ARTICLE IN PRESS

JID: NME [m5G;April 13, 2017;16:33]

Nuclear Materials and Energy 000 (2017) 1–5

Contents lists available at ScienceDirect

Nuclear Materials and Energy

journal homepage: www.elsevier.com/locate/nme

Evidence of a thermo-diffusion pinch on particle transport in FTU discharges close to density limit

O. Tudisco*, C. Meineri, G. Apruzzese, O. D'Arcangelo, E. Giovannozzi, M. Marinucci, C. Mazzotta, G. Pucella, and FTU team

ENEA, Fusion and Technologies for Nuclear Safety Department, C.R. Frascati,via E. Fermi 45, 00044 Frascati, Italy

ARTICLE INFO

Article history:
Received 25 July 2016
Revised 9 March 2017
Accepted 15 March 2017
Available online xxx

ABSTRACT

In FTU, the density profile in the presence of large MARFE becomes more and more peaked with increasing density, forming strong density gradients close to the radial region affected by the MARFE. The temperature at the edge drops to few eV, driving a drop of the whole profile. The estimated particle source cannot justify the change of the density gradient, which instead is well-explained by a change of the pinch. A thermo-diffusion term well-describes the pinch evolution and the experimental behavior of the density at those radii where temperature measurements are reliable.

1. Introduction

Studies on density limit in the Frascati Tokamak Upgrade (FTU), have shown that in high q discharges the Greenwald density limit can be exceeded, up to a factor 2, with ohmic heating and gas-puffing only [1]. This effect is more evident in the presence of low Z impurities, used for wall conditioning, such as B and Li and is always obtained in the presence of the so-called MARFE thermal instability [2], which cools down the plasma edge. After the MARFE shows up, the density profile undergoes a strong peaking, which allows the line average density to rise above the Greenwald limit.

FTU is a circular high magnetic field tokamak (B_T up to 8 T, $I_P < 1.6$ MA) of medium size ($R_o = 0.935$ m, a $= 0.30$ m). A toroidal limiter and a poloidal limiter made of Molybdenum are present. The vacuum vessel is conditioned with Boron before each experimental campaign. A Liquid Lithium Limiter is also available for experiments.

The causes that lead to the MARFE formation are not analyzed in this work, here we have only investigated the evolution of the density profile caused by the MARFE formation, in order to find out the changes occurred in particle transport coefficients.

The presence of a pinch term in particle transport is essential to explain the peaked density profiles observed in tokamaks in the absence of central sources, and is one of the main issues in plasma transport. The pinch predicted by neoclassical theory (Ware pinch) has the correct amplitude and can explain density profiles in some experiments [3], but it fails to explain peaked density profiles in full current drive experiments [4,5,6]. In such discharges, a pinch is still observed with negligible toroidal of electric field and non-collisional particle pinch generated by plasma turbulence is required.

In general, the particle flux can be modeled by

$$\frac{\Gamma_e}{n_e} = V + D\frac{\partial \ln n_e}{\partial r} + D_T\frac{\partial \ln T_e}{\partial r} + D_q\frac{\partial \ln q}{\partial r} + \ldots \quad (1)$$

where, together with the usual diffusion term proportional to the density gradient, a term proportional to the electron temperature gradient (known as thermo-diffusive) and one proportional to the gradient of safety factor q (known as curvature pinch) are also listed. V represents a pure convective term, which also includes the neoclassical Ware pinch. While the pinch due to the magnetic geometry is predominantly directed inward, the thermo-diffusive term, that becomes relevant for $\eta = d(\ln T_e) / d(\ln n_e) > 1$, can be directed inward or outward depending on the turbulence that dominates the transport process, and in particular it is inward if ITG modes are dominant and outward if TEM mode are prevalent [7]. Coefficients V, D, D_T and D_q of Eq (1) are used as free parameters to be tuned to reproduce the density profile evolution. It is clear that the number of free parameters is excessive and a reasonable reduction must be done. For the simulation presented here, together with the diffusion term proportional to the density gradient, we have chosen to use a single pinch term and in particular,

* Corresponding author.
E-mail address: onofrio.tudisco@enea.it (O. Tudisco).

