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LANDAU DAMPING WITH A TRANSVERSELY GAUSSIAN PULSED ELECTRON LENS

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Abstract

A pulsed electron lens produces a betatron tune shift along a hadron bunch as a function of the longitudinal coordinates, which is a longitudinal detuning. An example of transverse detuning is the tune shifts due to octupole magnets. This paper considers a pulsed electron lens as a measure to mitigate the head-tail instabilities. The analytical predictions are compared with the results of the particle tracking simulations. A pulsed electron lens is demonstrated to be a source of tune spread with two components: a static one, leading to Landau damping; and a dynamic one, leading to an effective impedance modification, which we demonstrate analytically and in our particle tracking simulations. The effective impedance modification can be important for beam stability due to devices causing longitudinal detuning, especially for nonzero head-tail modes. We explore two types of pulsed electron lenses: one with a homogeneous transverse distribution and another with a Gaussian distribution.

INTRODUCTION

Landau damping is [1] one of the mitigation measures against coherent beam instabilities [2, 3]. Recently, several works [4–8] studied mitigation of transverse instabilities by Landau damping with longitudinal detuning. Longitudinal detuning is detuning with longitudinal coordinates. One common type of longitudinal detuning is chromaticity. It depends on energy offset δ. Other examples of detuning with longitudinal coordinate z are a radio frequency quadrupole cavity (RFQ) or a pulsed electron lens (PEL).

Longitudinal detuning can be written as $\Delta Q(z,\delta) = \Delta Q(J_z,\varphi)$, where J_z, φ are the longitudinal action-angle variables. In contrast, transverse detuning, $\Delta Q(J_x,J_y)$ depends only on the transverse amplitudes J_x, J_y. This difference is because instability typically develops at the timescale of synchrotron motion. Transverse oscillations are much faster than longitudinal oscillations. Therefore only the amplitudes can be accounted for.

Figure 1 illustrates the layout of a PEL developed for the SIS100 heavy-ion synchrotron. An electron lens, in general, is a special device with its own low-energy electron beam. The electron lens acts as a nonlinear lens, where the electromagnetic field of the electron beam transversely focuses ion beam. A PEL was initially proposed for space-charge compensation [9] and investigated further in [10] for application in SIS100 heavy-ion synchrotron [11]. A prototype PEL is being developed [12, 13] to be installed in SIS18 heavy-ion synchrotron [14]. The authors of [4] showed that a PEL could also be a source of Landau damping.

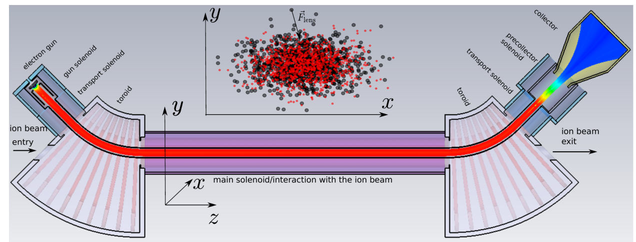

Figure 1: Schematic layout of a pulses electron lens. A transverse cross-section of ion and electron beams is shown above it in black and red, respectively.

Authors of Ref. [4, 5] demonstrated that longitudinal detuning can be split into two components. One is static detuning; it does not change during a synchrotron oscillation. Static longitudinal detuning was shown to be a source of Landau damping. This is similar to the transverse detuning (for example, from octupole magnets). Longitudinal detuning has another effect on the beam. It modifies the spectrum of head-tail modes. This leads to a modification of the effective impedance. Therefore, the dynamic detuning changes the instability growth rate and coherent frequency shift. This change is particularly large for nonzero head-tail modes.

PEL longitudinal detuning (with transversely homogeneous distribution) is described as

$$\Delta Q_y^{\parallel}(J_z,\varphi)/\Delta Q_{\max} = \underbrace{I_0^{(e)}\left(\frac{J_z}{2\varepsilon_z}\frac{\sigma_z^2}{\sigma_{e_\parallel}^2}\right)}_{\text{static}} + \underbrace{2\sum_{n=1}^{\infty} I_n^{(e)}\left(\frac{J_z}{2\varepsilon_z}\frac{\sigma_z^2}{\sigma_{e_\parallel}^2}\right)\cos(2n\varphi)}_{\text{dynamic}}, \quad (1)$$

where ϵ_z is the longitudinal rms emittance, σ_z is the rms bunch length, $\sigma_{e_\parallel}$ is the rms length of the electron beam pulse, $I_n^{(e)}(x) = e^{-x}I_n(x)$ are exponentially scaled modified Bessel functions of the first kind.

