1 Abstract

At the Wendelstein W7-AS the influence of non-vanishing toroidal current densities on stability is studied under various discharge conditions regarding heating and current ramp. Disruptive-like events accompanied by a fast energy loss are observed as low order rational resonances appear in the outer region of the plasma in discharges with significant contribution of net-toroidal current densities. A tomographic reconstruction of the emission in the soft x-ray wavelength region reveals the presence of tearing modes. A \( \Delta' \) code calculates numerically the stability of the tearing modes and its predictions are compared to the experimental observations.

2 Introduction

Quasi-axisymmetric stellarators (QAS) take advantage of bootstrap currents in providing a substantial fraction of rotational transform, \( \iota \). The requirement of externally generated rotational transform, \( \iota_{ext} \) is reduced and the design of the stellarator coils can be simplified. In ohmically heated W VII-A discharges the stabilization of current driven instabilities and the suppression of current disruptions has been observed at modest amounts of externally provided rotational transform (\( \iota_{ext} \geq 0.15 \)) [1].

Experimental studies of the influence of non-vanishing toroidal current densities on stability play an important role in the proper optimization of configurations. The Wendelstein W7-AS stellarator is especially suited for such an investigation since its experimental flexibility allows to apply a loop voltage to drive ohmic current and thereby to modify the profile of the rotational transform. Varying the heating scenarios gives access to a variety of different current density profiles and enables to investigate operational limits related to non-vanishing toroidal currents. Here first results of this study are presented. The applied analysis is described by examining one type of discharge in detail.
Figure 1: Time traces of the total rotational transform in 0.4 MW ECRH heated discharges with ohmic current drive (#47606, #47609–#47611, #47615, #47617–#47621). Stable discharges (marked by long dashes) are compared with those featured by the occurrence of an disruptive-like event. Out of these, one discharge (#47610, marked by a solid line) is examined in more detail here.

3 Experimental

On the Wendelstein W7-AS stellarator (major radius $R_0 = 2$ m, minor radius $a \leq 0.18$ m) the externally produced rotational transform is scanned within the range $0.301 \leq \lambda_{\text{ext}} \leq 0.565$ in order to compare a variety of different current profiles. In normal operation a feedback system controls the edge value of the rotational transform by inductive currents which are used to balance the bootstrap currents in order to minimize net toroidal currents. In the study presented here ohmic current drive is used to modify the profile of the rotational transform. Non-vanishing toroidal currents contribute to the total rotational transform, $\tau(r)$ and to first order the resulting total rotational transform is a sum of the externally provided rotational transform and the contribution due to plasma currents: $\tau(r) = \lambda_{\text{ext}} + \tau_p(r)$ [1]. A controlled current ramp up is used to modify the total rotational transform during a discharge. Some hundreds of ms into the discharge the current is raised to a certain level within 150 ms, kept at this level for about 200 ms and then decreased within 150 ms (figure 1). The value of the level of the ohmic current is varied within the range 0–40 kA in order to examine various ratios of the total rotational transform to the externally provided rotational transform. The gas flux is controlled in order to keep the line integrated electron density, $\int n_e \, dl$ at a constant level of about $1 \times 10^{19}$ m$^{-2}$. Net toroidal ohmic current is driven in discharges with combined or separate heating by electron cyclotron resonance (ECRH) and neutral beam power injection (NBI). The dependence of stability on the
direction of the net toroidal current is investigated in ECRH heated discharges by driving the current in the opposite direction during the current ramp. This allows to approach even low order rational surfaces, as for example $\tau = 1/3$, with significant net toroidal current and thus to investigate their influence on stability in a wide operational range. The effect of bootstrap current is examined in discharges with combined heating by ECRH and NBI without ohmic current drive.

Figure 2 presents the ratio of externally generated rotational transform to the edge value of the total rotational transform versus the externally provided rotational transform to demonstrate the operational range that is investigated in this study.

