Moderation of Target Loads Using Fuelling and Impurity Seeding on JET
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* See annex of F. Romanelli et al., “Overview of JET Results”, (Proc. 22\textsuperscript{nd} IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).

Preprint of Paper to be submitted for publication in Proceedings of the 19th International Conference on Plasma Surface Interactions, San Diego, California, USA.
(24th May 2010 - 28th May 2010)
ABSTRACT.
Operation with an all-metal, ITER-like wall on JET is scheduled from 2011. Adaptation particularly
of baseline ELMy H-mode \( (q_{95} \approx 3.5) \) to the new exhaust constraints involved has been explored by
systematic scans of deuterium fuelling and seeding with extrinsic impurities neon or nitrogen. Peak
heat load between ELMs on the outboard target can be strongly reduced by fuelling (recycling), and
approach detachment with either seed species, for only \( \approx 10\% \) loss of normalised energy confinement.
Simultaneously, normalised plasma density and total radiation averaged between ELMs are not
simply increased, but at stronger fuelling can actually fall with increasing seeding, indicating some
redistribution of efflux power temporally and spatially. At highest nitrogen seeding, ELMs can also be
mitigated, even while the electron pedestal and confinement are largely preserved. Charge-exchange
recombination spectroscopy indicates a substitution of intrinsic carbon with extrinsic species.

1. INTRODUCTION
Numerous existing tokamaks operating with carbon-based plasma-facing components have observed
a propensity for fuel species to be retained in codeposited layers within the divertor, which if
reproduced in a burning device would lead to unacceptable accumulation of tritium [1,2]. This effect
has therefore substantially motivated a plan to construct the ITER next-step machine with all metal
calls for its activated experimental phase [3]. In order to begin gaining experience with its new
mix of materials, the JET device is being refitted and will begin operating from 2011 with the same
combination of a beryllium first-wall and a tungsten divertor [4,5]. These upgraded components
involve significantly revised constraints on tolerable loadings and surface temperatures [5], so
that ITER-relevant plasma scenarios being developed on JET must in turn be adapted to the new
limits. Simultaneously, intended reduction of the level of carbon impurity implies it will probably
be necessary to replace its typical dominance as an intrinsic radiator. The general strategy of
preparing for pulses in the ITER-like wall is outlined in a separate paper [6], but here we report
on systematic scans made in both deuterium gas fuelling and seeding with extrinsic impurities, in
order to explore the domain of moderated exhaust for least impact upon plasma performance. Both
neon and nitrogen, which exhibit contrasting radiation, ionisation [7] and recycling characteristics,
have been employed. We also concentrate upon high-triangularity Type I ELMy H-mode (EH,
\( B_t = 2.7T, I_p = 2.5MA, q_{95} \approx 3.5, \delta_{av} \approx 0.42, P_{in} \approx 16MW \)), which relates to the baseline phase of
ITER. Results are summarised for plasma responses throughout the scans, focusing particularly
upon underlying levels between ELMs and behaviour at the outboard divertor target. Inter-ELM
power loads compatible with its impending solid tungsten structure [8] are demonstrated.

2. BASIC STRATEGY AND ELM / PEDESTAL VALUES
Scans undertaken in deuterium gas puffing and neon or nitrogen seeding are depicted in Fig.1 .Each
point represents an individual discharge in terms of its average rates of adding electrons, assuming
full ionisation, over the periods of feedforward input; note, though, that seeding waveforms were
initially tailored to obtain roughly steady intensity of an associated VUV line in a spectroscopic
view of the divertor. Neon and nitrogen were also injected into the inboard (private-flux region)
and outboard (scrape-off layer) sides of the divertor, respectively. Ranges spanned in each gas were chosen to reach low, near-detachment power loads between ELMs on the outboard divertor target, as measured by a fast infra-red thermographic camera [9], here framing at =12kHz. An immediate contrast between neon and nitrogen seeding is that this criterion leads, with their alternative input locations, to levels about ten times higher for nitrogen to achieve the same exhaust effect. Partly this is attributable to greater prompt pumping of nitrogen owing to closer proximity of its inlet to the cryopumping ducts [6], but otherwise little effect of inboard versus outboard seeding was found. Pulses are also discriminated in Fig.1 to indicate those few instances where performance was degraded by significant MHD instabilities ((2,1) neo-classical tearing modes) during their flat-top phases.

Superimposed in Fig.1 are accompanying contours of central line-average electron density, normalised to the Greenwald value and time-averaged generally in a 2 s window during the steadiest, flat-top interval. For quiescent cases (ie without NTMs) it can be seen that stronger fuelling leads to higher density, up to or even exceeding $\langle n_{\text{Gw}} \rangle_t = 1$. In fact, one essential feature of these plasmas is that they were deliberately arranged to lie within the region of high-triangularity H-modes on JET where density can be increased without degrading confinement or the edge pedestal [10], while ELMs display a so-called retrograde, or decreasing, frequency variation [11]. On the other hand, seeding with either neon or nitrogen tends to lead to a fall in density again, a response with other important consequences, as seen below.

