*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-2.113 (2006)*

Transport simulations for W7-X

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The results of transport modeling for the W7-X stellarator are presented. A new 1-D transport code [1] is used to study confinement properties of the W7-X stellarator for the case of electron cyclotron resonance heating (ECRH). A set of reference calculations assuming neoclassical confinement plus anomalous contributions (dominant at low density and temperature) has been carried out. The plasma profiles determined in this way will be used to create a profile database which is needed for the development of diagnostics software. The energy confinement time and its dependence on global plasma parameters are compared with the prediction of the empirical scaling ISS95.

To model transport in W7-X, we use a predictive 1-D transport code which is under development [1]. The transport code is based on a system of equations, which consists of particle and power balance equations augmented by diffusion equations for the radial electric field and for the poloidal magnetic flux:

$$\begin{aligned}
&\frac{\partial n_e}{\partial t}+\frac{1}{V'}\frac{\partial}{\partial r}V'\Gamma_e=S_P,\\
&\frac{3}{2}\frac{\partial n_e T_e}{\partial t}+\frac{1}{V'}\frac{\partial}{\partial r}V'Q_e=P_e-\Gamma_e E_r,\quad \frac{3}{2}\frac{\partial n_i T_i}{\partial t}+\frac{1}{V'}\frac{\partial}{\partial r}V'Q_i=P_i+z_i\Gamma_i E_r,\quad n_i=\frac{n_e}{z_i},\\
&\varepsilon_0\frac{c^2}{V_a^2}\left(1+\frac{0.7}{\iota^2}\right)\frac{\partial E_r}{\partial t}-\frac{1}{V'}\frac{\partial}{\partial r}V'D_E\left(E_r'-\frac{E_r}{r}\right)=|e|\left(\Gamma_e-z_i\Gamma_i\right),\\
&\frac{\sigma}{2\pi R_0}\frac{\partial}{\partial t}\psi_p-\frac{1}{2\pi R_0\mu_0}\frac{1}{V'}\frac{\partial}{\partial r}V'\frac{\partial}{\partial r}\psi_p=j_{bs}+j_{cd}
\end{aligned}\tag{1}$$

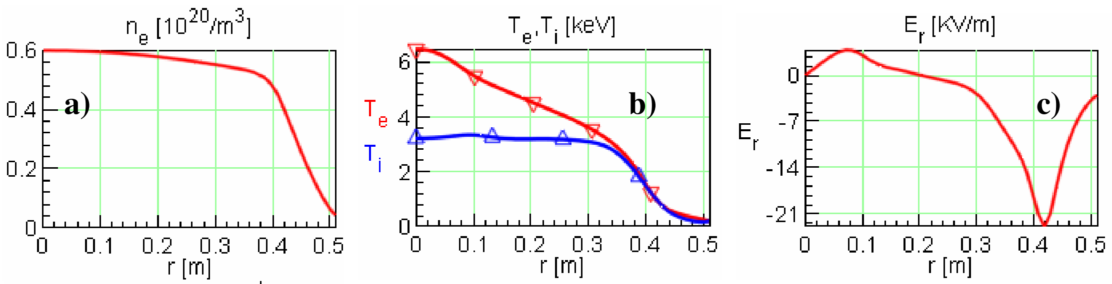
The neoclassical and anomalous fluxes in Eq. (1) are given by expressions:

$$\Gamma_\alpha^{neo}=-n_\alpha\left[D_{11}^\alpha\left(\frac{n_\alpha'}{n_\alpha}-\frac{z_\alpha E_r}{T_\alpha}\right)+D_{12}^\alpha\frac{T_\alpha'}{T_\alpha}\right],\qquad q_\alpha^{neo}=-n_\alpha T_\alpha\left[D_{21}^\alpha\left(\frac{n_\alpha'}{n_\alpha}-\frac{z_\alpha E_r}{T_\alpha}\right)+D_{22}^\alpha\frac{T_\alpha'}{T_\alpha}\right],$$

$$\Gamma_\alpha=\Gamma_\alpha^{neo}+\Gamma_\alpha^{an},\qquad Q_\alpha=Q_\alpha^{neo}+Q_\alpha^{an},\qquad \alpha=e,i$$

$$Q_\alpha^{neo}=q_\alpha^{neo}+\frac{3}{2}\Gamma_\alpha^{neo}T_\alpha,\qquad \Gamma_\alpha^{an}=-D_{ano}^\alpha n_\alpha',\qquad Q_\alpha^{an}=-\chi_{ano}^\alpha n_\alpha T_\alpha'+\frac{3}{2}\Gamma_\alpha^{an}T_\alpha$$

where n_α, T_α and Z_α are the density, temperature and charge number of electrons or ions and the prime denotes the partial derivative with respect to the effective radius *r*. For evaluation of the transport coefficients D^α_{jk} we use a dataset of transport coefficients calculated by the DKEScode [2]. In the simulation we determine self–consistently the neoclassical fluxes and the radial electric field, which strongly affects the transport at the low collisionality. The density is kept fixed and the equation for the poloidal magnetic flux is not used in these simulations. For simplicity we use a prescribed ECRH power deposition profile $P_{ECRH} \propto \exp\left(-(r-r_c)^2/w^2\right)$. In Fig. 1 the density and temperatures for the ECRH scenario along with the calculated radial electric field are shown for the case of central density $0.6 \cdot 10^{20}\mathrm{m}^{-3}$ and 3.32MW of slightly off-axis ECR heating. In the plasma center, the “electron root” with the positive electric field is seen. For higher density and the same heating conditions the “electron root” disappears and the electric field becomes negative throughout the entire plasma.



