RESONANCE PHENOMENA OVER A BROAD RANGE OF BEAM INTENSITIES IN AN ELECTRON STORAGE RING *

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Abstract

The University of Maryland Electron Ring (UMER) can operate over a broader range of beam intensities than other circular machines. Naturally, transverse and longitudinal space charge effects limit the ability to store beams. In UMER, the resonance properties of the machine in the two regimes of operation, emittance- and space charge-dominated transport, differ significantly. We report on experiments at 10 keV, with beams from 0.6 mA to 23 mA, corresponding to theoretical space charge incoherent tune shifts well over the Lasslet limit.

INTRODUCTION

Betatron resonance phenomena in circular accelerators have been known since at least the 1950's. A standard exercise in the design and operation of every circular machine is to find optimum operating points in the tune diagram. These points will normally correspond to maximum number of turns with minimum beam losses and degradation, conditions that are obviously desired for most applications. The University of Maryland Electron Ring (UMER) is no different in this regard, but the operation with high space charge, comparable to external focusing, modifies the resonance conditions in non-trivial ways. UMER is described in Chapter 7 of Ref. [1]; the latest developments in UMER are discussed in a number of papers in these proceedings.

Several numerical and theoretical investigations of "space-charge" resonances and instabilities in rings and linacs have been published in the last few years [2]. The results are normally compared with the performance of particular machines, but few systematic experimental investigations have been carried out. Thus, UMER provides a natural platform for additional studies in this area.

In this paper, we present results of experiments employing three beams. The main beam physics parameters are summarized in Table 1. The calculations rely on the smooth-approximation theory as presented in Ref. [1]. The experiment with the low-current beam is in the regime of emittance-dominated transport, while the experiments with the other two beams correspond to parameters in the space-charge dominated regime. Regarding language, we call the space-charge dominated regime a "high intensity" regime in the sense of the intensity parameter defined in [1] by $\chi = \sqrt{1 - (\nu/\nu_0)^2}$ (ν, ν_0 are the depressed and unde-

pressed betatron tunes, respectively). Other researches use "high intensity" in the sense of "high power", which does not always entail high space charge.

Table 1: Beam Current and Emittance and Calculated Transport Parameters. All three cases at 10 keV. The emittance is 4RMS, unnormalized, and $\epsilon_x = \epsilon_y$ is assumed.

Beam Current→ Emittance→	0.6 mA 5.5 μm	6.2 mA 16 μm	23 mA 20 μm
Nominal Tune, ν_0	6.14	6.14	6.14
Beam Radius, a (mm)	1.6	3.6	6.0
Intensity Parameter, χ	0.38	0.79	0.96
Tune Dep., ν/ν_0	0.79	0.46	0.19
Coherent Tune Shift	− 0.01	− 0.06	− 0.18
Incoherent Tune Shift	1.3	3.3	5.0

EXPERIMENTS

The three beam currents of the experiments are obtained by using apertures near the output of the thermionic electron gun. The same beam pulse duration of 100 ns was implemented in all cases; with this pulse, the bunch extends initially to fill almost half the 11.52 m circumference of the ring. The main ring diagnostics for the experiments of this paper are a wall-current monitor (WCM) and a beam position monitor (BPM). The WCM is placed in a glass break at a location labeled "RC10", almost half-way around the ring. Figure 1 shows a typical signal from the WCM for the 10 keV, 6.2 mA electron beam near the nominal tune. The beam losses that are observed after about 10 turns are ex-
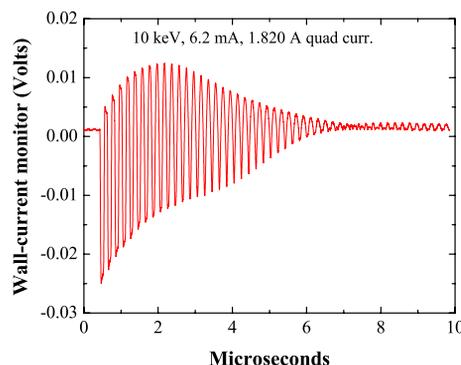

Figure 1: Example of wall-current monitor (WCM) signal (0.22 mA per volt). At 10.00 keV, there are 5.08 turns per microsecond.

