# LUMINOSITY OPTIMIZATION FOR A HIGHER-ENERGY LHC

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*Abstract*

A Higher-Energy Large Hadron Collider (HE-LHC) is an option to further push the energy frontier of particle physics beyond the present LHC. A beam energy of 16.5 TeV would require 20 T dipole magnets in the existing LHC tunnel, which should be compared with 7 TeV and 8.33 T for the nominal LHC. Since the synchrotron radiation power increases with the fourth power of the energy, radiation damping becomes significant for the HE-LHC. It calls for transverse and longitudinal emittance control vis-à-vis beam-beam interaction and Landau damping. The heat load from synchrotron radiation, gas scattering, and electron cloud also increases with respect to the LHC. In this paper we discuss the proposed HE-LHC beam parameters; the time evolution of luminosity, beam-beam tune shifts, and emittances during an HE-LHC store; the expected heat load; and luminosity optimization schemes for both round and flat beams.

## INTRODUCTION

The beam energy is a key parameter to raise the particle-physics discovery potential of the LHC, which motivates studies of scenarios for an LHC energy upgrade. A large R&D effort on superconducting magnets is still required to achieve – in industrial production – the high magnetic fields needed to increase the LHC beam energy by a factor two or more, but the current state of the art and recent progress with $Nb_3Sn$, $Nb_3Al$ and HTS materials provide reasons for optimism. High Energy Large Hadron Collider (HE-LHC) is the name given to the future LHC energy upgrade now under study at CERN [1, 2].

## BASIC PARAMETER CHOICES

The target dipole field strength for the HE-LHC is 20 T, about a factor 2.5 higher than for the present LHC. Considering the same geometry and filling factor (around 66%) for the bending magnets as for the nominal LHC this field corresponds to a beam energy of 16.5 TeV, to be compared with the 7-TeV design energy of the LHC. An initial luminosity value of $L = 2 \times 10^{34}$ cm$^{-2}$s$^{-1}$ has been defined, since at 16.5 TeV beam energy this would yield about the same radiation level in the interaction region as for the planned high luminosity upgrade, "HL-LHC", with a target luminosity of $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ at 7 TeV. The HE-LHC bunch spacing is 50 ns, with a total number of $n_b = 1404$ bunches per beam. This bunch spacing has been chosen to limit the heat load on the beam screen from synchrotron radiation (SR) and image currents, to ease the demands on the cryogenic system, and to keep the stored beam energy comparable to that of the nominal LHC, in order to facilitate machine protection. A further side benefit of the 50 ns bunch spacing is that it also reduces the severity of electron-cloud effects, the suppression of which, by other additional means (coatings and clearing electrodes), will also be considered.

The LHC design beam-beam tune shift is 0.01. To be conservative the same limit of 0.01 has been adopted for the HE-LHC baseline. We note that more than three times higher values have already been obtained in machine studies at the LHC without any harmful consequences for beam lifetime, luminosity lifetime, or beam emittance. The 400-MHz RF voltage of the HE-LHC is taken to be 32 MV, which is twice the present nominal value of 16 MV. The two times increased value keeps the synchrotron tune approximately the same as for the present LHC (which might be important for beam and particle stability). In order to maintain Landau damping, the longitudinal emittance is increased with the square root of the beam energy [3], to about 4 eVs. The crossing angle is chosen to provide a separation of $12\sigma$ at the parasitic encounters, which is higher than the $9.5\sigma$ separation of the nominal LHC, and ensures that long-range beam-beam effects are negligible.

The remaining parameters have been chosen to comply with the conditions mentioned above. Both flat and round beam options are considered.

## TIME EVOLUTION

We have developed an informatics tool that allows calculating relevant beam parameters and their evolution in time during a physics store. Table 1 lists some of the main HE-LHC parameters obtained as output of our program.

The stored beam energy of about 480 MJ is 32% higher than for the nominal LHC. The SR power is increased by about a factor of 18, which brings the total heat load close to, or beyond, the maximum cooling capacity of the existing LHC cryoplants.

The emittance evolution with time is determined by intra-beam scattering (IBS), SR damping, and the controlled emittance growth through the possible injection of pink noise. For round beams we consider

$$\left(\frac{d\varepsilon}{dt}\right)_{x,y} = \frac{\varepsilon}{\tau_{IBS,x}} - \frac{\varepsilon}{\tau_{SR}} + \left(\frac{\Delta\varepsilon}{\Delta t}\right)_{noise} .$$

In the flat-beam scenario the vertical IBS growth rate is taken to be a certain fraction of the horizontal rate, i.e. we assume there is some coupling (e.g. $\kappa_c = 0.2$) of the form:

$$\left(\frac{d\varepsilon_y}{dt}\right)_{flat} = \frac{\varepsilon_x}{\tau_{IBS,y}} - \frac{\varepsilon_y}{\tau_{SR,y}} + \left(\frac{\Delta\varepsilon}{\Delta t}\right)_{noise} .$$

