DESIGN AND CONSTRUCTION OF A 425-MHz CRYOGENIC (20 K) TWO-CELL DTL SPARKER*

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Abstract

A two-cell 425-MHz drift-tube linac (DTL) "sparker" for operation at 20 K has been designed and constructed to operate at >2 Kilpatrick accelerating voltage while transporting an H^- 5-MeV beam at currents up to 100 mA. Permanent-magnet quadrupole (PMQ) assemblies are installed in the input/output beam-transport system and in the cryogenically cooled cavity drift-tube and two half-cells. The cavity, cooled by a 700-W cold-helium gas refrigerator, is mounted inside a superinsulated high-vacuum chamber that is evacuated by a 360-ℓ/s turbomolecular vacuum-pump system. The cavity components (slug tuner, post coupler, drive loop) are fabricated from electropolished OFHC possessing a residual resistivity ratio of >200. The rf contacts for the cavity end walls are copper-plated Inconel X-750 C-seals.[1] The drift-tube stem, post-coupler stem, and slug tuner use gold-plated beryllium/copper Multilam[2] bands rf contacts. Initial experiments at 20 K have shown a cavity Q enhancement of 4-5. The experimental program includes characterization of the rf cavity beam loading, engineering design and construction, and thermal system response.

Introduction

A cryogenic DTL (CDTL) sparker has been developed that will operate at 20 K on the Los Alamos National Laboratory Accelerator Test Stand (ATS). The device, a two-cell DTL cavity (with a 2 βλ input and 1 βλ output, water-cooled beam-transport section) will accept the output beam of the 5-MeV, H^- ATS DTL. The 20-K drift-tube cavity parameters are based upon the final drift-tube cell of the 5-MeV ATS DTL and a similar two-cell ambient temperature sparker both of which permit comparison of rf and beam-loading characteristics.

The objectives for constructing this test device are several. The principal one is to investigate the rf stability of a highly beam-loaded cryogenic accelerating structure. Corollary objectives are investigation of the Q enhancement of an operating beam-loaded structure, investigating of practical engineering features necessary for design of a cryogenic accelerator, and measurement of surface electric field limits achievable at cryogenic temperatures.

The two-cell sparker assembly longitudinal cross section is shown in Fig. 1. The principal features of this system are the cold-helium gas-cooled two-cell rf cavity, the superinsulated vacuum envelope/cryostat, a 2 βλ PMQ input beam transport and 1 βλ PMQ output beam transport both of which are water-cooled, cold-helium gas manifolding and valves to permit flow balancing of the three, parallel flow path, helium-cooled zones, a turbomolecular vacuum pump for evacuation of the cryostat and cavity, and a beamline mounting and alignment support stand for stand-alone or ATS beamline operation. Also shown in Fig. 1 is the stepper-motor-driven, linear-actuator slug tuner and manually adjustable post coupler, both of which are cooled with cold-helium gas.

Figure 2 shows the detailed configuration of the cryogenic rf cavity. In this cross section, the cryogenically cooled PMQ end-wall half-cells and the PMQ drift-tube end wall C-seal rf contacts, drift-tube stem Multilam contact,

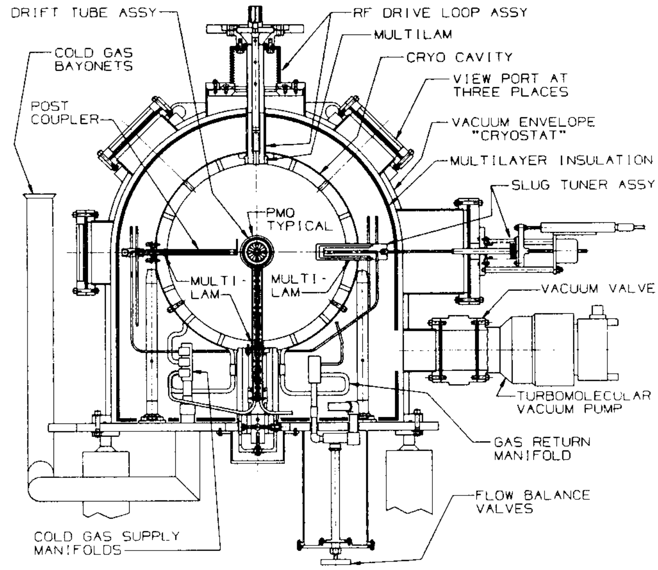

Fig. 1. Transverse cross section.

