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The Scientific Case for a JET D-T Experiment

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ABSTRACT.
After the first high power D-T experiment in JET in 1997 (DTE1), when JET was equipped with Carbon PFC's, a proposed second high power (up to ~40MW) D-T campaign (DTE2) in the current Be/W vessel will address essential operational, technical, diagnostics and scientific issues in support of ITER. These experiments are proposed to minimize the risks to ITER by testing strategies for the management of the in-vessel tritium content, by providing the basis for transferring operational scenarios from non-active operation to D-T mixtures and by addressing the issue of the neutron measurement accuracy. Dedicated campaigns with operation in Deuterium, Hydrogen and Tritium before the D-T campaign proper will allow the investigation of isotope scaling of the H-mode transition, pedestal physics, heat, particle, momentum and impurity transport in much greater detail than was possible in DTE1. The D-T campaign proper will include validations of the baseline ELMy H-Mode scenario, of the hybrid H-mode and advanced tokamak scenarios, as well as the investigation of alpha particle physics and the qualification of ICRH scenarios suitable for D-T operation. This paper reviews the scientific goals of DTE2 together with a summary of the results of DTE1.

1. INTRODUCTION

JET conducted a first D-T experiment, the 'Preliminary Tritium Experiment' (PTE) in 1991 [1]. Using only 0.2g of tritium, it featured a number of trace tritium pulses and only two pulses with a significant tritium content ($n_T/n_e \leq 11\%$). It's main aims were to validate the JET transport codes, assess the tritium retention and demonstrate safe tritium handling and removal in view of the DTE1 experiment in 1997, as well as to demonstrate 1 MW of fusion power, achieving 1.7MW. Another small experiment, the 'Trace Tritium experiment' (TTE, $n_T/n_e \leq 3\%$) took place in 2003, with the aim of characterizing Tritium particle transport in a variety of operational scenarios [2,3]. JET's only full power D-T experiment so far, DTE1 [4-7] achieved up to 16MW of fusion power transiently in hot-ion H-modes corresponding to $Q = P_{fusion}/P_{in}$.=0.6, 8MW (Q = 0.2) in transient discharges with an ITB and about 4MW for a duration of over 4 s in ELMy H-mode, corresponding to Q=0.2. Only the latter is an ITER scenario. It demonstrated alpha particle electron heating in line with expectations [8] and investigated several potential ITER ICRH methods, including the currently favoured 2nd harmonic tritium scenario [9,10]. It also provided insights in the isotope dependencies of H-mode access [11], confinement [12,13] pedestal [14] and ELM behavior [15]. One of the most important lessons of DTE1 was arguably the realization of the substantial tritium retention in a device equipped with Carbon PFC's [16] and the difficulty of removing tritium trapped in carbon co-deposits [17,18]. This motivated the redesign JET PFC's, referred to as the 'ITER-like Wall' (ILW, [19]), which uses Be PFC's in the main chamber and tungsten for the divertor and was successful in reducing retention rates by an order of magnitude [12].

Whilst DTE1 provided essential experience for DT plasma operation, it had a number of shortfalls, such as a lack of machine time for isotope studies in Tritium, a lack of discharges in Advanced Tokamak (AT) scenarios for studying alpha particle instabilities at q_{min}~2, the poor resolution of profile diagnostics and the absence of alpha particle diagnostics. DTE1 was mainly focused on achieving high performance (in terms of Q) in transient scenarios, which are not relevant for ITER, let alone for a future reactor. By contrast, the aim of the proposed DTE2 is specifically to help preparing for future ITER operation in the current all-metal ILW JET vessel by validating ITER operational scenarios (baseline ELMy H-mode, hybrid and AT), documenting the effects of isotope mass, investigating alpha particle physics, demonstrating tritium handling, inventory control and removal and by testing ICRH schemes, validating ITER diagnostics [21-23] and addressing a range of technology tasks [24]. This approach is expected to help mitigating risks to ITER operation, potentially leading to substantial savings in time and resources. In DTE2 JET will have significantly higher NBI and ICRH heating power than in DTE1, a D-T compatible pellet injector for fuelling and ELM control as well as upgraded and new diagnostics for plasma parameters [21] and for fusion products [21-23]. Essential diagnostics tests for ITER include an in vessel neutron calibration with a 14MeV neutron source [21].

It is planned to devote a significant amount of experimental time to address the issues of isotope scaling by including Hydrogen and Tritium campaigns lasting ~2 months each, prior to a ~3 months D-T campaign with close to 100 high power discharges. The breadth of the scope of DTE2, together with the higher available power and NBI injection energy (120keV) and the longer duration of the heating pulses lead to a required neutron budget several times the one available for DTE1, justifying a proposed neutron budget of 1.7×10^{21} 14MeV neutrons for DTE2 and equal to the maximum still allowed to be produced at the JET site. The main differences between DTE1 and DTE2 are summarized in table 1. The use of Tritium, the production of an unprecedented 14 MeV neutron yield, together with the preparation and implementation of safety measure, will provide the opportunity to perform a number of technological studies in support of ITER operation and safety, discussed elsewhere [24]. In the following sections we will discuss the scientific scope of DTE2 in the light of experience gained in DTE1.

