Divertor Performance in Reduced-Technical-Objective/Reduced-Cost ITER

A. S. Kukushkin, H. D. Pacher[a], G. Janeschitz, D. Coster[b],
D. Reiter[c], R. Schneider[b]

ITER Joint Central Team, Garching Joint Worksite, Garching, Germany
[a] EFDA CSU, Garching, Germany; [b] Max-Planck IPP, Garching, Germany;
[c] FZ Jülich, Jülich, Germany

The possibility of reducing the ITER machine cost without changing the overall programmatic objectives by a reduction of the size (including divertor size) and the fusion power is currently being analysed by the JCT and the Home Teams. Increased plasma triangularity could improve the confinement but creates a second x-point near the top, leading to higher power loading near the strike points of the outer separatrix. Initial studies of the effect of size reduction on divertor performance using the B2-Eirene code package are presented for various design options (Fig. 1). The power entering the edge plasma ranges from 100 MW to 150 MW, and the same assumptions are used for the transport coefficients as previously [1]. The plasma consists of D-T (represented by D in calculations), He, and C ions. The He density at the innermost closed flux surface is specified at first, and then adjusted to yield a throughput equal to the helium production rate. The pumping duct is located below the dome in the private flux region (PFR). Physical and simplified chemical sputtering at the lower targets provide the source of C [1]. The operation window results are summarized below mostly in terms of power load vs. density and helium concentration vs. particle throughput.
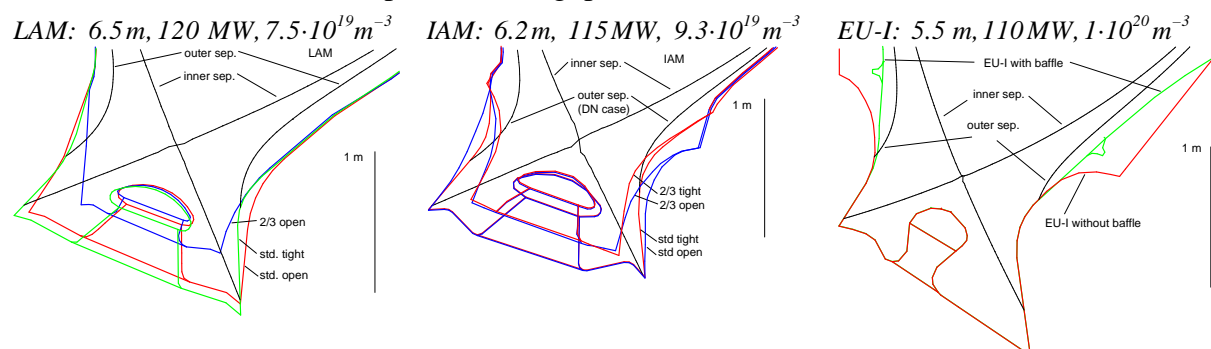
LAM: 6.5 m, 120 MW, 7.5·10^{19} m^{-3}   *IAM: 6.2 m, 115 MW, 9.3·10^{19} m^{-3}*   *EU-I: 5.5 m, 110 MW, 1·10^{20} m^{-3}*

Fig. 1a. Design options of ITER divertor with vertical targets and their variations considered in the present paper. The plasma major radius, R, and nominal values of the power entering the edge plasma (P_{in}) and the line-average density (n_{av}) are also given (cf. R = 8.1 m, P_{in} = 200 MW and n_{av} = 1·10^{20} m^{-3} for the FDR ITER [2])

In the Monte-Carlo code used to calculate neutral particle transport, pumping is simulated by absorbing equal fraction of all particles at the duct entrance. This results in different pumping speeds for DT and He, probably because the neutral-neutral collisions which could equilibrate the neutral pressure in the PFR are not yet taken into account and geometric effects are therefore more pronounced. For ITER parameters, the helium-related quantities *(n_{He}, p_{He}, Γ_{He})* can approximately be scaled linearly together [3], because the edge helium concentration is relatively low and the reaction rates and radiation emissivity are not high, so that He-He interactions and He effects on the rest of the plasma can be neglected. The helium throughput is therefore adjusted to match the

Fig. 1b. LAM standard as above and flat target

fusion power with the correct ratio of pumping speed for helium and for the fuel gas, yielding the upstream helium density.

