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Physics Analysis of Divertor Modifications in ITER

A.S. Kukushkin[1], H.D. Pacher[2], V. Komarov[1], M. Merola[1],
V. Kotov[3], D. Reiter[3], G.W. Pacher[4]

[1] *ITER Organization, Cadarache, France;* [2] *INRS-EMT, Varennes, Québec, Canada;*
[3] *FZ Jülich, Jülich, Germany;* [4] *Hydro-Québec, Varennes, Québec, Canada*

In the course of the ITER design review it was found that the divertor dome as originally designed imposes severe requirements on the accuracy of the plasma position control system. Taking into account previous modelling results [1], an alternative design with a somewhat smaller dome shifted away from the separatrix, (F53, Fig. 1), which tolerates larger excursions of the separatrix branches, was proposed, and a series of B2-Eirene (SOLPS4.3) code runs was performed to determine the implications of these modifications for the divertor performance. Moreover, further analysis of the ITER magnetic system and current experimental data revealed a concern that the reference x-point position might not be attainable if the plasma current profile were flatter, $l_i \cong 0.65$, than the reference case (0.85) and that then the separatrix would strike the dome. Accordingly, a dedicated design effort developed a divertor configuration accommodating a wider range of magnetic equilibria, achieved by a further reduction of the dome and an outward shift of the inner target. The inner divertor is then somewhat shorter and the wetted area there smaller, which could in turn have a detrimental effect on the power loading (particularly with impurity seeding, see below). In order to explore this effect quickly, we selected a rather extreme design variant where the inner target was displaced outwards by as much as 20 cm, (F55, Fig. 1), and examined two configurations: the reference equilibrium with $l_i = 0.85$ and a flat-current equilibrium with $l_i = 0.63$. The modelling parameters were the same as in [1]. Fluid equations are solved for the transport of ions and electrons (B2), and the neutral transport part (Eirene) employs a non-linear Monte-Carlo modelling taking into account the neutral-neutral collisions together with elastic collisions between the neutrals and ions and the most essential molecular interactions with ions. The Monte-Carlo algorithm now allows multi-processor parallel execution in the MPI environment. The plasma consists of D (representing both D and T), He, and C ions and atoms and D_2 molecules. Molecular fuel is puffed in at the top and pumped out from the bottom with a moderate outflow of D ions from the core to simulate the core fuelling. The helium ion source from the core is proportional to the fusion power, the targets are carbon and the walls are assumed to be carbon-covered, and carbon is released from the surfaces by physical and chemical sputtering.

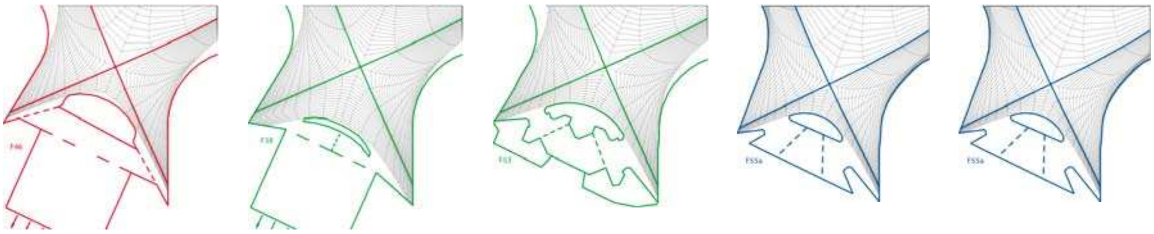

Fig. 1. Dome geometry, left to the right: F46 – the original reference geometry [2]; F38 – reduced dome used in [1]; F53 – smaller dome; F55 – shifted modified dome and inner target, flat current equilibrium l_i = 0.63; the same F55 with reference plasma equilibrium. Dashed lines show partially transparent structures giving access to the pump ducts.

Initial results indicate only moderate effects of the dome modification on the peak power loading of the targets and on the helium pumping. Fig. 2 shows the results as a function of the normalised neutral pressure in the divertor, μ ([3]; full inner divertor detachment is at $\mu = 1$). Since for the flat-current case, detachment of the inner divertor is found to occur at a 30% lower neutral pressure, μ is increased correspondingly for that case so that the detachment state of all cases is the same. The peak temperature at the inner divertor is then the same for all cases (Fig. 2). As shown in Fig. 2, the peak power loading for the standard equilibrium with l_i = 0.85 decreases as dome size decreases (F38 and F53) and then decreases further (F55). (For the latter case, the power load, usually maximum on the outer divertor, actually peaks on the inner divertor.) For the flat-current equilibrium, the peak power load is higher, but similar to the original dome F46 (Fig. 2). The proposed modification therefore has no adverse effect on the operational flexibility of the ITER divertor as concerns the power load.

