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HIGHER ORDER CORRELATIONS IN COMPUTED PARTICLE DISTRIBUTIONS*

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ABSTRACT

The rms emittances calculated for beam distributions using computer simulations are frequently dominated by higher order aberrations. Thus there are substantial open areas in the phase space plots. It has long been observed that the rms emittance is not an invariant to beam manipulations. The usual emittance calculation removes the correlation between transverse displacement and transverse momentum. In this paper, we explore the possibility of defining higher order correlations that can be removed from the distribution to result in a lower limit to the realizable emittance. The intent is that by inserting the correct combinations of linear lenses at the proper position, the beam may recombine in a way that cancels the effects of some higher order forces. An example might be the non-linear transverse space charge forces which cause a beam to spread. If the beam is then refocused so that the same non-linear forces reverse the inward velocities, the resulting phase space distribution may reasonably approximate the original distribution. The approach to finding the location and strength of the proper lens to optimize the transported beam is based on work by Bruce Carlsten of Los Alamos National Laboratory.

1. INTRODUCTION

The motivation for this paper comes from the studies[1] by the authors of a photocathode injector system for a linear accelerator intended to be used for a Free Electron Laser (FEL). This work was done in collaboration with Sheffield *et al.*, of Los Alamos National Laboratory and followed along the lines of the system reported by Fraser.[2]

The methods used were reported by Hanerfeld,[3] and involved the extensive use of a Particle in Cell (PIC) program called MASK.[4] Similar methods have been employed by Jones and Peter[5,6)] using different programs. Their results, while differing in detail, are substantially consistent with the results from MASK. The results generally do not show the very low emittance needed for an FEL.[7] It is possible to carefully adjust the program diagnostics to match the experimental conditions and get substantial agreement. The end result however, is that a significant fraction of the emitted charge must be eliminated from consideration.

A different approach has been followed by McDonald[8] and by Carlsten and Sheffield.[9] They have used versions of the code PARMELA to follow the beam through a longer section of the beginning of the accelerator than is practical using a fully electromagnetic PIC code. The significant conclusion of these studies is that it is possible to adjust components in such a way that emittance growth that occurs early in the injection process can be substantially reduced in subsequent beam manipulations.

While most electron beam systems are emittance dominated, the laser photocathode is a space charge dominated system. For space charge dominated systems which have been studied for the application of intense heavy ion beams for Heavy Ion Fusion, it has long been observed that rms emittance is not conserved.[10] Carlsten has gone one step further and established a systematic way to examine sources of emittance growth and to design systems, principally solenoid lenses, to recover the emittance.[11] The design process is analagous to inserting sextupole lenses at selected positions in a magnetic beam transport system. The intent of the present study is to specifically test Carlsten's method for a simple case of a short slug of charge in a drift tube with a short solenoid lens to refocus the beam.

2. TRANSPORT SIMULATION

The beam transport simulation was made using the PIC code MASK. A short slug, 350 picoseconds long, carrying 10.8 nanocoulombs, is injected into a drift tube at 100 keV. The longitudinal distribution of the slug is trapezoidal and the transverse distribution is for a uniform beam. Thus the problem fits the conditions for Carlsten's criteria for "linear" forces on the beam particles. Note however, that the radial forces are not the same on the ends of the slug as in the middle. The initial conditions are for a perfectly parallel beam with zero emittance. The injection conditions were deliberately chosen to be low energy to avoid the generation of transient rf fields that could complicate understanding.

A composition picture of the bunch as it traverses through the drift section is shown in Fig. 1. Note that only one bunch is in the problem at a time. A short solenoid lens is located with its center at Z = 28, 32 and 36 cm, respectively, for different runs. With the nominal magnetic field (B_o), the focal length of the lens was found to be 22.2 centimeters.

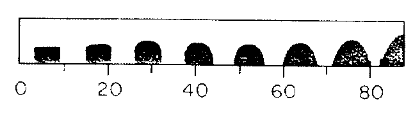

Fig. 1. Particle density plot from MASK showing a slug of charge, entering from the left, passing through a focusing lens and continuing essentially parallel.

As the beam begins to expand transversely, the weak forces at the ends of the slug fail to force the outer particles away as fast as occurs in the center of the slug. This results in the fan-shaped distribution shown in the first frame of Fig. 2, which is located at Z = 9 cm. The remaining frames of Fig. 2 are located after the solenoid lens and are at Z = 30, 56, 60, 75, and 87 cm., respectively. The focusing lens is located at Z = 28 cm for the results shown in Fig. 2. Ellipses superimposed on the particle distributions are appropriate for the phase space area and correlation for emittance given by

$$\epsilon_n = 4\left[\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2\right]^{1/2} \qquad (1)$$

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The last two frames in Fig. 2 show some particles branching away from the main ensemble. These are particles that have crossed the axis because of their lack of space charge forces. Although these particles do not affect the emittance calculations significantly, they do signal the onset of what Carlsten[11] calls α_{crit}, where $\alpha = 1/f$, f = focal length, and α_{crit} is the focusing strength which begins to cause crossovers.

28 cm. This results in a prediction of $\alpha_L = 0.068$, or focal length L = 15 cm, compared to the physical value of 22.2 noted earlier.

Having found that a reasonably precise location for the emittance minimum exists for a fixed magnetic field, B_o, it is interesting to try to vary the magnet to further reduce that minimum emittance. Accordingly, runs were made with $B = B_o \pm 5\%$.