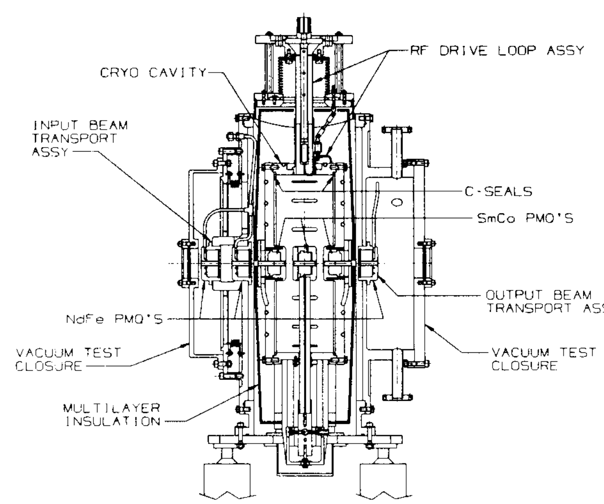

Fig. 2. Longitudinal cross section.

and cryogenically cooled drive loop are shown. Type-T, miniature, stainless-steel-sheathed thermocouples and miniature semiconductor diodes[3] are installed at several locations on the rf cavity and the cold-helium gas distribution piping inside the cryostat. Figure 3 (the sparker assembly) and Fig. 4 (the rf cavity installed on the assembly base plate) show the features of the device as it has been assembled for operation.

Design Features

Features of the sparker design that are specifically noted are (a) the rf contacts, (b) PMQ assemblies, (c) drift-tube assembly, (d) slug-tuner installation, (e) drive-loop assembly post coupler, (f) thermal insulation-vacuum cryostat system, (g) helium cold-gas heat-transfer system, and (h) rf-cavity, mechanical thermal-isolation devices.

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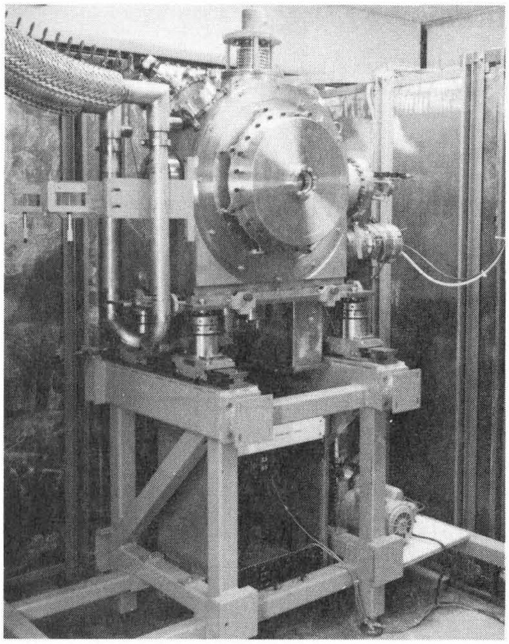

Fig. 3. CDTL in off-line test.

Two principal rf contact types are used in the cryogenic rf cavity: copper-plated, Inconel X-750, fully heat-treated, 1/4-in. free-height C-seals used between the copper end walls and the cylindrical side wall, and gold-plated beryllium/copper Multilam bands used in the internal gland grooves between the slug tuner, post coupler stem and drive loop, and the rf cavity penetrations. C-seals have been used in room-temperature rf contact structures at Los Alamos since 1981[4] where they were used for the rf contact on the ATS-RFQ vane base to cylindrical rf cavity. Although C-seals have been used in commercial and aerospace cryogenic applications,[5] this is the first known application of the C-seal to a high-power cryogenic rf structure. Multilam bands have been used in room-temperature rf structures at Los Alamos since 1983,[6] where they were used on the end-wall tuners of the ATS RFQ2. These devices have been used in several applications subsequently, the most recent device for which operational testing has been performed being the room-temperature two-cell DTL (RTDTL). The RTDTL uses C-seals at the rf cavity end wall to cylindrical side wall rf contact and Multilam bands at its drive loop to side wall, slug tuner and post coupler to side wall, and end wall to half-drift-tube rf contacts. The half-drift-tube to end wall Multilam contact has been operated at surface current levels up to 32 000 A/m, with some discharging of the rf contact area being observed after disassembly but not observable during operation. Typical dc current-carrying operation of these contacts as stated by the manufacturer are 5 900 A/m (150 A/in.) with short-circuit pulsed ratings of as much as 29 500 A/m (7 500 A/in.) permissible under experimentally determined conditions.

