AN OUTLOOK ON LHC OPERATION AND ON FUTURE PROJECTS AND STUDIES

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- The present: LHC in the 10's
  - LHC energy
  - The race towards luminosity

- The 20's: the HL-LHC project
  - Aiming at 3000 fb^{-1}

- The 30's: FCC studies
  - Aiming at 100 TeV centre of mass

- In run I, LHC energy has been 3.5 TeV and 4 TeV
  - Unforeseen limitation, due to weakness in the interconnections
    - This caused the 2008 incident
  - In 2008 one sector was pushed to 6.6 TeV showing a training longer than expected – only in 3000 series magnets
- Major consolidation in LS1
  - Shunt being added to cure interconnection the problem [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]
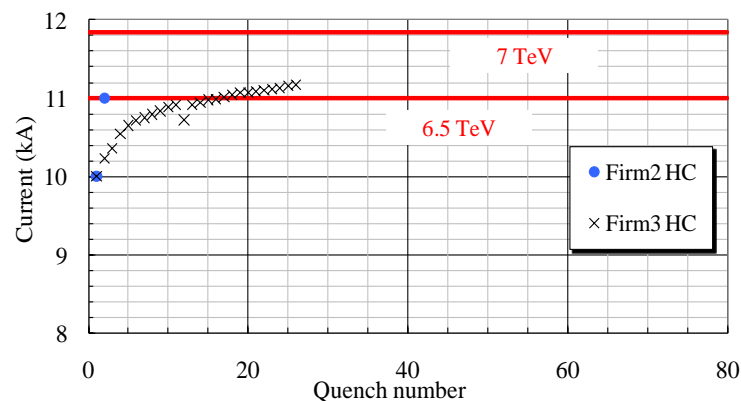
The training of sector 56
[HC and MP3 team]

- ## 2014: decision to train LHC at 6.5 TeV
  - Compromise between time, risk and energy for physics reach
  - 1-2 week to train one sector, in the shadow of hardware commissioning
  - Expected ~100 quenches, we went to 6.5 TeV with 174 quenches
    - A bit worse then expected, but we got there
  - First data about the whole LHC
    - 3000 series confirmed to be weaker (~1/3 of the magnets quenched)
    - First data about the whole LHC: magnet production not uniform
  - Effort sto understand what happened are ongoing
- ## In 2015 and 2016 very smooth run at 6.5 TeV
  - 1200 dipoles working at 7.7 T, with 20% margin
- ## At the end of 2016, two sector to be pushed towards 7 TeV
  - This would mean working with the dipoles at 14% margin
  - According to these results, LHC energy may stay at 6.5 TeV or go towards 7 TeV

- ## 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

Nominal luminosity: 10^{34} cm^{-2} s^{-1}
(considered very challenging in the 90's, pushed up to compete with SSC)

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

- Equation for the luminosity

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

- 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)

- The beam-beam limit (Coulomb)

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

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

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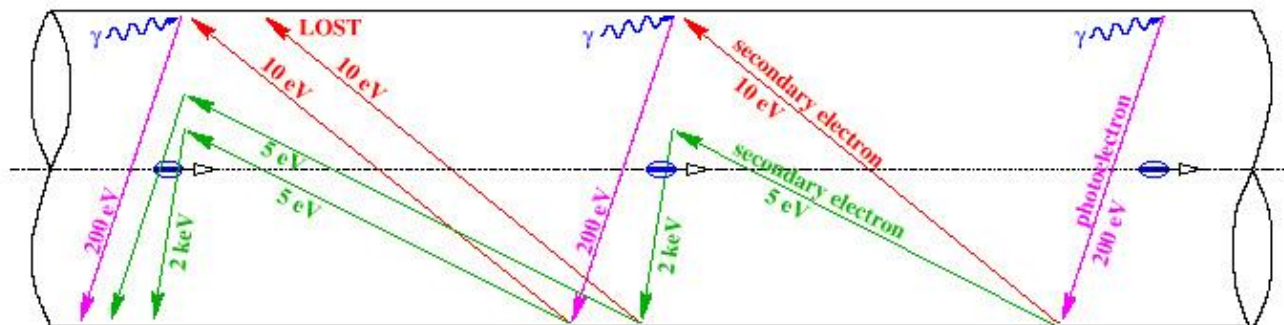
		Nominal	Ultimate	September 2012	2012 MD*
N_b	(adim)	1.15E+11	1.70E+11	1.55E+11	2.20E+11
ε_n	(m rad)	3.75E-06	3.75E-06	2.50E-06	1.70E-06
ξ_{IP}	(adim)	0.0034	0.0050	0.0068	0.0142
N_{IP}	(adim)	2	2	2	2
ξ	(adim)	0.007	0.010	0.014	0.028

* 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)

