HIGH POWER VARIABLE COUPLERS FOR LADDER AND SPOKE TYPE RESONATORS

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Abstract

Superconducting RF structures such as spoke resonators [1] have been developed which will accelerate very low velocity ions. This opens up the possibility for the use of these resonators in high power proton accelerators at energies as low as the output energies of typical RFQs. Most similar resonators have been used for the acceleration of ions requiring only low RF power input. In new applications such as for the Accelerator Transmutation of Nuclear Wastes (ATW) and Accelerator Production of Tritium (APT), higher RF power will be required because of the larger beam currents. This paper discusses some higher power variable coupler concepts that could be used with these structures.

1 COUPLING METHODS

The RF coupler power requirements for spoke resonators for the ATW and APT accelerators are in the range of 40kW to 100kW. These power levels are modest so coaxial couplers are good candidates for this application. The methods that can be used for coupling to the resonator are:

- Inductive loop coupler.
- Inductive slot coupling.
- Capacitive.

Loop coupling is not desirable because loop couplers are very susceptible to multipacting and the loop is usually immersed in the high cavity magnetic fields thus dissipating more power. In addition, unless the loop and coax center conductor are made superconducting, the loop provides a thermal path between the normal conducting center conductor and the superconducting cavity leading to larger cryoplant heat loads.

Examples of inductive slot coupling are shown in Figures 1 and 2. In both cases the coax center conductor is thermally detached from the superconducting cavity. Variable coupling is achieved by moving the coax center conductor to increase the end capacitance (Figure 1) and by moving the magnetic field maximum of the coupler standing wave relative to the coupling slot (Figure 2) while simultaneously varying the end capacitance.

Slot coupling has some advantages. The vacuum conductance from the RF window to the cavity is lower, decreasing the cavity cryo-pumped gas load.

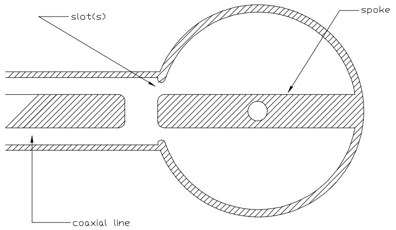

Figure 1. Case 1

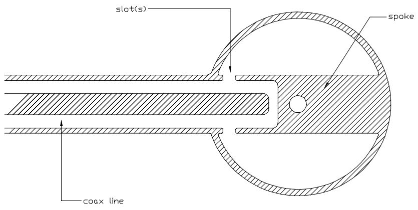

Figure 2. Case 2

The coax center conductor thermally radiates to the coax outer conductor instead of directly to the cavity walls where fields are higher. In addition, if some multpacting occurs in the coax, it will probably not extend into the cavity volume. Disadvantages of slot coupling are: the cavity and coax volume is more difficult to clean, the coupling to the spoke center conductor is asymmetric, possibly exciting deflecting modes or causing power flow field asymmetries. Multipacting in the slot area could also be a problem.

Variable capacitive coupling is the easiest to implement. An example is shown in Figure 3.

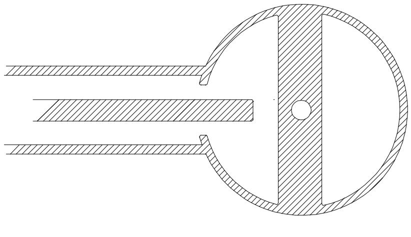

Figure 3. Capacitive coupling.

If the coupler is oriented perpendicular to the spoke, field asymmetries due to mode excitation and power flow are minimized. This type of capacitive coupling needs larger center conductor insertion into the cavity volume

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because of the low electric fields at the symmetry plane. The result is that the thermal radiation load to the cavity walls is larger.

Fortunately, if multipacting occurs at the cavity-coax transition, it will have minimal effect on the cavity performance since the cavity fields are very low at this position and the likelihood of a quench or Q degradation is smaller.

Many other coupling configurations are possible, but only Cases 1 and 2 in the above figures will be discussed further.

2 TRANSMISSION LINE MODELS

2.1 Case 1

The transmission line model for Case 1 slot coupling is shown in Figure 4.