The <u>design options</u> are the variants presently being considered: LAM ("Low Aspect Machine"), IAM ("Intermediate Aspect Machine") and EU-I ("European IAM") (Fig. 1).   The peak power load on the divertor, shown in Fig. 2a compared to FDR ITER [4], is similar at the same density for all FDR and RTO/RC ITER versions. The variation of the order of 20% can result
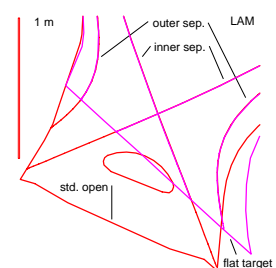
from differences in detail of the geometry (e. g., angle – see below). Note that 60 to 70 % of the input power is radiated in these cases. The resulting helium concentration at the core edge is plotted as a function of the peak power in Fig. 2b. The limits for these quantities are also indicated there, showing that all the devices have a finite operating window in this space, provided the correct upstream density is set. IAM is first limited by c_{He} whereas EU-I and LAM are first limited by peak power.
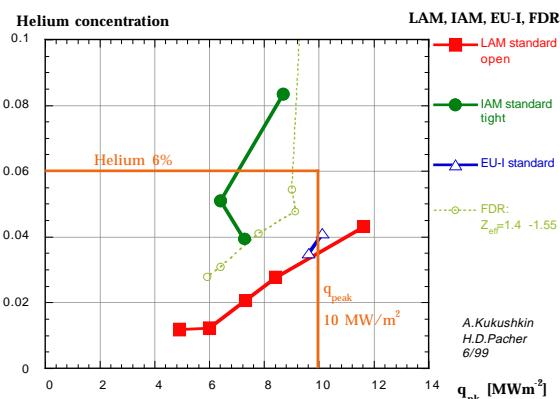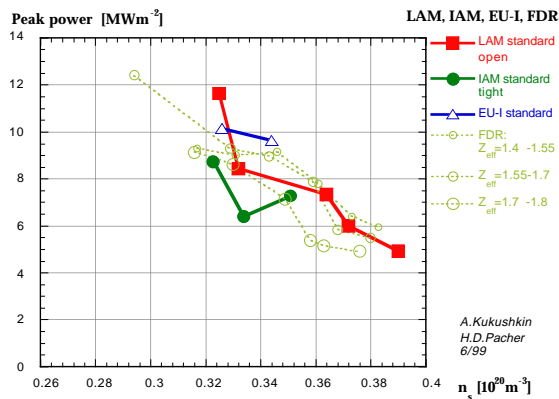

Fig. 2a. Peak power load on the divertor for RTO/RC and FDR ITER options vs. upstream density

Fig. 2b. Helium concentration at the core-edge interface vs. peak power load

Effect of a double null. To see the sensitivity of the divertor operation to the up-down asymmetry of the divertor configuration, density scans have been done for three LAM equilibria differing by the separation of the two separatrices in the outer mid-plane, Δ_{sep} (3, 2, and 1 cm). The power delivered by particles to the top divertor surfaces naturally increases with a decrease of the Δ_{sep} value, becoming significant at $\Delta_{sep} \approx 1$ cm, Fig. 3a (this value will however be sensitive to the assumptions on the cross-field transport). The peak power to the bottom target first increases as Δ_{sep} is reduced, then decreases (Fig. 3b). This can be explained as the result of two competing effects: when the configuration becomes more symmetric, the top divertor takes part of both the power and the particles from the bottom one. The reduction of particle flux reduces the carbon influx (in the calculations, only the bottom plates are carbon) and thus the total radiated power, and appears before the reduction of power since the density profile is normally broader than the energy profile. Peak power loading of the top divertor target remains below 2 MW/m² for $\Delta_{sep} \geq 1$ cm. When $\Delta_{sep} \geq 3$ cm, the power load on the top is similar to that on the first wall.
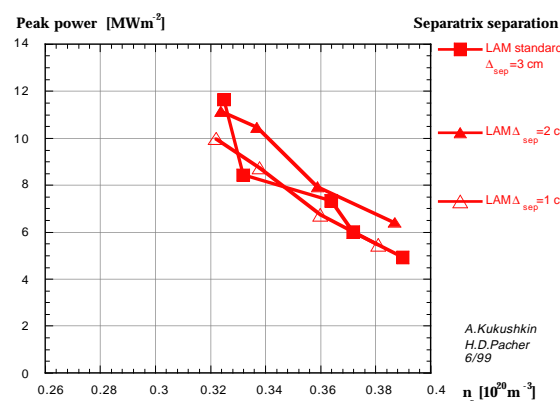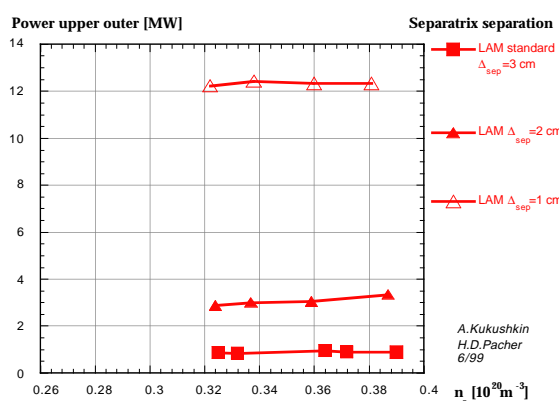

