Recent developments in the structural design and optimization of ITER neutral beam manifold

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Abstract
This paper describes a new design of the neutral beam manifold based on a more optimized support system. A proposed alternative scheme has presented to replace the former complex manifold supports and internal pipe supports in the final design phase. Both the structural reliability and feasibility were confirmed with detailed analyses. Comparative analyses between two typical types of manifold support scheme were performed. All relevant results of mechanical analyses for typical operation scenarios and fault conditions are presented. Future optimization activities are described, which will give useful information for a refined setting of components in the next phase.

Keywords: ITER neutral beam manifold, optimized design on supports, structural seismic analysis

(Some figures may appear in colour only in the online journal)

1. Introduction

ITER (International Thermonuclear Experimental Reactor) is an experimental reactor for demonstrating the scientific and technical feasibility of ‘burning’ deuterium-tritium to produce 500 MW of fusion power for hundreds of seconds. The mixture of gases, with proportional deuterium and tritium as the fuel of the ‘burning’ plasma, is provided by the tritium plant (TP) and injected into the torus by a dedicated fuelling system. The neutral beam (NB) manifold is a major subsystem of the ITER fuelling system with a complex combination pipes, and it is designed to supply H\textsubscript{2} and D\textsubscript{2} gases to the heating and diagnostics NB injectors [1–5].

During the final design (FD) phase of the NB manifold, the design has been completely based on a defined configuration management model [6]. After the FD review, the design scheme of the NB manifold suffered several design changes due to crashes with the tokamak cooling water system piping and building penetration. In order to implement this project change request, the ITER Organization Central Team modified the NB manifold routing (figure 1). Figure 2 shows the layout of the NB manifold in the B1 level of building.

With the updated configuration, a new NB manifold design and relevant analyses are necessary to verify the engineering feasibility of the system. Additionally, a structural integrity assessment during FD revealed that the NB manifold design has potential for more robust structure performance [7, 8]. Therefore, the optimization activities on structures and supports need to be considered in the new design.

2. Design of the re-routed NB manifold

The design of the entire NB manifold is presented with the currently available embedded plate (EP). Moreover, typical load cases are used to evaluate the feasibility of the manifold design.

2.1. Design description

The basic configuration of the NB manifold, as shown in figure 2, is dictated by the geometry positions of connected NB injectors, interfacing points with the TP. This results in a configuration that is routed from the TP and through the vertical shaft to the upper level.
In order to simplify the assembly on-site and minimize the workload, the manifold is designed in a series of basic modularized units, for example a straight section and an elbow junction. To ensure high reliability, the components of the manifold are highly preferred to be butt-welded. As shown in figure 3, the internal support aims at bearing the seismic load and dead weight of the internal pipes (gas supply pipes and evacuation pipe) of the manifold. The internal supports are installed at appropriate positions and are connected to the evacuation pipe by spot welding.

The basic function of the external support is to bear the gravity of the manifold. In addition, the layout of the external supports considers the global stiffness and EP locations, and so on. As shown in yellow in figure 2, the ITER design group provides these currently available EPs.

2.2. Design by analysis of the manifold with current EPs

The structural assessment in the FD phase indicated that earthquakes are the most severe loading case for the NB manifold. The main reason is that the number of external supports and penetrations are very limited [7, 8]. With the currently available EPs, it is necessary to verify the reliability of the entire NB manifold to protect against structural failure due to seismic loading.

The finite element (FE) analysis is adopted to study the design scheme with currently available EPs. Figures 4 and 5 show the NB manifold FE model (pipe element) and its constraints. In the two ends of the NB manifold (yellow triangles), both guard pipe and internal pipes are fixed. At concrete penetration (purple circle in figure 4), the guard pipe is fixed in the horizontal direction and is free along the pipe axial direction. External supports (gravity supports), shown in blue with the legend of a single triangle in figure 4, are compliance with the locations of EPs and only provide constraint in the vertical direction. Since there are visual differences, it seems that the constraints at the top of figure 4 do not match the EP position in figure 2. As a matter of fact, the outside support components, which fix the EPs, support the guard pipe of the manifold. Other external supports (guide supports, two blue triangles in figure 4, except the special one in the red circle) are supposed to provide the horizontal constraints. In addition, the external support, shown in the red circle of figure 4, not only provides the constraint in the vertical direction but also restrains the horizontal direction perpendicular to the pipe axis. Internal supports fix on the evacuation pipe and only provide the radial constraints on the gas pipes. The internal supports can move in the guard pipe along its axial direction. With a defined set of coupled degrees of freedom, the coupled relations are used to represent the weight of an internal support.

