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### Title

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## **Particle-in-Cell Simulations of the Dynamic Aperture of the HCX\***

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### **ABSTRACT**

The HIF-VNL High Current Experiment (HCX) [1] is exploring transport issues such as dynamic aperture, effects of quadrupole rotation, and the effects on the beam of non-ideal distribution function, mismatch, and electrons, using one driver-scale 0.2 microcoulomb/m, 2-10 microsecond coasting K<sup>+</sup> beam. 2D and 3D simulations are being done, using the particle-in-cell (PIC) code WARP to study these phenomena. We present results which predict that the dynamic aperture in the electrostatic focusing transport section will be set by particle loss.

**KEYWORDS:** heavy ion fusion, ion linear accelerator, dynamic aperture

### **INTRODUCTION**

The High Current Experiment (HCX), an experiment of the U.S. Heavy Ion Fusion Virtual National Laboratory located at LBNL, employs a driver-scale beam to investigate transport limits for heavy ion fusion induction linac drivers. The beam is a coasting K<sup>+</sup> beam which is transported through an alternating gradient (AG) lattice of electrostatic quadrupoles. The quadrupole electrode radius has been selected to eliminate the dodecapole field component (i.e., electrode radius = 8/7 x aperture radius). At present the current, I, is 185 mA at 1 MeV, for preliminary experiments and commissioning. Expected eventual parameters are 555 mA at 1.8 MeV. In this report, the dynamic aperture of the HCX, transport lattice, which is expected to be similar to an electrostatic-focus section of a driver, is investigated, using the transverse 2D version of the particle-in-cell (PIC) simulation. code WARP [2]. Since the dynamic aperture sets the amount of

charge allowable in a single beam, and therefore the number of beams and beam radius needed to transport enough charge to implode the target, it will also determine the radius of the induction cores surrounding the multiple beam array in a driver, and the number of focusing elements. It thus has a significant impact on the design of future experiments and the cost of the driver.

## **SIMULATION MODEL**

The PIC simulations reported here followed a transverse slice of the beam through 50 periods of AG lattice. The beam energy was assumed to be 1.8 MeV. The HCX focusing fields were modelled at each  $z$  by means of multipole moments derived from a 3D solution of the Poisson equation, which included cylindrical quadrupole electrodes and the charged plates supporting them in the calculation. Moments up to  $\cos 10\theta$  were included, with a  $z$  resolution of 3.3 mm. Image forces for the same focusing structure, assuming perfect conductors, were calculated at each timestep using a capacitive matrix technique. The radius from the current channel center to the surface of the electrodes was 2.3 cm. A square conducting box at 4.9 cm bounded the 512 x 512 cell computational grid. 80 timesteps per lattice period of 0.4352 m were used, giving adequate resolution of the fringe fields. The beam in these calculations is space-charge-dominated, with phase advance per lattice period,  $\sigma_0$ , a factor of 7-9 below its undepressed value. The initial emittance was set to 5 times the thermal emittance of a 0.1 eV, 5 cm radius source for a beam of 576 mA, in line with present experimental results, and scaled with the square root of the current for other values, simulating the effect of changing the source diameter for the same diode/injector. This scaling neglects differences in injector aberrations with

beam size. Since ultimately the injector would be designed for the desired current, this is a reasonable approximation.

The dynamic aperture was explored using a semigaussian distribution function, since the driver is expected to have a similarly uniform beam. In order to simulate the effect of various aperture filling fractions in the driver, for several different values of the focusing strength, as measured by  $\sigma_0$ , the current was increased until beam quality suffered. In the HCX it is easier to explore the effect of aperture-filling by decreasing the focusing strength, while keeping the current constant. In the results below, this procedure is compared with the above constant- $\sigma_0$  method. As noted in a previous publication [3], nonlinear focusing forces and, to a greater extent, image forces, produce a mismatch in the beam, if it is matched assuming linear forces. The PIC code was therefore used to iterate on initial rms beam radii and angles until an rms matched (to +/- ~1-2%) beam was produced.

## **SIMULATION RESULTS**

Simulations were performed over 50 lattice periods for  $\sigma_0$  of 60°, 70°, and 80°, since the focusing strength of the driver is expected to be in this range. At each  $\sigma_0$  the beam current was increased until beam quality degraded. For each  $\sigma_0$ , particle loss began while emittance was still within acceptable bounds. Therefore the useable aperture is set for this lattice by particle loss, rather than by emittance growth. For 60° and 70° there was no emittance growth. At 80° a few percent growth was seen over the 50 lattice periods, and the same slow linear growth of emittance continued in 100 period simulations.

