# THE DEVELOPMENT OF SMALL-SCALE QUADRUPOLES TO OPERATE AT 20 TO 50 K*

D. J. Liska, R. H. Kraus, R. D. Brown, and J. R. Cost
MS-H821, Los Alamos National Laboratory, Los Alamos, NM 87545


## Abstract

The development of cryogenically cooled, high-frequency linacs at Los Alamos necessitates that small quadrupoles be developed to operate inside the drift tubes at temperatures as low as 20 K. A program has been undertaken to procure some of these quads, designed to critical specifications, and to test them for field-gradient and harmonic-distortion changes when taken down to the 20- to 50-K operating range and cycled many times back to room temperature. In this application $SmCo_5$ and $Sm_2Co_{17}$ will be used. Both low-temperature operation and resistance to radiation damage are required of these critical components; therefore, the test program also involves exposure to high radiation fluxes in the Omega West reactor at Los Alamos, coupled with post-irradiation field tests.


## Drift-Tube Design

Post-coupler-stabilized drift-tube linacs (DTLs) are normally designed to an empirical, diametrical relationship:

$$0.225\lambda \le \frac{D-d}{2} \le 0.28\lambda , \qquad (1)$$

where D = tank diameter,
d = drift-tube diameter, and
$\lambda$ = free-space wavelength.

One of the proposed DTL designs at Los Alamos is an 850-MHz system intended to operate at 20 K. A typical tank diameter is 21.7 cm with a drift-tube diameter of only 4.1 cm. With these diameters, Eq. (1) reduces to the following at 850 MHz:

$$\frac{D-d}{2} = 0.249\lambda . \qquad (2)$$

A drawing of the drift tube with a quadrupole enclosed is shown in Fig. 1. Because the coolant is supercritical liquid hydrogen at 20 K, the drift-tube cooling channels must be able to sustain pressures > 20 atm. A minimum annealed-copper thickness of 1.5 mm is required as an overlay for the cooling channels so that sufficient hoop strength can be provided. With the dimensions shown in Fig. 1, the quadrupole diameter is only 3.3 cm. The quadrupole weight is approximately 106 g. Tiny quads of this nature are so expensive that we sometimes express their weight in carats (5 carats/g). The price tag on prototype models of such quads is $10 to $20 per carat.

Given the restrictions of the high-frequency drift-tube body, the maximal gradient-times-length impulse product for tapered pole tips can be derived as follows:

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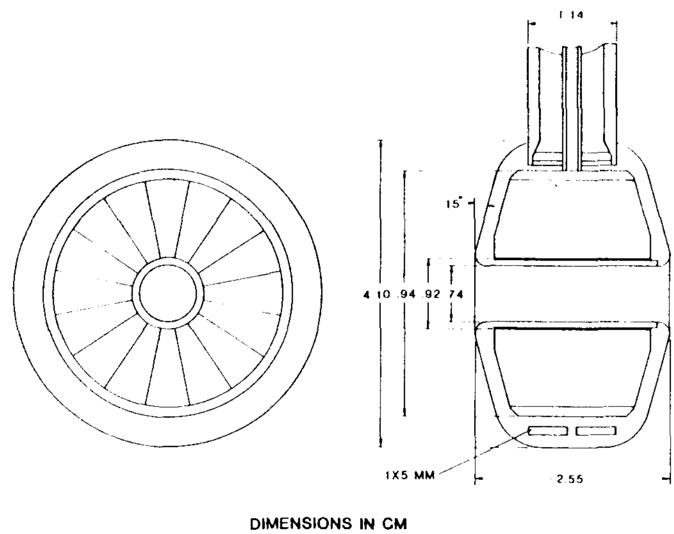


Fig. 1. Small-sized drift tubes and quadrupoles required at 850 MHz.

$$GL_e = 2B_r K_n \left| \left(L_I + \frac{R_M(L_I - L_O)}{(R_O - R_M)}\right)\left(\frac{1}{R_M} - \frac{1}{R_O}\right) - \frac{(L_I - L_O)}{(R_O - R_M)} \ln \frac{R_O}{R_M} + L_I\left(\frac{1}{R_I} - \frac{1}{R_M}\right)\right| . \qquad (3)$$

The terms $B_r$ and $K_n$ are defined according to K. Halbach[1]: $B_r$ equals remanent field; $K_n$ is a function of number of segments, 0.94 for 16 elements; $R_I$ is the inner radius of magnetic material; $R_M$ equals radius at shoulder; $R_O$ is outer radius of magnetic material; $L_I$ equals maximum length, and $L_O$ equals minimum length.

