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** See annex of M.L. Watkins et al, "Overview of JET Results ", (Proc. 21 st IAEA Fusion Energy Conference, Chengdu, China (2006)).*

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ABSTRACT
The impurity seeded type-III ELMy H-mode is proposed as an integrated ITER scenario. At JET this scenario has been demonstrated up to plasma currents of 3MA with nitrogen as seeding gas. Detached divertor operation is achieved with significantly reduced steady state and transient heat fluxes. By operating in a high triangular magnetic configuration, very high central line-averaged electron densities are reached (up to $1.1 \times 10^{20} m^{-3}$). The impurity sources and impurity concentration in the plasma core were investigated for a broad range of plasma conditions in those highly radiating plasmas. The results are compared to an integrated model of the plasma edge and plasma core. On the basis of this modelling extrapolations to ITER are done with neon seeding, giving more confidence that these radiative plasmas will have a power amplification factor in excess of 10.

1. INTRODUCTION
One of the most severe problems for fusion reactors is the power load on the plasma facing components. Technically only loads of less than 10MW/m2 in steady state and less than $0.5 MJ/m^2$ [Fundamenski08] during transients of 250μs duration, caused by so-called Edge Localized Modes (ELMs), are acceptable. This effectively means that the unmitigated type-I ELMy H-mode is not acceptable for ITER. The challenge is to develop alternative scenarios, which combine sufficient energy confinement to achieve fusion power amplification factors of Q=10, with benign heat loads to the plasma facing components.

The radiative type-III ELMy H-mode seems a possible solution for such an integrated ITER scenario. Most notably the transient heat loads due to type-III ELMs are acceptable with even the most stringent boundary conditions. For instance, on JET the transient energy loads due to type-III ELMs onto the outer divertor target were reduced to $2 kJ/m^2$ [Rapp02] which corresponds to a ratio of divertor heat load to total stored energy of $\Delta W_{ELM}/W = 0.0003$, which is approximately 0.1% of the pedestal stored energy. The results on JET were achieved in experiments carried out with nitrogen seeding to mitigate the transient and steady state heat flux to the divertor. Significant radiative dissipation of the ELM energy was only observed at very small ELMs of ~10kJ [Rapp02, Rapp04]. With the assumption that the ELM energy lost at the pedestal will increase by about a factor of 3, when lowering the collisionality to ITER values, a pedestal stored energy for type-III ELMy H-mode of about 110MJ and an increased wetted area of a factor 2 the power loads in ITER of type-III ELM can be estimated to be approximately $0.3 MJ/m^2$. The drawback of the type-III ELMy H-mode is that the confinement is reduced by ~ 8-20% compared to the type-I ELMy H-mode base scenario. The reduction in stored energy can be regained by either (a) increasing the plasma current or (b) increasing the core confinement. Increasing the plasma current to I_p=17MA on ITER and hence reducing the edge safety factor to 2.6, would allow Q=10 operation at a confinement enhancement factor of $H_{98(y,2)}$= 0.75. This operation scenario was demonstrated at JET, with most normalized parameters within the ITER operation domain [Rapp05]. However, the confinement enhancement factor ($H_{98(y,2)}$= 0.73) and the effective plasma charge (Z_{eff} =2.2) were marginally outside the operation range and needed improvement.

2. EXPERIMENTS AT HIGH DENSITY

In the last JET campaigns (2006, 2007) the operation domain of this strongly radiating type-III ELMy H-mode was extended to higher plasma current (3MA) and hence higher densities. Higher confinement was reached ($H_{98(y,2)}$=0.83) by optimized fuelling. The fuelling rate in those discharges is $\Gamma_D \sim 8\text{x}10^{22}\ s^{-1}$ and $\Gamma_{N2} \sim 0.4 - 1.5\text{x}10^{22}\ s^{-1}$. Electron densities of up to $1.1\text{x}10^{20}\ m^{-3}$ (N^{GW}=1) were reached. At those high densities the Z^{eff} was reduced down to 1.4 as figure 1 shows. However, the Z_{eff} is decreasing stronger than the simple $Z_{eff} - 1 \propto P_{rad}/n_e^2$ scaling suggests. To investigate this behaviour further, a heating power scan was performed in which the normalized beta βN was increased from 1.5 to 1.9. During this heating power scan the radiative power fraction of 70% was kept constant by radiation feedback control acting on the nitrogen gas injection. Simultaneously the electron density was kept the same at about $1\text{x}10^{20}\ m^{-3}$. By this, P_{rad} was increased from 10.7MW to 16.8MA approximately. This resulted in an increase of the nitrogen fluxes of about a factor 4 in the divertor and on the main chamber walls, when going from a β_N of 1.5 to 1.9. In this scan the Z_{eff} was varied between 1.4 and 2. In figure 2 nitrogen fluxes at the edge, Z_{eff} and P_{rad} are shown versus the nitrogen plasma core concentration, as derived from charge exchange recombination spectroscopy (CXRS).

