OBSERVATIONS AND MEASUREMENTS OF ANOMALOUS HOLLOW ELECTRON BEAMS IN THE DUKE STORAGE RING*

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Abstract

Anomalous hollow electron beams have been recently observed in the Duke storage ring. With a single bunch beam in a lattice with a negative chromaticity, a hollow beam can be created. This beam consists of a solid core beam inside and a large ring beam outside. In this paper, we report the measurements of the hollow beam phenomenon, including its distinct image pattern and spectrum signature, and its evolution with time. By capturing the post-instability bursting beam, the hollow beam is a unique model system for studying transverse instabilities, in particular, the interplay of the wakefield and lattice nonlinearity. The hollow beam can also be used as a tool to study linear and nonlinear particle dynamics in the storage ring.

INTRODUCTION

In an electron/positron circular accelerator, the charged particles circulating around the accelerator are confined in a six-dimensional phase space volume. In the transverse directions, the potential well is provided by the magnetic lattice; the longitudinal trapping is provided by the radio-frequency (RF) system which also compensates for the beam energy loss due to radiation. At the low beam current limit and away from resonances, the natural equilibrium beam distribution is Gaussian in all dimensions. The development of advanced storage ring light sources and collider rings aims at confining more charged particles into an increasingly smaller phase space volume.

Non-Gaussian beams can be realized by trapping charges in islands of nonlinear resonances. For example, resonance trapping has been successfully used for multi-turn beam extraction of a proton synchrotron [1]. On the other hand, the observed non-resonant equilibrium beam distribution in the electron/positron storage ring, thus far, has always been a solid beam. The distribution and quality of the beam can be adversely impacted by the wakefield which can give rise to instabilities. The beam instability can either change the beam distribution or cause a beam loss. For example, the single bunch transverse instabilities can cause a fast beam blowup and consequently, a beam loss. This blowup instability sets a limit on the maximum single bunch current. Because of their importance to the accelerator performance, the single-bunch instabilities, both transverse and longitudinal, have been the subject of many intense studies in the recent years [2, 3, 4, 5, 6, 7, 8, 9].

* Supported by U.S. AFOSR MFEL grant F49620-001-0370 and U.S. DoE grant DE-FG05-91ER40665
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BEAM DISTRIBUTIONS AND SPECTRA

During our single bunch threshold studies in 2003 and 2004, we observed anomalous hollow electron beams in the Duke storage ring (Fig. 1); these were first observations of single-bunch, non-resonant, non-solid, transversely split electron beam distributions. A more detailed report on the hollow beam phenomenon is found in [10]. The term "hollow beam" in this paper is used to describe an anomalous electron beam distribution with a transverse projection consisting of a large ring beam outside and a small core beam inside. At some instance after being created, the solid core beam can be almost invisible due to a small amount of charge. The most critical lattice parameter to establish such a hollow beam is the slightly negative horizontal chromaticity, as small as $\xi_x = -0.07$. With a negative chromaticity and certain tune settings, the initial solid beam would blow up horizontally when a small external excitation is applied. Instead of losing charges, the blown-up beam is captured at a large transverse amplitude, forming a hollow beam distribution as shown in Fig. 1. All our results reported in this paper were measured with a single bunch beam at 274 MeV. The horizontal chromaticity, ξ_x, was typically between -0.4 to -0.5 while keeping the less critical vertical chromaticity close to zero. Other important Duke storage ring parameters are listed in Table I.

