DARHT-II LONG-PULSE BEAM-DYNAMICS EXPERIMENTS

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Abstract

When completed, the DARHT-II linear induction accelerator (LIA) will produce a 2 kA, 18 MeV electron beam with more than 1500 ns current/energy "flat-top." In initial tests DARHT-II has already accelerated beams with current pulse lengths from 500 ns to 1200 ns full-width at half maximum (FWHM) with more than 1.2 kA peak current and 12.5 MeV peak energy. Experiments will soon begin with a ~1600 ns flat-top pulse, but with reduced current and energy. These pulse lengths are all significantly longer than any other multi-MeV LIA, and they define a novel regime for high-current beam dynamics, especially with regard to beam stability. Although the initial tests demonstrated the robustness of the DARHT-II LIA to BBU, the < 1200 ns FWHM pulse lengths were too short to test the predicted protection against ion-hose instability. The present experiments are designed to resolve these and other beam-dynamics issues with a ~1600 ns pulse length beam.

INTRODUCTION

Commissioning of DARHT-II is proceeding in three phases. The first phase was a demonstration that the DARHT-II technology could produce and accelerate a beam of electrons [1,2]. The second phase includes a demonstration of beam stability for the full pulse length of the final configuration. The major beam dynamics concerns for the accelerator are corkscrew motion, the beam breakup instability (BBU), and the ion-hose instability.

The long-pulse stability tests are just beginning. To date we have produced and accelerated ~1200 ns FWHM beam pulses, much like the un-crowbarred pulses of the initial experiments [2]. We have also produced injector pulses with a full ~2.0 µs flat top. The results of these beam experiments are reported here.

ACCELERATOR

The 88-stage Marx generator that powers the injector diode for DARHT-II is capable of producing a 3.2 MV output pulse that is flat for 2 µs, but we are operating it at 2.5 MV to provide a greater margin of protection for the insulating column.

Table 1: DARHT-II Parameters

Configuration:	**A**	**B**	**Final**
Beam Current (kA)	1.2-1.3	1.3	2.0
Pulse Length (µs)	0.5-1.2 FWHM	0.8 FWHM 1.6 µs Flat	1.5 Flat
Diode Voltage (MV)	3.0	2.5	3.2
Injector Cells	8	6	6
Injector Cells (MeV)	1.2	0.6	1.1
Injector Energy (MeV)	4.2	3.1	4.3
Installed Accelerator Cells	64	50	68
Active Accelerator Cells	61-62	42	68
Exit Energy (MeV)	12.5	7.3	17

After leaving the diode, the beam is accelerated by large-bore (36 cm diameter beam tube) induction cells to 3.5 MeV. Eight of these completed the injector in the initial experiments (configuration "A") and six of these are now installed for the long-pulse stability experiments (configuration "B"). Following the injector, there is a

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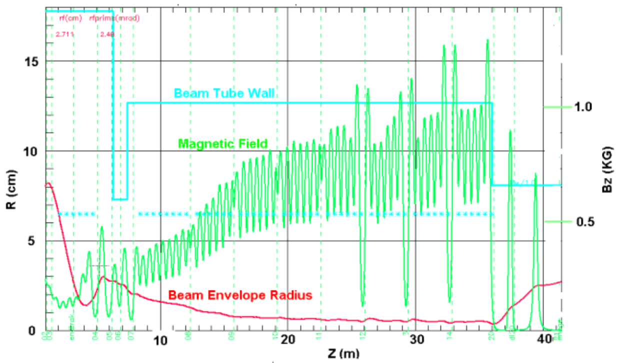

Figure 1: DARHT-II tune for long-pulse stability experiments (configuration B).

special transport zone designed to scrape off the long rise time, off-energy beam head. As in the initial experiments [1,2], this beam-head clean-up zone (BCUZ) is presently configured to pass the entire beam head, and the timing of the induction cells is set to accelerate the ~500 ns risetime, off-energy beam head, as well as the flat top. The magnetic tune through the BCUZ compresses the beam to the smaller radius needed to match into the main accelerator.

The main accelerator consists of smaller-bore (25.4 cm diameter beam tube) "standard" induction cells for the long-pulse stability experiments. Several of these are presently inactive. The magnetic tune through the main accelerator gradually increases to a field of more than 1 kG on axis to suppress BBU. The tunes for these experiments were designed using the XTR envelope code [3]. For the initial experiments self-consistent initial conditions for XTR were established using the TRAK ray-tracing code [4, 5]. For the present experiments we are using the LSP particle in cell code [6] to provide initial conditions.

