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ECRH and transport simulation for W7-X

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The W7-X stellarator being built at IPP-Greifswald will be equipped with a flexible ECRH system designed for 30 minutes operation with total power 10 MW generated by 10 gyrotrons [1]. The ECRH system will be the main heating source during the initial stage of W7-X operation. At low to moderate densities, heating is with the 2nd harmonic of the extraordinary mode (X2 at 140GHz and B=2.5T) with low-field-side launch in a bean-shape plane. High-density and high-β regimes above the X2-cut-off density, i.e. from $1.2\times10^{20}m^{-3}$ to $2\text{-}2.4\times10^{20}m^{-3}$, are accessible using the 2nd harmonic of the ordinary mode (O2).

In the present work the high performance O2-heating scenarios for W7-X are investigated by means of predictive simulations using a new 1-D transport code [2]. Neoclassical core confinement with empirical anomalous transport at the plasma edge is assumed [3]. The anomalous diffusivity scales inversely with plasma density in the region of high density gradient and exponentially decays towards the plasma axis. The radial electric field, electron and ion temperatures are advanced self-consistently with a calculation of the power deposition profiles by the ray-tracing code TRAVIS [4]. The shape of the density profile with a gradient region of about 10cm is fixed. The modeling is performed for the standard magnetic configuration, which is optimized for maximum confinement. Configuration of the ECRH heating system used in simulations is shown in Fig. 1.

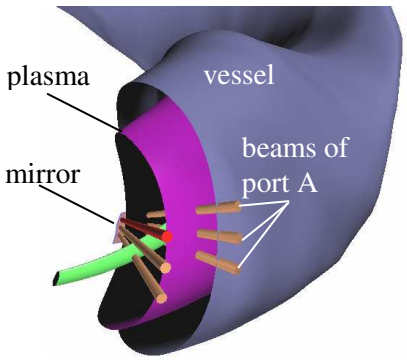

Fig. 1. Geometry of the ECRH beams; only six beams from 12 (10 plus 2 spare)[1] are shown: three beams (right) launched through port A and three beams(left) launched through port E; the other six beams are located symmetrically in the next module; the reflecting stainless-steel liners between ports are not shown. The beam in red is the spare beam.

To prevent overheating of the vessel and in-vessel components by the shine-through radiation a reflecting mirror is foreseen opposite to the ECRH launchers, thus allowing the second pass absorption of the microwave beam and thereby significantly reducing the focused non-absorbed ECRH power. However, preliminary calculations [1] have shown that single-pass absorption of the power decreases from 80% to 50% when the density increases from $10^{20}m^{-3}$

to $2.3\times10^{20}m^{-3}$ due to unfavorable temperature dependence and even after two passes of the microwave beam the non-absorbed ECRH power can be high. To increase absorption, the third pass of beams is provided by the reflecting stainless-steel liner installed on the outer side of the vessel between the ECRH ports. In the simulations described below all beams are aimed to the reflecting mirrors and the ray tracing code simulates three-pass absorption. The beams propagate at angles optimized with respect to the absorption efficiency for O2 or X3-mode operations; refraction effects are quite small even at high density; see also Fig. 4a.

The heating efficiency of the O2-mode strongly depends on plasma parameters, especially on electron temperature, because the optical thickness is proportional to T_e^2. The electron temperature in turn decreases with density increase as predicted by scaling laws [3] leading to absorption degradation and finally to thermal collapse. The ECRH power scans for the standard magnetic configuration have been performed for densities of $0.8\text{-}2.3\times10^{20}m^{-3}$ and O2-mode (140GHz at B=2.5T) heating from 0.5MW to 10MW with on-axis power deposition. The value of magnetic field has been chosen to have the ECRH resonance zone on the low-field-side (LFS) with respect to the magnetic axis in order to meet the most favourable conditions for O2-mode absorption. The simulations have been started from low density at given power using off-axis X2-heating (100% single-pass absorption) with simultaneous ramp-up of the density. Then below the X2-cut-off density, the polarization has been changed to O2-mode and density has been increased till O2-cut-off.

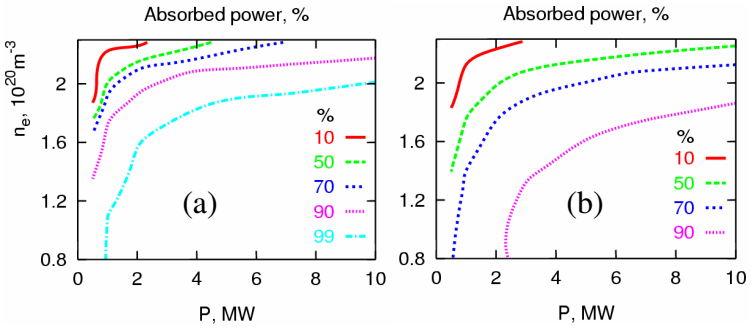

Fig. 2. Percentage of absorbed power for the three-pass scheme of O2-mode heating as a function of input power and plasma density: (a) after three passes; (b) after the first pass.

