*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-5.129 (2007)*

Analysis of ECCD scenarios for different configurations of the W7-X Stellarator

N.B. Marushchenko, V. Erckmann, H.P. Laqua, H. Maaßberg, Yu. Turkin

Max-Plank-Institut für Plasmaphysik, EURATOM-Association, Greifswald, Germany

In the W7-X stellarator (under construction in Greifswald, Germany), the toroidal mirror ratio $B_{\rm max}/B_{\rm min}$ on axis can be varied significantly, from 1.004 to 1.22 for the "low-mirror" and the "high-mirror" configurations, respectively (for the "standard" configuration $B_{\rm max}/B_{\rm min} = 1.09$). The corresponding trapped-particle fractions on axis are varied due to ripples from $f_{\rm tr} \simeq 0.02$ for "low-mirror" up to $f_{\rm tr} \simeq 0.45$ for 'high-mirror", while $f_{\rm tr} \simeq 0.3$ for the "standard" configuration. Through its dependence on the toroidal mirror ratio value, mono-energetic bootstrap current coefficients are largest for the "low-mirror" configuration. In particular, the bootstrap current was minimized for the "high-mirror" configuration, whereas the neoclassical confinement is optimum in the "standard" configuration. The total plasma current affects the edge value of the rotational transform, which may fall outside the required range for proper island divertor operation without external field compensation. Due to the absence of an ohmic transformer, electron cyclotron current drive (ECCD) will be used for compensating the bootstrap current. Since the ECCD efficiency is quite sensitive not only to the plasma parameters, but also to the magnetic configuration, it is an important task to estimate properly the range of ECCD values taking into account all features of the magnetic configuration, and to check its ability to counteract the residual bootstrap current. It is necessary to take special care for high densities where the ECCD efficiency is reduced.

The numerical tools for calculating the ECCD efficiency developed to date do not cover completely the range of collisional regimes for the electrons involved in the current drive, especially in stellarators. Nevertheless, the collisionless limit (with trapped particles taken into account) is quite reasonable, especially for the regimes with moderate densities and high temperatures. In this work we analyze the requisite ECCD scenarios for operating the different magnetic configurations with help of the ray-tracing code TRAVIS [1]. The (adjoint) Green's function applied for the ECCD calculations is formulated with momentum conservation taken into account [2]; this is especially important and even critical for those scenarios, where mainly bulk electrons are responsible for absorption of the RF power (e.g. when obliqueness of launch is not high).

The ECRH system in W7-X is designed for continuous operation with a total injected power up to 10 MW at 140 GHz [3] (the resonance magnetic field is $B_0 = 2.5$ T). In the density range $n_e < 1.2 \times 10^{20}$ m^{-3} the X2 scenario (extra-ordinary mode at the 2nd harmonic) is applicable, and for higher densities, up to 2.4×10^{20} m^{-3}, the O2 scenario will be applied. Due to the high optical thickness of the plasma for the X2-mode, there are no strict launch conditions for this scenario, and this freedom can be used for tailoring a desired deposition and current drive profile. The O2 scenario is much more limited because of low optical thickness of the plasma for the expected range of parameters. The most attractive way for the O2 scenario is to preheat plasma by the X2-mode, to change then the polarization from X- to O-mode by means of rotation of the corrugated mirrors, and to increase the density to the requested value [4,5]. In order to prevent an overheating of the wall by the shine-through power and to control its reflection, mirrors at the inner wall are installed, and all beams planned for O2 operation must be directed to these mirrors. In the calculations, three passes are taken into account for the O2 scenario. Because of symmetrical location of the mirrors about the launch ports, only five beams out of ten can be launched in the same direction, and operation with maximal counter-ECCD is possible only with a total power up to 5 MW.

The calculations were done for five different beams launched from the ports E10 and A51 with 1 MW power for each beam. Both X2 and O2 scenarios are modelled for the same fixed launch conditions for the three different magnetic configurations. If after two passes through the plasma less than 90% of the power was absorbed, this scenario was excluded from consideration. The plasma profiles and bootstrap current were calculated by the 1D transport code [4] (for details, see also [5]) coupled self-consistently with the ray-tracing code TRAVIS [1]. The transport modelling is based on the DKES database of monoenergetic transport coefficients, and thermal transport coefficients are obtained by energy convolution with Maxwellians. The DKES code [6] uses as collisional term only the pitch-angle Lorentz operator without momentum conservation, leading to an overestimate of the bootstrap current with dependence on Z_{eff} (in present calculations, $Z_{\text{eff}} = 1.5$ is used).

