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Global stability of elevated-q$_{min}$, steady-state scenario plasmas on DIII-D

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Recent experiments on DIII-D have utilized the new off-axis neutral beam injection (NBI) power to achieve β_N = 3.8 with n = 1 ideal stability limits up to β_N = 6. The NBI upgrade adds two additional co-current, off-axis, beams giving a total of 8 MW of on- and 7 MW of off-axis NBI power for advanced tokamak (AT) scenario development in these experiments. In addition, 1.6 MW of electron cyclotron (EC) power is used as an additional off-axis heating and current drive source. These off-axis current drive sources broaden the current and pressure profiles to better couple to the vessel wall thereby raising the ideal-wall, low-n kink stability β_N limits.

Despite higher ideal stability limits with the additional off-axis current drive capabilities, a majority of these high-q$_{min}$ discharges are limited by tearing modes. Past analysis indicates discharges with higher ideal stability limits have higher tearing mode stability limits[1]. However, these recent experiments, with the additional off-axis beam power, have increased the ideal-wall limit without apparent improvement in tearing mode stability. The DCON stability code[2] is used to calculate the ideal-wall and no-wall stability limits. At the time of tearing mode onset, the ideal-wall β limits range between β_N = 4.2-5.7, no-wall β limits between β_N = 2.8-3.5, and achieved experimental β_N = 2.5-3.8, Fig. 1. In three of the discharges, tearing modes form with an ideal-wall β limit of $\beta_N > 5$ and experimental $\beta_N < 3$. Clearly, increasing ideal stability limits has not been sufficient for preventing the frequent appearance of tearing modes in these discharges. Furthermore, it is observed that tearing modes frequently form when β_N is near the no-wall stability limit. None of the discharges exceed the no-wall β limit by more than 10% despite ideal-wall stability limits that exceed the no-wall limits by 50%. With the additional beam power available, these discharges are stability, not power, limited. A better understanding of tearing mode onset physics and avoidance requirements is needed for this regime.

