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A SLOW TUNER FOR SUPERCONDUCTING HELICALLY LOADED RESONANT CAVITIES†

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Abstract

We have developed a concept for a device to control the static resonant frequency of superconducting helically loaded cavities over a wide range and have applied this concept to the particular problem of the Karlsruhe proton accelerator. Basically, the device consists of a Nb plunger attached to a dielectric cylinder which provides support and a path by which the plunger may be cooled with liquid helium. Model tests on the second Karlsruhe cavity show that two such plungers can give a tuning range of 100 kHz at high field levels without significant surface field enhancement or disturbance of the flatness. Furthermore, with radiation pressure induced static frequency shifts of up to 500 kHz, they permit constant frequency operation at arbitrary axial field levels without surface fields significantly in excess of those present at maximum axial field and without significant flatness disturbance. Related materials problems have been studied and will be discussed.

I. Introduction

In this paper we will discuss the conceptual design of a device which may be used to adjust the resonant frequency of superconducting resonant cavities. Although applicable to various kinds of cavities, we will discuss its application only to the special case of helically loaded cavities. Furthermore, we will consider only slow changes in the resonant frequency as distinguished from fast or dynamic tuning. Thus, the device is called a "slow tuner".

Helically loaded cavities are of interest for several reasons. The primary one for us is the construction at Karlsruhe of a superconducting proton linear accelerator. This has been described previously by Citron[1] and is discussed in several papers at this conference. In addition, helically loaded cavities are also being considered as a possibility for elements in heavy ion linear accelerators.

Cavities of this type have two features which bear directly on the slow tuning problem. First, because of the nature of the helix, it is difficult to build the cavity so that it has an exact predetermined frequency. Second, the shift in resonant frequency caused by radiation pressure can be very substantial. A rather extreme example of this effect can be seen in the first cavity of the Karlsruhe accelerator (reported on at this conference) which has a radiation pressure induced frequency shift of about 1 MHz at its design field levels. The importance of this effect depends on the situation. In a fixed profile machine such as the Karlsruhe accelerator, cavities will probably be operated at only one field level. If this field level can be varied slightly, the radiation pressure induced frequency shift can itself be used as a slow tuning device, probably obviating the need for a tuner of the type described here. However, if the cavity field level must be varied, as will probably be the case in a heavy ion accelerator, some sort of slow tuner will be required and in fact must be an essential part of any viable design.

II. Conceptual Design

Since it was not clear whether a slow tuner would or would not be needed, we addressed ourselves to the problem of developing a conceptual design for the Karlsruhe accelerator cavities. Many ideas were considered. Most of these suffer from practical difficulties and were discarded. The design which was adopted is shown schematically in Fig. 1. In essence, the device is a plunger mounted at the midplane of a helical element (where the radial electric field is strongest) in such a way that it can be moved in a direction perpendicular to the axis of the helix. In the present design, the plunger is fabricated of thin niobium sheet and is filled with liquid helium for cooling.

If the plunger were supported on a metallic element, energy would be propagated up the coaxial transmission line formed by that element and the outer metallic cylinder. In order that this energy not be dissipated as resistive losses it would be necessary to terminate the line in a superconducting sliding seal or a superconducting flexible element such as a bellows. (Conventional quarter wave traps are not practical due to the long wavelength). We were not comfortable with either of these ideas so we chose to support the plunger on a dielectric cylinder with the idea that our outer cylinder would act as a waveguide in cutoff mode rather than as a coaxial transmission line. The use of a cylinder provides a path by which helium may be supplied to the plunger. To shield the lower

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niobium-dielectric joint from high fields it was placed in a reentrant position within the plunger.

The upper end of the dielectric cylinder is supported by a piston which in turn is moved by a mechanism not shown in Fig. 1. A flexible vacuum seal is made by a bellows surrounding the assembly as shown in Fig. 1. The design of these elements is relatively straightforward and will not be discussed further.

