Improving fast-ion confinement in high-performance discharges by suppressing Alfvén eigenmodes

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We show that the degradation of fast-ion confinement in steady-state DIII-D discharges [1] is quantitatively consistent with predictions based on the effects of multiple unstable Alfvén eigenmodes on beam-ion transport (Figs. 1a and b). Simulation and experiment show that increasing the radius of $q_{\rm min}$ is effective in minimizing beam-ion transport (Figs. 1c and d). This is favorable for achieving high performance steady-state operation in DIII-D and future reactors.

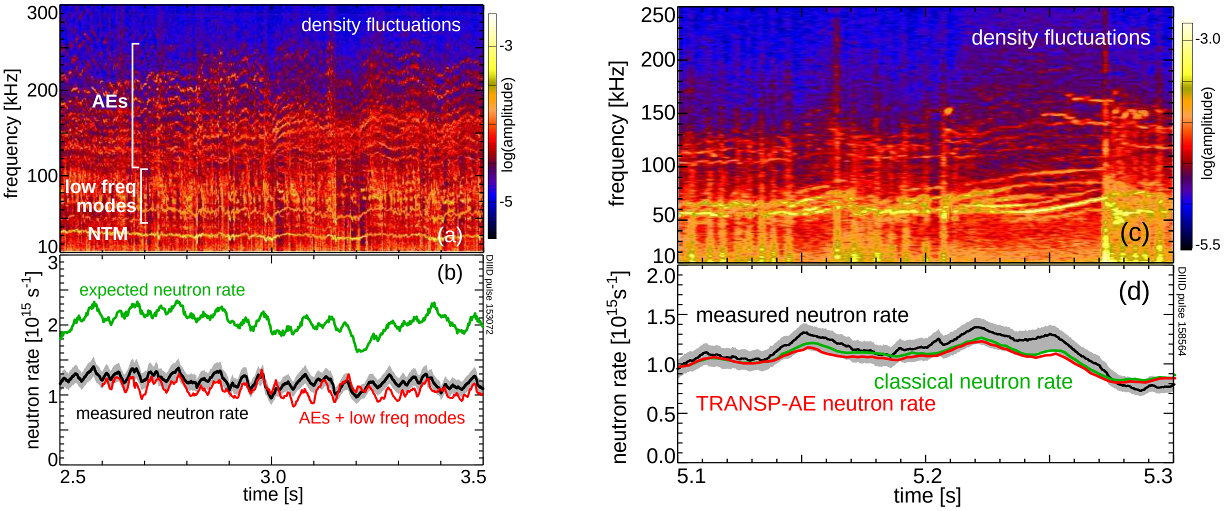

FIG. 1: (a) Observed density fluctuations in a high-performance steady-state target discharge with a multitude of AEs and (b) high levels of AE-induced fast-ion transport as deduced from neutron measurements (black experimental, green classical, and red the neutron rate with the effects of AEs and low frequency modes included). (c) and (d) show the same quantities for a high-$q_{\rm min}$ high β_p discharge with an increased radius of $q_{\rm min}$. The measured neutron rate (black) compares well to the classical neutron rate (green) and the neutron rate with the AE effects are included (red).

Anomalous fast-ion transport has been problematic for reaching a steady-state regime in DIII-D because the fast-ion loss reduces the neutral-beam current drive and it is limiting the β, needed to drive a sufficient bootstrap current for reaching steady state. Reducing the fast-ion transport down to classical levels will help in achieving non-inductive current-dominated discharges.

During the steady-state phase of neutral beam heated DIII-D discharges with high $q_{\rm min}(> 2)$ and high poloidal $\beta(> 2)$ a rich spectrum of Alfvén eigenmodes (AEs) is observed on multiple diagnostics such as the CO_2 interferometer as can be seen in Fig. 1a. The AEs appear in the TAE and EAE range of frequencies. On occasions the spectrum also shows lower-frequency modes in the beta-induced Alfvén eigenmode frequency range. The neutron rate as predicted by the TRANSP code using classical slowing-down and pitch angle scattering for the beam ions overestimates the measured neutron rate by a factor two as can be seen in Fig. 1b. When the effects of the AEs and other low-frequency modes on the fast-ion population are included self-consistently in TRANSP by using the kick model [2] which takes into account the resonant

