EUROPEAN FUSION DEVELOPMENT AGREEMENT

JET

EFDA–JET–CP(02)02/17

K-D Zastrow, M. Brix, R Dux, K-H Finken, C Giroud, M.G von Hellermann,
D. Hillis, P.D Morgan, M.G. O'Mullane and A.D Whiteford

Helium Ash Simulation Studies with Divertor Helium Pumping in JET Internal Transport Barrier Discharges

Helium Ash Simulation Studies with Divertor Helium Pumping in JET Internal Transport Barrier Discharges

K-D. Zastrow[1], M. Brix[2], R Dux[3], K-H. Finken[2], C. Giroud[4],
M.G von Hellermann[4], D. Hillis[5], P.D Morgan[1], M.G. O'Mullane[6],
A.D. Whiteford[6] and contributors to the EFDA-JET workprogramme*

[1]*Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, UK.*
[2]*Forschungszentrum Jülich GmbH, IPP, Euratom Association, Jülich, Germany.*
[3]*Max-Planck-Institut für Plasmaphysik, Euratom Association, Garching, Germany.*
[4]*FOM Instituut voor Plasmaphysica, Associatie Euratom, Nieuwegein, NL.*
[5]*Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, USA.*
[6]*Dept. of Physics and Applied Physics, University of Strathclyde, Glasgow, UK*
** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

Preprint of Paper to be submitted for publication in
Proceedings of the 29th EPS Conference, (Montreux, Switzerland 17-21 June 2002)

ABSTRACT

Improved core confinement by the formation and sustainment of an internal transport barrier (ITB) is seen as a possible route to steady state tokamak operation because of the potential of this regime for full non-inductive current drive. Such a regime must have a sufficiently fast chain of He transport from the core to the edge, and from the edge to the divertor, such that He can be pumped effectively. If one of the links of this chain is not fast enough, He ash will accumulate and the fusion reactions will self-extinguish. This can be quantified by measuring the ratio of the He retention time to the energy confinement time [1]. If small levels of additional impurities are present, the requirement is for $\tau_{He}^* / \tau_E < 10$ to obtain steady state burn conditions. With additional impurities the requirement becomes more strict, e.g. $\tau_{He}^* / \tau_E < 5$ with the upper limit of five corresponding to e.g. carbon concentrations of 3%. The relationship between He retention time and He replacement time, $\tau_{He}^* = \tau_{He}/(1-R_{eff})$, defines R_{eff} i.e. the global recycling coefficient. We note that Reff is not the same as the edge recycling coefficient since central source and edge source are not characterised by the same replacement time. Nevertheless, without He pumping R_{eff} is close to unity and the He retention time becomes very large. The potential for pumping under these conditions is expressed by the He enrichment factor, i.e. the ratio of the partial pressures of He and D^2 in the sub divertor region (at the pump throat) to the ratio of He^2+ to D^+ in the plasma core, $\eta = (p_{He} / 2p_{D2}) / (n_{He} / n_D)$ which needs to be larger than 0.2 for stationary operation of ITER [2].

1. INTRODUCTION

In JET ELMy H-Modes the ratio of particle to energy confinement is favourable, and He can be pumped at a satisfactory rate [3,4] in agreement with results from many other tokamaks. Results from experiments in JT-60U ITB discharges indicate increased He retention in the core [5,6]. Also there is concern that, since ITB discharges to date tend to be characterised by lower edge density than ELMy H-Mode plasmas, the potential for pumping of He might be reduced, i.e. η might be too small.

In JET it was found that impurities accumulate in the plasma core for ITB discharges with large values of β_N at high magnetic field [7,8], with higher Z impurities exhibiting the strongest peaking. This has been explained by a reduction of the turbulence driven diffusion coefficient, D, in the presence of inward convection, v, where the latter was found to be in agreement with neo-classical predictions. As shown in Fig. 1, He is also subject to this accumulation. The helium density near the axis (R=3.14m) increases and it decreases outside the ITB. While this is interesting in its own right, it does not answer the question what τ_{He}^*/τ_E would be with a central source under these conditions. The reduced diffusion, which acts on the gradient, can easily result in strongly peaked density profiles with a central source, but then again the same reduction in turbulence will be responsible for the improved energy confinement time, and it is only the ratio of these that we are concerned with. If the peaking is mainly due to inward convection, this might not be very efficient at retaining a central source since it acts on the density.

