Nucl. Fusion **45** (2005) 1700–1707 doi:10.1088/0029-5515/45/12/026

Effect of the dynamic ergodic divertor in the TEXTOR tokamak on MHD stability, plasma rotation and transport

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Received 10 December 2004, accepted for publication 11 October 2005
Published 29 November 2005
Online at stacks.iop.org/NF/45/1700

Abstract
With the dynamic ergodic divertor in TEXTOR fundamental effects of the coupling of external magnetic field perturbations to the confined plasma have been studied. The non-linear coupling between external ($m/n = 12/4$) and internal modes ($m/n = 3/1$) has been investigated. The critical perturbation field ($m/n = 3/1$) for the excitation of an $m/n = 2/1$ tearing mode depends not only on the magnitude but also on the direction of the toroidal angular momentum input by neutral beam injection (NBI). Below the excitation threshold of this mode a toroidal spin-up of the plasma has been observed, which only depends on the strength of the perturbation field. It is independent of both the rotation direction of the external perturbation field and the toroidal angular momentum supplied by the NBI.

PACS numbers: 52.55.Fa, 52.30.-q, 52.55.Tn, 52.35.Vd

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The importance of magnetic field stochastization for stability and transport in both tokamaks [1, 2] and stellarators is increasingly being recognized. In stellarators the characteristic magnetic island structure is utilized in the island divertor and has led to the discovery of the high density H-mode [3]. In tokamaks, indications exist that certain MHD instabilities can be controlled or even suppressed with helical magnetic field perturbations: (a) it has been suggested that the interaction of neoclassical tearing modes (NTMs) with different helicity results in a stabilization of the less unstable one [4][5]. Similarly, the application of an external helical magnetic field perturbation should result in the stabilization of the NTM. Indeed, first experiments show an effect, although the simultaneous braking of the plasma rotation was also accompanied by a confinement loss [5]; (b) another application is the mitigation of edge localized modes (ELMs) [6, 7]. Here, recent experiments show the disappearance of strong low frequency ELMs, while maintaining the H-mode pedestal pressure and thus the plasma confinement [8]. In all these

[5] While in [4] the ratio of parallel to perpendicular heat conduction has been assumed to be $\chi_{||}/\chi_\perp = 10^8$, a more realistic value of $\chi_{||}/\chi_\perp = 10^{10}$ leads to a reduction of the stabilizing interaction of the modes with different helicity.

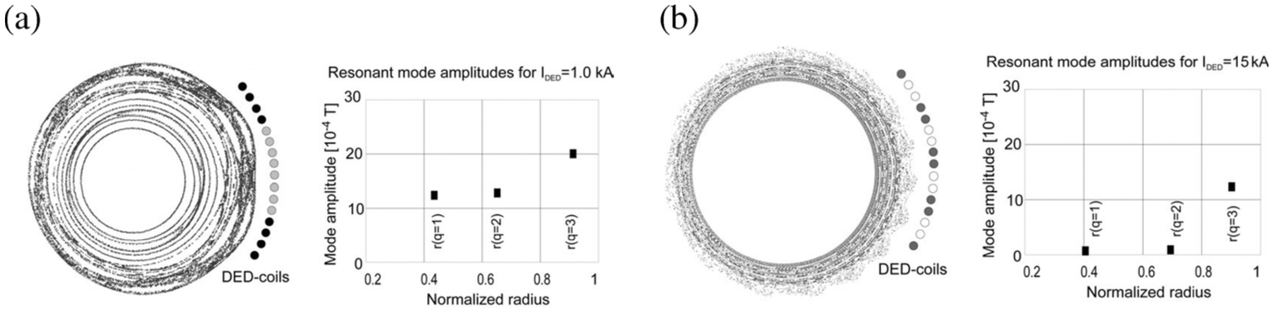

Figure 1. Poincaré plot of magnetic field topology with (static) DED for (*a*) the $m/n = 3/1$ and (*b*) the 12/4 configuration, calculated from a superposition of the perturbation field (for DED currents, $I_{\mathrm{DED},3/1} = 1.0$ kA and $I_{\mathrm{DED},12/4} = 15$ kA and a plasma equilibrium with an edge safety factor of $q_a = 4.5$ for the 3/1 and $q_a = 3.3$ for the 12/4 configuration). Also shown are the underlying amplitudes of the magnetic field perturbation for the $m = 1$, 2 and 3 components at their resonance positions.

cases a critical question is the interaction of the magnetic field perturbation with the magnetically confined plasma and to what extent the beneficial effect of avoiding certain instabilities is outweighed by possible adverse changes of the plasma confinement. For the latter a particular interest lies in the behaviour of the plasma rotation or viscosity under the influence of such helical magnetic field perturbations.

In the TEXTOR tokamak a new system of helical magnetic field coils has been installed. The unique feature of this dynamic ergodic divertor (DED) [9, 10] is the capability of applying rotating magnetic perturbation fields with a frequency of up to 10 kHz. The system consists of 16 perturbation coils (four quadruples) plus two additional coils for the compensation of the magnetic field imperfections at the feeder regions of the coils. The coils wind helically around the inner, high field side of the torus (major radius $R = 1.75$ m, minor radius of the circular plasma cross-section typically $a = 0.47$ m) with a pitch corresponding to the magnetic field lines of the flux surface with a safety factor of $q = 3$. Depending on the coil connections, principal mode numbers of the DED are $m/n = 12/4$, 6/2 or 3/1. While the $m/n = 12/4$ mode decays rather quickly, affecting mainly the plasma edge, the perturbation field of the $m/n = 3/1$ configuration penetrates deeply into the plasma (figure 1). Accordingly, the main application of the first is the study of the DED concept [11], while the latter is mainly used to study the MHD wave excitation, plasma braking or acceleration [12] and error field amplification. The intermediate $m/n = 6/2$ configuration has not been used up to now.

