Tests of Beta = 0.1 and Development of Beta = 0.2 Lead Plated Quarter Wave Resonators

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Beta = 0.10 Quarter Wave Resonator

A prototype lead plated copper quarter wave resonator has been built for the University of Washington Superconducting Booster. The design of this resonator followed that of Brennan and Ben-Zvi.[1] The drift tubes were built in Israel, and are identical to those built for the Weizmann Institute quarter wave resonators. The other dimensions of the resonator were similar to those of the Weizmann Institute unit, except the radius of the outer conductor was increased by one cm and the resonator was made slightly longer to reduce the frequency from about 160 to 150 MHz. This extra one cm in radius was used to increase the gap between the center and side drift tubes, so that the UW resonator had 5 cm gaps while both the design discussed by Brennan and Ben-Zvi and the resonators they built had 4 cm gaps. Both our resonator and the one they built had side drift tubes extending 2 cm radially inward, while the one discussed in Ref. 1 had 3 cm drift tubes. We anticipated that this increased gap would reduce the surface field at the center drift tube; however upon further consideration, it seems unlikely that it had much effect. The larger gap does decrease the gap transit time factor (by only about 2%) and increases the optimum velocity by about 17%. In addition, the larger diameter gives a larger stored energy but also, for the same average field, 12.5% more energy gain. Fig. 1 is a drawing of the resonator. With the 5 cm gaps between drift tubes, adjustments of both the gaps produce a frequency shift of 85 kHz/mm. Adjustments of the bottom gap (7 cm from drift tube bottom to bottom plate) produce a shift of about 10 kHz/mm.

From bead measurements on a brass model resonator we determined the ratio of stored energy to average accelerating field to be 0.063 Joules/(MV/m)^2. Average accelerating field is defined to be the energy gain an optimum velocity particle of unit charge obtains, divided by the inside diameter of the outer conductor (18 cm). The actual resonator has an eigen frequency of 148.90 MHz.

The resonator was lead plated at the State University of New York at Stony Brook by two of the authors (A.G.S. and R.C.). The plating technique was that described by Burt,[2] with some modifications which had been developed at the Weizmann Institute and some that were developed with this resonator. The main modifications involved heating the plating bath to about 31 degrees C, filtering the bath while plating, using an anode bag, and punching holes in the anode. The anode was a lead sheet which was formed into a cylinder and suspended in the volume between inner and outer conductor. A current of 2.7 A was used, and was turned on and off for 1 sec intervals. Total plating time was 12 hours. The resonator, when plated using these techniques, had a very smooth and shiny finish, in contrast to results from previous plating attempts with a room temperature bath, almost twice the current, and without the other modifications, which gave a poor finish (grainy and fuzzy).

Tests on the final plating of the resonator indicate that fields of 3.5 MV/m are obtained with 4.2 W dissipation. Calibration for these tests was carried out by determining the low field Q by measuring the decay time. Still at low field, stored energy is obtained from power and Q, and then from the bead test results average accelerating field is determined and the voltage probe is calibrated. With the minimum setting of the variable coupler, the amplifier was still somewhat over coupled, so it was necessary to correct for the external Q contributed by the amplifier. This external Q was 7.48×10^7. Calibration uncertainties are estimated to be 5%. A graph of the resonator Q vs average accelerating field is given in Fig. 2. These Q values have had contributions of the measuring probe removed. These data were all obtained with CW operation. The maximum CW power that the resonator could be run at before going normal was about 50 W.

