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Neoclassical Tearing Modes in DIII–D and Calculations of the Stabilizing Effects of Localized Electron Cyclotron Current Drive

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Abstract. Neoclassical tearing modes are found to limit the achievable beta in many high performance discharges in DIII–D. Electron cyclotron current drive within the magnetic islands formed as the tearing mode grows has been proposed as a means of stabilizing these modes or reducing their amplitude, thereby increasing the beta limit by a factor around 1.5. Some experimental success has been obtained previously on Asdex-U. Here we examine the parameter range in DIII–D in which this effect can best be studied.

INTRODUCTION

Neoclassical magnetic islands are expected to be the factor which limits the plasma beta in long-pulse reactor-grade tokamaks like ITER (1,2), and even in high performance discharges in present day devices the neoclassical tearing modes (NTMs) are seen to limit performance (3,4). The principal mechanism which causes growth of these modes is the removal of the bootstrap current within the islands, due to the reduction in the pressure gradient caused by the reconnection of the magnetic lines across the island. This helical perturbation of the current density reinforces helical magnetic field which causes the mode to grow on a slow resistive time. As progress is made toward discharges with a higher fraction of the plasma current carried by the bootstrap current, the NTMs will become a larger problem.

A conceptually simple way to stabilize the NTM is to apply a current within the growing island to replace the bootstrap current which is decaying (2,5–7). This feedback mechanism can be carried out through use of externally applied localized current drive. A likely approach is to use electron cyclotron heating (ECH) and current drive (ECCD) since the deposition can be easily localized and controlled. This approach has been successfully applied on ASDEX-Upgrade tokamak (4), where application of 800 kW of ECH power has partially suppressed the NTM and reduced the equilibrium beta degradation. In this paper, we present observations of the NTM in DIII-D and calculations of requirements on the ECH system to stabilize it.

Neoclassical Tearing Modes in DIII-D

Neoclassical tearing modes are often seen to limit performance in discharges in DIII–D with high normalized beta, $\beta_N = \beta/(I_{MA}/B_t\, a_m)$. Figure 1 shows the trajectory of the poloidal beta (β_p) for two H–mode discharges, one with weak negative central magnetic shear (#92524, which has $q_0 = 1.27$ and $q_{min} = 1.05$) and one with normal shear (#86144, which has $q_0 = 0.92$). The trajectories show that the plasma pressure is stable until a trigger event (an edge localized mode in the case of #92524 and a sawtooth in the case of #86144) generates an island larger than the seed island size, at which time the mode amplitude starts growing until it reaches a saturation level at larger island size and lower β_p. Magnetic data indicate that these are m=3, n=2 modes located near the q=3/2 surface. The traces also show that the mode growth is rather slow.

The usual theoretical approach to tearing modes is through the modified Rutherford equation, which gives the growth rate of the island width w (1,7):

$$\frac{\tau_R}{r_R}\dot{w} = r_R\,\Delta'(w) + \frac{c_{BS}}{w} - \frac{c_{PS}}{w} - \frac{c_{pol}}{w^3} + \frac{c_{CD}}{w}\, j_{ECCD} \qquad (1)$$

Here τ_R is the resistive time scale, r_R is the radius of the resonant surface, and $\Delta'(w)$ is the classical stability factor, assumed negative. The term c_{BS} is the destabilizing neoclassical drive proportional to β_p, the term c_{PS} is due to the stabilizing effects of the Pfirsch-Schluter currents also proportional to β_p, and the term c_{pol} is the stabilizing term due to polarization currents. The last term is due to the applied stabilizing currents. Note that both the bootstrap term and the term due to stabilizing current drive are inversely proportional to the island size. For island size w smaller than that of some threshold island size w_s, the island growth is negative, and for w larger than some saturation island size w_{sat} the island growth is again negative, for β_p above a minimum value. In between, the growth may be positive due to the effect of the second term. The curves for marginal (dw/dt = 0) are shown in Fig. 1 for the two discharges. Threshold island widths are seen to be in the neighborhood of 1 cm and saturation island widths are in the range 3 to 6 cm. The effect of the NTM in reducing the plasma pressure

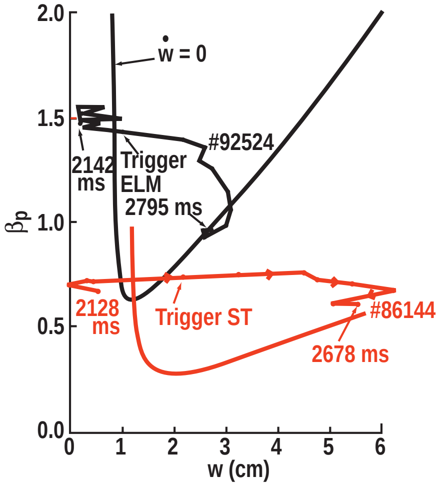

Figure 1. The trajectory in time of β_p of two discharges. #92524 has $\beta_N = 3.7$ and $H_{89P} = 3$, and #86144 has $\beta_N = 2.1$ and $H_{89P} = 2$. Also shown are the stability curves from Eq. (1) calculated for each discharge. Each dot on the data traces represents 50 ms.

is clearly much greater in the case of higher β_N. It is expected that as performance improves (i.e., as β_N and H become larger), the benefit of suppressing the NTMs will be of increasing value.