Equation (3) applies to many rare-earth quadrupoles. At Los Alamos we use neodymium iron boron ($Nd_2Fe_{14}B$) or samarium cobalt ($SmCo_5$ or $Sm_2Co_{17}$), all of which have high-remanent induction $B_r$. A typical $SmCo_5$ quad (having $B_r$ = 9.3 kG and the dimensions given in Fig. 1) will, by Eq. (3), generate a $GL_e$ product equal to 50.4 kG.

## Cryogenic Considerations

For reasons of improved structural stability, cooling effectiveness, and reduced rf surface resistivity, Los Alamos and other institutions are giving considerable attention to cryogenic cooling of accelerator structures. A convenient and inexpensive coolant is liquid hydrogen ($LH_2$ at 20 K), although referee coolants such as LNe or GHe will also permit operation in this temperature range. In a cryogenic DTL, the focusing quadrupoles contained in the drift-tube body are required to operate at the drift-tube temperature, namely 20 to 50 K. Not much is known about the behavior of quadrupole assemblies at such low temperatures. Some of the physical properties of rare-earth magnets have been measured, such as the coefficients of thermal expansion (CTE). Measurements done at Los Alamos are listed in Table I. Because the rare-earth magnetic material is made by a sintering process, anisotropic CTEs are inherent. The CTE in the direction of the intrinsic easy axis of magnetization differs significantly from the CTE perpendicular to the easy axis. This difference causes thermal distortions during cool down that can exceed the mechanical strength of the material when constrained, especially when cycled. A typical pole-tip segment is shown in Fig. 2 before and after cool down to 20 K. (Note: distortions are exaggerated.) It is not practical to try to predict these distortions and to machine the segments accordingly, because the distortions lie within grinding tolerances.

TABLE I. CTE MEASUREMENTS

| Material | Test Temp | Overall Coeff of Thermal Expansion Per K | | Theoretical |
|---|---|---|---|---|
| | | ↓ | → | |
| $SmCo_5$ | 33 $K_{avg}$ | $-1.11 \times 10^{-5}$ | $-1.48 \times 10^{-5}$ | - |
| Nd Fe | 33 $K_{avg}$ | $-0.36 \times 10^{-5}$ | $-0.42 \times 10^{-5}$ | - |
| DRL $SmCo_5$[a] | 213 K | $-0.7 \times 10^{-5}$ | $-1.3 \times 10^{-5}$ | - |
| Cu | 33 $K_{avg}$ | $0.92 \times 10^{-5}$ | | $1.09 \times 10^{-5}$ |

[a]Dayton Research Lab data, compliments of Herb Mildrum.

