MODELING ACCELERATION OF HIGH INTENSITY SPACE-CHARGE-DOMINATED BEAMS*

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Abstract

Accelerating gradually a space-charge-dominated beam can be fundamentally different from beams at lower intensities. At sufficiently high beam intensities the beam response to acceleration can excite resonances that are modified by space-charge leading to unexpected beam losses. This work examines acceleration of the beam of the University of Maryland Electron Ring (UMER) [1]. The physics of the high current, low-energy and space-charge-dominated electron beam, in UMER is applicable, on a scaled basis, to a large class of other beam systems [2]. We use the WARP particle-in-cell code to perform simulations that are compared with theoretical predictions. We also benchmark the simulation model against experimental data using the momentum compaction quantity.

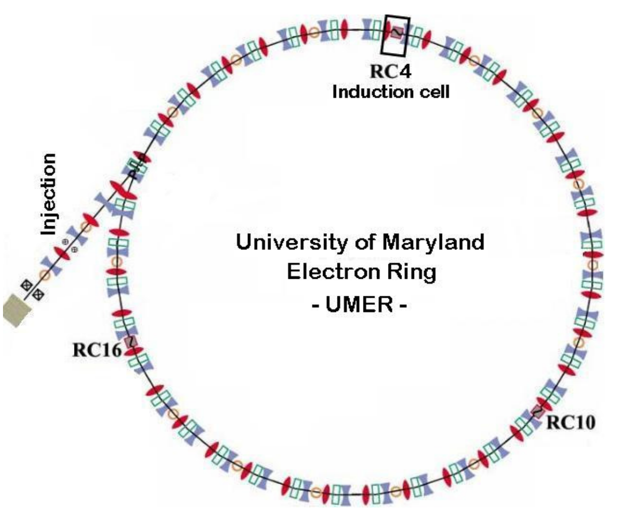

Figure 1: University of Maryland Electron Ring layout, showing the actual induction cell location at RC4, and the places for two additional induction cells at RC10 and RC16. The total circumference of the ring is 11.52 m, and the induction cells are equally distant from each other.

INTRODUCTION

In order to accelerate an ion beam to energies in the range of 50-100GeV, an attractive concept is the use of a recirculator. Employing a scaled experiment using a nonrelativistic electron beam, which already exists (UMER), we are addressing the physics of an ion recirculator, as is proposed for Heavy Ion Inertial Fusion (HIF) applications [3]. Due to the low energy and high perveance, the UMER beam accesses the same range of intensities as an HIF driver.

In this paper, we report on a theoretical and computational study for the design of an acceleration stage for UMER. Initially we take advantage of one induction module already installed in the machine, at RC4 as is showed schematically in the Fig. 1, which has been used for longitudinal compression at the moment [see B. Beaudoin work in this proceeding –FR5PFP058].

This initial study concentrates on what is the maximum energy we can accelerate to without much modification to the machine, so as to quickly access the physics of induction acceleration.

ACCELERATION STUDY

The Table 1 summarizes the expected parameters for different initial kinetic energies, calculated theoretically [4] keeping the current of the quadrupoles fixed on the full operating point, which means, using maximum quadrupole current possible.

Table 1: Beam Parameters as Function of Kinetic Energy

Parameter	10 keV	15 keV	20 keV
$\beta\gamma$	0.199	0.218	0.244
Peak Current (mA)	99.40	109.99	122.04
Generalized Perveance, K	0.00149	0.00124	0.00099
4*RMS unnorm. Emitt. (µm)	60	55	49
Zero-Current Tune ν_0	7.6	6.1	5.2
Beam radius (mm)	9.7	8.9	8.3
Tune Depression ν/ν_0	0.158	0.173	0.183

The unnormalized emittance is calculated knowing that the square root of the kinetic energy times the unnormalized emittance is a constant. The tune depression ν/ν_0 defines whether a beam is space charge dominated or emittance dominated. For $0<\nu/\nu_0<0.707$ the beam is space-charge-dominate, if not, is emittance-dominated beam. Therefore, UMER beam is space-charge-dominated during all the acceleration process.