This paper focuses on the influence of the DED on the MHD and transport properties of the plasma core, which also means that the emphasis lies on the $m/n = 3/1$ configuration. For the discussion of the divertor properties of the DED the reader is referred to complementary papers [11, 13]. First, the interaction of the $m/n = 12/4$ DED configuration with an intrinsic $m/n = 3/1$ tearing mode is presented. Subsequently, various results, obtained with the $m/n = 3/1$ DED configuration, will be discussed. This includes the effect of the DED on transport and plasma rotation at lower perturbation field amplitudes and the controlled excitation of tearing modes at higher amplitudes. The latter capacity has also been used to study the tearing mode avoidance or suppression by electron cyclotron resonance heating (ECRH) and current drive, which is presented in [14].

2. Interaction between external perturbation field ($m/n = 12/4$) and intrinsic tearing modes

The calculation of the non-linear coupling of NTMs with different helicities predicts a mutual stabilization of the modes, resulting in a survival of the more unstable mode only [4]. Applying the DED in the static $m/n = 12/4$ configuration, one aspect of this interaction, namely, the coupling of the external magnetic field perturbation with an intrinsic $m/n = 3/1$ tearing mode, has been investigated. Here, however, the interacting magnetic islands, being located at the same rational q-surface, have the same helicity.

In figure 2(*a*) the temporal evolution of such an intrinsic tearing mode is illustrated. Without DED the plasma (with a toroidal magnetic field, B_{T}, of 1.9 T and a plasma current, I_{p}, of 400 kA yielding an edge safety factor of $q_a \approx 3$) shows a weak $m/n = 3/1$ tearing mode at a frequency of 5.5 kHz. At 1.5 s the DED is switched on, resulting in a reduction of the mode signal. As far as we can tell from the corresponding spectrogram, the mode disappears without slowing down, in contrast to cases where modes lock to the externally applied field. In agreement with the experiment, the calculation indicates the existence of an $m/n = 3/1$ tearing mode before the application of the DED (see figure 2(*b*)). The experimental q-profile underlying the calculation had to be modified slightly to achieve tearing mode instability, which however still lies within the error bars of the measurement. This only shows that the tearing mode is only marginally unstable, which is at least qualitatively in agreement with the very weak experimental $m/n = 3/1$ signal. In addition, the calculation shows an $m/n = 12/4$ harmonic of the tearing mode with a smaller island width, which in the experiment is probably too weak to detect. After the DED field is turned on ($B_{r,12/4}/B_{\mathrm{tor}} = 5.2 \times 10^{-4}$ at $r = a$), the calculation reproduces the suppression of the intrinsic $m/n = 3/1$ mode which is replaced by a growing $m/n = 12/4$ island, imposed by the external perturbation. Assuming an arbitrarily fast raising time of the DED coil currents, the growth of the $m/n = 12/4$ mode in the plasma takes about 0.001 resistive time scales. In the calculation, the stabilization of the $m/n = 3/1$ mode by the applied $m/n = 12/4$ helical field is attributed to the change of the local current density profile at the $q = 3$ surface by the $m/n = 12/4$ island and the non-linear interaction between the $m/n = 3/1$ and 12/4 components.

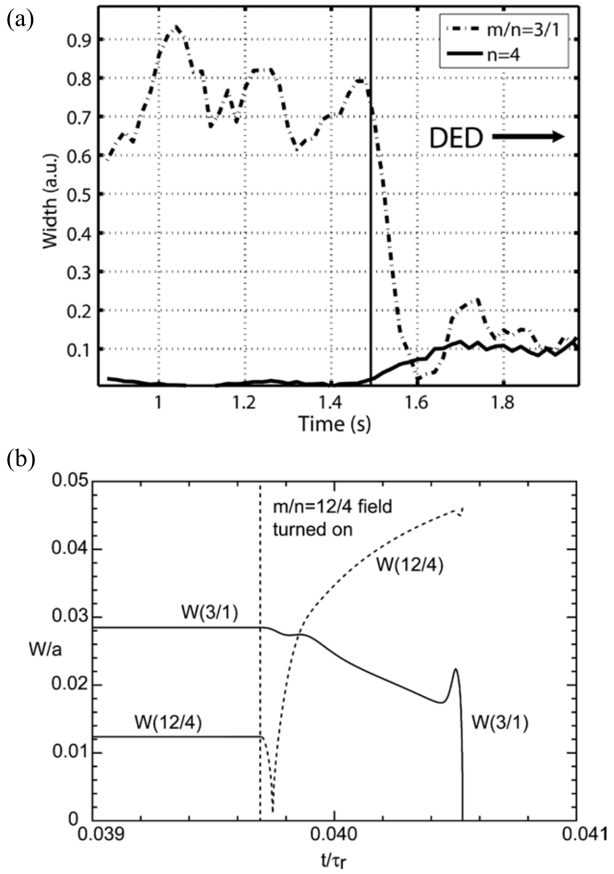

Figure 2. (*a*) Measured temporal evolution of the relative change of the island width (assuming $W^2 \sim$ amplitude of Mirnov signal integrated over the frequency band of the relevant mode normalized to the frequency of the mode) of an $m/n = 3/1$ and an $n = 4$ mode before and during the application of the (static) DED ($m/n = 12/4$ configuration). When the DED is switched on ($I_{\mathrm{DED}} = 7$ kA), the $m/n = 3/1$ mode vanishes. (*b*) Corresponding temporal evolution (time normalized to resistive time at the plasma centre $\tau_{\mathrm{r}} \sim a^2/T_{\mathrm{e}}^{3/2}$ which in the case shown is about 0.7 s) of the normalized magnetic island width, W/a, as predicted by the numerical calculation of the non-linear coupling between intrinsic mode and external perturbation field [4].

