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RESULTS OF ITER TEST BLANKET MODULE MOCK-UP EXPERIMENTS ON DIII-D

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GENERAL ATOMICS

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Results of ITER Test Blanket Module Mock-Up Experiments on DIII-D

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Introduction. A series of experiments was performed on DIII-D to mock-up the field that will be induced in a pair of ferromagnetic Test Blanket Modules (TBMs) in ITER to determine the effects of such error fields on plasma operation and performance. A set of coils producing both poloidal and toroidal fields was placed inside a re-entrant horizontal port close to the plasma. The coil currents were varied to produce up to 700 G toroidal field and 200 G poloidal field on the last closed flux surface at the outboard midplane, resulting in a localized ripple due to the toroidal field (TF) + TBM defined by $(B_{max} - B_{min})/(B_{max} + B_{min})$ up to 5.3%. This is more than four times that expected from a pair of representative 1.3 ton TBMs in ITER. The coils are also moveable along a major radius from shot-to-shot to assess the change in the error field effects with distance from the plasma. These experiments investigated the effects of the resulting localized error field on plasma startup, plasma equilibrium, H-mode access, H- and L-mode particle and energy confinement, plasma rotation, energetic particle loss, and interaction with rotating and locked MHD modes.

Effects at Low Performance. Very little effect of the TBM mock-up error field was observed in low performance plasmas up to TF+TBM local ripple of 3%. Plasma startup with and without the TBM mock-up fields was identical so the effect on startup appears to be negligible. Figure 1 shows the measured changes in H-mode threshold power for electron cyclotron heated, balanced neutral beam injection (NBI), and all co-NBI discharges as a function of input torque on the plasma with and without the TBM mock-up field at full current. The changes in threshold are within the error bars of the measurements indicating

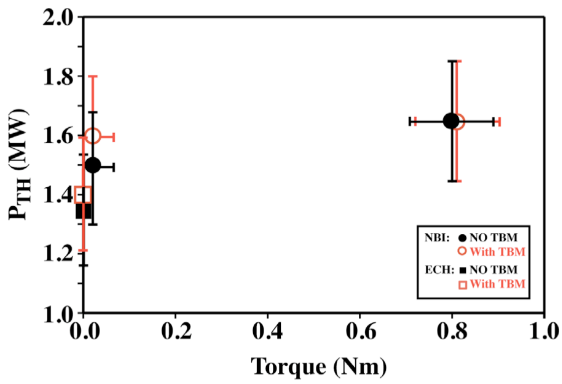

Fig. 1. Measured H-mode threshold power with (open red circles) and without (closed black circles) the mock-up TBM showing little effect on the H-mode threshold.

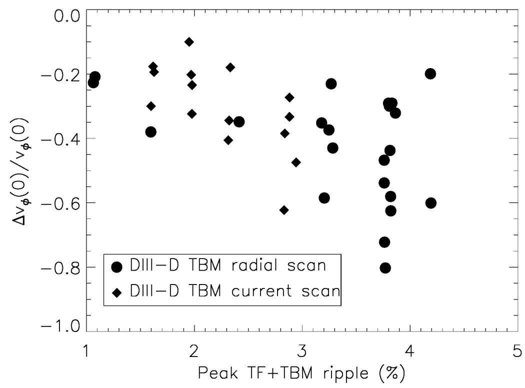

Fig. 2. Change in core plasma rotation velocity due to the TBM mock-up versus the peak TF+TBM ripple.

that there was little effect of the TBM mock-up field on H-mode access. There was also little or no effect of the mock-up TBM on particle and energy confinement in low performance L-mode plasmas.

