ITER Vacuum Vessel Supports

Final Report

Contract ENEA – EFDA

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Outline

Abstract

In the ITER experimental Tokamak reactor, high currents flow in the Vacuum Vessel (VV) during Plasma disruptions. The interaction between these currents and the toroidal-poloidal magnetic field produces high local forces. The direction of the electromagnetic forces acting on the VV can be upward or downward, while horizontal net force arises from the plasma tilting: their combination with the VV dead weight gives resultants both in vertical (up or downward) and horizontal directions.

The VV supports have to withstand all these forces, allowing only the slow radial displacements due to the thermal expansion.

Other local forces appear around the ports (discontinuities in the VV shell) during the pulse: these last forces have null resultant but produce local moments and ports distortions.

The present work includes the evaluation of the VV mechanical support structure and the following definition of alternative systems with additional suitable analyses.

In the present work a first identification and a preliminary verification of the proposed alternative solutions have been performed as well as additional analyses considered necessary to the design.

1. *Introduction*

The main task objectives were:

- to access the structural adequacy of the VV supporting system;
- to verify the analyses already existing;
- to suggest engineering solutions to the detected problems and propose alternative design concepts.

The work has been performed in two stages. In the first the real assessment has been performed and in the second the engineering solutions have been proposed and preliminary evaluated.

A brief summary of the previous intermediate activities is reported, with the aim to make a survey of the task activities during its progress.

The first activity was the check of the forces acting on the Vacuum Vessel on the basis of the reference data, on July 2007 [**1**],[**2**]. Total vertical forces of about 4 MN upward and 22 MN downward were in short the forces acting on the VV supports (see Appendix I Cap.1 "*Forces evaluation*").

With regards to the

- Vertical restraint system:
  - the increase of the Pot Bearing diameter from 0.960 m to ~1.5 m was the first result (see Appendix I Cap.2 / Par.2.a "*VV supports actual design / Materials*").
  - As regards the upward forces, the vertical ropes replacement with vertical rods or dampers was suggested (see Appendix I Cap.2 / Par.2.b "*VV supports actual design / Sizes and degree of freedom*").

- Toroidal restraint system:
  - the actual system shows potential risks and the "pendulum" system (W7-X) style was suggested as alternative solution. Other alternative solutions were briefly analyzed too (central rail and bended flexible plates). For more details see Appendix I Cap.2 / Par.2.c *VV supports actual design / Toroidal restraint system* and Cap.4 "*Toroidal Supports alternative solutions*"

- Vertical Supports alternative solutions.
  - In the first phase some alternative solutions were identified (see Appendix V: spherical bearing pads, connections rods (IGNITOR style) and radial bearing pads). Later on, three solutions were

selected: the flexible plates, the spherical joints (W7-X style) and the connection rods. Some analyses and considerations were made on these topics (see Appendix I Cap.3 *"Vertical Supports alternative solutions")* and the flexible plates system was identified as the most suitable among the alternative solutions.

The conclusion of the first phase was the choice to focus further analyses towards Pot Bearing and Flexible Plates solutions as Vertical Support Structure.

The radial restraint system was assessed as basically adequate. The implementation of two spherical joints at the ends of the radial arm was proposed and accepted by the IO. The improved radial system was kept for the reference design and for all the proposed alternatives.

2. *Vertical Supports / New Electromagnetic Forces*

The reference forces values, at least up to September 2007, remain that used in the previous analyses. Nevertheless the IO has in a later stage of the task execution presented some new evaluations on the last disruptions in JET. These seem to show new higher forces acting on the Vacuum Vessel.

These new vertical forces should be close to 40 MN downward and 10 MN upward (dead weight and horizontal component included) and the last analyses on both the two selected systems were performed taking into account these last values see Appendix II, III and IV.

2.a) Pot Bearing pads (Reference design)

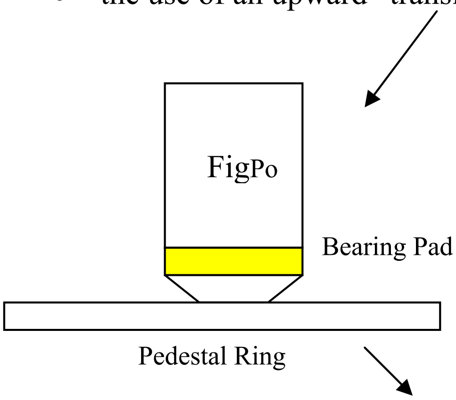
With reference to the Neoprene material characteristics, it is possible to consider the following values:

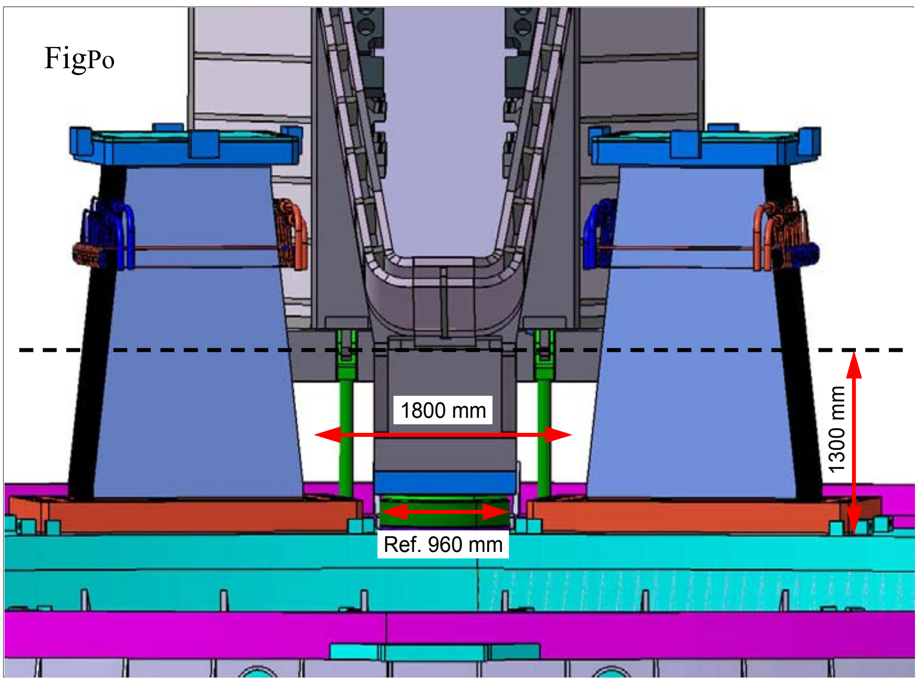
Neoprene transient compression limit = **80 MPa** (*Ref. K. Ioki, IO*)
= **average static pressure** = **20 MPa**
= **max static pressure** ≤ **40 MPa**

With the max vertical downward force equal to 40 MN and ϕ=960 mm the external bearing pad diameter, the **average** pressure of **80** MPa on neoprene is reached (with a net diameter = 800mm: the average pressure results equal to the Max local **80** MPa during transient. So the safety factor results equal to **1**).

In this case we have no safety margin but another possibility can be analyzed:

- the use of an upward "translated" bearing pad (see Fig.1).

