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Neoclassical tearing modes in TCV

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INTRODUCTION

Neoclassical tearing modes (NTM) have been observed in high β and low-collisionality discharges in a number of tokamaks. They often limit the achievable beta at values well below ideal MHD predictions. In contrast to conventional tearing modes, which arise from the free energy of an unstable current profile, neoclassical tearing modes are destabilized by a helical perturbation to the bootstrap current, which is generated by the flattening of the pressure profile across a seed island. The evolution of the radial island width, w, is described by the generalized Rutherford equation [1]:

$$\frac{\tau_R}{\rho_s}\frac{dw}{dt} = \rho_s\Delta'(w) + \rho_s\beta_p\left((a_{bs} - a_{GGJ})\frac{w}{w^2 + w_d^2} - a_{pol}\frac{1}{w^3}\right) \tag{1}$$

where τ_R is the resistive time on the resonant flux surface with a radius ρ_s and β_p the poloidal beta. The first term on the right hand side of (1) describes the conventional driving mechanism for tearing modes via the tearing parameter Δ', which itself depends on w. The destabilizing effect of the perturbed bootstrap current is proportional to a_{bs} and the, usually stabilizing, Glasser-Green-Johnson effect to a_{GGJ}. The threshold island width w_d is due to an incomplete flattening of the pressure profile caused by the finite heat conductivity across field lines. The term $\propto a_{pol}$ describes the neoclassical polarization current, which arises from the perturbed bootstrap current inertial response to a rotating perturbation. The effect of perpendicular heat transport and polarization currents is only important for small islands. For large islands and sufficiently negative Δ' the main stabilizing effect arises from the magnetic energy needed for the island formation. The width of the saturated island is then given by

$$w_{sat} = \beta_p \cdot \frac{a_{bs} - a_{GGJ}}{\rho_s\Delta'(w_{sat})} \cdot \rho_s \,. \tag{2}$$

OBSERVATION OF PRESSURE DRIVEN MODES

The TCV tokamak (major radius R=0.88m, minor radius a=0.25m) is now equipped with six 82.7GHz gyrotrons, each one of them providing 500kW of electron cyclotron resonance heating (ECRH) power at the second harmonic of the extraordinary mode. In experiments using up to 2.8MW of central ECRH power, an MHD mode was destabilized a few 10µs up to more than 1s after the onset of the additional heating power. A typical launching geometry using two gyrotrons can be seen in Fig. 1(a). Both beams include a tangential component and drive current in the direction of the ohmic current. About 300ms after the switch on of the ECRH (t=0.4s) an MHD mode starts to grow and saturates at a high level (Fig. 1(b)). The degradation of energy confinement is clearly visible on a soft X-ray measurement along a central chord (Fig. 1(b)). After the switch-off of one gyrotron (t=1.95s) and the resulting drop in beta, the amplitude of the mode decreases as it is expected for the saturated island width of an NTM (2). At the switch off of the last gyrotron the amplitude quickly decreases to zero.

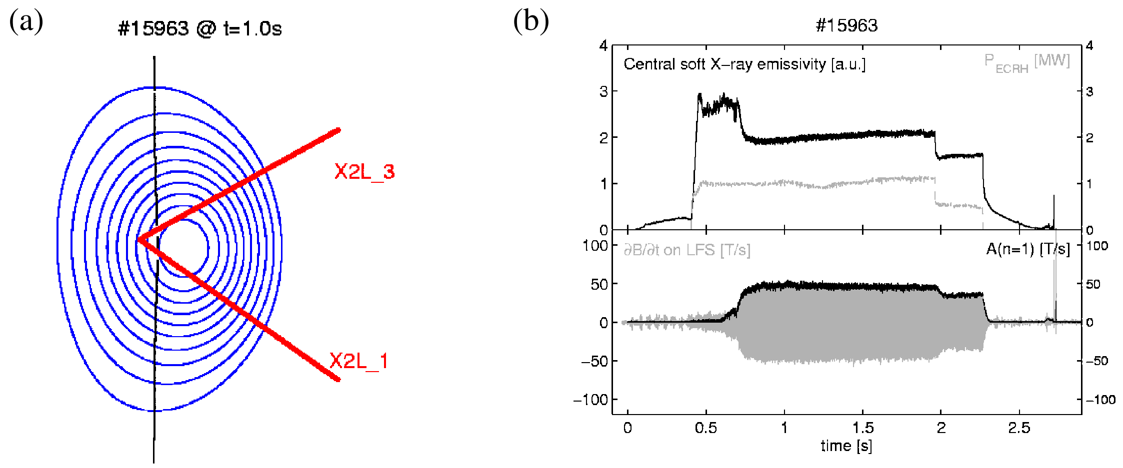

Fig. 1 (a): The poloidal plasma cross section and the ECRH launching geometry indicate a central power deposition at the second harmonic X-mode absorption layer. (b): During ECRH heating a drop in the central line integrated soft X-ray intensity is caused by an n=1 mode, which is seen in magnetic fluctuation measurements at the plasma edge.

