DESIGN AND SIMULATION OF AN EXTRACTION SECTION FOR THE UNIVERSITY OF MARYLAND ELECTRON RING*

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Abstract

The University of Maryland Electron Ring (UMER) is a low-energy scaled facility for the study of intense beam dynamics, relevant to higher energy, high intensity accelerators. Many parameters crucial to understanding high-current beam evolution, such as transverse emittance and longitudinal temperature, lend themselves to the use of interceptive diagnostics. We present plans to build a UMER extraction section, in order to enable turn-by-turn interceptive measurements. This paper presents a suite of simulations used to guide the design process and predict extraction performance, utilizing the WARP Particle-in-cell (PIC) code. After isolating a design based on centroid tracking, extraction acceptance is probed. Remaining questions include estimating the error tolerances of the modified ring and refining an enlarged dipole magnet design.

INTRODUCTION

The University of Maryland Electron Ring (UMER) is a small-scale experiment dedicated to the study of high intensity beam dynamics. The need for high intensity beams in modern accelerators is motivated by several applications, including observation of rare events in particle physics and greater power in medical accelerators. The 10 keV, 11.52 meter ring is a low-cost, accessible experiment, while the physics is scalable to intense proton or ion machines.

Beam intensities range from the emittance dominated to the space charge dominated regime, where the extremely dense electron bunch is governed by intra-beam Coulomb interactions. The tune depression in the ring varies from $\nu/\nu_0 = 0.85$ to $\nu/\nu_0 = 0.14$, which corresponds to $I = 0.6$ mA - 100 mA, nominally. Intensity in the ring is quantified as parameter χ, defined as $\chi = 1 - (\nu/\nu_o)^2$. In UMER, $0.28 < \chi < 0.98$ where $\chi < 0.5$ is considered emittance-dominated and $\chi > 0.5$ space charge dominated. [1].

The ring consists of 36 periods of alternating-gradient F0D0 lattice, with 36 dipoles, each providing $\sim 8°$ of bend (Earth's magnetic field contributes $\sim 20\%$ of total bending). Ring diagnostics include beam position monitors (BPMs) and transverse-imaging fast-phosphor screens, as well as a wall current monitor and energy analyzer. The addition of interceptive techniques, in particular a transverse emittance diagnostic, is highly desired. Until implementing extraction, we rely on old emittance measurements from first turn experiments [2] and estimation of beam quality through rms size, current profile and tomographic measurements [3]. The addition of an extraction line with energy and emittance measurements will allow us to probe the full 6D emittance for multiple turns of the beam. A full understanding of phase space evolution is the first step towards describing the equilibrium distribution in the presence of space charge, if such a state exists.

We define extraction section as the elements and beam pipe starting with the flange before the kicker and start of the diverging pipe, continuing out to the first flange in the extraction line. The final extraction section design must satisfy certain requirements of the ring and its users:

- Must minimally affect the current experiment. Preserving the optical properties of the lattice is crucial.
- Must have a compact design to fit densely packed ring lattice.
- Use a pulsed electric dipole rather than a pulsed magnetic dipole, to avoid large inductions and allow for a fast rise time.
- Extraction at $20°$ is optimal to meet space constraints.
- Must extract all beam currents available in UMER.

Previous work focused on creating a linear optics model, in order predict the optimal beam path location for an electrostatic kick [4]. Using transfer matrices for the thin lens approximation to reproduce the UMER lattice, we approximated the pulsed electrodes as a discrete kick and traced single particle trajectories. This simple system suggested the trailing edge of any ring dipole as the optimal location for a kick. Although the diverted beam will experience an opposing dipole field in the horizontally focusing quadrupole, the quadrupole effect is much weaker than the electric kick.

WARP SIMULATION

The linear optics model was only the first step to calculating the complex beam dynamics in the UMER extraction. For predictions based on field non-linearity and intense space charge effects, it is necessary to turn to a more comprehensive simulation. For this purpose, we use WARP [5], a PIC code designed to model intense beams in an accelerator system.

* Work supported by US Dept. of Energy Offices of High Energy Physics and Fusion Energy Sciences.

