

Reducing the L-H Transition Power Threshold via Neoclassical Toroidal Viscosity, Edge Rotation Reversals, and Shape Changes

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Initial experimental evidence shows that the L-H transition power threshold P_{th} can be reduced via Neoclassical Toroidal Viscosity (NTV) associated with applied $n=3$ non-resonant magnetic fields (NRMF) [Figs. 1 and 2], and, independently, via a fast reduction or reversal of intrinsic edge toroidal (co)rotation [Fig. 3]. It is also demonstrated that a small/moderate increase in lower triangularity reduces P_{th} [Fig. 4]. These actuators are shown to enhance local $E \times B$ flow and $E \times B$ shear just inside the LCFS. Rotation reversals reduce the L-H transition power threshold with unfavorable grad-B drift direction to values similar to P_{th} in favorable configuration.

Techniques for reducing P_{th} , or mitigating its increase with applied magnetic perturbations are crucially important for ITER, particularly in view of marginal auxiliary power in hydrogen plasmas during the PFPO-1 campaign. Several approaches are demonstrated here that increase the L-mode $E \times B$ shear preceding the L-H transition, and potentially open up a path to reduce or mitigate P_{th} in burning plasma experiments. Control of L-mode edge shear flow is accomplished using either externally applied NRMF torque, or by changing the edge rotation boundary condition. In addition, P_{th} has been reduced via small plasma triangularity changes (within ITER-relevant margins).

Initial evidence shows that a large NRMF torque applied via the C-coil (1) can reduce P_{th} at low ion edge collisionality [$\nu_i^*(\rho=0.95) \sim 0.15$] [Fig.1]. It is obvious from Fig. 1 that the NBI power required to access H-mode is reduced with applied NRMF. The power threshold (expressed approximately as $P_{th} \sim P_{NBI} + P_{OH} - dW/dt$ where the Ohmic power P_{OH} and the time derivative of the stored energy W have been taken into account) is reduced by $\sim 25\%$ (from ~ 4.3 MW without NRMF to ~ 3.15 MW with applied NRMF/NTV). The core radiated power is not separately measured but is estimated to be smaller than 80 kW. This observation of a reduction in power threshold with NRMF differs fundamentally from the power threshold increase observed with applied Resonant Magnetic Perturbations (RMP) due to edge stochasticity and increased edge toroidal co-rotation (2). In contrast, CER measurements here show a substantial reduction of the L-mode edge toroidal (Carbon) co-rotation with applied NRMF/NTV just before the L-H transition, qualitatively consistent with the direction of the expected NTV counter-torque [Fig.2]. As a consequence, $E \times B$ flow shear near the LCFS is found to increase via increased radial shear in the toroidal rotation term in the radial ion momentum balance. The (partial) ITER 3-D coil set available during the PFPO-1 campaign can be used to generate large NTV in the edge plasma layer, favored by the low collisionality expected in the ITER L-mode edge.

We have also investigated in detail the effect of magnetic geometry on P_{th} , and attribute the increased L-H power threshold with unfavorable grad-B drift direction clearly to reduced $E \times B$ flow shear due to higher edge toroidal co-rotation [Fig. 3(a)]. The L-H power threshold is shown to decrease monotonically with increasing $E \times B$ shear in the outer L-mode shear layer near the LCFS (shown via NBI torque scan, Fig. 3c), and does not depend on shear in the inner shear layer.

However, it has been observed that spontaneous local rotation transitions increase $E \times B$ edge shear flow preceding the L-H transition in balanced/low torque ITER-similar shape (ISS) plasmas in DIII-D. Fig. 3(b) shows radial profiles of toroidal edge rotation approaching the L-H transition. The rotation reduction/ reversal commences locally near $\rho=0.95$; the layer of reduced rotation then expands radially over several ms, providing sufficient $E \times B$ flow shear to induce the L-H transition. As a result, P_{th} in ISS plasmas can be reduced to values similar to those observed with favorable grad-B drift direction [Fig. 3(a)]. The threshold reduction occurs over a range in NBI torque but is most effective for balanced torque or with low counter- I_p torque. Reversal/ reduction of intrinsic edge co-rotation appears to be triggered by transient increases in edge power flow (via sawteeth crashes or radial transport avalanches).

In ISS plasmas, increasing the lower triangularity by $\sim 12\%$ results in a clear reduction in L-H power threshold (by $\sim 15\%$, shown here for hydrogen ISS plasmas (Fig. 4). A smaller data set in deuterium plasmas also demonstrates a $\sim 10\text{-}12\%$ reduction of P_{LH} at increased triangularity at low torque ($\leq \pm 0.2$ Nm). In the higher triangularity shape the outer divertor strike point was moved slightly further away from the lower divertor cryopump, which could also have affected divertor neutral pressure.

