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Achieving Steady-State Conditions in High-Beta Hybrid Scenario in DIII-D PPC

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Steady-state conditions with simultaneous high beta, high confinement and zero loop voltage have been achieved in 1 MA discharges in DIII-D using efficient central current drive in the hybrid scenario. While the usual "advanced tokamak" (AT) approach leverages off-axis current drive to maintain a high safety factor minimum ($q_{\min}>2$) for high bootstrap current fraction [1], these experiments in DIII-D demonstrate the potential for a different steady-state AT regime based on the hybrid scenario [2,3]. This approach is characterized by an anomalously broad current profile that suppresses sawteeth by maintaining $q_{\min}$ slightly above one, as well as excellent confinement (H_{98y2}=1.6) and stability (β_N=3.6) to m/n=2/1 tearing modes. These experiments show that the beneficial characteristics of hybrids are maintained when strong central current drive from electron cyclotron (EC) and neutral beams (NBs) is applied to increase the non-inductive current fraction to ≈100%. Interestingly, good alignment between the current drive and plasma current profiles is not necessary as the poloidal magnetic flux pumping self-organizes the current density profile in hybrids with an m/n=3/2 tearing mode [4].

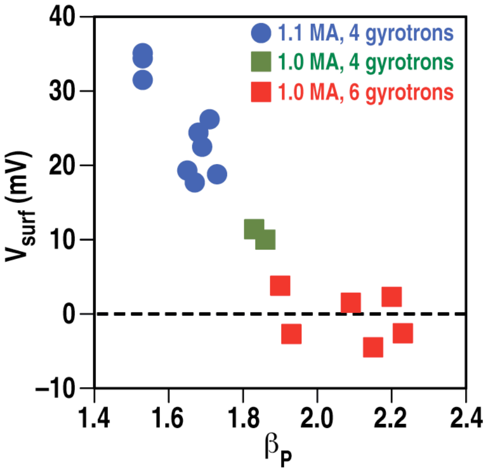

Fig. 1. Measured surface loop voltage as a function of poloidal β in hybrids with central current drive.

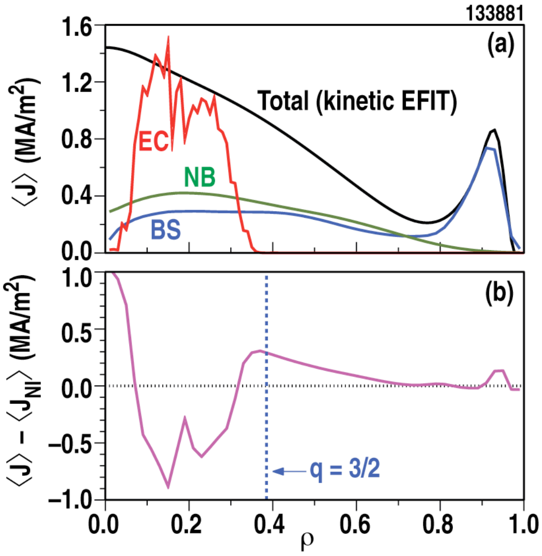

Fig. 2. (a) Total current density from EFIT, and modeled current density from EC, NB and bootstrap. (b) Difference between total EFIT current density and modeled noninductive current densities.

In hybrid discharges with central current drive, Fig. 1 shows that the surface loop voltage is driven down to zero for >1 τ_R when the poloidal beta is increased above 1.9 by raising the EC power to 3.05 MW and reducing I_P from 1.1 MA to 1.0 MA. Zero surface loop voltage is consistent with the calculated noninductive current. As seen in Fig. 2(a), hybrids can have slightly more than 50% bootstrap current fraction despite $q_{\min}$≈1; the other half of the plasma current is driven efficiently using central EC and NB current drive. The high on-axis current drive efficiency compensates for the moderate bootstrap current fraction. The current profile anomaly is displayed in Fig. 2(b), where the modeled noninductive current density is subtracted from the total current density determined by a well-constrained EFIT equilibrium reconstruction. Inside of the q=3/2 surface the current profile is predicted to be strongly overdriven, and time dependent TRANSP modeling shows that $q_{\min}$ should drop to ~0.8 by the end of the discharge. The fact that $q_{\min}$ remains above unity and sawteeth are suppressed shows that the hybrid scenario maintains an anomalously broad current profile even in the presence of strong central current drive.

Steady-state hybrid plasmas can achieve β_N=3.6 (β_T=3.4%) for the full duration of the NB pulse (>1 τ_R) without exciting the deleterious m/n=2/1 tearing mode. The theoretical stability limits are calculated by the DCON code using EFIT reconstructions constrained by the experimental pressure profile, motional Stark effect (MSE) polarimetry and a neoclassical calculation of the pedestal bootstrap current density. Figure 3 shows that the experimental β_N exceeds the no-wall n=1 stability limit ($\langle\beta_N\rangle$=2.9) while remaining well below the ideal with-wall n=1 limit ($\langle\beta_N\rangle$=4.3). It is interesting to note that the stabilizing effect of the wall in these plasmas, $(\beta-\beta_{\text{no-wall}})/(\beta_{\text{with-wall}}-\beta_{\text{no-wall}})\approx0.33$, is comparable to the AT scenario with $q_{\min}$>2.

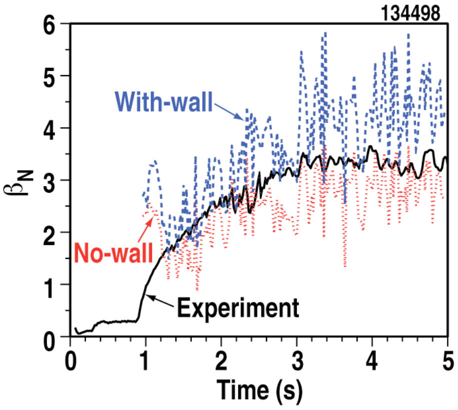

Fig. 3. Measured β_N for noninductive hybrid discharge compared to DCON calculations of the no-wall and ideal with-wall n=1 limits.

The thermal energy confinement time in these steady-state hybrids is excellent. Even with strong electron heating from EC, confinement factors of up to H_{98y2}=1.6 are achieved. The experimental electron density and electron/ion temperature profiles are well reproduced by the TGLF transport model. Measured changes in electron thermal transport, due to shape-induced pedestal changes or electron heating, parallel the predicted changes in the level of high-k turbulence. In particular, TGLF predicts that density profile peaking is stabilizing for the ETG mode and should result in lower electron thermal transport. Including finite beta effects in the TGLF modeling has a mild stabilizing effect, while the temperature profiles (at fixed density) are predicted to decrease by 12% on average if the effect of E×B shear is turned off in TGLF.

The high-β hybrid extrapolates favorably to steady-state scenarios in ITER and FNSF. Using the central EC current drive efficiency specified in the ITER Physics Basis, a zero-dimensional physics model demonstrates that attractive scenarios with Q_{fus}=3.5–3.8 exist for steady-state operation in these devices; higher gains can be obtained if higher efficiency NB current drive is utilized. Therefore, high-β hybrid plasmas with central current drive should be considered as an alternative method for achieving the fusion performance goals in steady-state scenarios in ITER and FNSF.

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[1] Taylor T.S. *et al* 1994 *Plasma Phys. Control. Fusion* **36** B229.
[2] Sips A.C.C. *et al* 2002 *Plasma Phys. Control. Fusion* **44** B69.
[3] Luce T.C. *et al* 2001 *Nucl. Fusion* **41** 1585.
[4] Petty C.C. *et al* 2009 *Phys. Rev. Lett.* **102** 045005.