COHERENT PHENOMENA OVER A RANGE OF BEAM INTENSITIES IN THE ELECTRON STORAGE RING UMER*

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Abstract

The University of Maryland Electron Ring (UMER) is designed for operation over a broad range of beam intensities, including those normally achieved only in linacs [1]. This is possible thanks to a combination of low-energy (10 keV) electrons and a high density of magnetic quadrupoles (72 over an 11.5 m circumference) that allow operation from 0.5 mA to 100 mA; that is, from the emittance dominated to the highly space charge dominated regimes. We present results of basic beam centroid-motion characterization, including measurements of the momentum compaction factor and natural chromaticity and dispersion. These are compared with results from computer simulations employing the code ELEGANT [2]. We discuss the techniques and challenges behind the measurements with fast beam-position and wall-current monitors.

INTRODUCTION

Working with a 10 keV, bunched, space charge dominated electron beam brings with it many special issues, including challenges in injection, matching, effect of the earth's field, timing and longitudinal beam blow up [3]. UMER is sufficiently different from most electron storage rings, almost all operating at relativistic beam energies, so that standard beam measurement and tuning technologies cannot be used or have to be creatively modified. The 0.6mA beam operates in the emittance dominated regime, albeit with an incoherent space charge tune shift well beyond the Laslett limit. The 6, 20, 80 and 100 mA beams currently available for experiments are well into the space charge dominated regime with incoherent tune shifts in multiple integer values [3][8]. Understanding the physics of these operating regimes is the motivation for building and operating UMER [1]. Work reported here focuses on the 0.6, 6 and 20 mA beams, treating the coherent beam effects from the approach of single particle dynamics. Recent progress in beam tuning is reported elsewhere [5]. This paper presents recent measurements of natural chromaticity, dispersion, momentum compaction and a comparison of results with the ELEGANT code, where space charge is not included. Simulations with full space charge are in progress using the WARP Code [5].

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CHROMATICITY AND DISPERSION

The natural chromaticity is defined by [4],

$$\eta_{x,y} = \frac{\Delta \nu_{x,y}}{\delta}, \quad (1)$$

where $\delta = \Delta p / p_0$ is the fractional deviation from the UMER momentum, p_0, corresponding to the 10 keV operating energy. All values of momentum are computed from the well-known formula (pc is in units of keV),

$$pc = \left[\left(T + E_o\right)^2 - E_o^2 \right]^{\frac{1}{2}} \quad (2)$$

where E_0 is the electron rest mass and T is the UMER operating kinetic energy, which is measured to ≤ .01%.

Because of space charge effects, the number of turns that can be stored in UMER are limited; the best case being ~ 200 turns with the 0.6mA beam, dropping off rapidly with beam current. Thus common measurement techniques requiring more than 1000 turns are not possible. However, the first 10 turns at 0.6, 6, and 20 mA can now be tuned to be essentially lossless before beam end erosion begins to be an issue [6]. Consequently, tunes and equilibrium orbit values are determined by measuring horizontal and vertical position on four consecutive turns at each of the 14 beam position monitors (BPM's) distributed around the ring. The displacement (horizontal or vertical) x_n at each BPM includes contributions [left to right in equation (3)] from the equilibrium orbit, dispersion, betatron function and BPM error [4],

$$x_{eo} = x_{co} + x_\delta + x_{n\beta} + \varepsilon_{BPM} \quad (3)$$

Assuming that x_δ and ε_{bpm} are small and setting the phase advance per turn, $\mu = 2\pi\nu$, the displacement amplitude on the nth turn is $x_n = x_{eo} + x_{n\beta}$, where

$$x_{n\beta} = \left(\cos 2\pi\nu + \alpha \sin 2\pi\nu\right) x_0 + \beta x_0' \sin 2\beta\nu \quad (4)$$

α and β are the usual Courant and Snyder parameters and x_0 and x' the initial position and slope. After some extensive algebra, one can eliminate x_0, x_0', α and β to get the "four turn" equation for the fractional tune [7],

$$\Delta\nu = \frac{1}{2\pi}\cos^{-1}\left[\frac{x_n - x_{n+1} + x_{n+2} - x_{n+3}}{2\left(x_{n+1} - x_{n+2}\right)}\right] \quad (5)$$

Unfortunately, equation (5) is very sensitive to errors due to noise and when the measured position of turn's x_{n+1} and x_{n+2} are close to each other. Measurements consist of recording position on 4 consecutive turns horizontally and vertically at each BPM and then averaging over the 14 (horizontal or vertical) tune values obtained by applying equation (5). Values for ν_x and ν_y outside the range of $\nu_{avg} \pm \sigma$, where σ is the standard deviation, are discarded, and a new ν_{avg} and σ are computed.

