DESIGN AND MODELING OF SUPERCONDUCTING RFQ STRUCTURES*

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Abstract

Tests of the first superconducting RFQ structure [1] indicated that high surface electric fields could be sustained in a quadrupole geometry. However, the geometry used in those tests was not appropriate for an accelerating structure and the area sustaining the high electric field was too small to assume that such fields could be achieved in actual RFQ structures. We have initiated a program to analyze and model a variety of geometries suitable for superconducting RFQ structures. We are also designing a niobium RFQ "sparker" to experimentally measure the surface electric fields that can be achieved on large areas in an actual RFQ structure.

Introduction

The first tests of a superconducting RFQ (SCRFQ) structure [1] produced cw surface electric fields of 130 MV/m at 64 MHz, far in excess of the fields that could be expected in a normal-conducting structure.

The high fields were obtained, however, over a smaller area than would be needed in an actual RFQ and in a geometry which was not appropriate for testing with beam. While the magnitude of the fields which can be sustained over large areas in an actual SCRFQ in an accelerator environment will have to be determined experimentally, the early results indicate that the superconducting rf technology may appreciably extend the applications of RFQ and even enable new ones [2].

The superconducting rf technology, however, brings its own set of constraints and characteristics which will need to be addressed if the full potential of SCRFQs is to be realized. Thus we have begun a research program to determine experimentally the surface fields that can be sustained in realistic SCRFQ geometries and at the same time a design and analysis program to develop RFQ geometries which take into account the constraints and characteristics of the superconducting rf technology. In this paper we report on some of our work concerning the design and modeling of SCRFQ structures.

Design Considerations for SCRFQs

Superconducting structures are characterized by high intrinsic Q and, correspondingly, narrow bandwidth. For low-current applications where beam loading will be negligible, superconducting structures can be sensitive to frequency variations caused by external noise and microphonics, and ponderomotive instabilities. This problem was resolved for low-velocity structures by a combination of electronic control and the development of mechanically stable geometries. Thus, mechanical rigidity will be a principal consideration in the design of low-current SCRFQs.

The manufacturing techniques used for superconducting structures are different than those used for normal-conducting structures and will have an impact on the electromagnetic and mechanical design. For example, the only joining method in high-current regions is electron-beam welding. Demountable joints are avoided or used only in low magnetic field regions, and sliding contacts have not been successfully developed for superconducting structures. Thus, the amount of adjustment that can be accomplished on a completed SCRFQ will probably be limited to mechanical deformation. Adjustments by sliding contacts and shimming which have been used extensively in normal-conducting RFQs will probably not be useful for SCRFQs. Thus the designs of SCRFQs will have to be robust, in the sense that the electromagnetic mode purity will need to be insensitive to dimensional inaccuracies.

Preliminary designs of high-current superconducting ion accelerators indicate that the transition between the RFQ and the "drift tube" cavities will take place at higher energy than in normal conducting accelerators, typically around 5 MeV/amu. Even taking into account the possibility of higher gradient, this indicates that the capability of building long SCRFQs might be beneficial. Since, for a given amount of mode mixing, the required manufacturing tolerances decrease as the square of the length [3], it is even more important to develop designs for high-current SCRFQs which are relatively insensitive to manufacturing inaccuracies.

The third important consideration in the design of SCRFQs is the necessity of cooling to remove the heat generated by the rf currents. Furthermore, for high-current RFQs, there will always be a certain amount of beam impingement, and additional cooling will be required to remove the heat deposited. Thus, the challenge for SCRFQs is to develop designs which are rigid, simple to manufacture, provide a quadrupole mode isolated from other modes, and are easily cooled.

Two main designs of RFQs have evolved in the last decade (see for example [3-4]). The first one, the 4-vane RFQ geometry, is basically a waveguide modified to emphasize the quadrupole TE_{21} mode. This geometry leads to

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designs which are conceptually simple, with a high degree of symmetry, and mechanically rigid. Its main drawback is that the dipole TE_{11} mode is often close to the quadrupole mode, and small perturbations of the quadrupole symmetry lead to strong mixing between the quadrupole and the dipole modes. The near degeneracy results from the fact that the fields in the four quadrants overlap only in a small region, near the beam line. Ways of removing the degeneracy by increasing the frequency of the dipole mode have been found such as strapping opposite vanes together by vane coupling rings [5]. Such a solution, however, would be difficult to reconcile with the manufacturing techniques of niobium resonators.

The other often-used design is the 4-rod structure. This structure relies more on a 'lumped element' design than the distributed design of the 4-vane geometry. Its main advantage is that the quadrupole mode is widely separated from other modes, resulting in a robust design. However, it is less attractive for SCRFQs, because it may be less mechanically rigid and more difficult to build and cool than a '4-vane' geometry.