http://dx.doi.org/10.1016/j.nme.2017.03.026
2352-1791/

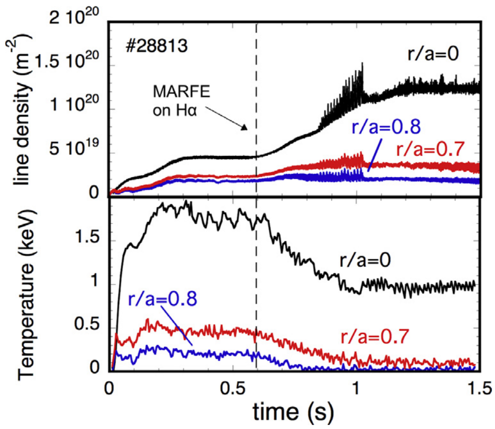

Fig. 1. Time evolution of density and temperature at plasma center and periphery. Vertical line shows the time at MARFE formation. The time at which MARFE appears on interferometer central chord is also marked.

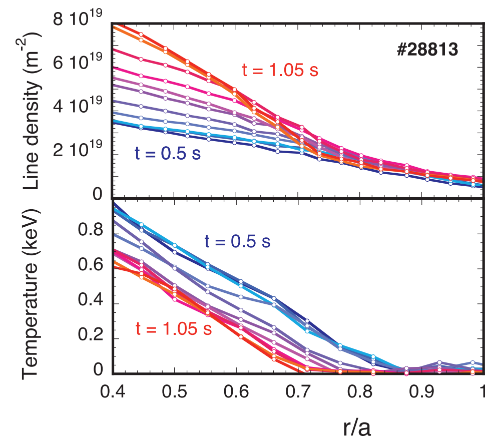

Fig. 2. The evolution of density and temperature profiles during the MARFE formation.

the thermo-diffusion one. This term has already been introduced in the past to explain the anomalous pinch observed in tokamaks [8,9] and to fit experimental density profiles [9,10].

The comparison of the different contributions of each term and the reason for our choice, is discussed in Section 3.

Furthermore, due to the presence of a large amount of neutral inside the MARFE, the source term can play a role also at inner radii, which makes the analysis more difficult, as another free parameter (the number of neutral at plasma edge) is introduced. For the estimation of neutral profile, a neutral diffusion code in the cylindrical geometry has been used. The contribution of the source to the core density, which eventually has been found to be negligible, is discussed in Section 5.

Density profiles have been measured using the scanning interferometer [11] whose vertical chords cover plasma columns from −1/3 of minor radius to low field side edge. It can resolve profile details having 32 independent chords with a 1 cm of spatial resolution. It has been possible to follow the density evolution and reproduce it with a simulation code only through detailed measurements of density profiles at the edge.

In the next section, the experimental measurements are presented whereas the terms used in the diffusion equation are discussed in Section 3. In Section 4, we discuss the relevance of the source term. Simulation results are shown in Section 5 and discussed in Section 6.

2. Experimental density and temperature evolution

In discharges close to the density limits in FTU, a MARFE is usually observed. MARFE appears on the visible camera as a toroidally symmetric band of intense annular emission located at high field side, close to the toroidal limiter of FTU. It is also observed on several diagnostics as D_α emission, bremsstrahlung and bolometry, when the MARFE crosses their line of sight.

An example of the time evolution of the density line integral on low field side chords and temperature is shown in Fig. 1, while radial profiles are shown in Fig. 2. After the MARFE appears on the D_α signal (vertical dashed line in Fig. 1), the temperature drops down starting from the plasma edge while the central density increases. When its amplitude becomes large enough, it is also observed on the scanning interferometer firstly on high field side chords and then progressively on low field side ones, as density oscillations, due the fast poloidal movement around the toroidal limiter (visible from 0.9 s in Fig. 1). In the region corresponding to the radial extension of MARFE, the temperature drops below the sensitivity of ECE diagnostics (50 eV) forming a cold blanket all around the plasma core. At the same time, a continuous peaking of density profile is observed, while density in the outer region remains almost unchanged (Fig. 1 and 2). The core density profile reconstruction is not obvious due to the presence of the MARFE contribution, poloidally asymmetric, that must be subtracted. The core density is determined by Abel inversion after excluding the inner cords, which are strongly affected by MARFE, and using the bottom values of oscillations on other chords. More details of the interferometer data treatment can be found in ref [12] where the agreement with Thomson Scattering measurements is also shown.