2. RESULTS WITH HE BEAMS

The He retention time in ITB discharges was studied using He neutral beams to provide a central source, in analogy to the production of He ash in a burning core. To this end, one of the two JET beam systems was converted to He beams with an injection energy of 70 keV. For the discharges in this study, ≈60% of the He is deposited within r/a ≈0.4 i.e. within the region enclosed by core ITBs.

He was pumped in these discharges by application of a layer of Argon Frost on the divertor Cryo Pump (AFCP). The He pumping speed varies as He and D2 are trapped, and was measured to be in the range of 80-90 m^3/sec before a pulse, and 20-30m^3/sec after a pulse. For comparison, the pumping speed for D2 is about 120 m3/sec. This provides effective edge density control by reducing the He recycling flux, as shown in Fig. 2, for He beam powers up to 2MW for up to 5 sec, and up to 3MW for 3sec. At least 14MW of beam power are required for strong wide ITBs as shown in Fig. 1 and are therefore not accessible at high magnetic field, and only weak core ITBs can be formed. At lower magnetic field, high values of $\beta_N \approx 1.5$ are accessible.

For the two discharges with He beams shown in Fig. 2, the He enrichment factor η is 0.58±0.28 without the AFCP, and 0.42±0.20 with AFCP. These values demonstrate that the low edge density of ITB discharges does not impede He removal. The discharge with AFCP has the best value for $\tau_{He}^*/\tau_E^{th}=5$ that was obtained in this series of experiments, because of its improved energy confinement as indicated by its value of $\beta_N = 1.4$. Note that in this study we use τ_E^{th} i.e. the confinement time for thermal ions and electrons since this gives a more conservative result. Due to beam injection and RF heating, our discharges have a ≈30% contribution to the stored energy from fast particles.

In Fig. 3 we show an ITB discharge in which Lower Hybrid Current Drive and heating (LHCD) was applied throughout to slow down the q profile evolution. Quasi steady state He exhaust is provided by the AFCP for the whole time, although the reduction of the He pumping speed becomes noticeable towards the end of the heating phase. ITBs located at r/aª0.4 are formed and collapse in a sawtooth-like fashion for the whole duration of the main heating phase, which can be seen in the associated changes in the global neutron yield, where the q=3 ITB is most marked. The barriers are also noticeable on the He density profile, and this is reflected in the radial profile of τ_{He}^* shown in the lower pane of Fig. 3. The variations in τ_{He}^* are not large in these weak ITBs.

In spite of the He pumping there is a background of He in the plasma before the application of He beams, i.e. an edge source. This source is not included in the calculation of τ_{He}^* in Fig. 3, which explains the initially high value and rapid reduction of τ_{He}^* during the first 0.5secs after He beam injection.

An overview of the results obtained in the two scenarios, with reversed q profiles prior to the application of the main heating, is shown in Fig. 4. The He source rate was varied by using one, two or three He Pinis, respectively. The highest He source rate is equivalent to that produced by 130 MW of a heating i.e. a total fusion power of 660MW. At 2.63T/2.2MA we studied strong ITBs and at 3.45T/2.4MA we studied quasi steady state ITBs where LHCD was used to slow down the current profile evolution. Strong ITBs with very high values of β_N and neutron yield at high magnetic field while retaining edge density control could not be obtained in these experiments due to the reduction in heating power associated with the conversion of half of the JET NBI heating system to He.

CONCLUSIONS

In all discharges, we find $5<\tau_{He}/\tau_E<10$ with the lowest value obtained for the discharge with the highest value of $\beta_N = 1.4$. This result was obtained in quasi steady state for a duration of up to $5\times\tau_{He}*$. The value of $\tau_{He}*$ in these discharges is still dominated by edge transport and recycling (i.e. lack of pumping) and none of the discharges exhibit a significant increase of $\tau_{He}*$ due to the presence of the ITBs. The He enrichment factor with pumping for all scenarios is in the range $0.40<\eta<0.60$ which is mainly a reflection of the fact that He is pumped, noting that without pumping, η rises up to $\approx$0.8. One question still open is, how $\tau_{He}*/\tau_E^{th}$ would behave for very high values of β_N at high magnetic field, i.e. for discharges like the one shown in Fig. 1. We have shown that the low edge density in these scenarios is not a problem, i.e. sufficient pumping can be achieved, and our results at high values of β_N and low magnetic field indicate that the improvement in τ_E^{th} might offset any increase in $\tau_{He}*$. The JET NBI systems are presently being upgraded, which means that it will be possible to perform experiments to test this hypothesis even if some of the beams are converted to He.