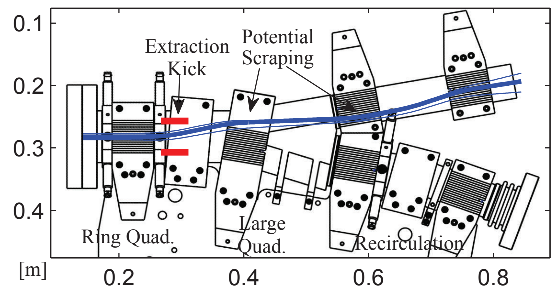

Figure 1: Centroid tracking for a matched 23 mA beam, in original extraction design. The best-possible centroid motion in this design was deemed too intractable for use with higher current.

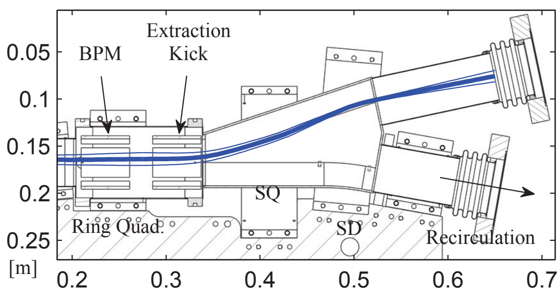

Figure 2: Centroid tracking for a matched 23 mA beam, in more recent design.

We wish to explore the extraction section with both 2D and 3D simulation. In this paper we present the results of 2D WARP simulation.

In the following simulations, we propagate a 2D transverse slice of the beam, with assumed infinite extent parallel to the beam pipe axis. We travel for 64 cm through the extracting period, in 1 mm steps, on a transverse grid of 256 square cells for the 5 cm diameter pipe. EM fields for static elements are calculated independently and imported as field values on a grid. We use 40k macro particles to simulate a beam of specified current, in the range $0 - 100$ mA.

We make use of the WARP bend element to closely follow the beam frame. The bend is a coordinate transform of the lab frame, achieved by a series of small rotations of the coordinate system and interpolation/rotation of field components. In the extraction simulation, we use bend elements over the applied kick and ring dipoles.

The dipole and quadrupole fields are generated using a simple magnetic field-solver, MAGLI [6]. The Earth's magnetic field is approximated by a constant-value hard-edged vertical dipole field of 400 mGauss, the average value observed in the ring. The horizontal field components are significantly weaker and are ignored in this analysis.

The electric kicker fields are generated by constructing the electrode geometry in WARP and solving over a 3D volume. The kicker geometry consists of four curved plates parallel to the inner pipe wall, with a voltage differential applied across two plates and two grounded plates in between.

Design Modifications

The zeroth-order design formulated with the linear model (see Fig. 1) was found to be ineffective in the 2D WARP simulation. The electrode location needed to be moved several centimeters upstream in order to avoid a bend in the pipe. Centroid tracking with a matched 23 mA beam reveals that due to this shift, as well as more realistic magnetic fields, as well as finite beam size and pipe aperture, scraping is unavoidable even for a well-behaved beam. Expanding the pipe aperture would require greater than 300% radial enlargement of a ring quadrupole, which was considered a poor magnet design.

Fine adjustment of kicker voltage and electrode length/location proved inefficient at establishing an acceptable trajectory, even for an on-axis mid-sized beam.

The new information provided by the WARP transverse slice code led us to adapt a new design, which places the kick upstream of a horizontally defocusing quadrupole. This allows the quad to help pull the beam out of the ring. Centroid tracking simulation for a matched beam at 23 mA is encouraging, as seen in Fig. 2.

This design requires two enlarged elements, a s-o-called Super Quad (SQ) and Super Dipole (SD). At radius $r = 7.1$ cm, the SQ aperture is 280% larger than the average ring quadrupole. The SQ will be a scaled-up version of a ring quadrupole, with printed circuits and a circular aperture. At horizontal width $d \approx 15 - 28$ cm, the SD circuit lends itself to a rectangular aperture rather than mimicking the circular design of the ring dipoles. The nature of the dipole circuits is still under discussion, as addressed in the last section.

Acceptance Studies

For the first attempt at gauging the relative acceptance of extraction versus recirculation, we implemented zero-current single particle tracking in the WARP simulation. We initiate 40,000 particles in a K-V beam distribution, which is uniform and circular in configuration space and follows a Gaussian distribution in angular space [7]. The K-V distribution was randomly seeded to fill the beam pipe radius (2.5 cm) with an rms angular spread of 0.3 radians. The single-particle mode was approximated by suppressing the WARP beam current on the order of 10^{-11}.

