JET Experiments in Deuterium-Tritium

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A key aspect of fusion research is operation with the deuterium-tritium (DT) fuel mixture of a future fusion reactor. The Joint European Torus (JET) was designed from the outset for such operation and is now the only device capable of using DT. In fact, the first ever significant amount of controlled fusion power was produced in the Preliminary Tritium Experiment (PTE) in JET in November 1991 when a plasma containing a dilute fuel mixture of just 11% of tritium in deuterium produced (*see figure* 1) a fusion power P_{fus} peaking at 1.7 MW and averaging 1 MW over 2 seconds, and a fusion power gain (*see Parker, chapter 4.3*) $Q_{in} = P_{fus}/P_{in} = 0.12$, where P_{in} is the input power. In the period from 1993 to 1997 the Tokamak Fusion Test Reactor (TFTR) at Princeton in the USA operated with DT mixtures and, using 50% tritium in deuterium, produced 10.7 MW of fusion power, with $Q_{in} = 0.27$. During May-June and September-November 1997, JET resumed DT operations with a broad-based series of experiments (DTE1) which addressed specific DT issues related to fusion power production, physics and technology for ITER (*see Parker, chapter 4.3*) and a reactor.

Fusion power demonstration

The high confinement H-mode (*see Campbell, chapter 2.1*) when heated at moderate density by high power neutral beam (NB) injection results in the plasma ions being much hotter than the electrons. This hot-ion H-mode is the traditional mode of high performance in a tokamak but is transient, being terminated by an MHD instability in the plasma edge (edge localised mode, ELM). During DTE1 records were set in a hot-ion H-mode discharge for fusion power, peaking at 16.1 MW and remaining above 10 MW for 0.7 seconds, with fusion power gain $Q_{in} = 0.62$. At the time of peak performance the energy content W was still increasing and the ratio of fusion power to net input power $Q_{tot} = P_{fus} / (P_{in} - dW/dt) = 0.94 \pm 0.17$, the value which Q_{in} would reach if a similar plasma could be obtained in steady state.

These discharges also validated the calculated factor of 210 between DD and DT fusion power, provided valuable information on controlling the DT mixture and showed clear plasma self-heating by the alpha particles produced by the DT fusion reaction. In particular, specially designed experiments in which the plasma mixture was varied from pure deuterium to nearly pure tritium provided an unambiguous demonstration of alpha particle heating, with the highest electron temperature showing a clear correlation with the maximum alpha particle heating power and the optimum DT mixture (≈40:60). In general these plasmas were MHD quiescent and, in agreement with theoretical predictions, showed no indication of Alfvénic instabilities driven by alpha particles (*see Campbell, chapter 2.1*).

