



# LHC TOWARDS THE FUTURE

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- The present: LHC in the 10's
  - LHC energy
  - The race towards luminosity
  - Unknowns and surprises
- The 20's: the HL-LHC project

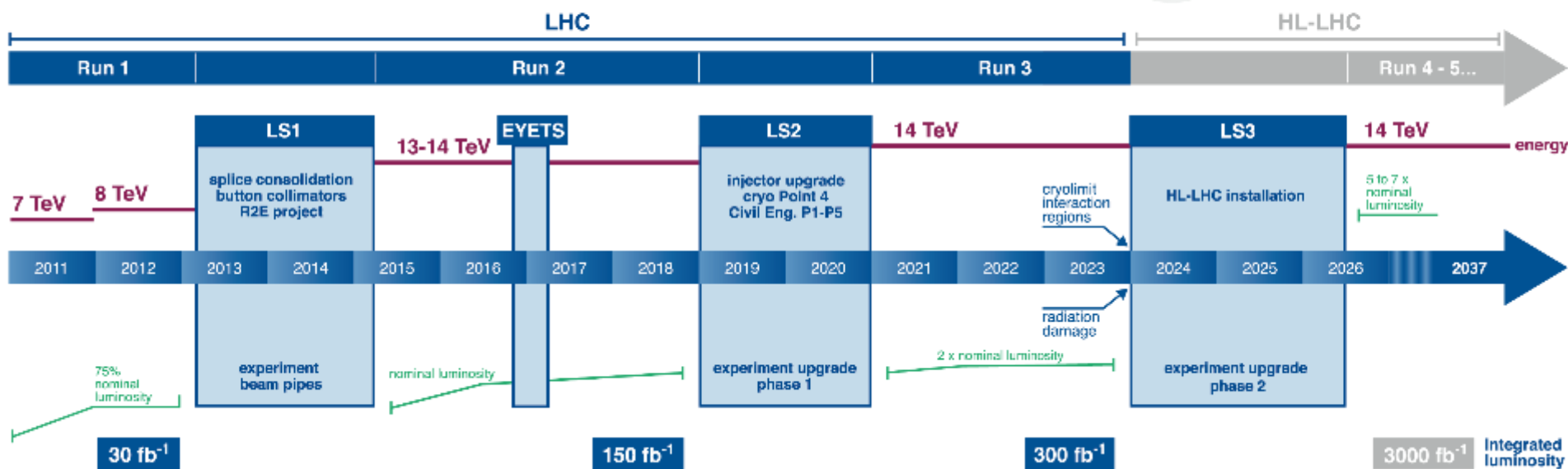


# THE LHC TIMELINE



- An accelerator runs 10 months a year, with a shutdown of 2 months around Christmas
  - Why in winter? Electricity is more expensive, so better running during summer than in winter
- Every 3 years, there is a longer shutdown (LS) of 1-2 years to make major interventions, and upgrades

## LHC / HL-LHC Plan



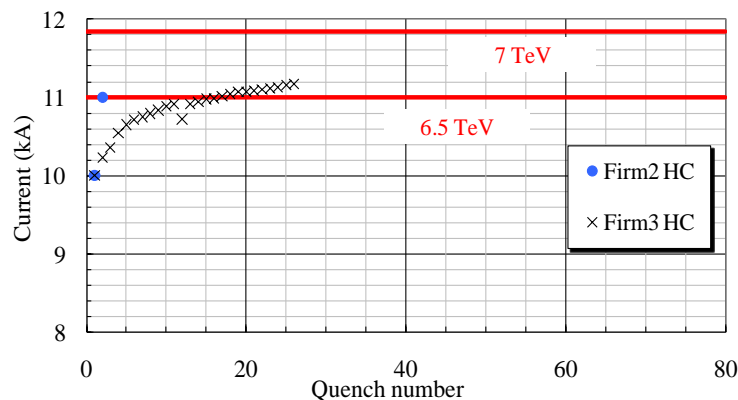
- In run I (2011 and 2012), LHC energy has been **3.5 TeV and 4 TeV**
  - Unforeseen limitation, due to weakness in the **interconnections**
    - This caused the 2008 incident
- Major consolidation in LS1
  - Shunt being added to cure interconnection the problem [J. P. Tock, F. Bordry, et al., IEEE Trans. Appl. Supercond. 2015 vol 25]
  - Problem solved!



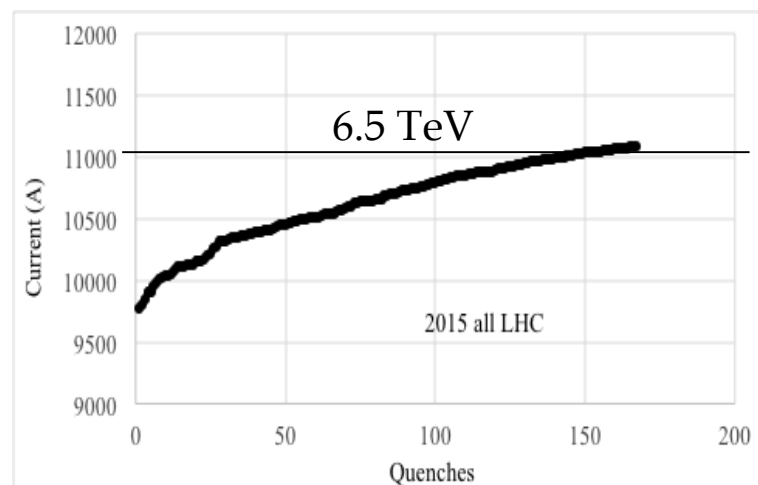
Cross-section of the interconnection and radiography showing missing continuity  
[F. Bordry, J. P. Tock and LS1 team]

- LHC energy is limited by magnets
  - Challenging design: at 7 TeV magnet operate at 86% of the maximum theoretical current reachable with that conductor and coil layout
  - This corresponds to 1.4 K « maximum local heating » (temperature margin) and few tens of mJ/cm<sup>3</sup> of maximum local energy deposition
- After a irreversible transition through the superconductor critical surface (quench), in the next powering the magnet reached higher performance (it trains)
  - Training in the installed magnet takes time (5-8 h to recover operational temperature) and entails some risks
  - 4 TeV operation reached without quenches

- In 2008, just before the incident, it was shown that 6.5 TeV could be reached with a limited number of quenches for one sector



The training of sector 56  
[HC and MP3 team]

