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MHD limits and plasma response in high beta hybrid operations in ASDEX Upgrade

V.Igochine[1], P.Piovesan[2], P.Bettini[2], T.Bolzonella[2], I.G.J.Classen[3], M.Dunne[1], A.Gude[1], P.Lauber[1], Y.Liu[4], M.Maraschek[1], N.Marconato[2], L.Marrelli[2], S.Mastrostefano[5], P.McCarthy[6], R.McDermott[1], M.Reich[1], D.Ryan[4], M.Schneller[1], E.Strumberger[1], W.Suttrop[1], G.Tardini[1] , F.Villone[5], D.Yadykin[7], the ASDEX Upgrade Team and the EUROfusion MST1 Team[*]

[1]Max-Planck-Institute for Plasma Physics, Garching, Germany

[2]Consorzio RFX, Padova, Italy

[3]DIFFER, Eindhoven, The Netherlands

[4]CCFE, Abingdon, UK

[5]DAEIMI, Universitá degli Studi di Cassino, Italy

[6]Dep. of Physics, University College Cork, Cork, Ireland

[7]Chalmers University of Technology, Gothenburg, S-41296, Sweden

[*]See appendix of H. Meyer et.al. (OV/P-12) Proc. 26th IAEA Fusion Energy Conf. 2016, Kyoto, Japan

E-mail contact of main author: valentin.igochine@ipp.mpg.de

Abstract. The improved H-mode scenario (or high β hybrid operations) is one of the main candidates for high-fusion performance tokamak operation, which offers potential steady-state scenario. In this case, the normalized pressure β_N must be maximized and pressure driven instabilities limit the plasma performance. These instabilities could have either resistive ((m=2,n=1) and (3,2) Neoclassical Tearing Modes (NTMs)), or ideal character (n=1 ideal kink modes). In ASDEX Upgrade (AUG), the first limit for maximum achievable β_N is set by NTMs. Application of pre-emptive electron cyclotron current drive at the q=2 and q=1.5 resonant surfaces reduces this problem, such that higher values of β_N can be reached. AUG experiments have shown that, in spite of the fact that hybrids are mainly limited by NTMs, proximity to the no-wall limit leads to amplification of external fields that strongly influences the plasma profiles: for example, rotation braking is observed throughout the plasma and peaks in the core. In this situation, even small external fields are amplified and their effect becomes visible. To quantify these effects, the plasma response to magnetic fields produced by B-coils is measured as β_N approaches the no-wall limit. These experiments and corresponding modelling allow to identify the main limiting factors which depend on the stabilizing influence of conducting components facing the plasma surface, existence of external actuators and kinetic interaction between the plasma and the marginally stable ideal modes. Analysis of the plasma reaction to external perturbations allowed us to identify optimal correction currents for compensating the intrinsic error field in the device. Such correction, together with analysis of kinetic effects, will help to increase β_N further in future experiments.

1. Introduction

The improved H-mode scenario [1] (or high β hybrid operations [2]) is one of the main candidates for high-fusion performance tokamak operation, which offers potential steady-state scenario. In this case, the normalized pressure, β_N, must be maximized and pressure driven instabilities limit the plasma performance. ($\beta_N = \beta(aB_t/I_p), \beta = 2\mu_0\langle p\rangle/B_t^2$; $\langle p\rangle$ is the volume average pressure, B_t is the toroidal magnetic field, a is the minor radius and I_p is the plasma current.) These instabilities could have either resistive ((m=2,n=1) and (3,2) Neoclassical Tearing Modes (NTMs)), or ideal character (n=1 ideal kink modes). In ASDEX Upgrade (AUG), the first limit for maximum achievable β_N is set by NTMs. Application of pre-emptive electron cyclotron current drive at the q=2 and q=1.5 resonant surfaces reduces this problem, such that higher values of β_N can be reached. In this regime, the plasma is marginally stable with respect to n=1 ideal modes. The actual beta limit depends on many factors, including the stabilizing influence of the conducting components facing the plasma surface, existence of external actuators (external n=1 perturbations, current drive, energetic particles) and kinetic interaction between the plasma and the marginally stable ideal modes. These factors are discussed in the next sections of the paper together with proposals for extension of the operation limits.

