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FIRST TESTS OF A SUPERCONDUCTING RFQ STRUCTURE

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Abstract

High surface electric fields have been obtained in the first tests of a superconducting rf quadrupole device. The rf quadrupole fields were generated between niobium vanes 6.5 cm in length, with an edge radius of 2 mm, and with a beam aperture of 6 mm diameter. In tests at 4.2 K, the 64 MHz device operated cw at peak surface electric fields of 128 MV/m. Virtually no electron loading was observed at fields below 100 MV/m. It was possible to operate at surface fields of 210 MV/m in pulses of 1 msec duration using a 2.5 kW rf source. For the vane geometry tested, more than 10 square centimeters of surface support a field greater than 90% of the peak field. The present result indicates that electric fields greater than 100 MV/m can be obtained over an appreciable area, sufficient for some accelerator applications. It also shows that superconducting rf technology may provide an extended range of options for rf quadrupole design.

Introduction

Several workers have suggested that superconducting rf technology might provide a good means for achieving cw-operable, high-field rf quadrupole (RFQ) devices.[1,2] A problem in developing such devices is that present RFQ cavity geometries are generally quite different from the geometries used for superconducting rf devices. Parameters which have proven critical in superconducting cavity development, such as maximizing mechanical stability and minimizing peak rather than rms values of surface magnetic fields, have not been the critical parameters in the development to date of normally-conducting RFQ structures.

For this initial trial, rather than take on all aspects of developing an optimized superconducting RFQ, we have modified an existing superconducting accelerating device, the Argonne niobium split-ring resonator[3], in order to use it as an rf "voltage platform" on which to mount a 7 cm long superconducting niobium RFQ vane structure. While the resulting device could with little modification be used to accelerate beam, it does not represent an optimum design as an actual accelerating structure.

The object of the experiment was not to produce the front end of an ion accelerator, but to determine, for a realistic vane geometry, the field gradients one can expect for cw operation of a superconducting RFQ device. In this way, we can begin experimentally to establish a range of parameters for the design of superconducting RFQ accelerating structures.

Resonator Design, Construction and Calibration

The split-ring assembly from an existing ATLAS resonator was modified, as shown in Figure 1, by replacing the drift tubes with shortened drift tubes to which the RFQ vanes were attached. Both the vanes and the drift tubes were made from high-thermal-conductivity Nb. The thermal conductivity of Nb is usually specified by the residual resistance ratio[4] which was about 250 for the material used.

The vanes were first welded to the drift tubes and the drift tube assemblies were chemically polished for 15 minutes in a 2:1:1 mix of phosphoric, nitric and hydrofluoric acids. The drift

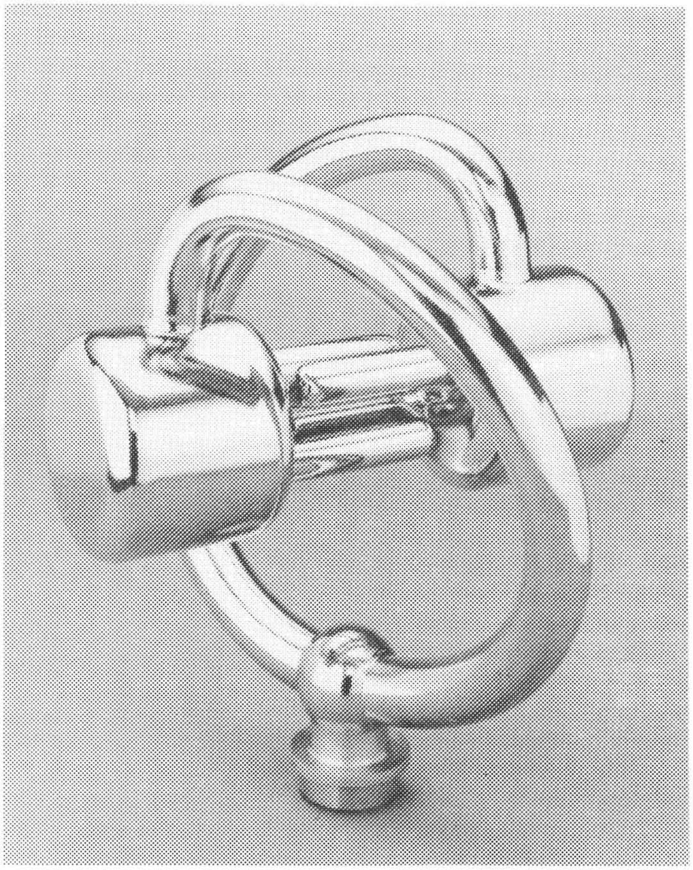

Fig. 1. Niobium split-ring assembly with RFQ vanes prior to being welding into the outer housing.

