LHC: past, present and future

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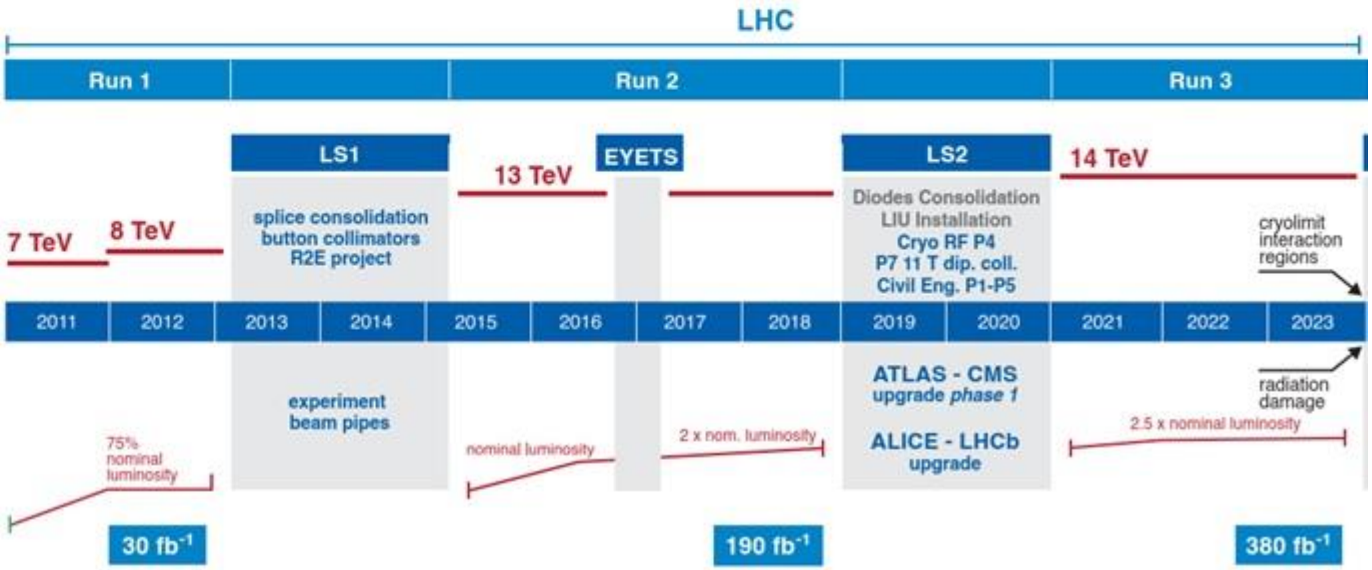
Italian teacher program, CERN 18 March 2019

CONTENTS

- Where are we?
  - Energy
  - Luminosity
  - Dirty beasts and the menace of spread
- Where are we going?
  - From 13 to 14 TeV (15 ?)
  - Towards 4000 fb^{-1}
  - Towards 35-100 TeV

2008-2018: FROM ASHES TO HIGGS

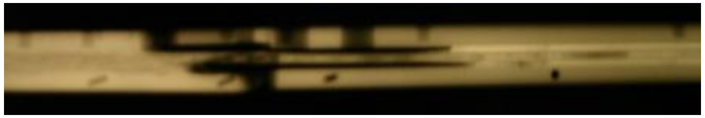


- 2008: Incident due to faulty splices

- 2009: Repair
- 2010-2012: Run at 7-8 TeV
- 2012: Higgs boson discovery

2008-2018: WHY 4 TeV ?

- In Run I energy limited to 4+4 TeV due to faulty splices
  - Unforeseen limitation, due to a weakness in the interconnection between the superconducting magnets
  - Repair in 2008 of the damaged sector
    - Cause of the incident was not removed, so energy limited by maximum current tolerable by the splices
    - Initial estimate was 3.5 TeV per proton beam (7 TeV center of mass)
    - Then brough to 4 TeV per proton beam



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

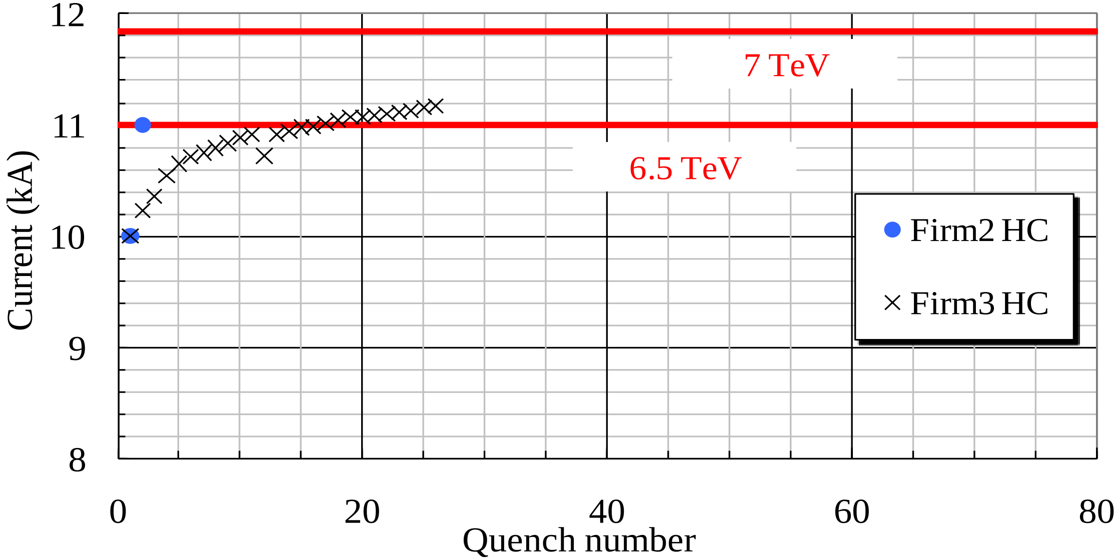
- Succesful consolidation of all splices in 2013-2014 (LS1) to remove this bottleneck

2008-2018: WHY 6.5 TeV ?

- After LS1, we met the second bottleneck in energy: training of the magnets
- Training is one of the most obscure and fascinating and phenomena of applied superconductivity
  - The magnet is designed to reach a maximum field of X tesla
    - When you first power, it reaches only a fraction of X (typically 70%), then it has a irriversible transition to normal state (quench)
    - This transition bring some zones of the magnet from 1.9 K to 300 K
    - The thermal and mechanical shock allow at the successive powering to reach a higher fraction of X tesla (the magnet trains)
  - It is extremely rare that a magnet reaches 100% of X tesla, typically training of a good magnet saturates at 90%-95%
  - Typically accelerator magnets operate at 70-90% of the maximum reachable field
  - This margin is quite expensive, how much is really needed is a open debate in our community
  - LHC dipoles at 8.3 T (corresponding to 7 TeV energy) run at 86% of maximum reachable field

2008-2018: WHY 6.5 TeV ?

- All LHC dipoles were trained above 8.3 T (7 TeV per proton) on individual test bench
  - Half of them were trained to 9 T (7.5 TeV per proton)
  - After installation, negligible retraining was expected (order 100 quenches for the whole machine to operate at 7 TeV)
  - Before the incident one sector was powered towards 7 TeV, showing a worse performance (20 quenches to reach 6.5 TeV in 1/8 of the machine)



Training of the 5-6 sector in 2008
[A. Verweij and MP3 team]

2008-2018: WHY 6.5 TeV ?

