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MHD Effects related to High-Beta Operation in WENDELSTEIN W7-AS

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In W7-AS quasi-stationary plasmas with volume averaged beta in excess of 3% have been achieved in optimised configurations [1,2]. Low mode number pressure driven instabilities can be avoided by adjusting the rotational transform. The plasma is mostly stable at high-β ($<\beta> >$ 2 %) presumably due to the larger magnetic well depth and shear. Surprisingly, even in unstable regimes the modes saturate typically at a harmless level. Current driven instabilities such as kink- and (neoclassical) tearing-modes as well as internal and major disruptions are eliminated by net current-free operation. Energetic particle driven Alfvén eigenmodes do not play a significant role due to the relatively low fraction of fast ions in the favoured high density regime.

Therefore, operational limits are typically determined by the available heating power, excessive density or deterioration of the plasma equilibrium if a critical value of the Shafranov shift is exceded, and/or the a stochastic field region at the boundary is formed [2].

The main topic of this paper are fast MHD events observed under certain conditions causing partial collapses of the plasma energy. This instability occurs preferentially at low rotational transform and at low electron temperatures as found by scans of configuration and

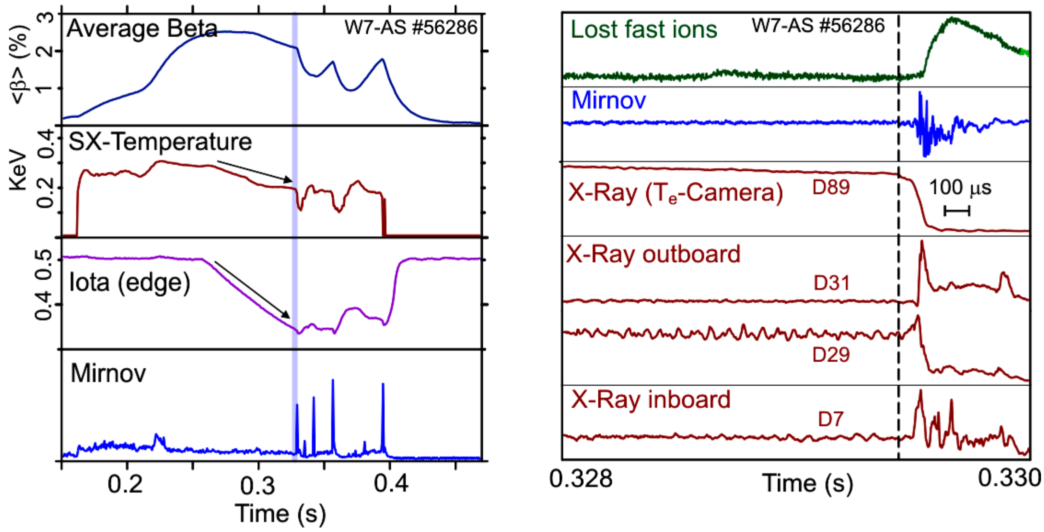

Fig. 1. Left: Dynamic change of the rotational transform by OH counter current drive (B = 1.25 T). The electron temperature decreases towards low iota followed by several fast edge MHD bursts causing crashes of the plasma energy and termination of the current ramp. The crashes occur at the edge without precursors within about 100 μs (right).

plasma parameters. In particular, the iota-dependence was studied in an extended range by driving Ohmic currents. With significant current in the co-directon (iota is increased), a tokamak-like iota-profile is formed, and (m,n) = (2,1) and (5,3) tearing modes with subsequent disruptive-like phenomena are observed if the corresponding rational surfaces are in the current gradient region [1,3]. Fast MHD crashes are typically found in counter current drive experiments, when iota has been decreased significantly. Such a case is shown in Fig. 1. The current ramp is started after the plasma beta has reached its maximum value, as measured by a diamagnetic loop. During the ramp the rotational transform decreases accompanied by a deterioration of the confinement. The central electron temperature at the time of the crash is around 200 eV as deduced from 2-foil X-ray intensity measurements. The right part of Fig. 1 shows the rapid evolution of the first event which occurs without precursor activity within ~ 100 µs. Included are different X-ray signals, a Mirnov probe signal with perturbation amplitudes reaching up to ~ 100 T/s, and the signal of a fast ion loss detector. As in the case of large ELMs, the thermal collapse starts close to the plasma boundary as deduced from the location where the X-ray signals are inverted.

