TECHNICAL NOTE

DEFINITION OF THE WATER CHARACTERISTICS FOR THE COOLING SYSTEM OF THE ELLIPTICAL CAVITY COUPLER

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1. INTRODUCTION

To power supply the ESS medium \( \beta \) elliptical cavity, a coupler composed of a double wall-tube, a window with antenna and a doorknob transition will be used. Its architecture is presented hereafter:

Figure 1: Architecture of the coupler

The RF power injected into the coupler will reach 1.1MW peak with a “RF” duty cycle close to 5% at the frequency 704.42MHz. The antenna that links the doorknob to the cavity will be cooled thanks a water cooling circuit (the antenna is composed of two parts to allow the water flow inside, water flows in the center and returns on the periphery). This cooling circuit is represented in the following figure:

Figure 2: The antenna cooling circuit

To assure an efficient cooling, the characteristics of the water shall be determined (flow, \( \Delta T \) expected, conductivity…).
The aim of this document is to define the properties of the water used for the antenna cooling. To achieve this goal, we begin to estimate the RF power dissipated by the coupler antenna used in the ESS medium \( \beta \) elliptical cavity. Afterwards, we can evaluate the flow and the \( \Delta T \) between the cooling circuit ports.
2. ESTIMATION OF THE RF POWER DISSIPATED BY THE ANTENNA

To calculate the antenna dissipated power, we have modelled the doorknob transition in HFSS (from Ansoft) to check the S-parameter and to control the electric and magnetic field distribution. Afterwards, we have calculated the power dissipation in the antenna part between the doorknob and the cavity. The antenna material is copper.

2.1 Power dissipation at the doorknob transition level

In the HFSS simulation, we calculate the power dissipation in the antenna by considering the antenna external surface and the following equation:

\[
P_{ant\_doorknob} = \frac{1}{2} R_s \times \iint_{Surface} |J_s|^2 dS = \frac{1}{2} R_s \times \iint_{Surface} |H_t|^2 dS
\]

where \( R_s \) is the surface resistivity expressed by \( R_s = \sqrt{\frac{\mu_0 f}{\sigma}} \) and \( J_s \) is the surface current (Ht the tangential magnetic field). For copper, \( \mu = 4\pi \times 10^{-7} \) Hm\(^{-1}\), \( \sigma = 5.96 \times 10^7 \) S/m, \( f = 704.42 \) MHz; consequently, \( R_s = 6.8 \) m\(\Omega\).

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![Figure 3: E-field distribution (for 1.1MW)](image-url)
Figure 4: H-field distribution (for 1.1MW)

With the previous formula, and for an antenna length (external to the doorknob) of 200mm, we obtain a continuous dissipated power: \( P_{\text{ant\_doorknob}}(\text{CW}) = 386W \) for an input power 1.1MW.

**Conclusion:** By applying the duty cycle 5%, we can conclude that the antenna dissipated power at the doorknob level is worth: \( P_{\text{ant\_doorknob}} = 386 \times 5/100 = 19.3W \). (condition of travelling wave)

Nota: with the HFSS simulation, we can also estimate the magnetic field on the antenna surface (external to the doorknob): close to 1536A/m.

### 2.2 Power dissipation in the antenna after doorknob

The total antenna length from the doorknob to the cavity can be estimated from the coupler drawings:

- antenna at the window part: \( 310.55 + 154.84 - 15 = 450.39 \text{mm} \)
- antenna at the doorknob transition level: \( 476.1 - 9.82 = 466.28 \text{mm} \) (see details in the following figure)
Previously, we calculated the power dissipated by the antenna until the limit named “HFSS limit” in the Figure 5. The remaining antenna part can be divided into 2 parts:

* the part called “complementary antenna” in the Figure 5 (antenna outside the doorknob and without internal chokes whose total length is worth 55.75mm)
* the part closed to the ceramic (presence of internal chokes)

### 2.2.1 Complementary antenna

The complementary antenna (see Figure 5) to be considered owns a length: 450.39+466.28-356-55.75=504.92mm. For the next calculations, we fix the complementary antenna length to \( L_{\text{ant}} = 505 \)mm.

To evaluate the power dissipated in this antenna part, we use the same equation as previously:

\[
P_{\text{ant, complementary}} = \frac{1}{2} R_s \times \iint_{\text{Surface}} |H|^2 \, dS
\]

In travelling wave condition, we can estimate the magnetic field on the antenna surface by two means:

* by using the HFSS results: 1536A/m
* by using the following procedure:

**The antenna in the window and the double-wall tube owns a characteristic impedance \( Z_0 = 50 \)Ω.

**the power \( P_{\text{in}} \) injected in the antenna is worth 1.1MW peak. The current \( I \) on the antenna surface is worth: \( P_{\text{in}} = \frac{1}{2} \times Z_0 \times I^2 \) thus \( I = \sqrt{\frac{2 \times P_{\text{in}}}{Z_0}} \)
Numerical application: \( I = \sqrt{\frac{2 \times 1.1 \times 10^6}{50}} = 210A \)

**The relation between the current \( I \) on the antenna surface and the magnetic field \( H \) on the antenna surface is given by: \( I = 2\pi RH \). Thus \( H = \frac{I}{2\pi R} \)

where \( R \) is the antenna radius (here \( R=21.75\text{mm} \))

Numerical application: \( H = \frac{210}{2\pi \times 21.75 \times 10^{-3}} = 1537A \). This value is equivalent to the HFSS value.