Effects on Plasma Rotation. The toroidal plasma rotation was noticeably reduced even at the rather small local field perturbation of ~1% TF+TBM ripple. Figure 2 shows the change in core plasma toroidal rotation as measured with charge exchange recombination spectroscopy with and without the TBM mock-up on. Above 3% total local ripple, the drop in core toroidal rotation due to the mock-up TBM may exceed 60% and lead to locked modes and disruptions. The rotation drops by approximately the same proportion across the entire radial profile. The drop in rotation was the largest and most prevalent effect of the TBM mock-up error field across a broad range of conditions. The torque due to the TBM mock-up increases with increasing plasma rotation suggesting that the rotation reduction is due to non-resonant magnetic braking. The interaction of the TBM mock-up error field with n=2 and n=3 tearing modes in the plasma may also play a role in reducing the plasma angular momentum.

Effects on Mode Locking. Error field tolerance to locked modes was reduced in L and H-mode by the additional torque from the TBM error field. Ohmic experiments showed that it was necessary only to re-optimize the standard n=1 error field correction with the internal I-coils in the presence of the additional TBM mock-up error field to recover the same minimum threshold density for mode locking as without the TBM (Fig. 3). Calculations with the IPEC code [1] suggest that correction of the n=1 component of the TBM mock-up in DIII-D may remove the dominant torque that slows the plasma rotation. These results suggest that it may be possible to correct for the dominant n=1 torque due to the TBMs with error field correction

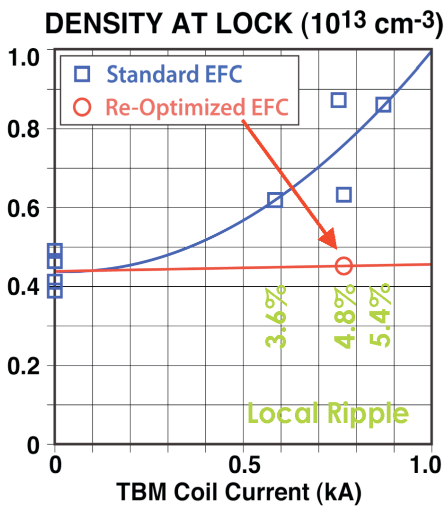

Fig. 3. Minimum density at which mode locking occurs vs mock-up TBM current with standard error field correction with the I-coils (blue) and with error field correction re-optimized including the mock-up TBM (red) showing that the same minimum density for mode locking can be recovered by re-optimizing the I-coil error field correction even with the TBM on.

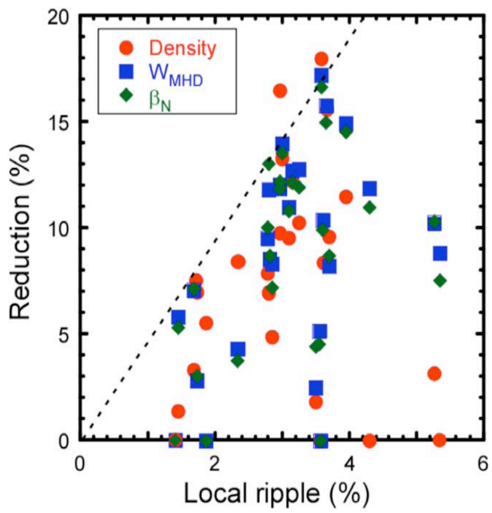

Fig. 4. Percent reduction in the line averaged electron density, plasma stored energy, and normalized β versus the local TF+TBM mock-up ripple in DIII-D. The dashed line indicates a rough maximum reduction versus ripple.

coils on ITER. However, future experiments are required to determine if n=1 error field correction alone can also be effective in H-mode plasmas.

Effects on H-mode Confinement. Although the effects of the TBM mock-up on confinement were small in L-mode, the effects increased in H-mode. Figure 4 shows that the reduction of line averaged electron density, plasma stored energy, and normalized β due to the mock-up TBM error field increase with the total local ripple in front of the TBM. Confinement is reduced by up to 15 – 18% for local ripple > 3% but is hardly affected at 1.5% local ripple. Figure 5 shows that the confinement reduction (a) increases with β_N and is (b) rather independent of electron collisionality (ν_e*) at the top of the H-mode edge pedestal. This latter result is in contrast to the reduced confinement with decreasing ν_e* observed on JET with increasing TF ripple [2]. Note that for $\beta_N < 1.5$, there was very little change in confinement.