ACKNOWLEDGEMENT

This work was performed under the European Fusion Development Agreement, and funded in part by EURATOM and the UK Department of Trade and Industry.

REFERENCES

[1]. D. Reiter, G. Wolf and H. Kever, Nuclear Fusion **30**, 2141 (1990)
[2]. See pp. 2420-2421 in "ITER Phyics Basis", Nuclear Fusion **39**, No.12 (1999)
[3]. D. Stork et al. EPS 1999, Maastricht
[4]. K-H Finken et al EPS 2001, Madeira
[5]. A. Sakasai et al, IAEA 1998, Yokohama
[6]. A. Sakasai et al, IAEA 2000, Sorrento
[7]. R. Dux et al. EPS 2001, Madeira
[8]. C. Giroud et al. EPS 2001, Madeira

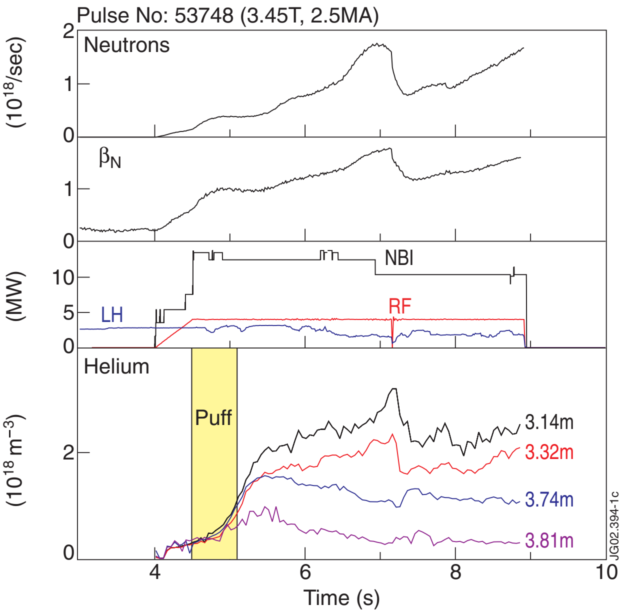

Figure 1: He is slowly introduced into a discharge with reversed q profile prior to ITB formation. He is not pumped (but there is good potential for pumping, i.e. η=0.79±0.30), Changes in the He density profile can be studied to reveal changes in v/D. ITBs are first formed on the reversed q profile region (t=5.5sec). The first strong ITB is located at q=3 (t=6.5sec). To avoid the β limit, the power is stepped down (t=6.9sec), the subsequent loss of the ITB results in a redistribution of He. The second strong ITB is located at q=2 (t=8.1sec)

