

LONG-PULSE BEAM STABILITY IN THE DARHT-II LINEAR INDUCTION ACCELERATOR*

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Abstract

The beam breakup instability has long been a problem for linear induction accelerators (LIAs). Although it is predicted to saturate in the strong focus regime relevant to LIAs most, if not all, LIAs have had pulse-widths too short to observe this effect. We recently completed BBU experiments on a 1.2 kA, 6.7-MeV configuration of the DARHT-II LIA having a 1600-ns pulse length, which is much longer than the saturation time. When we reduced the magnetic guide-field strength to observe BBU, the saturated growth was in agreement with theory. We used these results to deduce that BBU growth will be insignificant in the final 2-kA, 17-MeV DARHT-II configuration with the tunes that will be used. Another problematic instability for long-pulse LIAs such as DARHT-II is the ion-hose. We also performed experiments with the 6.7-MeV long-pulse configuration of DARHT-II in which we deliberately induced ion-hose by raising the background pressure far above its normal value. The results of these experiments were used to show that ion-hose will not be a problem for the final DARHT-II configuration.

INTRODUCTION

The major beam dynamics concerns for the DARHT-II accelerator are corkscrew motion, the beam breakup instability (BBU), and the ion-hose instability. These instabilities were not observed with nominal tunes and vacuum in the initial ~ 500-ns short-pulse tests. We have now produced and accelerated beams with a much longer, ~1600-ns “flat-top,” current pulse. In this article we describe experiments that use this long pulse accelerator to test the immunity of the final 17-MeV DARHT-II configuration to these instabilities. The accelerator, diagnostics and beam parameters for the initial short-pulse tests are described in ref [1] and [2], while the long-pulse accelerator, diagnostics, and beam parameters are described in ref. [3]. Because the parameters of the final 17-MeV configuration are different than those for the present experiments, we validated the stability of the final

configuration by scaling our present experiments to have the same amplification as the final configuration will have.

EXPERIMENTAL RESULTS

Beam Breakup Instability

In an infinitely long pulse, the maximum BBU amplification of a sinusoidal perturbation with amplitude ξ_0 at the accelerator entrance is predicted to be $\xi(z) = (\gamma_0/\gamma)^{1/2} \xi_0 \exp(\Gamma_m)[4-8]$ for the strong focus, weak accelerating gradient DARHT-II accelerator. The maximum growth exponent is $\Gamma_m = I_b N_g Z_{\perp} \langle 1/B \rangle / 3 \times 10^4$. Here, I_b is the beam current in kA, N_g is the number of gaps, the transverse impedance Z_{\perp} is in $\Omega/m.$, and $\langle 1/B \rangle$ is in kG^{-1} (the brackets $\langle \rangle$ denote averaging from the entrance to the axial position in the accelerator, z). In DARHT-II the guide field B , and γ are functions of z as well as the number of gaps. A sinusoidal excitation at the resonant frequency is predicted to grow to this maximum amplification and then saturate in time due to resistive energy losses in the cells. In DARHT-II the BBU grows rapidly out of seed motion such as the high-frequency corkscrew motion or random noise on the beam, since there is no sharp risetime to excite it. There is ample small-scale motion excited in the diode by vacuum tank RF modes and noise to seed the BBU. The time to grow to the maximum amplitude is $\tau_m = 2\Gamma_m Q/\omega_0$, which is less than 25 ns for all BBU modes of DARHT-II. Here, Q is the cavity quality factor and ω_0 is the mode resonant frequency. Because τ_m is so short, BBU growth from noise should saturate long before the end of our 1600-ns pulse.

The accelerator configuration used for these BBU experiments had fewer cells and lower current than the final, 17-MeV, accelerator configuration, so we reduced the guide field until the growth exponent at the exit was approximately what it would be for the final configuration. Fig. 1 shows the beam motion at the exit of the accelerator when the maximum growth factor was increased to more than twice that expected for the final 17-MeV configuration.

