Low-current, Space-Charge Dominated Beam Transport at the University of Maryland Electron Ring (UMER)*

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Abstract

The University of Maryland Electron Ring (UMER) is designed for the transport of low energy (10 keV), high current (100 mA) electrons in a 72-magnetic-quadrupole lattice over an 11.5 m circumference. With these parameters, and a typical single-particle phase advance per period of 76^0, space charge is extreme. However, high current is not necessary for establishing space charge dominated transport in UMER. In fact, low current (0.6 mA) beam transport in combination with longer full-lattice period can yield strong space charge conditions. All 72 quadrupoles are needed, though, to yield beams with relatively small cross sections, as required for emittance-dominated transport. We present design calculations for the low-current, high space charge regime in UMER, including the use of Collins-type insertions for matching into the ring lattice.

INTRODUCTION

The effects of space charge are relevant in the low-energy sections of many existing accelerators. Better understanding of these effects is also of major importance for the development of advanced accelerators that require higher current or, more generally, beams of higher quality. Since its inception around 2000, The University of Maryland Electron Ring (UMER) purports to address many issues of the physics of space charge dominated beams, from the electron source to injection/matching, beam transport and a host of questions in both transverse and longitudinal dynamics. The accompanying invited paper by R.A. Kishek et al [1] reviews the general features of UMER, while a number of other papers from other members of the UMER group present more detailed accounts of specific topics. In this paper, we discuss the beam physics in UMER whereby a combination of low current, longer lattice FODO period, appropriate focusing/steering, and the right conditions for injection/matching lead to strong space-charge dominated transport.

SCALING OF SPACE CHARGE

The role of space charge in beam transverse dynamics can be understood in terms of a single parameter. This parameter can be the tune depression ν/ν_0, or ratio of betatron oscillations with and without space charge, or, alternatively, the ratio of space charge force to external force at the effective beam radius in a uniform-focusing model of the actual periodic lattice. If we denote this ratio by χ, we can write [2, 3]:

$$\chi = 1 - \left(\frac{\nu}{\nu_0}\right)^2. \tag{1}$$

Clearly, the range of χ is from zero, in the limit of zero current, to 1 in the space charge limit. Another parameter, related to χ, can be used to express more transparently the role of external focusing and the beam quantities [4]:

$$u = \frac{K}{2k_0\epsilon}, \tag{2}$$

where K is the generalized beam perveance (sometimes also called "space charge parameter"), k_0 is the wavenumber representing external focusing, i.e., $k_0 = \nu_0/R$ in a circular lattice of radius R, and ϵ can be taken as the edge emittance (4RMS, unnormalized). By contrast to χ, u ranges from zero at zero current, to infinity at zero emittance. Further, it can be shown from the envelope equation (in the uniform focusing approximation) that u=1/2 when the *geometrical mean* of external and "emittance" forces equals the space charge force at the effective beam edge.

In UMER, we can implement electron beam transport with χ ranging from 0.32 to 0.97, or u from 0.20 to 3.0. From Eq. 2, we see that it is possible to obtain high space charge by simply reducing external focusing. This involves cutting the number of quadrupoles in the lattice by a factor of 2 or 4, thus increasing the full-lattice period S by the same factor. At the same time, the zero-current phase advance per period, $\sigma_0 = 2\pi\nu_0/N$ (N=number of full lattice periods in the ring), is kept constant. In effect, the bare tune ν_0 is reduced, since $k_0 = \sigma_0/S$.

To complement the equations above, it is interesting to note that the ratio of effective beam radii in the limits of zero emittance and zero current is given (in the notation of Ref. [4]) by

$$\frac{a_B}{a_0} = \sqrt{\frac{K/k_0^2}{\epsilon/k_0}} = (2u)^{1/2}, \tag{3}$$

as can be easily shown from the envelope equation in the uniform-focusing model. For any combination of space charge and emittance, however, the effective beam radius is better approximated by just adding a_B and a_0 in quadrature [4]:

$$a \simeq \sqrt{a_B^2 + a_0^2} = a_0\sqrt{1+2u}, \tag{4}$$

with the provision that $u \lesssim 5$ (χ=0.99 for u=5).

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BEAM AND LATTICE PARAMETERS

Table I summarizes the beam and lattice parameters of three modes of operation in UMER. The first two correspond to low current, one of which is emittance-dominated and the other one space-charge dominated. The tabulated k_0^2 values do not correspond to the quantity in the equations above but to hardtop values of the hardedge quadrupole models in UMER [5]. The effective k_0 in a uniform-focusing model is $k_0 = \sigma_0/S$, or ν_0/R, where σ_0=76^0, and R=1.83 m. The beam radii in Table I, on the other hand, are calculated from the solution of the envelope equations, but Eq. 4 gives surprisingly close results.

Table 1: Examples of low and high electron beam current in UMER. All three cases at 10 keV, σ_0=76^0. Emittance (in μm) is 4RMS, unnormalized.

