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A HIGH-INTENSITY DRIFT-TUBE LINAC WITH RAMPED ACCELERATING GRADIENT*

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Abstract

Ramped accelerating gradients in drift-tube linacs are made possible by post couplers with extreme differential coupling between adjacent accelerating gaps. By bringing the energy of the beam up through ramping, better overall control of longitudinal emittance can be accomplished and a more compact accelerator achieved. Such a machine has been designed at Los Alamos[1] and built through industrial participation with the Hanford Engineering Development Laboratory (HEDL), the Brobeck Corp., and Grumman Aerospace Corp. The design of the Ramped-Gradient Drift-Tube Linac (RGDTL) involved development of high-powered drive loops, specially instrumented drift tubes, and a new rotary-type dynamic tuner. The assembly of the machine from the industrial components has been completed, and it is now installed and in operation at the Accelerator Test Stand (ATS) in Los Alamos.

Design Features

The completed RGDTL is shown in Fig. 1. The system, which operates at 425 MHz, contains 29 free-standing drift tubes suspended from an overhead girder. Each second accelerating cell contains a post coupler with no tab but an acute angle to its stem (see Fig. 2). The bent stem permits a high degree of gap-to-gap differential coupling in order to establish the field ramp shown in Fig. 3. This is a cubic polynomial that raises the average accelerating gradient from 2.0 to 4.4 MV/m over a length of 150 cm.

Fig. 1 The 425 MHz ramped gradient drift tube linac

Fig. 2. High-differential coupling post coupler.

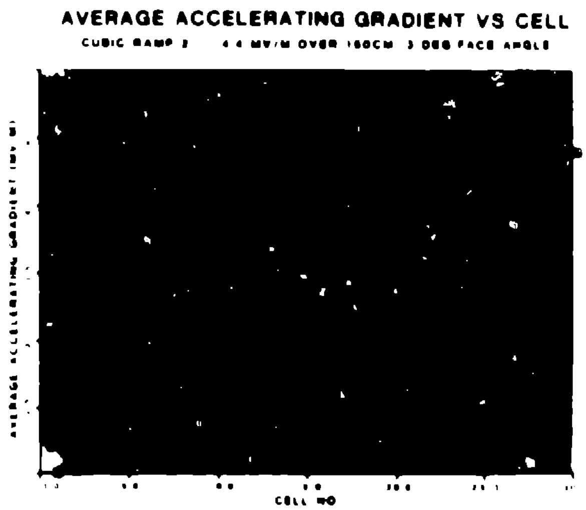

Fig. 3 Accelerating gradient established in the RGDTL.

Other features of the RGDTL that are of interest are the aluminum tank barrel and girder and the multiple drive ports equipped with two 500-kW drive loops. Copper loss power for the RGDTL is 391 kW. The linac raises the beam energy from 2.07 to 6.67 MeV and is rated at 100 mA H^-, so the total peak power is 851 kW. The use of high thermal conductivity materials throughout permits a rated duty factor of 5%. The drift tubes utilize permanent magnet quadrupoles (PMQs) made of neodymium iron boron that develop a focusing gradient of 20 kG/cm.

The RGDTL is the result of industrial participation between Los Alamos National Laboratory and Grumman Aerospace who built the tank, girder, post couplers, and slug tuners to Los Alamos specifications. The drift tubes were built by HEDL, and the quadrupoles by Brobeck Corp. Assembly tuning and alignment were done entirely at Los Alamos.

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Assembly

Assembly of the RGDTL by Los Alamos was a very challenging and collaborative effort (see Fig. 1). This effort involved participation from several different technical disciplines, including engineering, precision alignment, and low-power rf tuning.

The RGDTL is a 30-cell structure equipped with 29 full drift tubes, 2 half drift tubes on the ends, 14 post couplers, 2 drive loops, 2 slug tuners, 2 tuning bars, an elaborate cooling system, a hard and soft vacuum system, and a number of required peripherals. The tank barrel was copper-plated aluminum, although, as a result of a design error, it was necessary to bore the inside diameter in order to lower the frequency. This boring exposed the aluminum substrate and resulted in a 30%-lower Q.

