CHARACTERIZATION OF A RAMPED GRADIENT DTL: EXPERIMENT AND THEORY*

K. F. Johnson, E. A. Wadlinger, O. R. Sander, G. P. Boicourt, G. O. Bolme,
C. M. Fortgang, J. D. Gilpatrick, J. Merson, D. P. Sandoval, and V. Yuan
Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract

An experimental demonstration confirming the beam-dynamics of a Ramped-Gradient Drift-Tube Linac (RGDTL) was performed at Los Alamos National Laboratory. The RGDTL was designed to optimize on the requirements of maximum beam acceleration, minimum longitudinal and transverse emittance growth, and acceptable wall power loss. At low beam energies, transverse-magnet focusing is weak and the rf defocusing must be minimized. As the beam energy increases, stronger rf defocusing can be tolerated and the rf electric field gradient can increase. A detailed comparison of theory and experiment was carried out. Beam longitudinal centroids (output energy and phase) and transverse and longitudinal emittances were measured as a function of RGDTL rf field amplitude and phase. The longitudinal centroids were also studied as functions of input beam current, energy, and degree of bunching. Comparison between experimental data and theory was in good agreement.

I. INTRODUCTION

Proton or H^- drift-tube linacs (DTLs) can achieve accelerating gradients of 4 to 5 MV/m, whereas radio-frequency quadrupoles (RFQs) achieve gradients of typically 2 MV/m. It is desirable to provide a transition region between the RFQ and the high gradient DTL, which can be accomplished by the accelerator having a field ramp that smoothly connects the two field gradients. The Los Alamos RGDTL was designed to provide this transition region [1]. It automatically matches the beam from a low-velocity, low-field gradient device (RFQ) to a high-velocity, high-gradient device (DTL). In the design procedure the requirements of maximum beam acceleration, minimum longitudinal and transverse emittance growth, and acceptable wall power loss were optimized.

The RGDTL is a 425-MHz, 1.87-m-long structure containing 29 drift tubes, 14 post couplers, 2 tuners, and 2 drive loops. It has an axial, electric-field gradient that increases from 2.0 MV/m (RFQ gradient) to 4.4 MV/m over 1.5 m for accelerating H^- from 2.07 MeV (RFQ output energy) to 6.67 MeV. The structure's mechanical design, low-power tuning, and field stabilization measurements are reported in References 2 through 5.

An experimental demonstration validating the beam-dynamics of the RGDTL has been completed on the Accelerator Test Stand (ATS) [6]. The demonstration showed that a RGDTL with the desired stable-field distributions can be built and operated. Characterization of the RGDTL output beam confirmed that simulation codes accurately model the beam-dynamics of moderately bright beams in the RGDTL.

II. EXPERIMENTAL TECHNIQUE

The H^- input beam to the RGDTL was obtained from the ATS, 425-MHz, 2.07-MeV RFQ. The ATS was operated at a low duty factor (0.025%).

The experimental objective was to fully characterize the output beam of the RGDTL to allow for a detailed comparison to the simulation codes. To achieve this end, the output beam current, beam transmission, transverse centroids (position and angle in both planes), longitudinal centroids (beam energy and phase), and transverse and longitudinal phase-space distributions were measured for a variety of RGDTL operating conditions.

Available diagnostics for these measurements included three toroids and a Faraday cup (beam current and transmission), three capacitive probes [7] (longitudinal centroids), two pairs of slit-collectors (transverse centroids and phase-space distributions), LINDA [8] (longitudinal phase-space distribution), and an x-ray detector [9] (RGDTL rf field).

III. EXPERIMENTAL RESULTS

At low power, the RGDTL accelerating mode was tuned to 425 MHz with the desired ramped field distribution, and the field was stabilized against tuning errors. The tuning procedure is given in References 4 and 5, where the parameters to be adjusted, the goals of the adjustments, the tuning mechanisms used, and the various measurement techniques are described in detail.

The RGDTL was operated with dual rf drive loops with a master-slave configuration for amplitude control and independent phase control. The dual drive-loop coupling was determined at low power [10]. With beam, the operation of the dual rf drive system was established and shown to be stable and reliable.

The RGDTL rf electric field E_0 on axis can be determined from the energy spectrum of the x-rays generated within the cavity [9]. The x-ray energy spectra were measured versus cavity rf power. These data suggested that 470 ± 12 kW cavity power was necessary to achieve the design axial field, which is very close to the power level (460 ± 10 kW) predicted by SUPERFISH.

---

*Work supported and funded by the US Department of Defense, Army Strategic Defense Command, under the auspices of the US Department of Energy.

