EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(05)02–02

E. Joffrin, P. de Vries,R. Felton, X. Litaudon, T. Loarer,P. Lomas, D. Mazon,
V. Pericoli-Ridolfini, P. Thomas, V. Riccardo, A. Tuccillo, K. D. Zastrow
and JET EFDA contributors

Steady State and Stationary Long Pulse Operation in JET

Steady State and Stationary Long Pulse Operation in JET

E. Joffrin[1], P. de Vries[2],R. Felton[2], X. Litaudon[1], T. Loarer[1],P. Lomas[2], D. Mazon[1],
V. Pericoli-Ridolfini[3], P. Thomas[1], V. Riccardo[2], A. Tuccillo[3] K. D. Zastrow[2]
and JET EFDA contributors*

[1]Association EURATOM -CEA, CEA Cadarache, 13108 St Paul-Lez-Durance, France.
[2]EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK
[3]Associazione EURATOM-ENEA sulla Fusione, C.R. Frascati, Frascati , Italy.
** See annex of J. Pamela et al, "Overview of JET Results ",*
(Proc.20 th IAEA Fusion Energy Conference, Vilamoura, Portugal (2004).

Preprint of Paper to be submitted for publication in Proceedings of the
EPS Conference,
(Tarragona, Spain 27th June - 1st July 2005)

ABSTRACT.

In ITER relevant plasma scenario, the control of non-inductive currents and of the remnant ohmic current is an important challenge in scenario design and operation. The time scale for current diffusion is often the longest plasma time scale in a tokamak. Producing long duration discharges exceeding the current diffusion time scale can therefore strongly contribute to the validation of steady state ITER scenarios. In addition, X-point discharges of even longer duration (~1 minute) can also assist in the investigation of wall saturation and particle inventory arising on time scale even longer than the plasma resistive time.

This paper reports on the recent physical and technical progresses achieved in JET on the route towards long duration stationary discharges where inductively driven current is close to the fully relaxed profile. The heat and current transport analysis of these type III ELM H-mode discharges with Internal Transport Barrier (ITB) show interesting feature for the development of current and pressure control. Other long pulse experiments have also achieved L-mode discharges in JET for almost one minute and indicate that the deuterium retention in the tokamak amounts only 3% of the injected fuel.

1. EXPERIMENTAL SET-UP FOR PULSES EXCEEDING 10s DURATION IN JET.

In present JET high performance discharges, the duration (<10s) is usually smaller than the current diffusion time as soon as the central electron temperature exceeds 5keV. The pulse length is usually limited to less than 10s either by Joule over-heating of toroidal and poloidal field coils, power load on the divertor tile or limitation on the heating systems. At moderate toroidal field strength (≤2T), JET is capable of running the toroidal field coils for about 1 minute. At high field close to 3T, the pulse duration does not exceed 20s. Provided that the power injection and exhaust can run safely for these durations, it is possible to produce discharge with duration significantly beyond the resistive time scale.

To reach this goal, specific timing arrangements for Neutral Beam Injection (NBI) have been set up to produce 11 to 12MW of NBI power for 20s while minimising the increase of neutral pressure in the neutral beam drift ducts. In addition, power load limitations on divertor tiles have been carefully investigated by an experimental stepping stone approach towards high energy injection. The JET divertor is equipped with 4cm thick graphite horizontal tiles equipped with thermocouples. In qualitative agreement with the experimental data, simulations including front and back radiation of the tile have confirmed that for durations in excess of 10s, the tile temperature increase is not linear with the injected energy, thus allowing larger injected energy in JET at moderate power. Finally, for operating long pulse of one minute duration, a specific X-point magnetic configuration has been tuned to minimise the use of the central ohmic coil in the plasma formation phase and extend the X-point configuration phase.

