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On multistage development of ITER High Field Side Reflectometry diagnostic module design based on thermal stress numerical assessment

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ABSTRACT

The High Field Side Reflectometry (HFSR) is one of the ITER diagnostics which provides information about plasma state by measuring the electron density profile. Five various designs have been developed and studied since 2014 as a result of interaction of Peter the Great St. Petersburg Polytechnic University, NRC "Kurchatov Institute", and Fusion Centre. Multiphysics engineering finite-element analysis has been performed for each of the HFSR designs. The study deals with thermal loads which were discovered to be the most significant from structural integrity point of view. On the basis of the obtained results the decisions on introducing structural changes into individual parts of the diagnostics were made by the designers of the Kurchatov Institute.

Key features of the proposed mathematical model and results of numerical simulations, which demonstrate a stress state of the diagnostics, are given. The process of multistage diagnostic design development based on the finite element analysis results is presented.

1. Introduction

Reflectometry is one of ITER diagnostic systems that must ensure its correct operation. This is achieved through the analysis of the reflected form of emitted electromagnetic signal. As a diagnostic part of the ITER tokamak, HFSR provides measurements in the following functional categories [1]:

- Measurements for machine protection and plasma control;
- Performance evaluation and optimization;
- Additional measurements for physics understanding.

HFSR diagnostic module possesses a width application range and allows extracting a large amount of information about the plasma state, the key of which is the electron density profile.

HFSR diagnostics undergoes a strong action of different operating loads: inertial, electromagnetic, thermal etc. With regard to thermal loads, HFSR is subjected to non-uniform nuclear heating during plasma operation, high-intensity radiative heating of antenna, and substantial cyclic thermal loads during ITER life. Combination of these loads makes satisfying the strength requirements challenging. Finite element analysis process plays a vital role in design development.

2. Chronology of the HFSR redesigning

Since 2014, five different diagnostic designs have been considered (Fig. 1). A complete set of engineering multiphysics calculations (thermal, electromagnetic, stress-strain) was performed for each of them in order to assess design reliability and to improve it. The in-vessel part of the HFSR consists of an antenna, a 90° bend and its support, an intermediate plate between them, a waveguide line with welded flanges, waveguide casings, and a turn at the port entrance. Maximum thermal loads act on the in-vessel part of the diagnostic module (which is considered in this study) due to several reasons:

- The antenna, the 90° bend and its support are located in the gap between the blankets and undergo a direct plasma action;
- High-intensity non-uniform nuclear heating is presented inside the vacuum vessel.

The main design changes, implemented by the specialists of NRC "Kurchatov institute", concerned the waveguide casings, the port bend, as well as the 90° turn and its support. The design of casings, having the purpose of heat removal from waveguides, was radically changed from the original one. In spite of the fact that solid continuous structure

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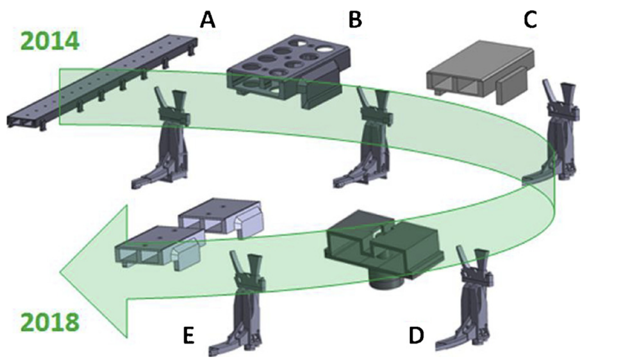

Fig. 1. Design development process of the HFSR (A – continuous waveguide casings / plate type support of the 90° bend; B – casings with holes / plate type support; C – short length solid casings / boss design of the 90° bend support; D – boss design of the supports; E – current design has the same general features as design C).

seems to be more effective with respect to waveguides cooling, high-intensity nuclear heating makes it necessary to reduce the material capacity of the casings. It is obvious that there exists a certain design, ensuring optimal cooling of the waveguides by radiation heat transfer with minimal heat release in the casings. Comprehensive research on the geometry of the casings was conducted by means of parametric optimization.