Fig. 3a. Total power delivered to the outer upper divertor target by the particles vs. upstream density for different separatrix separation: $\Delta_{sep} = 3, 2,$ and 1 cm

Fig. 3b. Peak power vs. upstream density for different separatrix separation

A *variation of the input power* was done for LAM. In addition to the standard value of P_{in} = 120 MW, a density scan for 100 MW and one point for 150 MW (corresponding to P_{fus} = 700 MW at $Q = 10$ or 1000 MW at ignition) were calculated. The higher powers require

higher density for acceptable heat loads and helium fractions, which may be counteracted in part by increasing the edge radiation (Fig. 4a and b).
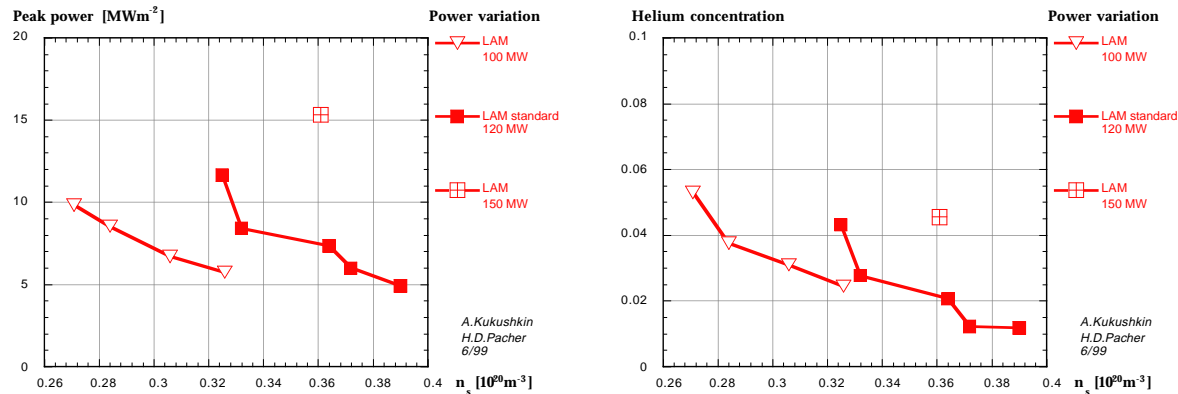

Fig. 4a. Peak power load vs. upstream density for different values of the input power

Fig. 4b. He concentration upstream vs. upstream density for different values of the input power