- After the LS1 consolidation of splices, it was decided to aim at 6.5 TeV operation
  - We expected order of 100 quenches, we needed with 172 quenches
  - With the confirmation of highly unexpected behaviours already observed in 2008 (see next sections about spread): magnets from Firm3 need many more quenches than the other magnets

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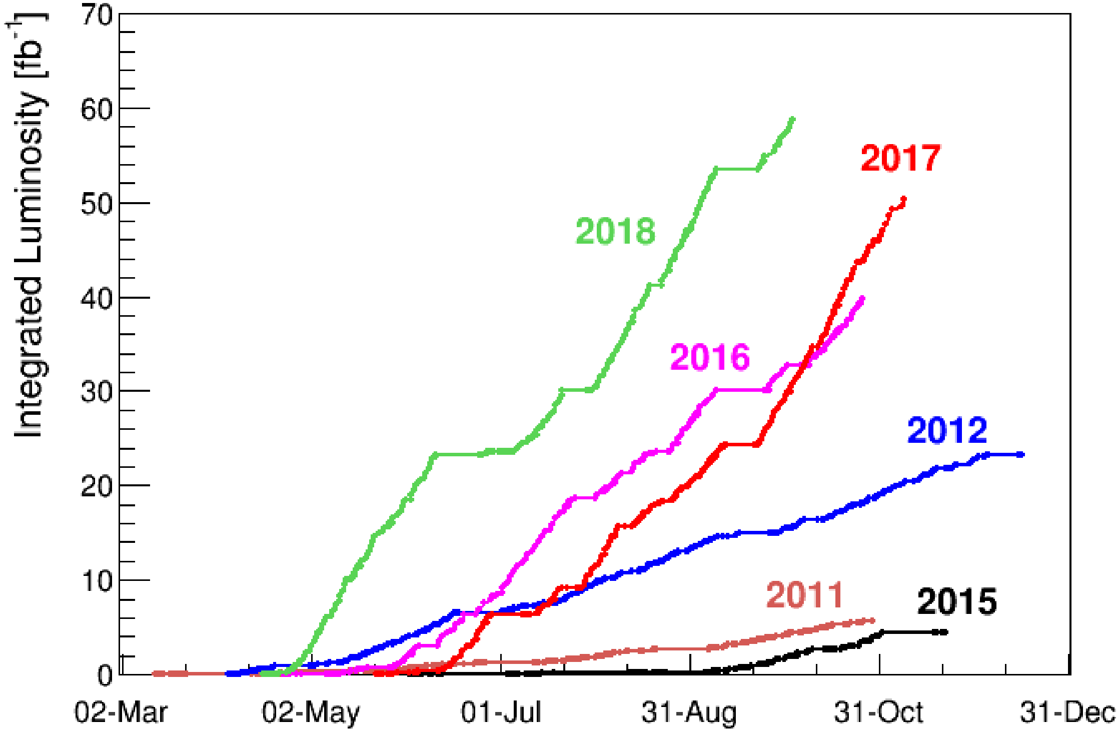
  - Towards 35-100 TeV

2008-2018: LUMINOSITY

- The spectacular progression of data accumulation



2008-2018: LUMINOSITY

- 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

2008-2018: LUMINOSITY

- 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/e_n)
  - Electron cloud (limit on n_b)
  - Squeeze (limit on $b^* e_n$)
  - Injectors (limit on N_b, n_b, e_n)

THE BEAM-BEAM LIMIT

- The beam-beam limit (Coulomb)

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

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

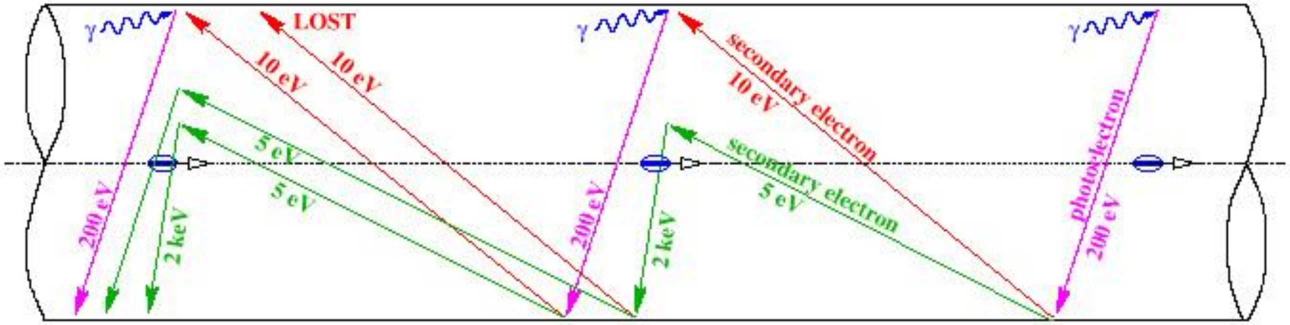
- N_b Number of particles per bunch ε_n transverse size of beam
- One cannot put too many particles in a “small space” (brightness)
  - Otherwise the Coulomb interaction seen by a single particle when collides against the other bunch creates instabilities (tune-shift)
- This is an empirical limit, also related to nonlinearities in the lattice
  - LHC has very low nonlinearities → larger limits
  - LHC behaves better than expected: beam-beam up to 0.03 tolerable
  - LHC in 2018 has run with 0.015 beam-beam parameter

		Nominal	Ultimate	2012	2012 MD	2018
N_b	(adim)	1.15E+11	1.70E+11	1.55E+11	2.20E+11	1.10E+11
ε_n	(m)	3.75E-06	3.75E-06	2.50E-06	1.70E-06	1.80E-06
ξ_{IP}	(adim)	0.0037	0.0055	0.0075	0.0157	0.0074
N_{IP}	(adim)	2	2	2	2	2
ξ	(adim)	0.007	0.011	0.015	0.031	0.015

THE ELECTRON CLOUD LIMIT

- The electron cloud

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



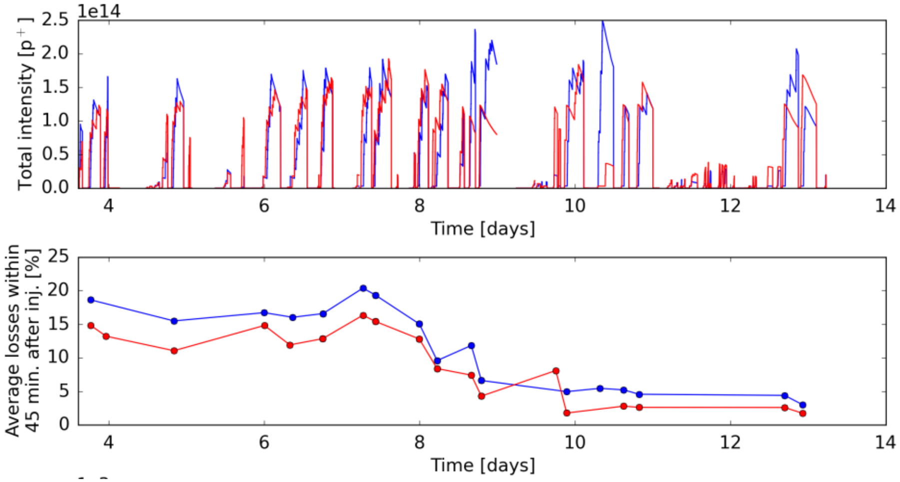
Mechanism of electron cloud formation [F. Ruggiero]

