Impact of neon seeding on fusion performance in JET ILW hybrid plasmas

C D Challis[1], E Belonohy[2], A Czarnecka[3], D Frigione[4], C Giroud[1], J Graves[5], J Hobirk[6],
A Huber[7], E Joffrin[8], N Krawczyk[3], K Lawson[1], M Mantsinen[9,10], K McClements[1],
T O'Gorman[1], S Silburn[1], A Sips[2], E Solano[11] and JET Contributors*
[1]*CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK.*
[2]*JET Exploitation Unit, Culham Science Centre, Abingdon, OX14 3DB, UK.*
[3]*Institute of Plasma Physics and Laser Microfusion, Hery 23, 01-497 Warsaw, Poland.*
[4]*ENEA for EUROfusion, via E. Fermi 45, 00044 Frascati (Roma), Italy.*
[5]*EPFL, CRPP, 1015 Lausanne, Switzerland.*
[6]*Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching, Germany.*
[7]*Forschungszentrum Jülich GmbH, 52425 Jülich, Germany.*
[8]*CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.*
[9]*ICREA, Barcelona, Spain.*
[10]*Barcelona Supercomputing Center, Barcelona, Spain.*
[11]*Laboratorio Nacional de Fusión, CIEMAT, Avda Complutense 40, 280040 Madrid, Spain*

Impurity seeding is being investigated in present tokamaks as a technique for divertor heat load mitigation by radiating exhaust power from the plasma, which has application to future devices such as ITER (e.g.[1]). With the installation of an ITER-like metal wall (ILW) in JET, heat load mitigation is required to allow high power heating (~40MW for ~5s), as envisaged for future DT experiments. Divertor strike-point sweeping provides the primary method for reducing the peak divertor surface temperature [2], but impurity seeding is being investigated as another option. Despite favourable results with N seeding in terms of heat load mitigation compatible with good plasma confinement in metal wall tokamaks [3,4], the study reported here focusses on Ne seeding due to its operational compatibility with the JET tritium handling facility. In this study at 1.4MA, a plasma current 'overshoot' was used to create a wide region of low magnetic shear with q_0~1, typical of JET hybrid plasmas [5], but β_N was limited to ~2.2 (corresponding to H_{98}~1 without seeding) to allow the core fusion performance to be assessed before the onset of performance degrading tearing modes. 16.3MW of neutral beam heating was used. Radio frequency heating, which is often used with the ILW to mitigate central impurity accumulation, was not applied due to the low magnetic field (~1.9T), which is not optimal for central RF heating. The Ne seeding rate was increased from pulse to pulse keeping

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* See the author list of "Overview of the JET results in support to ITER" by X. Litaudon et al accepted for publication in Nuclear Fusion

all other machine parameters constant. The analysis time window (1.7-1.95s after the start of the NBI heating) was chosen to avoid periods where large 3/2 modes were seen. The maximum level of Ne injection provided an increase of ~40% in the number of electrons injected between the start of the NBI pulse and the analysis time window with respect to the D fuelling.

The rise in the peak divertor surface temperature up to the analysis time (measured using an infrared camera and averaged over ELM cycles) was reduced by a factor 3 as the Ne seeding was increased, despite the modest increase in the total radiated power (measured using a bolometer camera), as illustrated in Fig.1. In Fig.2 it can be seen that the inter-ELM heat load has a peaked 'footprint', which was strongly reduced by Ne seeding as the divertor plasma approaches detachment, whereas the broader ELM power 'footprint' was only weakly affected. The combination of reduced inter-ELM heat loads and divertor re-attachment during ELM events has been reported previously for impurity seeding experiments (e.g. [6]) and helps to explain the selective reduction of the narrow divertor temperature peak seen in Fig.2 with only a modest plasma radiation increase.