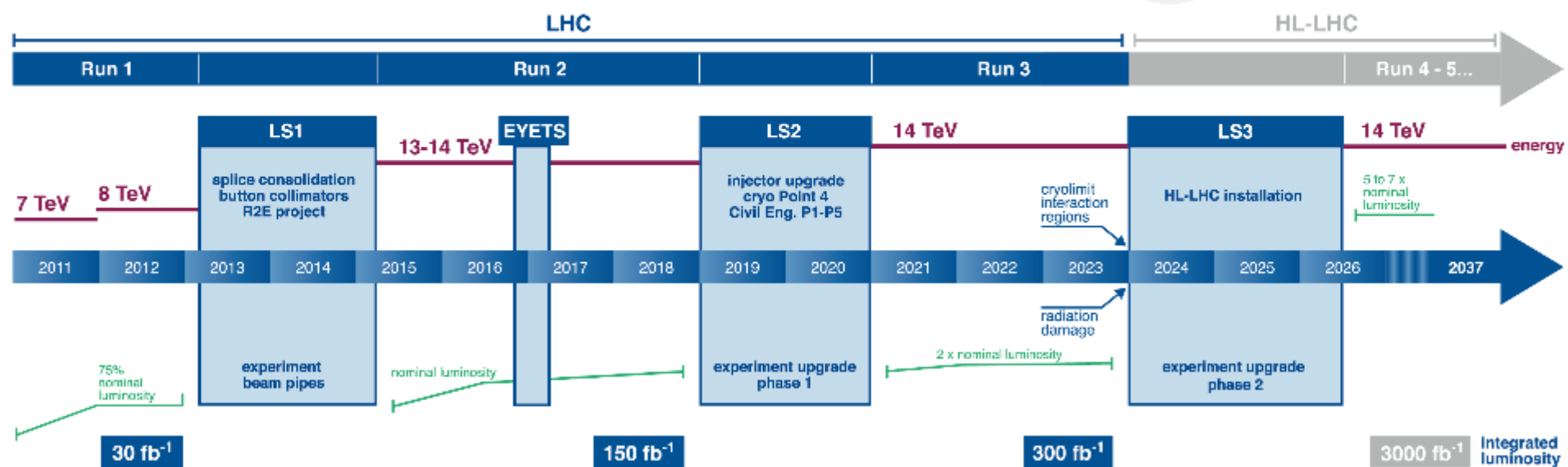


- In 2014: decision to train LHC at 6.5 TeV
  - Compromise between time, risk and energy for physics reach
  - 1-2 week to train one sector, in the shadow of hardware commissioning
- Expected ~100 quenches, we went to 6.5 TeV with 174 quenches over 1232 dipoles

## LHC / HL-LHC Plan



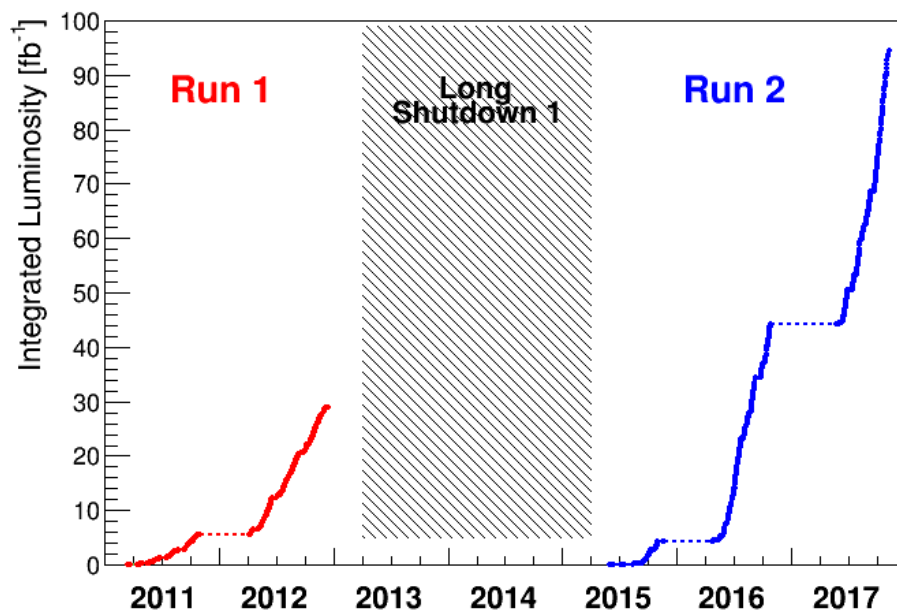
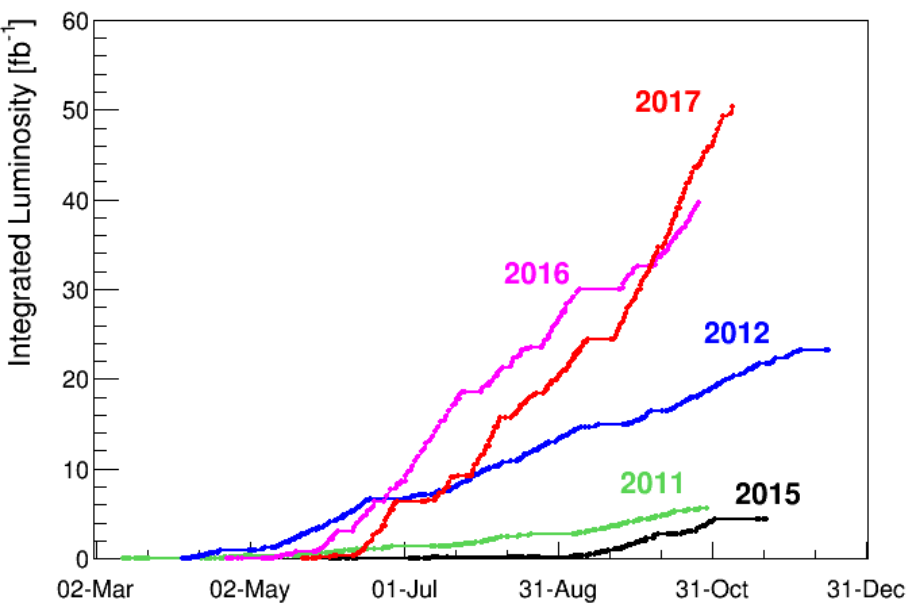
High  
Luminosity  
LHC



- In RunII, 2015-2017, we had very smooth operation of the LHC at 6.5 TeV
- Decision to target 7 TeV for RunIII, after 2021



- The present: LHC in the 10's
  - 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



Accumulation of data in the LHC proton proton runs [R. Steerenberg, Evian workshop 2017]

- Equation for the **luminosity**

$$L = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \epsilon_n \beta^*} F = \frac{c}{4\pi} \frac{\gamma}{l} \underbrace{N_b^2}_{\text{Beam intensity}} \underbrace{n_b}_{\text{Beam intensity}} \underbrace{\frac{1}{\epsilon_n \beta^*}}_{\text{Beam geometry}} F$$