Finally, the power dissipated by this antenna part is worth:

\[
P_{\text{ant, complementary}} = \frac{1}{2} R_s \times \iint |H|^2 \, dS = \frac{1}{2} R_s \times H^2 \times 2\pi R_{\text{ant}} \times L_{\text{ant}}
\]

Numerical application:

\[
P_{\text{ant, complementary}} (\text{CW}) = \frac{1}{2} \times (6.8 \times 10^{-3}) \times 1537^2 \times 2\pi \times (21.75 \times 10^{-3}) \times (505 \times 10^{-3}) = 554W
\]

**Conclusion:** With the duty cycle 5%, we can conclude that the power dissipated by the complementary antenna is worth: \( P_{\text{ant, complementary}} = 554 \times 5/100 = 27.7W. \) (condition of travelling wave)

### 2.2.2 Antenna part with internal chokes

The power dissipation of the antenna close to the ceramic (internal chokes) is estimated thanks to another HFSS simulation. In this simulation, only the air/vacuum part around the ceramic is represented.

**Figure 6: HFSS simulation of the window**
We calculate the power on the surface shown in the following figure with the equation

\[
P_{\text{ant,choke}} = \frac{1}{2} R_s \times \iint_{\text{Surface}} |Ht|^2 \, dS
\]

**Figure 7: Internal choke surface**

**Conclusion:** For travelling wave and duty cycle 5%, we obtain \( P_{\text{ant,choke}} = 11 \) W

2.3 Whole power dissipation in the antenna

The power dissipated by the whole antenna is the sum of the three previous calculated powers:

\[
P_{\text{total}} = P_{\text{ant, doorknob}} + P_{\text{ant, complementary}} + P_{\text{ant, choke}} = 19.3 + 27.7 + 11 = 58 \text{W} \text{ (condition of travelling wave)}
\]

Moreover, if the ceramic used in the window owns dielectric losses equal to \( \tan \delta = 3 \times 10^{-4} \), the power dissipation (in the worst case) reaches to 33W in the ceramic (standing wave condition, duty cycle 5%) or 9.3W (in travelling wave). These values come from the HFSS simulation of the window. (see Figure 6)

The dielectric losses in the ceramic are calculated with the equation:

\[
P_{di} = \frac{1}{2} \omega \varepsilon_0 \varepsilon_r \times \iint_{V_{\text{ceramic}}} |\mathbf{E}|^2 \, dV \quad \text{with} \quad \tan \delta = \frac{\varepsilon''}{\varepsilon_r} \quad \text{where} \quad \varepsilon_r = \varepsilon_r' - j \varepsilon_r'' \quad \text{and} \quad \omega = 2\pi f,
\]

Thus:

\[
P_{di} = \frac{1}{2} \omega \varepsilon_0 \varepsilon_r \times \tan \delta \times \iint_{V_{\text{ceramic}}} |\mathbf{E}|^2 \, dV
\]

Where \( \varepsilon_r \) is the permittivity of the ceramic, \( \mathbf{E} \) is the electric field.

To sum up the different evaluations, we can write by considering the antenna power dissipation and the ceramic losses:

* in travelling wave condition, duty cycle 5%, the total power dissipation is worth 58+9.3=67.3W
* in standing wave (coupler set up on the cavity), duty cycle 5%, the power dissipation due to “HFSS doorknob antenna” and “complementary antenna” is closed to 2*(19.3+27.7)=94W. With the HFSS simulation, we estimate the maximum power at the “ceramic/choke” level for ceramic losses and choke dissipation: 41W. Thus, the total dissipation wall is worth 94+41=135W.
Conclusion: we can estimate a maximum power dissipation of 135W (standing wave) or 67.3W (travelling wave) for the coupler antenna, duty cycle 5%.

3. ESTIMATION OF THE WATER FLOW

To dissipate the RF power, we have to define the water flow to optimize the ΔT. For this purpose, we apply the following equation:

\[ Q = m \cdot C \cdot \Delta T \]

where \( Q \) is the transferred energy (J), \( m \): the mass of the fluid (ie water), \( C \) the heat capacity (for water \( C=4180 \text{ J kg}^{-1}\text{ K}^{-1} \)), and \( \Delta t \) the temperature variation.

