PARTICLE-IN-CELL SIMULATIONS OF THE HIGH CURRENT EXPERIMENT*

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Abstract

The particle-in-cell code WARP has been used to simulate beam dynamics for the intense ion beam of the High Current Experiment. First a study was done of the dynamic aperture of the alternating-gradient electrostatic quadrupole lattice of the experiment, including nonlinearity due to image forces and imperfections of the focusing lattice field. It was found that particle loss, rather than emittance growth, determined the usable aperture. Simulations of transport in the High Current Experiment were then performed, and the results compared to measured data. We present the results of both of these studies.

INTRODUCTION

The High Current Experiment (HCX) [1], a Heavy Ion Fusion Virtual National Laboratory experiment located at LBNL, employs a driver-scale beam to investigate transport limits for heavy ion inertial fusion induction linac drivers. The beam is a coasting K^+ beam, which is transported through an alternating gradient FODO lattice. At present the current, I, is 185 mA at 1 MeV, and the lattice consists of a ten-electrostatic-quadrupole alternating-gradient system, followed by four magnetic quadrupoles. Expected eventual parameters are 555 mA at 1.8 MeV.

In this report, the dynamic aperture of the HCX electrostatic 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]. The dynamic aperture is an important cost factor for a heavy ion fusion power plant accelerator. In the driver, multiple (~100) beams will be accelerated in parallel through common induction cores. An increase in the aperture necessary for each beam will have a large impact on the radius of the induction core and focusing structures, and thus on the size, weight, and cost of the accelerator.

Two sets of results are reported here. In the first, scaling studies were performed with an initially semigaussian beam, varying the current and undepressed betatron tune of the lattice, in order to find the dynamic aperture of the system for an idealized beam. In the second, the simulation was initialized with a particle distribution function synthesized using data from the upstream end of the HCX experiment, just after the matching section, in order to compare the results with experiment.

* Supported by the Office of Fusion Energy Science, US DOE, contract numbers DE-AC03-76SF00098 and W-7405-Eng-48.

SIMULATION MODEL FOR DYNAMIC APERTURE SCALING STUDIES

We discuss first the calculations made to determine the dynamic aperture of an alternating gradient focusing lattice assumed to consist of the HCX electrostatic lattice, lengthened to 50 lattice periods in order to have sensitivity to longer-length-scale effects. The quadrupole structure is shown in Fig. 1. The quadrupole electrode radius was selected to eliminate the dodecapole field component (i.e., electrode radius = 8/7 x aperture radius). The HCX focusing fields were modelled at each z by means of multipole moments derived from a 3D solution of the Poisson equation for the HCX quadrupoles, which included in the calculation the cylindrical quadrupole electrodes and the charged plates supporting them. Moments giving potential values greater than 1.5% of the quadrupole potential at a radius of 85% of the quadrupole aperture (aperture =2.3 cm, given by the quadrupole electrode surface) were included, with a z resolution of 0.85 mm. Image forces for the same focusing structure, assuming perfect conductors, were calculated at each timestep using a capacitive matrix technique. A square conducting box at 4.9 cm bounded the 512 x 512 cell computational grid. 80 timesteps per lattice period (lattice period = 0.4352 m) were used, giving adequate resolution of the fringe fields.

The simulations followed a transverse slice of the beam through 50 periods of alternating gradient lattice. The beam energy was assumed to be 1.8 MeV. The initial emittance was set to 5 times the thermal emittance of a 0.1 eV, 5 cm radius source for a beam with I=576 mA. It was then scaled with the square root of the current for other values of the current, 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 approximation seems reasonable. The emittance values used correspond to a space-charge-dominated beam, with phase advance per lattice period, σ, a factor of 7-9 below its undepressed value.

An initially semigaussian distribution function was used for the scaling study because the driver is expected to have a similarly uniform beam. In order to simulate the effect of various aperture filling fractions in the

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driver, for each of several values of the focusing strength (as measured by the undepressed betatron phase advance, σ_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-σ_0 method.

