Sensitivity of the ITER Operating Window to Variation of Transport, Magnetic Field, and Elongation

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Introduction

This paper investigates the effect of H-mode confinement degradation in the operational space of ITER due to:

a) the absence of toroidal rotation.
b) reduced field operation for the hypothetical case that superconductor performance is somewhat less than specified
c) the effect of reduced elongation at the specified superconductor performance for the hypothetical case that the plasma vertical stability has to be increased
d) and the required changes in machine size to recover the original operating space

Description of the Simulations

The transport model used in the simulations is the Integrated Core Pedestal SOL (ICPS) model [1.2] as recently described in detail in [2] and the edge-based density limit, which plays an important role in delimiting the operating space, is fully defined in [3,4].

In [2] and all preceding work, the ballooning limit is given by the *S*-α diagram shown on Fig. 1 calculated from theoretical formulas including aspect ratio, elongation, and triangularity [5], but with the limiting α determined from this diagram multiplied by an enhancement factor of two, in order to fit experiments on JET and Asdex-UG with beam heating. Recent experiments indicate that, in the absence of toroidal rotation resulting from toroidal momentum input, the pedestal may be less high and that the confinement may be reduced by ~10%. For the JET simulation, such a reduction of confinement is obtained if the enhancement factor on α is reduced from 2.0 to 1.0 (fig.2), i.e. the limit is closer to the theoretical value for ballooning stability. The ICPS simulation shows that the H-factor with respect to the 98y2 confinement scaling then reduces from 0.92 to 0.81 at the same density.

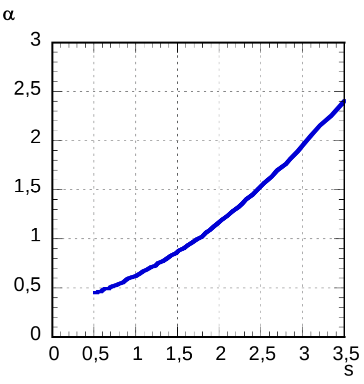

Fig.1 - S-α diagram for the ballooning limit.

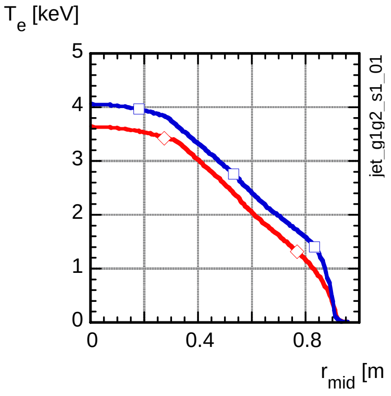

Fig. 2 - T_e profiles for JET with enhancement factor 2 (blue) and 1 (red)

The effect of the reduction of the pedestal parameters in ITER can be examined in two ways: at the same density (the same way as for JET) or at the same fusion power (increasing the density to compensate for the reduced pedestal parameters). Each comparison is carried out at a constant fraction of the edge-based density limit (which depends on power). At constant density of $1.2 \times 10^{20} m^{-3}$, the effect on performance is perceived to be dramatic, leading to a decrease of *Q* from ~30 to ~9. Conversely, if the comparison is carried out at similar fusion power of e.g. 750 MW, *Q* is affected only marginally, dropping from 18 to 17.4, so that then the reduction is perceived to be benign. Clearly, point comparisons are insufficient to appreciate the effect on ITER performance and the operational space available must be determined.

Determination of the Operating Space of ITER

Scans are carried out at given central densities ranging from 0.6 to 2.4x10^{20} m^{-3} (along the light blue lines of fig. 3). At each density, the highest auxiliary power is such that the edge-based density limit is attained ($f_{sat\text{-}n}$=1) with the gas puffed flux adjusted to obtain the desired peak divertor power load (e.g. 10 MW/m^2 in these simulations). The auxiliary power is then reduced in a step-wise fashion, with simultaneous adjustment of the gas puffed flux, yielding a rise of Q and a decrease of the fusion power. The central density is determined primarily by direct core fuelling. At given fusion power, the auxiliary power input for any density is bounded below since the plasma temperature drops below the optimum resulting from the fusion reactivity. Conversely, this limit can also be thought of as the maximum alpha power attainable at high density for given input power. With better confinement, this low temperature limit will not exist and the plasma will ignite, with the fusion power then limited by the maximum $f_{sat\text{-}n}$. Requiring lower (higher) peak divertor power load demands higher (lower) gas puffing and therefore moves the $f_{sat\text{-}n}$ curves to the right (left) on the plot of P_α against Q.