Z_{eff} as well as P_{rad} are linear increasing with the nitrogen core concentration and nitrogen fluxes at edge as expected, and (Z_{eff} -1) is proportional to P_{rad}. The linear increase of Z_{eff} with the nitrogen concentration suggests that the carbon concentration is not changing with increasing nitrogen fuelling and remains constant at a level of approximately 1%. This is surprising since one would expect an increase of carbon release by physical sputtering since the nitrogen fluxes onto the plasma wall components are increased by a factor of 4. From the nitrogen fluxes into the plasma and the nitrogen concentration in the core also the fuelling efficiency can be calculated $S = \Delta N_N/(\Gamma_N \tau_P)$ [Strachan03]. With the assumption $\tau_E = \tau_P$ of a fuelling efficiency of S=0.018 has been evaluated for the fuelling efficiency of nitrogen from the outer divertor. It should be noted that nitrogen is not a recycling impurity, however for some good measurements τ_P has found to be up to a factor of 1.6 higher than τ_E, meaning that the fuelling efficiency could be as low as S=0.01.

In the following the carbon sources in those highly radiating discharges are examined. The divertor carbon source is derived from the CIII line emission at 465nm and the approximation $\Gamma C = 5\text{x}10^6 (I^I + I^O)$ for the divertor fluxes, where I^I and I^O are the carbon CIII light in the inner and outer divertor [Strachan03]. With reduced power to the target the divertor carbon fluxes are reduced (figure 3) as shown previously [Rapp05]. However, for the high current, high density discharges the divertor carbon source only varies 20%. Figure 4 shows a comparison of the carbon source from the divertor to the main chamber wall. Similar to the divertor carbon sources, the main chamber carbon sources do not depend on power and not on the nitrogen fluxes into the scrape-off-layer (SOL).

Figure 5 indicates that the chemical erosion does increase slightly. The increase of the chemical erosion could be due to the higher target surface temperatures at the higher power fluxes to the target. In those discharges the surface temperature is always below the maximum temperature of the chemical erosion yield [Philipps00]. However, the surface target temperature depends also on the discharge history and hence could also explain the scatter in the chemical erosion yield. The deuteron particle flux does not increase in this scan. This suggests, that the physical sputtering must be the minor release mechanism and that the chemical erosion determines the carbon erosion in those high density highly radiating discharges.

Figure 4 also demonstrates that the carbon source in the divertor is about a factor of 50 larger than the carbon source in the main chamber. However the impurity screening is higher in the divertor than from the main chamber wall [Strachan03, Strachan08]. In comparison to the type-I ELMy H-mode the carbon source in the main chamber is lower for the type-III ELMy H-mode. This is consistent with observations that the transient heat loads due to type-III ELMs is deposited completely in the divertor, while for the type-I ELMy H-mode part of the ELM energy is deposited on main chamber components. This, as a consequence, leads to a lower fuel retention in the type-III ELMy H-mode, when compared to the type-I ELMy H-mode [Loarer08].

Taking a fuelling efficiency from the divertor of approximately 0.02, together with a carbon source in the divertor of $\Gamma_C=1x10^{22}$ s^{-1} would lead to carbon core concentrations of about 0.7%, which translates into a base Z_{eff} of 1.2. This is consistent with the Z_{eff} without the contribution from nitrogen as observed in figure 2.