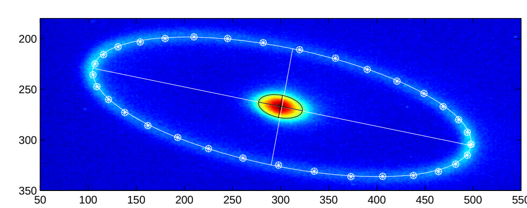

Figure 1: Hollow beam image captured at a dipole synchrotron port plotted in pseudo-color. The electron beam energy is 274 MeV and $I_b = 0.44$ mA. The core and ring beams are fit to ellipses which are described by $\frac{(x'-x'_0)^2}{a^2} + \frac{(y'-y'_0)^2}{b^2} = 1$, where $x' = x\cos\phi - y\sin\phi$, $y' = x\sin\phi + y\cos\phi$. The ring beam ellipse is determined using local peaks in the radial direction which are indicated by small circles. The ellipse parameters are $a = 200$, $b = 58.5$, $\phi = -0.192$ (the ring beam) and $a = 23.2$, $b = 11.1$, $\phi = -0.185$ (the core beam). Beam images in Fig. 1 and 3 are measured in pixels; the size of a pixel is $14.7(\pm 0.5)$ μm.

By varying lattice parameters, in particular, the lattice tunes, the size and the shape of the ring beam can be altered. The sizes of the ring beam and core beam can be determined by fitting to ellipses as shown in Fig. 1. Using the fit ellipses, the size of the ring and core beams can be compared; horizontally, the ring beam can be more than 10 times the rms core beam size. In Fig. 1, the horizontal ring beam radius, $a = 2.94 \pm 0.10$ mm which corresponds to a horizontal phase space area of 6.6 ± 0.6 mm-mrad, a significant portion of the available horizontal aperture of about 40 mm-mrad. Assuming a linear optical response of the imaging system, the charge in the beam can be estimated using the integrated light intensity of the image. Typically, the charge in the ring beam can be several to 10 times as high as the charge in the core beam.

Operation Energy [GeV]	0.27 - 1.2
Circumference [m]	107.46
RF frequency [MHz]	178.55
Harmonic number	64
Damping times [ms] @ 274 MeV	
Horizontal (τ_x)	890
Vertical (τ_y)	826
Energy (τ_E)	399
Natural chromaticity (ξ_x, ξ_y)	$-10, -9.8$
Betatron tunes (ν_x, ν_y)	9.11, 4.18
Momentum Compaction (α_c)	8.6×10^{-3}

Table 1: The Duke storage ring parameters.

With a hollow beam, very distinct beam spectra have been observed (Fig. 2). The betatron tune spectra (the upper plot) are measured using a network analyzer. The horizontal fundamental tune line (ν_x), its harmonics ($2\nu_x$, $3\nu_x$, $4\nu_x$), and their companion harmonics ($1-4\nu_x$, $1-3\nu_x$ $1-2\nu_x$ $1-\nu_x$) stand out profoundly. In fact these tune lines are so strong, with a signal level typically 20 to 35 dB higher than that of a solid beam, similar spectra are observed by measuring the self-excited betatron signals. In addition to the synchrotron sidebands ($f_s = 19.4$ kHz), the signals associated with the difference frequency between $4\nu_x$ and $1-4\nu_x$ with a $df \approx 70$ kHz also show up as sidebands to $2\nu_x$, $3\nu_x$, $4\nu_x$ and their companion harmonics – two such stronger sidebands are labeled as $5\nu_x$ and $1-5\nu_x$ in the plot. It is worth pointing out that the vertical betatron signal is not visible in the spectra plotted with a linear scale, completely overwhelmed by horizontal tune signals. The synchrotron spectrum measured using a spectrum analyzer and a stripline receiver also shows a very distinct behavior. The lower plot of Fig. 2 shows very strong self-excited betatron sidebands, about 25 dB above the beam revolution signal. These sidebands are otherwise invisible with a solid beam. During the above spectrum measurements, the observed hollow beam images appear fuzzier than those shown in Fig. 1 due to a larger beam current.

