NIOBIUM RESONATOR DEVELOPMENT 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 $\beta_p = 0.15$. 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 $\beta_p = 0.12$. 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.

Introduction

Most of the development work on superconducting cavities has been done in connection with high-energy electron accelerators¹⁻⁵ and heavy-ion boosters for electrostatic accelerators.⁶⁻⁹ While the former have accelerated beams of several mA current, the latter have accelerated only μA 's. 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.¹⁰

Most superconducting resonators for heavy-ion acceleration span a band in eigenfrequency-velocity space from roughly $f=50$ MHz, $\beta=0.01$ to $f=200$ MHz, $\beta=0.2$.¹¹ 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 $\beta_p=0.15$, and a coaxial half-wave structure at $f=355$ MHz which was optimized for $\beta_p=0.12$.

Coaxial Quarter-Wave Resonator

A schematic of the coaxial quarter-wave resonator appears in Fig. 1. The inner conductor was formed from 0.16-cm-thick sheet niobium of high RRR value (200-250) and held 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.¹² The copper extracted heat from the niobium, a relatively poor thermal conductor, and transferred it to an adjacent liquid helium reservoir. The bore-hole diameter was selected to be 2.5 cm

to reduce the likelihood of beam impingement, and the length of each gap was 1.6 cm. All welds were made with an electron-beam welder.

Figure 1. 400 MHz coaxial quarter-wave resonator; $\beta_p=0.15$.

The axial electric field profile was measured by pulling a 6.4-mm-diameter brass bead along the beam axis.¹³ The average (wall-to-wall) accelerating gradient calculated from this profile was $E_{acc} = (10.7 \text{ MV/m})/J^{1/2}$. Calculation of the transit-time factor versus particle velocity¹⁴ indicates that this cavity can efficiently accelerate ions of energy in the range 4-40 MeV/amu. The properties of the resonator are summarized in Tab. 1.

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

Frequency	400 MHz
β_p	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 n

^{a)}at an accelerating field of 1 MV/m.

^{b)}calculated from Ref. 15.

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Surface Preparation

The quality factor (Q) of the resonator is strongly influenced by the condition of the cavity surface. Among the contaminants which degrade performance are adsorbed hydrocarbons and non-superconducting metallic inclusions. The niobium pieces were periodically anodized so that the surfaces could be inspected for inclusions, which were then mechanically removed. The area was repaired by a combination of hand polishing and chemical etching. All components of the resonator were treated to remove contaminants and to promote the growth of large crystals on the niobium surface. This involved a series of electropolishing and chemical polishing and, for the pieces fabricated from niobium sheet, annealing at 1200 C under vacuum.

Special care was taken to prepare the surfaces of the inner conductor and shorting plate. The surface treatment began with electropolishing in a 17:3 solution of H_2SO_4 and HF, 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. 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 closure weld. The final treatment was a chemical polish using a 2:1:1 solution of H_3PO_4 , HNO_3 and HF. Initially, a brief polish was done to remove approximately 25 μm from the niobium surface in the region of the closure weld. 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 revealed what appeared to be small residual weld beads. Therefore, a chemical polish was done to remove an additional 50 μm from the surface. Subsequent testing yielded the results described below.

Testing Procedure and Results

To provide rf power, a drive antenna, attached to a variable coupler, was installed at the beam entrance aperture of the resonator. An rf pickup probe was installed at the beam exit aperture. After installation in the cryostat, the resonator was baked at 80 C for approximately 14 hours in a 10^{-6} torr vacuum. The liquid nitrogen tank was then filled to precool the resonator to about 90K, after which the liquid helium tank was filled to cool 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. Several multipacting levels appeared as the power input to the cavity was increased. These levels processed out very rapidly, however, to the point where no remaining multipacting levels were observed.

After multipactor processing was completed, a Q-curve was measured. As shown in Fig. 2, 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.

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

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.

Frequency shift due to radiation pressure was less than 0.5 Hz/(MV/m)². Frequency noise due to ambient vibration was of the order of 1 Hz.

Coaxial Half-Wave Resonator

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 to reduce the likelihood of beam impingement, 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.

Figure 3. 355 MHz coaxial half-wave resonator; $\beta_0=0.12$.

The axial electric-field profile, which was measured by pulling a 6.4-mm-diameter brass bead along the beam axis, is similar to that of the quarter-wave resonator. The average (wall-to-wall) accelerating gradient calculated from this profile was $E_{acc} = (9.1 \text{ MV/m})/J^{1/2}$. The transit-time factor versus particle velocity is likewise similar to the quarter-wave resonator, with the exception that the resonator is optimized for $\beta_0=0.12$. The properties of the resonator are summarized in Tab. 2.

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

Frequency	355MHz
β_0	0.12
Energy gain ^{a)}	70.0 kV
Peak surface E field ^{a),b)}	32 MV/m
Peak surface B field ^{a),b)}	52 G
Energy content ^{a)}	12 mJ
Geometrical factor QR_0	53.3 Ω

^{a)}at an accelerating gradient of 1 MV/m.

^{b)}calculated from Ref. 15.

Surface Preparation

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. All niobium pieces were ultrasonically cleaned prior to chemical polishing and e-beam welding.

The niobium resonator components were chemically polished at various stages of the fabrication process. The preliminary polishings removed damaged niobium surfaces resulting from mechanical stress introduced during the piece-forming steps. After the closure welds were completed, a final chemical polish was done to eliminate microscopic defects. The chemical polishing procedure consisted of immersing the niobium piece in a 2:1:1 solution of H_3PO_4 , HNO_3 , and HF , respectively, for 20-30 min. Approximately 60 microns of Nb were removed by this process. The piece was then rinsed in a 5% solution of H_2O_2 and then with deionized water of semiconductor purity. After the final chemical polish the resonator was stored in a deionized water bath for approximately 48 hrs. The final step prior to rf testing of the cavity was to clean ultrasonically the structure in a high-purity methanol bath.

Testing Procedure and Results

To provide rf power, a fixed coupling loop was installed at the port of one of the end plates of the resonator. An rf pickup loop was installed at the port of the other end plate. After installation in the cryostat, which for this experiment was surrounded by mu-metal to shield the resonator from ambient magnetic fields, the resonator was baked at 80 C for approximately 18 hours in a 10^{-6} torr vacuum. The interior of the resonator remained evacuated during cool-down. After precooling with nitrogen, the dewar was filled with liquid helium beyond the top of the resonator. 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.

No serious difficulties were encountered in processing out the few multipacting levels which appeared early in the experiment. After multipactor processing was completed, a Q-curve was measured by monitoring the forward, reflected and pickup powers. As shown in Fig. 4, Q varied from 7.7×10^5 at low rf field amplitude to 1.2×10^6 at the highest field achieved. 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. The x-ray intensity monitored on the outside of the cryostat was $>200 \text{ mR/hr}$ at high rf fields, indicating that electron loading in the form of field emission was present. Upon calibrating a NaI(Tl) photon detector and measuring the energy of the bremsstrahlung from the most energetic electrons, the average accelerating gradient was calculated and found to agree with the gradient calculated from the forward and reflected powers at the cavity.

Figure 4. Q-curve for the 355 MHz half-wave resonator.

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.

Frequency shift due to radiation pressure was less than 0.7 Hz/(MV/m)². Frequency noise due to ambient vibration was of the order of 20 Hz.

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.

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