0-7803-0135-8/91$01.00 ©IEEE

The RGDTL rf amplitude and phase set-points were determined using the phase-scan technique [11]. This technique utilized the capacitive probes [7] to measure the energy and phase centroids of the beam as a function of the RGDTL rf amplitude and relative rf phase. A comparison of the data to single-particle simulations provides the signature for determining the operating set-points of the RGDTL. In this procedure, it was assumed that beam centroids are unaffected by space-charge and that the centroid behavior can be predicted by single-particle simulations. Both assumptions are reasonable if the particles in the bunch experience forces that depend on the magnitude of their displacement from the synchronous particle. Figure 1 compares experiment and simulation. The data indicate that a cavity power of 448 kW gives a gap voltage near the design value (~3% high). This result is in good agreement with the x-ray data and SUPERFISH calculations.

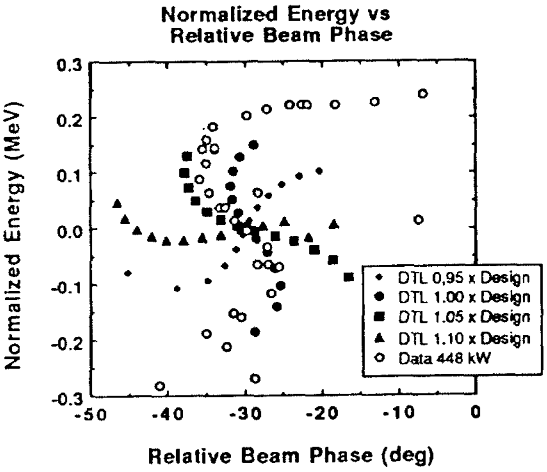

Figure 1. A comparison between RGDTL data at 448 kW and simulations at 0.95, 1.00, 1.05, and 1.10 times the design gap voltage. Relative output beam phase is used to facilitate a comparison of curve shapes. The simulations indicate that a cavity power of 448 kW gives fields that are near design specifications.

Additional phase-scans were taken where the input energy to the RGDTL was varied above and below the design input energy. This variation was accomplished by operating the ATS buncher cavity (located between the RFQ and RGDTL) in its accelerating or deaccelerating modes. The experimental results were again in good agreement with simulations.

Phase-scans were made at both low-beam currents (~20 mA) and high-beam currents (78 to 80 mA). The rf amplitude and phase set-points, as determined from the phase-scans, were independent of beam current. This result supports our assumption that beam centroids were unaffected by space charge.

Operating the RGDTL at its rf amplitude and phase set-points gave >97% beam transmission at both high- and low-beam currents which was as predicted from simulations. For quiet beams, a relative uncertainty of ~2% on beam transmission measurements was possible.

The longitudinal phase-space distributions of the RGDTL output beam were measured using LINDA [8]. These measurements were made as functions of RGDTL rf cavity power (five different levels), rf phase (three settings), and longitudinal match of the input beam. These measurements tested the RGDTL beam dynamics with different space-charge forces, external longitudinal focusing forces, and input phase-space distributions.

To study longitudinal matching to the RGDTL, data were taken with the ATS rf buncher either off or operating in its bunching, debunching, accelerating, and deaccelerating modes. The measured longitudinal Courant-Snyder (CS) parameters of the RGDTL output beam were compared to simulations using the mismatch factor (MMF) where MMF = 0 corresponds to achieving the design CS parameters. With the rf buncher off (standard ATS operation), the data and simulations are in good agreement (MMF = 0.08). For all rf-buncher modes, MMF was less than 0.2, showing that the output beam CS parameters were insensitive to the longitudinal match. In general a practical criteria of MMF < 0.3 is considered to indicate "agreement" with simulations.

The longitudinal emittance of the RGDTL output beam was measured at different RGDTL rf power levels and phases. A comparison of the rms longitudinal emittance at the optimum RGDTL power and phase set-points ($0.10 \pm 0.02\ \pi$ MeV-deg) to a previous measurement of the RFQ rms longitudinal emittance ($0.08 \pm 0.02\ \pi$ MeV-deg) indicates no longitudinal emittance growth in the RGDTL. The error on the emittance measurement is ~20% and reflects the scatter in the data. Within the limited range of RGDTL rf power and phases explored, the rms longitudinal emittance was insensitive (within experimental error) to both rf power and phase, as expected.

The RGDTL output beam transverse phase-space distributions (horizontal and vertical) were measured using a standard slit and collector technique [12]. These measurements were made as functions of RGDTL rf cavity power (five power levels), rf phase (three settings), and longitudinal match of the input beam.

Using the MMF, the measured transverse CS parameters of the RGDTL output beam were compared to simulations. At the optimum RGDTL rf power and phase set-points, there was good agreement between data and simulations. The MMF was 0.30 and 0.08 for the horizontal and vertical planes, respectively. Unlike in the longitudinal plane, large MMF (~1) were obtained in both transverse planes for non-optimum RGDTL operating conditions. As expected the output transverse CS parameters were independent of the longitudinal match of the input beam. In the ATS RGDTL experimental configuration, it was not possible to vary the transverse match of the RGDTL input beam.

