Impact of light impurities injection on n=1 core MHD activity at JET

E.Alessi[1], G.Pucella[2], E.Giovannozzi[2], C.Giroud[3], D.B.King[3], I.S.Carvalho[4], L.Frassinetti[5], S.Wiesen[6], A.Kappatou[7], N.Vianello[8,1], M.Wischemeier[7], D.L.Keeling[3], M.Baruzzo[2], M.Maslov[3], X. Litaudon[9], S. Gerasimov[3], R.B.Henriques[3], C. Perez von Thun[10], H.J.Sun[3], M.Lennholm[3], A.Parrot[3], M.Zerbini[2], I.Coffey[11], K. Collie[3], J.Fontdecaba[12], Z. Huang[3], I. Jepu[3], D. Kos[3], E. Litherland-Smith[3], M.P. Poradzinski[10], Z. Stancar[3], D. Taylor[3], M.Brix[3], P. Carvalho[3], A. Chomiczewska[10], Z. Ghani[3], J. Karhunen[13], E. Kowalska-Strzeciwilk[10], K. Lawson[3], S. Menmuir[3], R.B. Morales[3], E. Pawelec[14], G.Petravich[15], S.Silburn[3], B. Thomas[3], A. Tookey[3], Y. Zayachuk[3], A. Widdowson[3], A. Boboc[3], the EUROfusion Tokamak Exploitation Team+ and JET Contributors*

[1]Institute for Plasma Science and Technology, CNR, 20125 Milano, Italy. [2]Fusion and Nuclear Safety Department - ENEA C. R. Frascati - Frascati (Roma), Italy. [3]UKAEA, Culham Campus, Abingdon, OX14 3DB, UK. [4]ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St Paul Lez Durance Cedex, France. [5]Division of Electromagnetic Engineering and Fusion Science, KTH Royal Institute of Technology, Stockholm SE. [6]DIFFER - Dutch Institute for Fundamental Energy Research, 5612 AJ Eindhoven, The Netherlands. [7]Max-Planck-Institut für Plasmaphysik, Garching, Germany. [8]Consorzio RFX, Corso Stati Uniti, 4, Padova, 35127 Italy. [9]CEA, IRFM, F-13108 Saint Paul Lez Durance, France. [10]Institute of Plasma Physics and Laser Microfusion (IPPLM), Hery 23, 01-497 Warsaw, Poland. [11]Astrophysics Research Centre, School of Mathematics and Physics, Queen's University, Belfast, BT7 1NN. [12]Laboratorio Nacional Fusión. CIEMAT. Av Complutense 40. 28040 Madrid. Spain. [13]VTT Technical Research Centre of Finland, P.O. Box 1000, 02044 VTT, Finland. [14]Institute of Physics, University of Opole, Oleska 48, 45-052 Opole, Poland. [15]Centre for Energy Research, 29-33 Konkoly Thege Miklós street 1121 Budapest, Hungary.

*See the author list of + "Progress on an exhaust solution for a reactor using EUROfusion multi-machines capabilities" by E. Joffrin et al., and of * "Overview of T and D-T results in JET with ITER-like wall" by C.F. Maggi et al. to be published in Nuclear Fusion Special Issue for 29th IAEA FEC (London, UK, 16-21 October 2023)*

1. Introduction

Experiments at JET with seeding of different impurities demonstrated that improved core confinement and partial detached divertor can be achieved by injection both of Neon (Ne) and of Nitrogen (N) [1]. Stationary operations in D-T plasmas for a high performance ITER Baseline Ne-seeded scenario have been recently demonstrated [2,3]. Present contribution is focused on results obtained with D plasmas at I_P=2.5 MA, B_T=2.8T (q_{95}=3.3) [3] to study the effects of different light impurities such as Ne, N and Argon (Ar) on the core n=1 MHD activity. Baseline scenario (q_0<1) is affected by sawteeth crashes (ST) which occur periodically depending on the q profile and ion plasma equilibrium [4]. In this scenario a continuous 1/1 kink mode is usually observed in between two STs. Changes on the behavior of MHD 1/1 activity were observed during the development of the Scenario, due to the changes on the amount and on the kind of the impurities injected. As instance, the injection of light impurities is meant to influence the plasma core rotation [5], which in turns affects the behavior of the 1/1 MHD. Inversely, the characterization of such activity can give information on the impact that injection of light impurities has in the plasma core region.

