Conceptual design of a sapphire loaded coupler for superconducting radio-frequency 1.3 GHz cavities

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This paper explores a hybrid mode rf structure that served as a superconducting radio-frequency coupler. This application achieves a reflection $S_{(1,1)}$ varying from 0 to -30 db and delivers cw power at 7 KW. The coupler has good thermal isolation between the 2 and 300 K sections due to vacuum separation. Only one single hybrid mode can propagate through each section, and no higher order mode is coupled. The analytical and numerical analysis for this coupler is given and the design is optimized. The coupling mechanism to the cavity is also discussed.

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I. INTRODUCTION

Superconducting radio-frequency (SRF) technology is widely implemented in various accelerator projects around the world [1]. Designs for superconducting cavities and couplers have been optimized by the TESLA collaboration for two decades. Continuous wave (cw) coaxial-type input couplers have been optimized for different purposes through three generations [2–4]. One of the major optimization goals is to reduce the static heat [5]. We present a new hybrid input coupler structure to reduce the static heat loss.

Coaxial couplers conduct rf power in a coaxial TEM mode. To achieve this, one needs to convert the rectangular waveguide TE₁₀ mode from a klystron into a coaxial TEM mode by a door-knob structure. Then, the coaxial line transmits the rf power with various impedance matchers to a flange on the cavity beam pipe receiver. Similarly, waveguide couplers transmit TE₁₀ mode and couple this mode directly to the cavities. Once a waveguide is manufactured and mounted, it is hard to change the coupling factor to the cavities. Waveguide and coaxial designs accomplish a reflection less than -30 db to get a good rf power match.

In this paper, we introduce a new input coupler design. This design avoids physical contact between the outer conductor from the input waveguide and the cavity receiver. The structure can deliver rf power at a level of 7 KW without a calculated multipacting barrier. The static cryogenic losses range from 2.785 to 5.351 W on a TTF-3 coupler when the average power level limit is about 6 kW

[5]. The CEBAF waveguide coupler has a static cryogenic losses around 19 W when input power is 8 kW [6]. Meanwhile, this new coupler produces a negligible static thermal loss <1 W when it delivers the same rf power, and the details will be shown in the following sections. The whole coupler, shown in Fig. 1, can be divided into three sections. The left section is a transition that converts power from an rf source into a sapphire rod. The middle section is the sapphire rod transmission line. The right part is a convertor which transfers the rf power to the cavities by a coaxial cable.

II. GENERAL CONSIDERATION

A. Introduction of hybrid modes

Hybrid modes were first found by Snitzer in 1961; they are more universal modes than the transverse electric (TE) and transverse magnetic (TM) modes [7]. These hybrid modes have both electric and magnetic field components along the propagation direction.

In the modern optics fiber industry, the fundamental hybrid mode is HE₁₁, which is widely used for conveying signals [8]. Dielectric rods in an optical fiber can be used for rf transmission [9,10]. Inside these rods, fields can be expressed by a series of Bessel functions. Fields outside of the rod are usually evanescent modes in the radial direction, and surface modes propagate in the Z direction. The evanescent mode is known as radiation mode with continuous spectrum, and the outside radial fields can also be depicted by a series of modified Bessel functions. In the Z direction, inside and outside fields should have continuous boundary condition on the dielectric and vacuum interface [11]. The dielectric rod inside a circular waveguide is illustrated in Fig. 2.

We assume that the rod radius is a . Without the $e^{-j\beta z - im\phi}$ term, the fields' amplitudes between the sapphire rod and the outer conductor are described as follows:

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FIG. 2. A section of a sapphire loaded waveguide. Blue denotes a dielectric rod with radius a and permittivity ϵ_1 , and white denotes vacuum with radius b and permittivity ϵ_2 .

FIG. 3. Transverse field pattern of the HE11 mode. This mode can be understood as a combination of TE11 and TM11.

FIG. 4. Field pattern of LP11 mode. The electric and magnetic fields are perpendicular and linear (courtesy of Elements of Photonics, Volume II).