Detailed measurements indicate that fast ion losses due to the TBM mock-up error field appear to be small under all conditions. At high NB power ~ 6 MW, however, a substantial increase in the temperature of the plasma facing carbon tiles just in front of the TBM mock-up was observed (> 200 °C) with the TBM at full current for ~2 s compared to < 10 °C rise in a similar plasma without the TBM, each with a 4 cm outer gap between the plasma and first wall. Calculations with the SPIRAL code [3] suggest that this enhanced heat load on the tiles in front of the TBM mock-up could be at least partially due to locally increased NB fast ion

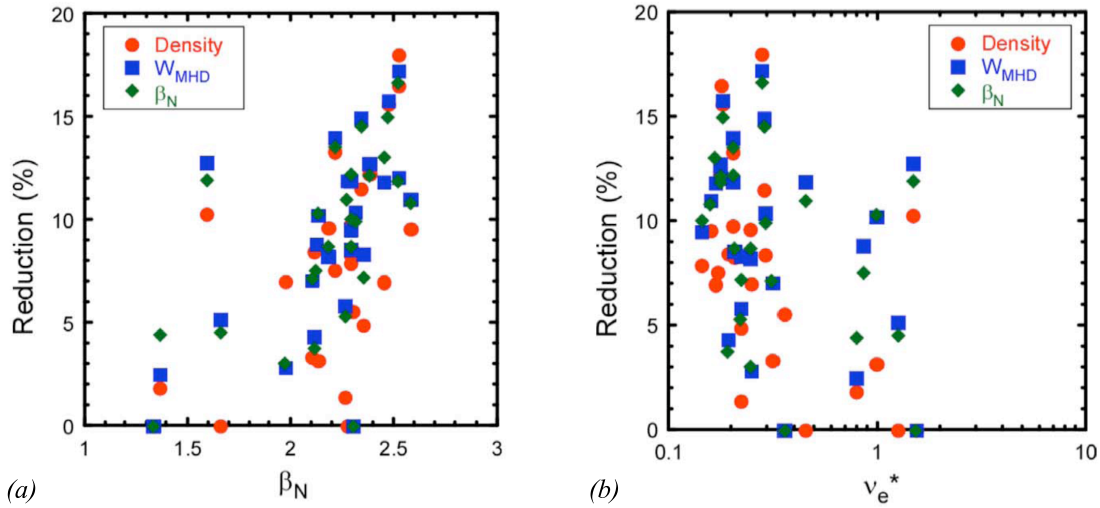

Fig. 5. (a) Percent reduction in line averaged electron density, plasma stored energy, and normalized β vs normalized β during the mock-up TBM showing that the confinement reduction increases with increasing β_N. (b) The same quantities vs the electron collisionality at the top of the edge pedestal showing no clear dependence on ν_e.*

losses. First wall heat loads due to fast ion losses in ITER are calculated to be well within the first wall tile heat load limits including the effects of the TBMs [4].

Implications for the ITER TBM Program. The results of these experiments suggest that in ITER: (1) it is not essential to reduce the ferromagnetic mass for initial plasma operation since their effects are likely to be small in low performance plasmas; (2) to minimize the risk of interference at high plasma performance, the TBM designs should be optimized to reduce the TBM-induced ripple; (3) recessing the TBMs further from the plasma than necessary for heat flux considerations does not substantially reduce the TBM ripple effects; and (4) the largest effect of the TBMs is likely to be a reduction in plasma rotation. Since the 1 MeV N-NBI on ITER will impart little momentum to the plasma, the expected plasma rotation in ITER will be dominated by transport driven intrinsic plasma rotation, which is not well understood. Future TBM mock-up experiments on DIII-D are needed to determine if n=1 error correction is sufficient to maintain plasma toroidal rotation also in H-mode.

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