A *divertor length variation* (see Fig. 1) was done for the LAM and IAM options, as well as for the FDR ITER [4], to see the consequences of shortening the divertor. The shape of the divertor targets was modified so as to keep the "wetted area" near the separatrix strike point approximately the same. The variation of the peak power loads on the outer and inner targets is shown in Fig. 5. Whereas in LAM the peak load on the outer target is rather insensitive to this change, both FDR and IAM show a considerable increase of this crucial parameter with a shorter divertor. However, the radiated power remains the same. In LAM, we also see an increase of the peak power load at the inner divertor target. The reason for such different behaviour of the LAM, FDR, and IAM divertors is not yet clear, but this indicates the increasing risk of unacceptable conditions on the targets if the divertor were shortened.
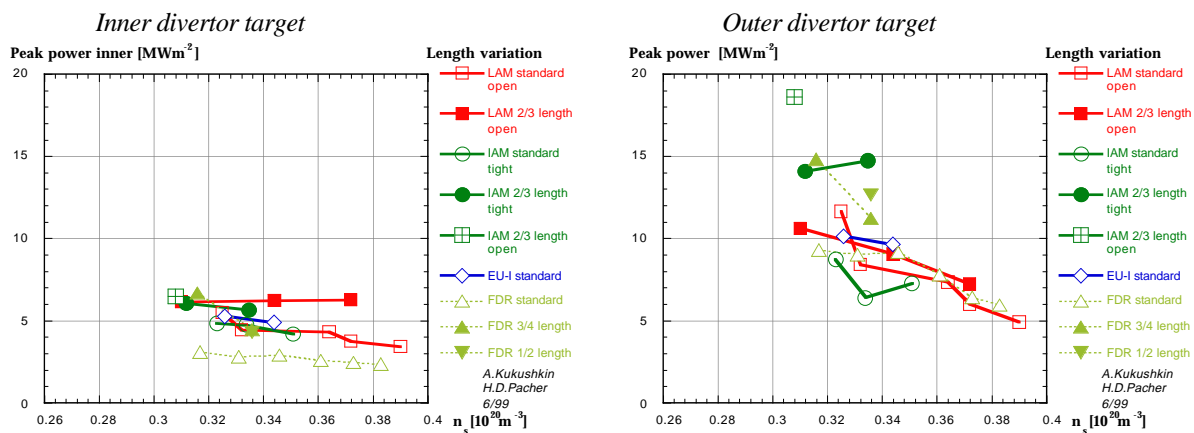

Fig. 5. Variation of the peak power load on the targets with upstream density for different divertor length

The helium concentration upstream is found to depend mostly on the DT throughput, Fig. 6. This gives a lower boundary of 200 Pa·m³/s (with necessary margin) for the DT throughput to provide $c_{He} \leq 6\%$. Changes in the pumping speed, target angle, or power (not shown here) do not change the curve but changes in geometry do (Fig. 6).

The *effect of the baffle* was studied for the EU-I case (Fig. 1), and no variation of peak power loads or helium concentration was found when the baffle was removed. For a partially attached plasma, the recycling in the outer part of the SOL is low and so is the density of neutrals there, and therefore the baffle has little effect. If these results are confirmed, a significant cost reduction could result from simplification of the first wall baffle modules.

A *variation of target angle* to the magnetic surfaces was performed to optimise the divertor shape for LAM and IAM. For IAM, the beneficial effect of a smaller grazing angle is weak, and for LAM, it is even reversed, Fig. 7. With the tight divertor, the carbon concentration in the

plasma decreases, despite a higher sputtering source. It is not yet clear whether this is related to the ion or to the neutral transport.
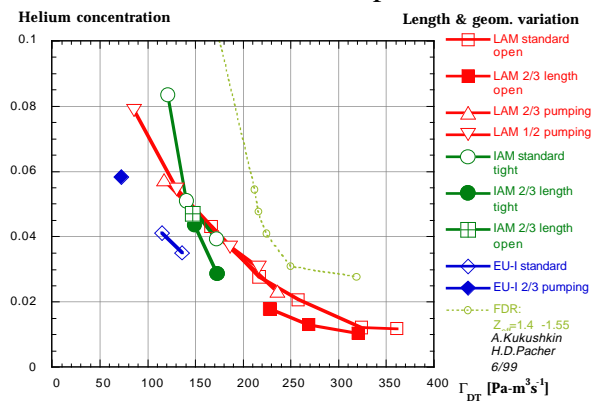

