LIMITATIONS OF INCREASING THE INTENSITY OF A RELATIVISTIC ELECTRON BEAM*

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Abstract

A 7 cm cathode has been deployed for use on a 3.8 MV, 80 ns (FWHM) Blumlein, to increase the extracted beam current from the nominal 1.7 kA to 2.9 kA. The intense relativistic electron bunch is accelerated and transported through a nested solenoid and ferrite induction core lattice consisting of 64 elements, exiting the accelerator with a nominal energy of 19.8 MeV. The principal objective of these experiments is to quantify the space charge limitations on the beam quality, in addition to its coupling with the corkscrew and the beam breakup (BBU) instabilities. Time resolved centroid measurements indicate a reduction in BBU >5x with simply a 20% increase in the average B-field used to transport the beam though the accelerator. A qualitative comparison of experimental and calculated results are presented, which include axial BBU amplitude with different accelerator lattice tunes.

INTRODUCTION

Relativistic electron beams used to study fundamental nuclear physics or provide intense sources of photons are challenged with instabilities to overcome when increasing the intensity of the beam. One of particular interest is the beam breakup (BBU) instability which manifests itself as a transverse magnet coupling to destroy the beam quality. BBU was first observed in the 1960s [1] and reported in detail by Stanford Linear Accelerator Center scientists in 1968 [2]. Shortly after its discovery, BBU was studied for the first time in detail on the Advanced Test Accelerator, a linear induction accelerator [3].

The first axis of the Dual-Axis Radiography for Hydrodynamic Testing (DARHT) facility is exploring the limitations of increasing the intensity of the electron beam for future radiographic capabilities. DARHT Axis-1 is unique for these studies because it is relatively simple to change the cathode emission size to increase or reduce the total current and therefore change the space charge of the beam while holding everything else constant. In order to effectively increase the intensity of the beam, the BBU instability must be quantitatively understood and effectively reduced. Beam Position Monitors (BPMs) provided time resolved centroid and BBU measurements.

EXPERIMENTAL SETUP

The experimental configuration used to study the BBU instability was the DARHT Axis-1 linear induction accelerator (Fig. 1). The accelerator is composed of a 4 MV Blumlein injector [4] and 32 Blumleins [5] used to drive at total of 64 induction cells (2 cells per Blumlein). The linear induction accelerator is broken up into 8 cell blocks consisting of 8 ferrite induction cores in each cell block for a total of 64 induction cells and 65 anode-cathode gaps. Each induction cell has the ability to impart 250 keV of energy into the beam for a total of 16 MeV in addition to the 3.8 MeV acquired in the diode.

Beam Position Monitors

The transported beam current and centroid is monitored by BPMs at the end of each cell block and internal to each cell block, so there is a BPM every 4 cells with axial spacing between 185-224 cm. The BPMs consist of 8 B-dots, or inductive monitors, oriented azimuthally every 45°. There are 4 position B-dots, 1 top and bottom for ±y measurements and 1 left and right for ±x measurements.

The ±x and ±y B-dots in each BPM were used to measure the BBU amplitude throughout the accelerator. This was done by measuring the unintegrated Δx and Δy which was sampled up to 8 GHz. A fast Fourier transform was applied to the signal over ± 50 ns in addition to the