In Ref. [4], authors discussed transverse detuning $\Delta Q(J_x,J_y)$ and longitudinal detuning $\Delta Q(J_z,\varphi)$ and their linear combination $\Delta Q(J_x,J_y) + \Delta Q(J_z,\varphi)$. This corresponds to having, for example, both octupole magnets and a PEL in a single accelerator.

The dispersion relation for this case was given in Ref. [4]

$$N_1\Delta Q^{-1} = \int \frac{\frac{\partial \Psi_0}{\partial J_y} J_y |H_l^{p_0}|^2 \mathrm{d}J_z \mathrm{d}J_x \mathrm{d}J_y}{Q_{\mathrm{coh}} - Q_{y_0} - \langle \Delta Q_y^{\parallel}\rangle_\varphi - \Delta Q_y^{\perp} - lQ_{s_0}}, \quad (2)$$

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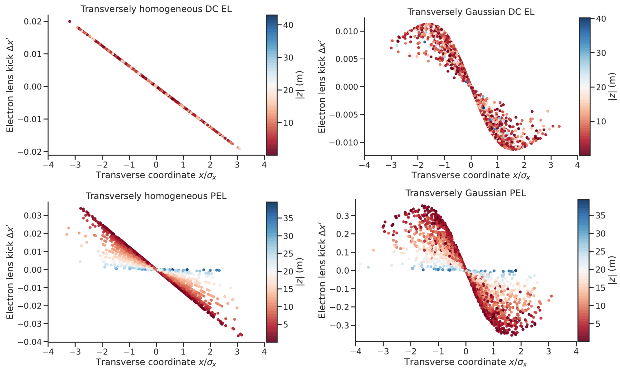

Figure 2: Kicks received by ion beam particles in the simulations from four different electron lens configurations. On the top row, DC EL with homogeneous transverse distribution (left) and Gaussian transverse distribution (right). On the bottom row, PEL with homogeneous transverse distribution (left) and Gaussian transverse distribution (right). The colour bar indicates the magnitude of the longitudinal position of a particle in the bunch.

where N_1 is the normalisation; Ψ_0 is the particle distribution; $H_l^{p_0}$ is a special function that depends on the dynamic component of longitudinal detuning; Q_{coh} is the coherent tune shift in the absence of Landau damping; Q_{y_0} is the bare tune; $\langle \Delta Q_y^{\parallel} \rangle_\varphi$ is the static component of longitudinal detuning; $\Delta Q_y^{\perp}$ is the transverse detuning; l is the head-tail mode number; Q_{s_0} is the synchrotron tune.

A more general combination of transverse and longitudinal detuning is $\Delta Q(J_x, J_y, J_z, \varphi)$. This corresponds to, for example, PEL with a transversely Gaussian distribution. In this contribution, we consider the case of transversely Gaussian PEL in the particle tracking simulations following Ref. [15]. We compare it to previous results of Ref. [4] for a transversely homogeneous PEL, a DC electron lens DC EL [16] (DC EL), Landau octupoles (LO) and a radio-frequency quadrupole cavity (RFQ) [8].

SIMULATION SETUP

In this contribution, we employ particle tracking code PyHEADTAIL [17]. For example, this code has been used for Landau damping studies and instabilities in [4–7]. It offers the flexibility to select a transverse electron distribution for the electron lens, such as homogeneous, Gaussian, or parabolic. The electron lens current can be constant or follow a Gaussian distribution that matches the ion beam longitudinal profile.

Figure 2 demonstrates kicks received by an ion beam from four different versions of an electron lens. In all four plots, each dot represents a different macroparticle. The colour map indicates their longitudinal position in the bunch. The top left plot shows a transversely homogeneous DC EL. In this case, all particles receive a linear kick depending on their transverse position. A transversely nonlinear kick from transversely Gaussian DC EL is shown in the top right.

