LHC Luminosity Upgrade Plan

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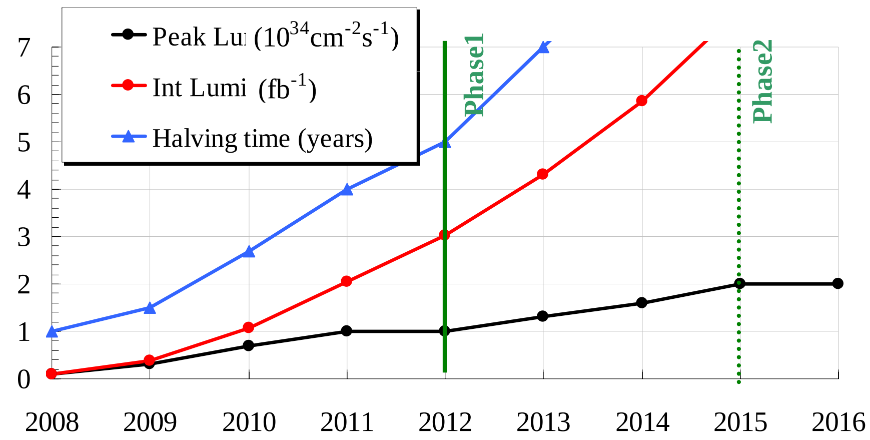
- Motivations for the luminosity upgrade
- How to remove bottlenecks
- Actions
- Technologies

MOTIVATIONS

- Aim of the phase I (2012)
  - If nominal is reached, go up to the maximum peak luminosity that can be tolerated by experiments without any detector upgrade (so-called ultimate) $L \sim 2 \times 10^{34}$ [cm^{-2} s^{-1}]
  - If nominal is not reached, remove the bottlenecks so that the nominal can be recovered
    - For instance: if beam current is not reachable, increase focusing from β^*=55 cm to 35-25 cm to reach nominal
- Aim of phase II (2016-17)
  - After some years (~5) at nominal/ultimate luminosity, a big boost is needed → factor 5-10 is needed
    - Otherwise the time to halve the statistical error becomes huge)
  - Go up to $L \sim 10 \times 10^{34}$ [cm^{-2} s^{-1}]
  - This involves detector and injector upgrade
  - All solutions that can be envisaged should be adopted
  - Challenge: energy deposition



A guess of luminosity versus time in absence of phase II upgrade inspired by J. Strait work in 2002

PEAK LUMINOSITY

- Peak luminosity equation

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

Constants — Beam intensity — Beam focusing

- Constants
  - ε_n : transverse normalized emittance (LHC aperture, injectors) [3.75×10^{-4} cm rad]
  - γ : relativistic factor (energy of the machine, type of particles) [7461]
  - f_{rev} : revolution frequency (size of the machine) [1.12×10^{4} s^{-1}]
- Beam intensity
  - N_b: number of particle per bunch [1.15×10^{11}]
  - n_b: number of bunches [2808]
- Beam focusing
  - β^*: beta function in the IP (transverse size of the beam) [55 cm]
  - F: geometrical loss reduction factor [0.86]

Bottlenecks

- Present baseline $L=10^{34}$ [cm^{-2} s^{-1}]
- Will we reach the baseline ? Bottlenecks
  - The collimation scheme shows that the impedance is not tolerable
    - If this estimate is confirmed we have either to
      - Keep $\beta^*=55$ cm and reduce beam intensity of 60% → go to 0.16×10^{34} (catastrophe!)
      - Keep the intensity and reduce $\beta^*=80$ cm to be able to open the collimator gap → go to 0.76×10^{34} (much better) – today we expect to lose 25% w.r.t. nominal peak luminosity
  - Beam focusing: the triplet aperture is today, by design, the bottleneck
    - LHC was designed to go up to $\beta^*=25$ cm except the IR triplet and D1
    - Enlarge the IR triplet aperture would also ease collimation [R. Assman et al, LIUWG 11 November 2007]
  - Beam current: will we reach the nominal values ?
    - Luminosity ∝ square of the no. of particle per bunch → if we just lose 20% we have 2/3 of the nominal !
    - This parameter is determined both by injectors and by the LHC performances
    - Example: an alternative filling scheme having $n_b=2592$ is being considered → 8% luminosity loss [W. Herr et al, LTC 14 February 2007]
- Experiments can bear up to $L\sim2\times10^{34}$ [cm^{-2} s^{-1}]

