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ACCESS AND SUSTAINED HIGH PERFORMANCE IN ADVANCED TOKAMAK INDUCTIVE DISCHARGES WITH ITER-RELEVANT LOW TORQUE

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GENERAL ATOMICS

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Access and Sustained High Performance in Advanced Inductive Discharges with ITER-Relevant Low Torque

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Recent experiments on DIII-D have demonstrated that advanced inductive discharges with high normalized fusion gain approaching levels consistent with ITER Q=10 operation can be accessed and sustained with very low amounts of externally driven torque. The major obstacle in developing these discharges was found to be increased susceptibility to m/n=2/1 neoclassical tearing modes (NTMs) as the torque is decreased. If left unmitigated, these modes generally slow and lock, terminating the high performance phase of the discharge. Electron cyclotron heating (ECH) has proven to be an effective method of avoiding such modes, allowing stable operation at high beta (β_N>3) and low torque (<1 N-m), a portion of operating space that has otherwise been inaccessible. Significant levels of edge intrinsic torque are measured in these discharges, consistent with a previously determined scaling [1].

Advanced inductive discharges with normalized fusion performance $G=\beta_N H_{89}/q_{95}^2$~0.35 approaching the value needed for Q=10 operation on ITER (G~0.42) have been produced using a torque of approximately 1 Nm (Fig. 1). This level of torque is anticipated to drive a similar amount of rotation as the beams on ITER, via simple consideration of the scaling of the moment of inertia and confinement time. These discharges have achieved β_N~3.1 with H_{98}~1 at q_{95}~4, and have been sustained for the maximum duration of the counter neutral beams (NBs). To reach these conditions, ECH configured for current drive near the q=2 surface with broad deposition was utilized for 2/1 NTM mode suppression, although no effort was made to ensure optimal alignment between the driven current and the q=2 location.

Plasmas using zero net neutral beam torque from the startup through the high β phase have also been created. Using only modest amounts of EC power (~1 MW), the 2/1 NTM could be limited in size sufficiently (though still appreciable $|B_\theta|$~10 G) to allow stable operation at β_N~2.5, limited by confinement and the available balanced NB power. Figure 2 shows that the discharge maintains fairly stationary conditions for approximately 1 s, during which time the rotation frequency is very low (~1 kHz), and remarkably flat across most of

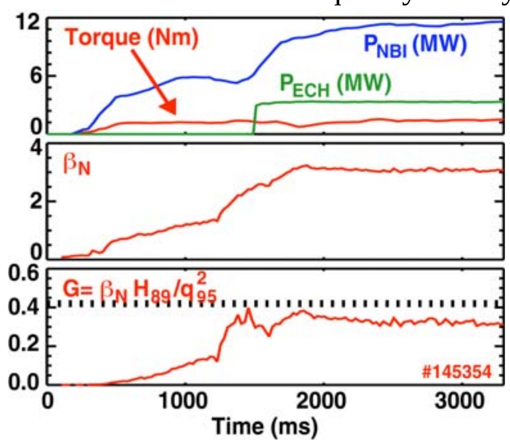

Fig 1. Plasma shot illustrating high normalized fusion performance G~0.35 achieved with ***low*** torque startup.

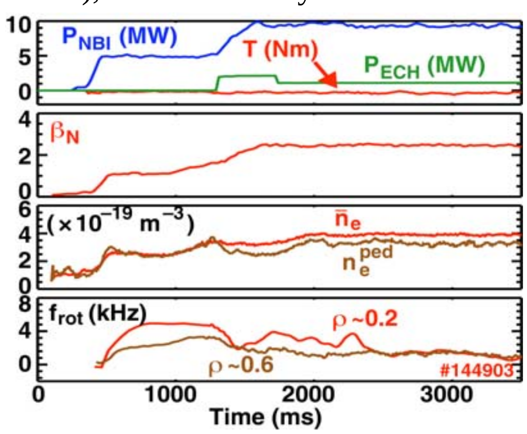

Fig. 2. Advanced inductive discharge produced and sustained with ***zero*** net torque at β_N~2.4 and rotation ~1 kHz.

