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CONCEPTUAL DESIGN OF AN IDEAL VARIABLE COUPLER FOR SUPERCONDUCTING RADIOFREQUENCY 1.3GHZ CAVITIES*

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Abstract

We explored another over-moded structure that could serve the variable coupling for SRF purpose. This application is to fulfil variation of S11 from 0 to -20db with CW power of 7 KW. The static heat loss in the coupler is trivial from calculation. An advantage of this coupler is that the thermal isolation between the 2K and 300K section is considerable by vacuum separation. Within this coupler, only a single propagation mode is allowed at each section, and thus, the fact that no energy is converted to high order mode bring almost full match without loss. The analytical and numerical calculation for a two window variable coupler is designed and optimized. A RF power variation is illustrated in the scattering matrix and coupling to cavity is also discussed.

INTRODUCTION

Superconducting radiofrequency technology is widely implemented in various accelerators and collaborations around the world [1]. Superconducting cavities and input couplers have been optimized in Tesla collaboration for two decades. TTC-3 coaxial type input coupler is optimized for different purposes through three generations. Two of major optimizations goal are reducing the static heat loss and minimizing electric field on the vacuum windows. Here we design a new over-moded input coupler structure to reducing the static loss.

We introduced a new input coupler without physical contact from the input waveguide and cavity receiver. The structure can convey 7KW CW RF power without calculated multipacting barrier, while produces equivalent dynamic loss and negligible static heat loss. The whole coupler shown in Fig. 1 can be divided into three sections. Left part is the transition from RF source to sapphire loaded converter. Middle is the sapphire guided transmission line. Right part is a convertor to cavity with a given iris.

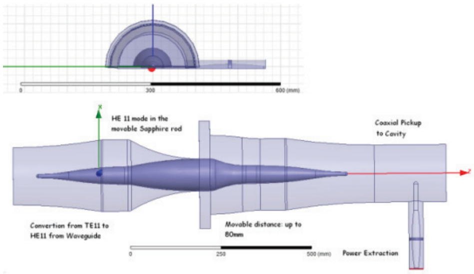

Figure 1: Geometry structure of this HE11 mode power coupler.

GENERAL CONSIDERATION

Hybrid modes are first labelled by Snitzer in 1961[2], and it is more universal mode than the standard TE/TM modes. These modes have both Hz and Ez components and TE and TM modes come together.

In a modern optics fiber industry, HE11 mode is widely used for convey signals [3]. A simple dielectric rod can be used for RF transmission. Inside of this rod, fields can descripted by a series of Bessel functions, while fields outside of the rod are usually evanescent modes in radial direction and surface modes in Z direction. The evanescent mode is the radiation mode with continuous spectrum, and the outside fields can be depicted by modified Bessel functions. In the Z direction, both inside and outside fields should continue on the dielectric and vacuum interface as shown in figure 2.

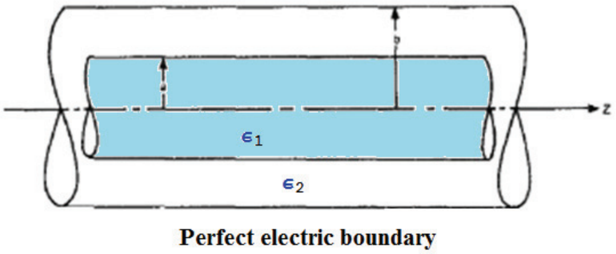

Figure 2: The sapphire loaded waveguide.