2. Influence of the external conducting structures on the plasma stability

In ASDEX Upgrade, the plasma is far from the wall. The main conducting structures located close to the plasma boundary are a Passive Stabilizing Loop (PSL) and antennas of Ion Cyclotron Resonant Heating (ICRH). Linear MHD calculations (CAS3D) were coupled with realistic 3D modelling of these external conducting structures (STARWALL) which allows to calculate the "no-wall" , $\beta_{N,no-wall}$, and "ideal-wall", $\beta_{N,ideal-wall}$, stability limits for our plasmas [3]. Results of calculation for two different discharges are shown in figure 1. The operational point represented by $\beta_{N,exp,th}$ is slightly below the "no-wall" limit in both cases. This value assumes only thermal particles for proper comparison with MHD codes. Total normalized beta takes into account also fast particle pressure and can exceed the "no-wall" value predicted by the codes (figure 1a). The stabilizing effect of presently installed external conductors (PSL and ICRH antennas) is relatively small and difference between "no-wall" and "ideal wall" limits for these two cases is 0.15 and 0.44 for #32456 and #29100 respectively in terms of normalized beta.

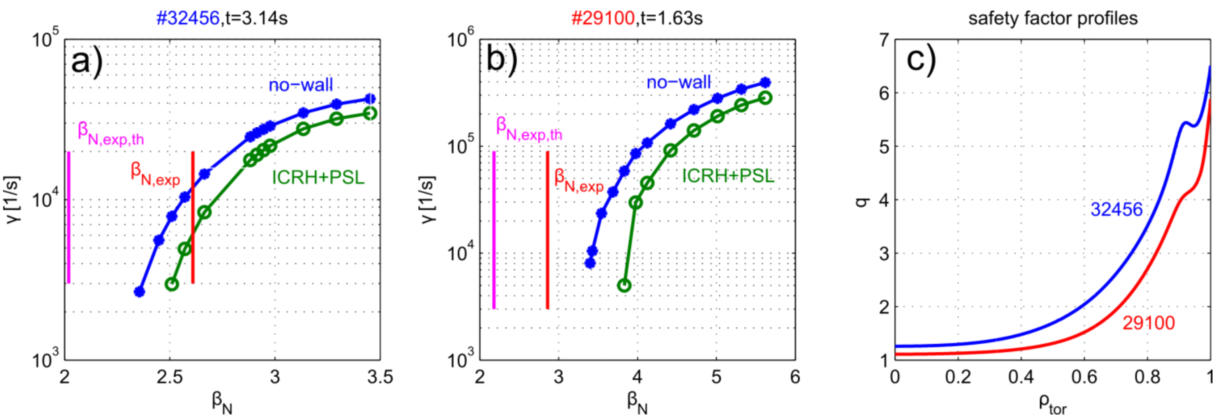

Figure 1. Results of the linear stability analysis for discharges 32456 (figure a) and 29100 (figure b) are shown together corresponding safety factor profiles (figure c). On figures (a) and (b) the following values are shown: growth rates without conducting wall ("no-wall", blue curve); growth rates assuming perfectly conducting PSL and ICRH antennas ("ideal wall", green curve); total experimental beta with fast particles ($\beta_{N,exp}$, red line); experimental beta assuming only thermal particles ($\beta_{N,exp,th}$, magenta line).

Thus, installation of additional conducting structures is required to extend this region. In this case, stabilization of resistive wall modes (RWMs) will be important. The other option is optimization of the pressure and the current profiles, which shifts the "no-wall" limit and makes the q-profile flatter. This is limited by keeping the central value of the safety factor above unity and the non-inductive current fraction close to 100%.

3. Influence of kinetic effects on the mode stability

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 [4]:

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

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, 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 2a assuming experimental profiles.

