Design of a scaled recirculator for Heavy Ion Inertial Fusion

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Abstract. An alternative concept for Heavy Ion Inertial Fusion (HIF) is the use of a recirculator to accelerate ion beams to energies in the range of 50-100 GeV [1]. The physics of an ion recirculator can be explored by means of scaled experiments in a compact machine like the existing University of Maryland Electron Ring (UMER). UMER has been successfully used for the study of the fundamental physics of space-charge-dominated transport using a 10 keV electron beam with up to 100 mA of current (or 10 nC per a 100 ns pulse) [2]. 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 computational study for the design of an acceleration stage for UMER using an induction cell. Using the two-dimensional transverse slice model in the particle-in-cell code WARP we show that it is possible to accelerate the UMER beam up to 20 keV without major modifications to the machine. Such acceleration enables future experiments on transverse resonance crossing and studies on longitudinal pulse behavior.

Introduction

The physics of the space-charge-dominated electron beam transport is applicable, on a scaled basis, to a large class of other beam systems [3]. In order to accelerate an ion beam to energies in the range of 50-100 GeV, an attractive concept is the use of a recirculator, as is proposed for Heavy Ion Inertial Fusion (HIF) applications [1]. Because the recirculator concept entails the repeated passage of the beam through the same lattice, emittance growth, halo formation and possible beam losses and activation of the vacuum pipe are major concerns. In addition, the crossing of betatron resonances as the beam accelerates is not sufficiently understood for space-charge dominated beam transport.

Employing a scaled experiment using a nonrelativistic electron beam at the University of Maryland Electron Ring (UMER), we are able to address the physics of an ion recirculator. The UMER lattice includes three induction gaps equally spaced in the ring, although at the present moment just one induction gap is in operation, for longitudinal focusing and acceleration [4]. The UMER lattice comprises 36 FODO (focusing-defocusing) cells in an 11.52 m circumference. The beam parameters are: 0.5-100 mA beam current at 10 keV nominal energy; 1.6 - 13 µm, normalized, 4 x rms emittance; < 10 mm average beam radius. The operating tunes are in the range $v_{0x,y}=5.0 - 8.0$. With these parameters, tune depressions in the range 0.14 - 0.9 are possible, which cover those envisioned in a future HIF driver [2].

We report on a computational study using the particle-in-cell code WARP [5] for the design of an acceleration schedule to double the nominal energy of 10 keV, turning UMER into a recirculator. We address the transverse beam dynamics issues involved in accelerating the UMER beam to the
maximum possible energy achievable without ramp the bending dipole magnets or implementing any other major change in the machine operation. A future paper will look at accelerating to higher energies under more general operating conditions.

**WARP simulations**

WARP is a multi-dimensional particle-in-cell and accelerator code [5]. Using the two-dimensional transverse slice model of the WARP code we explored the consequences of the acceleration on UMER. The two transverse dimensions are $x$ and $y$ in the lab frame, in a right handed Cartesian system with $x$ on the horizontal and $y$ on the vertical. Using these coordinates, the unnormalized $4 \times$ rms emittance is

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

where brackets $\langle \rangle$ indicate average over a certain distribution. The horizontal coordinate of the beam centroid is $\langle x \rangle$, defined as the center of the charge particle distribution, and the effective beam $x$-semi axis (envelope $x$-size) is

$$
2\left[\left\langle (x - \langle x \rangle)^2 \right\rangle \right]^{1/2}. 
$$

The WARP simulations with initial kinetic energy at 10 keV, using one induction gap to accelerate, are conducted to investigate a realistic acceleration schedule for UMER. The goal is to find the best feasible design, which ideally keeps a reasonable beam quality, minimizing particle losses and emittance growth, with no engineering changes. In order to do so we tested different parameter combinations such as beam energy, beam current, centroid displacements and envelope matching. A matched beam envelope has the same periodicity of the focusing lattice as the solution of the Kapchinskij-Vladimirskij (KV) envelope equations. We also tested numerical parameters, e.g. number of particles, resolution and time step. The initial particle distribution is semi-Gaussian in all simulations; this distribution corresponds to a uniform density in configuration space, but a Gaussian profile in velocity space.

Since the planned experiments for acceleration in UMER will include longitudinal beam confinement [4], the simulations incorporate the main effect. In the simulations this is taken in consideration by changing the weight of particles as the current increases due to the compression of the beam longitudinally. Analytical calculations show that the current increases from 99.4 mA at 10 keV to 122.04 mA at 20 keV. The paper concentrates, however, on the transverse dynamics as the longitudinal dynamics play a secondary role.

After choosing an acceleration schedule, we explore the limits imposed by such acceleration using different values of bare tune using different sets of current values.

Preliminary results show that one gap of 50 V, i.e., increasing the beam energy by 50 V per turn is a viable option for initial experiments on acceleration in UMER. A simulation with an idealized quadrupole/dipole lattice (no strength or mechanical errors) using a 23.5 mA beam is shown in Figure 1. The graphs illustrate the evolution, over some 100 turns, of (a) kinetic energy, (b) centroid oscillation and (c) $4 \times$ rms unnormalized emittance. The centroid motion remains stable, despite the growing amplitude of the oscillations caused by the constant bending dipole fields (i.e., no ramping).

