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Strongly radiating type-III ELMy H-mode in JET – an integrated scenario for ITER

J. Rapp [a,*], G.F. Matthews [b], P. Monier-Garbet [c], R. Sartori [d], Y. Corre [c], T. Eich [e], R. Felton [b], W. Fundamenski [b], C. Giroud [b], A. Huber [a], S. Jachmich [a], P. Morgan [b], M. O'Mullane [b], H.R. Koslowski [a], M. Stamp [b], contributors to the EFDA-JET work programme [1]

[a] *Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, EURATOM Association, TEC, 52425 Jülich, Germany*
[b] *UKAEA/Fusion Association, Culham Science Centre, Abingdon OX14 3EA, OXON, UK*
[c] *Association EURATOM-CEA sur la Fusion Contrôlée, Cadarache, 13108 Saint-Paul-lez-Durance, France*
[d] *EFDA, CSU-Garching, 85748 Garching, Germany*
[e] *Max-Planck Institut für Plasmaphysik, 85748 Garching, Germany*

Abstract

As solution to the problems of transient and steady state energy exhaust the type-III ELMy H-mode is proposed. In recent experiments at JET it has been demonstrated that with seeding of nitrogen a radiative power fraction of 95% can be achieved, reducing the steady state and transient heat flux to acceptable values. Though the confinement of these discharges is reduced as well. Nevertheless, the ITER operational domain for $Q = 10$ does foresee operation at confinement enhancement factors of $H_{98(y,2)} \approx 0.78$ at higher plasma currents ($I_p = 17$ MA). It has been demonstrated at JET that an integrated scenario with type-III ELMs is feasible.

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1. Introduction

One of the most severe problems for fusion reactors is the power load on the divertor target plates, which has to be limited in steady state to 10 MW/m^2. In order to reduce the power load in the divertor to those values radiation cooling is necessary. For the ITER reference scenario a radiative power fraction of 75% is required [1]. Currently, in most fusion devices, carbon, which is the most commonly used divertor target and wall material, determines the radiative power fraction. However, looking to future devices like ITER with tungsten

* Corresponding author. Address: EFDA-JET CSU, Culham Science Centre, Abingdon, OX14 3EA, UK. Tel.: +44 1235 464970; fax: +44 1235 464415.
E-mail address: juergen.rapp@jet.efda.org (J. Rapp).

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divertors and metallic walls (Be or W), radiation due to intrinsic impurities will be minimal, and seeding of additional impurities becomes essential. Furthermore, transient heat loads due to ELMs have to be reduced to values below 40 MJ m^{-2} $s^{-1/2}$. It is predicted that for the type-I ELMs in ITER [2] the ablation limit and the heat load due to type-I ELMs is comparable, making this scenario a marginal solution for ITER. Alternative solutions have to be found. Establishing very attractive scenarios like the type-II ELMy H-mode [4] at JET was not possible yet, which puts clear doubts on their accessibility in ITER. Another scenario, the type-I ELM pace making by frequent pellet injection [3], was hampered by technical difficulties at JET so that an extrapolation to ITER is just not possible currently. Even the type-I ELMy H-mode has not been maintainable in JET with radiative power fraction larger than 75%. As third solution to the problems with transient heat loads to the divertor the type-III ELMy H-mode (for the definition of ELM types see [5,6]) with impurity seeding [7] is proposed. The major advantage of this regime is that it is robust and has been obtained in all large tokamaks. It has been demonstrated that the transient heat fluxes in this regime can be as low as 2–5 MW/m^2 and that electron temperatures in the divertor of less than 10 eV are feasible [7]. However, ELM mitigation by radiative dissipation of the ELM energy was only observed for the smallest type-III ELMs, and this has been shown to be consistent with EDGE2D/NIMBUS modelling [8]. For ITER such a radiative dissipation of ELM energy is not expected, since the ELM energy will be in excess of several megajoules. Hence, the ELM energy loss has to be limited. It is predicted that for ITER-like pedestal collisionalities, type-III ELMs are acceptable [9,8].