The SL-2 (Seismic Level 2—equivalent to Safe Shutdown Earthquake) seismic load was selected as the severe loading case in this study [6, 10]. A multipoint response spectrum method was used to calculate the deformations and von Mises stresses (table 1). Obviously, the 90° elbow located at the top of the vertical segment (as shown in figure 6 with ‘MX’) is the weakest component in the manifold due to the lack of external support at the upper part of the vertical segment (figure 2).

Moreover, the SL-2 + DW (dead weight) + P (pressure) load combination is used to evaluate the structural mechanical performance because of this load combination is classified as service level D [7–10]. The DW is calculated based on SS316L density (8000 kg m$^{-3}$). The P includes two parts, one is the difference pressure of each gas supply pipe (0.5 MPa), and the other is the difference pressure applied on the evacuation pipes (~0.095 MPa). Table 2 illustrates the maximal deformation and
von Mises stress under DW + P + SL-2. Since the allowable stress, \( S_{m} \), is 115 MPa, it can conclude that the stress can satisfy the evaluation criteria to protect against the plastic collapse failure mode (the corresponding evaluation criteria is \( P_m < 2S_m \), \( P_L < 3S_m \)). \( P_m \) is the general primary membrane equivalent stress, \( P_L \) is the local primary membrane equivalent stress, \( P_b \) is the primary bending equivalent stress. In a conservative way, the maximum \( P_m \) is taken as the von Mises stress to calculate the margin [11, 12]. However, the maximal deformation, 110.81 mm, is infeasible from the engineering design viewpoint.

In the shaft, there are adjacent piping system around the NB manifold, and the lateral distance between the pipes indicated in the CAD Manual should be less than 200 mm [13]. Therefore, the design scheme with currently available EPs has the hazard to crash with the adjacent system. These results of the typical loading case demonstrate that the additional external supports in the horizontal directions near the peak deformation locations is necessary to decrease the deformation.

### 3. Optimized design and analysis

In the optimization design, a solution scheme was presented in the face of the challenging requirements and conditions. In addition, detailed analyses were carried out to check the structure integrity under gravity, pressure and seismic loads.

#### 3.1. Optimized design

Based on the analyses results in section 2, the vertical manifold segment located in the shaft of level L3 (as shown in blue in figure 7) enhances the entire structural stiffness. The most effective way is to constrain the horizontal movement of this segment with additional available EPs. In addition, the manifold horizontal segment with two 90° elbows (as shown in the left red circle of figure 1 and green in figure 7) need a gravity support to withstand the dead weight from the vertical segment.

Figure 7 shows the NB manifold segment located at level L3 of the building and available EPs (orange boxes). Since the distance between the upper two EPs and the manifold is

<table>
<thead>
<tr>
<th>Loading case</th>
<th>Maximum deformation (mm)</th>
<th>Maximum von Mises stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL-2</td>
<td>108.49</td>
<td>186.96</td>
</tr>
<tr>
<td>DW + P</td>
<td>2.32</td>
<td>40.54</td>
</tr>
<tr>
<td>DW + P + SL-2</td>
<td>110.81</td>
<td>227.50</td>
</tr>
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</table>

### Table 1. Summary of the maximum deformation and von Mises stress of manifold under SL-2 seismic loading.

<table>
<thead>
<tr>
<th>SL-2 seismic load</th>
<th>Maximum deformation (mm)</th>
<th>Maximum von Mises stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excitation in the horizontal X direction</td>
<td>16.080</td>
<td>35.665</td>
</tr>
<tr>
<td>Excitation in the horizontal Y direction</td>
<td>18.737</td>
<td>43.372</td>
</tr>
<tr>
<td>Excitation in the vertical direction</td>
<td>73.673</td>
<td>107.922</td>
</tr>
<tr>
<td>Sum of the maximal values</td>
<td>108.49</td>
<td>186.958</td>
</tr>
</tbody>
</table>

### Table 2. Summary of the maximum deformation and von Mises stress under DW + P + SL-2.

**Figure 3.** NB manifold structural cross section (left) and internal support (right).

**Figure 4.** NB manifold FE model and its external constraints.
about 1.85 m, these two EPs both provide horizontal constraints for the vertical segment (left in figure 8). In order to prevent manifold bend under vibration, the EP on the level L3 floor (the bottom orange box in figure 7) is also used to provide the horizontal constraints (right in figure 8). Furthermore, the gravity support (3 in figure 9) on the manifold horizontal segment (green in figure 7) connects the current EP that is used for guide support (blue circle in figure 4).