Physical limitations: Number of particles per bunch

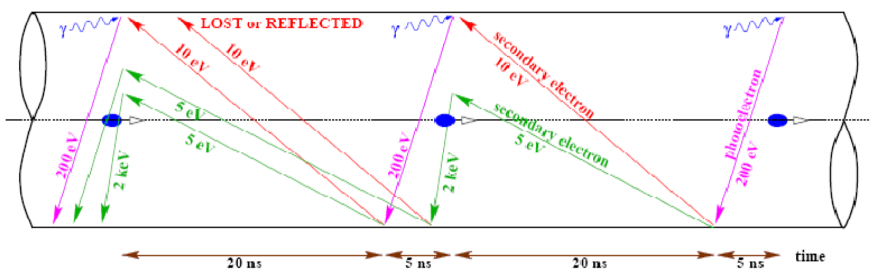
$$L = \frac{f_{rev}\gamma}{4\pi\varepsilon_n}(N_b)^2 n_b \frac{F(\beta^*)}{\beta^*}$$

- Number of particle per bunch N_b is limited by the beam-beam effect, i.e., the Coulomb interaction between colliding bunches
  - The beam-beam parameter is defined as $\xi = \frac{r_p}{4\pi}\frac{N_b}{\varepsilon_n}F(\beta^*)$
  - Empirical experience on machines prove that one can run as long as $\xi<0.015$ – having three experiments this means $\xi<0.005$
  - For the LHC baseline a safety margin with F=1 (instead of 0.86 as we have) has been taken
  - This gives an upper bound on $N_b=1.15\times10^{11}$
  - Switching off one experiment, we can go up to $N_b=1.7\times10^{11}$ (ultimate), but we need an upgrade of the injectors

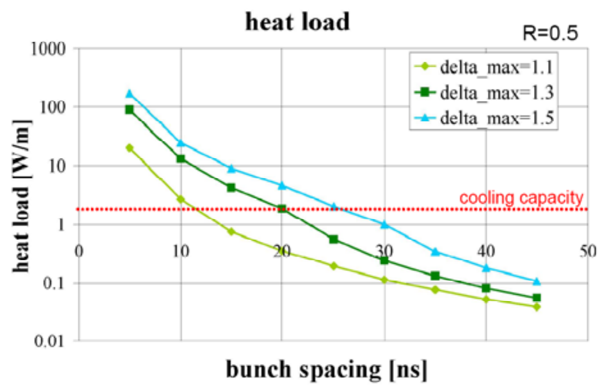
Physical limitations: Number of bunches

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

- The number of bunches n_b (i.e. bunch spacing) is limited by different factors, among them the electron cloud effect
  - Nominal n_b=2808 bunches → bunch spacing of 25 ns
  - Limits given by simulations and some experiences on machines: shorter spacing has to be excluded – larger can be possible
    - Doubling n_b, the bunch spacing becomes 12.5 ns and it looks not feasible (heat load for e-cloud + image current)



Mechanism of electron cloud build up, courtesy of F. Ruggiero



Heat load induced by electron cloud versus bunch spacing, F. Zimmermann LTC, 6th April 2005

PHYSICAL LIMITATIONS: FOCUSING

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

- The focusing is presently limited by the aperture of the quadrupoles Q1-Q3 around the IP (the so-called triplet)
  - The beta function of the beam in the quadrupoles is $\propto 1/\beta^*$
  - The present aperture of 70 mm limits β^*=0.55 cm
  - Changing the triplet, one hits the hard limit of the chromaticity correction at
    - Nb-Ti triplet β^*=0.17 cm Nb_3Sn triplet β^*=0.14 cm

[E. Todesco et al, CARE LUMI-06   J. P. Koutchouk et al., PAC 07]