3. EXTRAPOLATION TO ITER

The new results of those high density radiating type-III ELMy H-modes have been added to a database of other nitrogen seeded type-III ELMy H-modes, including data from the former Mk-I, Mk-II, Mk-IIGB and Mk-SRP divertors. The Z_{eff} data from the new high density discharges extended the database to the lower end of the Z_{eff} scaling. In addition the scaling was re-evaluated taking into account the radial transport of the impurity ions. As already shown for radiative discharges on TEXTOR the radiation efficiency depends on the radial transport [Telesca00].

$$P_{rad} \propto C_z n_e L_k(T_e,\tau_p)$$

with L_k being the cooling rate for the impurity in the coronal equilibrium modified for radial transport. This means that in the presence of transport the impurities can radiate at higher temperatures than in coronal equilibrium. In addition we assume the ionization time of the impurity to be and the effective particle confinement time to be approximately close to the global energy confinement time . Including those modifications, the scaling law is described as:

$$Z_{eff} = 1 + 40 P_{rad} Z^{0.12} \tau_E S^{-0.94} n_e^{-1.5} a_{min} R^{-1}$$

and yields a good fit to the experimental data (see figure xxx). It should be noted that the regression with respect to the impurity charge Z and plasma surface S has not been changed and is kept as a result of the previous multi-machine and multi-species regression [Matthews99]. On the basis of this scaling the Z_{eff} for ITER can be estimated. For the high density 17MA scenario with a fusion power of 400MW and a confinement enhancement factor of $H_{98(y,2)}$=0.75 a Z_{eff} of 1.9 is predicted, excluding any contribution from Helium. This is a little above the assumptions made for ITER. However, details of the radial impurity transport and profile effects in the temperature and density profiles are not taken into account. For example experimentally it is often found that the Z_{eff} profile is hollow [Matthews99].

Therefore a comparison with an integrated model [Zagorski03] has been done. This integrated model, COREDIV, has been benchmarked to the nitrogen seeded JET discharges at high current [Zagorski08]. The integrated model was able to match the experimental cases quite well. On the basis of this benchmarking simulations for ITER have been done for neon seeding. In all cases the carbon erosion from the divertor is strongly reduced, leading to a diminishing carbon core concentration. Neon is the dominating core impurity leading to Z_{eff} of approximately 1.5. However, the model cannot predict the Be erosion in the main chamber appropriately, which leads to an underestimation of the Z_{eff}.

Altogether, the latest experiments at JET on the strongly radiating type-III ELMy H-mode and the simulations with an integrated model have shown that all parameters are compatible with a Q=10 operation at 17MA. However, for the standard 15MA ITER scenario a reduction of the power amplification factor to Q=6 is expected.

CONCLUSIONS

The operation domain of the highly radiating type-III ELMy H-mode has been extended to higher densities and hence lower plasma core pollution. The main impurity in those discharges is the seeded element nitrogen. Carbon remains at a level of approximately 0.7% in the plasma core. The carbon sources seem to be independent of the nitrogen content and fluxes at the edge at those high densities, suggesting that physical sputtering is minimal and chemical erosion is dominating the carbon fluxes in those at least partially detached plasmas with type-III ELM edge. The latest experimental results and results from numerical modelling demonstrate the viability of this regime as an integrated scenario for ITER.

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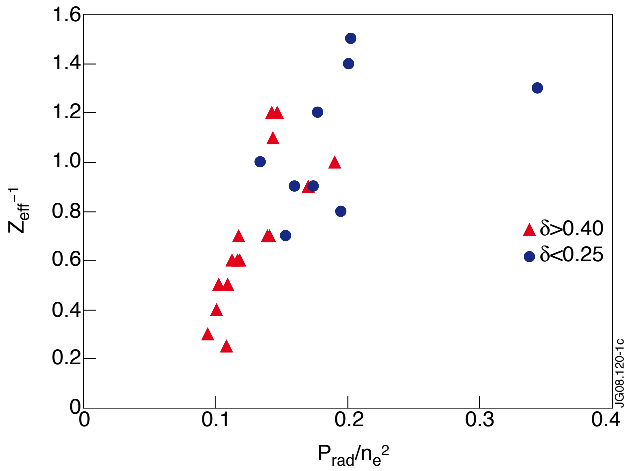

Figure 1: Z_{eff}^{-1} versus the empirical scaling P_{rad}/n_e^2 for nitrogen seeded type-III ELMy H-modes for high and low trianguarity

