EUROPEAN FUSION DEVELOPMENT AGREEMENT
JET

EFDA–JET–CP(01)08-12

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**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
7th IAEA TCM on Energetic Particles,
(Gothenburg, 8-11 October 2001)

Abstract.

The large physical size of the JET Tokamak, its heating systems and diagnostics, and its capability to operate with full Deuterium-Tritium (D-T) plasmas, including high power Tritium Neutral Beam Injection (NBI), give it unique possibilities in fast particle research in fusion plasmas. These have already been used to generate significant (2-3MW level) power in fusionα-particles in the 1997 DT campaign. Recent JET experiments have concentrated on two important scenarios of relevance to Next Step tokamak devices: the ELMy H-mode plasmas and plasmas with strong Internal Transport Barriers (ITBs). The achieved progress will help in preparation for a possible second D-T Experiment on JET. Fast particle studies have also been carried out recently using ICRH-accelerated particles and external-excitation methods to study AlfvØn Eigenmodes (AEs). Looking towards the future, the capability of JET will be enhanced by upgrades to the NBI system, ICRH system and various diagnostics. Results of the first JET D-T experiment (DTE1) form a basis on which to elaborate a second D-T experiment (DTE2) which could be proposed after these enhancements. The α-physics part of this programme would be divided between the investigation of α-particle confinement, heating and loss processes in the Integrated scenarios (where the discharge is as close as possible to an ITER-relevant scenario), and dedicated α-physics experiments, with specially prepared plasmas. In ELMy H-mode plasmas the fusion performance could reach Q (= P_{fusion}/ P_{input}) of ~ 0.33 at the highest combined heating powers, corresponding to $\langle\beta_\alpha\rangle \sim 6\ 10^{-4}$, allowing a test of the margins of TAE stability in quasi steady-state conditions. The Integrated scenario-fast particle programme could concentrate on the instabilities and heating in plasma regimes with strong steady-state ITBs, with expected Q values ~ 0.58 and $\langle\beta_\alpha\rangle \sim 2\ 10^{-3}$, demonstrating the compatibility of these operating scenarios with alpha effects. Excitation of TAEs by α-particles in the plasma core could also be studied in such integrated scenarios. An issue which will receive attention is the confinement of MeV energy ions in the centre of ITB plasmas with strongly reversed shear, where the low current- density in the centre may lead to the α-particles entering loss orbits. In preparation for a DT campaign, studies of triton burn-up in Deuterium ITB plasmas will begin in the 2002 experimental campaigns. Special afterglow experiments to measure TAEs after the termination of the (stabilising) NBI have already been explored in JET deuterium ITB scenarios and would be planned for DTE2. It is intended to develop special versions of ITB plasmas with dominant Ion heating which would maximise the sensitivity to degradation of α- heating effects.

1. INTRODUCTION AND OVERVIEW

The JET Tokamak has unique capabilities for Fast Particle Research. These are based upon the following design parameters and installed hardware:

- large physical machine size and high plasma current capability, so that MeV ion orbit widths are small compared to the plasma minor radius and hence such ions are inherently well confined (for 3.5 MeV alpha particles or 1 MeV tritons, the banana orbit widths at plasma currents above 3 MA are less than 60% of the minor radius, even for deeply-trapped particles);
- deuterium-tritium (DT) plasma capability to enable generation and study of significant population of fusion α-particles;
- powerful Ion Cyclotron Resonance Heating (ICRH) capable of accelerating injected and minority plasma ions to MeV energies, where they can be used in simulation studies of fusion products;
- Neutral Beam Injection (NBI) capable of long pulse operation with $^{3}\mathrm{He}^{0}$ and $^{4}\mathrm{He}^{0}$ beams, which can act as the seed for further RF acceleration and also provide central thermal α population;
- inherently low Toroidal Field (TF) ripple, <1% at outboard mid-plane for large bore plasmas, plus the ability to operate with variable TF Ripple and allow ripple effects to be distinguished from other fast particle effects;
- coils for excitation and detection of Alfvén Eigenmodes (these excitation coils are presently limited to low toroidal mode numbers n);
- gamma ray spectroscopy, neutron and Neutral Particle Analyser (NPA) diagnostics for fast particle and fusion product studies.

In addition, the focus of the research programme on JET, first under the JET Joint Undertaking (1983-1999) and subsequently under EFDA has, increasingly from the mid-1990s onward, been aimed at the establishment, characterisation and improvement of operational scenarios of importance to Next Step Tokamak devices. The principal project of this type, which has been supported extensively by the JET programme, is the International Thermonuclear Experimental Reactor (ITER). Support for ITER has been the highest priority of research at JET since 1996.

JET is capable of plasma operation in configurations where the shape parameters and the safety factor (q) are similar to those of the proposed ITER device [1] and also has a magnetic divertor. It has thus been possible to develop the standard ITER scenario, the ELMy H-mode, to a level where the plasma transport and stability properties are well-characterised at plasma parameters which are closer to those of ITER than any other existing machine. Moreover, JET s heating and current drive systems (NBI, ICRH and Lower Hybrid Current Drive — LHCD) have been used with careful programming of the plasma current waveforms to obtain modes with enhanced energy confinement properties. These are characterised by magnetic shear profiles which are optimised to be flat (OS) or reversed (RS) in the inner part of the plasma. The plasmas obtained exhibit strong Internal Transport Barriers (ITBs) inside which elevated temperatures and densities can be sustained, thus offering improved fusion yield performance. Such plasma scenarios are candidates for the so-called *Advanced Tokamak* plasmas which are also to be investigated on ITER [1].

The effect of populations of fast particles, especially 3.5 MeV α-particles from DT fusion reactions, on the stability and confinement of such integrated plasma scenarios is of key importance for the realisation of a burning tokamak plasma. Addressing fast particle physics effects in integrated scenarios of relevance to ITER has been identified as an important part of the JET programme, together with specific alpha particle physics studies.

In this paper we describe the latest developments in the ELMy H-mode and ITB plasmas on JET, with particular reference to the existence and control of fast particle effects. The Fast Particle research component of the near-term (2002) JET programme is discussed and the near- and medium-term enhancements to the machine are described. Finally the outline of the proposed next JET DT experimental campaign is discussed. The 1997 DT experience on JET is also reviewed as a basis on which a second DT experiment (DTE2) could be developed.

2. RECENT JET RESULTS – INTERACTION WITH FAST PARTICLE EFFECTS

2.1 PROGRESS IN DEVELOPMENT OF ITER ELMY H-MODE SCENARIOS ON JET

Extensive characterisation of the ELMy H-mode has been carried out for several years on JET ([2,3,4]). Substantial progress has been made recently in the ability to operate in the ITER shape configuration (see Fig 1), at densities up to the Greenwald Limit ($n_e \sim n_{GW,}$, where $n_{GW} = I_p/\pi a^2$) and with good confinement properties [5], as in Fig 2, which shows the JET ELMy H-mode operating space for currents in the range 1.8-2.7MA. This has been achieved with the following techniques:

- — highly triangular shapes and operation at high power with high gas fuelling, showing improved confinement and ELM behaviour;
- — operation with a radiating mantle , resulting in no confinement time or density degradation, while strongly reducing the heat load in the divertor ; and
- — use of high-field side pellet fuelling with an adapted pellet fuelling cycle.