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 the beam was rms-matched to +/- ~1-2%.

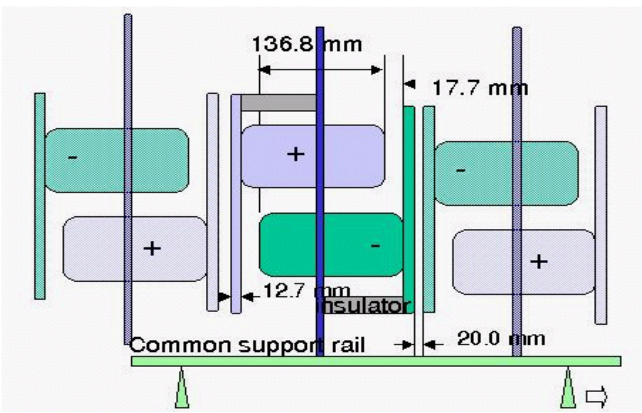

Figure 1: An HCX electrostatic quadrupole

SCALING STUDY RESULTS

Simulations for the scaling studies were performed over 50 lattice periods for σ_0 of 60°, 70°, and 80°, since the focusing strength of the driver is expected to be in this range. At each σ_0 the beam current was increased until beam quality degraded. For each σ_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 (0.04 π mm-mrad) was seen over the 50 lattice periods, and the same slow linear growth of emittance continued in 100-period simulations. In all cases the final phase and configuration spaces of the beam particles were unremarkable, except for a slight diamond-shape in configuration space, due to image forces (see Fig. 2 for final phase and configuration space plots).

Particles are lost from the calculation if they reach the radius of the quadrupole electrode surface (0.23 m). The simulation does not generate electrons and gas when particles hit the wall, as would occur in the experiment. Therefore the amount of loss for a given set of conditions is not considered realistic, though it is indicative of the extent of the halo formed and the approximate z position of the beam when particle loss begins. It was found that for σ_0 of 60° and 70°, eliminating particle loss and the attendant electron and gas production required using ≤ 80% of the radial aperture. More aperture must be added if the beam is mismatched, has more halo, or is misaligned. For σ_0 = 80°, loss began when the beam filled 70-75% of the aperture, and was always larger than for the lower σ_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 [3], which may be indicative of the boundary of stability for the envelope mode for space-charge-dominated beams.

In another set of calculations, the beam current was held fixed at 555 mA, while σ_0 was decreased from 60° 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 major radius was about 80% of the physical radial aperture. Phase spaces were similar to the runs at constant σ_0. This gives confidence that exploring the aperture by decreasing the lattice focusing strength will give information relevant to the driver case.

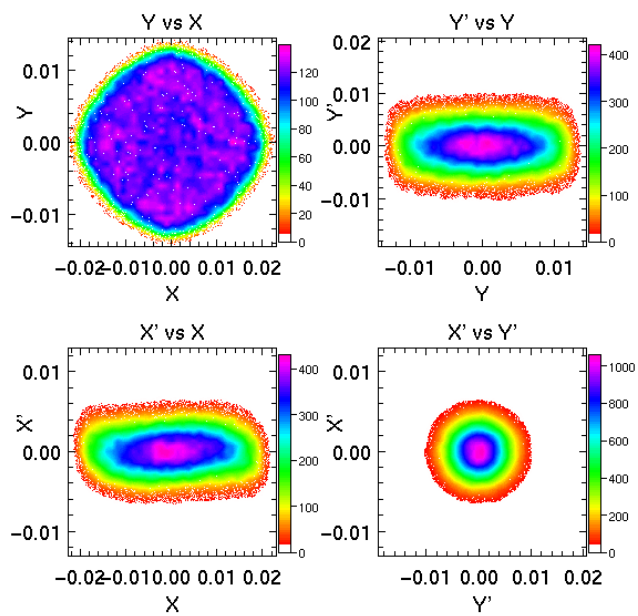

Figure 2: Configuration and phase space contour plots after 50 lattice periods for σ_0=60°, I=849 mA (fills 86% of radial aperture). Units of x and y are meters.

