DESIGN AND TEST OF A SUPERCONDUCTING STRUCTURE FOR HIGH-VELOCITY IONS

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Abstract

Following the successful development of a niobium coaxial half-wave structure [1], we have designed, built and tested a new half-wave geometry: the spoke resonator. This geometry is better suited for high frequency resonators and for the acceleration of high velocity ions. The prototype cavity is a 2-gap structure resonating at 855 MHz, and optimized for particle velocity of 0.30 c. It is easier to manufacture than the coaxial half-wave resonator and the geometry can be straightforwardly extended to multigap designs. Rf-tests have been performed on this cavity both prior to and after high temperature annealing. An accelerating gradient of 7.2 MV/m (cw) and 7.8 MV/m (pulsed) was observed at 4.2 K. After annealing, a low power Q_0 of $1.2x10^8$ was observed with small Q degradation due to field emission at high accelerating fields.

Introduction

Most of the development work on superconducting resonators has been done in connection with high-energy electron accelerators [2-4] and heavy-ion boosters for electrostatic accelerators [5,6]. While the former have accelerated beams of several mA current, the latter have accelerated beams of only μA current. Our development efforts have concentrated on investigating superconducting structures for acceleration of high-current ion beams to high velocity.

The eigenfrequency-velocity space for heavy-ion acceleration using superconducting cavities spans a band from roughly f=50 MHz, $\beta=0.01$ to f=200 MHz, $\beta=0.2$ [7]. These low-velocity structures are typically based on a resonant line with the beam traversing the high-voltage region. We are extending this resonator class to higher frequencies and velocities. We have previously reported on the development of a coaxial quarter-wave structure at f=400 MHz which was optimized for $\beta_o=0.15$ [8], and a coaxial half-wave structure at f=355 MHz which was optimized for $\beta_o=0.12$ [1]. The present effort extends this work to higher frequency (855 MHz) with a geometry suitable for acceleration to velocities higher than 0.5c.

Resonator Design and Fabrication

A schematic of the spoke resonator appears in Figure 1. This resonator is electromagnetically similar to the coaxial half-wave resonator we tested earlier [1]. The fundamental electromagnetic mode is that of a half-wave TEM transmission line shorted at both ends with a voltage maximum at the center. Besides the similarity, however, the spoke geometry offers some advantages over the coaxial one. First it lends itself to close inspection of the inside surfaces until the last closure weld, and second it can be used as a building block to form multigap structures. The electromagnetic design was done using a combination of analytical modeling [9] and numerical modeling using SUPERFISH and MAFIA [10]. The axial electric field profile, shown in Figure 2, was measured by pulling a 3.2-mm-diameter brass bead along the beam axis [11]. Within the measurement error, the measured accelerating field profile agreed qualitatively and quantitatively with that obtained by calculation. The average (wall-to-wall) accelerating gradient calculated from this profile was $E_a = (13.25 \text{ MV/m})/J^{1/2}$. The associated plot of the energy gain versus particle velocity is given in Figure 3. It indicates that this cavity can efficiently accelerate ions of energy in the range 10-100 MeV/amu. The properties of the resonator are summarized in Table 1 below.

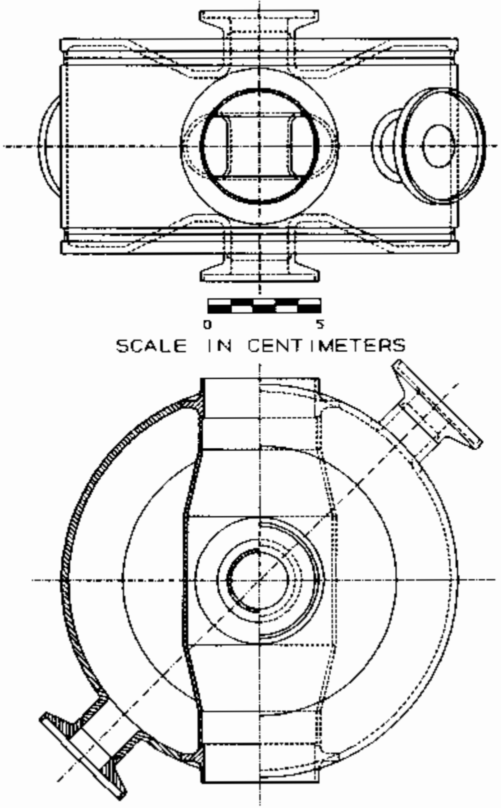


Fig. 1 855 MHz, $\beta_0=0.30$, 2-gap spoke resonator.

