SUPERCONDUCTING RESONATORS FOR THE UNIVERSITY OF WASHINGTON BOOSTER LINAC

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Abstract: We have developed two models of a 150 MHz quarter wave resonator -- one with optimum beta=0.10 and one with optimum beta=0.21. These are lead-plated copper structures. The prototype beta=0.10 resonator was tested successfully a year ago and gave average accelerating fields of 3.5 MV/m with 4.2 Watts dissipated. It is quite similar to the resonator developed by the second and third authors.[1] We have made and tested several more of this model. A prototype beta=0.21 resonator has been completed, but weld flaws have prevented definitive tests. In order to minimize surface electric fields in the high-beta resonator, there were some modifications in the drift tube shape beyond those required to change the optimum beta. These quarter wave resonators have a wide transit time factor curve and are extremely rigid mechanically. Variations in eigen-frequency due to mechanical vibrations are less than 1 Hertz. Maximum attainable fields are limited by field emission.

Beta = 0.10 Quarter Wave Resonator

To date, six beta=0.10 quarter wave resonators have been built for the University of Washington Superconducting Booster. The resonators are made of OFHC copper and the insides are lead plated. Of the six built, four have been plated and tested. (One of these had improperly installed side drift tubes, and did not perform in tests as well as the others.) The design of these resonators followed that of Brennan and Ben-Zvi,[1] whose design has been replicated and installed at the Weizmann Institute. The dimensions of the present resonator are 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. The extra one cm in radius was used to increase the gap between the center and side drift tubes, so that the UW resonator has 5 cm gaps while both the design discussed by Brennan and Ben-Zvi and the resonators they built had 4 cm gaps. The larger gaps decrease the gap transit time factor (by only about 2%) and increases the optimum velocity by about 17%. In addition, for a given average field, the larger diameter gives a larger stored energy but also there is 12.5% more particle energy gain from this resonator than from the Weizmann Institute one. Figure 1 is a drawing of the resonator. Adjustments of both the nominal 50 mm 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 the prototype resonator we determined the ratio of stored energy to the square of the average accelerating field to be 0.063 Joules/(MV/m)^2. We also calculated the transit time factor (shown in Fig. 2) from the field profile measurement. We define average accelerating field to be the energy gain per electron charge that an optimum velocity particle obtains, divided by the inside diameter of the outer conductor (18 cm). Thus the transit time factor for the optimum velocity particle is included in the average accelerating field.

The prototype resonator was lead plated at the State University of New York at Stony Brook. The remaining ones were plated at the University of

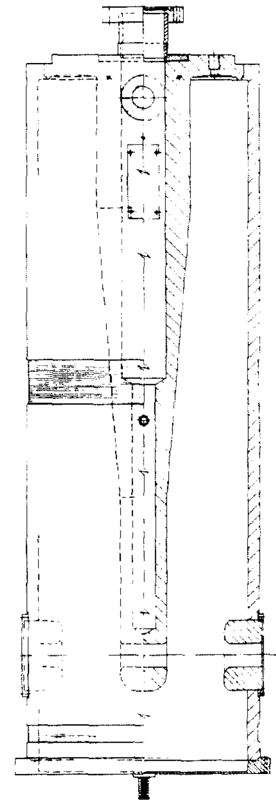

Fig. 1 The low-beta quarter wave resonator.

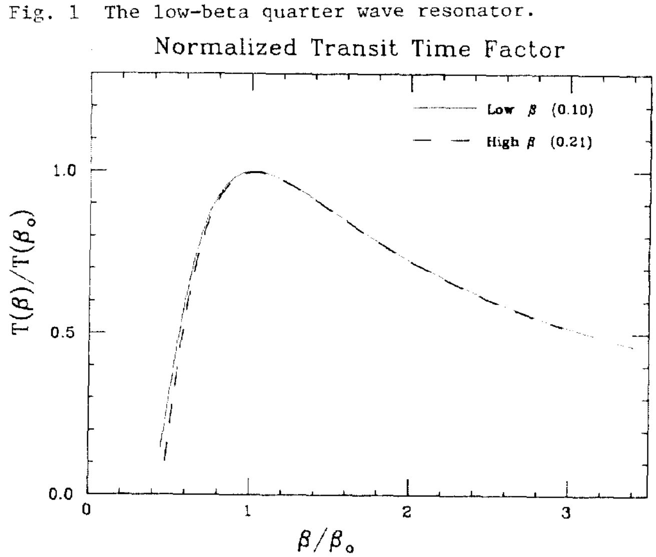

Fig. 2 Transit time factors vs. beta. As we define the average accelerating field to include the effects of the transit time factor at the optimum velocity, we normalize the velocity dependence of the transit time factor to 1. We have plotted curves as a function of the ratio of velocity to optimum velocity for both resonators. These results are calculated using field profiles obtained from bead pull measurements.

