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High Power NBCD Analysis at W7-AS

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Introduction: At the W7-AS Stellarator mainly net-current-free discharges are performed, where the feedback-controlled ohmic current compensates both the bootstrap current and the neutral beam current drive (NBCD). In this study we focus ourself on the case of high power tangential NB injection (50 keV with injection angle of about 22°).

Two opposite scenarios are investigated in detail: high density discharges with very low temperatures, characterised by a very short slowing-down time of the beam ions ($\tau_{\rm sd} < 1$ ms) with very high $\langle\beta\rangle \simeq 3\%$ ($B \leq 1$ T) and "high performance" discharges at moderate densities, but fairly high temperatures and $\tau_{\rm sd} \sim 10$ ms. These cases are belonging to quite different collisional regimes, having consequently very different current drive efficiencies. With the divertor installed in W7-AS the impurity concentration was significantly reduced (typically $Z_{eff} < 1.5$), and the NBCD efficiency is significantly affected by the friction of passing with trapped particles.

Modelling: The ion slowing-down contribution of the NBCD is obtained by Fokker-Planck simulation (FPTM code [1]). In this simplified approach, the "birth" profile of the fast NBI ions is used and the slowing-down is estimated with radial drift effects neglected. Generally, good agreement of the thermal power deposition profiles is found compared to Monte Carlo slowing-down simulations. However, for the high $\langle\beta\rangle$ scenario at low field, the deviation of the fast ion orbits from the flux surfaces may become important. The electron response (Ohkawa current) is calculated following Refs. [2, 3]. In this approach a Green's function formalism is used with electron momentum conservation leading to the Ohkawa current after convolution with the ion slowing-down distribution function. In the collisional limit [2], the effect of the magnetic field topology is negligible whereas in the collisionless limit [3] only passing electrons contribute to the Ohkawa current with additional momentum loss by friction with the trapped electrons. Therefore, the collisionless approach leads to an upper limit and the collisional approach to a lower limit for the total NBCD density. With vanishing fraction of trapped particles, $\langle f_{tp}\rangle \to 0$, both approaches become identical. A more realistic model depending on the collision frequency is missing, so far.

Both the bootstrap and the ohmic current densities are calculated by means of the DKES data-base of mono-energetic neoclassical coefficients for the specific W7-AS configurations (with energy convolution for evaluating the thermal neoclassical transport matrix). As in the DKES code only the simple Lorentz form of the pitch angle collision operator is used, a modified energy convolution based on Spitzer's function is applied for calculating the bootstrap current and the parallel conductivity coefficients. The radial electric field, E_r, is computed from the ambipolarity condition and used for estimating the bootstrap current density. The effect of E_r on the total bootstrap current is not significant (increasing the electron and decreasing the ion contribution for $E_r < 0$), only for very strong $|E_r| > \iota B v_{th} r/R$ the ion bootstrap coefficient is significantly reduced.

All the estimations of the different current density profiles are based on the measured profiles of n_e, T_e and T_i as well as on Z_{eff} (here assumed to be $const.$).

High density discharges: In the high-$\langle\beta\rangle$ discharges at $B = 0.9$ T with 3.8 MW NBI input power (the heating efficiency is only 70%), high densities $n_e \approx 2.5 \cdot 10^{20}$ m^{-3} were obtained, but with very low temperatures, $T_e \simeq T_i \simeq 0.25$ keV. Even in the central region, these discharges are within the Pfirsch-Schlüter regime, $\nu^* = \nu R/v\iota > 1$. With the very short slowing-down time under these conditions, the nonthermal ion fraction is very small, and the linear Coulomb operator with Maxwellian background ions is used in the Fokker-Planck calculations.