- RunI (2011-2013) has been based on 50 ns spacing
  - This limited the number of bunches to 1300 bunches
  - Was cured by scrubbing of surface with intense beam
- RunII (2015-2017) has been based on 25 ns
  - Most of the run with 2200 bunches
    - 2800 bunches not reached due to other limitations (injectors, transfer lines)
    - Operation has been smooth, with large heat loads but managebles
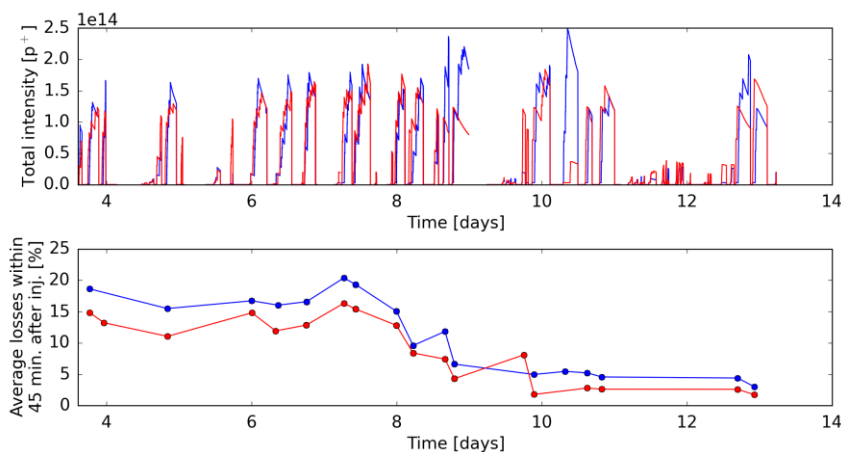
Reduction of beam losses during the scrubbing run
[G. Rumolo, et al., LMC August 2015]

- Optics: squeezing the beam

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

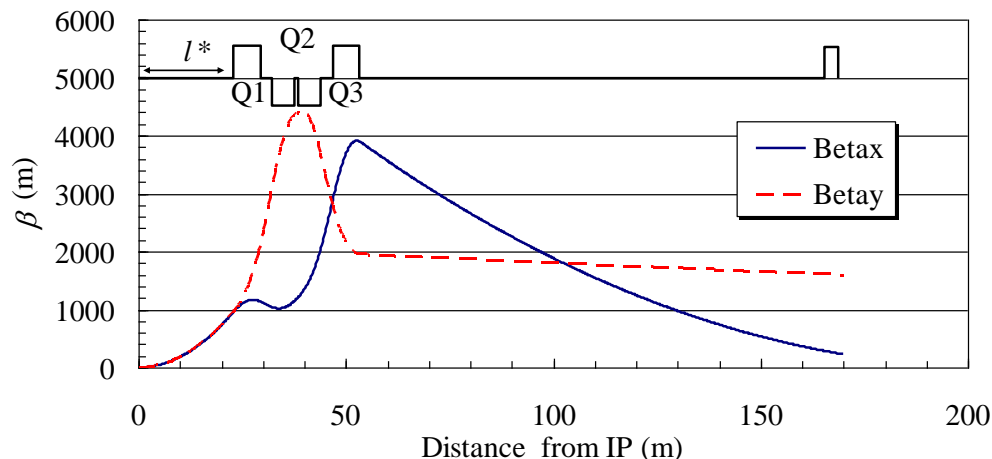$$|x(s)| = \sqrt{\frac{\varepsilon \beta(s)}{\gamma_r}}$$

  - Size of the beam in a magnetic lattice
  - 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

- 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 $\beta^* = 55$ cm with 70 mm aperture IR quads

- In RunI, less energy $\rightarrow$ larger beam $\rightarrow$ higher β^*

  - But lower emittance, so at the end we manage to run at 60 cm

- In RunII, we started at 80 cm

  - Then we progressiveley moved down to 60 and then to 40 cm

  - This is possible thanks to very good aperture (larger than expected) and smaller beam emittance (2.0 mu instead of 3.75)
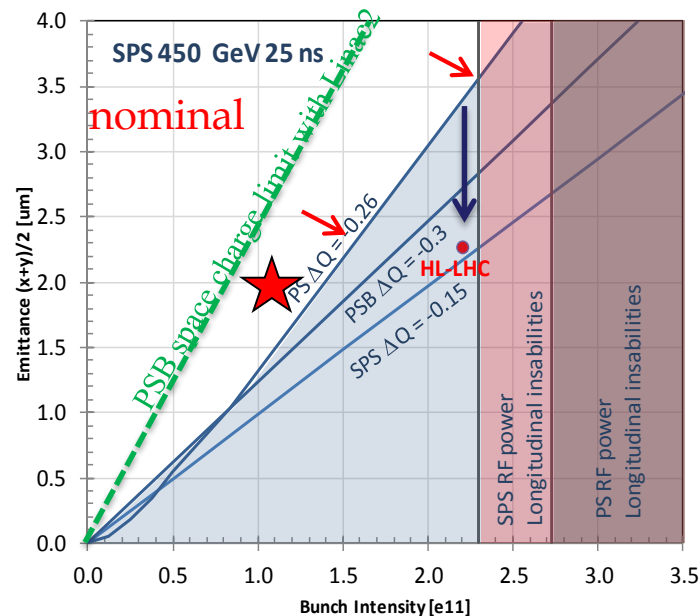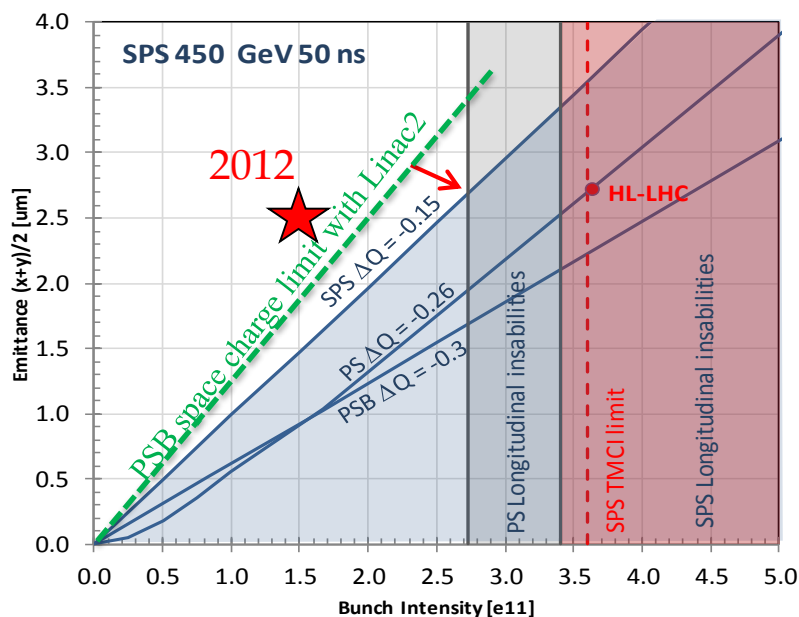
- The injector chain limits

