Non-linear effects in electron cyclotron current drive applied for the stabilization of neoclassical tearing modes

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Introduction

Safe operation of tokamak fusion reactors at high beta requires control of neoclassical tearing modes (NTMs). NTMs can be stabilized by electron cyclotron current drive (ECCD) inside the magnetic islands associated with the NTM. The ECCD replaces the missing bootstrap current inside the island that is responsible for the growth of NTMs. Its stabilizing effect depends on both the current drive efficiency and the precise power deposition profile. Generally, the CD efficiency is assumed to be a constant, independent of the power deposited. However, due to the smallness of the volumes associated with the flux surfaces around the O-point of the island, the EC power density inside the island can exceed the threshold for non-linear effects [1, 2]. We investigate the non-linear CD efficiency by ray-tracing and bounce-averaged, quasi-linear Fokker-Planck calculations in the presence of magnetic islands. The case we study is discharge nr. 26827 ($B_t = 2.6$ T, $I_p = 1$ MA, $T_e(0) = 3.7$ keV, $n_e(0) = 6.6 \times 10^{19}$ m^{-3}) of ASDEX Upgrade [3] which features an $m/n = 3/2$ NTM[1]. Fig. 1 shows the experimental equilibrium with a $3/2$ magnetic island superimposed as described in [4]. ECCD at 140 GHz is injected from a top mirror with a toroidal injection angle of $\phi = -8^{\circ}$. The ECCD beam, which is focused near the region of power deposition, is modelled in the TORAY ray-tracing code [5, 6] by a set of rays with a FWHM of 1.7 cm in the vertical direction and FWHM of 3° in the toroidal injection angle. The rays propagate tangential to the flux surfaces in the power deposition region.

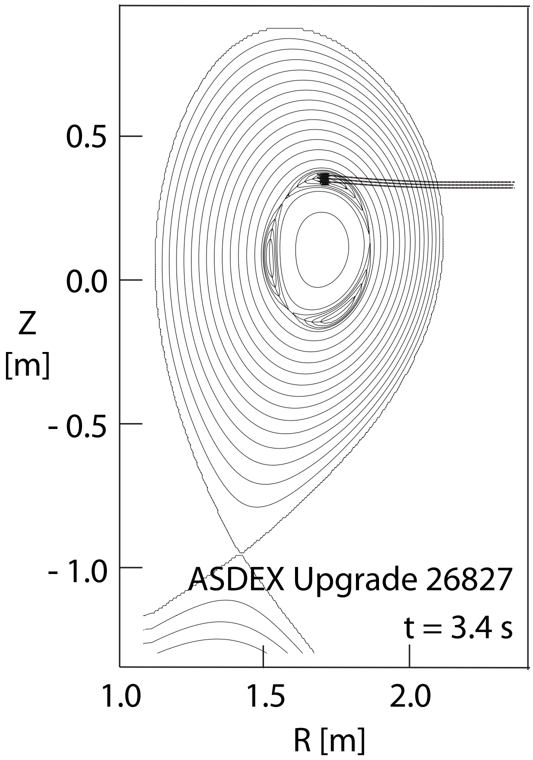

Figure 1: Result of TORAY ray-tracing for ASDEX Upgrade discharge 26827.

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[1] The T_e and n_e profiles are taken from the IDA integrated data analysis diagnostic of ASDEX Upgrade.

ECCD in the unperturbed equilibrium

We first study ECCD in the unperturbed magnetic equilibrium. Fig. 2 shows the power deposition and the current drive efficiency along the central ray as calculated with either TORAY or the bounce averaged quasi-linear Fokker-Planck code RELAX in the low power, linear regime. TORAY uses a relativistic calculation of the absorption coefficient and an adjoint calculation of the current drive efficiency based on the subroutines developed by Lin-Liu [7] extended with the current response function as derived by Marushchenko [8, 9] for a momentum conserving electron-electron collision operator. RELAX uses the relativistic Maxwellian background collision operator with a correction for momentum conserving electron-electron collisions [10]. The results show a satisfactory agreement between the two calculations. When the ratio of the absorbed power density over the square of the electron density exceeds the threshold [1]

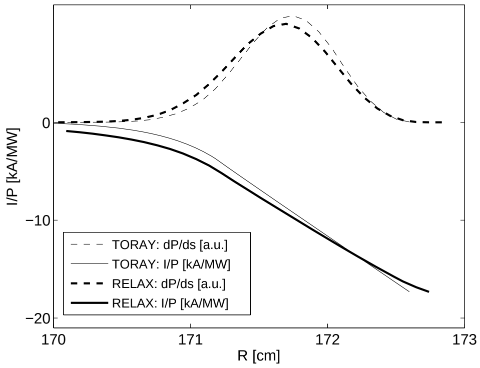

Figure 2: Power absorption and current drive efficiency along the central ray of the ECCD beam as function of major radius.

$$H \equiv p_{\text{ECCD}}\left[\text{MW/m}^3\right] / \left(n_e\left[10^{19} m^{-3}\right]\right)^2 \gtrsim 0.5 \tag{1}$$

non-linear effects must be expected. Below we will refer to H as non-linearity parameter. For a 1 MW ECCD beam the power deposition profile in the unperturbed equilibrium has a maximum corresponding to a value of the non-linearity parameter of $H_{max} = 0.1$. When the injected power is increased such that $H_{max} > 0.5$, Fokker-Planck calculations show a nonlinear reduction in the absolute value of the global current drive efficiency. This decrease in the global CD efficiency is explained as follows: the quasi-linear flattening of the distribution function near the resonance shifts the peak in the dP/ds profile to a smaller major radius R. That broadens the power deposition profile with more power reaching the regions where the CD efficiency is lower (cf. Fig. 2). As a consequence, the global CD efficiency decreases.