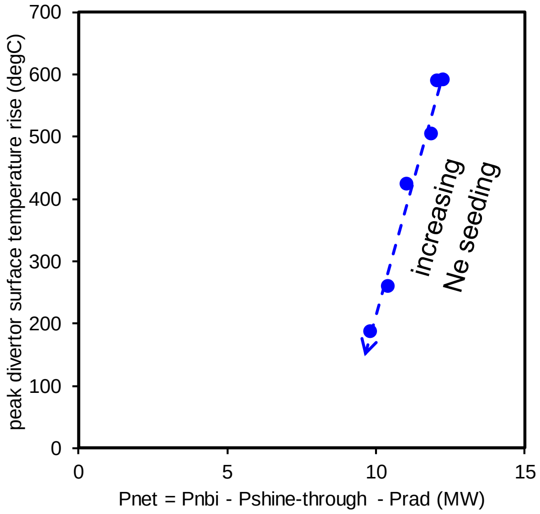

Fig.1 Peak divertor temperature rise over first 1.8s of NBI heating pulse (averaged over ELM cycles) versus net heating power for Ne seeding scan.

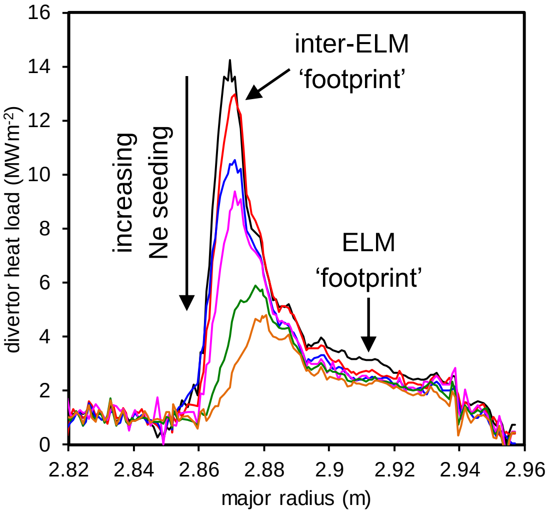

Fig.2 Divertor power load at 1.7-1.95s after start of NBI heating pulse (averaged over ELM cycles) versus radial position on divertor tile.

The plasma density increased with Ne seeding, as seen in AUG experiments [7], but in contrast with previous JET ILW experiments with different plasma shape, divertor configuration and D gas rates [8]. In the study reported here the density increase was balanced by a reduction in temperature such that β_N and the energy confinement time were unchanged, as seen in Figs.3 & 4. Z_{eff} increased from ~1.5 to ~2.8 as the seeding rate was increased while the neutron rate was reduced by ~38%. Although the impact of Ne seeding on fusion power was smaller than the reduction in peak divertor surface temperature, as seen in Fig.4, these results motivated an analysis of factors responsible for the reduction in fusion performance.

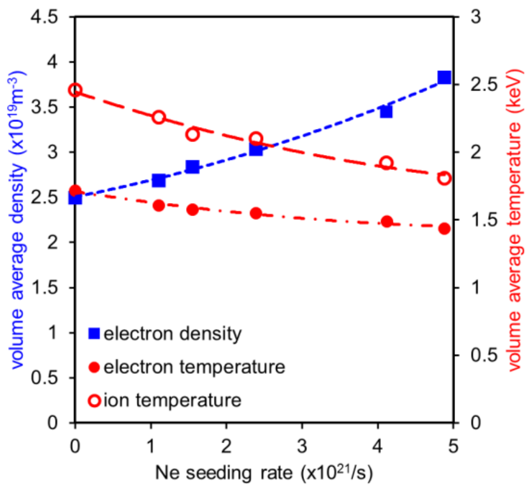

Fig.3 Plasma density and temperature during analysis time window (t_{NBI}+1.70 to t_{NBI}+1.95s) versus Ne seeding rate (in electrons/s averaged during t_{NBI}-0.3s to t_{NBI}+1.7s).

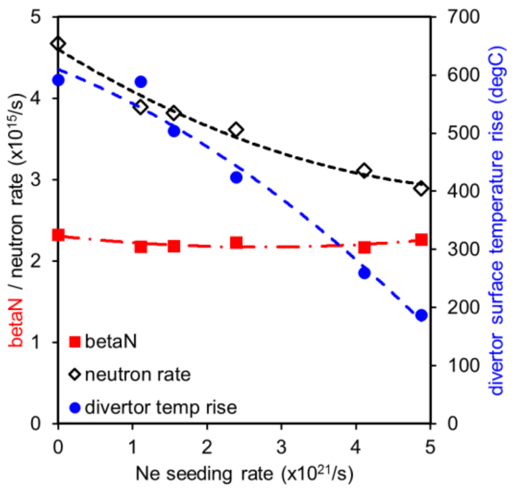

Fig.4 Peak divertor temperature rise (as plotted in Fig.1), $\beta_{N,total}$ and neutron rate during analysis time window versus Ne seeding rate.