- 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)

THE ELECTRON CLOUD LIMIT

- Electron cloud has been observed where expected in RunI during 50 ns intensity ramp up
  - Was cured by scrubbing of surface with intense beam
  - In RunI we operated in a reliable way with 1300 bunches at 50 ns
- RunII worked with 25 ns as baseline
  - Looks non trivial but feasible
  - More sensitive to other effects (see section on spread and strange beasts)
    - 2556 bunches reached instead of the nominal 2808
    - Scrubbing run effective



THE OPTICS LIMIT

- Optics: squeezing the beam

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

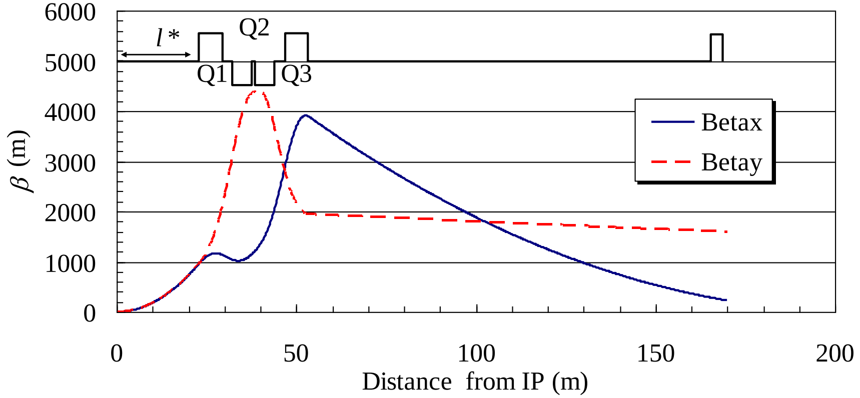
  - Size of the beam in a magnetic lattice
  - Luminosity is inverse prop to ε and β*

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

- In the free path (no accelerator magnets) around the experiment, the *β** has a nasty dependence

  with *s* distance to IP

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



Beta function close to the interaction points

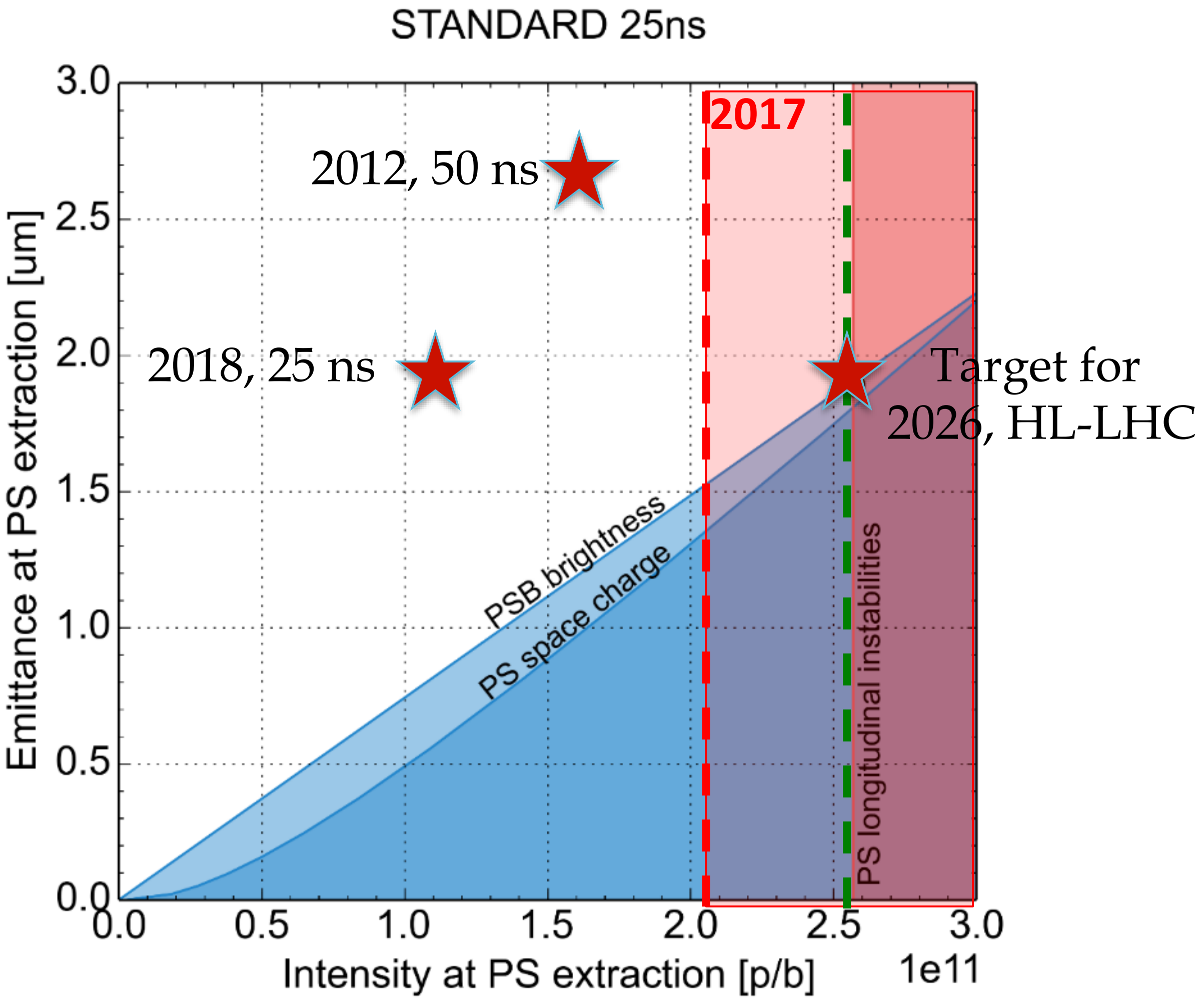
- The limit to the squeeze is the magnet aperture
  - Key word for magnets in HL LHC: not stronger but larger

THE OPTICS LIMIT

- 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 → larger beam → higher β^*
    - But lower emittance (2.5 instead of 3.75 μm), so we manage to run at 60 cm
- In RunII, we arrived to run at 25 cm

THE INJECTOR LIMIT

- Injectors can provide beams with only a given combination of parameters



2008-2018: LUMINOSITY

- Summary of conditions in the runs
  - Note: in 2018 we started using levelling to reduce pile up

