Evidence of thermo-diffusive pinch in particle transport

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Abstract. In presence of large MARFE in Frascati Tokamak Upgrade (FTU), density and temperature profiles undergo to a strong modification as consequence of the temperature drop at edge. The edge temperature drop drives a collapse of the whole temperature profile, in a self-consistency way. A large cold annular area is formed at the end of the process. Density profile in particular starts to increase in the central region, while periphery density remains almost unchanged, with a consequent increase of the density profile peaking. A region with strong density gradient appears close to the cold plasma region. In order to reproduce such profile evolution by a diffusion code a thermo-diffusive pinch has been introduced. This single term, in addition to usual diffusion term, can describe the radial and temporal change of profiles with good approximation, without requiring any change in diffusion coefficients.

Source term has also been estimated by using a neutral diffusion code, finding that its role remains limited to the plasma periphery even though the presence of the extended cold plasma region. The time evolution of source term cannot account for the change of the density gradient, which requires a strong increase of the particle pinch term. The necessary variation of the pinch term is compatible with the modification of the characteristic length observed in the temperature profile, which has suggested the introduction of the thermo-diffusive term.

1. Introduction

The problem of diffusion of ionized particle towards the plasma center in tokamak devices, is still not well understood. In experiments on perturbation of density profiles [1,2] it has been found that the particle transport coefficients are not compatible with the values foreseen by neoclassical theory, a consequence of the fact that transport is dominated by microturbulence. Unfortunately, from turbulence theory, no simple expression is available for experiment comparison, so, a general expression is used for the description of the particle flux [3]:

$$\frac{\Gamma_e}{n_e} = U + D\frac{\partial \ln n_e}{\partial r} + D_T\frac{\partial \ln T_e}{\partial r} + D_q\frac{\partial \ln q}{\partial r} + \cdots \qquad (1)$$

where the various terms can be assessed by the turbulence theory but this requires complex code simulations for each density and temperature profile. Understanding the relevance of each term in previous expression, is quite important for the correct modeling of the transport mechanism. However, this is not an easy task as the different thermodynamic forces (ne, Te, q, etc..) are strictly related and cannot be varied independently.

In this paper, we report the simulation of density evolution, in a set of discharges performed at Frascati Tokamak Upgrade (FTU), that clearly shows the relevance of diffusive and thermo-diffusive terms (second and third in (1)) with respect to the other terms. In these discharges a sensible density peaking is observed at high density, subsequent the formation of a strong MARFE thermal instability [4] at plasma edge. They have been obtained in an experimental campaign dedicated to density limit studies in ohmic plasmas, in which it has been found that, at high q, the Greenwald density limit can be exceeded, by up to a factor 2, even with gas-puffing only [5], as a consequence of the peaking of density profiles. In fact, these profiles are in agreement an "edge Greenwald limit" where peripheral chords are used instead of central one[5]. This effect is more evident in presence of low Z impurities, as B and Li, used for wall conditioning. The presence of a strong MARFE seems to be the key to get density peaking and to raise the density above the Greenwald limit. Density profiles have been measured using the FTU scanning interferometer [6], with 32 independent chords of 1 cm separation, which is able so resolve very thin details.

The density profile peaking is associated to a drop of the edge temperature in a wide external region [7], caused by the thermal collapse at the edge that led to the MARFE formation. The extension of such a region can be large up to ¼ of minor radius, and temperature inside MARFE can be as low as 1-2 eV. At this temperature recombination dominates, and a huge numbers of neutral particles are present in the MARFE region, which can be diffused to the center of plasma column giving rise to a non negligible source term, that can contribute to the density peaking. Large part of the present work has been dedicated to the evaluation of such contribution.

In section 2 the experimental data will be presented, while the flux and source terms are discussed in section 3 and 4 respectively. Results are presented in section 5.

