Fusion Engineering and Design xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Multi-physics analysis of a 1 MW gyrotron cavity cooled by mini-channels

A. Bertinetti[a,*], K.A. Avramidis[b], F. Albajar[c], F. Cau[c], F. Cismondi[d], Y. Rozier[e], L. Savoldi[a], R. Zanino[a]

[a] NEMO Group, Dipartimento Energia, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[b] IHM, Karlsruhe Institute of Technology, Kaiserstraße 12, 76131 Karlsruhe, Germany
[c] Fusion for Energy, c/Josep Pla 2, 08019 Barcelona, Spain
[d] EUROfusion, Boltzmannstraße 2, 85748 Garching, Germany
[e] Thales Electron Devices, Rue Marcel Dassault 2, 78140, Vélizy-Villacoublay, France

HIGHLIGHTS

- A 1 MW gyrotron cavity, cooled using mini-channels, is numerically investigated.
- Electro-magnetic, thermal-hydraulic and thermo-mechanical simulations are performed.
- A multi-physics iterative approach is adopted to find the cavity working condition.

ARTICLE INFO

Article history:
Received 3 October 2016
Received in revised form 1 May 2017
Accepted 4 May 2017
Available online xxx

Keywords:
Nuclear fusion
Electron cyclotron heating
Gyrotron
Resonance cavity
CFD

ABSTRACT

The interaction cavity of the European 170 GHz, 1 MW Continuous Wave (CW) gyrotron for ITER, which could also be water-cooled using mini-channels as recently proposed, experiences during operation a very large heat load (>15 MW/m^2) localized on a very short (<1 cm) axial length. Such heat loads are typical for high power gyrotrons.

As the thermal deformation of the cavity influences the electromagnetic field structure and consequently the gyrotron operation, the analysis of the cavity performance requires the simultaneous solution of the coupled thermal-hydraulic, thermo-mechanic and electro-magnetic fields. In this paper, the thermal behaviour of the cavity under nominal heat load is computed first by CFD. Then a 3D thermo-mechanical model of the cavity is developed, based on the temperature maps computed by CFD, to evaluate the resulting deformation of the inner cavity surface. Finally the deformation is used to compute the updated heat load coming from the electromagnetic field generated by the electron beam in the deformed cavity, which becomes the input for a new iteration of the thermal-hydraulic, thermal-mechanical and electromagnetic analyses. It is shown that this iterative procedure converges to a self-consistent heat-load/temperature-field/deformation-field picture in nominal operating conditions, without exceeding a temperature of ~230 °C on the inner surface of the cavity.

1. Introduction

In the frame of the development of the European 170 GHz, 1 MW, CW gyrotron for ITER [1], the most critical sub-assemblies, such as the interaction cavity, are being fully qualified. During operation, the interaction cavity of a high power (1 MW) gyrotron experiences a very large heat load (>15 MW/m^2), localized on a very short (<1 cm) axial length, where any thermal deformation should be carefully assessed to guarantee the gyrotron performance required for ITER [2]. Among the different strategies which can be considered for the cavity cooling [3], we focus here on the use of mini-channels (MC) [4] drilled for the water flow in the annular region around the cavity, as shown in Fig. 1.

In this paper we consider equally spaced mini-channels drilled in the Glidcop sleeve all around the gyrotron cavity made of Glidcop also (see Fig. 1b). The manufacturing constraints allow a maximum number of 64 channels in the annular region, semi-circular in shape

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* Corresponding author.
E-mail address: andrea.bertinetti@polito.it (A. Bertinetti).

http://dx.doi.org/10.1016/j.fusengdes.2017.05.016
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Please cite this article in press as: A. Bertinetti, et al., Multi-physics analysis of a 1 MW gyrotron cavity cooled by mini-channels, Fusion Eng. Des. (2017), http://dx.doi.org/10.1016/j.fusengdes.2017.05.016

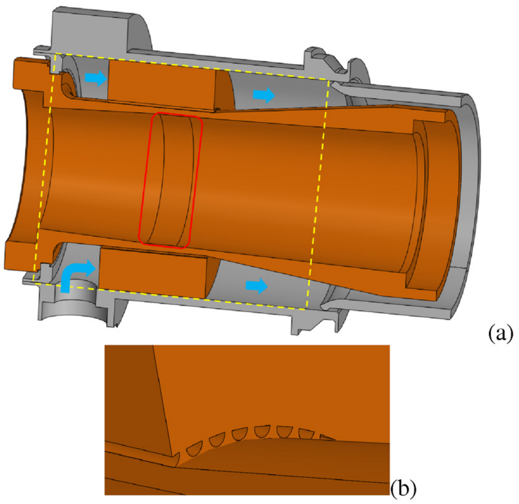

Fig. 1. CAD model of the gyrotron cavity equipped with mini-channels (a) and zoom in the region of the mini-channels block (b): the location of the heat flux peak is highlighted by the red box, the flow direction is specified by the blue arrows and the portion of the cavity used in the simulation is highlited by the yellow box. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