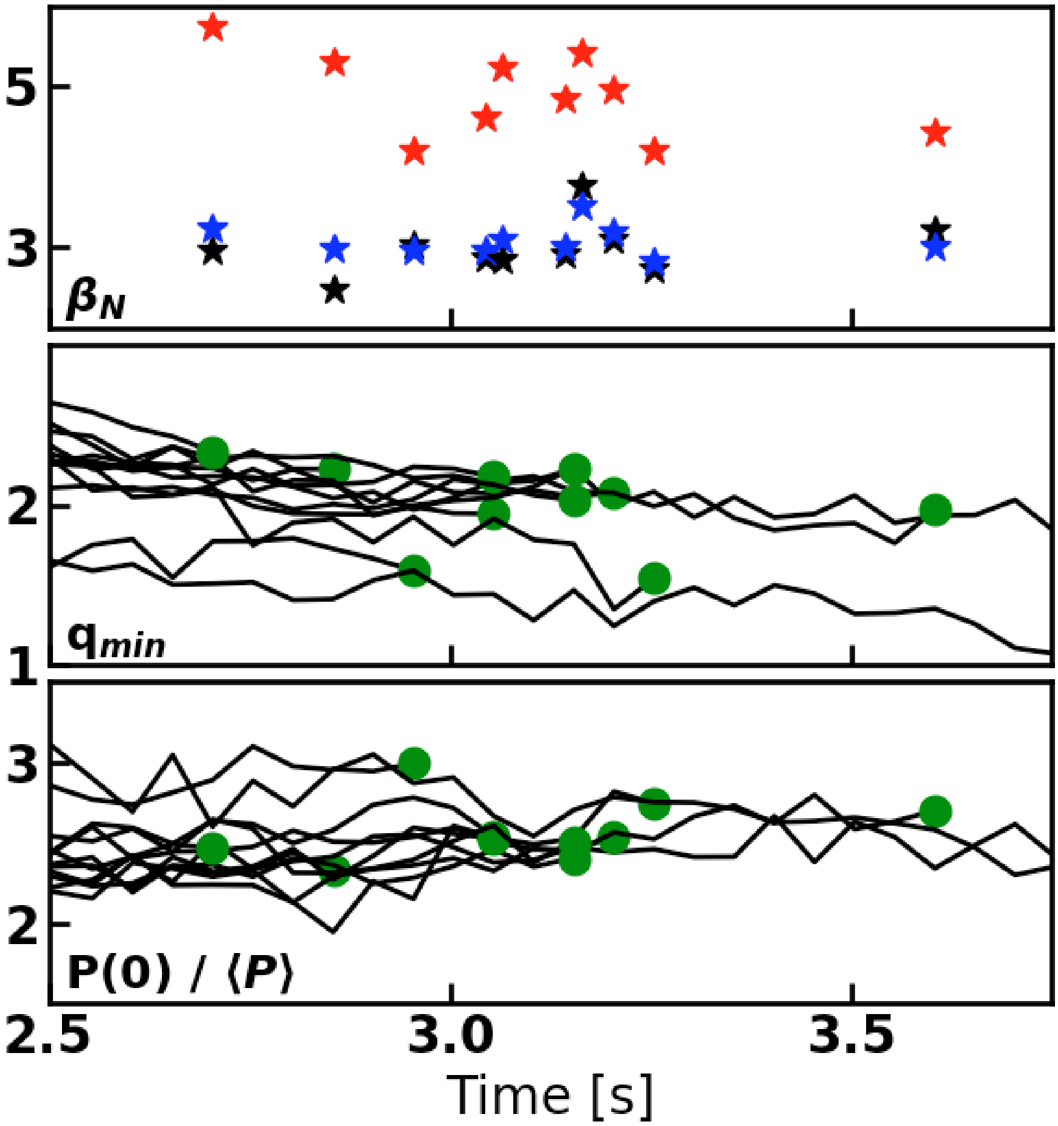

Figure 1: n=1 Ideal-wall (red) and no-wall (blue) β limits compared to the plasma β (black) at time of tearing mode onset for multiple discharges. Evolution of q_{min} and peaking factor shown up to the appearance of the 3/1 tearing modes (green circles).

Large tearing modes in these plasmas are m/n = 3/1 and result in a confinement reduction of $\approx$50%. A majority of the tearing modes have a 5/2 tearing mode precursor, which causes a relatively minor reduction in confinement. Tearing modes occur in 10 of 12 discharges shown in Fig. 1 with the tearing mode onset indicated by a circle. After the tearing mode forms, the plasma confinement does not recover in a majority of the discharges.

q_{min} > 2 operations eliminate the 2/1 rational surface from the plasma and avoid deleterious fast-ion modes. However, confinement reduction from 3/1 tearing modes have been significant enough to prevent higher β_N operation in this regime. Timing and onset of tearing modes do not show a clear relationship to broader current (higher q_{min}) or pressure (lower pressure peaking factor) profiles for operations near q_{min} = 2.

The highest β_N with the new off-axis NBI capabilities compared to a similar discharge with all on-axis NBI power was achieved with q_{min} = 1.1-1.5, Fig. 2. This discharge achieved ideal β_N stability limits near 6, significantly higher than the reference discharge with only on-axis beam power. Feedback control with 3D fields was applied in both discharges to maintain optimal error field correction and resistive wall mode stabilization. In addition, this result was achieved despite a reduction in available EC power from 2.9 to 1.6 MW.