3. Effect of external perturbation field ($m/n = 3/1$) on transport and plasma rotation at low perturbation amplitude

The $m/n = 3/1$ helical magnetic field of the DED penetrates deeply into the plasma and thus strongly influences the transport and stability properties of the core plasma [15]. The general course of the experiments, discussed here, is outlined in figure 3. The plasmas were operated at $B_{\mathrm{T}} = 2.25$ T and $I_{\mathrm{p}} = 300$ kA, resulting in an edge safety factor of $q_a = 4.5$. After discharge initiation the first neutral beam injection (NBI) is applied. NBI is required for the measurement of the toroidal plasma rotation by charge exchange recombination spectroscopy (CXRS) and can constitute a significant source of toroidal angular momentum. As TEXTOR is equipped with two NBI systems, oriented in opposite directions (co- and counter- with respect to the plasma current), the momentum not only depends on the power level, but also on the balance between the contributions from the two beam lines. Once

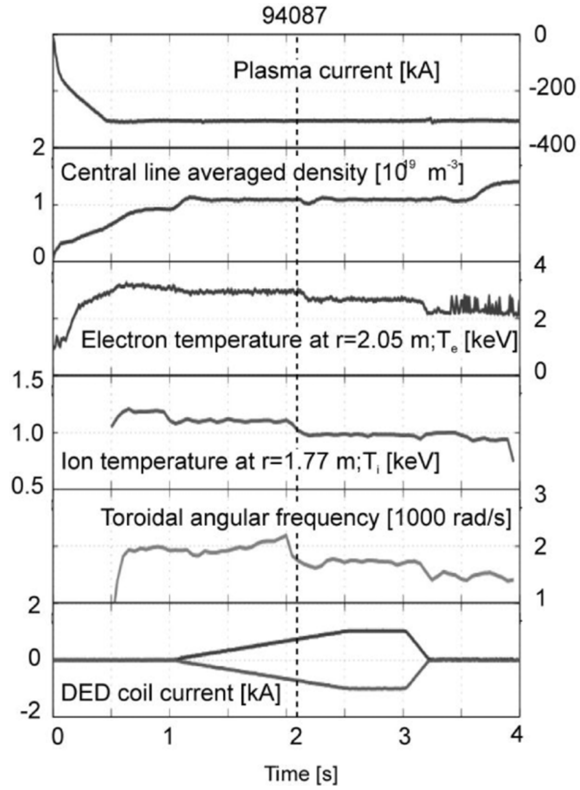

Figure 3. Time traces of discharge parameters where static DED fields with $m/n = 3/1$ have been applied. The measured DED coil currents are slowly ramped up or down depending on polarity (bottom trace), until an $m/n = 2/1$ tearing mode is induced, indicated by the vertical line.

the plasma has reached stationary conditions with respect to plasma current, heating power, electron and ion temperature and electron density, the DED coil currents are slowly ramped up to a pre-programmed level. This level is kept constant for about half a second, after which the DED is turned off again.

The influence on the toroidal plasma rotation has been studied for different combinations of perturbation field rotation direction and frequency: static perturbation without rotation, 1 kHz in the direction of the plasma current (co-rotation) and with the same frequency opposite to the plasma current (counter-rotation). Figure 3 shows the time evolution of characteristic parameters with static DED and low NBI power (0.3 MW, corresponding to about the Ohmic heating power). During the application of the perturbation field two phases can be distinguished. First, at low perturbation amplitude, temperature and density profiles do not change. Remarkably the toroidal angular frequency rises by about 20% with regard to the rotation produced by NBI alone. The second phase is characterized by the formation of an $m/n = 2/1$ tearing mode, once the current per DED coil exceeds a critical value of about 0.8 kA, which corresponds to a magnetic field perturbation of 1.0×10^{-3} T at the $q = 2$ surface. The dependence of this critical perturbation field on plasma parameters, such as density, beta or toroidal rotation velocity is discussed in section 4. The formation of the induced tearing mode is accompanied by significant reductions of temperatures and rotation frequency. The electron density shows only a small dip at the onset of the tearing mode and recovers immediately,

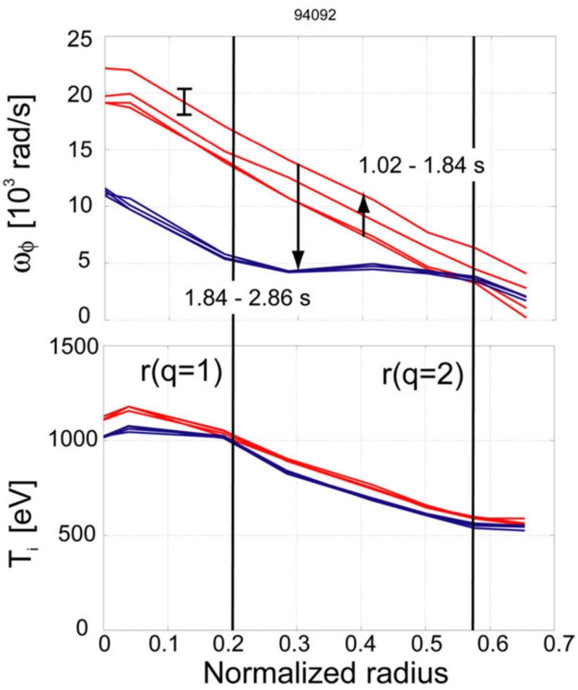

Figure 4. Temporal evolution of the radial profiles of toroidal rotation and ion temperature with static DED (the typical error bar for the plasma rotation is indicated). Before the onset of the tearing mode between 1.02 and 1.84 s, the angular frequency increases monotonously over the whole profile. The onset of the tearing mode reduces the central temperature peaking and flattens ω_ϕ between the $q = 1$ and 2 surfaces.

caused by the feedback control of the density. Set to a level of $2 \times 10^{19}\,\mathrm{m}^{-3}$, the loss of particle confinement is compensated by a stronger gas fuelling. The observed dip is a consequence of the finite response time of the feedback control system. Integrating over the profiles of temperatures and densities, the corresponding loss of thermal energy amounts to 12%.

