Design Study of a Prototype 325MHz RF Power Coupler for Superconducting Cavity

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Abstract

We present design studies of a prototype RF input Power Coupler, which provides RF powers to 325MHz cavities up to 18.5kW in CW mode. The prototype power coupler is a coaxial capacitive type with single ceramic window. In or-der to optimize the RF coupler design, we performed multi-physics simulations, including electromagnetic, thermal, and mechanical analyses

Design Requirements

Table 1. Design requirements of the input coupler

Parameters	Values	Unit
Resonant frequency	325	MHz
Pass band ($S_{11} < 0.1$)	3	MHz
S_{11} at 325MHz	≤-30	dB
Operating Power	18.5	kW
Q_{ext}	4×10^6	-

Electromagnetic Simulation

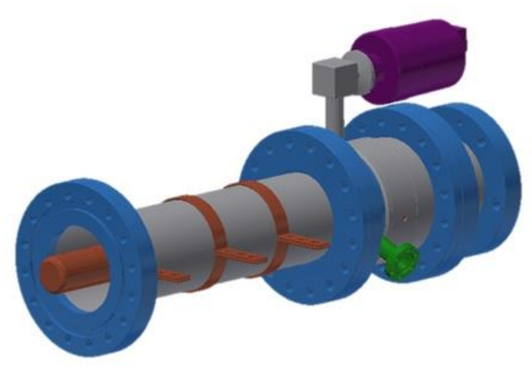

Figure 1. General view of power coupler

- Based on conventional 50Ω coaxial transmission line.
- Three diagnostic ports for vacuum, arc, and electron pick-ups
- Three thermal interceptors for 4.5K, 40K, and 77K.

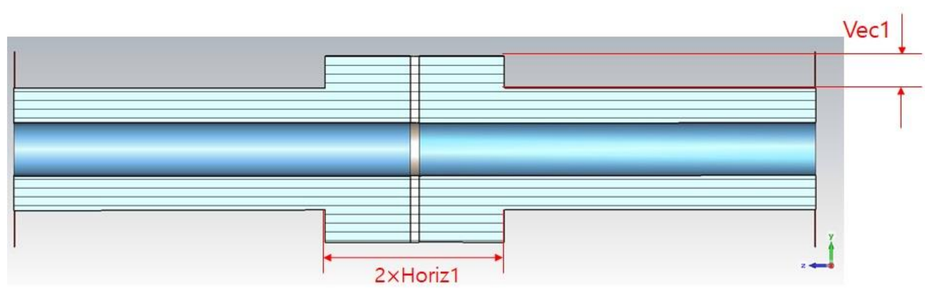

Figure 2. Geometric change of ceramic part

- Diameter (Vec1) and Length (Horiz1) variations
- Figure 3 and 4 shows the effect of vertical/horizontal length change