We have investigated designs which have the advantages of both the 4-vane and 4-rod designs and provide a continuous evolution between the two. This intermediate geometry seems well suited for SCRFQs and may also have advantages for normal-conducting RFQs.

In an ideal RFQ design, the quadrupole mode would have the lowest frequency and be widely separated from the dipole mode. In the typical 4-vane geometry, however, the quadrupole mode frequency is close to the dipole mode frequency and slightly higher. This near degeneracy can be understood in lumped-element representations of both modes of oscillations, which are identical, except for a small additional capacitance between opposite vanes for the dipole mode [6]. This results from the fact that there is no overlap of the magnetic field of adjacent quadrants. Since, in the dipole and quadrupole modes, magnetic fields in adjacent quadrants have opposite configuration, providing an overlap or coupling of the magnetic fields would remove the degeneracy and increase the frequency splitting.

We have pursued this idea by calculating with MAFIA [7] the frequencies of the dipole and quadrupole modes of an infinite waveguide of the 4-vane geometry with periodic cutouts through the vanes shown in Fig 1. These cutouts allow magnetic coupling between adjacent quadrants. The results of the numerical calculations are shown in Table 1. It can be shown by energetic arguments that, this way, the quadrupole mode frequency is lowered by an amount between one and two times the decrease of the dipole mode frequency. This conclusion is supported by Fig. 2 which summarizes all the results. Thus, with cutouts which are large enough, one obtains a geometry which is still simple, with a high degree of symmetry, but, at the same time, has a quadrupole mode which is lower and widely separated from the dipole. This geometry also offers a continuous evolution from the 4-vane to the 4-rod geometry. In the most extreme case of large cutouts, the structure consists of 4 rods periodically supported by posts located in a quadrupole pattern.

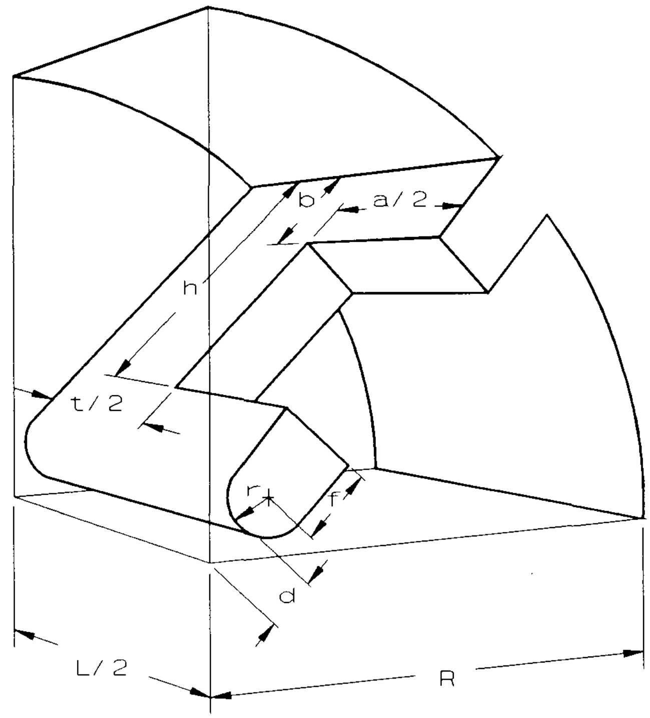

Fig. 1 Schematic drawing of one quadrant of the periodic quadrupole waveguide. The full geometry can be obtained by a reflection around an end face and has a periodicity L.

TABLE 1

Results of MAFIA calculations for various cutouts of the vanes

R = 12 cm, d = 1.0 cm, r = 1.0 cm

L (cm)	t (cm)	a (cm)	h (cm)	b (cm)	Quad. (MHz)	Dipole (MHz)	fd-fq (MHz)
25	25	0	-	-	292.4	282.2	-10.2
25	21	4	2.7	0	291.2	281.2	-10.0
25	21	4	5.4	2.7	291.2	281.2	-10.0
25	21	4	8.1	5.4	291.6	281.5	-10.1
25	21	4	5.4	0	290.2	280.4	- 9.8
25	21	4	8.1	2.7	290.7	280.8	- 9.9
25	21	4	8.1	0	289.7	280.0	- 9.7
25	13	12	2.7	0	273.8	271.0	- 2.8
25	13	12	5.4	2.7	272.6	270.4	- 2.2
25	13	12	8.1	5.4	276.4	272.5	- 3.9
25	13	12	5.4	0	263.5	263.9	0.4
25	13	12	8.1	2.7	258.7	260.0	1.3
25	5	20	2.7	0	232.5	244.8	12.3
25	5	20	5.4	2.7	229.5	242.0	12.5
25	5	20	8.1	5.4	237.7	247.0	9.3
25	5	20	5.4	0	211.0	227.3	16.3
25	5	20	8.1	2.7	214.5	228.7	14.2
25	5	20	8.1	0	202.1	218.1	16.0
20	5	15	8.1	0	225.1	236.8	11.7
30	5	25	8.1	0	183.8	201.2	17.4