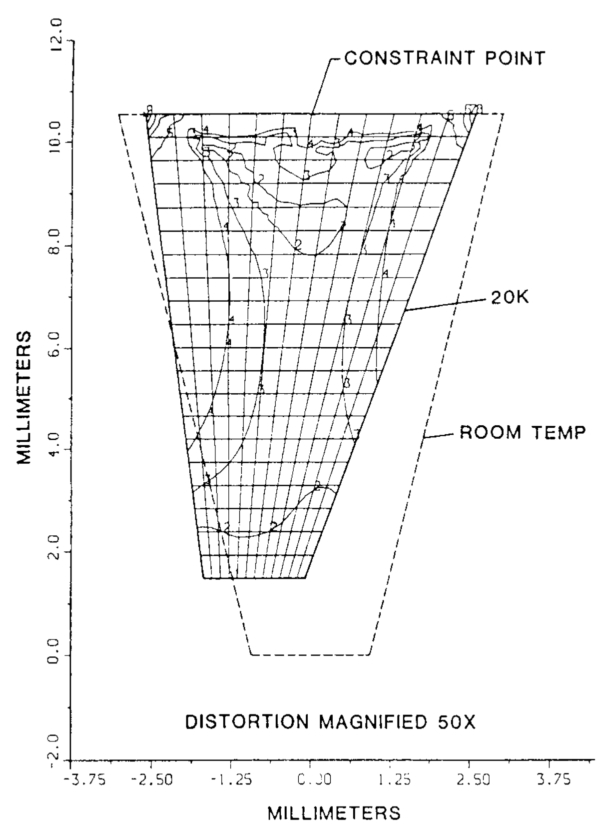


Fig. 2. Thermal distortion of Sm-Co quadrupole segment caused by difference in expansion coefficients.

At Los Alamos, we have taken the pragmatic approach to solving the problem of cryogenic quadrupoles. We have designed the quads to room temperature specifications and attempted to allow, where possible, for cryogenic and radiation effects in the design; however, we have not provided adjustable features, exotic machining, etc. We will test these quads at 20 K and cycle them. If they fail, we will have to engage in a major developmental program.

## Description of the Cryogenic Experiment - Status Report

From two magnet vendors, we are purchasing eight quadrupoles manufactured to Los Alamos specifications. Each vendor uses a different mechanical design for assembling his magnets and each has selected different grades of $SmCo_5$ and $Sm_2Co_{17}$ as part of the contract. Thus, we will have two different mechanical designs using several materials to test cryogenically and under radiation.

The tests will be performed in the Dewar shown in Fig. 3. The quadrupole under test is held between copper ballast blocks in a suspended housing that is cooled with gaseous helium. A search coil is inserted through the bore of the quad and rotated to measure the field gradient and harmonic content. The quadrupoles will be tested at room temperature to assure compliance with the specification. They will then be tested over the range of 20 to 50 K in the same setup to determine changes in gradient and harmonic distortion. Finally, they will be thermally cycled between room temperature and 20 K to observe drift in properties.

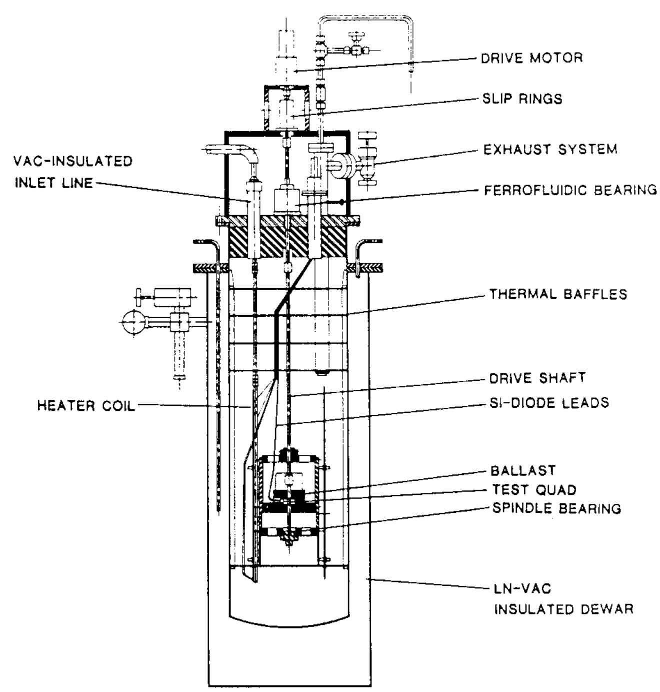


Fig. 3. Cryogenic test Dewar for full quadrupole testing at 20 K.