3. Diffusion equation

The density profile evolution has been investigated using the particle conservation equation for electrons in cylindrical coordinates,

$$\frac{\partial n}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r} r\Gamma + S \tag{2}$$

where Γ is the particle flux and S is the source term of electrons. The particle flux is given in general by Eq. (1), but here the simplified form

$$\Gamma = -D\,\frac{\partial n}{\partial r} + Un \tag{3}$$

is used, where a diffusion term is explicitly considered, due to density gradient while all the other terms are included in U, which represent the non diffusive transport.

This model has been used to determine coefficients D and U in the density perturbation experiments [13,14] where small density variations are induced by modulated gas puffing. By neglecting sources, the flux is determined by the time variation volume integrated density

$$\frac{\Gamma}{n} = \frac{1}{nr}\int r\frac{\partial n}{\partial t}dr.$$

Comparing it with the density gradient, coefficients D and U can be retrieved from the linear fit of experimental data, using

$$\frac{\Gamma}{n} = -D\frac{\partial(\ln n)}{\partial r} + U.$$

This technique has been applied to discharges with density peaking in presence of MARFE for two narrow time intervals: at the beginning and at the end of the density rise, in which density variation remains small. Results for $r/a = 0.65$ (red circles) and $r/a = 0.73$ (blue squares) in two intervals (0.8–0.9 s and 0.95–1.1 s) are shown in Fig. 3. For each radius, the guiding lines, have the

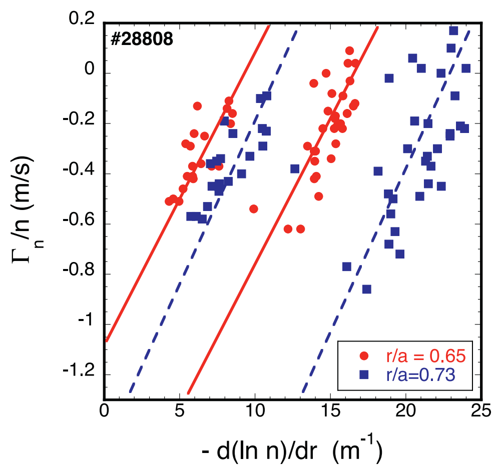

Fig. 3. Normalized particle flux versus normalized density gradients for shot 28808, at radii $r/a = 0.65$ (red circles) and 0.73 (blue squares) for two different time intervals: 0.8–0.9 s and 0.95–1.1 s. Data are compatible with same D coefficient (slope) and different U (offset). The lines are drawn only for slope reference. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

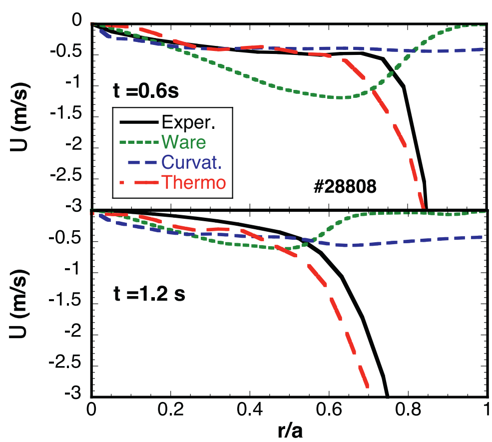

Fig. 4. Different contribution to the particle pinch for shot #28808 before and after the appearance of the MARFE. Experimental pinch required (black solid line) is plotted with the Ware pinch (green short dashed line), the curvature pinch (blue dashed line) and the thermo-diffusion pinch (red long dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

same slope (i.e. same Cenge D coefficients) and different offset (i.e. different U coefficients) indicating that the data are compatible with D constant in time. Even though the phenomenon is not a perturbation, this result can be taken as an indication to reduce the number of parameters in simulations. The profile of D could not be obtained with this data, so it has been assumed almost flat at the center and rapidly increasing at the edge ($D= D_o+ (D_e-D_o)(r/a)^{\alpha}$ with $D_o = 0.1$ m^2/s, $D_e = 1$ m^2/s and $\alpha = 10$, high enough to keep central D flat), for all the simulation time.

