Ultra-Low Current Beams in UMER to Model Space-Charge Effects in High-Energy Proton and Ion Machines

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Abstract. The University of Maryland Electron Ring (UMER) has operated traditionally in the regime of strong space-charge dominated beam transport, but small-current beams are desirable to significantly reduce the direct (incoherent) space-charge tune shift as well as the tune depression. This regime is of interest to model space-charge effects in large proton and ion rings similar to those used in nuclear physics and spallation neutron sources, and also for nonlinear dynamics studies of lattices inspired on the Integrable Optics Test Accelerator (IOTA). We review the definitions of beam vs. space-charge intensities and discuss three methods for producing very small beam currents in UMER. We aim at generating 60μA – 1.0mA, 100 ns, 10 keV beams with normalized rms emittances of the order of 0.1 – 1.0μm.

INTRODUCTION

Research in The University of Maryland Electron Ring (UMER) has made leading-edge contributions to several areas in the physics of space-charge (SC) dominated beams: beam tomography and halo, beam stability, matching and betatron resonances, debunching and longitudinal confinement, soliton trains, longitudinal shock compression and others [1-3]. The initial motivation (i.e. intense beams for heavy-ion fusion drivers) has been expanded recently to include nonlinear dynamics studies in lattices inspired on the Integrable Optics Test Accelerator (IOTA) at Fermilab, but space-charge (SC) effects must be reduced significantly [4]. Furthermore, SC effects are increasingly important for new and upgraded large storage and accumulator proton and ion rings, but some of these are user facilities with limited time for beam physics experiments. Examples of these machines are the Spallation Neutron Source (SNS) at Oak Ridge national Laboratory, and the heavy-ion synchrotrons ("SchwerIonenSynchrotron") SIS-18, and SIS-100 in Germany.

The incoherent tune shift from small (relative to the bare horizontal tune ν_{0x}), direct (incoherent) SC effects is given by [5]:

$$\Delta\nu_x = \nu_{0x} - \nu_x = \frac{r_{e,p}}{\pi}\frac{N}{\beta^2\gamma^3}\left[\varepsilon_x\left(1+\sqrt{\frac{\varepsilon_y\nu_{0x}}{\varepsilon_x\nu_{0y}}}\right)\right]^{-1}\left(\frac{q_s^{\,2}}{A}\right)\left(\frac{F_xG_x}{B_f}\right), \tag{1}$$

where the first factor contains the classical radius of the electron or proton, the second one the number of particles per bunch N and the relativistic β and γ, and the third one the un-normalized, rms emittance terms. The last two factors include the charge state q_s, the mass number A, and parameters related to image forces (F_x), type of distribution (G_x), and bunching factor (B_f). Over a *broad* range of energies and beam currents in machines in operation, the tune shift is $\Delta\nu_x = 0.1 - 0.5$. In UMER, typically $\Delta\nu_x = 1.0 - 5.0$.

Further, "beam intensity" is loosely defined as proportional to N, with "space-charge limited" meaning $\Delta\nu$ less than 0.5 (Laslett criterion [6]). However, "SC intensity," χ, as introduced independently by Reiser and Davidson, is related to $\Delta\nu/\nu_0$, not just to N [7]. For small SC effects [8],

$$\chi \simeq \frac{2\Delta\nu}{\nu_0} = \frac{KR_m}{\varepsilon\nu_0},\ K = \frac{I}{I_{0e,p}}\frac{2}{\beta^3\gamma^3}. \qquad (2)$$

In Eq. (2), K is the beam perveance or SC parameter [7], R_m the machine average radius, and $I_{0e,p}$ is a characteristic current equal, approximately, to 17 kA for electrons, and 31 MA for protons. For ions the characteristic current is 31MA×A, approximately, where A is the mass number. For the sake of simplicity, we have omitted the subscript "x" in the tune in Eq. (2). Note also that the ratio R_m/ν_0 is the single-particle average betatron function. Although increasing the operating tune would be an obvious way to reduce SC intensity in UMER, the reduction would not be substantial, because the tune would be limited to a maximum of around 8.9 (standard ν_0 is around 6.6.) Moreover, practical problems would arise with overheating of the quadrupole magnets.

