Investigation of a Mini-Channel Cavity Cooling Concept for a 170 GHz, 2 MW Coaxial-Cavity Gyrotron

S. Illy[1], K. A. Avramidis[1], P. T. Brücker[1], G. Gantenbein[1], P. C. Kalaria[1], S. Ruess[1], M. Thumm[1],
and J. Jelonnek[1]
[1] Karlsruhe Institute of Technology, Karlsruhe, 76131 Germany

***Abstract*—The maximum heat load on the cavity wall of high power fusion gyrotrons is one of the major limiting technological factors for the operation of the tube. To achieve the requested output power, efficiency and pulse length, a very efficient cooling of the interaction structure is mandatory. In this work, the performance of a mini-channel cavity cooling system for a 170 GHz, 2 MW coaxial-cavity gyrotron is numerically investigated, including the development of a mock-up test set-up for experimental validation.**

I. INTRODUCTION

High-frequency (100 GHz – 300 GHz), high-power (~ 1 – 2 MW) gyrotrons are the prominent RF sources for Electron Cyclotron Resonance Heating and Current Drive systems in thermonuclear fusion experiments [1]. For ITER, a 2 MW, 170 GHz coaxial cavity gyrotron and a 1 MW, 170 GHz hollow cavity gyrotron have been developed by the European GYrotron Consortium (EGYC) in cooperation with the industrial partner Thales [2]. In these gyrotrons, the nominal ohmic heat-load of the cavity is high (~ 2 kW/cm^2). Consequently, an effective cavity cooling system is mandatory to avoid cavity deformation, frequency downshift [3] and to maintain the cavity temperature within material strength limits (e.g. 250°C for Glidcop) for long-pulse / Continuous Wave (CW) operation.

In the KIT 170 GHz, 2 MW short-pulse coaxial-cavity gyrotron, up to now a simple annular gap cavity cooling system is used [4]. The cooling performance of this system is numerically evaluated in [5], indicating that a safe temperature limit of 250°C could be only maintained up to a pulse length of 150 ms. Therefore, an advanced cooling system is required to increase the pulse length and to improve frequency stability. In [6], the effectiveness of a mini-channel cavity cooling system is studied for the 170 GHz, 1 MW hollow-cavity EU gyrotron. In the present work, systematic design studies of a mini-channel cavity cooling system for the 170 GHz, 2 MW coaxial cavity gyrotron are presented.

II. MINI-CHANNEL CAVITY COOLING

The mini-channel approach is investigated numerically by simulations with ANSYS Fluent®. The overall aim is, to reduce the wall temperature of the cavity so that CW operation of the gyrotron should be possible. To reduce the computational effort, we focused on the highly loaded part of the 170 GHz, 2 MW coaxial cavity (not including the moderately loaded up-taper) and only an 18° wide slice with periodic boundary conditions in azimuthal direction has been considered to reduce computational efforts (see Fig. 1). For the thermal-hydraulic part of the simulations, the SST $k - \omega$ turbulence model [7] has been chosen, for the structural mechanical part, the properties of the dispersion strengthened copper alloy GLIDCOP AL-15® are used for the solid parts. The azimuthally symmetric heat load profile applied to the inner surface of the simulation model corresponds to the cavity load profile of the 170 GHz, 2 MW gyrotron under nominal operation conditions with a peak power density of approximately 1.7 kW/cm² [8].