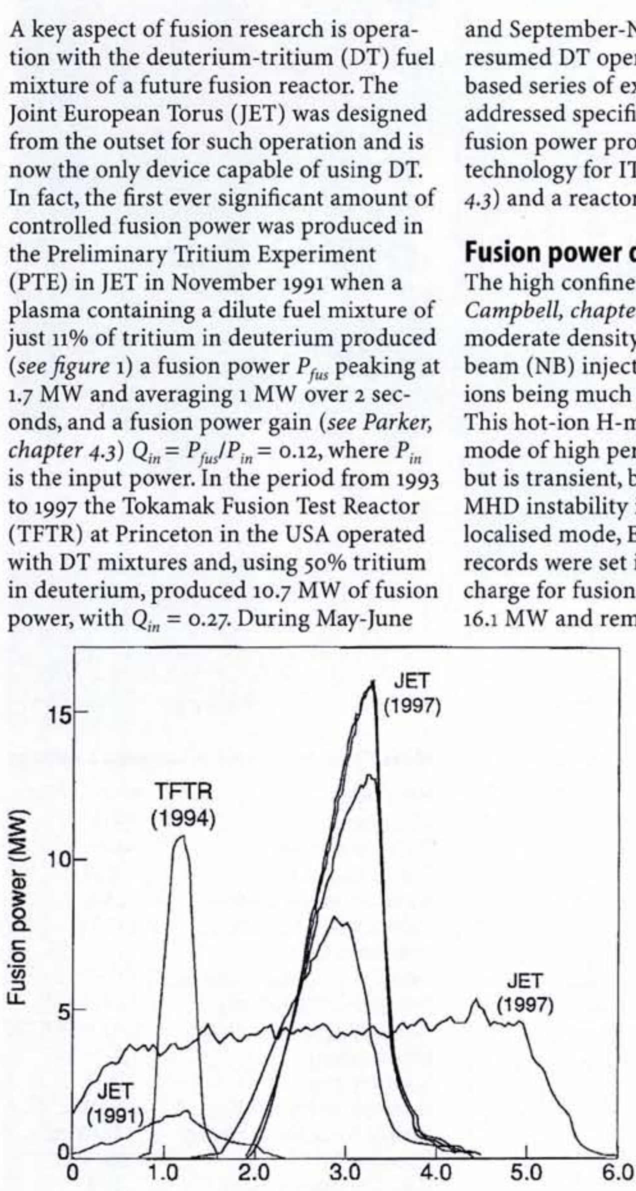

FIG 1 Fusion power development in JET and the Tokamak Fusion Test Reactor

Standard operating conditions

The ELMs which limit peak fusion performance in the hot-ion H-mode can also help maintain steady plasma conditions, albeit under conditions of lower fusion performance. Such an ELMy H-mode with regular, repetitive ELMs is foreseen as the standard mode of ITER operation and, during DTE1, the first ELMy H-mode experiments in DT were carried out. In particular, a steady-state discharge with the ITER shape and q-value and an input power of 24 MW produced a record fusion energy (21.7 MJ) and a fusion power gain $Q_{in} \approx 0.18$ for the full duration (3.5 seconds) of the applied heating power. More generally, the major physics objectives for DTE1 were the evaluation of ITER reference ion cyclotron resonance frequency (ICRF) heating scenarios and the effect of isotopic mass (A) on the threshold power and confinement of the ELMy H-mode.

In 50:50 DT and tritium-dominated plasmas with a minority concentration of ^{3}He, strong heating of the plasma ions was observed, leading to ion temperatures up to 13 keV. A minority concentration of deuterium in a tritium plasma at a power level of 6 MW also produced strong ion heating and a steady-state record value of $Q_{in} \approx 0.22$ for more than 2.5 seconds. These results are in excellent agreement with code calculations which extrapolate well for efficient bulk ion heating on the way to ignition in ITER.

The threshold power for access to the

Why DT?

Deuterium and tritium will be the fuels of the first generation of fusion power stations because the DT reaction has the largest fusion cross-section at the temperatures both foreseen for such a reactor and already realised in present-day laboratory experiments.

H-mode is a key issue for ITER and its dependence on isotopic mass was determined from JET experiments in which the DT mixture was varied from pure deuterium to nearly pure (90%) tritium, together with pure hydrogen experiments which were performed soon after DTE1. The H-mode threshold power was shown to have roughly an inverse dependence on isotopic mass. This is very significant since, in comparison with previous results obtained in deuterium, it predicts a 33% reduction in the power needed to access the H-mode in pure tritium (for example, during the start-up of a discharge) and a 20% reduction in the power needed to maintain H-mode conditions during high fusion-power operation.

Energy confinement in ELMy H-modes is not understood theoretically, but good empirical scalings have been obtained from similarity experiments (basically, the 'wind tunnel' approach) which match all of the dimensionless parameters of an ignited ITER, except for the ratio of larmor radius to size. These experiments show that the global energy confinement time extrapolates to ignition conditions in ITER (*figure* 2) and depends only weakly on isotopic mass. This can be interpreted by separating the plasma into core and edge contributions determined by different physical processes, with different mass dependences which, overall, give little mass dependence and can be related to theory.

Advanced operating conditions

The active control of plasma pressure and current profiles in deuterium discharges in JET and other tokamaks has led to significantly better fusion performance than the ELMy H-mode. A key feature of these optimized shear scenarios is a strong transport barrier inside the plasma within which energy transport losses are reduced towards the lowest theoretical levels (neoclassical transport). During DTE1, JET demonstrated, for the first time, the formation of strong internal transport barriers in DT. Furthermore, these barriers were established with similar powers to those required in DD, in contrast to the lower H-mode threshold power found in DT. In addition, the peaking of the plasma pressure profile was successfully controlled close to the maximum permitted by pressure gradient-driven stability limits and, although full optimization was not possible in the time available, 8.2 MW of fusion power was produced.

