RECOVERING MEASURED DYNAMICS FROM A DC CIRCULATING SPACE-CHARGE-DOMINATED STORAGE RING*

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Abstract

Space-charge becomes increasingly significant at high beam intensities such as used in FEL injectors and heavy ion inertial fusion drivers, where it dominates the beam dynamics. The University of Maryland Electron Ring (UMER) is a high intensity circular machine that is dedicated to the study of long path length space-charge-dominated beam physics on a small scale. Over multiple turns, longitudinal space charge effects cause the tail and head of an electron bunch to expand and interpenetrate, eventually resulting in a “DC beam”. This leads to complications when trying to measure the beam with UMER’s AC coupled diagnostics. Three techniques have been developed to recover the information from the beam. Two “knockout” techniques implement invasive pulsed electric kicks to the beam in combination with either a fluorescent imaging screen or a current monitor. A third technique based on integration of the wall-current signal provides a non-invasive method to study the DC beam dynamics. Experimental results from all three methods are compared. The DC beam profile can then be studied over long trajectories and the existence of any loss mechanisms can be determined.

INTRODUCTION

In a high intensity particle beam, transverse and longitudinal beam dynamics are greatly affected by space charge. The study of these beam dynamics is largely the focus of experiments with UMER’s high intensity 10 keV electron beams.

In the absence of longitudinal focusing, space charge causes the head and tail of a long uniform beam bunch to erode and expand [1,2]. This longitudinal expansion in the beam continues until the head and tail interpenetrate, creating a direct current (DC) component to the beam. Over time, the AC component continues to evolve into DC until the ring is uniformly filled with a DC beam. UMER’s diagnostics, however, are AC coupled, so the DC beam component appears as beam loss on the wall current monitor (WCM).

To recover the information lost in UMER’s diagnostics, we introduce two new methods to generate the beam loss profile and provide updates on a third. For each of these methods, we inject a 100ns 6mA-peak electron beam bunch into UMER, an 11.52 m circumference electron storage ring. At 10 keV, the circulation time is approximately 197 ns, so at injection the beam fills approximately 50% of the ring.

BEAM KNOCKOUT WCM TECHNIQUE

The beam knockout technique comprises a single-pulsed voltage applied across two parallel plates. In the past, experiments were performed to knock out a portion of the beam to regain an AC component [3]. However, in this case the knockout pulse length is 300 ns to ensure that the entire length of the circulating beam is knocked out. UMER’s sixth diagnostic ring chamber (RC6) is loaded with a transverse electric pulsed kicker oriented vertically so that the beam undergoes ¾ of a betatron oscillation before being deposited to the beam dump at RC8. The wall current monitor is located at RC10 just after the beam dump, so the kicked beam will not reach it.

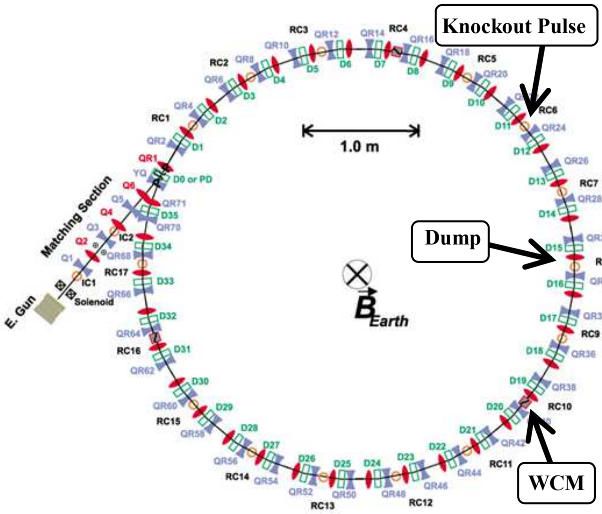

Figure 1: Diagram of UMER with key features labeled for the knockout experiment: the knockout pulser at RC6, the beam dump at RC8, and the WCM at RC10.

As shown in figure 2, the knockout pulse can be applied at any point in the beam lifetime. In this experiment, we applied the knockout in 20 ns increments in the beam lifetime, injecting a new pulse for each iterate. The pulse-to-pulse wall current monitor signal remains very consistent.

The exponential decays immediately following each kick in Figure 2 correspond to the RL relaxation time of the wall current monitor circuit. Notice that the voltage does not return to zero. This is due to an unknown background signal that modulates at 60 Hz, likely due to ground loops in the electronics.

