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FULLY NONINDUCTIVE SCENARIO DEVELOPMENT IN DIII-D USING NEW OFF-AXIS NEUTRAL BEAM INJECTION CAPABILITY

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Fully Noninductive Scenario Development in DIII-D Using New Off-Axis Neutral Beam Injection Capability

EX-S

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The new capability of off-axis neutral beam injection (Fig. 1) and increased electron cyclotron power have expanded the range of achievable and sustainable current and pressure profiles on DIII-D, leading to demonstration of nearly stationary plasmas with q_{min}=1.5 and β_N=3.5 for 3 s or 2 resistive equilibration times ($2\tau_R$). Separate experiments with q_{min}>2 have sustained β_N=3 for 1 s. In all cases, the attainable β_N and duration is limited by the available NBI power or energy. Importantly, the current and pressure profiles achieved in these cases have predicted ideal-wall n=1 kink mode β_N limits above 4, suggesting a path towards fully steady-state operation. In addition, these advances are providing an improved platform for assessing the current and pressure profiles of interest for developing the physics basis of steady-state scenarios in future tokamaks. Here, steady-state means the current is driven fully noninductively (i.e., $f_{NI} \equiv I_{NI}/I_p$=1 with $j_{ohmic}(\rho)$=0) by NBI, RF, and bootstrap current drive.

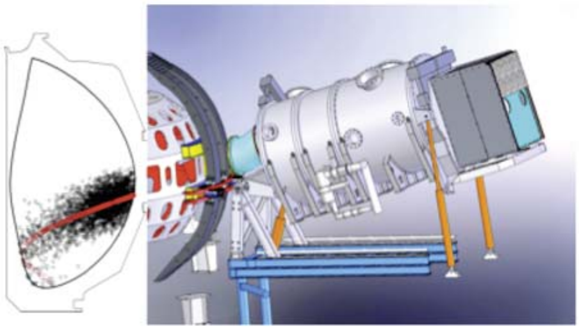

Fig. 1. 5 MW of off-axis neutral beam injection 16.5° to horizontal on DIII-D has improved access to advanced scenario current profiles.

With 5 MW off-axis NBI and ~ 3 MW of off-axis ECCD, nearly stationary plasmas were sustained for two current profile relaxation times ($2\tau_R$=3 s), with $q_{min}\approx$1.5, $\beta_N\approx$3.5, $f_{NI}\approx$70%, and performance that projects to $Q\approx$5 in an ITER-size machine (Fig. 2, red traces). This surpasses earlier results in similar plasmas lacking off-axis NBI and with less ECCD power that were stationary for $1\tau_R$ (Fig. 2, black traces). The duration of the high β_N phase was limited only by the available NBI energy. Low-order tearing modes were absent. ECCD was

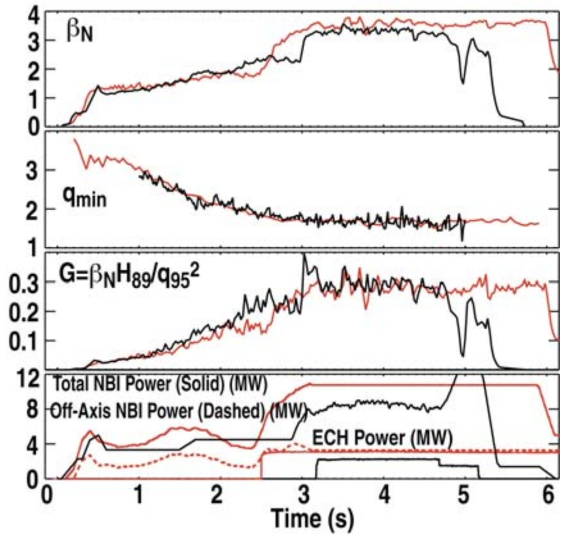

Fig. 2. High performance quasi-stationary plasma duration extended by using off-axis current drive.

applied broadly at ρ~0.2-0.6. Dynamic error field correction was required to minimize the resonant component of the error field. Active MHD spectroscopy measured a nearly linear plasma response amplitude with increasing β_N. The response increased faster above $\beta_N \approx 3.1$, indicating a proximity to the no-wall *n*=1 limit. The longer, $2\tau_R$, stable high β_N operation reduces the likelihood that the current profile will continue to evolve to one that is unstable to a tearing mode at β_N=3.5. The predicted ideal-wall *n*=1 kink mode β_N limit is >4. To achieve higher f_{NI}, higher β_N is needed to increase the bootstrap current, and higher q_{min} will decrease the required external current drive near the axis.

