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DESIGN AND MEASURED CHARACTERISTICS OF MINIMUM LOSS LOW-VELOCITY HELIX RESONATORS*

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Summary

The design and performance of helix resonators operating at room temperature are described. The resonators are analogous to $\lambda/2$ transmission lines shorted at both ends, and they oscillate at a frequency of 50 MHz. If slightly flattened 1/4 in. diam tubing is used to construct the helix, the resonators combine high shunt impedance with adequate coolant flow for high duty factor operation. Calculated and measured shunt impedances for different resonator phase velocities are given. The highest measured shunt impedance was 31 MΩ/m, for a resonator with a phase velocity equal to 0.04 c. For a steadily applied field of 1.25 MV/m, and a water pressure of 1500 psi, various helix designs have cooling water temperature rises of 10-22 C. Two coupling arrangements which provide 50 ohm resistive input impedance at resonance are described. The resonant frequency can be tuned by a threaded 3 in. diam copper plug mounted in the cylindrical wall. A facility for testing resonators at full power is described.

Introduction

The use of helix-loaded resonators for accelerating heavy particles has been discussed in the literature . A resonator of this type is formed by mounting a conducting helix inside a concentric cylinder, as shown in Fig. 1. There has been considerable recent interest in these resonators as low phase velocity linac structures. A heavy ion accelerator has been proposed by the Los Alamos Scientific Laboratory based on the use of 50 MHz half-wavelength helix-loaded resonators operating at room temperature. The resonator phase velocities range from 2.3 to 8.4 percent of the velocity of light. Each resonator will be independently phased to optimize the energy gain and beam characteristics of different ion species.[5]

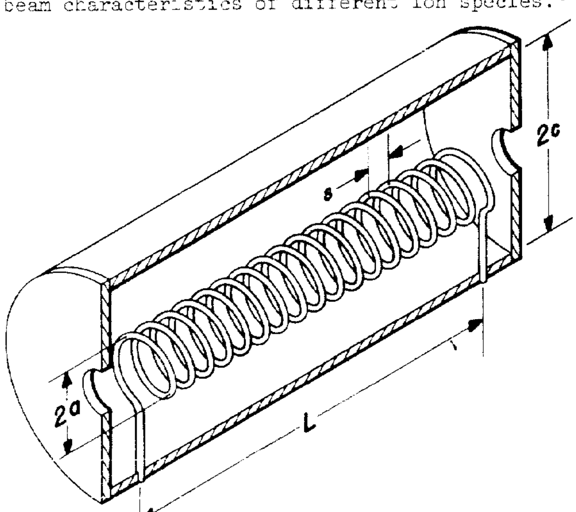

Fig. 1. Side-terminated helix resonator.

We report here the results of studying three resonator design problems. These are: (1) shunt impedance optimization with adequate cooling for high duty factor operation; (2) RF power coupling into resonators from a 50 ohm line; and (3) resonant frequency trimming for alignment of a series of resonators.

Calculating and Measuring Shunt Impedance

For a given resonant frequency, the maximum shunt impedance Z that can be achieved in a helix-loaded resonator is a function of β (the ratio of the phase velocity to the velocity of light). We use sheath model theory[6,7] to calculate Z and β' of an infinitely long helix-loaded waveguide excited at 50 MHz. Curves and equations published in Ref. 3 are used to find those values of helix pitch s, helix radius a, and shell radius c, which produce the maximum value of $Z(\beta')$ for each value of β' (the prime refers to the waveguide).

Our interest is in $Z(\beta)$, where β refers to a $\lambda/2$ resonator. End effects in the resonator cause β to differ considerably from β', for the same values of s, a, and c. We use the theory of Ref. 1 to calculate the length of resonator which will oscillate at 50 MHz, and to calculate β. We then assign the previously calculated maximum value $Z(\beta')$ to β for the resonator.[8] The smooth curves in Fig. 2 were generated by this procedure. They show a broad maximum in $Z(\beta)$ between $.03 < \beta < .05$, with lower values both above and below this range.