2. Power exhaust and influence of divertor geometry

Impurity seeding as a solution to power exhaust was first theoretically considered [10] and then carried out in many experiments [11–15] using nitrogen, neon, argon, silicon and other high-Z gases for radiation cooling in L-mode, RI-mode, type-I ELMy H-mode and type-III ELMy H-mode. The JET results presented in this paper are related to nitrogen seeding in type-III ELMy H-modes. The main reason for the use of nitrogen is the low ionisation potential, which leads to a strong radiative divertor and low radiation from the core plasma [16]. For nitrogen, the radiative power fraction f_{rad} shows a linear increase with the ratio of divertor radiation to plasma bulk radiation P_{div}/P_{bulk}. This nitrogen seeded type-III ELMy regime leads to a partially detached H-mode. But it should be remarked that for ITER 2–3 times higher separatrix temperatures (180–270 eV in ITER, ≈90 eV in JET) and pedestal temperatures (≈2 keV in ITER, 0.6–1.0 keV in JET) are expeceted. Thus for a similar type-III ELMy H-mode on ITER neon will most likely have to be used instead of nitrogen. But depending on the type-III H-mode threshold also argon might be a candidate seeding impurity for ITER.

Feedback control of radiation cooled plasmas up to radiative power fractions of $f_{rad} = 95\%$ was demonstrated with an improved real time control algorithm. This algorithm uses bolometric signals. In Fig. 1 the successful feedback of the radiation power with a preset step function is shown. No overshooting of the radiative power fraction occurred, which is important at radiative power fractions close to 100%. In those experiments the deuterium fuelling was kept at a constant rate throughout the feedback phase. At these high radiative power fractions, the carbon influx in the divertor is reduced significantly. Fig. 2 shows the C-flux from the outer divertor target derived from CII with Eq. (1).

$$\Gamma_C^{\mathrm{odt}} = \frac{I_{\mathrm{CII}} S/XB_{\mathrm{CII}}}{I_{D_\alpha} S/XB_{D_\alpha}} \times J_{\mathrm{sat}}^{\mathrm{odt}}, \tag{1}$$

where I_{CII} and I_{D_α} are the intensity of the carbon and deuterium lines and $J_{\mathrm{sat}}^{\mathrm{odt}}$ is the integrated ion saturation current from the outer divertor target. The S/XB values are taken accordingly to the temperature and density infront of the strike point, except for low temperatures where it is assumed that CII radiates at a third of the ionisation potential. The reduction of the C-flux in the outer divertor is almost a factor of 3. The effective

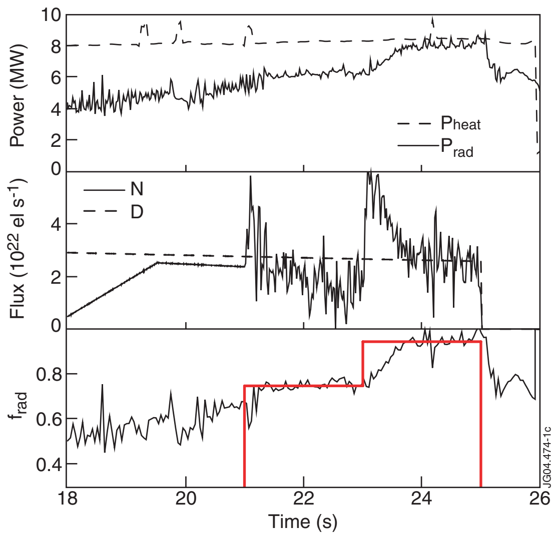

Fig. 1. Overview of discharge #58720, 2.2 MA/2.4 T, high clearance equilibrium, low-δ: Feedback of radiated power using bolometric signals. Particle fluxes of gas introduction module in divertor from D and N in electrons/s. Pre-programmed step function from 75% to 95% radiated power fraction and the response of the plasma radiation.

