SPACE CHARGE EFFECTS FOR THE ERL PROTOTYPE INJECTOR LINE AT DARESBURY LABORATORY

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Abstract

Daresbury Laboratory is currently building an Energy Recovery Linac Prototype (ERLP) that will operate at a beam energy of 35 MeV. In this paper we examine the space charge effects on the beam dynamics in the ERLP injector line. A Gaussian particle distribution is tracked with GPT (General Particle Tracer) through the injection line to the main linac to calculate the effect of 3D space charge in the dipoles. The nominal beam energy in the injection line is 8.3 MeV and the bunch charge 80 pC. The effects of space charge on the transverse and longitudinal emittance are studied for various electron beam parameter settings.

INTRODUCTION

Daresbury Laboratory is currently building an Energy Recovery Linac Prototype (ERLP) that will serve as a research and development facility for the study of beam dynamics and accelerator technology important to the design and construction of the proposed 4th Generation Light Source (4GLS) project [1]. Because of the relatively low beam energy of 8.3 MeV in the transfer line between injector and main linac, the space charge growth can be significant depending on the input emittance. This article gives several estimates of space charge effects in the injector line as well as comparisons between them. The first two estimates have already been described in some detail in a previous report [2] so only the results will be shown for comparison. The third is new and was done using the General Particle Tracer (GPT) code [3, 4]. The first two estimates - using ASTRA and an analytical formula [5] - involve only drifts and quadrupoles, since dipoles cannot be modelled with the present version of ASTRA. The GPT estimate includes the effect of bending magnets. To model dipoles GPT uses a full-featured anisotropic multi-grid space charge routine, described in detail in [3, 4]. Despite the fact it does not model bending magnets, the analytical formula for a drift was found to give a reasonable estimate of emittance growth in the injector line for ERLP.

All models considered use Gaussian longitudinal and parameters and top hat transverse distributions as it was found that these give good estimates of emittance increase in all cases, although the real phase space distribution is non-monotonic. Previous estimates [2] have shown that in our case the use of the expected phase space distribution (generated using ASTRA) can give apparent increases in the rms calculated emittances due to the strong tails in the distribution.

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SPACE CHARGE IN A DRIFT - ANALYTICAL FORMULAE

For a coasting beam with an elliptical beam cross section [5], the electric field inside the beam ($x^2/a^2 + y^2/b^2 < 1$) may be given by

$$E_x(x, y) = \frac{4I}{\nu}\frac{x}{a(a+b)}$$

$$E_y(x, y) = \frac{4I}{\nu}\frac{y}{b(a+b)}$$

where a and b are the transverse beams sizes, $I = I(s)$ is the current and $\nu = \beta c$ the longitudinal velocity. If we assume that the average kinetic energy of the transverse particle motion (or temperature) is much less than the electrostatic potential energy, then we have a laminar beam and can approximate the linear space charge effect by a defocusing quadrupole field (in both x and y planes) whose strength is given by

$$\frac{1}{F_x} = -\frac{4I(s)}{(\beta\gamma)^3 I_0}\frac{L}{a(a+b)}$$

where L is the drift length, s is the longitudinal coordinate, with a similar expression holding for the vertical plane. The condition for laminarity (for a circular beam with $a = b$) may be written as

$$\frac{\epsilon}{\beta_{x,y}} \ll \frac{2I}{(\beta\gamma)^3 I_0} \qquad (1)$$

where ϵ is the non-normalized transverse emittance, $\beta_{x,y}$ is the Twiss value in either the x or y plane, and γ, β are the relativistic factors. Using the sigma matrix transformation, the new Twiss parameters may be found from the starting values and hence the new emittance is given by

$$\epsilon_x = \epsilon_{x_0}\sqrt{1 + \beta_{x_0}^2\left[\left\langle\frac{1}{F_x^2}\right\rangle - \left\langle\frac{1}{F_x}\right\rangle^2\right]} \qquad (2)$$

where an average over the bunch length has been taken and the bunch is treated locally as a coasting beam. Details are given in Ref. [2].