The crosses in Fig. 2 depict the highest measured shunt impedances of a series of designs covering the velocity range of interest. The measurements are made by a perturbation method[1,6] in which a sapphire bead is pulled along the resonator axis.

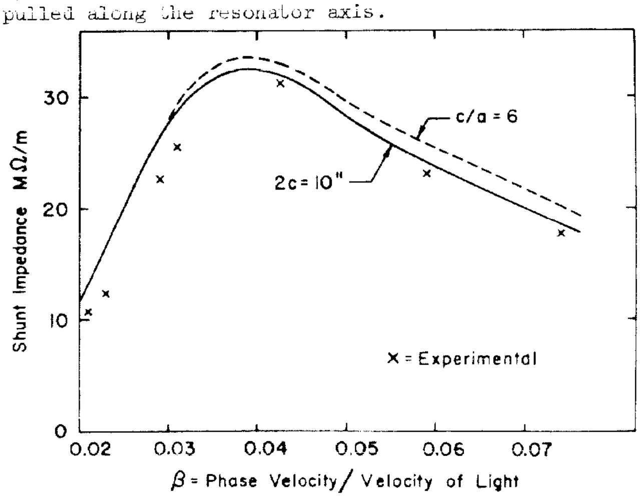

Fig. 2. Measured and calculated shunt impedances $Z(\beta)$.

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Additional Guides for Resonator Design

We have a number of empirical guides for obtaining large Z in helix-loaded resonators: (1) Side-terminated helices, as shown in Fig. 1, have Z's about twice as large as end-terminated helices (which extend to the end plates). (2) The spacing between the ends of the helix and end plates should be $\geqslant 3$ s. (3) For $\beta < .05$, the pitch should be the minimum value compatible with the next requirement. (4) The pitch should be > 1.5 d, where d is the thickness of the helix tubing in the axial direction.[9] (5) The shell radius should be greater than three times the helix radius. (6) To obtain symmetrical axial field distributions, the helix should be accurately centered in the outer shell, and to maintain high Z, the helix should be wound with small errors in the turn-to-turn spacing. In the future we may study programmed variations in pitch to obtain higher Z values.

Cooling the Helices

In order to achieve $\beta < .05$, helices must be wound with a small pitch and a large radius. If 1/4" diam round tubing is used, the shunt impedance is low, because the spacing between turns is small, and this increases the reluctance for the radial magnetic field. Smaller diameter tubing reduces the coolant flow, and hence the duty factor for high power operation. We have found that winding helices of flattened 1/4" tubing achieves both a high shunt impedance and adequate cooling. In order to increase the spacing between turns, the helix is wound with the major axis of the tubing radial.

We have made shunt impedance measurements on seven different helices, which were installed successively in the same shell, to form a resonator with $\beta = .03$. The helices were identical except for the cross section of the copper tubing. We also calculated the relative flow of cooling water in the seven helices, and the temperature rise for an axial electric field of 1.25 MV/m. The pressure head used in the calculations was 1500 psi, and the length of tubing was 600 cm. The results of the shunt impedance measurements[10] and the cooling calculations are given in Table 1.

Table 1. Measured shunt impedance, and calculated relative coolant flow and temperature rise for seven different helices in the same resonator ($\beta = .03$ and s = .78 cm). The wall thickness of the copper tubing was .076 cm, and the coolant temperature rise is for an axial electric field of 1.25 MV/m.

Tubing size (inches)	Radial dimen. (cm)	Axial dimen. (cm)	Shunt Imped. (MΩ/m)	Relative Coolant Flow	Temp. Rise (Celsius)
3/16 rd.	.476	.476	18.2	0.56	22
1/4 rd.	.635	.635	10.8	1.76	12
1/4 flat	.645	.582	13.5	1.72	10
1/4 flat	.665	.528	14.2	1.59	10
1/4 flat	.744	.470	16.0	1.39	10
1/4 flat	.792	.391	18.3	1.00	12
1/4 flat	.923	.312	18.6	0.53	22

The second line from the bottom of Table 1 is considered to be the best compromise between high shunt impedance and small temperature rise. The highest measured shunt impedance, 31 MΩ/m, (see Fig. 2) was for a resonator containing a helix wound with this cross section. The other measured shunt impedances in Fig. 2 are for 3/16 in. diam round tubing.