## Description of the Search Coil and Quad Mapping System

The drift-tube quadrupole's magnetic-measurement system consists of four basic components: the magnetic measurement coil, the drive motor and encoder, the magnet mounting fixture, and the cryogenic control system and cryostat. The magnetic measurement coil will measure the integrated gradient-length product, the harmonic content, and the magnetic center of a magnet. The coil is a state-of-the-art design incorporating electron-beam techniques to reduce the physical size of the coil to a minimum, which reduces measurement errors, particularly in the harmonic content. The design requires that the magnetic measurement coil must cycle in temperature with the magnet.

The drive system allows precise position information with every coil measurement at least 4000 times per rotation of the coil within the magnet. These data are used in the analysis of the magnet field strength and harmonic content. The magnet mounting fixture (Fig. 3) holds the DTL magnet in a precisely known and reproducible orientation to the position encoder to accurately determine the phase angles of the quadrupole field and the harmonics relative to the hardware. The cryostat and cryogenic controller provide precise temperature control, from 20 K to room temperature, in which to make the measurements of the DTL magnets.

### Permanent-Magnet Materials Studies - Status Report

The Ground Test Accelerator (GTA) under design at Los Alamos is dependent on the proper functioning of the DTL-focusing quadrupoles in cryogenic and high radiation environments. We have studied the behavior of various permanent magnet (PM) materials in cryogenic environments. Neodymium iron boron materials undergo a phase transition (around 77 K) in which the material loses approximately 10% of its magnetic field strength, and further degradation is observed below 40 K. Samarium-cobalt materials (both the 1-5 and 2-17 alloys) appear to suffer no field decrease between room temperature and 4 K. We observed a 3% to 4% increase in the measured magnetic-field strength of the 2-17 alloy at 4 K compared to room temperature.

Radiation studies have already shown that Sm-Co magnets can tolerate extremely large doses of gamma radiation without observable effect on the magnetic characteristics. Investigators at Jülich, however, have observed significant magnetic field degradation after exposure to large neutron fluences. Initial calculations indicate that DTL magnets may experience fluences of several times $10^{15}$ neutrons/cm$^2$ during a year of normal operation of the GTA accelerator. We have endeavored to determine the effects of radiation damage at these neutron doses and as a function of temperature.

Initial results[2] indicated that both alloys of Sm-Co magnets showed no measurable decrease of magnetic field after irradiation with up to a few times $10^{15}$ neutrons/cm$^2$. Further studies, however, indicated that this is only true for magnetic materials in the absence of an external bucking field. A bucking field is one in which an external field is applied to a piece of PM material causing the lines of magnetic flux to be oriented opposite to the alignment of the easy axis in the PM. We have calculated that portions of the DTL magnets will experience bucking fields of ~ 6 kG. When PM materials were irradiated in the presence of such a bucking field, significant degradation of the PM material was observed. At an irradiation temperature of −80°C, the decay ranged from <1% to ~ 9% for Sm-Co magnet materials irradiated to a fluence of $2 \times 10^{15}$ neutrons/cm$^2$. For the limited number of materials tested to date, it appears that there can be large differences in radiation-induced decay for PM materials of the same Sm-Co family that differ in energy product. At present, the most radiation-resistant materials are from the $Sm_2Co_{17}$ family. To check the effect of irradiation temperature, additional irradiations were run at temperatures as high as 150°C. These tests indicated that the decay was more rapid for a given material at higher temperatures.

These studies are in their infancy and are continuing. The design of the DTL magnets can tolerate essentially no degradation of the PM materials; thus it is crucial that we answer the questions raised by the preliminary data discussed above. We intend further detailed studies that will investigate the effects of neutron irradiation to Sm-Co permanent magnets as a function of magnet temperature, alloy, and manufacturer. Part of these studies will be devoted to radiation-damage tests on four duplicates of the quadrupoles being procured for cryogenic testing.

### References


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2. J. R. Cost, R. D. Brown, A. L. Giorgi, and J. T. Stanley, "Radiation Effects in Rare-Earth Permanent Magnets," Mat. Res. Soc. Symp. Proc. **96**, 321-327 (1987).