Washington Nuclear Physics Laboratory. The plating and chemical polishing techniques were those originated at Caltech and described most recently by Burt,[2] with some modifications which had been developed at Stony Brook, at the Weizmann Institute and at the U. of Washington. The main modifications involve 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 is a lead sheet which is formed into a cylinder and suspended in the volume between inner and outer conductors. A current of 2.6 A (about 3.5 mA/in^2) is used, and was turned on and off for 1 (0.1) sec intervals at Stony Brook (at UW). Total plating time was 12 hours.

Tests on the successfully plated resonators indicate that average accelerating fields of 2.35 to 3.24 MV/m are obtained with 3.0 W and fields of and 3.24 to 3.76 MV/m are obtained with 6.0 W dissipation. As 6 W of cooling is conservatively available, our design field of 3.0 MV/m seems readily attainable. A graph of the resonator Q vs. average accelerating field is given in Fig. 3 for the three successfully plated

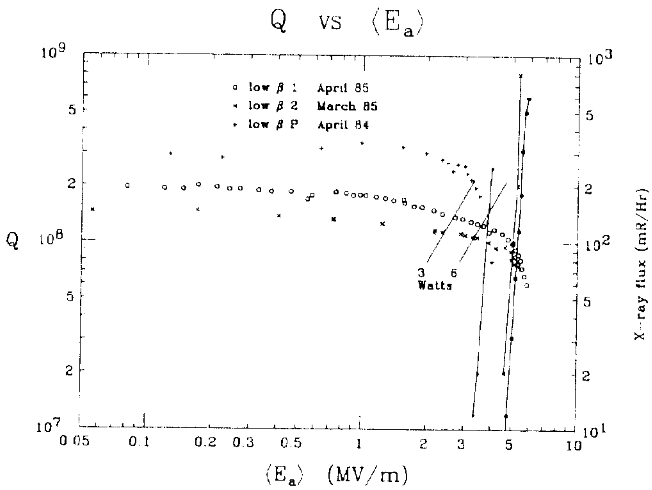

Fig. 3 Q vs. Average Accelerating Field for tests of the low-beta quarter wave resonators. The resonator serial numbers are indicated. Resonator P is the prototype. The nearly vertical lines show x-ray flux versus field. Diagonal lines are drawn to illustrate Q vs. Field for constant power levels of 3 or 6 Watts.

resonators. These data were all obtained with CW operation. The maximum CW power that the resonators could be run at before going normal was about 50 W. On the same graphs we show the x-ray flux measured about 30 cm from the test cryostat wall. The very rapid increase in x-rays at the same time that the curve of Q vs. E bends down indicates that the excess power is being consumed mainly by field emitted electrons. The fact that the curve is quite flat before the onset of measurable x-ray emission indicates that there are not significant defects in the superconducting lead that grow with increasing currents. Helium conditioning was performed prior to measuring those data. Before helium conditioning, the "corner" of the curve occurred at lower fields, typically 1 to 1.5 MV/m.

During the tests of the production resonators, they were first warmed to about 80 C for about 24 hours. When the vacuum reached 5×10^{-6} Torr or better, rf power was applied for a few hours, during which time multipactoring was observed. Then the nitrogen shield was filled and the vacuum reached the low 10^{-7} or high to 10^{-8} Torr range. Then the resonator was cooled with liquid nitrogen. During the cooling with nitrogen, the multipactoring usually ceased or at least reached a point where it would occur only if the applied rf power was carefully tuned to bring the resonator field just to the multipactor level. After this multipactor conditioning, in some cases we had no multipactoring at helium temperature and in other cases we would occasionally be bothered by multipactoring during the first hour or two of the tests.

Beta = 0.21 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. Some scaling laws are relevant in making this choice. If the frequency is not changed, the length remains the same. Then 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 frequency of transverse mechanical vibrations 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 will have lower frequencies, but these have not been observed to modulate either the high- or low-beta resonator. The power dissipated in field emission scales as the third power of the radius, since the area for field emission (mainly the surface of the center drift tube) scales as the second power and the voltage is proportional to the radius. As field emission sets in rather sharply, this disadvantageous scaling should only require reduction of the field by a small amount. Modifications in geometry may reduce the ratio of peak surface electric field to average accelerating field, and thereby more than recover the accelerating fields lost by the disadvantageous scaling.

