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Author(s): Carl Ekdahl, et. al.

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Los Alamos
NATIONAL LABORATORY

FIRST COMMISSIONING EXPERIMENTS AT DARHT-II

Carl Ekdahl, E. O. Abeyta, L. Caudill, K. C. D. Chan, D. Dalmas, S. Eversole, R. Gallegos, J. Harrison, M. Holzscheiter, J. Johnson, E. Jacquez, B. Trent McCuistian, N. Montoya, K. Nielsen, D. Oro, L. Rodriguez, P. Rodriguez, M. Sanchez, M. Schauer, D. Simmons, H. V. Smith, J. Studebaker, G. Sullivan, C. Swinney, and R. Temple, LANL, Los Alamos, NM 87545, USA
Y. J. Chen, and T. Houck, LLNL, Livermore, CA 94551, USA
E. Henestroza, S. Eylon, W. Fawley, and S. S. Yu, LBNL, Berkeley, CA 94720, USA
H. Bender, W. Broste, C. Carlson, G. Durtschi, D. Frayer, D. Johnson, K. Jones, A. Meidinger, K. Moy, R. Sturgess, and C. Y. Tom, Bechtel Nevada, Los Alamos, NM 87544, USA
T. Hughes, and C. Mostrom, Mission Research, Albuquerque, NM 87110

Abstract

The second axis of the Dual Axis Radiographic Hydro-Test (DARHT) facility will provide up to four short (< 150 ns) radiation pulses for flash radiography of high-explosive driven implosion experiments[1]. To accomplish this the DARHT-II linear induction accelerator (LIA) will produce a 2-kA electron beam with 18-MeV kinetic energy, constant to within ± 0.5% for 2-μs. A fast kicker will cleave four short pulses out of the 2-μs flattop, with the bulk of the beam diverted into a dump. The short pulses will then be transported to the final-focus magnet, and focused onto a tantalum target for conversion to bremsstrahlung pulses for radiography. DARHT-II is a collaborative effort between the Los Alamos, Lawrence Livermore, and Lawrence Berkeley National Laboratories of the University of California.

The first tests of the second axis accelerator were designed to demonstrate the technology, and to meet the modest performance requirements for closing out the DARHT-II construction project. These experiments demonstrated that we could indeed produce a 1.2 kA beam with pulse length 0.5-1.2 μs and accelerate it to 12.5 MeV. These de-rated parameters were chosen to minimize risk of damage in these first experiments with this novel accelerator. The beam showed no evidence of the BBU instability for these parameters. In fact, we had to reduce the magnetic guide field by a factor of 5 before BBU was observed.

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. These tests were accomplished at reduced parameters to minimize risk of damage to this new accelerator. Table 1 shows the parameters for these experiments compared with the final parameters expected when all phases of commissioning are completed.

ACCELERATOR

The 88-stage Marx generator that powers the injector diode for DARHT-II will produce a 3.2-MV output pulse that is flat for 2-μs. The rise time of this pulse at the diode is ~500 ns, but to minimize risk of damage in these initial experiments, the Marx generator was configured to produce a shorter, 1.2-μs FWHM pulse, which was even further shortened on most shots with a diverter switch.

Table 1: DARHT-II Parameters

	Initial Experiments	Final Parameters
Beam Current	1.2-1.3 kA	2.0 kA
Pulse Length	0.5-1.2 μs (FWHM)	2.0 μs (FlatTop)
Diode	3.0 MeV	3.2 MeV
8 Injector Cells	1.2 MeV	1.4 MeV
Installed Accelerator Cells	64	70
Active Accelerator Cells	61-62	70
Exit Energy	12.5-12.7 MeV	18 MeV

After leaving the diode, the 3.0-MeV beam was accelerated by eight large-bore (36-cm-diam beam tube) induction cells to 4.2 MeV. The beam next enters a special transport zone designed to scrape off the long rise time, off-energy beam head. For these first experiments, this beam-head clean-up zone (BCUZ) was configured to pass the entire beam head, and the timing of the accelerator was set to accelerate the entire beam, including the off-energy beam head. The magnetic tune through the BCUZ compressed the beam to the smaller radius needed to match into the main accelerator.

The main accelerator consisted of 64 smaller-bore (25.4-cm-diam beam tube) "standard" induction cells for phase one experiments. Two or three of these were inactive. The magnetic tune through the main accelerator gradually increased to a field of more than 1 kG on axis to suppress the beam-break-up (BBU) instability. The magnetic tune for these experiments was designed using two beam dynamics codes [2]. First, the TRAK electron-gun design ray-tracing code [3] was used to establish initial conditions at the anode (initial radius, divergence, emittance) for the XTR envelope code [4] at the operating A-K potential of the diode. Then, the tune was developed for the energy flattop of the beam using the accelerating voltages that were expected to be applied to the gaps. Finally, the lossless transport of the off-energy beam head was computationally verified using XTR simulations in steps of 100-kV A-K potential, with initial conditions from individual TRAK simulations.