In order that the plunger not accumulate excessive charge, a resistive path to ground must be provided. This function is performed in the present design by a cylindrical carbon resistor which is placed on the axis of the dielectric cylinder. It was found empirically that the thickness of the carbon film could be adjusted so as to provide a relatively low resistance to ground while not affecting attenuation in the transmission line above the plunger.

The reentrant housing for the plunger shown in Fig. 1 is an artifact of the large radius of the Karlsruhe cavities. In a cavity with a smaller outer radius, this housing would not be used.

III. Materials and Fabrication

The material chosen for the dielectric support cylinder and resistor rod was high purity Al_2O_3, i.e. alumina. This choice was motivated by several considerations. First, high purity alumina has a loss tangent at helium temperature of less than 10^{-6}.[2] Second, it is a strong material, third, it has thermal contraction properties similar to niobium. Finally, it is available at relatively low cost.

The first fabrication problem that we will discuss is that of the joint between the alumina and niobium elements. We have begun small development programs on both brazed and epoxied joints. At this time our efforts on brazing have not progressed far enough to have reportable results. We have had, however, good success with epoxy joints. In particular, we have fabricated two test assemblies, each consisting of an alumina tube with niobium end caps which have the same joint geometry as is shown in Fig. 1. These were joined using Epoxydhard BN 710 epoxy[3] and then vacuum tested while being thermally cycled between room temperature and 1.8°K. Each piece was thermally cycled 4 times, subjected to thermal shock by rapid immersion in liquid nitrogen and then retested at 1.8°K. There was no evidence of leakage or diffusion in any of these tests (sensitivity: 3×10^{-9} torr ℓ/sec).

The other fabrication problem which we will discuss is that of resistors. We found that we could easily fabricate resistors by coating alumina rods with Aquadag[4] and then baking the rods at 100°C to evaporate the water in the Aquadag. Resistors of this type were stable with respect to both mechanical handling and thermal cycling to 1.8°K.[5] The resistance was found to increase by a factor of about 4 when the temperature was lowered from room temperature to 1.8°K.

IV. Model Tests

In order to better understand the electrical properties of the tuner, we constructed room temperature models of two elements of the tuner. The first was a model of the transmission line formed by the outer cylindrical housing, alumina support cylinder and resistor. The model consisted of a cylinder containing a fixed and a movable element. The fixed element was a 50 Ω coaxial line which terminated within the cylinder. The movable element was an insulated piston which reproduced the geometry of the tuner plunger. By exciting the "plunger" element with a transmitter and measuring the power transmitted to the 50 Ω element, we could measure the attenuation within the line.

There are three important results from our measurements with this model. First, the measured attenuation within the line without any dielectric elements was 1.17 dB/mm at 90 MHz. This is in good agreement with the calculated attenuation for the presumably dominant TM_{01} mode. For the geometry shown in Fig. 1, this results in an attenuation of ~ 90dB.

Second, insertion of glass elements which simulate the final alumina elements produced no observable change in attenuation at a level of -50dB. (Set by the relative insensitivity of our detection apparatus). We have not solved the exact electromagnetic equations for the situation shown in Fig. 1 i.e., a dielectric rod surrounded by a dielectric cylinder surrounded by a metallic conductor. However, the results of Chambers[6] for the simpler case of a dielectric rod within a metallic cylinder indicate that the cutoff frequency for our geometry should be substantially above our operating frequency of 90MHz in agreement with the measurement described above.

Third, we constructed a resistor similar to that proposed for the final design and measured the attenuation in our transmission line model as a function of the resistance value. (The resistance value was changed by sanding the resistor). We found that at values in the order of 1K ohm there was essentially no attenuation. As the resistance was increased, the attenuation increased rapidly, reaching a value of 70dB at a resistance value of 150K ohm. (This was the limit of sensitivity in these measurements). At 90dB attenuation, the extrapolated resistance value is 400k Ω. For safety, we assume a resistance value of at least 1M ohm. In the worst case, with the plunger withdrawn, the plunger will have a capacitance of ~ 7×10^{-11} farads giving a time constant of 7×10^{-5} sec for decay of charge accumulated on the plunger.