2. Methods

STs are detected by a (ST detector) code based on electron temperature (T_e) measurements from the ECE radiometers at JET. The ∂T_e increment, after 10ms, is evaluated at each radii and normalized by the T_e averaged in 10ms. A radial (core) region is selected, and relevant crashes involving all measurements in the selected area are detected. Thresholds are posed on the sum of the normalized ∂T_e, and on the ratio with the central ∂T_e. This procedure allows selecting relevant crashes in a coherent way along all phases of the discharge. Furthermore, the inversion radius (R1) by comparing the ECE profiles after and before (±5ms) the detected crash. In the analyzed database, the ECE radiometer was set to cover the q=1 region allowing to detect the inversion radius both in the low and in the high field side, then allowing to approximately estimate the position and the width of the q=1 surface.

Weak annular sawteeth (AST), which provide reconnections close to q=1 surface without affecting the plasma core, are observed in some cases (few percent of the total amount of STs composing the database) to appear between two main ST crashes. The role of these weak AST should be further detailed, in present work it has been decided to set the ST detector in a way to discard these events as they could lead at underestimating the period (P1) between two STs.

Amplitude (A1) and frequency (F1) of the inter-ST 1/1 activity are measured by standard MHD analysis on magnetic measurements [6]. Standard MHD analysis at JET also estimates the modes radial position under the assumption, as for (Neoclassical) Tearing Modes [7], that MHD modes are dragged by the main ion population. The mode fluctuation frequency is compared with the measurements of the local ion rotation measured by Charge eXchange Recombination Spectroscopy. Applying such a procedure on the present dataset, it is observed a good agreement between that the radial 1/1 position ($r_{1/1}$) estimated by MHD analysis and R1 estimated by the ST detector at time of the ST crash ($r_{1/1} \geq$ R1). Furthermore, $r_{1/1}$ is seen to grow within two STs. This study will be further detailed comparing also the profile obtained by ECE-Mirnov cross-correlations [6].

The analysis here presented aim at correlating the features of n=1 core MHD with other plasma quantities to highlights the impact of light impurities injection on the core plasma region. Different plasma quantities (e.g., the central line density $<n_e>$ or the effective Z_{eff}) are averaged between two ST crashes and linked to the latter ST (R1 and P1). The average is applied also to A1 and F1 estimate.

3. Dataset

The changes on the n=1 core MHD activity are here investigated on a set of pulses subject to injection of different amount and kind of impurities: Neon (Ne), Nitrogen (N) and Argon (Ar). All pulses have same plasma current and magnetic field (I_P=2.5MA, B_T=2.7T), comparable heating and main gas influx regimes. In Table 1 impurity species, number of pulses, range of injected impurities flow rate Γ_{Imp}, D flow rate Γ_D, and heating are reported for each subset.

Table 1. Main parameters for pulses with impurity seeding

Impurity	**# Pulses**	**Γ_{Imp} [10^{22}el/s]**	**Γ_D [10^{22}el/s]**	**NBI [MW]**	**ICRH [MW]**
Neon	8	0.5-1.8	3.8-3.9	24-30	4-5
Nitrogen	4	1.5- 5.5	4.1	24-25	3-5
Argon	3	0.5-0.8	3.5	26-28	4-5

A database of 8 (unseeded) pulses with no injection of impurities is added to confirm that the slight differences on heating and on density regimes are almost negligible. Pulses in this dataset have same I_p, B_T and NBI (25MW), but different Γ_D (from 2 to 9 10^{22} el/s) and heating. ICRH heating has not been applied in a first set of 4 pulses (ICRH=0MW), while an ICRH heating of 3MW (ICRH=3MW) has been applied in the other dataset. Table 2 reports and compare the main characteristics of seeded and unseeded pulses.

Table 2. Main parameters for pulses with and without injection of impurity.