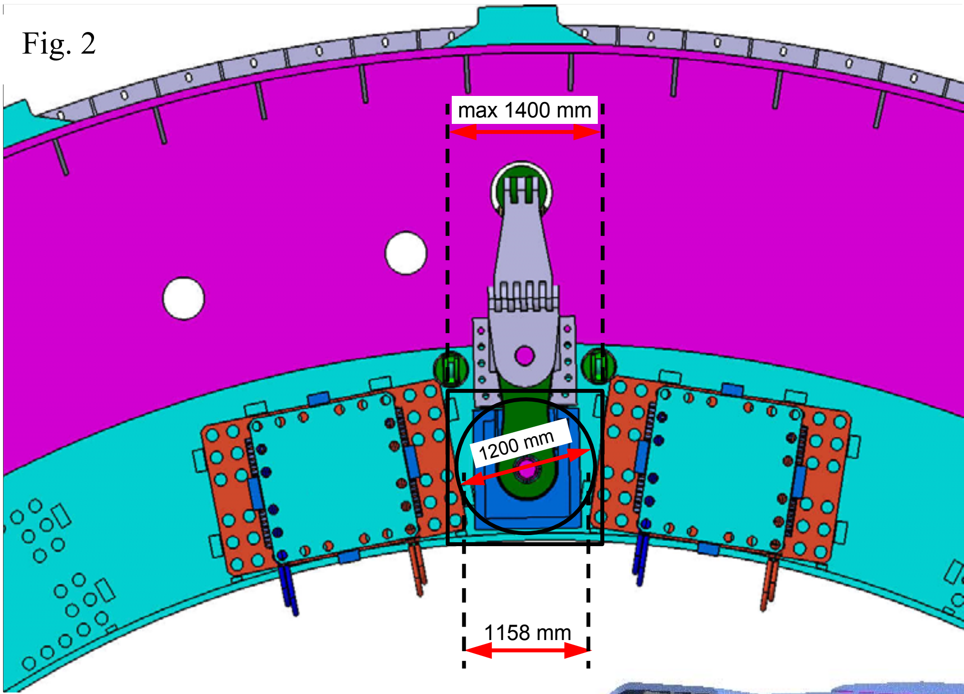




In this case the toroidal dimension of the pod bearing pads can increase up to a maximum of about 1800 mm.

In the radial direction (Fig.2) the maximum neoprene diameter should be around **1200 mm**. In every case, changing the neoprene diameter from <u>800 to 1200 mm</u> results in an area increment of about **2.3** times and an average pressure less then **35 MPa** (against the previous ***80 MPa***).

Fig. 2



The figure 3 shows a sketch of the larger-sized pot bearing pad upward translated.

In the sketch the red lines represent the connection towards the pedestal ring and the VV “foot”.

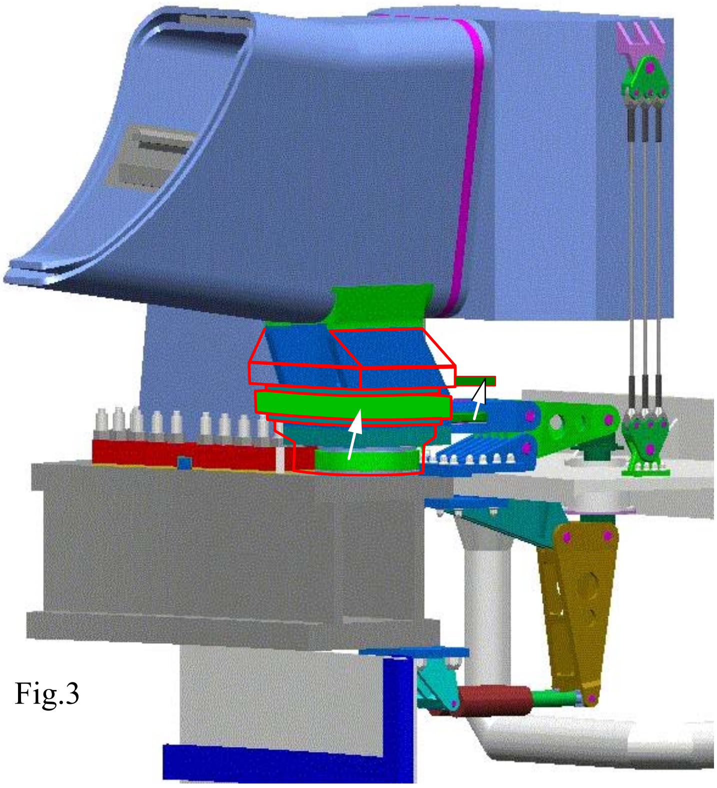


Fig.3

During the upward disruptions, the vertical upward and horizontal forces imply some net upward resultants. The max value of 10 MN upward per support was estimated.

The figure 4 shows the long rods and ropes groups foreseen to prevent vertical detachment between VV and bearing pads.
With reference to the meeting (*28 June 2007* Appendix V), the use of not preloaded tie-rods is to be avoided. Two systems can replace the previous one:

- the use of very stiff rods or
- an ad-hoc rope preloading that avoids to increase the pressure on the neoprene (see Appendix V par.1.b)

The preferred solution is the use of vertical **dumpers** (see fig1 of the Appendix III as example of shock absorber).
In this case, two dampers 5000 kN each are necessary and diameters around 550 mm with minimum 1.7 m length are the standard dimensions.

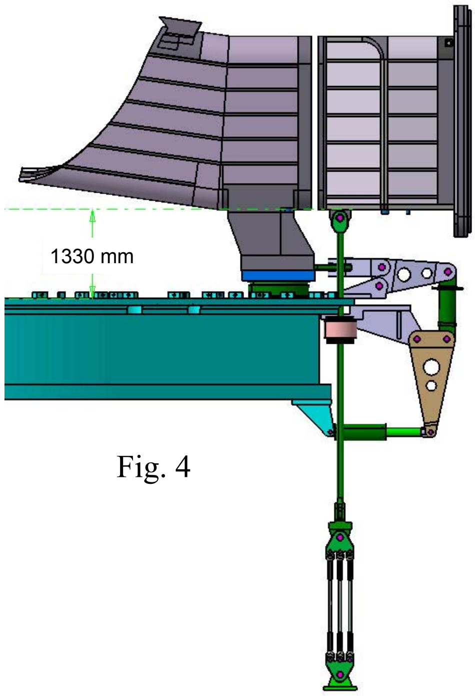


Fig. 4

Both diameter and length do not seem compatible with the space between ports / pedestal ring (1.3 m height) and with the presence of the radial restraint.

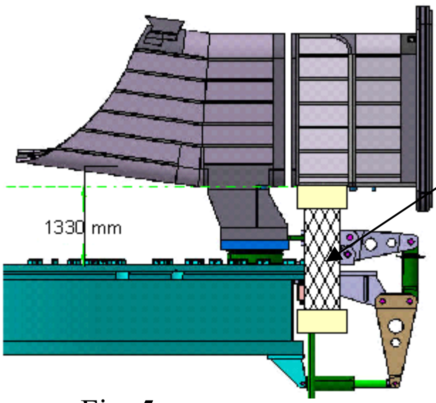


Fig. 5

The figure 5 shows a sketch of the port with the dumper and the anchoring blocks, with the purpose to see the order of magnitude of the components.
The use of dumpers with "**unidirectional upward**" effect is necessary (otherwise high vertical load could damage the device, during downward VDE / for mechanical snubbers see the web page "www.basicpsa.com/company-info.htm").

The only way to reduce the dumpers dimensions is the reduction of the axial force, through the amplification of the displacement Port→Damper. This can be achieved using the horizontal space between Port and Ring (or under the Ring) instead of the vertical one (see Fig 6.a).
Maintaining two dampers with their full dimensions, another solution is the translation of their location downward replacing the ropes groups in Fig.4.

The scheme of Fig 6.a shows the solution in which only one dumper is necessary (the horizontal device); the other elements are connections between Port and Ring. These last connections form an articulated structure attached to the Port/Ring side through Cardan or spherical joints (see Figures 6.a and 6.b).

