ITER DIAGNOSTIC PORT PLUG DESIGN

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Many of the ITER diagnostic systems will be mounted in the equatorial and upper ports of the torus, supported by removable structures known as 'port plugs'. The port plugs support the diagnostics and provide functions of baking, cooling, and neutron shielding. They must operate reliably in the demanding ultra-high vacuum, high radiation environment of the ITER tokamak for many years.

Recent work on the mechanical design of the equatorial port plugs is reported, including a proposal for a new conceptual design, which uses the lid of the port plug as a structural member. The design of a complex component like this is an iterative process considering the interaction of the features of the port plug structure, neutron shielding components and diagnostic components with the electromagnetic forces induced in the structure by plasma disruptions.

These electromagnetic forces are recognised to dominate the requirements for the strength of the structure. Much work has been carried out on this topic by other people, but generally this has been based on models which make assumptions about the boundary conditions. An ANSYS electromagnetic model of a half-sector of ITER has now been developed by UKAEA, to study the induced forces in the equatorial port plugs.

I. FUNCTION OF THE PORT PLUG

The equatorial and upper ports on the ITER tokamak are distributed around the machine symmetrically. Of the equatorial ports, six are dedicated to diagnostic systems, and two are used for ICRF heating systems, which although not identical, share many of the same requirements. The basic requirements are to:

- Close / seal the port on the vacuum vessel
- Support contents, including components of different diagnostic systems in each port
- Support the Blanket Shield Module (BSM) and supply water to it
- Bake the port and the contents during vacuum conditioning, using high pressure water
- Cool the contents during plasma operation
- Provide effective neutron shielding

The port plug itself is a stainless steel box structure, approximately 2m high, 2m deep and 3 m long. During vessel conditioning, the water will be supplied at a pressure up to 4.4 MPa, ensuring that it will not boil at the required temperature of 240°C. During plasma operation, water will be supplied at 100°C to cool the components which are actively heated by the plasma, neutrons and gamma radiation from the plasma. The water in the shielding modules inside the port plug plays an important role in the reduction of the neutron fluence into the port cell [1]. This reduces the activation of components in the port cell, where human access will be possible for limited periods during machine maintenance times. The port plug also bakes the single walled port extension, and thermal analysis indicates that this has significant influence over the choice of design for the cooling channels in the port flange and the port plug itself.

Because the port plug is so close to the plasma, it will experience large forces and torques during plasma disruption events. As the plasma current decays rapidly, it induces eddy currents in all nearby conducting structures. The eddy currents then interact with the remaining magnetic fields from the toroidal and poloidal field coils, and large forces and torques are therefore generated. Various models have been accepted as worst case scenarios for different machine components, and several disruption scenarios have been selected for analysis of the port plugs, ref. [2] and [3].

As an example of one of the diagnostic systems that will be mounted in an equatorial port plug, ref [4] describes many aspects of the Thomson Scattering Core LIDAR system which is one of the occupants of equatorial port 10.

II. ENGINEERING ANALYSIS REQUIRED

The range of engineering considerations makes the design of the port plugs very challenging and interesting. The electromagnetic loads have severe implications for the structure of the port plug, and preliminary structural analysis suggests that, assuming a nominal peak stress of 30 MPa, the walls of the plug should be between 40 and 130mm thick, depending on the assumptions that are used. The whole structure has to be able to withstand repeated thermal cycling, at the same rate as the rest of the torus, so thermal analysis is required to ensure that the structure is not unduly stressed (stainless steel has a very low thermal conductivity). Hydraulic analysis is important to ensure that the flow to the various components is distributed appropriately. Those items at the front of the port plug require higher flows of cooling water, and it is important not to waste flow though the rear shield modules. Having proposed a mechanical structure, modal analysis will be needed to avoid resonance that could build large amplitude vibrations.