FIG. 5. Field patterns of HE11 mode in the center transmission section of the coupler. Part (a) is the magnetic field pattern at a snapshot at 7 kW rf power flow. Part (b) is the linear electromagnetic field at one snapshot.

FIG. 6. Illustration of the double arc structure: the position of the red dot is one optimization parameter within a given length. Two solid lines are parts of two circles. Those solid are circumscribed at the red dot. The solid lines form the baseline of the outer conductor. Blue is the sapphire rod and yellow is copper.

When $\rho \geq a$

$$\begin{aligned} E_z(m, \beta_s) &= A K_m(\alpha_s \rho) \\ \eta_2 H_z(m, \beta_s) &= B K_m(\alpha_s \rho). \end{aligned} \quad (1)$$

The fields' amplitudes inside the sapphire rod are described as follows:

When $\rho \leq a$

$$\begin{aligned} E_{zs}(m, \beta_s) &= C J_m(\chi \rho) \\ \eta_2 H_{zs}(m, \beta_s) &= D J_m(\chi \rho). \end{aligned} \quad (2)$$

K_m is a modified Bessel function of the second kind; J is a Bessel function of the first kind; η_2 is the wave impedance; α_s, χ are the wave numbers in the sapphire and vacuum material; and A,B,C,D are the amplitudes of the field. Other transverse fields can be calculated from

$$\begin{aligned} E_t &= \frac{-i\omega\mu}{\lambda^2} \left[\nabla_t H_z \times \hat{z} + \left(\frac{\beta}{\omega\mu} \right) \nabla_t E_z \right] \\ H_t &= \frac{-i\omega\mu}{\lambda^2} \left[\hat{z} \times \nabla_t E_z + \left(\frac{\beta}{\omega\mu} \right) \nabla_t H_z \right], \end{aligned} \quad (3)$$

where λ and β are the propagating wavelength and propagation constant in this system.

Moreover, the relation of the wave number on each side is

$$\begin{aligned} \beta_s^2 + \chi^2 &= k_0^2 n_1^2 \\ \beta_s^2 - \alpha^2 &= k_0^2 n_2^2, \end{aligned} \quad (4)$$

where n_1 and n_2 are the reflection indexes in two materials and k_0 is the free space wave number in the open space.

On the sapphire interface, $E_z H_z E_\phi H_\phi$ are continuous. We can derive the equations from both the sapphire and vacuum sides, and the 4×4 equations matrix has a determinant that must be zero in order to obtain nontrivial solutions [12]. For those fields, a modal equation for wave number β_s is written as

$$\begin{aligned} & \left[\frac{J'_m(u)}{u J_m(u)} - \frac{K'_m(v)}{v K_m(v)} \right] \left[n_1^2 \frac{J'_m(u)}{u J_m(u)} - n_2^2 \frac{K'_m(v)}{v K_m(v)} \right] \\ &= \left(\frac{m\beta}{k_0} \right)^2 \left(\frac{1}{v^2} + \frac{1}{u^2} \right)^2 \\ &u = \chi a \\ &v = \alpha_s a. \end{aligned} \quad (5)$$

In these functions, when m is zero, the left side breaks into $\frac{J'_m(u)}{u J_m(u)} - \frac{K'_m(v)}{v K_m(v)}$ for a simple TE mode or $n_1^2 \frac{J'_m(u)}{u J_m(u)} - n_2^2 \frac{K'_m(v)}{v K_m(v)}$ for a TM mode. When m is not equal to zero, a series of hybrid modes are developed. The surface-wave modes intertwine and propagate in the Z direction and have a discrete spectrum. Each mode has a cutoff frequency at which its wave number approaches zero [13]. The lowest mode, HE11 mode, has a cutout frequency at the first root of $J_1(V) = 0$, where the normalized frequency V is denoted $k_0 d (n_1^2 - n_2^2)^{1/2}$. Because $J_1(0)$ equals zero, the cutoff frequency for the HE11 mode is 0 Hz. Higher nth order hybrid modes have cutoff frequencies at nth root for $J_1(V)$. In order to avoid their propagation, we need to design our coupler operation frequency below the second higher order mode. The HE11 mode has a field pattern as shown in Fig. 3. A detailed 3D field pattern will be illustrated in further context.