Given D, U can be obtained from the density profile in steady state both phase before and after the MARFE formation. Neglecting the source term, and assuming steady state we can find U setting $\Gamma = 0$ in Eq. (3), which gives $U = D/n \;\; \partial n/\partial r$.

The values of U, for a specific pulse, are plotted in Fig. 4 (black solid line) together with the contribution of some terms of Eq (1), calculated using JETTO code. The Ware pinch contribution (green dashed line) has the correct radial behavior up to half minor radius, but decreases in the region where density gradients increase and a strong pinch is required. Furthermore, the Ware pinch decreases as the density increases, in contrast with the experimental pinch behavior. This is due to the increase of collisionality from 0.4 to 2.0 which compensates the increase of electric field as a consequence of the increase of plasma resistivity. The curvature pinch (blue dashed line), proportional to $\nabla q/q$, is also plotted, using a coefficient $D_q = 0.05$ m^2/s. Also this term reproduces the pinch trend up to half radius, but it completely misses the variation of the pinch in the high gradient region ($0.5 < r/a < 0.8$). The only term that reproduces the variation in this region is the thermo-diffusive term, shown in Fig. 4 with a coefficient $D_T = D_q = 0.05$ (red long dashed line). It is worth saying that the curvature pinch and the thermo-diffusion term have the same amplitude and shape in the inner region at both times, so that we cannot exclude that more than one combinations of the two terms can be used for the simulation. For instance, assuming $D_q = 0.05$ m^2/s and $D_T = 0$ m^2/s for $r/a < 0.5$ and $D_q = 0$ m^2/s and $D_T = 0.05$ m^2/s elsewhere, we can also reproduce the required pinch for the simulation. The number of combinations increases considerably taking into account also the Ware pinch and assuming that the coefficients can change in time.

Anyway, for the sake of simplicity, we will use the thermo-diffusion term only, also because the problem of other contributions, although physically relevant, cannot be settled with the present data only due to the ohmic constraint and to the gas puff fueling.

Coefficient D_T has been assumed to be flat in radius and constant in time and its amplitude has been chosen in order to keep the initial density profile steady if no changes occur in temperature profiles.

4. Evolution of the source term

The neutral diffusion code, NENNE (based on ref [15]), used for the calculation of the neutral distribution is a 1D cylindrical code, where plasma is assumed poloidally symmetric. Its inputs are the experimental temperature and density profiles and the number of neutrals at last closed surface. The neutral free path length and their probability of ionization, charge exchange or recombination are calculated, via Monte Carlo technique. Particles exiting the plasma boundary are reintroduced inside the plasma with a recycling coefficient.

In the presence of MARFE, the density and the temperature at the edge become poloidally asymmetric, as the density changes from 1.5×10^{20} m^{-3} at the center of MARFE to 0.5×10^{20} m^{-3} at the poloidal position diametrically opposite (low field side). To keep plasma pressure constant inside the flux surface, the temperature changes accordingly and reaches values as low as 2–3 eV inside the MARFE [2,16,17].

To apply the code to the MARFE case, the plasma parameters in periphery has been symmetrized poloidally and set equal to the MARFE central values, which gives an overestimation of the neutral density and hence of the sources.

The temperature profile, below 10 eV, has been modeled as an exponential with a decay length of few centimeters, similar to the SOL profile. The decay length is used as a free parameter within reasonable range, so that the temperature is kept above 1 eV within the last closed surface. This approximation has been made only for the source calculation and not for the calculation of the thermo-diffusion pinch in simulations.

Taking into account the MARFE density and temperature ($n_M = 1.5\times10^{20}$ m^{-3}, $T_M = 2$–3 eV), assuming corona equilibrium and considering ionization and recombination rate, we have estimated that the neutral particle density ranges between 10^{18} m^{-3} and 10^{21} m^{-3}. The amount of the neutral particle at the edge has been varied, as free parameter, within such parameter range.

