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Ph. Chappuis, C. Damiani, C. Guerin, F. Hurd, A. Loarte, P. Lomas,
A. Lorenz, J. Paméla, A. Peacock, C. Portafaix, J. Rapp, V. Riccardo,
F. Rimini, G. Saibene, J.F. Salavy, Y. Sauce, E. Solano, E. Thomas,
P. Thomas, E. Tsitrone and M.P. Valeta

The Design of a New JET Divertor for High Triangularity and High Current Scenarios

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Ph. Chappuis[1], C. Damiani[2], C. Guerin[3], F. Hurd[4], A. Loarte[4], P. Lomas[5], A. Lorenz[2], J. Paméla[2], A. Peacock[4], C. Portafaix[1], J. Rapp[2], V. Riccardo[5], F. Rimini[1], G. Saibene[3], J.F. Salavy[3], Y. Sauce[3], E. Solano[2], E. Thomas[1], P. Thomas[1], E. Tsitrone[1] and M.P. Valeta[3]

[1] *Euratom-CEA Cadarache, CEA/DSM/DRFC, 13108 St Paul lez Durance, France*
[2] *EFDA-JET CSU-Culham, OX14 3DB Abingdon, UK*
[3] *CEA/DM2S, Saclay, 91191 Gif sur Yvette, France*
[4] *EFDA, CSU-Garching, IPP, Boltzmann Str 2, 85748 Garching, Germany*
[5] *Euratom-UKAEA/Fusion, Culham, OX14 3DB Abingdon, UK*

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ABSTRACT.

A new divertor (MKII-HP) has been designed to be implemented in JET as part of a possible enhancement programme of the JET facility (JET EP). The aim is to handle up to 40 MW of injected power during 10 s with plasma triangularities up to 0.5 while keeping enough flexibility for other scenarios. The divertor is shaped to optimise the wetting fraction without exposing sharp edges or metallic parts and the general design allows for high halo currents.

1. INTRODUCTION

A new divertor (MKII-HP) was designed to be implemented in JET as part of a possible enhancement programme of the JET facility (JET EP). The purpose of the enhancement would be to further prepare the ITER operating phase and support key design choices, in particular with regard to ELMy H-mode operation in ITER-like configurations (high triangularity) at high plasma currents.

The JET Enhancement proposal included an increase of the additional heating power to a level of approximately 40MW in particular with the addition of a new ECRH and ICRH systems. The full exploitation of these auxiliary systems would necessitate an improvement in the power handling of the JET divertor.

The new divertor has therefore been designed to effectively achieve the objectives of the enhancement proposal in terms of plasma physics and technology.

2. DIVERTOR PHYSICS & REFERENCE SCENARIOS

In high power, ELMy H mode plasmas, the average triangularity eases the access to high confinement and density regimes and therefore is foreseen as one of the key parameter for the ITER performances. JET is the unique machine able to reach plasma parameters relevant for this next step machine and to study the tritium related technology. The axisymetric gas box divertor installed in the vessel is limited in power handling capacity for high triangularity discharges.

The physics program for JET EP has generated 18 reference scenarios which belong to 3 families: high triangularity; low triangularity; and advance tokamak. From these 18 a set of 4 high priority equilibrium were selected and are the bases for the divertor design (Figure 1).

3P5MA_HD

This configuration has an average triangularity of 0.5 and is the basis for the matched triangularities to ITER (bottom triangularity of 0.56 and top triangularity of 0.42).

4MA_HD2

This configuration has the highest average triangularity (0.49) one can achieve at 4 MA within the forces on the TF-coils.

2P5MA_HDHB, $\beta_{pol} = 2.5$

This configuration will be used to test the influence of the triangularity on the performance of an ITB discharge. Furthermore in the view of ITER, the steady state of a high β_{pol} ITB discharge has to be demonstrated.

4MA_OS (#47413 LIKE)

This extreme configuration was used in DTE1. Because of the high current it will also be used in a potential DTE2 campaign to study alpha particle confinement. Investigation of AT scenarios will be exploring triangularities and plasma current ranges.

In JET the lower triangularity is mainly limited by the divertor shape and optimisation of the profile can increase the power handling capacity. For flexibility, the divertor has also to be designed to cope with scenarios allowing the studies of high β_N and q plasmas or NTM stabilities and ITBs. To maintain the high plasma performances, the divertor has to keep a pumping capability identical to MKIIA Figure 2.