Dataset	**# Pulses**	**β_N**	**Z_{eff}**	**Bulk radiation [MW]**	**$<n_e>$ [$10^{20}m^{-2}$]**
Neon	8	1.4-2.4	2-3.5	8-10	21
Nitrogen	4	1.4- 2	1.4-1.8	6-7	21-23
Argon	3	1.4-1.7	1.7-2.1	12-17	21-25
ICRH=0MW	4	1.2-1.4	1.7-1.9	2.5-5	15-22
ICRH=3MW	4	1.2-1.4	1.5-1.8	3-5	15-22

Injection of impurities results in increased Z_{eff} and plasma core (bulk) radiation, it is also seen that improve the plasma performances (β_N) [1]. In the present dataset, pulses with injection of N and Ne both achieved improved performances and stationary ELMy H-mode conditions. Pulses with injection of Argon suffered of uncontrolled density that lead to H-L back transition. Increase in density resulted in high radiation from the plasma core at lower Z_{eff}, with some impact on the stability of the 1/1 inter-ST activity (A1).

4. Analysis

The main features of n=1 core MHD activity were found to mainly depend on the confinement β_N, as shown in Figure 1. The analysis for the unseeded pulses shows that heating mix has some impact on the stability (A_1) and rotation (F_1) of the 1/1 inter-ST modes. A large impact of the ICRH heating is found in low density regimes, where P1 can be lengthened of 2. The general behavior is that all the q=1 MHD features (R1, P1, A1 and F1) increase with β_N, and then with the impurity concentrations and flow rate. High bulk radiation in Ar pulses resulted in lower A1. Differences in F1 (Figure 1 bottom plot) are found as function of the atomic mass (M) of the injected impurities. At same β_N, differences in N and Ne are due to higher rotational shear in Ne pulses. For Ar pulses, the ExB rotation (w_{edge}, R=3.7m) at the plasma edge is two times larger than for N and Ne pulses, where w_{edge}~β_N, and the rotational shear is sensitively smaller. A linear correlation is found, independently from M, between l_i and F1, indicating that, at higher M, higher l_i are required to achieve comparable β_N. The comparison of results from N and Ne pulses seem to indicate a changes in the rotational shear as function of M. Further analysis are needed to understand the different rotational profiles found for Ar pulses with higher w_{edge} and lower rotational shear than expected at given β_N.

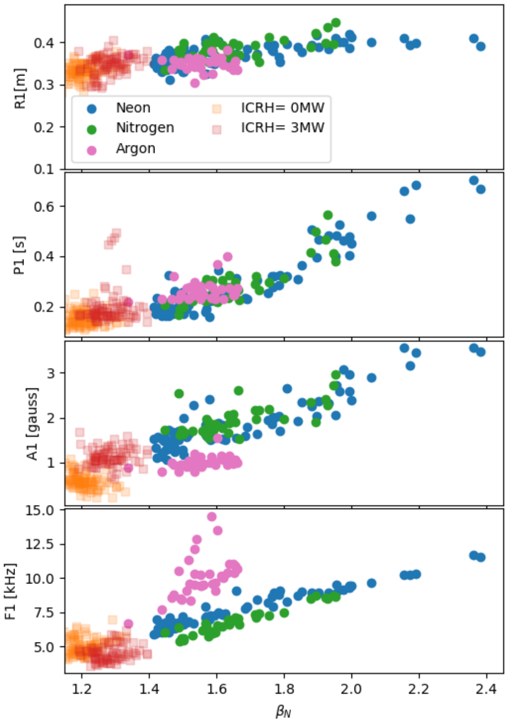

Figure 1. Features of n=1 core MHD activities in pulses with injection of impurities (Neon, Nitrogen, Argon) and without (ICRH=3MW, ICRH=0MW). MHD activities is compared as function of β_N.

Acknowledgements. *This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.*

References: [1] C. Giroud et al. 2021 IAEA Fusion Energy Conference CN-286/P3-977; [2] C. Giroud, 26th International Conference on Plasma Surface Interaction (PSI-26), Marseille, France, 12-17 May 2024; [3] I.S. Carvalho et al. this conference; [4] S. Nowak 2023 IAEA Fusion Energy Conference; [5] M. Marin et al 2023 Nucl. Fusion 63 016019; [6] E. Giovannozzi et al. this conference; [7] P Buratti et al 2016 Nucl. Fusion 56 076004.