DARHT-II is heavily instrumented with beam and pulsed-power diagnostics [2]. In addition to diagnostics that monitor performance of the Marx generator, there are capacitive dividers in the diode vacuum to measure the actual diode voltage waveform. Each induction cell has a resistive divider to measure the voltage waveform delivered by the pulse-forming network. There are beam position monitors (BPMs) in the diode anode region, one at the exit of the injector cells, one in the BCUZ, one at the entrance to each block of six cells, one at the accelerator exit, and one just before the imaging target. The BPMs are based on arrays of azimuthal B-field detectors [7, 8], and also measure the beam current. Streak and framing cameras produce images of beam-generated Cerenkov and optical transition radiation (OTR) light from targets inserted in the beam line. Finally, a magnetic spectrometer is used to measure the beam-electron kinetic energy.

RESULTS AND DISCUSSION

Results indicated that the injector cells accelerated the beam without loss of current within the ~2% uncertainty of the measurement [2]. Some of the beam head and tail was then scraped off in the BCUZ throat, and very little

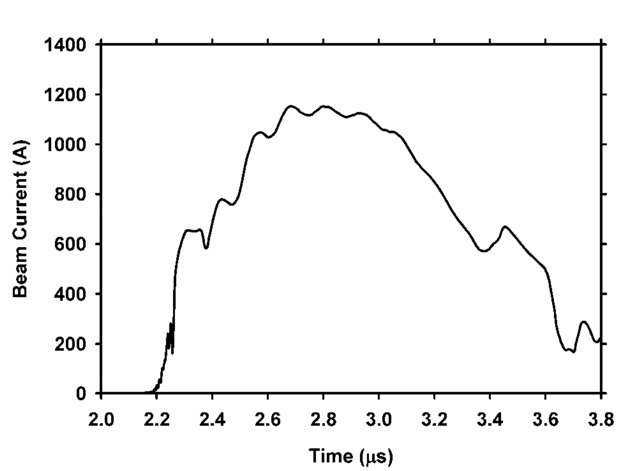

Figure 2: 1200-ns FWHM beam pulse at exit of accelerator in initial experiments (configuration A).

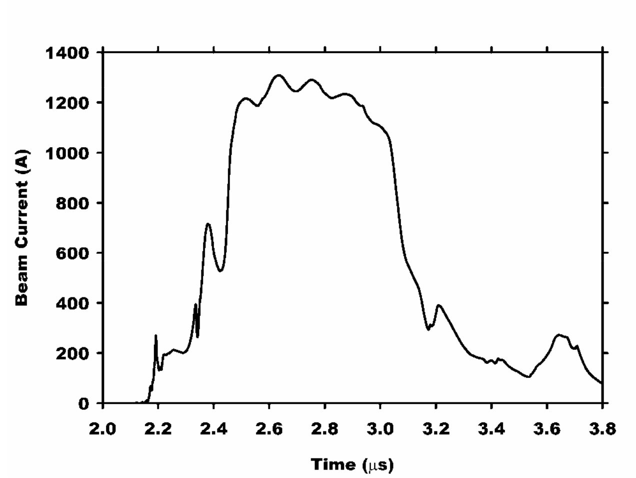

Figure 3: 800 ns FWHM beam pulse at exit of accelerator in initial experiments (configuration B).

further loss occurred as the beam was accelerated through the remaining accelerator cells [1,2]. Fig. 2 shows the beam current exiting the accelerator for one of the 1200 ns pulses produced in the initial experiments (configuration A). Because of the lower injected electron energy in the stability experiments (configuration B), the loss of beam in the BCUZ was more pronounced. Fig. 3 shows the beam current exiting the accelerator for one of the 800 ns pulses produced during the start up of the stability experiments. (N.B. The new cathode installed for the stability tests produces as much current at 2.5 MV diode voltage as the old cathode did at 3.0 MV. This is ~93% of the current predicted for our diode by both the TRAK ray-tracing gun-design code and the LSP PIC code.)