2. Density and temperature behavior in presence of strong MARFE

The MARFE instability is caused by a reduction of the parallel electron conductivity at high density, that prevents the redistribution of the power flowing to the edge. The low-field side cools down and local radiation losses increase with a consequent further decrease of the temperature. More information on such phenomenon can be found on ref [4]. There is a density threshold for the MARFE formation, that in FTU in presence of light impurity (B, Li) is about half of the density limit [5]. At density well above the threshold, the MARFE becomes larger and the drop of temperature extends up to 1/3 of minor radius. MARFE appears on the visible camera as an intense emission band toroidally symmetric, close to the toroidal limiter of FTU (Fig 1), and it is also observed on several diagnostics, as H_α emission, bremsstrahlung and bolometry. It can also be observed by inner vertical chords of scanning interferometer, up to central one, but only when its poloidal extension becomes relevant. Density and temperature inside the plasma shell connected with MARFE is strongly asymmetric. In fact density in MARFE core is of the order of bulk density, while at opposite side in poloidal section it is about 1/10 of such value [8]. Temperature must undergo to an opposite variation to keep pressure constant in the shell, going from 1-2 eV in the MARFE core, at which radiation of light impurity has its peak, to 10-20 eV in opposite side. Such temperature is below the range of sensitivity FTU temperature diagnostics, this introduces a large uncertainty for the calculation of diffusion terms where temperature is required.

An example of the time evolution of the density and temperature is shown in fig 2. At about 0.5 s temperature, measured by ECE diagnostic, starts to drop from the edge, at the same time density on central cord increases more than the periphery chords which remains almost unchanged. Oscillations on density observed at about 0.8 s are the consequence of the up and down movement of the MARFE when its poloidal extension is large enough to reach central chord. In fig 3 some density and temperature profiles at the selected times are shown. In about 1/3 of radius the temperature drops below the sensitivity of the diagnostics (50 eV), which can be considered as the radial extension of the MARFE. In the same radial extension, density profiles do not change sensibly, while the central chords undergo a significant increase, with a clear change of profile slope at the transition between the MARFE shell and the plasma bulk.

The radial correlation between variation of density and temperature, can be more clearly observed from fig 4. Here, inverse of characteristic length of temperature ($L_T(r)^{-1} = d(lnT)/dr$) is plotted versus the density one ($L_n(r)^{-1} = d(\ln n)/dr$), for several times. Correlation is more evident at late times when the variation of characteristics length along the profile is quite large.

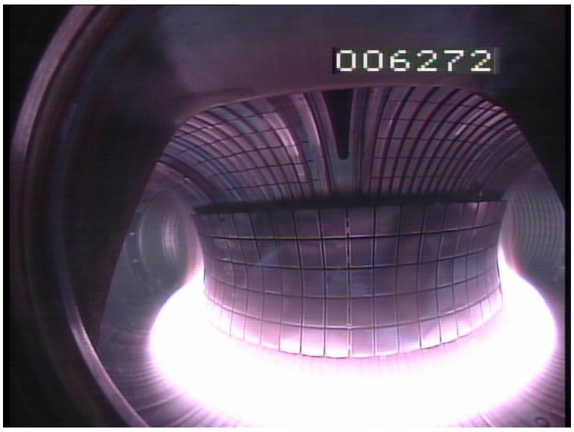

Fig 1: *Picture of MARFE (white belt on top) in a high density discharge of FTU.*

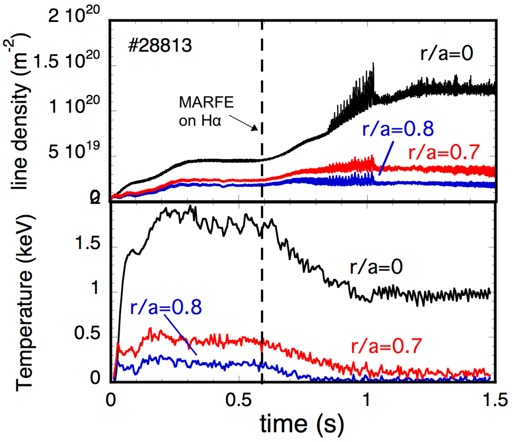

Fig 2: *Time evolution of density and temperature at plasma center and periphery. Vertical line shows the time at MARFE formation*

