Investigation of impurity confinement and transport under different ECRH power conditions in plasmas of the TJ-II stellarator

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INTRODUCTION. In previous works, the confinement and transport properties of light and heavy impurity particles have been studied with spatial resolution in the TJ-II stellarator as function of density, working gas (H/D) as well as charge and mass of the injected ions [1]. The impurity confinement in electron cyclotron resonance heated (ECRH) plasmas of the TJ-II exhibits moderate confinement times of order 5 ms at low densities (0.2-0.6 × 10^{19} m^{-3}), when the core plasma has a positive radial electric field, E_r. However close to, or beyond, the density value where the transition to negative E_r occurs, a significant rise in impurity confinement time is observed [2].

The goal of the present experiment is to study the influence of ECRH power level on the confinement and transport of LiF and Fe injected by laser blow-off [3] into quasi-stationary TJ-II hydrogen or helium plasmas. For this, the relaxation decay time in different chord-integrated radiation monitors is measured for three power levels in order to investigate how impurity confinement degradation with injected power compares with that reported for global energy confinement time in the stellarator scaling law [4,5]. Selected cases are analysed with spatial resolution of the decay of local global radiation profiles reconstructed from bolometer array signals and transport simulations performed with the STRAHL code [6].

The paper is organized as follows: first, an overview of the experiment is given. Second, the results of impurity confinement times from a power scan in both hydrogen plasmas and helium plasmas are reported. Finally, the behaviour of local confinement times is addressed and simulations with the transport code STRAHL are presented.

EXPERIMENTAL. This experiment was performed in the TJ-II, a four-period, low magnetic shear stellarator with major and average minor radii of 1.5 m and ≤ 0.22 m, respectively [7]. Plasmas are generated by ECRH operated at the second harmonic, (f = 53.2 GHz, P_{ECRH}< 500 kW). Electron density profiles (for line-averaged density, from 0.45-

0.6×10^{19} m^{-3} depending on the heating power) are rather flat whilst the electron temperature profiles are peaked with central values in the range 0.8 to 1.5 keV. Light (LiF) and heavy (Fe) impurities are injected by laser blow-off into plasmas created using the standard TJ-II magnetic configuration [3]; both materials were deposited onto sapphire substrates as a thin film with 1 μm thickness. The laser power is optimized in order to minimize the perturbation in plasma confinement while also observing impurity radiation. Next, to monitor the impurity injection with space and time resolution, bolometer and soft X-ray detector arrays are available, as well as a normal incident VUV spectrometer. Reproducible discharges with solely ECRH and good control with constant density along discharges are required as stable target plasmas. However, electron densities that are sufficiently high to ensure good Thomson scattering density and temperature profiles are required. Consequently, performing an ECRH power scan while keeping the target electron density at a constant value is challenging. In TJ-II the ECRH power-deposition location can be controlled by adjustment of the toroidal field or by poloidal and/or toroidal steering of the launched microwave beams for a fixed magnetic field, the latter is the method employed here. The ECRH power scan is performed from 230 to 500 kW. In order to help clarify these different features, either hydrogen or helium are used as the working gas.

RESULTS AND DISCUSSION. First, we performed an ECRH power scan in hydrogen plasmas with the gyrotrons focused at the magnetic axis. For this LiF and Fe were injected. The results of this scan are shown in Fig. 1(a) where the average decay times of the perturbation, measured using central soft X-ray channels, are plotted for several injected discharges. The data fitting, ($\tau = \tau_0 \times (P_{ECRH})^p$), shown in this plot as continuous lines, demonstrates a degradation of impurity confinement with power with an exponent that varies from p = -0.59 for LiF to -0.92 for Fe. This parameter was found to be p = -0.54 for Al in the W-7AS [8]. A degradation in impurity confinement with ECRH injected power has been also measured in the TCV Tokamak [9], but with a more moderated exponent, -0.21. In contrast, the degradation parameter for the global energy confinement time was determined to be -0.74 in TJ-II [4] and -0.6 in the ISS04v3 stellarator scaling law [5].

In Fig. 1(b), a plot of impurity confinement of Fe versus line-averaged density is shown for a power scan in He plasmas. The confinement time in this case does not exhibit as clear a behaviour as in the hydrogen plasma case. However, a significant difference with the mass of the main plasma ion is seen only at the lowest power (150 kW) between hydrogen and helium plasmas as shown in the Fig. 2(a).

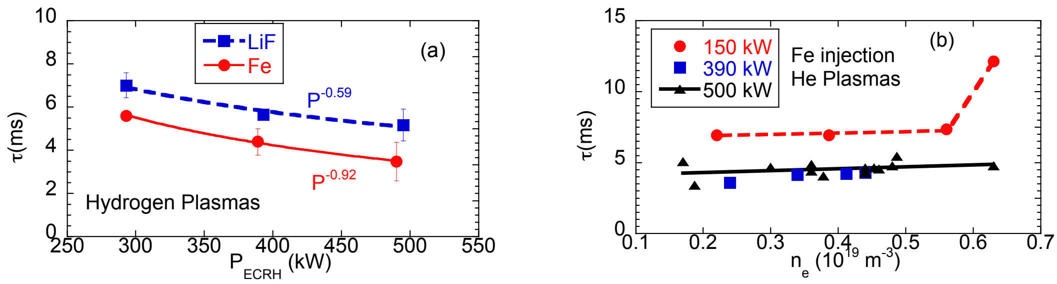

Fig. 1. Plots of impurity confinement time, τ, in TJ-II plasmas with different working gases: a) in H_2 plasmas where Fe and LiF are injected, a degradation of confinement similar to τ_E is exhibited (n_e: 0.54-0.6×10^{19} m^{-3}) and b) in He plasmas where Fe is injected a less clear behaviour with the injected power is observed.