The effect of the proposed divertor modification on the core plasma fuelling and helium removal is also shown in Fig. 2. The DT ion density at the separatrix, although some 20% higher than for the original divertor, is lower than for the smaller dome F38, and a strong density gradient in the pedestal region is still required to provide the necessary plasma density in the core (~ 10^{20} m^{-3}). The variation of the neutral particle influx across the separatrix is minor and the influx remains small in magnitude, 20-30 Pa-m^3/s. Since this is insufficient to fuel the core (which requires > 100 Pa-m^3/s [4]), the need for extra core fuelling is unchanged with the modified divertor. The conditions for helium removal (separatrix density and neutral influx) become worse by a factor 2-3 for the modified divertor with the reference equilibrium (Fig. 2), a smaller deterioration than for the complete dome removal discussed in [1]. Nevertheless, the helium level remains low (edge density <10^{18} m^{-3}, neutral reflux < 1 Pa-m^3/s) so that, as demonstrated by integrated modelling of the core plasma performance in ITER [4, 5], the resulting helium level in the core is low and therefore this increase of the helium does not degrade the ITER operation significantly. On the whole, the proposed divertor modification fits the qualitative picture developed in [1]: a reduction of the dome renders the divertor more in-out symmetric, which is beneficial for the peak power loading on the targets but somewhat detrimental for helium removal.

