

LANDAU DAMPING BY ELECTRON LENSES*

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Abstract

Usual methods to control the instabilities, such as octupole magnets, beam feedback dampers and use of chromatic effects, become less effective and insufficient. In contrast, Lorentz forces of a low-energy, magnetically stabilized electron beam, or “electron lens”, easily introduces transverse nonlinear focusing sufficient for Landau damping of transverse beam instabilities in accelerators. Unlike other nonlinear elements, the electron lens provides the frequency spread mainly at the beam core, thus allowing much higher frequency spread without lifetime degradation. For the parameters of the Future Circular Collider, a single conventional electron lens a few meters long would provide stabilization superior to tens of thousands of superconducting octupole magnets. This talk is a modified version of our paper [1].

INTRODUCTION

Suppression of the collective instabilities is typically achieved by a joint action of feedback systems and Landau damping [2,3,4]. For multi-bunch beams, such feedbacks usually suppress the most unstable coupled-bunch and beam-beam modes. However, having limited bandwidths, these dampers are normally inefficient for the intra-bunch modes and Landau damping is needed for their suppression. To make it possible, the spectrum of incoherent, or individual particle frequencies must overlap with frequencies of the unstable collective modes, thus allowing absorption of the collective energy by the resonant particles. The frequency spread can be generated by nonlinear focusing forces, such as those due to the space charge of an opposite colliding beam in colliders, or by nonlinear - usually, octupole - magnets. The first option is not available at one-beam facilities, but even in the colliders, it does not exist at injection and until the beams are brought in collision, generating a significant tune spread through the beam-beam head-on interaction. Thus far, commonly used are octupole magnets with the transverse magnetic fields on beam’s axis of $B_x + iB_y = O(x + iy)^3$ which generate the transverse, or betatron, frequency shifts proportional to the square of particles’ amplitudes [3]. For higher energy E of the accelerated particles, the octupoles become less and less effective: the corresponding frequency spread scales as $1/E^2$ due to increasing rigidity and smaller transverse beam size, while the instability growth rates scale only as $1/E$, since the transverse beam size is not important for them. As a consequence, one needs to increase the strength of these magnets accordingly. For example, in the Tevatron proton-antiproton collider, with $E \approx 1$ TeV, there were 35 superconducting octupole magnets installed

in 1 m long package cryostats and operated with up to 50A current [5], while in the 7 TeV LHC, 336 superconducting octupole magnets, each about 0.32 m long, operate at the maximum current of 550 A [6] – and even that is not always sufficient to maintain the beam stability above certain proton bunch intensities. The anticipated 50 TeV beam energy in the proton-proton Future Circular Collider (FCC-pp, [7]) would require a further factor of more than 60 in integrated octupole strength [8], which makes stabilization by octupoles greatly impractical.

Another very serious concern is that at their maximum strength, the octupoles induce significant non-linear fields and dangerous betatron frequency shifts for the larger amplitude particles, destabilizing their dynamics. This leads to increased rate of particle losses, and therefore, higher radiation load [9].

To provide a sufficient spread of the betatron frequencies without beam lifetime degradation, we propose the use of an electron lens – a high brightness low energy electron beam system [10,11]. Here, we calculate the accelerator beam coherent stability diagrams for various sizes of the electron beam, simulate numerically the effect of the electron lenses on incoherent particle dynamics and compare it with the case of octupoles. Major parameters of the electron lens devices for effective suppression of coherent instabilities are presented as examples for the LHC and for the FCC.

STABILITY DIAGRAMS

The Lorenz force acting on an ultra-relativistic proton from a low energy electron beam with velocity $\beta_e c$ and current density distribution $j_e(r)$,

$$e(E_r + B_\theta) = \frac{4\pi e(1 + \beta_e)}{\beta_e c} \frac{1}{r} \int_0^r j_e(r') r' dr' \quad (1)$$

is diminishing at large radius r as $\sim 1/r$, therefore, outside of the electron beam, the corresponding betatron frequency shifts $\delta\omega_{x,y}$ drop quadratically with the proton’s transverse amplitudes $A_{x,y}$. For a round Gaussian-profile electron beam of rms transverse size σ_e , the amplitude dependent tune shift $\delta\omega_x / \omega_0 \equiv \delta\nu_x$, where ω_0 is the proton revolution frequency, equals to [16]:

$$\delta\nu_x = 2\delta\nu_{\max} \int_0^{1/2} \frac{I_0(\kappa_x u) - I_1(\kappa_x u)}{\exp(\kappa_x u + \kappa_y u)} I_0(\kappa_y u) du; \quad (2)$$

$$\kappa_{x,y} = \frac{A_{x,y}^2}{2\sigma_e^2}; \quad \delta\nu_{\max} = \frac{I_e m_e \sigma_x^2 L_e}{I_A m_p \sigma_e^2 4\pi\epsilon_n} \frac{1 + \beta_e}{\beta_e}.$$

Here $I_{0,1}(x)$ are the modified Bessel functions, L_e is the length of the electron beam, I_e is the electron current, I_A is the Alfvén current, m_e and m_p are electron and proton masses, ε_n is the normalized rms emittance, or the action average, of the proton beam, $\sigma_x = \sqrt{\varepsilon_n \beta_x / \gamma}$ is the beam rms size, where β_x is the ring beta-function at the lens location and γ is the relativistic factor. The two transverse emittances and beam sizes at the lens position are assumed to be identical. The tune shift versus amplitude parameters $A_{x,y} / \sigma_e$ is shown in Figure 1.