The outcome of this analysis is shown in Figs 3 and 4. The yellow ellipses in these figures represent emittances of $\epsilon_x = 950\mu m$ and $\epsilon_y = 900\mu m$, the approximate value admitted in recirculation. Although difficult to compare quantitatively, due to the asymmetric, non-elliptical acceptance in extraction, comparison shows that the 1-turn zero-current ring acceptance is comparable to that of the extraction. Some small amount of clipping occurs, but we expect the UMER beam to inhabit a smaller region of phase space. However, as we expect very different behavior in the presence of space charge, we must estimate acceptance for a

ISBN 978-3-95450-122-9

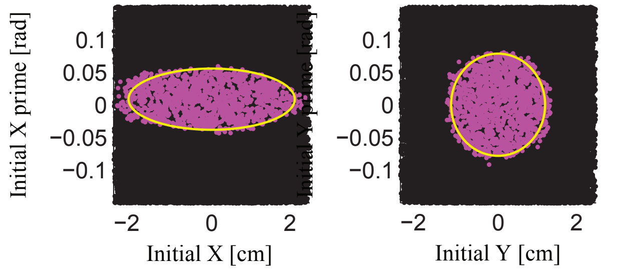

Figure 3: "Zero-current" acceptance of recirculation. X,Y axes correspond to particle initial condition. Black particles are lost on the absorbing boundary, magenta particles survive through one turn (11.52 m).

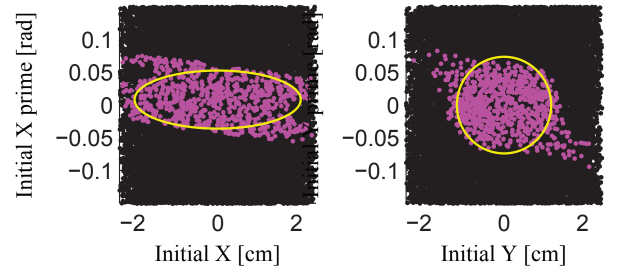

Figure 4: "Zero-current" acceptance for extraction. See Fig. 3. Particles propagate 64 cm through extraction.

variety of beam currents.

For non-zero currents, we must first identify a matched beam. We require the matched beam to have less than 0.5 mm envelope variation per cell advance, when measured between quadrupole mid planes. The second step is to calculate the maximum accepted emittance for one turn. This is achieved by loading matched beams of various emittances and varying the initial emittance value until no particles are lost, using the pipe wall as the absorbing boundary. Lattice errors in the actual ring will likely depress the simulated acceptance value. The final step is to propagate identical matched beams through the extraction section and identify the maximum accepted emittance. This might be complicated by steering issues; the extraction might prefer slightly off-axis beams, which could be achieved through steering dipoles. For now, only on-axis matched beams will be considered. This analysis remains ongoing.

CONCLUSIONS AND FUTURE WORK

The extraction design should not change significantly from the current model. The last major question is the nature of the large dipole element (SD). Before installation it will be necessary to calculate acceptance for all beam currents and quantify the error tolerances in the modified ring.

Dipole Magnet Design

The current extraction design requires a wide-bore dipole magnet to encompass both the beam pipe and diverging pipe. For a basic two-coil dipole, the horizontal aperture must be $d \approx 28$ cm to accommodate the wide pipe and remain centered over the recirculating beam path. However, this design results in a significant field gradient over the single-pass extraction line and significant opposite polarity "wings" at the longitudinal edges. While the wings can be abated by clever circuit design, the horizontal gradient drastically reduces the acceptance. An alternative is a "reverse-field" dipole, with a sharp polarity switch between the beam paths such that the extracted beam is bent away from the ring by the dipole. This would require small adjustments to the beam pipe design.

Error Analysis

Before installation, we must understand the effect of the new, enlarged magnet elements on normal ring operation. In particular, we must quantify the sensitivity of the ring on magnet errors. Previous studies have quantified emittance growth when subject to various errors [8]. We plan to implement a similar analysis to predict the effect of magnet nonlinearities, beam mismatch, quadrupole rotation in the presence of the new, enlarged ring elements.

ACKNOWLEDGMENTS

We thank Alex Friedman, Dave Grote, and Jean-Luc-Vay for their support of the WARP code, as well as Ellen Wetzel and Tim Petro for their contributions to magnet design.

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