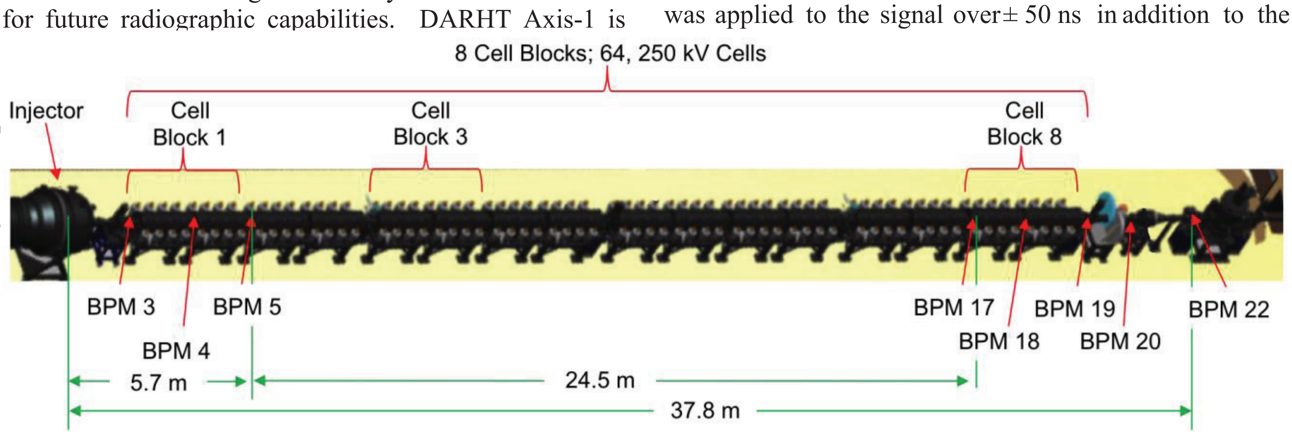

Figure 1: Model of the DARHT Axis-1 accelerator, consisting of the 4 MV injector, 64 induction cells and BPM located after every 4 cells.

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pulse length of the beam. The frequency spectrum was then integrated from 600-900 MHz to determine the BBU intensity

BEAM BREAKUP INSTABILITY

The BBU growth along the accelerator is characterized by the equation [6]:

$$\frac{\xi}{\xi_o} = \left(\frac{\gamma_o}{\gamma}\right)^{1/2} \exp \Gamma_m, \qquad (1)$$

where ξ is the measured BBU amplitude and ξ_o is the measured at the entrance of the accelerator. The amplitude decreases with acceleration to ½ power and increases exponentially with the growth factor, Γ_m

$$\Gamma_m = \frac{1}{c} I_b N_g Z_\perp \left\langle \frac{1}{B} \right\rangle, \qquad (2)$$

where c is the speed of light, I_b is the beam current, N_g is the number of gaps, $Z_\perp$ is the transverse impedance, and $\langle 1/B \rangle$ is the average of the inverse magnetic field strength.

TRANSPORT AND BBU MEASUREMENTS

We began tuning the 2.9 kA beam envelope using the nominal tune for the 1.7 kA beam and the initial conditions measured from a sweep of the first transport magnet (Fig. 2). These measurements were also compared with calculations made with the TRAK code [7] and provided the initial conditions at z = 167 cm of a = 35 mm and a' = -17.5 mrad. Initially it was assumed because of the high space charge ($K = 6 \times 10^{-4}$) of the beam coming out of the gun we could not converge the beam envelope too steeply because it would overfocus in the low or field-free regions between cell blocks. This first attempt is shown in Fig. 2 for Tune 4 where a gradual increase of the magnetic field from 360 G at the beginning of the first cell block to > 800 G at the end of the second cell block we were able to gradually converge the beam envelope down to ~13 mm. Evidence of the space-charge force quickly increasing the 2.9 kA beam radius between the cells is shown at z = 650 cm in Fig. 2(a). Initially only three magnets were changed in cells 8,9, and 10 to tune the envelope of the 2.9 kA beam from the nominal 1.7 kA tune, this is evident for the <B> calculated in Fig. 2(b) where there is only a slight difference after cells 5-8 (z = 572 cm) and cells 9-12 (z = 796 cm).

After initially attempting Tune 4 and examining Eqs. 1&2 it was expected that the BBU should increase by exp(2.9/1.7) ~ 5.5. However, after quickly investigating the signals on the downstream BPMs it was apparent that there was a substantial amount of BBU, which manifests itself as RF superimposed on the beam envelope. The top row of Fig. 3 shows the BBU on the raw signal of the 2.9 kA beam is ~20x higher than the 1.7 kA beam. After performing a fast Fourier transform over the 200 ns window of interest the frequency spectrum indicates nearly a ~40x increase in BBU. Both data sets indicate the BBU spectrum ranges from 700-850 MHz. Each of the cases shown here are a single shot representation of the average BBU amplitude for 5 shots.