The results of scans are shown in Fig. 2. It is seen that nearly full absorption is achieved in a wide range of density and input power; see region below 99% curve (cyan) in Fig.2a; the single-pass absorption for these conditions is higher than 70%; see Fig. 2b.

The time traces of the plasma parameters for the 10MW O2-mode scenario are shown in Fig. 3. Initially the $0.6\times10^{20}m^{-3}$ plasma is heated by 5MW X2-mode; see the temperature and power deposition profiles in Fig. 3ab. Then the heating is switched to O2-mode with the same input power. The central power deposition increases the electron temperatures leading to temperature decoupling and increasing of a positive radial electric field E_r within the central

ECRH deposition zone (dashed curve in Fig. 3c). The simulation is continued by ramping-up the density (magenta curve in Fig. 3c) till $2\times10^{20}m^{-3}$. At the density $10^{20}m^{-3}$ the heating is increased to 10MW; see Fig. 3c. Strong heating increases the electron temperature and consequently E_r; the ion temperature also increases due to the strong collisional coupling at high densities. The final temperatures are shown in Fig. 3d, for the density profile see Fig. 6a. The following plasma parameters are reached: $n_iT_i\tau_E=5.5\times10^{20}m^{-3}$ $keV{\cdot}s$, $\tau_E=0.66s$; and volume averaged $<\beta>=6.5\%$. It should be noted that the high-β plasma changes the magnetic configuration; the magnetic field at the axis is reduced due to the Shafranov shift and the diamagnetic effects. Therefore the ECRH resonance zone can be moved to the high field side. In this case the O2 absorption can degrade due to the decrease of the electron temperature in the resonance zone. Careful modelling is needed to optimize experiment with high-β plasmas.

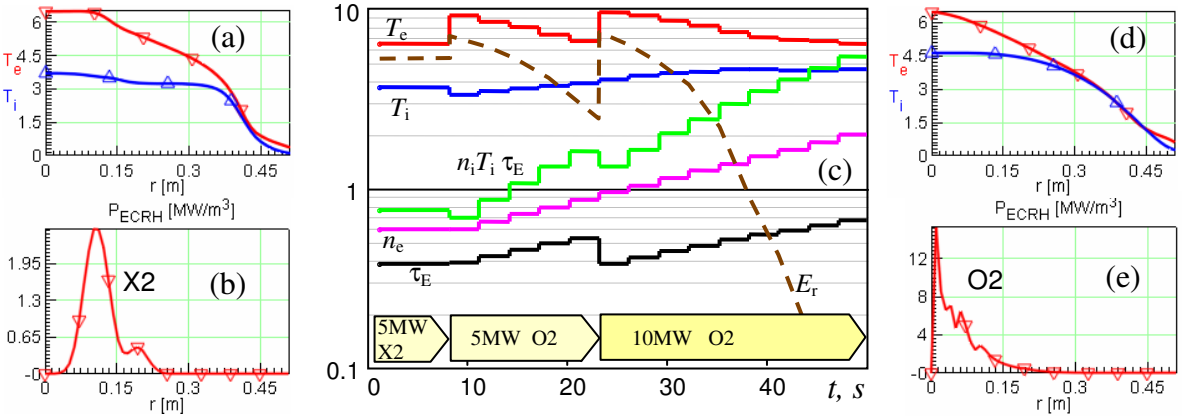

Fig. 3. (a) initial temperature and (b) power deposition profiles; (c) time evolution of the main plasma parameters: central T_e, T_i, triple product $n_iT_i\tau_E$ in $10^{20}m^{-3}$ keV·s, central n_e, energy confinement time τ_E, the maximum value of E_r in kV/m within the central ECRH deposition zone, i.e. for radii less then 15cm; (d,e) final temperatures and ECRH deposition profile.

In Fig. 4 the projections of the beams to the poloidal and equatorial planes are shown. The intensity of red spots on the rays are proportional to the absorption rate, most of the ECRH power (>70%) is absorbed at the first pass.

