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Probing Resistive Wall Mode Stability Using Off-axis NBI

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Abstract. DIII-D experiments with off-axis neutral beam injection (NBI) show increased resistive wall mode (RWM) damping as the fraction of NBI power is shifted off-axis. Measurements of the plasma response to slowly rotating, applied n=1 perturbations decrease in amplitude as the fractional mix of off-axis NBI power is increased at constant normalized beta, indicating increased damping of the RWM. This reduction of the plasma response amplitude due to the off-axis injection is observed in repeatable plasmas over a range of plasma rotation values. Present day tokamaks are routinely able to operate above the ideal MHD no-wall beta-limit predicted for n=1 external kink instabilities, and a theory incorporating kinetic modifications to the ideal MHD RWM dispersion relation is consistent with the parametric dependencies of experimental stability measurements. The present theory includes several mechanisms that lead to an exchange of energy between the RWM and kinetic particle populations, including damping due to passing ions near rational flux surfaces. Transport simulations based on reconstructions of the experimental equilibria show a decreased trapped ion fraction as the off-axis NBI power is increased, an effect that can lead to increased kinetic damping. However, ideal MHD calculations based on the experimental equilibria also indicate increased RWM damping with increased off-axis NBI power, restricting the possible magnitude of changes in kinetic damping. The observed increase in RWM damping due to off-axis NBI provides a new test for passive stability models needed to predict performance limits in ITER and future burning plasma devices.

1. Introduction

Understanding the damping of the resistive wall mode (RWM) instability is a critical topic for projecting the performance of present-day tokamak plasmas to future burning plasma devices. The RWM arises from the interaction between long-wavelength plasma external kink modes and eddy currents in nearby conducting structures (i.e. walls) induced by the perturbed flux of the mode. Unstable RWMs are potentially disruptive instabilities, usually leading to severe degradation in plasma confinement. Ideal MHD theory predicts that RWMs are unstable when the normalized plasma pressure $\beta=2\mu_0 \langle p\rangle/B_0^2$ exceeds a critical value referred to as the no-wall β-limit. Here, $\langle p\rangle$ is the volume-averaged plasma pressure and B_0 is the magnetic field on axis.

However, tokamak devices are able to attain stable operation above the no-wall limit [1–3]. The observed damping of the RWM in this regime is consistent with a theory incorporating kinetic modifications to ideal MHD, allowing for exchange of energy and torque between the RWM and kinetic particle populations [4]. For example, kinetic theory includes resonances between the bounce and precession drift frequencies of thermal trapped ions and the plasma rotation. The predicted damping due to these resonances is consistent with the transition to instability at an intermediate level of rotation in NSTX and the non-monotonic rotation dependence of RWM damping in MAST and DIII-D [5–7]. The inclusion of the damping due to super-thermal beam ions is needed to explain the observed stability over a broad range of plasma rotation values in DIII-D plasmas [7].

External magnetic fields with spatial structures that couple to the kink mode can drive a damped RWM response in stable plasmas [8]. Magnetic measurements of the driven plasma response δB^{plas} can be used to constrain terms in stability models, providing a means of non-destructively assessing the proximity to the marginal stability point [9,10]. At fixed plasma parameters, the dependence of δB^{plas} on the driving frequency of a rotating external perturbation is consistent with a single-mode model, with a pole near the natural rotation frequency of the RWM, about 10 Hz in DIII-D [9]. An important consequence of the single mode model is that the plasma response amplitude increases monotonically as marginal stability is approached [8].

A recent modification to the neutral beam injection (NBI) system on DIII-D allows for one of the four beam-lines to be tilted at an downward angle up to 16.5 degrees from the plasma midplane for off-axis injection. When the plasma current and vacuum toroidal field directions are chosen so that the field line pitch is favorably aligned with the off-axis beam, broader equilibrium profiles, increased beam-driven current, and a decreased fraction of trapped particles f_{trap} are expected [11]. Experimental measurements with individually energized beam sources have qualitatively confirmed the expected broadening of the beam pressure profile and decrease in f_{trap} with off-axis NBI in the favorable field pitch configuration [12]. The off-axis injection capability provides a new tool to access novel equilibrium and kinetic particle distribution states for testing RWM stability theories. With all else constant, the decrease in f_{trap} is expected to result in increased kinetic damping of the RWM from passing ions. In the experiments described here, 10% changes in f_{trap} and the peaking of the total pressure profile were correlated with a factor of 2 change in δB^{plas} as the fraction of off-axis NBI power was varied. Preliminary linearized ideal MHD stability calculations are qualitatively consistent with the observed trend in the plasma response, but a calculation of the kinetic damping has not yet been carried out. In Sec. 2, measurements of δB^{plas} with variations in the injected off-axis NBI power are described. Equilibrium and transport analysis of a discharge with off-axis NBI are discussed in Sec. 3, and RWM damping measurements are compared with ideal MHD stability theory in Sec. 4.