## Accelerator features

Energy of the machine 7 TeV

Length of the machine 27 km

## Beam intensity features

$N_b$  Number of particles per bunch  $1.15 \times 10^{11}$

$n_b$  Number of bunches  $\sim 2808$

## Beam geometry features

$\epsilon_n$  Size of the beam from injectors: 3.75 mm mrad

$\beta^*$  Squeeze of the beam in IP (LHC optics): 55 cm

F: geometry reduction factor: 0.84

**Nominal luminosity:**  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

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

- Equation for the **luminosity**

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

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

## ● The **beam-beam** limit (Coulomb)

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

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

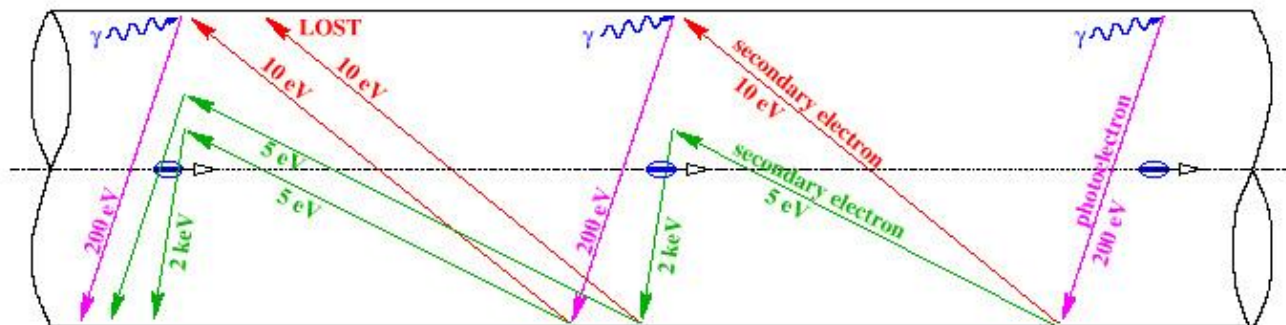
- $N_b$  Number of particles per bunch       $\varepsilon_n$  transverse size of beam
- One cannot put too many particles in a “small space” (brightness)
  - Otherwise the **Coulomb interaction** seen by a single particle when collides against the other bunch creates instabilities (tune-shift)
- This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

|                 |         | Nominal  | Ultimate | September 2012 | 2012 MD* |
|-----------------|---------|----------|----------|----------------|----------|
| $N_b$           | (adim)  | 1.15E+11 | 1.70E+11 | 1.55E+11       | 2.20E+11 |
| $\varepsilon_n$ | (m rad) | 3.75E-06 | 3.75E-06 | 2.50E-06       | 1.70E-06 |
| $\xi_{IP}$      | (adim)  | 0.0034   | 0.0050   | 0.0068         | 0.0142   |
| $N_{IP}$        | (adim)  | 2        | 2        | 2              | 2        |
| $\xi$           | (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**

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

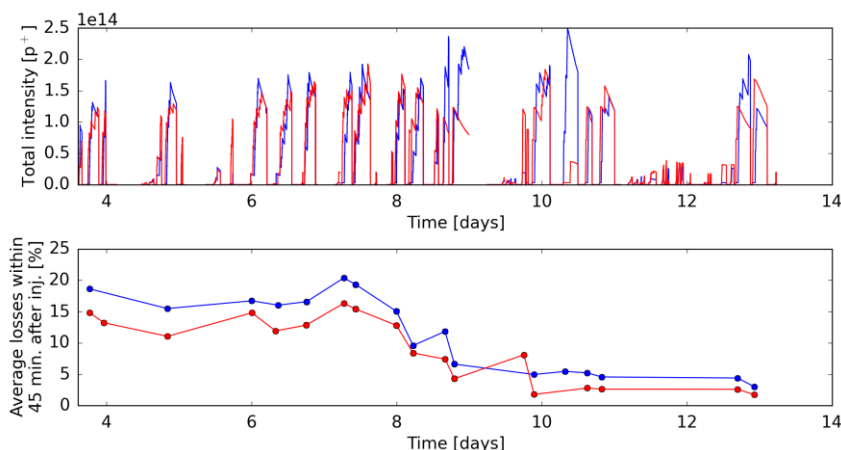


Mechanism of electron cloud formation [F. Ruggiero]

- 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)  $\leftrightarrow$  spacing (time)  $\leftrightarrow$  number of bunches  $n_b$ 

|       |                   |       |                   |                               |
|-------|-------------------|-------|-------------------|-------------------------------|
| 7.5 m | $\leftrightarrow$ | 25 ns | $\leftrightarrow$ | 3560 free bunches (2808 used) |
|-------|-------------------|-------|-------------------|-------------------------------|

- Electron cloud has been **observed where expected in RunI during 50 ns 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
- In RunII we operated with 25 ns
  - Scrubbing run effective
  - Number of bunches went up to 2556 – then limited by the ULO to around 1900
  - Electron cloud is critical but manageable



Reduction of beam losses during the scrubbing run  
[G. Rumolo, et al., LMC August 2015]

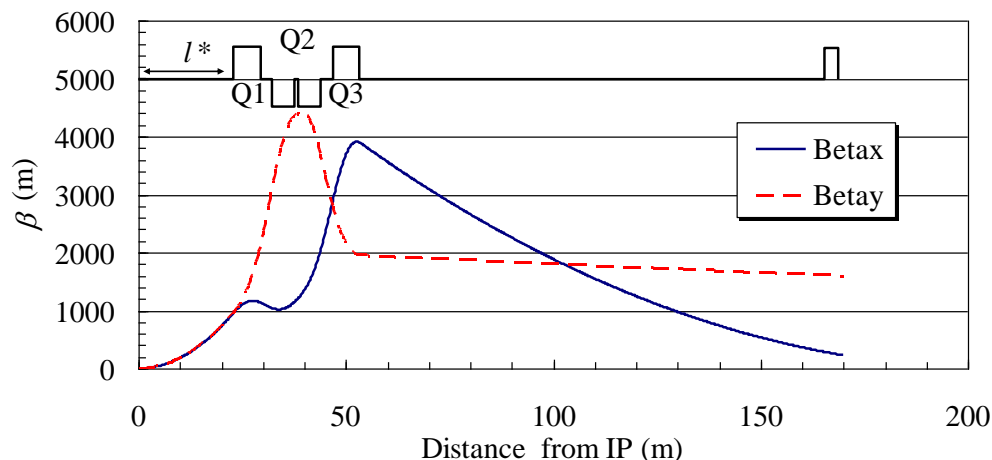
- Optics: **squeezing the beam** 
$$L = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \epsilon_n \beta^*} F = \frac{c}{4\pi} \gamma \frac{1}{L} N_b^2 n_b \frac{1}{\epsilon_n \beta^*} F$$

- Size of the beam in a magnetic lattice
- Luminosity is inverse prop to  $\epsilon$  and  $\beta^*$

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

- In the free path (no accelerator magnets) around the experiment, the  $\beta^*$  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

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

- Size of the beam in a magnetic lattice

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

- LHC was **designed to reach  $\beta^* = 50$  cm** with 70 mm aperture IR quads

- This aperture had no margin - when beam screen was added, one had to lower the target  $\beta^* = 55$  cm (and recover  $L=10^{34}$  cm<sup>-2</sup> s<sup>-1</sup> by slightly increasing bunch intensity from  $10^{11}$  to  $1.15 \times 10^{11}$ )