The previous considerations assume a resistor of uniform thickness over the length of rod. In practice, it may be necessary to reduce further the thickness of the resistor near the plunger to reduce resistive losses due to high electric fields in this region.

The second model which we constructed was one of the second accelerator cavity described elsewhere at this conference. (This model was of course used for other measurements as well as those to be described here). For these measurements, two model slow tuners were constructed and placed over the second and fourth helices of the cavity. These are the seventh and ninth helices of the accelerator are so labeled in Figs. 2-4 and in the subsequent discussion.

In Fig. 2, we show the dependence of the cavity resonant frequency on the position of the plungers. As can be seen, plunger No. 7 has a much greater effect than No. 9. We believe that this occurs because helix No. 7 is excited to higher axial and radial field levels than No. 9 because this cavity was tuned for constant surface field in contrast to the first cavity which was tuned for constant axial field.

In Fig. 3, we show the change in flatness caused by the tuners as a function of frequency shift. By flatness, we mean the following. Consider the axial electric field as a function of longitudinal position along the cavity. In general there are 4 positions where peak fields occur. These are between helices 6 and 7, 7 and 8, 8 and 9, and 9 and 10. (The fields at the outer ends of helicies 6 and 10 are reduced by end effects.) Label these peak fields as Pij where ij = 6 and 7, 7 and 8, etc. Let ΔPij = 1-Pij (perturbed)/ Pij(unperturbed). Let ΔP(Max) be the largest value of the four ΔPij and ΔP(Min) be the smallest value of the four ΔPij. Then we define the change in flatness $\Delta F = (\Delta P(Max) - \Delta P(Min)) \times 100\%$.

The fields were measured using the usual frequency perturbation technique.[7] For these measurements, the perturbing object was an aluminum oxide cylinder 19 mm long and 7 mm in diameter.

The results of these measurements are clear. When both plungers are kept at equal distances from their respective helices, (that is, moved in or out together) the cavity may be tuned over a large frequency range without significant disturbance of the flatness. For example, at Δf = 600 kHz, $\Delta F < 4\%$. This value of ΔF is in the order of the uncertainty of the initial adjustment of the flatness. On the other hand, if only one plunger is used, the disturbance of the flatness is relatively high. This is in agreement with other preliminary measurements and our intuitive understanding, both of which suggest symmetric placement of plungers within the cavity. For example, if only one plunger is used, it should be placed at the middle of the cavity.

The most significant field perturbation caused by the plungers is of the radial electric field in the region between the plungers and the helices. In the following discussion we will describe measurements of the surface radial electric field at positions adjacent to the plungers and the effect on these fields of the plungers. The measurements were again made using the frequency perturbation technique.[7] The perturbing object was a 6 mm diameter Stycast ball (κ = 10) which moved along an axis parallel to the axis of the cavity in a plane containing the cavity axis and the plunger axes at an average distance of about 7 mm from the outer surface of the helices. The points of particular interest are at the midplane of helices 7 and 9, i.e., at the points nearest the plungers. Here the field is radial and suffers the largest enhancement due to the presence of the plungers.

In this series of measurements we measured the field at these points in both the unperturbed and perturbed case and computed the ratio. For the geometric situation described above, we believe this ratio is a good measure of the surface field enhancement caused by the plungers.

In Fig. 4, we show the results of these measurements for the case where the plungers are equidistant from their respective helices, i.e., where they are moved in and out together. The dependent variable in this figure is the ratio described above. Two features are evident. First, the field enhancement is high, reaching an average value of about 2.3 at Δf = 600 kHz. Second, the field enhancement is different for the two plungers, again because of the asymmetric tuning of the cavity described above. In actual practice, the position of the plungers would be adjusted to produce equal field enhancement so that the field enhancement for the cavity would be the average of the values shown in Fig. 4.

Fortunately, the large field enhancement produced by the plungers is mitigated by the following consideration. The radiation pressure induced frequency shift is negative. That is, the cavity frequency decreases as the field levels are increased. The frequency shift produced by the plungers is also negative, i.e. the cavity frequency decreases as the plungers are inserted. This means that when the plungers are used to compensate for radiation pressure induced frequency shift, they will be inserted at low field levels and withdrawn as the field levels are increased. Thus the enhancement of the fields caused by the plungers tends to be compensated by a reduction in the absolute field level.

