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Complete Suppression of Neoclassical Tearing Modes with Current Drive at the Electron-Cyclotron-Resonance Frequency in ASDEX Upgrade Tokamak

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Noninductive current drive has been performed in the tokamak ASDEX upgrade by injection of radiofrequency waves at the second harmonic of the electron-cyclotron frequency in order to suppress unwanted disturbances of the magnetic-field configuration. The current has been driven parallel [co−electron cyclotron current drive (ECCD)] and antiparallel (counter-ECCD) to the plasma current to compare the effect of heating with direct current drive in the magnetic island. For the first time it has been shown experimentally that total stabilization of neoclassical tearing modes is possible with co-ECCD. The experiments verify the role of direct current drive as opposed to local heating.

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The operating regime of tokamaks at high β (ratio of plasma pressure to magnetic field pressure) and low collisionality is in many cases limited by the occurrence of the so-called neoclassical tearing mode (NTM) [1,2]. This instability breaks up the nested flux surfaces of a tokamak and creates regions of closed magnetic field lines within the plasma (magnetic islands) leading to an increased heat transport in radial direction and to a degradation of confinement. The occurrence of the NTM is related to a component of the toroidal current, known as bootstrap current, which is due to a radial diffusion of particles. The growth of the NTM is enhanced by reduction or even loss of the bootstrap current. Thus, if NTMs can be suppressed it can be expected that the performance and economy of a possible fusion reactor and the actual β limit of tokamak experiments can be improved. Therefore, a method is required to control and/or stabilize these modes by changing the local current profile and replacing the missing bootstrap current. Experiments with rf waves at the electron-cyclotron (EC) resonance frequency have been proposed by [3,4]. Stabilization of the usual tearing modes, which are driven by an unfavorable plasma current density gradient, has been demonstrated experimentally by [5,6]. One of the main advantages of ECRH experiments is that the rf power can be launched very flexibly into the plasma, and good localization of the power deposition at the resonant surface can be achieved due to the very narrow beams and strong absorption. In that case the missing bootstrap current can be replaced by auxiliary heating in the island or by driving an additional noninductive current within the

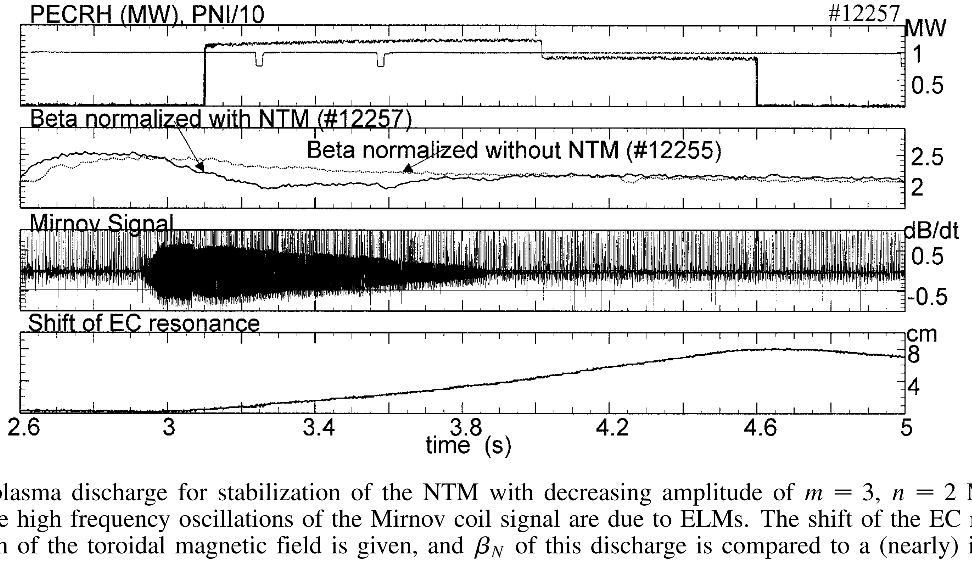

FIG. 1. Typical plasma discharge for stabilization of the NTM with decreasing amplitude of $m = 3$, $n = 2$ Mirnov coil signal during ECCD. The high frequency oscillations of the Mirnov coil signal are due to ELMs. The shift of the EC resonance position due to the variation of the toroidal magnetic field is given, and β_N of this discharge is compared to a (nearly) identical discharge without NTM.