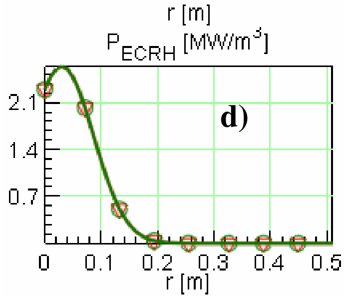


Fig 1. Plasma profiles for the case of 3.32MW of ECRH: (a) the electron density; (b) the electron (∇) and ion (Δ) temperatures; (c) the radial electric field; (d) ECRH power deposition profile. τ_E=0.517sec

Corresponding to Fig. 1, neoclassical transport coefficients D^{α}_{jk} and anomalous heat conductivities χ^{α}_{ano} are shown in Fig. 2. Based on the experience of the W7-AS campaign [3] we choose the diffusion model to be neoclassical in the bulk plasma and anomalous at the edge. In the region of a high gradient of the density the anomalous transport coefficients are taken in the form $D^{e}_{ano} = \chi^{e}_{ano} = \chi^{i}_{ano} \propto 1/n_e$ with exponential decay towards the center of the plasma. To maintain ambipolarity the relation $D^{i}_{ano} = D^{e}_{ano}$ is imposed.

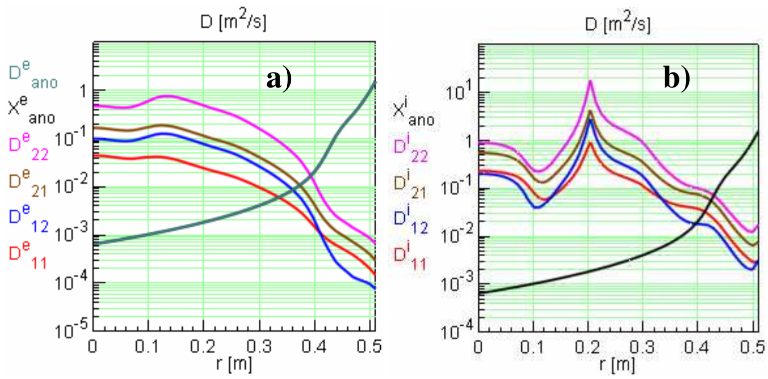


Fig 2. Electron (a) and ion (b) diffusion coefficients; black curves are the anomalous heat conductivities χ^{α}_{ano}

The results of transport modeling for different ECRH powers and plasma densities are shown in Fig. 3. The energy confinement time scales with the plasma density as: $\tau_E \propto \langle n_e \rangle^{-0.8}$. Power dependencies are depicted in Fig. 3(right); the confinement time is proportional to $P^{-0.5}$ for the low density case and $\tau_E \propto P^{-0.7}$ for the high density case.

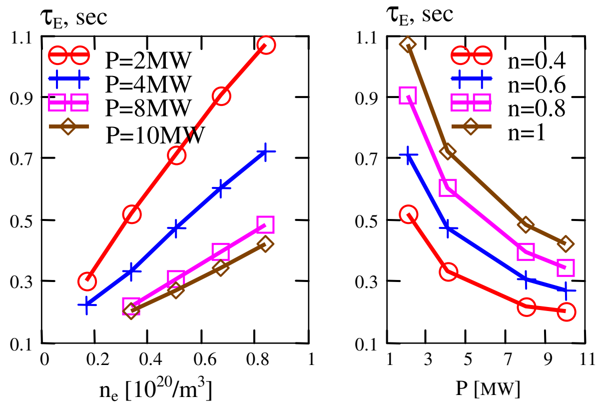


Fig 3. Dependence of the energy confinement time on the line average density(left) and on the ECRH power (right)

The almost linear scaling of the energy confinement time with the plasma density is an indication of neoclassical $1/\nu$ transport of electrons. The calculated energy confinement times are compared with ISS95 scaling: $\tau^{ISS95} = 0.079 a^{2.21} R^{0.65} P^{-0.59} \langle n_e \rangle^{0.51} B^{0.53} \iota_{2/3}^{0.4}$.