- In RunI we reached 60 cm

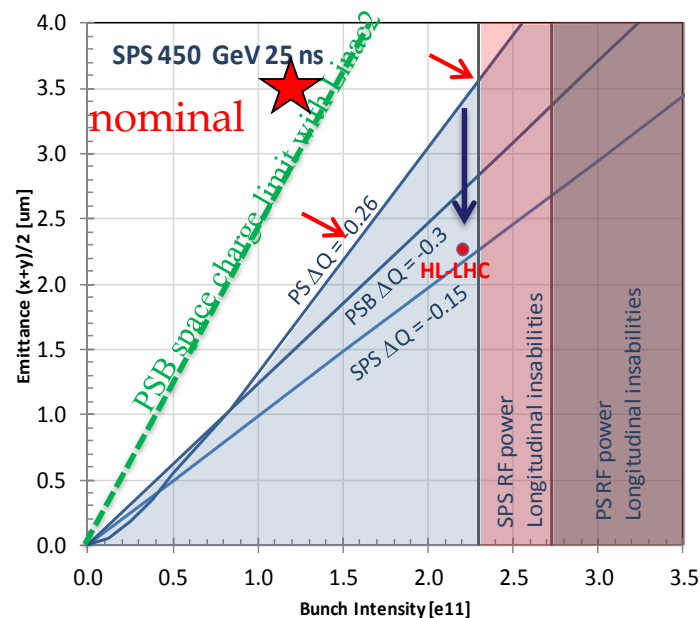
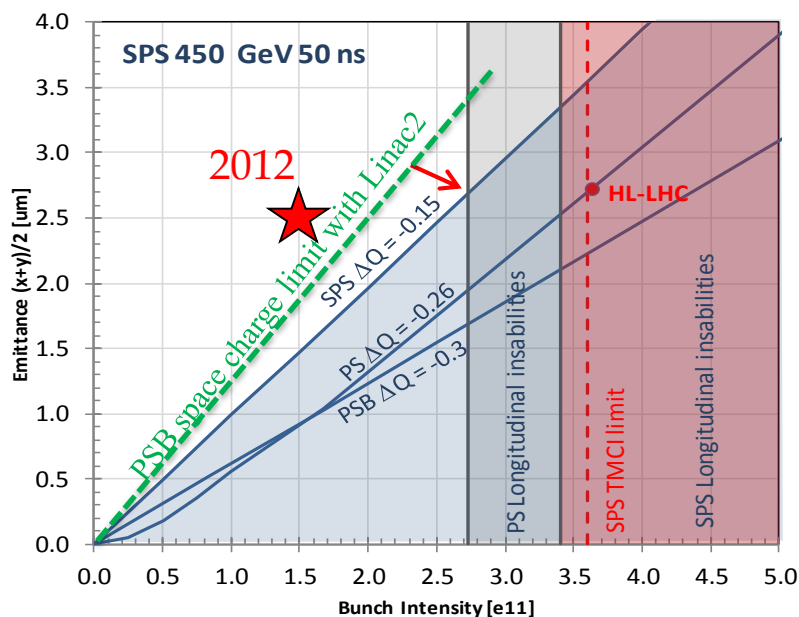
- In RunII, we started at 80 cm and we ended reaching 30 cm

- The key is a much smaller emittance from the injectors, and margins taken in the aperture of the magnets

## • The injector chain limits

- Emittance  $\varepsilon_n$  vs intensity  $N_b$
- This relation also depends on the bunch spacing  $n_b$

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



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



# LHC IN THE 10'S: THE RACE TOWARDS LUMINOSITY



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

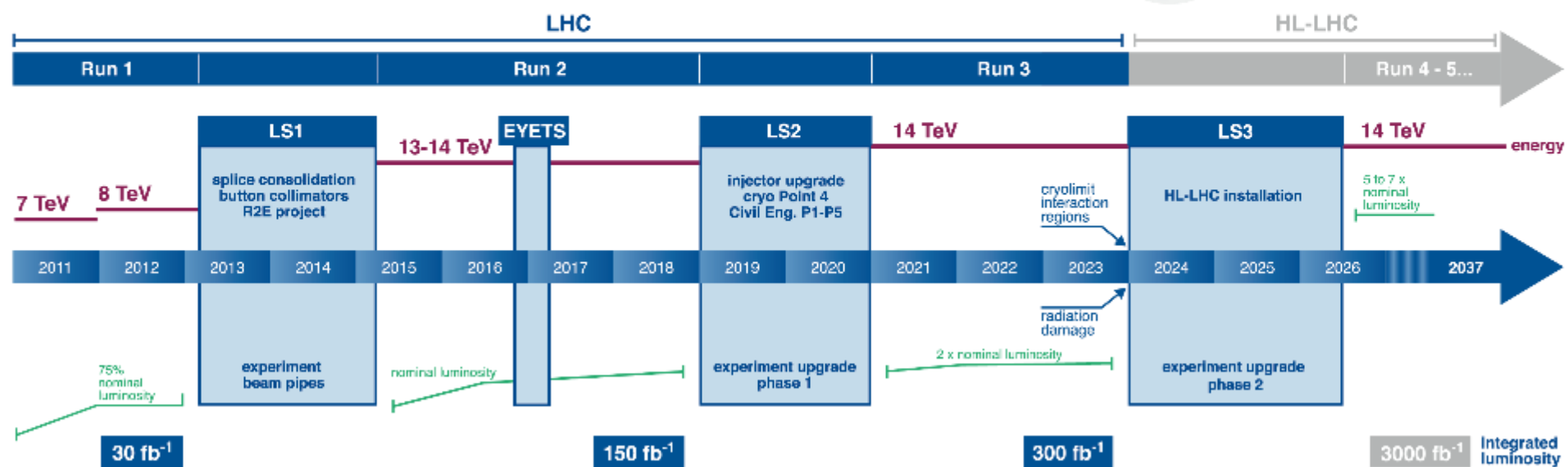
|              |                                    | Nominal         | 2011           |      | 2012           |      | 2015           |      | 2016           |      | 2017 8b4e       |      |
|--------------|------------------------------------|-----------------|----------------|------|----------------|------|----------------|------|----------------|------|-----------------|------|
| $N_b$        | (adim)                             | 1.15E+11        | 1.50E+11       | 1.70 | 1.60E+11       | 1.94 | 1.15E+11       | 1.00 | 1.15E+11       | 1.00 | 1.30E+11        | 1.28 |
| $\epsilon_n$ | (m)                                | 3.75E-06        | 2.40E-06       | 1.56 | 2.50E-06       | 1.50 | 3.50E-06       | 1.07 | 2.20E-06       | 1.70 | 2.00E-06        | 1.88 |
| $n_b$        | (adim)                             | 2808            | 1380           | 0.49 | 1380           | 0.49 | 2244           | 0.80 | 2220           | 0.79 | 1900            | 0.68 |
| $\beta^*$    | (m)                                | 0.55            | 1.00           | 0.55 | 0.60           | 0.92 | 0.80           | 0.69 | 0.40           | 1.38 | 0.30            | 1.83 |
| spacing      | (ns)                               | 25              | 50             |      | 50             |      | 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 |
| X angle      | ( $\mu$ rad)                       | 142.5           | 185            |      | 185            |      | 185            |      | 140            |      | 150             |      |
| F            | (adim)                             | 0.840           | 0.836          | 1.00 | 0.748          | 0.89 | 0.770          | 0.92 | 0.732          | 0.87 | 0.638           | 0.76 |
| L            | ( $\text{cm}^{-2} \text{s}^{-1}$ ) | <b>1.00E+34</b> | <b>3.6E+33</b> | 0.36 | <b>6.7E+33</b> | 0.67 | <b>5.0E+33</b> | 0.50 | <b>1.5E+34</b> | 1.50 | <b>2.10E+34</b> | 2.10 |
| pile up      |                                    | 26              | 19             |      | 36             |      | 16             |      | 50             |      | 81              |      |
| $\sigma_z$   | (mm)                               | 75.5            | 90             |      | 90             |      | 90             |      | 75             |      | 75              |      |
| $\gamma$     | (adim)                             | 7448            | 3724           |      | 4256           |      | 6916           |      | 6916           |      | 6916            |      |
| $\sigma^*$   | (mm)                               | 1.66E-02        | 2.54E-02       |      | 1.88E-02       |      | 2.01E-02       |      | 1.13E-02       |      | 9.31E-03        |      |