2. Impact of Off-axis NBI on RWM Damping

The impact of off-axis NBI on RWM damping is assessed in lower single-null high confinement regime plasmas. RWM stability is measured by applying a 0.4 kA, n=1 AC perturbation the DIII-D non-axisymmetric internal coil array [I-coil, Fig 1(a)]. The perturbation rotates in the toroidal direction at 20 Hz, and the synchronous, n=1 radial field plasma response, $\delta B^{plas} = B - B^{vac}$ is measured using a toroidal array of external saddle-loop sensors on the DIII-D midplane [Fig 1(a)] as in Ref. 9. The plasma response values reported here are normalized to the perturbing coil current I^{coil}. The n=1 vacuum pickup B^{vac} in the sensors due to the applied coil perturbation is 0.4 G (1 G/kA).

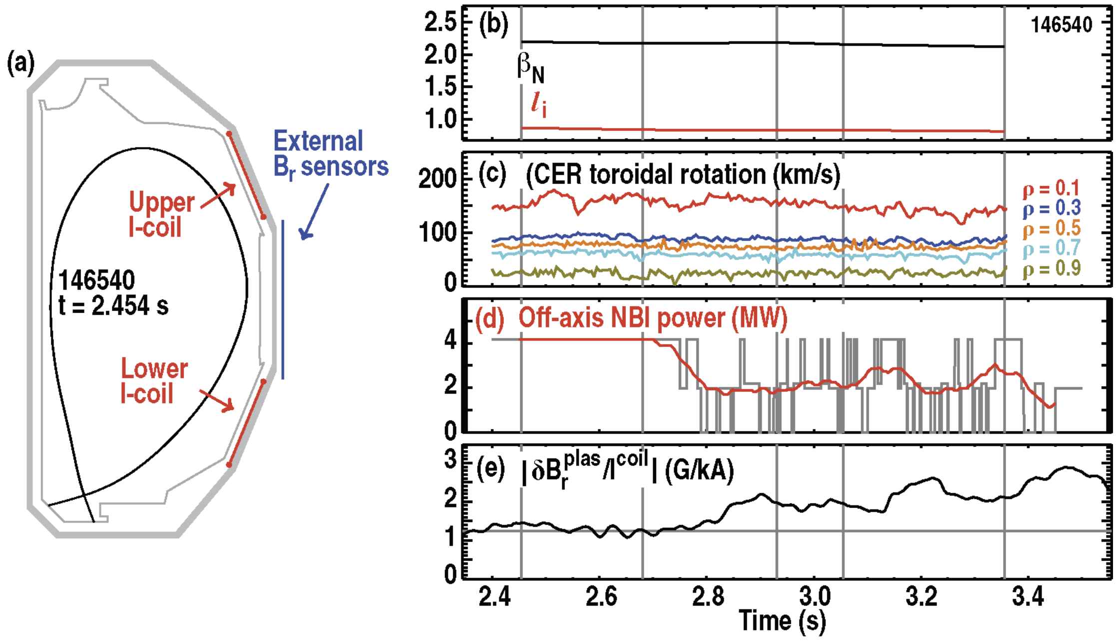

FIG. 1. (a) Plasma cross-section and positions of I-coil and external B_r sensor arrays. Time-evolution of (b) normalized beta and plasma internal inductance, (c) CER spectroscopy rotation chords, (d) off-axis NBI power, and (e) measured plasma response amplitude. Vertical lines indicate times of equilibrium and stability analyses.

