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Rotation dependence of tearing mode excitation by external perturbation fields on TEXTOR

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The TEXTOR tokamak is equipped with the Dynamic Ergodic Divertor (DED) [1]. The DED consists of 16 helical coils mounted on the high field side of the torus. The helical pitch of the coils corresponds to the $q = 3$ surface of the plasma. The DED can be operated with the poloidal and toroidal mode numbers $m/n = 3/1$, $m/n = 6/2$, and $m/n = 12/4$. The external perturbation field can be static (dc) or rotating (ac) with frequencies up to 10 kHz.

The DED, when operated in the $m/n = 3/1$ configuration, allows the intentional excitation of an $m/n = 2/1$ tearing mode due to the strong $m/n = 2/1$ side band of the magnetic perturbation. The mode is locked to the DED field (i.e. it is locked in the tokamak frame when a static DED field is applied) and the onset threshold (i.e. current in DED coils) is highly reproducible. The DED perturbation field is resonant to the $q = 3$ surface, but the first mode which excited (i.e. the mode with the lowest threshold) is the $2/1$ tearing mode and not the $3/1$ mode. This behaviour can be attributed to the shape of the current density profile which is monotonous and yields an stability index Δ' which is only slightly negative for the $2/1$ tearing mode, and much stronger stability for the $3/1$ tearing mode. Indeed, the latter one has found to be unstable, too, but at much larger perturbation coil currents. Parametric studies have shown that the mode onset threshold of the $m/n = 2/1$ tearing mode scales approximately linear with the line integrated electron density, in good agreement with the results reported from other tokamaks [2].

TEXTOR has two tangential neutral beam injectors, oriented in direction of the plasma current (co-NBI) and in opposite direction (counter-NBI). The power of each neutral beam, and hence the injected momentum, can be precisely controlled by movable apertures in the beam line. This allows to investigate the influence of plasma rotation while keeping beta constant.

A previous study of the influence of plasma rotation on the mode onset threshold has been done on JET [3]. The error field threshold increased much stronger with co-NBI heating than

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ICRF heating with the same power. This effect has been attributed to the stabilizing influence of plasma rotation at the mode rational surface. Jet experiments with counter-NBI (in reverse *B* configuration) did confirm the rotation dependence [4]. In contrast to this results, TEXTOR experiments showed a significant increase of the mode threshold with ICRF heating power. Neutral beam co-injection was found to have a destabilizing influence on the mode excitation threshold, whereas counter-NBI led to an increase of the error field threshold [5].

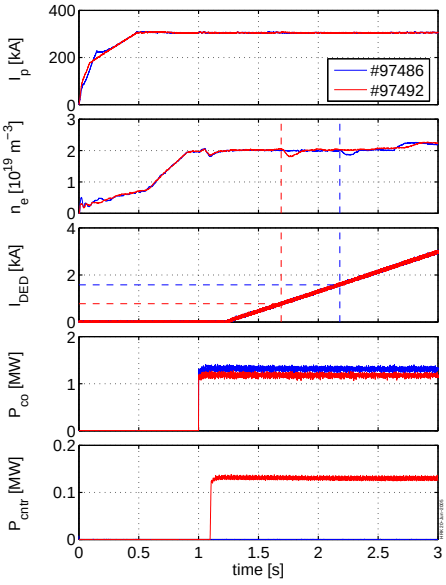

Figure 1: Time traces of two discharges with slightly different beam composition.

An example of an experiment where the DED perturbation field is used to seed a $m/n = 2/1$ tearing mode in the plasma is shown in figure 1. Both discharges shown are almost identical: they have a magnetic field of 2.25 T and a plasma current of 350 kA, corresponding to a safety factor of the last closed flux surface of $q_a \approx 4.5$. The line-averaged electron density is about 1.8×10^{19} m^{-3}. The total heating power (ohmic + NBI) amounts to 1.42 MW. For these plasma conditions the locked $m/n = 2/1$ tearing mode is found to saturate at an amplitude (width) of 15 to 20 % of the plasma minor radius, but does not initiate a disruption because of the sufficiently large edge safety factor.

The sudden onset of the $2/1$ tearing mode is indicated by a small drop of the line-averaged density. The only difference of both discharges is a slightly different composition of the neutral beam power. Discharge #97486 (blue lines) has only co-NBI heating, and discharge #97492 (red lines) has a little bit of counter beam heating (≈ 0.13 MW), the co-beam has been attenuated by the same amount in order to keep the total heating power constant. The dashed lines mark the times and DED coil currents when mode onset is observed. The discharge with pure co-injection requires a significantly higher perturbation field in order to seed the $2/1$ tearing mode. The addition of a small fraction of counter-NBI results in a considerable lowering of the mode onset threshold. This behaviour has been reproducible found in several discharges made during experimental sessions on different days.