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tube assemblies and the split ring arms were then annealed for 6 hours at 1190 °C. After welding was completed, the assembly (vanes, drift tubes and split-ring arms) was chemically polished again for 30 minutes. The split-ring was then welded back into the original resonator housing and the inside of the whole resonator was electropolished for 50 cycles. The resonator was assembled in a dust-free environment and then allowed to stand for three days filled with semiconductor-quality deionized water.

The resonator was drained and dried, then mounted in a test cryostat and evacuated. During pumpout, the resonator was warmed to about 50 °C for 24 hours and reached a vacuum of a few times 10^{-7} torr prior to cooldown. During the cryogenic test, rf power was coupled into the resonator through an adjustable magnetic coupling which could be varied from over-critical to very weak coupling.

The absolute rf field level was calibrated by the standard technique of measuring both the input power P while critically coupled and also the intrinsic resonator rf decay time τ. These two numbers determine the total rf energy content U of the resonator as $U = P * \tau$. The relationship between energy content and drift tube voltage was obtained by a perturbation measurement (bead pull test) which measured the electric field on axis as a function of the total rf energy content; the voltage was obtained by integrating the measured electric field from the resonator outer wall up to the face of the drift tube. Because the dimensions of the drift-tube and RFQ vane assembly are much smaller than the free-space wavelength, a quasi-static, near field approximation is quite accurate. Thus the code POISSON could be used to calculate the electric field on and near the vanes in terms of the voltage on the drift tubes.

The geometry of the quadrupole field region is shown in Figure 2. The aperture diameter is 6 mm, the vane edge radius is 2 mm and the minimum distance between vanes of opposite voltage is 3.1 mm. POISSON yields the result that, at a voltage difference of 200 kV between adjacent vanes, the peak surface electric field is 80.3 MV/m and that 10 cm^2 of area support a field greater that 90% of the peak field. We estimate the experimental error in determining the field level to be of the order of 5%.

We have not corrected the calibration for the rf-voltage drop along the vanes. The vanes can be considered as short (7 cm) sections of essentially TEM transmission lines, much shorter than the wavelength (470 cm), thus the voltage will be constant along their length to a fraction of a percent. We also have neglected any field enhancement at the end of the vanes. This field enhancement will be small since the radius at the end of the vane (10 mm) is much larger than the edge radius (2 mm). Both the above effects cause the actual fields to be higher than the quoted fields.

During a second test of the structure we measured the spectrum of the x-rays generated as a result of field emission, the cut-off in the spectrum corresponds to the intervane voltage. At the operating field the x-ray cutoff indicated an intervane voltage of 209 kV which is in agreement with a voltage of 174 kV calculated by the procedure described above.

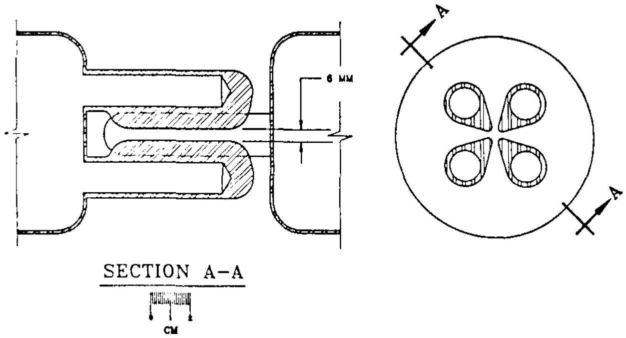

Fig. 2. Geometry of the vanes generating the rf quadrupole fields.

The peak surface magnetic field can be scaled from the value measured in the unmodified split-ring resonator by a factor which depends only on the change in frequency caused by the addition of the RFQ vanes. We estimate that for a peak surface magnetic field of 740 gauss, which is routinely achieved in cw operation of the unmodified ATLAS split-ring resonators, the peak surface electric field would be 211 MV/m. For pulsed operation, surface magnetic fields 50% higher can be sustained in the unmodified resonator. Thus, even at the field levels achieved, magnetic-field related processes should not limit the high-field performance of the present RFQ structure.