  - Emittance ε_n vs intensity N_b

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

  - This relation also depends on the bunch spacing n_b

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

- 50 ns allow larger intensities and smaller emittances

- Pushing up these limits is the aim of the injector upgrade

- In RunI, we reached at 4 TeV 70% of nominal luminosity at 50 ns operation

- In Run II, we reached at 6.5 TeV 150% of nominal luminosity at 25 ns

		Nominal	2012 sept	w.r.t. nom	2016 july	w.r.t. nom
N_b	(adim)	1.15E+11	1.55E+11	1.82	1.10E+11	0.91
ε_n	(m)	3.75E-06	2.50E-06	1.50	2.00E-06	1.88
n_b	(adim)	2808	1380	0.49	2200	0.78
β^*	(m)	0.55	0.6	0.92	0.4	1.38
spacing	(ns)	25	50		25	
E	(TeV)	7.0	4	0.57	6.5	0.93
F	(adim)	0.86	0.86	1.00	0.75	0.87
L	$(cm^{-2} s^{-1})$	**1.00E+34**	**7.0E+33**	0.70	**1.5E+34**	1.50
pile up		26	37		50	

- For the moment, no evident bottlenecks in operation

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  - LHC Energy
  - The race towards luminosity

- The 20's: the HL-LHC project
  - Optics and intensity

- The 30's: FCC studies
  - Aiming at 100 TeV centre of mass

- CERN Project, EU funds for the design study, preliminary design report done www.cern.ch/hilumi [L. Rossi]
  - The target: after reaching 300 fb⁻¹ in 2022, we need 3000 fb⁻¹ in 2024-2035

- 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^*)

		Nominal	HL-LHC	
N_b	(adim)	1.15E+11	2.20E+11	3.7
ε_n	(m)	3.75E-06	2.50E-06	1.5
n_b	(adim)	2808	2808	1.0
β^*	(m)	0.55	0.15	3.7
spacing	(ns)	25	25	
E	(TeV)	7.0	7.0	1.0
F	(adim)	0.86	1	
L_{max}	(cm⁻² s⁻¹)	1.00E+34	2.0E+35	20.1
L_{lev}	(cm⁻² s⁻¹)	1.00E+34	5.0E+34	
pile up		26	132	

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

- 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

  - Many ways to do levelling

    - With crossing angle
    - With separation
    - With β^*
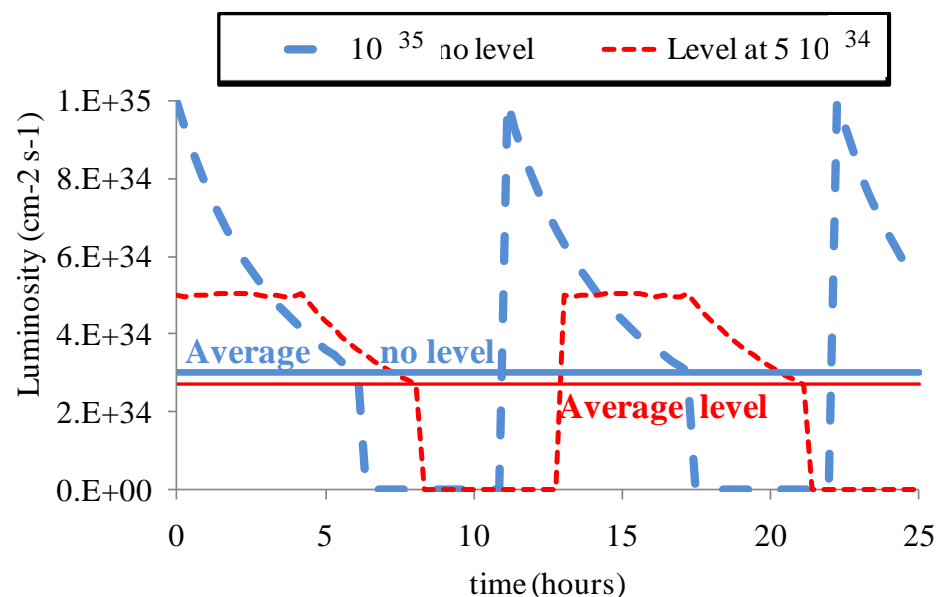
Luminosity levelling principle (with a factor 10 shown)

- Main result: similar integrated lumi but lower pile up

  - That's the desiderata of experiments

- How to get a factor four from the optics ?