As the energy gain is proportional to the radius, it seemed best to maintain the fundamental frequency and to double the resonator radius to obtain higher beta. This approach may be limited by stored energy increases, which cause an increase in 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.

Considerations of the geometry on the peak surface electric field are very important. We have improved on the ratio of peak to average accelerating electric field found in the low-beta resonator. The peak surface field is on the spherical regions of the center drift tube. By increasing the size of the center drift tube by more than the amount we increase the other radial dimensions, we can reduce the surface electric fields. However, as the loading capacitance doubles in the basic doubling of the radii, additional increases in the size of the center drift tube will increase it further.

Since the voltage at the end of the resonator for a given current at the top plate is proportional to the cosine of the ratio of load to characteristic impedence, increased loading capacitance causes a second order decrease in the shunt impedence. Because increased loading capacitance requires a shorter resonator, the increase in stored energy is also a second order effect. Thus some increase in loading is tolerable.

Thus, the major design compromise considered for the high-beta resonator was between increasing loading and decreasing peak surface fields. To calculate 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 corresponding ratio 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. First we used the calculated 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 the 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 impedance (Z_0) at a given z (longitudinal coordinate) is given by the usual result for a uniform coaxial structure. Using $Z_0(z)$ and the wavelength, we calculated the current and voltage as a function of z beginning at the voltage node. At the end of the center conductor the current is not zero. The appropriate load capacitance to produce the calculated voltage to current ratio was determined. This calculation also gave the ratio of peak voltage to peak current, from which we can obtain the ratio of average accelerating field to peak magnetic field. The maximum surface magnetic field (assuming smooth surfaces) is about 250 Gauss at 3.5 MV/m, for both resonators. This field can be compared with the critical magnetic field of about 500 Gauss for lead at 4.5 K.

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 about 18 degrees. 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 given 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 an additional 20%. 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. 4.

Measurements made using a brass model of the high-beta resonator indicate that the ratio of the stored energy to the square of the averaging accelerating field is 0.252 Joules/$(MV/m)^2$.

Our prototype high-beta resonator has some cracks in the interior weld. During the lead plating process, these cracks admitted various chemicals that then leached out under vacuum and etched away the lead surface in their vicinity. Consequently, the Q of the resonator was poor at low fields, and got worse as the field was increased. For one test we were able to cover the cracks with an indium-silver solder. The lead plated well over the solder, and the low field Q was measured to be 4×10^8, about as expected. With increasing power, however, the Q suddenly dropped. We think this drop was due to the poor heat transfer properties of the rather thick layer of solder. Using thinner layers, we were unable to cover the cracks satisfactorily. We are presently building a second resonator.

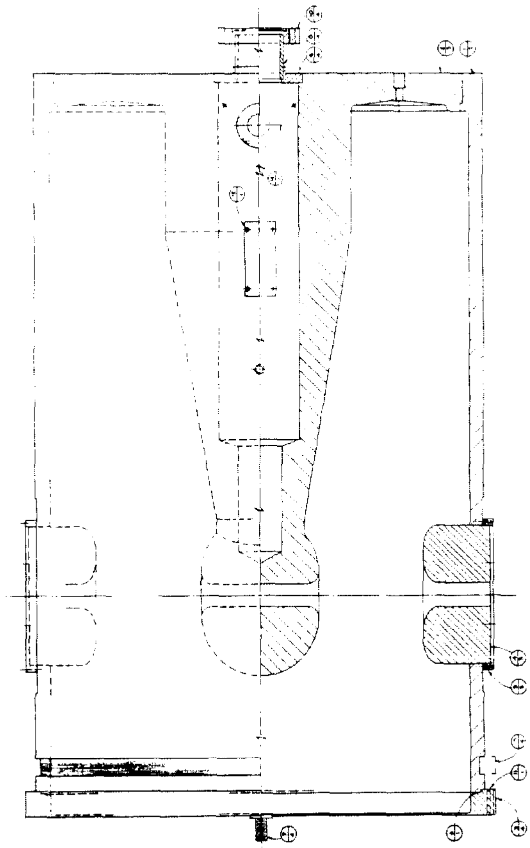

Fig. 4 The high-beta quarter wave resonator.

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[2] W.W. Burt, Advances in Cryogenic Engineering Materials 29, 159 (1983).

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