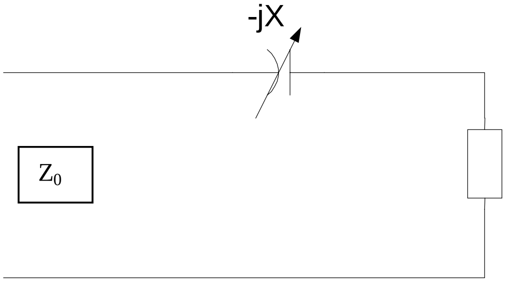

Figure 4. Transmission line model Case 1.

The cavity impedance Z shown above includes the effects of beam loading. The reflection coefficient for this case is given by:

Where:

$$\Gamma = \frac{\beta - 1 + \eta + \frac{X}{Z_0}\left(2Q_0\delta + \eta\tan\varphi\right) - j\left[\frac{X}{Z_0}(1+\eta) + 2Q_0\delta + \eta\tan\varphi\right]}{\beta + 1 + \eta + \frac{X}{Z_0}\left(2Q_0\delta + \eta\tan\varphi\right) - j\left[\frac{X}{Z_0}(1+\eta)\right]}$$

β=coaxial line to cavity coupling factor

η=beam loading factor (P_{beam}/P_{cavity})

ϕ=synchronous phase

δ=cavity detuning factor ($\Delta f/f_0$)

Q_0=cavity unloaded Q

X=reactance of coax-end capacitance

Z_0=transmission line impedance

The conditions for perfect matching are:

$$X = Z_0\sqrt{\frac{\beta - 1 - \eta}{1+\eta}}$$

$$\delta = -\frac{\eta}{2Q_0}\left[\tan\varphi + \frac{X}{Z_0}\left(\frac{1+\eta}{\eta}\right)\right]$$

For high Q systems the above reduces to:

$$\delta = -\frac{\eta}{2Q_0}\left[\tan\varphi + \frac{X}{Z_0}\left(\frac{1+\eta}{\eta}\right)\right]$$

$$X = Z_0\sqrt{\frac{\beta}{\eta} - 1}$$

Notice that the expression for X implies that if the coupling is adjusted for one beam loading condition, the cavity can always be matched for smaller beam loading by adjusting the coax-end capacitance. In other words

$$X = Z_0\sqrt{\frac{I_{design}}{I_{operating}} - 1}$$

As an example take a 355 MHz spoke cavity [1] matched for 100mA at an energy gain of 1MeV and operate it at 20mA:

$$Q_0 = 10^8$$

$$P_{cavity} = 10W(estimate)$$

$$P_b = 20kW$$

$$\eta = 2{,}000$$

$$\varphi = -60^0$$

Matching requires:

$$X = 2Z_0$$

$$\Delta f = -950Hz$$

$$\beta = 10^4$$

For a 50Ω coupler, the coax-end capacitance C would have to be 4.4pF, a value easily obtained.

The corresponding external Q is then 10^4.

2.2 Case 2

The transmission line model for this case is shown in Figure 5.

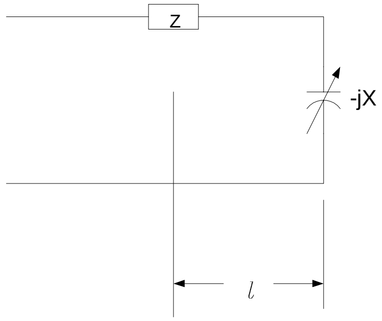

Figure 5 Transmission Line Model for Case 2.

The slot location for the above case is at the Z impedance location a distance *1* from the end of the coax. Defining an effective electrical length for the coaxial line from the slot to the end of the coax as:

$$\theta^1 = \theta - \psi \qquad \theta = \frac{2\pi l}{\lambda}$$

$$\psi = \tan^{-1}\left(\frac{X}{Z_0}\right)$$

The matching conditions for $\eta >> 1$ are:

$$\cos\left(\theta^1\right) = \frac{\eta}{\beta}$$

$$\delta = \frac{\eta \tan\theta^1 - \tan\varphi}{2Q_0}$$

Applying this to the same beam conditions as the example for case 1 above we get:

$\theta^1=78.5^0$ $\Delta f=11.76$kHz C=19.3pF for $\theta=54^0$ $\beta=10^4$

In this case the coax-end capacitance is more difficult to obtain and the length of the coax center conductor has to be accommodated in the spoke of the resonator.