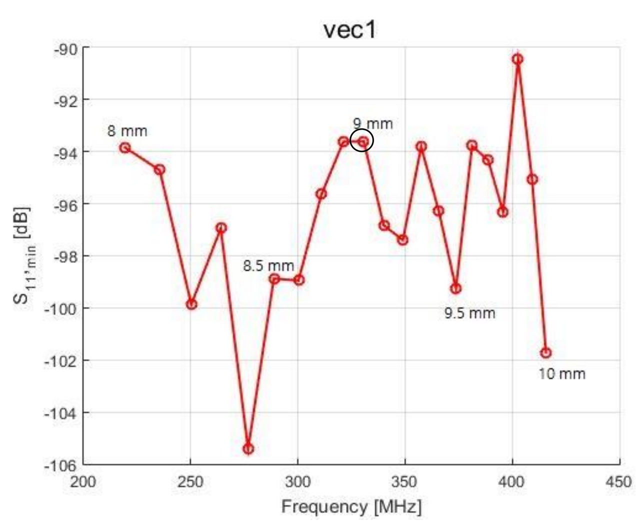

Figure 3. Effect of vertical length change

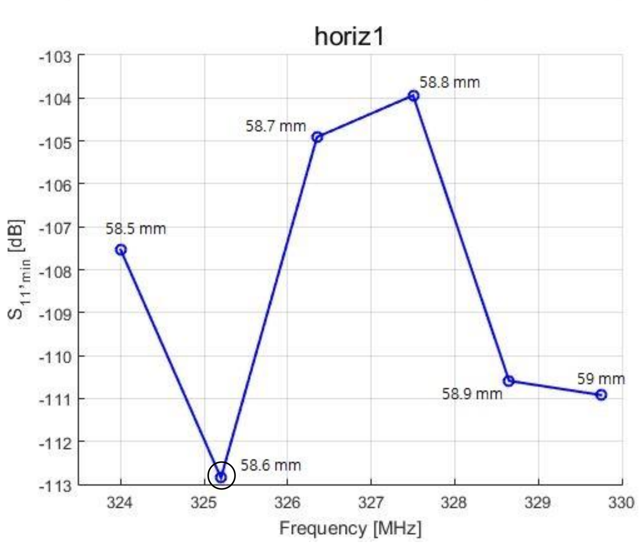

Figure 4. Effect of horizontal length change

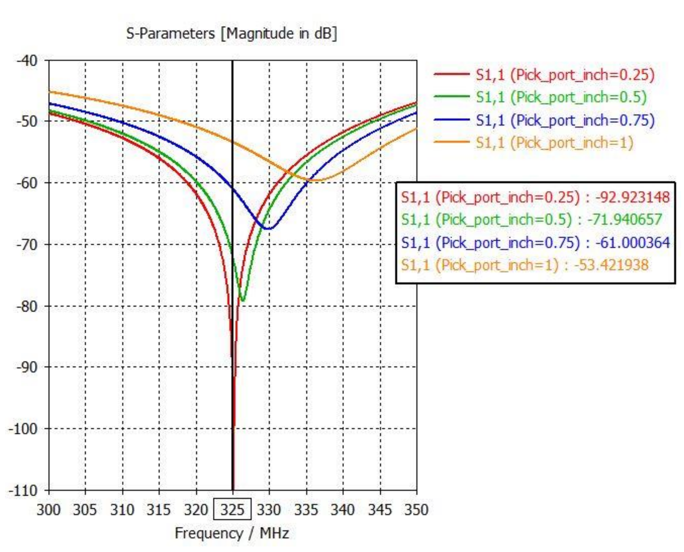

Figure 5. Effect of pick-up port diameter change

- The pick-up port diameter had significant effects to S_{11}
- Figure 5 shows the reflected power change due to diameter change of pick-up port

RF characteristics

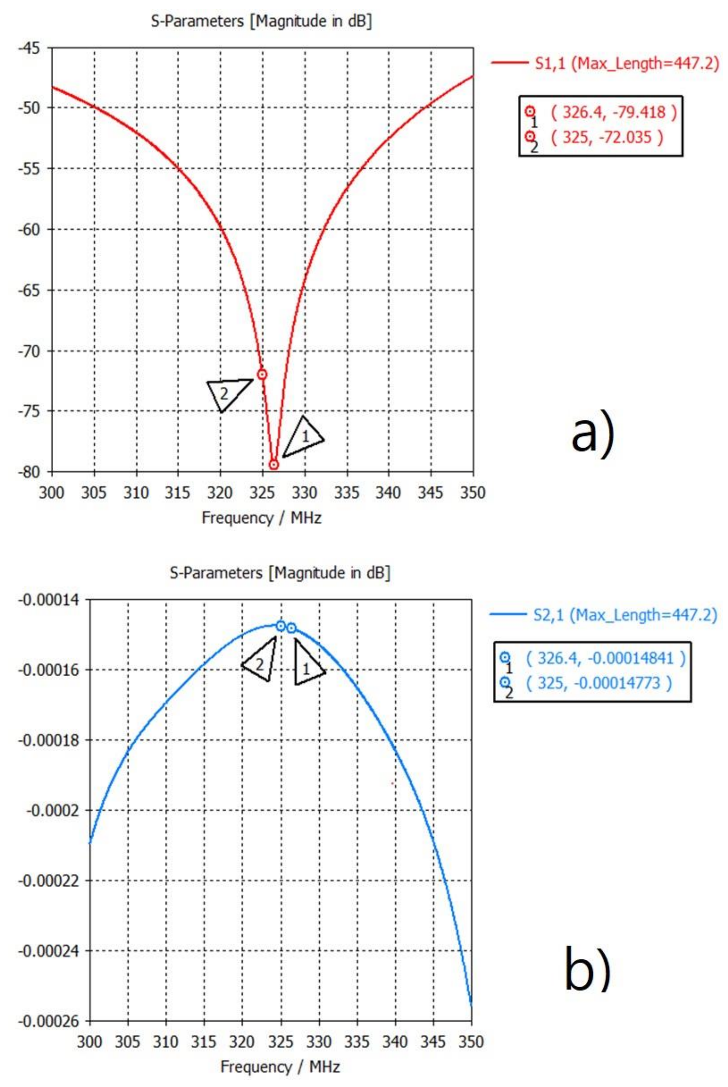

Figure 6. a) Reflected power (S_{11}) b) Transmitted power (S_{21}) of power coupler

