Cooling concepts for the CVD diamond Brewster-angle window

G. Aiello[1], T.A. Scherer[1], D. Strauss[1], K. Avramidis[2], J. Jelonnek[2], T. Franke[3,4], M.Q. Tran[5]
[1]IAM-AWP, [2]IHM, Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Germany
[3]EUROfusion Consortium, Boltzmannstrasse 2, D-85748 Garching, Germany
[4]Max-Planck-Institut für Plasmaphysik, Boltzmannstrasse 2, D-85748 Garching, Germany
[5]Swiss Plasma Center (SPC), EPFL, CH-1015 Lausanne, Switzerland

***Abstract*—The chemical vapor deposition (CVD) diamond Brewster-angle window is a very promising broadband radio-frequency (RF) output window solution for frequency step-tunable high power gyrotrons foreseen in nuclear fusion devices like DEMO. Since gyrotrons operate in the megawatt-class power range, active cooling of the output window during operation is mandatory for long pulse operation. In this paper, different indirect cooling layouts were investigated and compared by finite element method (FEM) thermal and structural analyses. Scenarios with different power and frequency beam were taken into account in the analyses.**

I. INTRODUCTION

FREQUENCY tunable gyrotrons able to switch their operating frequency in steps of around 2-3 GHz may be needed for control of plasma stability in DEMO [1]. In this scenario, a diamond Brewster-angle window is a very promising key component as its configuration allows working in a broad frequency range with minimum reflection of the millimeter (mm) waves. In the frame of the Heating and Current Drive (HCD) Work Package (WP) of the Power Plant Physics and Technology (PPPT) programme launched by the EUROfusion Consortium [2], diamond Brewster-angle windows are being investigated for long pulse gyrotron operation.

The typical configuration of the diamond Brewster-angle window consists of a CVD-diamond disc brazed to two copper waveguides (WGs) at the Brewster angle of 67.2°. The operation of this window concept was successfully shown for a high power gyrotron (~1 MW) working in the short pulse regime (< 10 ms) without any cooling of the window [3]. In this case, a window with an elliptical shaped diamond disc of 140 mm major axis and 1.7 mm thickness was used resulting in a window aperture of 50 mm.

As a consequence the key challenges in the window development towards long pulse operation are the manufacturing of sufficiently large diamond discs, the proper joining of such discs to the WGs via brazing or other techniques able to reduce the manufacturing residual stresses in the window, and the design of a cooling layout able to guarantee a proper removal of the heat absorbed in the window during the beam transmission.

In this paper, different cooling layouts were investigated by FEM thermal and structural analyses considering different power and frequency scenarios. For safety reasons, water is separated from the diamond disc since, in case of failure of the joining between the disc and the WGs, this design choice prevents the coolant from damaging the internal parts of the gyrotron (indirect cooling concept).

II. METHODS

The geometry of the Brewster window used in the analyses is reported in Fig. 1. The diamond disc has an elliptical shape with major axis of 140 mm, minor axis of 75 mm and a thickness of 1.7 mm. The copper WGs are cylindrical with inner diameter of 50 mm, thickness of 1 mm and total length of 170 mm. Symmetry along the major axis of the disc allowed analyzing only half of the window geometry. Three geometrical configurations of the cooling channels were considered in the analyses and they are shown in Fig. 2. The approach was to first investigate the simplest cooling configuration given by cylindrical channels, then to consider channels able to follow the geometry of the disc as outer elliptical channels and finally to consider channels inside the WGs like inner elliptical channels. In addition, the cooling performance of each configuration was checked by varying the distance of the channels from the diamond disc.

Thermal analyses were carried out to calculate the temperature distributions in the window according to three HE_{11} beam scenarios: 2 MW at 170 GHz, 1.5 MW at 240 GHz and 2 MW at 240 GHz. The absorbed power in the disc at the Brewster angle was first calculated according to [4] using the loss tangent value (3.5×10^{-5}) which was experimentally measured at the center of the Brewster-angle disc mentioned in [3]. The three beam scenarios respectively led to an absorbed power in the disc of 1094 W, 1159 W and 1545 W. Then, the heat generation load was applied to the disc by the Bessel function of order zero which describes the power pattern of the HE_{11} beam inside the WG.

The heat exchange coefficient applied to the cooling interface was calculated by book equations considering an inlet water mass flow rate of 20 l/min. The coefficient is 4283 W m^{-1} K^{-1} for the cylindrical and outer elliptical channels while it is 8946 W m^{-1} K^{-1} for the inner elliptical channels. The latter channels have a higher coefficient as their cross section is almost half than the one of the other channels. The temperature distributions resulting from the thermal analyses were afterwards applied in structural analyses of the window to calculate the correspondent thermal stress distributions in the diamond disc.

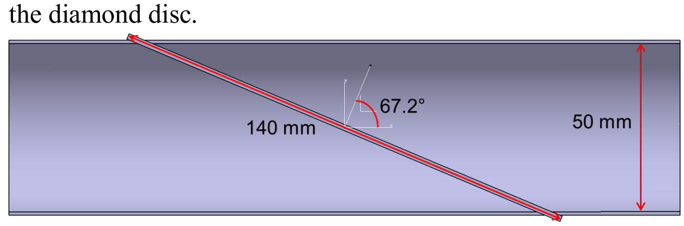

Fig. 1. Geometry of a typical diamond Brewster window.