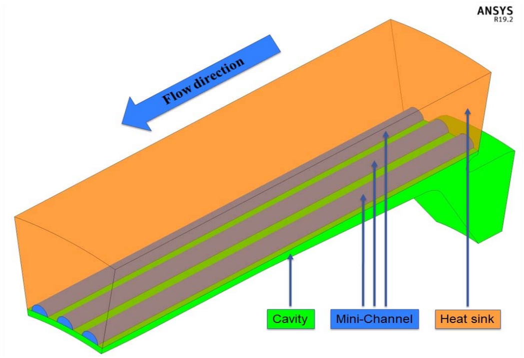

Fig. 1. Schematic view of the selected mini-channel cavity cooling

Further investigations aimed to determine the influence of channel radius, number of channels, inlet mass flow and the distance of the channels to the heated surface. Each of these parameters is varied separately while keeping all other parameters constant. The maximum cavity wall temperature and pressure drop corresponding to the specific channel radius are presented in Figure. 2 (assuming a wall thickness between cooling channels and heated inside of 3.95 mm). Obviously, the decrease in hydraulic diameter increases the heat transfer coefficient significantly. The convective heat transfer to the cooling water is also increased by increasing the temperature gradient between fluid and inner wall, which can be done by reducing the wall thickness, indicated in Figure 3 for a channel radius of 1 mm.

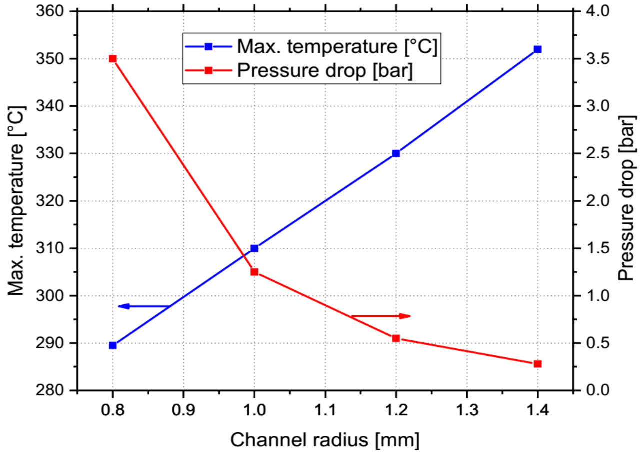

Fig. 2. Maximum temperature and pressure drop versus the channel radius.

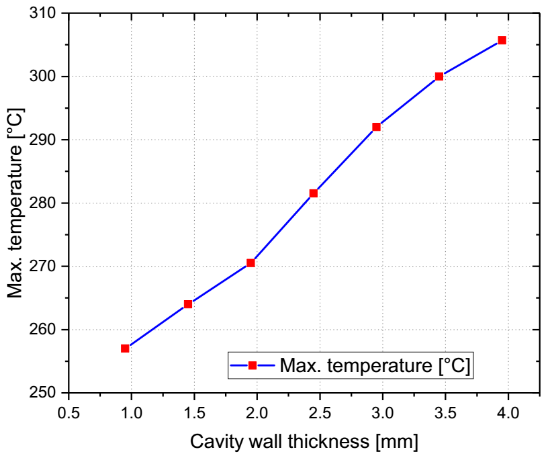

Fig. 3. Obtained maximum temperature versus the cavity wall thickness.

After a systematic parametric analysis, optimized physical and operation parameters could be obtained, which are listed in Table 1. With 60 parallel channels with semi-circular cross-section of 1 mm radius, a distance from the channels to the cavity inner wall of 0.95 mm and a water flow rate of 62 l/min, one obtains a maximum temperature of 261°C; this value is slightly overestimated due to the fact that heat flow in longitudinal direction is not permitted by the used boundary conditions and the limited size of the model. The corresponding steady-state temperature profile on the cavity structure is shown in Figure 4. The obtained results indicate that the proposed cooling system allows the operation time to be increased towards CW operation.

As a next step, an iterative multi-physics simulation will be performed to determine the cavity deformation with the proposed cooling concept and the impact on the cavity RF properties.

III. TESTS WITH EXPERIMENTAL MOCK-UP

At the moment, the designed heat sink is under experimental investigation using an internally developed mock-up test set-up, which is based on heating the inner surface of the structure with a gas burner (see Figure 5) [9]. Another concept, using inductive heating is also under consideration.

Table 1. Physical and operating parameters of the optimized mini-channel design for a 170 GHz, 2 MW coaxial cavity gyrotron.