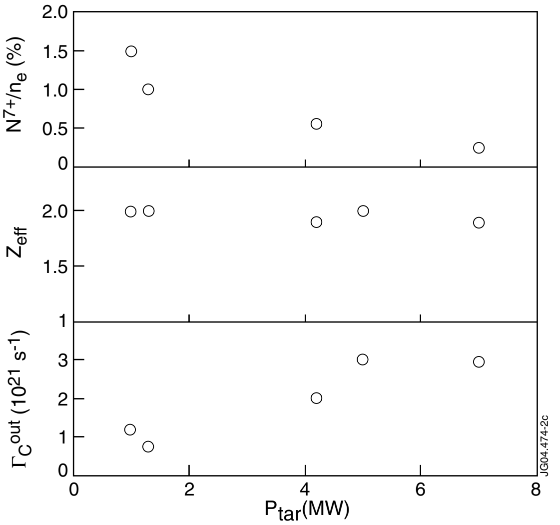

Fig. 2. Carbon fluxes from outer divertor target, Z_{eff}, central nitrogen concentration as function of convected/conducted power to the target, $P_{\mathrm{tar}} = P_{\mathrm{heat}} - P_{\mathrm{rad}}$, for nitrogen seeded pulses (2.5 MA/2.4 T high clearance equilibrium, low-δ).

charge Z_{eff} of the plasma does not change and stays around 2. The intrinsic impurities C, Be and others are replaced by N, which increases to a core concentration of 1.5%. The nitrogen concentration profile is hollow (see also [7]). At those high radiative power fractions $\geqslant$80% the seeded impurity (nitrogen) is the main radiator.

At JET extensive studies of radiation cooled plasmas in different divertor configurations (Mk-I, Mk-IIA and Mk-IIAP) have been carried out [15,16]. The experiments described in this paper were carried out in the more closed gas box divertor Mk-IIGB, which was installed in 1998. Comparison of the radiative divertor behaviour in different divertor geometries has revealed no major differences. The maximum achieved radiative power is independent of divertor geometry [16]. Only the degree of detachment (DoD) is influenced by the divertor closure, meaning complete detachment occurs at lower radiative power fraction in closed divertor configurations [15,7]. In 2001 the septum between the inner and outer divertor was removed, which should enable communication of neutrals between the two divertors and hence might influence the detachment behaviour. Since this gas box type geometry is also foreseen for ITER, the influence of the septum is assessed here. The total radiated power spacial distribution is not different. In both cases with and without septum radiative power fractions of more than 90% can be achieved and the main part of the radiation comes from inside the separatrix above the X-point (see Fig. 3). The detachment process itself is quite similar. A more detailed analysis of the detachment process and the highly radiating region near the X-point with and without septum in density limit discharges did not reveal any significant difference [17]. As in the density limit discharges the septum has no influence on the pumping speed for (a) vertical target and (b) horizontal target configurations. Also the fuelling efficiency is very similar with and without septum. However the fuelling efficiency depends on the fuelling location in the poloidal cross section. Fuelling from the inner divertor has a higher fuelling efficiency than from the outer divertor [18]. This has not been changed when the septum was removed.

3. Integrated scenario

It has been proven that strongly radiating type-III ELMy H-modes can solve the problems of power exhaust. High radiative fractions and small energy losses due to ELMs characterise this regime. In between ELMs the divertor is detached [7], and at highest radiative