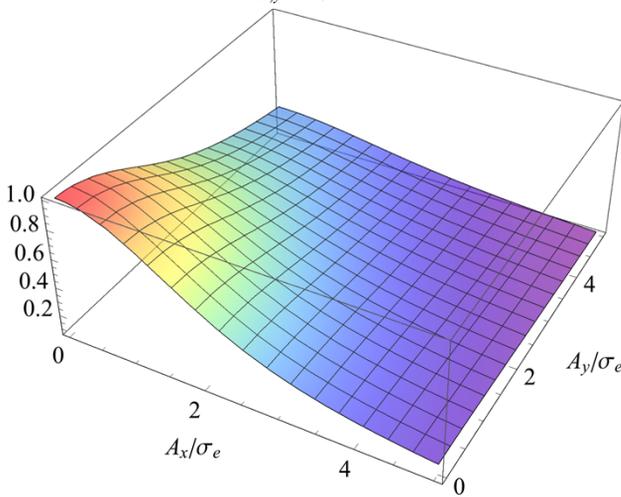


Figure 1: The incoherent tune shift by the round electron lens, $\delta\nu_x / \delta\nu_{\max}$, versus the particle transverse amplitudes, Eq. (2).

When the coherent tune shift Δq is much smaller than the longitudinal, or the synchrotron, tune, $\Delta q \ll \nu_s$, which is typical for high-energy colliders with feedbacks on, the beam stability is conventionally quantified by means of the stability diagram [3]:

$$D(\Delta\nu) = - \left(\int \frac{J_x \partial F / \partial J_x}{\Delta\nu - \delta\nu_x + i0} dJ_x dJ_y \right)^{-1} \quad (3)$$

Here F is the normalized phase space density as a function of actions $J_{x,y}$, so that $\iint dJ_x dJ_y F(J_x, J_y) = 1$; the symbol $i0$ stands for an infinitesimally small positive value in accordance with the Landau rule [2]. The function $D(\Delta\nu)$ maps the real axis in the complex plane onto a complex plane D , showing the stability thresholds for the coherent tune shifts Δq ; the beam is unstable if and only if there is a collective mode whose tune shift stays above the stability diagram D . In case of octupoles, the incoherent tune shifts are linear functions of the actions:

$$\begin{aligned} \delta\nu_x &= c_{xx} J_x / \varepsilon_n + c_{xy} J_y / \varepsilon_n; \\ \delta\nu_y &= c_{yx} J_x / \varepsilon_n + c_{yy} J_y / \varepsilon_n. \end{aligned} \quad (4)$$

For the LHC at 7 TeV with $\varepsilon_n = 2.5 \mu\text{m}$, its 168 Landau octupoles per beam, fed with the maximal current of 550 A, provide the nonlinearity matrix with $c_{xx} = c_{yy} = 1.05 \cdot 10^{-4}$; $c_{xy} = c_{yx} = -7.4 \cdot 10^{-5}$ [4]. The corresponding stability diagram for the positive sign of Landau octupoles is shown in Figure 2.

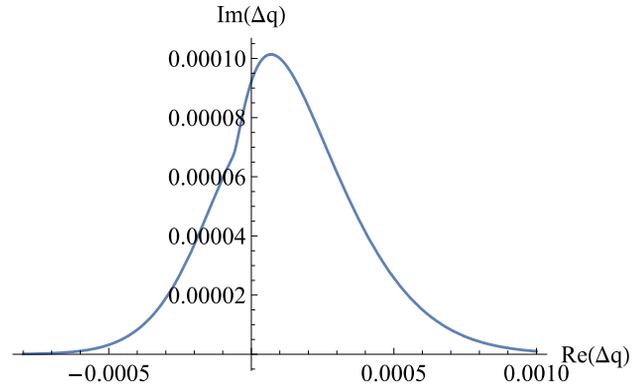


Figure 2: Stability diagram for the 7 TeV proton beams in LHC at the maximal strength of the Landau octupoles.

For the electron lens, the stability diagram, Eq.(3), with the tune shift $\delta\nu_x$ given by Eq.(2), is presented in Fig. 3 for various electron beam sizes and the same current density at the center; both real and imaginary parts of the diagram are in the units of $\delta\nu_{\max}$.