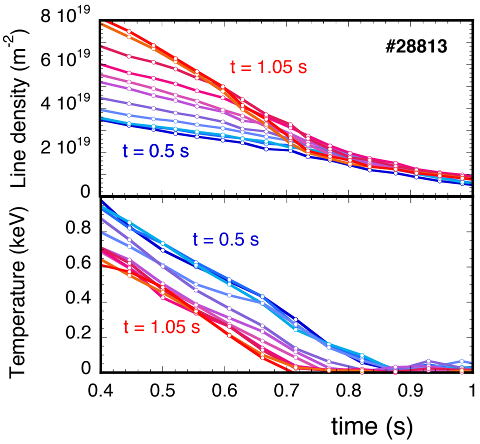

Fig 3:*Density and temperature profile evolution during the formation of MARFE.*

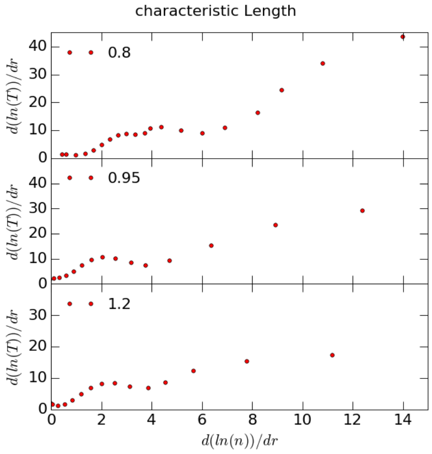

Fig 4; *Plot of temperature characteristic length (L_T) versus the density one (L_n) for several times for shot #28808.*

The particle continuity equation in cylindrical coordinates, can be written as

$$\frac{\partial n}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r\Gamma + S \qquad (2)$$

which states that the number of particle inside a closed volume, can change for the particle flux through the boundary Γ or because there are sources (and wells) of particle S inside that volume. In general, Γ is expressed by eq (1), where many thermodynamic forces are taken into account. Practically, only two terms are usually used for the flux in simulations, $\Gamma = D\, \partial n/\partial r - U\, n$, where a diffusion term due to density gradient is explicitly considered while all the other terms are included in the function U, which represents the non diffusive (convective) transport. This two terms are usually of opposite sign, so that the diffusion tends to transport particle from center to periphery while the other term represents a pinch (usually $U<0$) that pushes particles against the density gradient from periphery to center.

The transport coefficients in tokamak plasma core, where the source term can be neglected, has been experimentally determined by perturbation experiments [1,2]. Values obtained for FTU are very different from the neoclassical predictions [1]. The same technique has been applied to density evolution during MARFE, assuming that the whole variation is caused by a sudden modification of transport coefficients that remain constant during density evolution [3]. In a limited set of discharges in which MARFE occasionally disappears, and density evolution has an opposite behavior also the coefficients in absence of MARFE have been determined. The comparison of the two cases has shown that the reason of the density peaking is an increase of the particle pinch U. This result has been used to fix the D coefficient shape, in all simulations. The experimental values, found in ref [3] and reported in fig 5, have been fitted with expression $D = D_o + D_e(r/a)^m$, where D_o, D_e, and m are free parameters. Once fixed D the pinch can be determined by using density profile in steady state phase before the MARFE formation. At this time, the source term can be neglected, and assuming steady state we can find U imposing $\Gamma=0$, and hence $U = D/n\, \partial n/\partial r$. If we apply the formula to the profile in the steady state after the MARFE, we get a much lager pinch as expected. The two pinches profiles are shown in fig 6. In the hypothesis that the pinch can be driven by the temperature gradient, i.e. that $U = D_T / T_e\, \partial T_e/\partial r$, using the values of U of fig 6 and its respective temperature profiles, the D_T profiles before and after the MARFE, have been inferred ($D_T = U\ T_e / \partial T_e/\partial r$) and shown in fig 7. It must be noted that D_T values are meaningful only in the intermediate region, because at edge there is a large uncertainty for the low temperature and the effect of sources and at center for the fact that the temperature gradient, which is at denominator, is close to zero for the presence of sawteeth. D_T profile has been assumed to be constant and flat along the whole minor radius, and its value has been fixed close to the computed one as shown in fig 7 (red line).

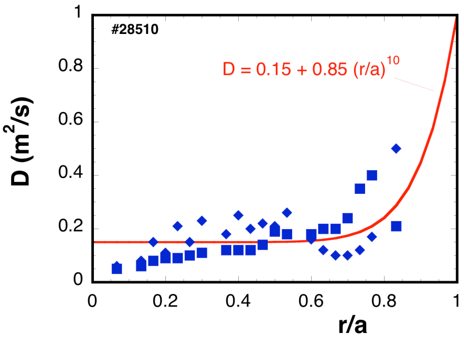

FIG.5.Diffusion coefficient used in the simulations. Dots are experimental points obtained in ref [7].

