EXPERIMENTAL RESULTS IN SUPERCONDUCTING NIOBIUM RESONATORS FOR HIGH-BRIGHTNESS ION BEAM ACCELERATION

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Abstract

Two niobium resonant cavities for high-brightness ion beam acceleration have been constructed and tested. The first was based on a coaxial quarter-wave geometry and was optimized for phase velocity β_0=0.15. This cavity, which resonates at 400 MHz in the fundamental mode, operated at an average (wall-to-wall) accelerating gradient of 12.9 MV/m under continuous-wave (cw) fields. At this gradient, a cavity Q of 1.4×10^8 was measured. The second was based on a coaxial half-wave geometry and was optimized for β_0=0.12. This cavity, which resonates at 355 MHz in the fundamental mode, operated at an average accelerating gradient of 18.0 MV/m under cw fields. This is the highest average accelerating gradient achieved to date in low-velocity structures designed for cw operation. At this gradient, a cavity Q of 1.2×10^8 was measured.

I. Introduction

Most of the development work on superconducting cavities has been done in connection with high-energy electron accelerators and heavy-ion boosters for electrostatic accelerators.[1-3] While the former have accelerated beams of several mA current, the latter have accelerated beams of only μA current. The resonators described in this paper mark the first steps toward the development of compact superconducting linear accelerators for high-current, high-brightness ion beams.[4]

Most superconducting resonators for heavy-ion acceleration span a band in eigenfrequency-velocity space from roughly f=50 MHz, β=0.01 to f=200 MHz, β=0.2.[5] The most successful low-velocity structures are based on some form of resonant line with the beam traversing the high-voltage region. Thus, our development approach involves extending this resonator class to higher frequencies and velocities. In turn, we have constructed and operated a coaxial quarter-wave structure at f=400 MHz which was optimized for β_0=0.15, and a coaxial half-wave structure at f=355 MHz which was optimized for β_0=0.12.

II. Coaxial Quarter-Wave Resonator

A schematic of the coaxial quarter-wave resonator appears in Figure 1. The inner conductor was formed from 0.16-cm-thick sheet niobium of high RRR value (200-250) and was filled with liquid helium during testing. The outer conductor was fabricated from a cylinder comprised of a 0.16-cm-thick sheet of niobium which was explosively bonded to copper. The copper, a good thermal conductor, extracted heat from the niobium, a relatively poor thermal conductor, and transferred it to an adjacent liquidhelium reservoir. The bore-hole diameter was selected to be approximately 2.5 cm to reduce the likelihood of beam impingement, and the length of each gap was approximately 1.6 cm. All welds were made with an electron-beam welder. The bottom plate of the resonator was located relatively far from the inner conductor so that the rf fields at this plate would be weak. This allowed the plate to be demountable, enabling easy access to the interior surfaces of the cavity.

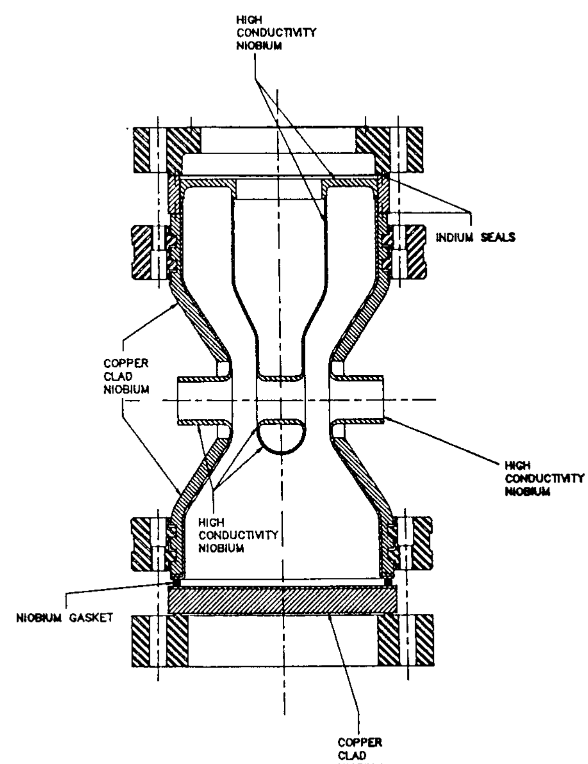

Fig. 1 400 MHz coaxial quarter-wave resonator; β_0=0.15.

Table 1. Properties of the coaxial quarter-wave resonator.

Frequency	400 MHz
β_0	0.15
Energy gain[a)]	63.5 kV
Peak surface E field[a),b)]	3.2 MV/m
Peak surface B field[a),b)]	58 G
Energy content[a)]	9.6 mJ
Geometrical factor QR_s	38.3 Ω

[a)] at an accelerating field of 1 MV/m.
[b)] calculated from Ref. 6.