		Nominal	2011		2012		2015		2016		2017		2018	
N_b	(adim)	1.15E+11	1.50E+11	1.70	1.60E+11	1.94	1.15E+11	1.00	1.15E+11	1.00	1.17E+11	1.04	1.10E+11	0.91
ε_n	(m)	3.75E-06	2.40E-06	1.56	2.50E-06	1.50	3.50E-06	1.07	2.20E-06	1.70	2.25E-06	1.67	2.00E-06	1.88
n_b	(adim)	2808	1380	0.49	1380	0.49	2244	0.80	2220	0.79	2556	0.91	2556	0.91
β^*	(m)	0.55	1.00	0.55	0.60	0.92	0.80	0.69	0.40	1.38	0.40	1.38	0.25	2.20
spacing	(ns)	25	50		50		25		25		25		25	
E	(TeV)	7.0	3.5	0.50	4.0	0.57	6.5	0.93	6.5	0.93	6.5	0.93	6.5	0.93
X angle	(μrad)	142.5	185		185		185		140		150		150	
F	(adim)	0.840	0.836	1.00	0.748	0.89	0.770	0.92	0.732	0.87	0.712	0.85	0.603	0.72
L	(cm^{-2} s^{-1})	**1.00E+34**	**3.6E+33**	0.36	**6.7E+33**	0.67	**5.0E+33**	0.50	**1.5E+34**	1.50	**1.70E+34**	1.70	**2.29E+34**	2.29
pile up		26	19		36		16		50		49		66	
σ_z	(mm)	75.5	90		90		90		75		75		75	
γ	(adim)	7448	3724		4256		6916		6916		6916		6916	
σ^*	(mm)	1.66E-02	2.54E-02		1.88E-02		2.01E-02		1.13E-02		1.14E-02		8.50E-03	

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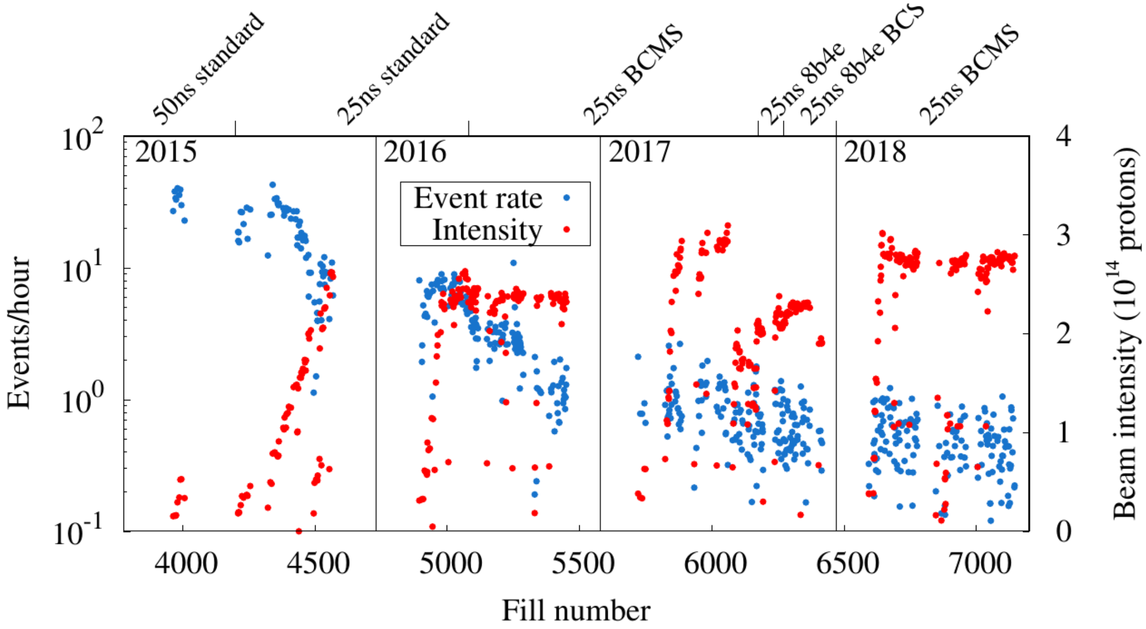
DIRTY BEASTS

War of the worlds (B. Haskin, Paramount, 1953)

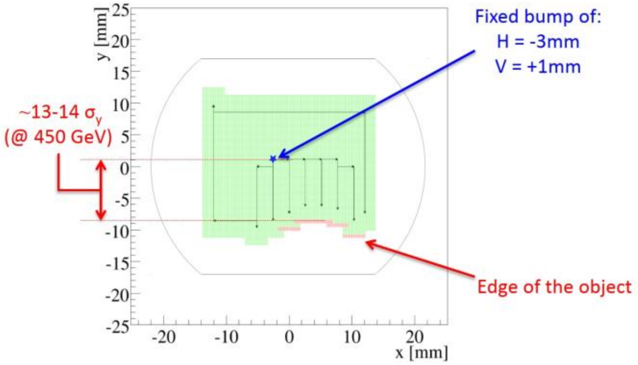
- And the UFO appeared in Geneva …
  - Particles of dust moved by the beam (electrostatics), rapidly burned by the beam
  - Losses can cause interlocks of beam related to beam loss monitor
  - Very worrying in 2015, but conditioning visible so not an issue today
  - What after the large intervention of LS2 ?



Number of UFO (above given threshold) observed in past years
(F. Bordry, HL-LHC meeting 2018)

DIRTY BEASTS

- ULO (2015 and 2016)
  - Unidentified Lying Object in cell 15 right of point 8
  - Provoking UFO and beam losses
  - Frozen object, visible with beam scan, of few mm on the bottom of the vacuum chamber
  - Bypassed by a chicane via orbit correctors

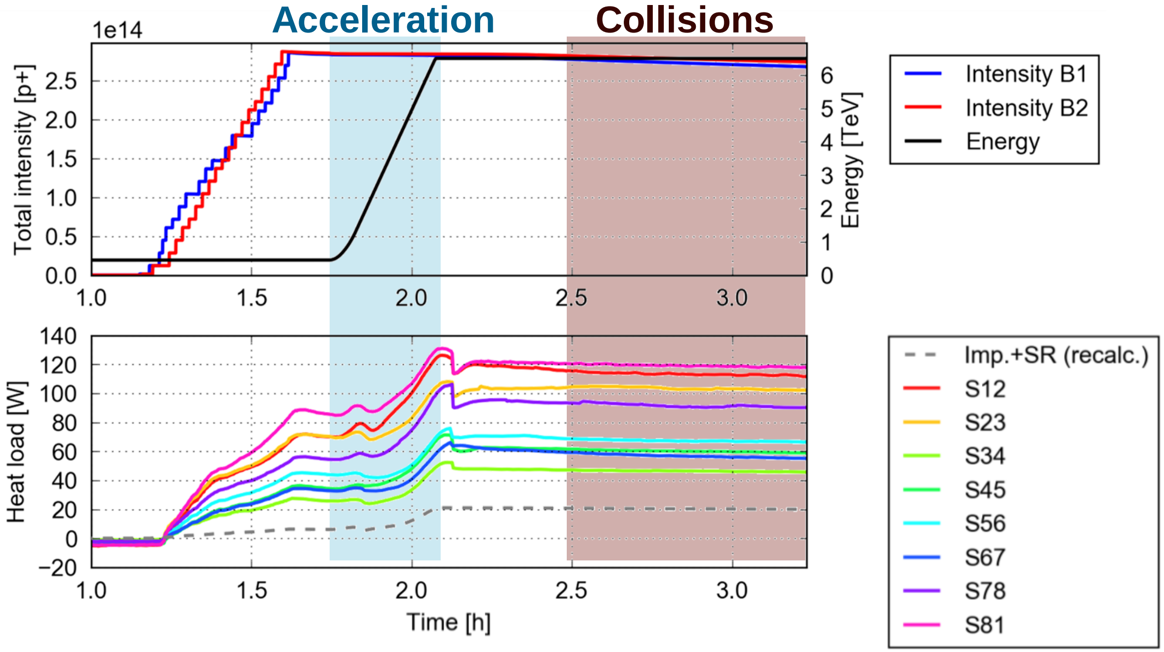


D. Mirarchi, Evian workshop 2015

- 16L2 (2017 and 2018)
  - Significant beam losses in cell 16 left of point 2, affecting operation in 2017 and 2018
  - Air inlet during cool down is the most probable cause
  - Bypassed by changing the pattern of bunches