ECCD in the presence of a locked island

We now study ECCD in the presence of locked islands of different sizes. Fig. 3 illustrates the power deposition profiles for a 1 MW ECCD beam in the case of a 4 cm wide island as measured on the low field side mid-plane. In the case of a single helicity magnetic perturbation closed magnetic surfaces exist which are given by the surfaces of constant helical flux.

The power deposition profile is obtained as a function of this helical flux. It is plotted in terms of the normalized low field side minor radius x_{LFS} crossed by the helical flux surface in the poloidal cross section of the plasma in which the O-point of the island is in the low field side mid-plane. The three different profiles correspond to different phases of the island such that the power deposition is centered around the O- or X-point and at an intermediary phase. The peak power density and, consequently, the likelihood of non-linear effects is strongly dependent on the phase of the island.

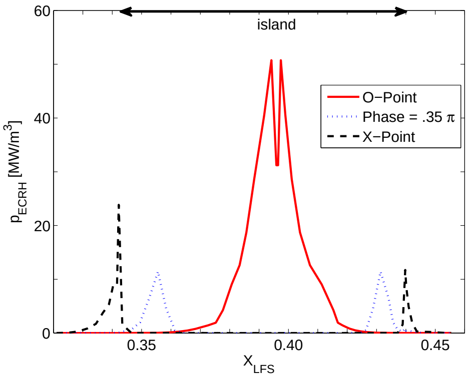

Figure 3: Absorbed power profiles calculated with RELAX for power depositions at three different phases of a locked island

In Fig. 4 we present the results of RELAX calculations for the injection of a 1 MW ECCD beam in a geometry including a locked island of 2, 4 and 8 cm width for different island phases. The results are given in terms of the peak value $H_{\max}$ of the non-linearity parameter (1). The thin solid black line represents the value of $H_{\max}$ in the unperturbed equilibrium, while the thick black line indicates the non-linear threshold. Circles represent cases in which the peak value is attained inside the island and crosses cases in which the peak value is attained on the separatrix. In case of deposition around the O-point the non-linear threshold is clearly exceeded.

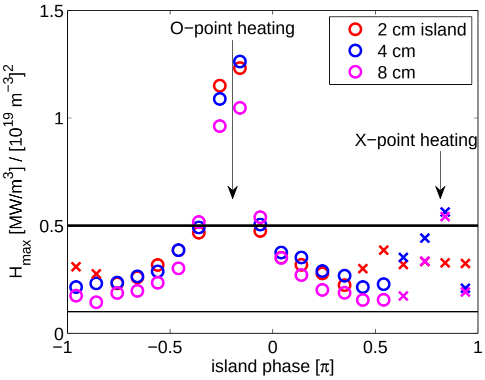

Figure 4: $H_{\max}$ as a function of island phase for $w_{island} = 2$, 4, and 8 cm

The non-linear effects introduced by exceeding the threshold have been studied in series of RELAX calculations for injected powers in the range of 1 kW to 10 MW. These results are summarized in Fig. 5, which depicts the global current drive efficiency as a function of the peak non-linearity parameter for the island sizes of 1, 2, 4, and 8 cm. As in the unperturbed equilibrium case, the non-linear effects are seen to result in a reduction of the absolute value of the current drive efficiency. The effect however, appears to depend on the island size. This is because the relative volume of the region in which H exceeds the threshold is a function of the island size as well. An averaged non-linearity parameter over the deposition profile can be defined as

$$< H > \equiv \frac{\int H p_{\mathrm{ECCD}} \mathrm{d}V}{\int p_{\mathrm{ECCD}} \mathrm{d}V}. \qquad (2)$$

When the results are plotted as a function of this averaged non-linearity parameter (indicated by the red curves), the data for all different island sizes overlap and coincide with those of calculations in case of the unperturbed equilibrium (not shown).

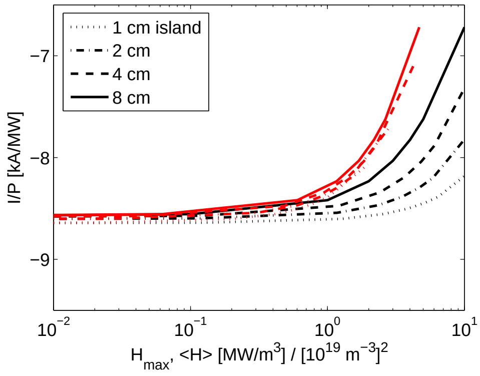

Figure 5: Global ECCD efficiency.

Conclusions

We have calculated the non-linear ECCD efficiency in the presence of magnetic islands. The plasma parameters are taken from ASDEX Upgrade discharge nr. 26827 which features an $m/n = 3/2$ NTM [3]. The main conclusions are: 1) The geometry of the closed flux surfaces in the case of NTMs results in higher local absorbed power densities of the ECCD applied for NTM control. 2) While the absorbed power density stays well below the nonlinear threshold in the case of the unperturbed equilibrium, the threshold is exceeded significantly for an injected power of 1 MW in case of deposition around the O-point of the island. 3) Nonlinear effects result in a global decrease of the ECCD efficiency in contrast with earlier claims [11]. 4) The significance of the non-linear effects is best parameterized by a profile averaged non-linearity parameter as defined in (2). Even at 4 MW the expected non-linear effects in the current drive efficiency do not exceed 10% for the ASDEX Upgrade parameters used in this study.

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