The inner and outer conductors were formed from 0.16-cm-thick and 0.32-cm-thick sheet niobium, respectively, of high RRR value (200-250). All welds were made with an electron-beam welder. There were no demountable joints in this cavity.

The Q_0 of the resonator is strongly influenced by the condition of the cavity surface. High RRR niobium is a relatively soft metal, therefore precautions were taken to minimize surface abrasion during the fabrication process. Niobium pieces were periodically anodized so that the surfaces could be inspected for inclusions of foreign material. Macroscopic defects were removed mechanically and the area was repaired by a combination of hand polishing and chemical etching.

Table 1. Properties of the half-wave spoke resonator.

Frequency	855	MHz
β_o	0.30	
Energy gain[a)]	60	kV
Peak surface E field[a)]	3.3	MV/m
Peak surface B field[a)]	78	G
Energy content[a)]	5.7	mJ
Geometrical factor QR_s	60	Ω

[a)] at an accelerating field of 1 MV/m.

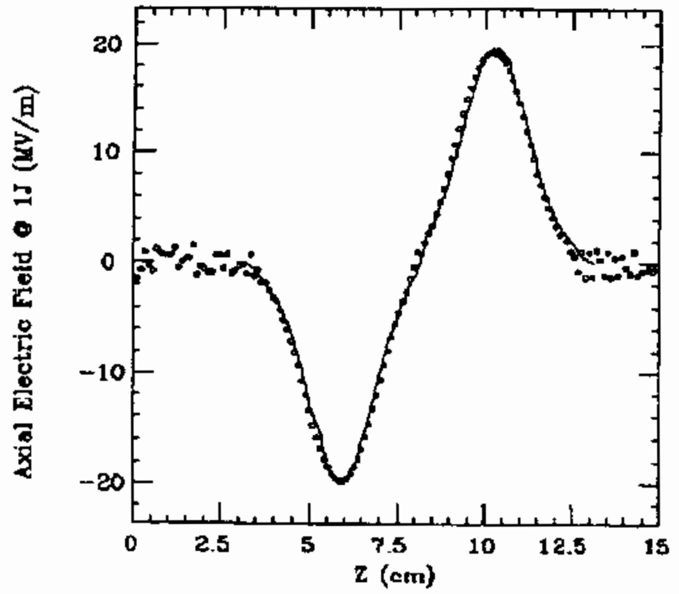


Fig. 2 Accelerating field of the spoke resonator at an energy content of 1 J. The circles are from the bead test and the solid line is from MAFIA.

The resonator components were chemically polished to remove damaged niobium surfaces resulting from mechanical stress introduced during the piece-forming steps. After the closure welds were completed a final chemical polish was performed to eliminate weld spatter and sharp edges which could not be identified by visual inspection. The chemical polishing procedure consisted of immersing the niobium piece in a 2:1:1 solution of H_3PO_4, HNO_3 and HF. Approximately 60 microns of Nb were removed by this process. The cavity was then rinsed in a 5% solution of H_2O_2 to remove insoluble niobium salts. This was followed by rinsing and storing the resonator in deionized water of semiconductor purity.

After the initial rf test the resonator was heat treated to remove possible hydrogen contamination introduced during the chemical polishing procedure. The annealing process also promotes the growth of large crystals on the niobium surface. The cavity was annealed at 1200 C under vacuum of 4×10^{-7} torr for approximately 13 hours (5 hours at full temperature).