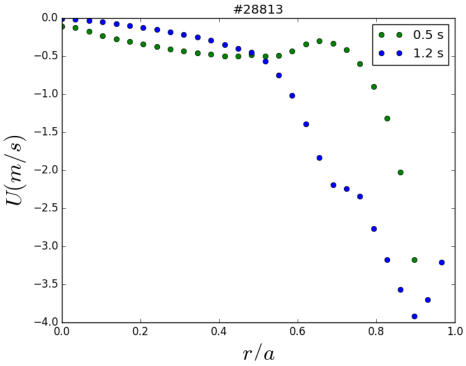

FIG.6.Particle pinch computed at t=0.5 s and t=1.2 s, in zero source approximation for shot #28813

Up to now, sources have been neglected, but the presence of the MARFE in a large radial region, and the strong D_α emission from such area, indicate the presence of huge amount of neutrals, This suggests that sources could play a role in the density evolution. In addition to the variation of the pinch term, an alternative scenario has been considered, in which transport coefficients are constant and source term provides particles deep enough into the plasma accounting for the density peaking. Simulations with both scenarios are reported in section 4.

3. Neutral particles in presence of MARFE

The calculation of the neutrals distribution has been performed using NENNE, a 1D cylindrical code (based on ref [9]), which solves neutrals diffusion along radius of an infinite cylinder, with circular cross section and poloidal symmetry. Knowing local electron temperature and density, the program calculates the free path of a neutral before undergoes a collision and the type of collision (recombination, ionization or charge exchange) via a Monte Carlo algorithm. Particles exiting the plasma boundary, are reintroduced inside the plasma with a recycling coefficients R_c.

Although the cylindrical approximation is appropriate for FTU, having a circular cross section, the presence of MARFE breaks the poloidal symmetry condition, making the code non appropriate. To apply the code to the MARFE case, density and temperature at plasma periphery has been symmetrized setting profiles equal to those of the MARFE core, i.e. very high density and low temperature.

This is a quite rough approximations, which implies an overestimation of the neutral density, adding the lack of temperature measurements, the obtained calculations could be just indicative. The temperature profile measured by ECE has been extended below the sensitivity of diagnostics (50 eV) extending linearly the profile down to 10 eV, and continuing with an exponential function, similarly to the SOL profile, with a decay length of few centimeters till to the plasma edge. Considering the high density and low temperature in the periphery the mean free path of the neutrals results to be small, so that periphery shell is almost opaque to neutrals and only the neutrals close to the transition between periphery and bulk are relevant for the source calculation inside the bulk.

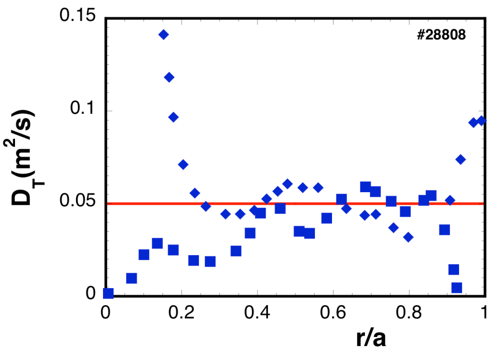

FIG.7.Thermo-diffusion coefficient used in simulations (red line). The dots are experimental points.

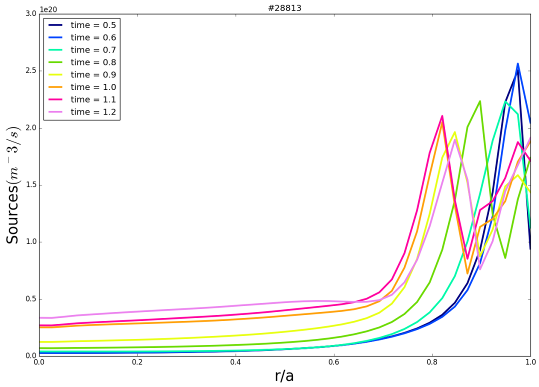

FIG.8.Evolution of source term during the MARFE formation, at an edge density of neutrals of 10^{20} m^{-3}.

Neutral particle density at last closed surface is a free parameter in the code. From the temperature and density values inside the MARFE it is possible to estimate its order of magnitude in corona equilibrium. In fact, the ratio between neutral particle density (n_n) and the electron density is given by $n_n/n_e = \alpha/R$, where α is the recombination rate and R the ionization one. The ratio α/R, for $n_e=10^{20}$ m^{-3} varies from 10 to 0.01 (three orders of magnitude) when temperature changes from 1eV to 2eV, so that, within this range of temperature, the neutral particle density ranges between 10^{21} m^{-3} and 10^{18} m^{-3}. In simulation, we used mainly a value of 10^{20} m^{-3}.

