F. Bordry, HILUMI kick-off, https://indico.cern.ch/conferenceDisplay.py?confId=257368]

A TENTATIVE SCHEDULE FOR NEXT 30 YEARS

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

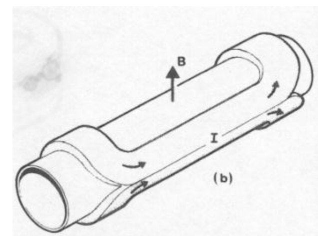


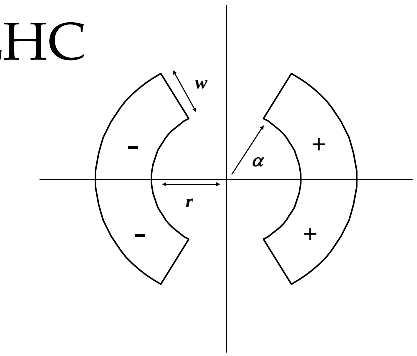
Using the LEP/LHC tunnel [L. Rossi, IPAC 2011]

- One of the main challenge are the magnets
  - First choice: current density – keep the same as the LHC

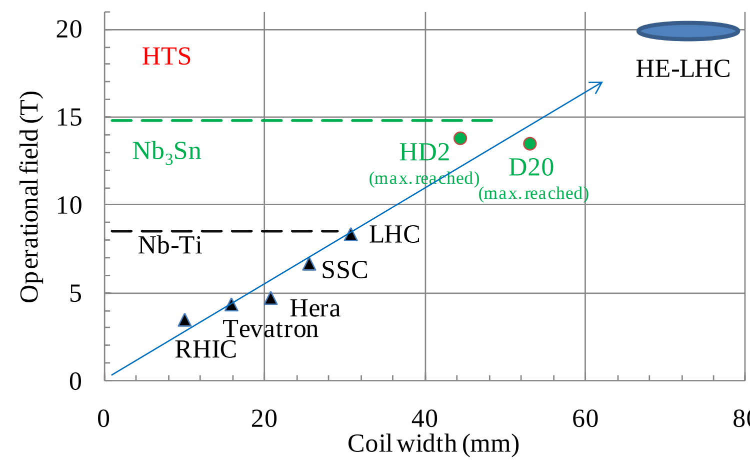
$$B \text{ [T]} \sim 0.0007 \times \textit{coil width} \text{ [mm]} \times \textit{current density} \text{ [A/mm}^2\text{]}$$

LHC: 8 [T]~ 0.0007 × 30 × 380





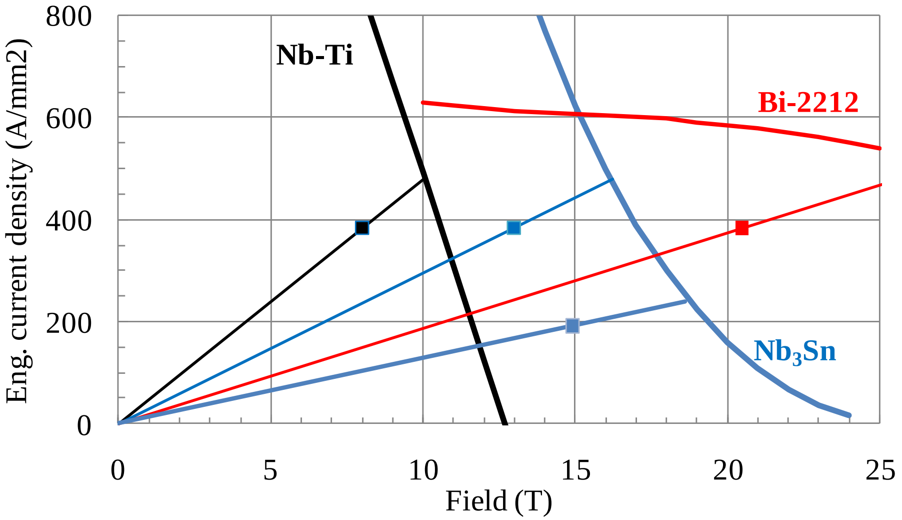
  - Accelerators used current density of the order of 350–400 A/mm^2
  - This provides ~2.5 T for 10 mm thickness
    - 80 mm needed for reaching 20 T
    - 60 mm needed for reaching 16 T
    - Coil size is still manageable