- In Run II, we reached at 6.5 TeV **twice the nominal luminosity, with nearly 100 fb<sup>-1</sup> accumulated in two years**
- Exceptional performance, still possible to improve ?

## LHC / HL-LHC Plan



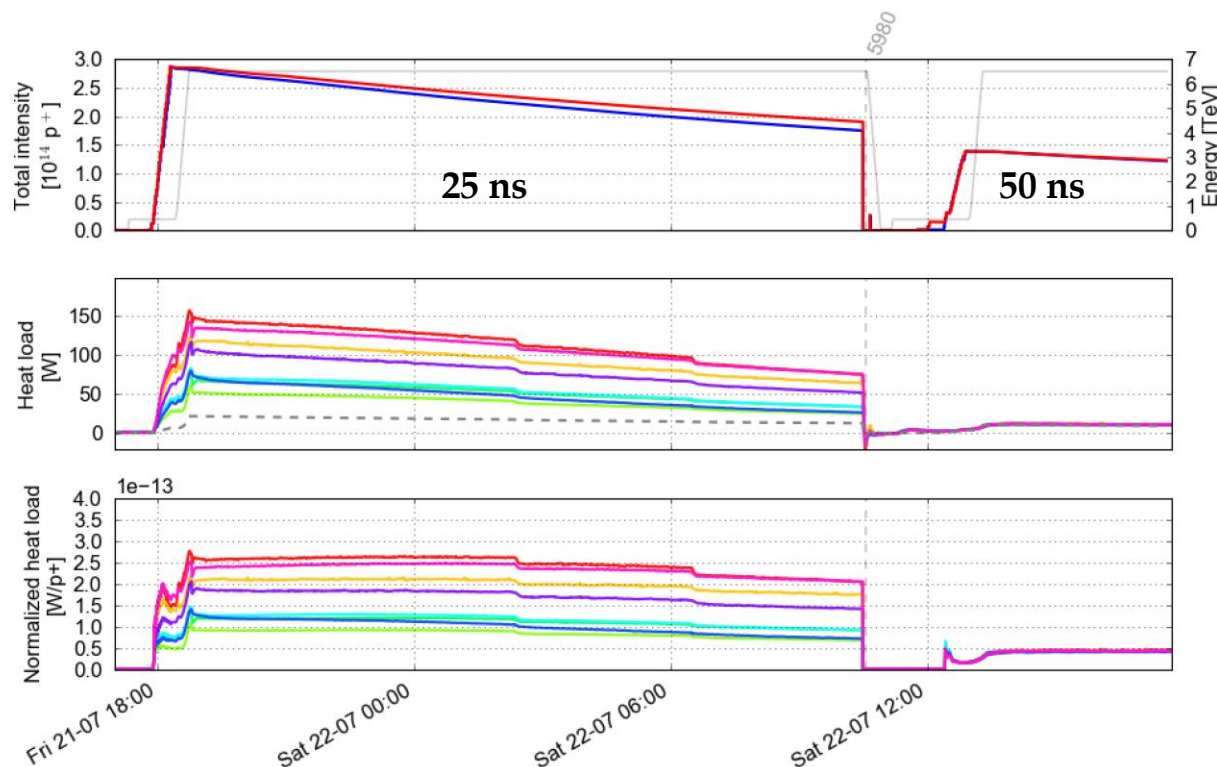
High  
Luminosity  
LHC



- 300 fb<sup>-1</sup> are expected by the end of the Run III
  - This value corresponds to the expected order of magnitude of triplet magnet lifetime due to radiation dose