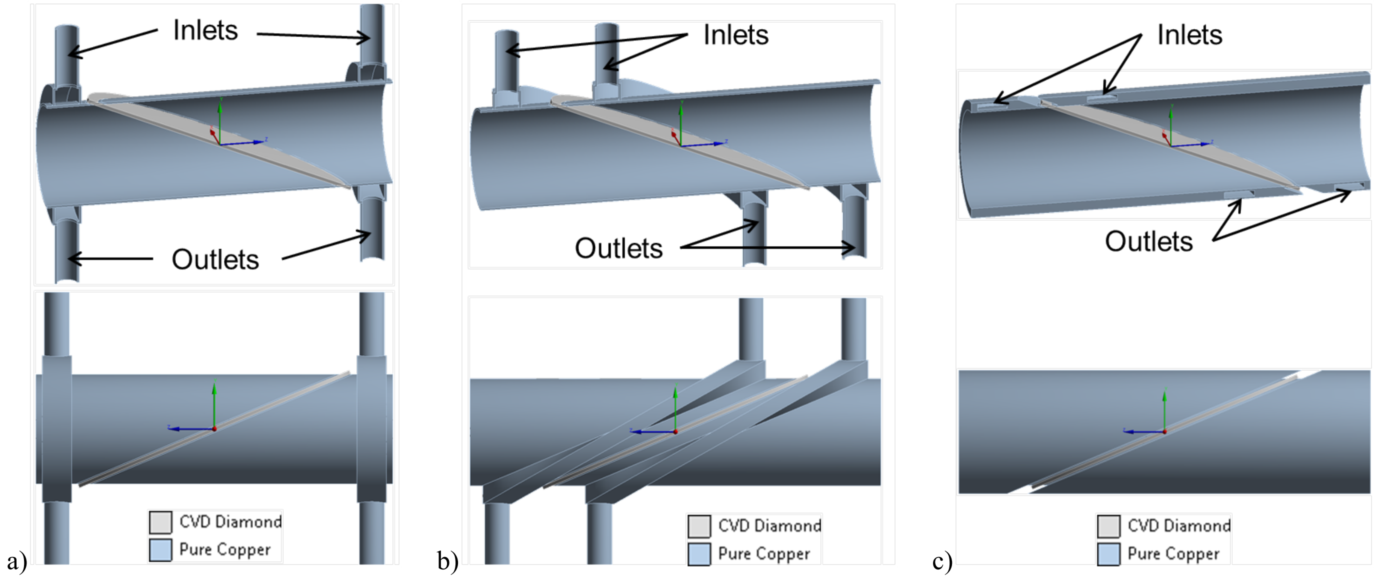

Fig. 2. Brewster window with cooling channels generated by a rectangular profile swept along a circumference (a), an elliptical curve outside the WGs (b) and an elliptical curve inside the WGs (c). The thickness of the WGs in (c) was increased from 1 mm (interface disc-WG) to 5 mm to accommodate the channels.

III. Results and Conclusions

The analyses showed the necessity of having cooling channels that follow the skewed position of the disc; otherwise the temperatures in the diamond disc due to the mm-wave losses result in values beyond the temperature limit (250–300 °C). In fact, the cylindrical channels lead to a maximum temperature of 416 °C located at the center of the disc already for the best beam scenario, 2 MW at 170 GHz. They do not represent thus a feasible cooling solution. On the other hand, even for the worst beam scenario of 2 MW at 240 GHz, both outer and inner elliptical channels work well as the resulting temperatures and stresses in the diamond disc are below the allowable limits.

For instance, Fig. 3 shows temperature and stress results for the Brewster-angle window with outer elliptical cooling channels. It can be observed that, even in the most severe beam scenario, the maximum temperature in the disc is below the limit. Then, going to 2 MW at 240 GHz, the temperature differences along the semi-major and semi-minor axes of the disc increase by a factor of about 1.55 leading obviously to greater thermal stresses in the disc. However, the stress distribution can be safely accepted considering a permissible stress for diamond of 150 MPa (ultimate stress is 450-500 MPa [5]). In fact, the stress distribution in the middle area of the disc becomes more severe as there is a larger area with stresses in the range 44-66 MPa and a new area with stresses ranging from 66 to 88 MPa appears. The stresses at the upper tip of the disc are the same (100-130 MPa) while the ones at the lower tip increase to 90-110 MPa. It should be also noted that stress singularities appear in the portion of the disc that forms a very sharp corner with the WG.

The inner elliptical cooling channels are more effective than the outer ones as long as the WG section with increased thickness is close to the diamond disc. The choice between outer and inner elliptical channels shall be based on their manufacturing feasibility and it shall be part of a separate study.

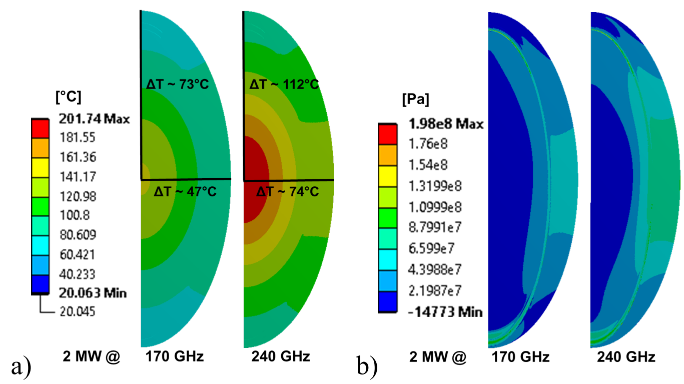

Fig. 3. Comparison of the temperature (a) and the maximum principal stress (b) distribution in the upper surface of the disc between the two extreme beam scenarios for the Brewster window with outer elliptical cooling channels.

Acknowledgements

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