Parameters	Values
No. of channels	60
Channel radius	1.0 mm
Cavity wall thickness	0.95 mm
Flow rate	62 l/min
Velocity of water in channels	10.9 m/s
Inlet pressure	1.66 bar
Pressure drop	0.65 bar
Maximum cavity temperature (with an inlet temp. of 27°C)	261°C
Maximum channel wall temperature	229°C
Water outlet temperature	< 84°C

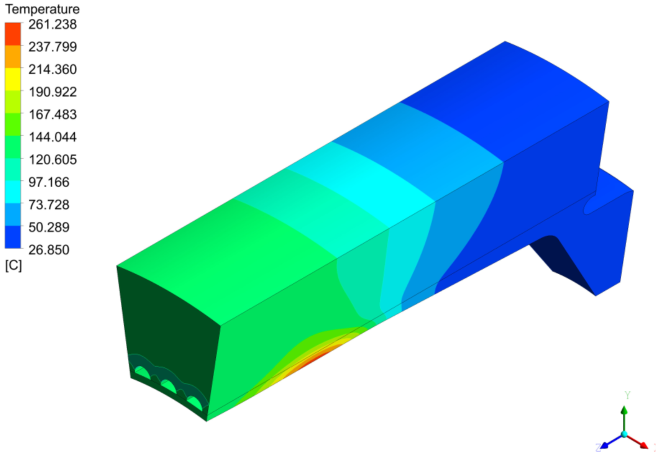

Fig. 4. Temperature profile on the cavity wall and heat-sink with the suggested mini-channel cooling configuration (18° section). The maximum temperature on the cavity wall is approximately 261°C.

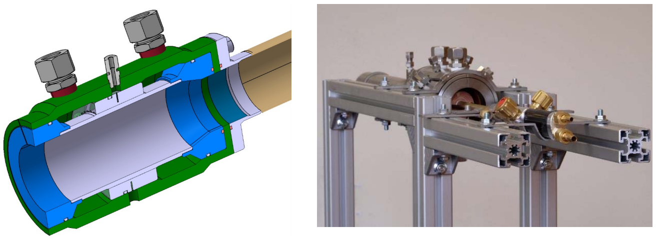

Fig. 5. Schematic drawing and photograph of the experimental mock-up.

IV. ACKNOWLEDGMENT

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. Part of the simulations was performed on the EUROfusion High-Performance Computer (Marconi-Fusion).

REFERENCES

[1] M. Thumm, *IEEE Trans. Plasma Sci.*, vol. 42, no. 3, pp. 590–599, 2014.

[2] J. Jelonnek, *et al.*, EPJ Web Conferences, vol. 187, no. 01009, 2018.

[3] K. A. Avramidis, *et al.*, *IEEE Transactions on Electron Devices*, vol. 65, no. 6, pp. 2308-2315, 2018.

[4] S. Ruess, *et al.*, Int. Journal of Microwave and Wireless Techn., vol. 10, no. 5-6, pp. 547-555, 2017.

[5] L. Savoldi, *et al*, 27th IAEA Fusion Energy Conf., Gandhinagar, India, 2018.

[6] A. Bertinetti, *et al.*, Fusion Engineering and Design, vol. 123, pp. 313-316, May 2017.

[7] ANSYS Inc., “ANSYS Fluent Theory Guide”, August 2017.

[8] P. Kalaria, *et al*, “Design Studies of Mini-Channel Cavity Cooling for a 170 GHz, 2 MW Coaxial-Cavity Gyrotron”, IEEE International Vacuum Electronics Conference (IVEC 2019), Busan, South Korea, April 2019.

[9] P. Brücker, et al., “Development of advanced cavity cooling systems for a 170 GHz, 2 MW coaxial cavity gyrotron”, 31st Joint Russian-German Workshop on ECRH and Gyrotrons, Lenggries, Germany, June 2019.