3. TILES DESIGN

The divertor profile (Figure 3) is optimised to shadow all structural elements and tile faces from close to normal particle flux. The principle is shown on Figure 4.

The dome apex is designed to allow the extreme strike points to reach the transition area permitting reverse flow from the private zone to strike reasonably this area.

The corner tiles have a poloïdal angle optimised for pumping and shadowing.

To prevent the illumination of any edge by very high power and shallow impinging flux tubes, the divertor tile faces are tilted in the toroidal direction with an angle calculated from the magnetic equilibrium analysis after taking in account a factor deduced from the lowest q ratio and from the maximum tolerances on the tile gap (Figure 5).

Power handling performance of the inertially cooled CFC armour tile was calculated considering a 1800ºC limit on carbon surface and a stress limit on the Inconel attachments. The maximum pulse length for the high priority scenario (Table I) satisfy the project requirements.

Mechanical analytical and finite element calculations (with the code CAST3M) have been performed to evaluate displacements and stresses in the tiles and in the carriers due to Eddy and Halo currents during disruptions and downward Vertical Displacement Event (VDE).

Table I: Maximum pulse length for the high priority scenario with 40 MW of injected power

Config	*Max average flux*	*Critical time*
3.5MA_hd (workhorse high δ)	8.4 MW/m^2	10.1 s
4MA_hd2 (higher I_p high δ)	8.12 MW/m^2	10.8 s
2p5MA_hdhb (advanced scenario)	5.9 MW/m^2	19.9 s
4MA_OS_swp15 (optimised shear)	8.18 MW/m^2	10.0 s

The halo current which flow in the tile through the carrier to the support structure is assumed as 30% (f_p) of the maximum plasma current (I_p) and the toroidal peaking factor (TPF) as 1.4 for downward disruptions according to the measurements.

The pads are electrical insulated and the current flow through the bolt to the carrier.

The eddy currents are calculated assuming a poloidal change of rate of 100T/s and a poloidal field of 1T.

A complete calculation was done on tile N°6, considered as the most critical, assuming a tile temperature gradient maximised by a long pulse and a disk spring preload equivalent to the maximum electro-dynamical force.

In all cases the stresses in the tile and the attachments remain acceptable. The analysis of the displacements show that the systems remains stable.

4. CARRIERS DESIGN

The carriers are the elements interfacing the tiles and divertor structure, they are aimed to maintain the tiles in a precise position and to carry the diagnostics. The toroidal distribution in 24 modules of wide & narrow carriers follows the vessel organisation. The divertor is installed by remote handling due to the high level of contamination (Tritium) of the vessel. Therefore weight limitation and space envelop free movement have induced a poloidal decomposition in 4 pieces (see Figure 6). Toroidally a wide and narrow pattern allows to have neighbouring tiles sit on the same pads which ensure a very tight surface alignment.

The design has been optimised for a casted preferred solution (allowing alternatives) and a prototype has been manufactured to check the quality and the material properties (Figure 7).

The electromechanical disruption stresses are calculated (Figure 8) as for the carbon tiles and are within the Inconel 625 properties. The carriers support the divertor diagnostics which are connected to the JET network through remote hand-able plugs. To simulate diagnostics installation & cabling, a set of wide carriers were manufactured by rapid prototyping (Figure 9).

5. DEVELOPMENTS

To validate the 3 D shadowing of any divertor component and provide design tools for thermal and thermomechanical calculation, a field lines tracing code has been developed (Figure 10).

A new high performance carbon material (Aerolor A035) was evaluated on the NBI test bed. This material (3^{rd} direction) could prevent the use of tie rods (necessary in the 2D material avoiding the delamination). High heat flux testing, up to 20 MW/m^2 and fatigue testing at 15 MWm^2 has demonstrated equivalent performance to the Dunlop 704 material.

CONCLUSIONS

A new Mark II divertor has been designed for the JET EP enhancements allowing ITER relevant plasma configurations. The designed performance allow flexibility for operation with the JET full performance.