The assembly first involved the preliminary alignment of the drift tubes relative to their magnetic centers. A thorough map of their geometrical centers was documented to be used later when an internal alignment relative to the tank is required. Once this documentation was accomplished, the drift tubes were then assembled in the girder. The girder permits accurate, off-line alignment and ease of maintenance because it can be easily removed from the tank body. In the case of the RGDTL, the removal feature was frustrated by warpage of the girder caused by a nonflat mating surface on the tank. Therefore, the final precision alignment had to be done inside the tank with the girder installed. The girder was then placed in a shallow slot and two tuning bars were attached. A metallic C-seal was used between the girder and the tank body for a sufficient rf contact. A number of tooling fixtures were then developed to align the drift tubes inside the tank body. The next step was to assemble and install the post couplers, which required shimming between two flanges outside the tank to allow for a post-coupler penetration adjustment that is required for tuning. Then the slug tuners were installed along with the vacuum pumps because both these components were located on the bottom side of the tank and housed inside the support structure. The next step was to install the cooling channels surrounding the aluminum tank. The thermal contact between the tank and the cooling channels was made by using a thermoconductive grease. The vacuum lines were then installed and an extensive leak check was made on the cooling lines, vacuum lines, and the vessel itself.

Alignment

The alignment requirements for the RGDTL are crucial to the DTL's performance. An adaptation of the Lawrence Berkeley Laboratory (LBL) method of drift-tube alignment using a current-carrying taut wire for determining the magnetic centers of the new high-powered permanent-magnet drift tubes was implemented.[2] The wire is fed vertically through each single drift tube before installation and is pulsed to determine the magnetic center relative to the drift-tube o.d. (see Fig. 4). The resulting data were then documented for later use in the internal alignment scheme of the machine to provide offsets for the drift tubes. Once the magnetic centers of these drift tubes were determined, the drift tubes were assembled in the overhead girder and a precision geometric alignment was made relative to the magnetic centers using a combination of optical transits (3.9 arc sec resolution), sight levels (3.9 arc sec resolution), and several unique alignment fixtures. Then the data were analyzed and used in the final internal alignment of the tank body. The final alignment inside the tank body was the most crucial and demanding aspect of the entire alignment scheme. This alignment had to be done inside the tank body using an ingenious setup consisting of a rail and carriage system. The rail system was first referenced to the critical reference datum located

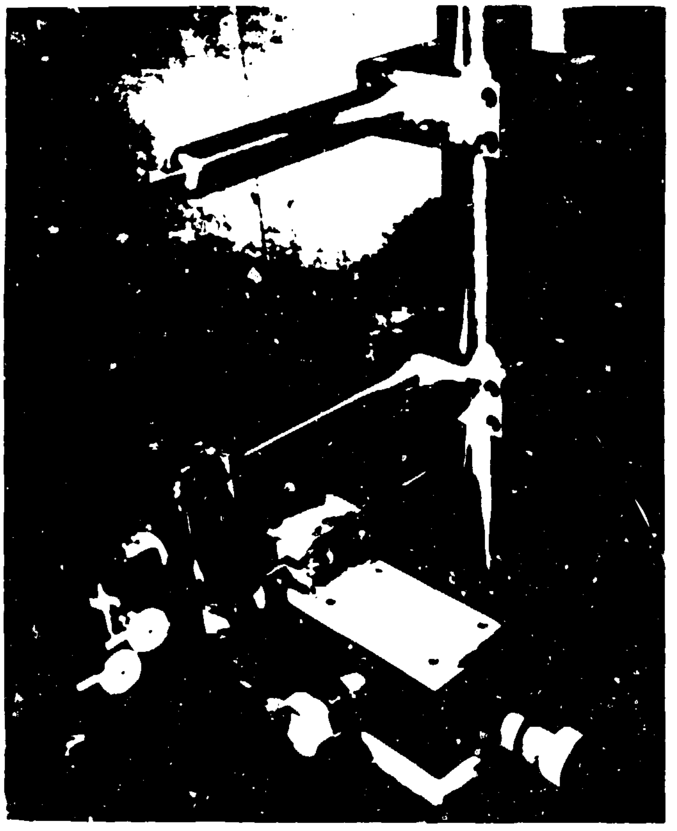

Fig. 4. Determination of drift-tube magnetic centers.

on the tank. This system allowed the carriage device, which was equipped with two digital dial indicators representing the X, Y axes (vertical, horizontal) and a linear encoder representing the Z axis (longitudinal), to move freely along the rails and to measure the positions of the drift tubes. With the use of an IBM computer, the data were then compared with the original precision girder alignment and the displacement was computed. This process was done iteratively, and the necessary corrections were made until the displacements were held relative to each of the drift tubes and the tank body to within ±0.02 mm.

