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THERMAL AND DEFORMATION ANALYSIS OF A 750 MHZ IH-DTL PROTOTYPE FOR MEDICAL APPLICATIONS*

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Abstract

This article presents an IH-DTL prototype, capable of accelerating carbon ion beams from 5 MeV/u to 5.5 MeV/u, for manufacturing and assembling validation in a hadrontherapy linac injector. A multi-physics study is made in CST Studio concerning steady-state thermal, stress and deformation analysis. Convenient water-cooling circuits close to drift tubes are simulated to evaluate field errors and frequency detuning as they can affect directly to beam dynamics.

INTRODUCTION

The H-mode accelerator interdigital structure, which operates in TE110 mode, has become an essential component for linac injectors used in the acceleration of both light and heavy ions due to its high efficiency for a velocity range below β ~ 0.15 [1].With this in mind, CIEMAT, in collaboration with the company Added Value Ind. Engineering Solutions (AVS), is manufacturing a prototype of a high-frequency IH-DTL within the IKERTU-II project, which aims to promote regional industrial activity in the field of medical accelerators. The prototype operates at 750 MHz and is designed to address the main challenges in the fabrication of a complete IH cavity for accelerating C^{6+} ion beams from 5 MeV/u in a hadrontherapy linac injector.

The objective of this work is to study the frequency shift of the IH-DTL 750 MHz prototype through thermal and deformation analysis, taking into account different metals for the structure cavity, as shown in Fig. 1. Additionally, this work explores different duty cycles and controlled-temperature levels for the same cooling system.

MODEL

The 750 MHz IH-DTL prototype was modeled in CST Studio Suite [2]. Scripts based on VBA macros were created for modeling every single cell of the IH prototype as a function of specific dimensions, which take into consideration the optimization studies of inner and end cells previously performed in [3–5]. In this way, the model of the cavity is made up of 10 cells and is housed inside a simplified rectangular prism of conducting material, as shown in Fig. 1, of approximately 130x140x250 mm^3. The transverse dimensions of the inner cavity are 90x100.4 mm^2 and the length is 211.2 mm.

The cavity is designed to have a total voltage of 1.08 MV to accelerate C^{6+} ion beams from 5 to 5.5 MeV/u. Figure 2 shows the field and voltage distribution along the cells of the structure. Considering the conductivity of copper walls, the expected instantaneous RF losses are 22.38 kW, however, this power will be fed into the structure with a duty cycle (dc) of 0.1 %.

Water-cooling circuits have been included for the RF power refrigeration of the structure. They consist of two 8 mm-diameter channels crossing the tank longitudinally, through which a water flow at a speed of 1 m/s is expected.[1]

In the present work, two models have been analyzed based on exactly the same geometry but with different materials (Fig. 1). The first one is made completely of OFE copper in the way that was thought in the original design, as it has been the case for other high-frequency resonant structures [6]. The second one corresponds to a preliminary mechanical design of AVS, which divides the model into six assembled parts. The ones that require high-precision machining performance are made of copper, they are the drift tubes and the stems. Shaping the frame of the cavity, we use stainless steel 316L for the bases of the stems, which include the two channels of the water-cooling circuit, and a 7075/T6 aluminum alloy for the lateral sides, in which the RF auxiliaries (coupler and tuners) will be integrated under vacuum sealing conditions. Nevertheless, all components are intended to be coated with copper on all the internal surfaces of the cavity, with a thickness five times greater than the skin depth (15 μm), to maximize electrical conductivity and, therefore, efficiency.

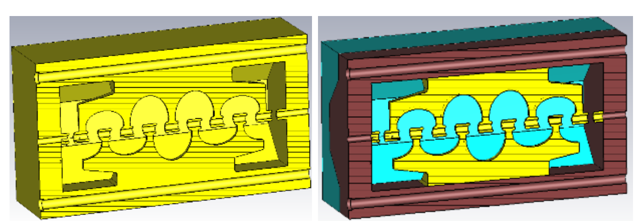

Figure 1: The left image is of the all-copper IH-DTL cavity. The right cavity is divided into copper (yellow), 316 L stainless steel (brown) and aluminum (blue) zone.

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[1] This corresponds to a convective heat transfer coefficient between copper and water of 3900 W/(m^{2}K) [6]. This is still a conservative value that has also been considered between aluminum and water for the mixed Cu-Al-Steel model.

