Boosting the performance of gyrotron resonators: optimization methods for longitudinal and azimuthal cooling

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One of the main challenges for the realization of future fusion reactors for energy production is the heat removal from many systems and components. One of these components is the resonant cavity of gyrotrons, a candidate technology for the Electron Cyclotron Resonance Heating, to be used as external heating of the plasma in magnetic confined fusion machines. During the normal operation of gyrotrons, MWs of power are transferred to the plasma in the form of radiofrequency waves, while a high amount of energy loss is released on the cavity inner wall, with a heat flux peak that can reach 25 MW/m^2. The resonant cavity constitutes the gyrotron component where the the interaction between the electron beam and the electromagnetic field occurs, determining the amplification of the RF wave at the desired frequency, thanks to its geometry and by a proper tuning of the magnetic field and beam parameters. Because of the importance of the cavity inner wall shape, its cooling plays a crucial role limiting the temperatures on the cavity inner wall, to limit the cavity expansion and hence the frequency down-shift of the output wave. Moreover, the peaked axial shape of the heat flux loading on the cavity inner wall, drives a similar temperature profile. In other words, high thermal gradient can be experienced in the cavity, leading to high thermal stresses, that could reach the yield strength of the material (Glidcop for European gyrotrons). In addition, the cooling system of the gyrotron sets a limit on the allowed pressure drop to around 6 bar for the cavity. The mentioned requirements are to be accounted for in the design of an efficient cooling system for the gyrotron cavity and bring to the need of an optimization study: the minimization of the frequency shift is required while monitoring pressure drop and stresses.

In the present dissertation, the problem of the cooling of the gyrotron cavity is faced through several strategies. Starting from the analysis of the already existing cooling solution and the proposed ones for the European gyrotrons, some improvements are proposed for them. Moreover, different optimization studies, making use of different optimization methods, are presented. The considered cooling strategies can be classified for the main direction of the coolant flow: longitudinal and azimuthal. For both, designs with and without ducts are considered.

Considering the longitudinal direction as the main one for the coolant flow, an optimized annular configuration is designed. An evolutionary algorithm is coupled to a thermos-mechanical model with finite elements, defining an optimization work in the thermos-mechanical field. The minimization of the displacements is aimed, to minimize the frequency shift, and avoiding yield strength. The obtained pressure drop is also under the allowed system limit. An advanced design with longitudinal mini-channels is also presented here, characterized by the reduction of the temperature peak and the pressure drops with respect to previous mini-channels designs. Both these solutions, the annular one and the mini-channels one, present better results compared to the actual cooling solution used for the European gyrotrons, the Raschig Rings one.

Concerning the design of cooling configurations exploiting the azimuthal direction of the flow, two optimization studies are presented here. They both use the adjoint-based topology optimization method. A solution using azimuthal microchannels is optimized in terms of flow rate distribution in the microchannels, to reduce the temperature gradients that lead to thermal stresses. In this case, the optimization work is done considering only the hydraulic physic of the problem. Two different strategies are compared: one aiming to an homogeneous flow rate distribution over channels with density following the heat load curve and the other based on equally spaced channels with a peaked flow rate distribution. The main outcomes are the better improvement of the cost function in the first case as well as the easier manufacturability of the geometry found. The second optimization work starts from a configuration that forces the flow in the azimuthal direction, without the use of ducts. In this case, the optimization problems is defined in the thermal-hydraulic field. Comparing the final result with the one obtained with the evolutionary optimization algorithm, the latter presented better temperature profile, with almost 70 $^\circ$ C less in the temperature peak. Further parametric studies could be conducted to obtain better results with the topology method.

Some validation studies have been conducted for the mini-channels cooling system, being the more advanced one in the exploration path toward an alternative more efficient solution for the cooling of European gyrotron cavities. The importance of the model validation is due to its double use of predicting gyrotron performances and guiding the design of new cooling configurations. A cavity mock-up equipped with straight mini-channels allowed the validation of the hydraulic part of the model. Thermal results were also compared from a second test campaign performed on a second cavity mock-up at KIT. In this work, the simulated temperature are higher than the measured ones and, even if similar qualitative profiles can be defined with the several thermocouples available, the quantitative discrepancies cannot be justified with the available information on the measurement uncertainties. Further test campaigns are scheduled with improved test set-up and measurement instrumentation.

Overall, by comparing the results of the different optimization strategies analyzed, the use of the longitudinal direction as main flow direction in the cooling presents higher sensitivity to the modification and optimization, remaining the preferable one to be further analyzed. The experimental activities are encouraging with respect to the models prediction of the designed cooling configurations.