PMQ assemblies used in this assembly are of two separate designs. The assemblies used in the cryogenic rf cavity are of the same $SmCo_5$, 16-segment type used in the 5-MeV flat-gradient ATS-DTL. These magnets are believed to be satisfactory for operation at 20 K, based upon brief in-house testing of physical and magnet stability to cryogenic thermal cycling from ambient to 77 K. The room-temperature PMQs are the same 16-segment NdFe assemblies as those used in the recently completed Los Alamos RGDTL; these PMQs are not believed to be magnetically stable at cryogenic temperatures.

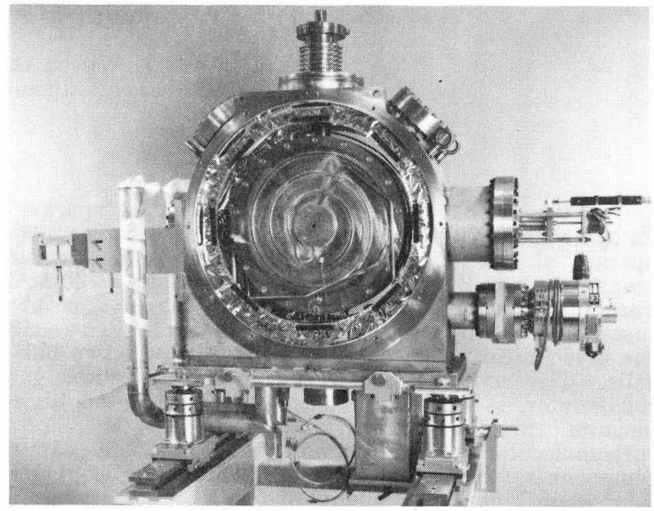

Fig. 4. CDTL Assemble - cryostat end closure removed.

The drift-tube assembly shown in Fig. 2 is a copper assembly, which contains one of the $SmCo_5$ PMQs, a single-pass cold-helium gas coolant channel, instrument holes in the drift tube and stem for two stainless-steel-sheathed, Type-T thermocouples and the required helium gas inlet and outlet piping. The assembly of this drift tube required a multistep process involving vacuum furnace brazing of the helium flow channels and drift-tube stem, and electron beam welding of a solid-copper end cap after installation of the PMQ. Detail design features of the DTL assembly by the fabrication contractors led to an assembly that provided a copper bore tube not sealed to the drift-tube body on one end. A defect in the brazed section of the drift-tube helium-coolant passage caused leaking of a small amount of helium into the unsealed bore tube of the drift tube; this leak, while unwanted, permits the uncooled system to operate at about 2-3 x 10^{-6} torr and 1-2 x 10^{-6} torr at 20 K, a condition we believe will not seriously affect the experimental plan for the CDTL. This experience, however, clearly demonstrates the hazard of using brazed assemblies in an area where braze leakage can cause unwanted gas sources.

The slug tuner installation shown in Fig. 2, shows the slug and its stepper-motor, linear-actuator drive. Included in this installation are thrust reaction struts to decouple the linear-actuation force of slug movement through its Multilam band from the rf cavity support legs, thereby preventing misalignment of the rf cavity from the beam-transport line of sight. Calibration of the slug tuner indicates a total frequency shift of ~ 400-kHz with a 228-kHz/in. sensitivity.

The reaction struts, although intended for stabilizing the rf cavity during slug tuner movement, are also being used to align the rf cavity with the beam transport along its horizontal plane. The struts, made of 6Al-4V Ti, mounted to G-10 fiber-glass, epoxy-resin thermally insulating pads, permit proper horizontal positioning at 20 K.

The 50-Ω coaxial drive-loop assembly has the difficult task of supplying all rf drive to the rf cavity at 20 K, providing thermal insulation to the 20-K assembly and linear insertion of up to 1 in. into the cavity, while providing a low-loss electrical rf contact and a high vacuum interface inside and outside of its coaxial cable interface with the CDTL. These features shown on Figs. 1 and 2 are provided through the use of a bellows-sealed outer wall, a ceramic inner coaxial-cable vacuum window, and a copper-plated stainless steel inner conductor over which a cold-helium gas-cooled thimble/drive loop slides on

Multilam bands . The sliding thimble is driven by a screw mechanism with a two-U-joint, sliding-shaft arrangement through an O-ring sealed, rotary vacuum gland. Multilam bands are also used between the drive loop and its housing as well as in the housing to cylindrical side-wall penetration of the cavity. The drive "loop" structure is formed from the helium-gas, inlet/outlet tubing that has been flattened and brazed with AWS BAg8 into a flat bar of 1/4 in. thickness by 1/2 in. width. Initial operations of the CDTL have shown the drive-loop, linear-insertion mechanism to lock up below about 100 K. There is also concern that the contractors use of BAg8 braze material in this area may lead to unexpected losses at 20 K where Q enhancement is one of the hoped for benefits of 20-K operation.