In figure 4 the temporal profile evolution of both ion plasma rotation and temperature is shown. Owing to technical restrictions, the CXRS measurement covers only the inner two thirds of the plasma, ranging from the centre to the $q = 2$ surface. During the first phase, when the DED coil currents start increasing, $\omega_\phi = v_\phi/R$ (where v_ϕ is the Doppler velocity obtained from CXRS) rises over the whole profile, while the ion temperature does not change. At the onset of the tearing mode ω_ϕ drops in the plasma centre by almost a factor of two, in contrast to the vicinity of the $q = 2$ surface, where it stays roughly constant with respect to the initial value without magnetic field perturbation. This results in a flat rotation profile between the $q = 1$ and 2 surfaces, as if in this region the plasma moved like a rigid body. The ion temperature does not show such a pronounced change, which is also reflected in the quite moderate drop of plasma energy. There are indications that the flat rotation profile between the two rational surfaces is caused by the coupling of the $m/n = 2/1$ tearing mode to a $m/n = 1/1$ mode at the $q = 1$ surface: the appearance of the tearing mode is accompanied by a coherent $m/n = 1/1$ kink like structure near the $q = 1$ surface, observed both on the multi-channel electron cyclotron emission measurement and the soft x-ray diode arrays. At the same time sawtooth oscillations disappear. The $m/n = 1/1$ mode could be

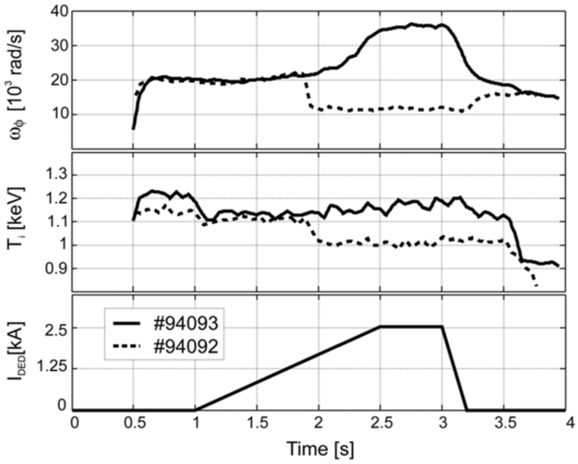

Figure 5. Temporal evolution of the central toroidal angular frequency and ion temperature for co- (——) and counter-rotating (- - - -) DED. The effective DED current amplitude, which is the same in both cases, is indicated by the trace in the bottom graph.

generated by the resonant component of the $m/n = 2/1$ mode at the $q = 1$ surface. Both modes rotate with the same frequency and are locked to the external perturbation field.

With the rotating DED field the temporal evolution of the experiment is basically the same as the one illustrated in figure 3. The only difference is that the DED coils are now supplied with ac currents to produce a rotating magnetic field perturbation. Rotating the DED with a frequency of 1 kHz opposite to the plasma current (counter-rotation) and NBI, the behaviour of the plasma is essentially the same as in the static case (figure 5). Consistent with the observations in the static case, the core plasma rotation does not completely brake or lock to the mode. Instead a finite co-rotation is preserved ($f = \omega_\phi/(2\pi) \approx 1\,\mathrm{kHz}$), while the DED perturbation fields are rotating with about the same frequency in the opposite direction.

The most prominent effect is seen when applying a co-rotating DED field. A tearing mode is not excited, although the effective DED current is clearly above the threshold required to excite a tearing mode in the static or counter-rotating cases. Instead, as illustrated in figure 5, the toroidal rotation continues to rise with the DED current to almost twice the initial level. The relation between central toroidal rotation and DED current amplitude for cases with different combinations of DED rotation and NBI direction and power levels is summarized in figure 6. Compared are cases with static DED and co-NBI (0.3 MW) co-rotating DED and co-NBI at different power levels (0.3, 0.5 and 1.5 MW), counter-rotating DED and co-NBI (0.3 MW) and co-rotating DED and balanced NBI (1.5 MW). To plot static and rotating perturbation field in the same graph, the measured DED coil current has to be multiplied by a factor of two in the static case and by 1.27 in the dynamic case. In the first case, this takes into account that at a given toroidal location the top half of the DED coils (two groups of four coils each, see also figure 1) have been supplied with the same current polarity. Accordingly, in the bottom half (also two groups of four coils each) the opposite polarity has been used. Thus, for a given current the maximum perturbation strength is generated. In contrast, in the dynamic case, the coils are fed with alternating sinusoidal currents, which have a phase