The support of the 90° bend was also subjected to significant changes. As a result of the completed set of numerical simulations the boss design of the support, which rather evenly transfers the load to the vacuum vessel, was chosen as the best one. Additionally, the recent design of the HFSR allows movement of the antenna along vertical direction of the tokamak in the area of the intermediate plate. This ability is purposed to help compensate for the thermal deformation of the waveguide channel.

3. New features of the HFSR mathematical model and recent results description

HFSR has a sufficiently large length and along this distance it experiences highly non-uniform loads, which can lead to high stresses. The main ways of heat exchange between the equipment in the vacuum vessel are thermal conductivity and radiation. The main imposed loads are direct heating of the antenna by plasma radiation and nuclear heating. In order to determine these loads, new approaches to finite element simulation have been proposed. The input information for a determination of nuclear heating is the data (Fig. 2) for the points, located along the surface of the vacuum vessel (Fig. 3) [2].

The problem is related to the transfer of the 2D data to the 3D solid finite element model. To perform that, the model was divided into several parts and for each of them, an equation of the curve, repeating the form of the waveguides, was found in the following general analytical form:

$$z = F(x) = \frac{p_1x^5 + p_2x^4 + p_3x^3 + p_4x^2 + p_5x + p_6}{x^4 + q_1x^3 + q_2x^2 + q_3x + q_4} \quad (1)$$

The values of nuclear heat generation shown in Fig. 2 were transferred to the points of those curves, depending on the length of the curve to the point. The nodes of the finite element model in a plane, perpendicular to the curve at a given point, were assigned a volumetric heat generation value, corresponding to this point. To determine the intersection point of the curve with a normal line from any particular node, the system of equations was solved numerically for each node of the mathematical model. Distribution of nuclear heating obtained through the implementation of this algorithm is shown in Fig. 4.

Further, the existing method for calculation of a heat flux, coming from the plasma to the antenna's horn, was modified. The initial approach was based on the division of the antenna surface into different parts that are equally inclined with respect to the plasma and have approximately equal shading (view factor values). Plasma was considered as a diffuse source of radiation, uniformly distributed over an