An example of evolution of source term profiles during the formation of MARFE, in pulse 28,808, is shown in Fig. 5. Here both

Please cite this article as: O. Tudisco et al., Evidence of a thermo-diffusion pinch on particle transport in FTU discharges close to density limit, Nuclear Materials and Energy (2017), http://dx.doi.org/10.1016/j.nme.2017.03.026

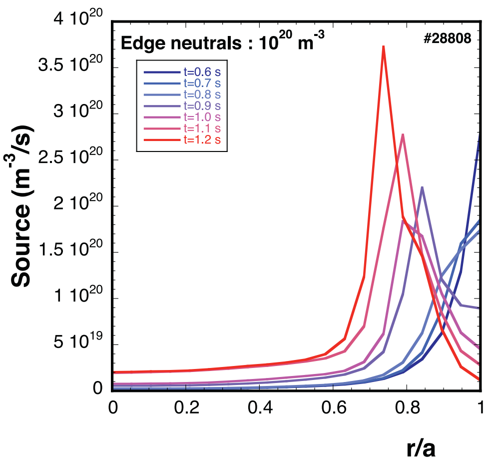

Fig. 5. Evolution of source term during the MARFE formation, for an edge density of neutrals of 10^{20} m^{-3}.

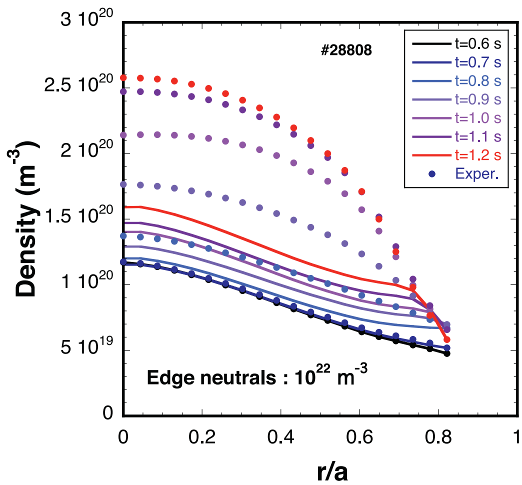

Fig. 6. Simulations of density profile, with constant D and U and high neutral particle density at edge. Dots are the experimental data.

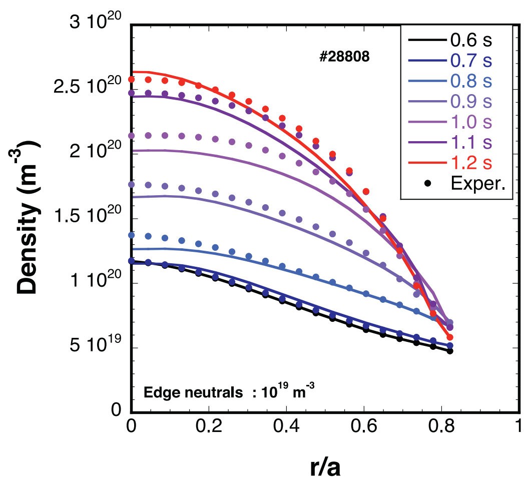

Fig. 7. Evolution of density profiles simulated using the thermo-diffusion term, and a small source contribution.

experimental density and temperature profiles have been used for the calculation. While the cold region at the edge expands toward the center, the peak of the source is progressively moving inward, however, remaining outside the region where the density increase is observed ($r/a < 0.7$). Penetration inside the central plasma remains small. The fast decrease of sources toward the plasma center is due to the lack of neutrals penetration in the high temperature region, while the decrease from the peak to the plasma edge is due to the strong recombination at low temperature. The approximations made on edge temperature affect this external region and not the tail toward the center where real temperature measurements are available. This gives a reasonable confidence of the goodness of the calculation of source term at plasma core.

5. Density profile simulations

The diffusion Eq. (2) has been solved numerically using experimental profile at the starting time as initial condition, while the measured density at an external radius has been used as boundary condition (typically $r/a = 0.8$, where temperature measurements are still reliable). The diffusion coefficient has been kept constant in all the simulations.