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Special care was taken to prepare the surfaces of the inner conductor and shorting plate after these two pieces were welded together. The surface treatment began with electropolishing in a 17:3 solution of sulfuric acid and hydrofluoric acid, respectively, to remove approximately 15 μm of niobium. This was followed by annealing in a 4×10^{-7} torr vacuum for approximately 13 hours at 1200 C (5 hours at full temperature). An additional electropolishing to remove another 135 μm of niobium was then performed. Afterwards, the piece was annealed a second time and welded to the outer conductor.

A final treatment of the niobium surfaces of the whole resonator was done to remove surface imperfections generated during the welding of the inner and outer conductors (e.g. weld beads, sharp edges, etc.). The geometry of the cavity made it difficult to design electrodes for concentrated electropolishing of this weld area. Consequently, the final treatment was a chemical polish using a 2:1:1 solution of phosphoric acid, nitric acid, and hydrofluoric acid, respectively. Initially, a brief polish was done to remove approximately 25 μm from the niobium surface in the region of the closure weld with successively less material removed away from this area. The resonator was then cooled and tested using the procedure described below, and an average accelerating gradient of 5 MV/m was achieved. The cavity Q degraded sharply above this level due to the onset of a thermal instability. Subsequent examination of the resonator's inner surface with a fiber optic probe revealed what appeared to be small residual weld beads in the general vicinity of the weld connecting the shorting plate and the outer conductor. Therefore, a second chemical polish was done to remove an additional 50 μm from the surface. Subsequent testing of the resonator yielded the results described below.

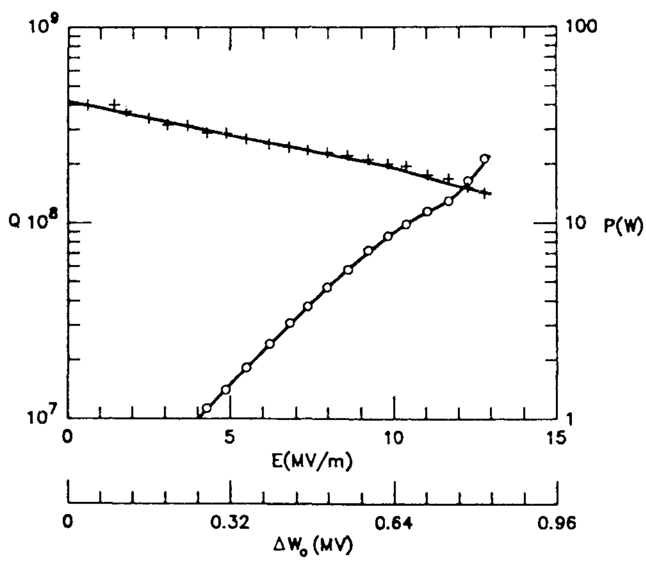

Fig. 2 Q-curve for the 400 MHz quarter-wave resonator.

At the beginning of the test, several multipacting levels appeared, they processed out rapidly, however. After multipactor processing was completed, a Q-curve was measured. As shown in Figure 4, Q varied from 4.1×10^8 at low rf field amplitude to 1.4×10^8 at the highest field achieved. Attempts to go higher in power resulted in a thermal instability in the cavity. X-ray radiation was monitored along the beam line with a detector located external to the cryostat. The maximum x-ray intensity observed was 17 mR/hr, indicating that field emission was always low. Accordingly, the power dissipated in the cavity was also low.

An average accelerating gradient of 12.9 MV/m was achieved with 21 W of rf power input to the cavity. This corresponds to an energy gain of 0.820 MV per unit charge. The associated peak surface electric and magnetic fields were approximately 41 MV/m and 750 G, respectively. Average accelerating gradients as high as 14 MV/m were achieved in the pulsed mode and were limited by a thermal instability. Because electron emission was low, no attempt was made to condition the cavity with either rf power or helium gas. The resonator was not shielded from ambient magnetic fields, so the degradation of Q with increasing field could have been due to losses from trapped flux in the superconducting niobium.

III. Coaxial Half-Wave Resonator

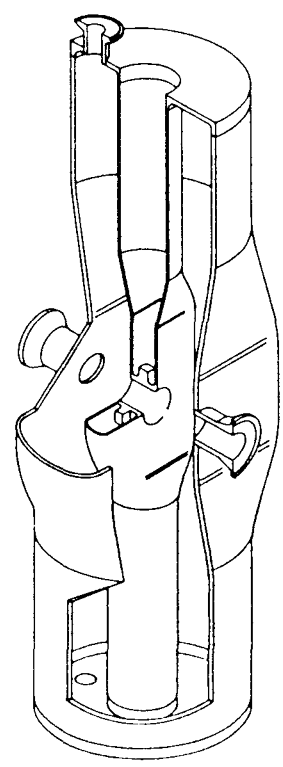

Fig. 3 355 MHz coaxial half-wave resonator; B_0=0.12.

