SYNCHROTRON RADIATION DAMPING, INTRABEAM SCATTERING AND BEAM-BEAM SIMULATIONS FOR HE-LHC

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Abstract

   The proposed High-Energy LHC project presents an unusual combination of strong synchrotron radiation (SR) damping and intrabeam scattering (IBS), which is not seen in present-day hadron colliders. The subject of investigation reported in this paper was the simulation of beam-beam effect for the HE-LHC parameters. Parameters of SR and IBS are calculated, and the luminosity evolution is simulated in the absence of beam-beam interaction. Then, a weak-strong numerical simulation is used to predict the effect of beam-beam interaction on particle losses and emittance evolution.

MACHINE AND BEAM PARAMETERS

   Main parameters of HE-LHC relevant for our calculations are presented in Table 1.

Table 1: Machine and beam parameters

Parameter	Value
Beam energy	16.5 TeV
Number of bunches	1404
Number of interaction points	2
Bunch population	1.3×10^{11}
Initial normalized transverse emittance	3.75, 1.84 (x,y) μm
Initial momentum spread	0.9×10^{-4}
RF voltage	32 MV
Beta-function at IP	1.0, 0.43 (x,y) m
Full crossing angle	175 μrad

PARAMETERS OF SYNCHROTRON RADIATION

   Calculation of synchrotron radiation integrals was based on current LHC optics V6.5. Main parameters of SR and equilibrium emittance were derived using the conventional formulae [1] (see Table 2):

$$U_0 = \frac{C_\gamma}{2\pi} E^4 I_2$$

$$\tau_{x,y} = \frac{ET_0}{U_0}, \tau_E = \frac{ET_0}{2\cdot U_0}$$

$$\frac{d\varepsilon_x}{dt} = -\frac{\varepsilon_x}{\tau_x} + \frac{55}{48\sqrt{3}} \frac{\hbar c}{T_0} \frac{r_0}{mc^2} \gamma^5 I_5$$

Table 2: Synchrotron radiation parameters

Parameter	Value
Synchrotron radiation integrals	I_2=0.002245 m^{-1}
	I_3=7.99$\times10^{-7}$ m^{-2}
	I_5=2.11$\times10^{-8}$ m^{-1}
Energy loss per turn	U_0=206.3 keV
SR power	67 kW
Emittance damping time	τ_x, τ_y=1.93 h
	τ_E=0.96 h
Normalized equilibrium emittance	0.01 μm
Equilibrium momentum spread	3.4×10^{-6}

   Note that the equilibrium emittance and momentum spread due to synchrotron radiation are much smaller than the initial values, and the damping time is significantly shorter than the expected store duration (10 hours).

INTRA-BEAM SCATTERING AND LUMINOSITY EVOLUTION

   Intrabeam scattering was treated in the smooth optics approximation by V.Lebedev [2] with the main parameters listed in Table 3.

$$\frac{d}{dt}\begin{pmatrix}\varepsilon_x \\ \varepsilon_y \\ \sigma_E^2\end{pmatrix} = \frac{Nr_0^2 cL_c}{4\sqrt{2}\beta^3\gamma^3\sigma_x\sigma_y\sigma_z\theta_\perp}\begin{pmatrix}\langle A_x\rangle_s \\ 0 \\ 1\end{pmatrix}$$

Table 3: Parameters of IBS

Parameter	Value
Lattice parameters (LHC V6.5)	$\langle\beta_x\rangle$=104.8 m
	$\langle\beta_y\rangle$=109.4 m
	$\langle A_x\rangle$=2.29
Horizontal emittance growth time	82 h
Longitudinal emittance growth time	72 h

   Evolution of the beam parameters and luminosity was then calculated via the numerical solution of the following system of equations:

$$\frac{d\varepsilon_x}{dt} = -\frac{2\varepsilon_x}{\tau_{SRx}} + \frac{d\varepsilon_{xSR}}{dt} + \frac{d\varepsilon_{xIBS}}{dt} + \frac{d\varepsilon_{xBB}}{dt}$$

$$\frac{d\varepsilon_y}{dt} = -\frac{2\varepsilon_y}{\tau_{SRy}} + \frac{d\varepsilon_{ySR}}{dt} + \frac{d\varepsilon_{yIBS}}{dt} + \frac{d\varepsilon_{yBB}}{dt}$$

$$\frac{d\sigma_E^2}{dt} = -\frac{2\sigma_E^2}{\tau_{SRE}} + \frac{d\sigma_{SR}^2}{dt} + \frac{d\sigma_{IBS}^2}{dt} + \frac{d\sigma_{BB}^2}{dt}$$

$$\frac{dN}{dt} = -N_{IP}\frac{L}{N_b}\sigma_{tot}$$

Here L is the luminosity, N_b is the number of bunches, σ_{tot} is the p-p interaction cross-section, N_{IP} is the number of IPs, indices SR, IBS and BB label the emittance growth (or damping) rates for synchrotron radiation, intrabeam scattering, and scattering at IPs, respectively. These growth rates are calculated at every step of numerical integration for current beam parameters.
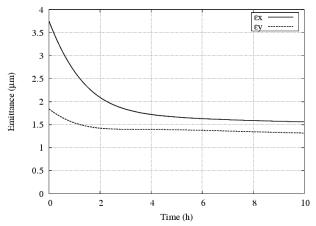