Figure 2 shows results from a simulation using the same 50 V gap as before but over 250 turns, and including errors. To test the robustness of the design in the simulations, we introduce 1% random errors in the quadrupole strengths, using a Gaussian distribution, as well as initial rms mismatch (envelope) and injection (centroid) errors. The results in Fig. 2 correspond to the worst-case scenario where acceleration was possible up to 20 keV even with a 15% mismatched beam envelope, which drives oscillation of a breathing envelope mode [6]. From left to right: (a) kinetic energy increases gradually to 20 keV; (b) $x$ and $y$ centroid coordinates decouple from each other, with the $x$ component oscillating and growing up to 24 mm, causing the centroid to hit the pipe and cause complete beam loss. The $y$ component doesn't oscillate, as expected for bending on the horizontal plane exclusively; and (c) envelope oscillations that are initially coupled and slightly decrease with energy growth. Also shown is the instant when the $x$ component reaches the pipe and complete beam loss occurs. This
occurs at the 235th turn, or 2,707 m. For UMER this is a remarkable result since our previous recent mark was 100 turns using 0.6 mA beam [4].

The simulation results shown in Figure 3 refer to a lower beam current of 7 mA, but a faster one-gap acceleration schedule of 1.0 kV per turn over 5 turns. The initial energy is 10 keV, and the nominal operating tune is close to 6.4. From (a), (b), and (c) we see that faster acceleration leads to faster instabilities, most probably caused by the mismatch between the beam energy and the focusing strength of the lattice. The maximum amplitude of the centroid oscillations is already 10 mm by the second turn, which brings the beam close to the vacuum pipe wall and can lead to additional instabilities, as for example through image forces [7]. The centroid oscillations (a) also point out to transverse resonance crossings, which are expected since the zero-current (bare) tune changes as the energy increases, from 7.6 at 10 keV to 5.09 at 15 keV. However resonance phenomena in this context must be carefully studied. The decreasing envelope pattern seen after some 2.5 turns in Fig. 3 (b) is due to particle losses as well as the breathing envelope oscillations from mismatch [6]. It is seen from (c) that the number of particles decays very quickly due to all these effects together.

![Figure 1](image1.png)

**Figure 1** - Ideal simulation using a 50 V/turn induction gap to accelerate a 23 mA electron beam from 10 keV to 15 keV over 100 turns. (a) kinetic energy change, (b) the x-component of the centroid oscillates relative to the pipe axis due to the lack of dipole ramping, and (c) the 4 x rms emittance growth seen is modest.

![Figure 2](image2.png)

**Figure 2** - Worst case scenario of acceleration of 23 mA electron beam with 50 V/turn induction gap. The simulation implements a combination of errors: 1% quadrupole strength errors and 15% mismatched envelope. (a) Kinetic energy increases to 20 keV, (b) x-component of the centroid oscillates and grows until reaching the wall, and (c) mismatched 2 x rms envelope oscillations until beam disappearance.
Conclusion

The existing induction module in UMER can in principle be used to accelerate electron beams with different acceleration schedules with no dipole ramping. Simulations with the WARP code show that, as expected, acceleration schedules that use lower increments in energy gain per turn help to maintain better beam stability. The simulations demonstrate the possibility to accelerate a 23 mA electron beam in UMER from 10 keV to 20 keV in some 200 turns. However, without ramping dipoles, better control of errors including envelope mismatch is necessary to keep centroid and envelope oscillations from leading to beam losses. Acceleration of a 7 mA beam to 15 keV seems much more feasible at this stage in the UMER project. It opens new opportunities for research in space-charge-dominated beams, especially in resonance crossing [8], an area relevant to HIF and other advanced accelerator concepts.

The results showed in this work are preliminary but are pointing towards the feasibility of acceleration in UMER without major changes to the machine. Currently, we are also studying the possibility to start beams at lower energies in order to have a bigger range for acceleration. The next stage of this research will involve detailed longitudinal dynamics studies using three-dimensional simulations in WARP.

The authors would like to acknowledge the US Dept. of Energy Offices of Fusion Energy Sciences and High Energy Physics, and the Office of Naval Research for funding this work.

References

[1] J. J Barnard, et al., in Phys. Fluids B: Plasma Phys. 5 (1993) 2698.
[2] R.A. Kishek, et al., Nucl. Instr. and Meth., in Phys. Res. A 544 (2005) 179.
[3] I. Haber, et al., Nucl. Instr. and Meth., in Phys. Res. A 606 (2009) 64.
[4] B. Beaudoin, et al., Proceedings of the 2009 Particle Accelerator Conference, Vancouver, CA, to be published.
[5] D.P. Grote, et al., Nucl. Instr. and Meth., in Phys. Res. A 415 (1998) 428.
[6] R.L. Gluckstern, Phys. Rev. Lett. 73, N. 9, (1994) 1247.
[7] K. Fiuza, R. Pakter, F.B. Rizzato, Physics of Plasmas, v. 13 (2006) 023101.
[8] A. Friedmann, et al., Nucl. Instr. and Meth., in Phys. Res. A, 415 (1998) 455.