ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-TUPLM22

OFF AXIS DEPENDENCE OF CURRENT DEPENDENT COHERENT TUNE SHIFTS IN THE UMER RING*

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Abstract

The University of Maryland Electron Ring (UMER) was built to explore space charge effects in the extreme – beyond the space charge limit of most existing storage rings. At the nominal operating kinetic energy of 10 keV, the beam is also non relativistic. We have experimentally verified that the current dependent coherent tune shift obeys the Laslett formula over a wide current range for a cylindrical geometry and non-penetrating magnetic fields when the beam is on axis; i.e. the average closed orbit displacement around the ring is essentially zero. In the current experiment this measurement is extended to the change in current dependent coherent tune shift as the average closed orbit is moved off axis. It can be displaced over approximately ± 5 mm of the vacuum pipe diameter of 50 mm. without loss of beam. Because the 36 bending magnets in UMER are very short, we treat each of them as a local kick and then increment each by a calculated small amount to achieve the desired, global closed orbit displacement. Experimental results are compared to predictions by Laslett and others.

INTRODUCTION

Space charge dependent incoherent and coherent tune shifts are of primary interest and very well studied for synchrotrons and storage rings operating with relativistic beams, but there is a lack of experimental studies for very non relativistic beams where $\gamma < 2$. The University of Maryland electron ring, UMER, operates in the very nonrelativistic regime, with a $\gamma = 1.02$.

Of particular interest is the coherent tune shift because coherent beam centroid motion is what beam position monitors measure; they cannot directly measure incoherent tune. Moreover, there is a well-established theoretical model developed by L. J. Laslett and others [1-3]. In 2011 the UMER group measured the space charge induced coherent tune shift at beam currents ranging from 0.6 to ~ 70 mA, showing very good agreement with the Laslett predictions [4]. The important restriction for that measurement is that the beam be centered in the beam pipe around the ring; equivalently the average equilibrium orbit displacement must be zero. To gain a feeling for how well the restriction was met, it was planned to measure the change in tune as the beam was scanned off center. Unfortunately, the alignment of the ring was not adequate. A complete disassembly, remounting and precision alignment in 2017, has finally enabled the measurement.

* Work supported by US Department of Energy Office of High Energy Physics, Grant No. DE-SC0010301.

EXPERIMENTAL CONFIGURATION

A recent detailed description of UMER can be found in references [5, 6]. Recent upgrades include a system of Helmholtz coils to cancel out the horizontal ambient magnetic field, a combination of the earth's field and building iron, and a small ferrite loaded rf cavity that can keep the beam bunched for up to 10^4 turns. Importantly, the Helmholtz coils enable vertical centering of the equilibrium orbit.

The space charge driven tune shift is strongly dependent on vacuum chamber geometry and fabrication. The chamber is round over essentially the entire 11.52 m circumference and is made of low permittivity stainless steel (316N) tubing. Discontinuities in the vacuum chamber include bellows (18), BPM's (14), glass gaps (3) and 24 cm of the injection section with an inner diameter of 8.0 cm, compared to 5.0 cm for all the rest. The ring is injected with a 50% fill, square pulse of length 580 cm. The physical simplicity of the vacuum chamber and the fact that the bunch is very much longer than any of the discontinuities allows treating the entire circumference as an identical, cylindrical boundary structure in the experiment. A list of the experiment's key parameters is given in Table 1.

Table 1: Parameters for the coherent tune shift versus beam current experiments. The characteristic current, I_0, is related to the classical radius of the electron, r_0, through $I_0 r_0 = ec$, e is the electronic charge and c is light velocity.

Circumference	1152 cm	Beam pipe radius, b	2.489 cm
Average radius, R	183.3 cm	Beam pipe wall, d	0.0508 cm
Kinetic energy, T	10 keV	Wall resistivity, ρ	7.4 x 10^7 Ω–cm
Relativistic, β	0.1950	Wall magnetization, μ_r	1.0
Relativistic, γ	1.0196	Characteristic current, I_0	17.05 x 10^6 mA

To ensure that the tune shifts are only a function of beam current, it is essential to use exactly the same optical parameters – steering and focusing strengths – for all the beam currents.

