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Analysis for shaping the ITER first wall

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ABSTRACT

A fundamental difference between ITER and present devices is the need to shield against 14 MeV neutrons. This has major consequences for plasma start-up/rampdown (su/rd) and also for protecting the first wall from plasma contact. This has led to design decisions: (a) not to place in front of the *n*-absorbing blanket a separate wall-limiter structure, (b) to modularize the blanket into ~400 remote handling compatible blanket modules (BM), and (c) to shape the front face of the BMs for plasma contact. Combined protection-su/rd options are considered here for the inner and outer wall with regard to optimal shaping. Unfortunately, the modularity of the BM system (inter-BM gaps and misalignments) requires shaping of the BM faces that increases peak power loads by ~10× relative to the ideal (continuous, circular) wall-limiter. Fortunately, the level may still be acceptable, ~2 MW/m^2, even for su/rd power of 7 MW.

1. Introduction

A fundamental difference between ITER and present devices is the need to shield against 14 MeV neutrons. This has major consequences for the ITER strategy for plasma start-up and rampdown (su/rd) and also for protecting the first wall from plasma contact. To the degree possible, the ~0.4 m thick neutron-absorbing blanket should be in front of all other structure and it must be repairable by remote handling (RH). This has led to the design decisions: (a) not to place in front of the blanket a separate wall-limiter structure akin to that in present tokamaks, (b) to modularize the blanket into ~400 RH-compatible blanket modules (BM), each ~1.5 m wide toroidally and ~1 m wide poloidally, and (c) to shape the front face of the BMs to be able to handle plasma contact. In the existing ITER design su/rd is dealt with separately by two movable port limiters which can be inserted radially inboard of the BM faces; however, since the BMs have to be designed to handle plasma contact anyway, it may be advantageous to design a BM system which also provides for su/rd. Such combined protection-su/rd options are considered here for the inner and outer wall (IW, OW) (Fig. 1) with regard to the issue of how to shape the BM face in order to: (a) minimize the peak deposited power flux density on the front face, $q_{\text{dep-face}}^{\text{peak}}$, while (b) ensuring that the BM edges are protected either by next-neighbor shadowing or by using sufficiently large set-backs of the edges that the peak deposited power flux density to any exposed BM edge, $q_{\text{dep-edge}}^{\text{peak}}$, is less than some required value, e.g., 0.1 MW/m^2.

Unfortunately, the modularity of the BM system significantly increases $q_{\text{dep-face}}^{\text{peak}}$ because of: (a) the Δ_{gap}, clearance gaps required around each BM (Δ_{gap} = 15–20 mm at most locations but equals the entire toroidal width of one BM at the outside midplane due to the 18 ports), and (b) the radial misalignment, Δ_{mis}, of one BM relative to another, which is up to 5 mm. This requires significant shaping of the BM face to protect the edges at the gaps, which causes the wall-limiter surface to depart substantially from the ideal one for power handling. The latter is a continuous surface conformal to the last closed flux surface (LCFS) at the midplane. It will be shown that this required shaping increases $q_{\text{dep-face}}^{\text{peak}}$ by an order of magnitude relative to the ideal. Fortunately, however, the absolute magnitude of $q_{\text{dep-face}}^{\text{peak}}$ may still be acceptable, ~2 MW/m^2, even for su/rd total power to the surface, P_{surface}, up to ~7 MW. Based on the recent assessments of Loarte, et al., [1], the plasma conditions in Table 1 are taken here to apply to su/rd in ITER.

2. Analysis procedure

The shape of the BM face is assumed here to be given by $x_{\text{BM}}(t,p) \equiv f_{\text{BM}}(t) + g_{\text{BM}}(p)$ where $f_{\text{BM}}(t)$ and $g_{\text{BM}}(p)$ are specified BM shape functions (or their equivalent, see below). The coordinate system is rectilinear with origin at the center of a specified BM face. The toroidal (poloidal) coordinate t(p) is in the toroidal (poloidal) direction tangential to the BM surface at (t,p) = (0,0). The 3rd coordinate, x, is orthogonal, pointing into the face. Closely related to x is the distance between the LCFS and the limiter surface which is approximated here by $\delta(\text{t,p}) = f(t) + g(p)$ where $f(t) \equiv f_{\text{BM}}(t) - f_{\text{plasma}}(t)$ and $g(p) \equiv g_{\text{BM}}(p) - g_{\text{plasma}}(p)$. This approximation involves small errors (of order $\delta^2/\rho_{\text{pp}}^2$, p^4/ρ_{pp}^4 and $t^4/\rho^2 tp$)