The fields inside of the core dielectric material are purely linear in the transverse plane; optics fiber physics calls these modes linear polarizer (LP) modes. Note the LP01 mode is the same mode as the HE11 mode. We will use this HE11 mode to deliver rf power in this new coupler design. LP11 is the next higher mode. Its electromagnetic field patterns inside of the core dielectric material are shown in Fig. 4.

The transverse rf fields are oscillatory in the dielectric material and evanescently decay in the surrounding materials. The field decay rate has an upper bound $\leq k_0 \sqrt{(n_1^2 - n_2^2)}$ according to Eq. (4), when β_s is zero. A higher decay rate indicates that the field is more confined with the dielectric rod area and the field power radiation is lower. To get the larger decay, larger n_1 is required. For this reason, we presume anisotropic sapphire $\epsilon(\sim 11.34)$ in the c axis and 9.27 in the perpendicular axis [14] and thus n is around 3.04 for transverse direction. We plan to use a single crystal sapphire rod, and its loss tangent is very low at low temperature and single sapphire can grow to a fairly large size with epitaxial technology [15]. This also means that if one can cleverly choose a design parameter β_s , the power decays fast outside of the rod, and thus the rf power is highly guided by the rod. In the optical case, a pair of reflective indices is chosen close to each other in order to get a weakly guided power. In this coupler design, we need a strong guided power to avoid the outer conductor. Note the wave phase velocity inside the rod is less than that of plane waves in the free space.

FIG. 7. Field pattern and scattering parameters in the converter section. Part (a) is the magnetic field's pattern at a snapshot at 7 kW rf power flow. Part (b) is the frequency response of this junction.

B. Fundamental design options

For the reasons mentioned above, the smallest wave number β_s should be chosen in order to get the quickest decay outside of the rod [16]. By tapering the radius, one can change the β_s in order to control the fields' pattern and couple rf power in or out of the dielectric rod. On the other hand, reducing the radius can increase the cutoff frequency

of the propagating modes. To calculate the cutoff frequency of the second higher order mode, HE₂₁ mode, assumed the same as LP₁₁ mode, the radius is expressed

$$d = \sqrt{\frac{V^2}{(n_1^2 - n_2^2)k_0^2}} = \sqrt{\frac{c^2 V^2}{(n_1^2 - n_2^2)\omega^2}}, \quad (6)$$

FIG. 8. Part (a) illustrates a structure of the center converter section. Blue is the sapphire rod, yellow is copper, and the grey area is filled with a vacuum that is sealed by a retractable bellow. Part (b) illustrates a magnetic field snapshot at 7 kW rf power flow. In the HFSS simulation, a perfect match layer boundary condition is used to estimate the rf power leakage.

where the normalized frequency V is the second root for $J_1(V)$ and is 3.84. k_0 is wave number for 1.3 GHz. Recall HE11 has no cutoff frequency. Now, we can determine the upper design limit for the dielectric rod.

Radius d in this equation should be small to prevent the HE21 mode from having a larger cutoff frequency than 1.3 GHz. Within the radius limit, a small diameter rod will result in the field extending a considerable distance beyond the surface transversely. A radius requires optimizing to obtain that only the HE11 mode can propagate in this rod. If a radius is beyond this limit, the HE21 mode is propagating; if a radius is below this limit, 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 this coupler to a power source, one needs to first convert rf power from a TE10 WR 650 rectangular