Interpretive simulations of the neutron rate were performed using the JETFUSE code, which approximates the trajectory of the NBI system as a single, zero-width pencil in the plasma equatorial plane for beam deposition, and determines the fast ion slowing-down neglecting pitch-angle, orbit and rotation effects. The beam-target and thermal fusion reactions are modelled following [9,10]. The increase in Z_{eff} with Ne seeding from visible bremsstrahlung emission measurements was consistent with the increase in Ne density from charge-exchange spectroscopy, suggesting that changes in fuel dilution were mainly due to Ne contamination. The plasma composition was modelled assuming the main impurity in the unseeded reference plasma was Be and that the concentration was constant over the plasma radius and throughout the Ne seeding scan. The Ne density profile was taken from charge-exchange spectroscopy measurements, which gave n_{Ne}/n_e up to ~0.015 in the plasma core.

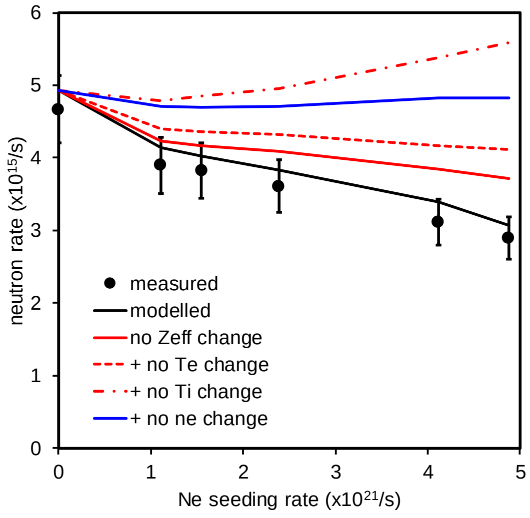

Fig.5 Measured & modelled neutron rate during analysis time window versus Ne seeding rate. The contributions of changes in Z_{eff}, T_e, T_i & n_e are shown by progressively replacing the parameters in the model for each pulse by the values from the unseeded reference.

Fig.5 shows good agreement between the measured and modelled neutron rate throughout the Ne seeding scan. To identify the factors responsible for the reduction in neutron rate with Ne seeding, the values of Z_{eff}, T_e, T_i and n_e were progressively replaced in the model for each pulse by the values from the unseeded reference plasma (see Fig.5).

The changes in plasma composition and density had relatively small, compensating effects on the neutron rate, whereas the temperature reduction, especially T_i, had the largest impact.

Two conclusions can be drawn from this analysis: (1) Ne seeding can provide effective mitigation of the peak divertor temperature in JET hybrid plasmas without significant impact on energy confinement, but with a penalty in terms of fusion performance mainly due to a decrease in plasma temperature as the density increases. Mitigation of a similar density increase with He seeding was achieved at JET by reducing the D gas injection rate [11], but reducing the D gas rate did not reduce the density in these Ne seeded plasmas; (2) In higher temperature DT plasmas with $T_i \sim T_e$ the impact on fusion power of a density change at constant β would be weaker due to the dependence $P_{fusion} \sim n_{fuel}^2.T_i^2$, whereas the effect of fuel dilution would be stronger for plasmas where thermal reactions dominate. For JET DT experiments where beam deposition and beam-target reactions are important, such an increase in density would be detrimental to fusion performance. However, it may be possible to combine low level Ne seeding with divertor strike-point sweeping to increase the margin for divertor temperature limits for modest reduction in fusion power, if the effective inter-ELM heat load mitigation reported here could be reproduced in high performance plasma conditions. Finally, it should be noted that an increase in central plasma radiation was observed with Ne seeding, suggesting an increase in mid-high Z metallic impurity contamination. This is consistent with previous observations with N seeding, which indicated that increased W sputtering due to ELMs when seeding was increased [4]. This suggest that further control of extrinsic impurities is required, e.g. by central RF heating, to achieve steady high fusion performance in JET.

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