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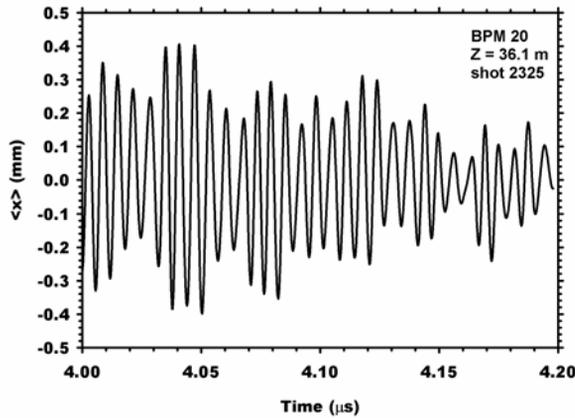


Figure 1: Beam motion in the horizontal plane at the exit of the accelerator during a 200-ns window near the end of the current flat top. The tune used for this shot was scaled to give greater growth exponent than the final configuration by a factor of 2.34.

To validate the theoretical scaling we Fourier analyzed the beam motion at each BPM and normalized the amplitude in a 20-MHz frequency band centered on the lowest resonant frequency (168 MHz) to the BPM at the accelerator entrance. From the growth law for the saturated amplitude a semi-log plot of $(\gamma/\gamma_0)^{1/2} \xi/\xi_0$ (where ξ/ξ_0 is the normalized amplitude) against $I_b N_g \langle 1/B \rangle$ should yield a straight line with slope proportional to the transverse impedance. Here, N_g is the number of gaps from the accelerator entrance to the BPM, and $\langle 1/B \rangle$ is the average from the entrance to the BPM.

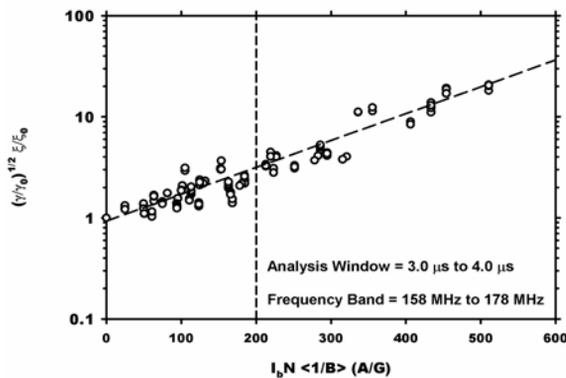


Figure 2: BBU amplitude growth through the accelerator for several shots with varying tunes and currents. The dashed line through the data is a least squares fit to the data, and is equivalent to the theoretical prediction for a transverse impedance of 184 Ω/m . The vertical dashed line is the value of $I_b N \langle 1/B \rangle$ for the final 17-MeV configuration with a nominal tune.

Using $I_b N_g \langle 1/B \rangle$ as the independent variable for this analysis enabled us to overlay data from many shots with various currents and tunes (Fig. 2). The least-squares fit to these data corresponds to a transverse impedance of 184

Ω/m . This is slightly less than the 193- Ω/m single-cell 168-MHz resonance peak measurement [5, 9], but greater than the 157- Ω/m average for the 20-MHz analysis band.

Ion-Hose Instability

Because of the long pulse of DARHT-II the ion-hose instability [10] was of some concern, and a substantial effort was paid to the accelerator vacuum. The theory of the ion-hose instability in a strong axial guide field such in DARHT-II has been developed in analogy to BBU by treating the ion forces as a continuous transverse impedance [11], and more recently through the use of an analytic model [12, 13]. The predictions of the analytic models are in agreement with PIC code simulations [13], including the saturation in time to a maximum growth exponent Γ_m in analogy to the BBU. Thus, just as with the BBU, the amplitude should be $\xi(z) = (\gamma_0/\gamma)^{1/2} \xi_0 \exp(\Gamma_m z)$. The theoretical maximum growth exponent in air is $\Gamma_m \approx 0.043 I_b \tau z \langle p / (Ba^2) \rangle$ for a pulse length τ (μs) at the end of z (m) [13]. Here, the background pressure p is in μTorr , the beam radius a is in cm, the guide field B is in kG, the beam current I_b is in kA, and the brackets denote the average over length as before. For the DARHT-II final 17-MeV configuration, $\Gamma_m \sim 1$ for a pressure of about 0.2 μTorr , so the vacuum system is interlocked to prevent accelerator operation if the pressure exceeds 0.1 μTorr . The normal base pressure is less than half the interlock pressure.

To produce the ion-hose growth that would be expected in the final configuration, we increased the base pressure by valving off the accelerator vacuum pumps, and bleeding air into the system. Fig. 3 shows the ion-hose motion at the entrance to the last cell block when we increased the base pressure to 6 times the equivalent interlock pressure.