The above mentioned stabilizing action of ICRF heating is illustrated in figure 2. The blue circles show a scan of the ICRF heating power, i.e. the plasma beta changes. For the highest ICRH power beta is approximately doubled when L-mode confinement scaling is assumed. The magenta squares shows a set of discharges where the sum of co-NBI and ICRH power was kept

constant, i.e. the momentum input to the plasma became larger at lower ICRH power. For all discharges shown the frequency of the ICRF heating was $f_{ICRH} = 32.5$ MHz, corresponding to a fundamental resonance at $R = 1.84$ m, close to the magnetic axis and well inside the $q = 2$ radius. For the rest of this paper it is assumed that there is no strong influence on fast particles on the stability of the $2/1$ tearing mode. Both sets of data points show a similar increase of mode seeding threshold with ICRH power. Interpreting this as a stabilizing effect of beta only, one would expect the magenta squares to be aligned along a horizontal line. There seems to be either a very small influence of beta, or a destabilizing effect of beam momentum injected in co-current direction.

In order to separate the effects of beta and rotation, and not to be disturbed by any fast particle effects, several scans of the plasma rotation by varying the neutral beam power balance while keeping the total power constant were done. The results are summarized in figure 3. The blue circles show the dataset from 2004 [5], the red squares and green triangles show data from recent campaigns. The critical DED coil current for $2/1$ tearing mode onset is plotted versus the plasma rotation measured by charge exchange recombination spectroscopy at a major radius of $R = 2.05$ m, which is close to the location of the $q = 2$ surface on the low field side of the torus. The red line connects the discharges shown in figure 1, the one with the small fraction of counter-NBI is at the lower left.

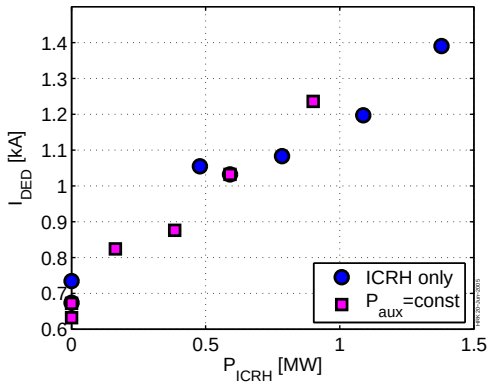

Figure 2: ICRH scans with and without constant beta.

All data show an enhanced mode onset threshold when a large fraction of counter-beam (negative rotation) is applied. The 2005 data show in addition an increased threshold for pure co-NBI pulses, what was not seen in the older dataset. A probable explanation could be that a recent re-alignment of the ion source allows for better momentum transfer. This is questioned by the absolute values of the toroidal rotation which are larger for the 2004 data. Anyhow, the charge exchange rotation data suffers from large systematic errors, what can for example be seen from the red squares where the point at highest rotation has less net momentum input in co-current direction than the pure co-NBI points nearby. The green triangles are another pair of discharges where one has pure co-NBI (upper right), and the other has a small fraction of counter-NBI (≈ 120 kW) added without reducing the co-beam, i.e. the total heating power is about 10 % larger. Again, this results in a large reduction of the threshold.

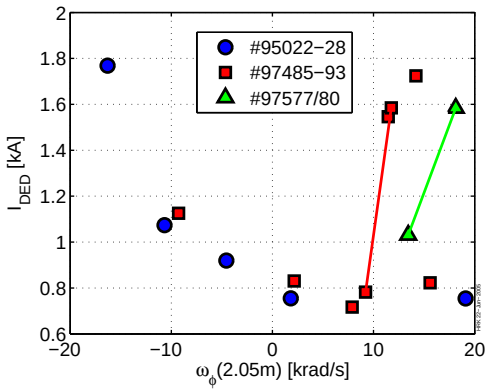

Figure 3: Plasma rotation scan using various NBI beam compositions.

The rotation data show that large plasma rotation in either co- or counter-current direction has a stabilizing effect. The dependence on the angular frequency shows an asymmetry, i.e. counter-rotation is always stabilizing whereas co-injection of momentum first lowers the threshold before stabilization sets in. This behaviour is not consistent with a model based on JET data [6]. The growth of the $2/1$ (neo-classical) tearing mode is described within the framework of the generalized Rutherford equation, taking into account additional contributions due to the perturbed bootstrap current in the island, the field line curvature, the ion polarization current within the island, and the influence of local current drive and heating [7]. The effect of the external perturbation field has to be considered, too. The influence of plasma momentum and rotation drive has to be taken into account, in order to describe the mode penetration and the associated rotation braking. The observed asymmetric response can be caused by either by ion polarization current effects, or by an offset of the (unperturbed) mode frequency in the restframe of the magnetic perturbation.

In summary, TEXTOR experiments on $2/1$ island seeding by external perturbation fields have shown a strong stabilizing influence of beta and a minimum of the critical perturbation field for particular values of the toroidal rotation velocity. This finding can probably be explained by the influence of the ion polarization current which can be stabilizing and destabilizing, depending on the mode frequency with respect to ion and electron diamagnetic frequencies [8], or can be due to rotational stabilization requiring stronger braking of a fast rotating plasma. Further experiments are required to resolve uncertainties of the present datasets, especially for the charge exchange rotation data.

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