- The point 1 is the minimum point of the reflected power
- The point 1 is the reflected power of the operating frequency

Thermal Analyses and Simulation

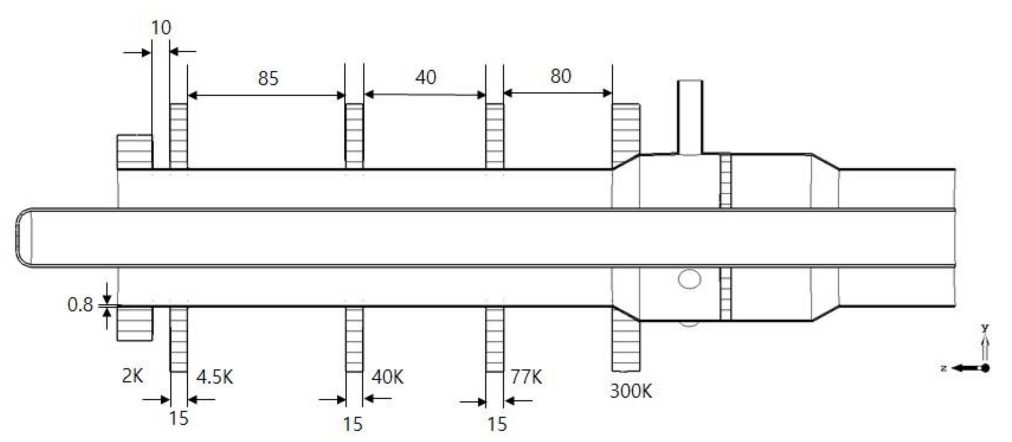

Figure 7. Scheme of a prototype power coupler for thermal analyses

- The thermal calculation method is below steps.

$$Thermal\ conductivity\ of\ STS316L \begin{cases} k_{4.5K} = 0.319\ W/m\cdot K \\ k_{40K} = 4.67\ W/m\cdot K \\ k_{40K} = 7.921\ W/m\cdot K \\ k_{77K} = 15.309\ W/m\cdot K \end{cases}$$

$$\begin{cases} COP_{2K,cooling} = \frac{2K}{300K-2K} = 0.0067 \\ COP_{4.5K,cooling} = \frac{4.5K}{300K-4.5K} = 0.0152 \\ COP_{40K,cooling} = \frac{40K}{300K-40K} = 0.1538 \\ COP_{77K,cooling} = \frac{77K}{300K-77K} = 0.3453 \end{cases} \rightarrow \begin{cases} \frac{COP_{2K,cooling}}{COP_{4.5K,cooling}} = 0.4407 = COP_1 \\ \frac{COP_{2K,cooling}}{COP_{40K,cooling}} = 0.0436 = COP_2 \\ \frac{COP_{2K,cooling}}{COP_{77K,cooling}} = 0.0194 = COP_3 \end{cases}$$

$$A = \pi(76.9/2\ mm)^2 - \pi(33.4/2\ mm)^2 = 1.9528 \times 10^{-4} m^2$$

$$\begin{cases} T_1 = 2.5K \\ T_2 = 35.5K \\ T_3 = 37K \\ T_4 = 223K \end{cases}$$

$$Q = k_{4.5K} A \frac{T_1}{X_1} + COP_1 k_{40K} A \frac{T_2}{X2} + COP_2 A \frac{T_3}{X3} + COP_3 k_{300K} A \frac{T_4}{X4}$$

$$Q_{min} = 0.4075W \rightarrow \begin{cases} x_1 = 10\ mm \rightarrow Q = 0.0156W \\ x_2 = 85\ mm \rightarrow Q = 0.1679W \\ x_3 = 40\ mm \rightarrow Q = 0.0624W \\ x_4 = 80\ mm \rightarrow Q = 0.1617W \end{cases}$$