COMPUTING THE TUNE SHIFTS

Coherent tune shifts of the betatron oscillation of the beam centroid (the first moment of the beam) are a function of the interaction of the current in the beam with the image current in the chamber wall. The defocusing force is, therefore, the Lorentz force between the beam and the induced image current. A particularly good summary of the physics can be found in chapter 8 of reference [7].

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Because the skin depth, δ_{wall}, is much less than $\sqrt{bd}$, where b is the chamber radius and d the tube thickness, there is no penetration of the beam generated magnetic self-field at the lowest relevant frequency, the ~ 5 MHz beam revolution frequency. So the non-penetrating Laslett equation for coherent tune shift from reference [7] is applicable,

$$\Delta Q^{coh}_{x,y} = -\left[\frac{N r_o}{\pi\beta^2\gamma}\langle\beta_{x,y}\rangle\right]\left[\frac{1}{B_f}\left(\frac{1}{\gamma^2}-\eta_e\right)\frac{\xi_1^{x,y}}{b^2}+\beta^2\frac{\varepsilon_1^{x,y}}{b^2}+\beta^2\frac{\varepsilon_2^{x,y}}{g^2}\right] \quad (1)$$

The η_e term, the neutralization factor, is zero in UMER. The Laslett parameter, ε_2, is for a dc magnetic image due to magnet pole faces. Since UMER air-core magnets have no poles, this term is zero. Noting that $Ne = 2\pi R\ \lambda$, $\beta c\lambda = I_{av}$, $r_o I_o = ec$, the average beta term, $\langle\beta\rangle = R/Q_o$, where $R = C/2\pi$ and Q_o is the zero current tune, Eq. (1) reduces to,

$$\Delta Q^{coh}_{x,y} = -\left[\frac{2}{\beta^3\gamma}\frac{1}{I_o}\frac{R^2}{Q_o^{x,y}}I_{av}\right]\left[\frac{1}{B_f}\frac{1}{\gamma^2}\frac{\xi_1^{x,y}}{b^2}+\beta^2\frac{\varepsilon_1^{x,y}}{b^2}\right]. \quad (2)$$

The geometry dependence of the tune shift is contained in the Laslett Coefficients, $\xi_1^{x,y}$ and $\varepsilon_1^{x,y}$. Also, any asymmetry in horizontal and vertical tune shifts is in the terms with the dual superscripts. The UMER geometry is cylindrical, and since the experiment does only x axis scans, we employ the off axis equations for the two Laslett coefficients for average beam displacement, x_b, only [3],

$$\xi_1 = \frac{b^2}{2}\frac{b^2+x_b^2}{\left(b^2-x_b^2\right)^2} \quad (3) \quad \text{and} \quad \varepsilon_1 = \frac{b^2}{2}\frac{x_b^2}{\left(b^2-x_b^2\right)^2}. \quad (4)$$

It is important to note that when the beam is on axis, i.e. x = y = 0, $\xi_1^{x,y} \rightarrow ½$ and $\varepsilon_1^{x,y} \rightarrow 0$ and Eq. (2) becomes, recalling that $I_{bm} = I_{av}/B_f$,

$$\Delta Q^{coh}_{x,y} = -\left[\frac{1}{\beta^3\gamma^3}\frac{1}{I_o}\frac{R^2}{b^2}\frac{1}{Q_o^{x,y}}\right]I_{bm} \quad (5)$$

This is the equation applicable to the on axis average equilibrium orbit = 0, scans for ΔQ_o^x versus beam current. Substituting Eqs. (3) and (4) into Eq. (2), and simplifying gives the model used in the x axis scans,

$$\Delta Q^{coh}_{x} = -\left[\frac{1}{\beta^3\gamma}\frac{1}{I_o}\frac{R^2}{Q_o^{x,y}}\right]\left[\frac{b^2+x_b^2}{\left(b^2-x_b^2\right)^2}+\frac{B_f\beta^2\gamma^2x_b^2}{\left(b^2-x_b^2\right)^2}\right]I_{bm} \quad (6)$$

For very relativistic beams the first term in brackets can be ignored, but not here.