2. SCIENTIFIC SCOPE AND DTE1 RESULTS

2.1 TRITIUM RETENTION AND REMOVAL

During DTE1, 35g of tritium were introduced into the JET vessel, of which about 11.5g remained after the last tritium pulse [16]. After DTE1, the tritium in-vessel inventory decreased to 6.2g or 18% of total T input following a series clean-up pulses in Deuterium [18]. The amount of Tritium recovered per pulse dropped by one order of magnitude over the 20 pulse series to below 0.1% of the remaining inventory in the vessel. The application of ICRH transiently improved Tritium removal rates. Most other clean-up efforts, such as ‘deuterium soaking’ (no plasma), Glow Discharge Cleaning and divertor baking at 135^0C were ineffective [16]. Venting, with a vessel temperature in the range 120-150^0C for 2 days, removed a further 0.6 g of tritium in form of HTO. Further venting at room temperature for several months during the post DTE1 shutdown released another 1.9 g of Tritium in the form of HTO. The remaining 3.7g of Tritium (10.6% of the tritium introduced) was mostly trapped in the form of Carbon co-deposits in cooled parts of the divertor, out of view of the plasma. In-vessel inspection after the campaign showed that most of the deposits had flaked off and fallen below the divertor [17]. A small amount of tritium, estimated to be about 0.2g, was found to have penetrated the bulk of carbon PFC's to depths of more than 3cm [25]. This may seem a negligibly small amount, however, given that such bulk retention leads to the build-up of a Tritium reservoir which is inaccessible to any form of surface treatment, it may represent a serious concern for an eventual reactor, where PFC exposure to tritium is continuous, rather than only pulsed, as in JET and even ITER.

One of the main tasks for the recent and current JET work programs has been to document and understand the retention of hydrogen isotopes in the ILW environment. The very positive results so far [18] will be complemented by isotope retention, exchange and removal experiments in Hydrogen and eventually also in Tritium. Whilst the physics of retention and removal is believed to be the same for all three isotopes, only experiments in Tritium will provide a demonstration of tritium accountability, a validation of retention measurements performed with Deuterium and Hydrogen and an accurate test of different removal techniques. JET needs 60g of Tritium on site for DTE2, which would be cycled 8-16 times through the vessel and NBI systems. In addition to the removal techniques tested in DTE1, JET will be able to test Ion Cyclotron Wall Cleaning [26] and divertor baking at 350^{o}C. Post-DTE2 sample analysis will provide measurements of long term Tritium retention in PFC's in different locations, in dust, as well in bulk materials. Only the usage of Tritium, measured with activation techniques such as employed in ref. [25] allows to detect the small amounts of the Hydrogen isotope that have diffused deep into PFC's and other in-vessel components. Other technological studies, relevant to ITER safety, will investigate the tritium outgassing from PFC materials and the release of airborne tritium during vessel venting.

2.2. ISOTOPE EFFECTS

The D-T campaign proper will be preceded by dedicated isotope campaigns in Deuterium, Hydrogen and, uniquely, in Tritium. Unlike DTE1 however, these isotope campaigns will be very extensive and aimed at a thorough characterization of the isotope scaling of H-mode access, pedestal and core energy confinement, as well as particle, impurity and momentum transport. DTE2 data will provide stringent tests for the most advanced gyrokinetic transport codes available today, enabling better predictions of the performance of ITER and future reactors.

DTE1 showed a clear reduction of the H-mode threshold power inversely with effective ion mass defined as $A_{eff} = (n_H + 2n_D + 3n_T)/(n_H + n_D + n_T)$, both in NBI and ICRH heated discharges [11]. Access to good confinement type I ELMy H-mode performance also showed an $1/A_{eff}$ scaling and type I ELMy H-modes were not achieved in Hydrogen plasmas due to insufficient NBI power (10MW) in Hydrogen. The recently upgraded NBI system is now capable of providing up to 14 MW when both NBI injector boxes are operated in Hydrogen. In JET-ILW the power threshold in Deuterium was found to be lower in the ILW and to be sensitive to the shaping and strike point location [27]. Assessing the combined effect of the ILW and ion mass on the H-mode threshold and on high performance H-mode access will be one of the tasks of DTE2 and the associated isotope campaigns.

