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

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Abstract

We present plans for multi-turn extraction of a 10 keV, 0.6-100 mA electron beam for use in the University of Maryland Electron Ring (UMER). The extraction section is motivated by the need for interceptive diagnostics for emittance measurements. We apply a linear beam optics model to optimize preliminary design. The WARP PIC code is used to simulate design performance in the presence of space charge effects and complex field configurations. Preliminary results from a transverse slice model in WARP show good agreement with the linear model and encouraging conservation of emittance through the proposed extraction.

INTRODUCTION

The University of Maryland Electron Ring is a circular beam transport system capable of containing a 10 keV electron beam for many turns of its 11.52 meter circumference. The current in the ring varies from 0.6 to 100 mA, exploring the realm of emittance-dominated beam dynamics to the extremely dense space charge dominated regime. As a small-scale and accessible machine, UMER functions primarily as a tool for high brightness beam dynamics studies.

The current range in the ring corresponds to a variation in the intensity parameter, $0.38 < \chi < 0.99$, where χ is defined as

$$\chi = \sqrt{1 - (\nu/\nu_o)^2}$$

for a tune depression ν/ν_o. For $\chi < 0.5$ the beam physics is emittance dominated while $\chi > 0.5$ is the space-charge regime, where beam growth is primarily due to Coulombic interactions [1].

The ring contains several beam position monitors (BPM) and wall current monitors (WCM), which are the primary diagnostics. Presently it lacks a system for turn-by-turn transverse diagnostics. Extraction into a diagnostic chamber would allow us to reconstruct the six dimensional phase space at multiple points in the beam lifetime [2]. We define the extraction section as the lattice half-cell containing a deflecting electrode and the start of a diverging extraction pipe.

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Injection of the beam into the ring is through a complicated pulsed magnetic system. Our goal is to design an extraction section using a pulsed electrical system rather than mirror the injection. In this way we hope to avoid the effects of magnetic induction on a fast pulsed dipole [3]. A complication of this approach is the energy gained by the beam electrons from the deflecting field. We hope to minimize this effect to preserve emittance through the extraction section. The goal is to have minimal impact on the existing ring lattice while attaining approximately a 20^o outward bend.

LINEAR DESIGN

The preliminary design consists of approximate kick location and amplitude for the extracted beam to bend at least 20^o and clear downstream ring elements. In our first model, we apply a discrete kick and propagate a single particle through the UMER lattice using linear beam optic matrices, written in MATLAB [4]. Because we aim to achieve horizontal extraction, we only use the 2 x 2 matrices necessary to describe motion in one plan.

Beam optics matrices are multiplicative, as the system of magnetic forces is strictly conservative. However, a deflecting electric field imparts energy to the system, and the matrix for the non-conservative field must be additive. An angular offset $\Delta\theta$ is added to the beam conditions (x, x')at the beam-line location where the kick is desired, as shown:

$$\begin{bmatrix} x_{out} \\ x'_{out} \end{bmatrix} = \begin{bmatrix} x_{in} \\ x'_{in} \end{bmatrix} + \begin{bmatrix} 0 \\ \Delta\theta \end{bmatrix}$$

A total angular offset of $\Delta\theta = \Delta x\prime$ is accrued within plates. We use the approximation $x' = v_x/v$ for small angles, where $v = v_{total} \approx v_z$ Therefore, $\Delta\theta = (v_{xf} - v_{x0})/v_z = at/v_z$. Substituting $F = ma = qE$ and also approximating that $t = l_{eff}/v_z$ yields:

$$\Delta\theta = \frac{qE}{m}\left(\frac{l_{eff}}{v_z^2}\right)$$

To predict optimal kick location and amplitude, we impart a discrete kick of $\Delta\theta$ (corresponding to some integrated electric field $\int E \cdot dl$) to a simulated particle at various locations along the beam line. Output parameters are measured at the transverse plane defined by the leading edge of the quadrupole downstream of the extraction section.