WARP SIMULATIONS

Particle-in-cell simulations exploring the consequences of the acceleration have been carried out using the two-dimensional transverse slice model of the WARP code [5]. WARP simulations increasing UMER beam energy from 10 keV to around 20 keV, using up to three induction gaps are being conducted. In the present work, we concentrate

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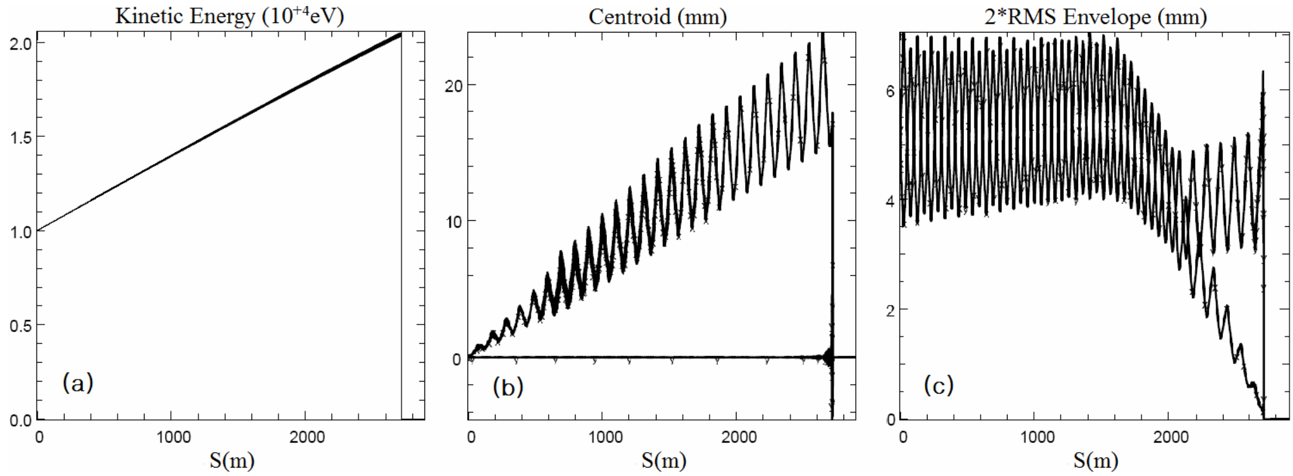

Figure 2: WARP simulation results for 23 mA beam in UMER with 50 V gap up to 250 turns. We present a scenario for acceleration to around 20 keV with a mixture lattice errors and mismatched beam envelope. From left to right, respectively: (a) kinetic energy increasing gradually up to 21 keV; (b) x and y centroid decoupled from each other, with x component oscillations up to 24 mm, which means centroid hitting the pipe and losing all the particles from this point; (c) envelope oscillations initially coupled and slightly decreasing with energy growth, showing the instant when the x component starts touch the pipe and losing particles, decoupling the x and y components until total beam disappearance.

on the actual acceleration schedule of UMER, using one induction gap applying a constant field of 50 V, although it has been tested using a broader range of configurations. The goal was to find out the best feasible design, which is the one that keeps a reasonable beam quality, minimizing particle losses and emittance growth, with affordable engineering changes in the future. It was concluded that lower increments in energy maintain the beam more stable, with less particle losses through centroid instabilities and halo formation.

Once a specific acceleration schedule was chosen, the main goal was to investigate the limits imposed by such a configuration, on the full operation point. We tested for different beam configurations including beam energy, current and/or radius, as well numerical parameters, like number of particles, resolution and time step.

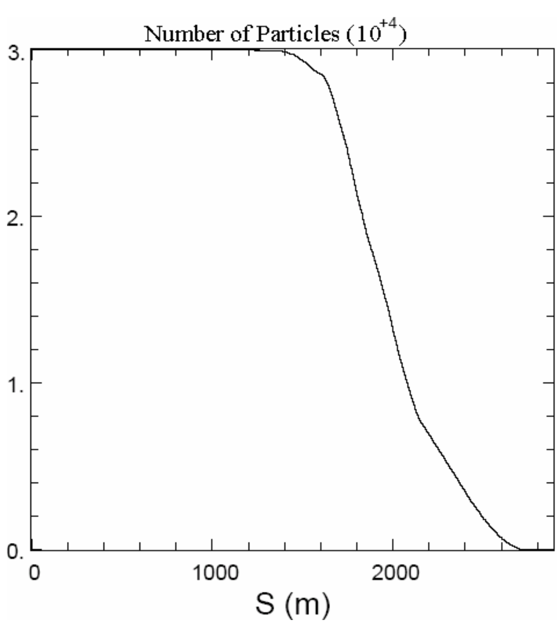

Figure 3: Number of Particles.

We used a semi-Gaussian distribution for the initial particle distribution of the 23.5mA electron beam with the relation between the beam and the pipe radius of approximately 20%. The initial energy used was 10 keV and the initial unnormalized 4*RMS emittance has the value of 39 µm in both transversal planes [6]. We compress the beam longitudinally in order to keep the length constant, to avoid longitudinal instabilities and further emittance growth.

To test the robustness of the design, we introduce 1% random errors in the quadrupoles in the simulations, using a Gaussian distribution, and centroid displacements simultaneously in position and momentum. We also tested the effect of the longitudinal energy spread of the particles.