Presuming the rod radius is *a*, without $e^{-j\beta z-im\phi}$ term, the field in sapphire rod and between outer conductor is described:

$$\begin{aligned}
&\textit{When} \quad \rho \geq a \\
&\qquad \mathrm{E}_z\ (\mathrm{m}, \beta_s]) = \mathrm{A}\ \mathrm{K}_m(\alpha_s\rho) \\
&\qquad \eta_2\mathrm{H}_z\ (\mathrm{m}, \beta_s]) = \mathrm{B}\ \mathrm{K}_m(\alpha_s\rho) \\
&\textit{When} \quad \rho \leq a \\
&\qquad \mathrm{E}_{zs}(\mathrm{m}, \beta_s]) = \mathrm{C}\ \mathrm{J}_m(\chi\rho) \\
&\qquad \eta_2\mathrm{H}_{zs}\ (\mathrm{m}, \beta_s]) = \mathrm{D}\ \mathrm{J}_m(\chi\rho)
\end{aligned}$$

Where K is modified Bessel function of the second kind, J is Bessel function of the first kind, η is the wave impedance, α and χ are the wave numbers in the sapphire and stuffed material and A,B,C,D are the amplitudes of the field.

Radius d in this equation should be small enough to prevent HE21 mode has larger cutoff frequency than 1.3 GHz. Within the radius limit, a small diameter rod will

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result in that the field extends for considerable distance beyond the surface transversely. A radius is optimistic for obtaining highly guided HE11 mode, if beyond, HE21 is propa gating, if below, the field is weakly guided. One can freely change the radius, in order to change the power distribution inside and outside of the rod.

To connect to the klystron power source, one needs to first convert TE10 WR 650 rectangular waveguide with a simple TE11 circular waveguide. The radius of this circular waveguide is chosen to accommodate only one TE11 mode. This circular waveguide would be the outer conducting wall of this sapphire load structure. Field power is transmitted into rod HE11 mode within the first taper rod. A dielectric rod with carefully chosen radius ratio of waveguide and dielectric rod confines the field inside its body rather than a waveguide. Once the power is highly guided in the rod so that the outside waveguide can by tapered down and seal on the sapphire for vacuum purpose. On the receiving side, both the rod and outside waveguide are tapered in order to push the power in rod into the TE11 mode into the waveguide. Since the RF waveguides from both ends don't contact each other, there is little static heat transfer, nor is the high temperature gradient. Meanwhile, a variable matching mechanism can be easily adapted when these two ends are movable respectively towards each other. Once the power is fully converted into the TE11 mode in the receiving end, one can simply convert this circular mode into coaxial mode to feed the cavity without changing the pre-existing main input coupler port on the beam axis. Note, for the vacuum isolation concerns, one can add another ceramic window inside coaxial cable.

SIMULATION

A superconducting radio frequent resonator is usually operating in L band, for example in our case 1.3GHz. A WR 650 rectangular waveguide conveys the power to the klystron and converts into the circular waveguide, which supports the TE11 mode with one polarization. This converter has been developed and widely used elsewhere. We use a circular waveguide of radius 100mm as outer conductor and a sapphire rod with redius of 25mm as inside conductor. The electromagnetic field pattern of the HE11 mode are calculated by HFSS software and illustrated in Fig.4. There is neither TE 11 mode nor TEM mode in the waveguide at 1.3 GHz. The scattering parameters are also shown in Fig.3, when the coaxial is matched. Other higher order modes are TE and TM waveguide guide modes and not sapphire guided modes.

The field decay outside of the rod can be altered by varying the radius by equivalently changing the β_s. A smooth transition is required to convert the circular waveguide to the HE11 sapphire loaded structure. Higher order modes are introduced to match the field patterns at the discontinuous interface. However, those modes are evanescent modes, which cannot propagate outside with a given length. A double arc structure achieves smooth transition. The configuration is shown in Fig.3.

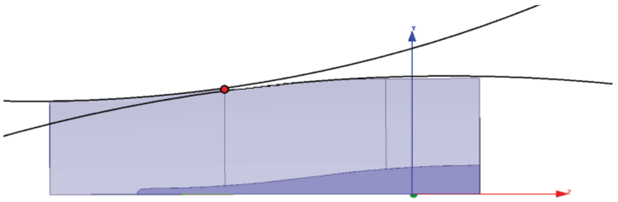

Figure 3: Illustration on double arc structure: the position of red dot is one optimization parameter within given length. Two solid lines are two parts of two circles and indicate the baseline of outer conductor, and at the red dot, they are circumscribed.