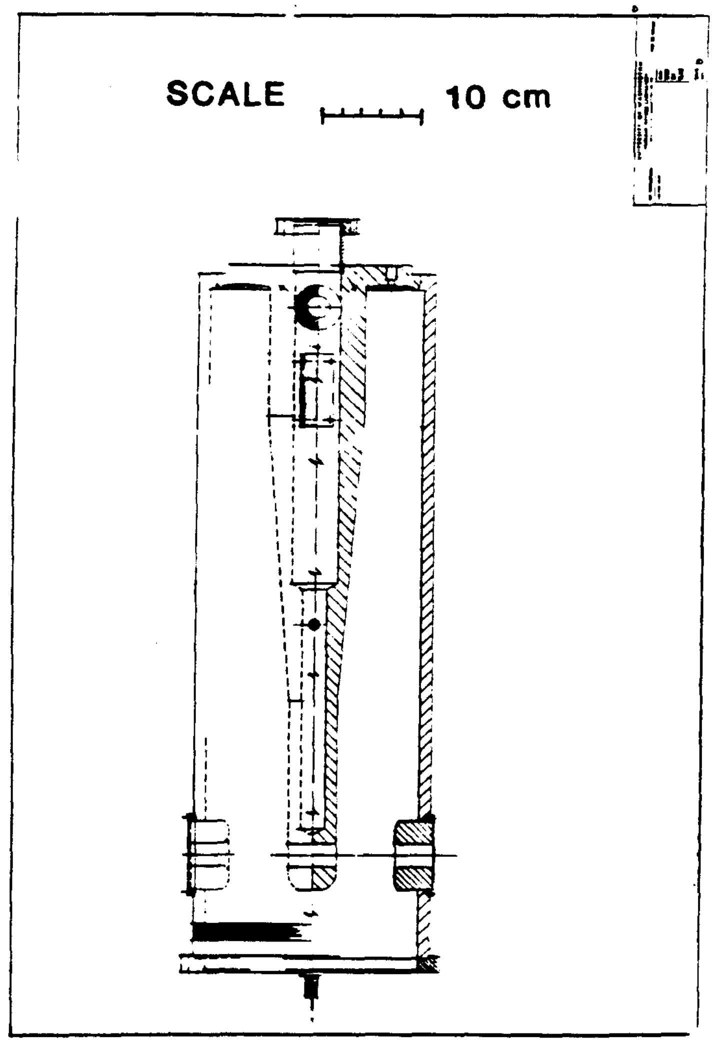

Fig. 1 The low beta quarter wave resonator.

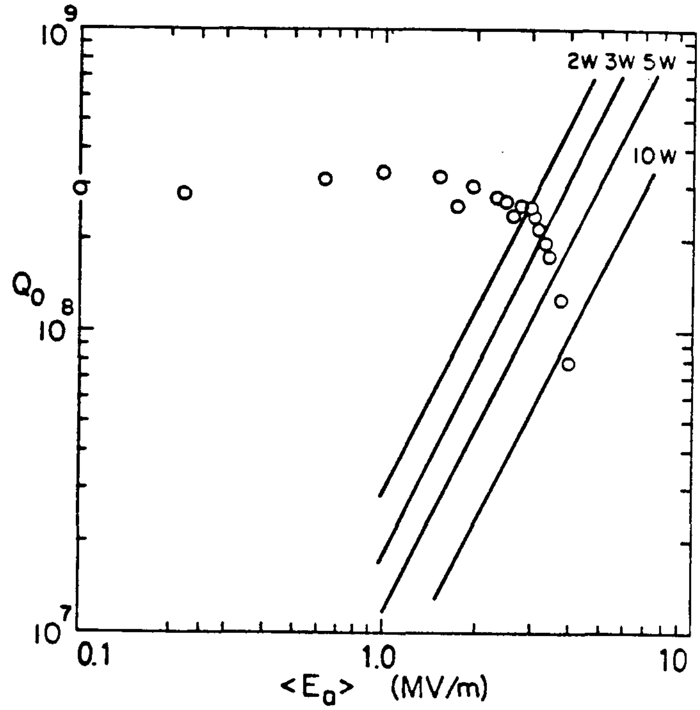

Fig. 2 Q vs. Average Accelerating Field for tests of the low beta quarter wave resonator.

Helium conditioning was performed prior to measuring those data. Before helium conditioning, the "corner" of the curve occurred at lower fields. Wherever the corner was located, rapidly increasing x-ray emission was observed, beginning at the corner and increasing by several orders of magnitude for a decrease in Q by an order of magnitude. Below the corner, no x-rays were detected. After conditioning, there were regions of field below the corner where the limit of x-ray observation was three orders of magnitude below the flux observed before conditioning. We take this to be strong evidence that the corner is due to field emission of electrons. Calculations (described below) indicate that the maximum surface magnetic field (assuming smooth surfaces) is 250 Gauss at 3.5 MV/m. This field can be compared with the 4.5 K critical magnetic field of about 500 Gauss for lead.