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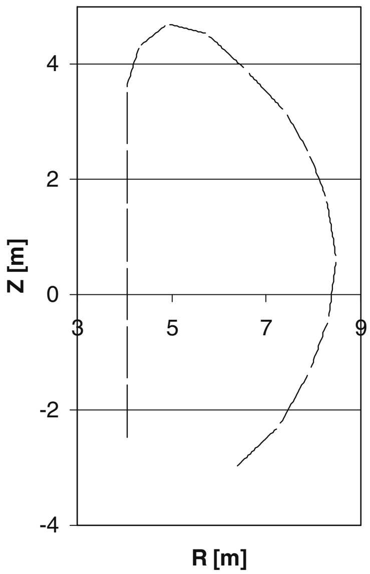

Fig. 1. The ITER Blanket Module (BM) wall system. The BM faces are not shown here as being shaped, although any shaping would be hard to see on this large scale. In the present paper we assume that IW plasmas can be centered vertically anywhere over BMs Nos. 3, 4 or 5, where cw numbering is 1–18 starting at the lower inside. For the outer wall we idealize the actual situation by assuming an imaginary vertical BM at the midplane; IW plasmas are assumed to be centered vertically at the center of the 4th BM. The IW (OW) has 18 (36) BMs in each toroidal row; however, at the OW midplane every 2nd BM is missing to make room for ports. Here it is assumed that all IW BMs are shaped identically. For the OW MP it is assumed that each of the 18 BMs has the same shape, as well as the BMs in the 18 poloidal columns above/below them; the other OW BMs may either be shaped or may be left unshaped but recessed relative to the shaped OW BMs.

relative to the true distance between the BM surface and LCFS, where $\rho_{pp}(\rho_{tp})$ is the plasma poloidal (toroidal) radius of curvature at the plasma MP. This approximation considerably simplifies the analysis and facilitates identification of important dependencies otherwise difficult to discern. For the plasma shape we use the approximation that $f_{plasma}(t) = \pm t^2/(2\rho_{tp})$ where the ($\pm$) sign applies to IW (OW) locations; for ITER $\rho_{tp} \equiv R_{wall} = 8.35$ (4.05) m. For both IW and OW $g_{plasma}(p) = -p^2/(2\rho_{pp})$ will be used. The plasma center is taken to be at ($p = p_{center}^{plasma}$, $x = -\rho_{pp}$) and for IW cases the effect of varying p_{center}^{plasma} is considered.

Since most of the power is in the toroidal direction it is important to optimize the toroidal shape of the BM face, in which case it is preferable to specify $f(t)$ [calculating $f_{BM}(t)$ from it] and then seeking a constraint on $f(t)$ to minimize $q_{dep-face}^{peak}$, while also requiring $q_{dep-edge}^{peak} \leqslant 0.1$ MW/m^2 say. Poloidal shaping is less important and for simplicity we simply prescribe the BM p -shape: $g_{BM}(p) = a_p|p|^m$ where a_p is given by $a_p = \Delta_{set-back}^{poloidal}/\Delta p_{1/2}^m$, with $\Delta p_{1/2}$ being half the poloidal width of the BM and m [dimensionless] and $\Delta_{set-back}^{poloidal}(\equiv g(\Delta p_{1/2}))$ [m] are prescribed shape parameters. For OW locations we assume a straight BM face poloidally, $\Delta_{set-back}^{poloidal} = 0$. Because the OW has poloidal curvature of the same sign as the plasma, the poloidal-facing edge of each BM is well shadowed-protected at the OW by the BMs above/below (even for Δ_{mis} = 5mm), Fig. 1, which are also assumed to be straight poloidally. This is not the case for the IW which is vertically straight and $\Delta_{set-back}^{poloidal} > 0$ is required there to protect the edges, i.e., these edges have to be chamfered, which appropriate choices of m and $\Delta_{set-back}^{poloidal}$ achieve.

