

MULTIPHYSICS ENGINEERING ANALYSIS FOR ITER DIAGNOSTIC FIRST WALL AND SHIELD MODULE DESIGN*

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ITER (*International Thermonuclear Experimental Reactor*) diagnostic first walls (DFWs) and diagnostic shield modules (DSMs) inside the port plugs (PPs) are designed to protect diagnostic instrument and components from a harsh plasma environment and provide structural support while allowing for diagnostic access to the plasma. The design of DFWs and DSMs are driven by 1) plasma radiation and nuclear heating during normal operation 2) electromagnetic loads during plasma events and associate component structural responses. A multi-physics engineering analysis protocol has been established at *Princeton Plasma Physics Laboratory* and it was used for the design of ITER DFWs and DSMs. The analyses were performed to address challenging design issues based on resultant stresses and deflections of the DFW-DSM-PP assembly for main load cases. ITER *Structural Design Criteria for In-Vessel Components* (SDC-IC) required for design by analysis and three major issues driving the mechanical design of ITER DFWs are discussed. Thermal fatigue total strain range between heating and dwelling phase on the 6 mm thick first wall dictates the maximum number of thermal cycles allowed. Stresses on DFW attachment tabs under disruption loads drive the design and optimization of the tab geometry and the bolt joint selection at the DSM interface. The DSM configuration can have a significant impact to the DFW design and the DSM-PP structure interface load transfer. The general guidelines for the DSM design have been established as a result of design parametric studies.

I. INTRODUCTION

ITER diagnostic first walls (DFW) and diagnostic shield modules (DSM) mounted inside the port plug structure are designed and installed to protect diagnostic instrument and components from a harsh plasma facing environment. The port plug assembly provides necessary structural support of diagnostic systems while allowing diagnostic access to the plasma.¹⁻² The DFW design is challenging due to the conflicting set of requirements for diagnostics protection from high plasma heating and nuclear radiation while allowing diagnostic viewing access.³ Figure 1 shows the upper and equatorial port plugs inside ITER Tokamak. All 6 first walls in an equatorial port can be

different due to different diagnostic access requirements. Figure 2 presents equatorial DFW design and attachment concept with DSMs inside the port plugs. The DFW has a 10 cm recess to avoid direct contact with plasma and to minimize halo current impact such that the ITER stainless steel (SS 316LN-IG) can be used as the first wall panel and the DFW main body.

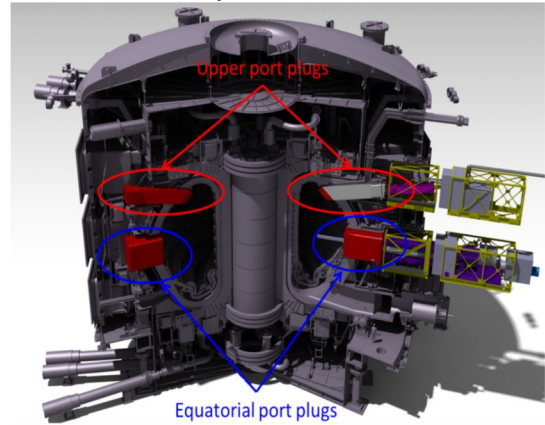


Fig. 1. ITER Tokamak and the equatorial and upper ports

The design of DFWs is largely driven by the high heating rate during normal plasma operation as well as large electromagnetic loads during plasma major disruptions and the Vertical Displacement Events (VDEs). The thermal loads on DFWs include 350 kW/m² surface heating due to plasma radiation and the nuclear heating with a peak ~8 MW/m³ on the equatorial DFW and 5 MW/m³ on the upper DFW during normal D-T plasma operation.⁵ The dominant disruption loads are 120~140 kNm radial moment and 80-130 kNm poloidal moment on an individual equatorial and upper DFW respectively. The moments were taken at mass center of the DFW based on the calculated elemental force density as a result of the interaction between eddy current and the magnetic fields during plasma disruptions. Since DFWs are attached to the DSMs at the three tabs via bolted joints, the design and analysis of the DFW and DSM is directly coupled with interface thermal and EM load transfer at the tabs. Each of the three DFW-DSM cassettes inside an equatorial port plug (one cassette for each upper port)⁴ is

supported by the PP structure via load bearing pads and a set of sliding rails attached to the PP structure.