The tune depression, which is more commonly used, is related to χ by $\nu/\nu_0 = (1-\chi)^{1/2}$, for *arbitrary* but *linear* SC. Because of UMER's low energy (10 keV), "K" is large even for the smallest beam currents I, which compensates for the small machine radius to yield significant SC intensities. *Both* the tune shift and the SC intensity χ are important for characterizing beam dynamics: the former is naturally relevant to betatron resonance crossing, while the latter can be related to beam stability in general. Despite obvious differences in injection methods, beam loss mechanisms, and bunch structure, UMER and the larger, planned or upgraded, high-energy ion rings share key features: significant SC effects, the absence of synchrotron radiation, and a modest number of turns (100 – 1000). However, we must reduce the ratio K/ε significantly in UMER to approach the tune shifts and SC intensities of the larger machines or Fermilab's future IOTA.

Table 1 summarizes parameters and calculations for 3 cases of UMER operation and 3 cases of large, high-energy rings. The standard operation at 10 keV, 6 mA (nominal) in UMER yields SC numbers close to the corresponding ones for a possible heavy-ion fusion driver [9]. Operation at 10 keV, 40 μA, using the DC electron gun method described below, yields a beam with large emittance and negligible SC parameters, as in a light source. Finally, the planned operation at 10 keV, 60 μA, with appropriate emittance, would correspond to the SC regime of the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. We refer to the SC regime of the proton accumulator ring at the end of the accumulation cycle (1,000 turns).

TABLE 1. Parameters relevant to direct space-charge in electron and ion rings.

Machine, Circumference	Kinetic Energy, $\beta = \upsilon/c$	Peak Current, RMS Emittance (norm.)	ν/ν_0, $\Delta\nu$
UMER, 11.52 m	10 keV, 0.195	6.0 mA, 1.3 μm*	0.63, 2.4
"	"	40 μA, 5.0 μm†	1.00, 0.005
"	"	60 μA, 0.13 μm‡	0.95, 0.3
HIF Xe^{+8} Driver, 429 m	10 GeV, 0.381	1.0 kA, 50 μm	0.66, 2.1
ALS (LBNL), 197 m	1.2 GeV, 1.000	400 mA, 3.5 nm	1.00, 0.00
SNS Acc. Ring, 248 m	1.0 GeV, 0.875	52 A, 120 μm	0.98, 0.15

*Typical operation.
†Experiment with DC electron gun.
‡Design goal.

Another important aspect of beam dynamics that justifies operation with ultra-low current beams in UMER is beam debunching. Without longitudinal containment, coasting beams in UMER, initially filling half the ring circumference, elongate until the two bunch ends meet after a number of turns. A one-dimensional fluid model allows us to calculate the "sound" speed C_S, i.e. the speed of charge rarefaction, and approximate debunching times according to [8, 10]:

$$C_S = \sqrt{\frac{eg\Lambda_0}{4\pi\varepsilon_0\gamma^5 m_e}},\ \tau = \frac{1}{4C_S}\left(C - L_b\right). \qquad (3)$$

The constant $\Lambda_0 = I_b/\beta c$ is the peak longitudinal charge density, and "g" is a form factor of order unity. "C" is the machine circumference (11.52 m) and L_b the bunch's length corresponding to 197ns. Since the leading and trailing tails of the bunch are not well defined, the debunching time as defined above is only a reference parameter.

Actually, the *space charge waves* inside the bunch collapse at a time 2τ [10]; further, beam current is still detected by the resistive wall-current monitor in UMER for times of the order of 4τ.

Table 2 summarizes results of longitudinal expansion for beams in UMER. With properly applied longitudinal focusing we can extend the number of turns by a factor of 40 for 0.6 mA and 10 for 6 mA.

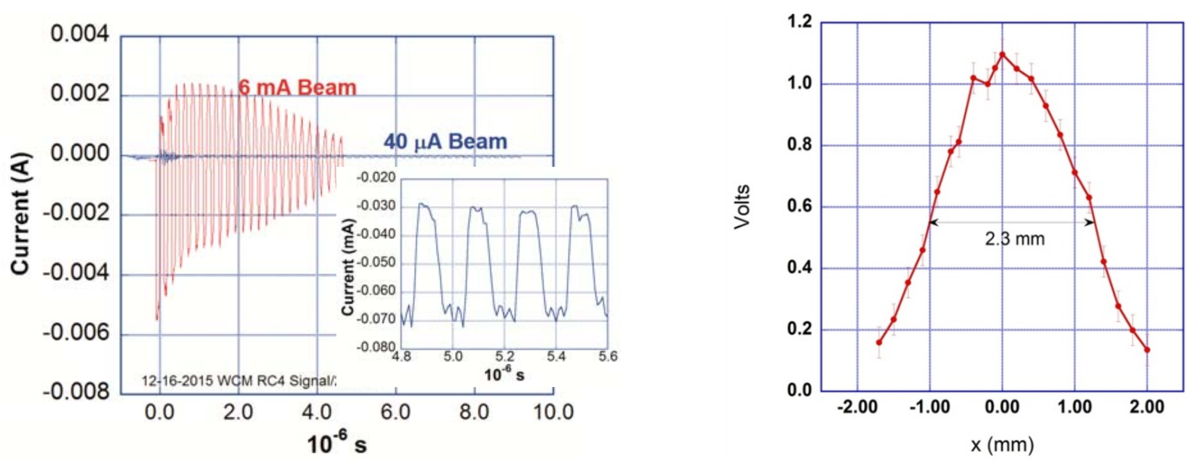
TABLE 2. Beam debunching in UMER is greatly reduced at low current.