Eq. (3) for the particle flux has been used to study the contribution of the source term with constant transport coefficients. The pinch term U was calculated to keep the initial profile in steady state, including particle sources at initial time. During the simulation, the density profile evolves due to the change induced in the source term by the drop of temperature. For shot #28808 the computed profile is shown in Fig. 6, together with experimental profiles (dots), with high neutral density at the edge (10^{22} m^{-3}). Even with such high neutral density, beyond the estimated range, the simulation fails to reproduce the evolution of the experimental profiles.

The effects of the source term remain limited to the edge. Even with a strong increase of the source, the pinch term is not large enough to carry particles inside the plasma core, so that the effects remain at periphery.

In order to reproduce the peaking of the density profile, transport coefficients U must change with time. As said, this can be made introducing an explicit dependence of pinch on temperature gradient $U = D_T / T_e \, \partial T_e / \partial r$, where D_T is a flat and constant coefficient.

The radial region of the simulation has been limited to $r/a < 0.8$, where experimental temperature remains valid at all times of the simulation. The approximation made on temperature profiles inside the MARFE does not affect the pinch term. As before, the density at $r/a = 0.8$ has been taken as boundary condition, and profile at $t = 0.6\,s$ as initial condition.

The simulation of density profile, shown in Fig. 7 and Fig. 8, has been obtained with $D_T = 0.053 \pm 0.01\ m^2/s$. Error has been estimated changing D_T, keeping fixed all other parameters, until the peak density has a change of 20%. The source term with an edge neutral density of 10^{19} m^{-3} has been used to reproduce the density evolution at periphery. The agreement obtained between experimental data and simulations is quite good. The source term affects only the external layer and can be neglected if the simulation is carried out in a more internal region ($r/a < 0.7$).

Some attempts to extend the simulation to the whole radius have been done but results depend deeply on the model of temperature used inside the MARFE, that is completely arbitrary. Although the exponential function, used to extend the temperature in the outer corona, is a reasonable approximation for estimating the source term, this is not acceptable to evaluate the thermo-diffusion pinch, which can have a strong impact on particle transport.

6. Discussion

The simulations carried out have shown that the change of inward transport of particles during profile peaking in FTU high-

Please cite this article as: O. Tudisco et al., Evidence of a thermo-diffusion pinch on particle transport in FTU discharges close to density limit, Nuclear Materials and Energy (2017), http://dx.doi.org/10.1016/j.nme.2017.03.026

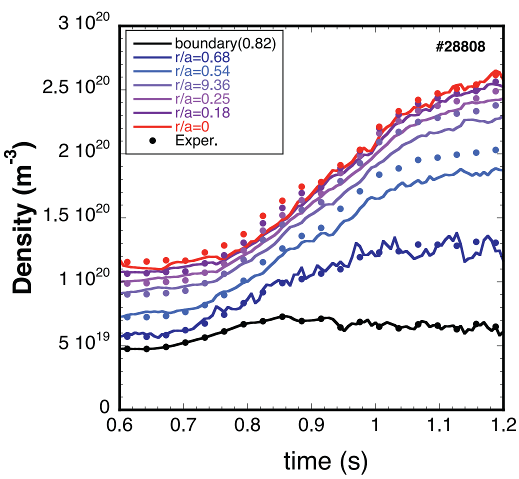

Fig. 8. Time evolution of the density at fixed radii.

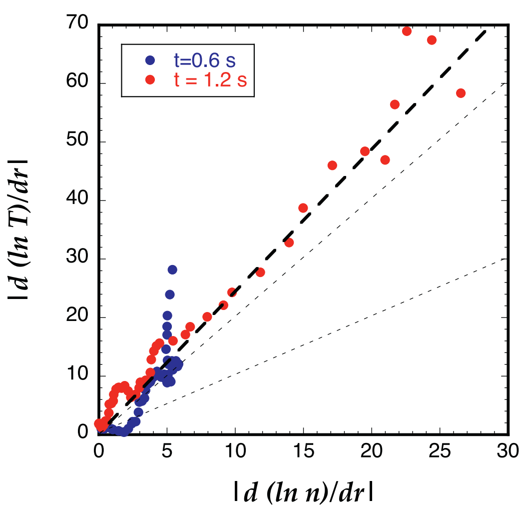

Fig. 9. Correlation of characteristic length of density and temperature along the radius, at two times.

density discharges can be described in terms of the change of characteristic length of the temperature profile, introducing a pinch term proportional to *d(ln T)/dr* (thermo-diffusion pinch). It is worth noting that the thermo-diffusion coefficient, that better reproduces the density evolution discussed in previous section, is about the half of the central value of diffusion coefficient ($D_o/D_T = 1.9$), which is close to the value found on ref [6] in full LH current-driven discharges. The same ratio is also obtained between the density and the temperature characteristic lengths, shown in Fig. 9, as expected for zero total flux (steady state and negligible sources).