For a Gaussian-distributed longitudinal distribution the current is given by $I(s) = I_{\max}\exp\left(-\frac{s^2}{2\sigma^2}\right)$, where s is the longitudinal coordinate, and

$$\left\langle \frac{1}{F_x^2} \right\rangle - \left\langle \frac{1}{F_x} \right\rangle^2 = \left(\frac{1}{F_x}\right)^2_{\max} \left(\frac{1}{\sqrt{3}} - \frac{1}{2}\right).$$

By using the above formula (2) it is now possible to approximate the emittance blow up in a drift. Provided the beam is laminar, agreement between this analytical formula and tracking with ASTRA has already been demonstrated in [2], both for drifts and also for a beamline which includes quadrupoles. To compare with GPT Figure 1 shows a particular case for an initial emittance of $\epsilon_{n_0} = 3$ μm. The parameters used were a 4 ps bunch length (1.2 mm) and a range of rms beam sizes from 1 mm to 16 mm.

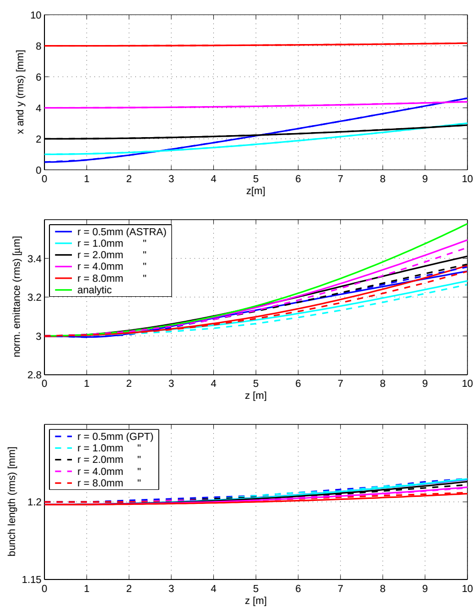

Figure 1: RMS beam size ($2r$ in plot), normalized emittance and bunch length increase for $\epsilon_{n_0} = 3$ μm.

INJECTOR LINE WITH QUADRUPOLES ONLY

To compare ASTRA with GPT for the ERLP injector, we performed an estimate of emittance growth that ignored dispersion by replacing dipoles with appropriately chosen quadrupoles to give an equivalent transverse focusing; both codes used identical distributions. The models were tracked with space charge and identical initial Gaussian distributions in both codes and a 4 ps (rms) bunch length. The comparison between these axially-symmetric models is shown in Figures 2 and 3.

INJECTOR LINE WITH DIPOLES

A full GPT simulation of the injector line including dipoles and space charge is shown in Figure 4: a comparison with ASTRA is of course not possible. However, we may compare the results given by GPT [4] together with

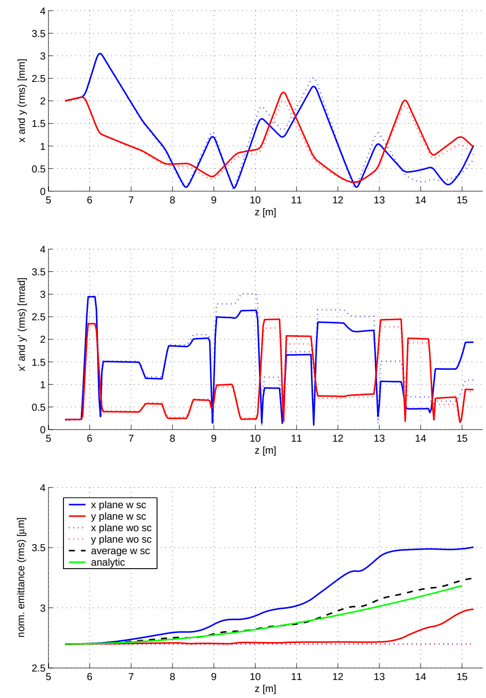

Figure 2: Transverse beam sizes, divergences and normalized emittance for a Gaussian distribution with space charge using ASTRA, together with the analytic estimate, for the axially-symmetric model.