The decay of $<\beta>$ during the counter current ramp is attributed to the approach of an equilibrium beta limit (β_{EL}), where flux surfaces start to degrade and thus enhanced transport sets in. The trajectory of $<\beta>$ against edge iota shown for a similar case in Fig. 2. While τ_E is expected to decrease with decreasing iota, in these cases the plasma beta is pushed against the equilibrium limit, as estimated from the VMEC equilibrium code assuming a critical Shafranov shift of $\Delta/a = 0.5$, and stays close to this until the end of the ramp. The ι profile undergoes a significant change during the current ramp, as shown on the right. The X-ray tomogram (inset) was obtained at the end of the ramp and coincides approximately with calculated flux surfaces close to β_{EL}.

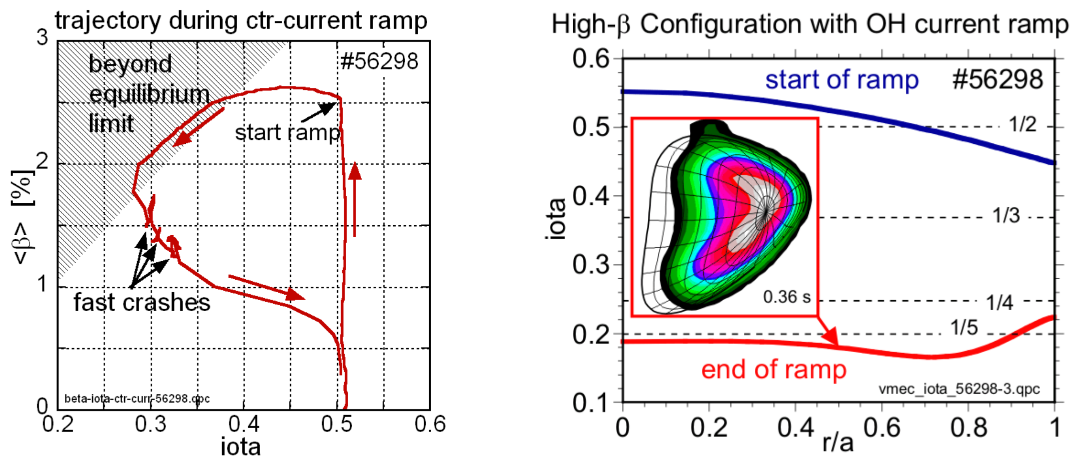

Fig. 2. Left: Evolution of beta as a function of the total edge transform in a discharge with an OH counter current ramp. As iota is ramped down, beta decreases keeping close to the estimated equilibrium limit where fast thermal crashes occur at a decreased temperature. Right: The current drive results in low iota with a flat profile. This is connected with a large Shafranov shift in the order of Δ/a = 0.5 as derived from X-ray tomography (inset).