A key area where fast particle effects play a role in the performance of the ELMy H-mode is in the interplay between the sawtooth instability and the destabilisation of Neoclassical Tearing Modes (NTMs). It is well-established experimentally that the magnetic perturbations associated with the precursors or collapse of the sawtooth oscillation can provide seed islands for the development of NTMs. This is more likely if the collapse comes at the end of a long sawtooth period [6]. The stabilisation of sawteeth by fast particles was established on JET originally in L-mode plasmas with substantial populations of fast particles from ICRH acceleration of minority ions [7]. Recent JET results in the ELMy H-mode show that where enhanced sawtooth stabilisation is achieved by ICRF-driven fast particles, a NTM is triggered after the eventual collapse of the sawtooth. The plasma β_N (where $\beta_N = \beta/\left(I_p/aB_T\right)$, with I_p in MA; a in m; and B_T in T) at the NTM onset is much lower than the target requirement for ITER, showing that the avoidance of the sawtooth stabilisation phenomenon is an important issue for the Next Step machines. An example from JET is shown in Fig 3. This figure also illustrates the effect of tailoring the fast particle content by changing the ICRF phasing to modify the ICRF-induced radial transport of the resonating hydrogen minority ions [8]. With a reduced fast particle pressure in the centre sawteeth are stabilised to a lesser extent and a much higher β_N value is achieved. These results point to the possibility of using fast particle population control by adjusting the phasing of ICRH as a mechanism of NTM avoidance, albeit in a limited range of scenarios. Other non fast-particle sawtooth stabilisation/ de-stabilisation methods involve the use of second harmonic ICRH ($2\omega_{ci}$) to produce Ion Cyclotron Current Drive (ICCD). The effect of ICCD on sawteeth stabilisation has been well-established via previous JET experiments [9-12].

This issue of sawtooth and NTM interaction is all the more important in reactor DT plasmas since long period or monster sawteeth, and their attendant strong magnetic perturbations on collapse, are also predicted to arise under ELMy H-mode conditions in plasmas with α-particle populations [13]. A current drive technique may be required on ITER as an NTM control mechanism as the fast particle distribution, being dominated by α particles, will be more difficult to modify.

NTMs have also been observed when simulating α-particle effects using combined ICRH and Helium NBI in recent JET ELMy H-mode experiments. Figure 4 shows the use of ICRF tuned to 3rd Harmonic heating of minority ^{4}He ions, in a discharge where the helium population was provided by the NBI system. Clear stabilisation of sawteeth occurs, followed by triggering of NTM at the sawtooth collapse. Fast particle effects are also seen [14] and discussed in section 2.3. The extrapolation of these results to fusion α-populations must be made with care since the ICRH induced populations are highly anisotropic

2.2 PROGRESS IN DEVELOPMENT OF ITER ITB PLASMA SCENARIOS ON JET

Plasmas where a strong Internal Transport Barrier (ITB) develops after the application of additional heating power in the current ramp-up phase at the beginning of the discharge, thus enabling high central temperatures and densities to be achieved, have now been investigated for some time on JET [15] as well as many other tokamaks [16-21]. The initial results on JET [15] were dominated by plasmas where the core magnetic shear was Optimised to be flat (OS) and within the measurement errors could be slightly negative. The new JET results from the 2000-2001 programme have achieved Reversed Shear (RS) profiles using LHCD.

The use of LHCD power coupled to the plasma during the early current rise phase, prior to the high power heating, has created q profiles where the central shear is negative. An example of the current profile control achieved is shown in Fig 5 where the amount of shear reversal is seen clearly to depend on the LHCD power coupled. Plasmas with significantly reversed central shear have achieved comparable performance to the OS plasmas in the high power heating phase but at significantly lower additional heating power and plasma current [22]. An example of one of the best pulses is shown in Fig 6 where the ITB is seen to be located at about 60% of the minor radius. This discharge, which could not be sustained due to termination by an ELM followed by what might be a n=1 kink-like instability, reached a normalised β_N value of 2∑4. In a NBI heated plasma with equal concentrations of deuterium and tritium (50:50 DT) in both the bulk plasma and the beams, this value of β_N would yield$Q_{DT}^{eq} \equiv P_{fusion}/P_{input}$ ~˚0Σ4-0Σ45. The development of such discharges to higher power, higher plasma current and higher ITER-relevant triangularity (δ), where a higher equivalent fusion yield could be expected, is an important goal of the JET programme.

Of equal importance is the development of this scenario towards steady-state conditions. Here the use of LHCD in addition to NBI and ICRH *throughout the high power heating phase* has given ITB conditions which have been sustained for up to 27 energy confinement times ($27\tau_E$) [23]. Such durations are comparable to the effective current diffusion time in the plasma. In addition ITB plasmas have been used in *Real time feedback control* experiments. Using feedback on the electron temperature profile (to maintain the critical value of $\rho_s/L_{Te} \geq 1.4\ 10^{-2}$, where ρ_s is the Larmor radius at the ion sound speed, and L_{Te} is the electron temperature gradient length) and the DD neutron rate, the input power time profile has been adjusted to keep an ITB plasma stationary for up to four seconds. During this period the plasma current is dominantly (up to 90%) provided by non-inductive means. At the moment this technique is only being used for discharges which are not near to MHD stability limits but a development programme is planned.

One of the key issues for ITB plasma scenarios is the confinement of α-particles within the ITB zone, especially for scenarios where the central shear is deeply reversed and the central poloidal field is consequentially low. Losses from isotropic distributions of fast particles in JET ITB plasmas have not yet been investigated experimentally. Some indication, from triton burn-up studies, of the excess loss of MeV energy particles has come from JT-60U studies with plasmas exhibiting reversed central shear [24]. Similar studies are planned for the JET 2002 programme. Simulations of *unperturbed* orbits of 3Σ5MeV α s [25] isotropically launched on the low field side near the foot of the Transport Barrier in a high current (3Σ4MA) JET OS plasma (with near flat central shear) show only a relatively small loss cone corresponding to around 5% of the α-particle population. An example is shown in Fig 7. The problem is undoubtedly worse in Reversed Shear (RS) plasmas but harder to model and diagnose. For example, the achievement of strongly reversed shear with LHCD leads in many cases to the formation of a current hole , i.e. a region in the plasma centre with no toroidal current, which may last throughout the ITB phase [26]. Measurements showing the presence of the current hole are available in the early part of the discharge (the target plasma). Later, the NBI applied for plasma heating interferes with the Motional Stark Effect (MSE) measurement capabilities, so the plasma equilibrium is not well-known for these discharges at the peak performance time. The JET MSE diagnostic is currently undergoing an upgrade to overcome this situation for the 2002 Experimental Campaign. The issue of trading off improved central plasma performance from RS plasmas against increasing central fast particle loss can thereby be addressed in a more rigorous manner.

2.3 Recent Fast Particle physics results on JET

JET experiments with ^{4}He plasmas in the 2001 programme have provided an opportunity for α-particle physics studies using ICRH power to accelerate 120keV ^{4}He ions injected by NBI [14,27] at the 2MW power level. In these experiments gamma-ray spectroscopy of the reaction ^{9}Be (α,n≥)^{12}C has given the direct evidence of ^{4}He ions with tail temperatures T_{tail} ≥1.1 MeV [28], and excitation of Alfvén Eigenmodes by fast ^{4}He ions have been seen for the first time on JET. In the ICRF heating experiments with ^{3}He minority ions the gamma-ray profiles [27,28] have also demonstrated the first direct evidence of ICRH-induced pinch [29] of resonating ^{3}He minority ions. Here the reaction ^{12}C(^{3}He,p≥)^{14}N is used to observe the profiles. Previously it has only been possible to infer the ICRH induced pinch from indirect evidence (mainly in the case of H minority) [8]. The results show that the +90^{o} phasing produces γ-emission from the plasma core, as expected from inward pinching of trapped ^{3}He ion orbits, which is followed by de-trapping of these orbits into co-current passing orbits. The -90° phasing displaces trapped ^{3}He ions outwards, leading to γ-emission in the high field side (from banana tips) [27,30].