An example of evolution of source term profiles, during the formation of MARFE, for pulse 28808, is shown in fig 8. The peak moves from edge toward the center as consequence of temperature drop. The peak is at almost fixed temperature, where ionization is still high and neutral density large, so that, it progressively it moves inward together with the foot of the temperature.

4. Simulation of the experimental data

In order to verify the effect of the change of source on density evolution, some simulations, with constant transport coefficients have been performed. U and D have been estimated compatibly with the steady state phase before the density raise (0.5 s). Boundary radius has been set to r/a=0.8, where density and temperature measurements remain valid for the whole simulation lapse. All approximations made on temperature profile in the previous section are not introduced in the simulations apart the effects on source term. Density profile at 0.6 s has been used as initial condition. A scan of neutrals at edge free parameter up to 10^{22} m^{-3} has been made and computed profiles with two source levels (10^{20} and 10^{21} m^{-3}) are shown in fig 9, where full lines are the computed profiles and the dots indicate the experimental profiles. All simulations are not able to describe the evolution of the experimental profiles. Density peaking can be simulated assuming that transport coefficients change with time.

Introducing the explicit dependence of pinch on temperature gradients ($U = D_T / T_e\, \partial T_e / \partial r$) makes the required variation, without any further hypothesis on transport coefficients.

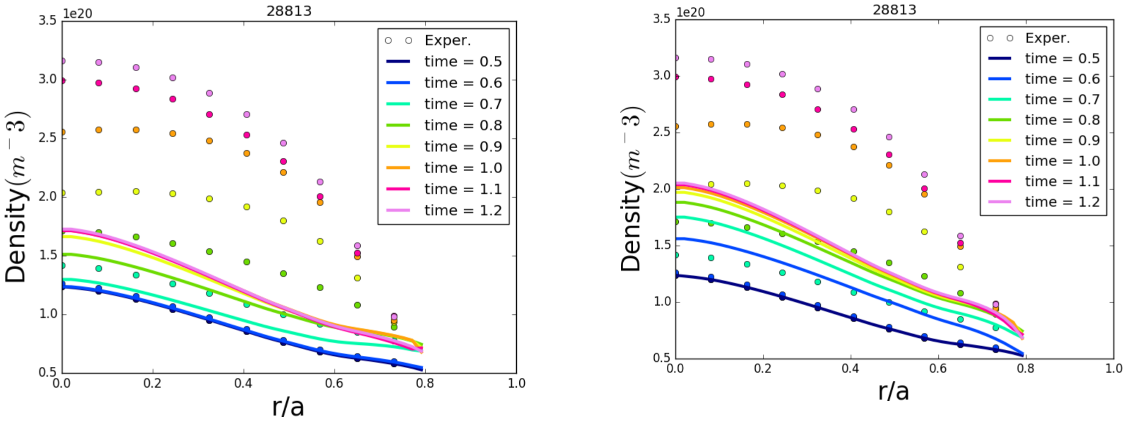

FIG. 9 : Simulations of density profile, with constant D and U, at two different neutral particle density at edge (10^{20} m^{-3} left and 10^{21} m^{-3} right)

The same limitation on radius ($r/a<0.8$) has been used here, so that the calculation of the thermo-diffusive term, which requires temperature profiles, is reliable. To avoid spurious features introduced by the gradient of experimental profiles, a smoothing of profiles has been performed before the gradient calculation. Time at $t=0.6$ *s* has been used as initial condition.

The profile simulations at several times are shown in fig 10 while the density evolution at fixed radii is reported in fig 11. Source term, as described in previous section, with edge neutral density of 10^{19} m^{-3}, has been used to reproduce density evolution at periphery. The agreement obtained with experimental data is quite good. The peculiar features of the profile evolution, as the formation of the large density gradient in the region 0.6<$r/a<0.8$ and the correct timing of the central density rise, are well reproduced.