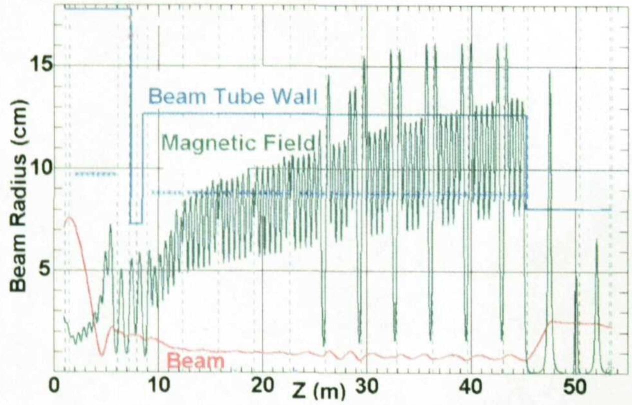

Figure 1. DARHT-II tune for commissioning experiments.

DIAGNOSTICS

DARHT-II is heavily instrumented with beam and pulsed-power diagnostics [5]. 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) at the entrance to each block of cells, as well as three more in the diode anode region, one at the exit of the injector cells, two in the BCUZ, and one just before the imaging target. The BPMs are based on arrays of azimuthal B-field detectors [6], and also measure the beam current. Streak and framing cameras produced images of beam-generated Cerenkov and optical transition radiation (OTR) light from targets inserted in the beam line. Finally, a magnetic spectrometer was used to measure the beam kinetic energy.

RESULTS

Results indicated that the eight injector cells accelerated the beam without loss of current within the ~2% uncertainty of the measurement [5]. Some of the beam head was then lost in the BCUZ throat, and very little further loss occurred as the beam was accelerated through the remaining 64 accelerator cells. These results verify that the magnetic tune indeed realized the design goal of negligible off-energy beam-head loss in the cells.

A striking feature of this diode was the 7.8-MHz oscillation on the main voltage pulse, which was about ±1.5% of the voltage at the peak. This is an LC oscillation caused by the capacitances and inductances of the injector structure. The fully accelerated beam kinetic energy was measured with the magnetic spectrometer to be >12.2 MeV for 500 ns, with a peak energy >12.5 MeV. The 7.8-MHz oscillation is clearly evident on this sensitive scale (Fig. 2), although it amounts to only ±0.4% of the accelerated beam energy. A resistive damping circuit to quench this oscillation is now being tested and could be installed if necessary.

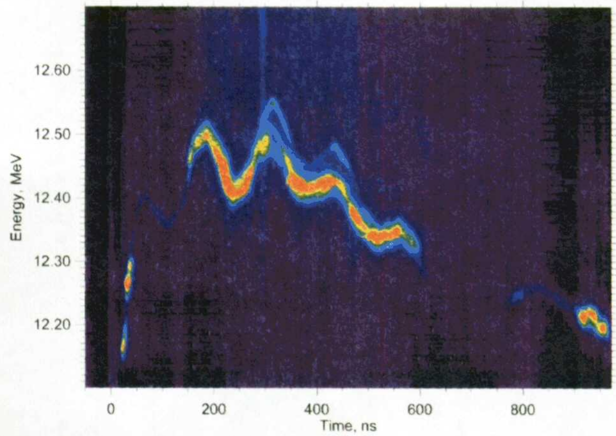

Figure 2. Streak camera readout of electron energy pulse showing the 7.8 MHz oscillation produced in the diode.

This 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 motion was modified by the bumpy solenoid magnetic field but was not amplified as the beam was transported through the accelerator, and remained less than 20% of the beam radius (Fig 3).

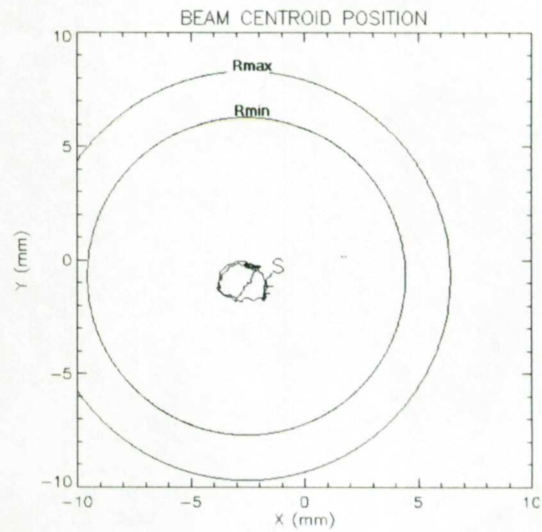

Figure 3. Beam position at accelerator exit during a 400-ns window around peak current compared with estimated beam size from XTR envelope code for a probable range of initial conditions. (S and F signify start and finish of trajectory).