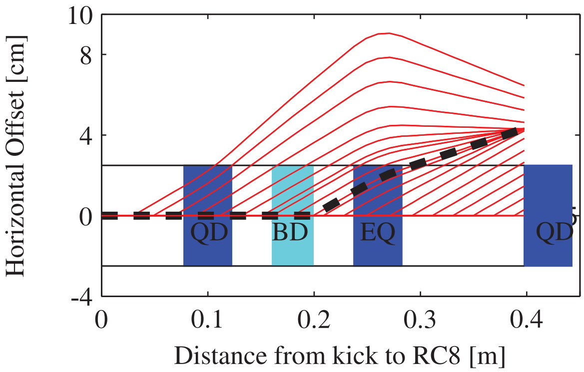

Figure 1: Various single particle trajectories (red traces) as a function of discrete kick location s, corresponding to a kick of $E_{int} = 6.2$ kV. Background diagram shows lattice element positions. Beam travels left to right. The ideal trajectory is marked by a heavy dashed line.

Three possible solutions for horizontal extraction were identified: a single kick, a pair of alternating kicks and a pair of reinforcing kicks. An exploration of the parameter space for x' and Δx in both two kick systems revealed the optimal kick locations. Even at optimal arrangement, the horizontal offset per degree of angular offset was inferior to that of an optimally located single kick. Furthermore, the single kick is the simplest system to model and implement. The linear model predicts an integrated gradient of 6.2 kV, well within the capabilities of a fast-pulsed electrode.

Single particle trajectories from a variable position kick can be seen in Fig. 1. The optimal trajectory corresponds to a discrete kick at the trailing edge of the dipole element. We designate the next element the perturbed beam passes through, a horizontally focusing quadrupole, as the extraction quad (EQ).

WARP SIMULATION

In order to predict the effects of a single kick extraction on a multi-particle beam with finite envelope and space-charge, we use the charged particle simulation code WARP. WARP allows simulation of ranged beam intensities in the proposed extraction, as well as complicated electric and magnetic field configurations with significant fringe fields.

WARP [5] is a particle-in-cell (PIC) Fortran code with Python interface, developed for studies of non-linear beam dynamics and equipped with packages for transverse slice, three dimensional and axisymmetric models. WARP contains a unique bend element, which transforms the gridded coordinate system around a semicircular bend of specified length and curvature.

Realistic models of the current ring lattice have already been created and benchmarked against experimental ring data. Creation of the extraction simulation involved modification of this model. All simulations mentioned use an 23 mA beam ($\chi \approx 0.90$) with an initial semi-Gaussian charge distribution. Our current approach uses the transverse slice package, which omits longitudinal dynamics and complications due to finite bunch length and axial substructure.

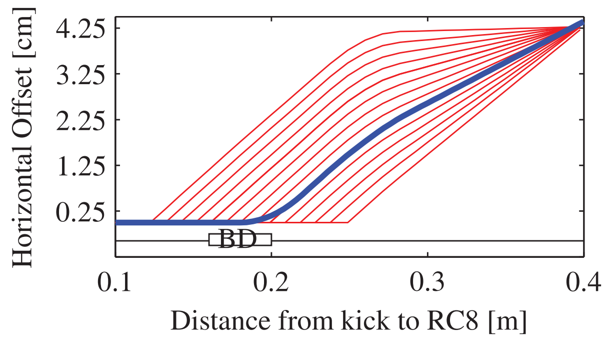

Figure 2: Comparison of WARP model with linear optics model. Red traces are single particle trajectories from the linear model, heavy blue trace the centroid trajectory from the hard edged WARP model

The first WARP simulation uses hard-edged ideal elements for the EQ and kick electrodes, while unmodified elements are defined using imported 3D magnetic field configurations developed for previous models of UMER. These are generated by numerically solving a user-specified current configuration (in this case, a printed circuit coil that follows the curvature of the pipe surface) with the magnetic field solver MAGLI [6]. Comparison of centroid trajectory in the hard-edged WARP simulation to the single particle trajectory in the Matlab linear optics analysis yields very close agreement (Fig. 2).

Modified Ring Elements

We model the kick electrodes as conducting objects in the WARP simulation. The conductor geometry consists of an enlarged beam pipe around two electrodes that follow the pipe curvature, each sweeping 90^o and given a voltage differential on the order of 7-10 kV. The electrode geometry can be seen in Fig. 3. In the transverse slice package, the Poisson solver is executed at each time step for a 2D geometry and does not contain longitudinal fringe fields.

