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β-Limiting Phenomena in ASDEX Upgrade

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1.) Introduction

For future fusion reactors with magnetic confinement it is necessary to maximize the fusion power output for a given magnetic field, both for economic as well as for technical reasons (e.g. critical fields of superconductors). This directly translates to a high stored energy and thus to a necessary high value of $\beta = 2\mu_0 < p > /B^2$ [1].

In toroidal magnetic fusion devices such as the tokamak or the stellarator, different factors may limit the achievable β. Two main distinct reasons are the equilibrium limit (when the Shafranov shift approaches the minor plasma radius) and the β-limit due to MHD activity. The equilibrium limit results in $\beta_{p,max} \approx 1/\epsilon$ and can thus be avoided by chosing a proper equilibrium configuration. In a tokamak, the second limit has been shown to roughly scale like $\beta_{max} \sim I_p/(aB) \sim \epsilon/q$ [2]. This so-called Troyon-limit led to the definition of $\beta_N = \beta/(I_p/(aB))$. The paper focuses on the MHD phenomena giving rise to the β-limit in ASDEX Upgrade, a medium size tokamak with ITER relevant geometry [3].

2.) Operational Aspects

The heating power necessary to reach a certain β depends on plasma geometry and parameters. For an energy confinement scaling $\tau_E \sim 0.05 \times HI_pR^{3/2}/P^{1/2}$ (derived from the JET-DIII-D scaling [4] with H-mode multiplier H), we obtain for ASDEX Upgrade ($R = 1.65$ m, $a = 0.5$ m, $\kappa = 1.6$) $P(\beta_N) = 2.15(\beta_N/H)^2B_t^2$. With an available heating power of 10 MW, using $\beta_{N,max} \approx 3$ and $H \approx 2$, β-limit studies can only be conducted at $B_t \leq 1.5$ T unless improved confinement occurs. Thus, our database is acquired at $B_t \leq 1.9$ T.

For the discussion of neoclassical tearing modes, the collisionality $\nu^* = \nu qR/(2\epsilon v_{\|})$ is an important parameter. It scales like $\nu^* \sim (n/T^2)(qa/\epsilon^2)$ whereas $\beta \sim nT/B^2$. Thus, at constant β, we find $\nu^* \sim (an^3/B^4)(q/\epsilon^2)$ and we have to use a scaling $n \sim B^{4/3}/a^{1/3}$ to match ITER in the dimensionless numbers β, ν^*, ϵ and q. For ITER parameters $B_t = 5.7$ T, $n = 1.25 \times 10^{20}$ m^{-3} and $a = 2.8$ m, we find that an ASDEX Upgrade shot at 1.5 T should be run at $n = 0.38 \times 10^{20}$ m^{-3}. The lowest possible density in ELMy H-mode is proportional to I_p, which itself is fixed by the requirement $q = 3$. For the example above (corresponding to $I_p = 0.8$ MA) the minimum density is about 0.5×10^{20} m^{-3}. Therefore, we cannot run at exactly the ITER dimensionless parameters: at the right q, the collisionality is higher by a factor of $(0.5/0.38)^3 = 2.4$. Increasing the density will increase this factor $\sim n^3$.

The β-limit may either occur as a saturation (W does not follow a rise in P), as a β-drop (W decreases with increasing P) or as a β-limit disruption. It has been shown before that in ASDEX Upgrade, below $q = 3$, the β-limit is disruptive whereas above $q = 3$, a saturation or drop occurs [5]. In [5], only the energy from magnetic reconstruction was considered; we have now found good agreement between these values and the total kinetic energy. From the Troyon-scaling, we would expect $\beta_{N,max} \neq f(q)$. In ASDEX Upgrade, we usually find $\beta_{N,max} \approx 3$ for $q \geq 3$, but for $q \leq 3$, $\beta_{N,max}$ drops with q to values around 2 for $q \rightarrow 2$ [5]. The highest values of β_N were achieved with the highest triangularity ($\delta \approx 0.4$). In this configuration, we transiently achieve $\beta_N \approx 3.3$ without I_p ramp.