THE MENACE OF SPREAD

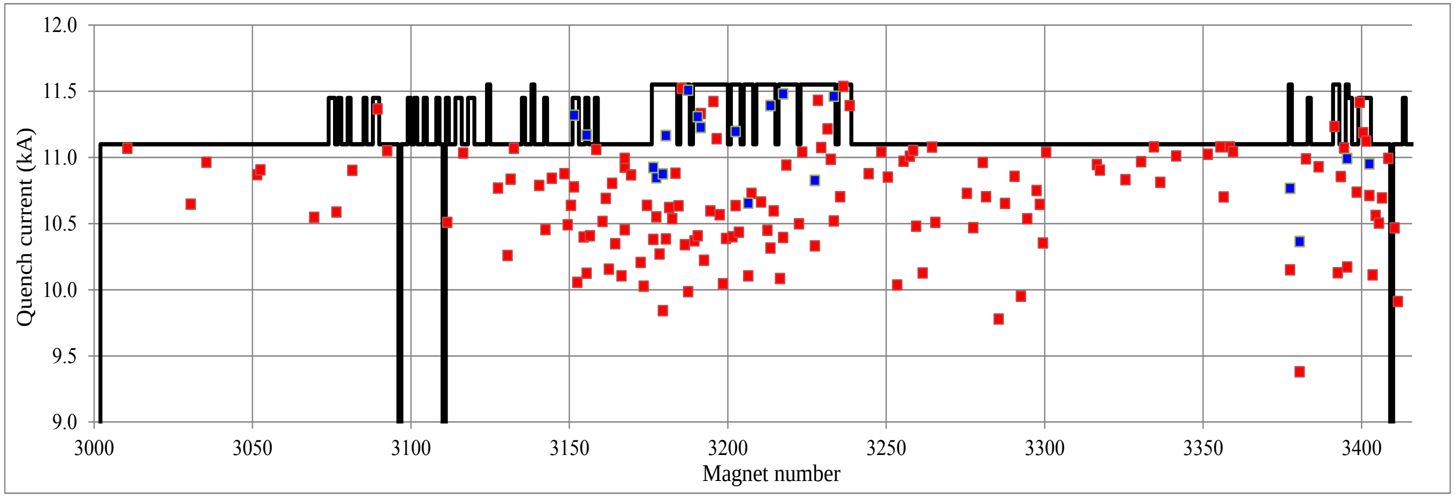
- Spread in arc performance observed in RunII
  - 4 consecutive arcs have a much higher (twice) heat load than the other 4
  - Source is most likely the electron cloud, generated by different surface properties (SEY, impurities?)
    - Not understood
  - The higher load sectors are touching the limit of cryogenics, could affect HL LHC



Heat load measured in the different sectors (G. Iadarola, LMC 2018)

THE MENACE OF SPREAD

- To reach 6.5 TeV, large spread between the three magnet manufacturers
    - Firm1: 5% of quenches
    - Firm2: 25% of quenches
    - Firm3: 70% of quenches
- Note that
    - All magnets made with the same design and procedures provided by CERN
    - Spread of performance is not only between producers, but also during time
    - This behaviour is one of the main enigma of the LHC magnets



Magnets of Firm3 quenching in the LHC tunnel to reach 6.5-6.7 TeV
(E. Todesco et al. IEEE Trans Appl Supercond 2017)

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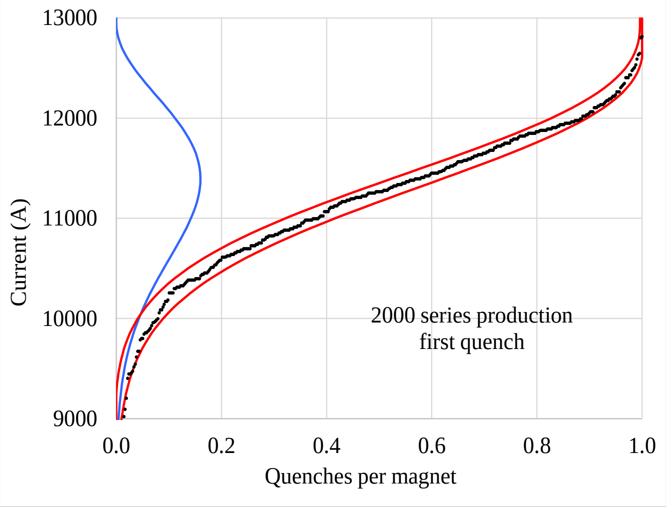
FROM 13 TO 14 TeV

- During the training to 6.5 TeV, two shorts appeared in the diode box of the dipoles
  - Due to weakness in design of diode insulation
  - Cured by a bold action: pulse of current to burn the short (A. Siemko and team)
  - It worked, but the management decided to go for a global diode consolidation in LS2 (J. M. Jimenez, J. P. Tock et al.)
  - This shall allow to carry on massive campaign of training if needed
- The decision of the management is to run at 7+7 TeV after LS2
  - Order of 500 quenches expected,