When the port tries to move vertically upward an axial force acts on the dumper and its value is related to the slope of the stiff connections.

For example with α=20°, the horizontal component is less then ~2 MN (=0.4 • 5 MN). In this way the new dumper dimensions are about 370 mm x 1.2 m and one dumper only is used.

The choice of the angle α has to be optimized taking into account the axial force and the foreseen maximum slow vertical displacement (if α is too small the hor. force is negligible as the slow vertical displacement; vice versa if α is too large the hor. force can be higher than the vertical one with unnecessary extra large available vertical displacement capability).

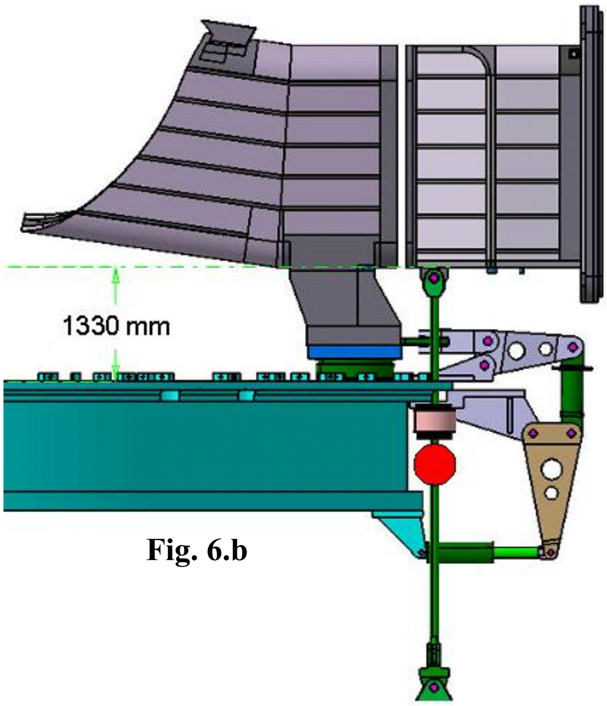
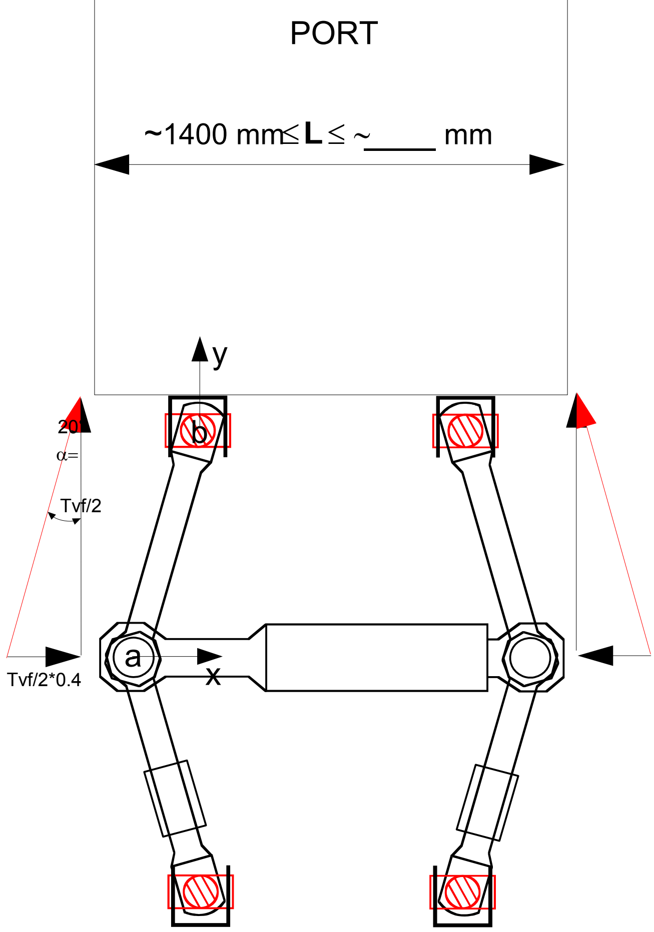


Fig. 6.b

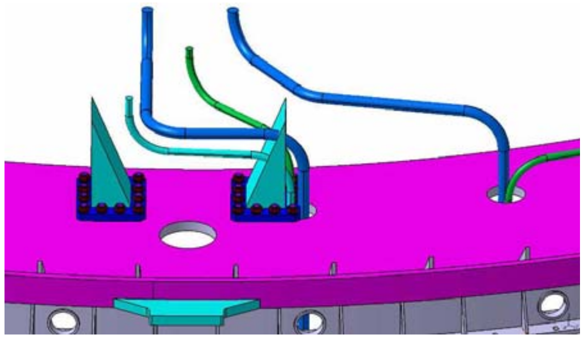
Tvf/2 = Total electromagnetic vert. upward force /2

$$\frac{\Delta y_b}{\Delta x_a} = \frac{2*(\cos\alpha_1 - \cos\alpha_0)}{(\sin\alpha_0 - \sin\alpha_1)}$$

Fig. 6.a



The Reference Toroidal restraint system is assessed not suitable. The wedge system has high risk of seizing for any VV deformation. In particular its function would require that both the restrain and the port extension are always controlled in their temperature difference.



A real good choice could be and when the vertical supports allow toroidal displacements, as in actual pot bearing (or spherical bearing) pads, the "pendulum" restraint system seems to be a really good choice.

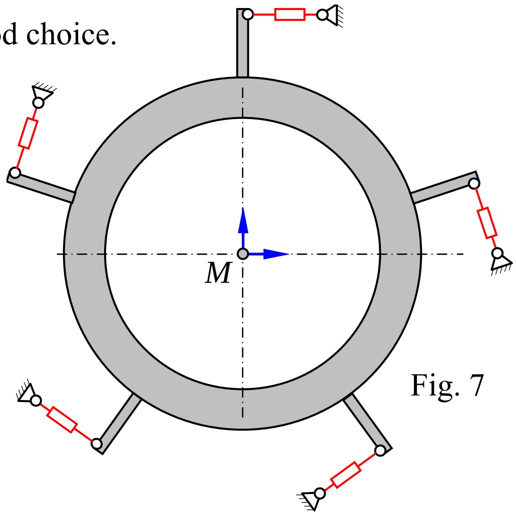


Fig. 7

The Figure 7 shows the ***W7-X*** Auto Centering System (see A.Cardella "*ITER Vacuum Vessel Support System*", Working Group Meeting, Cadarache 28 June 2007).

In the W7-X reactor no electromagnetic forces act on the Vacuum Vessel and the "pendulums" geometry is not a critical point.

In the Figure 8 it is possible to note the relative high L/D ratio

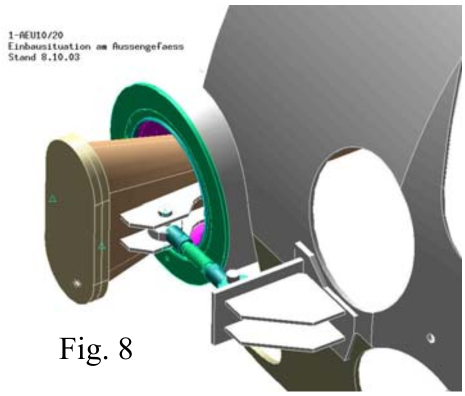


Fig. 8

The system allows Vacuum Vessel vertical displacements and radial thermal expansion with small toroidal rotations of the whole VV itself.