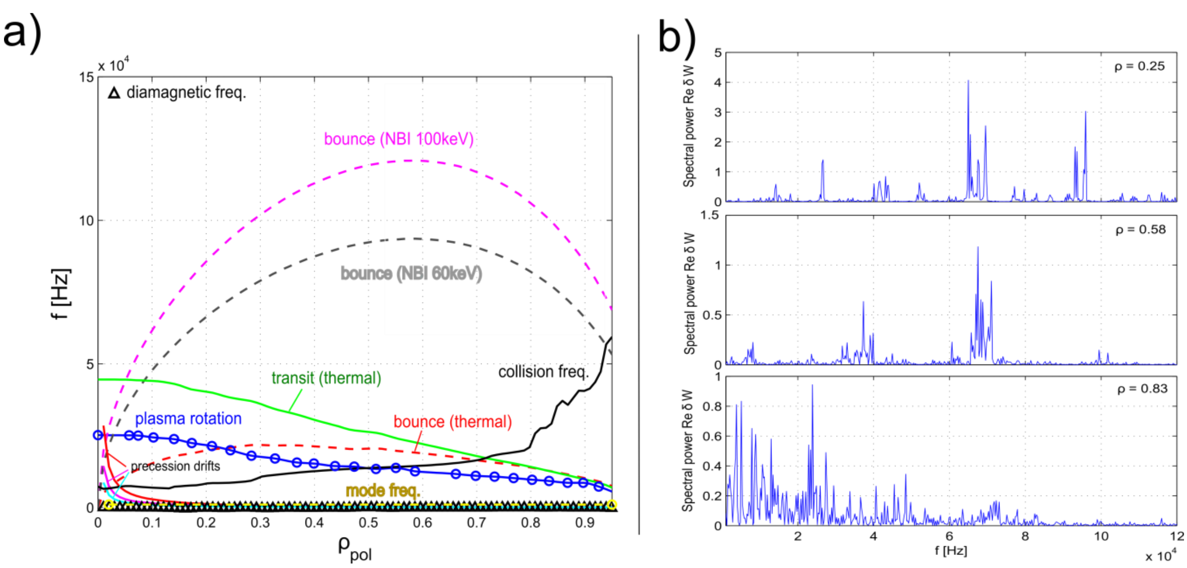

Figure 2. Analysis of discharge #29100 a) Main resonance frequencies and plasma rotation frequency are shown. b) Spectral analysis of $Re(\delta W)$ for different radial positions in the plasma. $Re(\delta W)$ was calculated with HAGIS code taking into account realistic particle distribution and mode structure.

The 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 2b shows results of HAGIS code [5] 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 1b. The results are shown in figure 2b. The real resonance frequencies are downshifted with respect to our simplified estimations, which is an expectable result for a realistic situation. 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 3). The spectral power density $Re(\delta W)$ at different radii for the full distribution function from TRANSP code is shown in figure 3a. (This is the same calculations as in figure 2b.) The other figures consider only part of the full distribution function from TRANSP for δW: only co-passing particles are considered in figure 3b; only counter-passing particles are taken in figure3c; only trapped particles are considered in figure 3d.

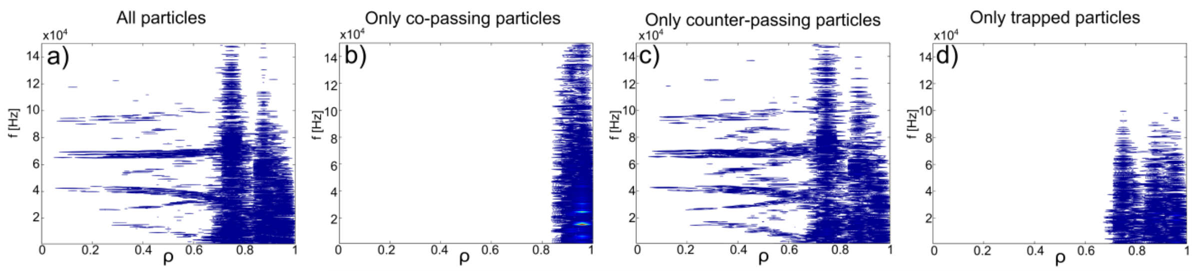

Figure 3. Spectral analysis of $Re(\delta W)$ from HAGIS code for #29100. a) All particles are considered (the same case as in figure 2b); b) Only co-passing particles are taken into account; c) Only counter-passing particles are taken into account; d) Only trapped particles are taken into account.

