Light impurities in JET plasmas: transport mechanisms and effects on thermal transport

N.Bonanomi[1,2], P. Mantica[2], C. Giroud[3], C. Angioni[4], J. Citrin[5,6], E. Lerche[7], P. Manas[4], C. Sozzi[2], D. Taylor[3], M. Tsalas[3,6], D. Van Eester[8] and JET contributors*

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK
[1] Università di Milano-Bicocca, Milano, Italy
[2] CNR - Istituto di Fisica del Plasma "P. Caldirola", Milano, Italy
[3] Culham Centre for Fusion Energy, Abingdon, OX14 3DB, UK
[4] IPP-Garching Garching bei Munchen, Germany
[5] FOM Institute DIFFER, 5600 HH, Eindhoven, The Netherlands
[6] CEA, IRFM, F-13108 Saint Paul Lez Durance, France
[7] LPP-ERM/KMS, TEC partner, 1000 Brussels, Belgium
**See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*

Puffing light impurities at the plasma edge is one of the way to reduce the heat loss on the wall of ITER and of a future reactor. Furthermore, ITER will have a first wall made of Beryllium and will use heating schemes with ^{3}He as minority species. Understanding how light impurities propagate into the plasma and which is their impact on the main ion temperature in the core is important in order to achieve optimal conditions for fusion.
A series of experiments was carried out in JET ILW L-mode plasmas (B_t= 3.3 T, I_p= 2 MA, $n_{e,0}$~ $3.5\cdot10^{19}$ m^{-3}) in order to study the transport of light impurities and their effects on core thermal transport. These discharges feature the presence of ^{3}He, Be, C, N, whose profiles are all measured by active Charge Exchange, although with different degrees of accuracy. The concentrations of the various impurities, relative to n_e, are C ~ 0.1% Be ~ 1%, ^{3}He ~ 6-8% and N ~ 0-1.2%. To study the effects on ion heat transport, ICRH power (4 MW) was deposited on- and off-axis mainly to ions in (^{3}He)-D minority scheme, in order to have a scan of the ion heat flux versus R/L_{Ti}, and also modulated for ion heat wave propagation. The discharges feature minimal NBI power (3 MW). Different types of profiles are measured for the various impurities as can be seen in *figure 1*. ^{3}He profiles tend to be peaked, with values of R/L_{3He} similar to those of R/L_{ne}. With increasing Z, the profiles of the impurities tend to be flatter in the core region $0.3<\varrho_{tor}<0.7$ and peaked in the very central region ($\varrho_{tor}<0.3$). The neoclassical transport, calculated with the code NEO [1], is negligible with respect to the turbulent transport outside ϱ_{tor}=0.2, as can be seen in *figure 2*. The flattening of the impurity density profiles with increasing Z could not be reproduced by our gyro-kinetic modeling using GKW [2] and GENE[3].

Impurity	Toroidal radius	EXP $R/L_{n,imp}$	QL $R/L_{n,imp}$	NL $R/L_{n,imp}$
$_2^3$He	0.33	2.5 ± 0.5	1.3	/
	0.5	2.8 ± 0.5	0.7	/
^{4}Be	0.5	peaked	0.7	/
^{6}C	0.2	2.5 ± 0.5	/	/
	0.5	0.5 ± 0.5	1.3	1
^{7}N	0.33	1.8 ± 0.33	1.3	1.6
	0.5	0.33 ± 0.33	1.5	1 - 1.3

Table 1: *Experimental (EXP) values of ^{3}He, Be, C and N peaking at different radii and values obtained with linear gyrokinetic simulations (QL) and with non-linear gyrokinetic simulations (NL).*

The results obtained with quasi-linear simulations and non linear simulations are reported in *table 1*. In order to calculate the theoretical value of $R/L_{n,imp}$, the plasma is considered with no sources for the impurities and the condition to fulfill is zero impurity particle transport: $\frac{R}{L_N}\left(\Gamma_{imp}=0\right) = -\frac{RV}{D}$, where RV is the convective part of the transport and D is the diffusive part.

