BEAM TRANSPORT IN ALTERNATIVE LATTICES AT THE UNIVERSITY OF MARYLAND ELECTRON RING (UMER)*

S. Bernal[†], B. Beaudoin, M. Cornacchia, D. Sutter, and R. A. Kishek
IREAP, University of Maryland, College Park, MD USA

Abstract

We discuss the motivation, general procedure and results of first experiments of beam transport with two alternative focusing schemes at UMER, a low-energy (10 keV), high-current (1-100 mA) electron storage ring. The new ring optics simplifies injection and RMS envelope matching, and gives us a larger number of beam position monitors (BPMs) per (un-depressed) betatron wavelength, all of which are desirable conditions for better orbit control. Furthermore, one of the new optics schemes is more symmetrical than the standard one, facilitating e.g. the implementation of quadrupole scans for betatron resonance studies. The alternative lattices also allow us to expand significantly on the tune parameter space available for the study of space-charge dominated beam transport.

INTRODUCTION

The successful operation of any accelerator depends on a judicious choice of operating tunes. Naturally, this choice is made based on a number of criteria all of which cannot be met simultaneously: avoidance of betatron resonances and instabilities, reduction of average dispersion and/or natural chromaticity, particular values of betatron function in certain regions, etc. For space charge dominated beam transport [1], in particular, a high density of quadrupoles is desired for tight focusing of relatively large beam currents (e.g. 100 mA for 10 keV electrons). But as presented before in PAC 07 [2], use of lower-current beams in combination with reduced focusing can also yield space-charge-dominated beam transport conditions. Furthermore, several focusing schemes are possible in UMER that in some cases make beam injection simpler and have more BPM diagnostics per betatron period than in the standard lattice. The optics in the lattice where only half the quadrupoles are used, for example, is more symmetrical than the standard lattice which includes two "irregular" quadrupoles at injection. Because of the higher periodicity of the new optics, systematic resonances (with "zero" current at least) are more widely spaced. Thus, the new lattice should provide a better basis for a number of studies that include betatron resonances with strong space charge.

The alternative lattices also allow us to expand significantly the operating tune range. For example, we can explore space-charge dominated beam transport with zero-current phase advances per period amply exceeding $\sigma_0 = 90^0$ without approaching the power limit of the ring

quadrupoles. Tiefenback and Keffe [3] conducted experimental studies at Lawrence Berkeley Laboratory of beam stability with strong focusing and space charge in the range $\sigma_0 = 45^0$ to 150^0 in a *linear* lattice, and later Lund and Chawla [4] explored in simulations the role of envelope "flutter", i.e. fast envelope oscillations - even when the beam envelope is matched, for promoting particles outside the beam core and inducing beam instability through resonant mechanisms. Additional effects from standard betatron resonances, dispersion and others are expected in a circular lattice like UMER.

Furthermore, UMER can address issues relevant to proton and heavy-ion high intensity storage rings; such as injection with large tune shifts and 6D phase-space evolution of coasting vs. contained bunches. In this regard, UMER is presently the only electron storage ring with this capability.

UMER LATTICES

The standard UMER lattice ("lattice I") employs 72 short magnetic quadrupoles distributed in groups of 4 on 18, 64-cm ring support sections. Each support section, except for the injector section, also includes two short bending dipole magnets and one diagnostic chamber with a BPM and a fluorescent screen. The matching section/injector contains 6 quadrupoles in a 1.2-m straight section and two wide-aperture quadrupoles, YQ and QR1, on the "Y" section.
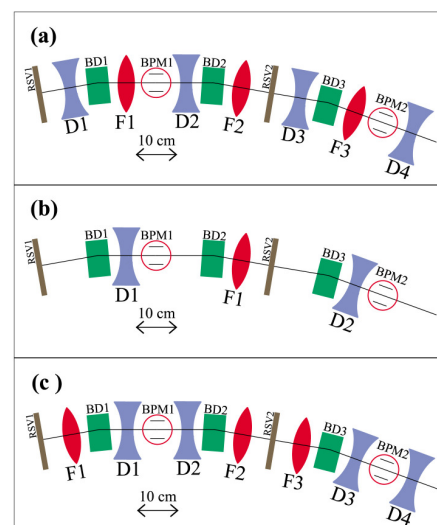

Figure 1: Three UMER ring lattices (injector not shown): (a) FODO lattice with 72 quadrupoles, (b) FODO with 36 quadrupoles, and (c) FODODOFO with 72 quadrupoles.

The standard lattice as well as two alternative lattice are illustrated in Figure 1. The first alternative lattice uses half the quadrupoles in the ring lattice and no YQ for injection; we label this lattice "lattice IV". The second lattice, "lattice VI", employs all the quadrupoles but with a different polarity layout: the quadrupoles on either side of the diagnostic chamber are defocusing.

