Identification of the beta limit in ASDEX Upgrade

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Tokamak plasma is subject to various resistive and ideal MHD instabilities which restrict the operation space of the device. For optimal fusion performance, it is preferable to operate the tokamak close to the stability limit with maximal possible pressure characterized by the value of normalized beta, β_N, and thus maximal fusion power $P \sim \beta_N^2$.

In ASDEX Upgrade, the limit for maximal achievable β_N is typically set by the resistive instabilities (tearing modes). If these instabilities are overcome or prevented, for example by pre-emptive electron cyclotron current drive, higher values of the normalized beta can be potentially reached. These values are limited by the onset of the ideal kink instability which is an ultimate limit for plasma stability. The actual limit depends on several factors, including the stabilizing influence of the conducting components facing the plasma surface. At present, the wall elements in ASDEX Upgrade are far from the plasma and the stability boundary is expected to be close to the "no wall" limit (no stabilizing wall effect). In this paper, two experimental indicators are used to detect the stability boundary in high β_N scenarios:

- Onset of the ideal kink mode at the beta limit
- Changes of the $\tilde{B}_{n=1}$ amplitude with increase of β_N

All discharges discussed in the paper were made with current over-shoot recipe [1]. This allows sustainment of a flat q-profile with q slightly above one. In order to understand the proximity of the stability limit, a slight increase of the q-profile was used in one of the discharges to shift the "no-wall" limit to a smaller value of β_N. This was archived by a different time delays in the current over-shoot phase which lead to increase of the q values in the region $0.5 < \rho_{pol} < 0.9$. The discharge is terminated by the onset of the n=1 mode at the relatively low value of β_N ($\beta_{N,\text{exp.lim.}} = 2.8$). The temperature perturbations measured by the ECE diagnostic (see fig.1) indicates a global structure for the unstable n=1 mode and constant phase of the perturbation suggesting that the onset of the ideal kink causes the discharge termination.