We will now make this argument on a more quantitative basis. Let f_1 = the frequency of the cavity at "zero" field level with the tuners withdrawn. Let f_m = the frequency of the cavity at the maximum operating field level with the tuners withdrawn. We define $\Delta f_{MAX} = f_1 - f_m$. Let f_o = the actual operating frequency of the cavity. Then $f_o \le f_m < f_1$. Note that the first inequality is required by the necessity of reaching the design field level. Let Δf_t = the magnitude of the frequency shift caused by the tuners and Δf_e = the magnitude of the radiation pressure induced frequency shift. Then $\Delta f_t + \Delta f_e = f_1 - f_o$. As mentioned above, it is not possible to pre-adjust the cavity so as to have an exactly predetermined frequency. We have defined this uncertainty as Δf_{FRICKE}. That is, $0 \le f_m - f_o \le \Delta f_{FRICKE}$. Let E = the radial electric field at the midplane of a helix adjacent to a tuning plunger. Since Δf_e is proportional to field level squared, we have

$E = E_{MAX}\left(\frac{\Delta f_e}{\Delta f_{MAX}}\right)^{1/2} \times R(\Delta f_t)$ where E_{MAX} is the value of E which occurs when $\Delta f_t = 0$ and $\Delta f_e = \Delta f_{MAX}$ and $R(\Delta f_t)$ is the experimental enhancement ratio shown in Fig. 4. Now

$$\begin{aligned}\Delta f_e &= f_1 - f_o - \Delta f_t \\ &= (f_1 - f_m) + (f_m - f_o) - \Delta f_t \\ &= \Delta f_{MAX} + (f_m - f_o) - \Delta f_t\end{aligned}$$

and
$$\frac{E}{E_{MAX}} = R(\Delta f_t)\left(\frac{\Delta f_{MAX}}{\Delta f_{MAX} + (f_m - f_o) - \Delta f_t}\right)^{-1/2}$$

This has its largest value when $f_m - f_o = \Delta f_{FRICKE}$. Therefore, we define

$$D(\Delta f_t, \Delta f_{MAX}, \Delta f_{FRICKE}) = \left(\frac{\Delta f_{MAX}}{\Delta f_{MAX} + \Delta f_{FRICKE} - \Delta f_t} \right)^{\frac{1}{2}}$$

and note that

$$\frac{E}{E_{MAX}} \leq \frac{R(\Delta f_t)}{D(\Delta f_t, \Delta f_{MAX}, \Delta f_{FRICKE})} .$$

Two D functions are shown in Fig. 4. It is clear that Δf_{MAX} = 500 kHz is a satisfactory situation while Δf_{MAX} = 1000 kHz is not. With Δf_{MAX} = 500 kHz and Δf_{FRICKE} = 100 kHz, the maximum absolute field enhancement would be about 10% and this would occur at the maximum operating axial field level of the cavity.

V. Conclusions

Because of resource and time limitations, we have not yet attempted to build a tuner of the type described here. With the general reservation that no design can be considered certain until tested, we believe that the design described here represents a reasonable solution to the slow tuner problem. Our model measurements indicate that the minimum number of tuners required per cavity is limited by surface field enhancement rather than flatness changes and depends sensitively on the radiation pressure induced frequency shift at maximum operating field level.

VI. Acknowledgment

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References

1. A. Citron, Proc. of 1970 Proton Linear Accelerator Conference, pg. 239.

2. K. Mittag, R. Hietschold, J. Vetter, and B. Piosczyk, Proc. of 1970 Proton Linear Accelerator Conference, pg. 257. The samples discussed in this reference were Type E37 manufactured by the firm Feldmühle AG, 731 Plochingen, West Germany. The Al_2O_3 elements shown in Fig. 1 are sizes which are available in the same material.