TIME EVOLUTION OF HOLLOW BEAM

Once created, the hollow beam evolves in cycles over time. With about 0.6 mA of the single bunch current, the period of the evolution cycle is about 7 to 8 minutes which consists of a long semi-stationary phase (about 98% of the time) and a rapid burst phase due to instability. After each burst, the ring beam charge and size are restored to a level similar to the previous cycle; in fact, ring beam size after a burst is rather repeatable, with less than 3% of variation in this experiment with six cycles. In addition, these bursts can be lossless, depending on lattice and beam parameters.

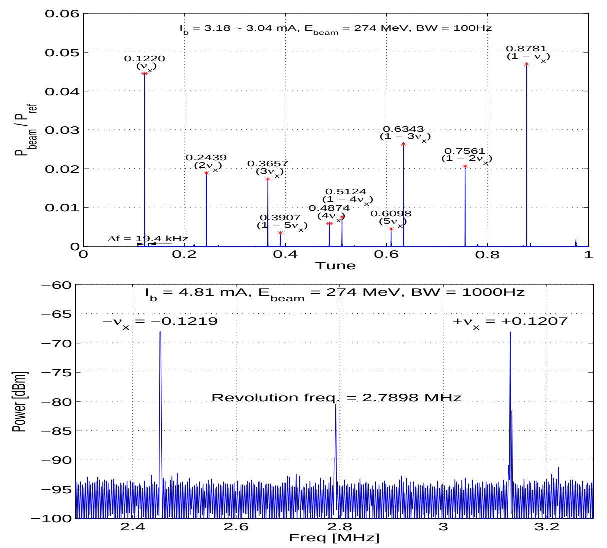

Figure 2: Measured betatron and synchrotron spectra of a hollow beam in a 274 MeV lattice with a horizontal chromaticity $\xi_x = -0.45$. Upper plot: measured betatron tune spectra which show the aggregated data from five consecutive measurements. Lower plot: measured synchrotron spectrum.

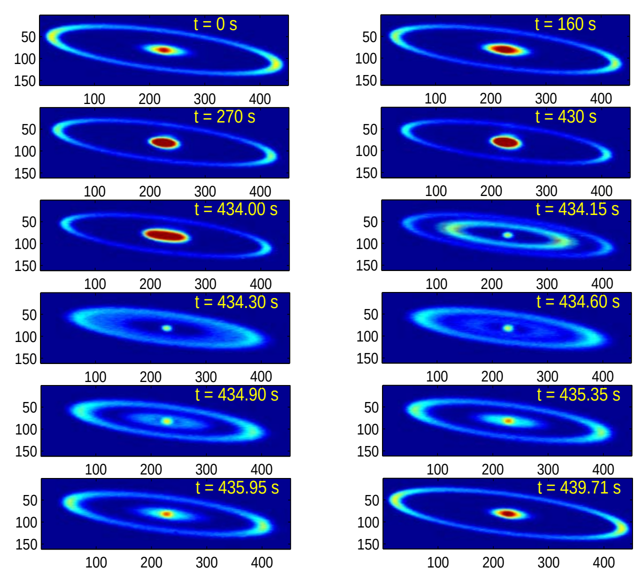

Figure 3: A series of images captured at various of times during a cycle of beam evolution. All images are plotted using the same intensity map. Single bunch current decreases from 0.558 mA at $t = 0$ s to 0.545 mA at $t = 440$ s.

Fig. 3 shows selected beam images from one of the evolution cycles. Immediately after a burst between $t = 0$ and $t = 430$ s, a semi-stationary phase with a slow beam evolution is observed. For the ring beam, the shape of the ellipse remains mostly constant while its size shrinks slightly by about 12%. This is accompanied by a reduction of its inte-

0-7803-8859-3/05/$20.00

grated intensity, which indicates a slow migration of charge from the ring beam to the core beam. In the meantime, the core beam gains the charge and its intensity increases by almost a factor of two. Its shape also undergoes a slow transition to become rounder – the ellipse axis ratio, a/b, changes from a value of 2.7–2.9 between $t = 0$ and $t = 220$ s to 2.1–2.2 between $t = 270$ and $t = 430$ s.