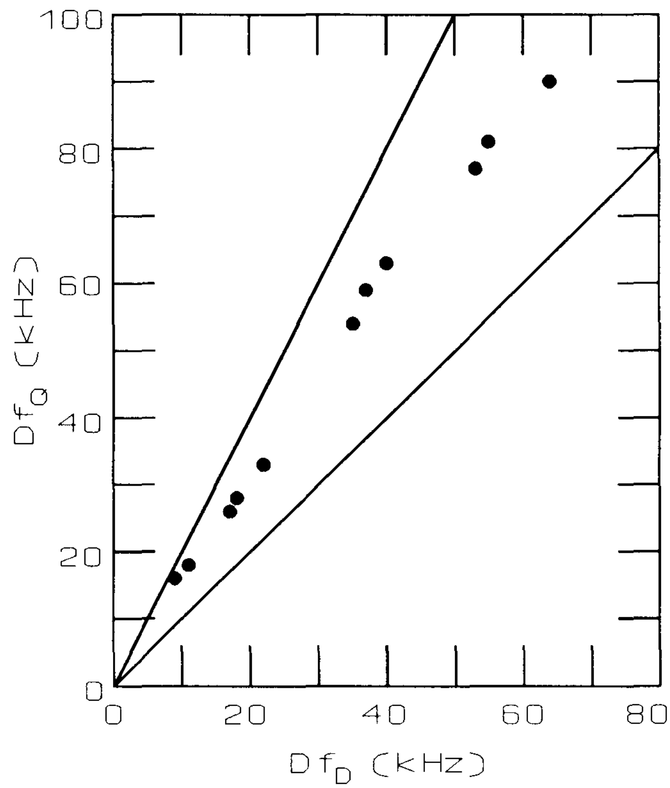

Fig. 2 Decrease of the quadrupole mode frequency vs. decrease of the dipole mode frequency for the geometry of Fig. 1 and the various cutouts shown in Table 1.

While MAFIA is very powerful in predicting various electromagnetic properties of the structure, it is quite time consuming to investigate their dependence on all the dimensional parameters and it does not give much physical insight. In the case of cutouts extending to the outside diameter of the structure (b=0 in Fig.1), a transmission line model can be developed to calculate the electromagnetic properties of the quadrupole mode of the infinite waveguide. The wavelength λ associated with the resonant frequency of the quadrupole mode satisfies the equation

$$2\tan\frac{2\pi h}{\lambda}\left\{\tan\left[\frac{2\pi}{\lambda}\left(\frac{L-t}{2}\right)\right]+\frac{\pi t}{\lambda}\right\} = \frac{\epsilon}{C}\left(\frac{2t}{g}+\alpha\right),$$

where C, the capacitance per unit length of the rod, is given in pF/m by [8]

$$C = \frac{39.365}{\cosh^{-1}\left(\frac{d+r}{r\sqrt{2}}\right)} + \frac{31.045}{\frac{d}{r}+1-\sqrt{2}} + 25.28\ln\left(1+\frac{f}{d+r}\right),$$

α is a constant which, for our dimensions, is of the order of 3 [9], and $g \simeq \frac{1}{2\sqrt{2}}(2R-h)-r$.

The right hand side of the characteristic equation for λ is valid for $t < L - \frac{\alpha g}{2}$. When $L - \frac{\alpha g}{2} < t < L$, then the right hand side is replaced by $\frac{\epsilon}{C}\frac{2L}{g}$.

This transmission line model has been used to calculate the quadrupole mode frequency for the geometry shown in Fig. 1 with b=0 and h=8.1 cm, for a wide range of cutout size a and period L. In all the cases the calculated frequency was within a few percent of that obtained by MAFIA.

This transmission line model can also be used to calculate other electromagnetic properties, such as the z-dependence of the voltage on the tip of the vane, the energy content, currents, shunt impedance, etc.

Conclusions

We have investigated numerically and analytically a family of resonator geometries which has attractive features for superconducting RFQs, namely, simplicity, ease of manufacture, mechanical rigidity and isolation of the quadrupole mode. Our plans include the development of a model to predict the frequency splitting between dipole and quadrupole modes as a function of cutout size and geometry. In parallel, a superconducting cavity designed to test this geometry and measure the surface fields that can be achieved is being developed.

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