THE PROS AND CONS OF CRYOGENIC ACCELERATORS: AN ENGINEERING POINT OF VIEW*

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Abstract

The design of cryogenic linacs is a challenging engineering task; however, significant improvements in accelerator performance are possible. Resistive power losses may be reduced by a factor of four or greater. Greater flexibility is possible in thermal management as a result of substantial increases in thermal conductivity for certain materials Radio frequency structures may be an order of magnitude more stable in terms of frequency shifts due to thermal transients resulting from very small coefficients of thermal expansion at cryogenic temperatures. Significant engineering problems must be addressed, such as the design of effective rf contacts that will not be affected by thermal cycling and the design of cryogenic mechanisms and dynamic components, such as frequency tuners, that operate reliably at cryogenic operating temperatures. The areas of high-power sparking and multipactoring have not yet been experimentally addressed. Both Los Alamos, Grumman Aerospace Corporation, and Boeing Corporation have built or are building and testing cryogenic accelerator structures. This paper will review the advances made in cryogenic technology applied to radio frequency quadrupole (RFQ) and drift tube linac (DTL) structures and will discuss the advantages and engineering challenges that these linacs present.

INTRODUCTION

Los Alamos National Laboratory and Grumman Aerospace Corporation are designing cryogenic accelerators for the Neutral Particle Beam (NPB) Program. Figure 1 is a photograph of the radio frequency quadrupole (RFQ) used in the Ground Test Accelerator (GTA) being designed by Los Alamos. The RFQ is designed to accelerate a proton beam from 35 KeV to 2.5 MeV and operates at 35 K. The GTA RFQ is but one element in a 24-MeV accelerator which has been designed for continuous wave (CW) operation but will only operate at a 2% duty factor to conserve rf power. The CW deuterium demonstrator (CWDD) being designed by Grumman is an accelerator that will accelerate a deuteron beam to 7.54 MeV under CW conditions at cryogenic temperatures. The design goal for these two cryogenic accelerators is to achieve higher levels of performance and efficiency in rf accelerators.

Cryogenic operation of rf accelerators offers the potential for higher rf efficiency and more stable operation in rf structures. The initial motivation for the design of cryogenic accelerators for the NPB program was the potential for lower rf power consumption resulting from smaller copper losses because of increased electrical conductivity of accelerator structures at cryogenic temperatures. Liquid oxygen and liquid hydrogen cryogens will be used on the NPB platform as an energy source to drive prime movers. The availability of refrigeration capacity in the form of cryogens provided the premise upon which to evaluate the potential gains of operating an NPB accelerator at cryogenic temperatures. Substantial gains in thermal conductivity, in addition to increased electrical conductivity, are possible at cryogenic temperatures and will allow much simpler cooling schemes to be employed in rf structures; in some cases, these cooling schemes provided the only viable means for handling the very high, local heat fluxes produced in these very compact high-power devices.