waveguide mode into a TE11 circular waveguide mode. The radius of this circular waveguide is chosen to accommodate only the TE11 mode, which is the lowest mode. This circular waveguide acts as the outer conducting wall of the sapphire load structure in Fig. 1. Field power is transmitted into the sapphire rod in the form of the HE11 mode within the first taper on the rod in Fig. 1(b). A radius ratio between the dielectric rod and circular waveguide is carefully chosen in order to confine the rf power inside the rod instead of the waveguide. Once the power is strongly guided in the rod, the outside waveguide can be tapered down to touch the rod. In this way, the vacuum is sealed and the sapphire rod acts as a vacuum window. At this center section, all the rf power is guided by the sapphire rod. Since the rf waveguides from both ends do not contact each other, there is little static heat transfer, nor is a high temperature gradient. On the receiving side in Fig. 1(c), both the rod and outside waveguide are tapered in order to push the power in the rod into the waveguide in the form of a TE11 mode. Meanwhile, a variable matching mechanism can be easily adapted because these two circular outer conductor waveguides are movable with respect toward each other [15]. When the rf power is fully converted into the TE11 mode in the receiving end, one can simply extract rf power from the circular mode by a coaxial cable. This coaxial antenna feeds the cavity without changing the current main input coupler port design on the beam axis. For the additional vacuum protection concerns, one can add another ceramic window inside the coaxial cable to isolate the cavities.

III. SIMULATION

A. Simulation by parts

An SRF resonator usually operates in the L band; for example, a TESLA shape cavity operates at 1.3 GHz. Power from a rectangular waveguide requires conversion into a circular waveguide. This type of converter has been developed and widely used elsewhere. We adopt a sapphire rod with a radius of 25 mm and a circular waveguide of radius 100 mm as the center section. The electromagnetic fields' pattern is calculated by HFSS software and the propagation mode is the HE11 mode, illustrated in Fig. 5. There is neither a TE11 mode nor a TEM mode in the waveguide at 1.3 GHz. The 3D HE11 fields' pattern is also shown in Fig. 5, when the sapphire loaded waveguide is matched. Other higher order modes are not propagating modes. The field decay outside of the sapphire rod is illustrated.

The field decay outside of the rod can be altered by varying the rod radius. This equivalently changes the β_z *per se*. A smooth tapering transition is required to convert the circular waveguide mode power into the HE11 mode in the sapphire rod structure. Higher order modes are introduced to match the field patterns at the discontinuous interface. However, those modes are evanescent modes,

FIG. 9. Scattering parameters in the converter section including air perfect match layer.

which cannot propagate outside with a given length. A double arc structure is implemented here to achieve such a smooth transition [17]. The configuration is shown in Fig. 6.

This double arc structure design technique can be expended on both the inner and outer conductor designs, and the circumscribed positions are the optimizing parameters for obtaining a match. Within a limited given transition length in the Z direction, the position of the red dot is optimized to obtain a match. By doing this optimization, the waveguide and the sapphire rod are reshaped and connected. The fields' pattern and frequency spectrum of this converter are illustrated in Fig. 7(a). Figure 7(b) shows that the return loss is less than -30 db and a large bandwidth.

In this design, rf fields decay very quickly from the sapphire rod surface radially. The outer conductor has little effect on these strongly guided rf fields, so we taper the outer conductor close to the rod surface to seal the vacuum. In Fig. 8, the sapphire rod (blue) and the outer conducting waveguide (yellow) are tapered together by two double arc structures. Because the rf power is strongly guided by the sapphire rod, the outer conductors do not need a physical contact between them to confine the rf power. This gap is a vacuum area, and this section also physically breaks the rf source and cavity receiver. This discontinuity of the outer conductor helps to reduce static thermal loss. To obtain an alignment and mechanical support, two copper plates are added and connected by a bellow far from the sapphire rod. These two plates must be large enough to ensure little rf field leakage because the rf mode is evanescent at this gap. The structure configuration is demonstrated in Fig. 8. Several parameters are optimized to get the fields' pattern in Fig. 8(b).