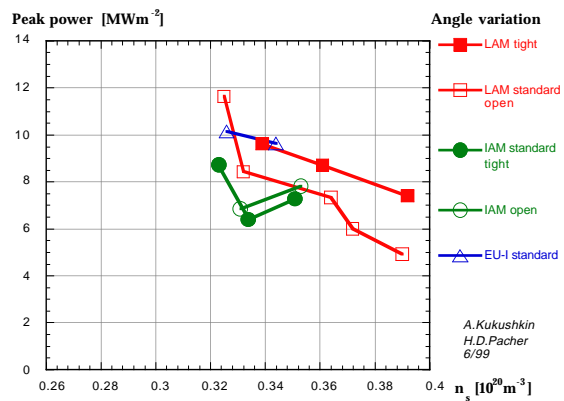Fig. 6 He concentration upstream vs. DT throughput

Fig. 7. Variation of the peak power with target inclination

A *flat target* option without a dome and with an outwardly slanted target in the region of the flux expansion close to the x-point, Fig. 1b, was also considered for the LAM parameters. This geometry favours complete detachment at rather low densities, Fig. 8a. However, the particle source due to ionisation inside the separatrix is a factor 2 higher than for the vertical target options for attached plasma at the same peak power, Fig. 8b. When the plasma detaches, this source becomes unacceptably high, even above the gas puffing rate.
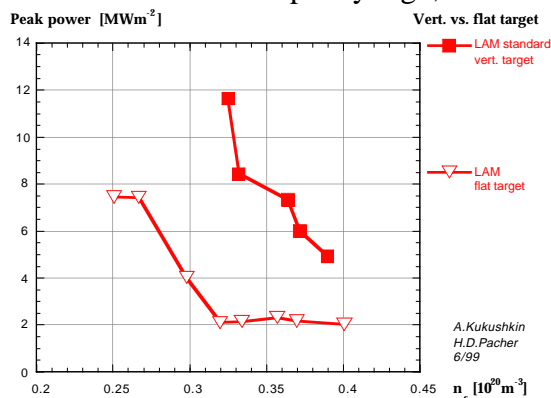

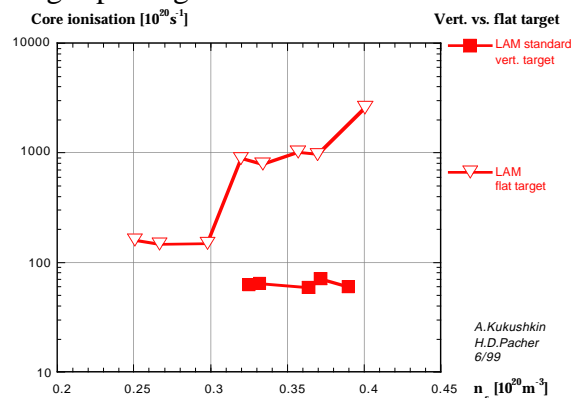Fig. 8a. Peak power load vs. upstream density for the vertical target and flat target LAM

Fig. 8b. Ionisation DT source in the core vs. upstream density for vertical target and flat target LAM

Conclusions

The peak power loading of the divertor targets for the different variants of the reduced size machine can remain in the same range of 5 to 10 MW/m^2 for the same range of the upstream plasma density (3.3 to 3.8·10^{19} m^{-3}) as in FDR ITER. This favours devices such as IAM and EU-I which have a higher Greenwald density and a higher operating density for steady state. It can be lowered by a moderate reduction of the input power. Power loading at the top should not be a problem as long as the outer separatrix remains more than 2 cm outside the inner one in the outboard mid-plane. The relative helium concentration upstream increases as the DT particle throughput is reduced, yielding a minimum value of 200 Pa·m^3/s with margins for the particle throughput. Tight baffling may be unnecessary because of the high screening efficiency of the plasma for these conditions. Shortening the divertor noticeably increases the risk of excessive power loads. Further modelling is required to optimise the divertor shape.

References
[1]   A. S. Kukushkin, H. D. Pacher, D. P. Coster, et al. 17th IAEA Fusion Conference, Yokohama, 1998
[2]   Technical Basis for the ITER Final Design Report, Cost Review and Safety Analysis (FDR). IAEA, Vienna, 1998.
[3]   S. I. Krasheninnikov, A. S. Kukushkin, and T. K. Soboleva, Nucl. Fusion **31** (1991) 1455.
[4]   H. D. Pacher, A. S. Kukushkin, D. P. Coster, et al. J. Nucl. Mater., **266–269** (1999) 1172.