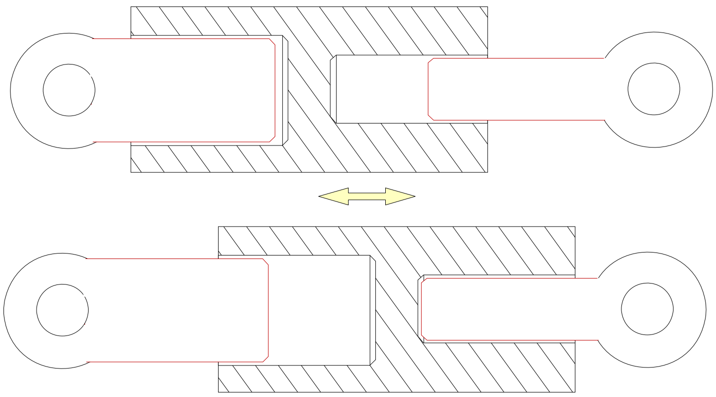
The "pendulum" solution for **ITER** reactor has to take into account several basic points:

- *the presence and the entity of the net horizontal force;*
- *the presence of the radial restraint system;*
- *during the disruption event, the opportunity to spread the reaction forces with different weights between radial and tangential ports* (to minimize the stress level in the Ports-VV connection).

In conclusion a pendulum system for ITER must be still dimensioned

During the task execution there were no possibilities to perform a detailed design and analysis of a proper toroidal restraint style W7-X and only a scheme of "pendulum" with variable axial stiffness has been proposed and shown in figure:

It will be possible to change with continuity the axial stiffness at constant pendulum length, if the screws pitches are identical.



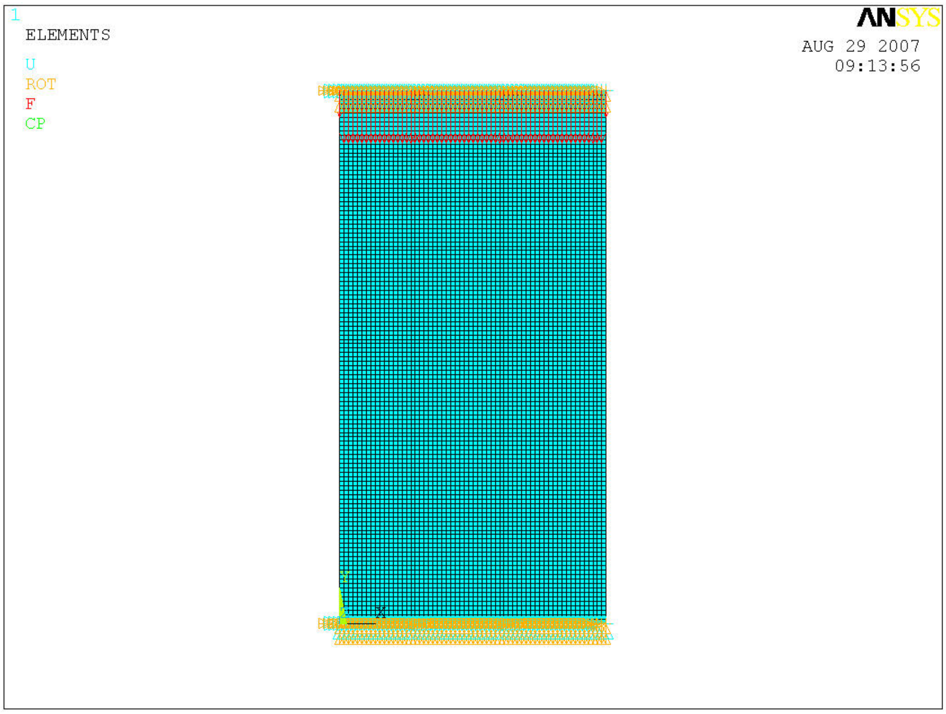
This could be fixed on one end to the lower port and on the other end to the pedestal ring.

2.b) Flexible Plates

In the present analysis, the reference solution is shown in the document "*Preliminary Assessment of Multi Flexible Plates VV Support* " – X.Wang, K.Ioki – ITER, August 7, 2007, Pag.4, Table 3.

The most suitable solution foresees **30** plates each **43 mm** thick and a more detailed ANSYS analysis was performed to compare the results.

The FEM model is shown in the figure below and describes one single plate grounded on the base. On the top of the plate, all the nodes are constrained with null rotations and a radial displacement (perpendicular to the sheet) of **20**, **30** and **40** mm. The total vertical force is equivalent to **25 MN** (previous Ref. Value; for the last one, **40** MN, see Tab.2).



The Tab.1 shows a summary of the results:

Tab.1 ***Flexible plates 2.4 m height***		*25 MN Vertical Force + Radial Displacements:*				*Allowable*
		20 mm	**30** mm	**40** mm		
Thickness = **43 mm**	Membrane stress, σ_m	16.2 MPa	16.2 MPa	16.2 MPa	<	141 MPa
n° of plates = **30**	Membrane + Bending, $\sigma_m + \sigma_b$	88.5 MPa	131 MPa	162 MPa	<	212 MPa
Width= **1200 mm**	Buckling margin, m_{cr} (*)	**12** (with μ=0.5)			>	3
Length = **2400 mm**	Radial space, ΔR	1580 mm				

(*) see formula (3) from X.Wang, K.Ioki - ITER, August 7, 2007 "*Preliminary Assessment of Multi Flexible Plates VV Support*"

The linearised stresses are calculated in the shell top position and along the path show in the Figure 9 (Vertical Load=25 MN; ΔR=30 mm).

It is possible to note the strong effect of the bending stress (in the 43 mm plate thick) against the low membrane stress.

The *radial elastic reaction (ANSYS)* results ~ **1.341 kN/mm per plate** (<u>40.2 kN/mm per support</u>).