The toroidal shape is almost perfectly optimized if $f(t)$ satisfies $e^{-f(t)/\lambda_q}f'(t) = C$, a constant, where λ_q = the specified power decay length (see [2,3] for stronger optimization assumptions). This results in a nearly uniform power loading of the surface, tending to minimize $q_{dep-face}^{peak}$ (which $\sim q_{\|0}C$), where $q_{\|0}$ is the parallel power flux density at the LCFS. Solving this differential equation with $f(0) = 0$ gives:

$$f(t) = -\lambda_q^{design} \ln\left(1 - Ct/\lambda_q^{design}\right), \tag{1}$$

where the superscript 'design' emphasizes that the BM shape has to be fixed at some stage and the effect of off-design values of λ_q^{actual} then needs to be assessed. The value of C is found from the requirement that $f(\Delta t_{1/2}) = \Delta_{set-back}^{toroidal}$, with $\Delta t_{1/2}$ being half the toroidal width of the BM and where $\Delta_{set-back}^{toroidal}$ is specified, thus:

$$C = \left(\lambda_q^{design}/\Delta t_{1/2}\right)\left[1 - \exp\left(-\Delta_{set\text{-}back}^{toroidal}\Big/\lambda_q^{design}\right)\right] \tag{2}$$

This makes clear why it is important to have as long an uninterrupted toroidal span as possible, since $q_{dep-face}^{peak} \approx q_{\|0}(\lambda_q^{design}/\Delta t_{1/2})$ varies inversely with this distance; for the ITER BMs $\Delta t_{1/2} = 0.7$ (0.7187) m for IW (OW), which is long by the standards of present tokamaks.

Ideally there would be no toroidal interruption at all, i.e., the ideal case of, say, an IW which is conformal to the plasma toroidally at the midplane, without gaps or misalignments. In this case the plasma-wetted poloidal extent $h_{wetted}^{pol} \approx 2\sqrt{2\lambda_q\rho_p^{eff}}$ where $1/\rho_p^{eff} = 1/\rho_{pp} - 1/\rho_{pw}$, and ρ_{pw} is the poloidal curvature of the wall or BM face), so that $q_{dep-face}^{peak} \approx P_{surface}/(4\pi R_{wall} h_{wetted}^{pol})$; (it can be shown that $q_{dep-face}^{peak} = P_{surface}e^{-1/2}/(4\pi R_{wall}\sqrt{\lambda_q\rho_p^{eff}})$ precisely). For the IW 7.5 MA su/rd condition, Table 1, and assuming $\rho_{pw} = \infty$, then $q_{dep-face}^{peak-ideal} = 0.144$ MW/m^2, an attractively low value. As noted earlier, however, the modularity of the BM system prevents this ideal from being approached by an order of magnitude. Consider first the effect of radial misalignment. For the least challenging situation, which occurs at $(t_{edge}, p_{edge}) = (\Delta t_{1/2}, 0)$ for p_{center}^{plasma}= 0, and also assuming $b \equiv (B_\theta/B_\phi)_{MP} \to 0$, it is evident that $\Delta_{set-back}^{toroidal} = \Delta_{mis}$ is (just) adequate to shadow-protect the toroidal-facing edge of the BM and thus $q_{dep-face}^{peak} \approx q_{\|0}\Delta_{mis}/\Delta t_{1/2}$. Assuming that all N (= 18 here) of the IW BMs are shaped similarly and assuming the magnetic pitch b is small enough, ($b < Nh_{wetted}^{pol}/2\pi\rho_{tp}$), then the ensemble of BMs constitutes, in effect, a continuous toroidal limiter so far as the sink action exerted on the plasma is concerned [4] and $q_{\|0} = P_{surface}/(4\pi R_{IW} b\lambda_q) = 32.2$ MW/m^2 for the IW 7.5 MA case, thus $q_{dep-face}^{peak} \approx 0.23$ MW/m^2, which is actually not a great increase over the ideal. This value of $\Delta_{set-back}^{toroidal}(p_{edge} = 0)$ is not nearly adequate, however, for $b > 0$ and $|p_{edge}| > 0$ even when p_{center}^{plasma}= 0. (When $b > 0$ the poloidal curvature of the plasma permits field lines to reach the edge which would be intercepted by the neighbour BM if b = 0.) Regarding p_{center}^{plasma}: vertical position control of the plasma may not be assured and, in any

Table 1
Assumed plasma conditions for su/rd. λ_q is power decay length assuming the set of BMs constitutes, in effect, a toroidal limiter, see text. $b \equiv (B_\theta/B_\phi)_{MP}$ is the magnetic pitch at the plasma midplane (MP). ρ_{pp} is the poloidal radius of curvature of the plasma at its MP.