The fractional part of the tune can also be measured by means of the Fast Fourier Transform (FFT). A BPM signal for some 40 turns is averaged over 16 ring cycles and the FFT of the signal is measured with a high band width oscilloscope. The tune is extracted from the observed upper or lower sideband.

Tunes (integer and fractional part) are also extracted directly from position data from the BPM's. The position value for the nth turn at a BPM located at s_i can be written using an alternate expression for the betatron motion from equation (4) as [4]

$$x_{ni} = a_n \beta^{\frac{1}{2}} \cos[\nu\phi(s_i)] + x_{eo}(s_i) + x(s_i) + \varepsilon_i \qquad (5)$$

The difference between the nth and mth turns at the ith BPM is,

$$x_{mi} - x_{ni} = A\cos[\nu\phi(s_i)] + B\sin(\nu\phi(s_i)) \qquad (6)$$

where it is assumed that the β value is the same at all BPM's (per the UMER design) and A,B and ν are obtained by fitting the $x_{mi} - x_{ni}$ values from the 14 BPM's. Under the assumption that the phases $\phi(s_i)$ are an integer number of lattice sections, they are given by $\phi(s_i) = 2\pi/I$, i=1 to 18, the number of ring sections.

To obtain the dispersion, $D(s_i)$ at the ith BPM using the relation $x = D(s)\delta(T)$, it is necessary to measure the equilibrium orbit at each BPM. The derivation of the four turn fractional tune formula (5) also provides an expression for the equilibrium orbit [7],

$$x_{eo} = \frac{x_2^2 - x_3^2 + x_2 x_4 - x_3 x_1}{3(x_2 - x_3) + x_4 - x_1} \qquad (7)$$

for the n=1 case. While less sensitive to error than equation (5), equation (7) still has accuracy issues when all four turn-by-turn positions at a given BPM are small.

If the x_{eo} values are recorded at all BPM's at the operating momentum p_o for 10 keV and if the kinetic energy is changed by ΔT, with corresponding momentum change $\Delta p = p - p_o$, then the change in equilibrium orbit Δx_{eo} at the ith BPM is related to dispersion by

$$\Delta x_{eo}(s_i, T) = D(s_i)\,\delta(T), \qquad (8)$$

where, as for the chromaticity, $\delta(T) = \Delta p/p_o$. At a given BPM, the ratio $D(s) = \Delta x_{eo}/\delta(T)$ should be constant over the range of values of momenta used in the scan.

Chromaticity and dispersion are measured at a range of kinetic energies obtained by adjusting the high voltage power supply on the UMER gun. Four turn position data is recorded for the first four turns in the ring and the corresponding momenta, tunes, and equilibrium orbits computed as described above.

The experimental results for $\eta_{x,y}$ at various beam currents are shown in table 1. The values are obtained from least squares fits of the data $\Delta\nu(T) = \nu(T) - \nu_o$ as a function of δ(T). The results for η_x derived from both four turn and FFT measurements are in good agreement with the ELEGANT simulation. The η_y values are not, but it has been clear for some time that both measuring and simulating vertical motion in UMER is difficult. Improving these is a major work in progress.

Table 1: Natural chromaticity data. * means that a value could not be determined with sufficient accuracy.

Beam Current	Measured (4 turn data)		Measured (FFT data)		Predicted (Elegant)	
I_{bm} (mA)	η_x	η_y	η_x	η_y	η_x	η_y
0.592	-7.6 ± 3.2	*	-7.1 ± 0.6	*	-7.9	-10.9
5.85	-7.4 ± 1.0	-8.3 ± 0.9	-7.1 ± 0.7	*	-7.9	-10.9
20.2	-7.9 ± 1.0	-8.4 ± 2.1	*	*	-7.9	-10.9

The results of measurement and simulation of dispersion are shown in figure 1. These show that globally there is a reasonable model of the ring, but not in detail. They also show the difficulty of modelling the vertical and horizontal effects of the earth's field and the need for a new, more accurate determination of ring optical element locations.

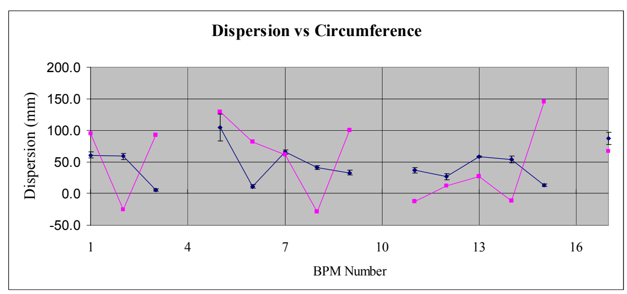

Figure 1: Measured horizontal dispersion for the 20 mA beam (blue) compared to the ELEGANT simulation (red).