The neutron shielding properties are also important [1]. Most diagnostic systems need access to the plasma but the scope for line of sight views is very limited. Optical labyrinths have to be constructed to ensure that the net attenuation factor for neutrons is of the order of 10^6. Modeling has shown that the distribution of steel and water in the port plug is important. At the front of the plug where the D-T reaction product neutrons have an energy of 14 MeV, the shielding is most effective if the steel content is of the order of 30%, using the 70% water to scatter the neutrons to lower energies. In the centre module, a 50:50 mix is most appropriate. By the back of the port plug the neutrons have lost much of their energy, and they have a spectrum quite similar to that seen in the shielding around fission reactors. Here it is beneficial to increase the steel content of the shielding to around 70%, to absorb as many neutrons as possible. This distribution is consistent with the role of water for baking and cooling.

There are also limitations on the mass of the assembled structure. The remote handling cask that will be used to transport the assembly to the hot cell for maintenance is expected to have a capacity to handle up to 45 tonnes, so this imposes limits on the amount of material that can be used for shielding. Ease and cost of manufacturing is also an important factor. It would be beneficial to have a single design that could be used for all of the diagnostic ports, and perhaps the ICRF ports. However, there may be technical reasons why this is not ultimately possible.

This range of engineering requirements leads naturally to the need for an iterative approach to the design of the port plug and its contents.

III. REFERENCE DESIGN AND A NEW CONCEPT

The reference design for the generic equatorial port plug uses a good solid design concept. Many ITER parties were involved in the generic design, fabricated from 130mm plate. The bottom and sides are welded and the top cover is bolted. Cooling / baking channels are deep drilled in the thick plates.

Modeling indicates that a 130mm thick structure is consistent with a philosophy where the strength of the port plug does not rely on the shear strength of the joints between the lid and the side walls of the port plug. Originally it was thought that the lid might be made up of several independent plates, each supporting a separate shielding module and its contents. However, it is now expected that the lid will be a single plate, and the analysis that is illustrated in Fig. 1demonstrates that the thickness can be greatly reduced if it is possible to use its strength as part of the structure as described in ref. [5]

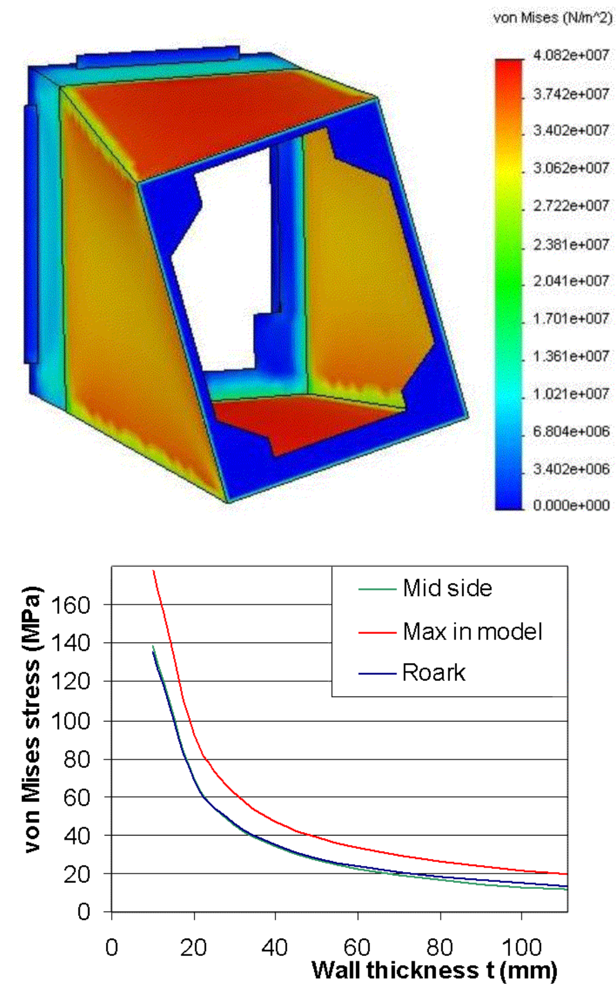

Fig. 1 - Typical stresses due to electromagnetic loading on port plug as a function of the wall thickness.

The reference design, is a very heavy construction – perhaps weight could be redistributed an used in neutron shielding modules rather than in the walls. There may be other concerns about the cost of construction – complex machining might be reduced, and the amount of steel required may be significant as it is expected that supplies of 316LN(IG) may be short. There are also many meters of weld with 4.4MPa water on one side and torus vacuum the other side. Water leaks to vacuum would lead to machine failure.