Operational field versus coil width in accelerator magnets

THE LHC TUNNEL IN THE 30'S: GUIDELINES FOR THE COIL MATERIAL

- What material can tolerate 400 A/mm^2 and at what field ?
  - For Nb-Ti: LHC performances - up to 8 T
  - For Nb_3Sn: 1500 A/mm^2 at 15 T, 4.2 K – up to 12 T
    - With lower current density 190 A/mm^2/m we can get to 15 T
  - If we want to reach 20 T, last 5 T made by HTS - we ask for having ~380 A/mm^2
    - Today in Bi-2212 we have not so far from there



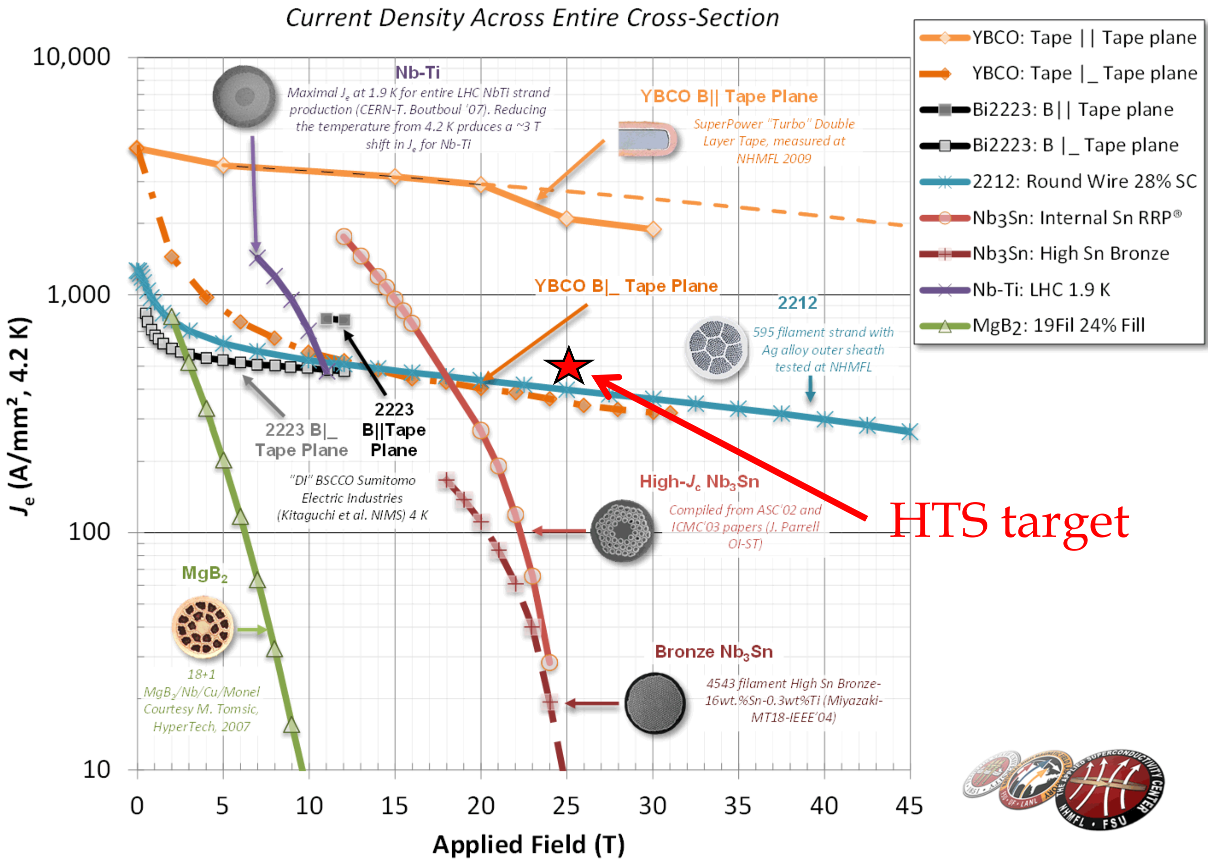
Engineering current density versus field for Nb-Ti and Nb_3Sn (lines) and operational current (markers)

THE LHC TUNNEL IN THE 30'S: WHAT IS CLOSE AND WHAT IS FAR

- Nb-Ti (up to 8 T): workhorse of accelerator magnets
- Nb_3Sn (up to 15 T)
  - ☹ Complex manufacturing – material becomes superconductive after winding with 650 C heat treatment for several days
  - ☺ Several tens of dipoles and quadrupoles short models (1 m)
  - ☺ Reached 13-14 T in dipole configurations
  - ☺ Potential up to 16 T demonstrated
  - ☺ A few long (3.4-m-long magnets) built with good results
  - ☹ Not yet used in accelerators