Application of ECH in DIII-D to Suppress the NTM

Experiments on the ASDEX-Upgrade tokamak have shown that localized ECCD, modulated at the island rotation frequency to correlate the corrective current drive with the passing of the island, is capable of reducing the NTM amplitude (4). The ECH system on DIII–D is well suited to such experiments (8). The system at present has three 1 MW gyrotrons at 110 GHz, which corresponds to the second electron cyclotron harmonic. The waves are launched as small beams which have a spot size perpendicular to the beam around 10 cm (a circle including 98% of the power) at the resonance. The damping length is typically a few cm along the direction of the beam, which is directed with a toroidal component to generate current. These dimensions, along with the ray and equilibrium geometry, determine the minimum interval in minor radius in which the current drive can be concentrated. The beams can be steered in the vertical direction between discharges. In the future, the beams will be independently steerable in both the vertical and toroidal directions and the system power will be raised gradually to 6 MW.

Note that the NTM is a rotating mode which sweeps past the ECH launcher at a frequency of typically 10 to 20 kHz. In order to achieve maximum efficiency, the ECCD system should generate current only within the islands. Perkins and Harvey (2) have shown that for the case of thin islands (i.e., the island width less than the ECCD profile) with perfect alignment of the ECCD with the resonant surface, the optimum approach is to modulate the ECCD at the rotation frequency with roughly 50% duty factor. Then the condition to prevent growth is given by $0.68\ j_{ECCD} > j_{BS}$. It should be emphasized that this is a condition on the driven current density, not the total driven current. The primary consideration is the current per cm normal to the flux surface, since in cases of interest the mode size along the flux surface is much larger than current drive profile in that direction. Because the stabilization criterion is on current density, the modulated ECCD is expected to be able to be able to drive the mode amplitude below the threshold island size, thereby achieving complete stabilization.

In the initial experiments the ECCD/ECH may not be modulated due to technical limitations on the modulation frequency. For this case, Perkins and Harvey (2) argue that stabilization of the NTM is not possible, but the mode amplitude may be decreased substantially, with the effectiveness falling off rapidly if the current drive is moved away from the resonant surface. Feedback can be used to keep the relative position of the resonant surface and the rf beam constant. The DIII-device uses a digital control system, including real time reconstruction of the equilibrium, from which the location of the rational q surfaces can be determined. Feedback of the radial or vertical position of the plasma can be used to maintain the desired localization of the driven current.

The TORAY ray tracing code is used to calculate the location and distribution of the driven current for a sample case using the equilibrium of discharge #86144. The toroidal magnetic field is 1.6 T (at the nominal major radius 1.69 m), placing the second harmonic resonance (1.95 T) at a major radius of 1.42 m. The density at the plasma center is $6\times10^{19}\ \mathrm{m}^{-3}$, and the cutoff density, for comparison is $6.2\times10^{19}\ \mathrm{m}^{-3}$ for the particular angle between the ray and the magnetic field, so significant wave refraction is found. At lower densities the refraction will be a weaker process and the sensitivity of the wave trajectory to the starting angles will be reduced. In addition, the driven current will be larger at lower density and higher temperature. So we conclude that a reduction in density to about 4×10^{19} m^{-3} is important. It is expected that pumping in the divertor can accomplish this.

The toroidal and poloidal angles of the launcher have been systematically varied to determine the launching conditions which give the maximum current density at the q = 3/2 surface, for fixed kinetic profiles and B_t = 1.58 T. The optimum launch angle is a toroidal angle of 15 deg from radial and a vertical angle of 110 deg. For this condition, the driven current is 28 kA/MW and the peak current density is 20 A/cm^2. The radial distribution of the driven current is 0.05 in relative minor radius (Fig. 2). Clearly, control of the radial location of the current can be carried out through toroidal steering.

This driven current density, 20 A/cm^2, is sufficient for stabilization of typical NTM modes is DIII–D. For discharge #86144 the bootstrap current density is about 20 A/cm^2 at the mid-radius, where the q = 3/2 surface is located. The total current density is an order of magnitude larger. To replace the lost bootstrap current, a driven current of order 20 A/cm^2 is needed. ECH power above 1 MW will provide margin.

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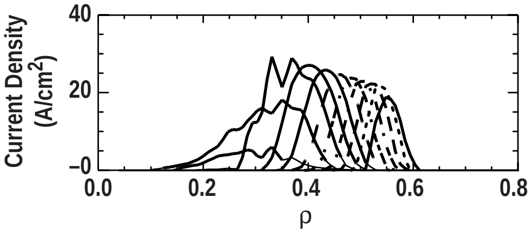

Figure 2. ECCD current density vs normalized minor radius ρ, for the discharge #86144, except the central electron density is reduced to 4×10^{19} m^{-3}. Profiles of driven current are presented for eleven toroidal steering angles (every 2.5 deg from 35 deg froom radial, which peaks at smallest r, to 22.5 deg). The central electron temperature is 5.1 keV.