Beta limit and plasma response to n=1 perturbations in ASDEX Upgrade

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Tokamak plasmas with high normalized pressure are subject to various resistive and ideal MHD instabilities. The actual limit depends on several factors, including the stabilizing influence of the conducting components facing the plasma surface, kinetic interaction between the plasma and the marginally stable/unstable MHD modes, existence of low order rational surfaces and external actuators (heating, external perturbations, current drive). It was shown in previous work that the plasma response to n=1 perturbations from B-coils [1] in ASDEX Upgrade tokamak increases with increase of normalized beta β_N ($\beta_N = \beta a B_t / I_p, \beta = 2\mu_0 \langle p \rangle / \langle B \rangle$). This is a typical indication of the proximity to the so-called “no wall” beta limit [2]. In the present work we continue to study different effects influencing plasma stability to global n=1 modes which allows us to extend the achievable β_N.

Kinetic interaction between n=1 mode and NBI particles

High β_N discharges were performed with dominant NBI heating in ASDEX Upgrade. The resulting plasma has high rotation and resonant interaction between the Doppler shifted mode frequency ($\omega_{E\times B} - \omega_{n=1}$) and plasma particles becomes possible. The analytical expression for changes of the mode energy δW gives clear ideas about possible resonant frequencies [3]:

$$\delta W \sim \sum_{l=-\infty}^{\infty} \frac{(\omega_{n=1} + i\gamma_{n=1} - n\omega_{E\times B})\frac{\partial f_j}{\partial \varepsilon} - \frac{1}{eZ_j}\frac{\partial f_j}{\partial \Psi}}{\langle \omega_d^j \rangle + l\omega_b^j - i\nu_{eff}^j + n\omega_{E\times B} - \omega_{n=1} - i\gamma_{n=1}}$$

where f_j is the distribution function of the particles j, ε is the particle energy, $\omega_{n=1}$ is the mode frequency in the plasma frame, $\gamma_{n=1}$ is the mode growth rate, Ψ is the magnetic flux,

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* See http://www.euro-fusionscipub.org/mst1

ν_{eff}^{j} is the collision frequency, Z_j is the effective charge. The first four frequencies in the denominator are: the precession drift frequency: $\omega_d = \frac{\rho_L}{r}\frac{v_{th}}{2qR_0}$ (for pitch angle $\Lambda = 1$); the bounce frequency: $\omega_b = \left(\frac{r}{2R_0}\right)^{1/2}\frac{v_\perp}{qR_0}$ (for $\Lambda = 1$); the collision frequency ν_{eff}, and the $E\times B$ frequency, where v_{th} is the thermal velocity, ρ_L is the Larmor radius, q is the safety factor value. The $E\times B$ frequency is $\omega_{E\times B} = \omega_\phi - \omega_{*i}$, where ω_ϕ is the toroidal plasma rotation frequency and ω_{*i} is the ion diamagnetic frequency. All these frequencies as a function of ρ are shown in figure 1a assuming experimental profiles. The presented frequencies show the upper estimation for possible resonances with passing particles for discharge #29100 with an unstable n=1 kink mode (pitch angle $\Lambda = 1$, no geometrical effects, etc.). Figure 1b shows results of HAGIS code [4] simulations for energy exchange between an $n = 1$ structure with multiple poloidal mode numbers (linear MHD code MARS) and a realistic distribution function (transport code TRANSP). HAGIS calculations of δW include resonant and non-resonant interactions in realistic plasma geometry for the same discharge as in figure 1a. The results are shown in figure 1b. The real resonance frequencies are downshifted with respect to our simplified estimations, which is an expectable result for a realistic situation.

