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

by

APRIL 2012
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This is a preprint of the synopsis for a paper to be presented at the Twenty-fourth IAEA Fusion Energy Conf., October 8-13, 2012 in San Diego, California.

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Work supported in part by the U.S. Department of Energy under DE-AC52-07NA27344, DE-FC02-04ER54698, DE-FG02-04ER54761, DE-AC02-09CH11466, DE-FG02-08ER85195, DE-FG02-08ER54984, DE-AC05-00OR22725, and SC-G904302

GENERAL ATOMICS PROJECT 30200
APRIL 2012
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Fully Noninductive Scenario Development in DIII-D Using New Off-Axis Neutral Beam Injection Capability

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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 $q_{\text{min}}=1.5$ and $\beta_N=3.5$ for 3 s or 2 resistive equilibration times ($2\tau_R$). Separate experiments with $q_{\text{min}} > 2$ have sustained $\beta_N=3$ for 1 s. In all cases, the attainable $\beta_N$ 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 $\beta_N$ 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., $f_{\text{NI}}=I_{\text{NI}}/I_p=1$ with $j_{\text{ohmic}}(\rho)=0$) by NBI, RF, and bootstrap current drive.

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 $q_{\text{min}}=1.5$, $\beta_N \approx 3.5$, $f_{\text{NI}}=70\%$, 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 $\beta_N$ phase was limited only by the available NBI energy. Low-order tearing modes were absent. ECCD was

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.

Fig. 2. High performance quasi-stationary plasma duration extended by using off-axis current drive.
applied broadly at $\rho \approx 0.2-0.6$. 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 $\beta_N$. The response increased faster above $\beta_N \approx 3.1$, indicating a proximity to the no-wall $n=1$ limit. The longer, $2\pi_R$, stable high $\beta_N$ operation reduces the likelihood that the current profile will continue to evolve to one that is unstable to a tearing mode at $\beta_N = 3.5$. The predicted ideal-wall $n=1$ kink mode $\beta_N$ limit is $>4$. To achieve higher $f_{NI}$, higher $\beta_N$ 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 $\beta_N$ with $q_{min} > 1.5$ using off-axis NBI, albeit with only 2 out of 5 MW of off-axis NBI available, transiently achieved $\beta_N = 4$ 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 $\beta_N$ 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 $\beta_N$ limit, and in the plasmas shown in Fig. 3 the changes increased the predicted limit from below to above $\beta_N = 4$. These plasmas achieved a maximum $\beta_N = 3.2$ limited by the available NBI power and reduced confinement ($H_{98} \approx 1$) relative to similar plasmas with lower $q_{min}$ ($H_{98} > 1$).

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 $\beta_N$ 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 $\beta_N = 3.5$. 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 $\beta_N$. Future experiments will employ increased NBI and ECCD power to identify a suitable $q$-profile within these constraints.

This work was supported by the US Department of Energy under DE-AC52-07NA27348, DE-FC02-04ER54698, DE-FG02-04ER54761, DE-AC02-09CH11466, DE-FG02-08ER85195, DE-FG02-08ER549874, DE-AC05-00OR22725, and SC00G804302.