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ADVANCES IN THE PHYSICS BASIS OF THE HYBRID SCENARIO ON DIII-D

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Advances in the Physics Basis of the Hybrid Scenario on DIII-D EX-C

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Experiments on the DIII-D tokamak have developed a long duration, high performance plasma discharge that is an attractive operating scenario for future burning plasma experiments [1,2]. This “hybrid scenario” is inductively driven, with bootstrap current fractions of 35%-50% and a central safety factor close to unity. While hybrid plasmas have a type-I ELMy H-mode edge, like the standard H-mode scenario, hybrids differ by having suppressed sawteeth, a higher β limit to the m/n=2/1 NTM, and remarkably good transport properties. Recent experiments on DIII-D have extended the hybrid scenario towards the burning plasma regime by incorporating strong electron heating, low torque injection, and ELM suppression from resonant magnetic perturbations (RMPs). Additionally, high performance hybrid operation has been demonstrated with reduced frequency of wall conditioning.

Initial hybrid experiments on DIII-D using co-neutral beam injection (NBI) obtained $T_i > T_e$ and high toroidal rotation, which are plasma conditions quite different from those expected in ITER. Raising T_e/T_i by injecting up to 2.4 MW of electron cyclotron heating (ECH) was found to reduce confinement and increase turbulence in hybrid plasmas. Figure 1 shows the increase in power spectrum amplitude at low wavenumbers, $k < 3\ \mathrm{cm}^{-1}$, measured by beam emission spectroscopy (BES), for ECH compared to NBI-only heating. Increased fluctuations were also observed near 7 cm^{-1} during ECH as measured by Doppler reflectometry. These comparisons are made at fixed β_N=2.6 and fixed toroidal rotation velocity. The H_{98y2} confinement factor was ~10% lower for hybrid plasmas with 2.4 MW of ECH.

Additional experiments on DIII-D have measured the effect of toroidal rotation on hybrid discharges by varying the injected beam torque. Hybrid plasmas with co-NBI have peaked toroidal rotation profiles with a central Mach number near $M_\phi \approx 0.4$, while for nearly balanced-NBI the toroidal rotation profile becomes flat and the Mach number can be reduced to $M_\phi \approx 0.04$. The beneficial characteristics of the hybrid scenario are maintained with low torque injection; for example, sawteeth remain suppressed and the stability limit for 2/1 NTM is at least β_N=3.0. As the toroidal rotation velocity is reduced by

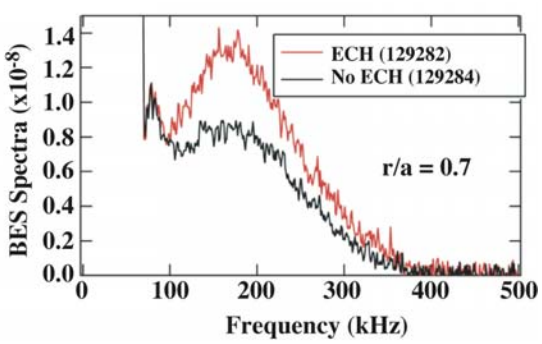

Fig. 1. Fluctuation power spectrum measured by BES with (red) and without (black) 2.4 MW of ECH in β_N=2.6 hybrid plasmas.

shifting from co-NBI to nearly balanced-NBI, the confinement factor is reduced from $H_{98y2} \geq 1.4$ to a value of $H_{98y2} \geq 1.1$, as good as conventional H mode with rotation. Modeling using the TGLF transport simulation code shows the increase in heat transport with lower NBI torque is consistent with the effects of the change in the E×B flow shear.

For the first time, large type-I ELMs have been completely suppressed in hybrid plasmas on DIII-D by applying edge RMPs with toroidal mode number *n*=3. This is an important advance in developing hybrid discharges as a baseline-operating scenario for ITER since such ELMs may cause unacceptable divertor erosion. This work builds upon the successful use of edge RMPs to suppress ELMs in the low collisionality, standard H-mode regime [3]. As seen in Fig. 2, ELMs are eliminated shortly after the RMP coil is turned on in ITER-shaped hybrid plasmas with β_N=2.5 and q_{95}=3.6. The RMP coil causes a substantial decrease in density, and the confinement factor drops from H_{98y2}=1.3 to H_{98y2}=1.0. The NTM island widths increase during RMP application, and the high performance phase of the plasma shown in Fig. 2 ends when a growing 3/2 NTM slows down and locks to the vessel wall. If β_N is lowered to 2.2, then complete RMP ELM suppression can be maintained without locking of the 3/2 NTM.

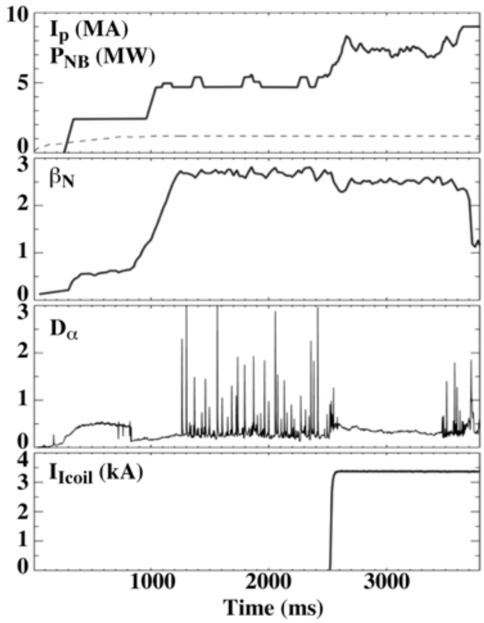

Fig. 2. ELM suppression by *n*=3 RMP: (a) NBI power (solid) and plasma current (dash), (b) normalized beta, (c) divertor D_α recycling signal, and (d) RMP coil current.

In both 2006&7 campaigns on DIII-D over 7000 seconds of plasma operation were conducted with no intervening boronizations. Throughout each campaign there was no noticeable decrease in hybrid performance. As shown in Fig. 3 the fusion gain factor, $\beta_N H_{89}/q_{95}^2$, (a) and the core carbon fraction (b) are not significantly different for hybrid shots that had very similar setup parameters but with greatly different intervening times since a boronization. The maintenance of good wall conditions over each of these campaigns was also seen in the impurity line emission and fueling/exhaust data from daily reference shots (not shown here).

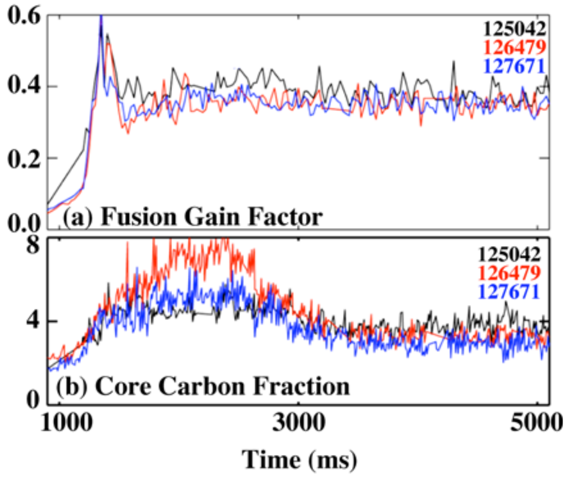

Fig. 3. The fusion gain factor (a) and the core carbon fraction (b) are shown for three hybrid discharges, taken 577 s (black), 6033 s (red), and 2094 s (blue) after the most recent boronizations. Shot 127671 (blue) was taken after a 6-week entry vent with no intervening boronization.

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