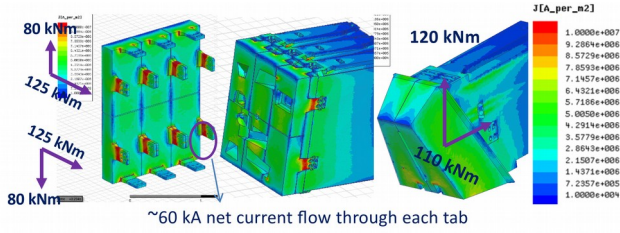


Fig. 2. Eddy current density and EM moments at mass center on equatorial and upper DFWs during disruptions.

In this paper, we review the main loads and the DFW and DSM design challenges for the port plug assembly. We introduce the analysis protocol and present results of the first wall thermal fatigue evaluation. We then discuss the EM and structural analysis for validating the DFW attachment tab and bolt design. We also summarize influence of the DSM configuration to the DFW design and interface stiffness requirements for the DSM design.

Various parametric studies involving electromagnetic, thermal and static structural analyses have been performed. Guidelines for the DSM design are established based on the interface stiffness requirements and the balanced load transfer between DFW-DSM assembly and between DSMs to the PP structure. The plate DSM configuration with a 10 cm-thickness around all sides is used as the baseline and it is shown to meet the DSM stiffness and load transfer requirements. Un-symmetric DSM configurations at the DFW interface will introduce unbalanced eddy current flow at the tabs, and insufficient stiffness will lead to increased tabs stress and deflection. The DSM configuration also influences the load transfer from DSM to the PP structure at the load bearing pads.

II. MAIN LOADS AND DESIGN CHALLENGES

The DFW design is dominated by plasma surface heating and nuclear volumetric heating during normal operation. Design of the attachment tabs and bolts are dictated by the EM disruption loads and load transfer among DFW-DSM and the PP structure during the plasma events.

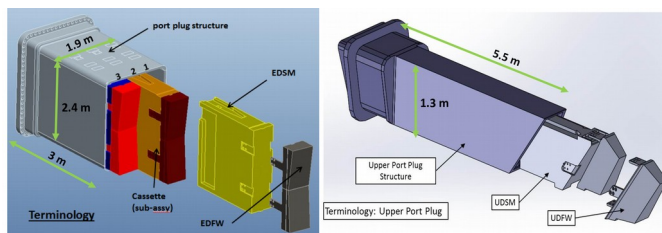


Fig. 3. DFWs and DSMs inside equatorial and upper port plugs

The major design challenges under two critical load cases include 1) Thermal fatigue issue of the 6 mm thick first wall under thermal and pressure loads during normal operation of 30,000 thermal cycles over the lifetime of ITER. 2) DFW tab and bolt joint strength at the interface and the DSM mechanical interface stiffness needed for load transfer during plasma disruptions and VDEs.

If stress due to pressure is insignificant compared to stress due to combined loads such as thermal, EM and seismic loads, the DFW and DSM design may be able to stay within the ESPN requirements for exemption from certain implication on the in-service inspection. Results of the single load case and combined load analysis show that the primary stress due to pressure is only a fraction of that due to the combined loads.³

Cooling circuit design is challenging for particular DFWs with customized aperture size and shape. Cooling channel width and routing is limited to the resultant maximum pressure stress of around 30 MPa and <0.3% total thermal strain range on the first wall panel for 30,000 thermal cycles per ITER SDC-IC requirements.³

III. ANALYSIS PROTOCOL

Two analysis models have been developed and used for various design parametric studies. A first wall model with detailed first wall cooling channel is used for thermal fatigue evaluation for first wall under pressure and thermal loads. The global models of generic DFWs without aperture and the equatorial port 03 DFWs with typical diagnostic cuts but no cooling circuit details are used for validating the DFW attachment tabs and bolts, and verifying structural integrity of DFW-DSM-PP assembly. A similar approach was used for the analysis of the upper port DFW-DSM-PP assembly.⁵