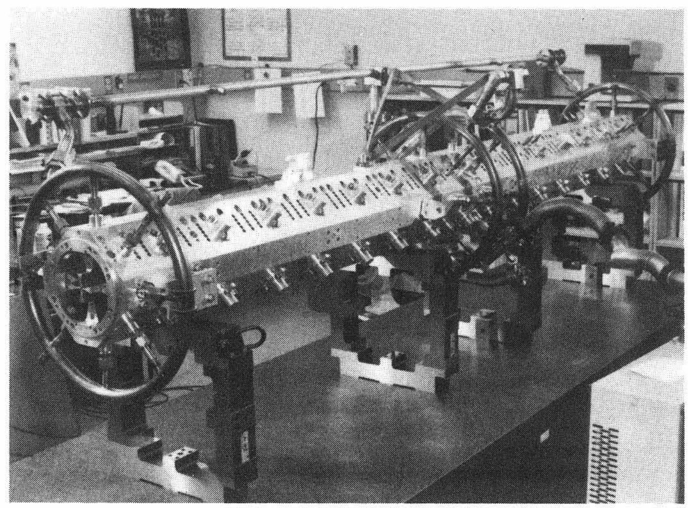

Figure 1 - Radio Frequency Quadrupole

Defining cryogenic operation for these accelerators is important. The operating temperature range of the accelerator is between 20 and 35 K. The rf structures are not superconducting; however, rf conductivity in the structures can increase by factors up to six at these temperatures. Because the structures are not superconducting, they are not subject to the phenomena of quenching, which can produce dramatic changes in resistive heat loads in superconducting structures. However, a significant nonlinearity in the temperature-dependent electrical conductivity of these cryogenic structures does exist and must be considered in the design. The GTA is designed to be cooled by either gaseous helium at a pressure of 16 bars for a 2% duty cycle or by supercritical hydrogen at a pressure of 22 bars for CW operation. The CWDD is designed to be cooled by neon.

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PROS AND CONS OF CRYOGENIC OPERATION

Cryogenic operation of rf cavities offers the opportunity to take advantage of higher rf conductivity, higher thermal conductivity, and lower thermal expansion in the structure. The rf power loss that normally occurs as a result of resistive losses in the cavity can be reduced by 75%. The efficiency of an rf cavity is most easily measured in terms of its quality or Q. The ratio of Q for a cavity at cryogenic temperatures to the ratio of Q for a cavity at room temperature is known as the Q factor and can be as high as six in a pillbox rf cavity with no joints. In cavities that are representative of actual rf structures incorporating rf joints, Q factors of four have been achieved. The temperature dependence of the Q factor is clearly illustrated in Fig. 2. Testing of various materials and surface-material conditions has shown that the rf conductivity is strongly affected by the surface preparation of the cavity, as well as the surface-material condition at rf joints. Machining techniques, heat treatment, and surface impurities strongly influence the rf conductivity at cryogenic temperatures. Eliminating local work hardening of the surface to maintain high rf conductivity is extremely important; this can be accomplished by minimizing the depth of machining cuts in the surface of the cavity and by using chemical or electrochemical polishing techniques to remove surface-hardened material. The performance of rf joints is strongly dependent on the surface condition of the materials in the joints. We are currently evaluating the effect of various surface preparations on rf conductivity across rf joints as well as evaluating the long-term effects of thermal cycling at rf joints.

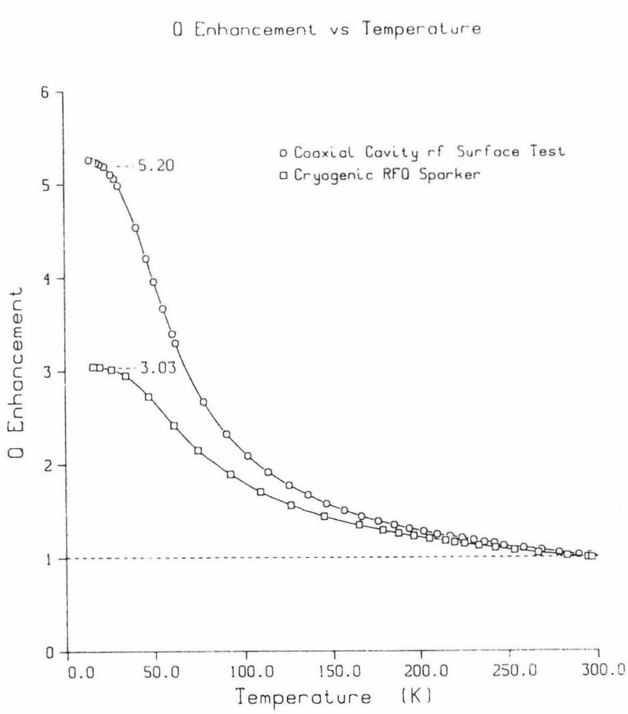

Figure 2 - Cryogenic Cavity Q Enhancement.