Beam Current → **Emittance →**	**0.6 mA** **5.5 μm**	**0.6 mA** **5.5 μm**	**23.5 mA** **20 μm**
Lat. Period, S (cm)	32	128	32
Ext. Foc., k_0^2 (m^{-2})	168.4	38.3	168.4
Beam Rad., a (mm)	1.4	3.7	4.9
Intensity, χ	0.32	0.76	0.95
Parameter u	0.20	0.79	2.1
Bare Tune, ν_0	7.60	1.90	7.60
Tune Dep., ν/ν_0	0.82	0.49	0.22

Figures 1a-b illustrate two basic lattice structures. The optics in Fig. 1a is especially suited for low-current, space-charge dominated transport; the geometry in Fig. 1b, on the other hand, is the standard one in UMER. In Figs.1a-b, D# and F# represent defocusing and focusing magnetic quadrupoles, BD# are bending dipoles, BPM# are beam position monitors, and RSV# represent steerers for vertical corrections. Not shown in Fig. 1 are the sets of Helmholtz-type coils employed for balancing the horizontal component of the earth's B-field.

CLOSED ORBIT AND RMS ENVELOPE MATCHING

The code WINAGILE [6] is used for closed orbit calculations with the two lattices shown above. In the model, the action of a constant vertical component of the earth's field B_y=0.4 G is represented with kicks of the order of 1 mrad every cm. Naturally, the closed orbit will depend on the bending dipole settings and the earth's field, leading to solutions with unique injection values x_0, x_0' for the horizontal offset and slope (relative to a reference trajectory that does not include the effect of the earth's B_y-field) at the entrance of the first ring section. Figure 2 shows results of closed orbits for the two lattices of Figs. 1a-b. The orbits are obtained by adjusting the bending dipole settings around the ideal values, i.e., those that undo the bending by the earth's field, until the centroid oscillations are small and symmetrical as possible relative to the vacuum pipe axis.

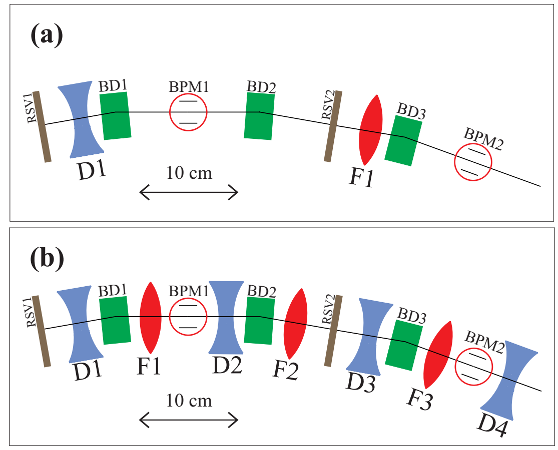

Figure 1: UMER lattices with (a) one quadrupole per ring section (S=128 cm) - one FODO cell shown, and (b) four quadrupoles per ring section (S=32 cm) - almost four complete FODO cells shown. See text for explanation of labels and Table I for beam parameters.

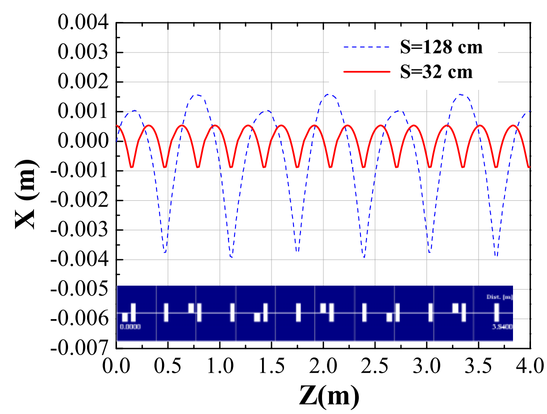

Figure 2: Closed orbits (shown over roughly 1/3 of the ring) obtained with the code WINAGILE for UMER lattices having full periods equal to S=128 cm (broken curve), and S=32 cm (solid curve). The vertical component of the earth's B-field is 0.4 G; the lattice for S=128 cm is shown at the bottom.

Some trial and error is required in obtaining the closed orbits described. For symmetry reasons, only every other bending dipole in the lattice illustrated in Fig. 1a is powered in the WINAGILE model, so BD1=0, BD2=67.2 mrad, etc, while all bending dipoles are given kicks of 35.2 mrad in the lattice represented by Fig. 1b. (In reality, "BD1=0" means that no compensation for the action of the earth's field is implemented with the dipole, so it is powered to provide a 10^0 bend, as if no earth's field were present.) The resulting orbit for the lattice with longer period is highly asymmetric, with excursions of almost 4 mm at the powered bending dipoles. The asymmetry can be understood from the fact that BD2 is not equidistant from the quadrupoles (Fig. 1a); other solutions where both BD1 and BD2 are powered differently to try to create a better orbit do not seem to work.

Despite the large offsets and asymmetry of the closed orbit in the lattice with fewer quadrupoles, more BPM diagnostics are available per FODO period, in addition to correctors that are closer (in a relative sense) to the quadrupoles (e.g., BD1 and BD3 in Fig. 1a) than in the standard lattice of Fig. 1b. In fact, if random errors in the dipole strengths, transverse tilt angle and also in the transverse placement of quadrupoles are implemented in WINAGILE, a closed-orbit correction scheme employing the bending dipoles and the BPM monitors works significantly better with the lattice with longer period.