Figure 4 presents the flow chart of the analysis protocol. The global EM and neutronics models (20 degree ITER VV sector due to symmetry) are developed in parallel to extract the disruption induced EM loads and the nuclear heating and DPA level on the DFW-DSM-PP structure for equatorial and upper ports. ATILA was the neutronics code used for nuclear analysis.² Surface heating model was established separately to calculate the distribution of plasma radiation heating on the first wall surface with various diagnostic apertures. The thermal and hydraulic analysis was performed using conjugated heat transfer approach in ANSYS CFX, in which heat transfer was resolved in both solid and liquid parts, and fluid dynamic analysis was performed simultaneously in the liquid part. This approach couples the liquid with solid interaction

and conservation of heat flux is assumed together with the non-slip wall boundary conditions for the liquid. The model takes the surface and volumetric heating as input and it outputs temperature, pressure drop and heat transfer coefficients for each DFW and DSM assembly. Detail of the analysis is described in a separate paper.⁵ Temperature distribution is used as an input for any subsequent combined load case structural analysis. In parallel, the elemental force density of the full PP assembly from MAXWELL transient electromagnetic analysis is mapped onto the Workbench structural model for combined load case analysis. This is necessary to extract primary stress on the attachment tabs.

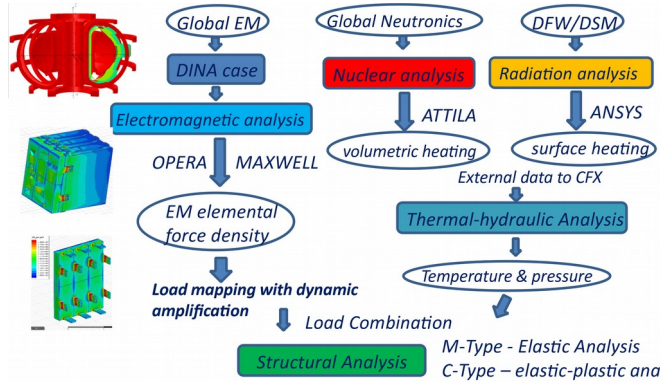


Fig. 4. Multi-physics engineering analysis protocol

IV. FIRST WALL EVALUATION

A first wall parametric model with varying thickness and cooling channels as shown in Figure 5 was used to find an optimal cooling scheme and maximum first wall thickness for the DFW. Finite element convergence studies were performed prior to preliminary design review to ensure an adequate mesh density and convergence is achieved. Results show that steady-state thermal analysis is much less sensitive to mesh size than the mechanical analysis for plastic strain range calculation. Elastic-plastic analysis was performed using the nonlinear bilinear kinematic hardening model of ITER SS 316LN-IG.⁷ The first wall thickness varies in the model from 4 to 9 mm along the toroidal direction and cooling scheme varies from circular to rectangular cooling channels. The rib thickness in the first wall cooling channel also varies from 5 to 8 mm. Figure 4 presents the surface heating applied on the first wall surface, the volumetric heating distribution and the temperature distribution from a steady state thermal analysis. The 340 C peak temperature is located at the thick side of the first wall with a circular cooling channel. This implies that a circular channel is worse than the rectangular channel in terms of the first wall cooling. This is due to a longer cooling distance exists in a circular

channel from the first wall surface to the cooling water surface. Bottom plots on Figure 4 show the equivalent plastic strain for the 1st and the 4th thermal cycles. The plastic strain is more uniformly distributed after a few thermal cycles. The maximum plastic strain is located at the sharp corner of the rectangular cooling channel with 1 mm corner radius. A corner radius of 5 mm was found to be close to optimal and thus used in the final DFW cooling circuit design.

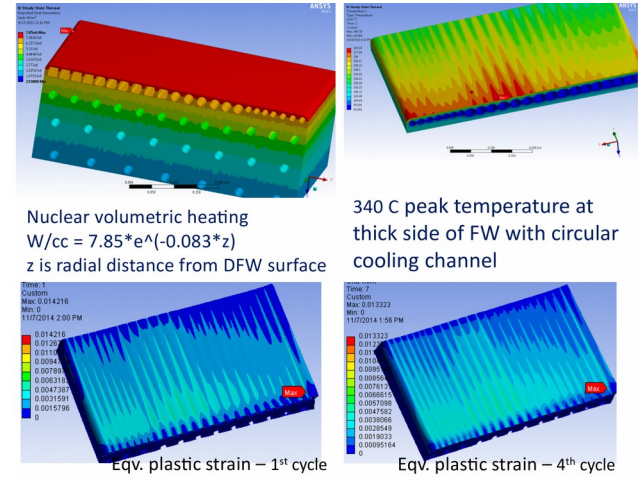
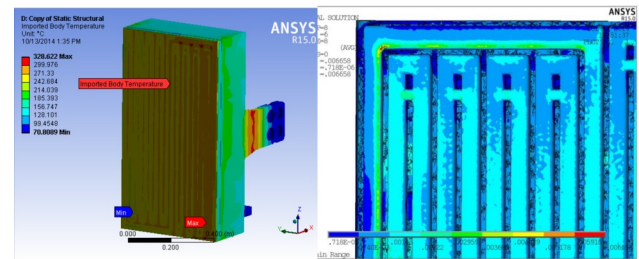