When operating the successfully plated resonator superconducting, multipactoring was observed and was a serious nuisance. In order to simulate conditions encountered in some previous tests when the surface had looked poor and when multipactoring under superconducting conditions was not a problem, we warmed the resonator up to above room temperature (about 75 to 80 ^{o}C) and bled water vapor into the vacuum system, raising the pressure to 3 x 10^{-5} Torr to reproduce the poor vacuum operation at the beginning of the earlier tests. We operated the resonator at moderate power levels (tens of watts) for one day, after which the water was turned off, and the vacuum returned slowly to the 10^{-6} range. After operating (warm) for two more days multipactoring showed signs of improvement even while the vacuum was in that range. After filling the nitrogen shield, the vacuum returned to the 10^{-7} range and multipactoring ceased. After cooling to helium temperature, no more multipactoring was observed. The superconducting tests were repeated and the Q curve showed no significant differences from the measurement before the warm up and multipactor conditioning. These results indicate that we have a technique for eliminating multipactor problems without damaging the superconducting surface.

Design of Beta = 0.20 Resonator

To build a higher beta resonator we had the choice of either increasing the radius of the resonator or increasing the frequency, or both. It is interesting to note that since the diameter of the quarter wave resonator is proportional to the particle wavelength and the length is proportional to the rf wavelength, the ratio of diameter to length is proportional to the particle beta, regardless of the frequency. (This relationship is based on the assumption that the side drift tubes protrude a given fraction of the radius into the resonator. The amount of protrusion of the side drift tubes is another parameter that can be adjusted to vary the resonator design beta.) Some scaling laws are relevant in making this choice. For fixed average accelerating field (ignoring capacitive loading) the power dissipated (resistively) is proportional to the radius, while the stored energy is proportional to the square of the radius. The loading capacitance is proportional to the radius (provided the space to the bottom plate is increased by the same factor as the radius). The impact of the loading capacitance is considered below, and found to be of secondary importance. The transverse mechanical vibration frequency of the center conductor is proportional to the radius, provided the wall thickness of the center conductor is scaled proportionately. Thus the vibration amplitudes will be reduced by an amount which is probably substantial, but not clearly determined. Radial vibrations of the outer conductor (which have not been observed to modulate the the low beta resonator) will have lower frequencies.

As the energy gain is proportional to the radius, it seems best to maintain the fundamental frequency and to increase the resonator radius to obtain higher beta. This approach may be limited by stored energy increases, which relate to the power necessary to control the phase of the resonator. As the rigidity of the quarter wave structure is high, it appears that the power required to phase lock will not be excessive. The fact that the voltage required for a given accelerating field in the high beta resonator will be double the voltage of the low beta unit causes some concern. As a voltage limitation (as opposed to surface electric field limitation) has (to our knowledge) not been observed in superconducting resonators, we will see whether such a limitation appears. The voltage at the 3 MV/m design field will be 600 kV in the high beta resonator.

Most important is consideration of the geometry on the peak surface electric field. We have tried to improve on the ratio of peak to average accelerating electric field found in the low beta resonator. For a fixed average accelerating field, the center conductor voltage must increase proportionately to the diameter of the outer conductor. For the cylindrical geometry, (with fixed inner conductor radius) the surface field is proportional to the voltage divided by the log of the ratio of inner and outer conductor radius. Thus the net effect for the low beta resonator of increasing the outer radius from 8 to 9 cm while maintaining a 2 cm inner radius was to multiply the surface field in the cylindrical regions by a factor of $(9/8)(\ln(8/2))/(\ln(9/2)) = 1.037$. The peak surface field is on the spherical regions of the drift tube, however. For a sphere within a spherical shell, the surface field on the inner sphere (radius R) is proportional to the voltage difference times $(1/R)(1/(1-R/R_0))$. For the low beta resonator an approximate value to use for R is 2.5 cm, since the center drift tube is 6 cm in diameter but 4 cm long. Then changing R_0 from 8 to 9 cm while increasing the voltage by a factor of 9/8 increased the peak surface field by $(9/8)(1-2.5/8)/(1-2.5/9) = 1.07$. The larger gap will tend to reduce this factor by some (probably small) amount. Also, in both the UW and Weizmann Institute resonators, the space between the center drift tube and the bottom (tuning) plate is the same, and corresponds to a radius of 10 cm. Perhaps the appropriate value to consider for R_0 is larger and less different for the two resonators. Then the ratio of surface fields would be somewhat larger. We can conclude that, including the effect of the gap transit time factor, for fixed average accelerating field the 9 cm radius resonator that we built has a peak surface electric field that is somewhat under 10% higher than the corresponding field of the 8 cm radius resonator built by Brennan and Ben-Zvi. For fixed average accelerating fields there are similar factors relating the peak magnetic fields in the two sizes of resonator. As the magnetic fields do not seem to be a serious limitation for these resonators, this effect is not important.