- To reduce β^* towards 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,

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

    i.e. 150 mm aperture quadrupoles
    - First upgrades aimed β^*=25 cm [F. Ruggiero, et al, LHC PR 626 (2002)]
- The quadrupole will rely on Nb_3Sn technology
  - Collaboration CERN-US-Hilumi
  - Based on US-LARP (LHC accelerator research program) efforts during the past 10 years
  - Important leap in technology, with huge impact on CERN future (FCC)

- 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 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 up to ~16 T
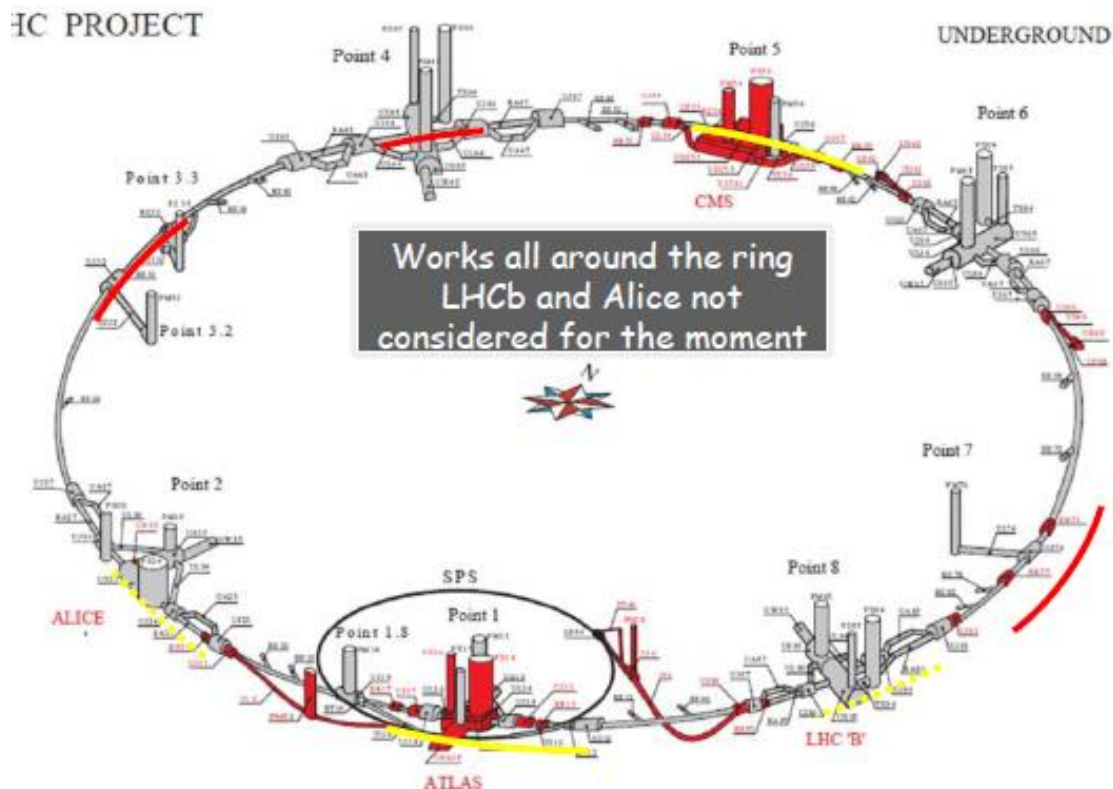 - For HL-LHC we will operate at 11.5 T peak field
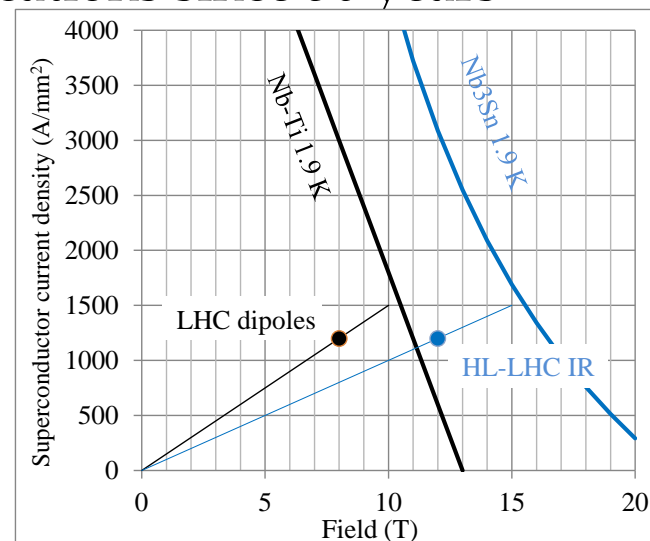
- HL LHC is not only new magnets in ~1 km of the the main ring, but also
  - Cryogenics upgrade
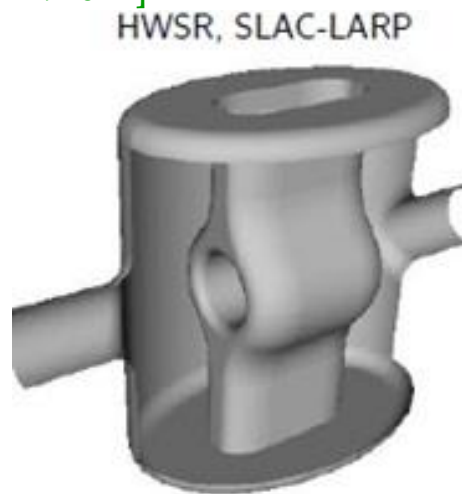 - Collimation upgrade
  - "Cold" powering
  - Crab cavities