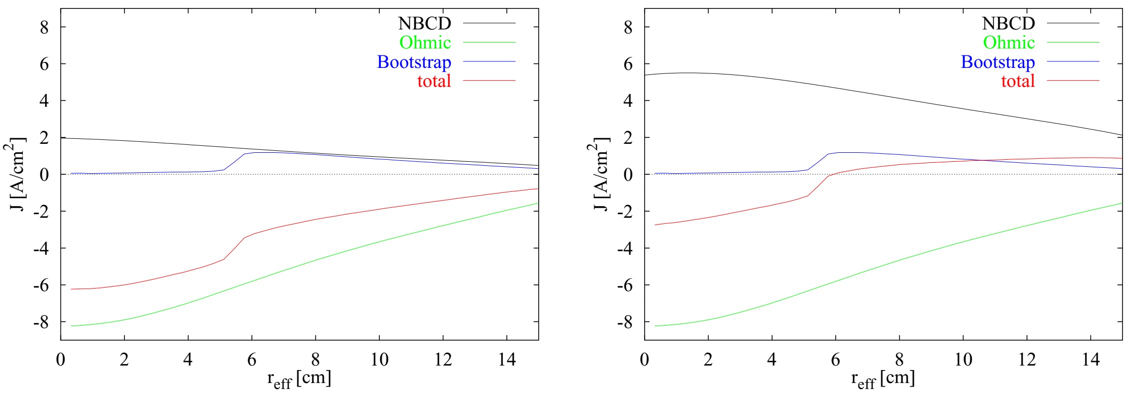

Figure 1: *Radial profiles of the current contributions for the "high density" discharge (#54022). On the left: the collisional limit ($Z_{eff} = 1.2$ and $\langle f_{tp}\rangle = 0$); on the right: the collisionless limit ($Z_{eff} = 1.3$ and with trapped electrons).*

In Fig.1 the radial profiles of the NBCD current densities for both the collsional and the collisionless limits are shown. The NB driven current in the collisionless limit ($I_{\rm NBCD} = 2.38$ kA, $I_{\rm bt} = 0.46$ kA and $I_{\rm OH} = -2.75$ kA) is in much better agreement with the current balance than in the collisional limit ($I_{\rm NBCD} = 0.65$ kA) where the electron Ohkawa current nearly cancels the ion slowing-down current. Only for unrealistic high $Z_{eff} \gtrsim 2$ the disagreement vanishes. These findings are in clear contradiction to the theoretical expectations.

“High performance” discharges: The discharges at moderate density, $n_e \approx 7 \cdot 10^{19} m^{-3}$ (well below the ECRH cut-off limit for 140 GHz, X-mode), are sustained by about 2 MW NBI input power and 1 MW ECRH; see Fig.2 for the density and temperature profiles and [4] for the energy balance with respect to the neoclassical prediction. The collisionality $\nu^* < 0.1$ is fairly low and at least the deeply trapped particles can be treated in the collisionless approach ($\nu\,\tau_b \ll 1$ where τ_b is the bounce time). The non-thermal ion density is fairly large, $n_b/n_e \gtrsim 0.1$, and a fully non-linear treatment of the Fokker-Planck term with bounce-averaging should be used (being still under development). Within such a treatment the momentum source of the NBI is balanced by the momentum sink of trapped (thermal) ions by friction and momentum loss to electrons and impurities (Maxwellian). In a 1st step, the linear bounce-averaged collision term was used for calculating the ion slowing-down current.

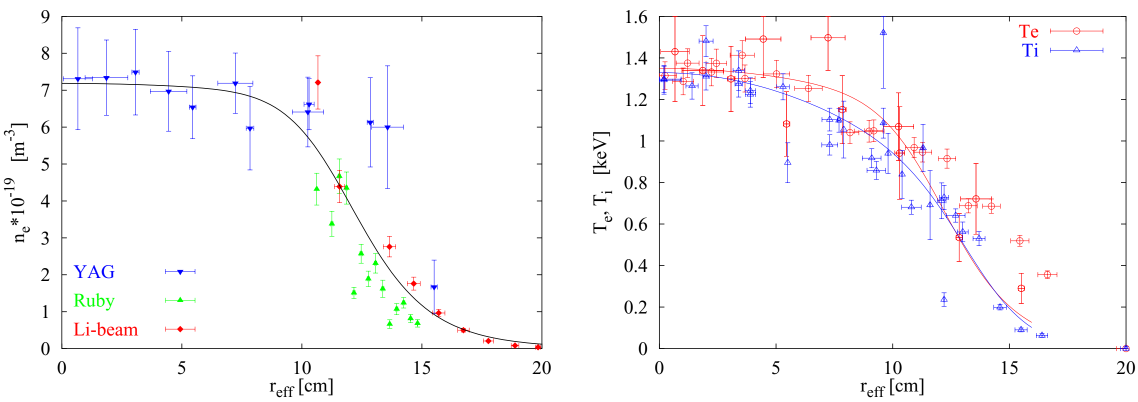

Figure 2: *Measured profiles of n_e and $T_{e,i}$ for ”high performance” discharges (#54285-54296).*