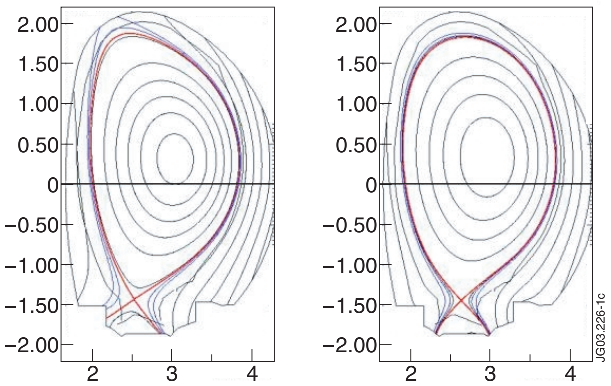

Figure 1: 3.5 MA_hd & 4 MA_OS plasma configurations.

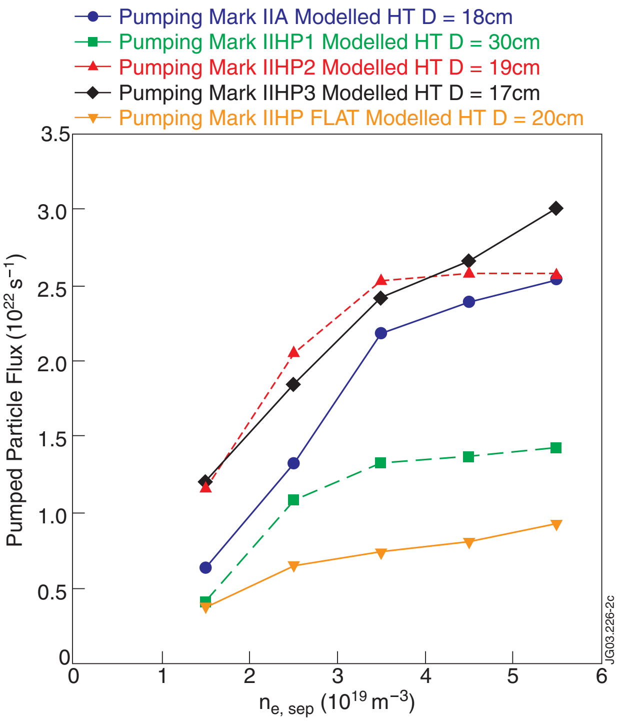

Figure 2: Comparison of pumping performances for various divertors.

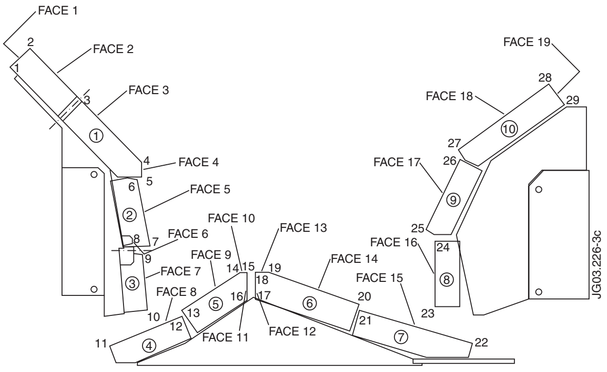

Figure 3: Divertor poloidal profile.

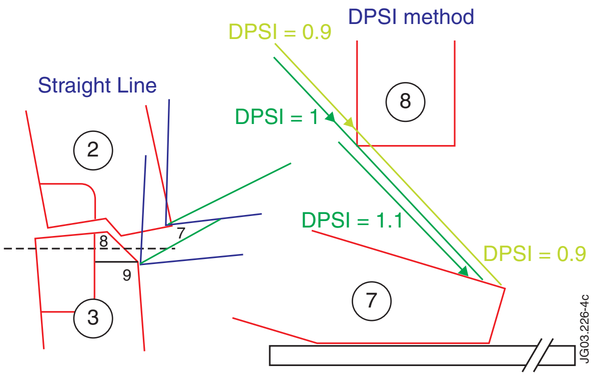

Figure 4: Methods for poloidal shadowing (straight line approximation and DPSI method).

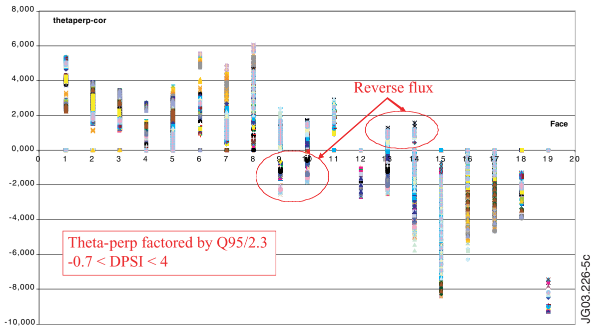

Figure 5: Toroidal flux tube angles (θ_{perp}).