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island with EC waves. Current drive (CD) is predicted to be more effective than heating, although CD experiments are always associated with heating [7].

In previous experiments at the ASDEX-Upgrade tokamak the partial stabilization of NTM by applying ≈800 kW of rf power has been successfully demonstrated [8]. These experiments have been performed with phased co–electron cyclotron current drive (ECCD) where the gyrotrons have been feedback controlled to launch their power in the *O* point of the island which is expected to be much more effective than *X*-point injection which has a destabilizing effect. However, it has been shown that stabilization can also be achieved by dc injection with practically the same efficiency [8,9]. Since this method is much simpler, we will in the following concentrate on dc experiments.

The plasma configuration has been a lower single null high confinement mode (H-mode) with edge localized modes (ELM) which is also planned for the International Tokamak Experimental Reactor. The inductively driven plasma current has been kept constant to 0.8 MA, with the feedback control system the particle density has been fixed at $\langle n_e \rangle \approx 5 \times 10^{19}\ \mathrm{m}^{-3}$. In such a configuration a rotating NTM with poloidal mode number $m = 3$ and toroidal mode number $n = 2$ may develop at the $q = 3/2$ surface, if β_N $(\beta_N = \beta[\%]/\{I_P[\mathrm{MA}]/(a[\mathrm{m}]B[\mathrm{T}])\}$, $\beta = 2\mu_0\langle p \rangle/B^2)$ is sufficiently high and a seed island above the threshold island size is triggered [10]. The normalized β_N was typically 2.2–2.8.

The magnetic field of this mode has been detected by Mirnov coils surrounding the plasma in poloidal and toroidal directions. Since they are sensitive to temporal variations of the magnetic field (dB/dt) the coil signals indicate changes in the amplitude or rotation frequency of the perturbed magnetic field structure. For the experiments shown here it has been verified that the rotation does not change significantly during mode stabilization and thus the signals of the Mirnov coils directly monitor the variations of the amplitude.

The electron-cyclotron emission (ECE) spectroscopy is measured from the low field side in order to avoid powerful 140 GHz radiation to reach the detectors. From these measurements the localization of the absorption (R_{dep}), which in our case took place at the high field side, the position of the island (R_{res}), and the island width can be reconstructed. A typical value of the saturated island width is 8–10 cm on the high field side at $r = 30$ cm (minor plasma radius) and a deposition width of $d = 4$–5 cm in agreement with ray-tracing calculations with the TORAY code [11].

For ECCD experiments three gyrotrons at 140 GHz have been used (second harmonic of the electron-cyclotron frequency with E field of the propagating wave perpendicular to the magnetic field B, $B = 2.5$ T), each delivering 0.4 MW of rf power to the plasma in dc operation. The injection was from the low field side of the tokamak and for the CD experiments the beams have been launched with an angle of −15° (co-CD) and +15° (counter-CD) with respect to the magnetic field. This is a compromise between the increasing CD efficiency and the broadening of the deposition width d of the rf beam with increasing angle. This still ensures that d is smaller than the island size w. Ray-tracing calculations with TORAY give a driven current of 12–13 kA at 1.2 MW rf power.

In previous experiments it has been shown that there is a small jitter in the position of the island from discharge to discharge which makes the exact positioning of the rf power difficult. In the experiments reported here the magnetic field has been changed slowly during a discharge (5% within 1.5 s) which also shifts the EC resonance by 5%, corresponding to 8 cm $(\Delta R/R_0 = \Delta B/B_0)$. The island position was measured to shift less than 2 cm by the ECE system. This technique allows one to match both positions in every discharge.