3 HFSS CALCULATIONS

The above transmission line calculations show that case 1 is the more practical of the magnetic coupling cases. To see whether such a coupling scheme is physically realizable, the spoke resonator from [1] was modeled in Ansoft Corporation's HFSS electromagnetic code and the external Q's were calculated for varying slot geometry and coax-end spacing, i.e. capacitance. Figure 5 shows the model of ¼ of the cavity.

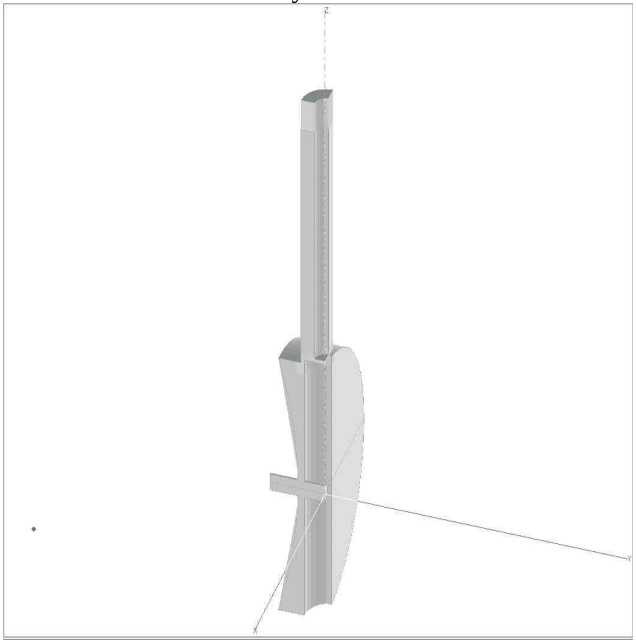

Figure 6. HFSS Model of Spoke Resonator

The coaxial line is a 50Ω line of 1.75" outer radius. There are two annular (moon shaped) coupling slots at the end of the coaxial line 0.25" wide and 0.25" deep whose angular dimension is varied to change the slot length.

Figures 7 and 8 show the variation of the calculated external Q with coax center conductor end gap and slot half angle respectively.

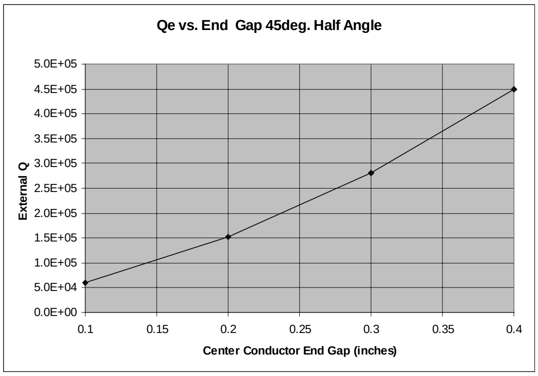

Figure 7. External Q Variation with Gap

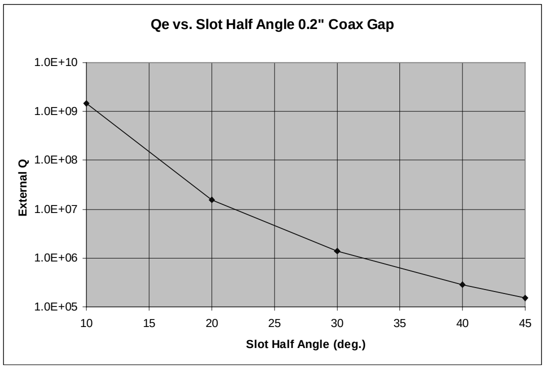

Figure 8. External Q Variation with Angle

The external Qs achievable with reasonable slot size and coax-end spacing are slightly higher than those needed for the example case but could be lowered further by making the slots shallower and adding a capacitive button at the end of the center conductor.

4 CONCLUSIONS

High power variable coaxial couplers magnetically coupled to spoke resonators appear physically realizable. These couplers have some desirable features that lower thermal radiation flux to the cavity surface, lower the vacuum conductance from the RF window into the cavity, and possibly make multipacting problems less likely.

5 REFERENCES

[1] K. Shepard et al., "Development of Niobium Spoke Cavities for a Superconducting Light-Ion Linac, Proceedings of the XIX International Linac Conference, Chicago Illinois, p. 956.