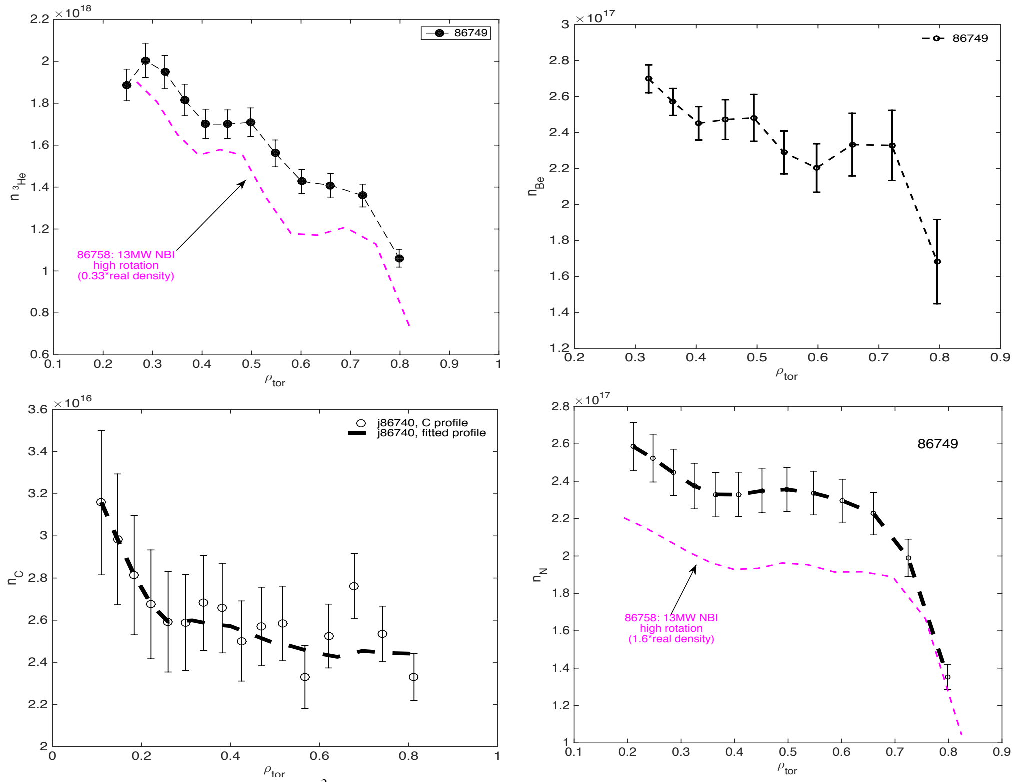

Figure 1: *Radial profiles of ^{3}He, Be, C and N densities measured by active CX spectrometry*.

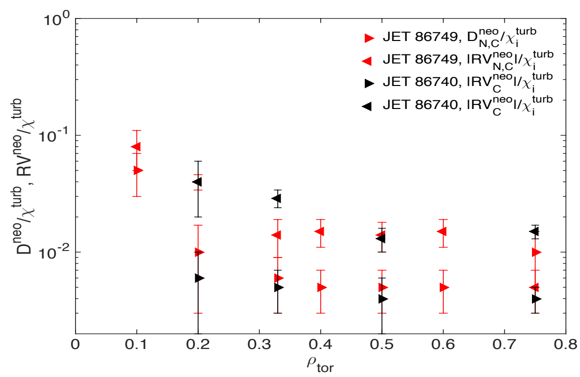

Figure 2: *Neoclassical/turbulent contribution to the impurity transport*.

The gyrokinetic simulations underestimate the peaking of ^{3}He and overestimate the peaking of the heavier impurities (C, N). The convective part of the turbulent particle flux can be written as [4]: $\frac{RV}{D} = \frac{D}{D}\left[c_T\frac{R}{L_{TN}} + c_u u' + c_p\right]$, where $c_T R/L_T$ is the thermo diffusive term, $c_u u'$ is the roto-diffusive term and c_p is the pure convective term. Using four species of the same impurity in the same simulation with different values of R/L_T, R/L_n and u', it's possible to study the different terms separately. This was done with N as impurity at ϱ_{tor}=0.5: from the simulation it appears that the most important terms in our case are the pure pinch and the thermo-diffusive ones, while the roto-diffusive term is negligible (~1/20 of the other terms).
Regarding the effect of Z_{eff} on the thermal transport, we focused our attention at two different

radii, ϱ_{tor}=0.33 and ϱ_{tor}=0.5, considering the discharges 86740, 86743, 86746(off-axis) for the case without N (Z_{eff} ~ 1.4) and the discharges 86749 and 86756(off-axis) for the case with N (Z_{eff} ~ 1.9). The main changes between the discharges with and without N are, except for the presence of N and the Z_{eff}, s/q and T_e/T_i . The profiles of the ion temperature and of the different parameters are shown in *figure 3*.