Anamorphic streak images (Fig. 4) of the beam after the accelerator exit showed that the elliptical beam profile had a Gaussian-like core containing ~80% of the current surrounded by a halo. Using a focusing-magnet scan the emittance of the Gaussian core was estimated to be less than 1000 p-mm-mr, which is the goal for the accelerator. The beam centroid motion seen in the streak images was in excellent agreement with the beam position measured with a nearby BPM.

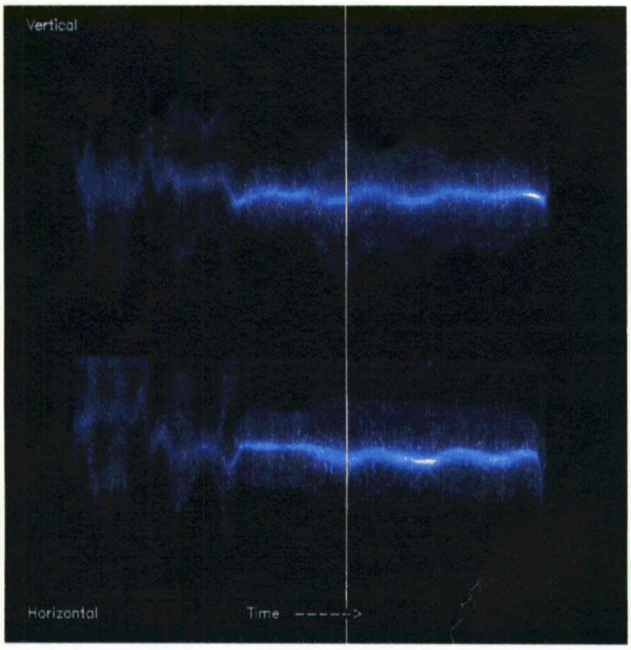

Figure 4. 1.0-μs anamorphic streak images of ~1.5-cm diameter beam. Top: Projection in vertical plane (anamorphically compressed in horizontal direction). Bottom: Projection in horizontal plane(anamorphically compressed in vertical direction). Time runs left to right.

We completed this first round of commissioning with tests of resistance to the beam-breakup (BBU) instability, which is suppressed by the magnetic guide field. No evidence of BBU growth was seen until the magnetic field strength was reduced by a factor of 5 throughout the 64 standard cells, at which point it became evident late in the pulse (Fig. 5). In an infinitely long pulse, the maximum amplitude of the BBU can be shown to grow like $\sqrt{\gamma_0/\gamma}\exp(\Gamma_m)$ through the length of the accelerator. In this growth law $\Gamma_m = I_b N_g Z_\perp \langle 1/B \rangle / 3\times10^4$, where the beam current I_b is in kA, the transverse impedance $Z_\perp$ is in Ω/m, and the average $\langle 1/B \rangle$ is in kG^{-1} [7-9]. The experimental results, coupled with this scaling, provide persuasive evidence that this magnetic tune will be more than adequate to suppress BBU with the final 2-kA current and full complement of 70 cells.

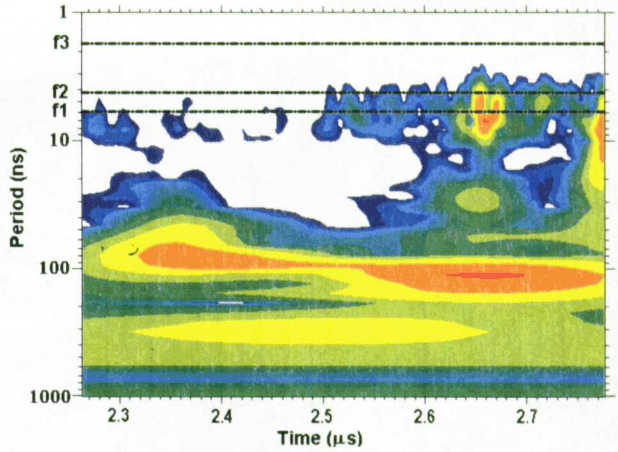

Figure 5. Frequency analysis of motion of the beam centroid with magnetic guide field reduced by factor of 5. BBU frequencies for the accelerator cells are f1=169 MHz, f2=236 MHz, and f3=572 MHz [10].

ACKNOWLEDGEMENTS

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REFERENCES

[1] "Status of the DARHT Phase 2 Long-Pulse Accelerator," M. J. Burns, et. al., PAC2001, Chicago, IL, June 2001, p. 325

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

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

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

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

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

[7] "Maximum amplitude of BBU growth in DARHT-II experiments," Carl Ekdahl, Los Alamos National Laboratory Report LAUR- , June, 2004

[8] "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)

[9] "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)

[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