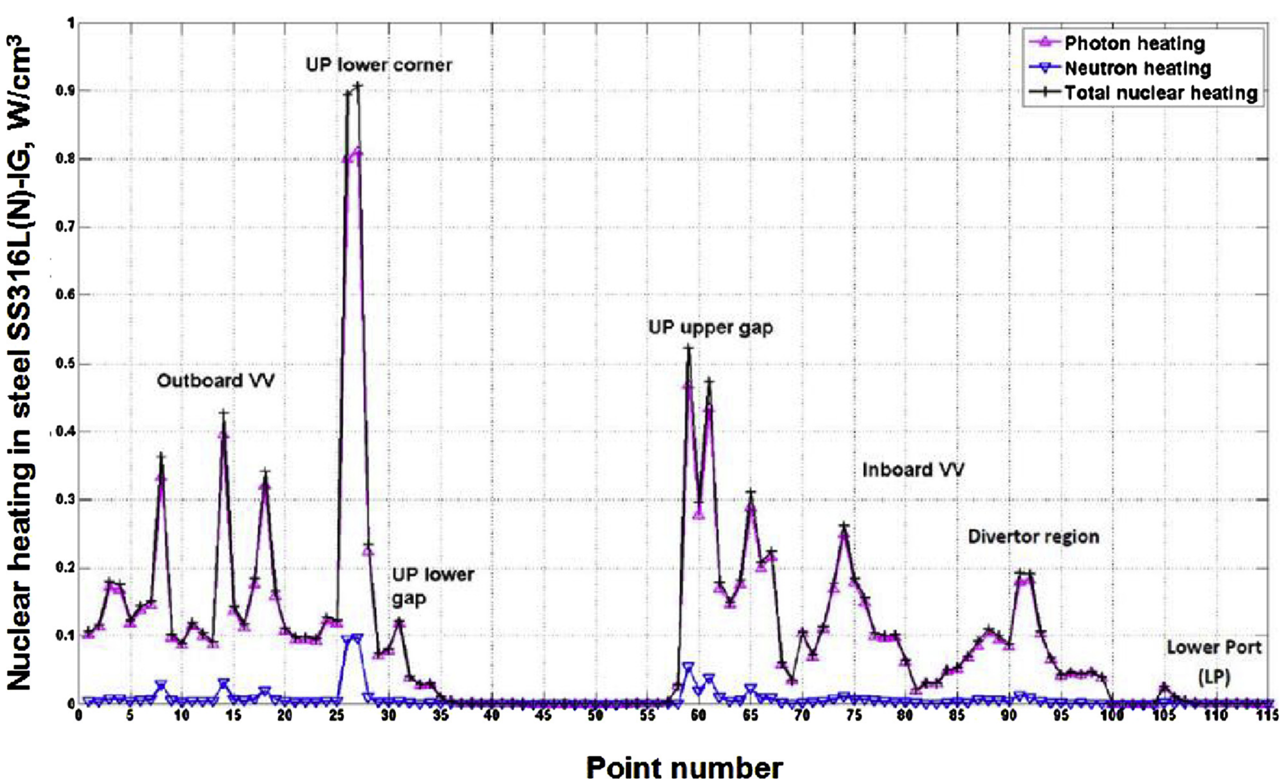

Fig. 2. Nuclear heating in steel structures, W/cm^3.

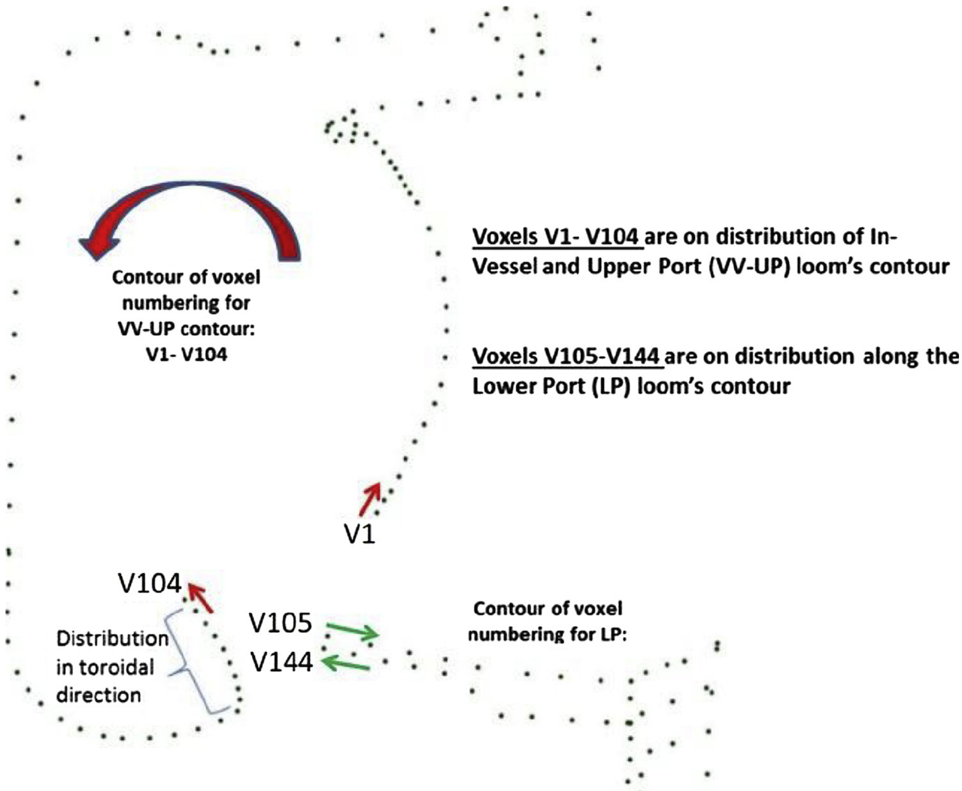

Fig. 3. Points inside the vessel, where nuclear heat values are extracted.

