HALO REGENERATION IN INTENSE CHARGED PARTICLE BEAMS*

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Abstract

Halo is one important limiting factor for the continuous and reliable operation of intense electron or ion beam facilities, such as FELs and spallation neutron sources. A halo population outside the core of the beam can lead to uncontrolled beam loss, electron cloud effects and activation of the beam pipe, as well as beam quality degradation.
In this study, we focus on the issue of halo removal, by means of beam collimation, and subsequent halo regeneration. We compare the particle-core model of halo creation to accurate, self consistent particle-in-cell (PIC) simulations. We show that under certain conditions the halo is regenerated even after collimation. This can only be understood within the context of collective effects, particularly in the case of intense beams.

INTRODUCTION

As diagnostic techniques become more sophisticated, the possibility to fully reconstruct the phase space distribution becomes a reality. In particular, pinhole scans, tomography [1] and Optical Transition Radiation [2] have been employed in the past with success at the University of Maryland Electron Ring (UMER) and other facilities. In order to take full advantage of these diagnostic techniques for the case of halo, a better understanding of the properties of the halo distribution around the beam is needed.

Evolution of the Beam Distribution Function

The equation describing the evolution of the particle distribution function f is the Vlasov equation given in Eq. (1):

$$\frac{\partial f}{\partial z} + \vec{x}' \cdot \frac{\partial f}{\partial \vec{x}} + \frac{q\vec{E}}{\gamma m v_0^2} \cdot \frac{\partial f}{\partial \vec{x}'} = 0 \quad (1)$$

where the independent variable is the distance z traveled, v_0 is the beam velocity which is assumed to be constant and we used $\vec{x}' = \vec{v}/v_0$ instead of $\vec{v}$, following the paraxial approximation. The electrostatic field $\vec{E}$ is a function f and needs to be calculated self-consistently through Eq. (1).
One equilibrium solution of Eq. (1) is the thermal equilibrium (TE) distribution function, defined by:

$$f(\vec{x}, \vec{x}') = C_0 \exp\left(-\frac{\gamma m v_0^2 H_\perp(\vec{x}, \vec{x}')}{k_B T_\perp}\right) \quad (2)$$

where we follow the notation in [3]. The dimensionless Hamiltonian $H_\perp(\vec{x}, \vec{x}')$ is defined in Eq. (3) and $T_\perp$ is the transverse beam temperature, given in Eq. (4).

$$H_\perp = \frac{1}{2}\vec{x}'^2 + \frac{1}{2}k_0^2\vec{x}^2 + \frac{q}{\gamma m v_0^2}\phi(\vec{x}) \quad (3)$$

$$k_B T_\perp = m_e v_0^2 < x'^2 > \quad (4)$$

THE PARTICLE-CORE MODEL

The particle-core model has been used extensively to study the creation of halo [4, 5, 6]. In terms of the Vlasov equation (1), we can view the particle-core model as breaking the particle distribution function $f(\vec{x}, \vec{x}')$ in two parts, f_c for the core of the beam and f_h for the beam halo. Assuming that we have an independent solution for f_c, the core of the beam, and ignoring terms of second order in f_h, we can write the linearized Vlasov equation for the halo in Eq. (5)

$$\frac{\partial f_h}{\partial z} + \vec{x}' \frac{\partial f_h}{\partial \vec{x}} + \left(-k_0^2\vec{x} + \frac{q}{\gamma m v_0^2}\frac{\partial \phi_c}{\partial \vec{x}}\right)\frac{\partial f_h}{\partial \vec{x}'} = 0 \quad (5)$$

Eq. (5) includes the important simplification that ϕ_c is independent of f_h, and thus needs to be calculated from f_c. This of course violates the self consistency of the model, since an independent envelope code, simulation or other model is needed for the calculation of f_c.