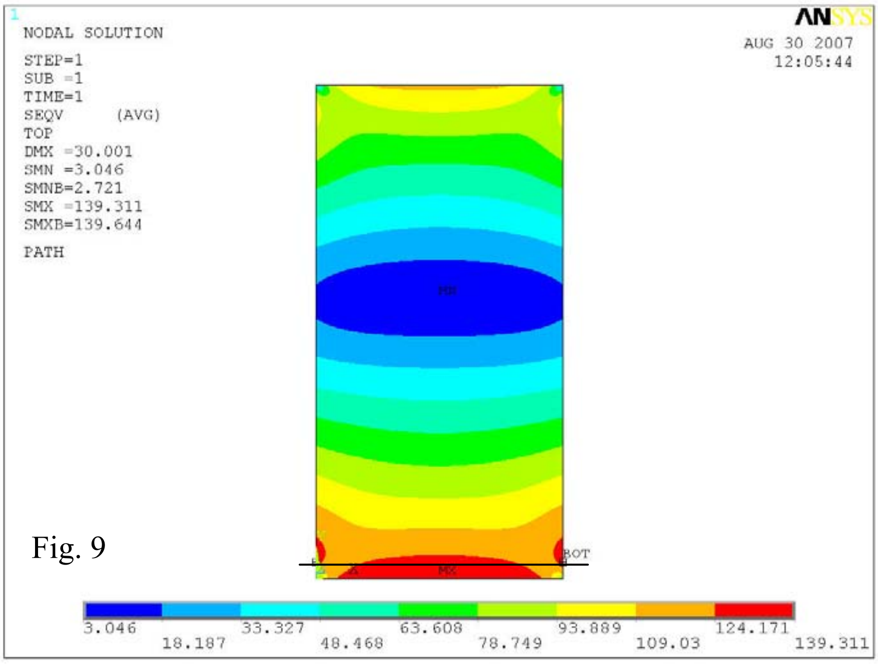
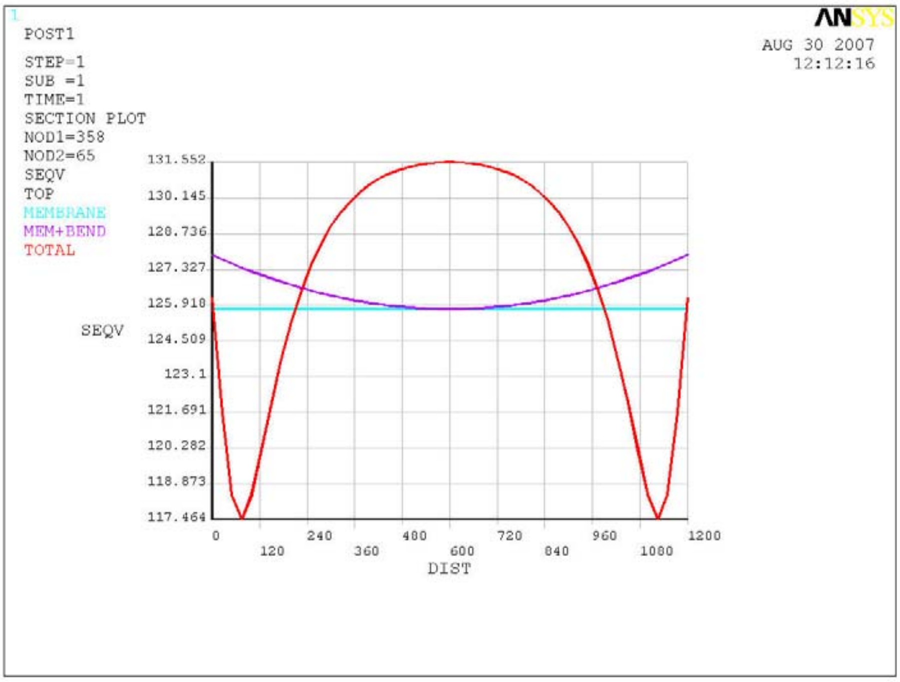


Fig. 9



Buckling margin:

From the linear elastic buckling calculation with ANSYS, a value of ~12.5 was obtained for the first eigenvalue. The starting position and the deformed shape are shown in Fig. 10 (to note the deformed starting geometry related to the operative condition, about 20 mm radially displaced.

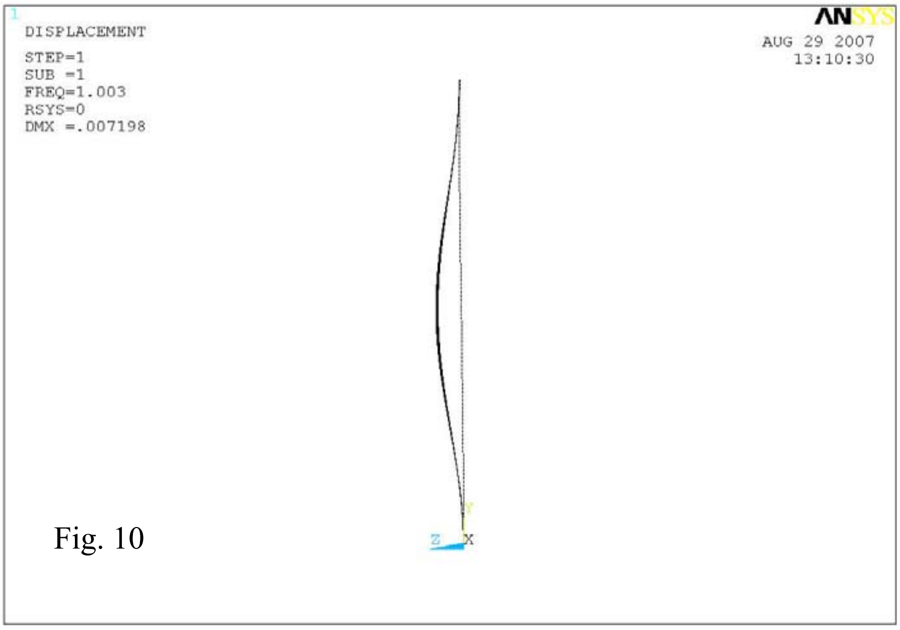
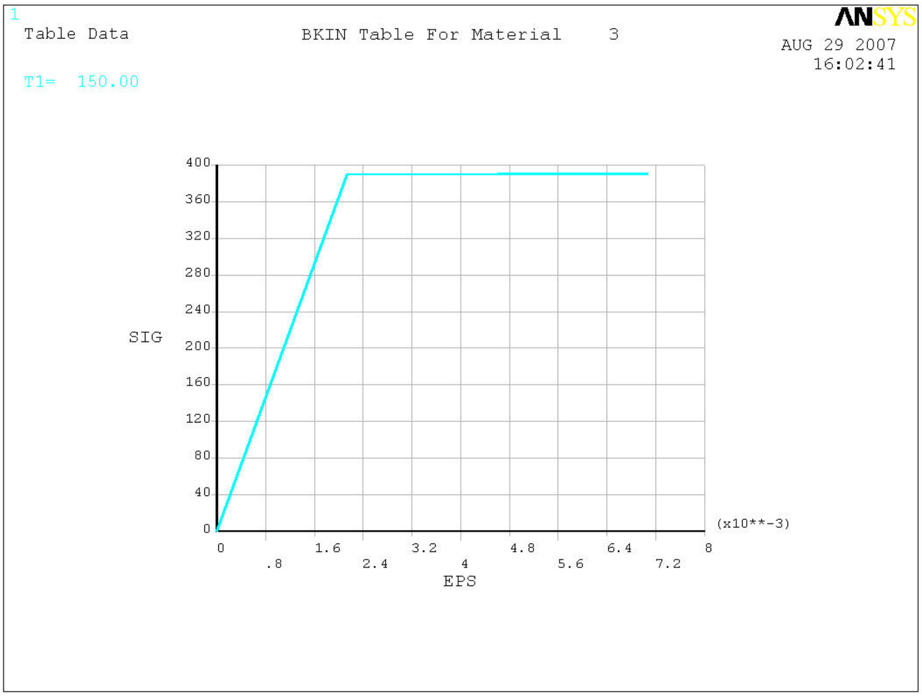
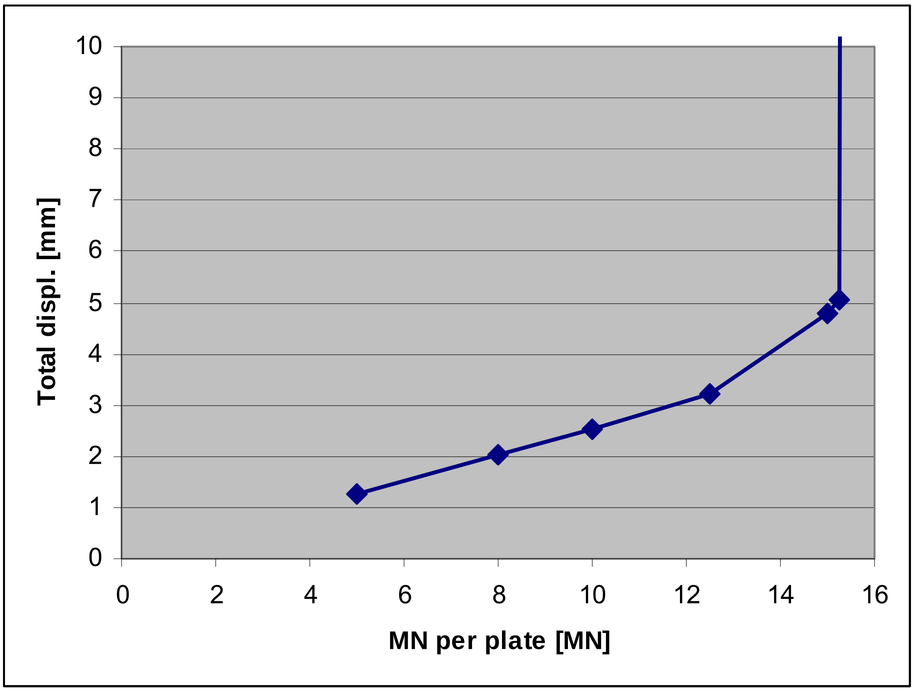


