OBSERVATION OF PEDESTAL ION TEMPERATURE SCREENING OF HIGH-Z IMPURITIES IN THE HYBRID SCENARIO ON DIII-D

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Significant screening of medium to high-Z impurities due to a steep T_i-gradient and relatively low n_e gradient is observed in Fusion Pilot Plant (FPP)-relevant low collisionality, grassy ELM pedestals in a hybrid scenario (q_{95}~5.2, β_N~2.6, H_{98}~1.3). This finding is particularly important for ITER, which has recently decided to install a full tungsten wall instead of a low-Z beryllium wall [1]. T_i-screening is expected to dominate in ITER pedestals [2] where it prevents W accumulation, while it is mostly negligible in current tokamaks due to steep density pedestals. T_i-screening was inferred from a multi-ion argon density measurement and confirmed by Ni and C measurements. An additional benefit of the hybrid scenario is impurity screening driven by a core MHD mode, which reduces W density near-axis by up to an order of magnitude.

Ion temperature screening approximately offsets the inward density pinch for the Ar impurity species in these plasmas. Neoclassical modeling of Argon pedestal V/D using NEO model [6] is shown in Fig. 1. V/D is a ratio of convection over diffusion which is in source free region and steady state case equals to $-\nabla n_z/n_z$. The modeling is based on the measured carbon T_i profile and includes C, B, and Ar species at 2.5%, 0.5%, and 0.5% concentrations. In contrast, predicted T_i screening in other ELMy H-mode discharges on DIII-D does not exceed 20% of the inward pinch even for extreme cases with pedestal top T_i ~ 4keV. The main reason for the unusually important role of T_i screening is a relatively flat electron density pedestal with $n_{e,sep}/n_{e,ped}$~0.45, compared to more typical values of 0.1-0.2, and high pedestal T_i ~2.3keV as shown in Fig. 1.

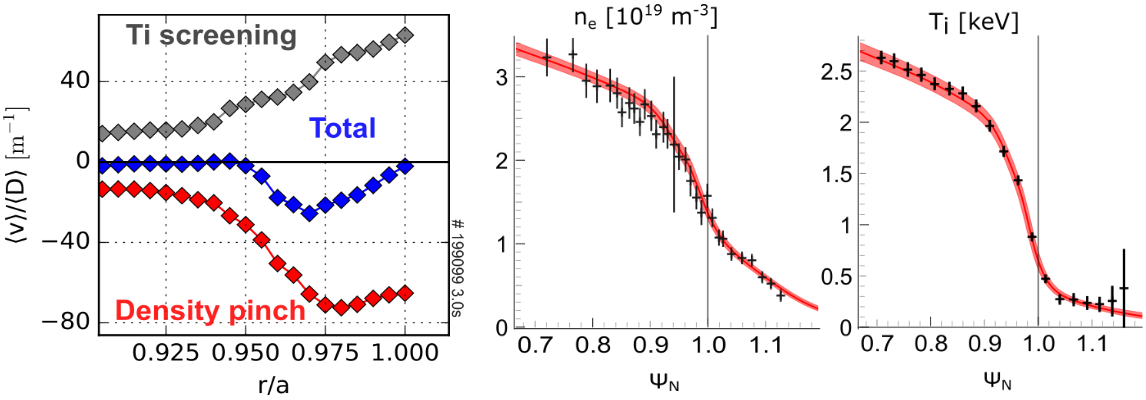

Figure 1 (left) *Neoclassical transport coefficients from NEO for Ar calculated in the pedestal of a grassy ELMs hybrid discharge. Blue is total convection, red is density driven inward pinch, gray is ∇Ti driven outward screening. (right) corresponding n_e and T_i profiles.*

Predicted neoclassical tungsten convection for W is slightly positive (outward) due to a higher ion-impurity friction. The main reason for a low pedestal density gradient is still under investigation; it is likely connected to a high SOL electron density causing an outward shift of the particle source. KN1D modeling [5] indicates a particle source location mostly outside of the separatrix. The source location is confirmed by the L_α emission profile measured by LLAMA diagnostics and D_α emission profile measured by the main ion CER on DIII-D.

The direct measurement of high-Z impurity density in the pedestal is a rather challenging task, because the steep density region is occupied by multiple charge states of this impurity. If only a single charge state is measured, its density will always show a steep drop as it approaches the cold region near the separatrix due to recombination, independently of the actual total density profile. Therefore, the density profile was inferred from temporally and spatially resolved charge exchange recombination measurements (CER) of multiple Ar ions during periodic Ar gas puffs. Ar^{15+}, Ar^{16+}, Ar^{17+} and Ar^{18+} densities in Fig. 2 were inferred using the impurity transport code

AURORA [3] in the OMFIT IMPRAD module. In addition to an impurity CER system, Ar^{16+} was measured also by main ion CER, which provided pedestal profiles with a high spatial resolution of 7mm every 100ms.