DTE1 results on global confinement scaling are somewhat uncertain with respect to ion mass scaling, owing mainly to the small number of discharges performed in Tritium and the low resolution of profile diagnostics. Whilst an analysis of the full set of available data confirmed an earlier international scaling law for ELMy H-modes [28], IBP97(y,2), with $\tau_{th} \propto A_{eff}^{0.2}$, an analysis only based on matched pairs of discharges with the same density and power yielded a mass exponent of 0.03±0.1, i.e. no discernible dependence [12]. Multi-machine analyses based on an extended dataset including JET DTE1 data (DB3v13) and aimed at reducing biases in IBP97(y,2) provided mass exponents in the range –0.04 to +0.16 depending on the selection of principal components included in the regressions [29]. Exponents in the range 0–0.2 are better than expected from Gyro-Bohm scaling ($\tau_{thGB} \propto A_{eff}^{-0.2}$). While an uncertainty of 0.2 in the mass exponents may seem small, it still translates to a ~30% uncertainty in Q_{DT} for ITER's target Q_{DT} of 10.

Interestingly, DTE1 confinement data were found to be supportive of a two term confinement scaling model with different exponents for the pedestal and the core [12]. Tritium H-mode plasmas had the highest pedestal-to-total stored energy fraction, up to 52%, as compared to a maximum of 42% for Deuterium plasmas. As a result, ELMs in Tritium plasmas were larger than in Deuterium plasmas (fig.1) at the same heating power, leading to stored energy losses as high as 18% and affecting the electron temperature to beyond mid-radius (Fig.2) [30,31]. These observations underline the urgency for the development of ELM mitigation strategies which are suitable for D-T operation in DTE2 and later in ITER.

Pedestals in Hydrogen were much smaller than in Deuterium. This was interpreted as a consequence of H-mode operation barely above the H-mode threshold in a type III ELMy regime, where lower performance is generally observed in Deuterium. As a result, DTE1 core confinement data had a mass exponent of -0.16, close to GyroBohm scaling, while the mass exponent for pedestal confinement was as high as 1. A later multi-machine analysis [32] however provided small positive mass exponents for both the core (0.2) and the pedestal (0.13). The large differences between these studies are attributed to poorly resolved and ill conditioned pedestal data in DTE1. It is instructive to compare DTE1 observations to recent experiments. Independent analyses of L-modes in DIII-D [33] and type I ELMy H-modes in JT60-U [34] have shown that the poor confinement of Hydrogen plasmas, as compared to Deuterium plasmas, is not merely due to operation in a type III ELMy regime. The non-linear simulations presented in ref. 33, which are in fair agreement with experimental data in Helium and Deuterium plasmas, show that Hydrogen confinement not only significantly under-performs Gyro-Bohm scaling, but is also lower than predicted by non-linear gyrokinetic theory. Although we are not interested in Hydrogen plasmas for fusion, predicting ion mass scaling using first principles models for all three isotopes will constitute both a challenge and a milestone for our understanding of transport in fusion plasmas.

2.3 ION CYCLOTRON HEATING IN D-T PLASMAS

All ICRH scenarios have their own characteristics and scenarios for plasmas with Tritium cannot be rehearsed in plasmas without Tritium. DTE2 would therefore have an important role in validating

ICRH scenarios for the D-T phase of ITER.

The $\omega = 2\omega_{cT}$ scenario is the most relevant scenario for ITER preparation in DTE2, but heating at $\omega = 2\omega_{cD}$ can also be of interest. Both these scenarios were tested in DTE1 [9] and the main features were reasonably well understood [35,36]. Since ICRH in DTE1 was mainly aimed at enhancing the performance of JET, further experiments should be aimed at studying physics aspects of direct relevance to ITER. ICRH calculations using the full wave code EVE [37] indicate that 2nd harmonic Tritium ICRH in JET (without additional NBI) has similar absorption properties as ITER in the current ramp-up phase, which is a phase where auxiliary heating should play an important role. Furthermore, absorption conditions representative of those in the ITER flat top phase can be approached by increasing the effective ion temperature by the presence of strong NBI, as foreseen in DTE2.

The absorption strength, as well as the ion heating fraction of the $\omega = 2\omega_{cT}$ scenario can be boosted by the addition of a small amount of ^{3}He, as observed in DTE1 for ^{3}He minority concentrations of 2-5%. This is particularly relevant for the ramp up phase where the $\omega = 2\omega_{cT}$ damping is fairly weak. When flat top conditions have been reached, the ^{3}He concentration can be allowed to diminish naturally. Calculations using EVE suggest that at little as 0.1% of ^{3}He is required to obtain comparable single pass absorptions in typical JET flat top plasmas without NBI and in ITER plasmas during ramp-up ($T_e(0)$~10keV, n_e~$4\times10^{19}m^{-3}$), with >70% of the power being absorbed on ^{3}He. Fig.3 demonstrates the similarity of the wavefields at $2\omega_{cT}$ during ITER startup and during the main heating phase at JET with 0.1% ^{3}He in both devices.