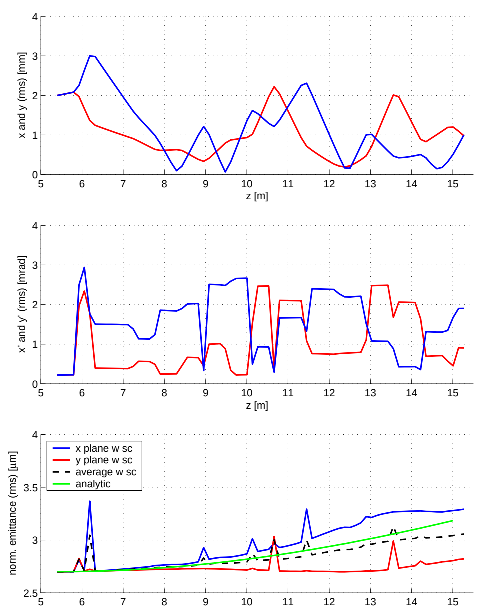

Figure 3: Transverse beam sizes, divergences and normalized emittance for a Gaussian distribution with space charge using GPT, together with the analytic estimate, for the axially-symmetric model.

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those using the Vinokurov approximation [5], and this is shown in the figure. Spikes in the emittance within the dipole magnets are artefacts arising from the way GPT calculates emittances in a curving trajectory: these should be disregarded. There is a remarkably good agreement between the emittance growth estimated analytically and the one modelled in GPT, except at the exit of the last dipole. The reason for the disparity in the last dipole is not yet understood.

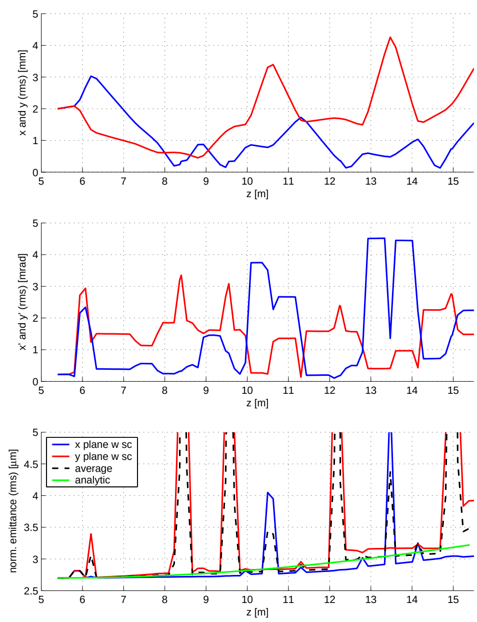

Figure 4: Transverse beam sizes, divergences and normalized emittance for a Gaussian distribution with space charge for GPT, together with the analytic estimate, for the injector model including dipoles.

Also shown in Figures 5 are the transverse and longitudinal distributions at the end of the injector line.

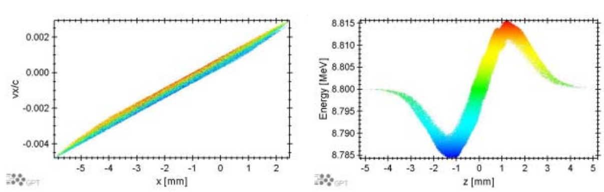

Figure 5: Transverse and longitudinal distribution at the end of the injector line of ERLP.

SUMMARY AND OUTLOOK

Good agreement between ASTRA and GPT is obtained in our parameter regime. Furthermore, the analytical formula due to Vinokurov still yields remarkably good estimates for the transverse emittance growth due to space charge even when dipoles are included, although full 3D calculation in GPT gives an emittance increase after the last dipole that is not expected from the Vinokurov estimate.

Tracking of the bunch from the exit of the booster to the entrance of the linac has shown that the emittance growth is acceptable, and verifies the Start-to-End estimates performed in [6].

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