The post coupler, used in the DTLs from which the CDTL design is derived, is of the resonant type. Although not needed in this two-cell device for stabilization, the post coupler will be required in larger DTLs of this type. It has therefore been included in the CDTL to evaluate its power-dissipation characteristics. It will be retracted in most experiments planned for the CDTL. The post-coupler stem has its own cold-helium gas inlet and outlet piping loop. A Multilam band is also provided as a contact between the stem and the cavity side wall.

The vacuum cryostat is provided by a stainless steel envelope and base assembly through which all electrical, coolant, and mechanical interfaces are made with the cryo rf cavity and the CDTL with other devices. Alignments features are included to allow aligning of the input and output beam transport PMQs with the cryo cavity and aligning of the CDTL assembly with the external ATS beamline. The envelope further provides the mounting and valving interface for the 360 ℓ/s turbomolecular vacuum pump, and superinsulation bats made of 15 layers of double-aluminized low-outgassing rate KAPTON[7] film and nylon interlayer netting separators. The cold-helium distribution piping manifolds, provided with flow-balancing valves on each of the three cooling loops to the cryo cavity, are inside the cryostat envelope. Inlet and outlet cold-helium connection to the cryogenic assembly is provided through vacuum-insulated, female bayonet connectors welded to the cryostat base plate. The base plate also provides electrical feedthroughs for the multiple thermocouple and semiconductor diode temperature sensors as well as two cavity pick-up loops mounted on the cryo cavity side wall. The rf cavity evacuation by the cryostat turbomolecular vacuum pump is provided by 12 slots, 1 cm wide and 6 cm long in the rf cavity side wall.

The thermal isolation cavity mounting supports are constructed of 3 Al-2.5V Ti 1-in.-diam thin wall tubes mounted to the cryostat base plate. Screw adjustments on each end of the four mounting supports and the slug-tuner reaction struts permit aligning the cavity with the input/output beam-transport section. Initial thermal cycling from ambient to cryo temperatures exhibits good horizontal position control and less than expected vertical control. Additional tests are required to characterize the mounting system.

Construction

Construction of the CDTL and its objectives of demonstrating the characteristics expected of a highly beam-loaded 20-K rf structure has clearly revealed many problems to be solved in a realistic full-configuration accelerator. Among the more difficult features encountered are (a) quality of the cryo rf cavity materials or coatings, (b) machining schedules and processes to be used in producing the required components, (c) surface finishing of the required components by using precision machine finishing, abrasive polishing, electrochemical polishing, and (d) electron beam/TIG welding and/or brazing of components when required.

Although all of these areas are important, it is believed that the quality of the rf component surface materials is of primary importance to the successful realization of high-performance cryogenic accelerators. A number of materials such as pure aluminum and beryllium appear to possess potentially useful properties; however, copper appears to possess the desired properties to the greatest extent. Copper can be used in the form of solid-copper structures or copper coatings if sufficient control of the physical properties can be realized. In the CDTL project, it was concluded that the use of solid copper was the best form when factors of availability, process development maturity, cost, etc., were evaluated. The copper chosen for this device is a high-purity oxygen-free type[8] and is expected to demonstrate a residual resistivity ratio (RRR) of 200 or greater. Realization of an RRR of 200 or greater requires control of all contaminants to produce total impurities of less than 32 ppm with particular care necessary to control iron to as low a level as possible but not more than 5-7 ppm.