2. 20s ITB STEADY STATE DISCHARGES FOR CURRENT AND PRESSURE CONTROL STUDIES

This type of discharge has been produced with the goal to establish a workhorse scenario for current profile control experiment. A toroidal field strength of 3T provides a balance between the maximum pulse length (~20s) and the current drive accessibility of the Lower Hybrid (LH) Wave while keeping type III ELM activity. In addition, the q profile formation in the LH-preheat phase has been tuned in order to trigger an ITB with large radial extend during the main heating phase. Wide ITBs are required to i) optimise the self-generated off axis bootstrap current, ii) increase the confinement on a larger volume iii) enhance wall stabilisation of the pressure-driven kink instability. Figure 1a shows a JET pulse (1.8MA and 3T) lasting almost 10s with $\beta_N = 1.6$, $H_{89} = 2$ and $q_{95} = 5.5$. This regime [1] has been operated at low density ($n/n_G = 0.4$) and uses 3MW of Lower Hybrid Current Drive (LHCD) to sustain the reversed q profile after it has been pre-formed in the early phase before 4s. The formation and evolution of the current profile has been analysed with CRONOS code and experimental data such as the internal inductance, loop voltage and far-infrared polarimetric measurements are in agreement with the equivalent modelled data. The simulation confirms that this regime is not fully non-inductive: $V_{loop} = 50mV$, with ~45% LH-current, ~25% bootstrap current and ~20% NB-current (Fig.1a). When the current plateau is reached, a positive ohmic current is still present at r/a~0.7. Owing to the slow inward diffusion of this remnant ohmic current (fig 1b), the current profile evolves from a hollow and broad profile at t=4s to a flat (perhaps slightly peaked) profile. When the main heating is applied ($P_{NBI} = 11MW$, $P_{ICRH} = 3MW$ at $t = 3.7s$) an ITB develops when q_{min} equals 3 and expands outwards up to r/a = 0.55 (Fig.2). A more central ITB (r/a = 0.3), possibly linked with the inner $q = 3$ surface, is also present and vanishes as the q profile becomes flatter. The modest strength of these ITBs ($\rho^*_{Te} = \rho_e / L_{Te}$~0.02) probably prevents the accumulation of impurities in the plasma core during this discharge as revealed by the impurity analysis presented in other works [2]. This type of regimes with wide ITB is quite reproducible and has been achieved successfully at various current, 1.6, 1.8, and 2.0MA in close to steady state conditions.

The slow evolution of the current profile occurs while the power flux and momentum input from the beams are roughly constant with time between 5s and 11s. Therefore, the variation in ITBs strength can be directly related to the q profile change. Between 5s and 11s the normalised gradient of the central ITB decreases as the negative shear is approaching zero suggesting that $\rho^*_T = \rho_i/L_T$ is a smooth decreasing function of the local magnetic shear. On the other hand, the external ITB evolves gradually towards a larger ρ^*_T as the local positive magnetic shear increases. Here, the magnetic shear is inferred from both the CRONOS analysis and the EFIT magnetic reconstruction. This behaviour is consistent with other studies [3,4] and suggest that the ITB strength could be a smoothly increasing function of the magnetic shear independently from its sign.

On this type of regime, trace tritium experiment have also been made to determine the diffusion and convective terms of tritium when an ITB is present in the discharge. These experiments have been led for various ITB strengths [5] and provide an interesting scan of the local temperature gradient (table I, below). For strong ITB (ρ^*_T~0.045) the diffusion coefficient is strongly reduced down to its neoclassical value, whereas in the case of weaker ITB (ρ^*_T~0.020) ITB, the diffusion coefficient is also reduced but to a lesser extend and not to its neoclassical value. The ratio χ_{eff}/D is the same for the two cases and of the order of 0.25 which is a usual value found in collisionless plasma [6]. This suggest that both particle and heat transport can be controlled in a smooth way by controlling ρ^*_T. The other point to note is that the pinch velocity, on the other hand, has the same value independently from the temperature gradient length L_T. This observation for discharges with very low parallel electric field (i.e. with negligible Ware pinch) may indicate that in the case of ITB with small L_T the negative pinch velocity is of the form: $V \sim D_{ql}.C_T/L_T$, where D_{ql} is the quasi-linear diffusion coefficient and C_T positive in regimes dominated by ion modes [6]. This suggests that V is dominated by thermo-diffusion and remains constant at the ITB location because D_{ql} decreases (by turbulence suppression) in the same proportion as L_T when going from a weak to a strong ITB.