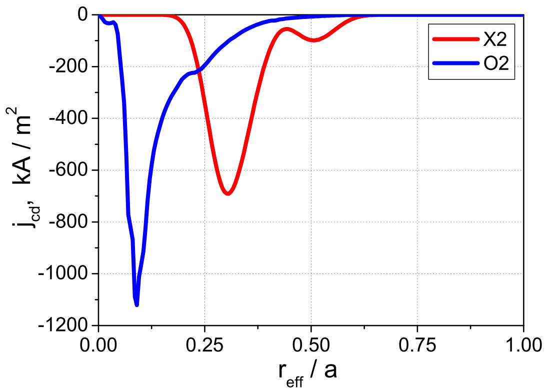

Figure 1: Summarized ECCD profiles for both X2 (red) and O2 (blue) scenarios for the standard magnetic configuration with $n_e = 0.8 \times 10^{20}$ m^{-3}.

In order to increase single-pass absorption of the O2-mode in optically "gray" plasmas, the resonance is shifted in the low-field-side direction by use $B = 2.53$ T on axis. In Fig.1, the ECCD profiles for both scenarios are shown (the corresponding deposition profiles have a very similar shape). These profiles summarize the contributions from all beams (with three passes taken into account for O2-mode), which produce the counter-ECCD, i.e. ECCD is directed against the bootstrap current. Note, that the ECCD (as well the deposition) profiles for X2 and O2 scenarios are quite different. Due to very high optical thickness, the location of the deposition (as well ECCD) profile for X2-mode is almost completely defined by the resonance location, and mainly a Doppler broadening is responsible for the width. The shape of the ECCD profile for X2 scenario is almost independent of the density, and only its value scales roughly as $1/n_e$ (see Fig.2). A temperature dependence is not strongly pronounced due to an absence of its strong variation: for n_e increased from 0.4×10^{20} m^{-3} to 1.0×10^{20} m^{-3}, T_e is varied from 7.3 keV to 5.0 keV, respectively. For the O2 scenario, the situation is much more sophisticated. First of all, the plasma is optically "gray" and a significant part (up to 20%) of the power is absorbed during a second pass (a third pass is of minor importance). The absorption of the O2-mode, being proportional to T_e^2, is very sensitive to the shape of T_e profile (n_e profile is almost flat). On the other hand, the T_e profile is defined mainly by the deposition profile. Due to this feedback, the resulting deposition (as well as ECCD) profiles for the scenarios with the resonance shifted to the low-field-side are rather independent of n_e, and its shape is quite similar to those shown in Fig.1. Again, the O2 driven current scales roughly as $1/n_e$.