the profile. Interestingly, the performance of the discharge was not improved by using additional EC power to completely suppress the mode, since the total power (NB+EC) required to achieve the same β_N was the same with or without the mode. Hence, the expected increase in confinement from suppressing the mode is offset by a reduction in confinement associated with the EC power. This appears to be a result of a combination of reducing the T_i/T_e ratio, together with the less favorable deposition of power at large radius. This clearly illustrates a disadvantage on relying on electron cyclotron current drive for mode control in a high gain scenario; it is critical for machine protection to be able to avoid a disruptive locked mode, but the cost in terms of confinement does not make it an especially attractive solution.

Quite generally, ECH was needed in order to access low torque, high β_N operation. Figure 3 shows the trajectory in β_N-torque space for discharges that do not utilize ECH. A region of instability is readily identifiable (although the 2/1 NTM limit cannot be characterized solely by these two quantities), and access to either lower torque or higher β_N has so far proved challenging without ECH. This is true independent of whether one ramps the torque down at high β_N, or ramps the β_N up at low torque. Improvements in NTM stability are also not observed with improved error field correction. However, with ECH applied, it becomes possible to avoid the 2/1 NTM and push past this barrier of instability, allowing access to higher performance low torque plasmas. In many cases in this data set, the ECH has been aimed to drive current near the q=2 surface, although this does not appear to be a critical element in order to gain the benefits of the ECH.

High β_N~3 discharges at low torque have been sustained using ECH (without current drive) deposited significantly inside of the q=2 surface. The insensitivity to the deposition position, together with the lack of need for current drive, suggests that the EC assists stability in a different way than that of simply replacing the bootstrap current caused by the flattening of the pressure profile in the island. Although the exact mechanism for the improved stability is not yet understood, one may speculate that the ECH leads to a direct modification of the classical Δ' stability parameter via changes to the conductivity and bootstrap profiles.

The high confinement typically associated with advanced inductive plasmas is notably degraded at reduced torque. The power demand increases approximately 70% at fixed β_N as the torque is ramped from all co-NBI toward balanced injection, and the confinement factor is reduced from H_{98}>1.5 to just above 1. Such degradation of confinement with reduced rotation has been attributed to reduced ExB shear stabilization [2], although other factors, such as subtle modification to the q-profile, may also play a role. The reduced confinement appears to be identical whether the plasma is initiated with high torque and ramped down, or formed initially with low torque. However, for plasmas started with low torque, ramping the torque back up to all co-NBI does not recover the higher confinement state associated with rapid rotation, suggesting a possible hysteresis in the confinement phase space with torque.

The intrinsic drive in these low torque advanced inductive plasmas is significant, ≈1.4 Nm. This value closely matches the expectation of the intrinsic torque from the previously determined empirical scaling constructed from DIII-D H-mode discharges, which includes contributions from the turbulent Reynolds stress and thermal ion orbit loss [1]. If the same scaling is applied to ITER scenario 2 parameters, one computes an intrinsic torque for ITER of around 2 Nm, considerably smaller than the expected neutral beam torque.

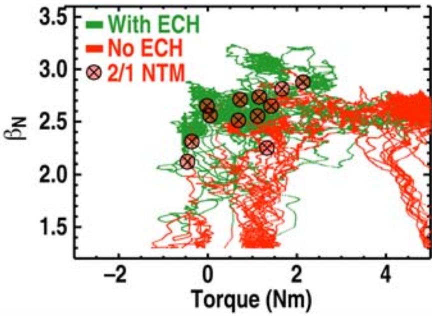

Fig 3. Trajectories highlight the difficulty in accessing high β_N low torque plasmas without ECH.

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