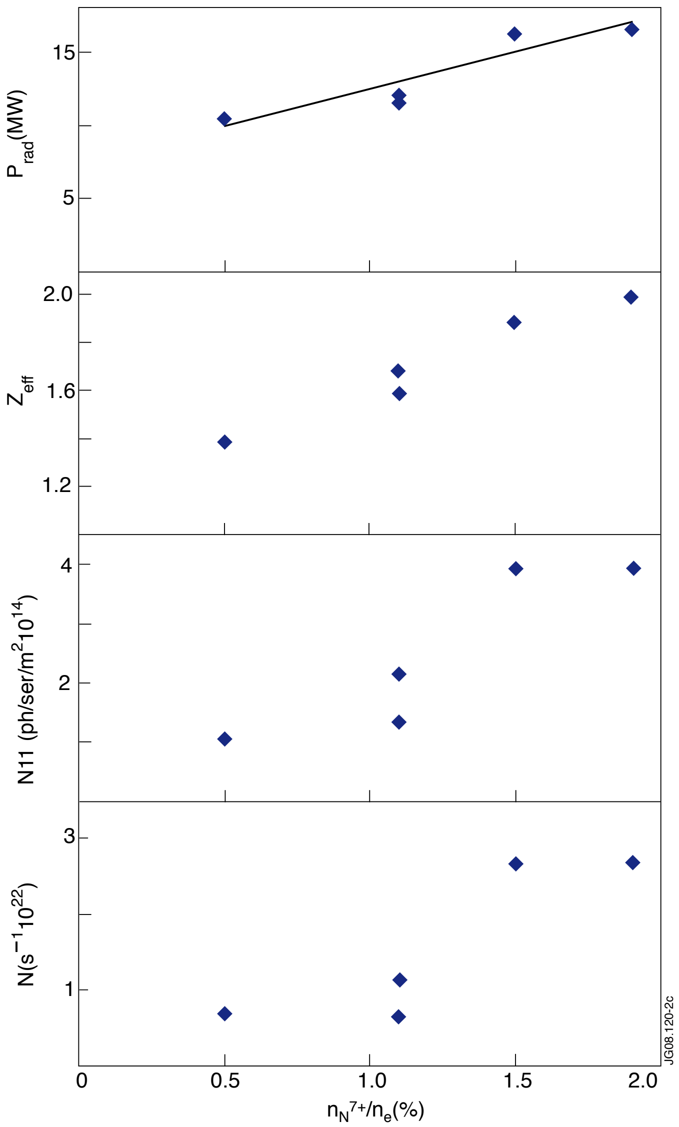

Figure 2: Heating power scan with fixed radiative power fraction (70%) and fixed electron density ($1x10^{20}$ m^{-3}); P_{rad} versus nitrogen core concentration; Z_{eff} versus nitrogen core concentration; c) NII versus nitrogen core concentration; d) nitrogen influx versus nitrogen core concentration

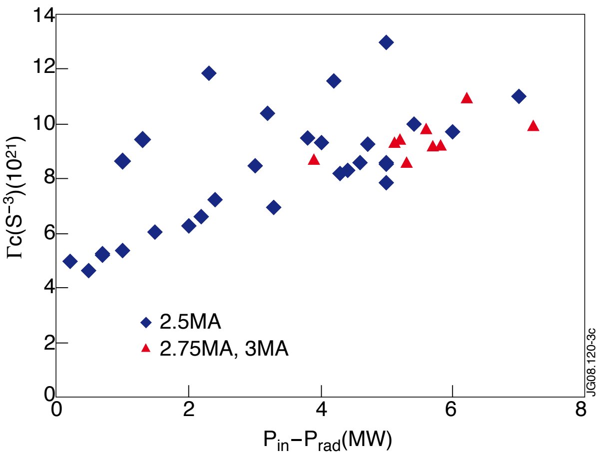

Figure 3: Carbon divertor flux versus power to the divertor target

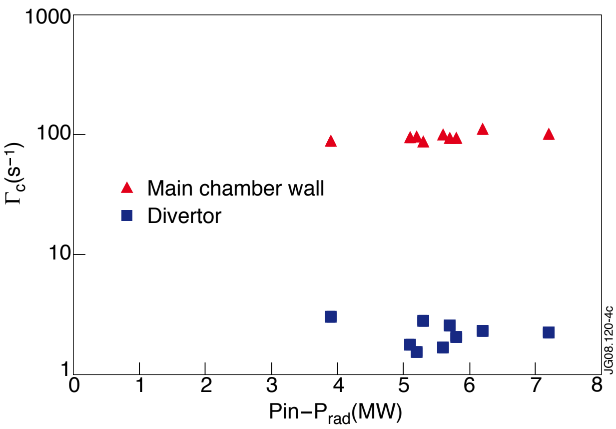

Figure 4: Carbon divertor and main chamber flux versus power to the divertor target