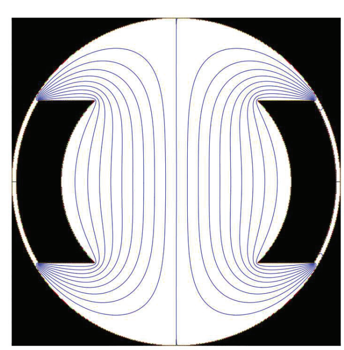

Figure 3: Cross-section of the kick electrodes in the enlarged pipe, generated using the WARP conductor module. Blue traces represent equipotentials.

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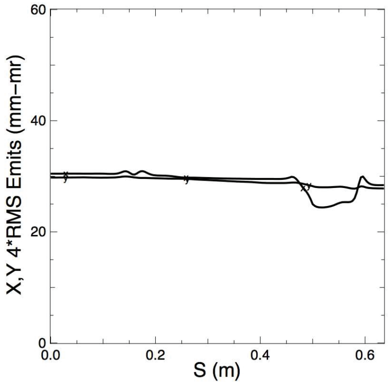

Figure 4: X and Y emittances as a function of z location (in meters) for two periods of the ring. Note variation in x-emittance around the first dipole (s = 0.16) and the extraction bend (0.48 m).

To avoid this over-simplification, we perform a field solve in the 3D WARP model, and import the field configuration into the transverse slice model. Performance with the 3D field is still being assessed.

We use MagLi to model the EQ as an enlarged ring quadrupole of radius $r = 6.5$ cm rather than the typical $r = 2.5$ cm (the beam pipe radius). Using an large EQ disrupts the lattice for the recirculating beam. Preliminary studies of the recirculating beam in an otherwise ideal lattice show that scaling the EQ gradient up by 7.5% compared to the typical ring magnets preserves the emittance out to 20 turns, for a 23 mA beam. More extensive simulations are required to gauge the effect of the enlarged EQ on a beam circulating for more than 1000 turns.

Preliminary Results

Preliminary WARP results are found for an ideal 23 mA beam, deflected by 4 cm length electrodes without fringe fields (which we expect will contribute significantly). It is necessary that the extraction scheme preserve beam emittance for accurate diagnostics. The emittance in the beam frame during extraction can be seen in Fig. 4. The two variations in x-emittance occur around bend elements in the simulation. If the beam centroid does not remain on-axis through the coordinate transformation in the bend element, there will be some interchange between longitudinal and transverse emittances. After the beam trajectory is once again nearly parallel to the pipe geometry, emittance is conserved to within 6% of the original value.

CONCLUSIONS AND FUTURE WORK

The single kick design developed in the linear model is the most promising extraction scheme. Preliminary WARP simulations in the transverse model, done in anticipation of the full 3D simulation, show good agreement with the linear model and encouraging conservation of transverse emittance through the extraction section.

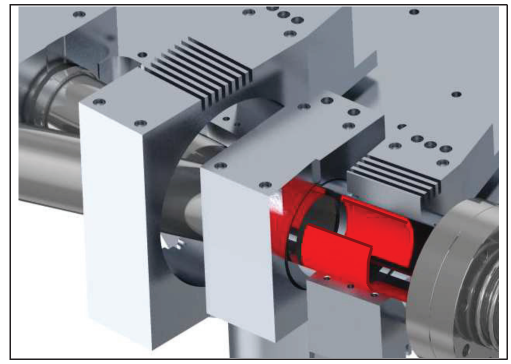

Figure 5: Cut-away drawing of extraction electrodes (red) and diverging extraction pipe.

A preliminary mechanical model has been developed, with diverging pipe, enlarged quadrupole and dipole magnets (Fig. 5).The drawing reveals that it will be necessary to place the kick electrode centered at the leading edge of the dipole casing, to allow room for high voltage leads. This forces the kick to be further upstream than was identified in the linear model (Fig. 1), but there is some flexibility in exact kick location allowed by the optics of the system.

The next modification to the extraction simulation will be to run the full simulation using the WARP 3D package. This will be attempted after the transverse model has been used to predict performance on beams of various intensity and beam quality.

ACKNOWLEDGMENTS

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