Works all around the ring
LHCb and Alice not
considered for the moment

- 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]

HWSR, SLAC-LARP

θ_c
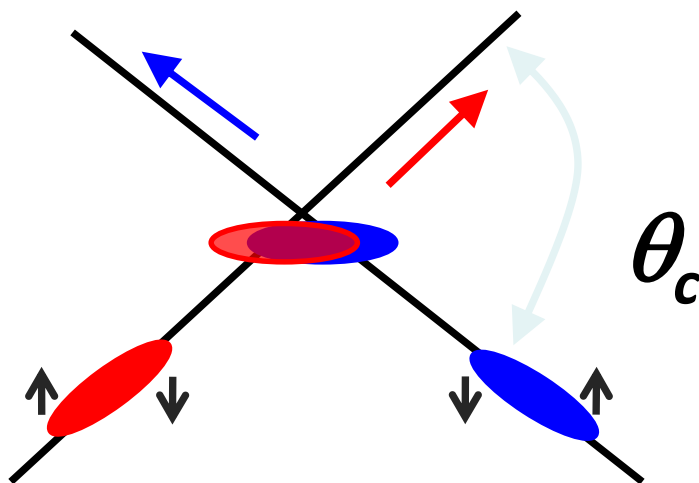
Crab crossing
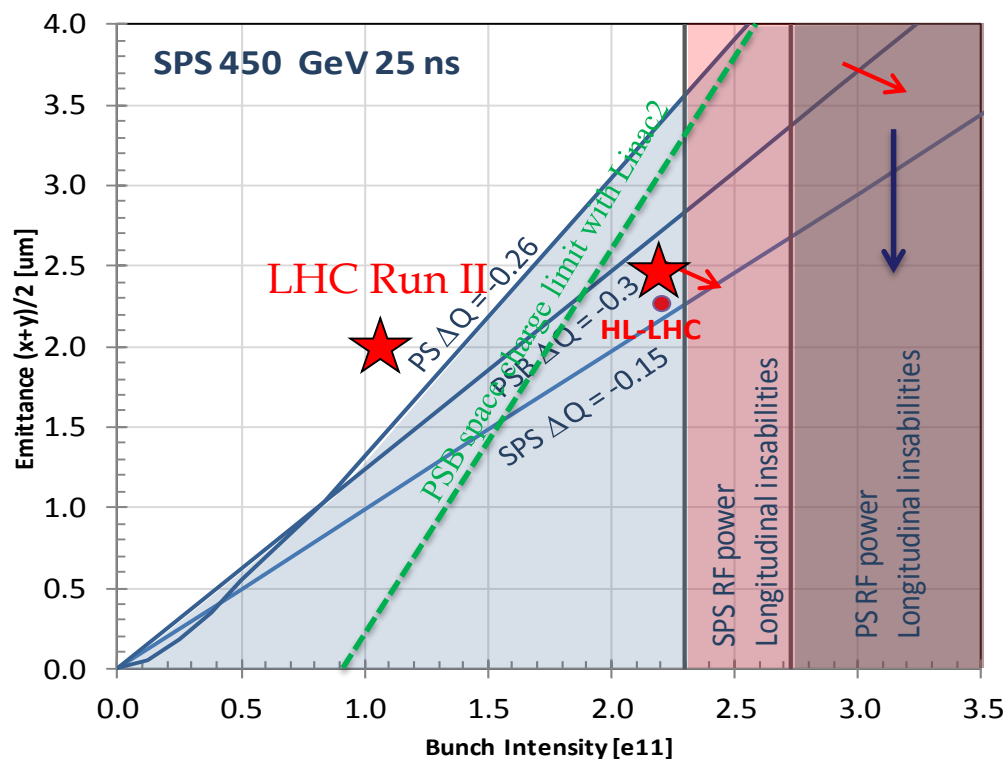
One possible option for the design of crab cavity