From Fig. 8, we can see that there is little electromagnetic field outside of this gap. Radio-frequency leakage will be addressed in the later context. In this HFSS simulation, the outer boundary is assigned with a perfect match layer (PML) boundary condition. When the rf power is incident on the PML surface, the power is fully absorbed regardless of its frequencies and directions. The leaked rf power of this system is accumulated on this layer. Scattering matrix parameters scanned for different frequencies are shown in Fig. 9. From these two scattering parameters, the leakage is calculated to be less than 1%, less than 7 W. The return loss is around -30 db at 1.3 GHz.

In order to further understand the rf leakage over this gap, a far field calculation is simulated in HFSS. The field pattern is shown in Fig. 10. In Fig. 10, the input rf power level is 7 kW from the left port. A background vacuum disk is added around the gap where the possible leakage can happen. The far field electromagnetic field is several decades smaller than the fields inside or around the sapphire rod. The Poynting vector integration over a PML area can give a power flow through this given surface. Power flow through this surface is calculated and plotted as a function of the gap length in Fig. 10(b). This figure shows that the power leakage has a level of less than 0.7 W when the coupler transmits 7 kW rf power. This study continues to lend evidence that the power is confined around the rod and a trivial percentage of rf power leaks out of this coupler system. The rf power leakage will be further reduced when a stainless steel bellow is added on this gap.

On the cavity side, rf power is need to be extracted from the sapphire rod. The inner sapphire rod is tapered down to reduce β and couple rf power out without reflection. A fewer number of higher order modes can be excited in

FIG. 10. (a) Far field magnetic field snapshot at 7 kW rf power flow. (b) The Poynting vector integration over the PML surface is plotted as a function of the gap length with a fit. This study shows the rf power leakage is negligible.

this transition, and that helps minimize rf power reflection. These higher order modes are evanescent and do not propagate. A double arc structure of the sapphire rod is optimized and the field pattern is shown in Fig. 11. Scattering matrix parameters are scanned at different frequencies and plotted in Fig. 11(b). It shows that the return loss is less than -30 db at 1.3 GHz.

We would like to design an rf power extractor to the SRF cavities, for instance, TESLA shape nine-cell cavity. This coupler is modeled at the beam pipe attached to the end cell. The coupler aperture is 40 mm, and the inner conductor has a diameter of 20 mm. It is convenient to isolate the cavity and coupler vacuums from each other at some optimized location in the coaxial cable.

To implement this, a ceramic window is added inside the coaxial transmission line, and the electric field in this ceramic window is minimized by properly decreasing the inner conductor radius. This design can enlarge the window area to avoid cracking. The window thickness is chosen to be 7 mm. It is not necessary to add a choke joint. The complete structure is merged in a 4 K environment. The coaxial extraction structure is shown in Fig. 12 with a snapshot of the rf field pattern when it conveys a 7 KW input rf power.

B. Final assembly

After cascading the parts above, one can obtain a full structure of this HE11 mode coupler. A good match is

FIG. 11. Geometry structure and scattering parameters in the cavity converter. (a) A snapshot of the magnetic field at 7 kW rf power flow. (b) The frequency response of this convertor.

ensured because each subsystem is optimized and obtains a good match individually. A whole structure geometer is plotted in Fig. 13 with different views.

As described above, the center part avoids physical contact between two outer conductor components. Radio-frequency power is strongly guided by the sapphire rod. Electromagnetic fields are plotted in Fig. 14 at 7 kW rf power flow.

In Fig. 14, the rf field distribution suggests that the field is strongly guided in the sapphire. Because of this, the electromagnetic field amplitude is weak in the gap area.

Thus there is no significant rf power leakage. However, this “open to air” gap structure effectively increases the thermal resistance and thermal path; thus, the temperature gradient in the outer conductor is reduced. This design can diminish the static thermal loss and save precious cryogenic capacity at 4 K.

It is ideal to have a large bandwidth around the operating frequency 1.3 GHz. After tuning the multifrequency in the HFSS, we obtain a return loss and transmission coefficients at a different frequency. The reflection $S_{(1,1)}$ is less than -40 db at 1.3 GHz, and the full width at half maximum

FIG. 12. Coaxial converter geometry and a magnetic field snapshot in the cavity converter at 7 kW rf power flow.