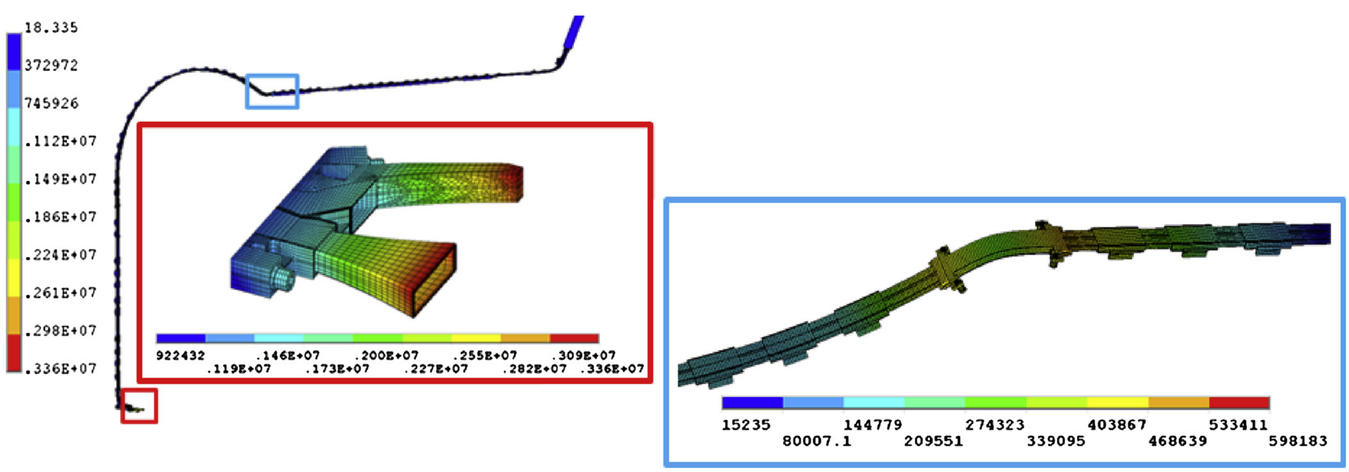

Fig. 4. Distribution of nuclear heating, obtained through the algorithm implementation, W/m^3.

infinite plane. It is known that the radiation flux density, coming from the plasma to the First Wall, has the value 500 kW/m^2. Thermal flux density was calculated with the formulas from [3] for each of the surfaces. For example, for diagnostic surfaces, which are parallel to the source plane (plasma) (Fig. 5), the formulas have the following form:

$$dq_b = \frac{I_0}{4\pi r^2} dxdt \cos^2\theta = \frac{I_0}{4\pi} d\phi d\theta \sin\theta \cos\theta \tag{2}$$

$$q_{rad} = \frac{2I_0}{4\pi} \int_0^{\frac{\pi}{2}} \sin\theta \cos\theta d\theta \int_0^{\pi} d\phi = \frac{I_0}{4} \tag{3}$$

$$\frac{q_b}{q_{rad}} = \frac{2}{\pi} \int_0^{\frac{\pi}{2}} \sin\theta \cos\theta d\theta \int_{\min}^{\max} d\phi = \frac{1}{2\pi} \int_0^{\pi} \sin\xi d\xi \phi \mid \min\max \tag{4}$$

where q_b is the radiation flux density on a surface, r is the distance between the source point and the observation point, θ is the angle of the view line to the normal at the observation point, I_0 is intensity of the radiation source, q_{rad} is radiation power on the front surface.

This approach has 2 key disadvantages. The first is related to the fact that integration limits defining the shading must be found manually from the FE model. This process is laborious and therefore increases the probability of a mistake. The second drawback consists in discreteness of determined heat flux values. In order to overcome these drawbacks, to determine heat flux values from the plasma by numerical methods and to minimize human participation, 2 problems were solved. The first problem is based on the radiation heat transfer theory in two-surface enclosure, which is defined by the following formula [4]:

$$\dot{Q}_{12} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{A_1\varepsilon_1} + \frac{1}{A_1F_{12}} + \frac{1-\varepsilon_2}{A_2\varepsilon_2}} \tag{5}$$

