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POWER COUPLER DESIGN FOR THE LUCRECE PROJECT

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Abstract

The LUCRECE project aims at developing an elementary RF system (cavity, power source, LLRF and controls) suitable for continuous (CW) operation at 1.3 GHz. This effort is made in the framework of the advanced and compact FEL project LUNEX5 (free electron Laser Using a New accelerator for the Exploitation of X-ray radiation of 5th generation), using superconducting linac technology for high repetition rate and multi-user operation. In this context, based on its large experience on coupler design and RF conditioning gained over the last 15 years, LAL laboratory is in charge of the design and the fabrication of RF couplers that could operate at up to 15-20 kW in CW mode. For this purpose, couplers based on Cornell 75kW CW couplers (RF power couplers for the CBETA ERL injector) are under consideration and will be adapted to the LUCRECE needs. Electromagnetic simulations and associated thermal heating will be discussed.

INTRODUCTION

The CBETA injector coupler was the first 1.3 GHz input power coupler to operate at relatively high power in CW mode (75 kW). The TTF3 design has been significantly modified to fulfill the ERL injector requirements [1]:

- The cold part was completely redesigned using a 62-mm, 60-Ω coaxial line (instead of a 40-mm, 70-Ω line) for a better power handling, more efficient heat load dissipation and to avoid multipacting.
- The antenna tip was enlarged and shaped for stronger coupling.
- The outer conductor bellows design (both in warm and cold coaxial lines) was adapted for better cooling (Heat intercepts were added).
- Forced air-cooling of the warm inner conductor bellows and "warm" ceramic window was added.

The Cornell coupler design was then used in several CW machine like ARIEL at TRIUMF (20 kW) [2] or BESSY VSR at HZB (10 kW) [3]. The following study aims to adapt the Cornell coupler design to our need in the framework of coupler prototyping for LUNEX5 machine project (20kW in CW mode). RF studies and thermal simulations results will update and complete the previous work [4]. The simplified geometry for the coupler, as described in the cited reference, will be used for EM simulations through ANSYS/HFSS and CST softwares.

RF SIMULATIONS

Starting from the Cornell coupler design, the geometry has been modified in order to match the 40-mm diameter size of the elliptic cavity flange (LCLS2 type). The studied solution updates the Cornell design with taper after the last bellow to fit the 40mm cavity flange. Due to the fixed antenna diameter, the impedance will vary linearly from 60 to 70 Ω, which should have negligible effect on the RF behavior especially at low power. Previously studied [4] solution with XFEL-type cold part would bring to much losses in the inner conductor. The heating in the ceramics has been induced by the EM

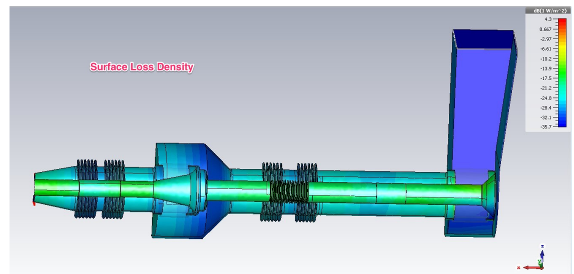

Figure 1: CST Surface losses density simulations for the hybrid tapered coupler.

wave that deposited power inside the ceramics and can be calculated via the following formula:

$$P_{Vol} = \epsilon \iint E^2 dV, \quad (1)$$

with $\epsilon = \tan\delta$ for the ceramics. Concerning the ceramics and at 10 kW input power in CW mode, the deposited power is few tens of watts. This will imply temperature rise during RF processing. The surface loss density has simulated on the tapered coupler (in Fig. 1) which shows that no abnormally high EM power is lost in the tapered coupler ending which confirms this solution. The coupling for the tapered hybrid geometry has also been simulated and is shown in Fig. 2. The non optimized coupling is already acceptable ($S_{11} < -25$) and will improve easily with antenna tune.