Alfvén Eigenmodes (AEs) studies have continued along two main avenues: excitation of AEs with external antenna and with ICRH-accelerated energetic ions. A programme of dedicated experiments on the dependence of the frequency and damping rate of low-n AEs on plasma parameters was performed in JET limiter and X-point configurations with high q(0) [31] and at various shapes of plasma cross-sections [32]. The dependence of the damping rate of low-n TAEs on the edge plasma shape, $\rho*$ (equal to ρ_I/a where ρ_I is the Ion Larmor radius and a is the plasma minor radius), and β_{bulk} (thermal plasma β) has been measured. It was found that a single n=1 TAE splits into various n=1 modes as β increases (corresponding to P_{NBI}≥ 3 MW). It is possible that this splitting is the same as the *forksplitting* mechanism, seen in high-n TAE experiments. There is however no obvious identified intense drive mechanism which might lead to the non-linearities present in the forksplitting effect. Analysis on this topic is still in progress. A strong increase in damping of low-n AEs with elongation and triangularity was observed. Finally the n=1 TAE damping rate shows no dependence on $\rho*$ up to values¥d3.5 10^{-3}, and decreases at higher $\rho*$ [33]. The excitation of AlfvØn instabilities with ICRH-accelerated ions in plasmas with deep shear reversal has revealed cascades of AlfvØn perturbations of increasing frequency [34]. These Alfvén wave cascades allow accurate determination of features of the q(r)-profile , the so-called MHD spectroscopy technique. As described in [34], the clustering of different toroidal mode number cascades in time allows the determination of when a particular q_{min} enters the plasma, and in some cases internal Electron Cyclotron Emission (ECE) and Soft X-ray (SXR) diagnostics allow the location of the cascade mode (and therefore of q_{min}) to be determined. Thus AlfvØn cascades are very promising for use as an MHD spectroscopy diagnostic, building on the theoretical understanding which has been achieved for these modes [35]. Overall, experimental studies of AlfvØn cascades have stimulated significant theoretical progress in Alfvén physics [35,36].

Neutral Particle Analyser (NPA) measurements of JET plasmas also show radial redistribution of energetic trapped ions in Optimised Shear (OS) plasmas with strong Internal Transport Barriers (ITB) when the ITBs are terminated by n=1 modes. Models have been developed to explain these phenomena [37].

Although not the main subject matter of this paper, the investigation of fast electrons, especially from runaway populations generated by disruptions, remains an important item in the JET Work Programme. Recent results [38] have shown that runaway formation has a strong dependence on q_{95}, peaking at $q_{95} \sim 4$. The absence of runaways at low plasma currents is due to an insufficient electric field, whilst at high currents, magnetic fluctuations probably suppress runaway generation.

3. PLANNED NEAR-TERM RESEARCH

3.1 The 2002 Experimental Programme

The 2002 JET Work programme features several proposed experiments relating to Fast Particle physics. A list of the main areas of work is as follows:

- ICRH induced sawtooth stabilisation on NTM seed islands;
- ICRH driven fast particles effects on plasma rotation, via a comparison of ICRH applied without generating fast particles i.e., by mode conversion;
- de-stabilisation of sawteeth by fast particles;
- AE stability of conventional scenarios and continuation of AE damping rate and NBI drive measurements;
- direct measurements of redistribution of fast particles due to Alfvén waves via experiments with ICRH ^{3}He minority heating using ≥ tomography to detect the fast ions;
- Alfvén cascades in OS/RS scenarios;
- AE/Energetic Particle Mode stability in plasmas with ITBs, including dependence of damping rate on shear and barrier gradients and mode frequencies on plasma parameters;
- triton burnup measurements in ITB plasmas to investigate the relative roles of the central plasma parameters and the central q profile in the generation and retention of fast particles;
- suppression of runaways using helium puffing and investigation of the effects due to error fields, using the new Error Field Correction Coils available in 2002.

Finally we note that the main plasma scenarios (ELMy H-mode and ITB plasmas) will be developed to higher current and higher density in the 2002 programme. In the former mode peaked density profiles will be pursued, which would allow studies of α-confinement in reactor-relevant plasmas in a possible DTE2 experiment. The ITB plasma research will also concentrate on the development of steady-state so that high performance phases which have long duration compared to the α-slowing down time might be achieved.

The ability of the JET Operating Team to run tritium delivery systems would be maintained as part of a proposed programme to run *Trace Tritium* plasmas (~ 1% T in D) during the 2003 campaign [39]. This programme would not involve Fast Particle physics, but would feature important particle transport experiments in ELMy H-mode and ITB plasmas.

3.2 PLANNED ENHANCEMENTS TO THE JET FACILITY

Important heating system upgrades are planned for JET which should enhance significantly the performance achievable in the standard scenarios and increase the reactor relevance of the additional heating both in a technological sense and in terms of improving the balance of heating power going to the plasma electrons.

The NBI system upgrade is planned to be completed by Autumn of 2002, when the last of the 130kV/60A (deuterium) Positive Ion Neutral Injectors (PINIs) are installed on Octant 8. These PINIs are also capable of operating at 130kV/42A in tritium. The increased NBI power available will be around 7-7.8MW for deuterium or tritium beams at Octant 8.

It is also planned that the ICRH system will be augmented in 2004 by an in-port ITER-like ICRH launcher capable of ~ 7.5MW delivery to the plasma. An outline of the design is shown in Fig 8. The ITER-relevant features include:

- resonant double-loop antenna;
- high power density with target at ~ $8MW.m^{-2}$ for $4\theta\Omega.m^{-1}$ coupling resistance;
- ELM resilience.

A summary of the heating power enhancements is given in Table 1.

Several diagnostic enhancements are planned for implementation in the 2002-4 timeframe. Many diagnostic enhancements in 2001-2002 are related to edge measurements while other earlier upgrades (mostly for 2002) will be of general use in characterisation and development of the ITB scenarios. These include the MSE upgrade, already mentioned in section 2.2, which will enable the measurement of q profiles in the high performance phase of ITBs without restrictions on the NBI power. There are also upgrades to the Real Time Controller Network, which will enhance the ability to perform feedback control on the ITB plasmas. Improvements in ECE for higher resolution measurements of T_e barriers will also be implemented.

For the longer term several diagnostics are planned. One group of diagnostics has general purpose (High Resolution Thomson Scattering, Charge Exchange Recombination Spectroscopy). Other diagnostics have specific implications for energetic particle studies: Faraday cups and scintillators (lost α s, α spectrum); Infra Red viewing camera (synchrotron radiation from runaways, lost α s); 2∑5MeV neutron Time-of-flight upgrade (energetic particles, reactivity); Magnetic Proton Recoil (MPR) diagnostic upgrade (α-knock-on effects on the 14MeV neutron spectrum, isotope measurements); and high-n TAE antennae.

The proposed TAE antenna system is designed to excite and measure TAEs with n=3-15, covering the range where the most unstable TAEs are expected in ITER (n>10) [40], in contrast to the present JET system, based on the Saddle Coils, which can only drive n=0,1, 2 AlfvØn Eigenmodes. The new system will be able to measure the damping rate (γ/ω) in real-time for n=6-15 and enable study of damping rates on bulk plasma β and drive achieved at specific β_{fast}. It is also expected that the DT plasma composition can be derived from frequency spectrum measurements of $f_{TAE} \propto 1/q\sqrt{A_{eff.}}$

4. FAST PARTICLE PHYSICS IN DEUTERIUM-TRITIUM EXPERIMENTS

The DTE1 results have been extensively reported previously [41-43]. These are briefly reviewed here (section 4.1) as a basis on which to elaborate a proposal for a second DT experiment on JET (section 4.2).

4.1 OVERVIEW OF FAST PARTICLE PHYSICS IN THE FIRST JET DEUTERIUM-TRITIUM EXPERIMENT (DTE1)

The DTE1 experimental campaign of 1997 was able to address fast particle issues in a limited way but nevertheless gained some important results in assessing heating by α-particles, TAE instabilities and fast particle effects in ICRF heating scenarios of relevance to DT plasmas.

Plasma scenarios with ITBs were not sufficiently developed for DT plasmas at the time of DTE1 [41]. The ELMy H-mode plasmas were validated in DT for quasi steady-state conditions (pulse lengths long compared to the energy confinement time) but the Q values were too low for significant α-particle population production [42]. As a result, the experiments on α-heating and the searches for TAE modes were largely conducted in the best DT fusion yield scenario available at the time, the *Hot Ion ELM-free H-mode* [43].