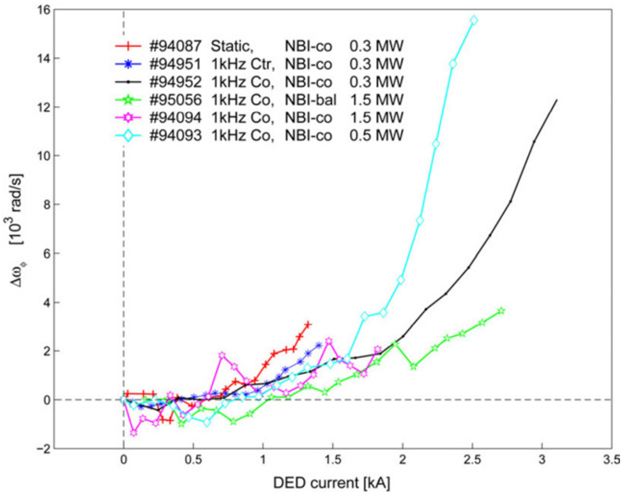

Figure 6. Dependence of the change of the central toroidal angular frequency, $\Delta\omega_\phi$, on effective DED current, $I_{\rm DED}$, before the onset of the $m/n = 2/1$ tearing mode for discharges with different combinations of co-, counter-rotating and static DED, and co- and balanced NBI at different power levels.

shift of 90° between each of the four groups (of four coils). This means that the effective current, which is proportional to the average magnetic field perturbation, is given by the time average of $I = I_0(|\sin(\omega t)| + |\cos(\omega t)|)$, resulting in a factor of approximately 1.27. Basically all cases in figure 6 show the same dependence on the perturbation amplitude: the change of the plasma rotation increases with the DED current. Only the level to which $I_{\rm DED}$ can be increased without inducing a tearing mode differs. Interpreting the strength of the DED current as the degree of ergodization [16], the strong dependence of $\Delta\omega_\phi$ on the DED current is supporting evidence that the magnetic field ergodization is the cause for the strong toroidal spin-up of the plasma.

A tentative explanation could be an enhanced radial transport of the electrons in the open field lines of the ergodic boundary together with the ambipolarity constraint for the ions. Estimated from the linear superposition of the external perturbation field (at a DED current of 1 kA which is roughly the level at which the tearing mode is excited) with the unperturbed plasma equilibrium, the Poincaré plot (figure 1) suggests some degree of perturbation from the plasma edge up to the $q = 2$ surface. On the high field side of the torus in front of the perturbation coils this corresponds to about 30% of the plasma minor radius. The calculation of the Chirikov parameter, however, indicates that true ergodization (Chirikov parameter of approximately 1 or larger) is only achieved in a thin layer (less than 4% of the minor radius) at the plasma edge. This leads to a charge separation which is counteracted by the build-up of a radial electric field, E_r. The direction of the observed increase of v_ϕ is consistent with such a mechanism, assuming that the $v_\phi \times B_\theta$ component in the force balance (with B_θ the poloidal magnetic field) is the dominant term of the change of E_r. This assumption is supported by a constant ion pressure gradient (the evolution of the corresponding ion temperature is shown in figure 4). Lacking the necessary diagnostic capabilities, it is, however, not possible to say anything about the poloidal plasma rotation in the region where v_ϕ is measured. The increase of v_ϕ also agrees with the

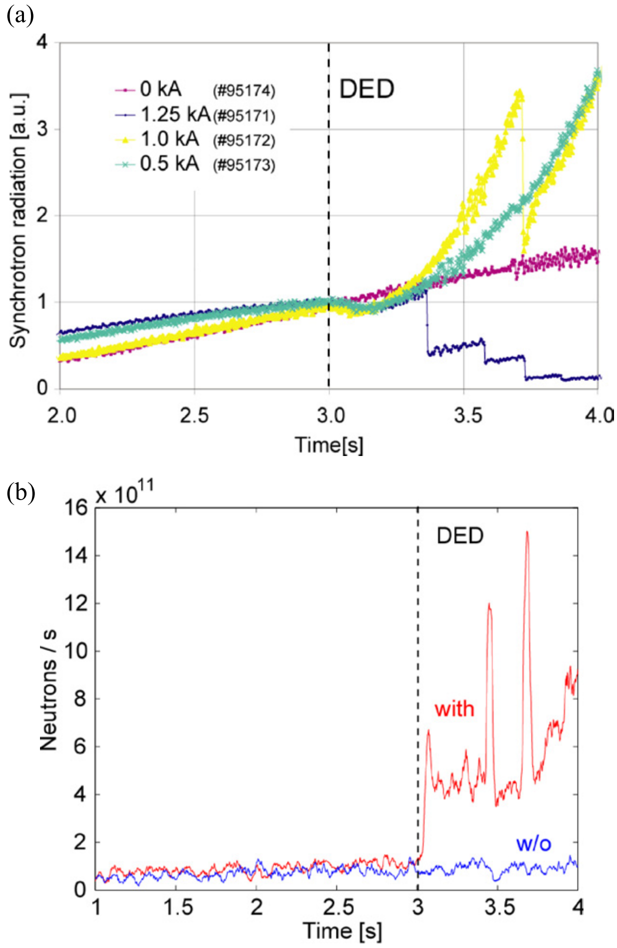

Figure 7. (*a*) Synchrotron radiation generated by runaway electrons, comparing discharges without DED and with different levels of DED currents. The DED is switched on at 3.0 s. Immediately after 3.0 s the different levels of perturbation current (0.5, 1.0, 1.25 kA) essentially cause the same decrease of the signals. (*b*) The loss of fast electrons also results in a strong neutron signal, produced by the impact of the fast electrons on wall components. Here, only the $I_{\rm DED} = 1.25$ kA case (#95171) is shown. The sharp drops in (*a*), corresponding to the burst in (*b*), indicate some kind of instability, which has yet to be identified.