Another key ingredient for the luminosity time evolution

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Table 1: Preliminary HE-LHC parameters for flat and round beams.

| **Main parameters** | **nominal LHC** | **HE-LHC (Flat)** | **HE-LHC (Round)** |
|---|---|---|---|
| Energy (TeV) | 7 | 16.5 | |
| Bending field (T) | 8.33 | 19.6 | |
| # of bunches | 2808 | 1404 | |
| Bunch population $N_b$ ($10^{11}$ ppb) | 1.15 | 1.29 | 1.30 |
| Initial normalized trans. emmitance ($\mu$m) | 3.75 | 3.75(x),1.84(y) | 2.59 |
| Initial normalized long. emmitance (eVs) | 2.5 | 4.0 | |
| $\beta_x^*$, $\beta_y^*$ (m) | 0.55 | 1.0, 0.43 | 0.6 |
| Stored Energy per beam (MJ) | 334 | 478.5 | 480.7 |
| SR power per ring (keV) | 3.6 | 65.7 | 66 |
| Dipole SR heat load (W/m/aperture) | 0.16 | 2.8 | 2.8 |
| SR Energy loss per turn (keV) | 6.7 | 201.3 | |
| Long. SR emittance damping time (h) | 12.9 | 0.98 | |
| Trans. SR emittance damping time (h) | 25.8 | 1.97 | |
| Long. IBS emittance rising time (h) | 61 | 64 | 68 |
| Hor. IBS emittance rising time (h) | 80 | 80 | 60 |
| Ver. IBS emittance rising time (h) | 400 | 398 | 300 |
| Crossing angle ($\mu$rad) | 285 (9.5$\sigma$) | 175.2 (12$\sigma$) | 188.1 (12$\sigma$) |
| Peak luminosity ($10^{34} cm^{-2} s^{-1}$) | 1.0 | 2.0 | |
| Events per crossing | 19 | 76 | |
| Beam life time (h) | 46 | 12.6 | |
| Optimum avg. int. luminosity per day ($fb^{-1}$) | 0.47 | 0.78 | 0.79 |

is proton burn off:

$$\frac{dN_b}{dt} = -\frac{\sigma_{tot} L n_{IP}}{n_b} ,$$

where $\sigma_{tot} \approx 100$ mbarn denotes the total cross section, and $n_{IP} = 2$ the number of interaction points.

Further options include keeping the longitudinal emittance constant (through controlled longitudinal blow up) as well as leveling by varying the crossing angle. Several cases have been considered, e.g. with and without a constant longitudinal emittance or with either constant or decreasing crossing angle. The principal results are almost the same for all the different situations considered. Both longitudinal emittance and crossing angle can, therefore, be kept constant during a physics store, without any significant loss in integrated luminosity.

## LUMINOSITY OPTIMIZATION

The IBS rise times computed with MAD-X (using extended Conte-Martini formulae [4, 5]) are much longer than the radiation damping times. This has the consequence that, if no countermeasures are taken, the transverse and longitudinal emittances quickly shrink and the beam-beam tune shift increases to potentially unacceptable values. This and the possible loss of longitudinal Landau damping can be counteracted by injecting transverse and longitudinal noise for 3D emittance "blow up" [6]. This control allows maintaining a constant tune shift (e.g. equal to 0.01) during the whole physics run. Fig. 1 shows the emittance evolution, for both flat and round beams, during a physics store with and without controlled emittance blow up. The luminosity evolution for the case with controlled blow up, is illustrated in Fig. 2, which also demonstrates the equivalent performance of flat-beam and round-beam collisions. Fig. 3 presents the time evolution of the corresponding integrated luminosities.

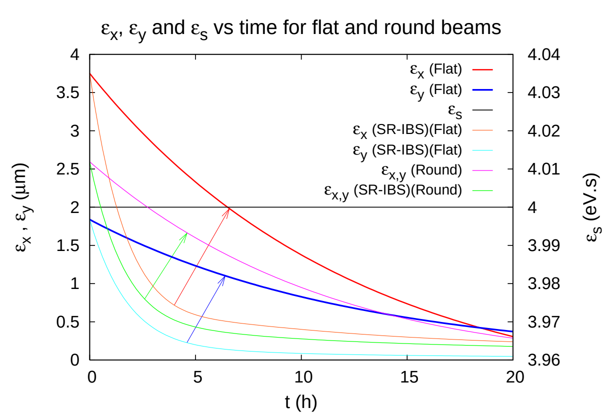


Figure 1: Evolution of the HE-LHC emittances, for flat and round beams, during a physics store with controlled blow up and constant longitudinal emittance of 4 eVs plus constant crossing angle (the thicker lines at the top), and the natural transverse emittance evolution due to radiation damping and IBS only (thinner lines at the bottom), again for constant longitudinal emittance and crossing angle.