4.1.1 α-heating experiment

α-heating was demonstrated in the ELM-free H-mode by observing the excess electron heating occurring in a set of nearly identical DT discharges. These were heated at a constant level of NBI power, but the plasma D:T mixture (and the ratio of D:T in the input NBI) was varied from pure D through to 90% T. The α-particle production in the discharge set varied as the product $n_D n_T$ and was hence a maximum for the 50:50 discharge. In the absence of significant α-losses the maximum electron heating should therefore occur for the 50:50 mixture. This was indeed seen in practice [43] as shown in Fig 9. The α-heating of electrons was similar to that achieved by comparable minority ICRF-heating of deuterium plasmas. This result implies strongly that no significant α-losses due to instabilities occurred in these plasmas, but it is important to realise that the maximum volume averaged β associated with the α-particles in these discharges was $\langle\beta_\alpha\rangle^{max} \sim {}^\circ 4 {}^\circ 10^{-4}$, and this is well below the likely threshold for α-driven TAE modes to occur in such plasmas (see section 4.1.2 below). There is thus a strong incentive to repeat such studies at higher values of $\langle\beta_\alpha\rangle^{max}$.

Another interesting result obtained in this discharge series was the dependence of the sawtooth period on the isotopic composition of the plasma and beams with predominantly tritium plasmas having the longest sawtooth period. Modelling indicates that this phenomenon can be attributed to a rise in the NBI fast ion pressure arising from the mass dependence of the slowing down time [44]. More recently, quantitative modelling of sawtooth stabilisation in discharges with pure deuterium NBI has been carried out [45]. Such phenomena, which may impede NTM seed control via ICRH, may require further modelling and experimental activities in DT. Generally NTM studies in DD or DT plasmas would benefit greatly from increased power and current drive capabilities.

4.1.2 TAE mode experiments

In the record-breaking high fusion yield plasmas obtained in DTE1 [41] with 12-16MW of fusion power, $\langle\beta_\alpha\rangle^{max}$ was ~8 10^{-4} —10^{-3}, about half the value foreseen in ITER, with central $\beta_\alpha(0)$ values up to 6°10^{-3}. No TAE modes were seen at these levels. The absence of TAE activity contrasted strongly with the clear TAE°activity in DT discharges subjected to >°5MW of ICRH tuned to 2nd harmonic tritium resonance ($2\omega_{CT}$) [46]. This is seen in Fig 10(a), (b). The TAE modes in the ICRH case°arise from MeV energy tritons in the RF-driven population. The absence of α-particles driven TAEs in the high fusion yield case is plausible. The stability calculations for the most unstable (n=6,7) TAEs show, Fig 10(c), that the limits in the core (within flux surfaces where the inverse aspect ratio $\varepsilon = {}^{r}\!/\!_{R} \leq 0.1$) are barely reached by the α-population in these discharges, whilst the stability limit in the bulk plasma is a factor of ~2 higher than $\langle\beta_\alpha\rangle^{max}$ [47].

Other results on TAEs in DT plasmas have involved the observation of TAEs (n=5) driven by NBI fast ions ($T^o \rightarrow T$ plasmas, $D^o \rightarrow D$ plasmas). The plasmas involved were deliberately run at low TF values (< 1T) to make the NBI ions super -Alfvénic. Power thresholds for the activation of TAE modes agreed with the CASTOR-K code calculations [48], which also explained the absence of TAEs in the equivalent $H^o \rightarrow H$ plasma case (due to insufficient beam power). It is noticeable that the Alfvén Eigenmodes were *not* correlated with the loss of NBI Fast Ions. This did occur in those discharges where Fishbone instabilities were simultaneously observed.

4.1.3 Fast Particle effects in ICRF heating

The main ICRH scenarios foreseen for ITER are the helium-3 minority, (^{3}He)DT, and the second harmonic tritium ($2\omega_{CT}$) schemes. These were tested in DTE1 but at relatively modest power levels [49,50]. The performance of the $2\omega_{CT}$ scheme was found to be degraded due to a combination of fast particle effects. Trapped orbits of tritons with tail temperatures $T_{tail} \geq$°4MeV intersected the walls, causing a power loss ~ 20%. Large orbit width effects led to a broadening of the power deposition profile, thus further reducing confinements. Also sawteeth probably caused considerable redistribution of fast tritons from the core further contributing to the power loss [50,51]. By adding a few percent of ^{3}He in these D-T plasmas, i.e., adopting the (^{3}He) DT scheme, the plasma performance was greatly improved. This was found to be due to predominant ICRH-absorption by the ^{3}He minority ions. These heated the bulk plasma ions efficiently because of their high critical energy and the moderate tail temperature. It should be noted that fewer problems due to fast tritons are expected in ITER due to the large machine size [52]. Future DT-relevant ICRH work on JET will focus on developing techniques to improve the performance of these schemes at higher power levels than used in DTE1 (see below).

4.2 FAST PARTICLE RESEARCH IN A PROPOSED SECOND DEUTERIUM-TRITIUM EXPERIMENT

A proposal for a second DT experiment (*DTE2*), to follow the JET Enhancements made in2004, has been made and discussed during the Enhancement review process. No decision has yet been made to conduct such an experiment. The proposed DTE2 programme would cover a wide range of DT physics issues in five main sub-programmes:

- validation/ demonstration of the *ELMy H-mode scenario in DT*, including operation at high current near the Greenwald density limit with acceptable ELMs and demonstration of various improvements to the scenario with investigation of the isotope scaling of NTMs;
- a programme investigating and validating the *Optimised Shear/ Advanced Tokamak scenario in DT*, including measurement of isotope effects related to ITBs, a demonstration of the regime in steady state and investigation of α-particle confinement and heating effects;
- a specific programme of *α–particle physics*;
- a programme of *Heating physics* relating to further development of ITER relevant ICRH heating scenarios in DT plasmas; and
- a *Tritium technology* programme including investigation of tritium retention and tritium reprocessing components.

The α–particle physics programme is clearly dedicated to Fast Particle physics, but this also plays a significant role in the Heating physics programme. It is also intended to maximise the fast particle research content in the two scenario based programmes, which will demand an extensive development programme in deuterium plasmas

During DTE1, investigation of α-particle physics was limited to specially prepared plasmas (such as the Hot Ion ELM-free H-mode) that were not based on ITER reference scenarios. Recent progress in both ELMy H-mode and in Advanced Tokamak modes (OS/RS) opens the perspective of DTE2 studies of α-particle heating/Fast Particle instabilities in more ITER-relevant plasma scenarios. One of the aims of the scenario development programme on JET is thus to provide high performance in regimes which are as close as possible to the ITER model.

The emphasis on investigation of fast-ion effects in Integrated Plasma Scenarios , as described in 4.2.1 and 4.2.2, will have the potential advantage that transport will be studied in the presence of many TAEs, not solely limited to one mode.

A crucial parameter for any α-physics is the length of the steady-state phase of the scenario. A goal of $\tau_{scenario}$°>°5*$\tau_{S\alpha}$ (where $\tau_{S\alpha}$ is the α-particle slowing-down time) is being set.

4.2.1 α-particle behaviour in†'Integrated plasma scenarios' : ELMy H-mode

For the ELMy H-mode the steady-state periods are already achieved, the limit of the ELMy H-mode phase being set by machine parameter limitations such as thermal limits in the heating systems and coils. The most important ELMy H-mode programme aims for DTE2 are: to establish the DT ELMy H-mode at the Greenwald limit with a demonstration of tolerable ELMs; to establish the scaling to ITER of any improved ELMy H-mode regimes (especially involving profile peaking); and to perform studies of NTM stabilisation and onset due to the interactions from the DT-relevant ICRH scenarios, and their respective fast particle populations, on seed islands for NTMs. In addition to these key goals and further to the DTE1 studies, α-particle physics could be investigated in the ELMy H-mode, although with some limitations as shown below.