Another noteworthy scenario is the ‘Tritium rich D-minority’ scheme. In DTE1 this scheme led to a record Q=0.22 for ICRH only with 6 MW of D-minority ICRH in a plasma with 90% Tritium and 10% Deuterium [9]. This scenario may allow easier access to the H-mode in the early part of an ITER discharge, thanks to the favorable H-mode threshold scaling with ion mass and increased alpha power and hence heating power from the production of ~100keV reactive Deuterium ions. Later in the discharge, the Deuterium concentration could be raised to 50%. Other important scenarii to investigate in DTE2 may include Fast Wave Current Drive, minority Hydrogen heating and sawtooth control with ^{3}He ICRH near the q = 1 surface, as proposed for ITER [38]. The mission for DTE2 would also include the determination of optimum concentration for minority schemes and likely parasitic absorption by impurities and alpha particles.

2.4 FAST PARTICLE MODES AND ALPHA PARTICLE TRANSPORT

During DTE1, JET unfortunately had no alpha particle diagnostics and our experimental knowledge of alpha particle behavior stems essentially from the TFTR device [39-41]. The main outcome of TFTR experiments was that in the absence of MHD activity, such as sawteeth [41], tearing modes, kink modes and Kinetic Ballooning Modes, the alpha particle velocity and spatial distribution was consistent with classical slowing down and orbit physics, which includes first orbit losses, collisional diffusion and stochastic ripple diffusion [41-43]. Contrary to expectations for both TFTR [41,42] and JET [7,44], alpha driven Toroidal Alfvén Eigenmodes (TAE’s) were only observed in discharges with reduced or reversed magnetic shear and $q(0) \approx 2$, after the switch-off of the NBI. In TFTR, these TAE's did not produce measurable alpha particle transport [41,42].

In normal shear high performance D-T discharges, such as TFTR supershots and JET hot-ion H-modes, ideal MHD TAE modes are now understood to haven been stabilized by various damping mechanisms or, as seen in JET stability calculations using CASTOR, to have been absent from the TAE gap (i.e. non existent) due to the high pressure of the background plasma [44]. Kinetic TAE modes were present in JET according to CASTOR calculations [44], but were too strongly damped to become unstable, despite v_α/v_{Alfven}~1.6 and alpha normalized pressures β_α of up to 0.7%, approaching those expected for ITER (v_α/v_{Alfven}~1.9, β_α~1.2%).

While it may seem ironic that significant redistribution was only observed by well known MHD instabilities, such as sawteeth, rather than by TAE's, it would be erroneous to conclude on the basis of DTE1 and TFTR results that TAE's are unimportant for ITER. As a result of the ~4 times smaller ratio of alpha orbit width to major radius $\rho^*_\alpha = \rho_\alpha/R$, the TAE excited spectrum in ITER is expected to be peaked at much higher and hitherto unexplored mode numbers. These differences, arising from machine size and operating field, preclude a simple, direct extrapolation of JET results to ITER [45]. Instead, the entire theoretical frame work of fast particle instabilities in the presence of alpha particles and other fast ions needs to be validated by accurate measurements of mode spectra, damping and drive. The JET active TAE antennae, which can excite TAE's with toroidal mode numbers up to ~30, can measure the net damping (damping rate minus growth rate) of a wide range of stable TAE's, i.e. TAE's which are not detectable by passive magnetic probe measurements [46]. By the same token, these active measurements allow to distinguish between stable, damped modes and the absence of modes, e.g. resulting from the background pressure effect [44]. The independently phased antenna straps allow excitation of modes propagating in the co- and the counter toroidal directions, which interact differently with fast particles, allowing a separation of the damping and of the fast particle drive, both of which can then be compared to theoretical predictions. The TAE growth rates scale as q^2 and hence will depend on the operating scenario. Alpha driven unstable TAE's are most likely to occur in advanced tokamak (AT) scenarios with q_0,q_{min}~2. JET is now equipped with lost and confined alpha particle diagnostics capable of measuring alpha particle transport, be it due to TAE's or other MHD modes [21-23].

2.5 ALPHA PARTICLE HEATING AND OTHER ALPHA PARTICLE EFFECTS

Beyond the possible excitation of fast particle modes addressed above, alpha particles are expected to heat the electrons and may prevent heavy impurity accumulation as reported e.g. with Electron Cyclotron Heating in AUG and ICRH in JET [47]. They may have an undesirable stabilizing effect on sawteeth, leading to eventual large crashes and seed islands for Neoclassical Tearing Modes. If this is the case, one of the tasks of DTE2 would be to check if ICRH sawtooth de-stabilization can counteract the stabilizing effect of alpha particles [38].