(FWHM) is around 10 MHz. In Fig. 15, a leakage coefficient is given as

$$10\text{Log}(1 - S_{(2,1)}^2 - S_{(1,1)}^2), \quad (7)$$

where $S_{(1,1)}$ and $S_{(2,1)}$ are reflection and transmission coefficients.

This leakage is less than -40 db from 1.2 to 1.4 GHz, and the leakage rf through this gap is less than 0.7 W with input power at 7000 W. A good rf match condition is reached at this point.

IV. OTHER CONCERNS

A. Variability of match

There are two separate outer conductor sections in this coupler design: one segment is attached to the cavities, while the other part is connected to the rf source with the sapphire rod mounted on it. Between these two parts, there is an opening gap. The gap length can be adjusted by moving one section close to the other. This gap leaves us a movable mechanism to change the reflection coefficient. Power delivery to the cavities can be redistributed without changing the coupling coefficient to the cavity. The retractable mechanism can be further demonstrated in Fig. 16.

FIG. 13. Geometry structure of this HE11 mode power coupler. (a) Transaction view. (b) Parallel view. Blue is sapphire, green is the alumina window, and yellow is copper.

FIG. 14. Electromagnetic fields in this HE11 mode power coupler with input power 7000 W. Yellow is copper.

FIG. 15. Scattering parameters: S(1,1) (red), S(2,1) (blue) and leakage (green) are shown as a function of frequency with full match condition.

FIG. 16. Demonstration of retractable moving mechanism of this coupler. The left section can move from position 1 to position 2 (yellow is for copper wall, blue is for sapphire rod, orange is copper inner conductor and green is for ceramic window). The reflection and transmission coefficients will change accordingly.

FIG. 17. The relation of scattering parameters $S(1,1)$ (red), $S(2,1)$ (blue), leakage (green) and open gap length is plotted. Radio-frequency power conserves in this coupler system.

In Fig. 16, these two segments can move closer and farther, hence the vacuum gap length is effectively decreased and increased. Little rf leakage is still ensured and shown in Fig. 10(b), because the power is strongly guided by the sapphire rod. However, the rf scattering parameters are changed during this movement. The scattering parameters are plotted as a function of the gap length, as shown in Fig. 17. The leakage coefficient (green) is still less than -37 db, thus confirming that the rf leakage is insignificant. The gap will be connected with a stainless steel bellow.

S parameters with a changing gap distance are shown in Fig. 17. The difference of the gap distance between a match and a mismatch is around 70 mm. This difference recommends an operable working distance of this coupler and also suggests a guided wavelength of hybrid mode inside of the sapphire rod. Figure 18 shows the frequency spectrum at the mismatch where the two ports have -40 db isolation.

B. Multipacting

Microwave multipacting phenomena can be found in a wide variety of passive devices [1,16]. Simulation software

FIG. 18. Scattering parameters: $S_{(1,1)}$ (red), $S_{(2,1)}$ (blue) are shown as a function of frequency with full mismatch condition.

FIG. 19. Multipacting study by Spark 3D: This study shows that mutipactors are found at 7275, 7350 and 7500 W, but no multipacting barriers are found at 7000 W.

such as ACE 3 P and Spark3D can calculate the secondary electrons number evolution over a period of time [18]. The simulation is based on electron trajectory tracking and the second electron emission physics model. At a given field level or rf power flow in rf components, if the surviving electrons number increases within a certain period of time, it is considered that there is a multipacting barrier at this field gradient or power flow. Second electron yield (SEY) curves from Ref. [19] are used in this study. The

multipacting study of this coupler is illustrated in Fig. 19. This result suggests that no multipacting barrier is found under cw power of 7.25 kW.