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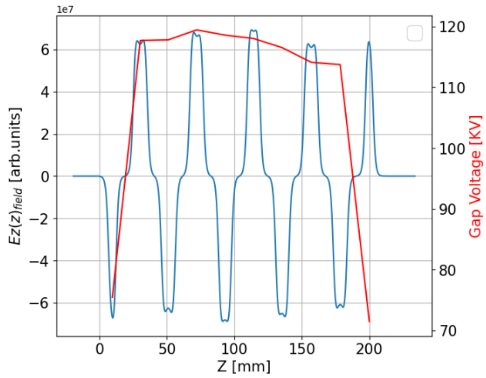

Figure 2: Electric field in z-direction (blue). Gap voltage of each of the cells obtained in CST (red).

METHOD

Ohmic losses from surface currents can reduce the efficiency of the cavity, resulting in heat generation caused by the Joule effect. This heat causes an increase in temperature and subsequent deformation of the cavity. These local displacements cause changes in the inductance and capacitance of the RF system, depending on whether they occur in the drift tube zone or in the cavity's external walls. As a result, the frequency of the system decreases in each of the studied cases.

To compare the maximum temperature, displacement, and frequency shift differences between the two prototypes, a series of simulations are performed in CST using nominal parameters of a duty cycle of 0.1 % and a cooling water temperature of 25 °C. We summarize in Table 1 a selection of thermal and mechanical properties of the materials that were considered in this study.

For this purpose, the CST software employs the finite element method [2]. The steps followed, as shown in Fig. 3, are: 1. Analyze the electromagnetic fields generated in the cavity and calculate their resonant frequency. 2. Calculate the temperature increase in the different parts of the structure caused by the surface heat distribution obtained from the electromagnetic simulation, taking into account the material properties and cooling system. 3. Obtain the displacements resulting from the temperature changes. 4. Study the frequency shift caused by these displacements in an electromagnetic analysis of the cavity.

Table 1: Material Properties of Copper, Aluminum and Stainless Steel 316L Used in the Thermal Simulations [7].

	Cu	Al	Steel 316L
Thermal conduct. [W/m/K]	401	130	14.3
Mass density [kg/m^3]	8930	2810	7969
Electric conduct. [MS/m]	58	-	-
Specific heat (0-100°C) [J/kg/K]	390	960	480
Young's modulus [GPa]	120	72	193
Coeff. of the thermal expansion [1E-6/K]	17	21.6	16

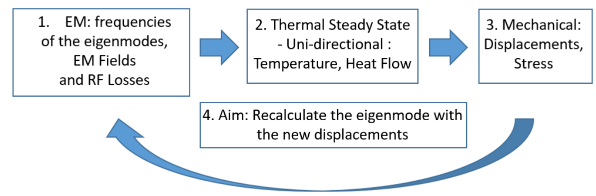

Figure 3: Diagram of the analysis process using CST.

Afterwards, a study is carried out by modifying the nominal parameters (duty cycle and cooling water temperature), which cause significant changes in the thermal analysis [6].

RESULTS

All-copper cavity

In Fig. 4, it can be observed that the highest temperatures are found in the IH-DTL drift tubes, with the first section experiencing a temperature increase of up to 1.46 °C. This increase then spreads towards the stem, reaching the girder.

For the mechanical simulation, the displacement boundary condition is set to zero on each of the external faces outside the cavity. The purpose of this boundary is to simulate the most extreme case where the hightest mechanical shifts inside the cavity occur.

Also, the obtained displacements are more significant in the drift tubes. In the central cells they are mainly vertical, but there are also significant longitudinal deviations in the drift tubes at the end cells, reaching up to 9.6 μm.

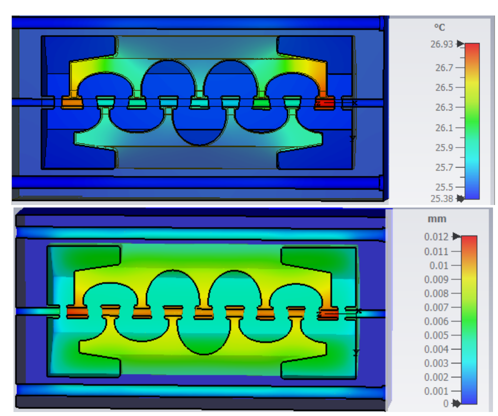

Figure 4: Thermal and mechanical simulations for nominal parameters (dc = 0.1 %, T_{water} = 25 °C, v_{water} = 1 m/s) for the copper cavity.

Mixed cavity

In this case, even though the cavity is composed of three different materials, the internal geometry is kept unchanged,

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therefore the resonance is produced at the same frequency under cold conditions. By having a copper coating, the same power loss density distribution, and therefore surface heat distribution, is also generated as in the previous case.