Alpha particle electron heating in line with expectations from similar experiments in pure D using ICRH was observed in a dedicated set of transient hot ion mode discharges in DTE1, where the T/(D + T) ratio was varied from 0 to 92% [8]. The electron temperature was seen to increase by 0.9keV per MW of alpha heating, with a maximum central T_e increase of nearly 2keV (from ~10keV) for a 60% D/(D + T) ratio [5]. There was however a surprising, little known and even less understood ion heating effect in these discharges, as T_i was observed to increase by 2.6keV per MW of alpha heating (from ~13 to 18keV) and the overall confinement time was slightly higher at the largest alpha particle power [7], as shown in Fig.4. A similar observation appears to have been made on TFTR [48]. Classically slowing down alpha particles do not transfer any significant power to the thermal ions. A TRANSP transport analysis assuming classical orbit slowing down, i.e. pure electron heating by the alphas, indicated a reduction of ion diffusivities with alpha power, suggesting that the alpha particles may somehow have improved ion confinement, e.g. by promoting the formation of a modest transport barrier. Recent theoretical work, backed up by experimental evidence, suggests that fast particles, via their contribution to β, may have a profound effect not only on MHD, but also on confinement by stabilizing turbulence [49, 50]. Detailed investigations in DTE2, aimed at reproducing the effects seen in DTE1, should allow us to assess how important fast particle stabilization is likely to be in ITER and eventually in a reactor.

An intriguing alternative interpretation was suggested in the form of ion heating via Compressional Alfvén Waves (or other plasma waves in the ion cyclotron range of frequencies), excited by the alpha population [51]. These waves may gain energy through their interactions with fast ions and transfer it to the thermal ions in the form of ion cyclotron emission (ICE). No corresponding ICE measurement was available during DTE1, however ICE up to high harmonics of the ion cyclotron frequency (for the plasma edge at the LFS midplane) and clearly related to the density or pressure of fusion products, was observed in the JET PTE campaign and earlier[52], as well as in TFTR [51]. A direct transfer of power from the alpha population to the thermal ion population via plasma waves, especially if it could be controlled by externally imposed ICRH waves, as proposed by Fisch ('alpha channeling' [53]), would have multiple benefits. It would provide direct ion heating, it would reduce the alpha slowing down time and pressure and hence also reduce the undesirable effects of the alpha population, i.e. their likelihood of inducing fast particle and beta limit instabilities and their stabilizing effect on sawteeth, while allowing for a larger share of the total plasma pressure to be provided by the thermal population, thereby boosting fusion power for a given total operating beta, $\beta_{tot} = \beta_{th} + \beta_{fast}$. With a shorter slowing down time, alphas would also be less affected by periodical MHD induced redistributions and losses. The DTE2 campaign should aim at investigating these alpha particle effects in stationary conditions and in much greater detail than was possible in DTE1.

3. TOWARDS DTE2

Performance projections for the proposed DTE2 campaign, making use of the recently available NBI power upgrade (35MW/120keV) are so far based on Carbon Wall discharges produced before the change to the ILW. In the baseline scenario with $I_p = 4.5$MA and $B_T = 3.6$T, assuming $H_{98} = 0.85$, $Z_{eff} = 2$, as in a D reference discharge and for $P_{NBI} = 25$MW, a fusion gain factor Q ~0.2 is expected using TRANSP simulations. A range of predictions with $0.1 < Q < 0.4$ are obtained for AT scenarios with q_0~2 and Ip in the range 1.8-3.4MA. In Fig.5 we show fusion power predictions for a range of hybrid scenarios made using the in-house code JETFUSE for different values of the plasma current (blue and red lines and bars), based on a hybrid scenario discharge with $H_{98} = 1.3$ and $\beta_N = 3$. A realistic operating point has also been simulated by CRONOS [54] (yellow dot), corresponding to $Q = 0.45$.

The first results from the ILW phase, obtained in 2012, show a significantly lower Z_{eff} and somewhat lower H_{98} in baseline H-mode, resulting from a lower pedestal, than during the carbon phase, except when nitrogen seeding is used [55]. The most recent results, obtained in 2013, are encouraging, with higher H_{98} in both baseline and hybrid scenarios. In the hybrid scenario, $H_{98} = 1.4$ and $\beta_N = 3.4$ has achieved so far in ILW, which is equal to the best performing hybrids obtained with the Carbon Wall, however the duration of the high performance phase of hybrids needs to be extended. So far, at the time of writing, no AT scenarios have been developed with the ILW. The above projections should be taken as indicative, since performance simulations will have to be revised when more operational experience with the ILW will have been gained.