These figures show that co-passing particles are not important. Counter-passing particles are important at all radii and at different resonant frequencies. Trapped particles are important for $\rho \geq 0.7$. Different NBI sources produce different amount of co-passing, counter-passing and trapped particles depending on the beam direction. Moreover, some of the beams can be slightly tilted between the discharges. (Experiment on sawtooth stabilization show that even this small tilting of the beam strongly influence (1,1) mode stability [6].) Thus, variation of NBI sources is one of the possible optimization options to increase the achievable beta by identification of the maximal stabilizing influence on the n=1 mode. For this study, the same analysis as in figure 3 will be performed for each NBI source geometry separately.

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

In typical H-mode plasmas in ASDEX Upgrade, resonant perturbations from B-coils [7] are well screened and have no influence on NTM behaviour. Our high beta experiments have shown that, in spite of the fact that hybrids are mainly limited by NTMs, proximity to the no-wall limit leads to amplification of external fields. As far as the threshold beta value, $\beta_{N,crit}$, is crossed, the external field is strongly amplified and the influence on the plasma becomes clearly visible (for example changes of the plasma rotation after 2s in figure 4). The dependence on beta is crucial. In the presented example, the effect on the plasma rotation becomes only important for $\beta_N > \beta_{N,crit} = 2.3$ (in this case, $\beta_{N,no-wall} \approx 3.0$). The difference between this critical beta and the "no-wall" in our experiments is between 0.7 and 0.9.

