RESULTS FROM THE LAST DD AND DT JET CAMPAIGNS IN THE FRAMEWORK OF THE EUROFUSION TOKAMAK EXPLOITATION ACTIVITY

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The Overview reports on the results from JET-ILW (W divertor, Be first wall) during its final two years, focusing on physics topics and plasma scenarios relevant to ITER and DEMO. Building on knowledge from the DTE2 campaign, the program culminated in the DTE3 campaign, providing unique insights for future burning plasmas. During this period, the JET scientific program was part of a broader Tokamak science initiative by EUROfusion, aiming for coordinated use of European Tokamaks. JET's unique characteristics in size, power, and isotope operation expanded the parameter space, enhancing confidence in extrapolating plasma scenarios to ITER and DEMO. JET's scientific campaigns, including DT operation capabilities, laid the foundation for extrapolating plasma scenarios, covering core-edge integration, pedestal physics, isotope effects, W screening, no-ELM scenarios, plasma control, and fuel retention.

JET ITER baseline plasmas[1] addressed the core-pedestal-exhaust integration in deuterium (D-D) and in deuterium-tritium (DT) reaching a partially detached plasma, while keeping a hot pedestal ($T_{i,ped}$=1.5 -1.9keV) and high confinement ($H_{98(y,2)} \geq$ 0.85-0.98), extending the scenario into wide current range (2.5MA-3.2MA). The scenario, close to the foreseen ITER shape, investigated a high triangularity plasma, with both the strike points sitting on the vertical tiles and q_{95}=2.7-3.3 exploiting Ne impurity seeding as tool for heat flux mitigation. As Ne-seeding increases, the confinement improves compared to unseeded high-fuelled plasmas, primarily due to enhanced pedestal pressure, core density peaking, and reduced W core contamination. Beneficial isotope confinement scaling allowed the achievement of a Ne-seeded integrated scenario at 3MA in DT with partially detached divertor (P_{in}=34MW, f_{gw}=0.75, β_N ~2) with stationary conditions over 20 energy confinement times. On-going analysis and modelling activities are taking place to understand the complex interplay of underlying physics governing the core, pedestal and exhaust integration.

Understanding the **source and transport of tungsten (W)** in high-performance plasma is crucial, especially with ITER Organisation's decision to use W for the first wall. ITER plasmas are expected to have strong neoclassical pedestal screening of W due to high ion temperature and low density gradients. Leveraging on previous observations [2] W screening efficiency have been explored in DD and DT hybrid plasma scenarios with improved data quality and further neoclassical model investigation [3] . Tailoring of NBI heating and gas fueling schemes allowed achievement of low pedestal gradient, with high ion temperature (up to 3 keV), and low collisionality, while avoiding W erosion and accumulation. The pulse design was adapted for DT mixed isotope discharges, considering known isotope effects on ELM frequency and size. The FACIT code is being used to understand whether the observed experimental screening can be attributed entirely or partially to neoclassical effects. Studies on W erosion aimed at distinguishing net and gross erosion and assess the impact of different hydrogen isotopes and impurity content. Findings indicate increased prompt re-deposition at increasing magnetic fields and higher sputtering rates with increasing isotope mass, with no significant changes in erosion and deposition patterns for different isotope compositions. In seeding discharges a strong role of Ne in increasing sputtering yield has been observed.

At expected ITER plasma conditions, the pedestal is expected to be limited by peeling modes with a large ratio of n_e^{sep}/n_e^{ped} [4] . For the first time in a metallic device, **peeling limited pedestal** were achieved in JET contributing to current model validation and boosting the confidence towards ITER extrapolation[5] , . JET achieved peeling limited scenarios at high q_{95} (up to 8.5), via a combination of low current and large toroidal field (up to 1.4MA and 3.8T). exploring ITER relevant parameter space (with $\nu_{ee^*} \approx 0.15$ and $\rho^* \approx 0.002$) with most unstable mode numbers observed between $n = 1 - 5$. Density scans showed a positive correlation between pedestal pressure and density, with no substantial dependence on separatrix density, in contrast with JET ballooning-limited behavior. Isotope mass scans, from pure D to T-rich plasma, confirmed that, similarly to what observed in ballooning limited plasmas, increasing isotope mass enhances pedestal density and pedestal pressure without significantly affecting temperature This confirms the beneficial isotope confinement improvements also in pedestal condition closer to the ITER foreseen one.