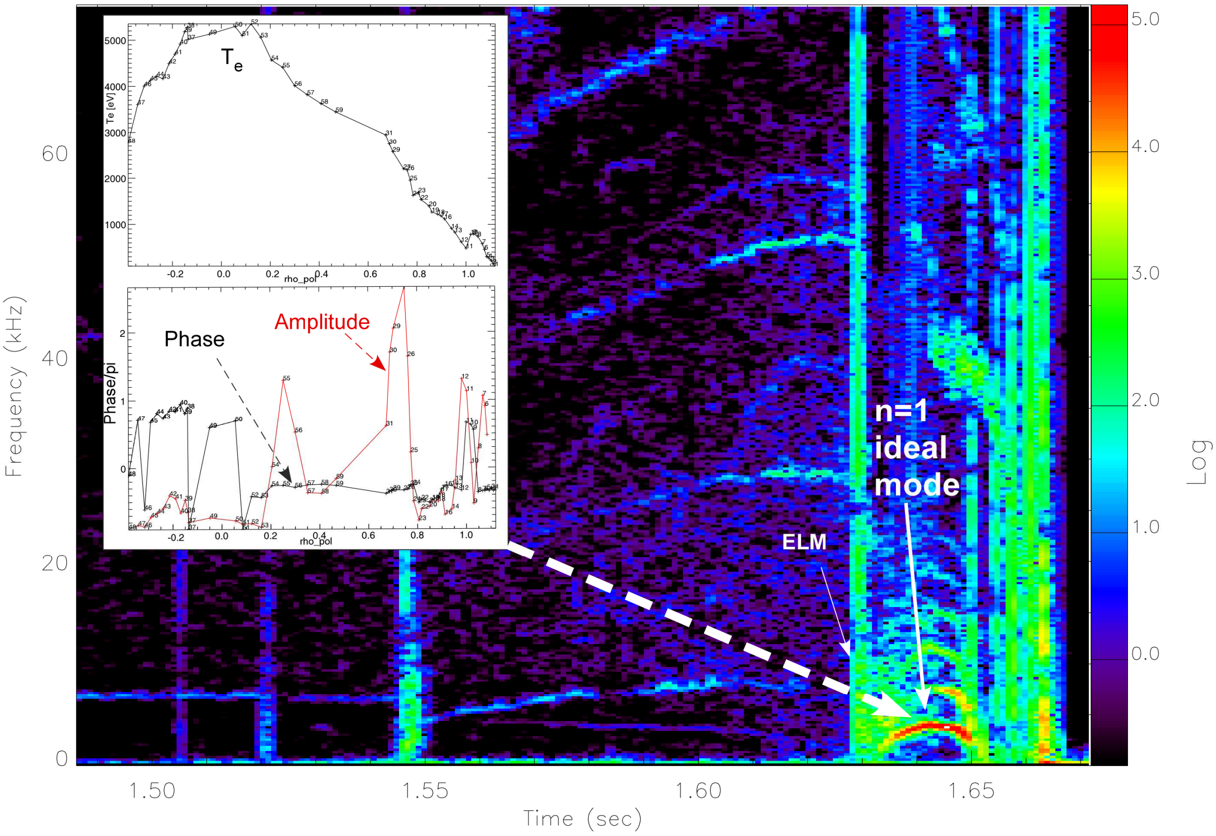

Figure 1. Spectrogram of the discharge #29100 with unstable n=1 ideal mode. Temperature profile, amplitude and phase of temperature perturbations are shown on the insert (from ECE measurements).

Recently installed internal active saddle coils (B-coils) [2] were used to probe stability of the plasma by the Resonant Field Amplification (RFA) technique. The B-coils set consists of two rows of coils above and below mid-plane at the **low field side** of the tokamak. Each row consists of eight coils at different toroidal positions. The external perturbations with toroidal mode number $n=1$ were produced using these coils. Resulting resonant response of the plasma, $\tilde{B}_{n=1}$, is measured by the sensor magnetic coils at **the high field side** of the torus (one row of 4 coils with toroidal extension of each coil Δφ=90°). The diametrically opposite coils are pair-connected to measure the n=1 component of the normal magnetic field. Sensor coils are located far from the active B-coils and detect only the plasma response: (signal names: north - $SATn$; south - $SATs$; east - $SATe$; west - $SATw$):

$$SATnsI = \int_{10ms} (SATn - SATs)\, dt\,,$$

$$SATewI = \int_{10ms} (SATe - SATw)\, dt\,.$$

The amplitude of the n=1 component is defined as following:

$$\tilde{B}_{n=1} = \sqrt{SATnsI^2 + SATewI^2}/2 \ .$$

The plasma response, $\tilde{B}_{n=1}$, grows with beta as shown in figure 2a. There is a clear difference between the case with slightly elevated q-profile, terminated with the onset of n=1 (#29100, blue points), and the other cases with more flat q-profiles (for example #29054, green points). This difference disappears if one plots the same values versus "relative" pressure, subtracting the value of β_N corresponding to the no-wall limit (see figure 2b). This demonstrates that the plasma response grows approximately identically when approaching the no-wall stability limit and suggests also that all cases shown are close to the stability limit. The "no-wall" values of β_N were calculated with the MARS-K code [3] using the experimentally measured equilibrium profiles for discharges #29054 ($\beta_{N,no-wall} = 3.5$) and #29100 ($\beta_{N,no-wall} = 2.7$). The corresponding CLISTE [4] reconstruction of the profiles, as well as the results of the stability calculations, are shown in figure 3. The equilibrium reconstructions were based on external magnetic probes and flux loops and measured kinetic profiles. It is interesting that experimentally measured growth rate of n=1 mode (black square) is close to the predictions of MARS-K code. The other discharges (#29052, #29098) are assumed to have similar values of no-wall β_N as in #29054, because of very similar discharge scenario. These results show that our discharges with flat q-profiles are close to the no-wall limit in spite of the limiting tearing mode which terminates the plasma confinement in most cases. The more flat q-profile gives expectedly higher no-wall values.