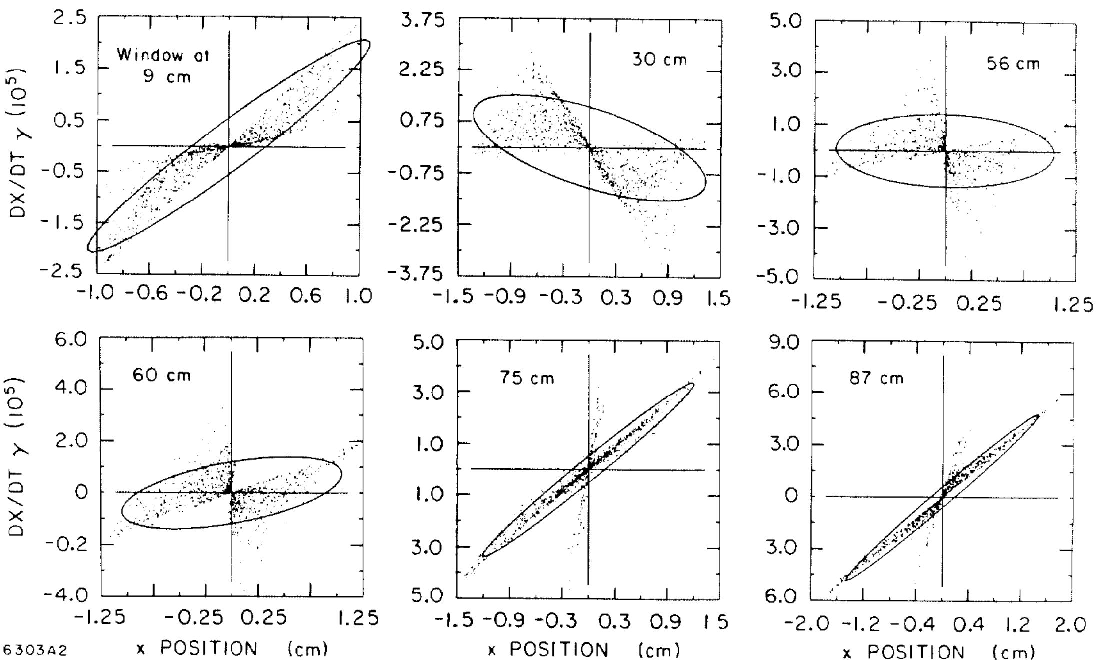

Fig. 2. Phase space plots from MASK following the case with the center of the focusing lens at Z = 28 cm.

Figure 3 shows plots of emittance vs. Z for three locations of the coil. It is notable that the minimum emittance is virtually the same for each of these curves. This is in agreement with Carlsten's conclusion that the emittance minimum can be projected arbitrarily far away. There are, of course, limits as in this instance, the lens cannot be any stronger because of crossovers and cannot be much weaker and still have the beam reconverge at all. Another practical limit of these simulations is that it is difficult to expand the length of the drift tube and retain the same mesh resolution. Thus we have not explored the location of the emittance minimum over a very wide range.

The emittance minimum does not occur near a beam waist, as expected, but is in fact somewhat downstream as found here. The low part of the emittance curve, plotted as a function of Z, all occurs after the beam waist. For the case of the center of the solenoid at Z = 28, the waist is at Z = 56 cm, which is very near the peak of the emittance curve. This may be because, for the reasons given above, there is very little convergence for this beam so that the waist is very near the lens. The emittance minimum for the case of the center of the solenoid at 28 cm, is at Z = 75 cm. The minimum emittance is expected to occur at a position z, measured from the center of the lens, if the focal strength of the lens is $\alpha_L = 1/f$, such that[11]

$$\alpha_L = 2\frac{z_1 + z}{z^2} \quad , \tag{2}$$

With the center of the solenoid at Z = 28 cm, the distance from the lens to the location of the minimum emittance, z, is 47 cm. The distance z_1 from the waist at Z = 0 to the lens center is

A slight, but perceptibly lower, minimum was found at 0.95 B_o, as shown in Fig. 4. The case for 1.05 B_o, not shown, resulted in higher emittance but was complicated by the crossover problem.

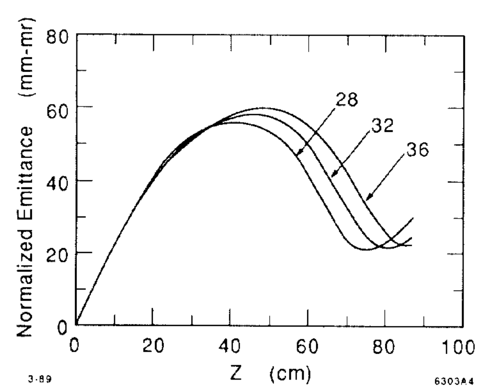

Fig. 3. Emittance vs. Z for three locations of the focusing lens.

3. CONCLUSIONS

The foregoing is a very preliminary look at some of the predictions of Carlsten's paper[11] in an attempt to find the logic in the disagreements between the methods of modeling. Qualitative agreement was found, especially with the shape of the

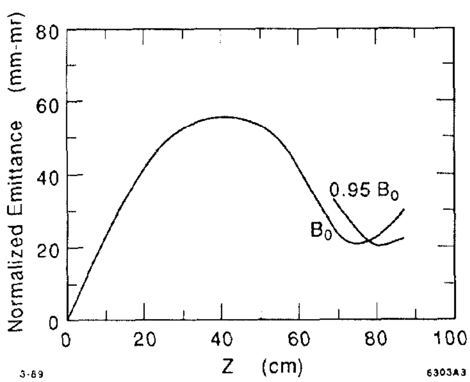

Fig. 4. Emittance vs. Z for the focusing lens at Z = 28 cm and two difference values for the magnetic field.

curve of emittance as a function of Z. Specific predictions of lens strengths and the location of the beam waist relative to the emittance minimum were not confirmed, but the cause for this has not been determined. It could well be that the conditions of the test are not ideal.

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