The different impurity confinement behaviour between LiF and Fe, in the case of He plasmas, is further illustrated in Fig. 2(b), where the confinement time for both injected impurities as a function of the line-averaged density is plotted. The different relative behaviour of LiF with respect to Fe for both low and high densities should be noted.

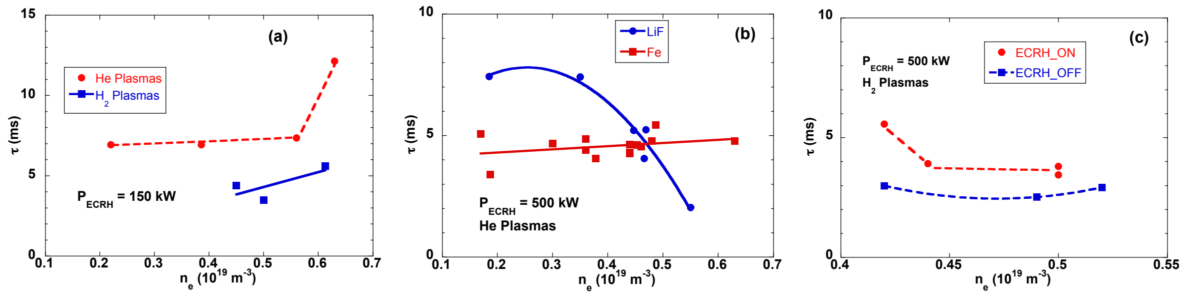

Fig. 2. Influence on confinement time of on/off-axis heating and main ion mass a) LiF and Fe confinement times as a function of density for H_2 and He plasmas at the minimum power (150 kW) and b) confinement times of LiF and Fe in He plasmas as a function of plasma target line-averaged density for maximum ECRH power (500 kW), c) Fe confinement time in H_2 plasmas for on/off-axis heating.

It is found here that not only the level of the injected power plays a role in impurity confinement, but also the radial position where the power is deposited. A difference in the impurity confinement time is observed between discharges with on-axis compared with off-axis heating (ρ = 0.33), as illustrated in Fig. 2(c) for different line-averaged density. These sets of dedicated discharges are performed at maximum ECRH power (500 kW) and injecting Fe.

In order to investigate more deeply the confinement time behaviour reported before, a study of the radial dependence of the impurity confinement time, using tomographic reconstructed local response from bolometric arrays, is performed. Results of this analysis are shown in Fig. 3(a) for three selected discharges with different on-axis ECRH power.

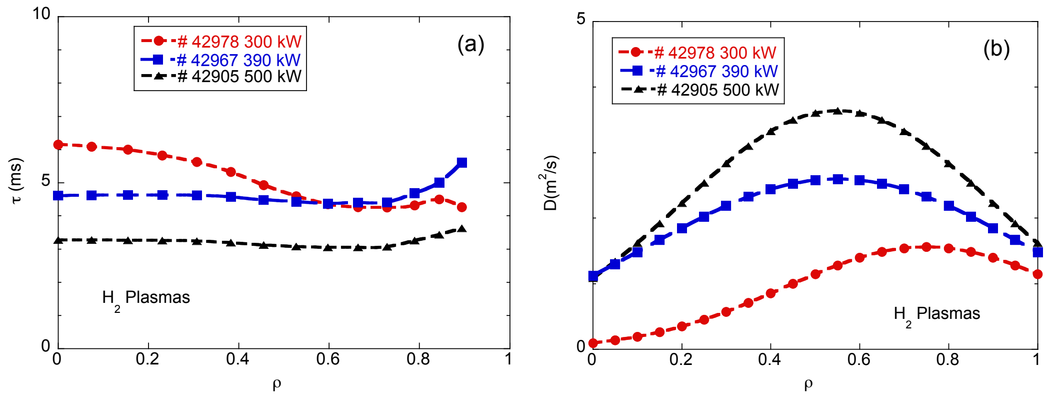

Fig. 3. Results of impurity confinement times and transport coefficients, as determined with the STRAHL code, versus normalized TJ-II minor radius: a) radial behaviour of confinement time for injections into discharges with different ECRH power; b) influence of ECRH power on impurity diffusion coefficients.

Finally, impurity transport analysis is aided here using the STRAHL code. Results of diffusion transport with spatial resolution are depicted in Fig. 3(b), for the same illustrative discharges as Fig. 3(a). Diffusion coefficients, without including any convection in the analysis, are used as it is considered that this is sufficient to account for the local global radiation power deduced from bolometer arrays. It is worthwhile noting that the diffusion coefficient, D, decreases with increasing heating power at the edge. The D radial profile is not very different from typical tokamak profiles, where the values are lower by at least an order of magnitude and increase towards the edge [10]. In summary, a degradation of impurity confinement time with increasing ECRH power is reported in TJ-II and compared with energy confinement degradation in this and other devices. A significant difference in confinement of LiF, with respect to Fe is observed over the density range studied. Transport analysis allow us to investigate the changes in the radial profile of impurity diffusion coefficient as a function of injected power. Finally, a significant variation in Fe confinement with the main ion mass (H versus He) is observed only at low ECRH power.

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