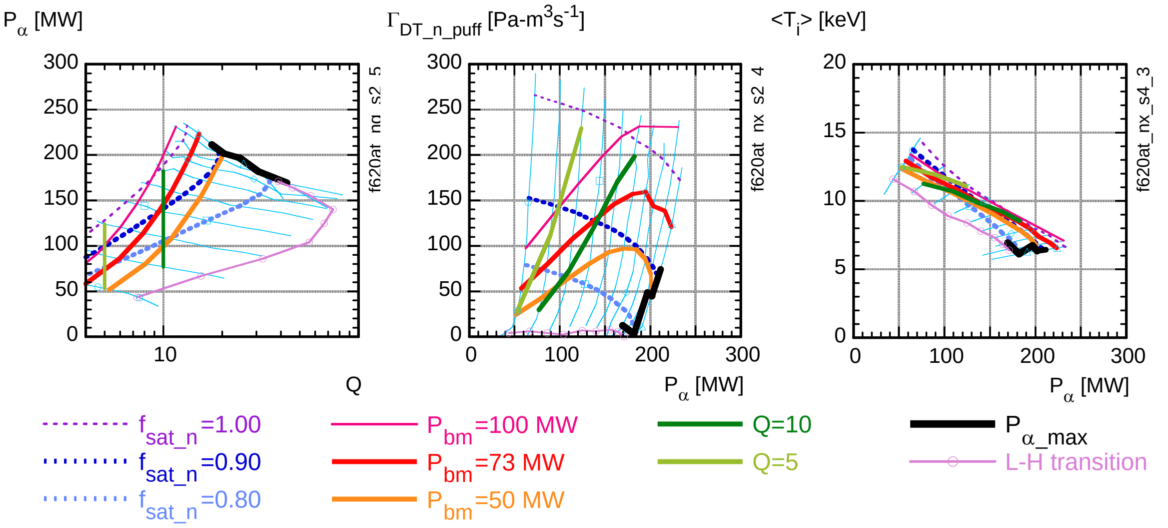

Fig. 3- Result of described scans at along constant density contours with decreasing additional power input: (a) P_α vs. Q, (b) gas puff vs. P_α, (c) average ion temperature vs. P_α, for ITER at full field at q_{pk} = 10 MW/m^2. α enhancement factor G = 1

In the P_α-Q plane (see fig. 4) the relevant operational space is thus delimited by (clockwise from left):

1. the minimum Q consistent with the ITER mission (=5, vertical line)
2. the available additional heating power (=73 MW)
3. the edge density limit for maximum throughput before detachment (f_{sat_n}=0.9)
4. the low T limit at high n which gives the maximum attainable alpha power P_{α_max}
5. the H-L back transition - a P_α-Q characteristic close to but outside the thin line "calc"
6. a horizontal line (not shown) at the lowest P_α consistent with the ITER mission

Fig. 4 shows that the reduction of the α enhancement factor from 2 (appropriate for toroidal momentum input) to 1 (appropriate for ITER) does not significantly reduce the maximum power but does reduce the window in Q so that, while Q remains high, ignition is no longer attained. A subsequent decrease of the superconductor current-field product (jxB) by 10% (95% B) reduces the operating window significantly, and, with a further decrease of 10%, the minimal values for the ITER mission are jeopardized.

The consequences of an increased vertical stability requirement at full field have been similarly examined. If the elongation of the plasma were reduced from κ = 1.7 to κ = 1.6, the operating diagram is almost exactly that shown here for 95% field.