This double arc structure design is implemented on both the inner and outer conductors, and the circumscribed positions are the optimizing parameters for obtaining a match. Within a limited given transition length and angel, the position of the red dot is optimized to obtain a match. By doing this optimization, the power of TE11 in waveguide is pressed into sapphire rod body.

After the TE11 mode is converted into the HE11 mode in sapphire, the field decays transversely beyond the surface. The outer conductor has almost no effect on the strong guided power, so we manage to taper the outer conductor down onto the surface, and thus, the sapphire rod acts like a window for vacuum purpose. In Fig.4, the sapphire rod (dark blue) is tapered up and the outer conducting waveguide (light blue) is tapered down by two double arc structures. On the positive z-axis, there is no outer conductor anymore and the power is guided by the sapphire rod. However, for mechanical support and alignment reasons, two copper plates are added inside of XY plane and cavity side waveguide. This is the open to the vacuum area and also a section breaking the RF source and cavity receiver. An outer conductor is added to attach to the cavity wall and these two plates forms a gap open to cryogenic vacuum. These two plates must be long enough to ensure no RF field leakage even there is electromagnetic at this gap in the final design. The structure configuration is demonstrated in Fig.7. There are three optimization parameters: two transition points for sapphire and outer conductor and final sapphire rod radius. This discontinuity in outer conductor will bring an advantage for the static thermal study.

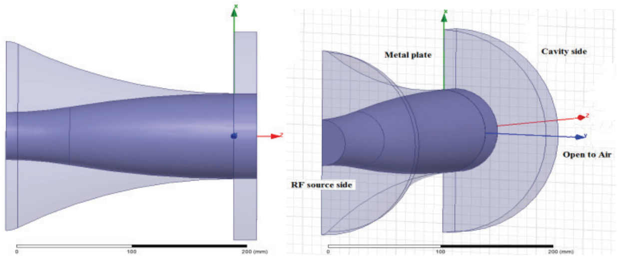

Figure 4: Field pattern and scattering parameters in the converter section.

Since the Tesla Test Research (TTR) shape 9 cell cavities are well developed, it is fairly expensive to remodel the end cell and the attached pipe line with a fundamental coupler hole. We would like to design a converter to change circular TE11 mode into the predetermined coaxial aperture on the TTR cavity. The coupler aperture is 40mm and inner conductor diameter is 20mm. On this coaxial cable, there is an ideal position to isolate vacuum from cavity and the coupler. A 7mm thickness ceramic windows is added inside the coaxial cable, and the electric field on ceramic windows is minimized by properly increase the inner conductor radius. It is not necessary to add a choke joint, since the complete structure is in the 4K environment. The structure of this TE11 to TEM is shown in Fig 5.

After cascading the parts as described above, one can obtain a full structure of this HE11 mode coupler. This section combination exercise ensures that each subsystem has a good match, however, it might be not the most compact structure. To get a compact design, a full structure optimization is needed. A whole structure geometer is plotted in Fig. 1.

As stated above, the center part has an 'open to air' component in which RF power is transferred only in the sapphire rod. The fields are plotted in the Fig.5.

Field distributions in Fig.5 suggest that the field is strongly guided in the sapphire (center). Since strong guided, there is no electric or magnetic field in the 'open to air' components. Thus there is no significant RF power leakage. However, this 'open to air' structure effectively breaks the possible temperature gradient in the outer conductor. RF passed through sapphire rod is pushed out, converted into the TE11 circular waveguide transmitted to the coaxial antenna and thus to accelerating cavities.