There are also concerns about distortion during assembly of the welded components of the case, and the effect on ability to meet tolerance requirements. It is difficult to model or predict weld distortions.

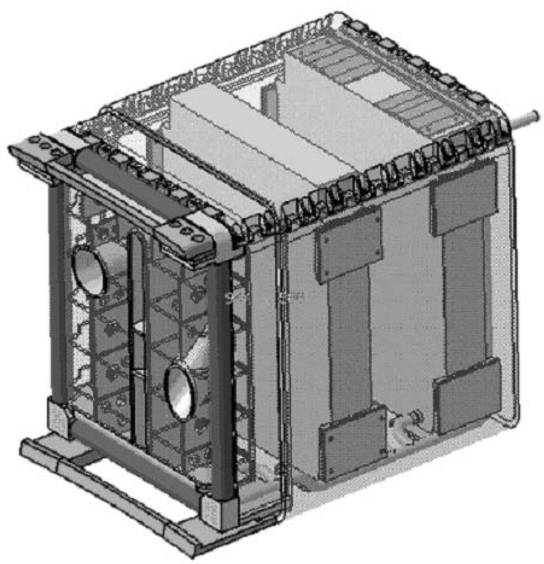

Fig. 2. One of several new conceptual designs for an equatorial port plug for ITER, with no active heating or cooling channels in the port plug case.

A new concept has been explored, as shown in Fig. 2, with 40mm thick walls, chosen from the analysis illustrated in Fig. 1. Instead of using direct cooling channels in the walls, various approaches to thermal contact to the diagnostic modules have been investigated. A tubular front frame for the port plug gives the benefit of improved cooling in the region that experiences the greatest nuclear heating.

Choice of neutron absorbing materials inside the shielding modules can have a large effect on the performance, and a boronated steel is proposed for the contents of the module, with an outer shell of stainless steel that is able to contain the high pressure water. The front diagnostic module plays a major role in shielding, and nuclear heating of the order of 10kW is expected.

IV. ELECTROMAGNETIC ANALYSIS

Since the dominant loads on the structure are electromagnetic in nature, it is important to have a good understanding of the behavior of field transients inside the port plug. Various organizations have adopted different strategies for the modeling, making different assumptions and in some cases introducing variables to their models as boundary conditions. In UKAEA at Culham it was decided to use the expertise of experienced EM modeling engineers to take an independent view of the problem including the actual currents in the coils to generate the background fields within the model. Results of this new independent analysis help us to gain confidence in the magnitude of the problem faced for the mechanical design. Peak torques of the order of 10MNm are expected in the worst cases.

The Catia model for a half sector of ITER has been successfully transferred into the well known finite element analysis package, ANSYS. This task in itself was not trivial. Catia models contain many discontinuities which are not noticed during normal use. However, when the models are ported to ANSYS these ‘features’ make it impossible to create an efficient mesh. For EM analysis there is an additional complication, namely that the mesh must be continuous not only within the solid parts of the structure, but also across the boundaries to the spaces between the solid elements and in the volume of the spaces. This is not a requirement for most structural or thermal FEA modeling. Preferably the nodes on all surfaces should also match.

The half-sector has now been successfully meshed, and the model contains the significant elements of the sector, including the toroidal and poloidal coils, the central solenoid and the vessel structure. This is a large model, containing about 250,000 elements, but runs acceptably on a power PC. By including all of these components in a single model it is possible to ensure that the risk of errors introduced by choice of boundary conditions is minimized. It has been possible to demonstrate that the magnitude of the fields from the coils is as expected, and to model the effect of a VDE compared with a disruption in which the core of the plasma remains stationary.

Initially, the port plug was represented as a simple structure, having two shells of different thickness surrounding a homogenous block. The properties of these items can be switched to simulate the effect of changing the thickness of the port plug case, and this set-up has enabled the model to be bench-marked against previous work by Rocella [3]. Adopting the assumptions that were made in this work, the new model produces results that are very close to previous findings. As another example, Fig. 3 shows the background toroidal field calculated in the new model, finding a value of 5.09T, where the expected value was 5.13T. This gives good confidence that the model will produce valid results as the assumptions are adjusted in future work.