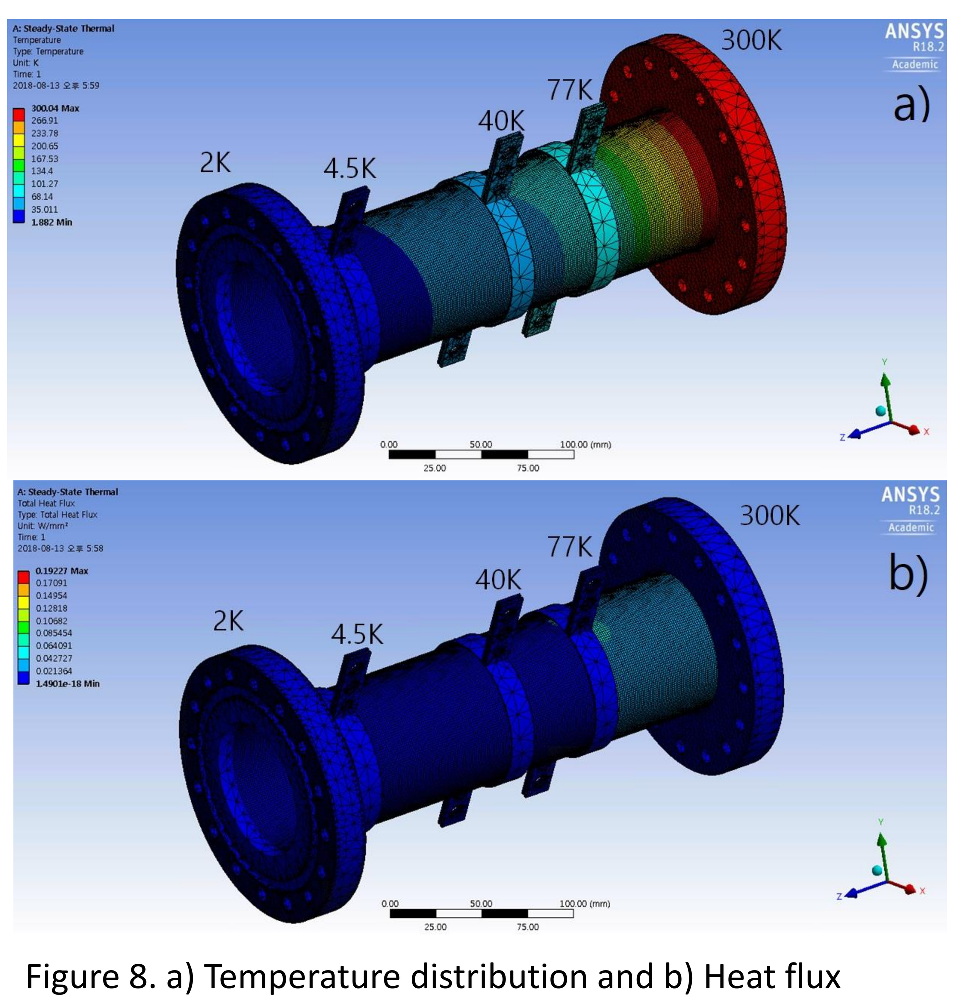

Figure 8. a) Temperature distribution and b) Heat flux result of static thermal load

Mechanical Simulation

- The force of three times of gravity acts on the antenna tip in the opposite y direction