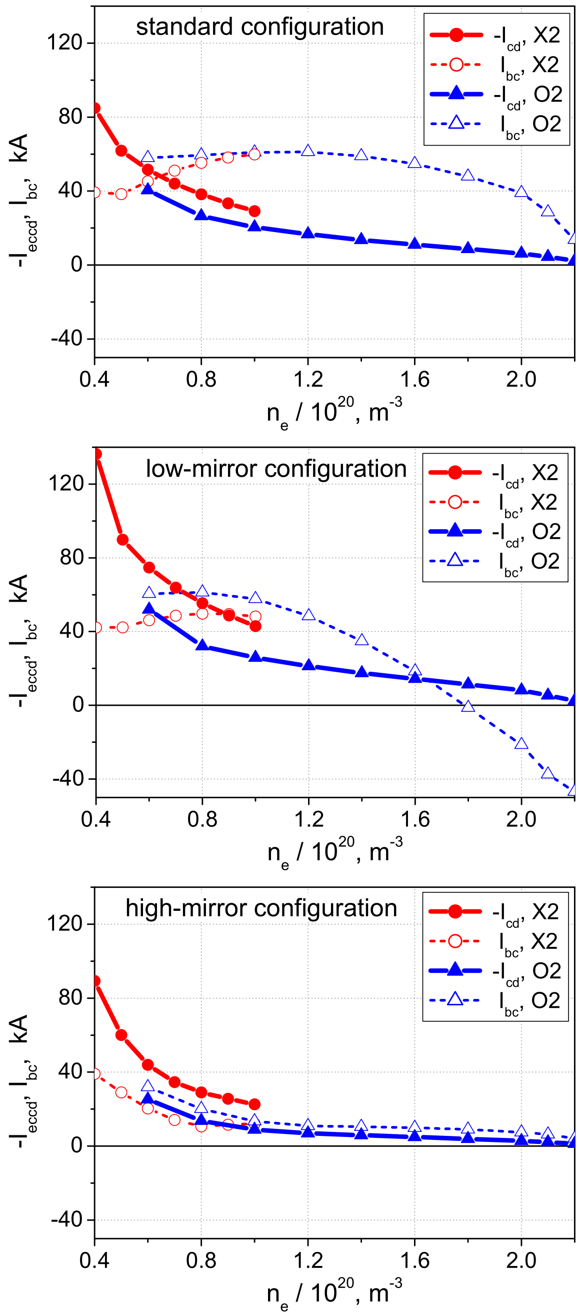

Figure 2: Density scan for different magnetic configurations. Both I_{cd} (solid) and I_{bc} (dashed) are shown. X2 and O2 scenarios are labeled by red circles and by blue triangles, respectively.

In Fig.2, the results of the density scan for the three magnetic configurations are shown. As expected, the current driven by X2-mode is larger than that of the O2-mode. The bootstrap current can be compensated by X2-ECCD for the “low-mirror” and “high-mirror” configurations. For the “standard” configuration (apart from the lower densities), this problem requires additional study. Full current control at high density (in operation with O2-mode) is only obtained for the “high-mirror” configuration.

In high-density operation at low ECRH power, the bootstrap current might exceed the maximum ECCD both for the X2- and the O2-scenarios. Only the "high-mirror" configuration was shown to have rather small bootstrap currents thus confirming the corresponding W7-X optimisation criterion. For the "standard" configuration with improved neoclassical confinement, however, ECCD control of the bootstrap current is only possible in X2-mode at lower density. With full current control by ECCD, only a few skin-times (i.e. less than 10 sec) are necessary to obtain stationary conditions for optimum divertor operation.

High density scenarios are also important for the W7-X island divertor operation since fairly high separatrix densities (about 0.4×10^{20} m^{-3}) are required. Consequently, the O2-scenarios are expected to be very important for longer discharges. For these conditions, however, only the "high mirror" configuration allows for bootstrap current control by ECCD. In particular for the "standard" configuration, another discharge scenario must be chosen to obtain stationary conditions. Here, the edge value of the rotational transform in the vacuum configuration must be reduced by the amount which is generated by the bootstrap current in the final steady state. The discharge is operated at low density and rather low heating power with strong co-ECCD (in X2-mode) up to roughly stationary plasma current, i.e. the desired island divertor configuration is reached. In this scenario, however, the evolution of the plasma current scales on the L/R-time (i.e. several 10 sec). Then, the density as well as the heating power can be ramped up and the co-ECCD is reduced with the increasing bootstrap current, i.e. the total current is controlled. The internal current densities and the ι-profile become stationary again on the skin time. Such a discharge scenario, however, is much more complex compared to the case of full ECCD control of the bootstrap current.

References

[1] N.B. Marushchenko *et al.*, *Proc. of the 16th Toki Conference*, Dec. 5 - 8, 2006, Toki, Japan, http://itc.nifs.ac.jp/index.html

[2] M. Romé *et al.*, Plasma Phys. Control. Fusion **40** (1998) 511

[3] V. Erckmann *et al.*, will be published in Fusion Sci. and Technol. **52** (2007)

[4] Yu. Turkin *et al.*, Fusion Sci. and Technol. **50** (2007) 387

[5] Yu. Turkin *et al.*, this conference, P1-148

[6] W.I. van Rij and S.P. Hirshman, Phys. Fluids B1 (1989) 563