MEASUREMENTS

Tune measurements are done using all 14 available BPMs on UMER. We employ two methods to measure experimental tunes, the so-called four turn formula [4, 8, 9] and the now common NAFF algorithm [10]. NAFF gives an improved experimental accuracy ($1/N^3$) over traditional FFT techniques ($1/N$) due to an added weight function, but it requires at least 16 turns at constant current and so has a systemic error starting at ~ 40mA coasting beam.

In order to scan x_b, the average value of the equilibrium orbit, $\langle x_{eo}\rangle$, in the x plane, the ring's dipoles have to all be incremented by an equal ΔI. This can be computed by using the single turn kick equation at each dipole and then summing these for all of the dipoles [7]. We have found the movement of x_b to be very linear in ΔI, as can be seen in the measurement shown in Fig. 1.

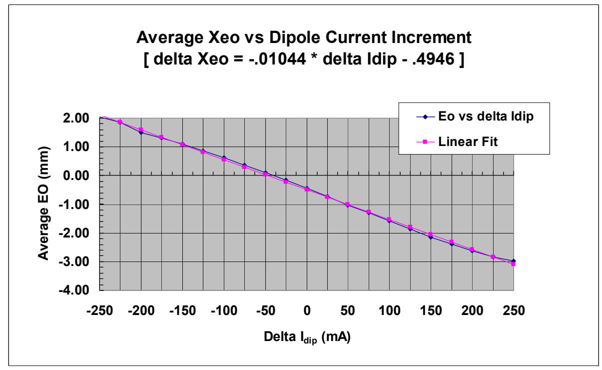

Figure 1: Plot of average equilibrium orbit displacement versus incremental dipole current over about ±10 % of the average dipole current of ~2.6 amperes for an I_{bm} = 6 mA scan in x_b showing the equilibrium orbit off center by ~ -0.5 mm for ΔI_{dip} = 0.

On Axis Scan

For this experiment, we first did a scan of ΔQ_o^x versus I_{bm} with the beam centered in both planes. Data is taken at five beam currents, I_b = ~ 0.6, 6.0, 20, 40, and 70 mA. This gives results similar to those from the 2011 experiment [4]. The result is shown in Fig. 2.

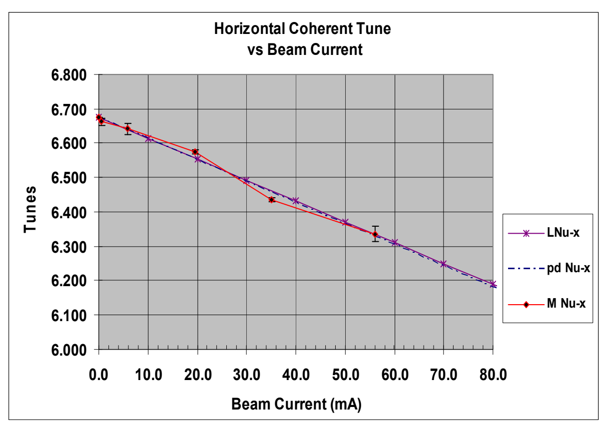

Figure 2: Measurement of the horizontal coherent tune shift as a function of beam current. The beam is centered; so equation (5) applies and is plotted as pd LNu-x. The fit to the data determined the zero current tune, Q_o = 6.674, required for all calculations. Pd Nu-x is the fitted line.

In order to analyze the results, a linear fit is done to the data to determine the zero current tune, Q_o, and the fitted slope. Q_o, is used in equation (5) to compute the predicted values where the quantity in brackets is the predicted slope

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and can be compared the fitted result. The fitted and predicted slopes are, respectively, -0.00617 ± 0.00043 and -.000607, an ~ 2% agreement.