The mode structure is determined from magnetic fluctuation and soft X-ray emissivity measurements. A toroidal array of magnetic probes identifies a dominant n=1 mode (Fig. 1(b)) rotating with 4 kHz in the direction of the electron diamagnetic drift. The poloidal mode structure is measured with an array of 38 magnetic probes in the poloidal plane. Owing to the highly elongated vacuum vessel, the interpretation of the measurements requires an inversion. The inversion method used is based on a model of a force and divergence free perturbation current along the equilibrium field lines on a resonant surface [2]. A Biot-Savart integration, using the modeled perturbation current distribution, reveals the eddy currents in the vacuum vessel and the magnetic field at the location of the pick-up coils. A comparison of phase and amplitude of the modeled mode and the measured magnetic perturbation field clearly identifies an m=2 mode. The mode is also seen in the tomographic reconstruction of soft X-ray emission measurements along 200 line-of-sights. A singular value decomposition of the reconstructed emissivity reveals an m=2 mode rotating with the same frequency. There have been also discharges showing a 3/2 mode with the same characteristics.
The island size can be calculated from the magnetic perturbation field $B_{\theta mn}$ measured at the plasma edge. In a cylindrical approximation assuming a constant perturbed flux across the island, a multipolar decay towards the edge, and an ideal conducting wall behind the probes the full island width w is given by

$$w = \left(8\left(\frac{b}{\rho_s}\right)^{m+1}\frac{B_{\theta mn}(b)}{\varepsilon_s n B_\varphi s_s}\right)^{\frac{1}{2}} \rho_s \,, \qquad (3)$$

where b is the distance between the probe and the axis, s_s the magnetic shear and ε_s the inverse aspect ratio of the resonant flux surface. The reconstructed island width is shown in Fig. 2. However, this reconstruction is very sensitive to the position and the magnetic shear on the resonant flux surface and depends on the uncertainty of the equilibrium reconstruction. An independent estimate of the island size is obtained from the confinement degradation. According to the Chang and Callen belt model [3], a confinement degradation $\Delta W/W$ in a centrally heated plasma can be caused by an island with a width $w = -\frac{1}{2}(\Delta W/W)/r_s \cdot a^2$. The energy drop is obtained from the SXR-emissivity measurement along a central chord, which is corrected for the change in density and results in an island width of 4.5cm, which is ~20% smaller than the value determined according to (3) (Fig. 2). This difference gives an estimate for the experimental uncertainty of *w*.

IDENTIFICATION AS A NEOCLASSICAL TEARING MODE

In order to identify the driving term of the mode, the evolution of its width *w* is tested against an island evolution described by the modified Rutherford equation (1). Fig. 2 shows that starting with the rapid growth at *t*=0.69s (corresponding to *w*=3cm) the evolution of the experimental island width agrees well with the prediction. Since the stabilizing effects of perpendicular transport and polarization currents decrease rapidly with w, w_d and a_{pol} were set to zero. Furthermore, Δ' was assumed to be stabilizing ($\Delta' < 0$). Since the classical ($\propto \Delta'$), and the neoclassical ($\propto a_{bs}$) driving term differ in their β_p and *w* dependence, the observed mode clearly shows the characteristics of a neoclassical mode. The rapid change of the saturated island width after the switch off of one gyrotron at *t*=1.95s is also characteristic, since β_p changes on a confinement time scale ($\tau_E \sim 5ms$) whereas Δ' changes on a longer current diffusion time scale ($\tau_R \sim 100ms$). Note, that it was not possible to obtain good agreement between the observed island evolution and the neoclassical model for small values of *w*, which will be discussed below.

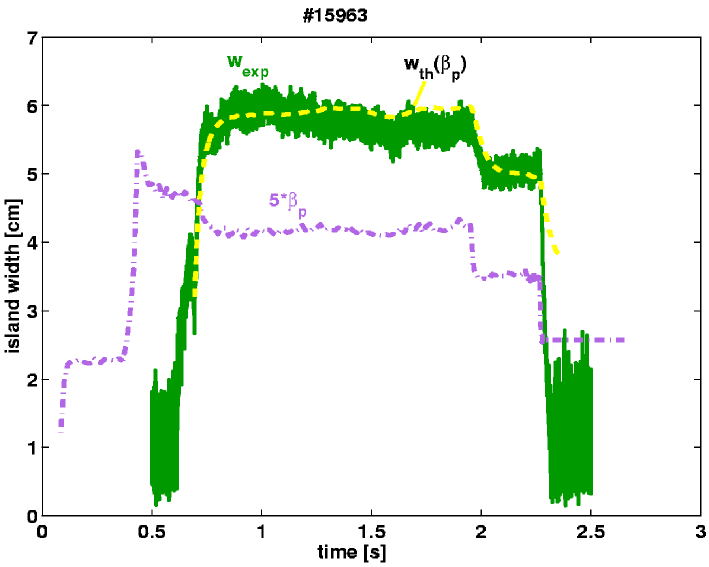

Fig. 2 The simulated evolution of a neoclassical 2/1 mode using constant coefficients and the experimental value of β_p is compared to the experimental island width derived from magnetic measurements.