Beam Current	"Sound" Speed C_S (m/s)	Approx. No. Turns To Debunch	Approx. No. Turns With Long. Focusing
60 μA	10^5	72	
600 μA	3×10^5	25	1,000
6.0 mA	8×10^5	9	100
21 mA	10^6	6	
104 mA	2×10^6	3	

METHODS OF PRODUCING ULTRA-LOW CURRENT BEAMS IN UMER

Independent control of current and transverse intrinsic emittance is desirable, but can only be partially realized in practice. We are working on three methods to produce ultra-low currents in UMER, with the goal of choosing the best method in terms of simplicity of implementation and current/emittance control.

- **DC Electron Gun**: Normally the cathode of the electron gun in UMER is pulsed and the control grid biased at 30 V DC. By reducing the grid bias and not pulsing the cathode, it is possible to obtain very low DC currents. This relies on "leakage" through the grid of the applied 10 kV DC. In addition, the time structure of the beam is given by the pulsed dipole used for injection and recirculation. Figure 1a below shows the multi-turn signals from a wall-current monitor of standard (6mA) and DC electron gun operations (40μA.) Debunching of the coasting 6 mA beam leads to loss of the AC signal from the wall-current monitor; the 40 μA beam, on the other hand, continues without beam edge erosion for many more turns. The transverse emittances (4×rms, un-normalized) were measured with the quadrupole-scan technique: $\varepsilon_x,\varepsilon_y = (300,100) \pm 20\mu m$. These values, when combined with beam current, energy, and external focusing, yield negligible SC effects. The main advantage of this method is its simplicity, but it is very difficult or impossible to control the resulting emittances.



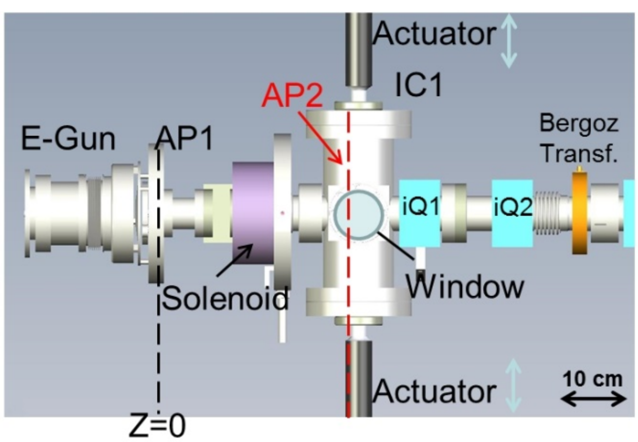
(a) (b)

FIGURE 1. (a) Beam current signals derived from a wall current monitor located at "RC4", about ¼ around the ring circumference in UMER. (b) Power profile of highly attenuated UV laser as measured by scanning a photodiode at the (equivalent) location of the UMER cathode.

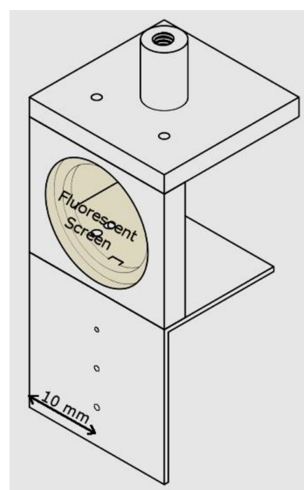
- **Photoemission**: We have used a UV laser at 355 nm, 5 ns to superimpose fast charge perturbations on top of thermionic beams. The perturbations have been useful to study soliton trains and other phenomena [1]. More recently, we have run our first photoemission-only, multi-turn beam at 1.6 mA, but would like to reduce the current more. The power profile at the cathode, as measured with a photodiode, is shown in Figure 1b; it covers a fair fraction of the 4 mm-radius cathode surface. The laser pulse is too short, but could be stretched to 50 – 100 ns with fiber optics delay lines. However, it would be more convenient and economical to use a different laser, one with much less peak power and longer pulse length. The main advantage of photoemission is not only the ease of varying the emitted current, but also the possibility, via optics, of controlling the intrinsic emittance by varying the laser spot at the cathode.
- **Apertures / Solenoid Focusing**: Our third method for obtaining low current is based on using two sets of apertures, AP1 and AP2, and solenoid focusing. Figure 2a shows the schematics of the first few elements downstream of the electron gun in UMER. As shown in Fig. 2b, the cube that houses fluorescent screen diagnostics in IC1 can be fitted at the bottom with a plate containing 3 apertures of varying radii. After viewing the beam and then adjusting its size with solenoid focusing, it should be possible to accurately position one of the apertures to obtain small beam currents. Some control over the resulting emittance should also be feasible.