I_p (MA)	$P_{surface}$ (MW)	λ_q (mm) IW (OW)	$b \equiv (B_\theta/B_\phi)_{MP}$ IW (OW)	ρ_{pp} (m) IW (OW)
7.5 (rd)	6.5	36 (9)	0.11 (0.175)	8 (3.5)
4.5 (su)	4	60 (15)	0.07 (0.11)	2.5
3.5 (su)	3.5	80 (20)	0.051 (0.081)	2
2.5 (su)	2.5	110 (27.5)	0.038 (0.061)	1.75

case, it may be desirable to use different values of $p_{\text{center}}^{\text{plasma}}$, e.g., for slow vertical sweeping to spread the power load. It can be shown that the minimum value ${}^{\min}\Delta_{\text{set-back}}^{\text{toroidal}}(p_{\text{edge}})$ to ensure shadow-protection of the toroidal-facing edges is given by:

$$
\begin{aligned}
&{}^{\min}\Delta_{\text{sb}}^{\text{tor}}(p_{\text{edge}}) \\
&\quad\approx \Delta_{\text{mis}} + \frac{(p_{\text{edge}} + b(\Delta t_{1/2} + \Delta_{\text{gap}}) - p_{\text{center}}^{\text{plasma}})^2 - (p_{\text{edge}} - p_{\text{center}}^{\text{plasma}})^2}{2\rho_{\text{pp}}} \\
&\quad+ a_p(|p_{\text{edge}} + b(\Delta t_{1/2} + \Delta_{\text{gap}})|^m - |p_{\text{edge}}|^m). \qquad (3)
\end{aligned}
$$

The value of ${}^{\min}\Delta_{\text{sb}}^{\text{tor}} \to \infty$ as $|p_{\text{center}}^{\text{plasma}}| \to \infty$; however, the value of δ also increases and for large $|p_{\text{center}}^{\text{plasma}}|$ the edge becomes 'self-protected', even if it is no longer shadow-protected, provided $q_{||0}e^{-\delta_{\text{edge}}/\lambda_q}$ is small enough, say <0.1 MW/m^2. Therefore the value chosen for ${}^{\min}\Delta_{\text{sb}}^{\text{tor}}$ is the smaller of that from Eq. (3) and that given by $q_{||0}e^{-\delta_{\text{edge}}/\lambda_q} < 0.1$ MW/m^2.