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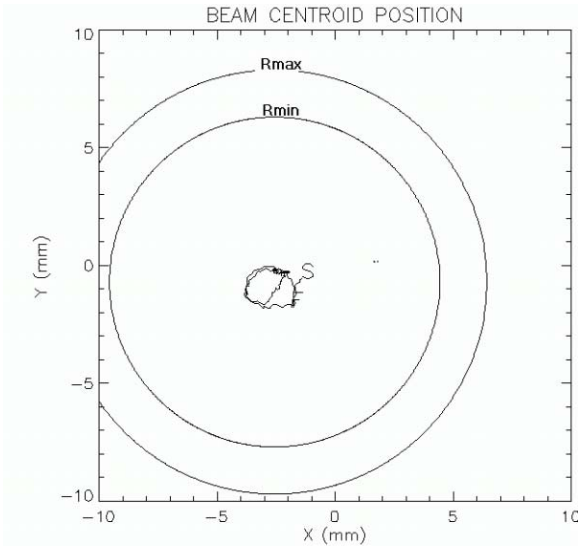

Figure 4: Beam position at accelerator exit during a 400 ns window around peak current compared with estimated beam size from XTR envelope code for a probable range of initial conditions. (S and F signify start and finish of trajectory).

Corkscrew Motion

A striking feature of the DARHT-II diode is the 7.8 MHz oscillation on the main voltage pulse, which damps out with a time constant of ~780 ns with no beam loading the diode. (The decay time decreases as beam current loads the circuit.) This is an LC oscillation caused by the capacitances and inductances of the injector structure. This energy oscillation in the diode caused a small (~ ± 1 mm) oscillation of the beam position as a result of an accidental magnetic dipole in the diode region. This linear motion was modified into corkscrew [9] as the beam transported through the bumpy solenoid magnetic field. However, it was not amplified, and remained less than 20% of the beam radius (Fig 4).

One concern about corkscrew motion is the possibility that it could seed the BBU. Obviously, the frequency of corkscrew resulting from the diode LC oscillation is far too low to be a problem in this respect. However, there are higher frequency RF modes predicted for our injector vacuum tank, so we examined data from long-pulse injector tests for corkscrew in the frequency range of BBU. Fig. 5 shows the current at the exit of the injector cells during one of the long-pulse injector tests.

The 7.8 MHz oscillations are such a strong feature of the beam motion that they completely dominate any frequency analysis. Therefore, we filtered them out using a narrow, 2 MHz wide, notch filter. The result of the filtered frequency analysis of dy/dt is shown in Fig. 6. (We analyzed velocity measurements because they are more sensitive to high frequency motion than position measurements by a factor of ω.) It is clear that there is substantial beam motion in the frequency range of the lowest BBU mode, with pronounced motion at 100 MHz. Presumably this is due to the 100 MHz RF mode

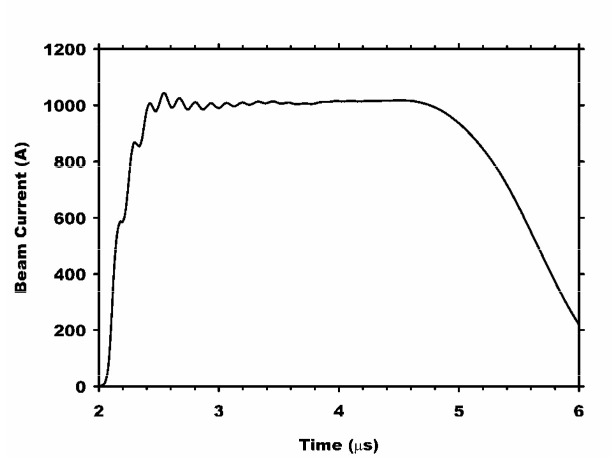

Figure 5: Injector current waveform for a long-pulse test shot.