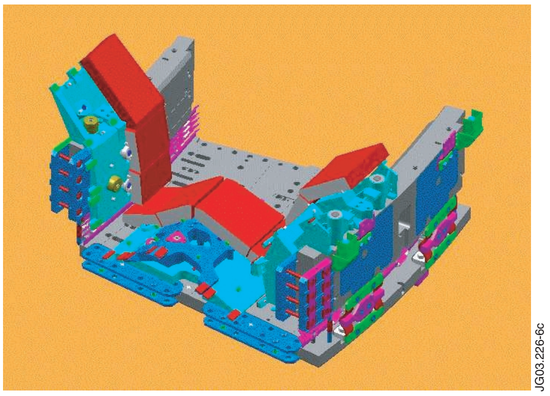

Figure 6: Model of 6 carrier.

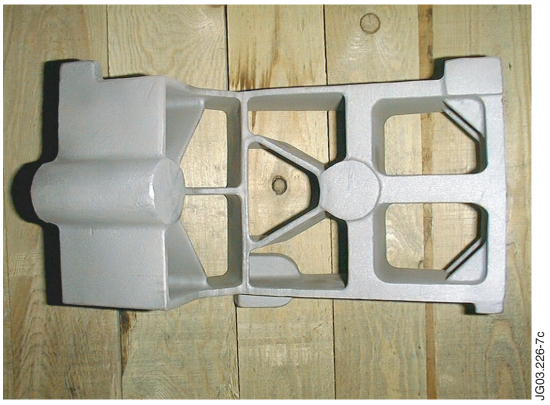

Figure 7: Vacuum castem and Hipped prototype of an Inconel 625 divertor carrier.

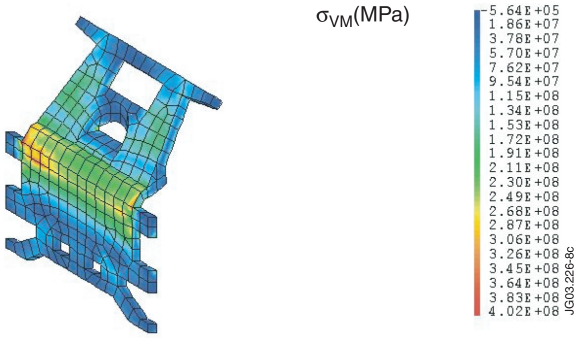

Figure 8: Von mises stresses in the inner carrier.

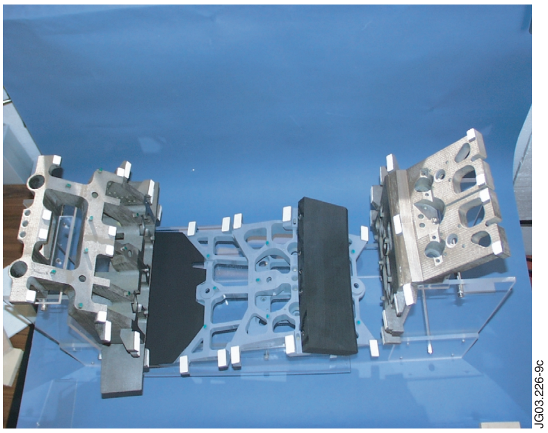

Figure 9: Wide carriers prototypes manufactured by rapid protyping.

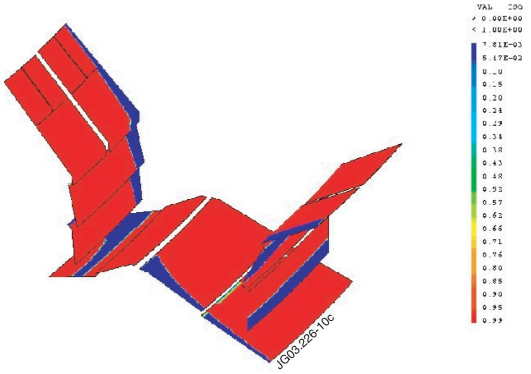

Figure 10: Shadowed (blue) area calculated by field line tracing.