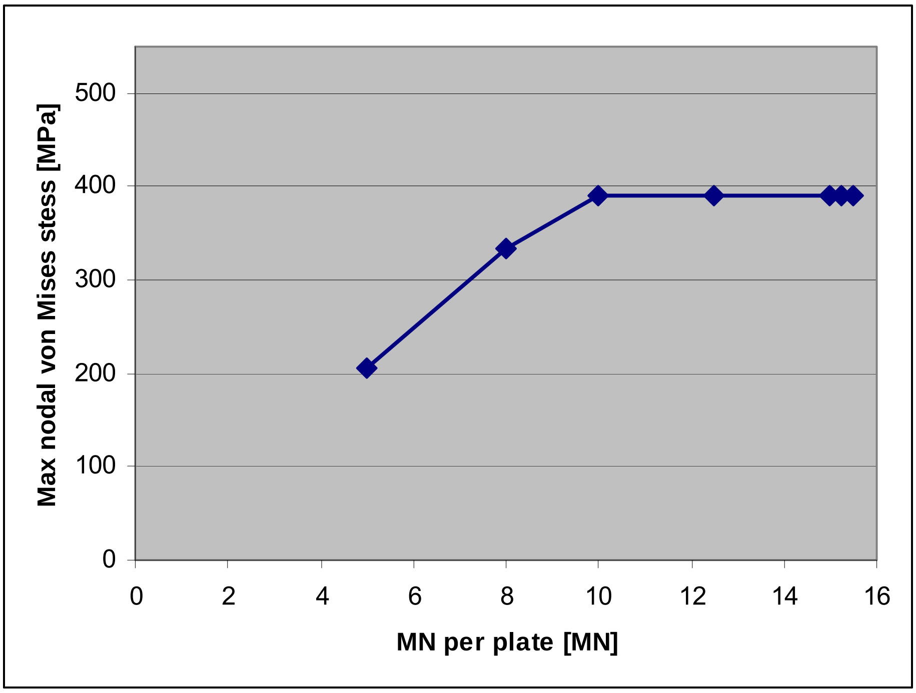
Fig. 10

With the aim to complement the previous elastic calculation, an elasto-plastic analysis was performed. As first approximation a bilinear material was used; E=182 GPa and the limit of the first elastic zone was set to 390 MPa:



The two figures below show the Total displacement and the max nodal von Mises stress versus the vertical force [MN] applied to the single plate. ***<u>Important note</u>****: the radial displacement of the top plate is maintained constant (and equal to 20 mm, in this case) because the radial/toroidal restraint system of all the VV supports is symmetric.*





It is possible to note that above 10 MN/plate starts a large plastic strain and above 15.25 MN/plate the system doesn't converge anymore.

The possible limit value could be **9** MN/Plate with a Safety Margin **SM** = **10.8**.

Note: 10.8=9/0.83 where 0.83 (= 25 MN / 30 plates) is the Ref. load on each plate.

⟶ New Electromagnetic vertical downward forces: **40 MN**

Tab.2 ***Flexible plates 2.4 m height*** **with 40 MN**		*40 MN Vertical Force + Radial Displacement:* **20** mm	**30** mm		*Allowable*
Thickness = **43 mm**	Membrane stress, σ_m	26 MPa	26 MPa	<	141 MPa
n° of plates = **30**	Membrane + Bending, $\sigma_m + \sigma_b$	97.3 MPa	135 MPa	<	212 MPa
Width= **1200 mm**	Buckling margin, m_{cr}	**7.4** (μ=0.5)		>	3
Length = **2400 mm**	SM against collapse (Elas-Plas)	6.8*		>	3
	Radial space, ΔR	1580 mm			
* 6.8 = 9 / 1.33 where 1.33 (= 40 MN / 30 plates) is the New Ref. load on each plate					

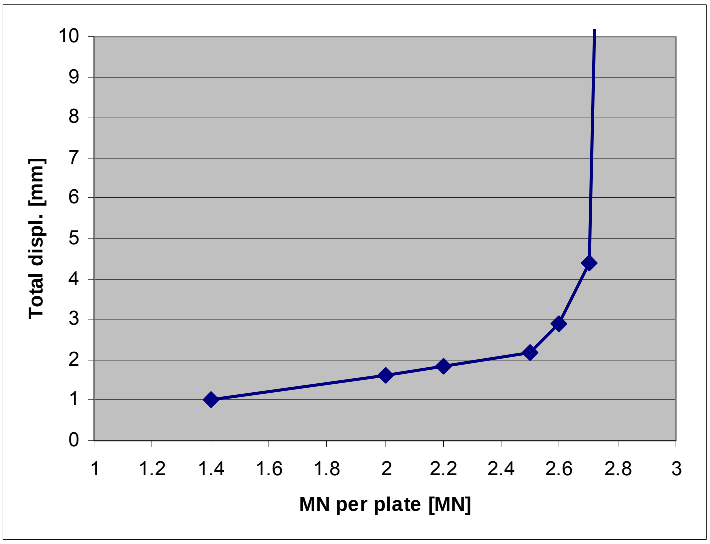
With the new vertical forces also, the analysis results show a large margin against the buckling and the limit conditions.

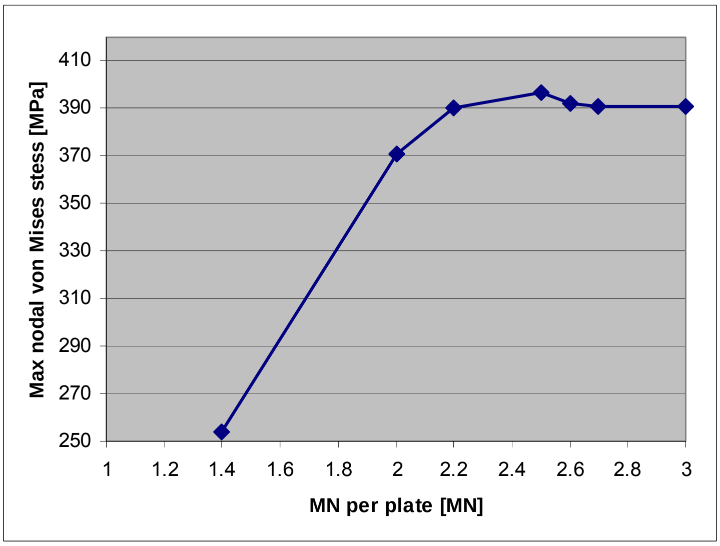
The possibility to reduce the global space is the next trial and only an example is shown in Tab.3:

Tab.3: ***an example with the Actual Allowable Space*** ***(Width =960 mm and Length = 1200 mm)***		*40 MN Vertical Force + Radial Displacement:* **20** mm		*Allowable*
Thickness = **16 mm**	Membrane stress, σ_m	43.4 MPa	<	141 MPa
n° of plates = **60**	Membrane + Bending, $\sigma_m + \sigma_b$	149 MPa	<	212 MPa
Width= **960 mm**	Buckling margin , m_{cr}	**2.5**	<	3
Length = **1200 mm**	SM against collapse (Elas-Plas)	3.3*	>	3
	Radial space, ΔR	1430 mm		
If ***width = 1100 mm*** *and* ***n° of plates = 70*** *then* ***Buckling margin***, $\mathbf{m_{cr}}$ = **3.3** >**3** and **ΔR = 1810 mm**				

In this case the Radial Reaction Force per plate is **0.45 kN/mm** (27 kN/mm per support).