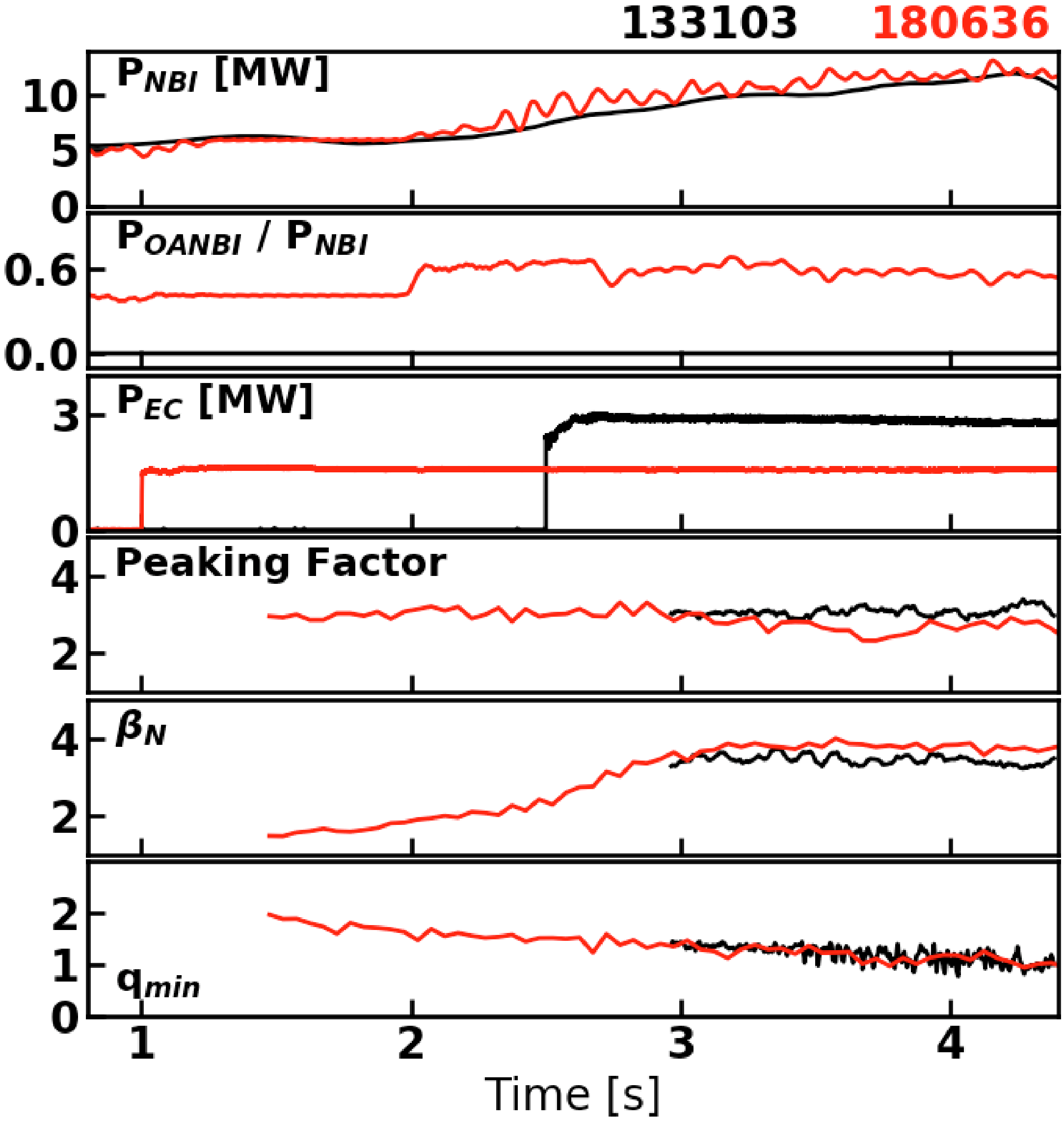

Figure 2: Before (black) and after (red) NBI upgrade.

Predictive TRANSP simulations aided the development of these discharges with increased off-axis NBI power. TRANSP runs of past discharges with majority on-axis beam power were modified to inject power with the new off-axis beam geometry. TGLF was used to evolve the temperature, density, and current profiles with the increased off-axis NBI power. These predictive simulations showed that early application of EC power raises q_{min} and increases the non-inductive current fraction of the plasma, which was observed in subsequent experiments. Broadening of the NBI current density profile with the new beam geometry was also accurately predicted using TGLF in TRANSP.

High fusion gain steady-state tokamaks are based on broad current and pressure profiles to achieve wall-stabilization of ideal-MHD kink modes at high β_N. The results discussed show that obtaining a high ideal-wall limit, while necessary, is not sufficient, as tearing modes still appear at lower β_N, usually around the no-wall limit. The relationship between the ideal- and no-wall stability limits and the current density and pressure profiles that determine tearing mode stability will be explored to better sustain higher β_N plasmas.

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[1] F. Turco, et. al, Physics of Plasmas 19, 122506 (2012).
[2] A. H. Glasser, Physics of Plasmas 23, 072505 (2016).

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