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(1) K.H. Burrell et al., Nucl. Fusion 53 (2013) 073038.

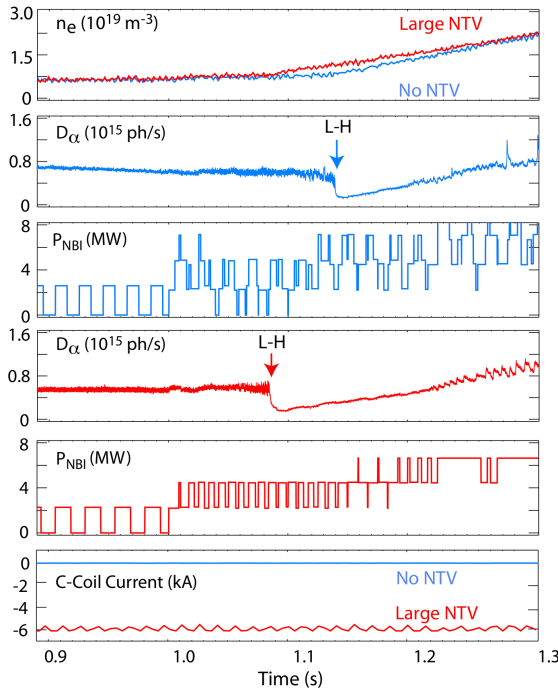


Fig. 1: Comparison of two L-H transitions without (blue) and with (red) strong NRMF applied in the DIII-D outboard midplane via the C-coil; shown are plasma line density, D_α signals, injected NBI power and C-coil current for both cases.

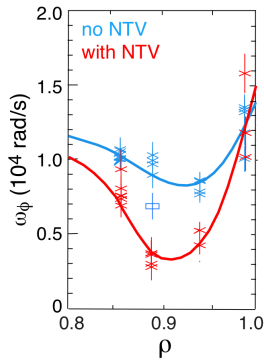


Fig. 2: Reduction of edge toroidal rotation: Comparison with two shots with zero NTV and high applied NTV.

Fig. 4: Dependence of threshold power P_{th} on applied NBI torque in ITER-similar-shape (ISS) hydrogen plasmas, for regular ISS lower triangularity ($\delta_L \sim 0.72$) and for slightly increased lower triangularity ($\delta_L \sim 0.8$) leading to power threshold reduction.

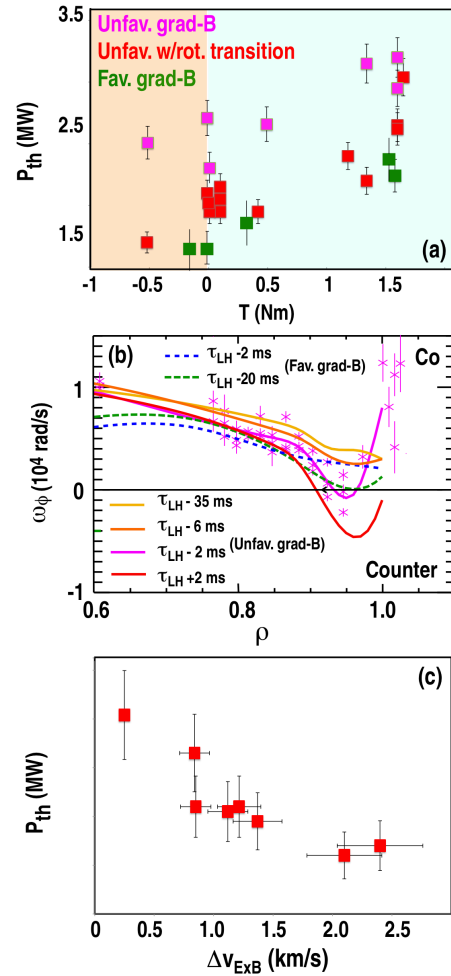


Fig. 3: (a) P_{th} for unfavorable grad-B; for unfavorable grad-B with L-mode rotation transitions, and for favorable grad-B, vs. applied NBI torque; (b) toroidal rotation profile for different times with respect to the L-H transition time τ_{LH} for favorable and unfavorable grad-B configuration; (c) P_{th} vs. ExB shear in outer shear layer ($\omega_{ExB} = \Delta V_{ExB} / dr$).

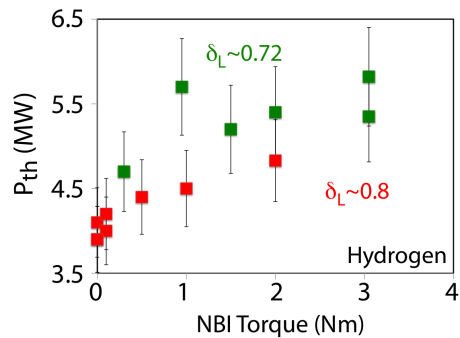


Figure 1:

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