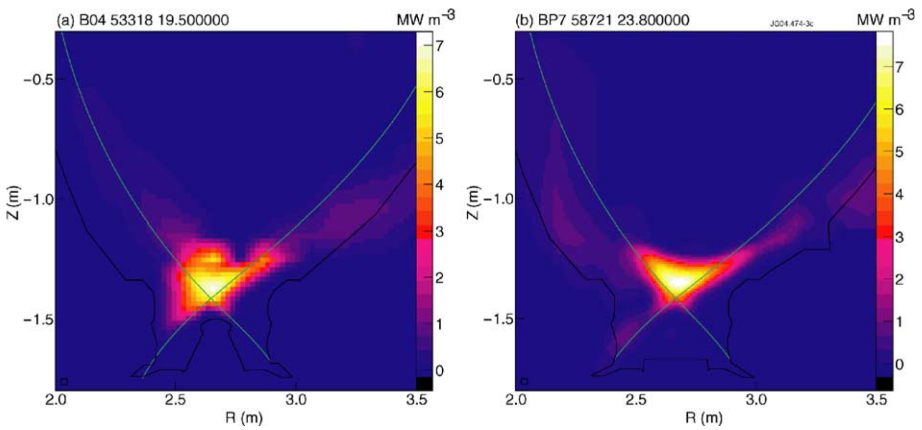

Fig. 3. Tomographic reconstructions of P_{rad} in the divertor: (a) with septum #53318, 2.5 MA/2.4 T high clearance equilibrium, low-δ; (b) without septum #58721, 2.2 MA/2.4 T high clearance equilibrium, low-δ.

power fractions ≈95% the inboard divertor is also detached during the ELM. However, the confinement is decreased as well. Nevertheless an operation with a $Q = 10$ at ITER would be possible with confinement enhancement factors $H_{98(y,2)} \approx 0.75$ at a plasma current of 17 MA. This requires operation at high densities normalised to the Greenwald density $f_{GDL} = 1$ and low edge safety factor $q_{95} = 2.6$. Hence the operation of JET was extended in that direction. This operation at low q_{95} did not have any detrimental effect on the integrated scenario in terms of sawtooth heat pulses or sawtooth triggered type-I ELMs. The build-up of the scenario was tuned to avoid the onset of Neoclassical tearing modes (NTMs) which could have a detrimental effect on the confinement. Furthermore by increasing the triangularity it was possible to increase the density by approximately 20% while keeping the confinement. This is shown in Fig. 4 for radiative type-III ELMy H-modes ($f_{rad} \geqslant 0.7$). At low q_{95} the $H_{98(y,2)}$ is slightly lower than for discharges with $q_{95} \geqslant 3.0$. In Table 1 the ITER requirements for a 17 MA discharge for $Q = 10$ are shown together with maximum values achieved so far at JET. Those maximum values have been achieved in different discharges, but not simultaneously. The best discharge so far achieves almost all ITER requirements, like normalised density f_{GDL}, normalised confinement $H_{98(y,2)}$, radiative power fraction f_{rad}, normalised beta β_N at relevant edge safety factor q_{95} and in a magnetic configuration close to ITER triangularity δ and elongation κ. Of course the plasma energy lost $\Delta W/W$ due to the type-III ELMs is within the acceptance level for ITER. In addition the dimensionless parameters like core collisionality, pedestal collisionality, separatrix collisionality and the normalised gyro radius are shown for discharge #59029 together with ITER. Both separatrix and pedestal collisionality of the discharge #59029 are close to the ITER values. Not surprising the core collisionality is very different from the ITER value. But this is not of much concern, since the energy confinement scaling [19] is only very weak depending on the core collisionality (see Eq. (2)).