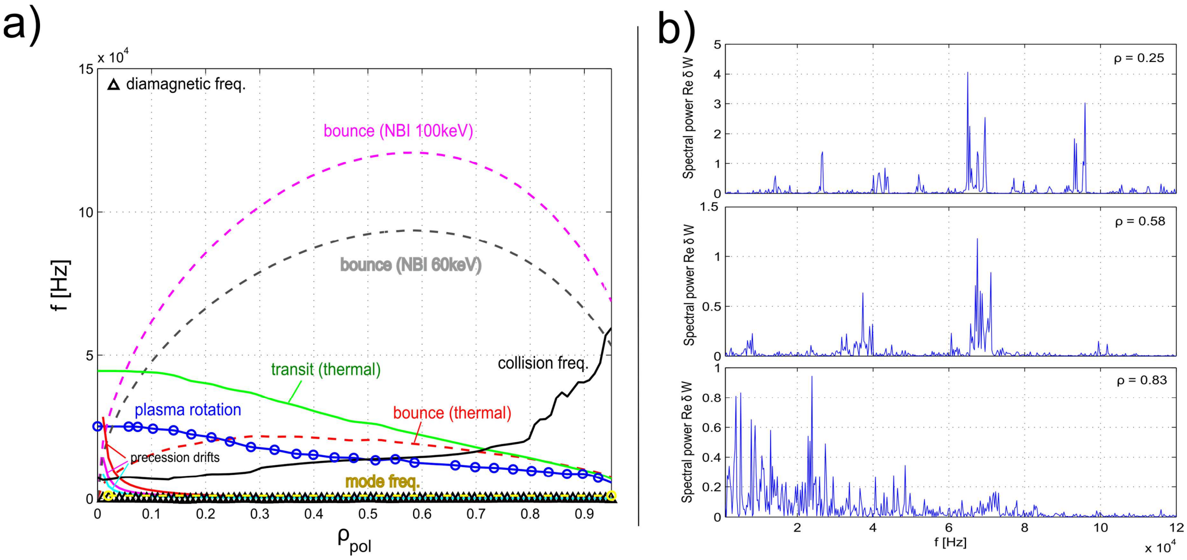

Figure 1. Analysis of discharge #29100 a) Main resonance frequencies and plasma rotation frequency are shown. b) Spectral analysis of $Re(\delta W)$ for different radial positions in the plasma. $Re(\delta W)$ was calculated with HAGIS code taking into account realistic particle distribution and mode structure.

The main interactions in the plasma core ($\rho = 0.25, \rho = 0.58$) are at high frequencies where the bounce resonances with NBI particles are important. The low frequency resonances become important close to the plasma boundary ($\rho = 0.83$). Spectral analysis of different particle species demonstrates the main players in the interaction of NBI particles with an $n = 1$ mode (figure 2). The spectral power density $Re(\delta W)$ at different radii for the full distribution function from TRANSP code is shown in figure 2a. (This is the same calculations as in figure 1b.) The other figures consider only part of the full distribution function from TRANSP for δW: only co-passing particles are considered in figure 2b; only counter-passing particles are taken in figure2c; only trapped particles are considered in figure 2d.

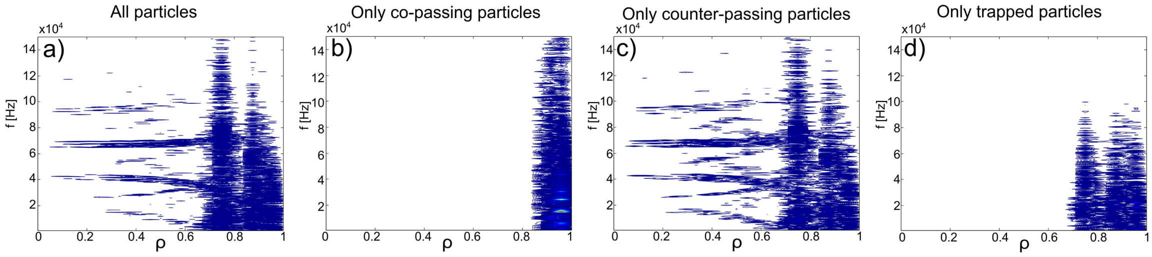

Figure 2. Spectral analysis of $Re(\delta W)$ from HAGIS code for #29100. a) All particles are considered (the same case as in figure 1b); b) Only co-passing particles are taken into account; c) Only counter-passing particles are taken into account; d) Only trapped particles are taken into account.

These figures show that co-passing particles are not important. Counter-passing particles are important at all radii and at different resonant frequencies. (Thus, radial NBI beams 1, 2 and 5, which produce the largest amount of counter-passing particles, play the dominant role.) Trapped particles are important for $\rho \geq 0.7$ (NBI 6 and 7). The next step will be an optimization of NBI start-up sequence to ensure maximal stabilization influence from NBI particles on the n=1 mode which should extend the achievable beta limit.

Influence of external n=1 rotated perturbations from B-coils

B-coils installed in ASDEX Upgrade were used for application of oppositely rotated perturbations in upper and lower row of coils. This produces constant changes of the pitch angle keeping the n=1 helicity of the perturbations unchanged. Reaction of the plasma to these perturbations becomes visible above the critical value $\beta_{N,crit} \approx 2.3$ (dashed line in figure 3a). Plasma displacement, estimated from temperature profile measurements ($\xi = -\widetilde{T}_e/\nabla\langle T_e\rangle$), shows visible changes above this $\beta_{N,crit}$ for differentially rotated n=1 perturbations (figure 3d). The same threshold is observed in experiments with rigid rotation of n=1 perturbations in similar plasma discharges. Independent measurements of the displacement close to the plasma boundary with 2D ECE Imaging system show amplitudes of the perturbations around 1 cm, which is in good agreement with our results [5]. The plasma rotation changes strongly through the radius as shown in figure 3c. Corresponding changes of the phase of the perturbation is shown in figure 3b. The dashed lines indicate maximal values of the rotation which corresponds to the same phase of n=1 perturbation. Explanation of such changes in the plasma rotation is not straightforward and probably related to neoclassical toroidal viscosity (NTV) torque difference for different pitch angles on n=1 perturbations. Detailed modelling with realistic profiles is foreseen for quantitative understanding of the effect. At the same time, the global nature of this effect and it dependence on normalized plasma pressure is clearly seen experimentaly.