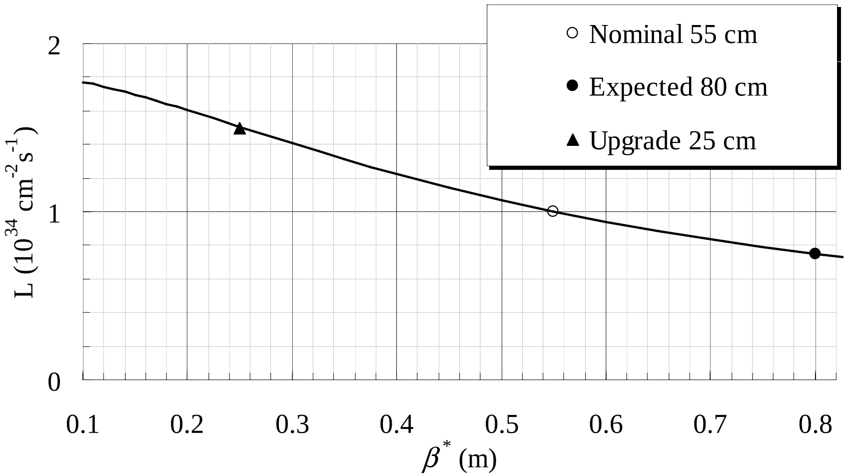
  - If the distance of the triplet from the IP is reduced from 23 m to 13 m **(extreme case),** one can further improve by ~25%
    - Nb-Ti triplet β^*=0.14 cm Nb_3Sn triplet β^*=0.11 cm

Physical limitations: Focusing vs geometrical factor

$$L = \frac{f_{rev}\gamma}{4\pi\varepsilon_n}(N_b)^2 n_b \frac{F(\beta^*)}{\beta^*} \qquad F(\beta^*) = \frac{1}{\sqrt{1+\phi^2(\beta^*)}}$$

- Luminosity is not $\propto 1/\beta^*$ - for β^*<25 cm the gain is marginal if the beam current is kept constant
  - Empirical scaling law: larger focusing induces large crossing angle and therefore more diluted collisions [Y. Papaphilippou, F. Zimmermann, Phys. Rev. STAB 10 (1999) 104001]
  - Going to 25 cm one gains ~50% w.r.t. 55 cm
  - ϕ is called Piwinski angle
    ϕ~0.64 for nominal→F~0.84

$$\phi = \frac{\vartheta(\beta^*)\sigma_z}{2\sigma(\beta^*)} \propto \frac{\sigma_z}{\beta^*}$$



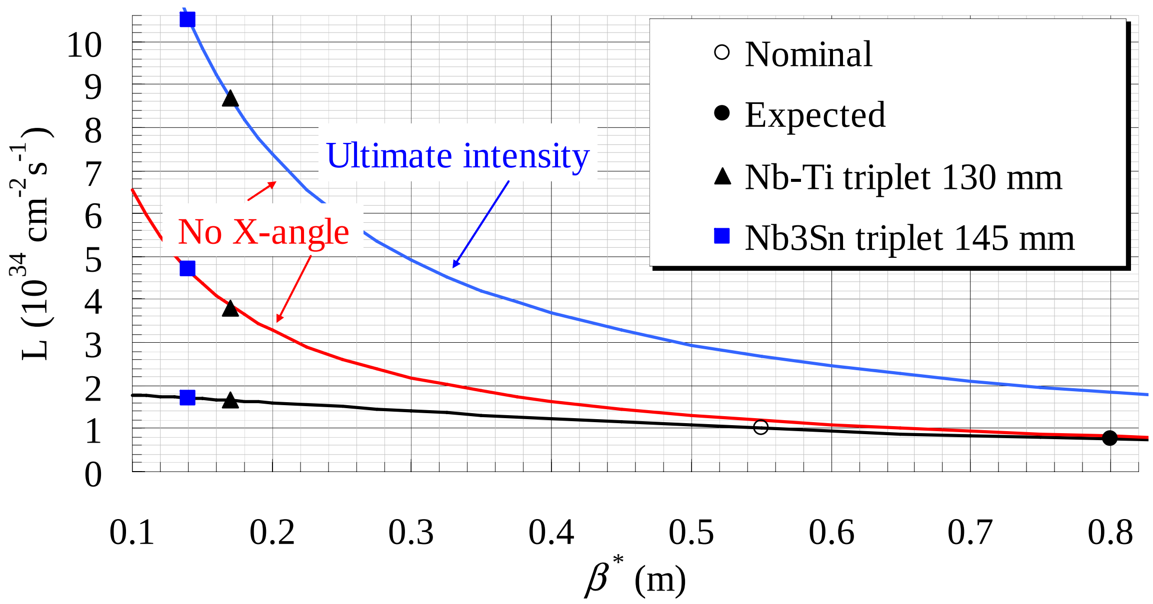
Luminosity versus focusing in case of constant beam current

UPGRADE BASED ON STRONGER FOCUSING (EARLY SEPARATION/CRAB CAVITY)