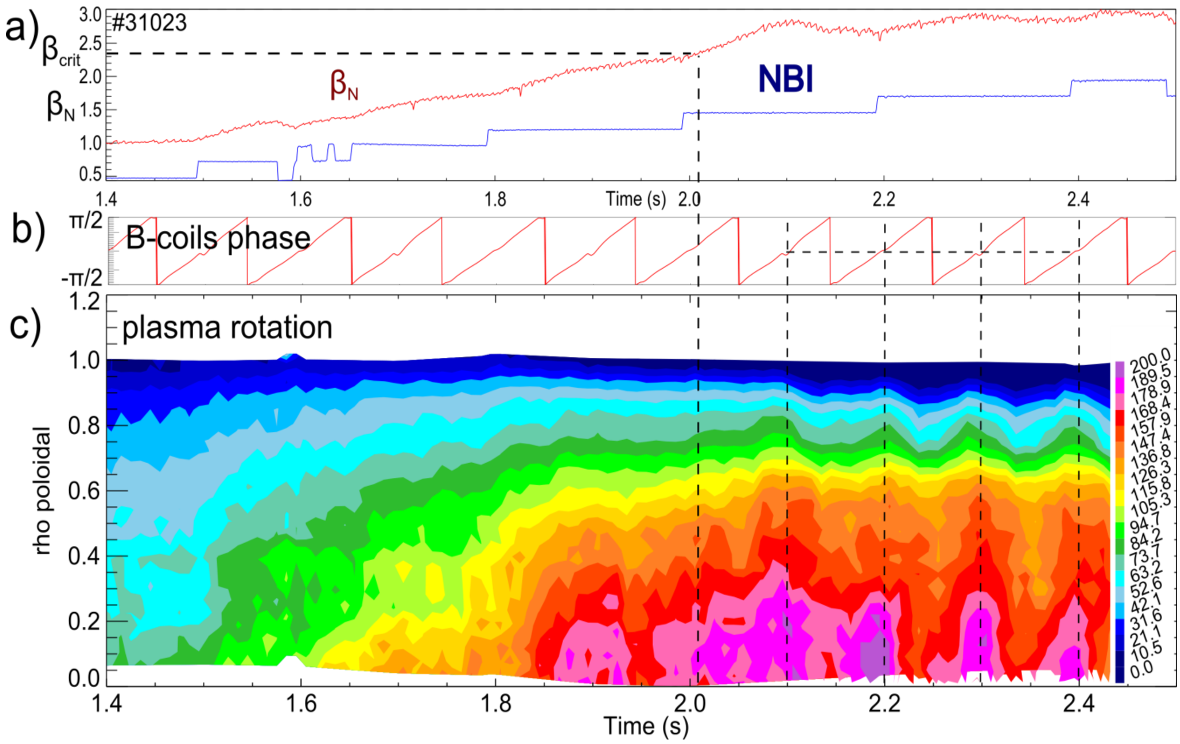

Figure 4. a) β_N and NBI power; b) differential phase of n=1 perturbation from B-coils indicates changes in pitch angle; c) plasma rotation

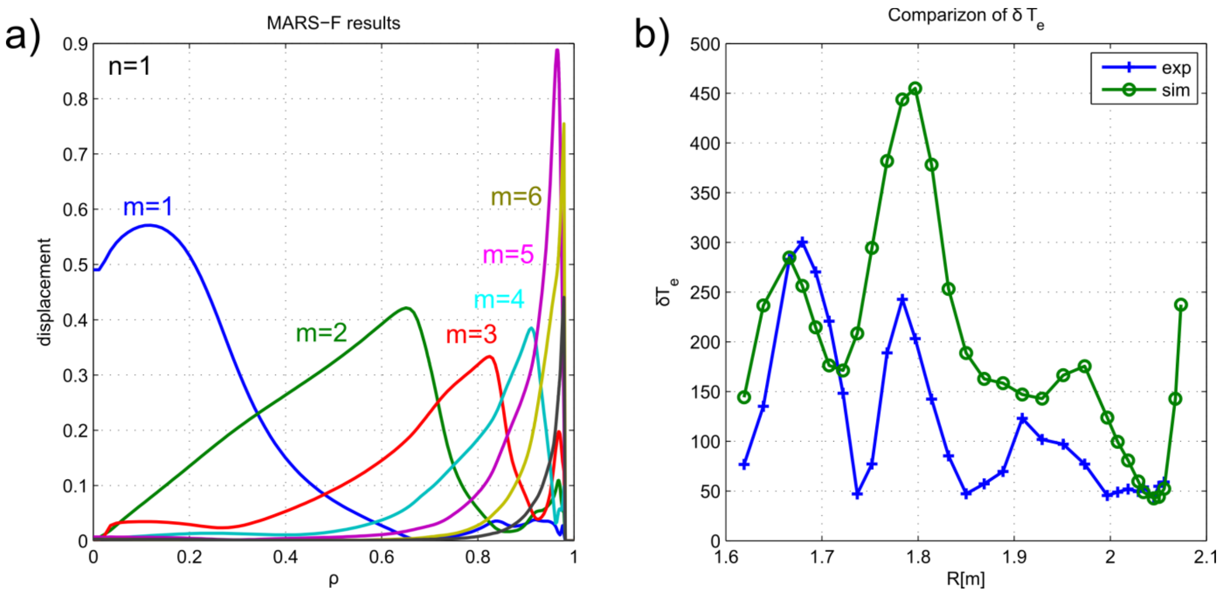

Figure 5. a) Displacement eigenfunctions for n=1 and different m-numbers from linear MHD simulations (MARS-F code, discharge #32138); b) Comparison of simulated temperature perturbations using the eigenfunctions from figure (a) and experimentally measured values.

Contrary to the advanced tokamak regime, the safety factor profile in the core in this scenario is not reversed (figure 1c). It has monotonic behaviour with flat central region and $q_0 \gtrsim 1$. The resulting perturbations in the plasma core have a strong (m,n)=(1,1) component, which is the main difference to the advanced regime, where this component is negligible (figure 5a). The resulting n=1 response is large and well observed in MHD diagnostics (ECE, SXR) and in the plasma rotation measurements. The full radial profile and poloidal structure of this response measured by these diagnostics agrees well with linear MHD simulations for ASDEX Upgrade [8]. An example of such a comparison of the amplitude of the temperature perturbations is shown in figure 5b. In addition to this response, the resonant field amplification robustly maintains the interaction between NTMs and B-coils if the mode is present in the plasma. Such an example is shown in figure 6.