    based on the observation that the quench

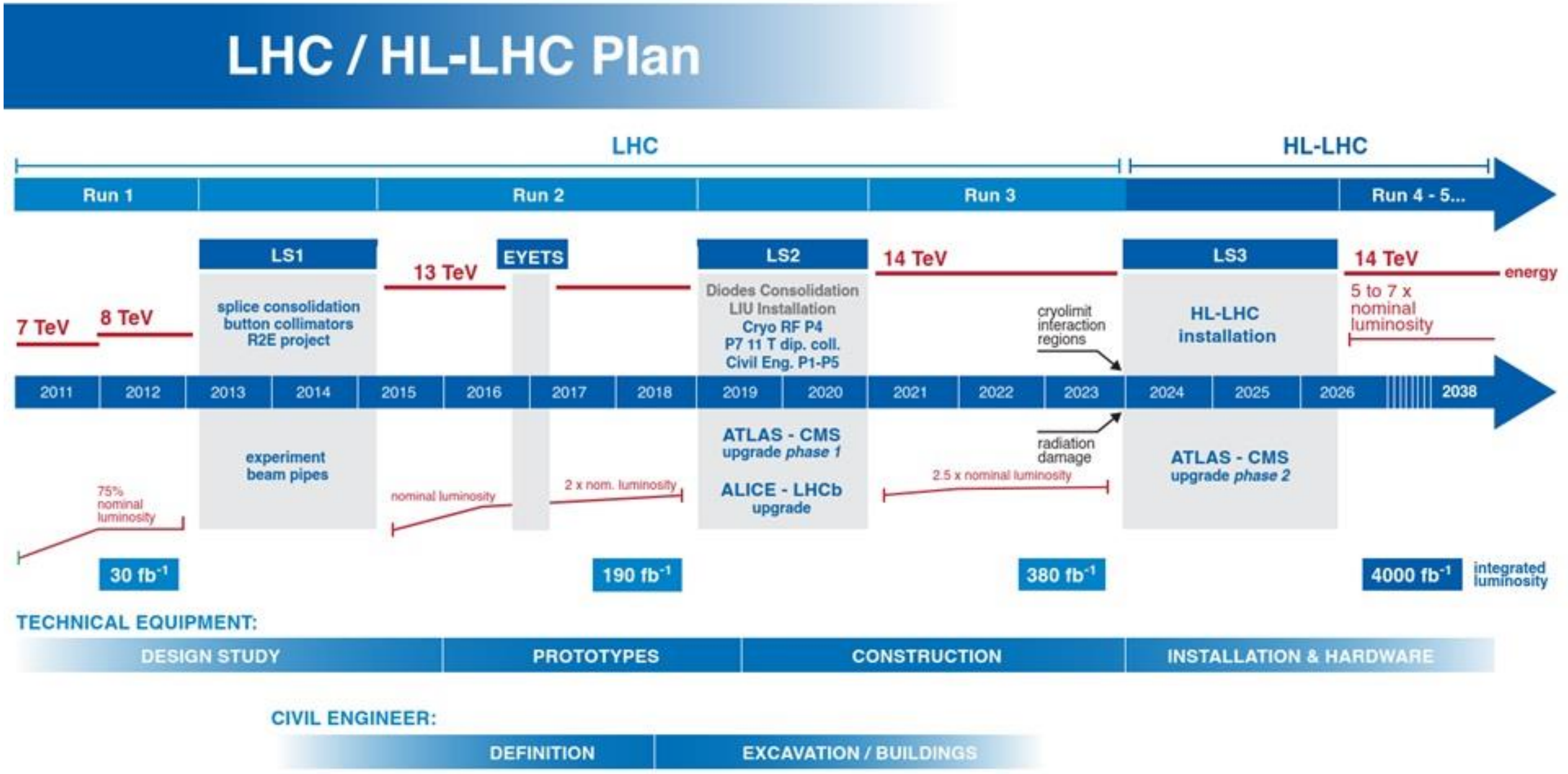
    distribution is not far from a Gaussian



- The training to 7 TeV will also tell us more about the possibility of training at 7.5 TeV (remote hypothesis, but not excluded)

THE 20's: TOWARDS 4000 fb^{-1}

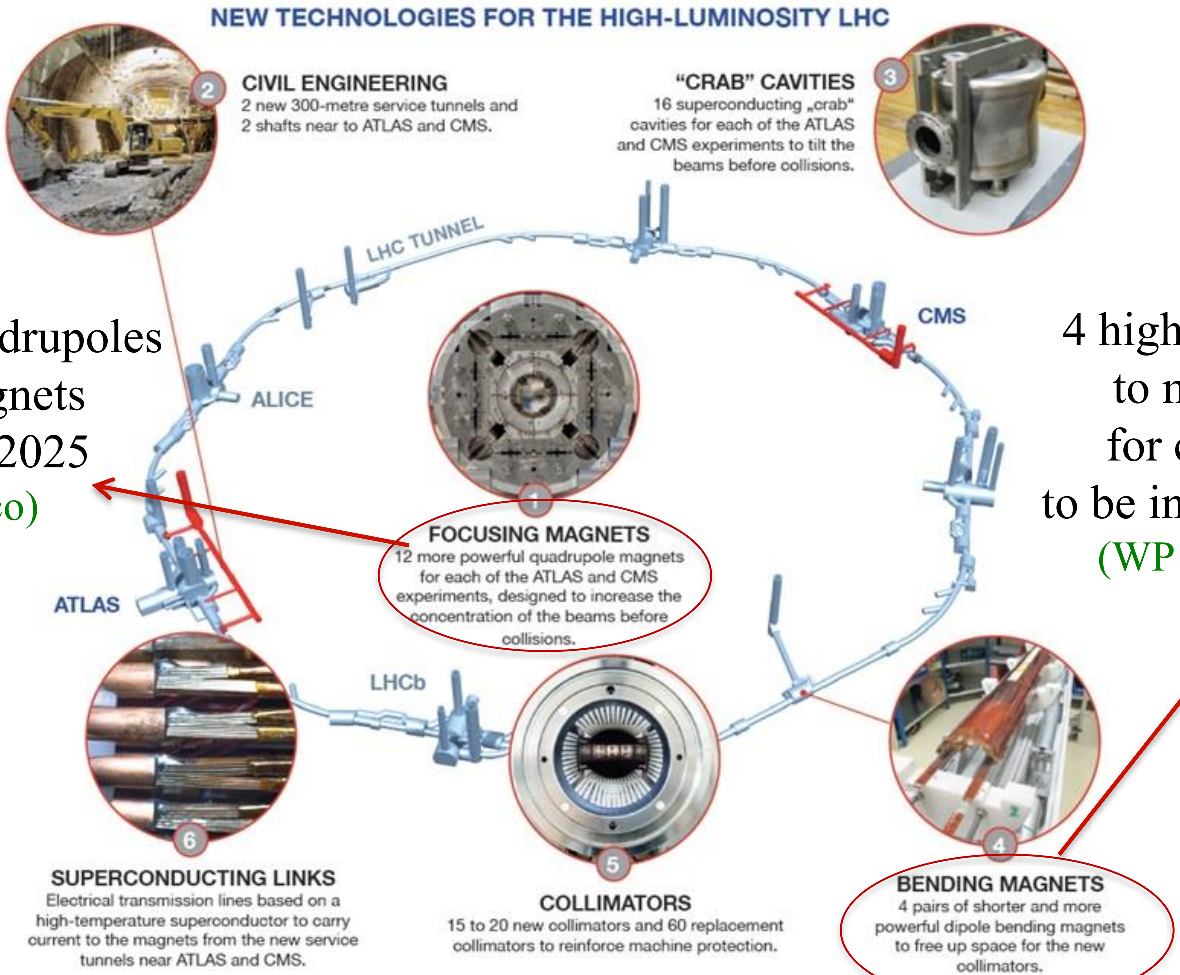
- HL-LHC project (L.Rossi)
  - 10 times more data in the decade 2025-2035



LHC UPGRADE

- Upgrade relying on several technological pillars

20 large aperture quadrupoles
+other 60 IR magnets
to be installed in 2025
(WP3, E. Todesco)



NEW TECHNOLOGIES FOR THE HIGH-LUMINOSITY LHC

CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near to ATLAS and CMS.

"CRAB" CAVITIES
16 superconducting „crab" cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS.

COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

BENDING MAGNETS
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

4 high field dipoles
to make space
for colllimators
to be installed in 2021
(WP11, F. Savary)

HL LHC main technologies [L. Rossi]

THE 20’s: TOWARDS 4000 fb^{-1}

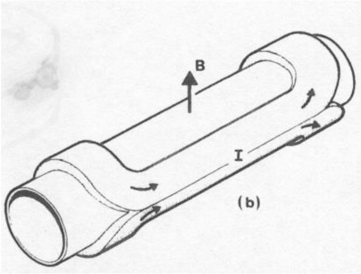
- HL-LHC project (L.Rossi)
  - 10 times more data in the decade 2025-2035
- How increase performance in such a good machine?
  - With 950 MCHF, 12 T magnets, and ten years work
- The path to more data
  - Double beam intensity to 2.2×10^{11} proton per bunch (together with LIU project)
  - Half the beam size by doubling the magnet aperture around the IR
  - Killing the adverse effects of crossing angle through crab cavities or flat beams
- Plus make use of two essential tools
  - Luminosity levelling (already operational since 2017)
  - Novel optics to correct chromaticity (ATS scheme, S. Fartoukh)

- In terms of magnets, HL LHC shall make use of a technology Nb_3Sn that has the potential of going from 8 to 16 T

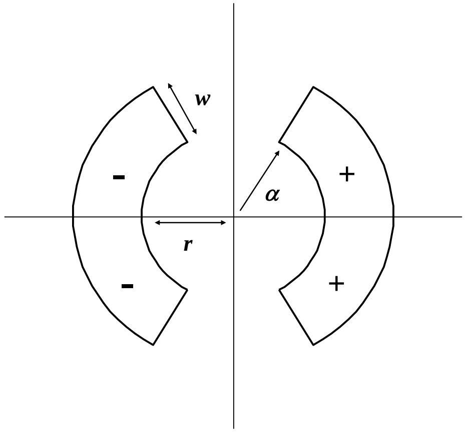
THE SCALE TOWARDS HIGHER FIELDS

- The 80’s: 4 T in Tevatron
  - Nb-Ti at 4.2 K, 15 mm coil
- The 90’s: 6 T in SSC prototypes
  - Nb-Ti at 4.2 K, 30 mm coil
- The 90’s: 8 T in LHC prototypes
  - Nb-Ti at 1.9 K, 30 mm coil
- The 00’s: 8 T in LHC
  - Nb-Ti at 1.9 K, 30 mm coil
- The 00’s: 10 T in LARP prototypes
  - Nb_3Sn at 1.9 K, 30 mm coil
- The 10’s: 12 T in HL-LHC
  - Nb_3Sn at 1.9 K, 35 mm coil

- The 20’s: aiming to 16 T in FCC
  - Nb_3Sn at 1.9 K, 50 mm coil

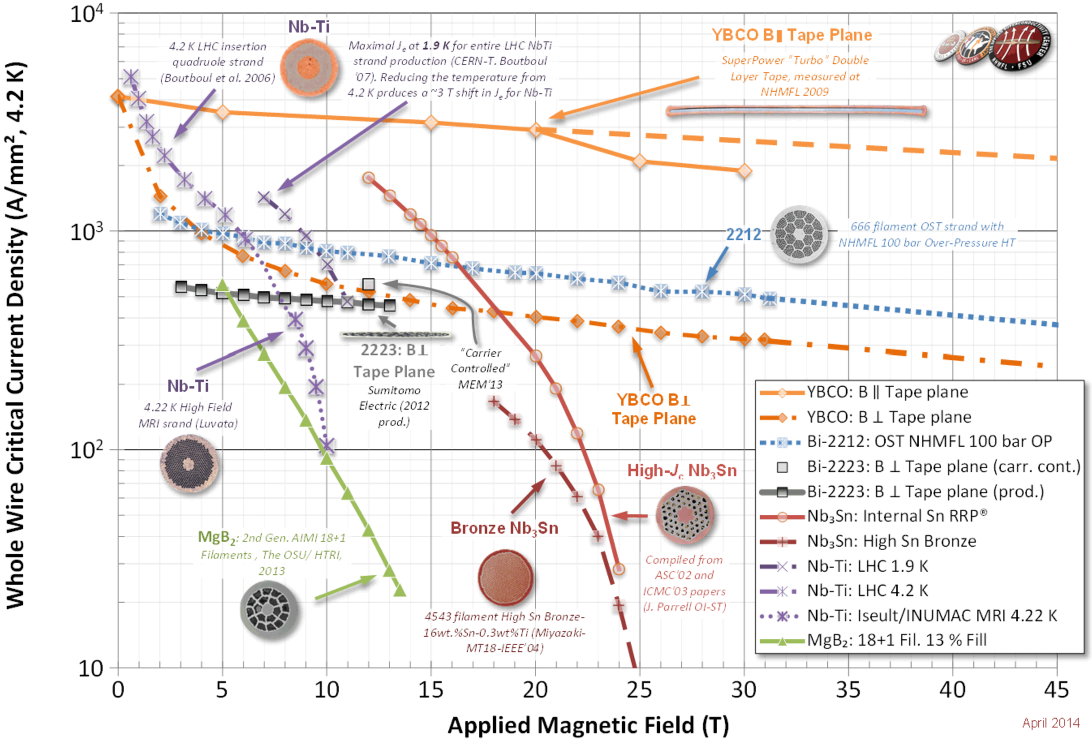


$$B[T] \approx 7 \times 10^{-4}\, j[\mathrm{A/mm}^2]\, w[\mathrm{mm}]$$



SUPERCONDUCTING MATERIALS TOWARDS HIGHER FIELDS

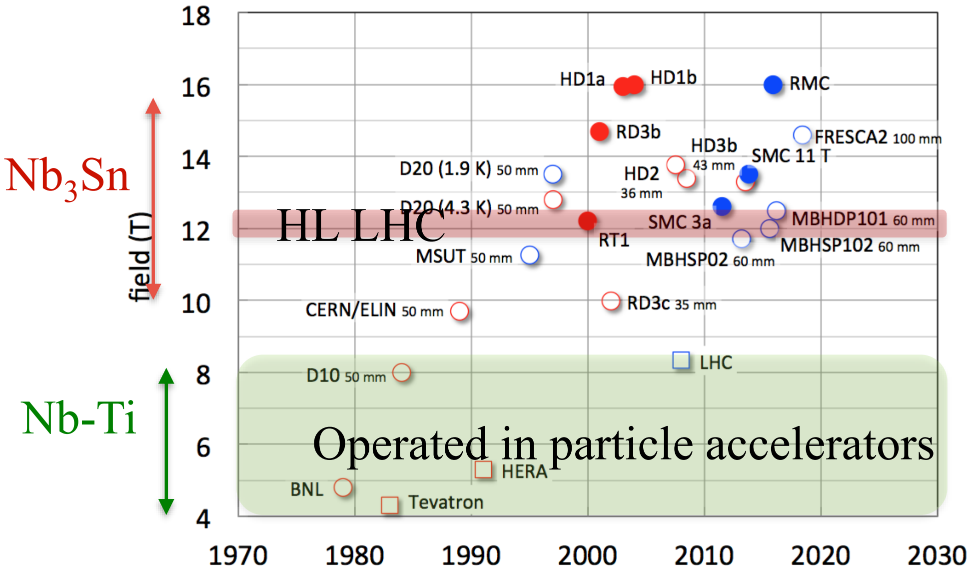
- Superconductivity is a quantistic property that is limited by temperature, magnetic field and current density
  - Usually everybody talks about temperature – for HEP the most relevant are current density (compact device) and field (max attainable field)
  - The hidden variable of this plot is the price – an essential ingredient