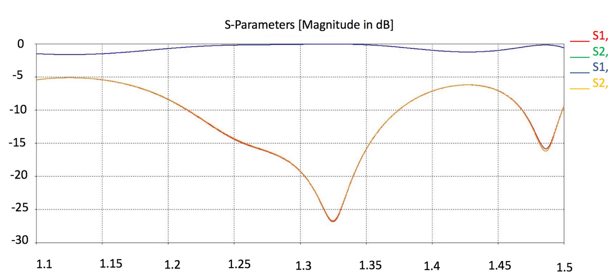

Figure 2: CST simulated S parameters for the tapered coupler.

In addition, needs concerning the external coupling to the cavity, to cover up to 1mA beam loading, imposes an external quality factor between 1.5×10^7 and 4.5×10^7. In order

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to achieve this level for the Q_{ext}, the coupler original antenna has been reshaped. The original antenna tip shape [1] gave an external quality factor range from 9.2×10^4 to 8.2×10^5 which is far below our needs for LUCRECE. The antenna tip shape has been updated according to the LCLS2 antenna tip which permits much stronger external coupling to the cavity. In the context of LCLS2, the following changes were made to the TTF3 ILC design [5]: The TTF3 couplers can move over a 15-mm range, which changes Q_{ext} by about 19% per mm. In order to access 10 times larger Q_{ext} for LCLS2, the antenna tip had been shortened by 8.5 mm keeping the same flare angle, and the cylindrical edge has been set to 3 mm.

Q_{ext} Calculation

The external quality factor is inversely proportional to the power used by the cavity. By measuring the latter, one can access the external quality factor. To simulate the external quality factor, the designed coupler is used coupled to a simplified single cell LCLS2 cavity type used for LUCRECE, to decrease the simulation time. If the cavity is used in free mode, with incident power (P_{inc}) injected, part of the power will be dissipated by the metallic walls, or will be transmitted to the beam. An other fraction will go back to the line containing the power coupler. By integrating the electromagnetic losses in a charge placed in the output line, one could extract the unused power by the cavity. The material of the dissipative and adapted charge, and its length, should be chosen carefully, because the reflected EM wave should vanish exponentially inside the material. Concerning the material properties, the limit conditions between vacuum and the charge material imposes the conservation of the impedance Z_0. On the other hand, the charge should also dissipate the EM power which imposes the imaginary part of ϵ and μ to be non zero. The dissipative charge electric and magnetic characteristics should be expressed as :

$$\epsilon = \epsilon_0(\epsilon_R + j\epsilon_i) \text{ with } \left|\frac{\epsilon}{\epsilon_0}\right| = 1 \text{ and } \epsilon_i = \sqrt{1-\epsilon_R^2}$$

$$\mu = \mu_0(\mu_R + j\mu_i) \text{ with } \left|\frac{\mu}{\mu_0}\right| = 1 \text{ and } \mu_i = \sqrt{1-\mu_R^2}\,.$$

In our simulations we used 80mm long adapted charge, with $\epsilon_R = \mu_R = 0.8$ and $\epsilon_i = \mu_i = 0.6$ ($\tan\delta = 0.75$).

The external quality factor is the ratio between stored energy inside the cavity and the power dissipated into the adapted charge ($P_{inc} - P_{cav}$), could the be expressed as :

$$\begin{aligned} Q_{ext} &= \omega\frac{U}{P_{inc} - P_{cav}} \\ &= \omega\frac{\epsilon_0 \iiint_{cav} \left|E_1^2\right| dV}{\epsilon_0\epsilon_i \iiint_{charge} \left|E_2^2\right| dV + \mu_0\mu_i \iiint_{charge} \left|H_2^2\right| dV}, \end{aligned} \tag{2}$$

where E_1 is the electric field in the cavity and E_2 and H_2 are respectively the electric and magnetic fields in the dissipative charge. The simulation setup under ANSYS/HFSS is shown in Fig. 3 contains a single cell 1.3GHz TTF3-type cavity, attached by a 40mm tube corresponding to the entrance flange diameter, ended with the simulated dissipative charge. Most of the geometry is parametrized in order to optimize the external quality factor, especially the antenna tip shape taken from TTF3-XFEL design.