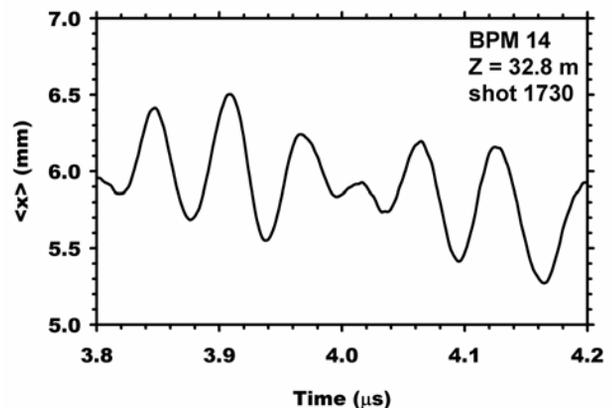


Figure 3: Beam motion at the entrance to the last cell block clearly showing the ion-hose motion when the maximum pressure was increased to the equivalent of 6 x 10⁻⁷ Torr in the final configuration.

For the tunes and low acceleration gradients used in these experiments the beam was space-charge dominated

through most of the accelerator, so we eliminated the unknown beam radius from Γ_m using the matched beam scaling $a^2 \sim I_b / (\gamma\beta B^2)$. This ansatz yields the independent variable $z \langle pB\gamma \rangle$ in which all parameters were measured, against which we plot $(\gamma/\gamma_0)^{1/2} \xi/\xi_0$, as we did in analysis of the BBU. Fig. 4 shows data from 6 to 8 BPMs taken with different pressure profiles. One striking feature of these data is that the amplitude saturates in z as well as in time, a nonlinear effect resulting from the diminished attractive force between the beam and ion channel at large centroid separation. For the final 17-MeV DARHT-II configuration $z \langle pB\gamma \rangle \sim 2$, so for an injector energy of 3.5 MeV there should be negligible amplification of ion-hose.

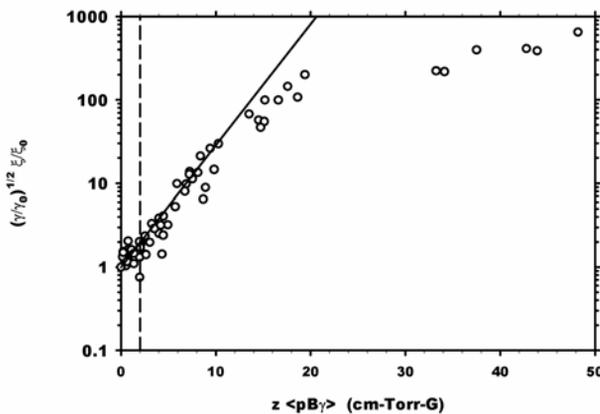


Figure 4: Amplification of ion hose motion through the accelerator. The vertical dashed line corresponds to the value of $z \langle pB\gamma \rangle$ for the final configuration. The solid line is the linear theory prediction for $\tau = 1.0 \mu\text{s}$.

To further check the theory we used noble gases and different tunes to confirm the scaling of the ion-hose frequency with ion mass M_i and beam/channel radius a . Theoretically the frequency should scale as $f \sim 1/(aM_i^{1/2})$. We used neon ($M_i = 20$ amu) and xenon ($M_i = 131$ amu) for these experiments, so comparing data for the same tune with these gases should give a frequency ratio of ~ 2.6 . We actually measured a ratio of 2.56. Then we varied the tune to one with a beam radius larger by a factor of three according to our envelope code. Comparing measured ion-hose frequency spectra for these two tunes we found that the frequency was greater by a factor of 2.54.

CONCLUSIONS

These experiments demonstrate that the maximum BBU amplitude in the final, 17-MeV DARHT-II accelerator configuration will be less than 2% of the beam radius with the nominal tunes that will be used. Using a variety of magnetic tunes we experimentally validated the theoretical scaling used to extrapolate our results to the final configuration.

The amplitude of the ion-hose instability was less than 2% of the beam radius even when we increased the

background pressure to a value greater than the equivalent of the final accelerator interlock pressure. The measured scaling of growth with pressure confirmed this in the parameter range of the final configuration. At substantially higher pressures the instability growth was observed to saturate with length as well as in time. We used a variety of background pressures to experimentally confirm the theoretical scaling. We also experimentally confirmed the theoretically predicted scaling of frequency with ion mass and beam size.

Based on these scaled experiments, we expect that the motion due to all of these effects will be less than 10% of the beam radius at the accelerator exit; well within the performance requirements for DARHT-II.

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