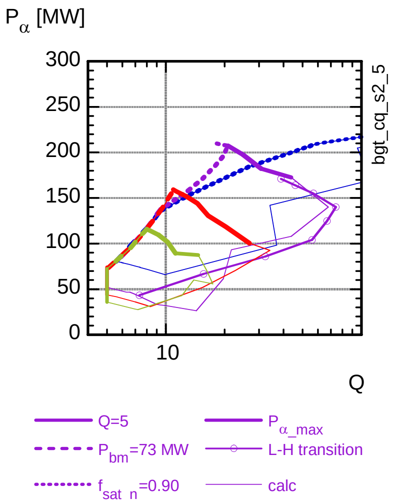

Fig. 4- Operational space limits for ITER with α-enhancement factor G=2 (blue) and 1 (purple) at 100% B; and with 95% (red) and 90% (green) at G=1.

In an attempt to recover some or all of the operating space lost if larger superconductor margin or greater vertical stability were required, we examine the effect of design changes which could be envisaged inside the ITER TF coils.

The height and width of the operating window can be characterized by the maximum P_α attained and by the Q which corresponds to this power. These quantities are plotted on fig. 5 for the different variations investigated.

Modified device parameter sets investigated

A possible avenue to recover the operational space lost due to reduced superconductor *j*x*B* could be a reduction of the inboard shielding thickness (incorporation e.g. of tungsten) thereby providing additional space for the plasma inside the same coils. The parameter sets shown in Table 1 are for a) a 10 cm reduction inboard at constant elongation (8.5 cm reduction top and bottom) and b) at constant plasma height (no reduction top and bottom).

A possible avenue to recover the operational space lost to larger vertical stability margin could be a larger major and minor radius plasma if steps can be taken to reduce the field ripple. The parameter set shown in Table 1 is for a 20 cm increase in major and minor radius at full superconductor *j*x*B* product.

Finally, parameter sets of somewhat larger machines are determined which have the same 0-D performance, and roughly the same burn flux and compressive vault stress as the full field ITER, but at ~10% reduced superconductor *j*x*B*. A very simple cost function based on a combination of TF energy and surface area and fitted to systems code runs would place these devices (A,B, and C of table I) at 1.07 of the cost of ITER.

Table 1- Modified device parameter sets investigated

		increased margin w. reduced shielding		*increased vertical stability*		*increased margin w. increase in 0-D confinement*		
	ITER	*const. κ*	*const. height*	*reduce d κ*	*larger R, a, red. κ*	A	B	C
R	6.20	6.15	6.15	6.20	6.40	6.45	6.47	6.40
a	2.00	2.05	2.05	2.00	2.20	2.15	2.31	1.91
A	3.10	3.00	3.00	3.10	2.90	3.00	2.80	3.35
κ	1.70	1.70	1.67	1.60	1.55	1.70	1.73	1.66
δ	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.33
B	5.30	5.08	5.08	5.30	5.13	5.00	4.37	5.91
I	15.1	15.5	15.0	13.8	15.2	16.03	16.92	14.00

Discussion and Conclusions

The implications of providing larger technical margins have been investigated by mapping out the accessible operational space. The transport model has been adjusted to reflect a reduction of confinement in the absence of toroidal momentum input, as appropriate for ITER, by reducing the ballooning limit from that calibrated to experiments with momentum input. This change does not reduce the attainable fusion power appreciably (from 230 to 210 MW) but does reduce the Q at maximum power from ignition to ~20.

A reduction in the superconductor *j*x*B* by 10% then reduces the operating window appreciably in both fusion power and fusion gain (160 MW at Q=11) and a further decrease by 10 % would have a maximum alpha power of 115 MW, barely above that required for the ITER mission, and the fusion gain Q at this power is below 10 (Fig. 5a).

If the shielding can be rendered more effective so that its thickness could be reduced inboard, top, and bottom, most of the loss due to the first 10% could be regained, whereas only a small gain would result if this were possible inboard only (Fig. 5b).