ONSET OF NEOCLASSICAL TEARING MODES IN TCV

Neoclassical modes have been observed in plasmas, which were heated with 0.8 to 2.8MW of central ECRH and always included on-axis co-current drive. The central electron density at the onset of the mode ranges from 1.2 to $3.0 \times 10^{19} m^{-3}$ and is limited by runaway-electrons at low densities and by refraction of the microwave beam at higher densities. At the onset of the NTM the electron collisionality, ν_{e*}, is low ranging from 0.02 to 0.04. The normalized ion collisionality, ν_* is typically 0.3-0.5. The normalized beta, β_N, ranges from 0.4 to 1.0. These values of β_N are well below the values observed in other experiments [1]. However, the strongly localized power deposition of ECRH has been seen to generate large pressure gradients which can locally generate large bootstrap currents. If the resonant surface is located within this high gradient region, the bootstrap fraction can be sufficient to destabilize a neoclassical island. Therefore, small changes to the deposition profile can greatly influence the mode amplitude. In experiments where the deposition was moved slightly outwards the island width decreased by 20% while beta stayed constant. A broadening of the deposition profile has suppressed NTMs in experiments where the plasma current was completely wave-driven [4]. In order to investigate the triggering mechanism the measured growth of the island is shown as a function of the island width (Fig. 3). The island has two distinct growth phases. The faster

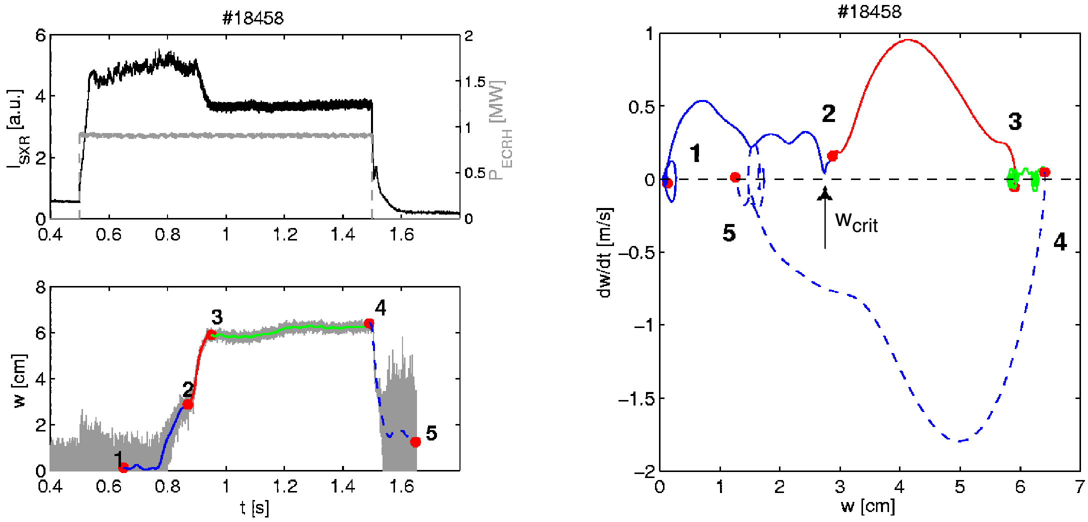

Fig. 3 The NTM is triggered by a conventional mode, which grows on a slow time scale and approaches saturation (2:t~0.87s). Once the critical island width w_{crit} is attained the mode growth on a faster time scale to its full width. After the ECRH is switched off (4: t~1.49s) the island width quickly drops (dashed line).

growth at larger mode amplitude corresponds to the neoclassical island evolution modeled for #15963 before (Fig. 2). The critical island width w_{crit} is approximately 2.8cm. It is suggested that a conventional tearing mode provides the seed island. The 2/1 mode structure shows no change between the two phases. The initial growth of 0.4m/s, which corresponds to $\rho_s\Delta' = 0.4$, decreases as Δ' decreases with *w*. The effect of Δ' is also visible at the switch-off of ECRH, when *dw/dt* drops with β on an energy confinement time scale to the value determined by Δ'. At such large values of *w,* Δ' is strongly stabilizing, but slowly increases with decreasing *w*. At *t*=1.6s it is close to its value prior to the onset of the mode.
The triggering by a conventional tearing mode explains the peculiar conditions under which NTMs were observed in TCV. Since the discharges also have to be unstable with respect to classical tearing, NTMs are only triggered in discharges where on-axis current drive generates peaked current profiles. A sawtooth induced seed island like they are observed on other experiments seems unlikely since they would not be sufficiently large to exceed the observed w_{crit}, which corresponds to approximately 10% of the minor radius.

ACKNOWLEDGEMENTS

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