Analyses and structure integrity estimation of the Upper Vertical Neutron Camera

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Abstract. Vertical Neutron Camera (VNC) is a multichannel neutron collimator intended to characterize the fusion plasma neutron source. The VNC diagnostics (together with the 55.B1 Radial Neutron Camera) will measure the time-resolved neutron emission profiles for both DD and DT ITER plasmas, providing evaluation of the fusion power density, \(\alpha\)-source density, neutron and \(\alpha\)-source emissivity profiles, ion temperature profile, fusion power, total neutron flux and others parameters. The VNC is composed of two fan-shaped collimating structures (lower and upper) that are located at different positions of the ITER Vacuum Vessel (VV).

Structural integrity assessment of the preliminary design of the Upper Vertical Neutron Camera has been performed. The design was updated based on the analysis results and in order to meet other ITER requirements. The thermal, mechanical, electromagnetic and seismic loads and load combinations were calculated and analyzed for the updated design. This article is focused on the normal operation thermal analysis and electromagnetic analysis, as the design changes mostly affect the thermal and electromagnetic interfaces within the structure. The important results were obtained; the article shows the considerable improvement in the construction performance.

1. Introduction

The aim of the neutron multichannel collimator is to measure the time-resolved neutron emission in the poloidal plasma cross section. These measurements can provide information on the total neutron yields, fusion power density profile, neutron emissivity profile and ion temperature profile. Knowledge of these profiles is essential to evaluate the energetic particle confinement, ion energy balance and particle transport.

VNC diagnostics will be installed into the locations shown in figure 1. Plasma is observed vertically along several Lines of Sight (LOS).

The lower system (Lower Vertical Neutron Camera) is mounted into supporting structure (the so-called Diagnostic Rack- DR) located inside the lower port #14 and has 6 channels, five of them are collimated. The lower system is out of the scope of this article.

The upper system (Upper Vertical Neutron Camera) is located inside the port plug structure in the upper port #18. It consists of two fan-shaped multichannel collimators with overall 6 LOS (3 in each fan). The neutron collimators pass through the Diagnostics Shielding Module (DSM), and the diagnostics first wall (DFW) of the UpP#18 [1].
Combination of the upper and lower LOS allows observing properly the entire plasma from the core to the plasma edge \((0 < r/a < 0.8)\).

This article is focused on the approaches and results of simulations made for the Upper Vertical Neutron Camera (UVNC).

2. UVNC design description
The UVNC is an in-vessel component, which means that it is located in the vacuum vessel and exposed to the extreme heat and electromagnetic loads from plasma source. In view of this fact, both the development and structural assessment of construction are rather challenging engineering processes. The design of the UVNC has been improved many times since its conceptual stage in order to withstand loading conditions and meet high ITER standards. This article is focused on two latest design stages of the UVNC: the Preliminary Design Review (PDR) design stage and UVNC design stage of the post-PDR update (currently latest design).

2.1 PDR design
The Upper Vertical Neutron Camera (UVNC) consists of two detector boxes independently attached to the Diagnostic Shielding Module (DSM) body. Each of the detector module halves is fixed to the DSM by 4 bolts. The bottom of the detector module is made as a dove tail for its positioning inside the DSM. Between two UVNC halves, there is a 25 mm slot made for the VUV diagnostic system.

![Figure 1. VNC locations in the Tokamak Building](image1)

![Figure 2. View of upper Port plug assembly with UVNC](image2)

The detector module contains 6 detector units (3 in each box) and is made of the SS316L stainless steel. Each detector unit is hermetically sealed within the water cooling box. These cooling housings are connected in parallel to the water pipes. The detector module assembly is shown in figure 3.

The detector module wall, upper plate and base plate are connected with bolts. Only the base plate has cooling channels. There are no gaps between the parts to provide large areas of heat exchange between the actively cooled base plate and other parts.

2.2 Post-PDR design
After the PDR stage, the UVNC design was improved by the UVNC design team with allowance for the structural integrity analysis results. Other issues not related directly to the structural integrity had to be considered by the design team in order to meet ITER requirements. Most significantly, the 2-mm gaps were added between all parts of the constriction in order to meet the vacuum requirements. The areas of heat exchange between the parts of the construction were reduced. The updated UVNC design is shown in figure 4.
3. Calculations and results

According to the System Load Specification [2], the following single load cases were considered: the dead weight, coolant pressure loads, seismic loads, EM loads due to EM transients, thermal loads, and interface loads. The design changes mostly affected the thermal and electrical interfaces between parts of the construction. This article contains summary of the thermal (normal operation) and electromagnetic analyses. Only in-vessel components of the UVNC structure were considered in this analysis.

3.1 Thermal and thermal-stress analysis

The transient thermal analysis using the finite element (FE) method was performed for the Normal operation mode. The computational model takes into account the UVNC and DSM.