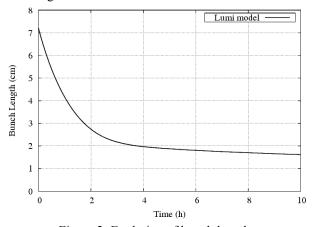Figure 1: Evolution of transverse emittances.
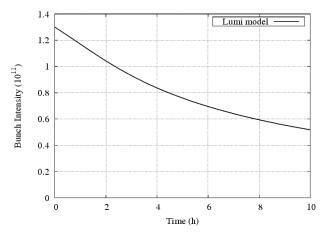

Figure 2: Evolution of bunch length.
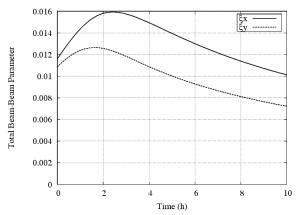

Figure 3: Evolution of bunch intensity.
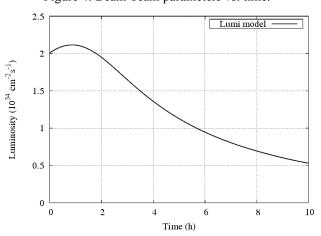

Figure 4: Beam-beam parameters vs. time.

Figure 5: Evolution of luminosity. Luminosity integral over 10 h is 450 pb^{-1}.

Figures 1-5 present the calculated evolution of beam parameters over a period of 10 hours. An important feature of the beam dynamics is the reduction of transverse emittances due to synchrotron radiation by approximately a factor of two. Combined with the beam intensity decay caused by luminous particle losses, this results in the increase of the total beam-beam parameter by 50% (from the initial value of 0.01 to 0.016).

BEAM-BEAM SIMULATION

Numerical simulation was performed with the use of weak-strong tracking code Lifetrac. A bunch of 5,000 macro-particles with weighted Gaussian initial distribution was tracked for 5×10^7 turns (which corresponds to 1.2 h of beam time) in order to evaluate the importance of beam-beam effects. The machine optics was represented by linear 6D maps, no long-range collisions were considered. The synchrotron radiation damping, quantum excitation and intrabeam scattering were represented by kicks applied once per turn. The code does not include particle losses due to luminosity and diffusion caused by scattering at the IPs.

Figures 6-8 present the results of numerical simulation along with the curves obtained using the luminosity evolution model described in the previous section. Numerical simulation did not produce any particle losses. One can see that beam-beam interaction does not cause additional emittance growth.
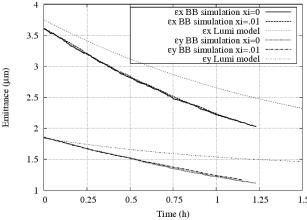

Figure 6: Beam emittances vs. time. Comparison of beam-beam simulation and luminosity model.
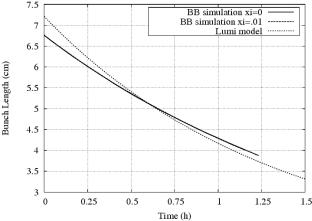

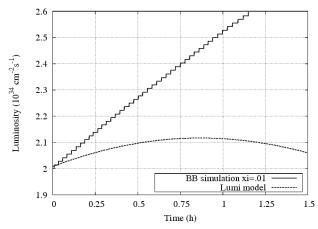Figure 7: Comparison of bunch length from numerical beam-beam simulation and luminosity model.

Figure 8: Luminosity vs. time. Beam-beam simulation and luminosity evolution model. Numerical curve is higher owing to the absence of the luminous beam decay in the model.

SUMMARY

Combination of parameters of the proposed High Energy LHC produces beam dynamics not observed at present hadron colliders. Synchrotron radiation causes emittance damping with the characteristic time of 2 hours. Intrabeam scattering, typically the dominant effect, is relatively weak with the initial emittance growth rate of 70 hours. As the beam emittance decreases, synchrotron radiation and intrabeam scattering come to equilibrium, a situation typical for low emittance electron damping rings. The resulting beam emittance is approximately half of the initial value. As the result, the beam-beam parameter experiences growth over the initial 2 hours of the store.

Numerical simulations with a weak-strong particle tracking code, which included major effects, predict that beam-beam effects would cause no particle losses. The evolution of beam emittance is not modified by beam-beam interaction. Modeling confirms that the luminosity integral of 450 pb^{-1} over 10 hours is achievable. The simulations employed a simplified accelerator model, in which no nonlinearities existed. Hence it is reasonable to expect extra losses due to machine nonlinearities.

REFERENCES

[1] A. Chao, M. Tigner, Handbook of Accelerator Physics and Engineering, World Scientific, 1999
[2] V. Lebedev, http://lhc-commissioning.web.cern.ch/lhc-commissioning/presentations/2010/VL_LHC_LuminosityEvolution.pdf