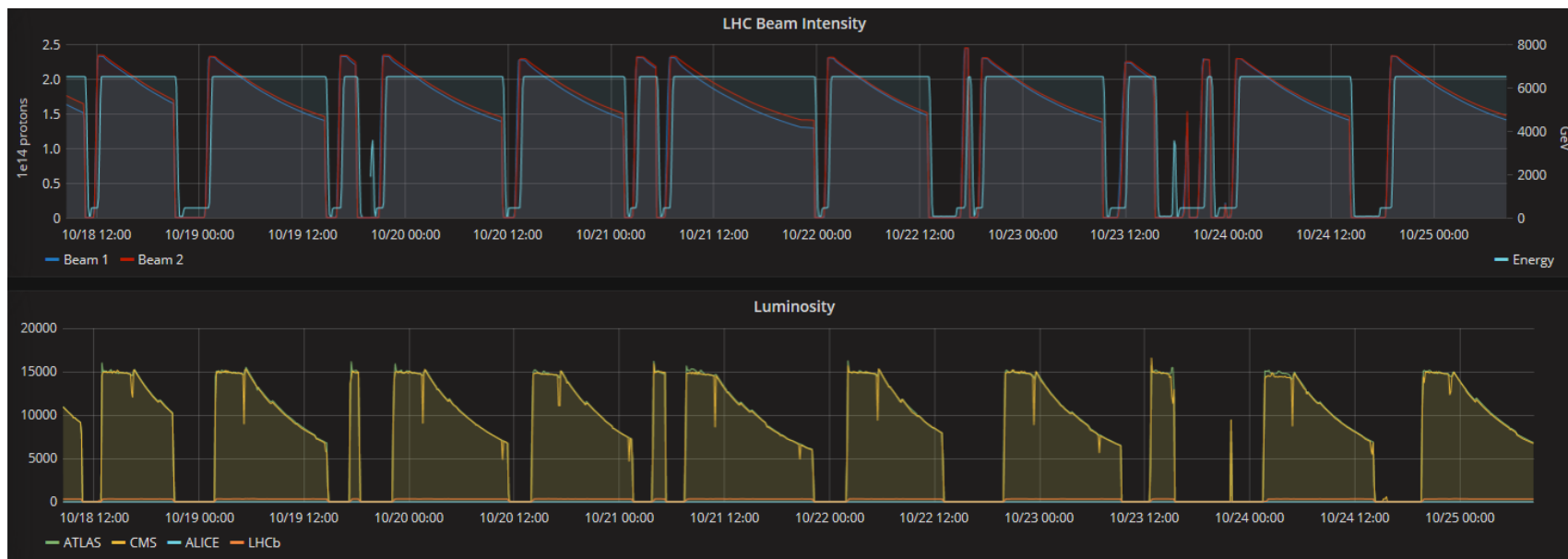
- Both enigma are related to **unexpected differences** in the behaviour of hardware manufactured with the **same recepies**
  - The first one limits the energy, the second the luminosity
- Training of the magnet limiting energy
  - 1232 magnets (plus 46 spares) built by three manufacturers, based on the same CERN recepit, over 4 years long production
  - Very strong differences in the behaviour of the three manufacturers are observed and not explained
  - To go to 6.5 TeV in 2015
    - Series 1000: few quenches over 400 magnets (1%)
    - Series 2000: 25 quenches over 400 magnets (5%)
    - Series 3000: 140 quenchs over 400 magnets (30%)

- Heat load on the beam screen limiting luminosity
  - The heat load in half of the machine is about twice than expected



Heat load on the beam screen during LHC run (lower figure, different colors are different sectors of the LHC)  
 [G. Iadarola, L. Tavian et al. Chamonix meeting 2018]

- With such a large luminosity, the pile up (number of collisions per crossing) increases too much
  - LHC design for 26, we cannot run at more than 50 otherwise we do not separate the different events
  - Levelling means burning less for longer times
  - Tried successfully in 2017, levelling at 50% more than nominal



- The present: LHC in the 10's
  - 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](http://www.cern.ch/hilumi) [L. Rossi]
  - The target: after reaching 300 fb<sup>-1</sup> in 2023, we need **3000 fb<sup>-1</sup> in 2026-2035**
- We need to gain a **factor four-five** (250-300 fb<sup>-1</sup> per year, from the beginning of HL-LHC)
  - Peak lumi 10<sup>35</sup> cm<sup>-2</sup> s<sup>-1</sup> is not acceptable for the experiments (pile up)
- A levelling is proposed at 5×10<sup>34</sup> cm<sup>-2</sup> s<sup>-1</sup>
  - To have this the LHC must be able to reach a peak lumi 2×10<sup>35</sup> cm<sup>-2</sup> s<sup>-1</sup>
- 20 larger than nominal:
  - Factor ~**5 from the beam**
  - Factor ~**4 from optics** (reducing β\*)

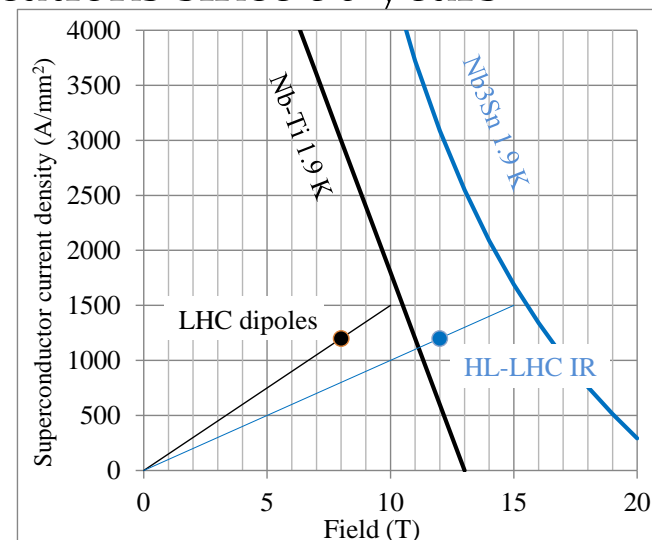
|                  |                                     | HL-LHC   |          |      |
|------------------|-------------------------------------|----------|----------|------|
|                  |                                     | Nominal  |          |      |
| N <sub>b</sub>   | (adim)                              | 1.15E+11 | 2.20E+11 | 3.7  |
| ε <sub>n</sub>   | (m)                                 | 3.75E-06 | 2.50E-06 | 1.5  |
| n <sub>b</sub>   | (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 <sub>max</sub> | (cm <sup>-2</sup> s <sup>-1</sup> ) | 1.00E+34 | 2.0E+35  | 20.1 |
| L <sub>lev</sub> | (cm <sup>-2</sup> s <sup>-1</sup> ) | 1.00E+34 | 5.0E+34  |      |
| pile up          |                                     | 26       | 132      |      |

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

- How to get a **factor four from the optics** ?
- To reduce  **$\beta^*$  to 15 cm** (factor four from 55 cm nominal) one needs larger aperture quadrupoles
  - $\beta$  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  $\beta^*=25$  cm [F. Ruggiero, et al, LHC PR 626 (2002)]
- The quadrupole will rely on Nb<sub>3</sub>Sn 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)

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

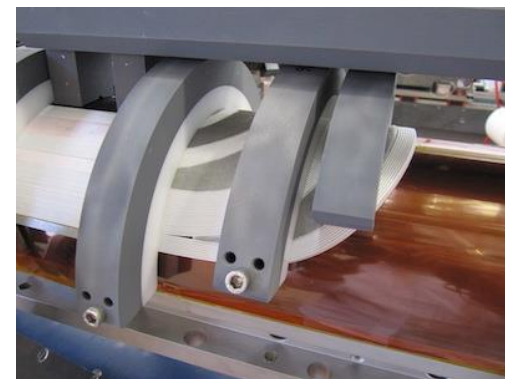
- Superconductivity takes place in some materials below thresholds values for **magnetic field**, **current density** and temperature
  - Thresholds called **critical surface**
  - Phenomena known since 100 years, applications since 50 years
    - Related to quantum mechanics
  - In a SC **electromagnet**, 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<sub>3</sub>Sn** has a wider critical surface, with possibility of **increasing up to ~15 T**
  - For HL-LHC we will operate **at 11.5 T peak field**



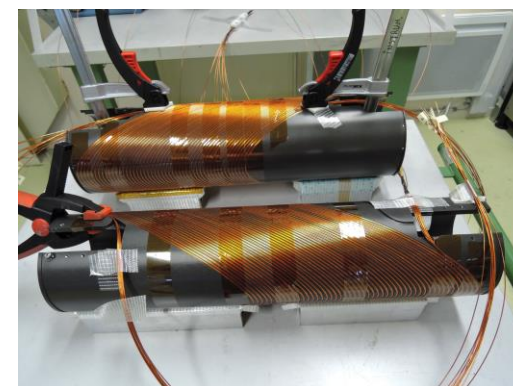
- Hardware construction ongoing



The structure of the 8-m-long Nb<sub>3</sub>Sn quadrupole  
(P. Ferracin, F. Lackner et al.)