- 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

- As LHC, HL-LHC is an international collaboration
  - Hardware assigned to several labs for design and model
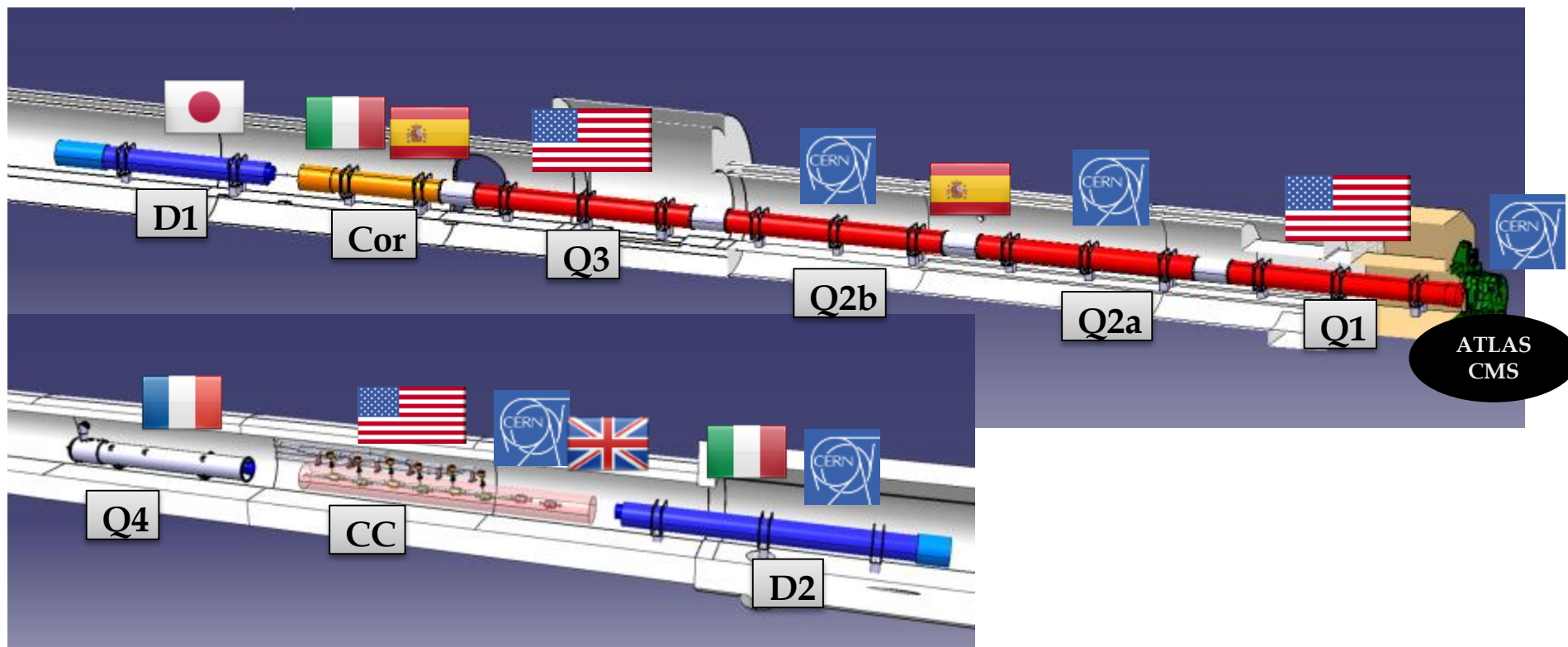
First baseline from Q1 to Q4, and contributions [F. Bordry, Washington FCC week]

HL-LHC: INTENSITY

- How to get the factor five from the beam ?
  - 25 ns option
- LIU: LHC Injector Upgrade project [M. Meddahi]

		Nominal	HL-LHC	
N_b	(adim)	1.15E+11	2.20E+11	3.7
ε_n	(m)	3.75E-06	2.50E-06	1.5
n_b	(adim)	2808	2808	1.0
β^*	(m)	0.55	0.15	3.7
spacing	(ns)	25	25	
E	(TeV)	7.0	7.0	1.0
F	(adim)	0.86	1	
L_{max}	(cm^{-2} s^{-1})	1.00E+34	2.0E+35	20.1
L_{lev}	(cm^{-2} s^{-1})	1.00E+34	5.0E+34	
pile up		26	132	

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

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THE HIGH ENERGY FRONTIER

- First ideas

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

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

- # The FCC study
  - ## Tunnel of 100 km with 16 T magnets to reach 50+50 TeV with proton collisions – plus possibility of e-e, e-h machine
- # Study group Future Circular Collider (FCC) established in 2013 [M. Benedikt, F. Zimmermann]
  - ## Opening event of the collaboration in Washington, March 2015 http://indico.cern.ch/event/340703/

A new tunnel in the CERN area

- A baseline is being established [D. Schulte, Washington FCC week]
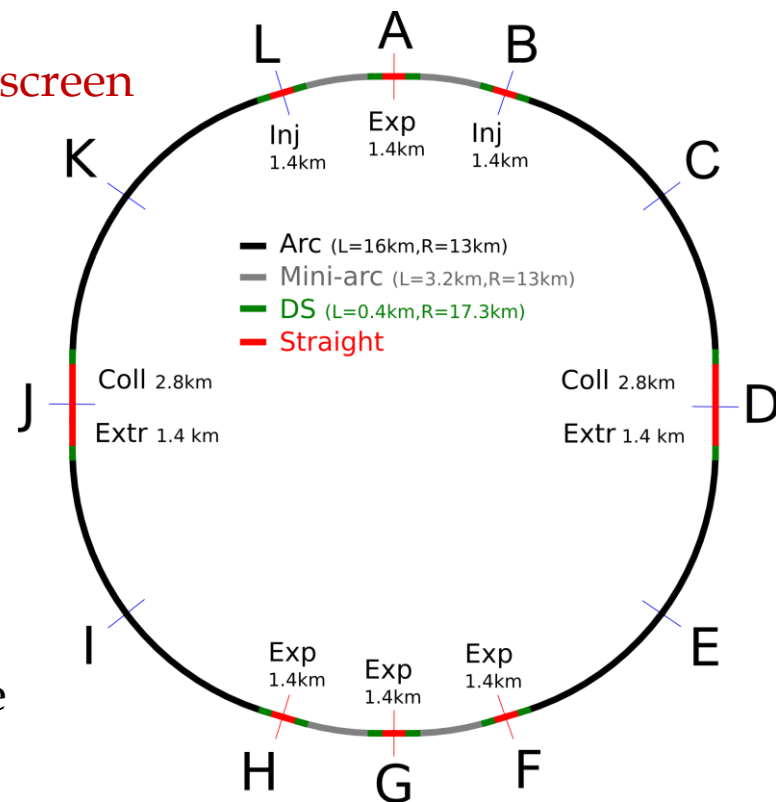 - Luminosity as in HL LHC
  - Emittance as in HL LHC
  - Moderate bunch charge
  - 25 ns operation
  - β^* of 1 m
  - Pile up 50% larger than HL LHC
  - No leveling
  - Looks reasonable