Numerical Results

Figure 2 points out a limitation test, using one gap of 50 V, i.e., increasing beam energy by 50 V per turn, where is showed, respectively, the increment of the kinetic energy, the centroid oscillation initializing from the zero, which is also the pipe axis, and the 2*RMS envelope evolution and Figure 3 shows how the number of particles decays. The break point in the 235th turn, at 2,707 m, refers to the time with there is no particles anymore, i.e., in which all the particles were lost by hitting the pipe.

The possibility to accelerate UMER beam up to 20keV is a very interesting result given by WARP simulation. It is worthy further investigation on different mechanisms to more efficiently control the centroid oscillations without ramping dipoles in the case of acceleration up to 20 keV. Although accelerating UMER beam up to around 15 keV seems totally affordable at the moment and it is already an important advance.

BENCHMARKING THE SIMULATIONS: MOMENTUM COMPACTION

Since the acceleration changes the beam momentum, and it is well known that particles with different momenta oscillate about different equilibrium orbits, to investigate the momentum compaction became an important issue in the acceleration context. Momentum compaction is defined as a measure for the variation in equilibrium radius due to a variation in momentum [4], expressed as $\alpha = (dL/L)/(dp/p)$. This is also the first-order effect of the chromaticity, which can leads to a changing of the betatron oscillation frequency, causing emittance growth. This variation in betatron frequencies can also drive the head-tail instability because they have phase difference between them, and the growth rate is proportional to the chromaticity.

The knowledge of the dispersion behaviour of the UMER beam will enable deeper understanding about the beam dynamics and give to us one more tool to improve the design of the machine.

Experimental Comparison

We compared the WARP simulation results for momentum compaction with the experimental measurements from energy scan at UMER, using the 23.5 mA beam in both cases.

The range in energy used in the numerical simulations was from 10 keV to 16 keV, taking data with 1 keV steps, using the induction gap of 50 V to accelerate the beam. In the experiment, the energy range is from 9.7 keV to 10.3 keV, taking data with 0.1 keV steps, and using 83% operational point. In the energy scan experiment, the energy beam is changed from the gun, since the source, and it is constant for each run.

It is showed in the Fig. 4 the results from the numerical data and from the experimental data with an agreement of about 92%. In both cases the resolution of the linear fit is very high as is possible to check though the variable R^2.

This information also works as a feedback about how reliable the WARP code is in simulating the UMER beam dynamics.

CONCLUSIONS

In the next stage of this research, Earth field will be considered, as well as longitudinal dynamics will be analysed using three-dimensional simulations on WARP.

The results showed in this work are preliminary but point towards the feasibility of acceleration on UMER without major technological changes in the machine. We also conclude that simulations using the WARP particle-in-cell code have been successful in explaining UMER beam behaviour. Accelerating the UMER beam even just up to 15 keV appears possible to opens new opportunities to research on space-charge-dominated beams.

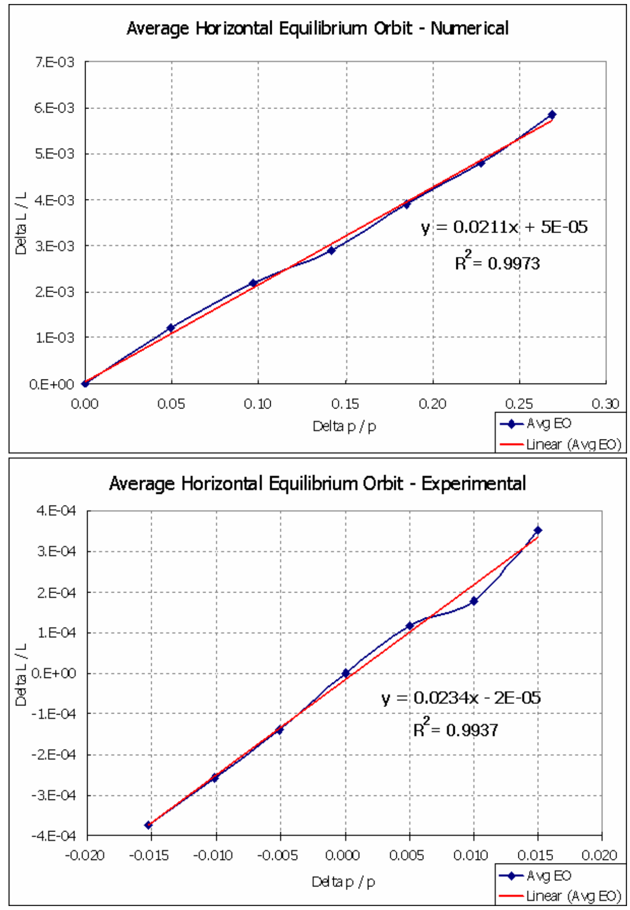

Figure 4: Comparison among numerical and experimental results for momentum compaction, by fitting data of the average of the horizontal equilibrium orbit as function of variation on momentum.

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