- Reduce β^* as much as possible

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

- Hypothesis: cannot increase bunch charge N_b beyond nominal
- Kill the crossing angle effect → set the factor F=1 through two means
  - D0: dipole to provide an early separation of the beams but head-on-collision with small crossing angle
  - Crab cavities: RF rotating the bunch to maximize the interaction area



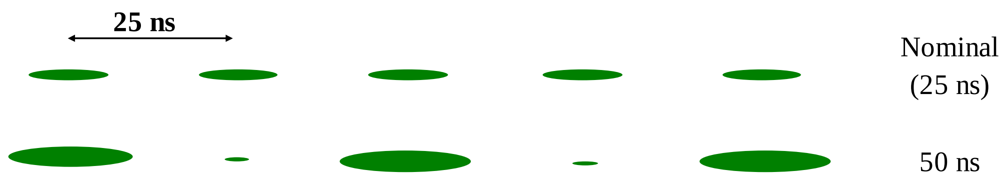
Luminosity versus focusing in case of constant beam current

- If these ideas work, one could gain a factor 4-5 with Nb-Ti or Nb_3Sn, and get to a factor 10 with ultimate intensity
- Challenge: D0 integration, proof of crab cavity

Upgrade based on larger current (Large Piwinski Angle Scheme)

$$L = \frac{f_{rev}\gamma}{4\pi\varepsilon_n}(N_b)^2 n_b \frac{F(\beta^*)}{\beta^*} \qquad \xi = \frac{r_p}{4\pi}\frac{N_b}{\varepsilon_n}F(\beta^*) < 0.015$$

- Reduce *F* and increase N_b keeping the beam-beam limit – we will gain in luminosity since it is proportional to $F\,(N_b)^2$
- Hypothesis: focusing not possible below β^*=25 cm → *F* is made small by increasing bunch length σ_z by 60% and doubling bunch space

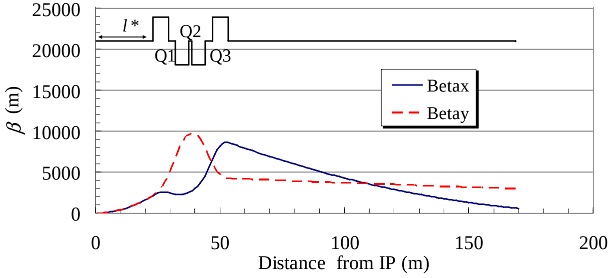


$$F(\beta^*) = \frac{1}{\sqrt{1 + \frac{1}{\beta^*}\frac{\gamma}{\varepsilon_n}\left(\frac{\vartheta(\beta^*)\sigma_z}{2}\right)^2}}$$

- N_b increased by 4.2 → N_b=4.9×10^11^ → gain a factor 16
- n_b decreased by 2 → n_b=1404 → lose a factor 2
- Challenges:
  - Upgrade of the injectors needed to provide this large bunch intensity (×4)
  - 50% larger beam current: need long-range beam-beam wire compensation
  - Machine protection, collimation

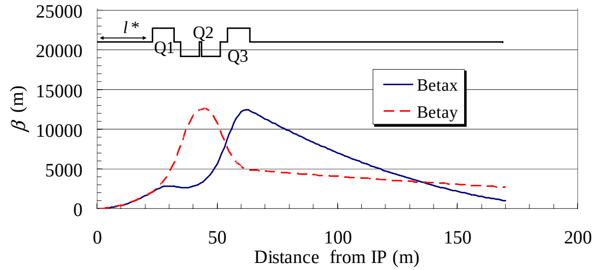
Technologies: IR Triplet

- A larger (longer) triplet
  - Aim: have a larger aperture to be able to go at β^*=25 cm or down to the limit imposed by chromaticity (β^*=14-17 cm)

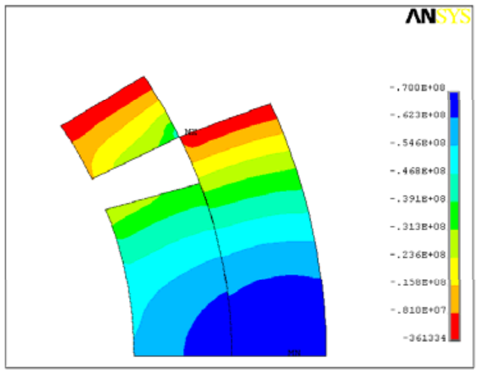


Today baseline of IP

- Two solutions
  - Nb-Ti magnets around 130 mm aperture, with a total triplet length of 40 m (10 m more than today) – to be used for phase I
  - Nb_3Sn magnets, a bit wider, more compact, to be used for phase II
    - Smaller β^*
    - **Better tolerance to energy deposition**