An increase in the plasma response amplitude $|\delta B^{plas}/I^{coil}|$ from 1 to 2 G/kA follows a step-reduction in applied off-axis NBI power from 4 to 2 MW (Fig. 1). During this time interval, normalized beta β_N is held constant near 2.2 using NBI feedback, and a plasma current ramp of 0.2 MA/s is used to maintain a plasma normalized internal inductance l_i between 0.87 and 0.81. The carbon impurity rotation profile measured using charge exchange recombination (CER) spectroscopy remains constant except for a slight decrease near the core. As the off-axis beam power is stepped down, the NBI feedback algorithm shifts more power to on-axis sources, with the result that the total power stays constant near 12 MW.

The reduction in plasma response amplitude with off-axis NBI, indicating increased RWM stability, is observed over a range of plasma rotation values. Figure 2(a,b) shows the dependence of the amplitude and toroidal phase-shift of the plasma response on toroidal plasma rotation near the q=2 surface, at constant β_N, q_{95}, and plasma density. The rotation is varied by adjusting the level of applied NBI torque. Due to changes in plasma energy confinement with rotation and the practical constraint that the off-axis beam tilt remain fixed during an experimental run day, it was not possible to complete full scans of the rotation range shown for all levels of off-axis NBI power and constant β_N=2.2. The falloff in plasma response amplitude on either side of the peak near 40 km/s has been attributed to damping due to resonances between the plasma rotation and the precession-drift and bounce frequencies of trapped ions [7]. In the rotation range between 55 and 70 km/s near q=2, increased damping of the plasma response with off-axis NBI power is clearly visible [Fig. 2(c,d)].

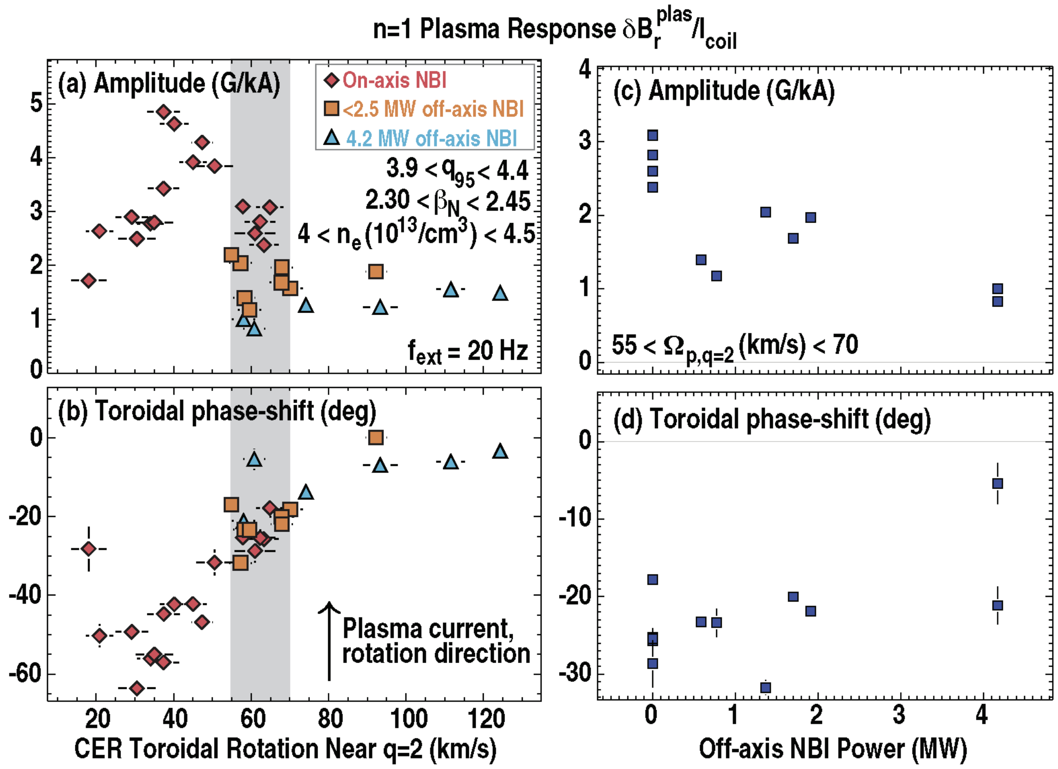

FIG. 2. Dependencies of measured plasma response (a,c) amplitude and (b,d) toroidal phase on toroidal rotation near q=2 (a,b) and off-axis NBI power (c,d), at fixed q_{95}, β_N, and density. The vertical grey band indicates the rotation range for the data shown in parts (c) and (d).