Off Axis Scan

The planned off axis scans proved to be very sensitive to beam steering, and this prevented getting data at greater than 40 mA. Also, measurement at 0.6 mA is very sensitive to BPM pick up noise and the 20 mA, scan sits very close to a half integer resonance, which does not cause large beam loss but is a problem. Consequently, only off axis scans for 6 mA and 40 mA were done successfully. The preliminary calculations to predict the off axis tune shift with equation (6) made it very clear that the measurement would be difficult because of the very small value of the non-current part in brackets, even at maximum $x_b \sim 3$ mm. The plots are shown in Fig. 3.

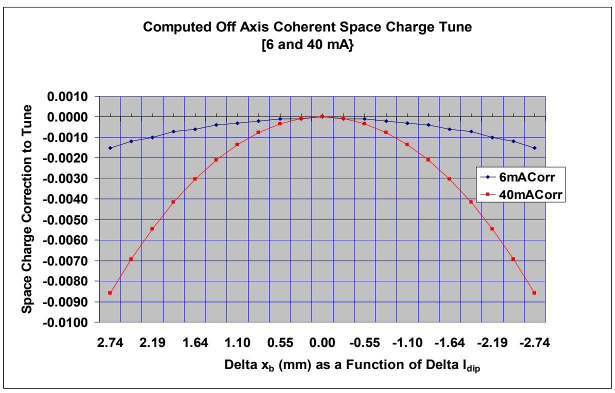

Figure 3: Computed off axis coherent tune shifts caused by space charge at 6 and 40 mA. For comparison purposes the curves are normalized to the $\Delta Q_o^x(x_b = 0)$ because the space charge zero current tune shift is much larger than the off axis variation.

With the first ring dipole scans, it became clear that the amplitude dependence of the betatron tune is larger than expected. Figure 4 shows scans at 6 and 35 mA.

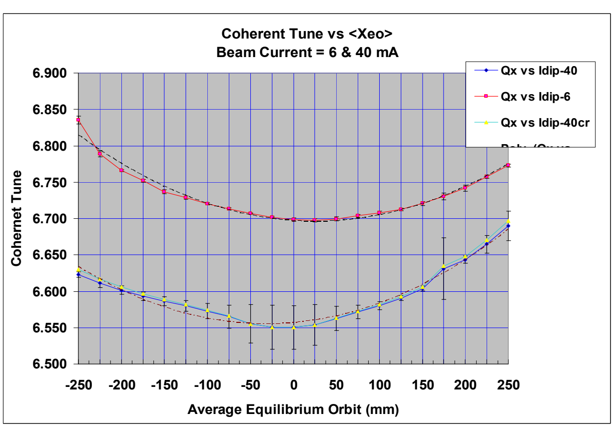

Figure 4: Space charge coherent tune shift as a function of sweeping a beam of axis. The space charge correction to the 40 mA curve for the difference between 6 and 40 m.

We now think that larger amplitude dependence is due to a bigger ring magnetic sextupole than has previously been confirmed. This is borne out by current resonance studies reported at this conference [11]. An off axis correction proportional to the difference 40-6 mA was applied to the 40 mA plot in Fig. 4, would move it toward the 6 mA curve, but it is too small to show.

We are in the process of setting up a simulation in the WARP code to verify both the sextupole dependence and the shape of the off axis scans, which are clearly skewed. It is not clear why this occurs because centering the beam before a scan doesn't seem to matter.

CONCLUSIONS

The planned modelling and initial set of experiments to measure the off axis coherent tune shifts predicted by the Laslett theory has been done. The calculations show that in a small ring the deviation is essentially negligible, and this is strongly confirmed by the measurements. The larger than expected amplitude dependence of the betatron oscillations will be a subject of further simulations and experiments. The ability to scan the equilibrium orbit while keeping the energy/momentum absolutely constant looks to be a useful experimental tool, but we need to understand the physics behind some effects, like the skewing of the tune amplitude dependence shown in Fig. 4.

ACKNOWLEDGEMENTS

Discussions with Professor Tom Antonson and Dr. Max Cornnachia have been particularly helpful as have many discussions with the rest of the UMER group.

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