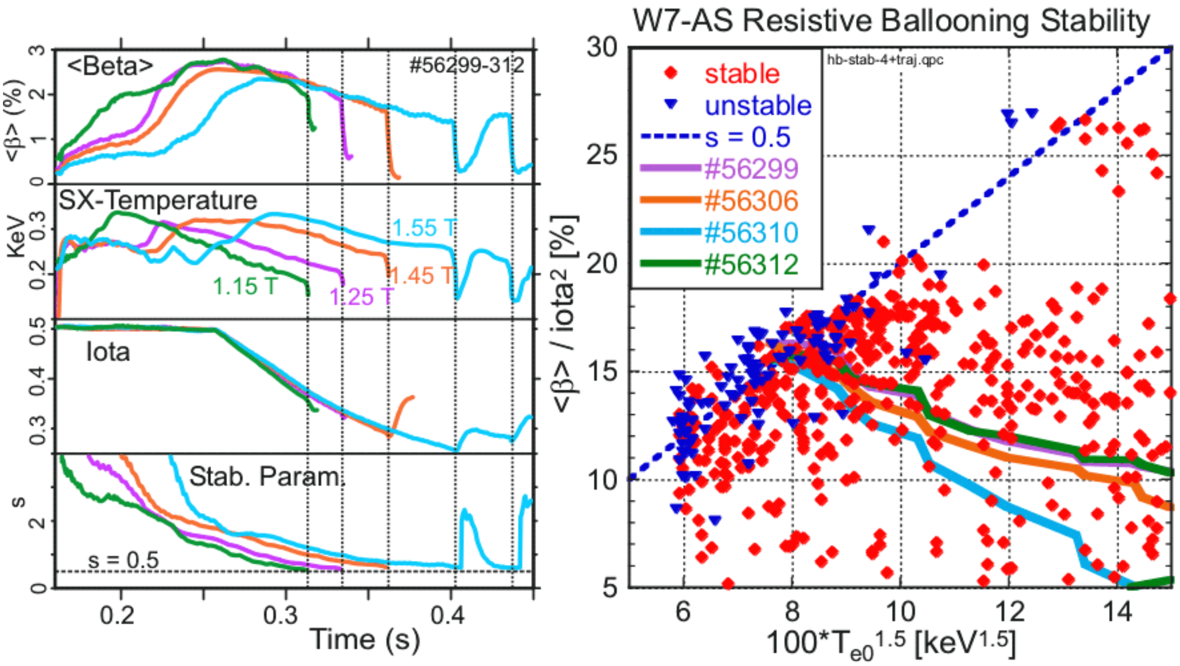

Fig. 3. Partial thermal crashes induced by fast MHD events. Left: magnetic field scan (1.05...1.65 T), in which a ramp of $\iota(a)$ was generated by inductive current drive (ctr) during the density plateau. The crashes occur close to s = 0.5, where $s \equiv 100\left(\iota^2/\langle\beta\rangle\right)\cdot T_e^{3/2}$ *($\langle\beta\rangle$ in %, T_e in keV). Right: database of $\langle\beta\rangle$ normalized to ι^2 versus $T_e^{3/2}$. The parameters just prior to MHD crashes (solid triangles) are close to the value s = 0.5 (dotted line). The solid lines are the trajectories of the discharges shown on the left.*

The observed scaling of the instability with plasma and configuration parameters is consistent with that of resistive ballooning modes, if linear growth rates [4] are used as a measure of the expected mode activity:

$\gamma \approx \left(\langle\beta\rangle/\langle\beta\rangle_c\right)\eta k^2/\mu_0 \propto \left(\langle\beta\rangle/\iota^2\right)T_e^{-3/2}$, where $\langle\beta\rangle_c \propto \iota^2$ is the ideal ballooning limit which roughly coincides with the equilibrium β-limit. Resistive effects have to be expected, since the magnetic Reynolds number close to the plasma boundary is in the range $S \sim 10^5$. The duration of the crashes (~ 100 μs, Fig. 1) is roughly consistent with resistive time scales provided that the radial extent of the perturbation is ≤ 10 % of the plasma radius.

By using $\langle\beta\rangle$ from diamagnetic energy, $\iota \approx \iota_{ext}$, and $T_e \approx T_e(0)$ from X-ray analysis, a critical "stability parameter" $s \approx 0.5$ was found, where s was assumed proportional to the inverse linear growth rate and defined by $s \equiv 100\left(\iota^2/\langle\beta\rangle\right)\cdot T_e^{3/2}$ ($\langle\beta\rangle$ in %, T_e in keV).