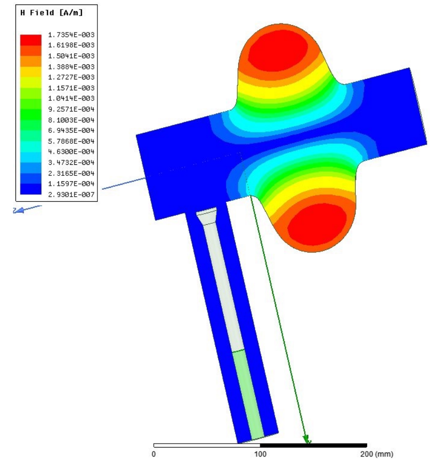

Figure 3: HFSS simulations layout for the Q_{ext} optimizations. The light green part of the tube corresponds to the described dissipative charge.

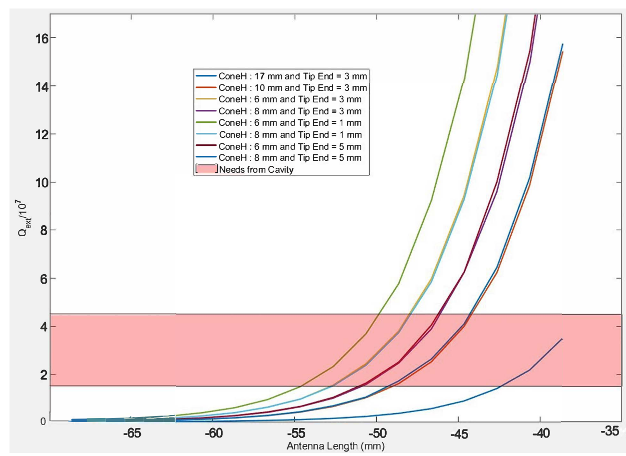

Figure 4: Q_{ext} versus the antenna penetration inside the cavity (smaller values correspond to deeper antenna penetration). The different curves are done with variating the antenna cone and its cylindrical end heights.

As shown by the studies for LCLS2, and confirmed by our simulations (shown in Fig. 4) the Q_{ext} improves when the tip cone is shortened [1]. Needs from the cavity side (shown as red box) could be obtained with antenna penetration between about 48mm and 54mm (few (<5) mm before the entrance of the beam pipe).

THERMAL STUDIES

The thermal studies have been performed using the Cornell coupler geometry shape, in order to understand what are the limitations for room temperature conditioning. We also considered different parameters to decrease the coupler heating with 20kW CW power, like the copper thickness.

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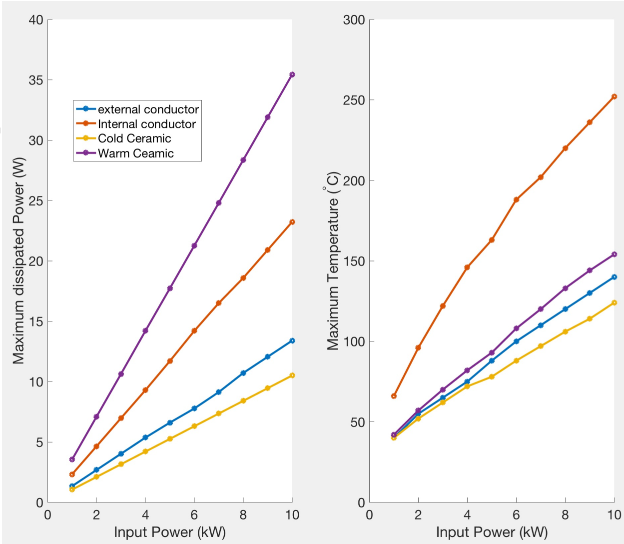

Figure 5: Variation of the temperature at different coupler location.