Fig. 5. First wall thickness parametric study

Figure 6 presents the temperature and total strain range distribution on the generic equatorial DFW between the heating and dwelling phase of 4 thermal cycles. Results indicate that a higher than allowable total strain range ($>0.3\%$) exists along the edge cooling channel and at the “L” shaped edge channel corner ends (bottom left in Figure 6). The general design guidance is to replace the “L” shaped edge channels by the stiffer “U” shaped channel shown in the bottom right of Figure 6. Similar consistent results and high total strain range locations were found from the generic upper port first wall model.⁵ Figure 7 showed the distribution of total strain range after 4 thermal cycles. A significant number of points showed a total strain range higher than 0.3%.



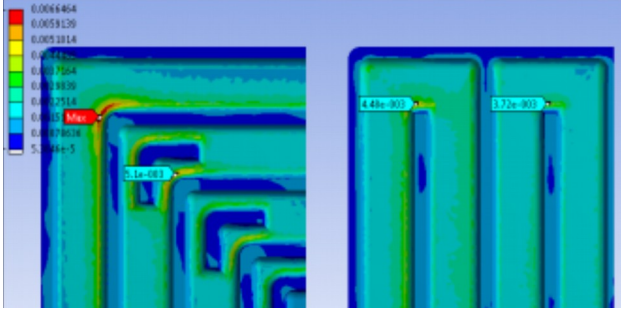


Fig. 6. Total strain range on the generic equatorial DFW.

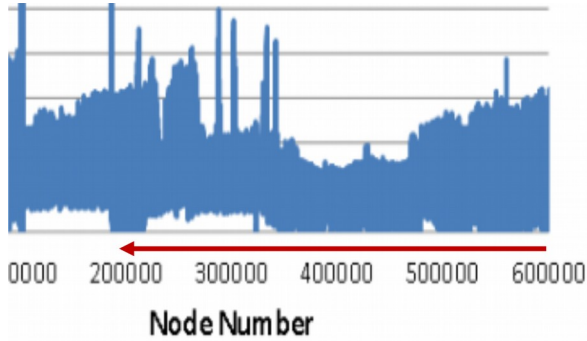


Fig. 7. Total strain range on the generic equatorial DFW.

VI. ELECTROMAGNETIC ANALYSIS

Electromagnetic analysis of PP assembly was performed using OPERA and MAXWELL global models.² Figure 8 presents the global MAXWELL model generated for the equatorial and upper port plugs. The 20 degree model includes TF, CS and PF coils and the plasma source **current** excitations. The structure components include the VV sector, neighboring Blanket Shield Modules, DFWs, DSMs and the PP structure.

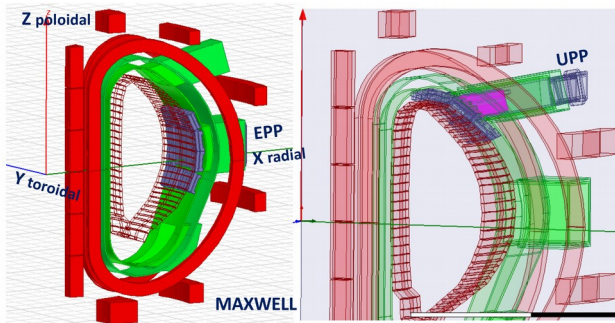


Fig. 8. MAXWELL models of equatorial and upper PP structure

Figure 9 presents the maximum loads on the equatorial DFWs during the worst case major disruption downward exponential decay of current in 16 ms (MDDWEXP16). The net current flowing through each DFW tab is ~60 kA. The symmetric plate DSM with 10 cm thickness around all sides was used as the baseline. The 10 cm thickness is