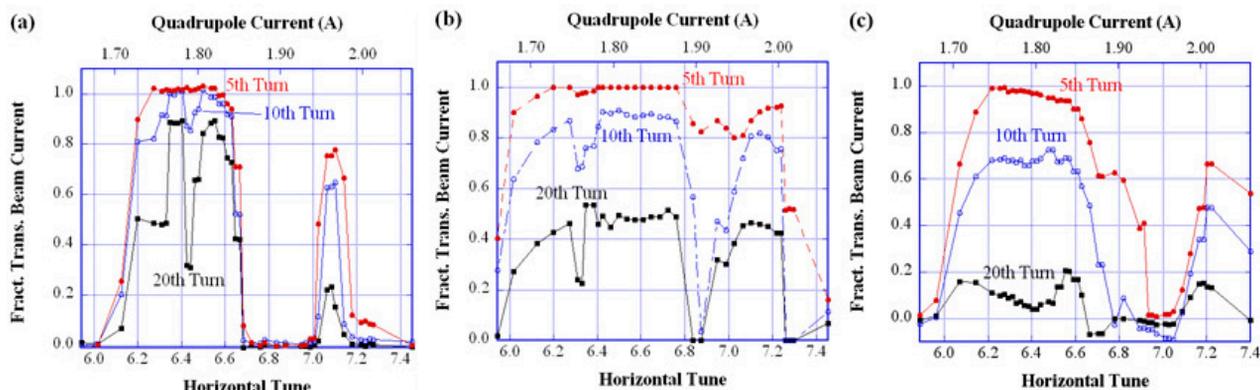**Beam Dynamics and Electromagnetic Fields**

Figure 2: Fractional transmitted beam current at the 5th, 10th and 20th turns (from wall-current monitor signals similar to Fig.1) as a function of ring quadrupole currents and measured horizontal tunes for experiments at 10.00 keV with: (a) 0.6 mA, (b) 6.2 mA, and (c) 23 mA electron beams (see also Table I).

aggerated by the fact that a DC component of current is not measured by the resistive WCM; this DC component develops as the bunch ends meet after a few turns. The effect is less pronounced for the low current beam.

The procedures for beam steering and rms-envelope matching are discussed in the papers by UMER members C. Wu et al. (FR5REP029) and R.A. Kishek et al. (FR5PFP061) in these proceedings . It suffices to say that it is challenging to inject, steer and match the beam when all three operations are coupled. Steering, in particular, has to be done carefully and with a clear picture of the action of the earth's field on a 10 keV electron beam. It should be noted also that the rms-envelope matching solution for a given beam current, at the nominal tune, is not changed as the tune scan proceeds; therefore, significant mismatch likely plays a major role far from the standard operating point.

All quadrupoles in the ring, except the two wide aperture quadrupoles in the inflector, were powered with currents varying from 1.67 A to 2.06 A, in steps of 0.01 A. The multi-turn beam current signals from the WCM were recorded for each operating point. The ratios of beam currents at the 5th, 10th and 20th turns to the injected current were computed from the WCM. Figures 2a through 2c show the transmitted current ratios as functions of quadrupole current and measured horizontal tune. Without longitudinal focusing to contain the bunch expansion and thus reduce any DC component of beam current in the ring, the measured ratios of transmitted current for the 20th turn are bound to be smaller than the actual values. However, from recent experience with longitudinal focusing of the low current beam (see paper FR5PFP058 by B. Beaudoin et al., these proceedings), the error is not significant for the 20th turn at low current.

In addition to the WCM signals, the fast Fourier transform (FFT) of the right plate signal from the BPM at chamber RC3 (3.1 m from the electron gun output) was recorded at a number of operating points. The FFT data was used to compute the fractional part of the horizontal tune from the

standard analysis of the location of side bands ("slow" and "fast" waves) relative to the zero and first harmonics of the revolution frequency peaks. The integer part of the tune, on the other hand, was derived from a fit to BPM-derived closed-orbit distortion (COD) data, as described in the accompanying paper by D. Sutter et al. (FR5PFP063). The fractional tunes derived from FFT have 2% errors; the errors are only 1% from orbit-data derived tunes.

Based on the detected stable region for the 6.2 mA beam (see Fig. 2b), from 1.760 to 1.870 A for the quadrupole currents, we searched for an optimum operating point (ν_x, ν_y) [$\nu_{x(y)}$: horizontal (vertical) tune] by powering the focusing and defocusing quadrupoles with different currents in that range. As before, the WCM signals were recorded at each pair of operating currents and the ratios of transmitted currents at the 5th, 10th and 20th turn were recorded. The results for the 20th turn ratios are illustrated in a contour plot in Figure 3.
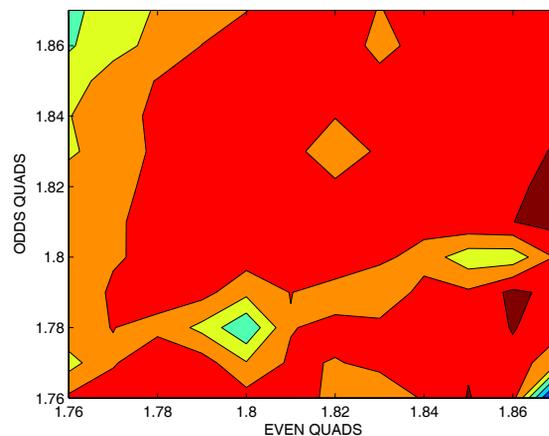

Figure 3: Fraction of transmitted current at 20th turn for 6.2 mA beam when the current of even and odd quadrupoles are varied. Optimum parameters (60% transmission) appear in dark areas like the one around (1.865,1.820)A; the dark red correspons to 50% transmission, orange is 40%.