  The plot in Fig. 3a illustrates the envelope of the 6 mA (nominal) beam over 30 cm from AP1 to AP2 for seven values of solenoid current. The two false-color pictures in Fig. 3b show the beam at AP2 with 0 and 5.5 A solenoid current.

  The 6 mA beam expands freely (solenoid current = 0 A) from a radius of 0.875 mm at AP1 to near 7 mm at AP2 (Fig. 3a). Thus, a second aperture AP2 of radius 0.7 mm would yield a new current of 60 μA past AP2, with an rms normalized emittance < 0.13 μm, as required (Table 1). Calculations of rms beam envelope matching into the periodic ring lattice with this scheme are under way.



(a)



(b)

FIGURE 2. (a) Schematics of the first few elements in the straight section of UMER: electron gun, plane of aperture disk (AP1), solenoid lens, diagnostic chamber 1 (IC1) with window, plane of second aperture (AP2), actuators, and first two quadrupole lenses. The actuator on the bottom is used for the laser mirror; the one on top houses fluorescent screen diagnostics. (b) New aperture plate (AP2) attached to the bottom of the fluorescent-screen cube – 3 small apertures are shown.

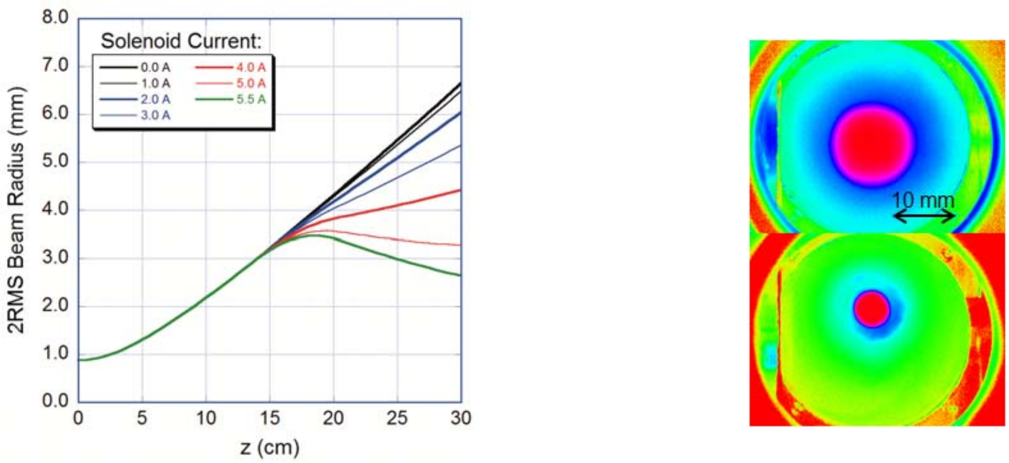


FIGURE 3. Left: 2×RMS beam envelope radius evolution from AP1 to AP2 for 7 values of solenoid current for the 6.0 mA (nominal) beam. Right: False color of beam images at upstream plane of AP2 for zero solenoid current (top) and 5.5 A (bottom).

SUMMARY

The original regime of strong transverse SC intensities in UMER is being extended to include the regime of small (perturbation) SC in large proton and ion circular machines. The new regime requires operation with "ultra-low" beam currents, around 60 μA as well as appropriate transverse emittance. Both the tune depression and tune shift are important to characterize incoherent SC effects. Significant reduction of SC is also needed for the non-linear dynamics studies currently under way in IOTA-inspired lattices. Further, the small-current beams would eliminate or greatly reduce the need for longitudinal focusing to prevent debunching. Three methods to achieve low beam currents are discussed: DC electron gun, photoemission, and a combination of apertures and solenoid focusing. Beam detection S/N and control, as well as envelope matching into the ring lattice will be investigated.

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