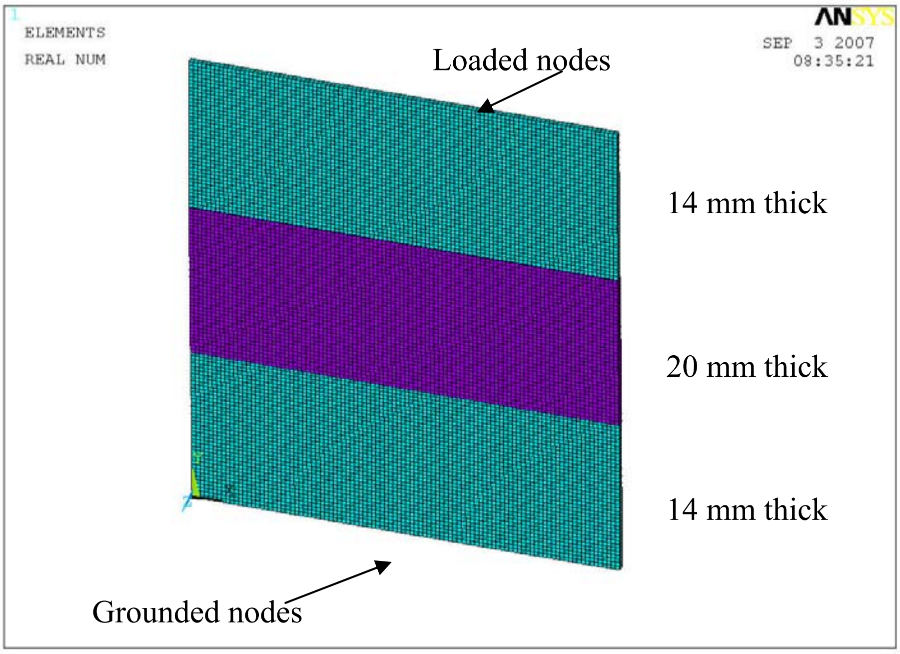
* 3.3 = 2.2 / 0.667 where 0.667 (= 40 MN / 60 plates) is the New Ref. load on each plate and 2.2 MN/plate derives from the two graphs below (summary of the elasto-plasto analysis)

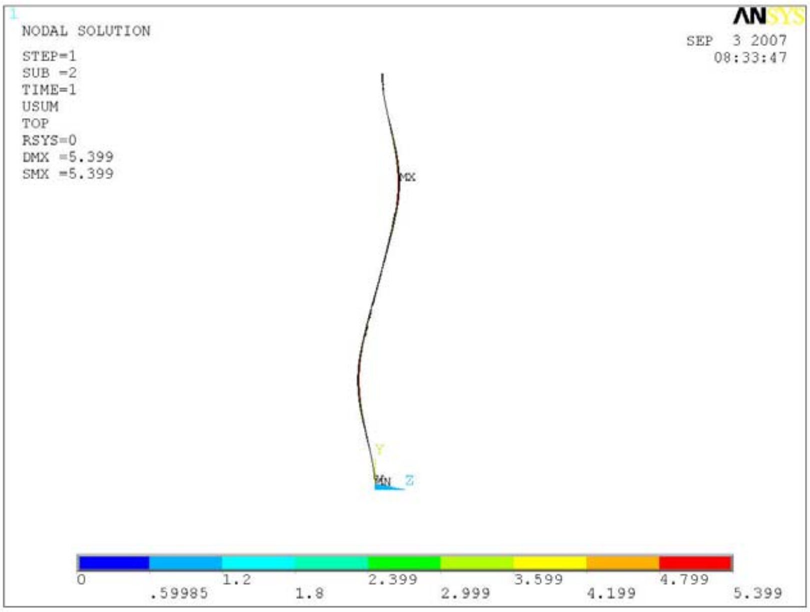




Unfortunately the buckling margin is very low and only increasing to 70 the number of plates and to 1100 mm the plates width it is possible to reach a value of 3.3, which is anyway low.

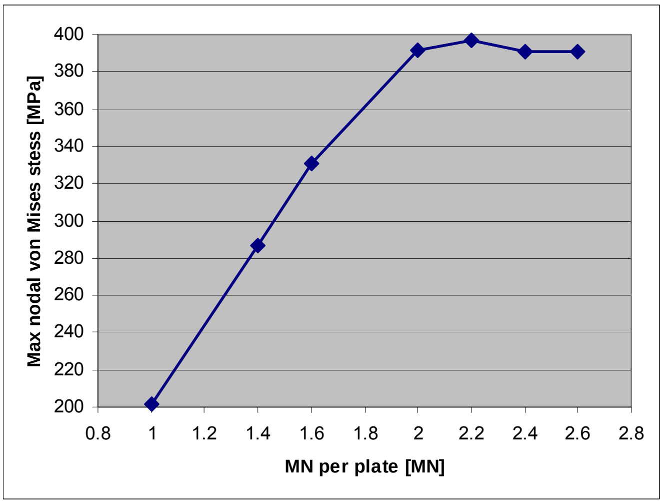
An interesting way to decrease the membrane stress (increasing the buckling margin) and the bending stresses, induced by radial displacements, is the use of two thicknesses along the flexible plates height. The figures below show an example of flexible plates (1200x1000) with **two thicknesses (14/20 mm)** and the deformed shape just before the collapse (2.6 MN; displacements [mm]):

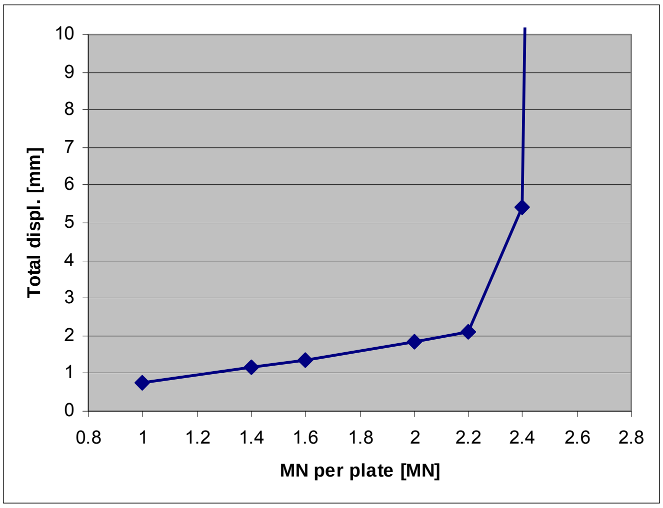




As in the other cases, Tab. 4 shows the global result of this type of plate:

Tab.4: ***an example with Length = 1200 mm; 2 thicknesses***		*40 MN Vertical Force + Radial Displacement:* **20 mm**		*Allowable*
Thicknesses = 14 / 20 mm	Membrane stress, σ_m	29 / 39.2 MPa	<	141 MPa
n° of plates = 70	Membrane + Bending, $\sigma_m + \sigma_b$	138.8 MPa	<	212 MPa
Width= 1000 mm	Buckling margin, m_{cr}	3.3	>	3
Length = 1200 mm	SM against collapse (Elas-Plas)	3.5*	>	3
	Radial space, ΔR	1670 mm		
* 3.3 = 2.0 / 0.57 where 0.57 (= 40 MN / 70 plates) is the New Ref. load on each plate and 2.0 MN/plate derives from the two graph below (summary of the elasto-plasto analysis)				





Unfortunately the application of this system is not enough to increase substantially the buckling margins.