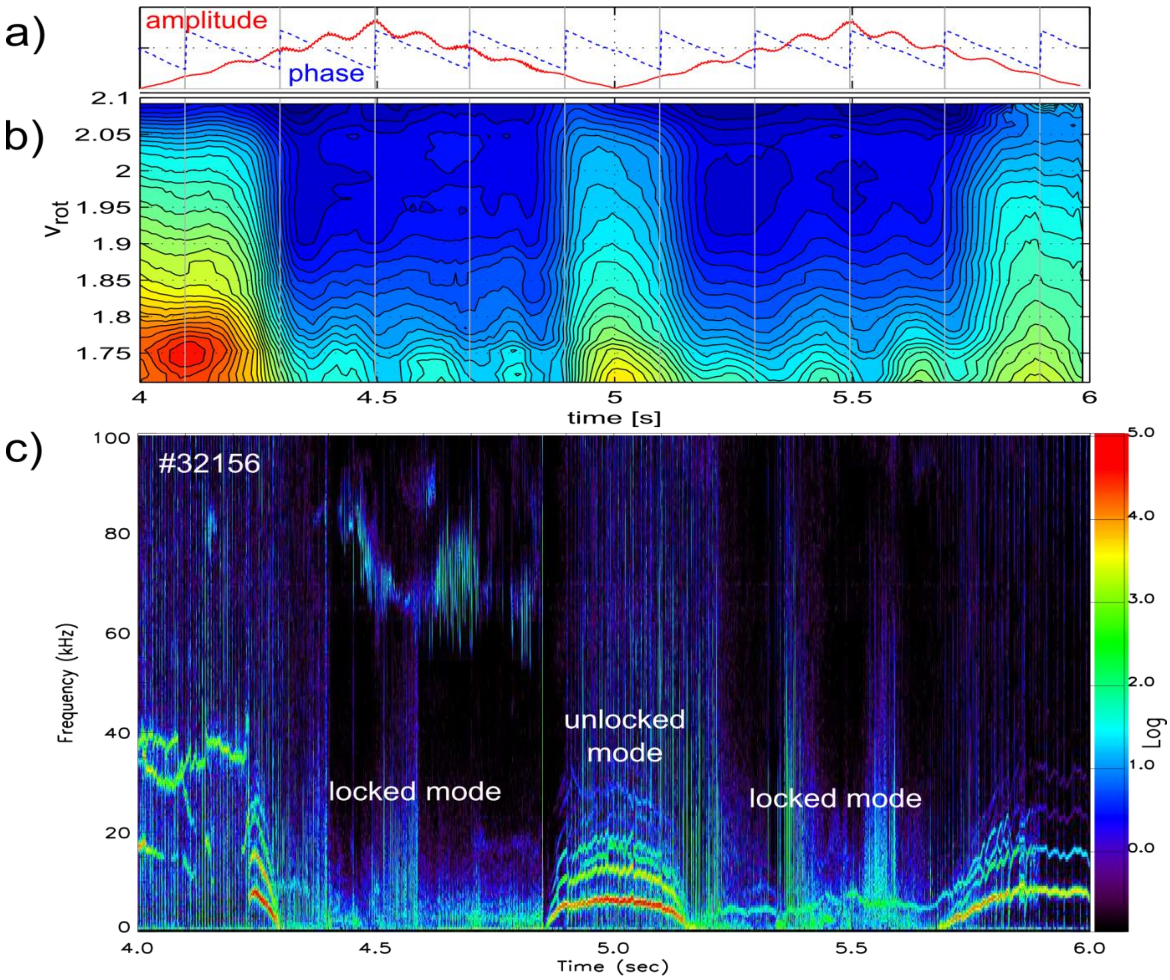

Figure 6. a) Amplitude and phase of B-coil current; b) plasma rotation; c) spectrogram of the magnetic signal.