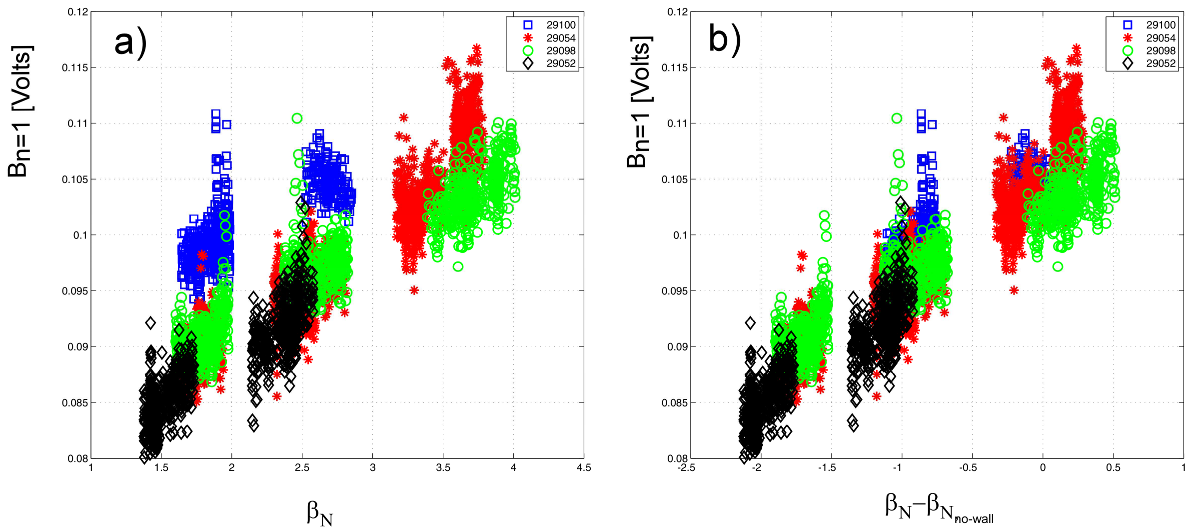

Figure 2. a) dependence of $\tilde{B}_{n=1}$ amplitude on β_N , b) dependence of $\tilde{B}_{n=1}$ amplitude on $\beta_N - \beta_{N,no-wall}$.

Some values located above the "no wall" limit in figure 2b could be associated either with uncertainties in the equilibrium reconstruction or with small stabilizing effect from passive stabilizing loop (PSL) and has to be investigated further. Current results indicate operations around the “no wall” limit. In general, experimentally obtained results are in good agreement with the results of the numerical modelling with linear MHD codes CASTOR-FLOW and MARS-K. These results also show the global character of the excited kink mode.