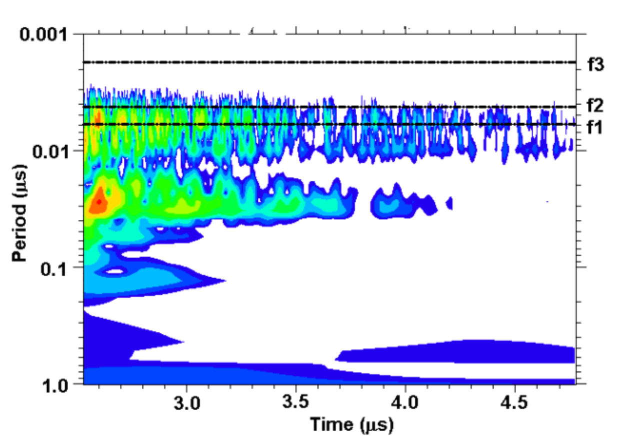

Figure 6: Frequency analysis of dy/dt during 2 ms flat top of current pulse. (The 7.8 MHz oscillations were filtered out for this analysis.)

predicted in early simulations of the injector vacuum vessel. Even through the measured rms amplitude of this high-frequency corkscrew is only ~ 100 micron, it could seed the BBU in the accelerator.

Beam Breakup

During the initial experiments on DARHT-II we tested the accelerator for its immunity to the BBU instability. BBU frequencies for the accelerator cells are 169 MHz, 236 MHz, and 572 MHz [10]. In an infinitely long pulse, the maximum amplification from the BBU is expected to be $(\gamma_0/\gamma)^{1/2}\exp(\Gamma_m)$ throughout the length of the accelerator, where $\Gamma_m = I_b N_g Z_\perp \langle 1/B \rangle / 3\mathrm{x}10^4$ [11-13] . Here, I_b is the beam current in kA, the transverse impedance $Z_\perp$ is in Ω/m, and the $\langle 1/B \rangle$ is in kG^{-1} (the brackets < > denote average over accelerator length). No evidence of BBU growth was seen in the initial experiments until the magnetic field strength was reduced 1/5 the value of the nominal tune throughout the

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accelerator, at which point the lowest frequency BBU mode became evident late in the pulse [1, 2]. In DARHT-II the BBU grows rapidly out of seed motion such as the high-frequency corkscrew or random noise on the beam, since there is no sharp risetime to excite it. (As shown in Fig. 6 there is ample motion to seed the BBU.) The time to grow to maximum is $\tau_m = 2\Gamma_m Q/\omega_0$, which is only a few ns for DARHT-II parameters. Here, Q is the cavity quality factor and ω_0 is the mode resonant frequency.

Because our data recording in the initial experiments was bandwidth limited (250 MHz), we would have been unlikely to observe the higher frequency BBU modes. However, since the beam was not disrupted with the nominal tune, those modes must have been benign. Moreover, we have yet to observe the higher frequency modes in our present experiments, in which we have much higher bandwidth (1 GHz) recording capability.

Ion Hose Instability

Because of the long pulse of DARHT-II the ion-hose instability [14] is of some concern, and a substantial effort has been paid to the accelerator vacuum. In a strong axial guide field such in DARHT-II, the growth rate of the ion hose in a distance ℓ is $f_e I_b \ell \xi / (\varepsilon_n I_0)$, where f_e is the fractional neutralization (proportional to the background pressure), ε_n is the normalized emittance, I_0 =17 kA, and ξ is a factor less than 2.8 [15]. The ion-hose frequency predicted for the present tune (configuration B) of DARHT-II is 12 MHz for N_2 gas.

When we had abnormally high pressures in the last two cell blocks of the accelerator we were able to observe the ion hose. (We estimate that the pressure was $>10^{-6}$ Torr in the center of the last two cell blocks, to be compared with our usual $<10^{-7}$ Torr background.) Fig. 7 shows the beam motion at the entrance to the last cell block, after filtering out the 7.8 MHz oscillations. The presence of the 10 to 12 MHz ion-hose is quite evident in this figure. Moreover, the motion is quite large compared with the 7.8 MHz corkscrew (compare with Fig. 3). The observed 10 to 12 MHz ion hose frequency is within the 10 to 18 MHz range predicted with a spread-mass model for air background gas and the beam size predicted by the XTR envelope code.