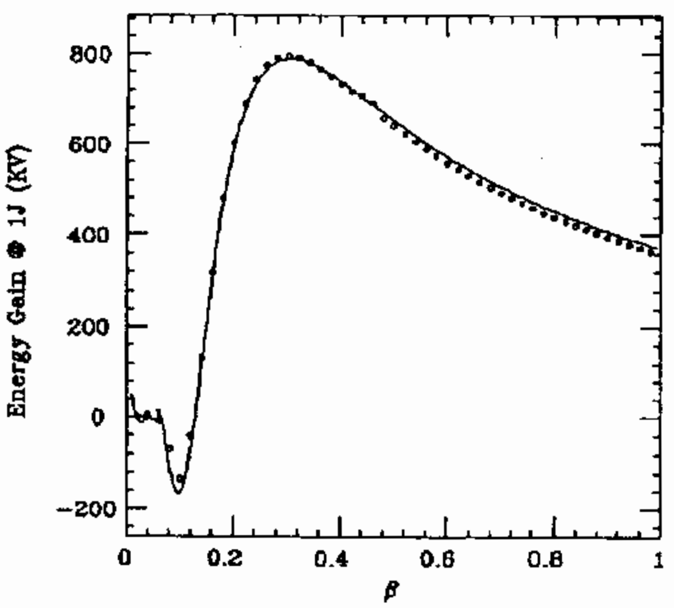


Fig. 3 Energy gain at an energy content of 1 J for various particle velocities. The circles are from the bead test and the solid line is from MAFIA.

Resonator Testing and Results

Because of its high frequency and the relatively low shunt impedance of low-velocity structures, this resonator is intended to be used at temperatures lower than 2.5 K. All the tests to date, however, have taken place at 4.2 K.

Rf power was coupled to the electric field within the resonator using a hermetically sealed variable coupler installed on a port on the outer conductor of the resonator. An rf pickup probe was installed on an opposing port. After installation in a LHe dewar, which for this experiment was surrounded by mu-metal to shield the resonator from ambient magnetic fields, the resonator was baked at 100 C for approximately 48 hours in a 10^{-6} torr vacuum. Effluent gases were monitored with an residual gas analyzer (RGA). With the resonator still at this temperature and pressure, the liquid nitrogen tank in the test dewar was then filled. The resonator cooled to 110 K in approximately 20 hours. The interior of the resonator remained evacuated during cool-down. The dewar was then filled with liquid helium beyond the top of the resonator, cooling the resonator to 4.2 K. All losses of power between the rf amplifier and the cavity were measured directly with a power meter after cool-down. A phase-locked loop was used to counter the effects of eigenfrequency noise due to ambient vibrations and microphonics. During the experiment, rf power was critically coupled to the cavity by suitably adjusting the position of the variable drive antenna. Multipacting levels appeared at low power when the cavity was first tested, however these processed out very rapidly.

A Q-curve was measured both before and after annealing of the resonator. As shown in Figure 4, the Q_0 improved by approximately 35% with annealing. In the rf-test performed after annealing the Q_0 varied from 1.2×10^8 at low rf field amplitude to 8.0×10^7 at the highest field achieved. A low level Q of 1.2×10^8 corresponds to a surface resistance of 0.5x

10^{-7} Ω which is in agreement with the expected value at 855 MHz and 4.2 K [12]. X-ray radiation was monitored along the beam line with a NaI(Tl) detector located outside the cryostat. The low x-ray intensity indicated that field emission was always low. Upon calibrating a NaI(Tl) photon detector and measuring the bremmstrahlung from the most energetic electrons, the average accelerating gradient was calculated and found to agree with the gradient calculated from power measurements and the energy content of the cavity.