THE LHC TUNNEL IN THE 30'S: WHAT IS CLOSE AND WHAT IS FAR

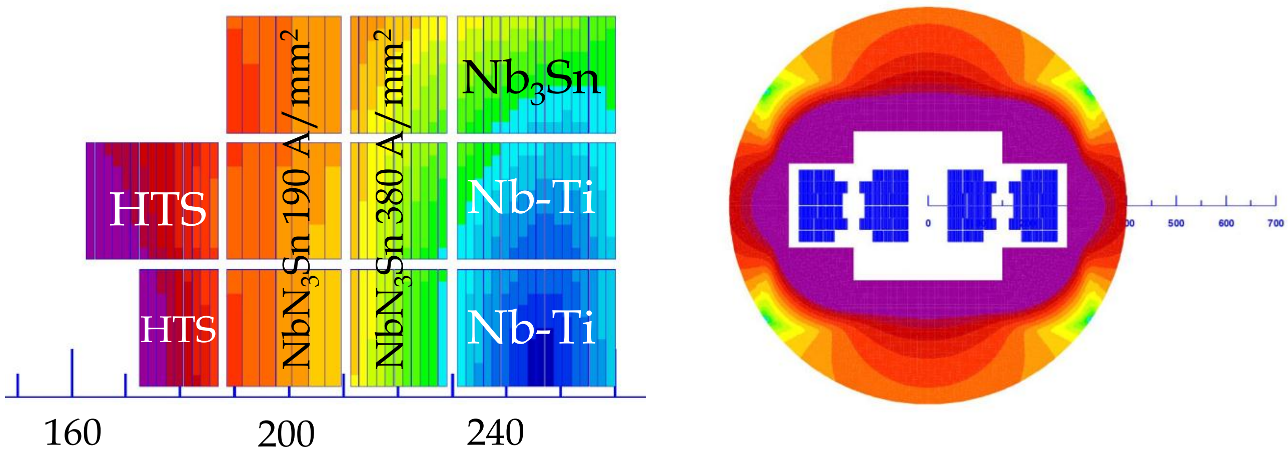
- HTS opens the way to higher and higher fields
  - Used to build solenoids, proved to work in the 20-30 T range



Current density versus field for several superconductors [from P. J. Lee NHMFL database]

The LHC tunnel in the 30's: dipole parameters

- Design is driven by the cost – grade as much as possible
  - Initial study made for 20 T, cases 15-16 T under study
  - One critical parameter: how much margin?
    - Using 80% rule, we should design for 25 T – 5 T margin – is it too much?
    - LHC at 6.5 TeV (80% rule) would have 2 T margin



Coil grading (one quarter of coil shown) and sketch of double aperture (coils in blue)
[E. Todesco, L. Bottura, G. de Rijk, L. Rossi, IEEE Trans Appl Supercond (2014) in press]

CONCLUSIONS

- The Fathers of the LHC designed a wise machine with the potential of reaching ultimate performance
  - At full performance one can expect 60 fb^{-1} per year (four times 2012), and 300 fb^{-1} at the horizon of the 20's
    - These 300 fb^{-1} are the lower estimate for the life of the inner triplet magnets
- The aperture of the triplet is a bottleneck to performance
  - So in any case better to replace with larger aperture. This will come in ~2022
- Coupled with crab cavities, larger triplet can give a factor four boost to luminosity
  - Together with the injector upgrade, one can get another factor five from beam intensity
- HL LHC can provide 3000 fb^{-1} at the horizon of the 30's

CONCLUSIONS

- HL-LHC can provide 3000 fb^{-1} at the horizon of the 30's
  - Enabling technologies: large aperture magnets and crab cavities
  - The could be the first application of Nb_3Sn to accelerators, pushing the operational field from 8 to 12 T
- CERN infrastructure and (especially) LEP tunnel is a precious asset of our lab
  - 20 T magnets would enable a 33 TeV hadron collider
    - No bottlenecks have been identified from the point of view of beam dynamics
- A 80-100 km tunnel would allow reaching 50+50 TeV
  - With 100 km ne would need 16 T magnet, which is not so far from our capabilities