determined by two factors: 1) the ~6-10 cm skin depth of SS during the 16-36 ms transient plasma disruption for ITER. The expected current quench time in ITER is 36 ms linear or an exponential time constant of 16-18 ms.⁶ 2) the torsional stiffness needed for load transfer at DFW to DSM interface. The removal of DSM front plate reduces the interface stiffness and **will significantly increase amount of eddy current flowing into the DFW tab**. Results from un-symmetric DSMs with one side plate removed show significantly unbalanced current flowing through the tab. It is thus important to maintain a symmetry DSM configuration. It is also recommended that diagnostic cuts shall be 3-5 cm away from the DFW tabs to avoid local stiffness reduction for a balanced EM load transfer from DFW tabs to the DSMs.

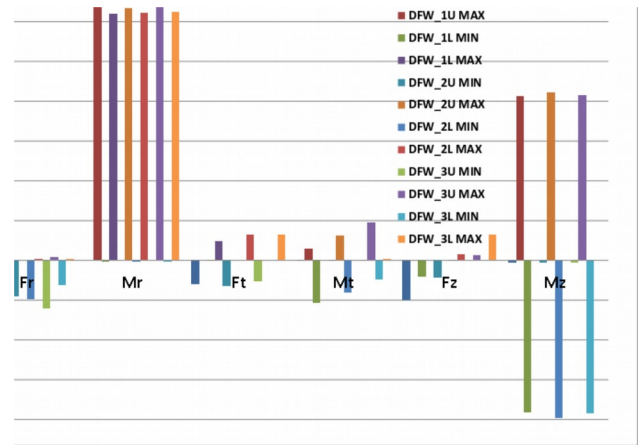


Fig. 9. EM loads and eddy current density on DFWs.

VII. STRUCTURAL ANALYSIS

The elemental force density from transient EM analysis is mapped onto ANSYS structural model with DFW, DSM, PP structure and auxiliary components such as load bearing pads, pins and bolts. Transient structural dynamic analysis established a dynamic amplification factor of ~1.5 for both equatorial and upper port plug.⁷ Static structural analysis using mapped elemental force density at the time step of maximum resultant EM loads has been performed for EM, thermal and combined load cases to validate system structural integrity. An uncertainty factor of 1.2 is also applied on top of the mapped EM loads.

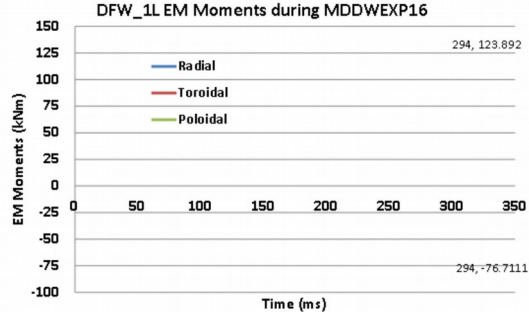


Fig. 10. EM disruption moments on upper equatorial DFW.

The global structural model including DFW, DSM and the PP structure has a fixed displacement boundary condition at the rear flange. Normal mode analysis shows that fundamental frequency of the 3 translational and 3 rotational modes of the full PP structure is higher from the model without port extension and VV sector. As a result, a larger total deflection is obtained from the model with the port extension and fixed boundary condition at the VV sector but stress on the DFW tabs has little difference from the two models. It was also found that more EM loads are transferred from DSM to the PP structure via the rear bearing pads for the model with the port extension and VV sector.

Figure 10 presents the structural model with bolt preload and DSM supporting rails. Bottom plots in Figure 10 also present deflection and equivalent stress of equatorial port 03 under EM loads from MDDWEXP16. The friction contact with 0.3 frictional coefficients was used between the tabs and the DSM interface, and between bolt heads and the tabs. **Bonded contact between DSM and the transverse load bearing pads and between load bearing pads and PP structure.** A preload of 80 kN was applied on each bolt to ensure a sufficient contact pressure at the tab interface. For the baseline plate DSM, 2/3 of loads are transferred from DSM to the PP structure via the rear load bearing pads. **This is unexpected because most eddy current are induced in the front part of the port plug assembly and the design of the load bearing pads is based on an uniform distribution of reaction loads on the pads. Non-uniform distribution of DSM to PP structure load transfer may significantly increase stresses on these load bearing pads and thus the DSM to PP structure attachment system may fail the design criteria.** It is thus recommended to remove the rear plate of the DSM to soften rear DSM stiffness to obtain a more balanced load transfer from DSM to the PP structure.

