MATCHING AND INJECTION OF BEAMS WITH SPACE CHARGE INTO THE UNIVERSITY OF MARYLAND ELECTRON RING (UMER) *

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Abstract

Beam matching is critical for avoiding envelope mismatch oscillations that can lead to emittance growth and halo formation, especially if the beam has significant space charge. Matching is rendered difficult for the University of Maryland Electron Ring (UMER) by the space charge, the compactness of the lattice, and the unique injection scheme where an offset oversized quadrupole is shared between the ring and the injector. This paper explores several schemes for optimizing the matching at injection, both analytical and beam-based. The approaches are tested using a particle-in-cell (PIC) code as well as experimentally.

The University of Maryland Electron Ring (UMER) is a research storage ring that is designed for scaled studies applicable to many larger machines. Using 10 keV electron beams at relatively high current (0.6 – 100 mA, adjusted by means of apertures in the gun), space charge forces are relatively strong. A description of UMER and the physics issues involved is discussed in Refs. [1-2], as well as several papers in these proceedings. Good beam control is a prerequisite for achieving reliable operation and a high-quality beam for experimental studies. There has been much work on centroid control (steering) before [3] and after [4] closing the ring. The latest work on centroid control [5], combined with judicious choice of operating point away from resonances [6], has resulted in reliable multi-turn operation. With the recent introduction of longitudinal focusing, we have propagated the lowest-current UMER beam over 250 turns, limited only by the injection electronics [7]. Operation at higher currents is more problematic, due in part to the larger average beam size, but also to the stronger effect of envelope mismatches on the beam.

It has long been known that envelope mismatches can lead to emittance growth and halo formation [8-10]. Skew envelope mismatches, resulting from possible quadrupole rotations, have been shown to be as detrimental to beam quality [11]. These negative effects can be ameliorated by proper rms envelope matching in the injection line. During the phased commissioning of UMER we have demonstrated substantial success in correcting for skew errors and in rms envelope matching, using beam-based control techniques [3]. At that time, the problem was made easier by the availability of view screens every two lattice periods, and also by the simpler injection scheme in which a fixed 10° bend replaced the Y-section, allowing the use of DC magnets for injection identical to the ones in the ring. Further progress has been made by recognizing that a more sophisticated definition of quadrupole effective length elicits greater accuracy from matching optimization codes that employ hard-edge magnet models [12].

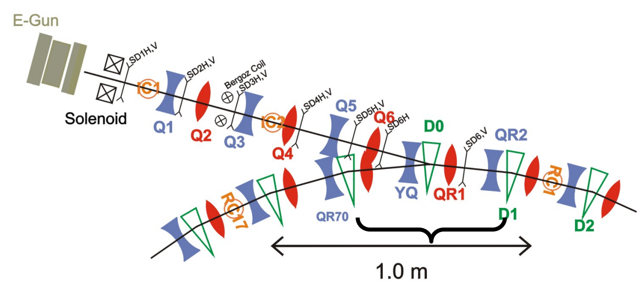

Figure 1: Schematic of the UMER injection line.

With the completion of the ring and commencement of multi-turn operation, the matching problem became more complicated. Because of the requirement to focus beams with high space charge, the UMER lattice is closely-spaced, with 72 quadrupoles at intervals of 16 cm center-to-center, interspersed with 36 bending dipoles. Given a physical magnet length of about 4 cm, this leaves mere 4-cm gaps between quadrupoles and dipoles, and 12-cm gaps on the sides without dipoles. The longer gaps are mostly occupied by diagnostic chambers, glass gaps for induction cells, and vacuum pipe flanges, leaving little room for injection. The solution we adopted for injection [13] (see schematic in Fig. 1) consisted of an oversized pulsed dipole (PD) around a glass gap, preceded by an oversized defocusing quadrupole (YQ) situated on the centerline between the injection line and the ring, and shared by the two. With proper steering, YQ assists PD in bending the beam, thus reducing the inductive load on the dipole which has to switch polarity in less than 100 ns. At the same time YQ maintains the periodicity of the lattice in the ring.

This design suffers from several drawbacks. The main difficulty relating to beam matching is the fact that YQ couples the steering and the matching: if the strength of the magnet is adjusted for optimizing the matching, the centroid orbit for both injection and recirculation is affected, and the beam needs to be re-steered. This constraint significantly hampers our ability to quickly scan large areas of parameter space, or to implement empirical matching schemes such as the one in Ref. [3].