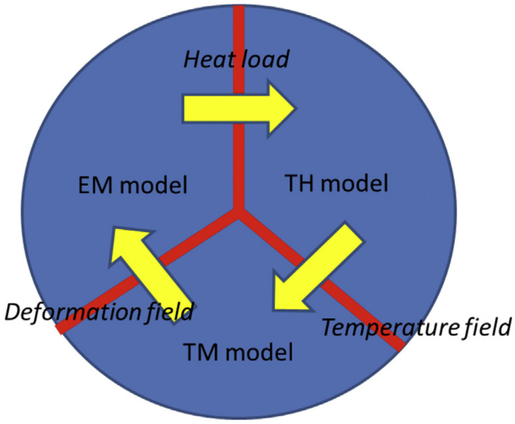

Fig. 2. Multi-physics approach and coupling between the different models.

with a diameter ϕ = 1.5 mm, 0.67 mm apart and 2 mm detached from the cavity heated surface.

2. Analysis approach

The approach adopted in the present paper is based on a coupled 3D multi-field analysis as summarized in Fig. 2:

- the electro-magnetic (EM) analysis, based on the actual (deformed) profile of the cavity, returns the heat load on the cavity inner surface, to be used in input for the thermal-hydraulic (TH) analysis.
- the TH analysis returns the thermal field of the cavity, to be used in input for the thermo-mechanical (TM) analysis.
- the TM analysis returns the cavity deformation, to be used in input for the EM analysis.

While the heat load reacts instantaneously to the deformation, and the deformation adapts instantaneously to the variation of the thermal field, the temperature field takes a few seconds to reach a complete stabilization in the cavity. However, since this longest timescale is much shorter than the operating time of the gyrotron in Continuous Wave (CW) operation, the analysis could be performed in a sort of steady-state fashion, starting from an initial heat load, obtained with the undeformed cavity, and iterating on the steady-state solution of the coupled problem, without the need of performing a time-dependent analysis.

The geometry used in the simulation is a simplification of the real cavity structure shown in Fig. 1: the external stainless steel envelop is removed, as well as the outlet part of the structure in order to remove a physical domain and to reduce the computational cost. The total length considered is ~80 mm.

3. EM model

For a given cavity inner profile, the high frequency (RF) electromagnetic wave in the cavity, generated from the electron beam, was calculated by the code-package EURIDICE [5], which simulates the beam-wave interaction. The heat load on the cavity wall is the average ohmic loading ρ (i. e. the ohmically dissipated power per surface unit), which was obtained using the well-known formula [6]:

$$\rho = \frac{1}{2\sigma\delta}|\mathbf{H}_t|^2 \tag{1}$$

Here, H_t is the tangential component of the RF magnetic field, σ is the electrical conductivity of the wall, and δ is the skin depth. The influence of both the roughness of the wall surface and of the temperature profile on the effective electrical conductivity were also considered.

4. TH model

For the TH simulations the commercial software STAR-CCM+ v10 [7] is used.

In order to reduce the computational cost, the simulated domain is halved according to the symmetry of the geometry. The coarsest computational mesh giving mesh-independent results is chosen as in [3].

The 3D, steady state, incompressible flow model, with the κ-ω SST turbulence closure [8] and "all y+" wall treatment is adopted. The VOF multiphase flow model is chosen, with the Rohsenow model [9,10] on in case of boiling onset. Temperature-dependent material properties are used, with the water properties evaluated at 9 bar, and the saturation temperature evaluated at the pressure computed at the heat load peak position (6.9 bar, giving T_{sat} = 164 °C).

An inlet mass flow rate of 22.5 l/min (on the halved domain) at a temperature of 26.85 °C, and an outlet (gauge) pressure of 0 bar are used as boundary conditions, while the solid in considered adiabatic, except for the inner surface where the heat load is applied.

5. TM model

The domain used in the TM simulation is restricted to the solid region (coloured in grey in Fig. 3) of the TH domain. The TM simulation is performed with STAR-CCM+ v10 [7]: a 3D, steady state, finite-element solid-stress model is adopted, with linear, isotropic and elastic material properties. The thermal stress is computed considering the zero-stress temperature as the inlet temperature of the fluid. The Glidcop density is 8690 kg/m^3, its thermal expansion coefficient is

1.85e-5 1/K and Young's modulus is 120 GPa. The constraints applied to the structure are shown in Fig. 3: the basement of the cavity is fixed on the gyrotron structure; the top part of the cavity (at the fluid outlet) is free to expand, as well as the external radial surface of the Glidcop where the mini-channels are drilled (this constraint should well represent the real structure).

Please cite this article in press as: A. Bertinetti, et al., Multi-physics analysis of a 1 MW gyrotron cavity cooled by mini-channels, Fusion Eng. Des. (2017), http://dx.doi.org/10.1016/j.fusengdes.2017.05.016