3. Schering AG, Berlin, West Germany.

4. Acheson Colloids Corp., Port Huron, Michigan, U.S.A.

5. We are indebted to H. J. Spiegel and G. Krafft for the thermal cycling measurements.

6. L. G. Chambers, Brit. J. of Applied Physics, 4, 39 (1953).

7. See, for example, P. Branham, Report 639, High Energy Physics Laboratory, Stanford University (1970), unpublished.

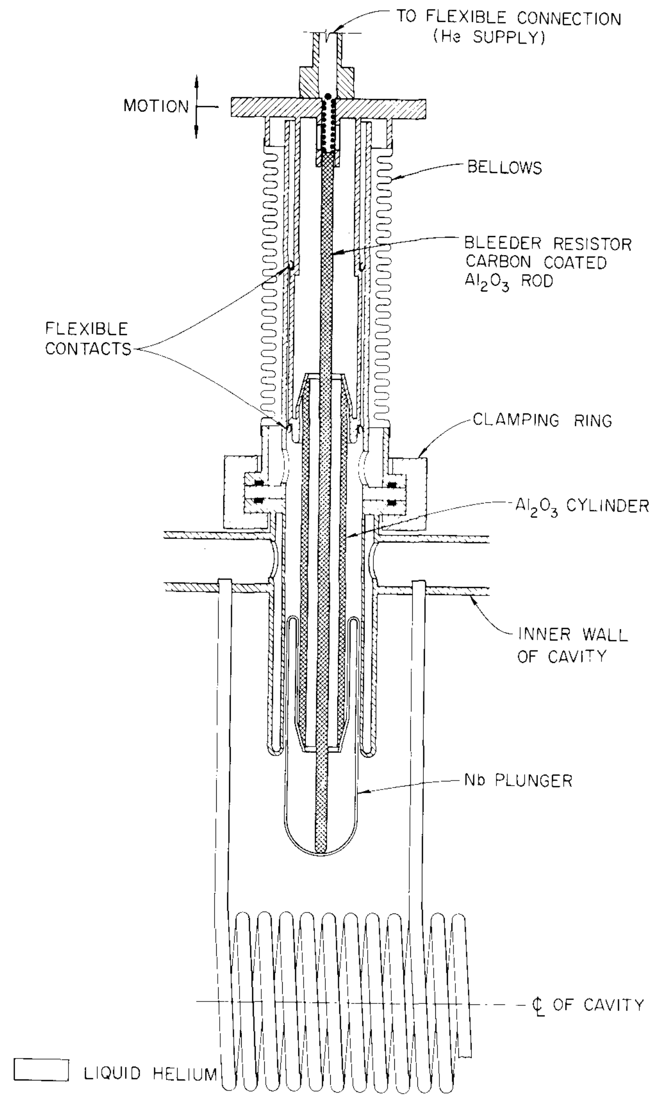

Fig. 1 A schematic view of the proposed slow tuner. Details such as welds, some "O" rings, bolts, etc. are not shown.

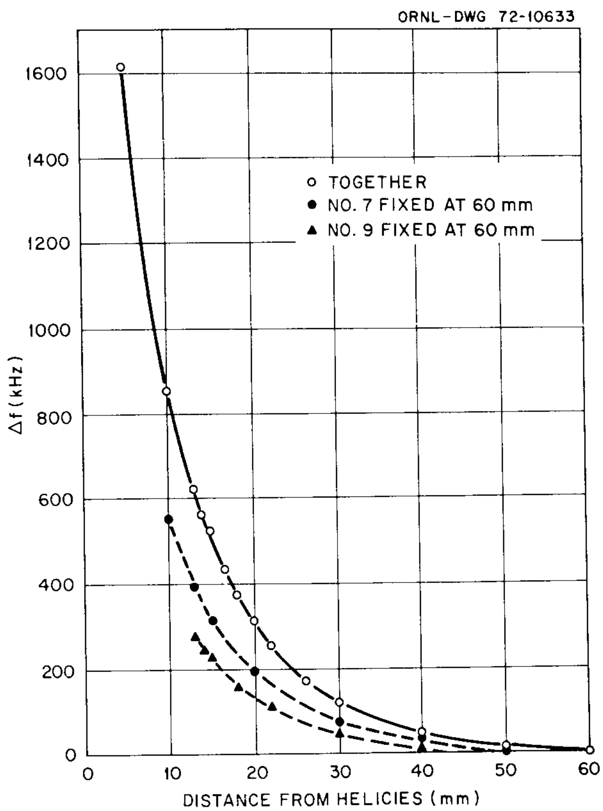

Fig. 2 Frequency shift, Δf, in kHz as a function of the distance, in mm, between the plunger and the outer surface of the helices.