The stability of cryogenic structures can be increased by an order of magnitude at cryogenic temperature because of much smaller coefficients of thermal expansion at these temperatures. The temperature-dependent effect of the coefficient of thermal expansion for AL 2219 and OFE copper can be seen in Fig. 3. Not only does the coefficient of thermal expansion become much smaller at lower temperatures, but also the slope of the coefficient of thermal expansion as a function of temperature becomes much flatter. These effects combine to produce much smaller thermal strains at cryogenic temperatures as a result of changes in power deposition on cavity surfaces. In turn, smaller cavity frequency shifts are produced, and a smaller cavity tuner range is required. The tuning rates of these tuners are also substantially lower because of the very flat slope of the temperature dependent coefficient of thermal expansion at cryogenic temperatures. This effect on rf cavity frequency response can be seen in Fig. 4: the flows are balanced in the major vane to produce a frequency response to thermal transients that results in the return of the cavity to its design frequency. This is accomplished by placing cooling channels in a manner to produce thermal gradients that result in off-setting changes in the inductance and capacitance of the cavity. The room temperature RFQ cavity produces a frequency shift ten times greater than the cavity operating at 35 K as a result of a step function thermal transient. The time constant for the cavity operating at 35 K is also much shorter than for the room temperature cavity. The RFQ cavity operating at 35 K requires a much smaller dynamic tuning range than a room temperature cavity and will return to its principal frequency more rapidly if dynamic tuners malfunction. When dynamic tuners are used to maintain the cavity on its design frequency during thermal transients, the rate at which the tuners must compensate for frequency shifts is much less in the cavity at 25 K. The maximum required tuning rate in the cryogenic cavity is 4 kH_z as compared with 30 kH_z in the room temperature cavity. This fact indicates that smaller, slower-moving tuners may be used in the cryogenic cavity.