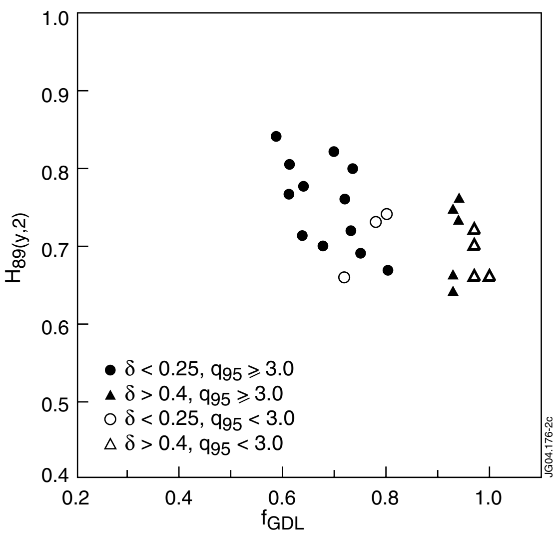

Fig. 4. Confinement enhancement factor $H_{98(y,2)}$ versus the normalised density f_{GDL}.

Table 1
Comparison of ITER scenario with JET pulse #59029

	ITER: $Q = 10$ at 17 MA	JET: #59029	ITER value/JET value	Range covered
I_p	17 MA	2.5 MA	6.8	2.1–2.5 MA
B_t	5.3 T	2.0 T	2.65	2.0–2.7 T
$1/\varepsilon$	3.1	3.2	0.97	3.1–3.2
δ	0.5	0.44	1.14	0.18–0.47
q_{95}	2.6	2.6	1.0	2.3–3.3
κ	1.86	1.73	1.08	1.65–1.74
$H_{98(y,2)}$	0.75	0.73	1.03	0.62–0.8
f_{GDL}	1.0	1.0	1.0	0.6–1.05
β_N	1.5	1.7	0.88	1.0–1.7
f_{rad}	0.75	0.8	0.94	0.65–0.97
Z_{eff}	1.7	2.2	0.77	1.5–2.5
T_e/T_i	1.1	1.2	0.92	
ρ^*	1.5×10^{-3}	3.8×10^{-3}	0.4	
ν^*	0.049	0.52	0.094	
$\nu^*_{ped,\parallel}$	0.21	0.53	0.4	
$\nu^*_{sep,\parallel}$	1.8–4	5.3	0.34–0.75	
$\Delta W/W$	⩽0.03	<0.015	2.0	

If the ITER value equals the JET value the ratio ITER value/JET value is 1; right column shows the range of values achieved (not simultaneously) in Mk-IIGB; the ITER values up to row 12 are taken from [1,20].

$$B_0\tau_{IPB98(y,2)} \propto \rho^{*-2.70}\beta^{-0.90}\nu^{*-0.01}M^{0.96}q_{95}^{-3.0}\varepsilon^{0.73}\kappa^{2.3}. \quad (2)$$

One still outstanding issue is the Z_{eff}, which is with 2.2 slightly too high. But one has to take into account that Z_{eff} is not a scaled quantity. However, future experiments at higher plasma currents should enable to decrease the Z_{eff} at high densities. Nevertheless, one should point out that there are still uncertainties in the H-mode power threshold in ITER, which might have an impact on the type-III ELMy H-mode operational domain. The scenario presented here is gas fuelled. In ITER such a type-III ELMy H-mode needs to be supported by pellet fuelling.

4. Conclusions

An integrated scenario for ITER has been demonstrated at JET. The energy exhaust during transients is expected to be acceptable for ITER-like conditions, i.e. collisionality. High radiative power fractions were achieved in open and closed divertors. The septum, which separates the outer and inner divertor in the MK-II Gas Box Divertor did not have any influence on the detachment and radiation behaviour. In those high radiative plasmas nitrogen is the main radiator and the carbon fluxes in the divertor are reduced by a factor of 3 approximately. High radiative power fractions up to 95% have been successfully kept stationary by feedback control using bolometric signals. The regime of the type-III ELMy H-mode has been extended to high densities of $f_{\mathrm{GDL}} = 1$ with just acceptable confinement of $H_{98(y,2)} = 0.73$ at low edge safety factors of q_{95}. This regime is the first in JET to be fully compatible with an ITER scenario at 17 MA for $Q = 10$ whilst meeting all edge requirements for steady state and transient power handling.

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