SIMULATIONS OF THE HCX BEAM

The HCX has been used to experimentally explore the dynamic aperture of the electrostatic quadrupole lattice. At this point measurements have been done for radial filling factors, a_{max}/R, (where "a" is the beam major radius and "R" is the quadrupole aperture radius) of 60% and 80% [4]. For both cases, the experiment showed no emittance growth, and particle loss consistent with charge-exchange loss from background gas. This is in agreement with the simulation results discussed above for the semigaussian beam, which for the length of the HCX

10-quadrupole lattice shows no beam loss or emittance growth. Background gas effects are not included in the simulation. However the HCX beam distribution function differs significantly from the semigaussian model. Therefore a simulation was performed for the 60% filling case, using as the initial distribution function a particle distribution determined by measurement.

The distribution function in the x-x', y-y', and x-y phase planes was measured using slit scanners just downstream of the matching section after the HCX injector. Monte Carlo methods [5] were then used to synthesize a distribution function from the data. Note that measurement in these three planes is not sufficient to uniquely determine the distribution function, so additional assumptions about the distribution were required. The choices made are discussed in detail in ref. [5]. A slice near the center of the beam pulse was transported in the simulation (and experiment) through the 10 electrostatic quadrupoles of the HCX lattice. The current was 175 mA with initial measured emittances of 0.43 π mm-mrad for x and 0.37 π mm-mrad for y, and σ_0=65°.

The results are shown in Fig. 3. Though there is rough agreement between simulation and data in final beam size and some features, such as the beam hollowing in configuration space, there is obvious disagreement in distribution function details. As discussed further in Ref. [5], data from a new prototype optical diagnostic [6] (slit + scintillator) indicates that there are distribution function correlations in planes not measured by the slit scanners, which therefore are not reflected in the synthesized distribution function. Optical diagnostics now in the development and design stage will provide these correlations, so that better agreement can be obtained. An important result of the studies reported here is that such previously unmeasured correlations must be included in order to obtain accurate predictions from the simulation.

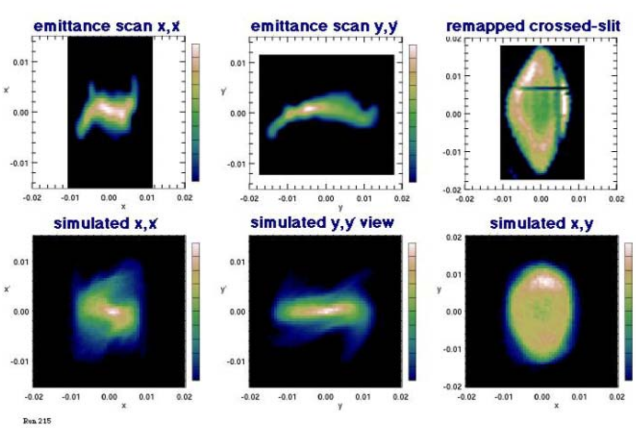

Figure 3: Distribution function in x-x', y-y', and x-y (from left to right) planes after 10-quadrupole transport in the HCX, from measured data (top row) and simulation.

CONCLUSIONS

2D particle simulations for a initially semigaussian distribution indicate that particle loss, rather than emittance growth, defines the dynamic aperture for the HCX electrostatic focusing lattice. For a well-matched centered beam with negligible halo and $\sigma_0 < 80°$, particle loss begins when the ratio of the beam major radius to the radial distance to the quadrupole electrode is approximately 80%. When σ_0 reaches approximately 80°, loss increases, and there is slow emittance growth ~ 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.

A simulation was also done for a distribution synthesized from slitscan measurements of the distribution function in the x-x', y-y', and x-y planes. The results show significant disagreement with experiment. Optical diagnostic data indicates that the possible source of the disagreement is the presence of correlations in planes not measured by the slitscanners. Diagnostics now being designed are expected to provide data needed to resolve the discrepancies.

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