Fig. 3 (left part) shows a magnetic field scan intended to change T_e, while keeping the magnetic configuration fixed. Here, the crashes occur at different values of $<\beta>$, T_e and ι, but all at the same value of s. The right part contains a high-β database including all cases where fast crashes were observed together with stable cases. In the diagram, $<\beta>$ normalised to ι^2 is plotted versus $T_e^{3/2}$. Almost all data are bounded by the dashed line representing the stability parameter s = 0.5. The data just prior to a crash (termed unstable and represented by different symbols) are in the vicinity of s = 0.5.

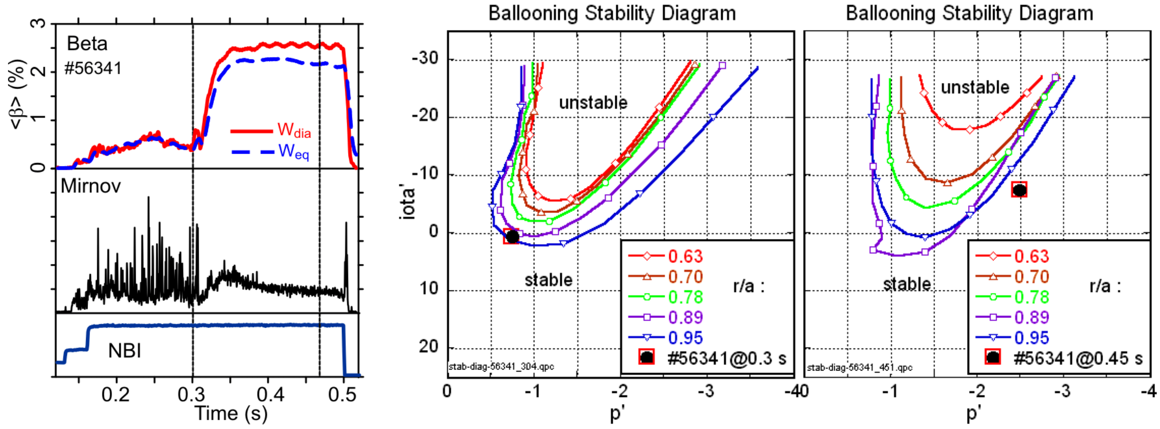

Fig. 4. Left: Spontaneous transition from an unstable low-β phase into a quiescent high-β regime in a configuration with enhanced modular ripple. The marginal stability contours (for different surfaces) are predicted for high-n ideal ballooning modes [5]. The calculations indicate that the pressure profile is kept close to the 1st stability boundary in the first phase (middle). After the transition the second stability regime is reached (right).

The explanation of the fast crashes in terms of ballooning modes is further supported by experimental results obtained in configurations of different modular magnetic field ripple. Fig. 4 shows a pronounced bifurcation of the plasma beta, which is controlled by the presence of strong ELM-like bursts and depends on the magnitude of the field ripple. The stability diagrams on the right are constructed using the analysis technique of Hudson and Hegna [5]. The infinite-n ballooning stability was calculated for the symmetric field line (field line label $\alpha = 0$ and ballooning angle $\eta_k = 0$). This is often, but not necessarily, the most unstable field line. According to these calculations, the plasma in the low-β phase is very close to the 1st stability boundary, whereas it is in the 2nd stability regime during the high-β phase. Calculations for a sequence of free-boundary equilibria with increasing β show that the plasma can access this regime along a stable trajectory, due to an increase of shear with plasma pressure and a deformation of the stability boundary. The relevance of the ideal threshold is not fully clear, since the phenomena of all crashes are very similar.

Resistive ballooning modes are not observed in optimized configurations, and they are not expected to be relevant in W7-X and in stellarator reactor regimes due to larger values of S and two-fluid effects [6].

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