Simulations of DT ELMy H-modes using the PRETOR code with the Enhanced JET power levels, as in Table 1 (up to 32MW NBI, split 19MW in T^o beams and 13MW D^o beams with 15MW ICRH) show that up to Q~0Σ33 (fusion power ~15.5MW) could be achieved at 4.5MA/3Σ4T based on extrapolations from DTE1. The 3.1MW of α-power produced would give a similar $<\beta_\alpha>$ (~6 10^{-4}) to that achieved in the record pulses of DTE1 [41], so that an ITER scenario discharge can be foreseen to test the margins of TAE physics in quasi steady-state compared to the transient conditions of DTE1. In these discharges the density is fairly high ($<n_e> = 9\ 10^{19}\ m^{-3}$), but with a moderate Greenwald factor ($<n_e>$~0Σ55-0Σ6*n_{GW}). A substantial fraction of the NBI power is deposited in the outer half of the plasma volume where the electron temperature is relatively low. Thus ~ 14 MW NBI power goes to the electrons, in addition to the RF power which goes dominantly to the electron channel. The α-power accounts for little more than 10% of the power to the electrons, reducing the chances of α-losses being detectable on the electron temperature, and emphasising the need for α-loss diagnostics (see section 3.2).

2.2.2 α-particle behaviour in†'Integrated plasma scenarios': Advanced modes

The ITB plasmas will probably form the main component of the development programme for integrated scenario work on α-particle physics. The recent JET results highlighted in section 2.2 have widened the possible routes by which the ITB scenario can be developed to high performance and steady-state. The situation may be summarised as follows:

— the Optimised (flat) Shear (OS) scenario has been achieved at high plasma currents (up to 3.6MA) and in quasi steady-state operation (~4-6 τ_E), but has not exceeded β_N ~ 2 at high current values;

— the Reversed Shear (RS) scenario has only been achieved at plasma currents up to 2.5MA, and exhibits transient disruptive behaviour at β_N ~ 2Σ4 whilst being sustainable in near steady-state (on a resistive time scale) by the application of LHCD at $\beta_N \leq$ 1Σ8.

The long pulse operation of the RS scenario satisfies the $\tau_{scenario}$ criterion relative to the α-particle slowing down time. Although a demonstration of this pulse *per se* in D-T would constitute one of the key goals in a DTE2, it presently has β values too low to be used as the basis of a fast particle study and hence the necessity for development of both OS and RS scenarios, which will be undertaken in the 2002 JET programme. One of the issues for LHCD-assisted steady state RS plasmas is the possibility of parasitic absorption of LHCD power by α-particle populations in a manner analogous to that seen in JET using ICRH-driven minority ions in the MeV range [53], where up to 30% of the LH power is absorbed. This phenomenon will be investigated on minority protons in deuterium RS plasmas in the 2002 Experimental campaign.

A confinement scaling is not yet available for the JET OS/RS plasmas. It is therefore necessary to use general arguments to estimate the potential of this scenario to contribute to the α-physics programme. Increasing the current to 3∑5MA in the RS scenario would give an increase in β, and a corresponding increase in fusion yield, $(\propto(nT)^2)$ even if the present β_N remained limited at ~°2∑4. The real gain in fusion yield however will come from increasing the β-limit in the OS/RS plasmas. A stability analysis of postulated Advanced Scenario plasmas with JET dimensions and characteristic of the OS regime and the RS regime with shallow shear reversal concluded [54] that the normalised β-limit for JET OS and RS plasmas would be β_N°~°2∑8-2∑9 for low inductance plasmas and a relatively wide range of minimum q values. This result does not take any account of the benefit of the JET vessel wall in improving stability. In the case of existence of an ideal wall at d=1∑3a, reference [55] shows that these values of β_N would rise to 3∑5-4∑0. The analysis of actual high performance OS discharges in JET shows that they generally terminated when β_N values were 15-20% above the no-wall limit [55], an indication of how the JET wall deviates from the ideal, but nevertheless showing that the real wall has some effect. We can thus expect that low inductance JET OS/RS discharges with optimised pressure profiles could be developed to β_N values 15-20% above the theoretical no wall limit i.e. β_N ~°3∑2-3∑4. The stability analysis shows that the broad pressure profiles should yield the best values of β. Recent JET results [22] do indeed indicate that the limiting β_N is inversely proportional to the ion pressure peaking factor, $p_i(0)/\langle p_i \rangle$ for such transient, MHD-terminated RS plasmas. Reducing this pressure peakedness is thus an obvious direction for development to improve β_N. As we are aiming for steady-state plasmas, we have assumed a modest target of a limiting value of β_N =3.0 at 3.5MA in steady-state.

An example of one of the best quasi-steady OS JET plasmas with an ITB (shot 47413) is shown in Fig 11 [56]. This discharge had Argon seeding in the divertor to control ELMs, and the value of n_D/n_e had declined to ~0∑7 at the end of the high performance phase. There was no particularly strong MHD activity at the termination of the high performance phase and there are good reasons to believe that the back transition occurred due to power starvation inside the ITB radius as the radiated power rose and the ICRH coupling deteriorated. Indeed a plot of the limiting β_N for many such discharges at 3∑4T and 3∑1-3∑6MA, as shown in Fig 12 [57], indicates that the β_N has not saturated at the highest input powers (18∑5MW NBI plus ~°10MW ICRH) and that the OS scenario at high current in JET is power limited. This limitation should be overcome in the post-Enhancement phase (see section 3.2).

A linear extrapolation of the β_N vs Power limiting envelope in Fig 12 produces an input power requirement of ~°36MW to attain β_N = 3 for OS plasmas at 3∑5MA and 3∑4T. Not only should this be easily attainable with the total power available after the Enhancement (see Table 1), but the enhanced ICRH power available (15+MW) will enable an optimisation based on altering significantly the balance of electron and ion core heating.

A TRANSP code simulation of the 50:50 DT analogue of OS shot 47413 has been performed in which the deuterium plasma was replaced by a plasma with the same parameters ($T_I(r)$, $T_e(r)$, $n_e(r)$

and Z_{eff}) with the hydrogenic content replaced by a 50:50 deuterium-tritium mixture. The NBI and ICRH powers were kept the same in the simulation with the D:T mix in the beams chosen to keep a 50:50 particle flux into the plasma for both isotopes. The simulation gave a predicted fusion yield of 10MW and a Q_{DT}^{eq}~ 0Σ34 as shown in Fig 11. About 58% of this yield is predicted to come from the thermal plasma ions $\left(P_{fus}^{th}\right)$ and about 42% from beam plasmas reactions $\left(P_{fus}^{bp}\right)$.

We denote the putative OS DT discharge at $\beta_N = 3$; I_p = 3Σ4MA; B_T = 3Σ4T as the OS DT prototype (OSDTP). The thermal : beam-plasma fusion balance will alter in going from the DT analogue of shot 47413 to the OSDTP as P_{fus}^{th} and P_{fus}^{bp} scale in different ways. P_{fus}^{th} scales as β^2 (and hence $\beta_N{}^2$) at fixed (I_p,B_T). For the scaling of P_{fus}^{bp} we must make the further assumptions that:

— the plasma purity remains the same in the higher power discharge;

— the percentage mix of NBI:ICRH power remains the same as in 47413, this is consistent with the unchanged T_e assumption.