A schematic of the coaxial half-wave resonator appears in Fig. 3. 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). The bore-hole diameter was selected to be approximately 2.5 cm, and the length of each gap was approximately 2.5 cm. All welds were made with an electron-beam welder. There were no demountable plates in this cavity, and thus the closure weld could not be inspected in detail. Accordingly, fabrication of this geometry is riskier than that of the coaxial quarter-wave geometry. This cavity is the first coaxial half-wave structure ever made.

The niobium resonator components were chemically polished at various stages during the fabrication process. The preliminary polishings were designed 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 phosphoric acid, nitric acid, and hydrofluoric acid, respectively, for 20 - 30 min. Approximately 60 microns of Nb are removed by this process. The piece was then rinsed in a 5% solution of H_2O_2 to remove insoluble niobium salts. This was followed by rinsing the piece with deionized water of semiconductor purity. After the final chemical polish the resonator was stored in a deionized water path for approximately 48 hrs. prior to mounting the rf pickup and drive coupling loops. The final step prior to rf testing of the cavity was to clean ultrasonically the structure in a high-purity methanol bath.

Table 2. Properties of the coaxial half-wave resonator.

Frequency	355 MHz
β_O	0.12
Energy gain[a)]	70.0 kV
Peak surface E field[a),b)]	3.2 MV/m
Peak surface B field[a),b)]	52 G
Energy content[a)]	12 mJ
Geometrical factor QR_S	53.3 Ω

a) at an accelerating gradient of 1 MV/m.
b) calculated from Ref.6

Early in the test several multipacting levels appeared as the power input to the cavity was increased. Critical coupling was established in the presence of this multipacting by varying the input line impedance. Once this was done, the multipacting processed out almost immediately to the point where no remaining multipacting levels were observed.

After multipactor processing was completed, a Q-curve was measured by monitoring the forward, reflected and pickup powers. As shown in Figure 4, Q varied from 7.7×10^8 at low rf field amplitude to 1.2×10^8 at the highest field achieved. In making these measurements, an average accelerating field of 10 MV/m was readily achieved. The cavity was then run overnight at moderate power (of order 10 W) to process out field-emission sites. An average cw accelerating gradient of 18.0 MV/m was then achieved with 40 W of rf power input to the cavity. X-ray radiation was monitored with a detector located external to the cryostat. The x-ray intensity at high rf fields was >200 mR/hr, indicating that electron loading in the form of field emission was present. Upon calibrating a NaI(Tl) photon detector and measuring the bremmstrahlung from the most energetic electrons, the average accelerating gradient was calculated.

The 18 MV/m gradient corresponds to an energy gain of 1.26 MV per unit charge. The associated peak surface electric and magnetic fields were approximately 58 MV/m and 936 G, respectively. Accelerating gradients as high as 10 MV/m could be generated with less than 2 W power input.

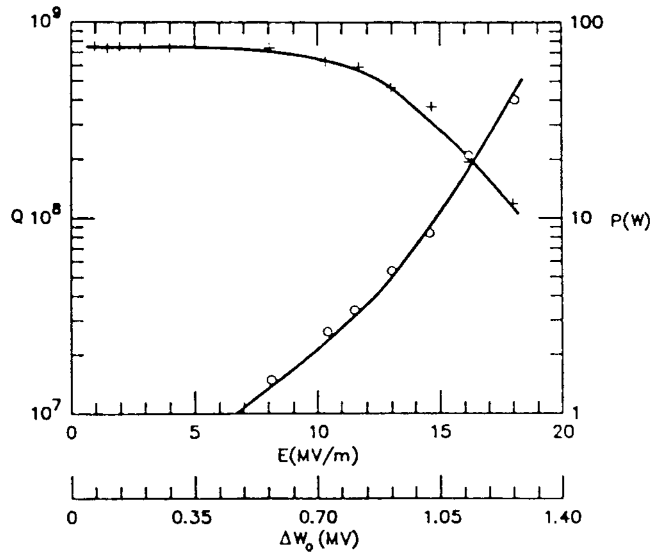

Fig. 3 Q-curve for the 355 MHz half-wave resonator.

IV. Conclusions

Niobium quarter-wave and half-wave structures have been constructed and operated. The half-wave structure achieved average cw accelerating gradients as high as 18 MV/m, which is a record for low-velocity superconducting resonators. The corresponding peak surface magnetic field was only 936 G, which is well below the rf critical field of niobium. Thus, these geometries provide the potential for even higher gradients.[10]

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