External n=1 perturbations slow down the (2,1) mode (triggered at 4.2s). The mode rotates together with external field during the locked mode phase. Reduction of the current in the B-coils leads to unlocking of the mode, which reaches almost its initial frequency. At the same time, the plasma rotation recovers only partially after the reduction of the external field (4.9s-5.1s in figure 6b). In this situation, even the strong reduction of β_N would not destroy the interaction between NTM and B-coils and locking/unlocking of the mode by external fields can be done well below $\beta_{N,crit}$. Thus, correction of error fields in high beta operations becomes important and this correction should be done in advance to avoid initial reduction of the plasma rotation.

5. Error field correction

The error field in ASDEX Upgrade tokamak is small and has no preferential position [9]. The reason for this behaviour is its dependence on currents in plasma shaping coils. Thus, the eror field will be different for each plasma shape. At the same time, the error field can be compensated for a particular scenario. In our case, plasma rotation measurements and ECE measurements provide the best indications for the plasma reaction even for a small external field. This field has three basic parameters for optimization: φ_{dif}, differential phase between the currents in the coils; φ_{tor} , toroidal phase; I_{coils}, current amplitude in the coils. The optimal parameters should compensate the intrinsic error fields and exert a minimal effect on the plasma. Vayring the amplitude and the phases in a set of similar discharges it is possible to identify settings which give maximal plasma reaction and maximal slowdown of the plasma rotation. The optimal correction values are opposite to these phase settings. The amplitude of the optimal compensation can be found by variation of the B-coils current amplitude. The optimal settings find in our experiments are: $\varphi_{diff} = 90^0;\ 200A < I_{coil} < 400A;\ +25^0 < \varphi_{tor} < 0^0$. This corresponds to 30% of maximal possible current in the B-coils and shows again that the intrinsic error field is small.

6. Conclusions and discussion

Operation close to the “no-wall” limit in ASDEX Upgrade is more challenging compared to the standard operation because of the resonant field amplification which starts to play a role at these pressures. As a result, not only the NTM control is required but also the correction of small error fields becomes important. There are several possible options for general optimization of plasma performance with respect to β_N in these regimes:

- Optimization of the current and pressure profiles to shift the “no-wall limit” to the highest possible values keeping the non-inductive fraction close to 100%.
- Installation of additional conducting structures to increase the distance between “no-wall” and “ideal wall” limits. In this situation, stabilization of the resistive wall mode between these limits becomes important.
- Optimization of NBI sequence to ensure maximal stabilizing effect on the kink mode.
- Correction of error fields to remove their influence on the plasma.

All these options could be done in parallel.

Acknowledgments

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References

[1] J.STOBER et al., “The role of the current profile in the improved H-mode scenario in ASDEX Upgrade”, Nucl. Fusion 728, (2007)

[2] T.C. LUCE et al., "Development of advanced inductive scenarios for ITER", Nucl. Fusion, 013015 (2014).

[3] E. STRUMBERGER et.al. „On fully three-dimensional resistive wall mode and feedback stabilization computations", Phys. Plasm.,15, 056110 (2008)

[4] B. HU, R. BETTI, J. MANICKAM," Application of the low-frequency energy principle to wall modes", Physics of Plasmas 12, 057301 (2005)

[5] S. PINCHES et.al." The HAGIS self-consistent nonlinear wave-particle interaction model", Computer Physics Communications, 111, p.133 (1998)

[6] I.T.CHAPMAN et.al., "The effect of off-axis neutral beam injection on sawtooth stability in ASDEX Upgrade and Mega-Ampere Spherical Tokamak", Phys. Plasm.,16, 072506 (2009)

[7] W. SUTTROP et. al., "In-vessel saddle coils for MHD control in ASDEX Upgrade", Fusion Eng. Des., 290 (2009)

[8] P.PIOVESAN et.al. "Impact of ideal MHD stability limits on high-beta hybrid operations", submitted to Plasm. Phys. Contrl. Fus., 2015

[9] M.MARASCHEK et.al., "Measurement and impact of the n=1 intrinsic error field at ASDEX Upgrade", 40th EPS Conference on Plasma Physics, Espoo, Finland, 2013, P4.127