### 3.2. Structural analyses

In structural analyses, the load cases, SL-2, DW + P, and SL-2 + DW + P, were used to check the structural reliability and compare with the previous results in section 2. Moreover, the boundary conditions were the same as in section 2 except for the additional external supports.

As shown in the red boxes of figure 9, three additional constraints were added. Constraints 1 (left in figures 8) and 2 (right in figure 8) restrain the horizontal directions to the guard pipe, and 3 only provides the a gravity constraint on the horizontal segment of the guard pipe.

The maximum deformations and von Mises stresses of the optimized scheme under SL-2 are listed in table 3. The maximal deformation decreased from 108.49 mm to 18.347 mm under the SL-2 loading case. Compared with figure 6, figure 10 shows the total deformation of the optimized structure under SL-2 excitation in the vertical direction. With the additional available EPs located on the L3 level, the excessive deformation appearing in the elbow of the upper vertical segment was mitigated effectively. In addition, the von Mises stress can satisfy the criteria with small margin (8.6%), the definition of margin is that the difference in per cent between the allowable value \( R_{\text{allowed}} \) and the calculated result \( R_{\text{calculated}} \), margin(%) = \( \frac{R_{\text{allowed}} - R_{\text{calculated}}}{R_{\text{calculated}}} \times 100\% \).

Table 4 shows the maximal deformation and von Mises stress of the optimized scheme under typical load cases. It is obvious that the maximal deformation decreases a lot in comparison with the results in table 2.
However, the maximal von Mises stress is 211.786 MPa under SL-2, almost 50% more than before optimization. In addition, the maximal von Mises stress under SL-2 + DW + P can satisfy the criteria with only 4.1% margin. Figure 11 shows the von Mises stress of the manifold under SL-2 seismic excitation in the vertical direction, and the segment near the end of manifold has the maximal stress (as shown in figure 11 with ‘MX’). Figure 12 shows the enlarged view on internal pipes with the maximum stress. Compared with figure 6, figure 10 shows that the maximal total deformation of the manifold vertical segment (in blue in figure 7) has been restricted less than 5 mm, and the reason for that is that the stiffness of this vertical segment has been enhanced with three additional constraints (locations 1, 2 and 3 in figure 9). Meanwhile, structural deformation is bound to occur on the more flexible segment, as shown in figure 10 with ‘MX’ and in green. In addition, the upper horizontal segment has larger deformation because this
segment is softer than the vertical segment. Therefore, as shown in figure 12, the internal pipe has the maximum stress, caused by the pipe deformation combined with limitation of the internal support. In order to decrease this larger stress, one effective modification is adjusting the position of the internal support (move the internal support along the direction of the red arrow in figure 12) to allow this segment of internal pipe to release structure deformation.

4. Conclusions

A re-routed NB manifold with currently available EPs was investigated from the structural viewpoint. In order to verify the design feasibility, design analyses were performed in detail, which demonstrated that the NB manifold does not protect against excessive deformation failure mode.

According to the results in section 2, the large deformation region is localized on the manifold vertical segment. An optimized design was implemented by adding appropriate external supports, and excessive deformation on the manifold was mitigated effectively. From the analyses on the optimized scheme, it was concluded that the structural design of the manifold has a margin to protect against plastic collapse and excessive deformation failure mode under the typical load cases. For finalizing the NB manifold design, more design activities will be performed in the future. These will be design optimization including the layout of internal supports.

Table 4. The maximum deformation and von Mises stress under DW + P + SL-2 with the optimized scheme.

<table>
<thead>
<tr>
<th>Loading case</th>
<th>Maximum deformation (mm)</th>
<th>Maximum von Mises stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL-2</td>
<td>18.347</td>
<td>211.786</td>
</tr>
<tr>
<td>DW+P</td>
<td>1.489</td>
<td>9.084</td>
</tr>
<tr>
<td>DW+P+SL-2</td>
<td>19.836</td>
<td>220.870</td>
</tr>
</tbody>
</table>

Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

References

[7] Cao C Z et al 2016 P1.005 Structural integrity analysis of ITER gas distribution system manifolds 29th Symp. on Fusion Technology (SOFT) Prague (Prague Congress Centre)