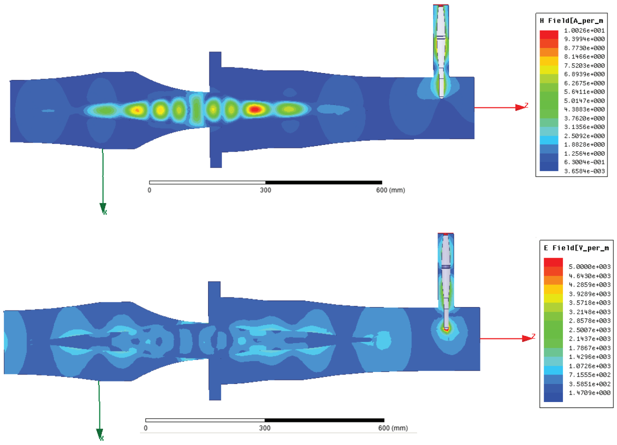

Figure 5: Electromagnetic fields in this HE11 mode power coupler with input power 1W.

The optimized narrowband coupler should enable S11 and S21 a changing range as large as possible at frequency of 1.3GHz. After sweeping the multiparameters above, one needs to obtain a S11 from 1 to 0 in order to achieve full match or full reflection. Fig.6 shows the optimized S reflection and matching parameters at a full matching condition. We have two separate parts in this coupler: one part is connected to the RF source and the other part is attached to the cavity pipeline. The sapphire is held by the tapered outer conductor and acts like a vacuum seal. Between these two parts, there is an opening to the cyro-module vacuum, though one can connect them with a bellow for longer thermal path. This structure leaves us with movable mechanics to change the forward power to the cavity side. This is another method to change the power transmission without changing the coupling of coaxial and cavity as in TTC 3 coupler [4]. The movable geometry and scattering parameters are shown in Fig. 7.

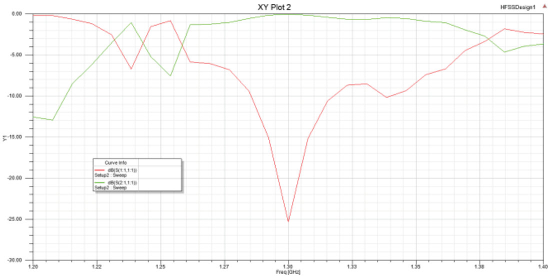

Figure 6: S11 and S21 scattering parameters are shown as a function of frequency with full match condition.

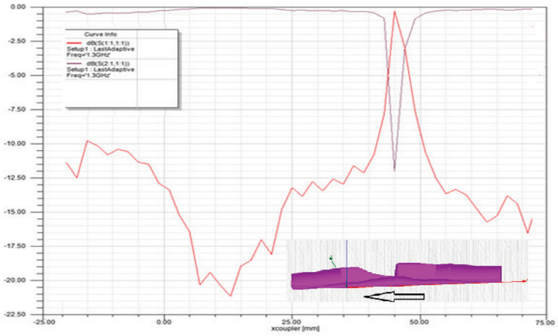

Figure 7: The relation of S parameters and open gap length.

CONCLUSION

A novel concept of a variable coupler is introduced and designed. Theoretical analysis has been simulated by HFSS. This variable coupler has the potential capability to deliver up 7 KW continuous RF power. Further optimization can make this coupler compact and suitable for a given configuration in cyro-module. The prototypes of the polarizer will be produced and tested for experimental soon.

REFERENCES

[1] H. Padamsee, J. Knobloch, and T. Hays, RF Superconductivity for Accelerators. 2nd Edition (Wiley and Sons, New York, NY, 2008).

[2] S.F.Mahmoud, "Electromagnetics waveguides theory and applications", The Institution of Engineering and Technology (December 1991)

[3] E. Snitzer. "Cylindrical dielectric waveguide modes" J. Opt. Soc. Am., 51, pp. 491-498 (1961).

[4] W.-D. Moeller for the TESLA Collaboration, Santa Fe, V.2, pp.577-581 (1999).