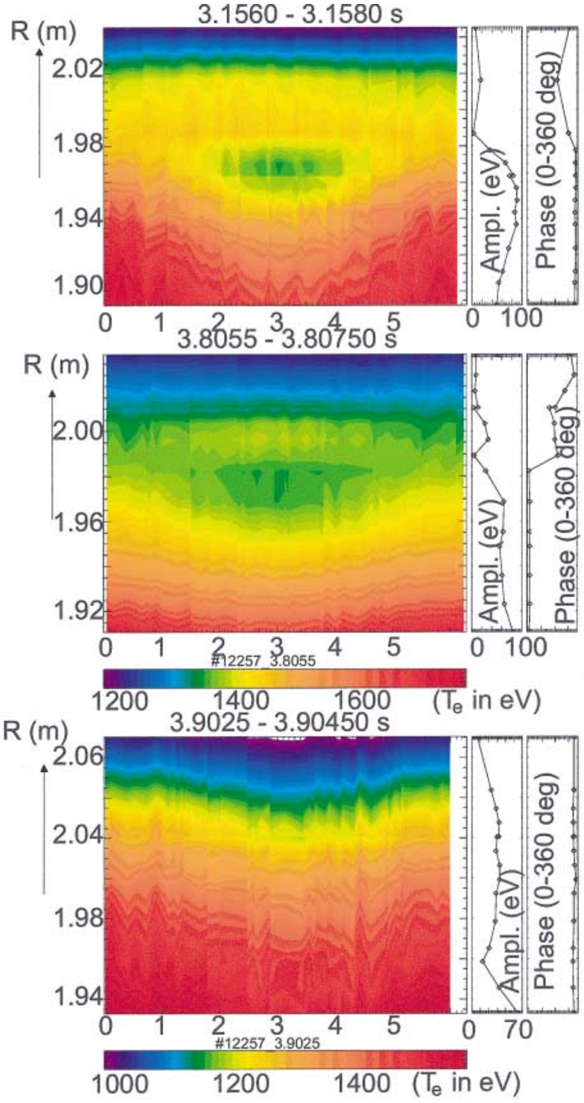

FIG. 2 (color). Reconstruction of island structure from ECE data. The electron temperature (in eV) is plotted versus the helical phase angle of the mode and the major radius at three different times.

The temporal evolution of a typical discharge for co-CD is shown in Fig. 1. The power of the neutral beam injectors (NBI) is constant (10 MW) and β_N increases to about 2.5. At the time $t = 2.9$ s a neoclassical tearing mode ($m = 3, n = 2$) is triggered and starts to grow, resulting in a decreasing β_N ($\approx$20%). At the time when the mode is fully developed the ECCD sources are switched on and simultaneously the scanning of the magnetic field starts. During this scan the absorption on the high field side is shifted towards the plasma center. If there is sufficient overlap of the absorption zone and the island in radial direction, the mode amplitude begins to decrease and finally vanishes ($\sim$3.9 s). The evolution of the island during ECCD can also be observed from ECE data. From the measurements with different ECE channels, which correspond to different radial positions as well as Mirnov coil data, the temperature profile across the island has been reconstructed [12]. In Fig. 2 three snapshots of the magnetic island are shown, where the electron temperature is plotted versus the major radius and the helical phase angle of the mode [13]. From this it is obvious that the initial island size becomes smaller during ECCD. At $t \sim 3.9$ s the $m = 3$, $n = 2$ island structure can be recognized any more. As a result the β_N value is increasing again and reaches the same value as in the absence of the mode. This is shown in Fig. 1, where the β_N value of a discharge with a NTM and a comparable discharge without a NTM is given. At the beginning of the ECCD β_N drops in the reference discharge. This behavior has been observed in several discharges and is considered to be a consequence of the decreasing density during ECCD and subsequent gas puffing of the density feedback system [14].