Particle loss as a function of percent filling of the radial aperture (i.e., ratio of beam major radius to radial distance to the focusing electrode surface, in percent) is shown in

Fig. 1. From this one can see that for  $\sigma_0$  of  $60^\circ$  and  $70^\circ$ , eliminating particle loss and the attendant electron and gas production would mean using  $\leq 80\%$  of the radial aperture. (It should be noted that the simulation does not generate electrons and gas when particles hit the wall, but only removes the particle from the calculation.) More aperture must be added if the beam has a larger mismatch, or a halo, or is misaligned. For  $\sigma_0 = 80^\circ$  loss begins when the beam fills 70-75% of the aperture, and is always larger than for the lower  $\sigma_0$ 's. This increased particle loss and the slight emittance growth mentioned above are likely to be caused by the same phenomenon seen in the experiments of Tiefenback [4] and calculations of I. Haber [5] in the 1980's, which may be indicative of the boundary of stability for the envelope mode for space-charge-dominated beams. The final phase and configuration spaces of the beam particles are shown in Fig. 2 for  $s=60^\circ$ , and radial filling factor of 86%. The beam is slightly diamond-shaped due to image forces, but otherwise the plots are unremarkable. Plots are similar for other values of  $\sigma_0$ , with a very small amount of "s"-ing in the x-x' plot for  $80^\circ$ .

In another set of calculations, the beam current was held fixed at 555 mA, while  $\sigma_0$  was decreased from  $60^\circ$  in order to increase the beam radius. This procedure is the easiest to use in HCX experiments. Again no emittance growth was observed, and particle loss began when the beam radius was about 80% of the physical radial aperture. Phase spaces were similar to the runs at constant  $\sigma_0$ . This gives confidence that this method of exploring the aperture will give information relevant to the driver case, though the limiting beam size occurred at much lower  $\sigma_0$  than is driver-relevant, namely,  $45^\circ$ .

## CONCLUSIONS

The simulations described here for a semigaussian distribution indicate that particle loss, rather than emittance growth, defines the dynamic aperture for the HCX electrostatic focusing lattice. Particle loss begins when the ratio of the beam major radius to the radial distance to the quadrupole electrode is approximately 80% for a well-matched centered beam with negligible halo. When  $\sigma_0$  reaches approximately  $80^\circ$ , loss increases, and there is slow emittance growth  $\sim$  a few percent in 50 lattice periods. Increasing the beam radius by (1) changing the focusing strength at constant current, and (2) changing the current at constant focusing strength, seem to give similar results for particle loss and dynamics.

#### **FIGURE CAPTIONS**

Figure 1. Particle loss is shown as a function of percent of radial aperture filled, for (1)  $\sigma_0$  of  $60^\circ$ ,  $70^\circ$ , and  $80^\circ$  with varying current, and (2) varying  $\sigma_0$  for  $I=555$  mA.

Figure 2. Configuration and phase space contour plots after 50 lattice periods for  $\sigma_0=60^\circ$ ,  $I=849$  mA (fills 86% of radial aperture). Units of x and y are meters.