The semi-stationary phase is followed by a burst phase of evolution. At $t = 434$ s, the core beam has accumulated such a large amount of charge that an instability develops inside which triggers the core beam breakup (from $t = 434$ to $t = 434.15$ s). The breakaway charge forms a new ring-shaped wave moving outward to meet the ring beam which shrinks inward (from $t = 434.15$ to $t = 434.30$ s). Part of the wave merges with the ring beam, part of the wave bounces back toward the core beam (from $t = 434.30$ to $t = 434.60$ s). Finally, both the core beam and ring beam settle down (from $t = 434.90$ to $t = 439.71$ s) which marks the beginning of a new evolution cycle.

The settling time of the ring beam can be obtained by analyzing the settling of its peak. The burst settling time (Fig. 3) is found to be 0.68 s, which is slightly less than one transverse damping time of the storage ring.

These kinds of hollow beams have been observed over a wide range of single bunch currents from 5.4 mA down to 0.12 mA. This current range is below the single bunch current threshold of about 5.5 mA limited by the transverse mode coupling instability with a zero vertical chromaticity as estimated from the measured vertical tune reduction with the increased bunch current. The fact that a solid beam can be maintained without breaking up over such a large current range strongly suggests a certain damping mechanism against the instability. The effective methods to drive apart a solid beam include introducing a horizontal orbit bump in the arc, driving a stripline kicker with an RF signal, and firing a horizontal injection kicker. After being driven apart, the ring beam and core beam can be forced to recombine by increasing the RF voltage by a factor of 3 to 5, followed by a few seconds of settling time. This type of RF manipulation works for a certain range of lattice tune settings. The detailed 3D distribution of the hollow beam has yet to be determined experimentally. It is also worth mentioning that during the commissioning of the Duke storage ring in 1995 interesting beam images with more than one ring were observed with a multi-bunch beam [11] while adjusting the higher-order harmonic tuners of the RF system. At the time, we believed that these unusual beam distributions were the result of the transverse coupled bunch instability. However, because of the lack of repeatability, no follow-up studies were performed.

CONCLUSION

Our preliminary studies seem to indicate the following mechanism for the formation of the hollow beam. In a lattice with a slightly negative horizontal chromaticity, transverse instability would first increase the beam emittance; this enlarged solid beam breaks up when a small external excitation is applied. The charge flying off the beam centroid is recaptured in a new potential well at a large transverse amplitude to form a ring beam due to the nonlinear focusing of the lattice; the remaining charge in the center damps down to form the core beam. The hollow beam then undergoes repetitive cycles of a slow charge migration in the semi-stationary phase and a rapid charge redistribution in the burst phase.

Creating a ring beam is a process of capturing the transverse instability. Consequently, the study of the hollow beam phenomenon provides unique opportunities to gain insight into the transverse instabilities and nonlinear dynamics in the storage ring. First, it remains a challenge to understand the mechanism which sustains the ring beam in the phase space; the semi-stationary nature of the anomalous hollow beam indicates a leaky potential well, which also awaits a theoretical explanation. Second, by capturing instability without losing current, the hollow beam phenomenon provides a powerful model system for studying transverse instabilities. In particular, this model allows the study of the delicate interplay between the wake field and lattice nonlinearity, which has been a missing piece of the puzzle in understanding the complex mechanism of transverse instabilities. Third, because of its large dimension, the ring beam can be used as an effective tool to study particle dynamics, both linear and nonlinear. For example, by extending the ring beam to large amplitudes, the nonlinear tune shift can be measured. Finally, with a fully coupled lattice, it is conceivable that a round annular electron beam can be generated in the storage ring. The annular pattern of radiation from a circularly polarized wiggler may find its use in certain science applications.

We would like to thank the Duke Free Electron Laser (FEL) lab engineering and operation staff for improving the storage ring stability and beam diagnostics and for assistance with the measurements.

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