It should be noted that once the mode is stabilized and the ECRH sources are switched off the mode does not reappear. This may be due to the fact that the β_N value does not recover to the initial value before the mode appeared. Another possibility is the changed sawtooth behavior during ECCD which may prohibit the creation of a seed island for the mode.

In the experiment shown above a toroidal launching of the mm-wave power has been applied in a way that a current parallel to the plasma current is driven, replacing the missing bootstrap current. Additionally the effect of heating in the island which reduces the resistivity will lead to a local increase of the current. In that case both effects contribute to the replacement of the bootstrap current within the island and thus lead to a reduction of the island size. In the case of counter-CD we have the same operating parameters as in the case of co-CD of the tokamak but reversed launching angle of the antennas. Here heating and CD are competing effects. We still have the stabilizing effect of heating, whereas counter-CD should enhance the island size. A representative result is shown in Fig. 3. The onset of the $m = 3$, $n = 2$ NTM is associated with a 10% reduction of β_N. After the EC resonance has been shifted by $\sim$7 cm the mode amplitude decreases and stays constant (also small increase of β_N). This behavior indicates that both mechanisms are of the same order. In contrast to the coinjection case the island size increases again after switch-off of the rf power. To verify that the saturation of the island size in the presence of counter-ECCD is not due to the limited shift of the EC resonance, an additional discharge with higher magnetic field has been performed.

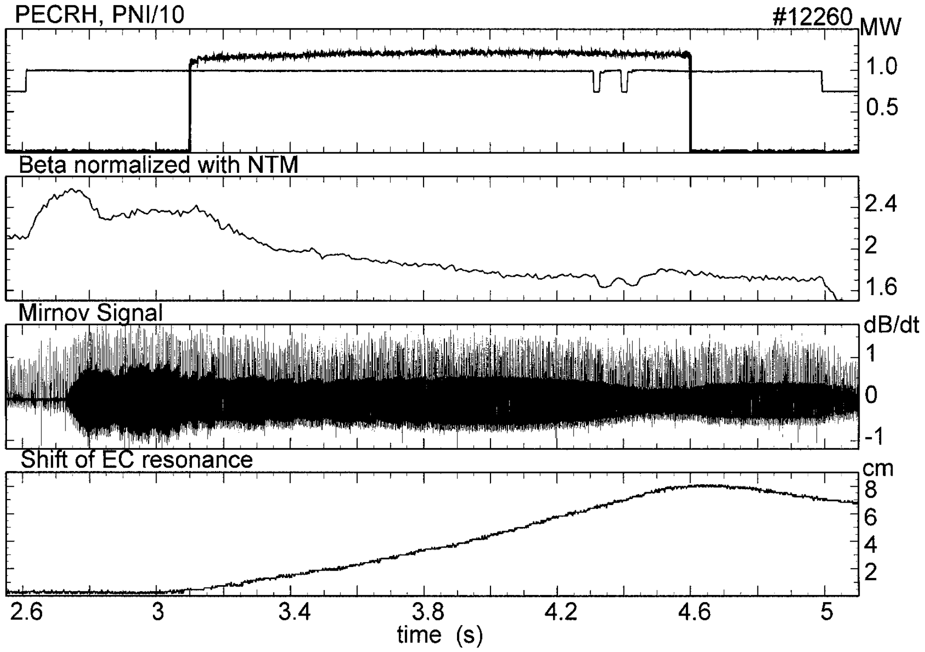

FIG. 3. Example of a counter-CD experiment. Within a small time interval a partial stabilization of the NTM can be observed. The reduction of β_N is induced by the onset of mode activities and application of ECCD.