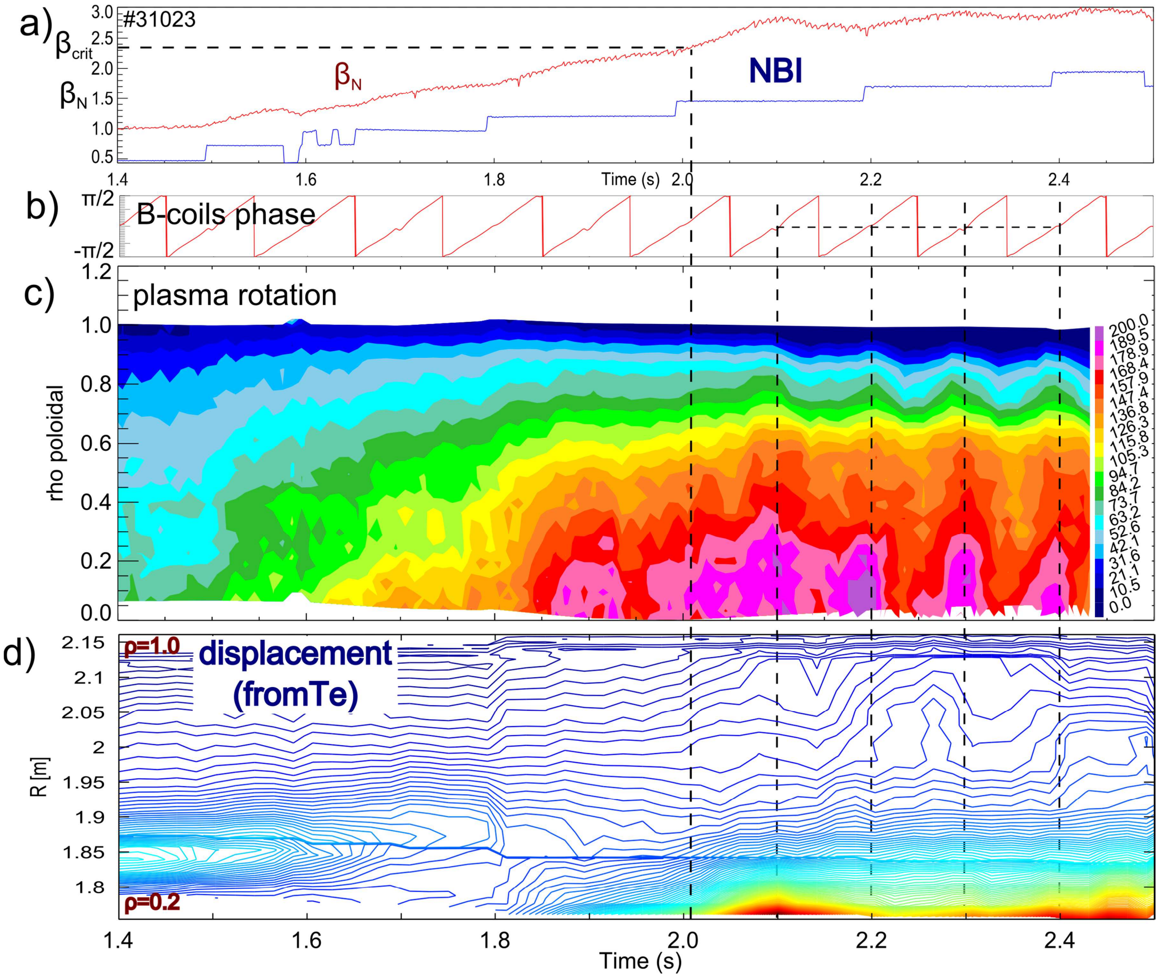

Figure 3. #31023 a) Normalized beta and NBI power; b) phase of n=1 perturbation from B-coils shows changes in pitch angle; c) plasma rotation measurements; d) displacement from ECE.

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References

[1]W. Suttrop et. al., 2009 Fusion Eng. Des. 84, 290
[2] V. Igochine et. al., 40th EPS Conference, 2013, P5.147 (http://eps2013.aalto.fi/?page=proceedings)
[3] B. Hu, R. Betti, J. Manickam, Physics of Plasmas 12, 057301 (2005)
[4] S. Pinches et.al. Computer Physics Communications, 111, (1998), p.133
[5] P. Piovesan et. al., this conference, P1.144