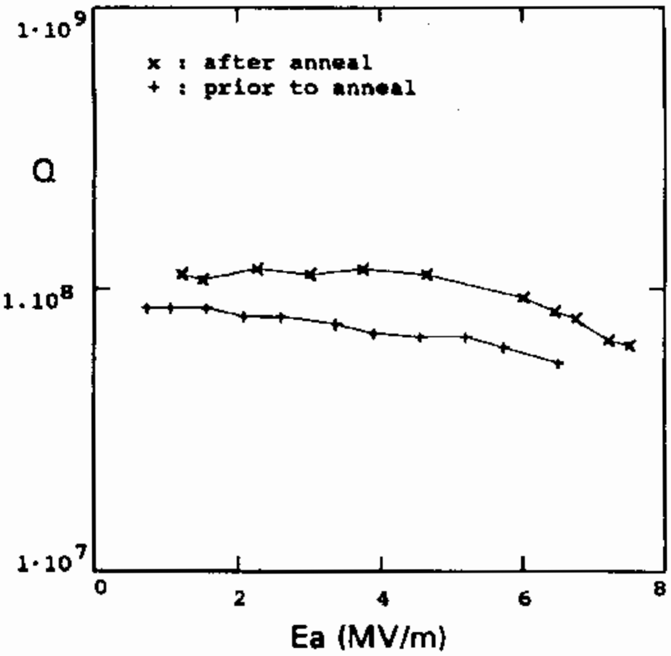
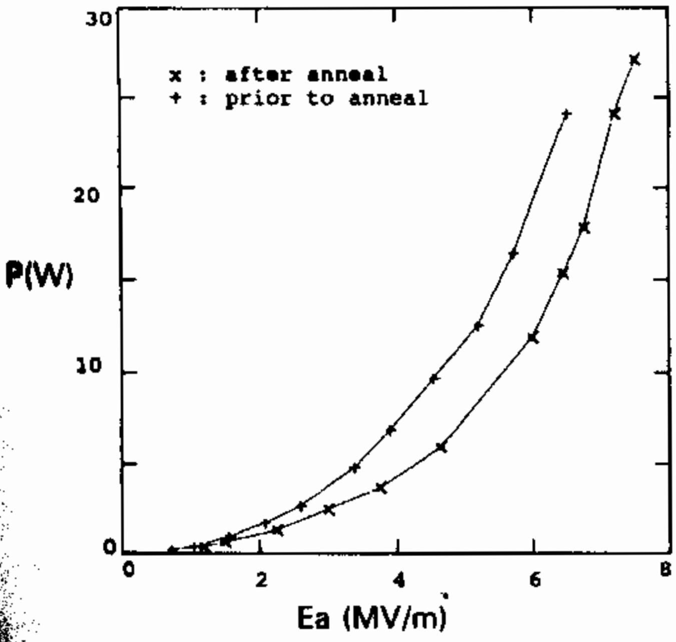


Fig. 4 Q-curve of the 855 MHz, β_0=0.30, 2-gap spoke resonator at 4.2 K.



5 Power dissipation in the 855 MHz, β_0=0.30, 2-gap spoke resonator at 4.2 K.

The power dissipated in the resonator during these tests is shown in Figure 5. An average cw accelerating gradient of 7.2 MV/m was achieved with 24 W of rf power input to the cavity after the resonator had been annealed. This accelerating gradient corresponds to an energy gain of 0.43 MV per unit charge. The associated peak surface electric and magnetic fields were approximately 24 MV/m and 560 G, respectively. Because electron emission was low, no attempt was made to condition the cavity with helium gas.

Conclusions

Prior to this work, the only superconducting structures which had been built and tested in the same range of frequency and velocity were a 720 MHz Alvarez structure and a Slotted Iris structure developed at Karlsruhe in the mid 1970 [13]. They achieved gradients of 3 and 5 MV/m respectively at 1.8 K. By contrast, our spoke resonator achieved an average cw accelerating gradients of 7.2 MV/m at 4.2 K, a limit set by the power dissipation in the cavity. The corresponding peak surface magnetic field was 560 G, which is well below the rf critical field of niobium. Thus, this geometry provides the potential for even higher gradients and will be further tested at lower temperature.

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