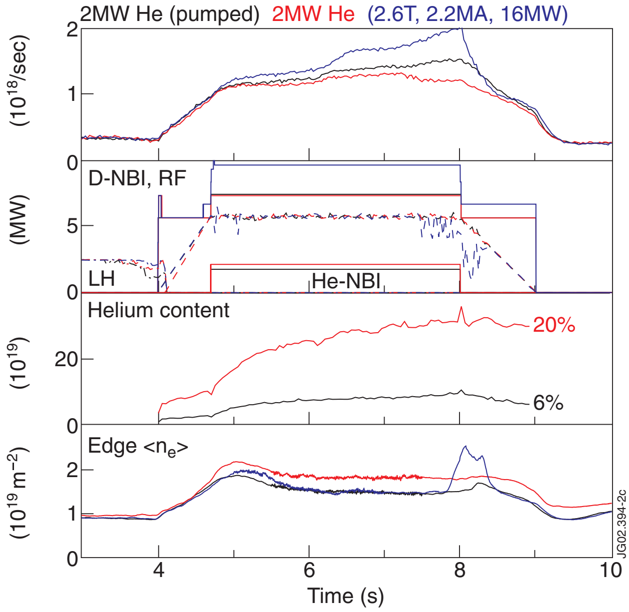

Figure 2: Comparison of three ITB discharges with identical current profile evolution and heating power. With 8 MW of D beams and 2 MW of He beams, but without He pumping (red), the edge density is increased compared to the D only reference pulse (blue). With He pumping (black), the edge density is controlled, and a reduction of the He core concentration from 20% to 6% is achieved. The discharge does not reach the same value of β_N as the reference pulse due to differences in beam deposition between He and D beams.

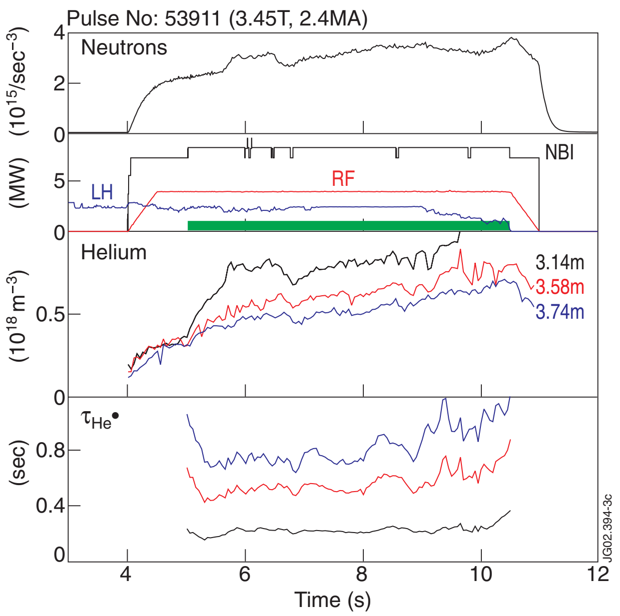

Figure 3: ITB discharge with identical current profile evolution and heating power as the discharge shown in Figure 1 up to=4.8 sec. With 1 MW of He beams (green), the edge density (not shown) is controlled for 5sec, while the pumping speed for He decreases during this time as indicated by the slight increase of the He density in the core. The formation of the q=3 ITB at t=5.6 and its collapse can be observed in the He density profile shape. A slight increase of τ_{He} can be observed in the core which is reflected in the global τ_{He}*.*

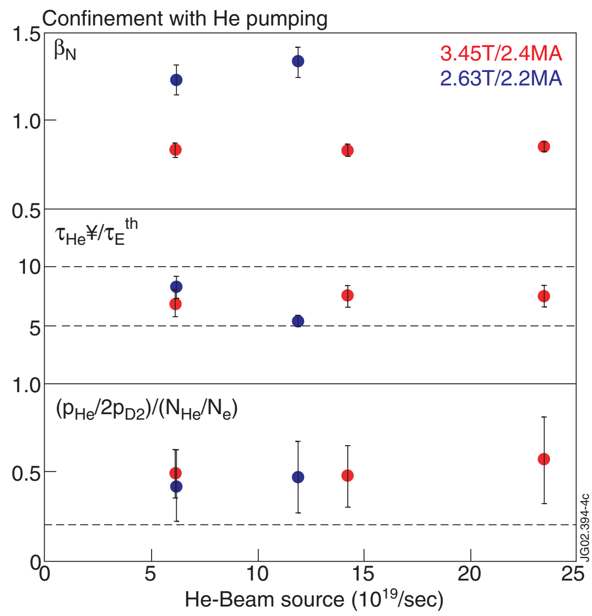

Figure 4: Overview of results for $\tau_{He}*/\tau_E^{th}$ and He enrichment factor η with He pumping for two reversed q profile scenarios. The best value for $\tau_{He}*/\tau_E^{th}$ was obtained for the 2.63T/2.2MA discharge shown in Figure 2, because of its improved energy confinement as indicated by its value of β_N = 1.4. The heating power to form an ITB with very high β_N at 3.45T/2.4MA (red) as in Figure 1 while retaining edge density control was not available due to the conversion of half the beams to He, and only core ITBs were obtained as shown in Fig. 3.