Critical surface of some superconducting materials at 4.5 K (unless specified) (courtesy of P. Lee)

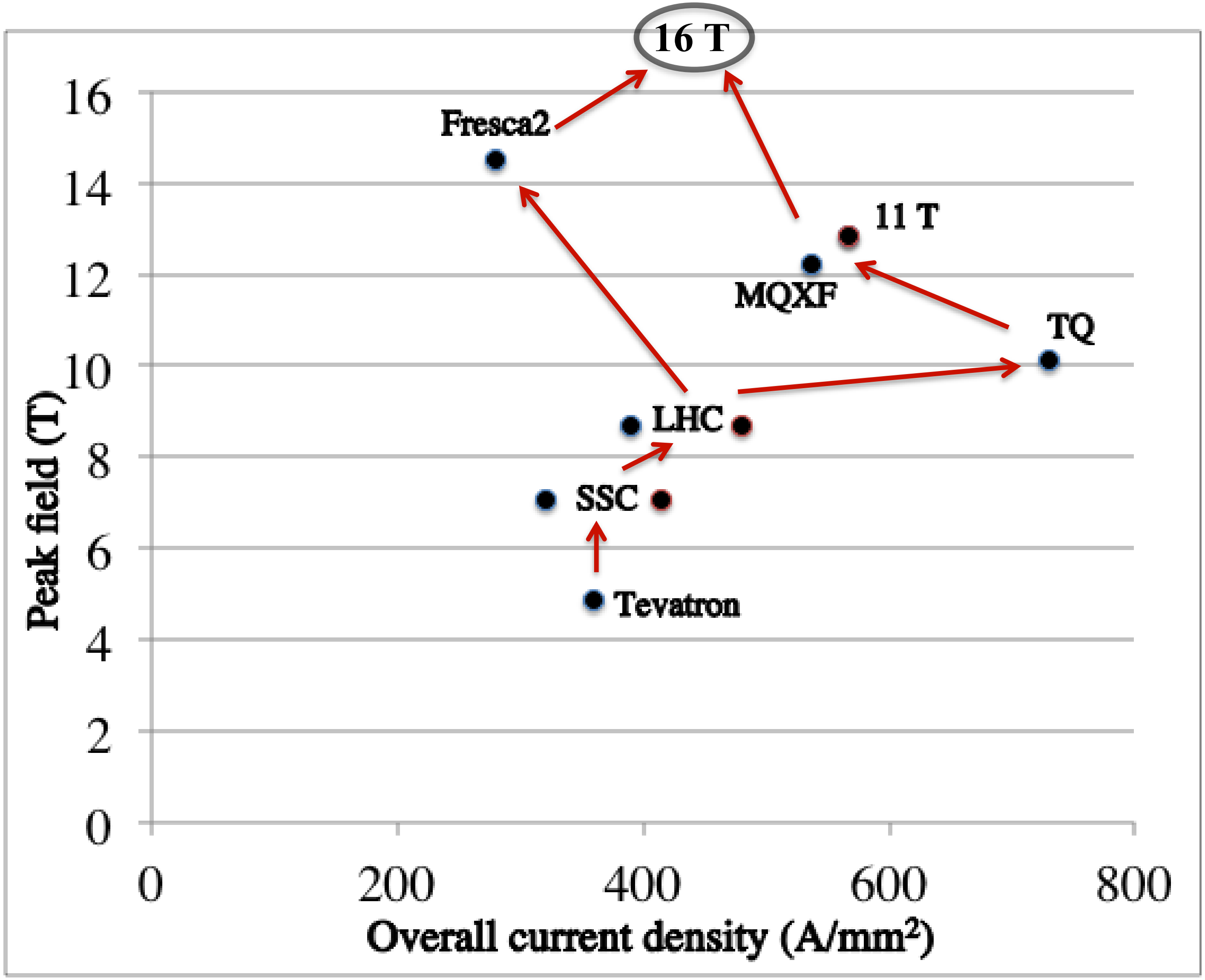
PRESENT ACHIEVEMENTS

- In accelerators:
  - Nb-Ti technology used in several machines, up to 8 T in the LHC
  - Nb3Sn technology to be used in HL-LHC (12 T range), full length prototypes under construction – short model program aiming at 16 T for FCC is ongoing
  - HTS technology being developed to build inserts to boost the field from 16 to 24 T – racetracks and short models providing 3-5 T have been built and tested in standalone configuration



Hall of fame of Nb-Ti and Nb$_3$Sn accelerator magnets [L. Bottura, MT25]

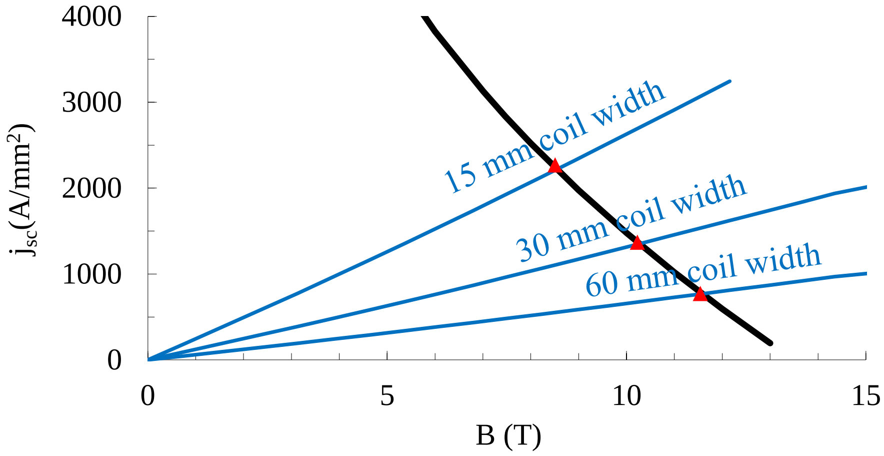
SUMMARY OF THE TESLA RACE



THE 30's: TOWARDS 30-100 TeV

- For an accelerator, more energy can be obtained through larger size (brute force) or larger field (technological advance)
- Having a magnet in the 14-16 T range, one can envisage two options
  - HE-LHC: replacing the LHC lattice with Nb_3Sn dipoles to double the LHC energy (around 30 TeV)
  - FCC: New tunnel of 100 km, with Nb_3Sn dipoles (around 100 TeV)

- Cost and time are a major point
  - The last teslas are very expensive and can take a lot of time



Critical surface for Nb-Ti: j versus B and magnet loadline

CONCLUSIONS

- LHC proves to be a very flexible accelerator, and reached ultimate luminosity at 6.5 TeV
- Plans for 2021-2023
  - Increase the energy to 7+7 TeV
  - Substantial interventions on the LHC, recover the pre-LS2 performance could take time
- Plans for 2026-2035
  - Ten times more data through a double beam intensity, half of beam size, and heavvy use of levelling and new optics
  - This will prove the ability of Nb_3Sn technology of providing 12 T magnets – 4 T jump in field for accelerator magnets
- After HL-LHC
  - Making use of Nb_3Sn technology at 16 T to increase energy to 30 TeV (in LHC tunnel) or to 100 TeV (in a new 100 km tunnel)
  - Possibility of boosting up to 20-25 T with HTS (under study)
  - Input of physics is essential …