Two approaches could now be adopted for further work on in-port components. For initial design of components inside the port plug it might be sufficient to use a matrix of worst case field transients for different locations in the plug. Straight-forward calculations could then be done quickly and repeated to optimize the component design. However, ultimately, it might be necessary to include the details of the components in the FEA model to study the effect of interactions between the components. This would be part of the final checking before a detailed design review of the whole port plug and its contents.

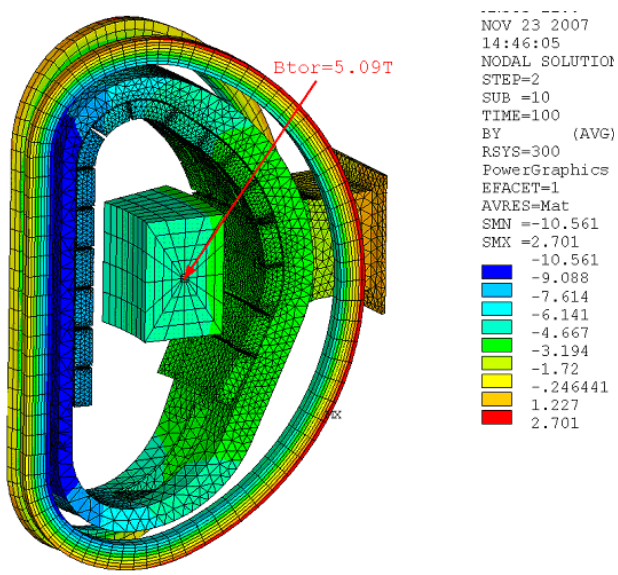

Fig. 3. Bench-marking the electro-magnetic model against established results for the design of ITER, the toroidal field is calculated to an accuracy better than 1%.

Recent findings have indicated that the worst disruption scenarios for the equatorial ports are those in which the plasma does not move, but it decays linearly. A generic worst case scenario has been developed and this could be applied to all the equatorial ports. Indeed it has also been used for preliminary analysis of the heating neutral beam duct liners which are in a similar position relative to the plasma.

However, it must be remembered that the contents of the port themselves have a significant effect on the field transients. Highly conductive components will experience very large forces and torques because the magnitude of the eddy currents induced in them is so large compared with components of lower conductivity. These eddy currents result in screening in some areas, and increase the magnitude of the field transients in other regions.

Modeling has been started for four scenarios, from ITER reference documents [2]. These have been chosen to represent linear and exponential plasma current decays, with either constant position plasma or an example VDE. A few of the recent results are summarized below, and work is now ongoing to analyze the effect of field transients on shielding modules mounted in different orientations inside the port plug.

IV.A Current loops through the port plug

Fig. 4 shows a representation of the currents flowing in the port plug and BSM. It is found that the induced current makes a loop between the port plug and the BSM increasing the total radial torque on the complete port plug by 30%. Halo currents are not considered but are expected to have a negligible effect.

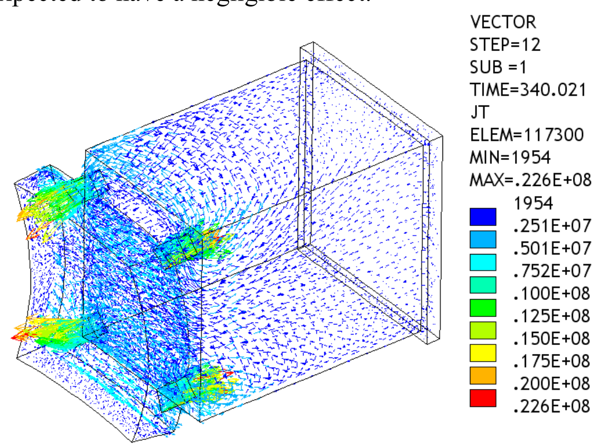

Fig. 4. Illustration of the current flow (A/m2) in the port plug and BSM at 21 ms after beginning of the plasma disruption, assuming good electrical connection to the port through the bolted flanges.