A tentative timeline for DTE2 and the associated isotope campaigns is outlined in Fig.6. Final scenario development, D reference discharges for isotope studies and a Helium campaign are to take place in 2015 and 2016. During the shutdown, Tritium non-compatible systems will be removed and, following a restart phase, the two NBI boxes will be converted to Hydrogen operation for the Hydrogen isotope experiments. The period of Hydrogen operation prior to experiments in pure Tritium assures that the neutron budget will not be affected by D-T neutrons resulting from residual Deuterons in the plasma, allowing for a long Tritium isotope campaign prior to DT operation, followed by tests of Tritium removal techniques. A final series of reference discharges in Deuterium will be produced, as required, to better match plasma conditions for isotope and scenario studies before a shutdown for retrieval of PFC samples for retention studies.

CONCLUSIONS

Whilst DTE1 was arguably the most significant milestone so far in the development of nuclear fusion energy, it left many open questions, particularly in relation to the ITER project, prompting the proposal of a second high power D-T campaign in JET. The proposed D-T campaign, 20 years after DTE1, offers a unique and ultimate opportunity to investigate fusion physics in Tritium and D-T plasmas before the first ITER D-T experiments at least 10 years later, as well as to test a number of crucial fusion technologies. The proposed campaign is to help minimizing risks to ITER, by demonstration the tritium management, by qualifying ITER operating scenarios and by demonstrating the feasibility of accurate calibrations and measurements of fusion products. Dedicated campaigns with operation in Deuterium, Hydrogen and Tritium will allow the investigation of isotope scaling of the H-mode transition, pedestal physics, heat, particle, momentum and impurity transport in much greater detail than was possible in DTE1, thanks to far superior diagnostics, providing a unique database for the development of predictive, theory based computational capabilities. The D-T campaign will include validations of the main ITER scenarios, i.e. the baseline ELMy H-Mode scenario, the hybrid H-mode and advanced tokamak scenarios, as well as the qualification of ICRH scenarios suitable for D-T operation. It will allow for a thorough investigation of alpha particle physics, including TAE physics, alpha particle transport and aspects of alpha particle heating which were observed in DTE1 and are not understood to this day. There can be no doubt that the next D-T campaign in JET will be every bit as exciting and fruitful as DTE1.

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	DTE1	DTE2
Year	1997	2017
14 MeV neutron budget	2.5×10^{20}	1.7×10^{21} (proposed)
Wall/Divertor	CFC/CFC	Be/W
NBI	~21 MW in D &T ~10MW in H	~35 MW in D & T ~14 MW in H
ICRH (H-mode)	2-4 MW	3-8 MW (includes ITER-like antenna)
LHCD	2-3 MW	2-3 MW
Pellets	Not available	D and H for pacing/fueling
ITER Scenarios	H-mode at q_{95}~3	H-mode at q_{95}~3, Hybrid, AT
Profile diagnostics	LIDAR Thomson scattering ΔR~10cm Δt~50-250 ms	High Resolution Thomson Scattering R~2cm, t~1-20 ms MSE, profile reflectometry
Fusion product diagnostics	2.5MeV-14MeV neutron cameras	New neutron & gamma detectors Active TAE antennae
Tritium in Active Gas Handling System / JET	20 g / ~100 g (incl. NBI)	60 g / 500-1000 g (incl. NBI)
Fusion Technology tasks	Long term retention CFC Activation samples	Long term fuel retention in Be/W Activation of ITER materials Radiation damage in functional materials Validation of neutronics codes (neutron streaming, shut down dose rates) 14 MeV neutron calibration

Table 1: Comparison of main JET capabilities in the DTE1 and DTE2 D-T experiments.

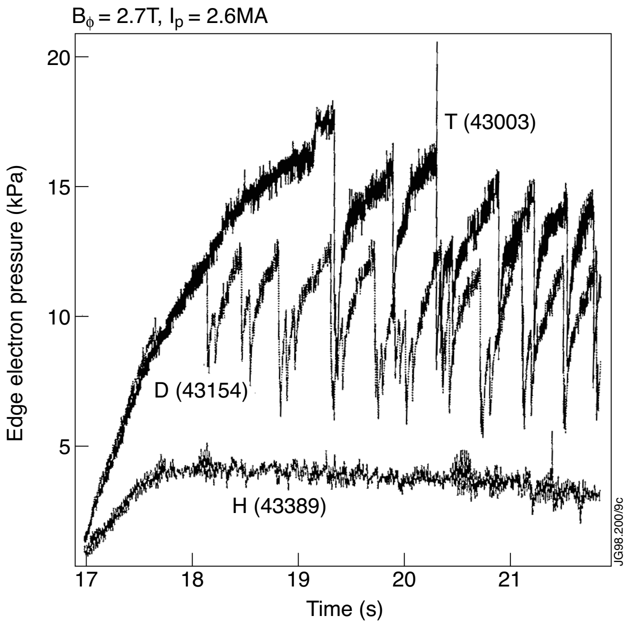

Figure 1: (left). Pedestal pressure evolution in DTE1 ELMy H, D and T discharges with 10MW of NBI.