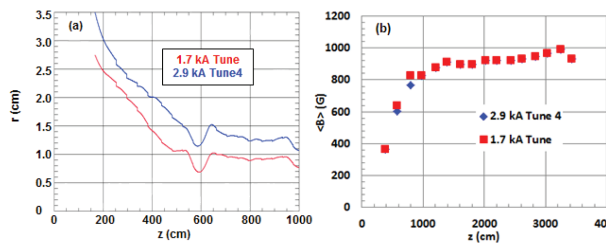

Figure 2: (a) Envelope comparison between the nominal 1.7 kA beam (red) and the first attempt at transporting the 2.9 kA beam (blue) in the first two cell blocks and; (b) <B> for 4 cells in each cell block for both tunes.

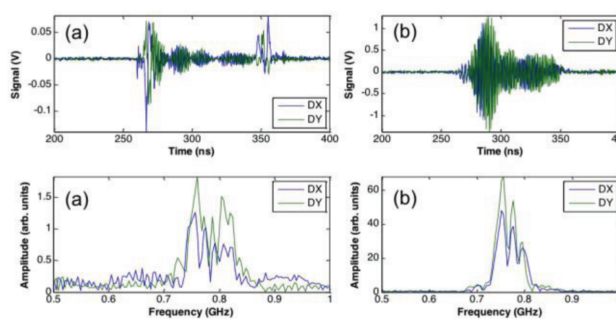

Figure 3: Top row: unintegrated Δx and Δy signals measured at BPM 20 (z = 36.1 m). Bottom row: fast Fourier transform of the signal above to indicate the amplitude and frequency of the BBU on the beam for: (a) the 1.7 kA beam; and (b) Tune 4 for the 2.9 kA beam.

A more detailed analysis made it apparent that the average BBU growth for the 2.9 kA tune was >10x higher than measured with the 1.7 kA beam (Fig. 4(a)). BBU is negligible for the nominal 1.7 kA tune until BPM07 (z = 980 cm) and the average measured value for 5 shots is $\langle\xi\rangle = 0.044 \pm 0.032$. The BBU amplitude for Tune 4 matches the 1.7 kA tune at BPM07 (CB 2) and then increases ~11x the amplitude of the 1.7 kA beam at BPM09, through the 3rd cell block. The error bars in Fig. 4(a) indicate the shot to shot variation of the BBU amplitude which ranges from 10-60% depending on the amplitude and location. Over the length of the accelerator BBU increases 500x for the 1.7 kA beam and $>10^3$x for Tune 4, leading to factor of ~28x higher BBU for the 2.9 kA beam at BPM 20 (z = 3.6 m) (Fig. 4(b)). Direct comparison of the BBU measurements for the 1.7 kA beam with the 2.9 kA beam clearly shows $\xi_{2.9}/\xi_{1.7} \gg \exp(2.9/1.7) \sim 5.5$. Applying a least squares fit to both data sets in Fig. 4(b) we are able to back out the slope of the exponential BBU growth and determine a measurement of the transverse impedance of the accelerator cells. The slopes are slightly different; the 1.7 kA data set yields 887 Ω/m and the 2.9 kA data set yields 1121 Ω/m. Each are within the measured and calculated cavity values of 400-1200 Ω/m over frequency ranges of 300-900 MHz.