Tables 1 and 2 summarize the lattice and beam parameters. The zero-current betatron phase advance per period is the same, $\sigma_0 = 67.3^0$, for all 3 lattices, but the alternative lattices have a full-lattice period, $S = 64$ cm instead of 32 cm for the standard lattice. We employ the two lowest-current beams in UMER, 0.6 and 6.0 mA. Several other focusing and injection schemes are possible in UMER, but only the two that we consider most promising are discussed here.

Table 1: Lattice and Beam Parameters for 0.6 mA, 8.0 μm (4× RMS, unnorm. emitt.) at 10 keV, 100 ns.

	Lat. I	Lat. IV	Lat. VI
Lat. period, S (cm)	32	64	64
Bare Tune, ν_0	6.73	3.36	3.36
Inc. Tune Shift, $\Delta\nu$	0.94	0.87	0.87
Tune Dep., ν/ν_0	0.86	0.74	0.74
Av. Beam Rad., a (mm)	1.7	2.5	2.5
BPMs/Betatron Per.[1]	2	5	5

[1] Undepressed

Table 2: Lattice and Beam Parameters for 6.0 mA, 26 μm (4× RMS, unnorm. emittance) at 10 keV, 100 ns.

	Lat. I	Lat. IV	Lat. VI
Lat. period, S (cm)	32	64	64
Bare Tune, ν_0	6.73	3.36	3.36
Inc. Tune Shift, $\Delta\nu$	2.4	1.9	1.9
Tune Dep., ν/ν_0	0.64	0.43	0.43
Av. Beam Rad., a (mm)	3.5	6.0	6.0

The space charge incoherent tune shifts ($\Delta\nu = \nu_0 - \nu$) and tune depressions quoted in the Tables are calculated using the uniform focusing approximation discussed in detail in e.g. chapter 4 of Ref. [1]. It should be noted that a simple form of the Laslett tune shift formula (with linear focusing and space charge but no image-forces) can be derived from either single-particle considerations or from the envelope equations in the smooth approximation; the results agree if the tune shift is small compared to the bare tune ν_0. The derivation from the envelope equation, however, does not require a small tune shift; the maximum tune shift would be just equal to ν_0, corresponding to a zero depressed tune, i.e. perfectly laminar motion which would occur ideally when external focusing and space charge forces are balanced and the emittance is zero or negligible.

For 0.6 mA, the incoherent tune shift is close to unity for all 3 lattices; the tune depression for transport in lattice I, though, indicates emittance-dominated conditions while the tune depressions for transport in the other two lattices indicate a borderline situation, i.e. about equal contributions from (linear) space charge and emittance.

Figure 2 shows the RMS periodic envelopes for 6 mA in the 3 lattices. Notice from the envelopes and the numbers in the Tables that the uniform-focusing approximation predicts the same average beam radii for lattices IV and VI. However, the "flutter" corresponding to lattice VI is significantly smaller than for lattice IV; this difference provides an opportunity to investigate the limits of validity of the uniform focusing approximation as well as the effects of envelope flutter on stability [4].
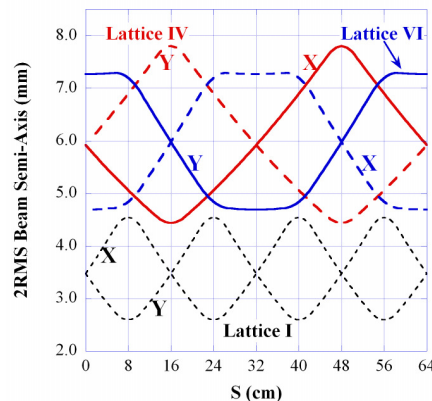

Figure 2: Beam envelopes for 6 mA, 10 keV, $\sigma_0 = 67.3^0$, for the lattices in Fig. 1a-c - see also the Tables above. For comparison, the vacuum pipe radius is 25.4 mm.

ORBIT CORRECTIONS AND MATCHING

We monitor the beam centroid position with 15 capacitive BPMs, one in the matching section and 14 on the ring. A convenient MATLAB program allows us to acquire the BPM signals and trace the horizontal and vertical components of the beam centroid orbit. In addition, we measure the beam current with a fast Bergoz transformer in the matching section and a wall-current monitor located in the ring chamber labeled "RC10", roughly half-way around the ring. Orbit corrections in the horizontal plane are done with 35 bending dipoles, while 18 short magnets placed between ring chambers are used for vertical corrections.