Experimental Results

Immediately upon cooldown, the structure exhibited multipacting barriers beginning at very low field levels (<10 MV/m surface field) which were conditioned completely away by the application of a few watts of rf power over a period of 2 - 3 hours. The observed multipacting behavior is typical of the unmodified ATLAS niobium split-ring resonators, and was found to be qualitatively unchanged by the addition of quadrupole vanes to the structure.

After low-power, cw conditioning to remove multipacting, the resonator was operated in a pulsed mode, using a 2500 watt rf source, at as high a field level as possible for about 30 minutes. The duty factor was one or two 10 msec pulses per second. Such high-power conditioning is the procedure currently used on the ATLAS superconducting linac to reduce high-field electron loading (presumably caused by field emission).

Figure 3 shows the resonator quality factor (Q) as a function of peak surface electric field at 4.2 K after conditioning. The qualitative behavior is typical of all split-ring resonators. The low-field Q is fairly constant and primarily determined by resistive losses associated with the rf surface magnetic field. Above 100 MV/m the losses increase rapidly with a corresponding decrease in Q. Fields of 128 MV/m could be sustained in cw operation and were limited by the inefficient cooling of the vanes. Higher fields could be achieved in pulsed operation by gradually reducing the duty factor. The maximum field was achieved using a pulsed 2.5 kW source, and 210

MV/m could be maintained for times in excess of 1 msec. The increased losses at high fields are due to electron loading (field emission), evidenced by the emission of x-rays and by the fact that the losses observed immediately on cooldown can be reduced by operating the resonator at high fields (conditioning).

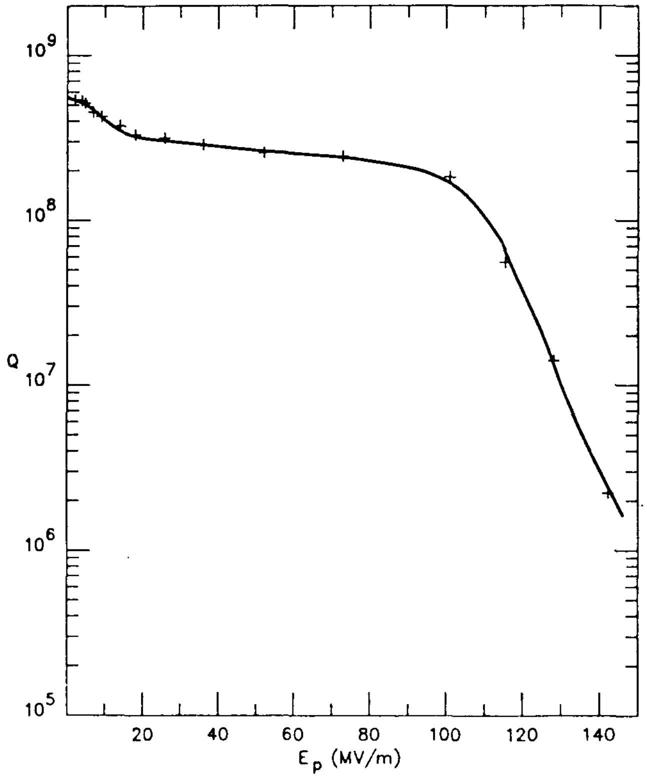

Fig. 3. Quality factor of the resonator at 4.2 K as a function of the peak surface electric field.

The cw fields which were achieved are comparable to those previously reported at higher frequency,[5] but were sustained over areas of the order of 10 cm^2 instead of a few mm^2. The pulsed surface electric fields are the highest which have been reported for superconducting niobium structures.

Electron loading is the field-limiting process in the present structure and will clearly be of prime importance in future designs. The present test demonstrates an RFQ vane structure requiring negligible rf power for surface electric field levels below 100 MV/m, 0.9 W per cm of RFQ structure at 115 MV/m, and 38 W/cm at 143 MV/m.

The RFQ structure is undergoing further testing after additional chemical polishing of the drift tubes and the vanes. Cw fields of 90 MV/m and pulsed fields of 110 MV/m have been achieved in preliminary results in this new series of tests.

Conclusions

There are several aspects of the present result that may have bearing on potential applications. The fields attained are substantially higher than expected for normally-conducting cavities of comparable frequency for either cw or pulsed operation.[6] Also, this initial superconducting RFQ device has operated at fields a factor of three higher than have been reported for cw operation of normally-conducting RFQ devices.[7] The present result indicates that superconducting rf technology may appreciably extend the range of options for RFQ design.

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