Pulse No:	Ip	B_T	ρ^*_T	D	V	χ_{eff}	R_{ITB}	ρ^*
61352	2.3	3.2	0.017	0.075	–0.2	0.35	3.35	0.016
61398	1.9	3.2	0.045	0.55	–0.2	2.1	3.3	0.015

Table I

Although this long pulse regime is operated at low density (n/n_G=0.4) and is not fully non-inductive, it provides an adequate target for implementing the control of the q profile together with the pressure profile up to the technical limit at JET (~20s). Given the technical constraints, a 20s duration ITB pulse has been attempted only once. Figure 3 shows this pulse for which a JET record of 326MJ of injected energy has been achieved during a type III ELMy H-mode discharge with NBI, ICRH and LHCD power coupled at the same time. Although the creation of an ITB at 3.65m is quite reproducible, the higher impurity concentration made it difficult to maintain the ITB beyond 9s. As a result Ti decreases whereas Te is maintain constant at 8.5keV for more than 20s. The initial current profile is the same as for discharge 58179 and reaches stationary conditions after 15s. This discharge also demonstrates that JET has the potential of handling large amount of injected energy. The bulk temperature of the tiles where the outer strike point is positioned increases by 300^{o}C but does not exceed a maximum of 400^{o}C, which is still within the operating limits.

3. ONE MINUTE DURATION X-POINT DISCHARGES FOR PARTICLE INVENTORY STUDIES

In JET, it was concluded from the 1997 tritium campaign that gas retention could reach more than 50% during a pulse, leading to an average T retention of 40% during the experimental campaign independently of the fuelling method (NBI or gas). The investigation of wall particle retention has benefited from the development of long plasma discharge of up to one minute duration in JET. In X-point configuration, the higher edge density and lower edge temperature than in limiter configuration and L-mode could help in identifying the long and short term retention contributions. For this goal, the toroidal field strength of 1.7T was chosen as a compromise between the target pulse length of one minute and the use of ion cyclotron frequency at 51MHz at the second harmonic of hydrogen. LH has also been used to heat the plasma and keep the flux consumption as low as possible with a plasma current of 1.8MA. The magnetic X-point configuration is created early in the discharge (typically 4s after breakdown). With this technique, up to 5 successive X-point configuration discharges exceeding 50s duration have been produced at JET over two days. Particle retention defined as the ratio: $(N_{injected} - N_{pumped}) / N_{injected}$ and inferred 35 sec after the end of the pulse, is about 3%. Since the different heating schemes used in this discharge have led to different recycling fluxes and exhaust, the gas injection rate has been adjusted by the density feedback system to keep a constant plasma density. During the steady state phases, the wall retention is noticeably increasing with the gas injection rate (e.g. at 25s on figure 4). This is also observed in short duration (<10s) ELMy H-modes in JET and ASDEX Upgrade [7] where wall retention can reach 25%. The long pulse achieved in JET confirms that low injection rate ($\sim 3.10^{21}$ particle/s) leads to a nearly full recovery of the gas injected during the discharge. On the other hand, the wall retention becomes significant when the injection rate is stronger ($\sim 3.10^{22}$ particle/s) like in ELMy H-modes. Finally, in the absence of disruption, these long discharges have also confirmed that the total quantity of gas recovered at the end of the pulse is generally negligible in the global balance and also depends weakly on the plasma discharge parameters.