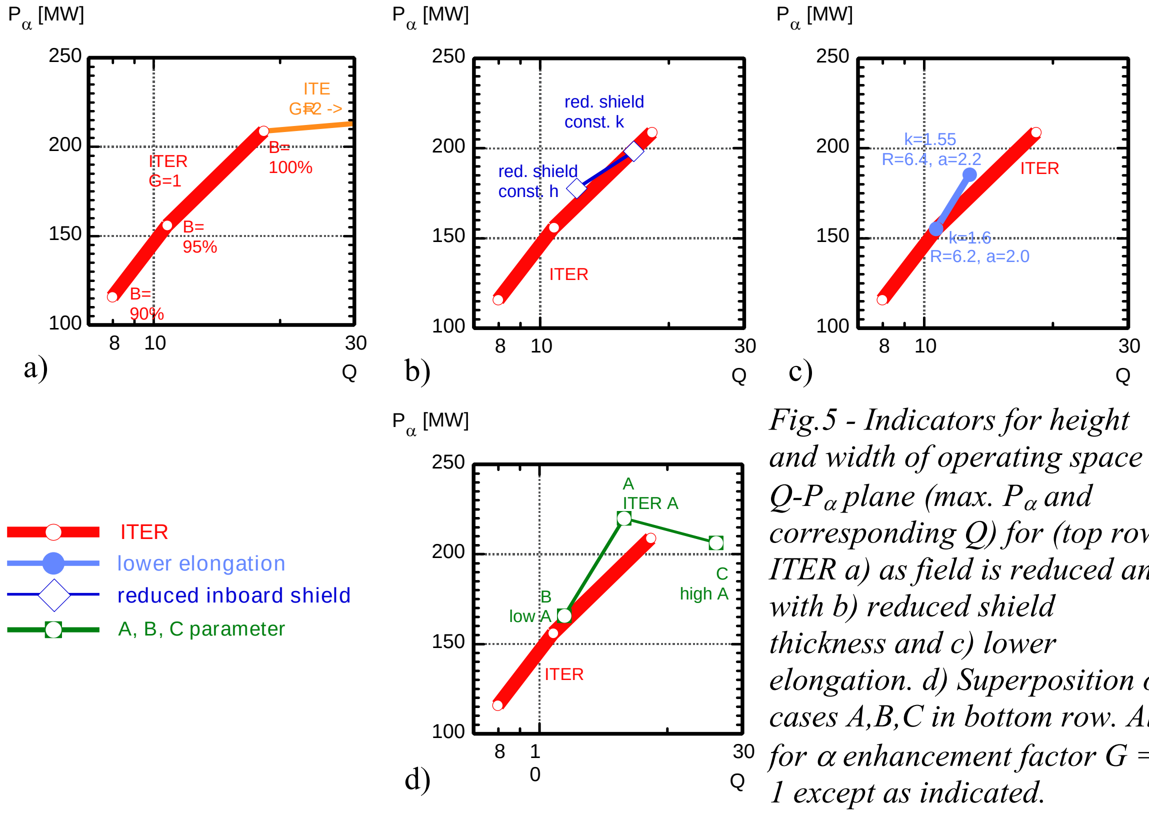

Fig.5 - Indicators for height and width of operating space in Q-P_α plane (max. P_α and corresponding Q) for (top row) ITER a) as field is reduced and with b) reduced shield thickness and c) lower elongation. d) Superposition of cases A,B,C in bottom row. All for α enhancement factor G = 1 except as indicated.

Increasing the vertical stability by decreasing the elongation from 1.7 to 1.6 at full superconductor *j*x*B* is almost exactly equivalent to a 10% reduction of this product at the original elongation. Occupying a larger part of the volume inside the toroidal field coils with plasma would mitigate the loss but not recover the original operational window (Fig. 5c).

To estimate what increase in machine size would recover the original performance but at the increased superconductor margin, alternative low, intermediate, and high aspect ratio parameter sets were created with simplified technical constraints and 0-D performance similar to that of ITER. The intermediate and high aspect ratio variants A, C exhibit operating windows similar to ITER at full field, whereas the low aspect ratio B is similar to ITER at 95 % field (Fig. 5d). The better performance of high aspect ratio machines in the 1-D modelling is directly attributable to the toroidal field dependence of the ballooning limit, which determines the pedestal height. If this limit were to degrade as the aspect ratio is increased, the advantage of the higher aspect ratio would be reduced or even nullified.

From integrated modelling, we have developed a description of the ITER operating window. The loss in operating space resulting from a hypothetical 5% reduction in field or 6% reduction in elongation could be largely recovered if some design changes were feasible or by a modest increase of machine size by 20-25 cm.

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