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We now compare three methods for beam matching: (A) using the code TRACE3D [14] and assuming the design UMER lattice; (B) a hybrid method where the TRACE3D optimization is augmented with detailed modeling using the PIC code WARP [15] of the more problematic lattice elements, namely the solenoid and the Y-section; (C) the same empirical matching algorithm described in Ref. [3]. We tested the solutions obtained from all three methods using WARP simulations with the full magnetic field model to verify matching, then tested the same solutions on the experiment, relying on view screen measurements for beam size.

Method A proceeds as follows:

(1) Optimize one lattice period in the ring to determine the target Courant-Snyder parameters α and β.

(2) Optimize a section consisting of QR71, YQ, QR1, and QR2 [curly bracket in Fig. 1] to determine those magnets' best settings such that α and β at the input and output of that section are identical with those in the ring. This is necessary to maintain the periodicity of the lattice during recirculation.

(3) Optimize the injection line quadrupoles Q2-Q5, given the measured initial conditions, such that the beam has the same α and β at the entrance to the Y-section.

We have some flexibility in step 3 since there are more magnets in the injection line than needed. We found it best to set Q6 to the same value as QR71, Q1 to about 60% of the strength of the ring magnets, and adjust the solenoid strength such that the beam reaches a waist at Q1 with a radius about the same as the average radius in the ring. The strengths of the solenoid and Q1 should be further adjusted depending on the beam current. We found that the 100 mA beam requires a stronger solenoid, while the 0.6 mA beam performs best with a weaker solenoid and with Q1 turned off. Ideally, the spacing between the gun and solenoid should be depend on the beam current [12], but unfortunately we do not have that flexibility at this time.

The main advantage of this method is that it is extremely fast. We have written Python scripts that automate the production of the TRACE input files, allowing the execution of this whole procedure in a matter of minutes. The main drawback is the lack of detail in modeling the magnets. In TRACE we found it best to use hard-edge quadrupoles with the definition of effective length in Ref. [12], and to omit the modeling of the dipoles, since a sector dipole model produced worse agreement with WARP. We found the solution to be sensitive to the axial location of the solenoid, which we also modeled as a hard-edge element. In reality, the solenoid fringe fields and nonlinearities can have a significant impact on the waist radius and location (of the order of 10%), which in turn impacts the matching solution. Furthermore, the hard-edge model is not as accurate for modeling YQ, which has extended fringe fields in which the beam follows an off-axis trajectory.

Method B significantly improves the accuracy of the solution by using WARP to implement some of the optimization steps. The most effective change is that we use WARP to simulate the beam from the gun output through the solenoid to some location between the solenoid and Q1. This is used as the new initial condition for the TRACE optimization in step 3. The process is still relatively quick as the change involves a single additional WARP simulation over a short (30 cm) distance.

In some cases, we also used WARP to perform the optimization over the Y-section in step 2, then running a WARP simulation backwards from the ring, through the Y, and into Q6 of the injection line to obtain the target condition at a plane between Q5 and Q6. TRACE is then used in the final step to optimize the straight injection line. The main advantage of this additional use of WARP is the more detailed model of the YQ magnets, which are included in WARP via arrays of magnetic field data calculated on a 3-D grid with 1 mm resolution, starting from the wire geometry of the magnets and applying the Biot-Savart law. Thus, each simulation particle experiences the a magnetic field that includes fringe fields and the nonlinearities interpolated to its actual trajectory. This method, with or without the additional step, represents a reasonable compromise between accuracy of the solution and speed of convergence.

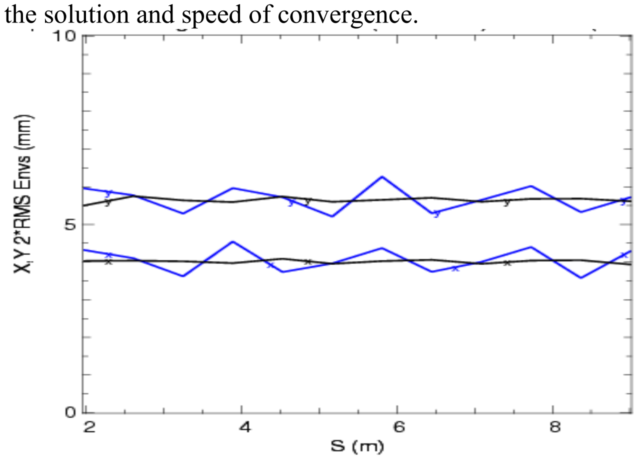

Figure 2: x-y beam envelopes in the diagnostic chamber locations before (blue) and after (black) simulated empirical matching of the 23 mA beam.