First-turn Steering

As the experience in UMER and larger rings shows, there is no clear-cut strategy for getting a second turn in a newly implemented ring beam line. Beam steering as in a linac normally does not succeed in a ring when significant injection errors are present; and even if injection errors are small, magnet misalignments can make it difficult to achieve a circulating beam. The conundrum consists in injecting near the closed orbit when this orbit is unknown from the start, and having to steer the beam without re-doing injection for every steering adjustment.

In UMER, we also have to deal with the effect of the ambient field on the 10 keV electron beam. Therefore, we

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begin by setting the currents on the 36 bending dipoles so their action, together with that from the local ambient field, yields a 10^0 bend around each dipole. At the same time, we turn off all vertical steerers. We set the matching solenoid and quadrupoles (Q1-Q6) according to calculated values for matching into a ring lattice with chosen operating bare tune and beam current (see below). Then we optimize injection for maximum transmitted current at RC10.

The use of compensated orbit bumps is also a standard technique that we have tested successfully in UMER. We have used the code ELEGANT [5] for calculations of the bumps and other (linear) optics modeling; the results demonstrate the soundness of the basic optics in the alternative lattices.

Multi-turn Optimization and Matching

Once a second turn signal is observed, we search for values of operating tunes that can lead to more turns. Additional steering and injection corrections are then tried independently. The process is repeated until we obtain maximum number of turns without losses. At the very minimum, 4 turns are required so we can apply a known prescription [6] for measurements of equilibrium orbit (EO) and fractional tunes.

RMS beam envelope matching is critical to achieve a first turn. We use a K-V envelope solver and optimizer written in MATLAB [7] to obtain envelope matching for the 0.6 and 6.0 mA beams using a solenoid and 6 quadrupoles. Two key advantages of lattice IV are that only one wide-aperture quadrupole (QR1) is used and that this quadrupole is not tilted relative to the ring quadrupoles as is YQ with standard injection; without YQ, it becomes possible to do quadrupole scans without affecting injection. Thus, QR1 acts as a perturbation quadrupole whose effect can easily be compensated by adjusting another ring quadrupole.

DISCUSSION

We began our tests of alternative lattice IV with the 6 mA beam (see Table 2) because of a significantly better S/N ratio in the BPM signals compared to the 0.6 mA beam. We aimed initially at zero-current phase advances per period, σ_{0x}, σ_{0y}, close to 86.9^0, i.e. tunes around 4.3, but we were forced to reduce them to 67.3^0, or tunes around 3.4, for 100 % transmitted current at RC10. (The reason for the original choice of higher bare tune is that we wanted to have a reduced average dispersion.) At the same time, we did new calculations of RMS envelope matching at the new operating point. At the time of writing, we are able to circulate the 6 mA beam up to 6 turns (lattice IV) but with significant beam losses and distortion of the current waveforms after the first turn, to the point that no useful first 4 turns are still available for equilibrium orbit measurements. We have kept the same settings for the main bending dipoles as for the standard lattice, except for the two dipoles on both sides of the injector (D35 and D1). The dipole settings, together with injection and envelope matching parameters for lattice I, have been optimized over the years to obtain over

100 turns of a coasting beam at 0.6 mA, and over 1,000 turns with a contained (longitudinally-focused) bunch, as reported before in PAC11 [8].

The beam losses and distortion of the current waveforms are very likely caused by beam scraping from injection errors and imperfect steering around the ring. This conclusion is supported by the fact that the smaller 0.6 mA beam cannot complete four turns under similar conditions of injection/steering as for the 6 mA beam, although the second turn is solid. For the same 0.6 mA beam, we also had to operate at a lower tune than the one originally intended, but full exploration of tune space including "forbidden" regions ($\sigma_0 > 90^0$) will be done only after a minimum number of lossless turns, say 10, are obtained. At the lower tune, near 3.4, the ring quadrupole current is 0.87 A, well below the maximum of 3.0 A. As mentioned before, the orbits of the low energy electron beams in UMER are sensitive to the ambient magnetic field, so the longer drift spaces of lattice IV make steering corrections more critical for achieving a closed orbit. Furthermore, corrections in the vertical plane are currently not as effective as for the horizontal plane, in addition to coupling of the two transverse motions from the ambient field and residual skew quadrupole errors. We will use Helmholtz coils for additional control of the vertical orbit, and also will re-level all quadrupoles to minimize skew errors.

Experiments with the other alternative lattice, lattice VI illustrated in Fig. 1c, have led to 100 % transmitted current through RC10, but injection and ring steering errors remain. In this lattice, as in the standard one, the presence of a tilted injection quadrupole adds complexity to tuning. One advantage of this scheme, though, is that the BPMs in the ring are in effect located at the center of "extended" defocusing quadrupoles. Computer simulations also indicate that the optics of lattice VI is sound despite not being as symmetrical as lattice IV.

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