Tuning

Once the drift-tube alignment, preliminary assembly, and all other mechanical checks were completed, the low-power rf tuning commenced. For most of the low-power tuning, the two copper end walls were replaced with aluminum end walls. These aluminum end walls are equipped with movable half drift tubes that serve as end tuners for tilt sensitivity measurements. The end tuner adjustment on each end of the RGDTL includes three micrometers to read the longitudinal position of the half drift tube. These half drift tubes contact the end wall through metallic rf seals. Post couplers both stabilize and ramp the longitudinal field distribution in the cavity.

Axial electric field measurements obtained by the bead-perturbation technique determine how to adjust the post couplers for the desired field ramp and for optimum stability against tuning errors.[3] Similar measurements of the post-coupler magnetic fields near the cavity wall show that peak power densities on post couplers in the steepest part of the ramp greatly exceed the power density on the tank wall.[4]

The design frequency of this particular structure is 425.00 MHz. Initial measurements without post couplers, tuning bars, and zero slug tuner penetration indicated a resonant frequency of 425.84 MHz. Fully loaded, the tank would resonate at 426.00 MHz. It was necessary to lower the frequency by several megahertz by boring out the inside diameter of the tank. Measurements of the resonant frequencies of the empty tank after each cut monitored the machining process. The inside surface of the RGDTL is now bare aluminum. For an all-copper DTL, the tank wall dissipates less than half of the cavity power. Because the resistivity of aluminum is 1.6 times that of copper, total structure power in the RGDTL is increased.

Test Results

The RGDTL was put on-line in June 1988. Two technical factors differentiated this system from the flat-gradient tank previously operated on the ATS: the range of field gradients produced by ramping and the dual rf drive loops. The first factor produces a wide spectrum of hard x rays, which complicates the use of x rays as a diagnostic tool for determining gap voltages. The second requires balancing the coupling and the power transmitted down the two drive lines so that the underdriven loop does not couple power out of the tank. Out-coupled power will appear on the directional coupler as a reflected signal and will erroneously indicate an improper match for the underdriven loop.

During the rf conditioning phase, the RGDTL displayed some marginal multipactoring at low power levels but has operated cleanly at all higher power levels. Evidently, the 3° angles on the drift-tube faces are very effective in inhibiting multipactoring in the gaps. Even though the rated wall-current losses were estimated to be 450 kW, rf conditioning was pushed to over 600 kW, which resulted in very clean rf surfaces. A total of 88 hours of operating time was devoted to rf conditioning and to the x-ray measurements in order to determine gap voltages.

Beams were undertaken at a low rf duty factor (0.1%). The beam pulses were 60 μs at 5 Hz (0.03%). A maximum current of 80 mA has been accelerated, with total current limited by upstream components in the beamline. Beam transmission efficiency exceeds 95% at a wall power dissipation of about 450 kW, very nearly the predicted level. This shows that the beam is being efficiently accelerated and, in fact, closely matches theoretical predictions. Furthermore, preliminary transverse and longitudinal emittance measurements do not indicate significant emittance growth caused by field ramping. Therefore, the concept of the RGDTL appears to be validated.

To date, a total of 333 hours of operating time on the RGDTL has been accumulated, with 23 hours of beam time. Except for the high x-ray fluences developed, which require a lot of shielding, operation has been relatively trouble free. This is the first ramped-gradient DTL put on-line, and its successful commissioning is one key to the state of the art high-brightness accelerators being designed today.

RGDTL-Related Developments

Drive Loops

The RGDTL was the first tank of a seven-tank accelerator system concept that was to be driven by 24 to 500 kW solid state amplifiers. Only the RGDTL was built, but it still required the development of appropriate drive loops of the type shown in Fig. 5. These units connect to standard 6 1/8 in. coaxial transmission line and are cut for a nominal 425 MHz operating frequency. They will operate with either alumina or rexolite windows. To reduce multipactoring, the vacuum side of the windows was titanium sputtered and the metallic surfaces were titanium nitrided using the process described in Ref. 5.

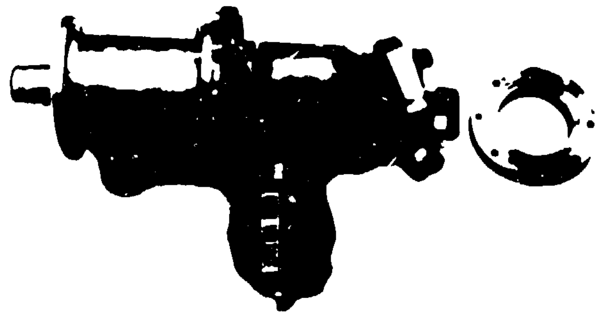

Fig. 5. The 1-MW 425-MHz rf drive loop.