We turn next to the shadow-protection of the poloidal-facing edges and estimating the value of ${}^{\min}\Delta_{\text{sb}}^{\text{pol}}$. The circular approximation for the equation of (the poloidal projection of) the field line that passes through the (top) edge point $(p, x) = (\Delta p_{1/2}, \Delta_{\text{sb}}^{\text{pol}})$ is $(x + \rho_{pp})^2 + (p - p_{\text{center}}^{\text{plasma}})^2 = (\rho_{pp} + \delta)^2$, thus $\delta = -\rho_{pp} + [(\Delta_{\text{sb}}^{\text{pol}} + \rho_{pp})^2 + (\Delta p_{1/2} - p_{\text{center}}^{\text{plasma}})^2]$. We solve for the contact point $p_{contact}$ of this circle and the poloidal shape of the surface of the BM located above, $g_{BM}^{above}(p) = x = a_p|p - 2\Delta p_{1/2} - \Delta_{gap}|^m + \Delta_{mis}$, accepting only the solution for p_{contact} that is real and single-valued. This occurs for one particular value of $\Delta_{\text{sb}}^{\text{pol}}$, which is then ${}^{\min}\Delta_{\text{sb}}^{\text{pol}}$. It will be shown below that the specific value of ${}^{\min}\Delta_{\text{sb}}^{\text{pol}}$ does not have very much effect on $q_{\text{dep-face}}^{\text{peak}}$ directly and while it contributes to ${}^{\min}\Delta_{\text{sb}}^{\text{tor}}$ through a_p, Eq. (3) (which does have a strong influence on $q_{\text{dep-face}}^{\text{peak}}$), it only does so for $p \sim \pm\Delta p_{1/2}$, which is not where $q_{\text{dep-face}}^{\text{peak}}$ occurs. The value used for ${}^{\min}\Delta_{\text{sb}}^{\text{pol}}$ is the smaller of that from the above analysis and that given by $q_{||0}be^{-\delta_{\text{edge}}/\lambda_q} < 0.1$ MW/m^2. The choice of value for the poloidal shaping parameter m has no influence on $q_{\text{dep-edge}}^{\text{peak}}$; however, too small a value of m leads to increased $q_{\text{dep-face}}^{\text{peak}}$ for $p_{\text{center}}^{\text{plasma}} \neq 0$(see below). For illustration we take for the IW: $m = 6$ and $\Delta_{\text{sb}}^{\text{pol}} = 0.1$ m, which the above analysis shows is adequate to shadow-protect the poloidal-facing edges for all the cases in Table 1; this results in values for the 4.5 MA case (which is the most challenging case since ${}^{\min}\Delta_{\text{sb}}^{\text{tor}} \propto b/\rho_{\text{pp}}$) of ${}^{\min}\Delta_{\text{sb}}^{\text{tor}} = 31$, 33, 35, 37, 48 and 73 mm for p = 0, 0.1, 0.2, 0.3, 0.4, 0.5 m, giving a p-averaged value of $\langle C\rangle = 0.04$. This BM shape is shown in Fig. 2 and for the IW 7.5 MA case the $q_{\text{dep-face}}$ distribution is shown in Fig. 3. The value of $q_{\text{dep-face}}^{\text{peak}} = 1.33$ MW/m^2 is about an order of magnitude higher than the ideal case but possibly still acceptable. This value is close to the simple estimate $q_{\text{dep-face}}^{\max} \sim q_{||0}\langle C\rangle = 1.29$ MW/m^2.This BM shape, i.e., using $\lambda_{\text{q}}^{\text{design}}[= \lambda_{\text{q}}(7.5\text{MA})] = 36$ mm and $\Delta_{\text{sb}}^{\text{tor}} = 0.035 + 0.08|p|$, results in fairly constant values of $q_{\text{dep-face}}^{\text{peak}}$ over

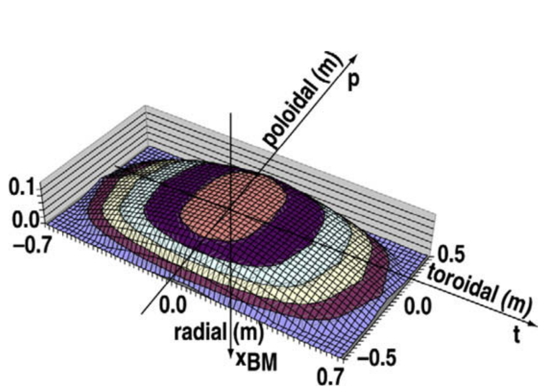

Fig. 2. The inner wall BM shape optimized for the 4.5 MA su/rd condition. For better clarity the quantity plotted vertically is actually $0.11 - x_{\text{BM}}(t, p)$ and the vertical scale has been greatly exaggerated.

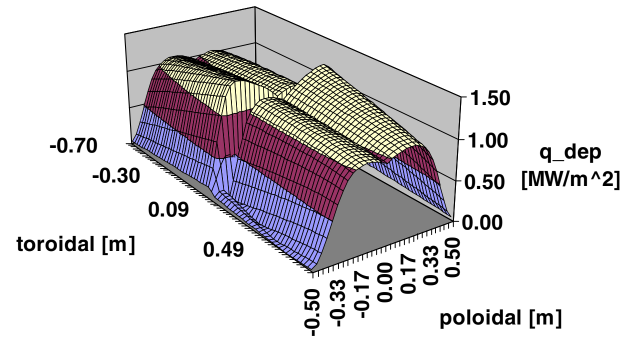

Fig. 3. The deposited power density distribution, $q_{\text{dep-face}}$, for the IW shape in Fig. 2 and for the 7.5 MA su/rd condition. The effect on the $q_{\text{dep-face}}$ pattern by shadowing due to the neighboring BMs is not shown.