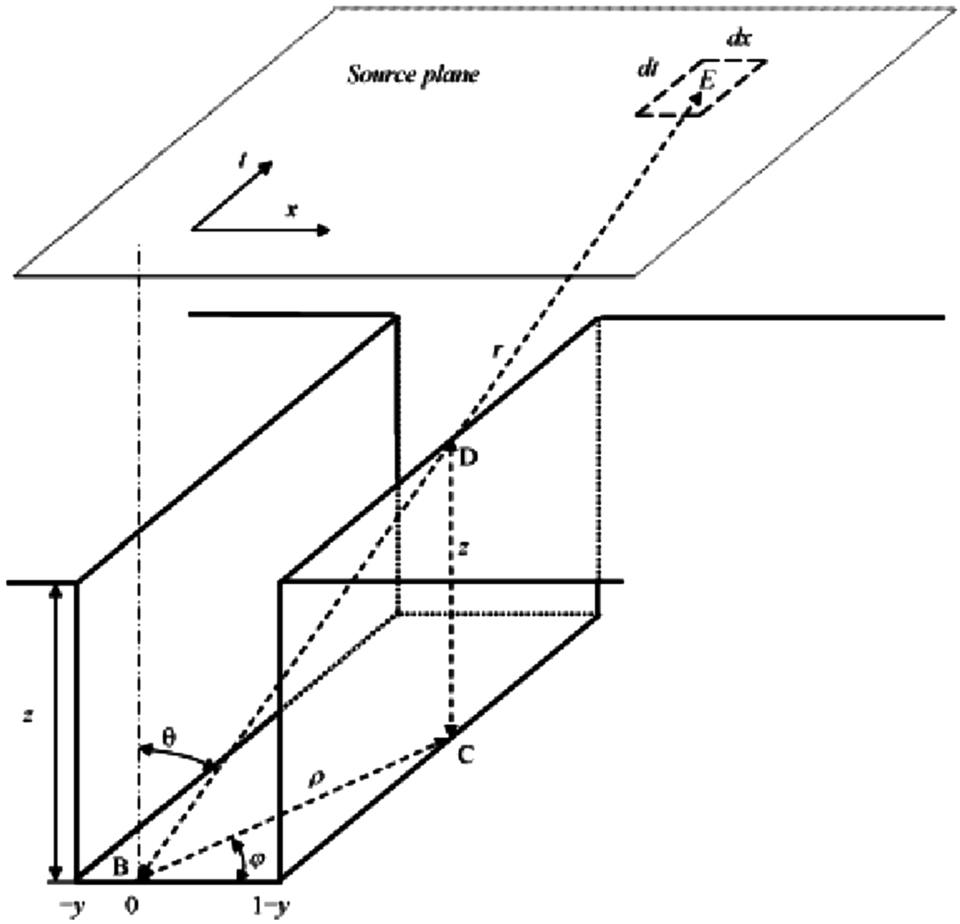

Fig. 5. Geometrical sketch of the problem for analytical calculation of heat fluxes.

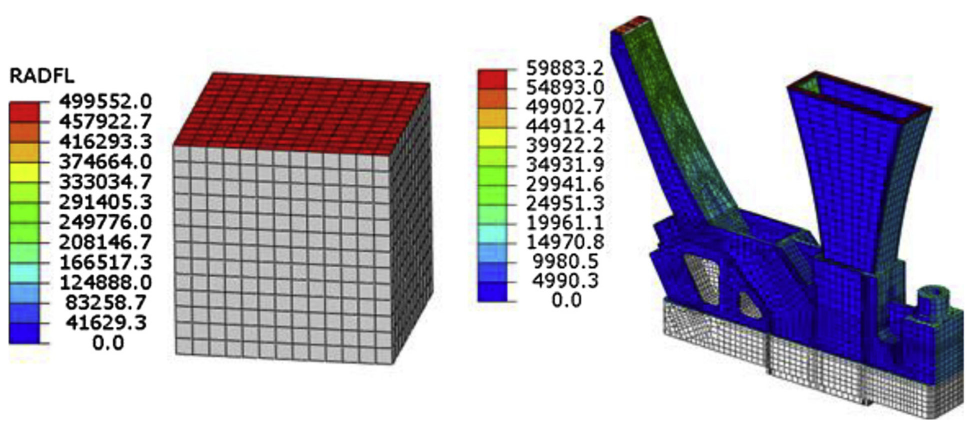

Fig. 6. The results of solving 2 problems on finding heat fluxes from the plasma.

where σ is the Stefan–Boltzmann constant, $T_{1,2}$ are the temperatures of 2 surfaces forming enclosure, $\varepsilon_{1,2}$ are the emissivity of these surfaces, $A_{1,2}$ are their areas and F_{12} is the view factor. It is known that the radiation flux density at the First Wall (surface 2) is q = 500 kW/m^2. This value can be obtained for different values of T_1, T_2, ε_1, ε_2. For simplicity of calculations, we suppose that all bodies placed inside a closed enclosure are approximately black, and the first wall has a temperature of 0 K. In this case we can find the temperature of the plasma surface (surface 1):