In the Normal operation mode, the UVNC is being heated by the nuclear energy released during thermonuclear reaction. The normal operation mode is simulated by 10 “heating-cooling” cycles during one working day. Heating means the application of heat generation to the construction, cooling means the absence of heat generation. For each cycle, heating duration is 500 sec and cooling duration is 1200 sec.

3.1.1 PDR design analysis

Figure 5 shows the estimated nuclear power density in the UVNC. The highest values are observed in the part of the construction, which is the closest to the plasma.

To obtain the wall heat transfer coefficient necessary for the thermal analysis, the thermo-hydraulic analysis of the UVNC cooling systems was performed using the ANSYS CFX software. The wall heat transfer coefficient values and the cooling system geometry are shown in Figure 6. The contact thermal resistance in the vacuum conditions was estimated based on [4].

Figure 7 shows the temperature distribution in the UVNC right-hand half (most heated) at the end of working day in Normal Operation mode.
The calculations show the acceptable temperature values (maximum temperature allowed is 350°C, but rather high temperature gradients at certain parts of the construction, for example, in the front part of the base plate close to the cooling channels.

The thermal-structural analysis was performed for the UVNC. Temperature map at time of reaching the highest thermal gradient is applied as a boundary condition. The stress assessment was performed according to the RCC-MR rules [3]. The linearized stress values do not exceed ones allowed by the criterion.

### 3.1.2 Post-PDR design analysis

The same analysis and stress assessment technique was used for the post-PDR design assessment. During the early stages of the post-PDR design development, it became clear that the addition of gaps considerably reduced the heat exchange areas between the parts of the UVNC. According to the PDR design analysis, the parts next to the neutron source with no active cooling have considerable temperatures. With the restricted heat exchange supposed in the new design, these parts will certainly get overheated. This issue was corrected during the design development and the base plate was redesigned to allow additional cooling of the front part. Also the heat exchange plate was added to help transferring heat between the base plate and the detector module walls/upper plate (see figure 4). Huge advantage of this solution is that it helps to keep existing fluid interfaces between the UVNC and the port plug. The cooling system of the post-PDR design and the wall heat transfer coefficient values are shown in Figure 9.

Figures 10–11 show the temperature and stress distributions in the UVNC right-hand half (most heated) at the end of working day in Normal Operation mode. The stress and temperature values are acceptable.

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**Figure 7.** Temperature map in the UVNC, °C  
**Figure 8.** Tresca equivalent stress in the UVNC, MPa  
**Figure 9.** Wall heat transfer coefficient for the coolant system channels, W/(m² K)  
**Figure 10.** Temperature map in the UVNC, °C  
**Figure 11.** Tresca equivalent stress in the UVNC, MPa
4. Electromagnetic analysis

The EM analysis is conducted for the VDE III and VDE II plasma disruption events [5, 6]. Results provided for the VDE III fast scenario, which is the most severe event in terms of the maximum force and moment values. The transient electromagnetic analysis was performed using the Ansys Maxwell software. The computational model is an extension of the model described in [7], and it takes into account the UVNC, vacuum vessel, blankets, toroidal field, poloidal field and central solenoid coils with their excitation. Plasma area was divided into areas (“filaments”) to produce more accurate results.

The computational model (shown in figure 12) was improved for the post-PDR design EM analysis in order to include also DSM and UPP #18; all corresponding electrical contacts were taken into account. The integral forces from the EM analysis are shown in figure 13 for the PDR design and in figure 14 for the post-PDR design.

![Computational model for EM analysis](image)

**Figure 12.** Computational model for EM analysis

![Integral force during VDE III, PDR design](image)

**Figure 13.** Integral force during VDE III, PDR design

The ponderomotive force volumetric density (at time of reaching the highest integral values) is shown in figure 15 for the PDR design, and in figure 16 for the post-PDR design. The stress analysis was performed with these loads taken as the boundary conditions.

The stress distribution obtained as a result of the structural analysis is shown in figure 17 for the PDR design and in figure 18 for the post-PDR design. The stress assessment was performed according to the RCC-MR rules [3]. The linearized stress values do not exceed ones allowed by the criterion.
Conclusions
Although all the basic single load cases and load combinations were analyzed, the final post-PDR design assessment is yet to be completed for publication. Results of the thermal normal operation and EM analyses are provided, as they have been the ones mostly affected by the design changes.

The engineering analysis of the Improved UVNC design has shown great improvement in the cooling systems performance, despite the reduction of the heat exchange areas.

In the updated UVNC design, the forces due to EM loads increased considerably; however, the corresponding structural analysis has shown that the stresses are still acceptable. It still could potentially become an issue and should be kept in mind in case of the future design update.

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