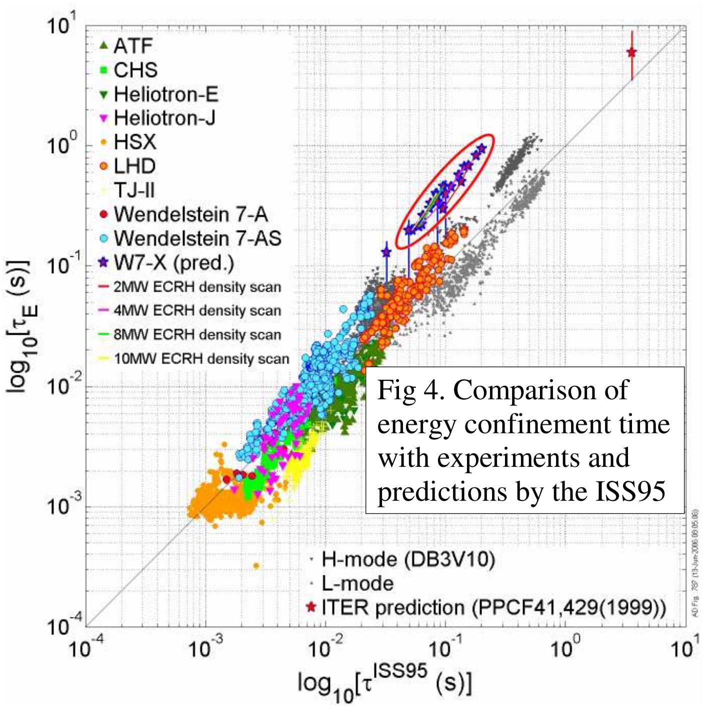
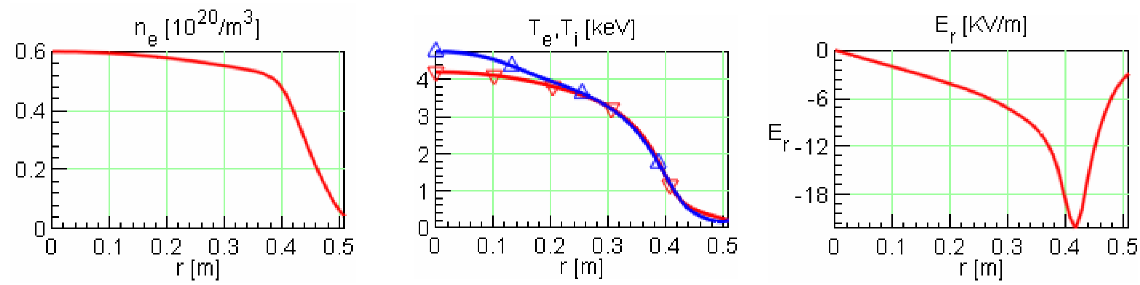


Fig 4. Comparison of energy confinement time with experiments and predictions by the ISS95

The points with predicted confinement time are plotted inside the red ellipse in Fig. 4. Our results demonstrate longer confinement time than that expected from the ISS95 scaling due to the predominance of neoclassical transport. This is consistent with the results of W7-AS campaigns where it was shown [3] that confinement was neoclassical in nature for $T \geq 1\text{keV}$ and that most W7-AS discharges had better confinement than predicted by ISS95 scaling [4]; see also the W7-AS data in Fig. 4. Strong neoclassical transport optimization leads to a further improvement of the plasma confinement in the W7-X.

For comparison with ECRH plasmas we have also simulated NBI-heated plasmas. For modeling of NBI heating, a newly developed fast NBI module is used. The pencil-beam approach is used for the calculation of the birth profiles. In a reasonable approximation, the slowing-down of the fast NBI ions on the flux surfaces is used, allowing a fast Fokker-Planck solver for the evaluation of the power deposition profiles. The modeling results are shown in Fig.5. We choose the simulation parameters in such a way to have the same heating power as in the case shown in Fig. 1. The energy confinement time is almost the same as in the ECRH plasma although ion and electron temperatures are closer to each other and plasma neoclassical transport follows the "ion" root.



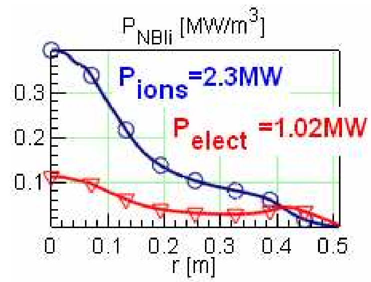


Fig. 5 Plasma profiles for the case of 3.32MW of NBI heating by neutral hydrogen: a) the electron density; b) the electron (∇) and ion (Δ) temperatures; c) the radial electric field; d) NBI heating power deposition profiles; beam line parameters: port AEK21, particle energy=60keV; $P_E : P_{E/2} : P_{E/3}$=50 : 30 : 20.

τ_E=0.505sec

SUMMARY

In the present work we have studied the energy confinement properties of W7-X assuming neoclassical diffusion in the bulk plasma and anomalous at the edge. The modeling has shown that the energy confinement time scales with the density and ECRHpower as $\tau_E \propto \langle n_e \rangle^{0.8} \cdot P^{-(0.5\ ..\ 0.7)}$. The confinement times are one order of magnitude higher than that of the W7-AS confinement times. We attribute this improvement to the neoclassical transport optimization in W7-X. We have also begun predictive modeling of W7-X NBI-heated plasmas. The plasma profiles determined in this way are used for creating a reference profile database which is needed for the development of diagnostics software.

REFERENCES

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