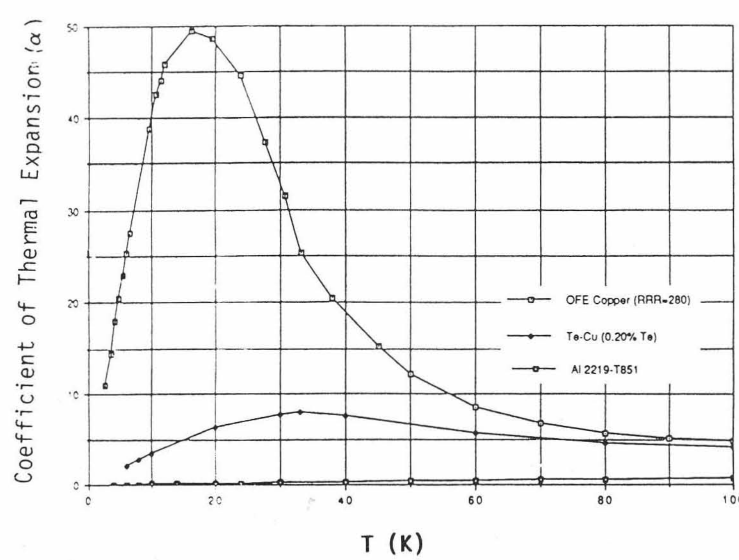

Figure 3 - Thermal Conductivity Comparison

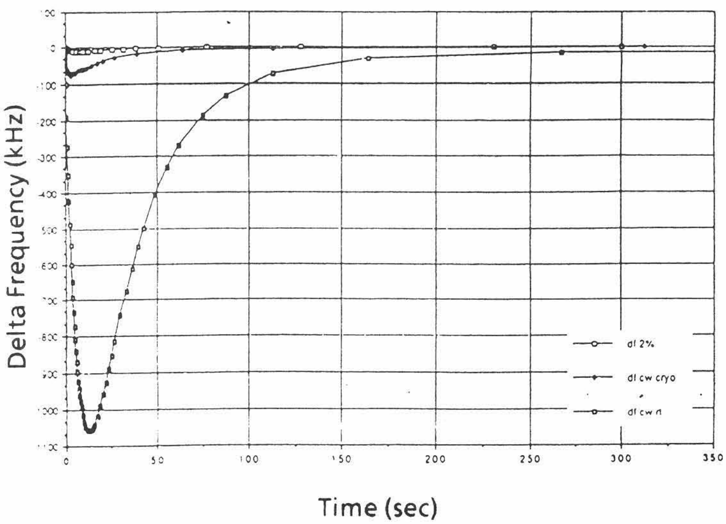

Figure 4 - Transient Frequency Response

The thermal conductivity of OFE copper increases by a factor of 60 at cryogenic operating temperatures. This substantial increase in thermal conductivity allows for increased flexibility in the design of cooling schemes for rf structures. Heat transfer by thermal conduction can play a predominant role in reducing the number of cooling channels and the size of cooling channels required within the structure. Increased thermal conductivity can also result in lower thermal gradients and a more uniform temperature distribution within the structure. High thermal conductivity provides a mechanism to dissipate locally high thermal fluxes to prevent thermal overloads and local melting of the structures.

Cryogenic operation of accelerator structures does result in significant problems. Refrigeration capacity is not an issue with NPB accelerators,because of the availability of cryogens on the platform; it is, however, clearly an important consideration in other applications. The decrease in rf power consumption does not offset the increase in power required for the refrigeration system. Other benefits to the performance of the structure, such as stability, cooling simplicity, and robustness, are difficult to compare in an absolute sense but will become obvious with operational experience. The alignment of cryogenically cooled structures is difficult to accomplish and predict a priori, because thermal gradients and temperature fields must be accurately understood ahead-of-time to predict the location of cryogenic components at operating temperatures. Direct measurements of component alignment at cryogenic temperatures is also very difficult because the vacuum insulating envelope must be penetrated to make these measurements, and the instruments used to make the measurement may be affected by the thermal gradients themselves. Cryogenic accelerators will be exposed to multiple thermal cycles as a result of operation and maintenance. The long term stability of materials used in rf structures and the performance of rf joints over a significant number of cycles are not well understood in these temperature regimes. Substantial stresses may be induced as a result of temperature cycles between dissimilar materials necessary in the design of rf structures. These combined effects are not well understood at this time and continued research in these areas are necessary.

Accelerators require mechanisms for tuning and component alignment, and in the case of cryogenic accelerators, these mechanisms must frequently operate at cryogenic temperatures. Designing mechanisms to operate at cryogenic temperatures reliably is very difficult because of different coefficients of thermal expansion and thermal gradients in the many components that are required in the mechanism. These differences can produce interferences in bearings, rotating shafts, and gears, which,in turn, can result in binding and failure of the mechanism. Most mechanisms require lubricants in bearings and gears to operate reliably; the characterization and performance of lubricants in this temperature range is not well understood and continued research in this area is also necessary. Research is also necessary for some of the materials used in cryogenic accelerators. One example is the samarium cobalt in the permanent magnet quadrupoles (PMQs) used in the DTL portion of the accelerator. Preliminary research has indicated that the field strength of these magnets increases between 6 and 8% as a result of cryogenic cooling. Fully characterizing the reproducibility of this increase is necessary to accurately design the magnet. Other material properties such as the temperature-dependent conductivity of copper oxides that form at the interface of rf joints also need to be characterized. Little is known of the effect of cryogenic operation on the rf conditioning and multipactoring of cavities, as well as the maximum attainable fields in the cavities.

CONCLUSIONS

It is difficult to compare quantitatively the pros and cons of cryogenic acceleration until additional experience is gained in their operation. The design, construction, commissioning, and operation of cryogenic accelerators such as GTA and CWDD offer an important opportunity to evaluate both the pros and cons of cryogenic accelerator operation. We must document operation results and continue research in the areas of cryogenic accelerator design that are not well understood.