Upgrade with 40m Nb-Ti triplet

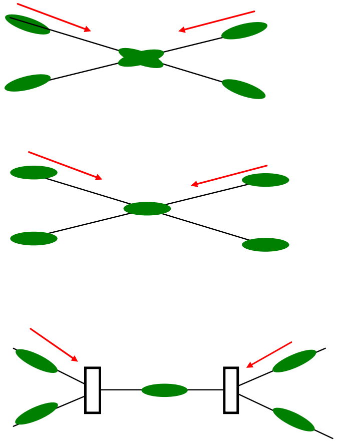


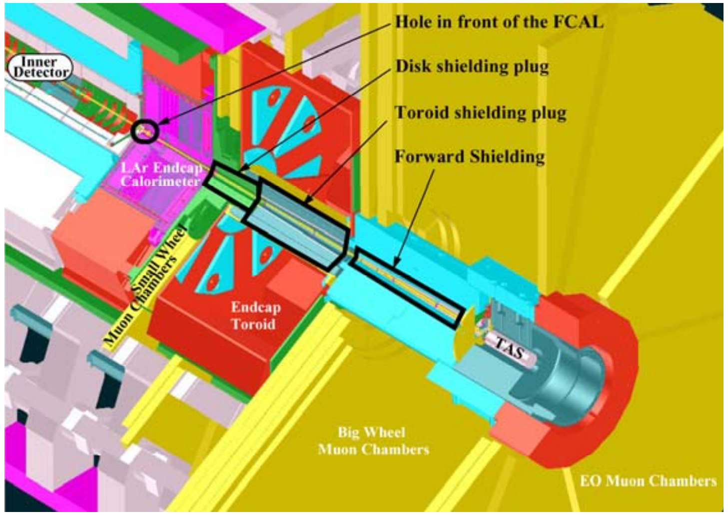
Estimated forces in the coil

- General challenges
  - Large aperture, large stress
  - Energy deposition
  - Good field quality

Technologies: Crab cavity and early separation dipole

- Crab cavity
  - Aim: kill the geometrical reduction factor that reduces luminosity for β^*<25 cm
  - Idea: the bunch is rotated longitudinally to maximize the collision area
  - Status: tested at KEK on **electron machine**: cavity works but no improvement on beam. More investigation and test needed. Scaled up for proton possible but not trivial.
- Early separation dipole
  - Aim: as crab cavity
  - Idea: Have zero crossing angle but separate the beams as soon as possible to avoid parasitic beam-beam interaction with a dipole (~5 Tm)
  - Challenges: has to be in the detector, **in a high radiation environment**
  - **It's asmall magnet: you can take as a consumable**
  - Status: integration studies ongoing
- Each technologies could not completely set F=1 **→ both could solve it completely**





Positions where D0 could be integrated

CONCLUSIONS

- Phase I upgrade (~2012)
  - To recover nominal or reach ultimate by being able to go up to β^*<25 cm
  - New IR triplet with ~130 mm aperture needed

- Phase II upgrade (~2016)
  - Common features to both schemes
    - Go at least to β^*=25 cm - this already done by phase I
    - Go at least to ultimate bunch charge [1.7×10^{11}] - this need upgrade of injectors
    - For this we need High FIELD (Gradient) Magnets with heat depo capability
  - Scenario I: early separation, i.e., strong focusing
    - Going to ultimate bunch charge
    - Push to β^* down 14 cm with Nb_3Sn triplet
    - Remove the adverse effect of crossing angle by
      - Crab cavity
      - Early separation dipole - High FIELD Magnets with huge heat depo capability
  - Scenario II: Large Piwinski angle
    - Go ~3 times the ultimate bunch charge [4.7×10^{11}]
    - Limit with beam-beam wire compensation the effect of larger charge

EXPENDITURE 2007

- 334,240CHF (commissioned research)
- 1,920 CHF Trip Tatsushi Nakamato to RAL (CARE-NED meeting)
- 5,495 CHF Trip Tatsushi Nakamoto to America labs for high field magnet technology

- Balance: 1,847,851 CHF