Taking into account the latest results achieved at the present LHC regarding beam-beam tune shift ($\Delta Q_{tot} \geq 0.03$ in two head-on collisions without evidence for a beam-beam limit), we can ask what would happen if we remove the constraints on the tune shift (which would be realized by continuous transverse blow up) and instead let

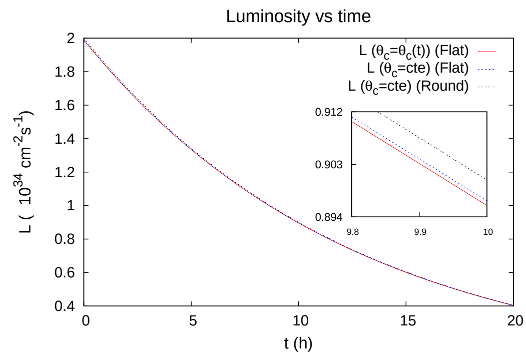


Figure 2: Time evolution of the HE-LHC luminosity, for both flat and round beams, including emittance variation with controlled blow up and proton burn off. Curves with constant or varying crossing angle lie on top of each other if the beam-beam tune shift is kept constant as assumed here.

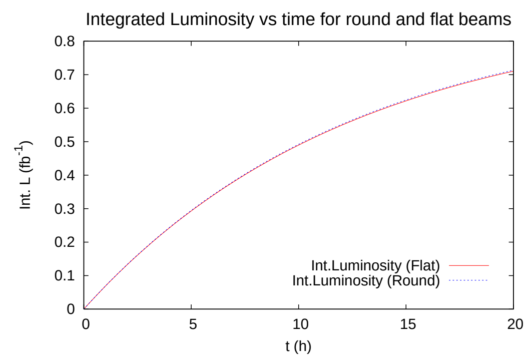


Figure 3: Time evolution of the HE-LHC integrated luminosity, for both flat and round beams, during a physics store including emittance variation with controlled blow up, keeping $\Delta Q_{tot} = 0.01$, and proton burn off.

the transverse emittances shrink under the influence of the radiation damping. Figure 4 shows the evolution of the tune shift for flat and round beams without controlled blow up, starting from an initial value of $\Delta Q_{tot} = 0.01$. For the round-beam option, the maximum beam-beam tune shift is more than 30% lower than for the flat-beam case. Round beams, therefore, appear more conservative. In both cases the luminosity peak-value increases during the store (see Fig. 5), resulting in higher values for the integrated luminosity. However, the relative gain in integrated luminosity of about 10% for the flat-beam case is much smaller than the associated increase in the peak beam-beam tune shift by more than a factor of 3.

## SUMMARY AND OUTLOOK

The proposed key parameters for the Higher-Energy LHC were reviewed and justified. A few beam-dynamics and optics issues have been highlighted, such as the fast radiation damping, the resulting potentially high beam-beam tune shifts, and the implied need for transverse and longitudinal emittance control.

For the HE-LHC we have developed a performance model to predict the luminosity as a function of time and to

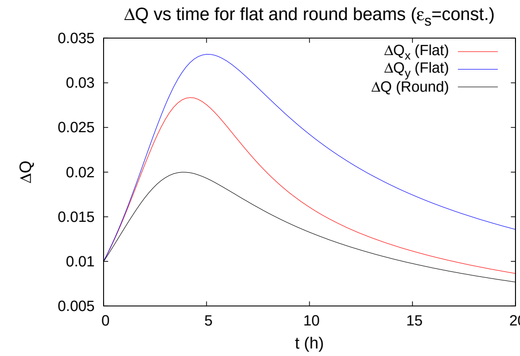


Figure 4: Time evolution of the HE-LHC tune shifts, for round and flat beams during a physics store including SR emittance shrinkage without controlled transverse blow up, and including proton burn off.

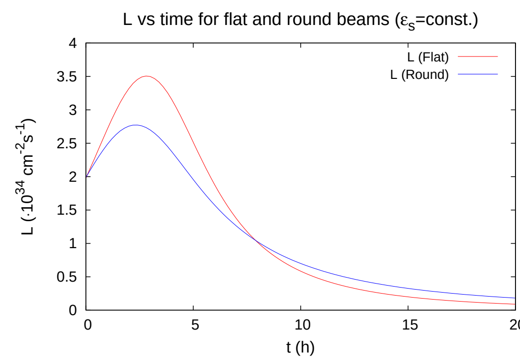


Figure 5: Time evolution of the HE-LHC instantaneous luminosity, for both flat and round beams, including SR emittance shrinkage and proton burn off, without controlled transverse blow up.

optimize the beam parameters. The same type of model can be applied to the nominal LHC and to its high-luminosity upgrades, HL-LHC, including constraints from beam-beam and electron cloud.

There are still many issues to be covered and to be further studied, especially ones related to higher energies. Regarding the beam parameters, in the future we plan to investigate the consequences of higher initial tune shifts as well as of different ratios for the transverse emittances when considering flat beams (e.g. $\varepsilon_x/\varepsilon_y \sim 10$) and to improve our model of intrabeam scattering for the vertical plane.

The realization of the HE-LHC will depend on the future availability and affordability of high-field dipole magnets.

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