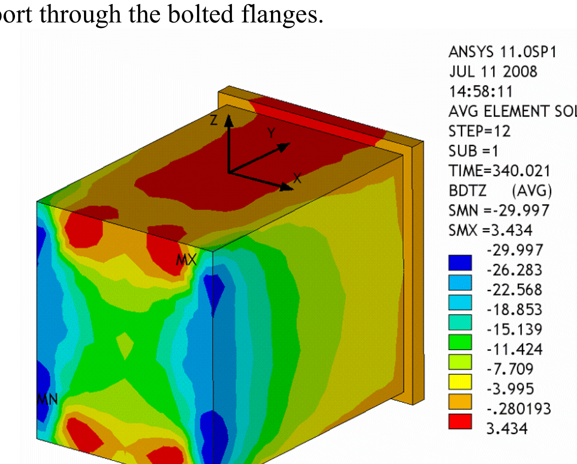

Fig. 5. Variation of time derivative of vertical component of flux density (T/s), 21ms after beginning of exponential plasma current decay.

IV.B Illustration of peak dB/dt values

Fig 5 shows a 3-D representation of the rapid variation of the magnitude and sign of field transients for a particular disruption scenario. The rapid spatial variation that is visible in this model shows that it is difficult and dangerous to interpolate between values calculated for field variations at known points in the structure. Specific calculations need to be carried out for the position of interest.

The clear structure in the results is mainly caused by current flow to and from the BSM. Local variations lead to large internal stresses. Different BSM mounting techniques might be explored.

IV.C Time variation of the peak dB/dt values

Detailed analysis of the field transients in different regions of the port plug reveal that the peaks are reached at different times in different locations. In one example it was found that the maximum radial torque and radial force were reached 21ms after the start of a linear current decay disruption in the outer shell of the port plug. By 30ms, the maximum value had dropped significantly, but moved to a location inside the port plug.

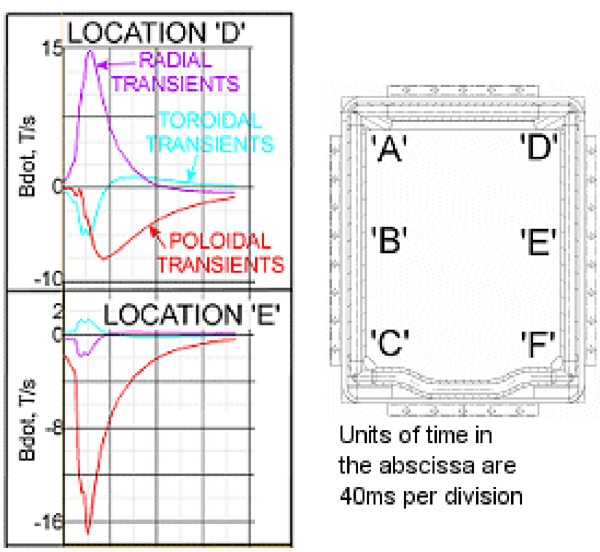

Fig. 6. Indication of the time variation of the components of the magnetic flux at two locations near the front of an equatorial port plug, for an example disruption scenario. The right hand figure is a view of the port plug from the plasma side.

The field transients associated with this example are illustrated in Fig. 6 for two locations. These findings are important because they quantitatively demonstrate that large internal forces and torques can be generated in the port plug, whereas the net values outside the structure are much lower. This has important implications for the strength of the internal components.

For equatorial ports, the worst case is a disruption with linear current decay, in a plasma without a VDE. For a constant position plasma, linear decay induces larger torque than exponential decay, and 20% higher than in a linear decay VDE. For a VDE, exponential decay induces 4% larger torque than linear decay.

V. CONCLUSIONS

A new concept for the design of an equatorial port plug has been presented, and it has been recognized that the electromagnetic effects on the port plug dominate the structural requirements.

A new EM model has been generated using ANSYS. It includes active components of the currents in coils and in the plasma itself. Benchmarking confirms good agreement with other EM models. Radial torque is the dominant factor for the port-plug loading, while the other factors look negligible. The details of the internal structure are important. The outer shell gives the largest contribution to torque, but the contents are also very significant and it is found that the internal forces are large compared with the total force on the port. The materials in the port plug have to be chosen very carefully

Future work will concentrate on analysis of the contents of the port plug, allowing optimized designs to be reached.

ACKNOWLEDGMENTS

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