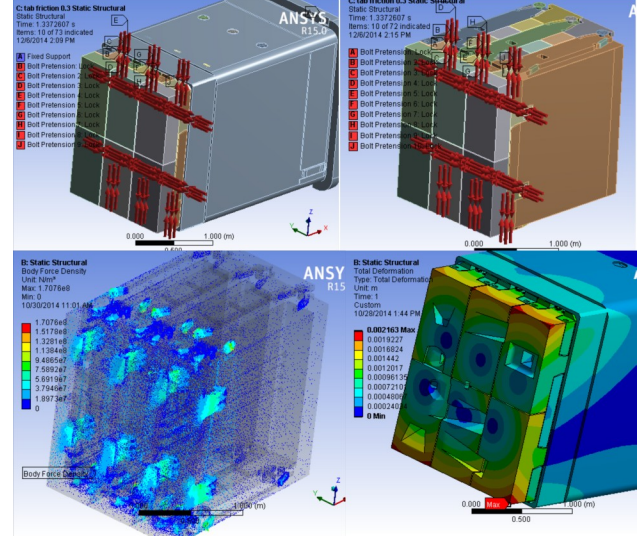


Fig. 10. EPP3 deflection and stress distribution under EM loads.

VIII. DSM CONFIGURATION

The influence of DSM configuration to the DFW design includes 1) EM load distribution and eddy current flowing through the DFW tabs at the interface 2) attachment tab and bolt stress with varying DSM stiffness 3) EM load transfer among the DFW, DSM and the PP structure. Our study showed that a generic plate DSM with 10 cm thickness around all four sides has sufficient stiffness required for EM load transfer. Un-symmetric DSMs with one side plate removed introduces unbalanced current flow through DFW tab and increase stress and deflection.

DSM configuration has a significant impact on the load transfer between DFW-DSM and the PP structure. Our study showed that more loads are transferred via the rear load bearing pads from the DSM to the PP structure. It is recommended to remove the rear plate of the baseline DSM so more balanced load transfer can be obtained from the DFW-DSM assembly to the PP structure.

X. CONCLUSIONS

Design analysis of ITER DFW and DSM is challenging in the harsh plasma facing environment with high thermal, electromagnetic and VV interface loads. A multi-physics engineering analysis protocol is established for validation of the component design and global structural integrity.

First wall thermal fatigue has been evaluated based on the total strain range from nonlinear elastic-plastic analysis for optimized thickness and cooling design. Attachment tabs and bolts are evaluated for various load cases to ensure the structural integrity and balanced interface load transfer. The design and analysis provided guidance for

the DSM design to meet the interface load transfer requirements to ensure a global structural integrity.

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REFERENCES

1. C. S. PITCHER et al, "Nuclear Engineering of Diagnostic Port Plugs on ITER", *Fusion Eng. Des.*, **87**, 667-674, 2012.
2. R. FEDER et al, "The Status of US ITER Diagnostic Port Plug Neutronics Analysis using ATTILA", *lab report*, PPPL-5025, 2013.
3. G. SANNAZZARO et al, "Development of Design Criteria for ITER In-vessel Components", *Fusion Eng. Des.*, **88**, 2138-2141, 2013.
4. Y. ZHAI et al, "Electromagnetic Analysis of ITER Diagnostic Equatorial Port Plugs during Plasma Disruptions", *Fusion Eng. Des.*, **88**, 547-550, 2013.
5. M. SMITH et al, "Analysis of ITER Upper Port Diagnostic First Walls", *Fusion Sci. Technol.*, accepted, 2015.
6. A. KHODAK et al, "Numerical Analysis of Coolant Flow and Heat Transfer in ITER Diagnostic First Wall", *Fusion Sci. Technol.*, accepted, 2015.
7. T. C. HENDER et al, "MHD stability, operational limits and disruptions", *Nucl. Fusion*, 2007. S128-S202.
8. S. PAK et al, "Dynamic Amplification Factor of the ITER Diagnostic Upper Port Plug", *IEEE Trans. Plasma Sci.*, **42**, 1977-1981, 2014.