		LHC	HL-LHC	w.r.t. LHC	FCC	w.r.t. LHC
N_b	(adim)	1.15E+11	2.20E+11	3.66	1.00E+11	0.76
ε_n	(m)	3.75E-06	2.50E-06	1.50	2.20E-06	1.70
n_b	(adim)	2808	2808	1.00	10000	3.56
β^*	(m)	0.55	0.15	3.67	1.1	0.50
f_{rev}	(s^{-1})	1.12E+04	1.12E+04	1.00	3.00E+03	0.27
spacing	(ns)	25	25		25	
F	(adim)	0.86			1	1.16
E	(TeV)	7	7	1.00	50	7.14
lenght	(km)	26.7	26.7	1.00	100	3.75
L_{max}	cm^{-2} s^{-1}	1.00E+34	2.0E+35	20	5.1E+34	5
L_{ave}			5.0E+34			
pile up		25	127		176	

- Goal of 250 fb^{-1} per year
- There is also an ultimate scenario
  - a kind of HL FCC , very challenging parameters, especially for radiation dose
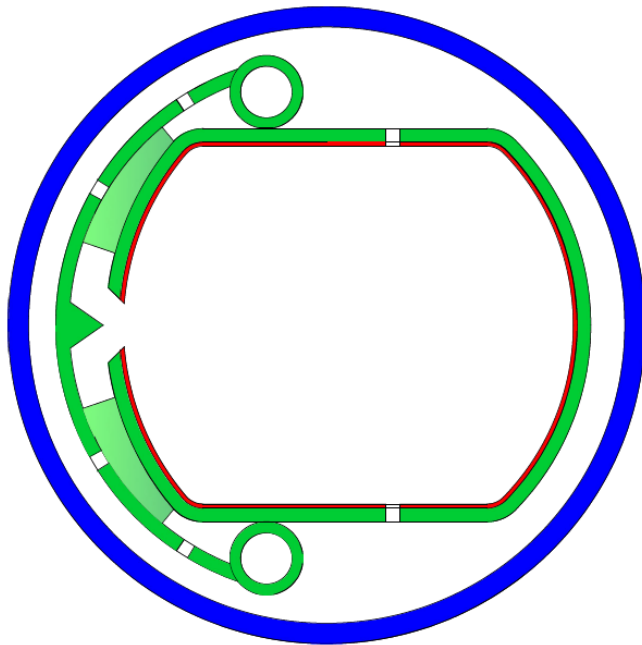- There is also an option for 5 ns operation

- A baseline is being established [D. Schulte WG]
  - 16 T magnets with Nb_3Sn technology (about 5000 dipoles)
    - Aperture of 50 mm
  - Double cell length from 100 to 200 m
  - 5 MW of synchrotron radiation on beam screen
    - It was 7 kW in the LHC
    - 50 K beam screen
  - Electrical consumption critical
    - 100 MW only of synchrotron
  - Shielding the magnet is essential
    - Tungsten insert of 1-2 cm
    - Reason for larger aperture
  - Radiation dose OK
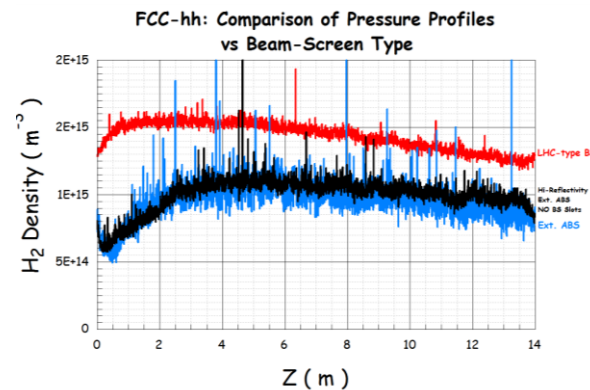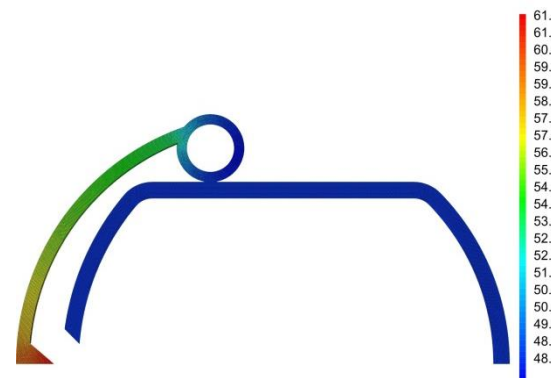   - Becomes very critical for the ultimate