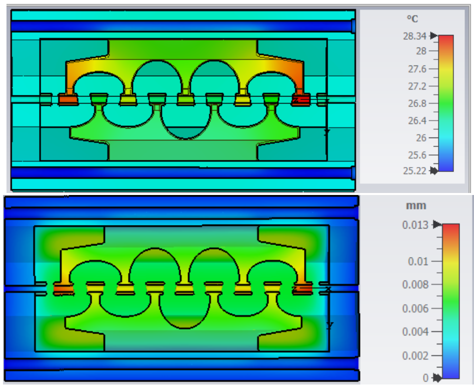

Figure 5: Thermal and mechanical simulations for nominal parameters (dc = 0.1 %, T_{water} = 25 °C, v_{water} = 1 m/s) for de mixed cavity.

In Table 2, results are compared to the all-copper cavity case at nominal conditions. It can be seen that the frequency shift is 35.9 kHz lower than in copper.

Both temperature and deformation distributions between the two cases are similar, although it is important to note that in the mixed cavity there is a temperature increase of more than 1 °C on its outer walls, due to a much worse thermal conductivity of aluminum. On the other hand, mechanical stresses have been analyzed considering more realistic displacement boundary conditions. The maximum equivalent von Mises stress levels for both cases are found to be less than 1 MPa on the edges of the magnetic profile of the cavity, still very far from the material stress yield.

Table 2: Maximum Temperatures, Displacements and Frequency Drift with Nominal Parameters (dc = 0.1 %, T_{water} = 25 °C, v_{water} = 1 m/s) for Copper and Mixed Cavity

	T_{max} [°C]	Displacement [mm]	△f [kHz]
Mixed	28.3	0.013	-130
Cu	26.9	0.012	-166

DUTY CYCLE AND WATER TEMPERATURE ANALYSIS

Fig. 6 analyses the frequency sensitivity as a function of different duty cycle and cooling water temperature values, for each type of cavity. This analysis aims to, on one hand, assess its ability to withstand higher powers without compromising dimensional tolerances, and on the other hand, evaluate the tuning range by online control of the cooling system temperature during operation. The difference between the two cavities in the cooling water temperature sensitivity is very small, but the duty cycle sensitivity difference is up to 91 kHz: $\delta f/\delta T_{water}$ = 29.5 kHz/°C y $\delta f/\delta\%$ =229 kHz/% for the copper cavity. For the mixed cavity, $\delta f/\delta T_{water}$ =17.3 kHz/°C y $\delta f/\delta\%$ =390 kHz/%.

It is also shown that the maximum temperatures as a function of cooling water temperature, as well as the frequency shift, are less sensitive than by varying the duty cycle.

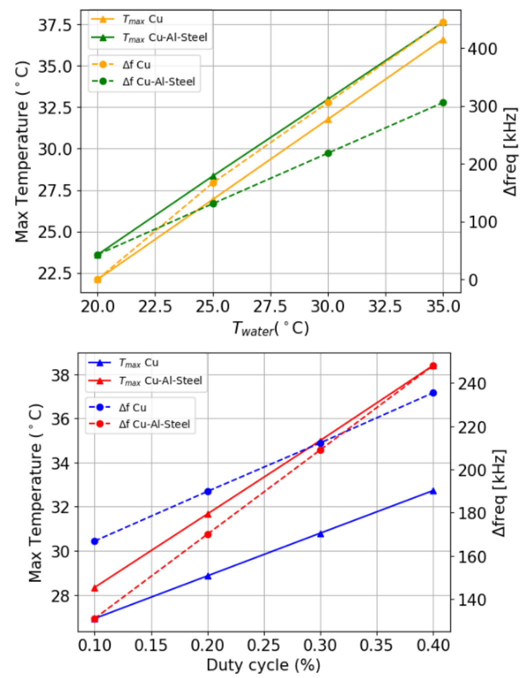

Figure 6: Maximum temperatures and frequency drift depending on the cooling water temperature (up) and the duty cycle (down) with a water velocity equal to 1 m/s, for the copper and mixed cavities.The frequency shifts are negative, but they are presented in absolute numbers.

CONCLUSION

This work presents thermal and mechanical simulations belonging to two IH-DTL 750 MHz options. Using the same structure, one cavity is made of copper material and the other of copper, aluminum and stainless steel. The results show that with the nominal parameters used, differences between both configurations are not significant. However, given the misalignments of the displacements, a beam dynamics study should then be carried out in order to indicate if a correction of the structure is necessary or not.

As for the frequency shift, an online tuning of the cavity by temperature-control water chillers is recommended to be implemented taking account of the used nominal thermal parameters, aiming to retune to the original frequency for which the cavity was designed.

Finally, as shown in the last study, it is important to consider these possible changes in the cavity can be increased due to a higher ambient temperature or duty cycle value, especially in the mixed cavity.

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