Helices of flattened 1/4 in. Type 304 stainless steel with .035 in. wall have been wound on a mandrel. During winding, the major axis of the tubing is maintained precisely radial by a guide. Straight sections of the flattened SS tubing have been pressure tested, and do not change shape up to 2,000 psi. At 3,000 psi the minor axis bulged .0015", and this distortion remained after the pressure was released. The helices are copper plated after winding.

Coupling Power into the Resonators

For resonator testing, RF power at 50 MHz will be delivered via a flexible 1-7/8 in. 50 ohm coaxial cable. The cable will terminate at a standard EIA flange mounted outside the resonator. Fig. 3 shows two coupling configurations which have a 50 ohm resistive input impedance. In the first configuration (internal coupling), RF passes through an 80 pfd capacitor, and is conducted by copper tubing through a ceramic insulator in the wall of the resonator. The point A at which the side arm attaches to the helix tubing determines the input impedance.

In a second configuration (external coupling), one end of the helix tubing is brought through the resonator wall via a ceramic insulator, and grounded outside the resonator. The RF passes through a 60 pfd capacitor to a clamp A on the tubing, which can be moved to achieve the correct input impedance. In this configuration the adjustment is made outside the resonator and the vacuum in the resonator is not disturbed. Since equally high shunt impedances were obtained with both configurations, the method of external coupling will be used for initial resonator power tests. If greater symmetry is required, an identical coupling scheme can be attached to both ends of the resonator, and driven in the push-push mode.

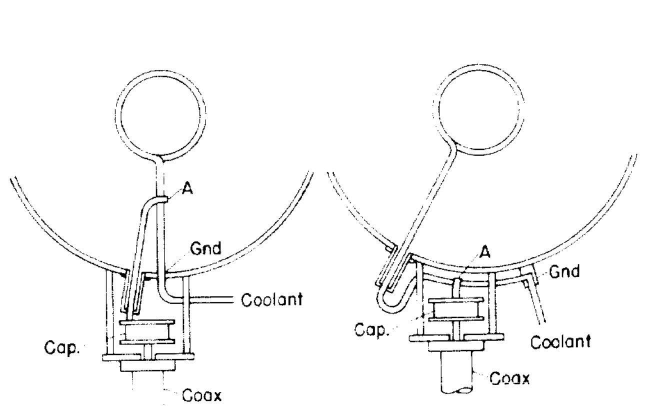

Fig. 3. Two configurations for coupling power into a resonator.

Mechanically Tuning the Resonant Frequency

To devise a satisfactory method for mechanically tuning a resonator, we have installed 3 in. diam copper plugs at several positions in the shell. The plugs were threaded, and the volume of the resonator could be changed by screwing them in or out. The most satisfactory location for a plug is on the cylindrical wall midway between the ends, where it perturbs the strong radial electric field. In this location, the effect of the plug on the axial electric field and the shunt impedance is minimized. The frequency shifted 4 to 7 kHz per mm of displacement along the resonator radius.

High Power Test Facility

A facility for testing prototype resonators at full power is nearing completion. The final stage of the generator supplying RF power consists of a 35 kW tunable power amplifier. The facility will provide cooling water at 1600 psi, and a frequency control loop. In the latter, a phase-sensitive detector locks the oscillator frequency to the natural frequency of the resonator.

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8. This approximate procedure circumvents calculating the losses in a $\lambda/2$ resonator. The justification is that the losses occur primarily in the helix, and not in the shell. The approximation is good only if there is adequate space (~ 2 cm) between the ends of the helix and end-plates of the resonator. The experimental measurements confirm the shape of the curves in Fig. 2.

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10. The resonator was used to test the relative effects of tubing with circular and non-circular cross sections, and the design was not optimized to obtain the highest values of Z.