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DISCUSSION

The low current beam survives with 90% transmission after 20 turns, over narrow bands between 6.30 and 6.40 horizontal tunes, or 1.77 to 1.78 A, quadrupole current (QC) (Fig. 2a). The beam displays a relatively sharp resonance near a half-integer horizontal tune (6.50, or 1.80 A QC, as in Fig. 2a), and a much broader resonance likely comprising third-integer and integer components (6.70 to 7.00 tunes, or 1.86 to 1.95 A QC). The 6.2 mA beam, which is space charge dominated, survives with 50% transmission after 20 turns over a broad tune range, from 6.40 to 6.70, or 1.78 to 1.87 A, QC (Fig. 2b). It also displays a sharp third-integer resonance at 6.3, or 1.76 A QC, and a second sharp decline between 6.7 and 7.0. Interestingly, for the first five turns, the 6.2 mA beam behaves better than the low-current beam, surviving with 80% transmission or better over almost the entire tune expanse (see red circles in Fig. 2b). The 23 mA beam, which is in the extreme space-charge dominated regime at injection, is circulated with 70% transmission after 10 turns over a tune range comparable but smaller than the one for 6.2 mA. Unlike the latter, it displays a broad resonance around 6.5, and an even broader region of beam loss where third-integer (6.67) and integer resonances overlap.

Finally, the search for the optimum operating quadrupole currents for the 6.2 mA beam (Fig.3) yields a relatively broad region with 60% transmission after 20 turns atround (1.865,1.820)A or corresponding *nominal* tunes of (ν_{0x}, ν_{0y})=(6.41,6.05). Work is in progress to produce a tune diagram after corrections from FFT data.

Clearly, there are two major factors in the beam evolution that affect any interpretation of the results presented here: beam losses and emittance growth. As explained above, the losses may be exaggerated, particularly for the low current beam. For the higher current beams, we conjecture that the faster debunching and beam losses are related: the growing beam size from envelope mismatch could lead to "coherent damping" through longitudinal-transverse effects, i.e. from beam interaction with the pipe through chromaticity+impedance. Emittance growth over many turns, on the other hand, is not known from experiments. However, from measurements over the first turn, but different injection conditions, we know that the emittance of the 23 mA beam almost doubles in that distance [3], which is also close to the depressed betatron wavelength (the characteristic length for "self-matching") at the typical operating tune.

Taking all these factors into consideration, one could argue that the initially space-charge dominated beam turns into an emittance-dominated one after a few turns, with many resonance crossings in the process. Assuming, for example, that the emittance of the 6.2 mA beam increases by a factor of 5 over 10 turns, the intensity parameter changes from χ=0.8 (Table I) to 0.3, in the emittance dominated regime, but still with a tune shift exceeding the Laslett tune-shift by a factor of 4.

Despite the complexity of the beam dynamics in UMER, it may be possible to relate our results to the existing theory of coherent beam resonance phenomena (see e.g. [4]). In its simplest form, the theory predicts a resonance condition given by $n/m = \nu_0 - C_{mk}\Delta\nu$, where n is the order of the resonance, (m, k) label the coherent beam modes, and $\Delta\nu$ is the space charge incoherent tune shift. The strength and geometry of the actual beam modes, on the other hand, will depend on the beam particle distribution and degree of mismatch. The theory is based on an equivalent K-V particle distribution [1] or a Gaussian distribution. It is to be investigated if "equivalent" beam modes and overall (RMS) depressed tunes can be defined for beams injected with extreme space charge as in UMER. In other machines like the accumulator proton ring at SNS, space charge is built up as current is stacked (multi-turn injection), so the shift in tune from incoherent space charge is gradual.

Regarding simulations, one of us (C. Wu) has employed the particle-in-cell code WARP [5] to investigate beam centroid behavior in UMER over a tune range (and beam current) variation comparable to the experimental conditions. As discussed in [6] and expected from theory, the linear resonances of the three beams of the experiment can be related to quadrupole transverse (offset) and strength errors. In addition, image forces impact the resonance points depending on the beam current (coherent tune shift), also in fair agreement with calculations (Table I).

In conclusion, the resonance properties of the UMER electron beams are very different in the two regimes of emittance-dominated and space charge dominated transport. The low current beam behaves more coherently, displaying sharp 1/2-integer and broad integer resonances, while the high current beams display resonances at other bare tune values, including third-integer. This is a somewhat surprising result given the few turns that these resonance take to develop. Significant tune spread across *and* along the beam bunch are bound to play a role in the observed behavior, especially for high currents. Much work remains to be done in both experiments and simulations for a better understanding of "space charge" resonances.

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