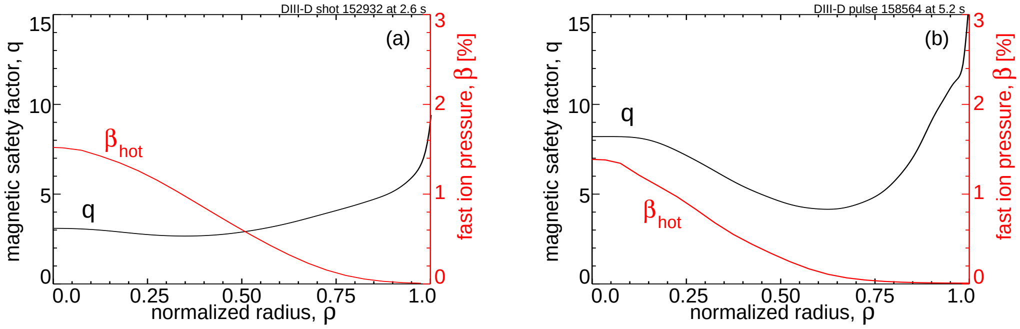

FIG. 2: Magnetic safety factor and fast-ion pressure profiles for (a) a typical discharge with high levels of AE activity and a significant neutron deficit and (b) a discharge where the AE activity is suppressed due to the misalignment between the fast-ion pressure gradient and $\mathrm{q_{min}}$.

effects between the modes and the fast-ions in a quasi-emperical way, the calculated neutron rate reduces to the measured one as is shown in Fig. 1b. This agreement with the measurement is remarkable because there are no adjustable parameters in the kick model.

The calculated large fast-ion loss is due to the unfavorable alignment of the AEs with the steep fast-ion pressure gradient. In typical DIII-D high-performance steady-state target discharges the steep fast-ion pressure gradient which drives the AEs lines up well with the minimum in the q profile (Fig. 1a) where the Reversed Shear AEs (RSAEs) are localized. By moving the location of $\mathrm{q_{min}}$ away from the steep fast-ion pressure gradient region (Fig. 2b) the RSAE drive decreases and RSAEs associated with higher order gaps are expected to disappear into the Alfvén continuum as was shown in [3].

The recipe for removing AE-induced fast-ion loss by elevating q(0) to suppress core-localized AEs and increasing the radius of $\mathrm{q_{min}}$ to weaken the RSAE drive is also favorable for achieving high β_p steady-state discharges in DIII-D and future reactors. Evidence that this approach mitigates fast-ion loss is found in low current high β_p discharges where it is easier to generate a large radius of $\mathrm{q_{min}}$ in DIII-D with exisitng current drive capabilities (Fig. 2b) [1]. In this case $\mathrm{q_{min}}$ was located near $r/a = 0.6$, well outside the steep fast-ion pressure gradient region as can be seen in Fig. 2b. In the density fluctuation spectrum only RSAEs are visible between 50 and 100 kHz (Fig. 1c) and some weaker AE activity above 100 kHz. ECE measurements confirm that the RSAEs are located at large radius. The ideal MHD code NOVA reproduces the location and frequencies very accurately and the kick model reproduces the observed neutron rate within experimental uncertainties (Fig. 1d). This indicates that the fast-ion confinement has returned to its classical value.

Moreover, an elevated monotonically decreasing q profile in the plasma center is also favorable for suppressing TAEs. It has been shown in [4] that TAEs move from the TAE gap into the continuum when the the normalized pressure gradient is increased above a critical value.

While conditions for AE suppression have been demonstrated at high $\mathrm{q_{min}}$, a challenge for DIII-D remains to produce a large radius of $\mathrm{q_{min}}$ in high-performance high-current plasmas that are required for steady-state reactors. Upgrades to DIII-D are planned with additional off-axis beams and increased ECCD and helicon current drive that are expected to increase the radius of $\mathrm{q_{min}}$ and test steady-state solutions for future fusion reactors.

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