3. Equilibrium and Transport Analysis

Axisymmetric equilibrium reconstructions were performed for five time-intervals in DIII-D (shot 146540) to provide a basis for transport and stability modelling. In addition to data from magnetic probes and flux loops, the reconstructions are constrained by motional Stark effect (MSE) measurements of the internal magnetic pitch angle, and transport calculations of the total plasma pressure and edge bootstrap current density. The reconstructed profiles of the pressure, current density, and safety factor are shown in Fig. 3(a-c). Following the reduction in off-axis beam power at t = 2750 ms, the core pressure increases with little or no change outside ρ=0.2. The q-profile decreases with time, consistent with the gradually increasing plasma current.

Profiles of the calculated toroidal rotation associated with the radial electric field, $\omega_E = -d\phi/d\psi$, density of fast beam ions, and trapped fraction are shown in Fig. 3(d–f). Here, ϕ represents the electrostatic potential and ψ the poloidal flux. The ω_E profile shows some core variation that does not appear to be well correlated with changes in the off-axis beam power or the plasma response amplitude. The beam ion density and trapped fraction profiles are calculated using the TRANSP code with the NUBEAM module [13,14], and increase slightly near the core and mid-radius (respectively), following the reduction in off-axis NBI power. The ratio of the volume-integrated fast to total stored energy remains constant at 0.3 for the times shown.

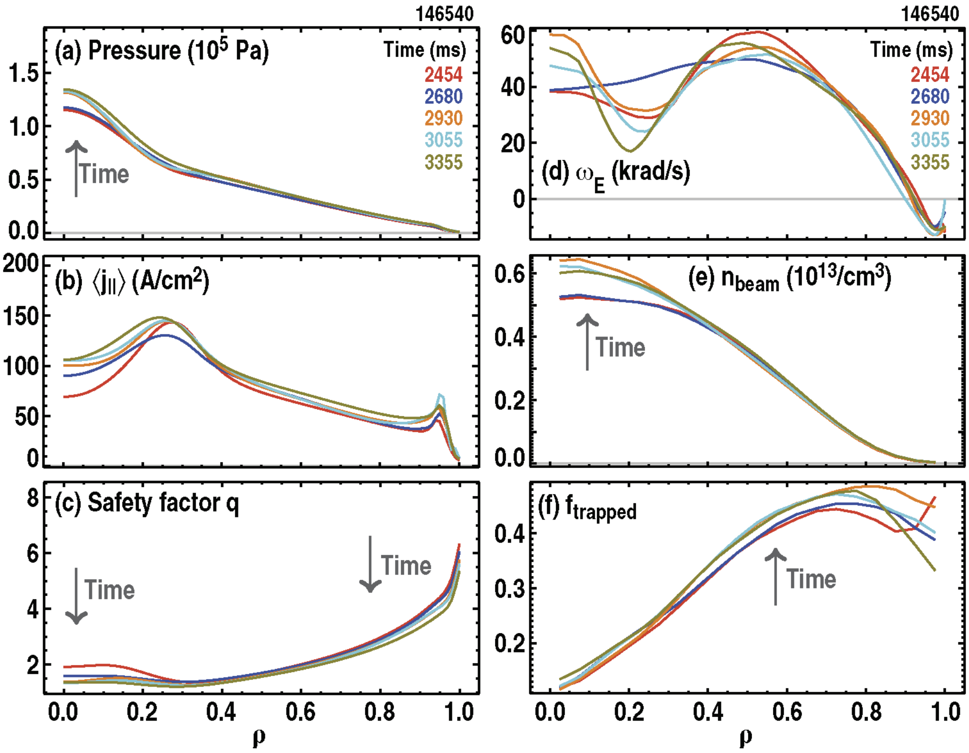

FIG. 3. Reconstructed (a) total pressure, (b) current density, and (c) safety factor; calculated (d) ω_E rotation, (e) beam ion density, and (f) trapped fraction profiles for five time-intervals during shot 146540.