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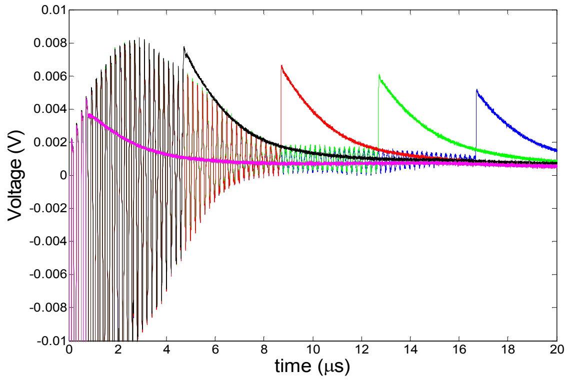

Figure 2: WCM traces of the knockout technique applied at various times in the beam lifetime of a 100ns, 6mA-peak beam bunch.

By measuring the difference in the voltage at the instance of the kick and the background AC component in the WCM signal, the DC profile can be reconstructed. Then by adding the AC portion to this DC profile, and by dividing this by the 4.545 Ohm resistance in the WCM diagnostic chamber, we find the total current in the ring as a function of time. By averaging this every 200 ns, we determine the total average current per turn.

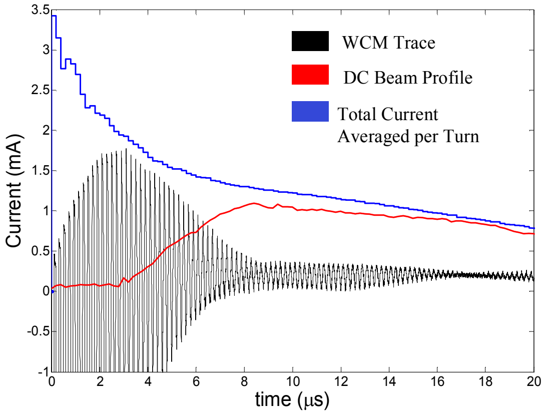

Figure 3: DC beam profile and average total current plotted with the wall current monitor background trace. The DC beam peaks at the first "DC Point" at ~9μs, and over time the current curve converges to the DC beam curve, indicating a ring uniformly filled with DC beam.

There are several interesting loss features of the averaged current curve. There seem to be two different rates at which the beam is losing current, and the transition or "elbow" of these rates occurs just after the head and tail of the beam bunch meet. This is verified by calculating the speed of the rarefaction wave [4]:

$$c_s^2 = g\frac{e}{4\pi\varepsilon_0}\lambda \qquad (1)$$

Here, e is the electron charge, λ is the line charge density, m is the electron mass, and

$$g = 2\ln(b/a) \qquad (2)$$

is a geometry factor, where b is the pipe radius and a is the beam radius. The beam ends ablate longitudinally from the center of the bunch at a rate of $2c_s$ in the beam frame, so in this case the head and tail should meet at roughly 4μs. After that, the loss rate in the ring remains constant. There is also a sharp drop off of current in the first few turns, accounted for by poor matching in this steering solution. Note that this is not the optimal solution for the ring; the analysis is done with an old operating point to illustrate features in the loss rate.

The WCM knockout technique is useful for its ability to not only generate the beam loss profile but also the DC beam profile. No other technique can accurately single out the DC beam portion. This can be useful when identifying loss mechanisms.

IMAGING TECHNIQUE

To verify the validity of the WCM knockout technique, we have employed other methods to measure the beam loss profile. If the beam dump in figure 1 is replaced with a 3ns-response phosphor screen, the electron bunch, when incident with the screen from the knockout, will produce a number of photons proportional to the beam intensity that can be captured by a camera. In this experiment, we use a gated PIMAX camera.

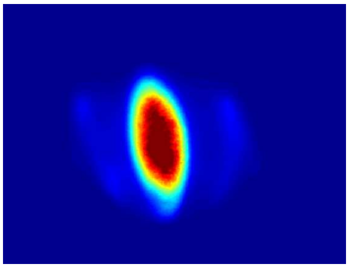

Figure 4: Sample Image of a 20 ns beam slice on the first turn of the UMER beam orbit.

By synchronizing the camera with the knockout using a time delay and 20 ns gate width, an image of the beam is taken for every knockout, capturing a 20 ns slice of the beam. An image is also taken for when the knockout pulse and beam are both off to get a background. Matlab's imaging analysis software produces a matrix of intensity values for each beam slice. Subtracting the pixel values of the background picture from each other picture, an accurate intensity value of each beam slice can be formed. When ten consecutive image matrices are added together, the result corresponds to 200 ns of beam, or approximately one entire turn (since the circulation time is 197 ns). By plotting these turns versus time and normalizing to current, the beam loss profile can also be reconstructed.