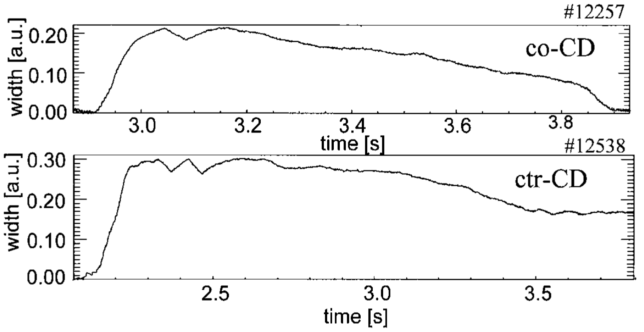

FIG. 4. Calculated island widths for a co-CD (top) and counter-CD (bottom) experiment. In case of co-CD the initial value of the island width ($w_0 = 0$) is reached after stabilization, and in case of counter-CD the island width is reduced to 55% only.

From the data of the Mirnov coils a relative measure for the island width w has been calculated by temporal integration and smoothing. In Fig. 4 w ($w \propto \sqrt{B}$) is given on a linear scale for a co- and counter-ECCD discharge. In the case of co-ECCD the island size is slowly decreasing. When the island is small enough, i.e., at 35% of the peak value, the island vanishes completely on a fast time scale (approximately 50 ms). In contrast, for counter-ECCD the island size reduction stops at approximately 55% of the saturated width.

Attempts have been made to model the evolution of the island width in the ECCD experiments with a MHD code, including the self-consistent evolution of the bootstrap current with the pressure profile as well as the external current drive [7]. The parameters of the numerical simulation have been chosen close to those of the experiment. In Fig. 5 the calculated island width (normalized to the minor plasma radius) is plotted versus the distance of the resonant surface ($r_{3/2}$) from the radial location of deposition (r_{dep}). The calculations reflect the experimental finding that the total suppression of the NTM can be achieved with co-ECCD experiments but not with counter-ECCD experiments for which the competing effects of island heating and current drive balance each other at a certain island width. The calculations show that the best position of EC resonance for reducing the island width depends on the values of the plasma current and the driven current and the correlated shift of the O point of the island [7]. As a result of these competing effects we obtain different positions for optimum co- and counter-CD which is in accordance with the experiments (compare Figs. 1 and 3).

The results of this paper demonstrate that ECRH/ECCD is an efficient method to suppress low-m/n NTMs in present day and future fusion devices. In particular, we have shown for the first time that the complete suppression of neoclassical tearing modes by ECCD is possible in a tokamak experiment with only 10% of the total auxiliary heating power. This offers the possibility to further extend the β limit in the tokamak ASDEX upgrade and thus to improve the performance.

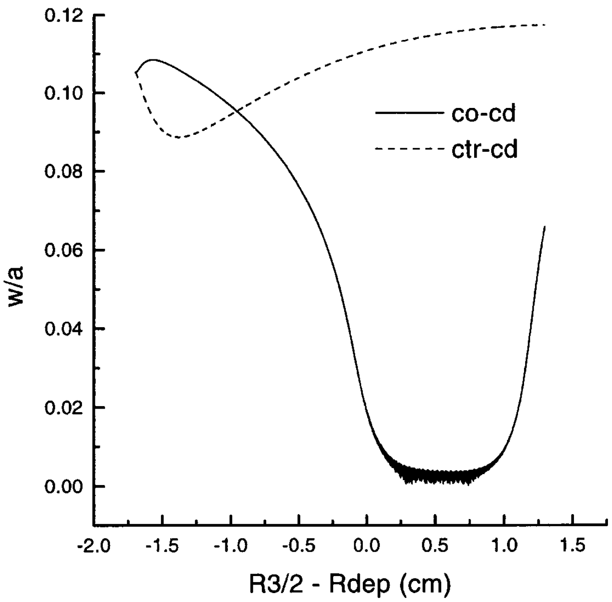

FIG. 5. Normalized island width for co- and counter-CD at different relative positions of island and power deposition.

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