— the rise in central pressure (nT) in extrapolating from shot 47413 comes from a rise in the density, and that hence T_I and T_e remain the same. This is reasonable as the aim of development of these discharges should be to make them more reactor-relevant, and the ion temperature in 47413 is already in the reactor regime [56]. The values of n_e and n_I thus scale as β_N, but the product of (n_I .$\tau_{s,\ NBI}$), where $\tau_{S,\ NBI}$ is the NBI slowing down time, remains constant in the extrapolation and this helps to calculate the beam-plasma fusion yield, as simply proportional to P_{NBI};

In summary, these assumptions allow us to scale the beam-plasma fusion yield as $\propto P_{NBI}$. The OSDTP discharge would thus be heated by 27Σ5MW NBI and 10Σ5MW ICRH. The scaling gives approximately 17Σ3MW of fusion power can be expected in the OSDTP discharge with Q_{DT}~0Σ46. The main uncertainty in this prediction is whether or not the β_N limit could be raised to 3. The rest of the prediction, even that of constant confinement as β is raised, is relatively conservative. The behaviour of OS/RS plasmas which are not power limited generally shows confinement initially increasing once a *strong* barrier is triggered, and the power limited OS plasmas at high current do not have the strongest of barriers. $<\beta_\alpha>$ values 1Σ2°10^{-3} are expected, similar to those expected in ITER. These would provide a test of the TAE stability limits. The *gradient* of the α–power would be much stronger than in the ELMy H-mode and the value of RΣ$\nabla\beta_\alpha$ is important for the driving term in the TAE instability [40]. The recent progress with the RS scenario gives confidence that these values can be achieved. Losses of α-particles from TAEs would be registered in the loss diagnostics, and the actual degradation in heating power, if any occurred, would be easier to see in this scenario as a substantial input (about half) of the power from (NBI+ICRF) would be going to the central ions [22]. The α-heating would constitute a ~°25% contribution to the electron heating globally, although its influence in the core would be much stronger and, since sawteeth are absent in these plasmas, it should be possible to see degradation if there are significant α-losses.

It is interesting to note that an extrapolation from the RS plasma in discharge 51976 (Fig 6) to an RS scenario DT plasma at β_N = 3; I_p = 3∑4MA; B_T = 3∑4T gives approximately the same expected fusion yield from a slightly lower input power (33MW), with Q>0∑5. This extrapolation was made using the entirely speculative assumption that the current and power scaling for confinement in RS plasmas behaves approximately the same as the ELMy H-mode (i.e., $\tau_E \propto I_p P^{-0.5}$).

4.2.3 Specific a-particle physics experiments

The α-heating experiment from DTE1 [43] can be repeated at much higher power. Following enhancements, it should be possible to perform a scan at P_{NBI}°=°27MW, whilst varying the ratio of the power in the tritium beams and deuterium beams. The aim of the development programme in deuterium plasmas will be to achieve a Q_{DT}^{eq}°~°0∑6 plasma at relatively low density such that the high electron temperature (>°10keV) means that the NBI power goes dominantly to the ions and the α-power will provide as much as 50% of the power into the electrons. Thus the electron heating can be tested at $<\beta_\alpha>$ values much closer to the stability limits (~°10^{-3}).

The target scenario for this development is still under discussion. It would be advantageous to avoid sawteeth and hence a version of the OS/RS plasma might be developed for NBI-only. Provided the plasma current is ~°3-3∑5MA (necessary to confine the α s) then the available power should mean that the discharge does not have to be performed at the present β-limit. On the other hand it is possible that a low density ELMy H-mode could be developed using pellet fuelling and edge pumping from JET s Divertor Cryopump to obtain a peaked-density profile which aids central heating deposition.

Another key experiment will be the study of α-particle drive of TAEs in the *absence* of stabilising NBI fast ion populations. This kind of experiment was originally developed in the TFTR DT programme [58,59]. Both fluid and kinetic codes have been used to predict that strong ion Landau damping of AlfvØn Eigenmodes in NBI heated high temperature plasmas can overcome the α-particle drive of these modes in the TFTR [60-62] and JET [47] DT plasmas. Alternatively the gyrokinetic PENN code [63,64], predicts that the plasma at high beta will broaden the high-n TAE spectrum so as to increase the mode conversion to AlfvØn- or kinetic-AlfvØn-waves at the plasma edge where high shear damping occurs. These damping mechanisms are predicted to be dominant unless the α-population becomes very large. To remove these stabilising terms it is planned to look for α-particle excited TAEs in the *afterglow* of a high performance plasma such as the ITB scenario. In such a scenario experiments are presently being developed in JET DD plasmas with ICRH accelerated minority fast ions taking the place of the α s in the afterglow phase [65]. An example of the time history of the applied power and the observed TAE spectrum in one such discharge is shown in Fig 13 [65]. A Reversed Shear (RS) plasma is prepared using LHCD pre-heat and is then heated to high performance with NBI and ICRH. At the power stepdown of the NBI (at t=7s), the applied ICRH produces fast ions which stimulate TAEs with mode numbers n=4-9. These experiments show that a broader n spectrum is excited in plasmas with definite shear reversal and that the ICRH power threshold (and hence the Fast Particle β) for TAE excitation is lower for RS plasmas than for OS plasmas. Such experiments, in addition to their development status for DTE2, are already providing important guidance on possible α-driven instabilities.

4.2.4 Fast particle effects in ICRF heating scenarios

The much larger ICRF power available in the post-Enhancement phase can only be used successfully if losses due to large orbits of high energy RF-driven tail ions and sawtooth redistribution of fast ions can be avoided. As previously indicated (section 4.1.3) this was a major problem with the $2\omega_{CT}$ RF heating scenario in DTE1, and is likely to affect the (^{3}He)DT scenario at higher power. It is planned to overcome this in the proposed DTE2 programme by the use of polychrome frequencies to locate fast particle resonances at different radial locations in order to reduce the average power density and average energy density of the resonating ions. Also ICRH operation in the sawtooth-free regimes of the ITB plasmas will be investigated.

5. CONCLUSIONS

JET capabilities in the field of fast particle physics are unique and, when combined with the programme of validation and development of ITER reference scenarios, create a powerful resource which can be exploited for fast particle physics with and without D-T operation.

The capabilities should further develop with improved heating systems (+7MW NBI at the end of 2002; +7-10MW ICRH at the end of 2004), and diagnostics (q profile measurements in all heating conditions; improved resolution of T_e and n_e profiles; alpha particle and TAE diagnostics).

The recent plasma scenario work on JET has produced ELMy H-mode plasmas with good confinement at the Greenwald limit and furthered the understanding of the interaction of fast particle populations with the stabilisation and triggering of NTMs. In the ITB plasma scenario, plasmas with deeply Reversed Shear (RS) have been developed and sustained for near steady-state conditions at lower values of β using LHCD. These RS plasmas will now be developed along with the Optimised Shear (OS) plasmas to establish steady-state plasmas at β_N values nearer to the theoretical values of 3.2—3.4.

The recent fast particle physics experiments on JET have identified several interesting phenomena, several of which will be further developed in the 2002 JET Experimental Campaign:

- the excitation of AlfvØn Eigenmodes by fast ^{4}He ions have been seen for the first time on JET;
- gamma-ray profiles have demonstrated the first direct evidence of ICRH-induced pinch of resonating minority ions (in this case ^{3}He);
- the dependence of the damping rate of low-n TAEs on the edge plasma shape, $\rho*$ and thermal plasma β has been measured showing: a single n=1 TAE splits into various n=1 modes as β increases; observing a strong increase in damping of low-n AEs with increased elongation

and triangularity; and showing no dependence of the n=1 TAE damping rate on $\rho *$ up to values¥d3.5 10^{-3}, and decreases at higher $\rho *$;

- the excitation of AlfvØn instabilities with ICRH-accelerated ions in plasmas with deep shear reversal has revealed cascades of AlfvØn perturbations of increasing frequency which will allow accurate determination of features of the q(r)-profile by the MHD spectroscopy technique;
- radial redistributions of energetic trapped ions in OS plasmas with strong ITBs have been seen when the ITBs are terminated by n=1 modes;
- the investigation of runaway populations of fast electrons generated by disruptions, has shown that runaway formation has a strong dependence on q_{95}, peaking at $q_{95} \sim 4$;
- the dependence of the sawtooth period in D-T plasmas from DTE1 on the isotopic composition of the plasma and beams can, according to modelling, be attributed to a rise in the NBI fast ion pressure arising from the mass dependence of the slowing down time. Similar quantitative modelling accounts for sawtooth stabilisation in discharges with pure deuterium NBI.