Layout baseline [D. Schulte]

- Arc (L=16km, R=13km)
- Mini-arc (L=3.2km, R=13km)
- DS (L=0.4km, R=17.3km)
- Straight

Inj 1.4km Exp 1.4km Inj 1.4km

Coll 2.8km Extr 1.4 km Coll 2.8km Extr 1.4 km

Exp 1.4km Exp 1.4km Exp 1.4km

First thoughts about a very challenging beam screen

FCC-hh: Comparison of Pressure Profiles vs Beam-Screen Type

Vacuum quality [R. Kersevan]

Beam screen geometry [R. Kersevan, C. Garion]

Heat transfer [L. Tavian]

- One of the main challenge are the magnets

  - First choice: current density – keep the same as the LHC

    B [T] ~ *0.0007 × coil width* [mm] × *current density* [A/mm²]

    LHC: 8 [T] ~ 0.0007 × 30 × 380
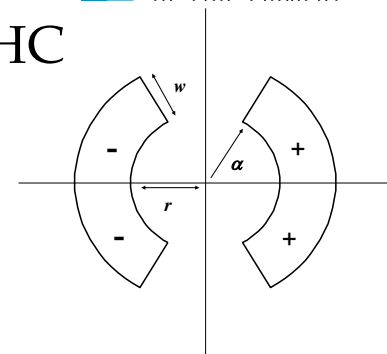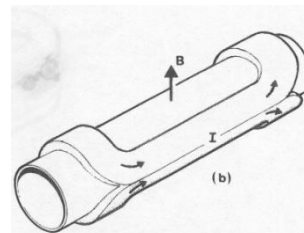
  - Accelerators used current density of the order of 350–400 A/mm²

  - 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

  - Present record is 13.5 T

    - Short model of acc magnet

  - CERN is building FrescaII

    - 13 T with potential of going to 15 T
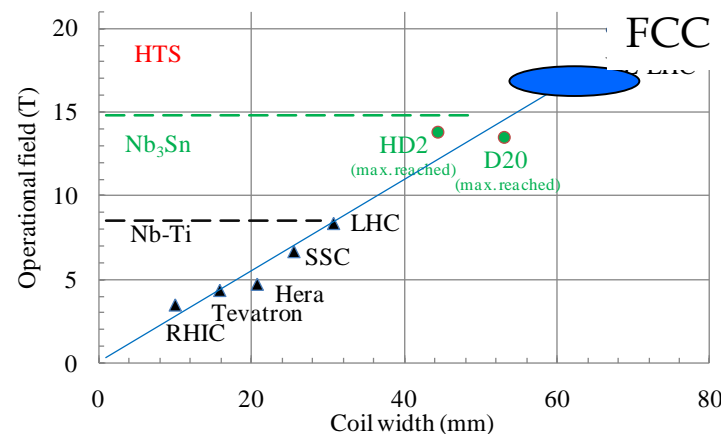
Operational field versus coil width in accelerator magnets

- What material can tolerate 400 A/mm^2 and at what field ?
  - For Nb-Ti: LHC performances - up to 8 T
  - For Nb$_3$Sn: possibly reach 16 T with grading
    - Studies led by D. Tommasini and L. Bottura - international collab.
    - Cost is an issue with present prices
  - If we want to reach 20 T, last 4 T made by HTS
    - Today in Bi-2212 and YBCO we have not so far from there
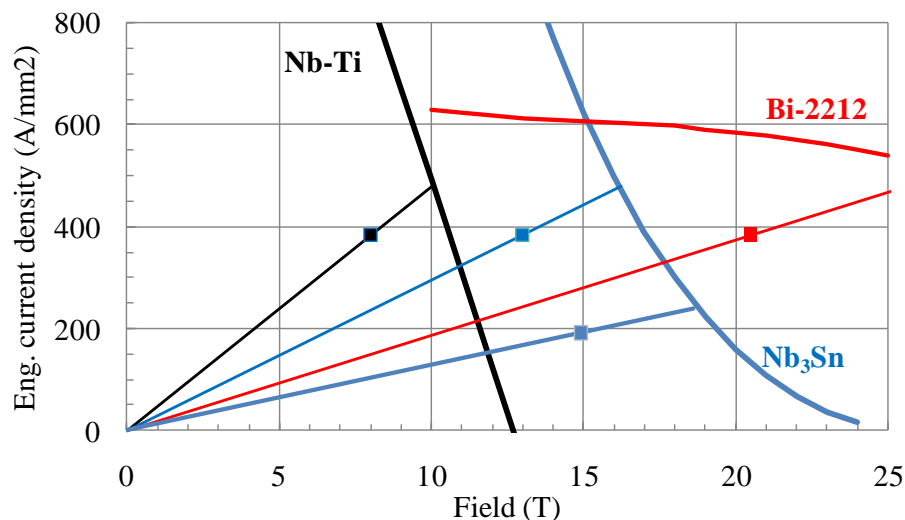
Engineering current density versus field for Nb-Ti and Nb$_3$Sn (lines) and operational current (markers)

- 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 ~2024

- 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

- 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
  - With another jump of 4 T, we can go to 16 T, the ultimate of Nb_3Sn

- A 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
  - No bottlenecks have been identified from the point of view of beam dynamics
  - The same magnets in the LHC tunnel would make an LHC doubler