REFERENCES

[1]. V. Pericoli-Ridolfini. EPS 2003

[2]. A. Tucillo et al., 20th IAEA FEC, Villamoura, Portugal 2004 in http://www-naweb.IAEA.org/napc/physics/fec.htm

[3]. O. Sauter et al., PRL 94,105002 (2005)

[4]. Sakamoto, Nuc. Fus. **44** (2004) 876-882

[5]. K. D. Zastrow, *Plasma Phys. Control. Fusion* **46** No 12B (December 2004) B255-B265

[6]. X. Garbet et al., Plasma Phys. Control. Fusion **46** (2004) B557-B574

[7]. V Mertens et al., 30th EPS Conference on Contr. Fusion and Plasma Phys., St. Petersburg, 7-11 July 2003 ECA Vol. 27A, P-1.128

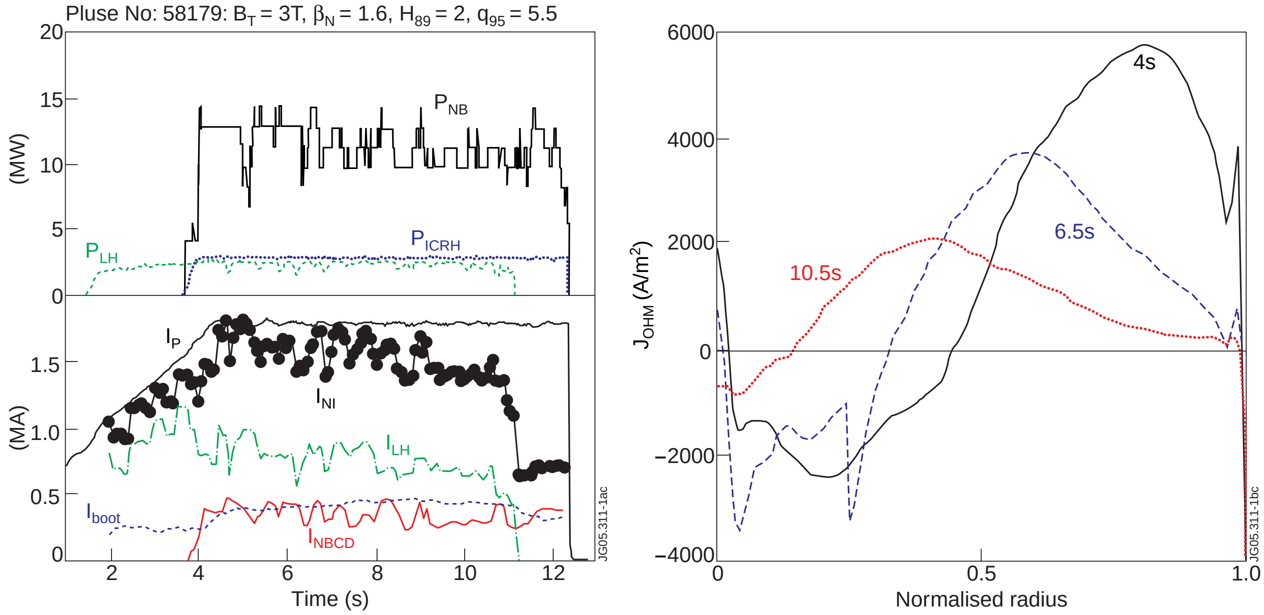
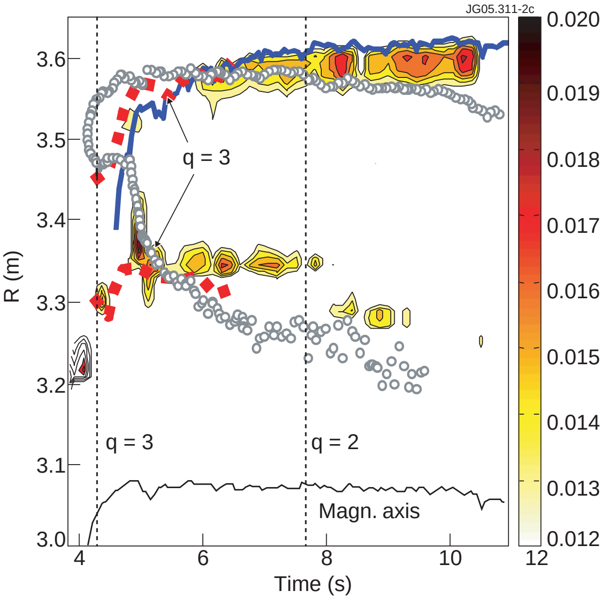