4. Comparison with Linear Ideal MHD Theory

Ideal MHD simulations of RWM stability are a necessary prerequisite to modeling kinetic stability contributions. Figure 4(a) shows the time-evolutions of the ideal MHD n=1 no-wall and ideal-wall stability limits for the series of equilibria shown in Fig. 3. The stability limits are obtained by self-similarly scaling the equilibrium pressure profile until a sign change in the ideal MHD energy principle δW, calculated using the DCON code, is obtained [15]. The no-wall and ideal-wall beta limits decrease as the discharge evolves, likely due to the simultaneous decrease in l_i and increase in the pressure peaking factor $p(0)/\langle p\rangle$ [Fig. 4(b)] [16].

An RWM dispersion relation of the form

$$\gamma\tau_w = \frac{\delta W^{\text{no-wall}}}{\delta W^{\text{ideal-wall}}} \quad , \qquad (1)$$

can be derived from ideal MHD theory, where $\delta W^{\text{no-wall}}$ and $\delta W^{\text{ideal-wall}}$ are the perturbed energies with and without a perfectly conducting wall at the location of the experimental wall and τ_w is the n=1 wall eddy current decay timescale, about 2.5 ms for DIII-D [17]. The ideal MHD growth rate is strictly real, because the theory does not include a mechanism by which the plasma can exert a torque on the RWM.

The single mode plasma response model can also be inverted to obtain the complex RWM growth rate consistent with the measured plasma response

$$(\gamma + i\omega)\tau_w = \frac{(\omega_{ext}^2 \tau_w^2 - i\omega_{ext}\tau_w)\delta B^{plas}/I^{coil} + M_{sc}^*}{(i\omega_{ext}\tau_w + 1)\delta B^{plas}/I^{coil} + M_{sc}^*} \quad . \tag{2}$$

Here, ω_{ext} is the angular frequency of the applied external perturbation and M_{sc}^* = 1.0+0.3i G/kA is an empirically determined coil — mode coupling coefficient [9].

A comparison of the ideal MHD growth rate calculated using Eq. (1) and the real-part of the plasma response growth rate from Eq. (2) is shown in Fig 4(c). Qualitative agreement is obtained between the calculations, but the ideal MHD calculation under-predicts the growth rate by roughly a factor of 3.

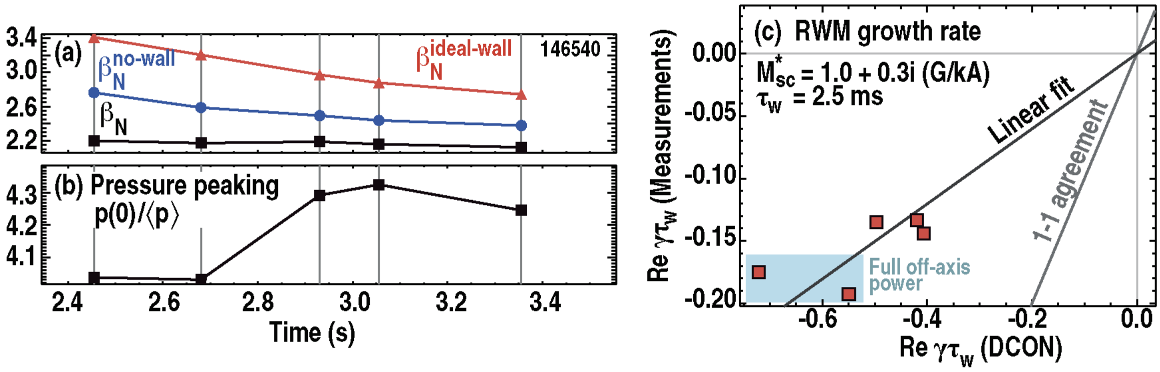

FIG. 4. Time evolutions of the calculated (a) normalized beta and n=1 no- and ideal-wall beta limits, and (b) pressure peaking factor for DIII-D shot 146540. (c) Comparison of the n=1 RWM growth rate calculated from plasma response measurements (vertical axis) and using the DCON code (horizontal axis). The diagonal lines represent (black) a linear fit of the measured to simulated growth rates and (grey) the locus of 1-1 agreement between the measured and simulated growth rates. Growth rates are normalized to n=1 wall eddy-current decay timescale τ_W=2.5 ms. The blue rectangle highlights data points from early in the discharge with the maximum level of off-axis power, 4.2 MW.

