MITIGATION OF ELECTRON CLOUD INSTABILITIES IN THE LHC USING SEXTUPOLES AND OCTUPOLES

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Abstract

Coherent electron cloud instabilities pose a serious limitation for luminosity upgrades in the Large Hadron Collider (LHC) at CERN. In particular, when bunch spacings reach below 50 ns, electron cloud formation is enhanced which in turn drives beam instabilities. The beam can be stabilised by shifting the tune and by increasing the tune spread using sextupoles or octupoles, respectively. The resulting values for the chromaticity and the detuning parameters must be selected with care, however, in order not to run into head-tail instabilities or to considerably reduce the dynamic aperture. A simulation study has been launched to estimate the parameters necessary for stabilisation of the beam under the influence of electron clouds.

INTRODUCTION

Coherent electron cloud instabilities pose a major limitation on the peak luminosity in the LHC [1]. The mitigation of this type of instabilities is roundly being investigated. The instabilities can be handled either passively by affecting the electron cloud build-up or actively by directly controlling the beam dynamics by means of the machine optics. As such, the electron cloud build-up can be suppressed by local solenoidal fields, by surface coating or by in-situ surface cleaning using scrubbing runs for example. Beam stabilisation through the machine optics, on the other hand, is performed by adjusting the chromaticity and detuning parameters using sextupoles and octupoles. Introducing sextupolar and octupolar fields however increases the machine non-linearities, thus, enhancing parametric and coupling resonances and reducing the dynamic aperture. The sextupolar and octupolar fields strengths must, therefore, be well selected in order to provide sufficient stabilisation with regard to collective effects while keeping non-linear resonances at a manageable level.

This study investigates the beam under the influence of electron clouds and its stabilisation purely from incoherent detuning, thus, explicitly disregarding any non-linearities imposed. That way, the collective effects and their mitigation can be investigated separately from any non-linear resonance phenomena.

The effect of the chromaticity and the detuning with amplitude on the electron cloud instability is investigated at 450 GeV and at 3.5 TeV.

NUMERICAL MODEL

In the numerical model the machine is composed of dipole, quadrupole, sextupole and octupole magnets together with evenly distributed electron clouds.

Sextupoles and octupoles introduce chromatic tune shift and detuning with amplitude given as

$$\Delta Q_{x,y} = \mp\frac{1}{4\pi}\oint \beta_{x,y}(s)\left(K_{x,y}(s)^2 \mp S(s)^2 D(s)\right)\delta\, ds\,,$$
$$\Delta Q_x = \frac{3}{8\pi}\oint O^2\left(\beta_x(s)^2 J_x - 2\beta_x(s)\beta_y(s)J_y\right)\, ds\,,$$
$$\Delta Q_y = \frac{3}{8\pi}\oint O^2\left(\beta_y(s)^2 J_y - 2\beta_x(s)\beta_y(s)J_x\right)\, ds\,.$$

$K_u(s)$, $S(s)$ and $O(s)$ are the quadrupolar, sextupolar and octupolar field strengths, respectively. $\beta_u(s)$ are the beta functions, $D(s)$ is the dispersion and J_u are the actions [1]. The chromaticity and the detuning parameters are accordingly defined as

$$\xi' = \frac{\partial \Delta Q}{\partial \delta}\,, \quad \text{and} \quad \alpha_{ij} = \frac{\partial \Delta Q_i}{\partial J_j}\,, \tag{1}$$

respectively. By means of this parametrisation the total tune variation translates to

$$\begin{aligned} \Delta Q_x &= \xi'_x\delta + \alpha_{xx}J_x + \alpha_{xy}J_y \\ \Delta Q_y &= \xi'_y\delta + \alpha_{xy}J_x + \alpha_{yy}J_y\,. \end{aligned} \tag{2}$$

The numerical studies are carried out using HEAD-TAIL [2]. The beam dynamics is calculated by alternate application of linear beam transport matrices and kick matrices in a second order symplectic manner (Leapfrog scheme). The linear beam transport matrices are computed according to the local Twiss parameters as [2]

$$\begin{aligned} M_{0\to1} &= N(s_1)R(\Delta\psi)N^{-1}(s_0) \\ &= \begin{pmatrix} \sqrt{\beta_1} & 0 \\ -\frac{\alpha_1}{\sqrt{\beta_1}} & \frac{1}{\sqrt{\beta_1}} \end{pmatrix} \\ &\times \begin{pmatrix} \cos\Delta\psi & \sin\Delta\psi \\ -\sin\Delta\psi & \cos\Delta\psi \end{pmatrix} \\ &\times \begin{pmatrix} \frac{1}{\sqrt{\beta_0}} & 0 \\ \frac{\alpha_0}{\sqrt{\beta_0}} & \sqrt{\beta_0} \end{pmatrix}\,, \end{aligned} \tag{3}$$

and the sextupole and octupole magnets are implemented purely via their effect on the particle detuning by means of the chromaticity and detuning with amplitude parameters according to eq. (2), as mentioned earlier. This leads to the phase advance per ring section

$$\Delta\psi = \frac{2\pi\, C}{s_1 - s_0}\left(Q_0 + \Delta Q\right)\,, \tag{4}$$

in eq. (3), where C is the ring circumference.