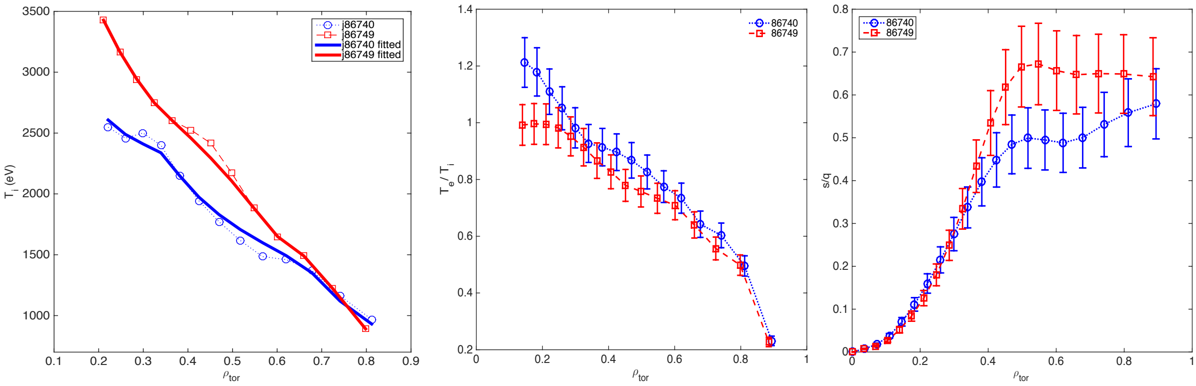

Figure 3: *Radial profile of T_i (left), T_e/T_i (center) and s/q (right) of the discharges 86740 (N=0%, blue circles) and 86749 (N~1%, red squares)*

The differences in s/q could be a secondary effect of the change of Z_{eff}, as it induces a change in the plasma resistivity and so in the current density in the plasma. Linear and nonlinear gyrokinetic simulations are used to study the effect of these differences. In all the simulations the experimental parameters are used as inputs, Miller geometry is used, main ions, N ions and electrons are retained as kinetic species. From linear simulations at ϱ_{tor}=0.5, using the input parameters form the discharge 86749 and varying s/q, T_e/T_i and the N concentration from 0 to 1.2 % (with respect to the electron density), it appears that the presence of nitrogen has a stabilizing effect on TEM, ITG and ETG (*figure 4*). On TEM possibly due to a higher collisionality [5], on ITG due to main ion dilution and on the high-k part of the spectrum due to a higher value of $Z_{eff}*T_e/T_i$ [6]. The higher s/q due to the higher Z_{eff} stabilizes the TEM, due to higher values of the magnetic shear [7], and the ITG due to higher values of s/q [8]. The stabilization of the various instabilities brings to more peaked profiles and in general to higher T_i/T_e values, that further stabilize the ITG [8,9], but destabilize the TEM/ETG. An equilibrium between the various instabilities determines the final profiles.

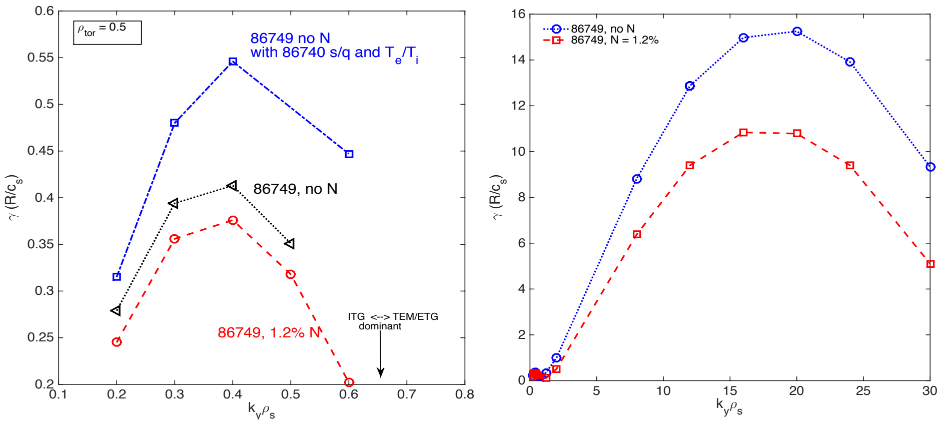

Figure 4: *Linear growth rate of the main instability as a function of k_y ρ_s, for low k_y values (left) and for high-k values (right).*

The nonlinear simulations, with the experimental parameters as input, can reproduce quite well the experimental ion and electrons fluxes and the ion stiffness(*figure 5*). In the nonlinear simulations, as in the linear simulations, the role of the nitrogen is visible.