The radial profiles of the current contributions together with the total current density are shown in Fig.3. The NB driven current in the collisionless limit which should be more appropriate for these conditions ($I_{\rm NBCD} = 23.6$ kA, $I_{\rm bt} = 19.7$ kA and $I_{\rm OH} = -34.6$ kA) fits the current balance as well as in the collisional limit ($I_{\rm NBCD} = 10.3$ kA). This result is more convincing than in the high density scenario since some electron Ohkawa current diffusion into the region of barely trapped electrons with a bounce-time much larger than for the locally trapped ones should be expected.

Conclusions: The accuracy of the current balance of NBCD, bootstrap and ohmic current is reasonable for the high temperature discharges whereas rather insufficient for the opposite

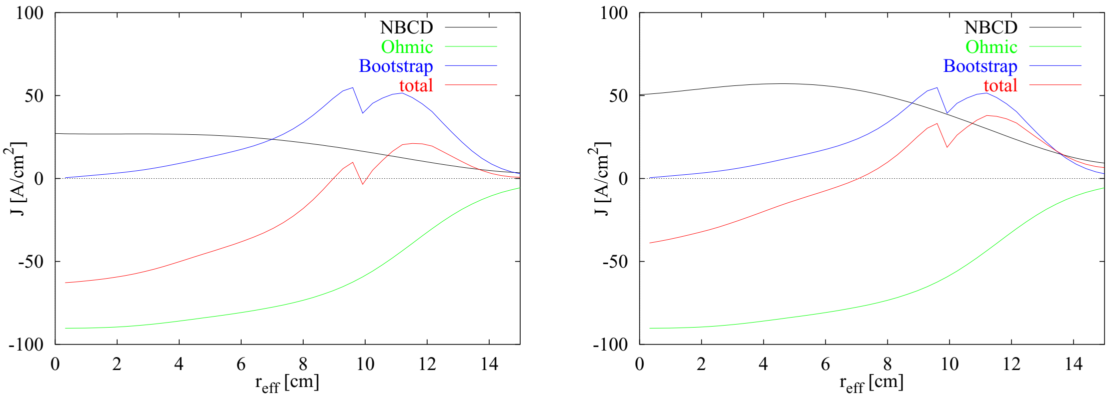

Figure 3: *Profiles of the current contributions for "high performance" discharges (#54285-54296) with* $Z_{eff} = 1.3$*. On the left: the collisional limit (*$\langle f_{tp} \rangle = 0$*); on the right: the collisionless limit (with trapped electrons).*

high density discharges. Especially for the later case, the bootstrap contribution is fairly small, and the ohmic current estimate seems to be fairly reliable. Consequently, the collisional limit of the NB driven current at the high collisionalities should be a much better guess than the collisionless one. But this prediction is not supported by the experimental results. If the estimated NB driven current is too small as indicated by the ohmic one, it is hard to find a resonable argument to increase the ion slowing-down contribution or to decrease the electron Ohkawa current. Uncertainties in the experimental density and temperature profiles seems not to be responsible for this disagreement, if only Z_{eff} is really small and the assumption of uniform the impurity profiles is correct.

In general, the ohmic current and the NBCD density profile are both fairly flat and cancel partly each other. For the high density case, the effect of the current density distribution on the rotational transform seems to be rather small (within the uncertaintay of the current balance). Nevertheless, the further analysis is needed for this type of discharges with $\langle \beta \rangle \simeq 3\%$, the highest found at W7-AS, with respect to a systematic stability analysis.

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