$$T_1 = \sqrt[4]{\frac{q}{\sigma}} = 1723.24K \tag{6}$$

This value was used in FE simulation of the problem (ABAQUS), and the heat flux density of 500 kW/m^2 on the First Wall was obtained (Fig. 6). Then we can use this value in the next step – the calculation of the heat fluxes coming from the plasma to the antenna, taking into account shading by the blankets. All the bodies forming the cavity are considered completely black as before. The surfaces of the blankets and antennas have a temperature of 0 K. Applying these parameters imposes that the surfaces don't emit, but absorb heat. Thus, we can easily discern the heat flux that comes to the antenna from the plasma. It is worth noting that unrealistic temperature values don't affect the overall result – correct distribution of the heat fluxes (Fig. 6).

The results of thermal stress analysis for the HFSR version 2017, functioning in inductive (500 MW, 400 s) and non-inductive (375 MW, 3000 s) ITER operating scenarios, are shown in Fig. 7 and Fig. 8 respectively.

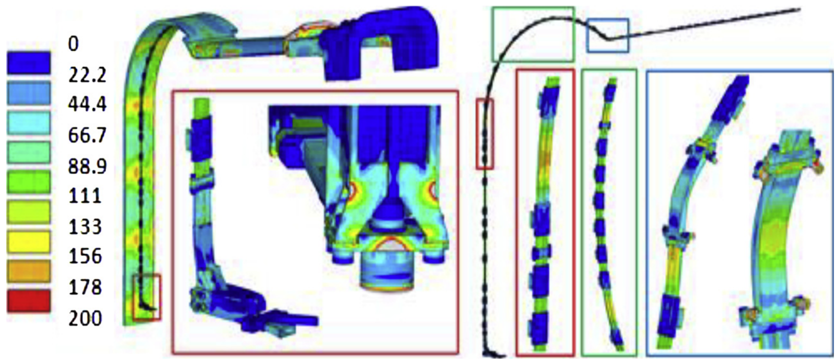

Fig. 7. Equivalent von Mises thermal stresses in HFSR, functioning in inductive heating mode, MPa.

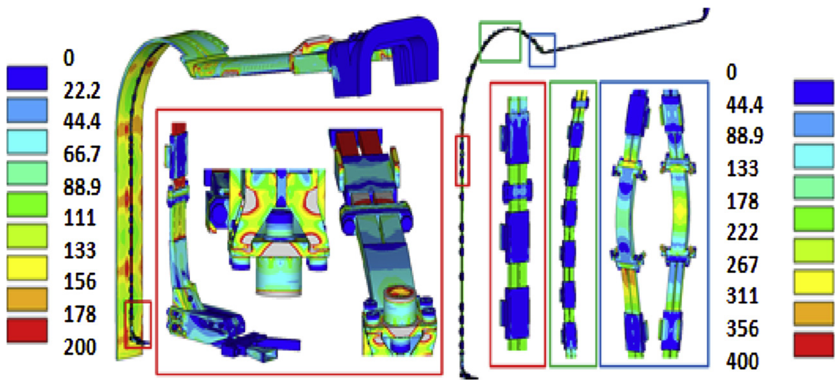

Fig. 8. Equivalent von Mises thermal stresses in HFSR, functioning in non-inductive heating mode, MPa.

As can be seen, high thermal stresses arise in the areas of welding supports to the vacuum vessel, in the port bend, and also locally in elements of the 90° bend and the intermediate plate. Thermal stresses in the waveguides locally exceed the value of 200 MPa. Nevertheless, the fact that they are made of Inconel - a material whose S_m value exceeds 400 MPa in the temperature range from 20 to 450 °, gives a reason to expect that their strength is ensured. In order to estimate the stress state of the antenna support under the action of cyclic thermal loads, a fatigue analysis has been conducted. This analysis has shown a possibility of fatigue crack initiation from the weld toe zone. Changes, which were introduced to the design in 2018 (mobile support under the antenna, as well as a redeveloped port bend) assume a decrease in the operating stresses in the HFSR.

4. Conclusions

Five different designs of the HFSR diagnostic module have been analyzed since 2014. During the simulations new original features were developed and added to the mathematical model to improve its accuracy. The results of the analysis showed that antenna support and port bend require significant design changes as earlier [5]. This report supported in part by Rosatom (contract - H.4a.241.19.18.1027) was prepared as an account of work for the ITER Organization.

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