The discharges are analyzed with respect to instabilities which cause the deterioration of confinement. Equilibrium flux surfaces and MHD mode structures are identified using first order regularization method which is applied to the emission measured in the soft x-ray wavelength region by a miniature soft x-ray system. The camera system consists of 8 cameras each with 32 lines of sight. Fitted with a 6 $\mu$m beryllium foil it detects soft x-ray radiation above 0.5 keV. See [2] and references therein for a description of the applied algorithm and the camera system.
4 Results and Discussion

Disruptive-like events with sudden and fast losses of energy are observed during the current ramp up as low order rational resonances appear in the outer region of the plasma in discharges with significant contribution of net-toroidal current densities. In some cases a modification of the current ramp up prevents an early termination of the discharge and enables to increase the rotational transform with minor effects on the diamagnetic energy content. Discharges with a current ramp up in the opposite direction remain stable. High frequency modes are observed as low order rational resonances appear in the outer region of the plasma in discharges heated by balanced NBI and ECRH without ohmic current drive. The current rise rate decreases and a deterioration of confinement is observed in these discharges that are characterized by a large contribution of bootstrap current density to the net toroidal current density.

In discharges with ohmic current drive, tearing modes are observed with mode numbers corresponding to the low order rational resonances present in the outer region of the plasma. Figure 3 shows the time traces for such a type of discharge (#47610). Starting at an externally provided rotational transform of 0.301 the ohmic current is raised up from 0 kA to about 30 kA in the ECRH heated discharge. The plasma energy, as derived from the diamagnetic loop signal, decreases at about 0.4 s into the discharge during the current ramp-up. Even though the current
decreases the applied loop voltage is able to adjust and thus to maintain a certain plasma current. The total rotational transform approaches the value of 0.48 during the following current ramp up. The Hα signal is enhanced and indicates an energy release. The amplitude of the fluctuations in the poloidal magnetic field, $\tilde{B}_\theta$, measured by the Mirnov coil increases and indicates enhanced MHD activity. The relative amplitude of the poloidal magnetic field, $\tilde{B}_\theta / B_\theta$, reaches about 14%. Like current disruptions in tokamaks the rapid current fall is followed by an enhanced hard x-ray signal indicating the runaway electron current. During a time interval before the en-

![Figure 4](image_url)

Figure 4: The upper panel shows the emissivity measured in the soft x-ray wavelength region. In the lower panel a rotating $m = 2$ mode is revealed by applying the method of singular value decomposition (SVD) to separate mode structures from the equilibrium emissivity. The overlaid flux surfaces are calculated using the VMEC code without taking into account the plasma current in this discharge (#47610).

energy release (marked by two vertical lines in figure 3) a rotating $m = 2$ mode is revealed by the tomographic reconstruction of the soft-xray emission (figure4). This observation is consistent with the radially resolved measurement of the electron temperature, $T_e$ derived from the electron cyclotron emission (ECE) which indicates a mode structure of even toroidal mode number (figure5).

In order to explain the disruptive-like events a $\Delta'$ analysis is applied and the predictions of this code are compared to the experimental observations. The free potential energy, $\delta W$ to drive tearing modes is expressed by:

$$\delta W = -4 \pi^2 R_0 \int_0^a \frac{r}{d} dr \left[ \left( \frac{d \Psi}{dr} \right)^2 + \frac{A}{r^2} \Psi^2 \right]$$

where $\Psi$ assigns the perturbed helical flux function, $\Psi = \frac{ir R_e}{m}$ with the radial magnetic field perturbation, $B_r$ and

$$A = m^2 + \frac{r}{\nu(r) - \frac{m}{\mu} B_\phi} \frac{d j_\phi}{dr}.$$  

The term $A$ represents a measure of the energy associated with the destabilizing effect of the equilibrium current gradient, $\frac{d j_\phi}{dr}$. A mode is unstable as long as $\delta W \leq 0$. The tearing mode
Figure 5: The contour plot of the radially resolved ECE measurement of electron temperature, $T_e$, indicates a mode structure of even toroidal mode number (discharge #47610) during the time interval around the onset of the sudden energy release. The tomographic reconstruction of the emissivity in the soft x-ray wavelength region (figure 4) is done at the timepoints marked by vertical lines.