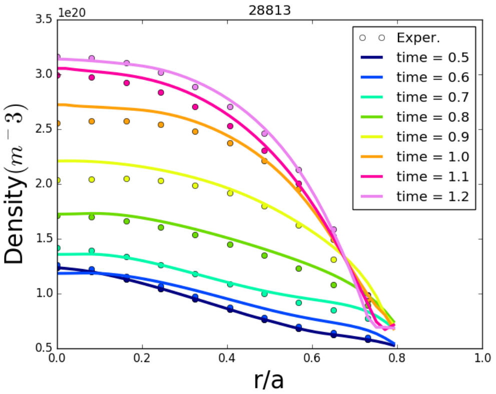

FIG.10.Evolution of simulated density profiles using the thermo-convective term, with neutral particles at edge of 10^{20} m^{-3}.

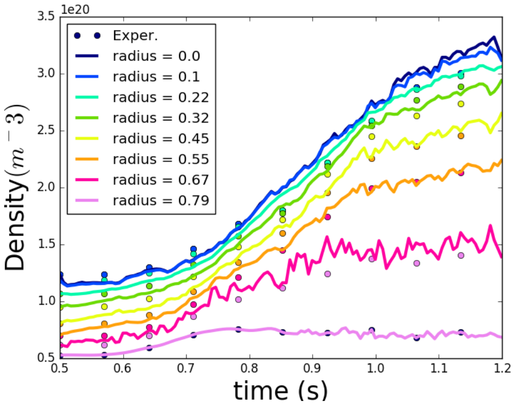

FIG.11.Time evolution of density at fixed radii

The simulation has been extended to the whole plasma column using the same assumptions on temperature profiles done for the source calculation. The thermo-diffusive pinch, calculated in the region with exponential temperature profile, is flat and its amplitude is $U=-D_T/\lambda$, where λ is the unknown decay length of temperature. Although this term is small, it acts in the region with large particle sources, so it could have a large effect on simulation. Nevertheless, a set of parameters has been found that reproduces the evolution of the whole density profile up to *r/a=1*, and the results are shown in fig 12 and 13. It's worth to say that a small change on the paremeters, produces a large change on the calculated profiles.

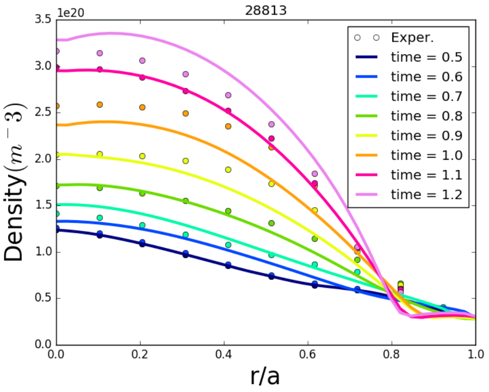

FIG.12.Evolution of the density profiles simulated using the thermo-convective term, and a small source contribution.

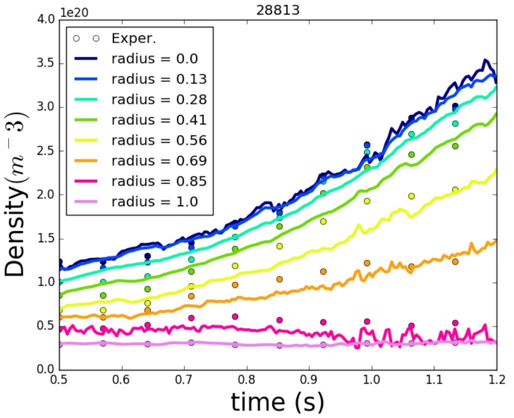

FIG.13.Time evolution of density at fixed radii

5. Conclusion

The simulations carried out have shown that inward transport of particles in FTU high density discharges, can be described in terms temperature characteristic length (thermo-convective pinch), wich well reproduces the main features of density evolution in highly dynamic discharges. Although this is a semi-empirical result, obtained in a limited range of parameters, it is a quite clear relation and it can be a good benchmark for comparison of transport theories. This term has already been introduced to deal with the anomalous inward particle transport of tokamak[10], as well as to describe the experimental density profiles[11].

The phenomenon has been highlighted by using detailed measurements via a scanning interferometer, with a high spatial resolution (1 cm), which has measured the peculiar evolution of the density profiles. So far, the model has been applied only to a special kind of discharges in which MARFE instability determines the change of edge parameters. More discharges, where a change of density is triggered by a temperature drop at the edge, induced by injection of low Z impurity, can also be used to test the model in different conditions, but the calculation of source term is more complex due to the presence of the impurity. Even though it has been shown that the contribution of impurity to the central density is negligible [12] the effect on source term at external radii can be relevant. The simulation of such discharges is in progress.

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