The proposed DTE2 experiment, which could be conducted after the programme of Enhancements to JET, offers the prospect of making significant gains over the results of DTE1 in the important areas of D-T demonstration and scaling of ITER reference scenarios; α–particle physics, including confinement and loss effects, in the scenarios of relevance to ITER; specifically-designed experiments to isolate α-particle physics; heating physics involving reactor-relevant ICRH schemes; and tritium technology projects. A set of experiments specifically designed to look at α-particle physics should be able to study heating by α–particles, and the accompanying α-loss measurements, at values of $<\beta_\alpha>$ up to more than 50% of those expected for ITER. Other experiments, which are already being successfully developed in deuterium plasmas, will look for TAE modes, in the absence of Ion Landau damping by NBI.

Considering the possible ITER scenarios in which to investigate α-particle effects, the ELMy H-mode is predicted (using the PRETOR code) to give a fusion Q~0.33 in a 4.5MA/3.4T discharge with 47 MW of additional heating (19MW T^0 NBI, 13MW D^0 NBI and 15 MW ICRH) at densities around $0.6n_{GW}$. This opens up the prospect of approaching the TAE stability limits, with $<\beta_\alpha>$ values ~ 6 10^{-4}, and such prospects would be improved if success were to be achieved in efforts to develop more peaked profiles for high current ELMy H-modes. For the ITB plasmas, the developments in the 2002 programme will aim to establish steady state conditions in both OS and RS plasmas at higher values of β_N than those presently achieved and, for the RS plasmas, at higher current. A target of $\beta_N \sim 3$, consistent with theoretical predictions for broad pressure profiles modified by the presence of the JET wall, would yield very useful DT plasmas from the α-physics standpoint. General scaling arguments based on quasi-steady OS plasmas show that a fusion Q~0.46 could be achieved at 3.4MA/3,4T with ~ 38 MW input power (27∑5MW NBI and 10∑5MW ICRH). Such plasmas would have $<\beta_\alpha>$ values ~ 1∑2 10^{-3}, similar to those of ITER and above the expected stability threshold for TAEs. The Enhanced JET power levels of ~45-47MW give some power margin for realisation of such plasmas if confinement scaling turns out to be unfavourable, and also allow an optimisation and investigation of the effects of varying the ion/electron heating balance by a significant amount.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the work of the large number of people involved in the EFDA-JET Work programme whose achievements are discussed in this paper. These include the EFDA-JET Task Force Leaders and deputies, and the staff from all the EU laboratories involved via the Task Forces in the JET Experimental programme; the UKAEA Team under F Briscoe in charge of operating the JET facilities; and the EFDA Culham Close Support Unit. Contributions from various US laboratories, PPPL, ORNL, MIT and GA and from the Japanese fusion programme (under the auspices of JAERI) are also acknowledged. This work has been performed under the European Fusion Development Agreement.

REFERENCES

[1] ITER-FEAT Outline Design Report, IAEA/ITER EDA/DS/18, (IAEA Vienna, 2001)
[2] The JET Team, presented by Cordey J G, Fusion Energy 1996 (Proc 16th Int Conf on Fusion Energy, Montreal 1996), vol 1 603 (IAEA, Vienna 1997)
[3] Loarte A D et al, Nucl Fusion **38**(1998) 331
[4] Matthews G F et al, Nucl Fusion **39**(1999) 19
[5] Ongena J et al Plasma Phys and Contr Fus **43**(2001)A11
[6] Sauter O et al, Phys Rev Letts **88** (2002) 105001
[7] Campbell D J et al, Phys Rev Letts **60** (1988) 2148
[8] Eriksson L-G et al., Phys Rev Letts **81**(1998), 1231
[9] The JET Team, presented by Gormezano C, Plasma Phys and Contr Nucl Fusion Research 1992 (Proc 14th Int Conf on Fusion Energy, Würzburg 1992) vol 1, 587 (IAEA Vienna 1993)
[10] Start D F H et al, Nucl Fusion **30** (1990) 2170
[11] Bhatnagar V P et al., Nucl Fus **34**(1994) 1579
[12] Mantsinen M et al., *Analysis of Ion Cyclotron current drive at* $\omega = 2\omega_{CH}$ *for Sawtooth Control in JET plasmas* Proc 28th EPS Conf on Contr Fus and Plasma Physics, Funchal, Portugal 2001, Europhys Conf Abstracts Vol 25A (EPS, Geneva 2001) 789
[13] Porcelli F et al, Plasma Phys and Contr Fusion **38** (1996) 2163
[14] Mantsinen M et al, *Alpha particle physics studies on JET with ICRH-accelerated He-4 beam ions* to be published in Proceedings of 7th IAEA Technical Committee on Energetic Particles in Magnetic Confinement Systems, Goteburg Sweden, 8-11 October 2001
[15] Becoulet A et al, Nucl Fusion **40** (2000) 1113
[16] Levinton F M et al, Phys Rev Letts **75** (1995) 4417

[17] Strait E J et al, ibid 4421

[18] Litaudon X and Equipe Tore Supra, Plasma Phys and Contr Fusion **38** (1996) A251

[19] Fujita T et al, Fusion Energy 1996 (Proc 16th Int Conf on Fusion Energy, Montreal 1996) vol 1 227 (IAEA Vienna 1997)

[20] Wolf R et al, Fusion Energy 1998 (Proc 17th Int Conf on Fusion Energy, Yokohama 1998) vol 2 773 (IAEA Vienna 1999), 1999 Fusion Energy (Proc 17th Int Conf, Yokohama, 1998) (Vienna:IAEA) CD-ROM File EXP1\12 and http://www.iaea.org/programmes/ripc/physics/start.htm

[21] Buratti P et al, Phys Rev Letts **82** (1999) 560

[22] Challis C D et al., *Influence of the q-profile shape on plasma performance in JET accepted for publication in* Plasma Phys and Contr Fusion, 2002

[23] Mailloux J et al., Phys Plasmas **9**(5)(2002)2156

[24] Tobita K et al., Fusion Energy 1996 (Proc 16th Int Conf on Fusion Energy, Montreal 1996) Vol 1, 497 (IAEA Vienna 1997)

[25] S D Pinches et al., Computational Physics communications **11** (1998)133

[26] Hawkes N C et al, Phys Rev Letts **87**(2001), 115001

[27] Mantsinen M et al., *Controlling the profile of ion-cyclotron-resonant ions in JET with the wave-induced pinch effect* accepted for publication by Phys Rev Letts 88, 2002.

[28] Kiptily V et al., *Gamma-ray diagnostics of energetic ions in JET* Invited Paper, 7th IAEA Technical Committee on Energetic Particles in Magnetic Confinement Systems, Goteburg Sweden, 8-11 October 2001, to be published in Nuclear Fusion

[29] Cheng L et al., Nucl Fusion **28**(1988), 389

[30] Johnson T et al. *Experimental Evidence for RF Induced transport of Resonant He-3 ions in JET* ibid [14]

[31] Jaun A et al., Plasma Plys Contr Fusion **43**(2001)A207

[32] Testa D and Fasoli A, Nucl Fusion **41** (2001)809

[33] Testa D et al., *Experimental studies of AlfvØn modes stability on the JET Tokamak* ibid [14]

[34] Sharapov S E et al., Physics Letters A **289** (2001)127

[35] Berk H L et al., Phys Rev Letts **87** (2001) 185002

[36] Briguglio S et al., *Particle in cell investigation of the non-liner saturation of Shear AlfvØn modes in hollow q-profile Tokamaks* ibid [14]

[37] Gondhalekar A et al., *Mechanism of Radial Redistribution of Energetic Trapped ions due to m=2/n=1 Internal Reconnection in JET Optimised Shear Plasmas* ibid [14]

[38] Gill R D et al, *Behaviour of disruption generated runways in JET* ibid [28]

[39] *Arguments for a Trace Tritium/Low neutron yield DT programme in 2002/3* (Stork D, on behalf of EFDA-JET Task Force DT), EFDA-JS-(00)10/3.6.1 (Nov 2000)