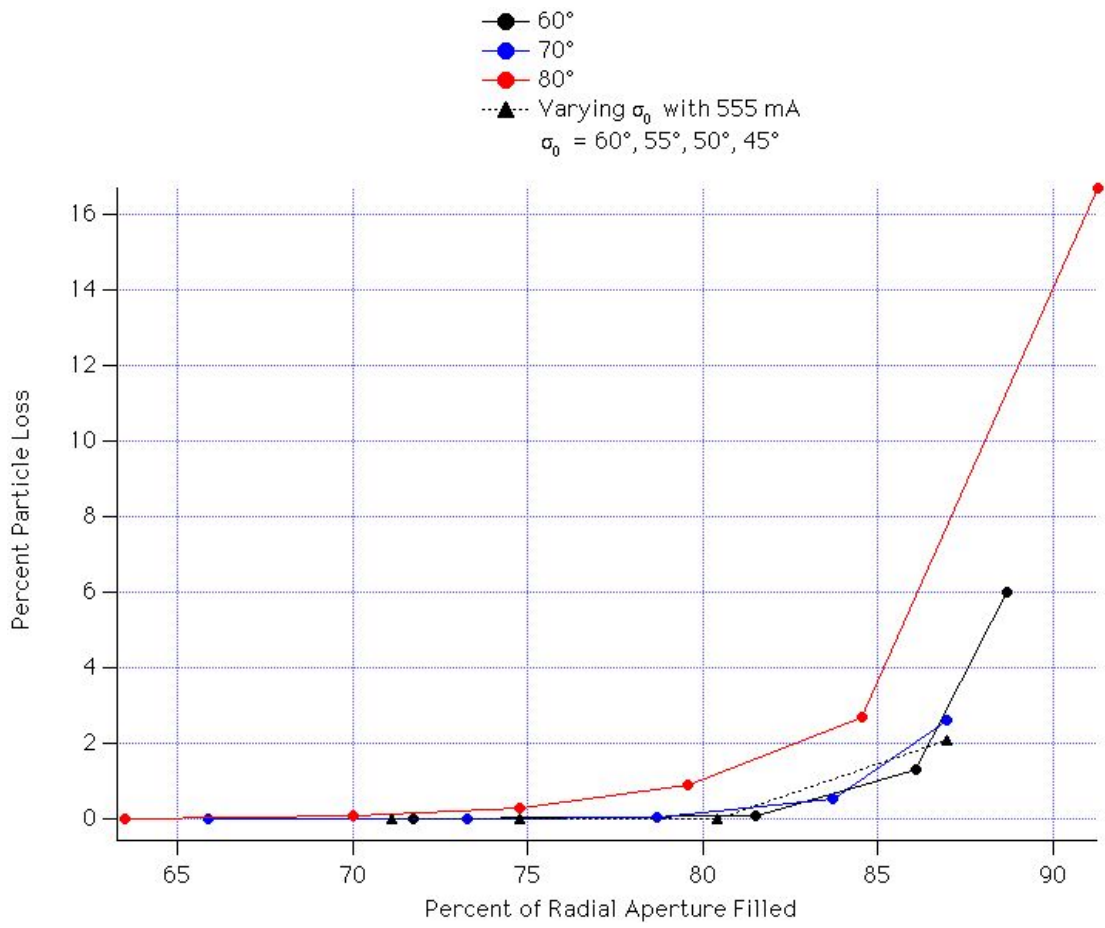
#### **REFERENCES**

[1]

[2]

[3]

**Don't forget DOE attribution.**



**Figure 1**

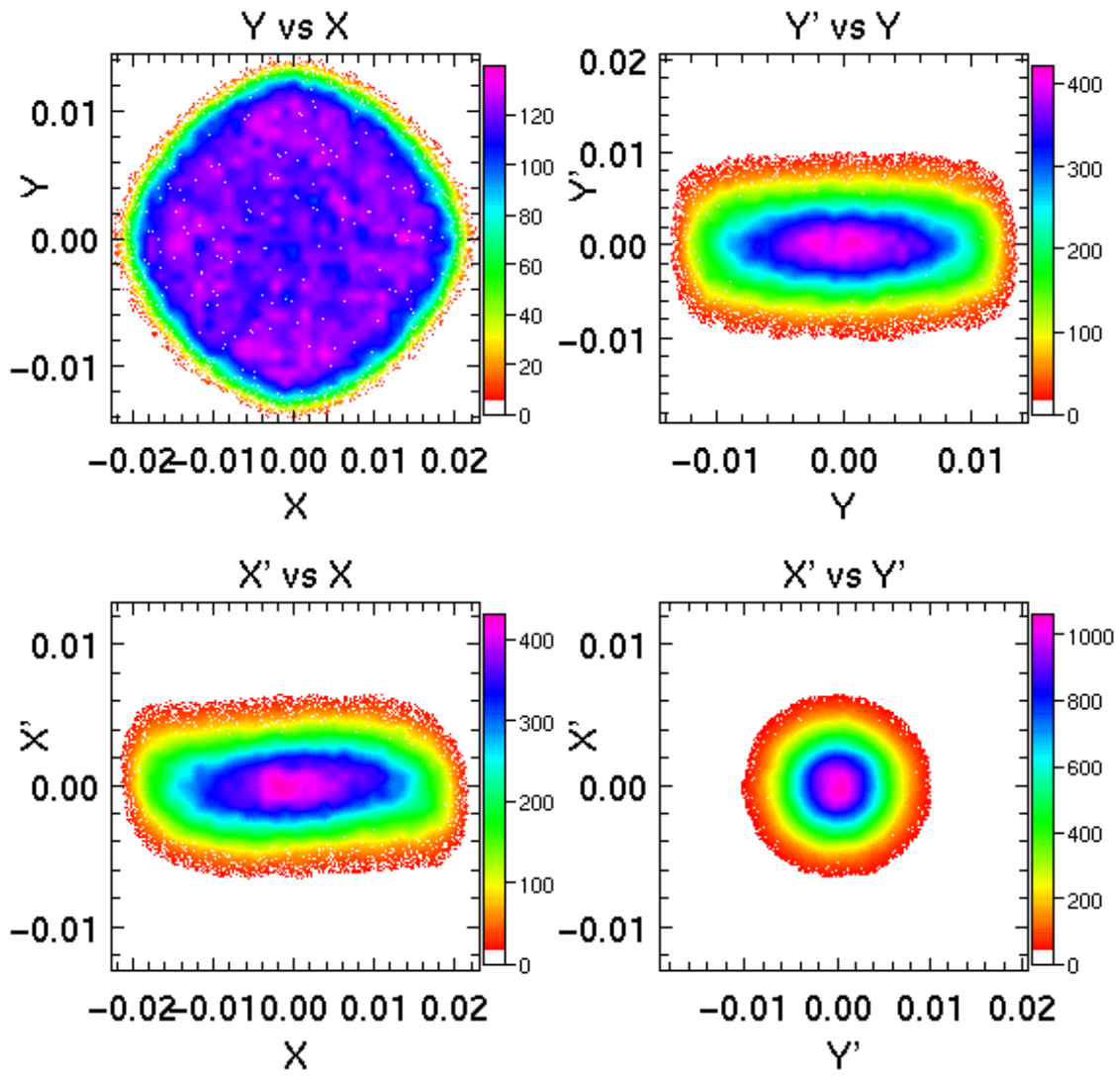


Figure 2