Method C attempts to match the beam empirically based on beam size measurements in the ring. Fig. 2 demonstrates its application to WARP-simulated data to optimize the injection line matching. While it can be made to work in WARP, its practical application to experiments is much more difficult. First, the process is tedious and time consuming, as it involves the collection of data at every screen in the first half of the ring while perturbing each of quadrupoles Q1-Q6 by a given amount. The matrix thus constructed is used to find a solution such that the x, y beam sizes in all the screens are as close as possible to each other (in a least squares sense) [3]. The screen measurements are then repeated to verify the matching. Since the screens are interceptive, this procedure involves the mechanical insertion and removal of each of nine screens at least twice, a process that can take easily half a day per optimization. Even when modeled in WARP, the procedure takes 7 simulations of one-turn each. Though it can be parallelized, it is much more time-consuming than Methods A or B. Second, the accuracy of this technique depends sensitively on having a good initial guess. Thus it can be applied as a second stage after Methods A or B, but may not give a good solution if started from an arbitrary mismatch. Finally, this method also depends on the linearity of the system over some 20 lattice periods in the ring. If the beam emittance increases as a result of an initial mismatch, then the matrix elements constructed from beam measurements by the downstream screens are not as accurate. This difficulty can be possibly overcome by a judicious weighting of data, but this has not been attempted.

The initial experimental tests of the different techniques were complicated by uncertainties in the initial conditions from the gun, as well as the presence of a halo in the beam distribution emerging from the gun [16]. The halo has since been removed by more accurate alignment of the cathode, but at the time of the experiment, was present in all the photographs of the beam. Of the matching methods discussed here, the best in terms of minimizing both the envelope oscillations and the number of particles in the halo is the hybrid method (B), in which we use WARP to model the beam through the solenoid, but use TRACE for everything else. Applying the more sophisticated empirical matching technique (method C) actually gave a worse result and a more prominent halo. Given the investment of time needed to implement empirical matching, iterating to improve the solution is not worth it at this stage.

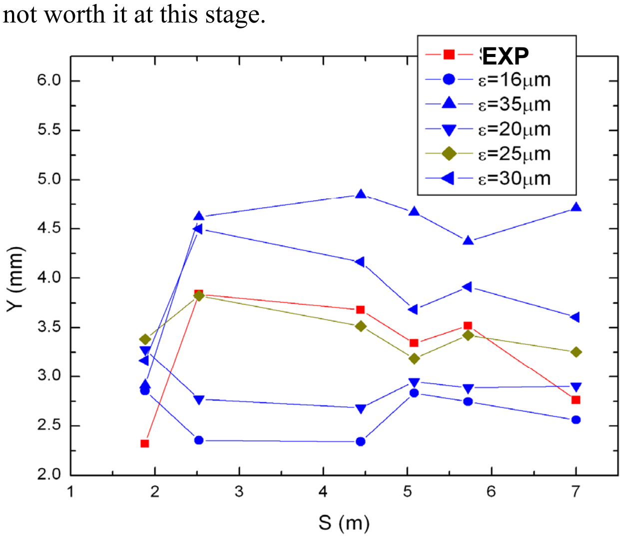

Figure 3: 2*rms Y envelope of the 7 mA beam in the ring: experiment (red) vs. WARP simulations assuming different initial emittance values. Settings of matching method B.

From a comparison of experimental data with WARP simulations under the same settings (Fig. 3), it is evident that something is amiss. The magnet models used in WARP, as well as its model of the lattice, have been verified extensively by comparison with other experiments, with steering data, and with other codes such as ELEGANT. The assumptions used for the initial beam conditions (size, slope, emittance) are a different matter. In the initial matching calculations, we have been relying on earlier measurements, which for instance estimated the (4*rms unnormalized) emittance of the 7 mA beam to be about 16 μm. A recent cathode change prior to this experiment meant that these numbers could have changed. Results from simulations with different initial emittances are indicated in Fig. 3. We note that an emittance of 25 μm produces the same average beam size in the ring as that obtained from experiment.

Whereas initially this prediction of a 25 μm emittance was thought to be unreasonably high for this beam, later experimental phase-space measurements using both tomography and a pinhole scan [17] have confirmed this value to within a 5% error bar. The measurements also obtained more reliable estimates of the initial beam envelope slope at the aperture.

In summary, a hybrid approach to beam matching using WARP to model the solenoid and TRACE3d to optimize the injection line magnets has been shown to produce best matching results. Success of this approach depends on accurate knowledge of the initial conditions as well as the lattice geometry and magnetic fields. Application of this approach using the most recent measurements for the initial conditions have resulted in a measurable improvement in transmitted beam current over multiple turns. For instance, even for the intense 100 mA beam, we have observed 7% more transmitted peak current over the first 4 turns. A more sophisticated empirical matching scheme, which is more tedious to apply, has resulted in worse beam quality in the ring. Having a non-interceptive beam size diagnostic in the future, however, can make it worthwhile to revisit that approach.

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