Tritium handling

The technology mission of DTE1 was to demonstrate the first industrial-scale plant—the Active Gas Handling System (AGHS)—for the closed cycle supply and processing of tritium. During DTE1, the JET torus was pumped continuously through the AGHS and was supplied with DT by the gas introduction and NB systems. The tritium was stored in uranium beds and processed in the AGHS to a purity of 99.4% by gas chromatography. In contrast to the PTE, when the total amount of tritium available was 0.2 g, there was no equivalent restriction for DTE1. The site inventory of 20 g of tritium was processed eight times by the AGHS, making the equivalent of 99.3 g of tritium available for DTE1.

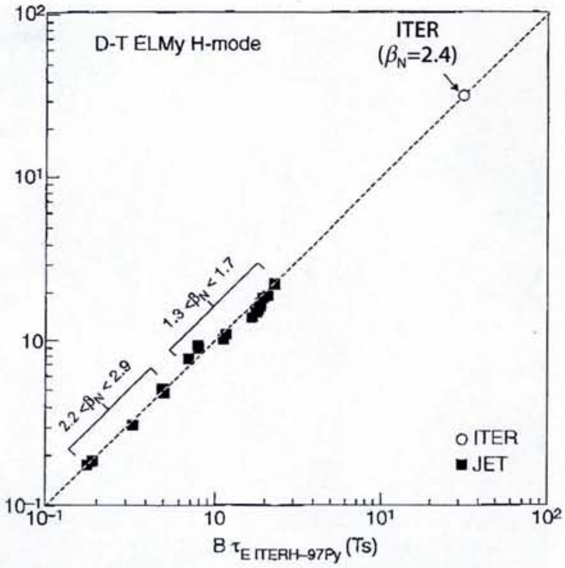

FIG 2 Thermal energy confinement time of DT pulses plotted in normalized form against the normalized ITER scaling, together with the value expected for ignition conditions in ITER

Nearly complete tritium recovery (> 98%) was achieved for the NB injector which operated in tritium, but about 30% of the tritium input to the torus was retained in the torus. Following the completion of the tritium experiments, the experimental campaign continued for about 2 months with operation with deuterium and hydrogen, after which the tritium inventory in the torus had fallen to 6 g, about 17% of the tritium input to the torus. This was over three times larger than had been expected from the tritium retention results of the PTE, and has been related to carbon films, saturated with deuterium and tritium and found in cold regions of the divertor. While most of the JET vessel was heated to 320°C, these cold regions, shadowed from direct contact with the plasma, were cooled to ≈50°C, allowing stable films to form with more than 40% hydrogen concentrations in carbon. (In contrast, at the time of the PTE, *ie* before the installation of a divertor, the whole vessel was maintained at 300°C.) The processes leading to the high-level of carbon erosion needed to form the films are still under investigation, and the location of the in-vessel tritium inventory is expected to be identified following post-mortem analysis of the flakes and in-vessel tiles.

Implications

These recent JET achievements add significantly to establishing the potential of fusion as a new and clean energy source. The DTE1 experiments set records in fusion power and fusion power gain, and the observed plasma self-heating by the alpha particles produced by the DT fusion reactions demonstrated the process by which ignition and thermonuclear burn will occur in ITER and in a reactor. The ICRF heating and H-mode threshold power and confinement studies in DT have allowed more accurate assessments of the heating requirements and ignition margin for ITER. The observed reduction in the H-mode threshold power with increasing isotopic mass increases the operational flexibility of ITER and the confinement studies confirm the ignition capability of ITER. The optimized shear results show that this operating regime can be established in DT and could, therefore, become a serious contender for steady-state high performance operation in a reactor. Extrapolation of the tritium retention results would result in unacceptably high tritium inventories in ITER (*see Raeder, chapter 4.1*), and the ITER divertor needs to be re-designed to take this fully into account. All these results confirm the lead position of JET and Europe in fusion research, and it is clear that JET will remain, for many more years, the most valuable support for ITER or any other next-step tokamak.

Further reading

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