$E \times B$ drift direction of such an ambipolar electric field. The independence from the DED rotation directions shows that a direct resonant coupling between the perturbation field and plasma [17, 18] can be ruled out as a mechanism for driving the plasma rotation. A change of plasma viscosity appears not to be the dominant either, although at higher values of DED current a larger scatter develops which may be caused by variations of the viscosity. However, there are two arguments why the viscosity does not seem to be responsible for the underlying effect: indirectly this can be concluded from the constancy of the plasma energy, if a coupling between heat and momentum transport is assumed, and more directly from the fact that the increase of v_ϕ is also seen when the net angular momentum, in case of balanced NBI, is zero. The finite viscosity would explain how the edge acceleration by the radial electric field is transferred to the plasma core. The plasma viscosity, derived from measurements in TEXTOR of the toroidal rotation velocity in the RI-mode, is about 50 to 100 times above the neoclassical level [19].

The existence of an additional loss mechanism by the ergodization is corroborated by experiments where at low densities runaway electrons have been generated and subsequently exposed to static DED fields. Figure 7(*a*) clearly shows that the runaway population (measured by the synchrotron emission in the infrared) is depleted immediately after the DED is turned on and before the tearing mode is excited. The initial increase of the synchrotron radiation before the DED phase is caused by the steady increase of the runaway population. After switching on the DED all signals start to drop, except for the reference case without the DED, which is explained by the effect of the ergodization on the runaway population. For the cases investigated, the runaway depletion does not depend on the perturbation current, which has been changed from 0.5 to 1.25 kA. Subsequently, two different observations can be made. First the signal increases even faster than before, which is accompanied by an increase of the loop voltage. The increase of the loop voltage could be the result of an effective decrease of the plasma cross-section (at constant plasma current) by the ergodization. Besides, an increased pitch angle of the runaways due to the ergodization would also cause a rise of the synchrotron radiation. The second observation are sharp drops of the synchrotron radiation, presumably indicating some kind of instability of the runaway population which has yet to be identified. In addition the neutron signal in figure 7(*b*), which stems from the impact of fast electrons on plasma facing wall components, shows a prompt increase when the DED is switched on. The sharp drops in figure 7(*a*) correspond to the bursts in (*b*). It should be noted that here, in contrast to the experiment outlined in figure 2, the DED is not ramped up slowly but switched on as fast as the power supplies permit. Although these measurements do not allow us to attribute a certain plasma region to the runaway losses, they suggest that the ergodization directly deteriorates the runaway confinement.

In conjunction with the formation of the $m/n = 2/1$ tearing mode there are more direct indications for a change of the radial electric field, given by three independent measurements of the edge electric field or components thereof. Details of these experiments are discussed elsewhere [11, 20]. Here, only the main results are summarized: (a) the floating potential measured by a rake probe and covering about 10% of the minor radius in the plasma edge clearly shows a change of the radial electric field with increasing DED current and thus ergodization [11]. However, the strongest effect is seen when the $m/n = 2/1$ tearing mode forms. Subsequently, the electric field indeed changes sign from radially inward to outward directed, which is consistent with an ambipolar field generated by the preferential loss of electrons. Since the probes can withstand only very low heat fluxes, these experiments had to be performed in Ohmic plasmas (similar $q_a = 4.4$ at $B_T = 1.89$ T, $I_p = 260$ kA) which have much lower power than the NBI heated plasmas in which the increase of the toroidal rotation was observed. (b) Also the measurement of the poloidal plasma rotation from the Doppler shifted C III emission at the plasma edge, located at about 1 cm inside the separatrix (of the ergodic divertor), drops with the formation of the $m/n = 2/1$ tearing mode to about zero rotation [11]. The corresponding $E \times B$ drift component changes from inward directed (towards the plasma centre) to zero. Further increasing the DED current, an $m/n = 3/1$ mode forms, and the plasma even starts to rotate in the opposite poloidal direction (now the corresponding $E \times B$ is outward directed). (c) Deducing the radial electric field from a poloidal correlation reflectometer, a similar picture arises [20]. While the initial increase of the DED current hardly causes a change, the onset of the $m/n = 2/1$ tearing mode results in a change of the sign of E_r between the normalized radii of 0.8 and 0.9 (from −4 to +4 kV m^{-1}). Taking these measurements together, they clearly show that the DED has an effect on the edge radial electric field once the tearing mode is excited. However one has to stress that below that threshold, where the strong increase of the toroidal rotation is observed, the evidence for a change of E_r is indirect only. Interpreting the tearing mode formation as an indicator