[1] $u = (x, y)$

[2] Throughout this study the smooth approximation was used.

The kick matrix is represented by the interaction of the beam with the electron cloud which is computed slice-by-slice using a 2D FFT-type Particle-In-Cell (PIC) solver.

For Landau damping to be effective, a sufficient overlap of the incoherent spectrum with the coherent modes is required in order to provide a sufficient supply of resonant particles to absorb energy into the incoherent motion. For TMCI-like instabilities it is therefore necessary to obtain a tune spread in the order of the synchrotron tune, which is already hard to achieve in practise [3]. For electron cloud instabilities (ECI) the situation becomes more complex as the electron cloud potential itself is strongly non-linear and introduces additional incoherent detuning. Hence, the incoherent tune spectrum reflects the combined impact of chromatic tune shifts and amplitude dependent detuning from sextupole and octupole magnets as well as from the interaction with the electron clouds.

Within this framework, both the chromaticity and detuning with amplitude are used to shift and to widen the tune spectrum in an attempt to regain stability.

SIMULATION STUDY

Simulations on the stabilisation of the electron cloud instabilities using sextupole and octupole magnets have been performed at 450 GeV and at 3.5 TeV for straight sections. The electron cloud densities were set to $4 \times 10^{11}\ \mathrm{m}^{-3}$ and $6 \times 10^{11}\ \mathrm{m}^{-3}$ for the two energies, respectively. These values generate instability rise times below 5 ms according to results found in earlier work [4]. Table 1 shows the optics and numerical parameter settings.

Table 1: The Parameters used for the Numerical Simulations

Bunch intensity	[ppb]	1.15×10^{11}
$\varepsilon_{x,\mathrm{norm}}$, $\varepsilon_{y,\mathrm{norm}}$	[µm]	2.5, 2.5
β_x, β_y	[m]	103, 106
Q_x, Q_y		64.28, 59.31
Bunch length (rms)	[m]	~ 0.1

Mitigation of ECI Using Sextupoles

Keeping the octupoles turned off and scanning the chromaticity ξ' from values 2 up to 30, figs. 1 and 2 show the coherent instability can be suppressed for values above $\xi' \approx 15$ at both 450 GeV and 3.5 TeV which is consistent with previous findings [5]. Only the vertical coherent motion is shown in the figures. The horizontal motion behaves the same for straight sections and remains stable in bending magnets. At these chromaticity levels, however, higher order headtail modes are no longer efficiently damped and may become unstable.

Mitigation of ECI Using Octupoles

The chromaticity is set to $\xi' = 2$. The octupole current I_{oct} is scanned up to 550 A which is the maximum available current that can be obtained from the power supplies. As

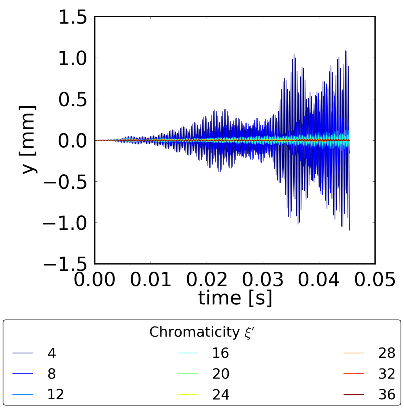

Figure 1: The vertical coherent motion under the influence of electron clouds at an energy of 450 GeV for different chromaticities.

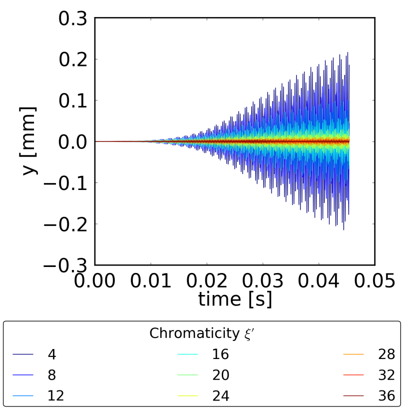

Figure 2: The vertical coherent motion under the influence of electron clouds at an energy of 3.50 TeV for different chromaticities.

opposed to chromatic aberration, detuning with amplitude is strongly energy dependent via the action $J = \varepsilon/2 = \varepsilon_n/(2\gamma\beta)$ where ε_n is the normalised emittance which is a Hamiltonian time invariant. Hence, at high energies detuning with amplitude becomes less effective.