We finally will conclude by showing the locations of the highest temperatures in the inner conductor, and the maximum power one could use in CW mode, without external cooling.

The Fluent-HFSS coupling allows evaluating the RF losses in HFSS during the electromagnetic analysis and considering them in Fluent for thermal analysis. This link between the two solvers imports the EM field as heat flux (W/m²) on the inner/outer conductor and (W/m3) on the Warm/Cold window. This functionality is created in Workbench. For this first part of the study, no cooling system is considered, except the outer conductors cooled by static air.

Thermal Simulations up to 10 kW CW

We increased the power up to 10 kW, at room temperature, without external cooling. At this power level, the coupler inner conductor could reach more than 250 $^{\circ}C$ and the ceramics more than 150 $^{\circ}C$. Usually, during RF conditioning, 60 $^{\circ}C$ interlock for the ceramics is used to prevent any damage. Higher power should be done quite carefully with well designed temperature measurements, especially near the inner conductor and the ceramics.

Simulations have been done by increasing the input RF power by 1-kW steps (see Fig. 5). The dissipated power as well as the maximum temperature follow linearly the input power (the thermal increase has some non linear component). Without external cooling, power should be limited to 5 or 6 kW CW, and to scan the full power range during the conditioning, one should consider external cooling (air cooling) for instance which might decrease the inner conductor temperature by thermal conduction, and the ceramics temperatures as well. In addition, dedicated temperature measurements should be provided, with fast interlocks systems.

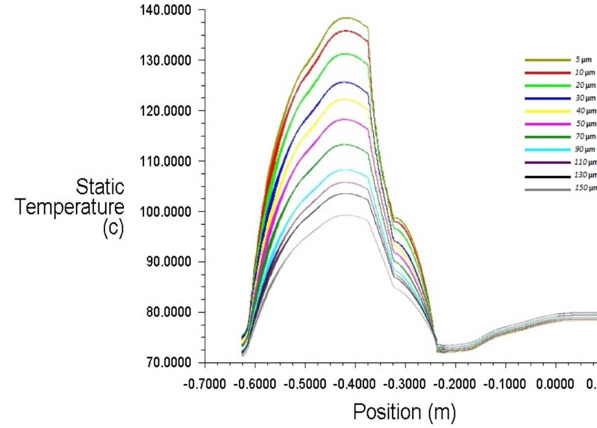

Figure 6: Influence of the deposited copper thickness on the coupler internal conductor temperature : simulations done at 4-kW input power.

Copper Thickness Effect

Larger is the copper plating thickness better becomes the heat dissipation from the internal inner conductor. This is due to its thermal conductivity that is much higher than that of stainless steel ($\lambda_{\text{stainless steel}}$ = 16 W/m K and λ_{copper} = 400 W/m K). By increasing the coper plating thickness from 30 µm to 150 µm, temperature should be reduced from at leased 30%, and by conduction, ceramic temperature should also drop.

CONCLUSION

A 1.3-GHz power coupler at 20-kW CW maximum power is currently being designed at LAL-Orsay. Starting from the Cornell 62-mm coupler design, EM and thermal studies are done using the HFSS software associated with Fluent inside Ansys Workbench. The Cornell coupler has been adapted to fit to cavity connection constrain, with taper after the last bellow. The antenna tip shaping has also been studied to fit the external quality factor needs from the cavity. Further investigations are on going in particular concerning the cooling solutions. Principal concerns come from foreseen CW room temperature conditioning: indeed heating the ceramics limit the input power to 5-6 kW. In addition, as it is foreseen to perform a pulsed RF conditioning prior to CW one, we need to consider multipacting simulation study, in particular for the taper region. Thermal studies have to be completed by including cryogenic simulations, to evaluate the heating power send to the cavity and find a balance between the different parameters.

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