Enhanced gas fuelling or seeding cause a marked change in the nature of ELMs occurring. As hinted, they first recover the decrease in frequency special to high-triangularity configurations [11], but as inputs rise they quickly tend to become compound and/or bursty in form, such that individual fluctuations are no longer unambiguously defined. The square root of variance in ELM frequency then generally equals or even exceeds its mean, implying it cannot be described well by a single number. For subsequent examination of inter-ELM average properties, therefore, selected intervals taken 50% - 90% of the way between successive, most distinct fluctuation maxima as detected by the fast infra-red camera are effectively representative rather than necessarily a precise identification of every ELM. Note that omitting the first half of each interlude is intended to avoid the post-ELM-crash dip and recovery phase manifested in most plasma properties.

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Although ELMs generally become complex, one clear measure of their amplitude is the mean peak power (MW) deposited on the entire outboard target over the ten largest transients in the chosen steadiest phase, usually for 2 s, of each pulse. The variation found is shown in Fig.2, correlated with time-averaged normalised energy confinement based upon profiles detected with a high-resolution Thomson scattering (HRTS) system and approximately corrected for non-thermal particles produced by dominant neutral-beam heating. Small changes between initial unseeded reference shots (highest blue symbols on the y-axes) in this and subsequent figures indicate the generally good reproducibility of plasmas between the two series. With either strong fuelling alone or neon seeding, ELM sizes are not substantially affected, at least until confinement is severely degraded. However at highest nitrogen seeding, ELMs are indeed strongly suppressed, even while $\langle H_{98y} \rangle_t$ is reduced by only ≈10% relative to weakly-fuelled, unseeded reference cases, and still
less compared to strongly-fuelled, unseeded plasmas. Respective electron pressure profiles for shots individually labelled in Fig.2 are compared in Fig.3 by overlaying HRTS measurements at times falling within 75%-90% of the interval between successive ELM peaks (Pulse No: 76689 is indistinguishable from Pulse No: 76682). While the electron pedestal is almost unaltered in better neon-seeded example Pulse No: 74316 from the reference Pulse No: 74312, it is only ≈15% lower both in well-confined nitrogen-seeded case Pulse No: 76682 with small ELMs, and even in neon-seeded one Pulse No: 74322 with considerably lower $<H_{98y}>$. This latter deterioration actually originates from ≈30% lower central electron temperature, consistent with intrusion of the extrinsic impurity into the core.

3. RADIATION AND DIVERTOR HEAT LOAD

With either seed species, radiation tends to be concentrated in the vicinity of the X-point, and Abel inversion of bolometer chords above the divertor suggests only moderate elevation of emission inside the pedestal, except at higher neon input. Measurements of total radiated power fraction, averaged between ELMs as explained above, are plotted in Fig.4, together with corresponding estimates of the “divertor” fraction, derived by subtraction of the aforementioned emission excluding the divertor. Note that error bars here and in all quantities averaged between ELMs, or over time including ELMs, are the square root of variance, but calculated separately above and below the mean to allow for asymmetric scatter. No H-mode plasma can be seen to exceed a total inter-ELM radiation fraction $E_{\text{tot}}^\text{rad} / E_{\text{in}}^\text{tot}$ of ≈60%, close to an empirical limit reported before on JET [12]. However, while $f_{\text{rad}}^\text{tot} / f_{\text{in}}$ tends to rise with stronger deuterium puffing alone, it increases monotonically with either neon or nitrogen seeding only at lowest fuelling level, and indeed at higher fuelling it actually falls as seeding is raised, increasing again only at the largest rates applied. Eventually this would then connect with the radiative Type III regime explored before [12]. Similar behaviour is reflected in the inter-ELM divertor radiation fraction too. Such an apparent paradox is at least partly related to the simultaneous decrease in plasma density, mentioned above, and is also qualitatively consistent with a roughly inverse variation in plasma diamagnetic energy $\partial E_{\text{dia}} / \partial t$, though within very large variances.

The key issue of divertor heat load is considered in Fig.5, where peak power density (MW × m$^{-2}$) detected thermographically on the outboard target has again been averaged between ELMs. Strong mitigation of $q_{\text{rad}}^\text{max}$ is clearly achievable with enhanced fuelling (recycling) alone [13], and by adding either neon or nitrogen it can be further suppressed, down to levels reaching the detection limit of the infra-red camera (≈1 MW × m$^{-2}$) and around which detachment may ensue. Onset of this condition is additionally supported by a clear fall in ion saturation current to target-embedded Langmuir probes, over which the outboard strike-point was swept late in the flat-top of each pulse, as well as by an increase in divertor intensity of n = 7–9 Paschen lines populated substantially by recombination (despite these signals being integrated in time-windows capturing ELMs). Evident also from the large scatter in unseeded cases at low fuelling, spread throughout the nitrogen test series, is a marked shot-to-shot legacy effect, ie incomplete removal afterwards, in the present carbon machine. Very low target load between ELMs can therefore be realised with either neon or
nitrogen seeding, for ≈10% loss only in normalised confinement, and for nitrogen combined with small ELMs too.