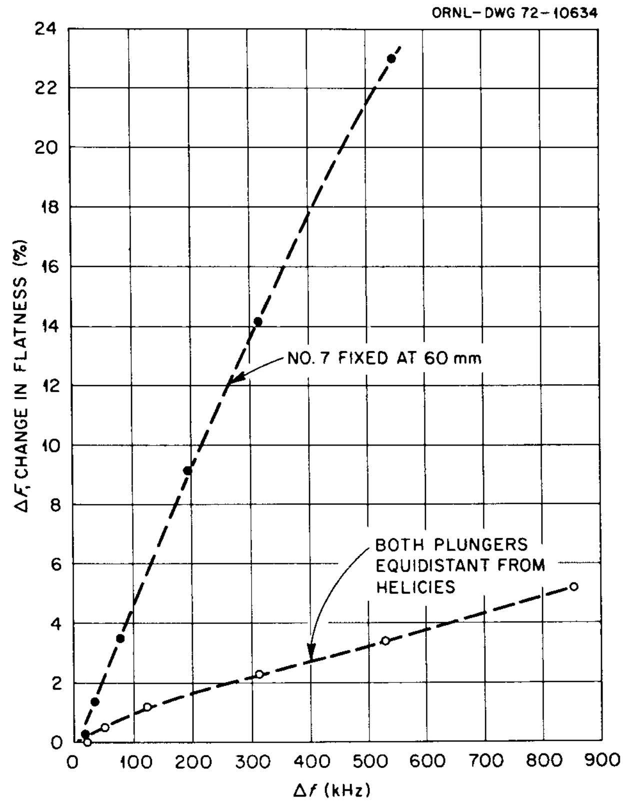

Fig. 3 Change in flatness, as defined in the text, as a function of frequency shift in kHz.

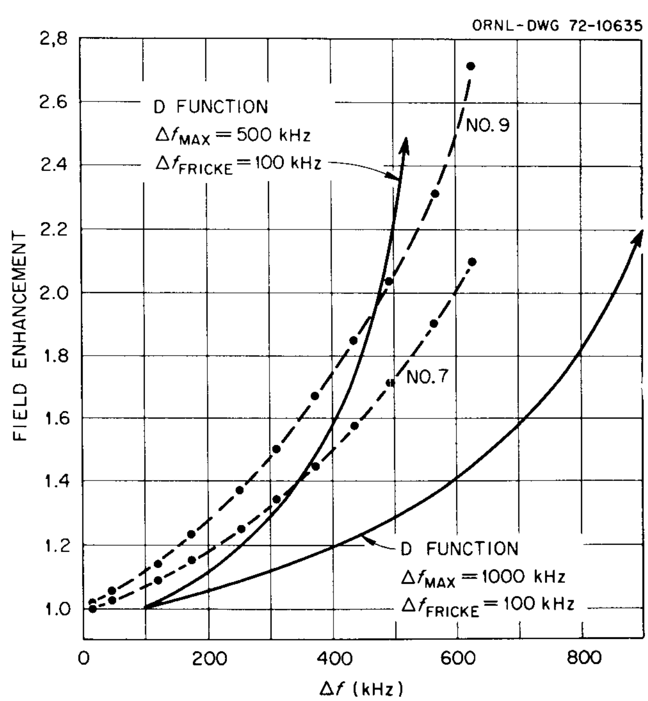

Fig. 4 The experimental points are the measured radial electric field enhancement, as defined in the text, as a function of frequency shift in kHz. The solid lines are the calculated D functions as defined in the text.