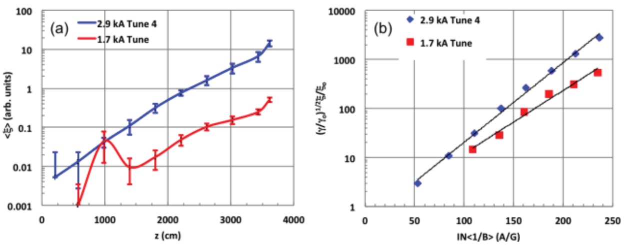

Figure 4: (a) Increase of the average BBU amplitude <ξ> over 5 shots due to the increased beam current from 1.7 (red) to 2.9 kA (blue); and (b) comparison of BBU growth along the accelerator. Each tune indicates a constant transverse impedance.

With this substantial growth in the BBU amplitude it was necessary to develop a tune with increased <B> along the length of the accelerator. The <B> in 4 cells of each cell block for each of the successive tunes and their corresponding envelopes are shown in Fig. 5. Each tune iteration brought the beam envelope down more steeply by increasing the <B> at the end of the accelerator, where the BBU amplitude was most apparent. Eventually we had to work our way upstream and begin tuning from the 1st cell block, in Tune 6, because of the lack of suppression.

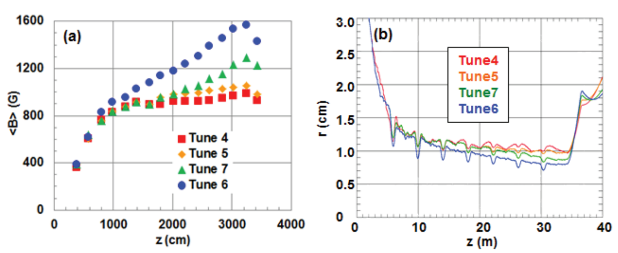

Figure 5: (a) <B> for 4 cells in each cell block used reduce BBU; and (b) the reduced 2.9 kA beam envelope for Tunes 4-7.

BBU at the upstream end of the accelerator is negligible for Tunes 5-7; it did not begin to become apparent until BPM 07 (z = 980 cm) as shown in Fig. 6(a). A reduction in <ξ> of ~5x is evident at BPMs 17-20 (z > 30 m) in Fig. 6(a) over tunes iterations from 4-6. The BBU growth along the accelerator for each successive tune is shown in Fig. 6(b). The initial BBU amplitude, ξ_o, is different for each tune contributing to the staggering of each curve. In addition the final product of growth factor, IN<1/B>, decreases for each successive tune as expected, from 237 A/G for Tune 4 to 194 A/G for Tune 6; an increase in <B> of 20%. Tune 7, which has a slightly reduced <B> compared to Tune 6, is shifted down on the BBU growth curve because its initial amplitude at BPM 7, 0.0275 >> <ξ> at BPM 7 for Tune 6. Each tune has nearly the same slope on the BBU growth curve (Fig. 6(b)) indicating the consistency in the transverse impedance of the induction cells in the accelerator lattice. The average transverse impedance for these four tunes is 1086 ± 26 Ω/m.

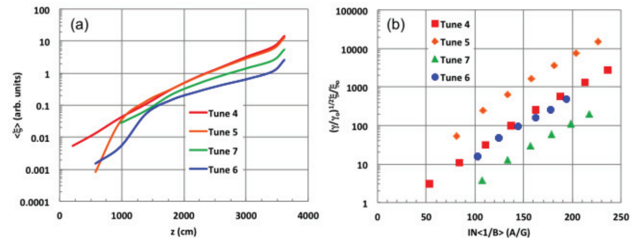

Figure 6: (a) Reduction in the average BBU amplitude, <ξ>, over 5 shots at each z-location due to the increased <B> with each successive tune; and (b) comparison of BBU growth along the accelerator for each successive tune. Each tune indicates a constant transverse impedance.

CONCLUSION

An increase in the intensity of the DARHT Axis-1 beam by 70%, with nearly the same transport lattice, lead to a ~28x increase in the final BBU amplitude. After several tune iterations, we successfully reduced the BBU amplitude 5x by simply increasing the <B> in the accelerator 20%. A more detailed explanation of these results and a further reduction in the BBU amplitude will be published elsewhere.

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