A complete description of the drive-loop development program is given in Ref. 6.

Instrumented Drift Tubes

Beyond 5 MeV, 425-MHz drift tubes are physically large enough to allow splitting the quadrupole into two equal segments and placing a fast rf diagnostic probe between the segments as shown in Fig. 6. By using such instrumented drift tubes along the beamline, diagnostic information such as beam current, beam position, micropulse profile, and energy can be determined. In addition, splitting the quads increases the granularity of the magnetic center misalignments. This increase in granularity has been shown to reduce transverse-emittance growth. Originally, over 20 instrumented drift tubes were intended for the seven-tank linac system. Only two instrumented drift tubes were actually fabricated, each using two 1.27-cm-long Nd-Fe-B PMQs as part of the RGDTL development program.

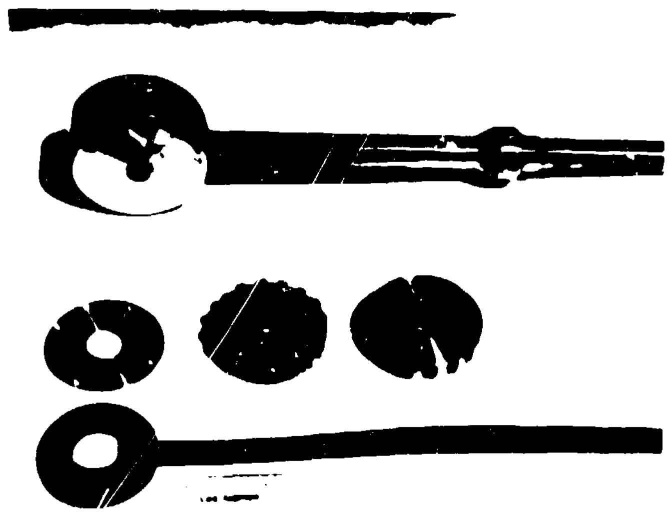

Fig. 6. Drift tube with split quad and strip line probe.

Rotary Tuner

A new type of frequency tuner was developed for the RGDTL as an experimental replacement for the standard slug tuners. This device utilizes a rotary paddle for smooth, linear, servolike motion. The unit is shown in Fig. 7. It connects into the tank through a small diameter port that shields the ferrofluidic seal from tank wall currents. Though the unit can operate with a servomotor, operation with a stepping motor provides a more convenient interface with computer controls.

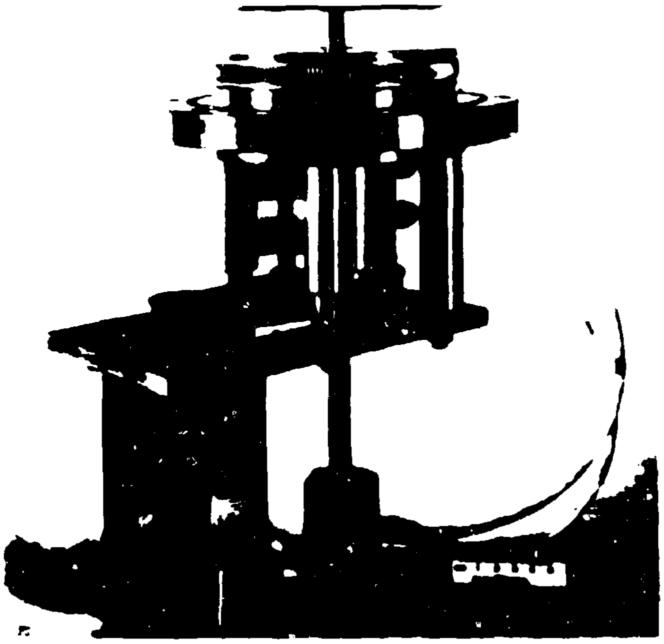

Fig. 7. Rotary tuner.

Conclusions

The RGDTL is a machine that achieves several important goals. It matches the low-accelerating gradient of the RFQ to a high-gradient linac in which it is easier to control longitudinal beam emittance. To meet these [illegible] demonstrated. Finally, the RGDTL has shown that compact accelerators can be designed by using fast ramps of the type described.

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