Table I lists the main parameters of the electron lens required to generate a tune spread $\delta\nu_{\max} = 0.01$ in the LHC. For the LHC parameters, such a lens provides approximately an order of magnitude larger stability diagram than the existing Landau octupoles all operating at their maximum current of 550 A. In the 50 TeV proton-proton Future Circular Collider, the same single lens would introduce the same tune spread $\delta\nu_{\max} = 0.01$, provided that the normalized emittance is the same and the beta-function scales as the energy, i.e. $\beta_x = 1.5 \text{ km}$ at the lens location in the FCC. To make similar stability diagram for the FCC, ~ 20000 LHC-type octupoles would be needed. The electron system parameters listed in Table I are either modest or comparable to the electron lenses already commissioned and operational for beam-beam compensation in the Tevatron proton-antiproton collider [13, 14] and in the Relativistic Heavy Ion Collider (RHIC) [15]. Given the flexibility of the electron lenses [10], they can be effectively used for proton beam stabilization at all stages of collider operation – at injection, on the energy ramps, during the low-beta squeeze, adjustment to collisions, and, if necessary, in collisions. Moreover, the electron current can be easily regulated over short time intervals and the electron lenses can be set to operate on a subset of least stable bunches in the accelerator or even on individual bunches, as was demonstrated in the Tevatron [16]. The increased betatron frequency spread $\delta\nu$ of about 0.004-0.01 induced by the electron lenses has been demonstrated in the 980 GeV

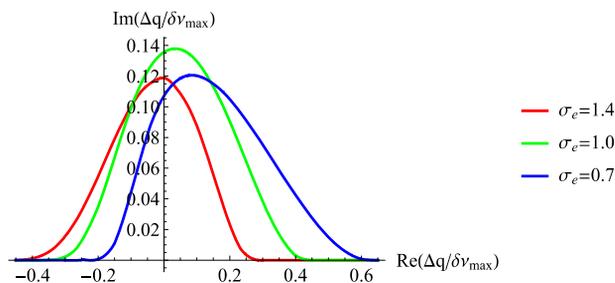


Figure 3: Electron lens beam stability diagrams are presented for various electron beam sizes (noted in units of the proton beam rms size), assuming the same current density at the center.

proton beam in the Tevatron [17] and in the RHIC 100 GeV polarized proton beams [18].

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CONCLUSION

Electron lenses are the proper Landau optical elements, since they can efficiently provide required nonlinearity where it is needed for beam stabilization, i.e. at the beam core, and do not introduce nonlinearity where it is detrimental for the lifetime, i.e. in the beam tails. Flexibility in the control of transverse electron charge distribution and fast current modulation allows the generation of the required spread of betatron frequencies by very short electron lenses with modest

Table 1: Electron beam requirements to generate the tune shift $\delta v_{\max} = 0.01$ in the 7 TeV LHC proton beams with $\epsilon_n = 2.5\mu\text{m}$.

Parameter	Symbol	Value
Length	L_e	2m
Betas	$\beta_{x,y}$	240m
E-current	I_e	0.8A
Fields	B_m / B_g	6.5/0.2 T

parameters, which have been demonstrated in the devices built so far. Landau damping by electron lenses is free of many drawbacks of other methods presently used or proposed – the lenses do not reduce the dynamic aperture and do not require numerous superconducting octupole magnets; they suppress all the unstable beam modes in contrast to available feedback systems which act only on the modes with non-zero dipole moment [4]; their efficiency will not be dependent on the bunch length as in an RF quadrupole based system, and corresponding single particle stability concerns due to synchro-betatron resonances will be avoided. All of this makes the Landau damping by electron lenses a unique instrument for the next generation high-current accelerators, including hadron supercolliders.

The technology of the electron lenses is well established and well up to the requirements of Landau damping in particle accelerators, as discussed above. Two electron lenses were built and installed in the Tevatron ring [13] at Fermilab, and two similar ones in the BNL's RHIC [18]. They employed some 10 kV Ampere-class electron beams of millimeter to submillimeter sizes with a variety of the transverse current distributions generated at the thermionic electron gun, including Gaussian ones. The electron beams in the lenses are very stable transversely being usually immersed in a strong magnetic field - about $B_g = 0.1-0.3$ T at the electron gun cathode and some $B_m = 1.0-6.5$ T inside a few meters long main superconducting solenoids. The electron beam transverse alignment on the high-energy beam is done by trajectory correctors to better than a small fraction of the rms beam size σ_e . The electron lens magnetic system adiabatically compresses the electron-beam cross-section area in the interaction region by the factor of $B_m/B_g \approx 10$ (variable from 2 to 60), proportionally increasing the current density j_e of the electron beam in the interaction region compared to its value on the gun cathode, usually of about 2-10 A/cm².

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