C. Operating temperatures setup

Operating temperatures of each component on this coupler are indicated in this section. However, the exact temperature of each thermal anchor can be customized based

FIG. 20. The operating temperature is labeled on each component. On the left side of the bellow is the rf source part and on the right side is the cavity. 10 K thermal anchors are set at the bottom of the outer conductor and 77 K thermal anchors are set beside the bellow. Thermal intercepts will be added on both side outer conductor walls. The sapphire rod operating temperature is 10 K.

on the available cryogenic capability. Here, we give suggestive guidance of operating temperature on this coupler.

In Fig. 20, the temperatures of each component are labeled. In order to reduce the loss on liquid helium, we should keep the temperature on the cavity side as low as possible. Because the only thermal connection between cavity and rf source side is the long stainless steel bellow which has very poor thermal conductivity, the static heat loss is small. Note, the temperature of sapphire rod is kept at 10 K by helium gas anchors. These two thermal anchors are set at the roots of the waveguide. Another two thermal anchors cooled by liquid N_2 will be added on both side of the bellow at 77 K. A thermal intercept will be added along the outer conductor wall on both cavity and rf source side. Based on local temperature of each component, their temperature-dependent material properties are used in the simulation to evaluate the rf loss in the next section.

D. Radio-frequency loss study

The maximum power flow of this coupler is determined by the maximum surface E field in the design. In Fig. 14, the maximum electric field of $\sim 4.5 \times 10^5$ V/m occurs at the tip of the coaxial pickup at rf power flow of 7 kW. This electric field is below the niobium breakdown electric field, which at the MV/m level at 1.3 GHz [20]. Sapphire breakdown power is more than 25 KW [21]. Beyond these breakdown limit, the structure is discharged and power is taken by the discharged arcing. One can adapt the flat antenna top design from the TESLA 3 coupler to minimize the electric field.

Now we estimate the dynamic rf loss from the outer copper conductor, the sapphire rod, and the alumina window at the temperatures stated in Fig. 20. We presume that the cryogenic system will have enough active cooling capability to remain stated temperatures in Fig. 20. In HFSS simulation, we use that sapphire and alumina window materials

have dielectric loss tangents of 1×10^{-9} and 0.44×10^{-4} respectively at 10 and 2 K temperature [22,23]. In this study, we use single crystalline sapphire rod thus presume the material is anisotropic [24,25]. This coupler reaches full match at 1.3 GHz. At cw power of 7 KW at 2 K, the total rf dynamic loss from the copper surface is 0.07 W; the alumina window dielectric loss is 0.32 W; and the sapphire rod dielectric loss is 0.04 W when the sapphire loss tangent is 10^{-9} at 10 K. The rf heat generation on these three components is plotted geographically in Fig. 21. The TESLA 3 coupler has a surface loss of 0.06 W at cw power of 2KW. Scalable surface dynamic loss for the TELSA 3 coupler would be 0.21 W, which is higher than the surface loss in this design. However, dielectric loss from alumina windows is quite high from current design. Further studies are undergoing.

E. Ghost modes study

The sapphire rod and ceramic windows are required to braze directly on the circular waveguide, and this sapphire/

TABLE I. Resonating frequencies in an eigenmode study in the hybrid coupler structure and their quality factors.

Mode	Frequency real (GHz)	Frequency image (GHz)	Q
1	1.1927	6.4598×10^{-5}	9231
2	1.2259	6.5706×10^{-7}	9.3290×10^5
3	1.2280	6.5762×10^{-5}	9336
4	1.2557	7.7953×10^{-6}	80542
5	1.2784	2.8910×10^{-5}	22109
6	1.3230	2.9783×10^{-5}	22210
7	1.3279	4.7965×10^{-7}	1.3842×10^6
8	1.3625	6.1710×10^{-8}	1.1040×10^7
9	1.3638	2.4534×10^{-5}	27793
10	1.3776	2.1478×10^{-8}	3.2070×10^7

FIG. 21. The rf power loss on (a) outer conductor, (b) alumina window, and (c) sapphire rod are plotted integrated over the surfaces and volumes. The losses are 0.07, 0.32 and 0.04 W respectively at 2 K when input rf power is 7 KW.

ceramic and niobium joint can hold ultrahigh vacuum [25]. Both dielectric components can trap electromagnetic modes inside of them. Those trapped modes, called ghost modes, generate excessive dielectric losses and raise the temperature of the dielectric disk. This is one of the major reasons for the punctures and the cracks observed in the vacuum windows.