In order to solve Eq. (5) we can use the method of characteristics, which effectively solves the Hamiltonian system described in Eq. (3), if the substitution $\phi = \phi_c$ is made. The potential ϕ_c can be calculated either from a simulation code, such as WARP, or by assuming a model for the beam core distribution, for example a uniform density, breathing core. In either of these cases, solving Eq. (5) is equivalent to solving the system:

$$\frac{\mathrm{d}\vec{x}}{\mathrm{d}z} = \frac{\partial H_\perp}{\partial \vec{x}'} = \vec{x}' \quad (6)$$

$$\frac{\mathrm{d}\vec{x}'}{\mathrm{d}z} = -\frac{\partial H_\perp}{\partial \vec{x}} = -k_0^2\vec{x} - \frac{q}{\gamma m v_0^2}\frac{\partial \phi_c}{\partial \vec{x}} \quad (7)$$

SIMULATION SETUP

In the following, we will assume a uniform focusing channel and an intense, non-relativistic electron beam, with a current of $I = 23$ mA and an initial emittance of $\epsilon_x = 48$ mm-mrad, corresponding to typical parameters for UMER. For a matched beam radius $a = 6.31$ mm, this leads to an external focusing force corresponding to $k_0 = \sqrt{10}$ m^{-1},betatron wavenumber depression ratio

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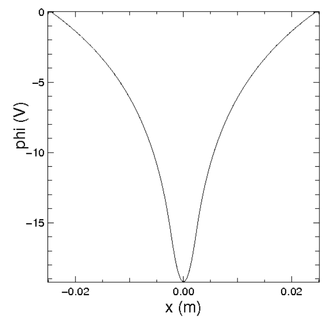


Figure 1: Plot of the beam self field due to space charge $\phi(x)$ for beam current $I = 23\text{mA}$

$k/k_0 = 0.3785$ and intensity parameter $\chi = 1 - k^2/k_0^2 = 0.85$.

For our simulations, we use the WARP particle-in-cell (PIC) code, which is self-consistent in the electrostatic approximation, and has been used with great success to model particle beams in the space charge dominated regime [7].

The initial distribution loaded into the simulation has the functional form of the TE distribution, but in order to launch an oscillatory mismatch mode, we set the initial beam radius to $r_i = 1.5a$ instead of the matched beam radius.

Distinguishing the Halo Particles

In order to distinguish the true halo population from the core of the beam, we draw an ellipse around the beam at each time step and label as halo particles all the particles outside of it, according to Eq. (8)

$$\frac{x_p^2}{X_{\text{rms}}^2} + \frac{y_p^2}{Y_{\text{rms}}^2} > \rho \tag{8}$$

where x_p and y_p are the particles positions in x and y respectively and X_{rms}, Y_{rms} the rms beam size in x and y. The parameter ρ is related to the ellipse axes and is empirically defined in terms of the beam distribution's standard deviation, in order to minimize the number of core particle outside the ellipse.

This way we have labeled, at the end of the simulation, all the particles that have ever ventured far from the beam core. We can now restart the same simulation, but already knowing which particles will eventually form the halo.

In addition, we know the self field due to space-charge of the beam, as shown in Fig. 1, and we can use it to find the solution of Eq. (5)

PROPERTIES OF THE BEAM HALO

Structure of the Parametric Resonance

In Fig. 2 we show the comparison of the PIC code particles (black) with the phase-space plot from the particle core model (red). In this case, we used the potential from a breathing mismatch mode, under the assumption of a uniform density beam. We find very good agreement in the outside resonant islands, but the core sizes differ. This is to be expected, since the detailed features of the beam distribution are ignored in the particle core model, but they obviously influence the core size and shape.