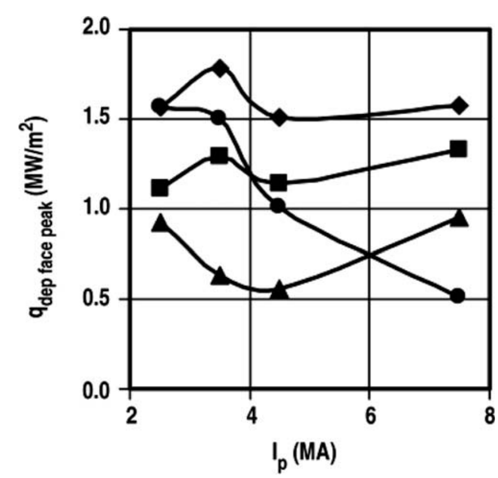

Fig. 4. Peak deposited power flux density for the four plasma current cases of Table 1. Diamonds: IW, $\lambda_q^{\text{design}}$ = 36 mm, p_{center} = 0.5 m. Squares: IW, $\lambda_q^{\text{design}}$ = 36 mm, p_{center} = 0. Triangles: OW, $\lambda_q^{\text{design}}$ = 17.5 mm. Circles: OW, $\lambda_q^{\text{design}}$ = 9 mm.

the 4 IW cases, Fig. 4; however, for the OW a value of $\lambda_{\text{q}}^{\text{design}} = 17.5$ mm results in a smaller spread than using $\lambda_{\text{q}}(7.5\text{MA}) = 9$ mm, Fig. 4. The effect of varying poloidal shaping parameters m and $\Delta_{\text{sb}}^{\text{pol}}$ is next illustrated for the example of the IW 7.5 MA case and for $p_{\text{center}}^{\text{plasma}} = \pm p_{1/2}$ (which is the value of $p_{\text{center}}^{\text{plasma}}$ which causes the largest $q_{\text{dep-face}}^{\text{peak}}$): for $m = 6$ (12), $q_{\text{dep-face}}^{\text{peak}} = 1.44$ (1.44), 1.58 (1.82), 1.61 (1.89) MW/m^2 for $\Delta_{\text{sb}}^{\text{pol}} = 0$, 0.1, 0.2 m, showing that the value of $\Delta_{\text{sb}}^{\text{pol}}$ is not important for $q_{\text{dep-face}}^{\text{peak}}$ but it is important not to use too sharp a chamfer, i.e., too large an m value, particularly if $p_{\text{center}}^{\text{plasma}}$ will differ from 0. The OW shape used $\Delta_{\text{sb}}^{\text{tor}} = 0.1$ m for all p, which is adequate to protect the toroidal-facing edges for all of the cases, even though $\Delta_{\text{gap}}^{\text{tor}}$ is extremely large for the OW, 1.477 m (since in every second toroidal location there is a port rather than a BM). The effect on the $q_{\text{dep-face}}$ pattern due to shadowing by neighboring BMs is not shown in Fig. 3 nor its positive consequences in Fig. 4. It can be shown that the effect of shadowing is to significantly reduce $q_{\text{dep-face}}^{\text{peak}}$ for the cases where $\lambda_{\text{q}}^{\text{actual}} < \lambda_{\text{q}}^{\text{design}}$. Since the largest values of $q_{\text{dep-face}}^{\text{peak}}$ occur for $\lambda_{\text{q}}^{\text{actual}} \geqslant \lambda_{\text{q}}^{\text{design}}$ this might not seem very helpful; however, there is a quite important positive consequence, namely that it is safe to optimize the shape for a small value of $\lambda_{\text{q}}^{\text{design}}$, i.e. for the highest P_{surf} cases, since shadowing will ensure that the resulting very high values of $q_{\text{dep-face}}^{\text{peak}}$ that would then otherwise occur for the cases having $\lambda_{\text{q}}^{\text{actual}} < \lambda_{\text{q}}^{\text{design}}$ in the absence of shadowing, will not in fact occur. This is an advantage not enjoyed by the unshadowed two-port limiter system [5] which therefore has to employ more conservative optimization of the surface shape. Also to be included in future work: (a) the effects of misalignment on $q_{\mathrm{dep-face}}^{\mathrm{peak}}$, (b) the need to include slots or holes in the BM faces for RH access, (c) protection of the wall at the top of the vessel where the 2nd X-point occurs.

3. Conclusions

The modularity of the ITER BM system (inter-BM gaps and misalignments) requires shaping of the BM faces that increases peak power loads by $\sim 10\times$ relative to the ideal (continuous, circular) wall. Fortunately, the level may still be acceptable, $\sim 2\ \mathrm{MW/m^2}$, even for su/rd power of 7 MW.

Acknowledgments

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