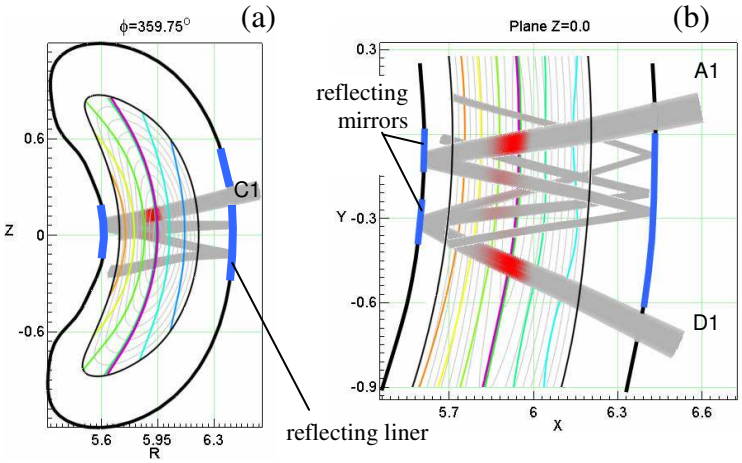

Fig. 4. Trajectories of ECRH beams: (a) poloidal plane with only one beam shown, (b) equatorial plane with the two beams going from mirror A1 of port E and mirror D1 of port A; magenta lines are the cold resonance positions; color lines in figures are the lines of constant magnetic field.

Finally, for comparison with O2 ECRH plasmas, we have simulated the plasma heated by "positive" NBI (p-NBI, 60 keV H^+); see Fig.5. In the p-NBI case, the main power is absorbed at outer radii, especially the low energy components of the beam. This leads to confinement degradation, whereas for the O2 case the much higher central deposition allows for higher temperatures and improved confinement times. Indeed for these heating parameters, τ_E=0.47*s* at <β>=4.2% and τ_E=0.66*s* at <β>=6.5% are obtained for p-NBI and O2 ECRH, respectively.

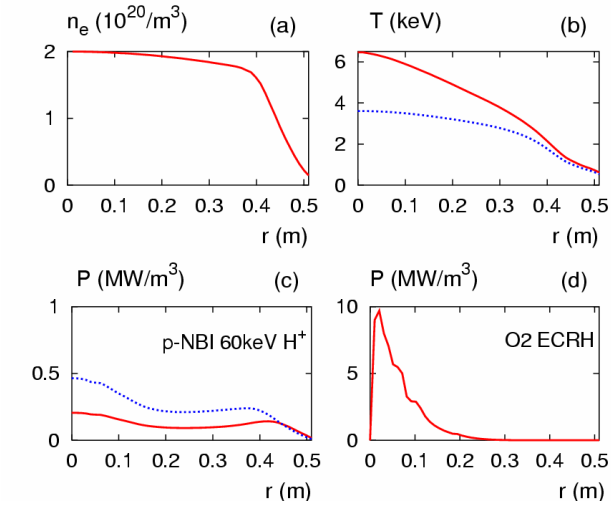

Fig. 5. (a) and (b): Plasma profiles for a 10MW heating simulation of W7-X. The solid line in figure (b) refers to O2 ECRH power depositions in plot (d). The dotted line in (b) refers to NBI power depositions shown in plot (c). The dotted line in (c) corresponds to the power deposited to ions.

SUMMARY

The O2-ECR heating efficiency is analyzed for various plasma parameters and heating conditions using ray tracing modeling coupled with a 1D-transport code. The transport modeling with the assumption of neoclassical core confinement has shown that high-β plasmas up to 6.5% are achievable at a magnetic field of 2.5T for the multi-pass O2-mode heating with overall absorption efficiency of 97%. The O2-mode heating scenarios look promising for high-density-operation regimes of W7-X with high separatrix density that is the most favorable condition for operation of the divertor. It is worth noting that the neoclassical predictions give an upper limit of plasma performance in W7-X. Further predictive transport simulations will be considered for high-β plasmas for which the moving of the resonance zone due to the Shafranov shift and the diamagnetic current can decrease absorption efficiency.

[1] V. Erckmann, P. Brand et al. Electron cyclotron heating for W7-X: physics and technology. *Fusion Science and Technology*, accepted for publication in 2007.

[2] Yu. Turkin, H. Maaßberg et al. *Fusion Science and Technology,* **50**, 387(2006)

[3] Yu. Turkin, C. D. Beidler et al. Transport Simulations for W7-X. *33rd EPS Conference on Plasma Phys.* Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-2.113 (2006)

[4] N. B. Marushchenko et al. in *Proc. of the 16th Toki Conference*, Japan, December 2006, http://itc.nifs.ac.jp/index.html