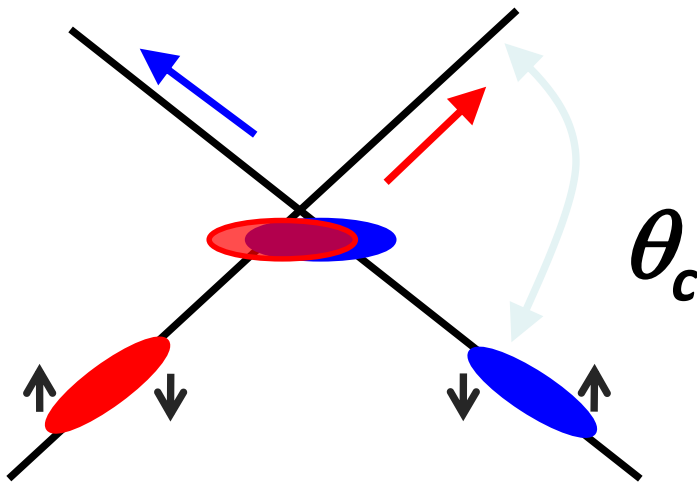


Orbit corrector from CIEMAT  
(F. Toral, J. C. Perez, et al.)

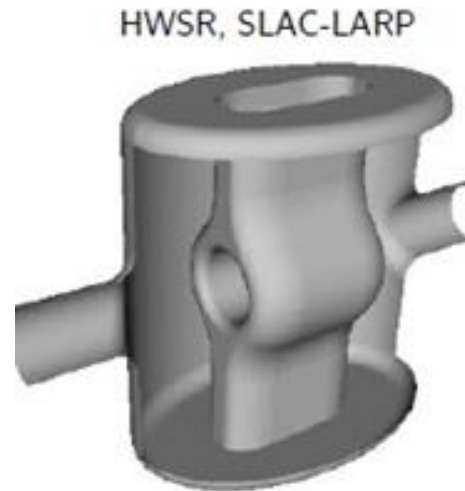


A CCT design for corrector  
(G. Kirby et al.)

- When going to very low  $\beta^*$ , (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