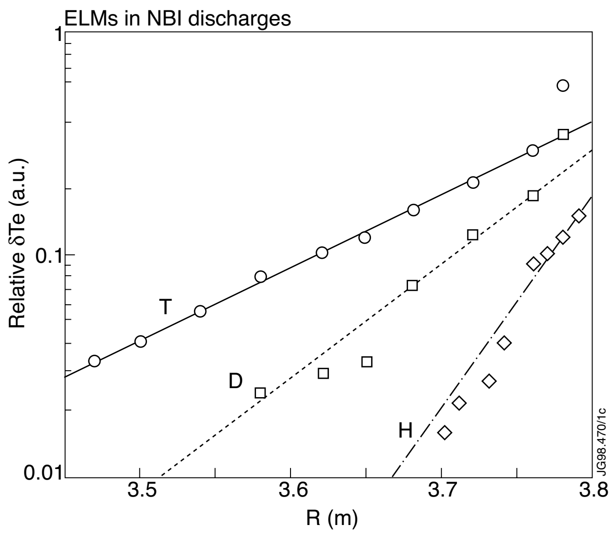

Figure 2: (right) Amplitude profile of T_e crashes due to ELMs in H,D and T discharges (from ref. 30).

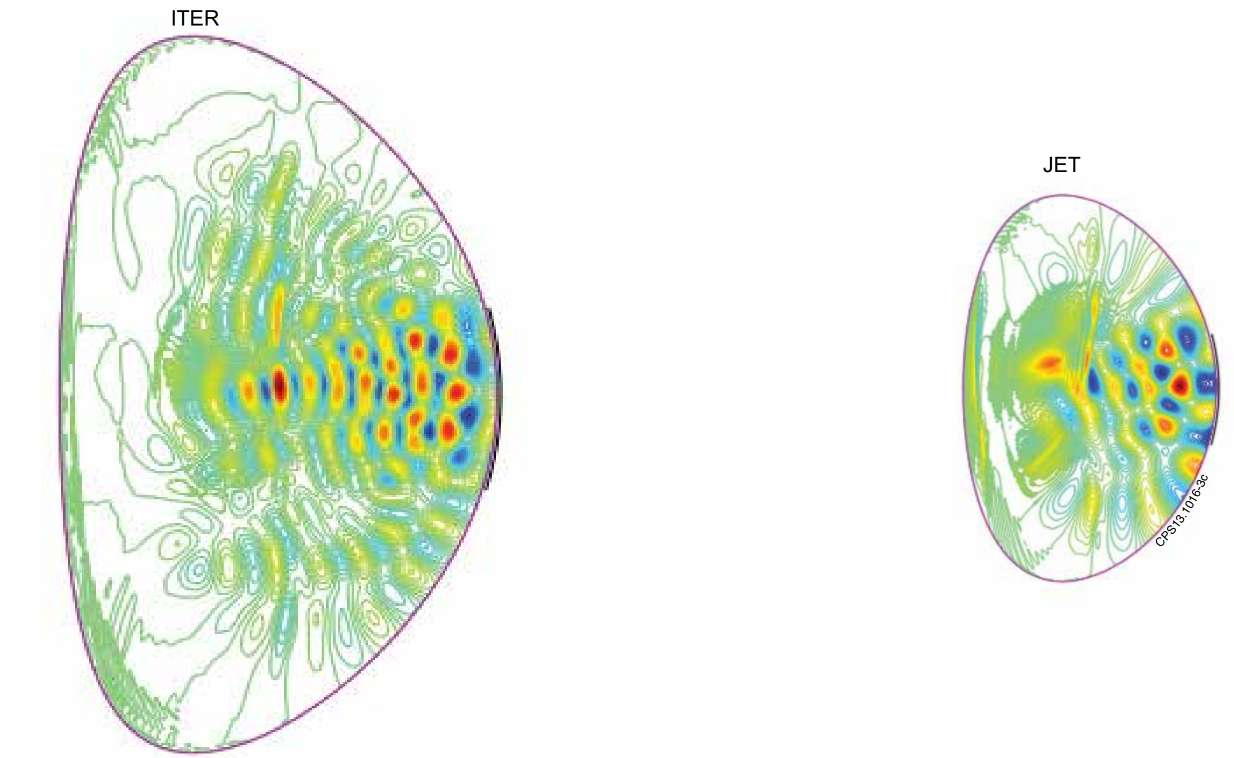

Figure 3: Simulations of E_+ (left hand polarised component of the wave electric field, which to lowest order give rise to the cyclotron absorption) for ITER start-up conditions (left) and JET (right) for 2^{nd} harmonic Tritium heating with 0.1% ^{3}He.