Table 1
List of values of D_T that reproduce the density profile evolution, when D_o is varied in the range 0.1–0.6 m^2/s with a step of 0.1 m^2/s.

D_o (m^2/s)	0.1	0.2	0.3	0.4	0.5	0.6
D_T(m^2/s)	0.053	0.095	0.14	0.18	0.23	0.27
D_o/D_T	1.9	2.1	2.1	2.2	2.2	2.2

The values of D_T found depend on the value used for D_o. In fact, changing both D_o and D_T, it is possible to reproduce the density evolution as well, provided that their ratio remains constant. In Table 1, are listed pairs of D_o and D_T that well simulate the experimental data, having fixed D_o and varied D_T until the experimental density was reproduced. Their ratio remains close to 2 in all cases analyzed. It must be said that for larger D_o, simulations, in particular the time evolution, become less accurate, so that the value of D_o cannot be increased indefinitely.

Anyway, this ambiguity does not affect our conclusion on the relevance of thermo-diffusion term in these experiments, as it is the only term that can fit the strong gradient of density, independently of the numerical value of the coefficient.

So far the model has been applied only to a special kind of discharges in which MARFE instability determines the change of the edge parameters. This technique can be applied also to discharges where the density peaking is driven by a drop of the edge temperature made by Neon injection, 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 increase of density is negligible [18] the effect on source term at external radii can be relevant. The simulation of such discharges is left for future work.

Reference

[1] G. Pucella, et al., Nucl. Fus. 53 (2013) 023007, doi:10.1088/0029-5515/53/2/023007.
[2] B. Lipschultz, J. Nucl. Mater. 145-147 (1987) 15.
[3] D.R. Ernst, Phys. of Plasmas 11 (2004) 2637.
[4] G.T. Hoang, Phys. Rev. Lett. 90 (2003) 155002.
[5] C. Bourdelle, Plasma Phys. Controll. Fus. 47 (2005) A317, doi:10.1088/0741-3335/47/5A/023.
[6] M. Romanelli, et al., Plasma Phys. Controll. Fus. 49 (2007) 935, doi:10.1088/0741-3335/49/6/016.
[7] C. Angioni, Nucl. Fus. 52 (2012) 114003, doi:10.1088/0029-5515/52/11/114003.
[8] B. Coppi, C. Spight, Phys. Rev. Lett. 41 (1978) 551.
[9] T. Antonsen, B. Coppi, R. Englade, Nucl. Fus. 19 (1979) 641.
[10] G. Becker, Nucl. Fus. 27 (1987) 11.
[11] O. Tudisco, et al., Fus. Sci. Tech. 45 (2004) 402.
[12] O. Tudisco, et al., Fus. Eng. Design 85 (2010) 902, doi:10.1016/j.fusengdes.2010.08.037.
[13] V. Zanza, et al., Nucl. Fus. 36 (1996) 825.
[14] K.E. Gentle, et al., Nucl. Fus. 32 (1992) 217.
[15] M.H. Hughes, D.E. Post, J. Comput. Phys. 28 (1978) 43–55.
[16] G. Sergienko, et al., J. Nucl. Mater. 290-293 (2001) 720.
[17] R Zagórski, H Gerhauser, Physica Scripta 70 (2004) 173.
[18] C. Mazzotta, et al., Nucl. Fus. 55 (2015) 073027.

Please cite this article as: O. Tudisco et al., Evidence of a thermo-diffusion pinch on particle transport in FTU discharges close to density limit, Nuclear Materials and Energy (2017), http://dx.doi.org/10.1016/j.nme.2017.03.026