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COMPATIBILITY OF INTERNAL TRANSPORT BARRIER WITH STEADY-STATE OPERATION IN THE HIGH BOOTSTRAP FRACTION REGIME ON DIII-D

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Compatibility of Internal Transport Barrier with Steady-state Operation in the High Bootstrap Fraction Regime on DIII-D

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Recent DIII-D experiments have demonstrated the potential of high bootstrap fraction operation with fully noninductive plasmas sustained for long durations with large-radius ITBs, bootstrap current fraction $f_{BS}\geq 80\%$, $\beta_N \geq 3$, β_T~1.5%, and good confinement even with low torque neutral beam injection (NBI). Such a high bootstrap current fraction plasma regime is desirable for steady-state tokamak operation because it reduces the demands on external non-inductive current drive. Typically, this regime is characterized by high β_N and an internal transport barrier (ITB), leading to concerns about stability limits and profile control with reduced external input (power). These experiments have increased confidence in the potential of the high bootstrap fraction approach for applicability to a steady state fusion reactor.

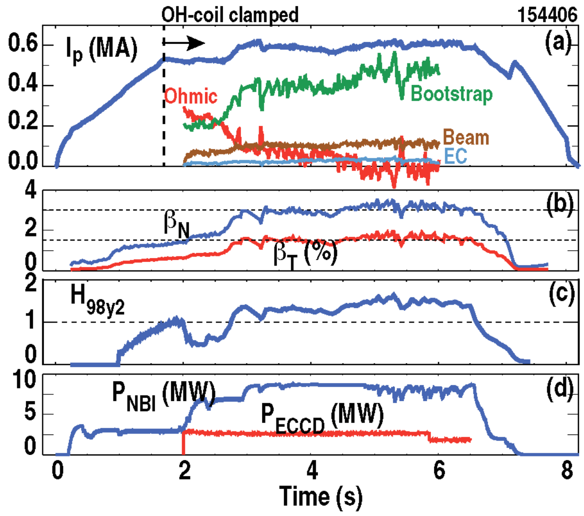

Fig. 1. Parameters for a discharge that reaches and maintains for almost 2 s a fully noninductive regime (154406). The transformer current is held fixed (clamped) after 1.7 s. (a) Plasma current and its various components, (b) β_N (blue), and β_T (red), (c) confinement enhancement factor over H-mode, H_{98y2}, and (d) injected heating and current drive power.

Building on earlier DIII-D work [1], the new experiments utilized an approach to fully non-inductive operation based on removing the current regulation by transformer control. Figure 1 shows time histories of several plasma parameters for a representative discharge. The plasma cross section is an upper biased double-null divertor shape, with elongation κ~1.86 and average triangularity (top and bottom) ~0.6. The toroidal field is B_T=2 T. After an approximate stationary condition is established (1.7 s), the current in the transformer coil is fixed, so that the plasma current is forced to relax non-inductively. A flattop at approximately 0.6 MA is maintained by increasing β_N and thus the bootstrap current fraction, until a 100% non-inductive condition is achieved and maintained for the rest of the discharge duration, limited by hardware constraints on DIII-D pulse length. The discharge achieves and maintains β_N~ $\beta_P\geq 3$ and β_T~1.5% using a total heating and current power of ~11 MW. This power includes ~5 MW of off-axis NBI (ρ~0.4), and 2.5 MW of off axis electron cyclotron current drive (ECCD) (ρ~0.5). The various current components plotted in Fig. 1(a) are calculated from experimental profiles by the TRANSP code. The bootstrap current fraction reaches 80%–85%, the NBI-driven current fraction is 15%–20%, and <5% of the total current is driven by EC frequency electromagnetic waves, since the efficiency of ECCD is very low at large minor radius.

This plasma exhibits excellent energy confinement quality, with confinement enhancement factor over H-mode confinement scaling H_{98y2}~1.5. Similar confinement was also obtained after reducing the NBI torque from ~6 Nm to ~3 Nm. This excellent confinement is associated with the formation of an ITB at large minor radius in all channels (n_e, T_e, T_i, rotation). Figure 2(a) shows representative radial profiles for T_e and T_i, both exhibiting a large gradient at ρ~0.7. In Fig. 2(b), the ion heat diffusivity calculated by TRANSP is shown to drop to the neoclassical predicted levels at ρ~0.7, indicating strong reduction of transport and confirming the presence of an ITB. Figure 2(c) shows a very broad bootstrap current profile that is fairly well-aligned with the total current profile, explaining why the minimum safety factor is high [Fig. 2(d)] and constant or slowly increasing, and the ITB is maintained at large minor radius for ~4 s, more than three times the current profile relaxation time, t_{CR} estimated to be ~1 s. Remarkably, high q_{min} is obtained even with reduced plasma current ramp-up rate, simply by also reducing the initial gas injection rate, and the ITB is formed well into the discharge evolution, after the L- to H-mode transition, and with Greenwald density fraction f_G~90% ($f_G = \bar{n}_e / n_G$, where $n_G = I_P/\pi a^2$ is the Greenwald density for plasma current I_P in MA and minor radius a in m). A further important result, providing evidence of dynamical stability, is that the ITB is maintained at large minor radius despite ELM perturbations, which become particularly large at the highest obtained β_N~3.5. Stability analysis shows that this β_N value is very close to the MHD stability limit with an ideal wall at the position of the DIII-D vessel. Indeed, these experiments used a large outer gap to reduce wall heating by prompt fast ion losses. However, detailed analysis shows that the fast ion losses are high (and anomalous) only during the β_N and density ramp-up phase. Once β_N and density reach flattop, the fast ion losses are reduced to near classical levels, despite the very high values of q_{min}. Future experiments will test an optimized outer gap waveform and methods of ELM control to enable a further increase of β_N and thus of I_P and β_T. It should be noted, however, that the levels of normalized fusion performance already achieved and sustained fully non-inductively (β_T~1.5%, f_{BS}~85%, f_G~90%), may be sufficient for economic electricity generation in a steady-state fusion reactor using available technology, as shown in recent ARIES ACT-2 reactor studies [2].

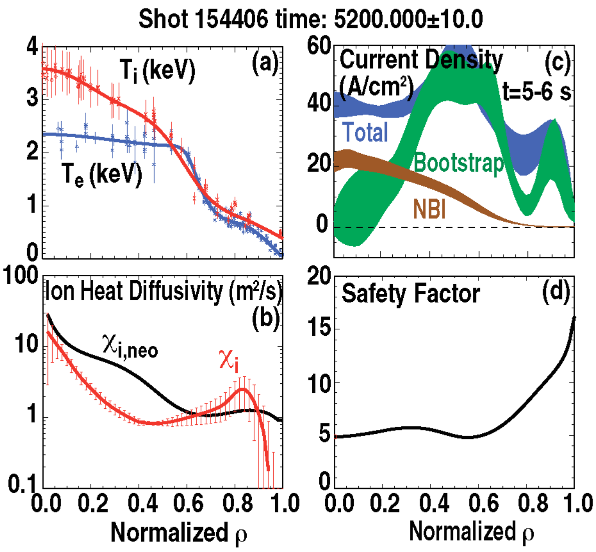

Fig. 2. Radial profiles for discharge 154406 in Fig.1 at t=5.2 s. (a) Ion and electron temperature, (b) ion heat diffusivity, compared to the neoclassical value, (c) current density profiles for the total current and its main components, and (d) safety factor.

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[1] P.A. Politzer, *et al.*, Nucl. Fusion **45** (2005) 417.
[2] F. Najmabadi, *et al.*, accepted for publication in Fusion Sci. Technol. (2014)