An eigenmode investigation is required to find their frequencies. The ghost mode resonance frequencies can be tuned away by adjusting the length of the sapphire rod and the thicknesses of the alumina window.

In this simulation, the thickness of the alumina window is chosen in the range of 3- and 3.5-mm to avoid 1/2 of

FIG. 22. Schematic of different misalignments for this couplers. The cavity and rf source side of the couplers have a misalignments: (a) *C*-axis tilted, (b) radially shift displacement, and (c) tilted with an angle.

the guided wavelength in the coaxial cable. An eigenmode result in Table I shows that, around operating frequency of 1.3 GHz, the nearest neighbor resonating frequencies of this design are 1.27 and 1.32 GHz. Their quality factors Q are 22109.6 and 22210.2 respectively. Our goal for external quality factor is around $\sim 10^5$; the affected bandwidth is a narrow band of 13 KHZ. Hence, the ghost modes are out of this bandwidth and can be safely ignored.

F. Misalignment study

Even though the two parts of this couplers are connected by a rigid bellow, there may still be several possible misalignments between them in this coupler. Those

misalignments can cause mismatch in the coupler and change scattering parameters. We have to evaluate and control those misalignments within an acceptable range. In this study, we discussed three major misalignment cases and their schematics are shown in Fig. 22: (i) the sapphire rod is anisotropic material and its permittivity has small difference between parallel and perpendicular to the c axis; (ii) the left part of the bellow with the sapphire rod is positioned radially off center but still parallel aligned; (iii) the left part of the bellow with the sapphire rod is tilted at an angle respect to the right side of the coupler.

For the first problem, when the sapphire rod is perfectly physical aligned, the c axis of the sapphire rod is tilted with

FIG. 23. The S11 parameter when the C-axis of sapphire rod is misaligned to the coupler axis.

FIG. 24. The return loss S11 is shown as a function of the coupler radically off-center misaligned.

an angle respect to the rod physical axis. We varied the c axis misalignment angle at range of ± 3 degree which is the maximum allowable range from the vender. Figure 23 shows this scattering parameter with c-axis tilting angle and we found that the S11 is less than -22 dB, therefore with such materials uncertainty, this coupler still has a good match.

To solve the second problem, the left side of the coupler is positioned radically off axis several millimeters respect to the right part of the couplers. Since this coupler utilizes HE11 mode which is a dipole mode, mismatch properties are different if the displacements are in different polarization

planes. We simulated two cases with displacement on x and y axis. In Fig. 24, we can see a good match (< -22 dB) can be reached if a radical misalignment is within the ± 2 mm range.

For the third problems, the left side of the coupler is tilted with an angle with respect to the right part of the couplers. Similar to the second case, there will be a difference if the coupler is tilted in different x and y polarization planes. Figure 25 shows the scatter parameter changes as a function of tilting angle in different planes. We found that a good match (< -20 dB) can still be obtained within a ± 3 degree tilting angle.

FIG. 25. The return loss S11 is shown when the coupler is misaligned with a tilted angle.

Considering three major cases of misalignment, we found that the coupler has the S11 return loss which are less than -20 dB in different cases, therefore this coupler design has a good misalignment tolerance range.

V. CONCLUSION

A concept of a novel coupler is introduced, and the prototype design of this coupler is given. Numerical analysis has been simulated by HFSS. This coupler demonstrates the potential capability to deliver up to 7 KW cw power at 1.3 GHz with a -30 db match. Further optimization can make this coupler more compact and suitable for an existing cryomodule configuration. The coupler will be manufactured and high power tested for experiments.

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