These considerations led us to try to reduce the peak surface fields when scaling the resonator up to obtain a higher beta. If we simply scaled up the radial dimension (as well as the space between the bottom of the center drift tube and the tuning plate) by two while maintaining the same length for the resonator, we would expect to get twice the beta with the same surface fields for a given average accelerating field. Since the beam hole in the drift tubes need not be increased, it is possible to reduce some of the curvature of the drift tubes in this scaling up process. The capacitance per unit length of the cylindrical part of the resonator will be unchanged, but the loading capacitance from the end of the center conductor will approximately double in this scaling up. Any further increases in the size of the drift tube that might be considered in order to reduce curvature (increase radii) to reduce surface fields will also increase the loading capacitance further. Increased loading will require a shorter resonator to obtain the same frequency, which is a convenience. Increased loading will also decrease the shunt impedence, since there is an increase the surface magnetic fields required to obtain a given average accelerating field. This effect is of second order in the ratio of load impedence to the characteristic impedence of the small diameter end of the resonator. The increase in magnetic field combined with the reduction in volume due to loading will generate a smaller increase in stored energy. Furthermore, the dominant mechanical vibration mode will have a higher frequency if the loading is increased, since the center conductor length must be reduced. Thus the vibration amplitude will be reduced, and the increase in stored energy will not have a deleterious effect on the resonator phase control. Depending on how much loading there is, these increases may or may not be significant.

The major design compromise considered for the high beta resonator was between capacitive loading and peak surface fields. Larger drift tubes (especially the center drift tube) will have lower surface fields and more loading. We performed a calculation of the surface electric field. We used a relaxation program with cylindrically symmetric geometry to determine the static potential. We modeled the center drift tube in this geometry by a piece of a sphere attached to the end of the center conductor. By considering spheres of various radii, we could estimate the surface field on the drift tube. These calculations indicated that the peak surface field on the low beta resonator drift tube was about 4.5 times the average accelerating field. This figure can be compared with the ratio for surface field in the infinite coaxial model, which is 2.99 for our radii and which has a minimum value of e when the outer conductor radius is e times the inner.

In order to estimate the capacitive loading, we performed two different calculations. We had calculated the surface fields on the drift tube. From the product of the area (the area that we used was that of the drift tube without the hole for the beam) and the average surface field we obtained the capacitance of the drift tube. The excess capacitance above that of the cylindrical surface of a coaxial center conductor extending to the bottom of the drift tube was considered to be the loading capacitance.

In the other case we calculated the distribution of current and voltage down the length of the coaxial center conductor. This calculation was based on the approximation that the fields are transverse, even in the region of the taper, so the characteristic impedence at a given z is given by the usual result for a uniform coaxial structure. Starting with a voltage node at the shorted end of the resonator, by using the characteristic impedance we determined the ratio of voltage and current amplitude as a function of the longitudinal coordinate, z, measured from the shorted end. Initially these were sin(kz) and cos(kz) (where $k = \omega/c$). Along the taper, where the characteristic impedance changed with z, we used a numerical calculation. At the end of the taper, phase shifted sin and cos functions were matched to the voltage and current. The drift tube was ignored, and the center conductor from the end of the taper to the maximum z was taken to be a cylinder. The maximum z for a given frequency was determined from model measurements. At the maximum z the current was not zero. The appropriate load capacitance to produce the calculated voltage to current ratio was determined.