While ITER plans to operate with RMP-mitigated scenarios, DEMO-class devices require robust small-ELM/no-ELM scenarios compatible with exhaust solutions and high separatrix density. Recent JET operations have been crucial in scaling promising DEMO no-ELM alternatives within the European fusion program. The **quasi-continuous exhaust (QCE)** regime, naturally free of type-I ELMs, combines high-density operation with high normalized stored energy and H-mode grade confinement. Implementing QCE on JET [6] benefited from previous work on ASDEX-Upgrade and TCV. Key factors include high shaping and large separatrix density, with proven compatibility for mixed-isotope operation, confirming a trend of larger pedestal density gradient in DT. JET's parameters, with unprecedented low υ_{ped}^* for a QCE regime and confirmed predictive modelling capabilities, indicate QCE as a likely candidate for future devices like ITER and DEMO [7] .

The **X-point radiator regime (XPR),** featuring confinement-mode grade confinement and high radiation, has been investigated as a candidate scenario for DEMO[8] . This scenario is characterized by the establishment of a cold and dense plasma within the confined region near the X-point. Maintaining the vertical position of the XPR region is crucial to avoid radiative collapse and ensure safe operation with H-mode-like confinement. JET's exploration of XPR benefited from developing real-time control of the radiation front using sensors and actuators compatible with DT operation. Well established Dynamical System Identification techniques allowed a rapid and successful deployment of such a control system. Stable performance was achieved with mixed impurities (Ar and Ne), and the scenario proved to be compatible with DT operation, showing in mixed isotope operation benefits in terms of overall confinement and stored energy. The scenario leads to the highest radiated power fractions reached at JET, exhibits mitigated ELMs without detrimental effect on plasma performance and proved resilience to transients as for example power cuts or pellets.

The last DT operation at JET investigated as well outstanding open from DTE2 operation. Novel ICRF heating techniques to increase bulk-ion temperature were tested, with a combination of intrinsic ^{3}Be and Ar impurities, exploring potential schemes for ITER exploitation Significant improvement of thermal ion confinement has been obtained with MeV-range fast ions and destabilized Alfvén Eigenmodes (AE)[9] expanding present knowledge in burning plasma condition. Main scenarios for sustained power developed in DTE2, were further explored extending JET baseline operation at 3MA and re-establishing the T-rich plasma scenario, setting a new fusion energy record of 69 MJ. Advanced real-time controllers addressed critical fusion reactor issues, including transitions into and out of burn and H-mode, H-mode plasma exhaust control, and identifying under-performing discharges. Effective closed-loop D/T fuel ratio control was demonstrated with Tritium and Deuterium injections via gas valves or pellets.

Studies on fuel retention and removal techniques continued using JET's DT mode. Measuring fuel retention via gas balance proved challenging in metallic devices, with no significant isotope effect observed on global in-vessel retention. The first in situ T retention measurements were performed using laser-based diagnostics. Laser-Induced Desorption Quadrupole Mass Spectrometry (LID-QMS) monitored DT fuel inventory during DTE3 and the T clean-up campaign. Laser-Induced Breakdown Spectroscopy (LIBS) investigated fuel retention and deposit composition on wall components. The T clean-up campaign post-DTE3 tested fuel recovery techniques such as baking, ion cyclotron wall conditioning (ICWC), and dedicated plasma discharges, achieving a 0.02% T content target in approximately 4 weeks.

After 40 years, JET ceased operations in late 2023. The data collected under near-burning plasma conditions will be crucial for future fusion research, aiding ITER and DEMO design.

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