The equation is given by:

$$
\frac{1}{r} \frac{d}{dr} \left( r \frac{d \Psi}{dr} \right) - \frac{m^2}{r^2} \Psi - \frac{\mu_0}{\mu_0 (1 - \frac{m^2}{m})} \frac{d j_b}{dr} \Psi = 0
$$

(3)

where the safety factor, $q$ is expressed as: $q = \frac{r B_0}{\mu_0}$.

The tearing mode equation (3) is solved in linear cylinder geometry for the current density profiles, $j(r)$ observed in the experiment. The current density profiles, $j(r)$ are derived as the sum of the bootstrap current density, $j_{bs}(r)$ and the ohmic current density, $j_{oh}(r)$. The bootstrap current density is calculated according to [3] in an axisymmetric configuration using mainly the electron density, $n_e(r)$ and electron temperature profiles, $T_e(r)$. Under the assumption of constant effective charge, $Z_{eff} = const.$, the ohmic current is derived from the radially resolved Thomson scattering data as: $j_{oh}(r) \propto T_e(r)^{3/2}$. $\Delta'$ gives the discontinuity of the solutions of equation (3) across the resonant layer, $r_s$ in terms of $\frac{\Psi'}{\Psi}$. It is defined by:

$$
\Delta' = \frac{\Psi'}{\Psi} \bigg|_{r=r_s+\epsilon}^{r=r_s-\epsilon} \quad \varepsilon \rightarrow 0.
$$

(4)

The sign of $\Delta'$ determines the stability of a mode, an unstable mode results in a positive $\Delta'$. The perturbed magnetic fields are calculated using the perturbed helical flux function, which is normalized to the saturated island width, $w$ given by:

$$
w = 4 \sqrt{\frac{R_0 \Psi}{r_s B_0 \psi'(r_s)}}.
$$

(5)
Figure 6 shows the results of such a $\Delta'$ analysis for a discharge terminated by a disruptive-like event (#47623). Heated by ECRH, discharge started at a externally provided rotational transform value of 0.35. The current is ramped up to about 21 kA as a sudden energy release is observed accompanied by a current decay. A $m = 2$ mode structure is seen in the tomographic reconstruction of the emission in the soft x-ray wavelength region. Initially the mode rotates, then it stops rotating and locks into one position. There it remains throughout the discharge. In some cases no initial rotation of the $m = 2$ is observed but the mode stays at one position throughout the discharge and gains in energy. The $\Delta'$ analysis derives a rather broad current density profile (figure 6) for the discharge (#47623). A low order rational surface ($\nu = 1/2$) is present in the outer region of the plasma ($r_{\text{res}}/a_{\text{plasma}} = 13.57/16.01 = 0.85$) where the current density is still significant. The $\Delta'$ analysis predicts a unstable mode ($\Delta' = 4.75$) of the toroidal mode number $m = 2$ and the poloidal mode number $n = 1$. It estimates a saturated island width to $w = 4.8$ cm. Figure 7 summarizes the results of the $\Delta'$ analysis for this discharge(#47623). The calculated pertubated magnetic field agree within one order of magnitude with the experimental measurement of the poloidal field fluctuations at the Mirnov coils.
Figure 7: Results of the $\Delta'$ analysis for discharge #47623 from top to bottom: the profiles of the perturbed magnetic fields, $B_r$ (full curve) and $B_\theta$ (broken curve), the profile of the perturbed flux, $\Psi$ and the term $A$, which represents a measure of the energy associated with the destabilizing effect of the equilibrium current gradient. A negative value of the term $A$ indicates stability (see equation (2)).

5 Conclusions

Contrary to former results obtained on the W7-A in ohmically heated discharges, disruptive-like events occur even at high values of externally generated rotational transform on the W7-AS. They are accompanied by a fast energy loss and they are observed as low rational resonances appear in the outer region of the plasma in discharges with significant contribution of net-toroidal current densities. A tomographic reconstruction of the emission in the soft x-ray wavelength region reveals the presence of $m = 2$ tearing modes. The stability of the tearing modes is numerically calculated using a $\Delta'$ code. First results of a $\Delta'$ analysis are consistent with experimental observations.

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References