Figure 1: (a) (left) and (b) (right) : Non inductive current components evolution for Pulse no: 58179. Above, inward diffusion of the remnant ohmic current as calculated by the CRONOS code.



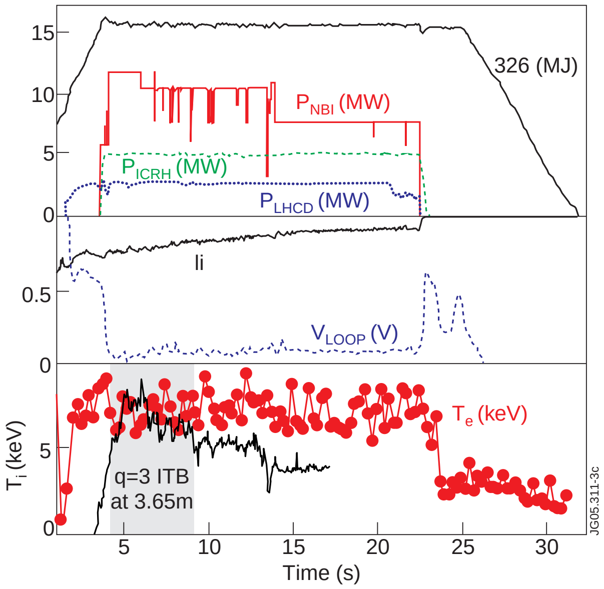


Figure 2: ρ$_T$ evolution for Pulse no: 58179 in time and space. The q=3 surface evolution computed by EFIT using MSE data (red dots), EFIT using magnetics only (blue line) and CRONOS simulation (open circles) are also indicated. Dashed lines indicates the occurrence of the q=2 and q=3 surfaces from MHD signals.*

Figure 3: Main plasma parameter evolution of the 20s long Pulse no: 62065.

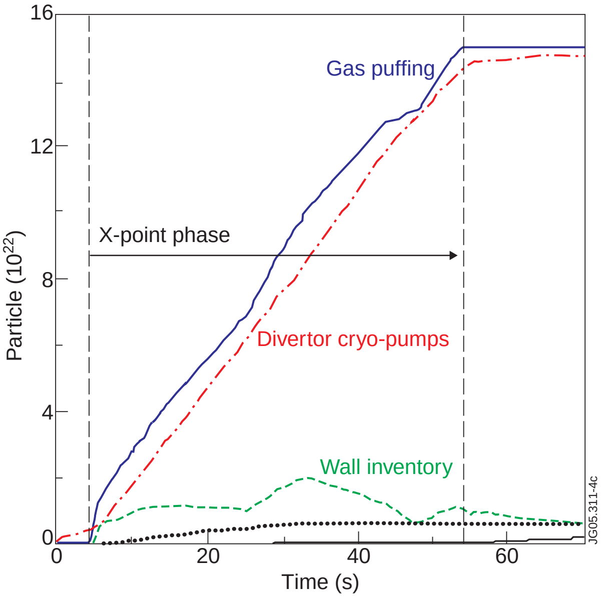


Figure 4: Particle balance for Pulse no: 56552 in X-point configuration (1.8MA, 1.7T).