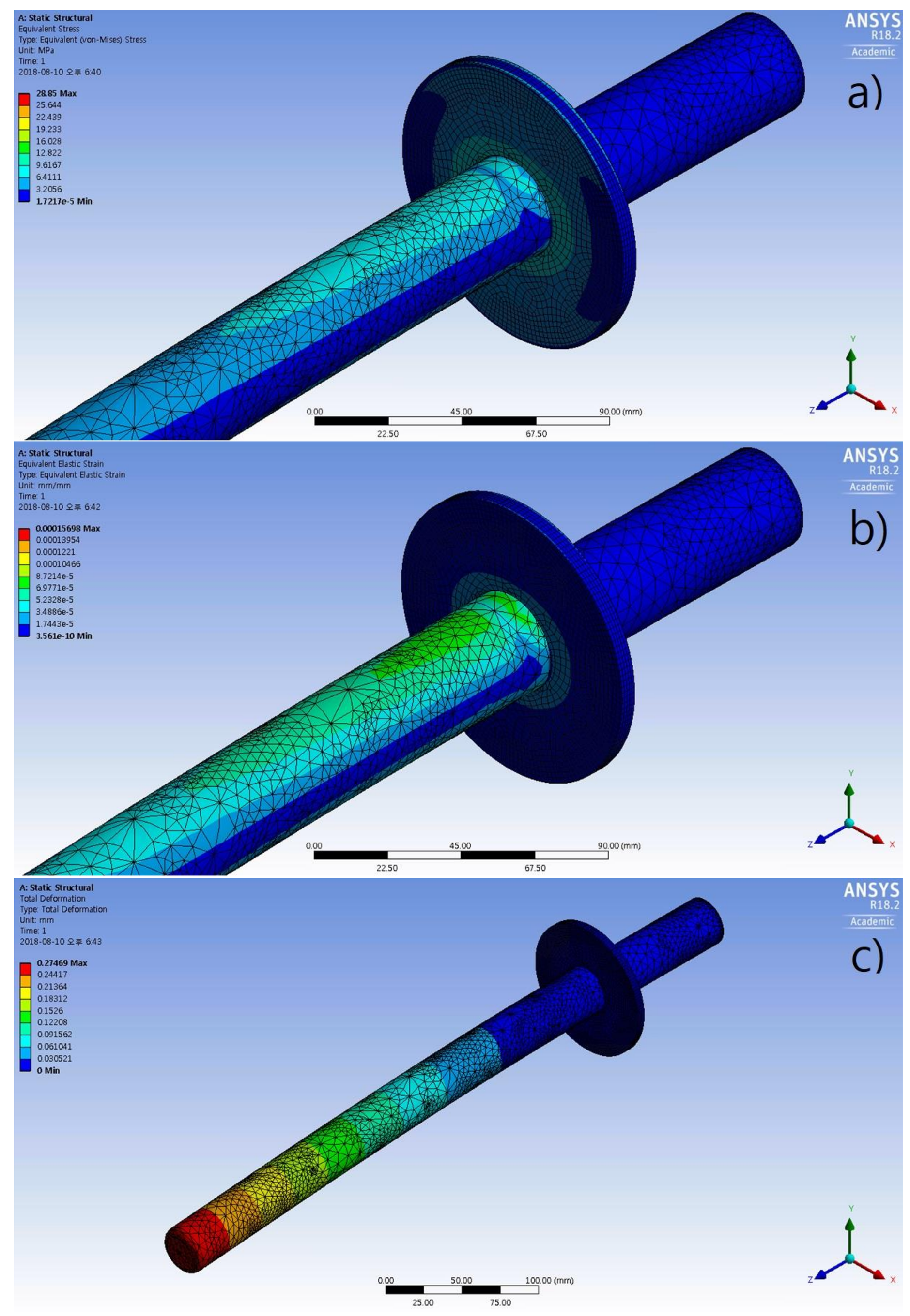

Figure 9. a) Stress, b) Strain, and c) Deformation of inner conductor and ceramic window

Table 2. Mechanical properties of copper

Oxygen/Halogen Free Copper	
Parameters	Values
Tensile Ultimate Strength	210 Mpa
Tensile Yield Strength	33.3 Mpa
Modulus of Elasticity	110 Gpa
Bulk Modulus	140 Gpa
Shear Modulus	46 GPa

Table 3. Mechanical properties of alumina

Alumina 99.7% (Ceramic Window)	
Parameters	Values
Tensile Ultimate Strength	260 Mpa
Compressive Strength	2940 Mpa
Modulus of Elasticity	360 Gpa
Flexural Strength	290 Mpa

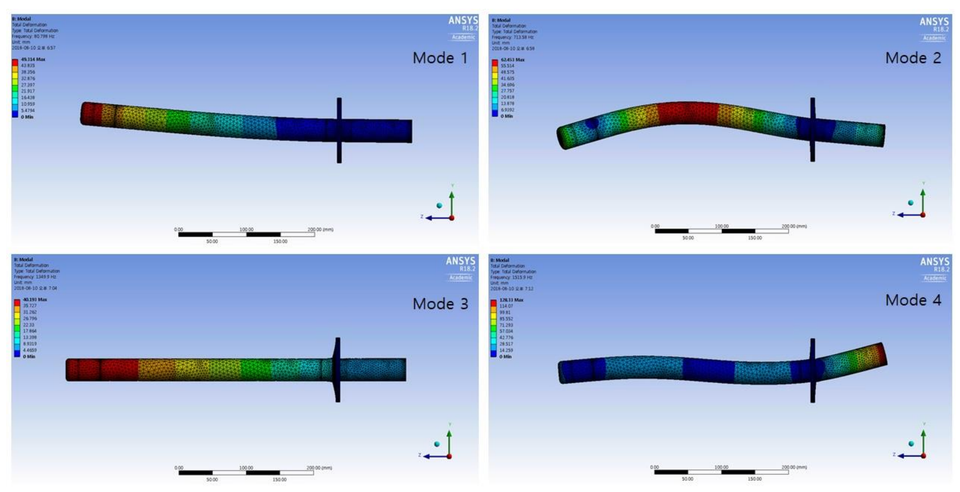

Figure 10. Vibrational modes of antenna

Table 4. Resonance mode frequency of the antenna

Mode	Frequency
Mode 1	80.8Hz
Mode 2	713.6Hz
Mode 3	1349.9Hz
Mode 4	1515.9Hz

Conclusion

We studied preliminary designs of the 325-MHz input coupler prototype for proton/heavy-ion superconducting cavities. The prototype will be fabricated and low-power tested in near future. Through such experiences, an up-graded version including a cooling scheme will be de-signed and fabricated.