The rms-normalized transverse emittances of the RGDTL output beam were measured at different RGDTL rf power levels and phases. A comparison of the rms transverse emittances at the optimum RGDTL power and phase set-points (0.025 ± 0.002 π cm-mrad horizontal plane and >0.022 ± 0.002 π cm-mrad vertical plane) to previous measurements of the RFQ rms transverse emittance (~0.026 ± 0.002 in both planes) indicates no transverse emittance growth in the RGDTL. The measured RGDTL vertical emittance is a lower limit because of some small beam scraping inside the capacitive probe at the RGDTL exit. The error on the emittance measurements is ~8% with background subtraction being the dominant component. Within the limited range of RGDTL rf power and phases explored, the transverse emittances were shown to be insensitive (within experimental error) to both rf power and phase, as expected.

The position and angle centroids of the RGDTL output beam were determined from the measured transverse phase-space distributions. The centroids indicated that some small mis-steering of the beam was occurring in the RGDTL. Later off-line checks of the RGDTL suggested two possible causes: (1) a misaligned quadrupole in the downstream end wall and (2) an internal braze failure that resulted in a water pressure bulge in the end wall. The bulge may have twisted or distorted the half drift-tube which supported the end wall quadrupole.

IV. SUMMARY AND CONCLUSIONS

During the commissioning process, the RGDTL performed as expected. The experimentally determined cavity power (two independent techniques) was in good agreement with the theoretical value. Beam transmission was greater than 97% with a maximum output current of 80 mA. Within experimental errors, transverse and longitudinal phase-space measurements do not indicate any emittance growth through the RGDTL. The measured output beam CS parameters are in good agreement with simulations. These results confirm the beam-dynamics predictions and thus validate the design codes and indicate that no major physics has been omitted.

The successful testing of the RGDTL has shown that compact DTLs utilizing ramped fields can be designed, built, and operated. They could be key elements in the high-brightness accelerators that are being considered in many advanced accelerator applications.

V. REFERENCES

[1] G. P. Boicourt and M. C. Vasquez, "Two New Possible Designs for the Ramped ATS-DTL," Los Alamos National Laboratory memo AT-6:85-180, November 27, 1985.

[2] D. J. Liska and L. B. Dauelsberg, "A Drift-Tube Linac Incorporating a Ramped Accelerating Field," in "Proc. 1987 IEEE Particle Accelerator Conf.," Washington, D.C., 1987, p. 1797.

[3] D. J. Liska et al., "A High-Intensity Drift-Tube Linac with Ramped Accelerating Gradient," in "Proc. 1988 Linear Accelerator Conf.," CEBAF-Report-89-001, June 1989, p. 652.

[4] J. H. Billen and A. L. Shapiro, "Post-Coupler Stabilization and Tuning of a Ramped-Gradient Drift-Tube Linac," in "Proc. 1988 Linear Accelerator Conf.," CEBAF-Report-89-001, June 1989 p. 128.

[5] J. H. Billen, "Analysis of Measured Poet-Coupler Fields in a Ramped-Gradient Drift-Tube Linac," in "Proc. 1988 Linear Accelerator Conf.," CEBAF-Report-89-001, June 1989, p. 131.

[6] O. R. Sander, et al., "Review of the Accelerator Test Stand Performance and Expectations," Los Alamos National Laboratory report LA-CP-89-489 (July 1989).

[7] J. D. Gilpatrick et al., "Synchronous Phase and Energy Measurement System for a 6. 7 MeV H- Beam," in "Proc. 1988 Linear Accelerator Conf.," CEBAF-Report-89-001, June 1989, p. 134.

[8] W. B. Cottingame et al., "Noninterceptive Technique for the Measurement of Longitudinal Parameter of Intense H^- Beams," in "Proc. 1985 Particle Accelerator Conference", IEEE Trans. Nucl. Sci., Vol. 32(5), p. 1871, 1985.

[9] G. O. Bolme et al., "Measurement of RF Accelerator Cavity Field Levels at High Power from the Characteristic X-ray Emissions," in "Proc. 1990 Linear Accelerator Conf.," Los Alamos National Laboratory report LA-12004-C, March 1991, p. 219.

[10] C. M. Fortgang and G. O. Bolme, "Dual Loop Drive on the RGDTL," Los Alamos National Laboratory memo AT-2:88-255, June 29, 1988.

[11] C. M. Fortgang et al., "Longitudinal Beam Dynamics of a 5-MeV DTL: A Comparison of Theory and Experiment," in "Proc. 1988 Linear Accelerator Conf.," CEBAF-Report-89-001, June 1989, p. 167.

[12] O. R. Sander, "Transverse Emittance: Its Definition, Applications, and Measurement," Proc. Accelerator Instrumentation, edited by E. R. Beadle and V. J. Castillo, (AIP Conf. Proc. No. 212, 1989), p. 127.