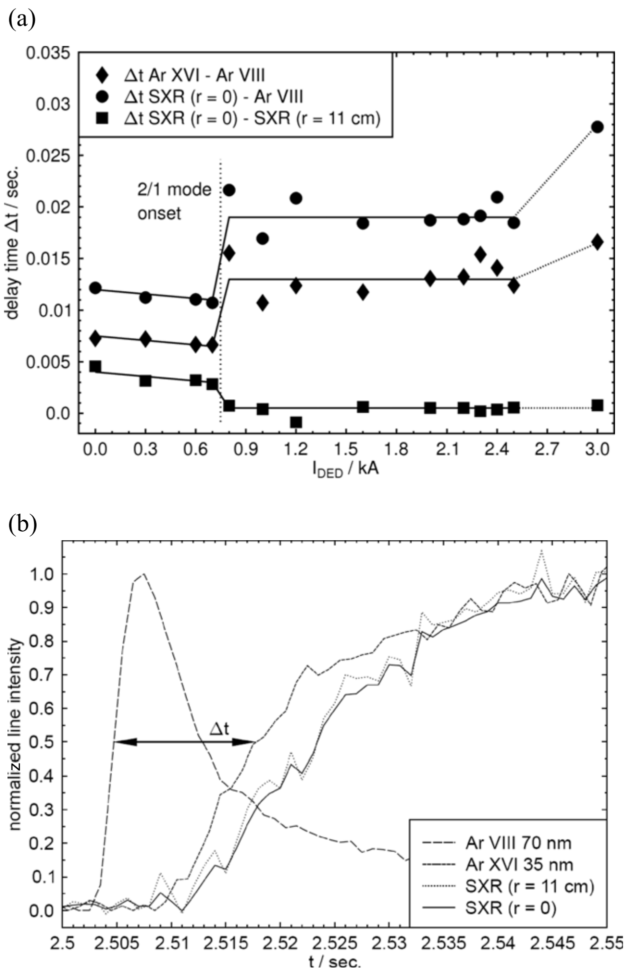

Figure 8. (*a*) Delay time between spectral line intensities during their increase in the plasma from different ionization stages after the injection of a short (2 ms) Ar puff into the discharge, where the Ar VIII emissivity is localized near the plasma edge, the Ar XVI emissivity around half minor radius and the SXR (mainly Ar XVII) emissivity in the plasma core, showing the change of radial inwards transport times of the argon ions within the outer and inner radial plasma regions. The definition of the delay time is illustrated in (*b*) for the $I_{DED} = 2.0$ kA case (#94791). The delay time is the difference between the rise times of the respective intensities, whereby Ar VIII is located at the plasma edge, Ar XVI at about half radius, and the SXR channel at $r = 11$, corresponding to $r/a = 0.2$. The time points are taken at half of the normalized intensities. As an example the delay time, Δt, between the Ar XVI and Ar VIII emissions is shown.

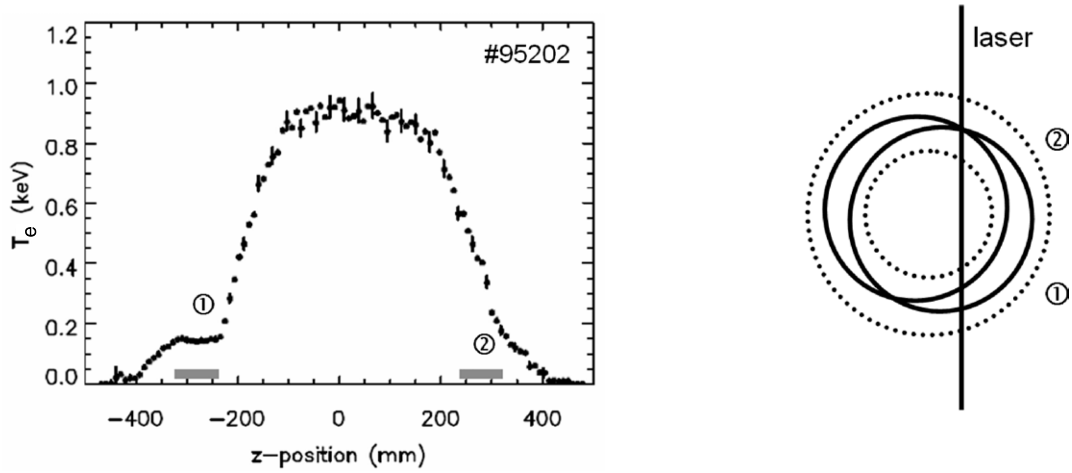

Figure 9. Electron temperature profile from Thomson scattering [21], clearly showing a shoulder from the magnetic island of the locked $m/n = 2/1$ mode (the profile is obtained by averaging over 9 Thomson spectra). The z-coordinate roughly corresponds to the minor radius of the plasma. Since, however, the line of sight is shifted by $\Delta r/a \approx 0.2$ away from the plasma centre, as sketched on the right-hand side, the profile is asymmetric: for negative z it goes through the O-point of the island (1), whereas for positive z only the X-point (2) is seen.

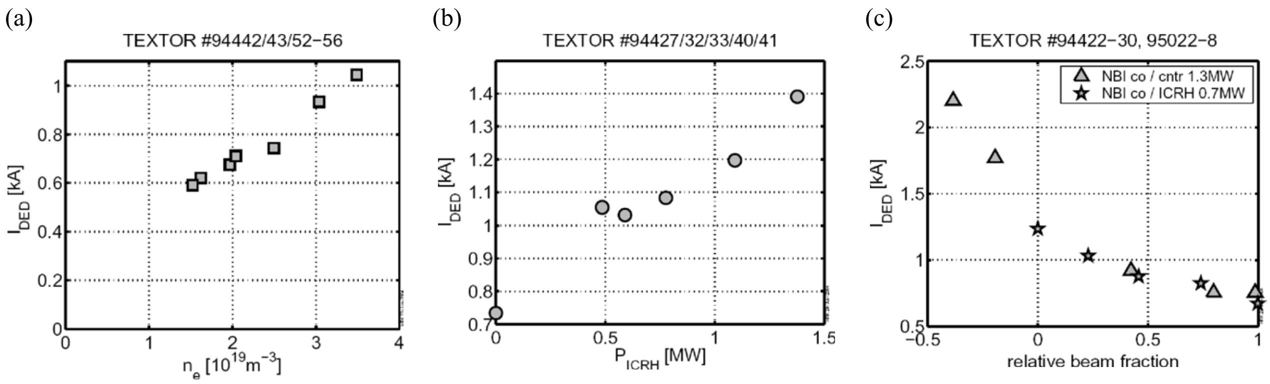

Figure 10. Dependence of the critical DED current (static operation) to excite a $m/n = 2/1$ tearing mode on (*a*) line averaged density, (*b*) ICRH power (plasma β) and (*c*) relative beam fraction (angular momentum). In (*c*) relative beam power fraction corresponds to $\omega_\phi \approx (-30 \text{ to} + 35) \times 10^3\,\text{rad s}^{-1}$.

for the increasing influence of the magnetic field perturbation, the measurements of the radial electric field show at least that in principle an effect is possible.