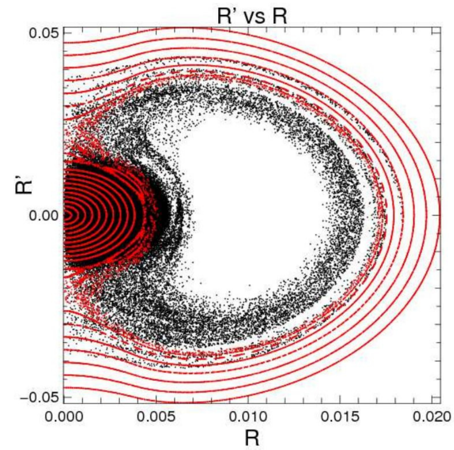


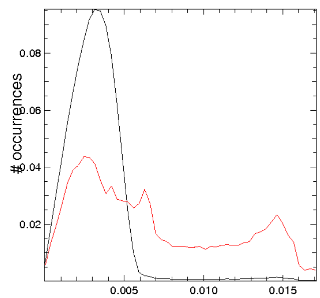
Figure 2: Comparison of WARP (black points) with particle-core model phase space (red lines) after 100 m or 400 envelope oscillations. No adjustable parameter.

Distribution of Halo Particles

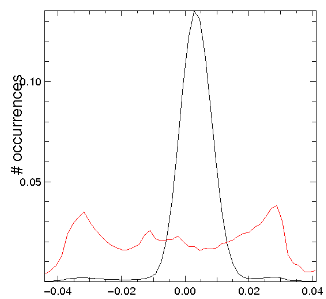
After the envelope oscillations have been damped and the halo has been fully formed, we have the distribution of the beam core and the beam halo as shown in Fig. 3. We note in Fig. 3(b) that while the main beam distribution in r' is monotonically decreasing for large $|r'|$ values, the beam halo distribution is not monotonic. Also, we see in 3(a) that a significant proportion of the halo particles are within the beam core at any given instant. These particles have high transverse velocities, and will hence be ejected from the beam core again. Nevertheless, this complicates the issue of halo removal by aperturing, since an aperture would only remove a portion of the halo, leaving the halo particles inside the beam core.

Halo Regeneration After Collimation

In our simulations we have the ability to remove the particles at the start of the beamline, which will eventually populate the halo. This will not affect the core of the beam, and in particular the beam will continue to be mismatched and perform axisymmetric oscillations. A simple view of the particle-core model would suggest that removing the resonant particles would prevent the halo from forming. Instead, we see that the halo is formed again, with new particles taking the place of the old ones, and in the same proportion as before. This is shown in Fig. 4

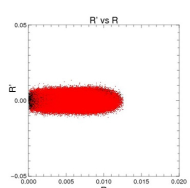


(a) Histogram of r values

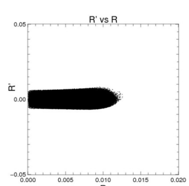


(b) Histogram of r' values

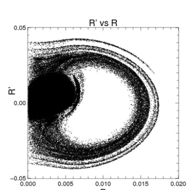
Figure 3: Histogram plots of r 3(a) and r' 3(b) for the main beam (black) and the halo (red). Note that all the histograms are normalized to unity area



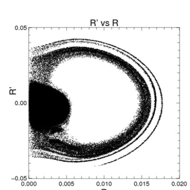
(a) Initial full beam



(b) Initial coll. beam



(c) Final full beam



(d) Final coll. beam

Figure 4: Ideal collimation process. The red (halo) particles in 4(a) are removed and we get 4(b). Propagating both by 100 m results in 4(c) and 4(d) respectively. The halo is still present in 4(d) despite the initial collimation.

CONCLUSION

We have studied the generation, evolution and regeneration of beam halo for an intense charged particle beam. Although comparisons with the self consistent PIC simulations agree well in the case of the resonance structures around the beam core, halo regeneration is not explained by the core model. Indeed, as long as the driving mechanism for halo creation (the mismatch oscillations) exists, the halo will be regenerated to the same extent. This happens because the space charge forces within the core redistribute the core particles, and hence new resonant particles take the place of the old ones.

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