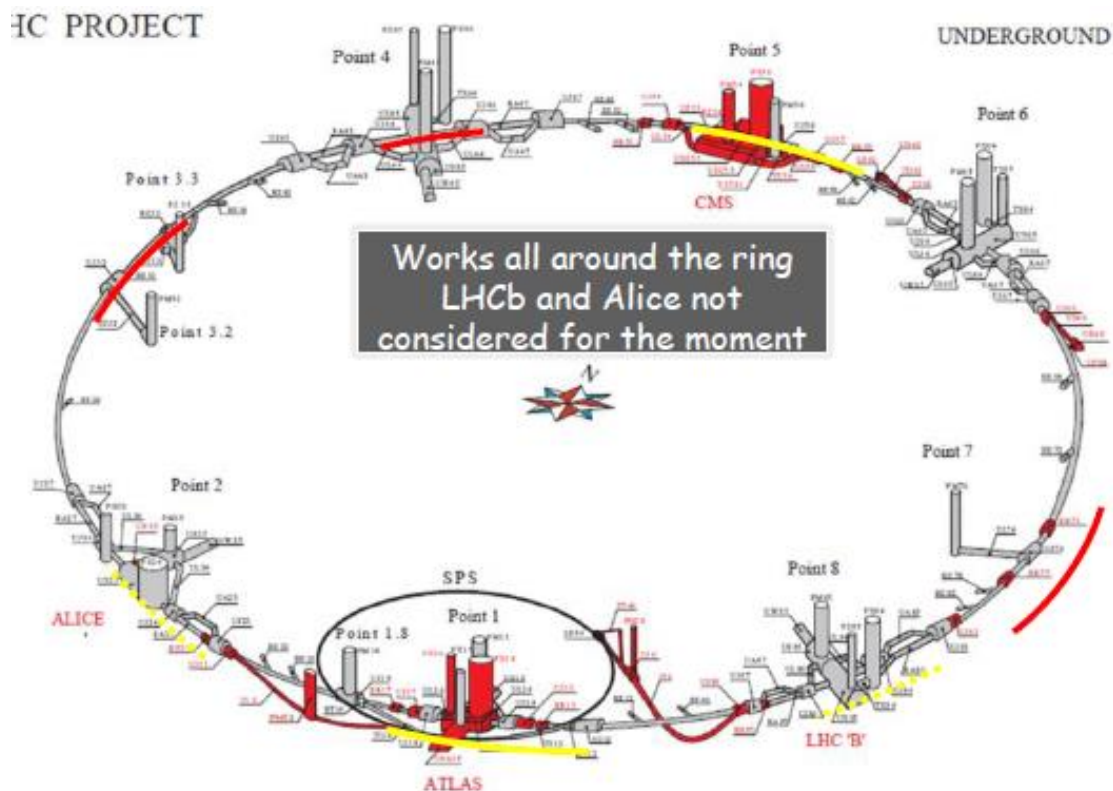
Crab crossing



One possible option for the design of crab cavity

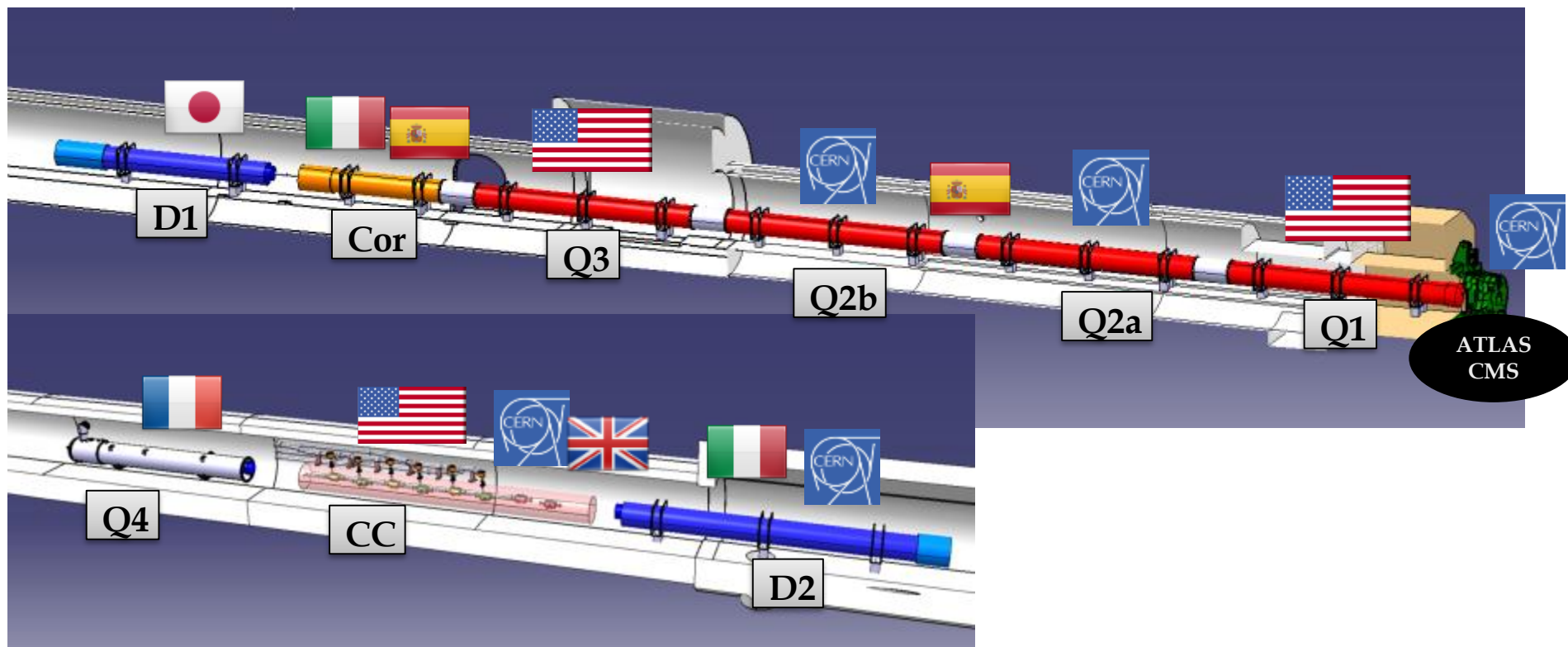
- Hardware has been built, successful test in some electron machines  
[WP4, E. Jensen, collaboration with many institutes]
- First compact crab cavities to be tested in SPS with protons

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



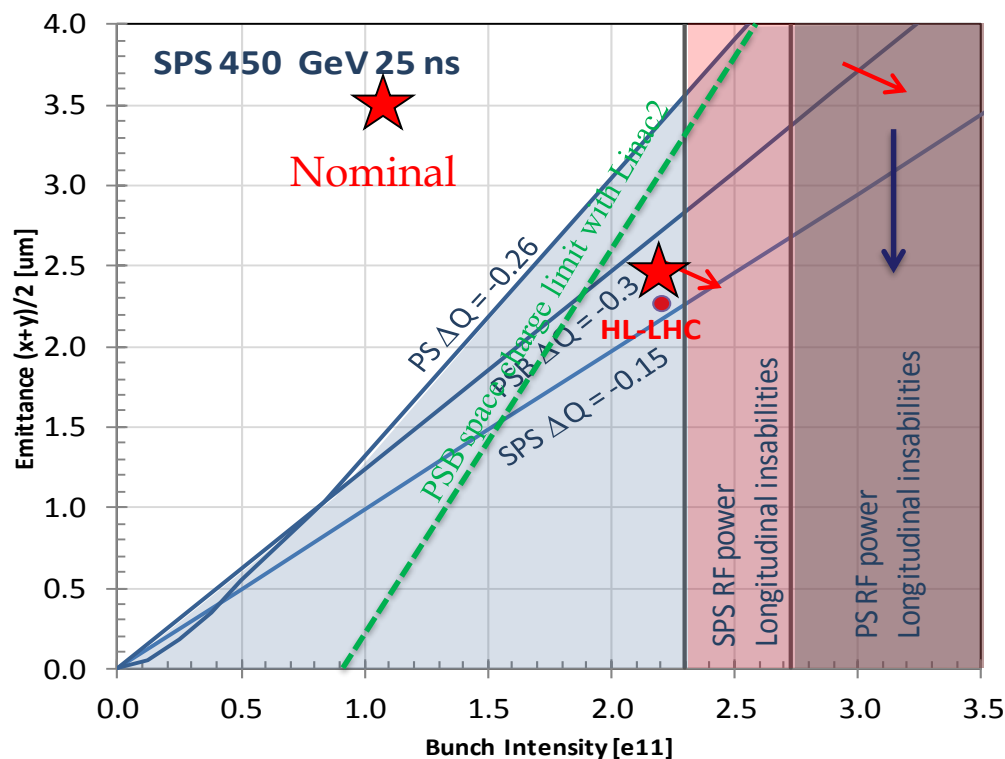


- As LHC, HL-LHC is an international collaboration
  - Hardware assigned to several labs for design and model



First baseline from Q1 to Q4, and contributions [F. Bordry, Washington FCC week]

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



|                  |                                     | HL-LHC   |          |      |
|------------------|-------------------------------------|----------|----------|------|
|                  |                                     | Nominal  |          |      |
| $N_b$            | (adim)                              | 1.15E+11 | 2.20E+11 | 3.7  |
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| $n_b$            | (adim)                              | 2808     | 2808     | 1.0  |
| $\beta^*$        | (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 <sup>-2</sup> s <sup>-1</sup> ) | 1.00E+34 | 2.0E+35  | 20.1 |
| $L_{\text{lev}}$ | (cm <sup>-2</sup> s <sup>-1</sup> ) | 1.00E+34 | 5.0E+34  |      |
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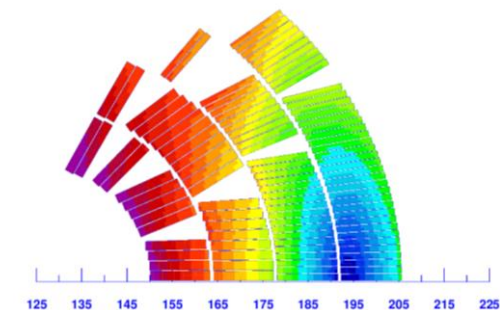


- The Fathers of the LHC designed a wise machine with the **that reached ultimate luminosity**
  - At full performance one can expect  $60 \text{ fb}^{-1}$  per year (four times 2012), and  $300 \text{ fb}^{-1}$  at the horizon of the 20's
    - These  $300 \text{ fb}^{-1}$  are the lower estimate for 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 2026
- 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  **$3000 \text{ fb}^{-1}$**  during the 30's

- A 100 km tunnel with a 16 T magnet would allow reaching 50+50 TeV
  - This is the goal of the FCC study (M. Benedikt, F. Zimmermann)



A new tunnel in the CERN area



A possible coil lay-out for 16 T magnet (INFN Genova and D. Tommasini)