Figure 3 shows that Landau damping can be achieved at 450 GeV for octupole currents around 200 A. Fig. 4 shows the incoherent mode spectrum relative to the coherent modes at this current level and reveals a sufficient supply of resonant particles for effective Landau damping [3]. Again, in practise the maximum octupole current is limited by the dynamic aperture of the machine to about 20 A for 450 GeV [6].

Figure 5 displays that the coherent motion is not suppressed at 3.50 TeV for any of the reachable octupole currents. Accordingly, fig. 6 reveals the loss of resonant particles through the narrowing of the incoherent mode spectrum at 200 A leading to a loss of Landau damping. As

[3] In the figures, the coherent mode spectrum is the spectrum for the full bunch, whereas the incoherent spectrum is the distribution of the dominant mode of each particle.

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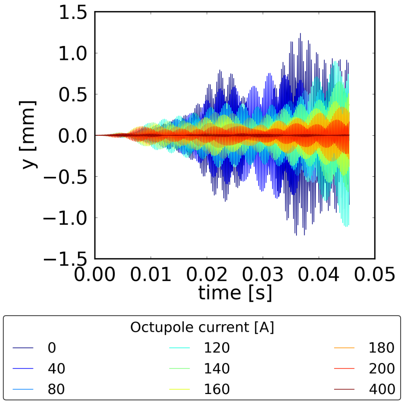

Figure 3: The vertical coherent motion under the influence of electron clouds at an energy of 450 GeV for different octupole currents.

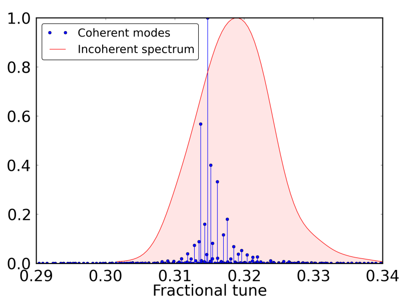

Figure 4: The coherent vs. incoherent mode spectrum. The large overlap indicated there are sufficient resonant particles contributing to Landau damping.

noticed above, detuning with amplitude is nearly ineffective at 3.50 TeV.

It must be concluded that, unfortunately, for electron cloud densities well beyond the coherent instability threshold, octupoles alone are not an effective method for beam stabilisation neither at injection energy and even less at higher energies.

CONCLUSIONS

Beam stabilisation above the ECI threshold in the LHC by means of sextupole and octupole magnets was investigated numerically at 450 GeV and 3.50 TeV using HEADTAIL. It was found that neither chromatic aberration nor detuning with amplitude seem to provide sufficient stabilisation within practical limits when the electron cloud density is well beyond the instability threshold limit. Chromaticity values of $\xi' \approx 15$ are required for stabilisation at both 450 GeV and 3.50 TeV. Octupole currents of up to 200 A must be provided for stabilisation at 450 GeV whereas the beam can not be stabilised by octupoles at 3.50 TeV. To understand better the impact of the sextupole and octupole magnets relative to the incoherent detuning introduced by electron clouds, future studies will attempt to separate the contribution of sextupoles, octupoles and electron clouds to the incoherent spectrum.

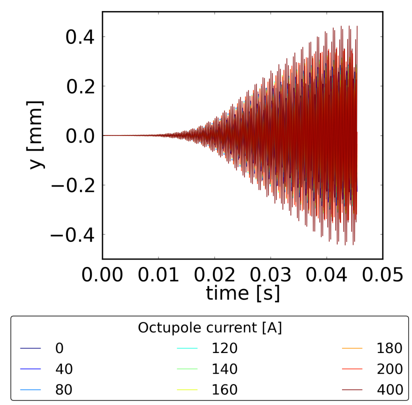

Figure 5: The vertical coherent motion under the influence of electron clouds at an energy of 3.50 TeV for different octupole currents.

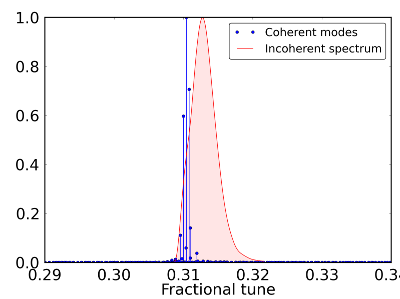

Figure 6: The coherent vs. incoherent mode spectrum. The incoherent spectrum is shifted away from the coherent spectrum and is too narrow to sufficiently cover the coherent modes.

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