In practice, the closed orbits may deviate from the calculated ones because of a number of factors: varying ambient field, residual injection errors, coupling of transverse components of motion from skew quadrupoles and dipoles, and space charge forces. The latter can be more detrimental for beam transport employing the lattice with longer period, especially since the closed orbit in that case requires a relatively large offset at half the bending dipoles.

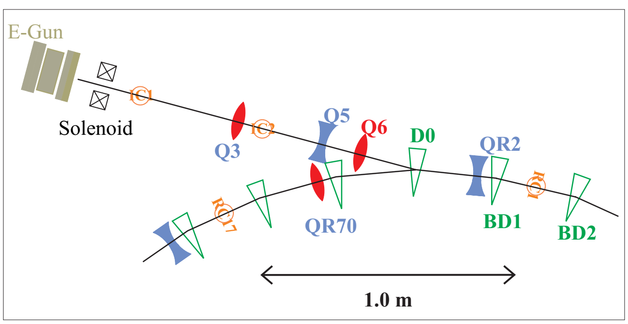

Figure 3: Collins-insertion geometry for matching/injection of low-current, space-charge dominated transport in UMER. See text for explanation of labels.

Another fundamental aspect of beam transport, RMS envelope matching, requires different approaches for the two lattices under consideration. Figure 3 shows the matching/injection geometry that works best for the low-current, long period transport problem (Fig. 1a). It is a Collins-type insertion [7]. A short solenoid and three printed-circuit (PC) magnetic quadrupoles (Q3, Q5, and Q6 in Fig. 3) are employed in the straight section following the electron source and before inflection into the ring lattice with a pulsed dipole (D0). Matching/injection for low or high current into the standard lattice of Fig. 1b, on the other hand, employs 3 additional PC quadrupoles in the straight section (Q1, Q2, and Q4, not shown in Fig. 3), and wide-aperture, Panofsky-type magnetic quadrupoles (not shown on Fig. 3), one on either side of D0. The Collins-type insertion is not only more natural to the matching problem of low-current, high space charge, but also avoids the use of injection through a tilted quadrupole. This wide-aperture quadrupole, upstream of D0, is necessary in the standard lattice for both envelope matching and for deflecting the beam into D0 [8]. Thus, the only drawback of not using standard injection is that D0 has to be powered with more current to compensate for the absence of the matching/injection quadrupole.

Figure 4 shows the results of RMS envelope matching calculations for low beam current with both the standard and Collins injection optics. It is clear that the Collins geometry leads to a more natural beam evolution into the periodic lattice, albeit with much stronger space charge. Initial experiments with Collins insertion in UMER have proved successful. To achieve multi-turn with this scheme, however, an upgrade of the recirculation electronics is needed.

In conclusion, high current is not a requirement for space-charge dominated beam transport, as it may be commonly believed. In UMER, the high density of quadrupoles permits the implementation of different schemes to accomplish emittance or space-charge dominated beam transport with the same low-current beam. This possibility greatly expands the parameter space that UMER can access for research in beam physics.

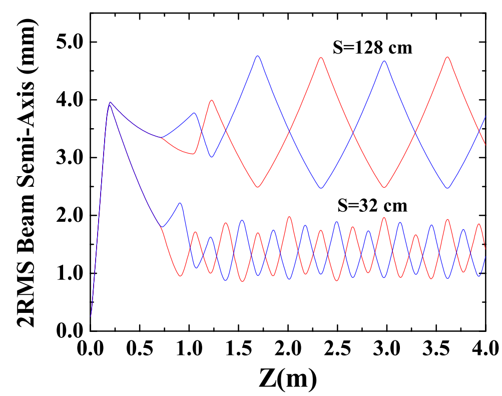

Figure 4: RMS Envelope matching calculations for low current (0.6 mA) in UMER with emittance-dominated (S=32 cm), and space charge dominated (S=128 cm) transport. See also Table I and Fig. 3.

REFERENCES

[1] R.A. Kishek et al, these Proceedings.

[2] M. Reiser, *et al.*, in Proc. of the 1999 Particle Accelerator Conference, New York, NY (IEEE, New York, 1999), p. 234.

[3] Ronald C. Davidson and Hong Qin, Physics of Intense Charged Particle Beams in High Energy Accelerators, (World Scientific, Singapore, 2001).

[4] Martin Reiser, Theory and Design of Charged-Particle Beams, (Wiley & Son, New York, 1994).

[5] S. Bernal *et al.*, Phys. Rev. ST Accel. Beams **9** 064202 (2006).

[6] P.J. Bryant, AC Division, CERN, CH-1211 Geneva 23. http://bryant.home.cern.ch/bryant/.

[7] T.L. Collins, Cambridge Electron Accelerator, CEA-86, July 10, 1961.

[8] H. Li *et al.*, in Proc. of the 2003 Particle Accelerator Conference, Portland, OR (IEEE, New York, 2003), p. 1676.

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