3. *Radial Supports / New Electromagnetic Forces*

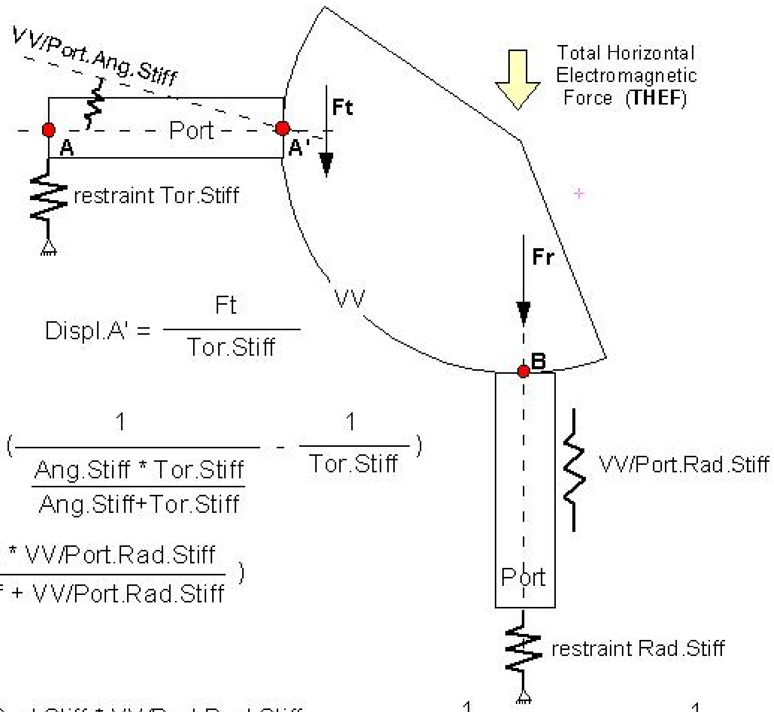
The new total vertical downward force of 40 MN includes the vertical component due to the electromagnetic horizontal force.

This force (new evaluations of the last disruptions in JET) results about **3** times higher than the previous one: **73 MN** against the previous 25 MN.

The mechanical levers system, designed for a total force of 25 MN (on the VV) , has to be reviewed on the basis of this new force acting during the VDE.

A possible alternative to the mechanical solution could be the hydraulic system (Appendix III), but it seems essential to have a right stiffness correlation between the toroidal and radial restraint systems. The choice of the toroidal restraint can not take place without the simultaneous identification of the radial restraint system.

A rough sketch shows the relations among the Vacuum Vessel ports and the Restraints stiffness (radial and toroidal). The stresses distribution in the joints between ports and VV are function of all the stiffnesses:



$$\text{Displ.A} = \frac{\text{Ft}}{\dfrac{\text{Ang.Stiff} * \text{Tor.Stiff}}{\text{Ang.Stiff}+\text{Tor.Stiff}}} \qquad \text{Displ.A}' = \frac{\text{Ft}}{\text{Tor.Stiff}}$$

$$\text{Stress A}' = \text{Displ.A} - \text{Displ.A}' = \text{Ft}\left(\frac{1}{\dfrac{\text{Ang.Stiff} * \text{Tor.Stiff}}{\text{Ang.Stiff}+\text{Tor.Stiff}}} - \frac{1}{\text{Tor.Stiff}}\right)$$

$$\text{Ft} = \text{THEF} - \text{Displ.B} * \left(\frac{\text{Rad.Stiff} * \text{VV/Port.Rad.Stiff}}{\text{Rad.Stiff} + \text{VV/Port.Rad.Stiff}}\right)$$

$$\text{Stress A}' \Rightarrow \left[\text{THEF} - \text{Displ.B} * \left(\frac{\text{Rad.Stiff} * \text{VV/Port.Rad.Stiff}}{\text{Rad.Stiff} + \text{VV/Port.Rad.Stiff}}\right)\right] * \left(\frac{1}{\dfrac{\text{Ang.Stiff} * \text{Tor.Stiff}}{\text{Ang.Stiff}+\text{Tor.Stiff}}} - \frac{1}{\text{Tor.Stiff}}\right)$$

Stress A' (Rad., Tor., VV/Port.Ang., VV/Port.Rad.)

4. *Recommendations*

During the execution of the task recommendations were given to IO for solving the problems or to improve the design; in the following list the recommendations are summarized.

General

- The Vacuum Vessel and Ports global model is essential to the evaluation of all the restraint systems. The IO is already aware of this problem and analyses have been performed, but these should be remade in the present design.
- The supporting system must be accessible and maintainable. IO has accepted the proposal and will develop the system.
- Double the number of supports from 9 to 18. The IO has discarded this proposal because of field weld joint problem and lack of access.

Present Reference Concept with Pot Bearings

- Active temperature control of PTFE and Neopren parts (limit T to e.g. 60°C). A suitable system will be designed by the IO.
- The use of ropes is to be avoided. The IO will discard the Ropes. IO has agreed and a dumper system will be used. A design concept has been developed in the frame of this task and has been proposed to IO.
- The reference toroidal/ centering restrain has been assessed not suitable. IO has agreed and will change the toroidal restrain. The W7-X type of pendulum system has been proposed to IO.
- Examine in detail the radiation damage to the PTFE and Neopren and propose a material characterization test campaign with and without radiation damage. IO has agreed and is planning to launch a task in the future. The use of controlled atmosphere has been proposed to avoid corrosion from activation products. IO has agreed but an implementation is to be studied.

Alternative Concepts

- Adapt the old ITER EDA design with flexible plates to the new loads and location:
  - Scoping studies have been performed and presented to the IO. These are promising and IO will examine in detail this option.
  - The radial dumper system should be kept also for this concept (see paragraph xx).
  - It is recommended to develop a solution for reinforcing the lower port in toroidal direction. IO has not yet expressed a final position on this, but will further study.

5. *Conclusions*

The two more detailed assessed VV Support systems are:

(1) Pot bearing + vertical upward restrain + toroidal system→ Vertical up/down + toroidal
(2) Flexible plates → Vertical up/down + toroidal

Main comparison between the two systems is:

- Both appears feasible. For both it is recommended to perform detailed analyses.

- The system (**1**) foresees commercially available devices (pot bearings, shock absorbers) while the "pendulum" (W7-X type) toroidal restraint system has to be analyzed.

- The system (**2**) results more robust and simpler, because in a single block are present all the restraints but it is not a commercial device, has a fixed toroidal stiffness which could be a problem for the lower ports and more vertical space is necessary to accommodate it.

- Common to both the systems (**1, 2**) is the <u>radial</u> restraint, which appears suitable with the reference forces but must be reviewed with the newly proposed higher radial forces.

References

[1] Design Description Document - DDD15 - Vacuum Vessel - September 2004

[2] A. Cardella "*ITER Vacuum Vessel Support System*", ITER Vacuum Vessel Design Review Working Group Meeting, Cadarache 28 June 2007