By using the water flow \( \Phi \) (in l/min or kg/min for water) instead of the mass, we can write:

\[ P = \frac{\Phi}{60} \cdot C \cdot \Delta T \]

Consequently, for the elliptical cavity coupler, we can define the following relation:

\[ \Phi \cdot \Delta T = \frac{60 \times P}{C} = \frac{60 \times 135}{4180} = 1.94 \]

The following table proposes \( \Delta t \) for different water flows:

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<thead>
<tr>
<th>( \Phi ) (l/min)</th>
<th>( \Delta T ) (°C)</th>
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<tr>
<td>2 l/min</td>
<td>0.97°</td>
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<tr>
<td>2.5 l/min</td>
<td>0.78°</td>
</tr>
<tr>
<td>3 l/min</td>
<td>0.65°</td>
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**Table 1: \( \Delta t \) in function of \( \Phi \)**

Conclusion: we can define a nominal water flow equal to 2 l/min to dissipate the RF power. With this value, the \( \Delta t \) will reach 0.97°.

4. CHARACTERISTICS OF THE WATER

During the water cooling of the antenna, we have to avoid chalky deposit. For this purpose, we require a water conductivity inferior to 1µS/cm (or in terms of resistivity, a resistivity superior to 1MΩ cm).

Nevertheless, this kind of water is rather aggressive with metals and can be hazardous for very thin metals. In the case of the antenna, the external antenna thickness is worth between 1 and 2mm, and the internal part thickness between 1.15 and 2mm. That is enough to guarantee no critical degradation.

To avoid also the aggressive behaviour of the demineralized water, we specify a pH in the range [6.5;7.5].

Concerning the water temperature of the cooling circuit, we have to estimate the radiated power brought by the antenna at the cavity level. For this purpose, we apply the equation:

\[ P_{\text{radiated}} = \sum_{S_1 \text{ and } S_2} \sigma(T_1^4 - T_2^4) \cdot \frac{1}{S_1 F_{1>2}} \left( \frac{1 - \varepsilon_1}{\varepsilon_1 S_1} + \frac{1 - \varepsilon_2}{\varepsilon_2 S_2} \right) \]
where $\varepsilon_1$ is the emissivity of the antenna (copper material, high estimate $\varepsilon_1=0.1$), $\varepsilon_2$ is the emissivity of the cavity (with multiple reflections, high estimate $\varepsilon_2=1$), $\sigma$ is the Stefan-Boltzmann constant $\sigma=5.67 \times 10^{-8} \text{ Wm}^{-2} \text{ K}^{-4}$, $S_1$ a piece of antenna surface considered, $S_2$ the cavity surface, $F_{1,2}$ the view factor for the piece of surface 1 to the surface 2 (from Howell, J.R., “A catalog of radiation configuration factors”, McGraw-Hill, 1982), $T_1$ the temperature of the antenna and $T_2$ the cavity temperature.

For the medium $\beta$ elliptical cavity, the antenna tip is set up at 61.26mm from the cavity axis. The cavity flange is at 123.8mm from the cavity axis. (The cavity radius is worth $135.8/2=67.9$mm). The radius of the antenna is equal to $R_{\text{ant}}=43.5/2=21.75$mm.

![Figure 8: Cavity and coupler flange](image)

The antenna length that penetrates inside the cavity (ie from the cavity flange) is equal to $L_{\text{ant, cav}}=123.8-61.26=62.54$mm. We approximate the antenna tip by a simple disk.

Numerical Application:

*For a water temperature of 20°C, we obtain: $P_{\text{radiated}} = 0.49W$

*For a 30°C water temperature, the radiated power becomes: $P_{\text{radiated}} = 0.56W$

NB.: The radiated power received by the cavity also includes contributions from the ceramic window and double wall tube radiation, while the numbers given above represent only the antenna radiation as a function of antenna temperature.

Changing the water temperature from 20°C to 30°C corresponds to an additional cryogenic heat load of 70mW for each coupler due to the antenna radiation power inside the cavity. For each cryomodule housing 4 cavities, the total additional cryogenic power due to a temperature increase from 20°C to 30°C is estimated at 0.28W.
5. CONCLUSION

In the worst case, the coupler antenna used with elliptical cavities will dissipate 135W (standing wave) for 1.1MW peak, duty cycle 5%.

The recommended characteristics of the water for the antenna cooling are the following:

* water conductivity lower than 1µS/cm (We can eventually tolerate a 2µS/cm conductivity).
* water pH in the range [6.5;7.5]
* nominal water flow: 2l/min (with this flow, the ΔT will reach 0.97°C).
* Changing the water temperature from 20°C to 30°C leads to an additional cryogenic heat load of about 0.28W per elliptical cryomodule.