Another extension of the Troyon-scaling has been proposed in DIII-D by including ℓ_i into

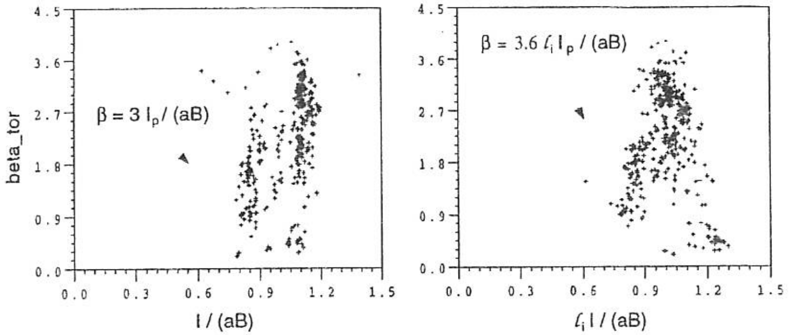

Figure 1: *Plot of* β *against the normalization* $I_p/(aB)$ *(left) or* $\ell_i I_p/(aB)$ *(right). Including* ℓ_i *can account for the high* β *cases obtained in* I_p *ramp-down experiments.*

the scaling [6]. In ASDEX Upgrade, we have varied ℓ_i by I_p ramp-down and thus achieved the highest values of $\beta_p \approx 3$ and $\beta_N \approx 4.5$. As shown in Fig. 1, including ℓ_i into the scaling also provides a reasonable fit to the ASDEX Upgrade data. Note that, due to a slightly different definition, our ℓ_i is about 10 % smaller than that of DIII-D.

3.) MHD Mode Behaviour at the β-limit

An analysis of the ideal kink stability of typical ASDEX Upgrade high β equilibria using the ERATO code [7] reveals stability for $\beta_N \leq 3.5$ even without a conducting wall with the limit given by the (2,1) mode. Including the ASDEX Upgrade vacuum vessel stabilizes this mode up to $\beta_N \approx 4.1$. The (3,2) mode appears at $\beta_N \approx 3.7$ without wall, but can also be wall-stabilized here. However, for $\beta_N = 4.1$, it cannot be stabilized and now dominates the mode pattern. The pressure gradient is usually below the critical gradient for ideal ballooning except at the plasma edge, where it is linked to the occurrence of type I ELMs in these discharges. Thus, ideal MHD cannot explain the usual limit of $\beta_N \leq 3.3$.

In the experiment, we can distinguish two types of mode activity giving rise to a β-limit:

$q = 1$ *activity:* β-saturation is mostly connected to activity on the $q = 1$ surface. This is often a continuous (1,1) mode which probably is connected to a (1,1) island (as it may last for several 100 ms, a time scale on which an internal kink should form an island). This mode leads to a saturation of β_N. In discharges with high beam power at nearly perpendicular injection, we also see fishbone bursts with a dominant (1,1) structure, but also higher helicity components [8]. Occurrence of repetitive fishbones may lead to a drop of β_N by less than 10 %. Usually, sawteeth persist, but their repetition rate slows down. The sawtooth losses do not play a significant role in the β-limit.

$q > 1$ *activity:* In addition to the (1,1) activity, we often see tearing modes on surfaces with $q > 1$. An example for a time sequence is given in Fig. 2. Here, initially a (1,1) mode exists. At $t = 1.84$ s, a (4,3) mode develops and, 40 ms later, a (3,2) develops. From the plot of the amplitudes of the different modes, it can be seen that the $q > 1$ islands drive the initial (1,1) mode and produce higher harmonics with equal toroidal mode number via toroidal mode coupling. During this sequence, β_N can drop significantly (by up to 30 %).

These tearing modes at high β are usually attributed to the neoclassical tearing mode where the island is driven nonlinearly by the loss of bootstrap current due to a flattening of the pressure inside the island [9]. In a more recent theory [10], it is found that, due to diamagnetic stabilization, a threshold island width W_{thr} exists below which no neoclassical

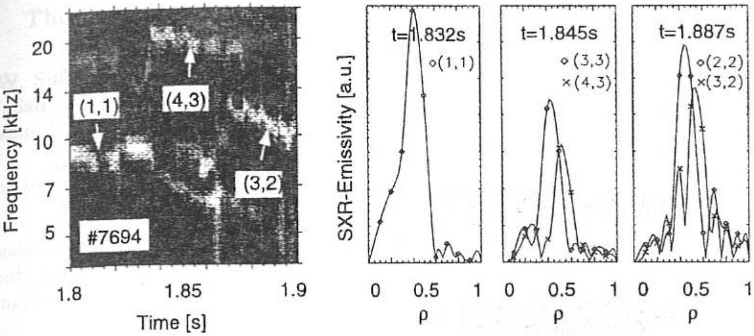

Figure 2: *Typical sequence of resistive modes at the β-limit. The left plot shows SXR-signal frequencies as a function of time, the right plots show the amplitudes of various modes from a deconvolution of SXR line integrals.*