5. Summary

Shifting 15% of the total NBI power from off-axis to on-axis injection results in a factor of 2 increase in the measured magnetic plasma response to an externally applied n=1 magnetic perturbation, indicating decreased RWM damping. The damping effect due to off-axis NBI persists over a range of plasma rotation values at constant β_N, q_{95}, and plasma density. The application of off-axis NBI results in both broader total pressure and fast ion density profiles, and a 10% reduction in the fraction of trapped ions at mid plasma radius.

Preliminary ideal MHD calculations show a trend in the RWM growth rate consistent with a growth rate estimation from plasma response measurements. However, the agreement is only qualitative: the ideal MHD calculation underestimates the growth rate by about a factor of 3. This underestimation is perplexing inasmuch as including kinetic damping terms would result in a further reduction of the calculated growth rate. In addition, previous studies have documented an overestimation of the plasma response amplitude by ideal MHD as β_N approaches $\beta_{N,no\text{-}wall}$ [18]. The most likely reason for this disagreement is uncertainty in reconstructions of the plasma equilibria. For example, a 10%–20% increase in the total pressure would be sufficient to put the equilibria above the no-wall limit, resulting in a gross overestimate of the RWM growth rate with Eq. (1). Previous DIII-D experiments with similar plasma shapes and global parameters yielded a no-wall limit scaling $\beta_{N,no\text{-}wall}$~$2.5l_i$ [19]. For the discharges reported here, the $2.5l_i$ scaling would result in a no-wall limit in the range of $2.0 < \beta_{N,no\text{-}wall} < 2.2$, moving the equilibria close to, or over the stability boundary. An additional potential source of uncertainty is the use of Eq. (1) outside its domain of applicability: $\delta W^{\,no-wall} < 0$ and $\delta W^{\,ideal-wall} > 0$. However, we note that in the scaled-pressure calculations used to determine stability limits, the δW values and poloidal structure of the least-stable DCON mode appear vary smoothly as the marginal stability point is crossed.

Small changes in quantities of interest for kinetic contributions to the stability, such as ω_E and f_{trap}, are observed as the off-axis beam power varies. The correlated increase in the passing ion population and the plasma response amplitude is consistent with the expectation of reduced kinetic damping. However, ideal MHD calculations based on the experimental equilibria also indicate increased RWM damping with increased off-axis NBI power, restricting the possible magnitude of changes in kinetic damping. A calculation of the kinetic energy principle δW_k is needed to assess the impact of these variations. Future work will focus on verifying the reconstructed equilibria and carrying out the δW_k calculation.

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References

[1] STRAIT, E.J., et al., Phys. Rev. Lett. **74** (1995) 2483
[2] GAROFALO, A.M., et al., Phys. Rev. Lett. **89** (2002) 235001
[3] REIMERDES, H., et al., Phys. Rev. Lett. **98** (2007) 055001
[4] HU, B., and BETTI, R., Phys. Rev. Lett. **93** (2004) 05002
[5] BERKERY, J.W., et al., Phys. Plasmas **17** (2010) 082504
[6] CHAPMAN, I.T., et al., Plasma Phys. and Controlled Fusion **53** (2011) 065022
[7] REIMERDES, H., et al., Phys. Rev. Lett. **106** (2011) 215002

[8] BOOZER, A.H., Phys. Rev. Lett. **86** (2001) 5059
[9] REIMERDES, H., et al., Phys. Rev. Lett. **93** (2004) 135002
[10] SHILOV, M., et al., Phys. Plasmas **11** (2004) 2573
[11] MURAKAMI, M., et al., Nucl. Fusion **49** (2009) 065031
[12] HEIDBRINK, W.W., et al., Nucl. Fusion **52** (2012) 094005
[13] BUDNY, R., Nucl. Fusion **34** (1994) 247
[14] PANKIN, A., et al., Comp. Phys. Communications **159** (2004) 157
[15] GLASSER, A.H., and CHANCE, M.S., Bull. Am. Phys. Soc. **42** (1997) 1848
[16] TURNBULL, A.D., et al., Nucl. Fusion **38** (1998) 1467
[17] HANEY, S.W., and FREIDBERG, J.P., Phys. Fluids B **1** (1989) 1637
[18] LANCTOT, M. J., et al., Phys. Plasmas **17** (2010) 030701
[19] REIMERDES, H., et al., Proc. 23rd IAEA Fusion Energy Conference, Daejeon, Korea, EXS/5-4 (2010).