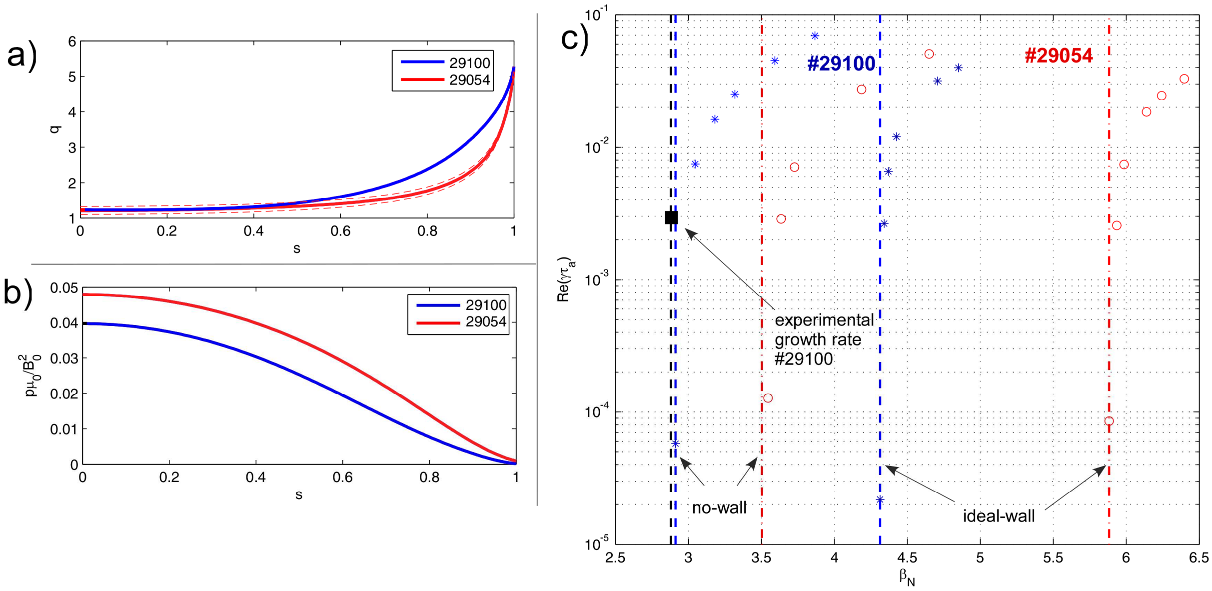

Figure 3. Results of the MARS-K code: a) safety factor profiles (dashed lines are estimation for the error bars); b) pressure profiles; c) calculated growth rates and limits. Conformal ideal wall at the position of the PLS was used for ideal-wall calculations.

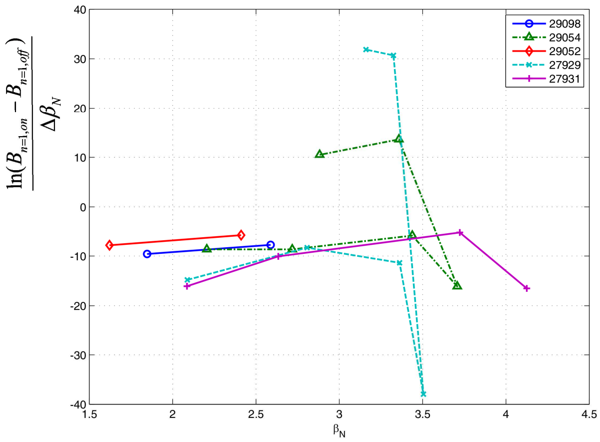

Figure 4. Dependence of the changes in $\Delta \ln \tilde{B}_{n=1}$ from $\Delta\beta_N$. Maximum should be located around the no-wall limit.

Experimentally obtained results are also compared with the method proposed Y. Liu for JET [5]. It was shown that the derivative of the logarithm of the RFA amplitude has its maximum approximately at the “no-wall” limit. In our case we detect only plasma perturbations $\left(\tilde{B}_{n=1}\right)$ and a similar quantity can be defined as: $\ln(\tilde{B}_{n=1,on} - \tilde{B}_{n=1,off})/\Delta\beta_N$, where “on” and “off” are referred to the phase with and without B-coil current. The RFA maximum is seen between $\beta_N = 3$ and $\beta_N = 4$ for the studied cases, which is similar to the previous results and confirms operations close to the no-wall stability limit (figure 4).

References

[1] J. Hobirk et al., Plasma Phys. Control. Fusion **54** (2012) 095001
[2] W. Suttrop et al 2009 Fusion Eng. Des. **84** 290
[3] Liu Y.Q. et al, 2008 Phys. Plasmas 15112503
[4] P.J. Mc Carthy et al., Plasma Phys. Control. Fusion **54** (2012) 015010
[5] Y. Liu et al., Plasma Phys. Control. Fusion **51** (2009) 115005