island will occur and thus one needs a 'seed island' of $W > W_{thr}$ to start neoclassical tearing. For $\nu_i/(\epsilon\omega*_{pe}) < 1$, this width is greatly reduced. To check this theory in ASDEX Upgrade, we performed a β-limit experiment where, at fixed I_p and B_t, the density was increased by a factor of 2. Following the scaling above, this corresponds to a change in ν^* by a factor of 8. Although there was no pronounced effect on $\beta_{N,max}$, the MHD behaviour changed: at the lowest collisionality, the rise in β was limited by (1,1) activity whereas at the highest collisionality, the sequence shown in Fig. 2 involving neoclassical tearing modes occured. For the whole collisionality scan, we are in the regime $\nu_i/(\epsilon\omega*_{pe}) < 1$, but due to $W_{thr} \sim \rho_{pi}$, the threshold island size decreases at constant β but lower temperature. It turns out that a comparison of local parameters at the (3,2) surface yields good agreement with this theory, assuming a seed island width of ≈ 2 cm [11]. The onset of such tearing modes usually coincides with ELMs or sawteeth, therefore it is likely that a seed island of the right helicity is produced by these events.

To independently prove that the observed islands are of neoclassical origin, we calculated the difference in bootstrap current ΔI_{bs} for a typical pressure profile at the β-limit when the pressure is flattened at the (3,2) surface in a region of 5 cm (corresponding to the saturated island width estimated from Mirnov analysis). Then, we calculate the width of the magnetic island produced by a helical current of magnitude ΔI_{bs} (for an 800 kA discharge at the β-limit, $\Delta I_{bs} \approx 3.5$ kA). The island width calculated in this manner is close to the 5 cm we started with, indicating that this would be a saturated neoclassical island. Also, these islands often grow linearly in $\tilde{B}$ for ≈ 10 ms, which is another feature of the neoclassical tearing mode [9]. Finally, for reasonable current profiles, one would always expect $\Delta' < 0$ for the (4,3) mode, so we have to rely on the neoclassical drive.

An interesting difference between the $q = 1$ and the $q > 1$ activity is their influence on the toroidal plasma rotation. Fig. 3 shows an example where a $q = 1$ limit occurs ($t = 1.3$ s). An increase in beam power leads to another rise in β followed by a drop due to the occurence of a (3,2) tearing mode. Only the (3,2) mode leads to a significant drop of toroidal rotation of the core (inside the (3/2) surface). This may be explained by an increase in the viscosity due to the MHD activity, and also by the interaction of the rotating (3,2) mode with the resistive wall and the static error field. Both effects would be much more pronounced for the (3,2) mode than for the (1,1) mode. Note that, as stated above, the (3,2) has a bigger effect on

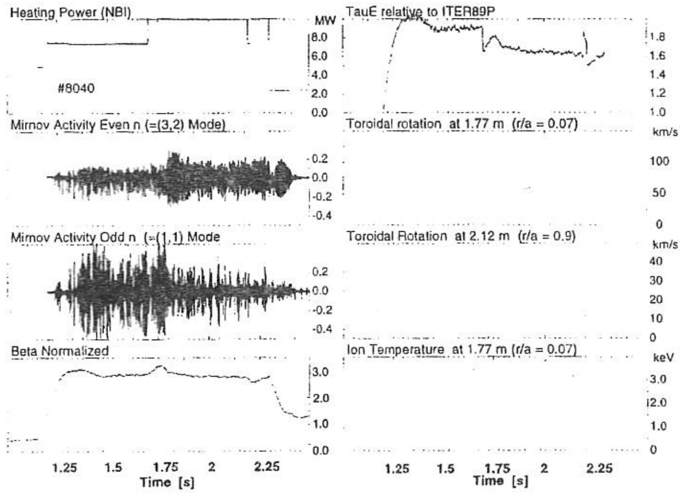

Figure 3: *β-limit by (1,1) activity (1.3 s) and then by a (3,2) tearing mode (1.78 s). The (3.2) mode has a significant influence on toroidal rotation of the core.*

confinement then the (1,1), as indicated by the decreased H-mode multiplier (for the same T_i and density, one needs more beam power).

Thus, we conclude that the β-limit with $q > 1$ mode activity in ASDEX Upgrade is mainly given by the stability of the neoclassical tearing mode. This is especially important as these modes sometimes 'accidentally' occur at β_N-values well below the values stated above, maybe due to a change in Δ' or due to an especially large seed island (there are examples down to $\beta_N = 2.4$). The β-drop introduced can be restored by increasing the heating power, but at the expense of a reduced confinement due to the mode as shown in Fig. 3.

Finally, it should be noted that β-limit disruptions in ASDEX Upgrade happen only several 100 ms after the occurrence of the actual β-limit and seem to be due to a loss of confinement caused by the (3,2) mode with subsequent H-L transition, and the occurrence of a MARFE causing a (2,1) mode. Thus, a typical β-limit disruption, as has been identified in TFTR [12], does not appear in ASDEX Upgrade, even at the lowest q-value of 2.3.

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