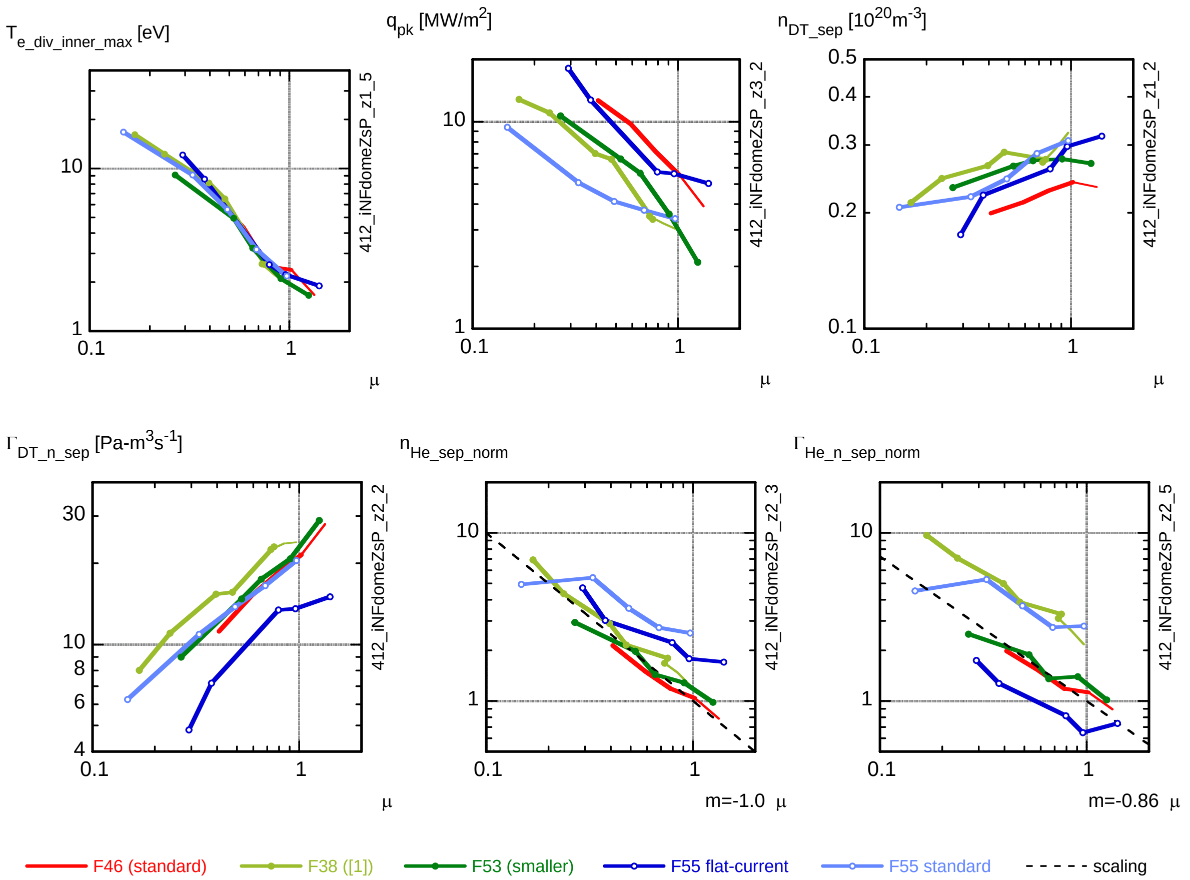

Fig. 2. Modelling results vs. normalized neutral pressure under the dome, μ [3], for the divertor geometries considered: (a) maximum temperature at the inner divertor target (b) peak power loading of the targets; (c) average fuel ion density at the separatrix; (d) fuel neutral influx to the core; (e) average helium ion density at the separatrix; (f) helium neutral influx to the core. The helium data are normalized to the helium production rate and pumping speed [3]. Data for a previously studied variant F38 are added to show the progression.

Analysis of the radiation load on the dome-supporting structures indicates that the power density there can reach 0.4 MW/m^2, Fig. 3, and this requires special design considerations. For this analysis, three operational points for the modified (F55) divertor were selected, corresponding to the low, medium, and high neutral pressure in the divertor. Then the radiation load on the structures in the PFR was calculated using the radiation source distribution calculated with the B2-Eirene code and taking into account shadowing by the dome and reflector plates.

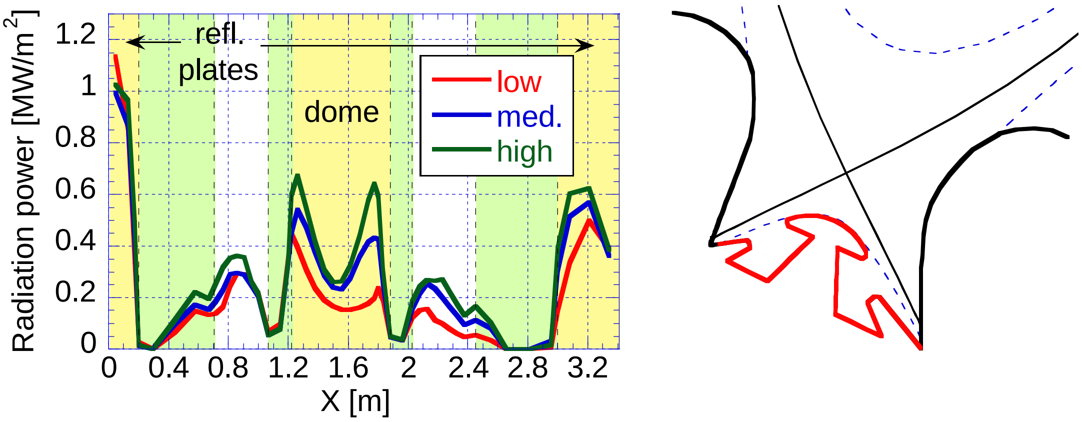

Fig. 3. Left: radiation power loads on the structures in PFR for the modified dome F53 for three operational points: at low density, intermediate, and near the high-density limit (full detachment) of the operational window. Right: Geometry layout for the evaluation of the radiation. The loads are given along the contour marked red, with x=0 at the inner divertor. The separatrix and the limits of the computational grid are also shown.

An important subsequent modification of the ITER divertor will be the transition to a tungsten target, which is now considered the baseline option for D-T operation. This will then require abandonment of carbon as the main radiator and introduction of a seeded impurity such as neon. A study of the operational window for carbon-less operation of ITER with the original divertor geometry was reported in [3]. It was found, in particular, that when the neon concentration at the separatrix exceeds the 0.5% level, the maximum peak power loading takes place at the inner divertor, albeit at a 30% lower level. Since our divertor modification involves a reduction of the plasma wetted area on the inner target, this can be an important factor in the design selection.

The design studies presented here are evolving towards a final (less shifted) profile for the divertor which satisfies both re-evaluated (somewhat less stringent) equilibrium control requirements and meets divertor performance goals. Further simulations are in progress, and it is expected that a decision on the first divertor design can be made soon.

This report was prepared as an account of work by or for the ITER Organization. The Members of the Organization are the People's Republic of China, the European Atomic Energy Community, the Republic of India, Japan, the Republic of Korea, the Russian Federation, and the United States of America. The views and opinions expressed herein do not necessarily reflect those of the Members or any agency thereof. Dissemination of the information in this paper is governed by the applicable terms of the ITER Joint Implementation Agreement.

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[5] G.W. Pacher, H.D. Pacher, A.S. Kukushkin, G. Janeschitz, this conference