The inferred pedestal diffusion in Fig. 2 approaches the neoclassical value ~0.5m²/s, indicating a negligible contribution of grassy ELMs on impurity transport. The neoclassical Ar diffusion is increased by a factor of five by friction with C and B ions and it will be thus smaller in metal wall machines like ITER. The inferred pedestal V/D ~35 m^{-1} is close to the predicted neoclassical value ~20 m^{-1} and well below the density pinch value ~75 m^{-1}. Further in the core, Ar and C densities are nearly flat up to the location of the core MHD mode.

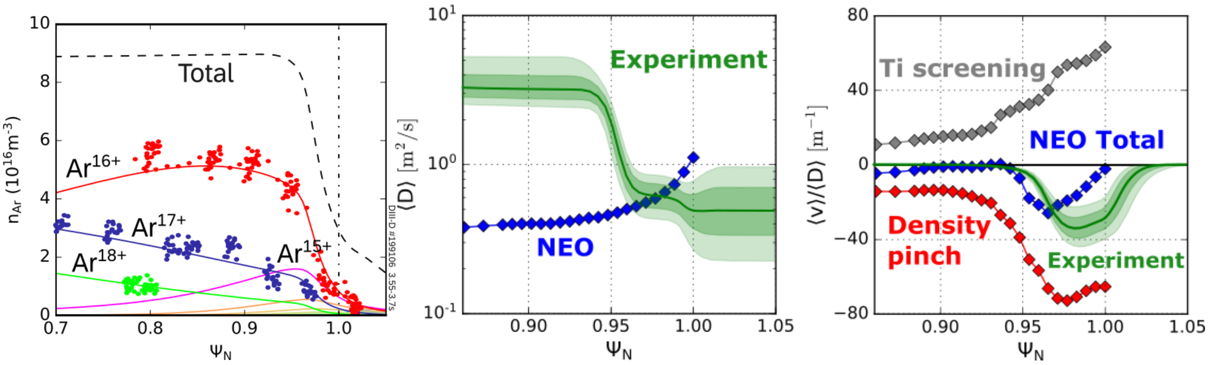

Figure 2 On the left are the measured pedestal Ar ion densities 100-300ms after the Ar puff, in the middle is the inferred Ar diffusion (green) compared with NEO (blue) and on the right is the inferred V/D compared with the neoclassical value.

The presence of an edge transport region was further independently investigated by C^{6+} and C^{5+} measurements and from Ni SXR radiation evolution and CER Ni^{25+} measurements following a random impurity event. Results are consistent with the Ar measurements; the total inferred carbon concentration in the pedestal was nearly flat.

Near-axis impurity transport was dominated by a saturated MHD mode, responsible for flux pumping in the hybrid scenario and driving outward impurity transport. If a large 3/2 mode was present, it drove an outward impurity flux and created hollow profiles of all impurities from carbon to tungsten inside Ψ_N~0.3. The outward flow increased with the impurity charge, and it created deep hollow profiles of W radiation. If 4/3+1/1 modes were present, it also drove an outward flow, but since the radius of the 4/3 mode is smaller, the effect was localized closer to the magnetic axis, inside Ψ_N~0.2. Impurity transport outside of the mode is rather fast, D/χ_i~10 and it is driven by a high level of ECH heating providing 25% of total heating power. The combination of a low pedestal pinch, fast core transport, and outward convection driven by MHD modes significantly improves the robustness of this scenario to impurity accumulation. Despite this, the ratio of impurity confinement time to energy confinement time is about two, similar to ELMy H-modes [4].

The effect of resonant magnetic perturbations (RMP) on the T_i-screening was also investigated. Application of n = 3 RMP with an I-coil current of 2.5 kA reduced the grassy ELM frequency from 1 kHz to ~0.5 kHz and partially suppressed type I ELMs. The pedestal electron density gradient was unaffected by RMP and the carbon density gradient decreased by 10%. An additional increase of the RMP current to 4.5kA reduced the pedestal electron density gradient by 10%. However, the change in Argon transport was small, below the experimental uncertainty of our inference. Further increases of RMP current led to mode locking and plasma disruptions.

In conclusion, experiments in a hybrid scenario on DIII-D indicate the presence of a significant T_i screening in the pedestal. The screening is comparable to the inward neoclassical pinch due to weak density pedestals and $n_{e,sep}/n_{e,ped}$~0.45, while the T_i gradient is still large η_i=L_{ne}/L_{Ti} ~ 3. Pedestal impurity transport was found to be in a close agreement with the NEO model [6]. Finally, grassy ELMs and RMP didn't have a measurable effect on pedestal argon transport.

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