MOMENTUM COMPACTION

The momentum compaction factor [4]

$$\alpha_c = \frac{\frac{\Delta C}{C}}{\delta} \qquad (9)$$

describes the fractional change in orbit circumference C(T) due to a fractional change in particle momentum δ(T). In UMER where the relativistic β = v/c is only 0.2 (v = 6 cm/ns) the change in C is velocity dominated. The nominal energy spread at the center of a 100 ns (6 meter) long bunch is 20eV. So we do not see much beam enlargement due to energy spread. Noting that $\Delta C = C - C_0$ so that

$$\frac{C - C_o}{C_0} = \alpha\delta + 1 \qquad (10)$$

and $C = v(T)t_{rev}$ and $t_{rev} = 1/f_{rev}$, 0ne the following two expression can be used to measure momentum compaction,

$$\frac{vt}{v_o t_o} = \alpha_c \delta + 1 \quad \text{or} \quad \frac{v f_0}{v_{0f}} = \alpha_c \delta + 1, \qquad (9)$$

where v, t and f are velocity, time and revolution frequency at the operating momenta of p and p_o, respectively.

Three approaches have been tried to measure α_c: 1. measuring the time of revolution, 2. measuring the frequency of revolution and 3. determining the average change in circumference from the average change of the x_{eo} values at all BPM's, each over a range of δ(T) corresponding to 9.7 keV ≤ T ≤ 10.3 keV.

Measuring the time of revolution directly by measuring time of arrival of successive bunches of the UMER installed wall current monitor has proved to be insufficiently accurate because of an erosion of the beam head and tail due to space charge and lack of an electromagnetic barrier bucket, now under development [6]. Measuring the revolution frequency via the same FFT technique used to measure tune and computing the frequency (of revolution) peak off-line with a Lorentz distribution has been more successful but is still marginal because the accuracy has been limited to about 1 kHz out of the 5.087 MHz nominal revolution frequency, and better than 0.1 kHz resolution is needed.

The third technique evolved from the chromaticity measurements where the equilibrium orbit x_{eo} is recorded at each BPM for each momentum set δ(T). We use a concept called the reference circle: UMER is designed as a 36 sided polygon with each side equal to 32 cm in length. But for the effect of the earth's field, the beam trajectory circumference would be 1152 cm. The distance from the center of UMER to each vertex (where the bending dipoles are located) is 183.57 cm. The circumference of a reference circle tangent to the ring at each vertex has this radius and a circumference of 1153.5 cm. Because of the earth's field, this turns out to be very close to the measured value for a 10keV beam. Dividing ΔC and C by 2π, gives reference radii ΔR=R-Ro and Ro. We have found that for each momentum scan, there is an average equilibrium orbit value $\langle x_{eo} \rangle$ obtained from averaging the 14 x_{eo} values at the BPM's computed using equation (7). We can then obtain a set of <xeo> values for each momentum used in the scan. From this data we compute a table of Δx_{eo} corresponding to the set of δ(T). Rewriting equation (7) with Δx_{eo} = ΔR and C_o=Ro, we have,

$$\frac{\Delta x_{eo}}{R_0} = \alpha_c \delta \qquad (10)$$

Ro = 183.57 cm is arbitrarily taken as the radius of the 10 keV reference circle since this corresponds closely to our best measured value and is consistent with the ring design. A least squares fit to the ratios $\Delta x_{eo}/R_o$ to the corresponding δ(T) gives the values shown in Table 2. The results are consistent with the Elegant simulation, and as expected, do not show any dependence on I_{bm} at this level of measurement accuracy.

Table 2: Momentum compaction data for three beam currents. The ELEGANT prediction is not current dependent, and so is the same for all currents.

I_{bm} (mA)	α_c (meas.)	ELEGANT
0.6	0.0287 ± .0124	0.0204
6	0.0223 ± .0029	0.0204
20.0	0.0234 ± .0008	0.0204

CONCLUSIONS

The modelling and measurement of coherent beam effects in highly space charge dominated beams using a single particle approach, has been shown to be effective. As expected, there appears to be no dependence of $\eta_{x,y}$ or α_c on I_{bm}. The dispersion measurements at I_{bm} = 20 mA appear to be consistent with the model developed in ELEGANT in general, but not in detail! Data has been taken for I_{bm} = 0.6 and 6.0 mA and will be processed soon. The next step is to apply these techniques to the 80 and 100 mA beams, a serious challenge.

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