In Figure 5, the imaging method is compared to the WCM knockout method. An operating point with fewer steering errors was used for this analysis. The drop in the second and third turn correspond to the beam “leaking” over the edge of the screen, seen as false loss in both the WCM knockout method and the imaging method.

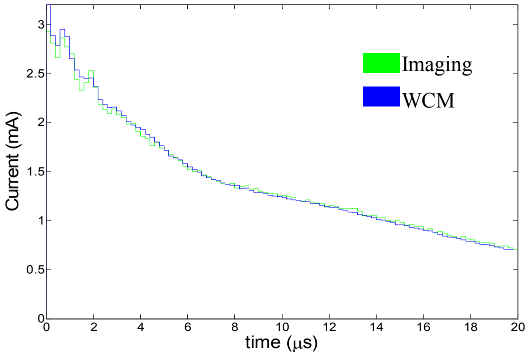

Figure 5: Imaging Method compared to the WCM Knockout Method. Average UMER beam Current per turn.

The benefit of this method over the other two is the images themselves. By looking at transverse sections of the beam, steering errors can easily be detected. However, analyzing the pictures has not yet resulted in the discovery of loss mechanisms. Images of the beam are also useful in the study of transverse beam dynamics, which is an active area of research in the UMER group.

INTEGRATION TECHNIQUE

The WCM can be modeled as a circuit with a resistor and inductance in parallel. Using Ohm’s Law and Kirchoff’s Law, the total current in the ring can be determined:

$$I_{beam} = \frac{1}{R} V_{scope} + \frac{1}{L}\int_0^t V_{scope}\,dt \qquad (3)$$

By integrating the raw WCM signal and taking into account the background fluctuation, the total ring current can be obtained. From that, the beam loss profile can be generated.

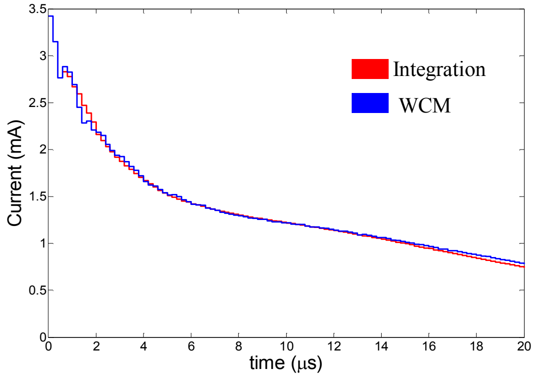

Figure 6: Integration method compared to the WCM knockout method. Each bin is the average UMER beam current per turn.

The advantage of the integration method is its potential for a fast, on-the-fly calculation of the beam loss profile. Using the integration algorithm, an entire beam loss profile for a given operating point can be generated within seconds in the control room.

CHALLENGES

While each technique has merit, there are a few obstacles to overcome when using each one. For both the WCM knockout technique and the imaging technique, it is important for the beam to be completely knocked out when the pulse is applied. Any residual current that “leaks” over the edge of the screen will appear as loss in both methods.

Steering errors in a non-matched beam particularly affect the imaging method. If the beam is shifting transversely turn-by-turn, the camera may not catch the entire intensity of the beam if it is outside the camera’s scope. Furthermore, if the beam is off its equilibrium orbit, a pulse can potentially kick the beam “too hard” and part of the beam will scrape along the wall of the pipe. This will appear as beam loss in the imaging method whereas the WCM knockout method will remain unfazed.

The integration method has its own challenges. While the aforementioned difficulties don’t affect the integration method, the background fluctuation can have an adverse effect. Even over a short period of time, shifts in the background signal are quite significant, greatly affecting the error propagation in the integration. We do not know for certain the origin of these fluctuations, but it is a focus of investigation for the UMER group.

CONCLUSIONS

High intensity space-charge-dominated electron beams have been observed to expand to the point of head-tail interpenetration over multiple turns. Utilizing the existing AC coupled diagnostics, we have developed three methods to recover the resulting DC component to the beam for the purpose of measuring total beam current. Taking into account various experimental obstacles, these three methods have shown great agreement with each other. With the confidence of an accurate beam loss profile, the UMER group plans to optimize its operating point and uncover beam loss mechanisms. A first step in understanding the loss mechanisms is to determine the loss rate’s dependency on bunch length. Experiments for this are underway.

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