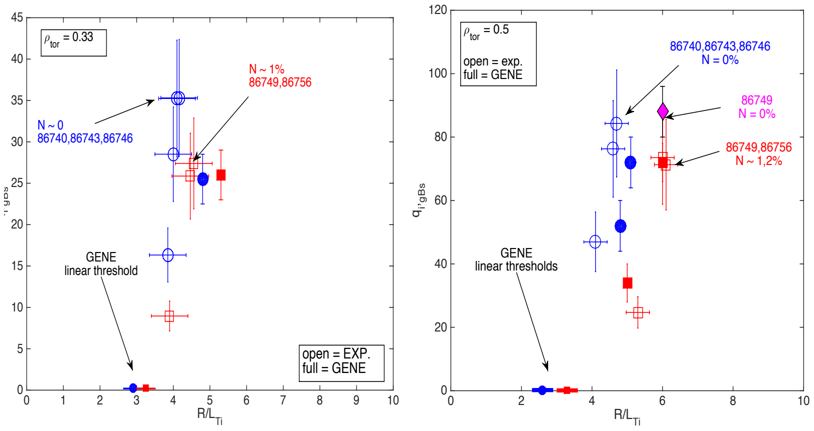

Figure 5: *$q_{i,gBs}$ as a function of R/L_{Ti} at ρ_{tor}=0.33(left) and ρ_{tor}=0.5(right) for the discharges without N (blue circles) and with N (red squares). The open symbols are the experimental points, while the full symbols are the nonlinear fluxes computed with the code GENE. The purple diamond is a simulation with the parameters of the discharge with N but without N, in order to study the effect of the N in the nonlinear simulations.*

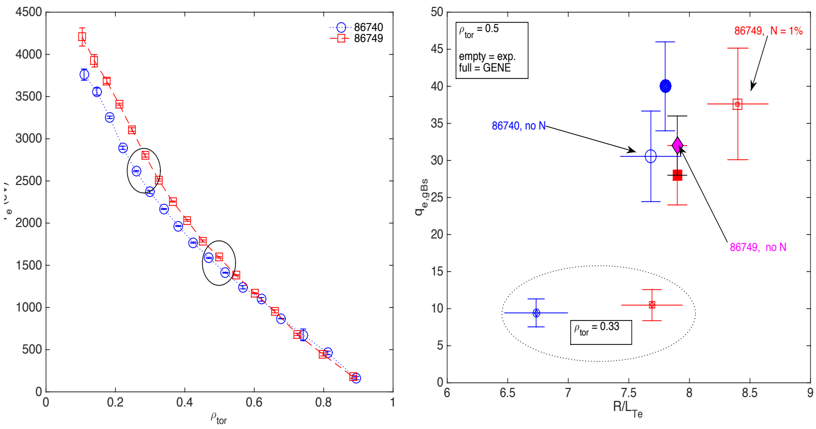

Figure 6: *Electron radial temperature profiles (left) and heat fluxes as a function of R/L_{Te} (right) of the discharges 86740 (blue circles) and 86749 (red squares).*

The effects of the higher Z_{eff} on the electron temperature profiles and heat transport can be seen in *figure 6*. The profiles in presence of nitrogen are more peaked with the same amount of heat flux. The nonlinear simulations reproduce quite well the experimental values. Adding the nitrogen has a stabilizing effect also on electrons: this can be due to a higher collisionality for TEM and related to the stabilization of ITG. Also a stabilization of ETG is possible, but multi-scale simulations would be needed in order to study properly its effect. Furthermore, in this case, the electron heat flux can be reproduced quite well with ion-scale simulations.

In conclusion, the profiles of four light impurities in a JET L-mode discharge with the ILW are shown. The experimental profiles tend to be peaked in the inner core region for all the impurities, but, as Z increase, the profiles tend to be flatter around mid radius. Our gyrokinetic simulations cannot reproduce this trend and indicate peaked profiles both in the inner core and in the outer core region. Neoclassical contributions could be important in the very central region, but cannot help to reproduce the profiles around mid radius. The overall observation is that puffing nitrogen, and so increasing Z_{eff}, has a stabilizing effect both on ions and on electrons heat transport. The main mechanisms are ion dilution, higher collisionality and a secondary effect of Z_{eff} on the plasma resistivity that act on the values of s and s/q through the q profile.

References

[1] E. Belli and J. Candy, Plasma Phys. Control. Fusion **50**, 2008.
[2] A.G. Peeters et al., Computer Physics Communications **180** , 2009.
[3] F. Jenko et al., Phys. Plasmas **7**, 2000.
[4] C. Angioni et al., Nucl. Fusion **52**, 2012
[5] F. Ryter et al., Phys. Rev. Letter **95**, 2005
[6] F. Jenko et al., Phys. Plasmas **8**, 2001
[7] N. Bonanomi et al., Nucl. Fusion **55**, 2015
[8] F. Romanelli, Phys. Fluids B 1 **5**, 1989.
[9] P. Migliano et al., Plasma Phys. Control. Fusion **55,** 2013.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.”