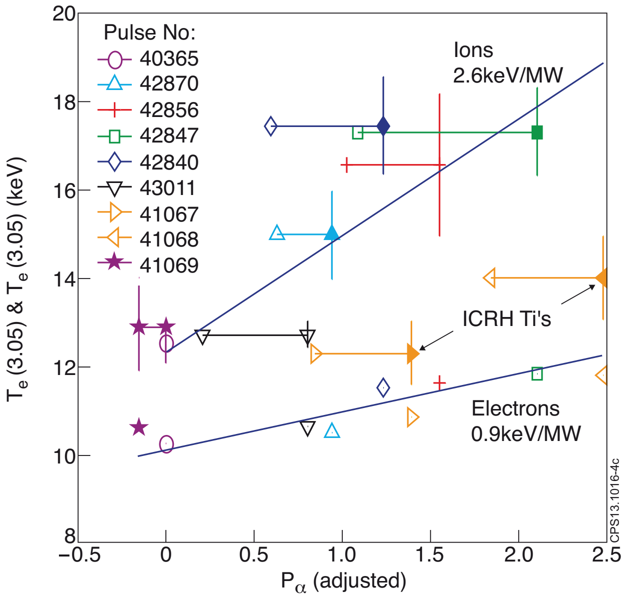

Figure 4: Electron and ion heating (oblique lines) observed in an alpha power scan in DTE1. ICRH (yellow bars) did not produce the ion temperature rise observed with alpha power. The alpha power was adjusted for small differences in discharge conditions. From ref. 7.

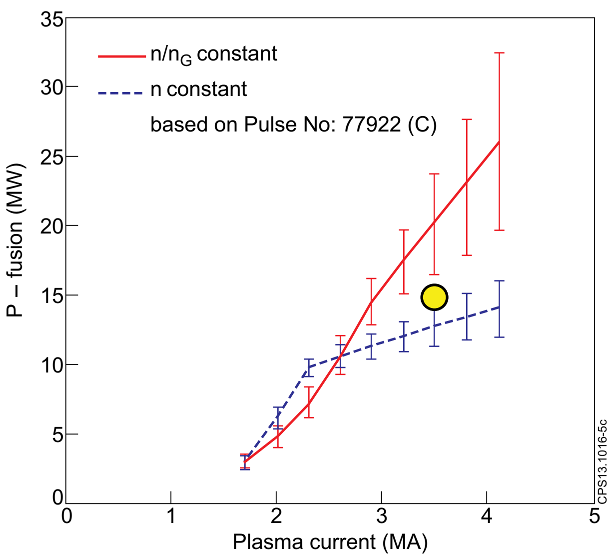

Figure 5: JETFUSE predictions of fusion power in hybrid scenarios discharges for different currents and assumptions for the plasma density. The yellow dot is from a simulation using CRONOS.

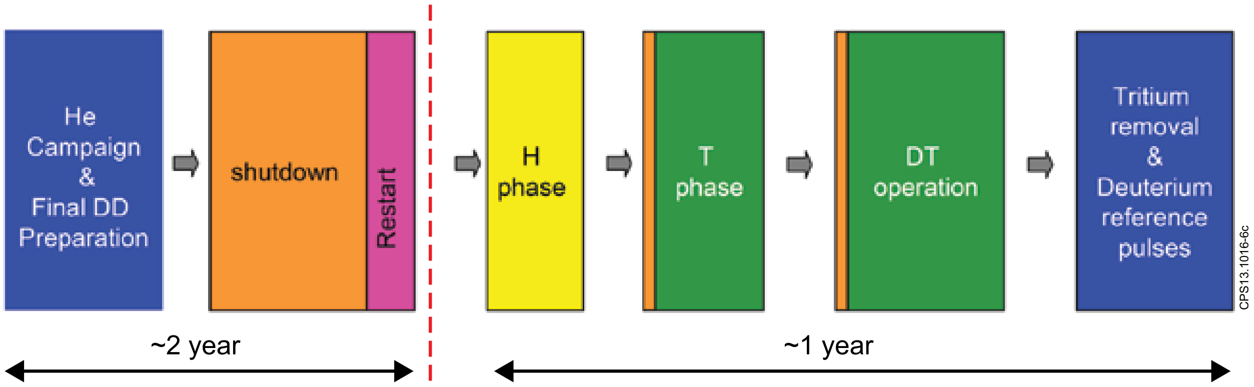

Figure 6: Tentative time line for DTE2 campaign and associated isotope campaigns. The Hydrogen campaign (H) is to start in 2017.