Preliminary attempts at achieving higher β_N with q_{min}>1.5 using off-axis NBI, albeit with only 2 out of 5 MW of off-axis NBI available, transiently achieved β_N=4 before a large off-axis fishbone mode caused a measured energetic particle loss, carbon influx, and a rapid loss of pressure, eventually resulting in a 2/1 tearing mode 300 ms later. Additional experiments to probe the β_N limit of q_{min}>1.5 plasmas with the full off-axis NBI power are planned.

Experiments to produce plasmas with q_{min}>2 showed that the use of off-axis NBI results in higher sustained q_{min}, with q_{min} at a larger radius (i.e. a broader current profile), and a broader pressure profile (Fig. 3). Modeling predicts that such profile changes increase the ideal-wall *n*=1 kink mode β_N limit, and in the plasmas shown in Fig. 3 the changes increased the predicted limit from below to above β_N=4. These plasmas achieved a maximum β_N=3.2 limited by the available NBI power and reduced confinement (H_{98}~1) relative to similar plasmas with lower q_{min} (H_{98}>1).

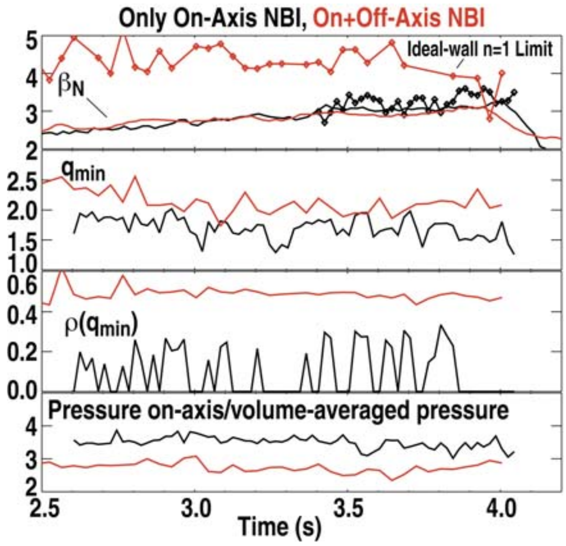

Fig. 3. Off-axis NBI broadens profiles, sustains q_{min}>2, and increases the predicted ideal-wall β_N limit (symbols).

During the *q*-profile scan with off-axis NBI, the most frequently observed instabilities were off-axis fishbones when q_{min}<2, *m/n*=2/1 tearing modes when q_{min}<2 and 5/2 and 3/1 modes when q_{min}>2. Ideal low-*n* kink or ballooning modes were not observed. Direct stabilization of modes with ECCD at specific rational surfaces was not used and is an option for future experiments.

These studies indicate that obtaining a sustained, high performance, f_{NI}=1 scenario involves a number of trade-offs related to the choice of *q*-profile. With q_{min}>2, there is a better match between the total on-axis current and the on-axis NBI current, 2/1 tearing modes are passively avoided, and off-axis fishbones are not observed. But the lower energy confinement means the predicted ideal-wall β_N limits above 4 are difficult to reach with the available heating power, and 5/2 and 3/1 tearing mode stability is still an issue. Nearly stationary plasmas with q_{min} between 1.5 and 2 have been found that are stable to tearing modes at β_N=3.5. These have higher energy confinement, but more external current drive is needed near the axis to achieve f_{NI}=1, and off-axis fishbones can limit β_N. Future experiments will employ increased NBI and ECCD power to identify a suitable *q*-profile within these constraints.

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