Table 1: Instability Properties for Detuner Model Simulations

ξ	**mode l**	$\Re\Delta Q_{\mathrm{inst}}/Q_s$	$\Im\Delta Q_{\mathrm{inst}}/Q_s$
0.1	−1	−0.052	0.017
0.5	−2	−0.017	0.009
Q_s	1.74×10^{-3}	η	3.45×10^{-4}

We focus on two cases of head-tail instability, mode −1 and mode −2, and keep the chromaticities linear while using a wakefield to drive the instability. Table 1 summarizes the instability properties without detuning. Head-tail mode zero case is not considered here because Landau damping is the only significant effect for this mode. In Ref. [4], the authors showed that for head-tail mode zero Landau damping strength is roughly equal to the root-mean-squared (rms) ΔQ_{rms} detuning. This holds for both transverse and longitudinal detuning.

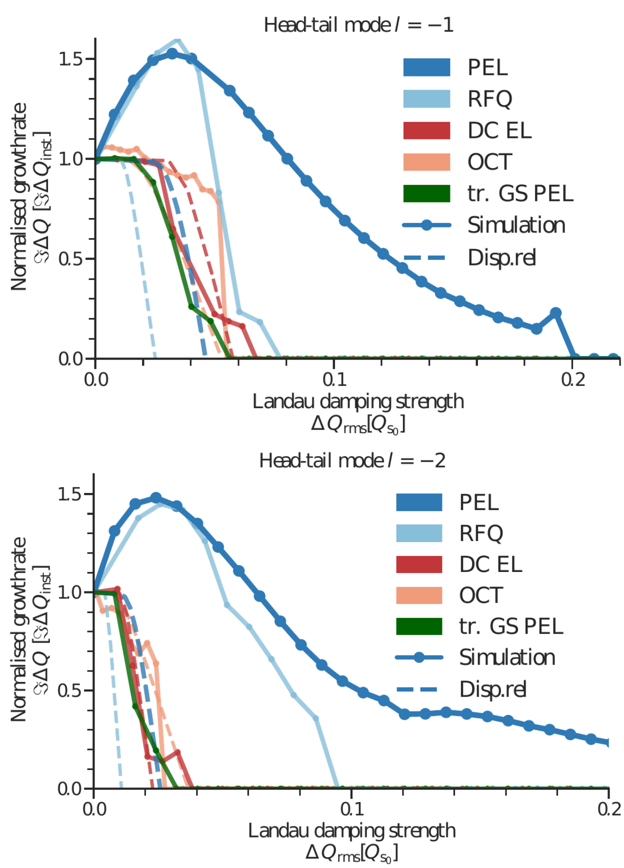

Figure 3: Instability growth rate (in simulations) dependency on the strength of Landau damping $\Delta Q_{\mathrm{rms}}/Q_{s_0}$ for head-tail mode $l = -1$ (top) and $l = -2$ (bottom). A PEL with a homogeneous transverse distribution of electron beam (dark blue), LO (yellow), a DC EL (red), an RFQ (light blue), a PEL with Gaussian transverse distribution of electron beam.

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RESULTS

Figure 3 shows the results of simulations with transversely Gaussian PEL (dark green). The figure shows how the growth rate of the instability changes with the strength of the Landau damping. The former is normalised to the growth rate without Landau damping. The latter is normalised to the synchrotron tuning Q_s.

These results are compared with the transverse detuning (octupoles in yellow, DC EL in red) and the longitudinal detuning (PEL in blue, RFQ in light blue). The approximation of Eq. (2) is shown in dashed lines with respective colours. Purely transverse detuning agrees with Eq. (2). In contrast, purely longitudinal detuning demonstrates instability amplification for small Landau damping strength. In Ref. [4, 5], this was attributed to the modification of the effective impedance by longitudinal detuning.

For the transversely Gaussian PEL, the initial amplification of the instability is absent. Instead, as in the case of transverse detuning, the instability growth rate decreases linearly with increasing Landau damping strength. The Landau damping strength required to suppress the instability closely matches that of a DC EL.

CONCLUSION

In summary, we considered a case of a transversely Gaussian PEL. This PEL configuration represents a combination of transverse and longitudinal detuning into a single device. We showed that in this configuration, PEL does not modify the effective impedance of the instability. The only effect observed in simulations is Landau damping. Combining transverse and longitudinal detuning in a single device will mitigate the effective impedance modification.

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