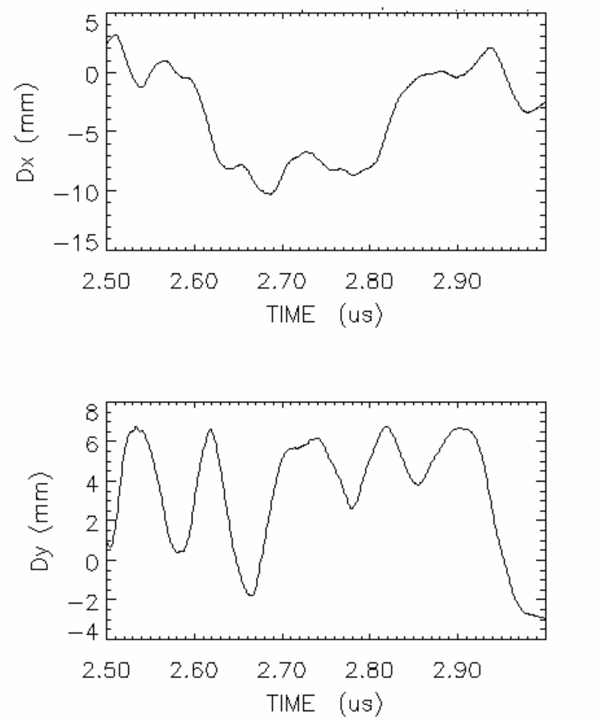

Figure 7: Beam motion at the entrance to the last cell block showing the 10 to 12 MHz ion-hose motion. (The 7.8 MHz oscillation has been filtered out of these data.)

CONCLUSIONS

The DARHT-II beam pulse has a large amplitude corkscrew at 7.8 MHz excited by LC oscillations in the diode. In addition, the are high frequency, small amplitude corkscrew gyrations which may seed the BBU. These may be excited by RF modes of the injector vacuum tank in the frequency range of the BBU. However, all experiments to date show that the accelerator is immune to BBU with the nominal tunes used, at least for a 1.2 µs FWHM pulse. We saw evidence of ion-hose instability due to abnormally high background pressure at the end of the accelerator. The observed frequency was that predicted by a spread mass model based on the accelerator tune. We are presently reconfiguring the injector to provide a pulse with a 1.6 µs flat top for further BBU and ion-hose experiments.

ACKNOWLEDGEMENTS

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REFERENCES

[1] "First beam at DARHT-II," Carl Ekdahl, et al., PAC2003, Portland , OR, May 2003, p. 558

[2] "Initial electron-beam results from the DARHT-II linear induction accelerator," Carl Ekdahl, et al., IEEE Trans. Plasma Sci. 33, 892 (2005)

[3] "Beam injector and transport calculations for ITS," Thomas P. Hughes, David C. Moir and Paul W. Allison, PAC'95

[4] "Beamline tunes for DARHT-II phase-1 commissioning," Carl Ekdahl, Los Alamos National Laboratory report LAUR-02-3921, June 27, 2002

[5] "Finite-element Methods for Electron Gun Design," Stanley Humphries Jr., ICOPS'96, and www.fieldp.com

[6] "Three-dimensional calculations for a 4 kA, 3.5 MV, 2 microsecond injector with asymmetric power feed," T. P. Hughes, R. E. Clark, and S. S. Yu, Phys. Rev. ST Accel. Beams 2, 110401 (1999)

[7] "Fourier-analyzing coil arrays for pulsed relativistic electron beam experiments," C. A. Ekdahl, Rev. Sci. Instrum. 55, 1221 (1984)

[8] "Aliasing errors in measurements of beam position and ellipticity," Carl Ekdahl, accepted by Rev. Sci. Instrum. (2005)

[9] "Corkscrew modes in linear accelerators," Yu-Jiuan Chen, Nuc. Instrum. Meas. A292, 455, (1990)

[10] "BBU and Corkscrew Growth Predictions for the DARHT Second Axis Accelerator," Y. J. Chen and W. M. Fawley, PAC2001, Chicago, IL, June 2001, p. 3490

[11] "Maximum amplitude of BBU growth in DARHT-II experiments," Carl Ekdahl, Los Alamos National Laboratory Report LAUR-04-3915, June, 2004, ADD Kelvin Neil

[12] "The control of beam dynamics in high energy induction linacs," G. J. Caporaso, Proc.1986 Linear Accel. Conf. (LINAC86) (published as SLAC-R-303), 17 (1986)

[13] "Beam emittance growth caused by transverse deflecting fields in a linear accelerator," A. W. Chao, B. Richter, and C-Y Yao, Nucl. Instrum. Methods 178, 1 (1980)

[14] "Electron beam propagation in the ion-focused regime," H. L. Buchanan, Phy. Fluids 30, 221, (1987)

[15] "Transverse instabilities from ion oscillations in the DARHT-II accelerator," R. Briggs, LBNL Engineering Note M7848, January, 2000

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