It has further been observed that the character of the finished component surface can have significant effect upon the losses to be expected in the copper at rf accelerator frequencies, i.e., >400 MHz.[9] These effects are minimized by making the surfaces of the rf components as smooth as possible with minimum metal "working" of the surface. Chambers, Ref. 9, has concluded that use of stabilized electropolishing of very pure, smooth-copper components produces the highest performance rf structures. The CDTL components were machined with common machining schedules using precision numerically controlled machines, nonsulfur-containing machine coolants, and carbide cutting tools. Commonly used, high feed-rate roughing cuts followed by low feed-rate finish cuts were used to produce surface finishes of approximately 32-microinch quality. These components were then assembled by vacuum furnace brazing with AWS BAg8 paste to form the major components of the rf cavity. These processes were then followed by electropolishing in a phosphoric-acid/chromic-acid water bath[10] consistent with prior experience at Los Alamos and as reported in Ref. 9. Visually, the surface finishes appear to be significantly smoother (< 2 microinch) than before electropolishing, but show evidence of surface anomalies not previously observed in other electropolished rf structure components. It is believed that the high feed rates used in the rough machining cuts have produced surface "working" that was not removed by the electropolishing procedure although the surface is smoother than that left by the as-machined finish cuts. It is likely that abrasive polishing before electropolishing would have improved the surface smoothness; however, it is not likely that the apparent anomalies in the surface material would be appreciably altered. The effect the surface has upon the operation of the CDTL is yet to be determined.

Electron beam and TIG welding processes were used very successfully in assembling the solid-copper rf components and copper piping of the cold-helium gas system, respectively. The drift-tube assembly made use of a precision electron beam apparatus to attach the face of the drift tube to the drift-tube body after installation of the PMQ. The use of electron beam welding for solid copper, not a commonly accepted joining practice, has been previously developed in the fabrication of the ATS buncher.[11] In this work, equally successful, electron beam welding was used by the contractors; electron beam conditions used were ~115 kV, 0.015 A, 0.030-in.-diam beam at required weld speeds to produce a weld penetration of ~0.250 in. TIG welding, also not commonly used for copper joining, was used in this work to join the thin-wall, small-diameter copper tubes of the helium gas distribution manifold piping.

The brazing processes used in this project produced results of lower acceptability. In this project, the use of CuSil (AWS BAg8) braze paste to bond copper coolant tubing to the rf cavity for thermal contact purposes was adequate; however, the resulting braze was very porous. When the component was subsequently immersed in the electropolish bath required for final finishing of the rf surface, the porous braze material absorbed the liquid chemicals that cannot be removed. The effects of this problem upon CDTL operation has not yet been evaluated. It has been possible to evacuate the CDTL to a vacuum level of $<1 \times 10^{-6}$ torr, which is believed acceptable for beam operation. It is further believed that any residual outgassing from this source will be reduced to insignificance when the cryo cavity is cooled to operating temperature. Other artifacts of the brazed assemblies such as the internal drift-tube cold-helium gas leak may not be as easily accepted. The effect of these brazing problems will be revealed as the experimental plan proceeds.

Refrigeration

Cooling of the rf cavity is provided by a cold-helium gas refrigerator that supplies 30 g/s of 20-K helium at 225 psi. The design heat-removal capacity under these conditions is 700 W. Analysis of the rf cavity design indicates that an accelerating gradient of 8 MV/m, at peak electric field of 45 MV/m in the drift-tube gaps (~2.3 times the Kilpatrick voltage) will produce cavity power losses of 520 W at 1% duty factor (10-Hz, 1-ms pulse width) with ~100 W additional losses because of thermal conduction and radiation heat gain in the cryostat structure and cold-helium gas transport piping. It therefore appears that the refrigerator's 700-W cooling capacity can easily accommodate the 620-W maximum power losses, thereby permitting investigation of a wide parameter space of accelerating structure operating conditions. The duty factor and power level "knobs" will permit easy establishment of operating conditions.

Conclusions

The CDTL that has been described will be operated off-beamline to characterize its rf power parameters. After off-line measurements have been completed and all functional controls and devices have been qualified, the CDTL will be installed on the ATS beamline for beam-loading measurements. Design and construction of this device has provided an understanding of important fabrication practices and necessary design features for a cryogenic rf structure. Although several of the features of the CDTL are not yet fully functional, all features appear to be correctable, for example, the movable drive loop. Fabrication processes have been used that appear to require additional development. Of specific importance are believed to be (1) improvement in the machining procedures to minimize the depth of "worked" material at the surface; (2) optimization of the electropolish bath chemistry and process variables of bath temperature, current density/voltage, and polishing time required to produce an acceptable rf surface; (3) an improved surface inspection procedure for in-process monitoring of the rf surface being produced; and (4) correction of the brazing procedure used. High-power rf operation of the CDTL will be necessary to evaluate the high voltage breakdown and Q enhancement resulting from the procedures used in this project.

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