Initially the monotonic decline in Fig.5 may appear surprising given the variation of $\langle f_{\text{rad}}^\text{nn} \rangle_{t}$ in Fig.4. However, comparison of total power (MW) arriving on the outboard target averaged between ELMs and just over time including ELMs shows that the latter decreases much less than the former, i.e. the proportion of efflux power emerging in ELMs themselves grows with seeding. Divertor tile energies integrated by embedded thermocouples also indicate a partial redistribution of exhaust to other surface elements, at least using nitrogen. Such a balance overall is supported by the insets in Fig.5, where the fraction of total input energy deposited on the outboard target by the plasma, from radiation-corrected thermography, is compared with total radiation fraction, each calculated over chosen flat-top intervals including ELMs. Within appreciable uncertainties, net target load thus reduces approximately in proportion to increasing radiated power, although some deterioration in the accuracy of bolometric estimates with neon input cannot be ruled out. Except for highest nitrogen seeding, some extra technique for active ELM mitigation would hence probably remain desirable.

4. PLASMA PURITY

Another essential criterion of plasma performance is its purity, monitored most simply by central line-average effective ionic charge. Time-average values (not excluding ELMs) in Fig.6 expose firstly the largest difference in machine conditions between the neon and nitrogen scans, viz their initial values (blue points on y-axes) were ≈1.5 and ≈2.0 respectively, though accompanying radiation fractions were very closely the same, as already seen in Fig.4. Thereafter Fig.6 reveals an expected gradual increase of $\langle Z_{\text{eff}} \rangle_t$ with either neon or nitrogen, but a clear weakening of this rise with higher fuelling. For strongest fuelling and seeding, $\langle Z_{\text{eff}} \rangle_t$ in H-mode is then exacerbated relative to reference cases only by ≈5% with neon and ≈15% with nitrogen. Crucially, core concentrations of principal impurities inferred from charge-exchange recombination spectroscopy also in Fig.6 show a steep decrease in carbon content, though levelling off just under 1.5%, as extrinsic species mount. Consequently, while total radiation fraction may appear to change rather little eg from unseeded to highest nitrogen points for strongest fuelling in Fig.4, important evidence is offered in Fig.6 of seeding nonetheless replacing intrinsic carbon, exactly as sought. This would be consistent with a reduction in the carbon source, owing to cooling of the edge plasma.

DISCUSSION AND CONCLUSIONS

Systematic scans of fuelling and seeding with either neon or nitrogen in JET high-density, high-triangularity ELMy H-modes have shown that inter-ELM power loads on the divertor outboard target can be achieved which will be compatible with its new tungsten structure in the ITER-like-wall upgrade. Conditions close to detachment can be accessed for ≈10% loss of normalised confinement, and with nitrogen this is newly combined with significantly moderated Type I ELMs. Apart from this latter effect, little other difference was observed between neon or nitrogen seeding. Charge-exchange recombination spectroscopy indicates a replacement of intrinsic carbon with extrinsic species, as
will be required for seeding to preserve radiated power in the ITER-like-wall environment. This process is consistent with a decrease in existing carbon sources owing to cooling of the edge plasma.

ACKNOWLEDGEMENTS
This work was supported by EURATOM and partly by the UK Engineering and Physical Sciences Research Council under grant EP/G003955 and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Figure 1: Matrix fuelling and seeding scans conducted, in terms of time-averaged gas inputs. Each point is a separate ELMy H-mode (EH) discharge, with neon (left) or nitrogen (right). Superimposed: contours of Greenwald fraction obtained during pulse flat-tops.

Figure 2: Average of 10 largest ELMs during flat-top intervals of EH cases in terms of power onto whole outboard target (upper), plus time-averaged normalised energy confinement (lower), for series with neon (left) or nitrogen (right). Points are colour-coded according to the level of fuelling.
Figure 3: Electron pressure profiles measured by Thomson scattering during the flat-tops of labelled pulses in Fig. 2, against normalised minor radius. Each colour corresponds to a separate profile captured just before an ELM.

Figure 4: Average inter-ELM total radiation fraction (upper), and estimate for the divertor (lower), for EH series with neon (left) or nitrogen (right).
Figure 5: Average peak power density between ELMs on the outboard target, during flat-tops of EH plasmas with neon (left) or nitrogen (right). Insets: accompanying plasma energy increment including ELMs deposited on outboard target, normalised by total energy input over the same interval, versus time-averaged radiation fraction again including ELMs.

Figure 6: Central line-average $Z_{\text{eff}}$ (top), plus charge-exchange measurements of impurity concentrations at normalised minor radius of 0.3, for carbon (middle) and extrinsic species (bottom). All quantities time-averaged during flat-tops of EH plasmas with neon (left) or nitrogen (right).