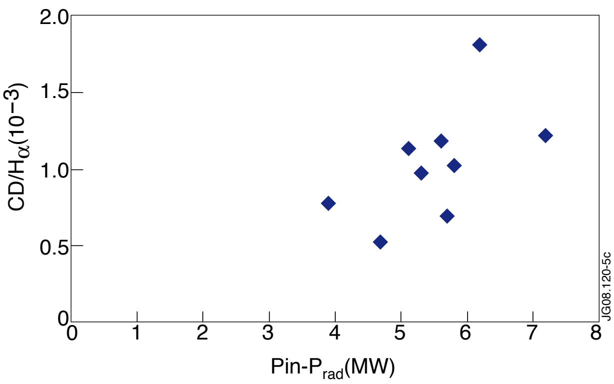

Figure 5: CD/H_α versus power to the target

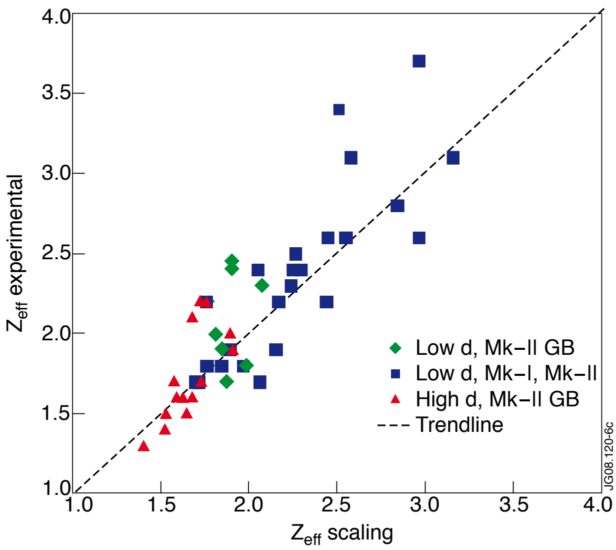

Figure 6: Experimental Z_{eff} versus new Z_{eff}-scaling

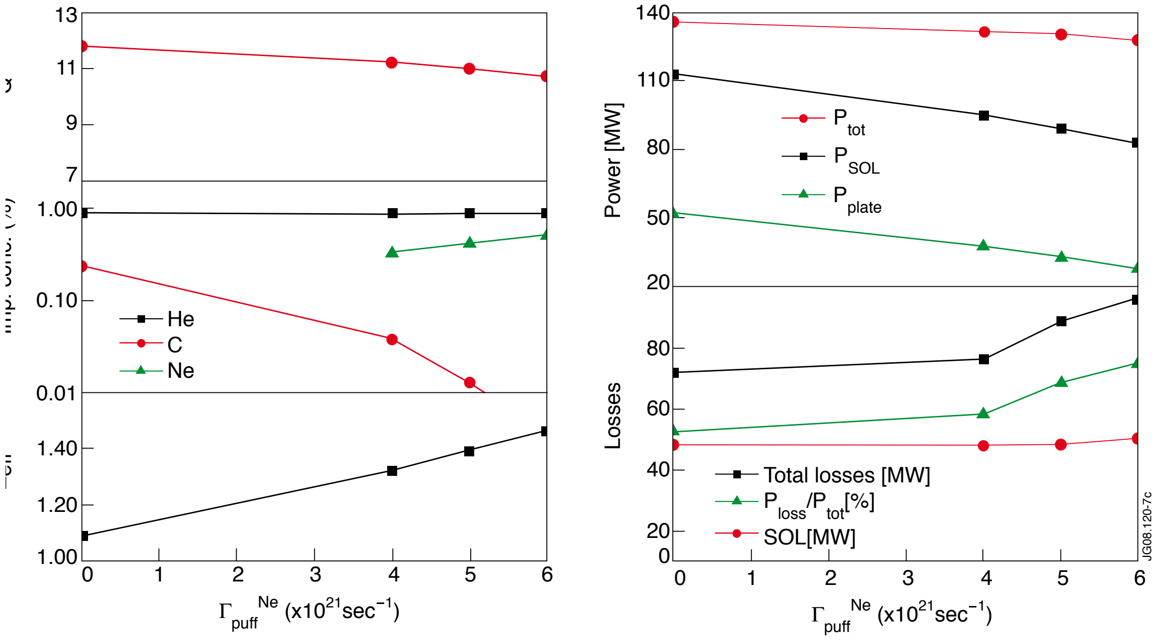

Figure 7: Predictions for ITER with COREDIV