These two calculations agreed, respectively predicting 1.6 and 1.7 pF for the loading of the low beta resonator. For the high beta resonator values of 4.2 and 3.8 pF were obtained for the final drift tube configuration. For the low beta resonator, the open end of the resonator is 7 degrees from the current node, while for the high beta resonator this figure is 18 degrees. Since the voltage decreases as the cosine of this phase angle, the effect for the low beta resonator is negligible, while for the high beta resonator the voltage is 5% less than the peak amplitude. Thus 5% more current is required to produce a given accelerating field than that which would be required for negligible loading.

By making the high beta drift tube 10 cm long and 14 cm in diameter (vs direct scaling of the low beta drift tube which would have been 8 cm long and 12 cm in diameter) we estimate that we reduced the ratio of peak surface field to average accelerating field by 10% while increasing the loading capacitance by 20%. The peak surface field limits the maximum attainable accelerating field, while this loading produces an acceptable increase in the current and stored energy. A larger center drift tube was considered, but given the uncertainties of the calculations, it was decided that exceeding about 20 degrees phase shift at the open circuit end of the resonator was unreasonable. A drawing of the resonator is given in Fig. 3.

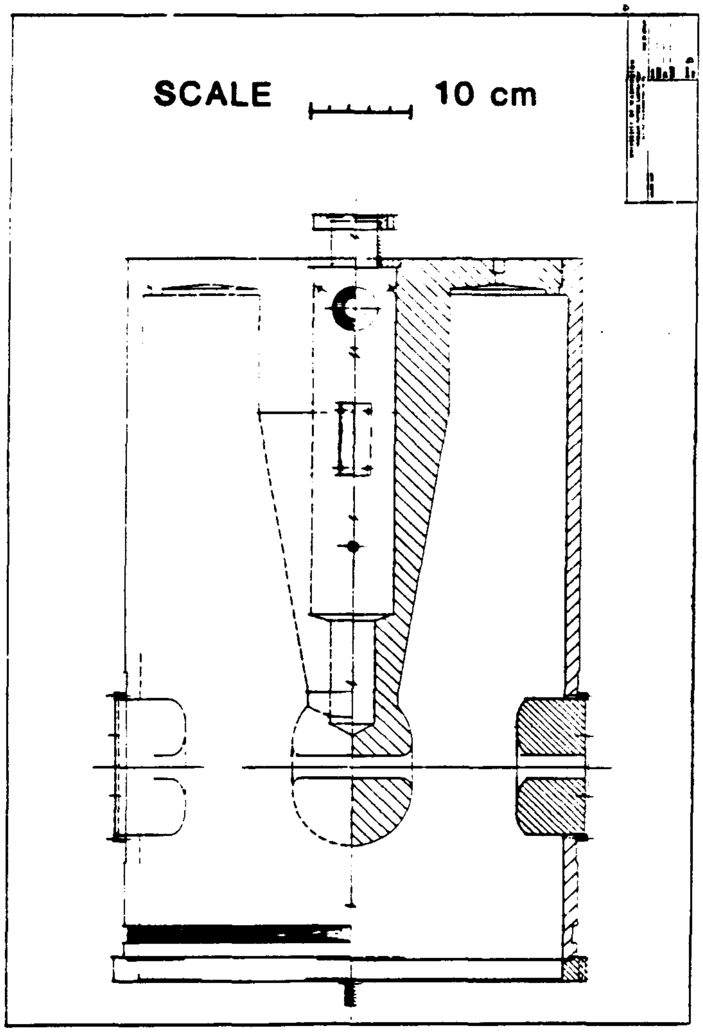

Fig. 3 The high beta quarter wave resonator.

Measurements made using a brass model of the high beta resonator indicate that the ratio of the stored energy to the square of the average accelerating field is .252 Joules/(MV/m)^2.

References:

1. I. Ben-Zvi and J.M. Brennan, Nucl. Instru. and Meth. 212 (1983) 73.
2. W.W. Burt and P. Paul, to be published