The evidence for changes of the thermal transport before the tearing mode sets in is not entirely conclusive. As indicated in figure 2, the thermal plasma energy does not change within the uncertainties of the underlying measurements. On the other hand, the ergodization of the plasma would suggest that at least a local degradation of the confinement is observed. While the postulation of an ambipolar electric field requires an ergodization at the plasma boundary, consistent with the constant increase of the toroidal angular frequency profile inside the $q = 2$ surface, the question also arises as to what extent the perturbation fields modify the transport in the plasma core. As illustrated in figure 8, transient impurity transport experiments with static DED indeed indicate a weak increase of the radial transport in both the plasma edge and core region with increasing DED current. However, clear changes are only seen after the onset of the $m/n = 2/1$ tearing mode: the radial inward motion of impurities within the plasma edge region is slowed down significantly, while the radial transport in the plasma core is strongly increased. Contrary to these observations, heat pulse modulation experiments with ECRH [14] suggest a reduction of the electron heat transport for those plasmas with the largest increase of toroidal angular frequency before the $m/n = 2/1$ tearing mode sets in. After the mode formation the heat pulse experiments confirm an increase of the radial transport.

4. Effect of external perturbation field ($m/n = 3/1$) on MHD stability at large perturbation amplitude

Evidence for the formation of an $m/n = 2/1$ tearing mode above a critical threshold of the DED amplitude is the local flattening of temperature and density profiles in the vicinity of the $q = 2$ surface (figure 9) [21]. In case the mode rotates, the analysis of the soft x-ray signals shows a phase inversion of the temporal modulation at the mode location. The helicity is deduced from the relative phase evolution of Mirnov coil signals, which are taken at different poloidal and toroidal positions. Once excited, the mode locks to the external magnetic field perturbation, i.e. for a static DED it does not move with respect to the plasma vessel. After the

DED is switched off, the mode persists, but starts to rotate. In some cases, the rotation of the tearing mode does not start immediately after the switch-off of the DED, but is delayed until the NBI also is turned off [22]. To obtain a stationary saturated mode an edge safety factor $q_a \geqslant 4.5$ is required. At lower q_a the plasma tends to disrupt. Instrumental for the formation of the tearing mode is the strong $m/n = 2/1$ side band of the 3/1 perturbation field. In combination with a tearing mode stability parameter, Δ', which is closer to instability at the $q = 2$ surface than at $q = 3$, this results in a preferable excitation of the $m/n = 2/1$ tearing mode. Nevertheless, at sufficiently large DED currents (typically > 2 kA, compared with ⩽1 kA for the 2/1 mode) an additional $m/n = 3/1$ tearing mode can be excited.

The excitation of the tearing mode is very reproducible, and the critical perturbation threshold varies with plasma parameters, such as density, plasma beta or toroidal plasma rotation [23]. In figure 10 the different dependences are shown.

The increase of the threshold with density is equivalent to an increase with collisionality, as the heating power is kept constant, and thus the temperature decreases. This dependence agrees well with earlier observations in COMPASS-D, DIII-D and JET [24, 25], which also show a linear dependence of the error field penetration on density. For the power scan ion cyclotron resonance heating (ICRH) was used to avoid a change of the momentum input. Clearly, increasing the heating power, i.e. raising β, has a stabilizing influence. This is in contrast to earlier findings in JET, where ICRH had only little influence on the threshold. The most interesting result is shown in figure 10(*c*). Here, the total heating power was kept constant, and only the relative neutral beam fraction, defined as $(P_{\rm co} - P_{\rm counter})/(P_{\rm co} + P_{\rm counter} + P_{\rm ICRH})$, was modified. Also electron density and temperature at the $q = 2$ surface were constant within a few per cent. The data clearly show that co-injection in the presence of a static DED perturbation is destabilizing, whereas counter-injection increases the mode threshold. An explanation for this observation is missing up to now. In any case, these results seem inconsistent with recent error field studies on JET, showing a penetration of the perturbation field which does not depend on the NBI direction [26]. One should however note that TEXTOR and JET plasmas differ considerably for instance with respect to collisionality.

5. Summary and conclusion

With the DED in TEXTOR important aspects of the interaction of magnetic perturbation fields and the MHD stability and transport properties of the plasma have been studied. The disappearance of an internal tearing mode ($m/n = 3/1$), when superimposing an external perturbation ($m/n = 12/4$), indicates agreement with theoretical predictions of the non-linear coupling of such modes. The interaction of the DED in the $m/n = 3/1$ configuration with the plasma shows a clear dependence of the tearing mode excitation threshold on density, beta and toroidal momentum input. The latter depends on the direction of the NBI, which was unexpected. The reason for this behaviour is still unknown. At magnetic perturbation field levels below the threshold for tearing mode excitation a strong toroidal spin up of the plasma in the co-current direction is observed, which is independent of the direction of the DED rotation. The observed rotation direction agrees with an ambipolar radial electric field, produced by an enhanced electron transport in an ergodic edge. The absence of substantial confinement changes and the independence of the momentum input by NBI suggests that the plasma viscosity does not play a dominant role.

Acknowledgments

This work, supported by the European Communities under the contract of Association between EURATOM-FZJ, FOM and IPP, was carried out within the framework of the European Fusion Programme. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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