OV1/2 XA9950711

PHYSICS OF HIGH PERFORMANCE JET DIVERTED PLASMAS IN D-T

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Since the last IAEA meeting, JET has completed studies of the more closed Mark IIA pumped divertor and carried out a series of deuterium-tritium (D-T) experiments (DTE1). These set new world records for fusion performance in the ELMy H-mode, the optimised magnetic shear regime and the ELM-free H-mode, and addressed crucial D-T issues of H-mode threshold, operating space, confinement, RF physics, Alfvénic instabilities, α-particle heating and technology for ITER.

The H-mode threshold power has been determined in deuterium plasmas (up to 4.2MA/3.8T), in plasmas with D:T mixtures of 40:60 and 10:90, and in hydrogen, and is found to scale inversely with atomic mass. Thus, the predicted threshold power for ITER is reduced by 33% in tritium (eg. during start-up) and 20% for high fusion power operation, thereby increasing operational flexibility. The edge electron density and temperature show no hysteresis between the L→H and H→L transitions, but show an upper boundary for Type I ELMs which is interpreted as an edge pressure gradient limit over a width which scales as an ion poloidal Larmor radius. The pedestal pressure increases with isotope mass, and this is interpreted as being due to the barrier width increasing. There is evidence from a comparison of ELMs with NB and ICRF heating that this width is determined by fast ions.

Energy confinement in the standard ITER steady state ELMy H-mode follows the ITERH-EPS97(y) scaling for a wide range of JET conditions (1-4.5MA, 1-3.8T, including D:T mixtures of 50:50). The D-T pulses, which consist of ρ^* scans at the ITER β_N (=2.2) and at β_N=1.3, a high β_N (=2.9) pulse, and a high fusion yield low q_{95} (≈2.6) pulse, are all well-fitted by this scaling, giving confidence that its close to gyro-Bohm ρ^* dependence is satisfied in D-T, which implies ignition in ITER. However, higher than Greenwald densities would be required for ignition, and energy confinement in JET with strong gas puffing degrades above 80% of the Greenwald density.

A weaker mass dependence of confinement than the $A^{0.2}$ of ITERH-EPS97(y) would be a better fit to the data and is consistent with gyro-Bohm transport ($A^{-0.2}$ dependence) in the bulk plasma, modified by a strong positive mass scaling of the pedestal energy. The gyro-Bohm nature of the bulk plasma is confirmed by TRANSP calculations and trace tritium experiments.

All ICRF heating candidate schemes for ITER were tested during DTE1, demonstrating strong bulk ion heating for both deuterium minority heating in a tritium plasma and ^{3}He minority heating in a tritium plasma. With 6MW in a D:T mixture of 10:90 at 3.7MA/3.7T, the first scheme produced 1.6MW of fusion power and a steady-state Q=0.22 for nearly 3s, terminating only when the power was switched off. The fusion power is in excellent agreement with PION code calculations, giving confidence in the predictions for ICRF heating in ITER.

The second scheme with 6.5% of ^{3}He in a 3.3MA/3.7T tritium plasma gave T_i=13keV and T_e=12keV with 7.6MW. In addition, second harmonic tritium heating was found to couple mainly to electrons on JET, but is expected to predominantly heat ions on ITER because the power density will be lower than on JET.

The ELMy H-mode set world records for high fusion power duration and energy (4MW for ≈4s and 21.7MJ at 3.8MA/3.8T) and the ratio of the fusion energy produced to the input energy was 0.18 over 3.5s (≈8τ_E). Performance was limited to β_N=1.3 by the available additional heating power (≈27MW).

In the optimised shear regime, internal transport barriers (ITBs) were formed in D-D with typically 18MW of NB and 6MW of ICRF heating. The central magnetic shear is low or slightly reversed, q(0)=1.5-2, the central pressure is high (up to 3.8bar) and close to the ideal MHD stability limit for most of the heating pulse, and the ion heat transport inside the ITB can be reduced to neoclassical levels. Even though the scenario had to be modified in D-T (largely due to the lower H-mode threshold power), strong ITBs were established for the first time in D-T (the threshold was not markedly different from that in D-D), and 8.2MW of fusion power was produced; full optimisation (the tritium concentration (≈30%) and β_N (≈1.9) were relatively low, and T_i (≈40keV) was high) was not possible within the imposed neutron constraints. A quasi steady-state discharge with both an ITB and an edge transport barrier was also produced, but will require considerable further development to justify reactor operation at reduced plasma current.

The ELM-free H-mode set world records in D-T fusion performance, with 22.3MW of NB augmented by 3.1MW of ICRF heating producing 16.1MW of fusion power and a ratio of fusion power to plasma input power of 0.6 (if a similar plasma could be obtained in steady state, the equivalent Q would be ≈0.9). Projections of D-T performance from D-D experiments were validated, the factor of 210 (expected from cross section ratios) between D-D and D-T fusion powers being realised. Magnetic fluctuation spectra showed no evidence of Alfvénic instabilities driven by α-particles, in agreement with the normalised α-particle pressure, β_α, being almost a factor of two below the instability limit. Clear evidence of α-particle heating was demonstrated, with the highest electron temperature showing a strong correlation with the maximum α-particle heating power at the optimum D:T mixture of ≈40:60, whilst the global energy confinement showed no significant isotope dependence when the tritium concentration was varied from 0% to 90% in otherwise similar discharges (3.8MA/3.4T, 10.5MW of NB heating). The α-particle heating is consistent with classical expectations for α-particle confinement and heating in MHD stable plasmas.

DTE1 also provided valuable operating experience with the key ITER and reactor-relevant technologies of tritium supply and processing, D-T mixture control, and tritium retention and clean-up. The technology mission of JET continued with the fully remote handled installation of the Mark II Gas Box divertor in an activated environment. New experimental results from this third stage of the JET divertor programme for ITER will be reported in the paper.