[40] See review by Putvinski S et al, Phil Trans R Soc Lond A**357** (1999) 493

[41] Keilhacker M et al., Nucl Fusion **39**(1999) 209

[42] Jacquinot J et al., ibid 235

[43] Thomas P R et al., Phys Rev Letts **80**(1998) 5548

[44] Nave M F F et al., Nucl Fusion 42 (2002) 281

[45] Angioni C et al., Plasma Phys Contr Fusion **44**(2002) 205

[46] Keilhacker M, Phil Trans R Soc Lond A**357**(1999) 415

[47] Sharapov S E et al., Nucl Fus **39**(1999) 373

[48] Borba D et al., Nucl Fus **40**(4) (2000) 775

[49] Start D F H et al., Phys Rev Letts **80**(1998) 4681

[50] Start D F H et al., Nucl Fusion **39**(3) (1999) 321

[51] Eriksson L-G et al., ibid 337

[52] Bergeaud V et al., Nucl Fus **40**(1) (2000) 35

[53] Testa D et al, Plasma Phys and Contr Fusion **41** (1999) 507

[54] Bondeson A et al., Nucl Fusion **39**(1999) 1523

[55] Huysmans G T A et al., Nucl Fusion **39**(1999) 1489

[56] Gormezano C, Plasma Phys and Contr Fusion **41**(1999) B367

[57] Gormezano C et al., contrib paper 27th EPS Conference on Contr Fusion and Plasma Phys, Budapest 2000, Europhys Conf Abstracts **24B**(2000) 245

[58] Chang Z et al., Phys Plasmas **4**(1997) 1610

[59] Nazikian R et al., Phys Rev Lett **78**(1997) 2976

[60] Spong D A et al., Nucl Fusion **35**(1995) 1687

[61] Fu G Y et al., Phys Plasmas **3**(1996) 4036

[62] Berk H L et al., Fusion Energy 1996 (Proc 16th Int Conf on Fusion Energy, Montreal 1996) vol 2, 439 (IAEA, Vienna, 1997)

[63] Jaun A et al., Nucl Fusion **39**(1999) 2095

[64] Jaun A et al., Nucl Fusion **40**(2000) 1343

[65] Sharapov S E et al., *Beam Afterglow Scenario for TAE Excitation in Optimised Shear JET plasmas ,* Proc 28th EPS Conf on Contr Fus and Plasma Physics, Funchal, Portugal 2001, Vol 25A, P2.012, 525(2001)

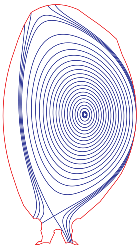
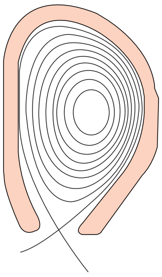
Table 1: Evolution of JET Heating Systems

NBI Upgrade (Autumn 2002)

NBI Species	**D**	**T**	
Octant 4 Injector	(not upgraded)	13MW@ 80keV	14MW@ 80keV
Octant 8 Injector	pre-upgrade	7∑8MW@ 140keV	11∑4MW@ 150keV
Octant 8 Injector	post-upgrade	15MW@ 130-140keV	Up to 19MW@ 130-150keV
Total	pre-upgradeNBI(DT mix) 30-32MW (typical)		post-upgrade 22-24MW (typical)

ICRH Upgrade (end 2004)

Present ICRH	A2 antenna system	3-10MW(depending on plasma conditions)
Improvements to A2 system	From 3dB couplers	2-3MW
New ITER-like Antenna	7.5MW	
Typical RF power	Post-Enhancement	15MW (power doubled)(12-17MW typical)

	SHAPING	
	 **JET** "ITER shape" Pulse No: 53299, 2.5MA/2.7T	 **ITER**
$H_{98\ (y,2)}$	0.91	**1.0**
$\beta_{N,th}$	1.90	**1.81**
n_e / n_{GW}	1.1	**0.85**
Z_{eff}	1.5	**1.7**
P_{rad} / P_{tot}	0.40	**0.58**
κ_χ, δ_χ	1.74, 0.48	**1.84,0.5**
q_{95}	3.2	**3.0**
τ_{pulse} / τ_E	15	**110**

JG01.416-1c

Fig. 1: Flux plot and parameters for the JET Pulse No: 53299 with an ITER-like shape compared to the equivalent ITER discharge for an ELMy H-mode.

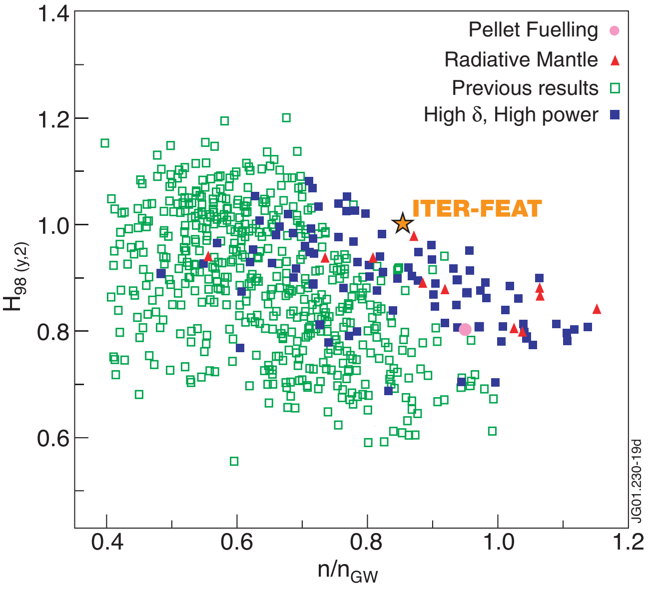


Fig. 2:Confinement enhancement factor relative to the ITER ELMy H-mode scaling ($H_{98}(y,2)$) plotted against the steady electron density as a function of the Greenwald limit (n/n_{GW}) for the JET ELMy H-mode steady —state database for $1.8 < I_p \leq 2.7$ MA.The classes of discharge from which the data come are denoted by the symbols. The previous results refer to those points obtained in experiments up to 31/12/99.

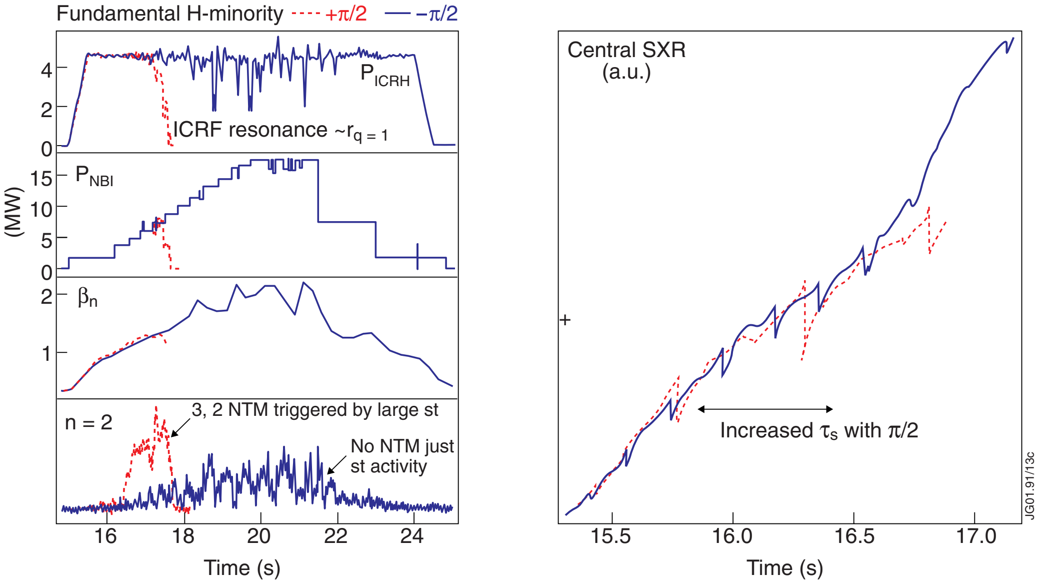
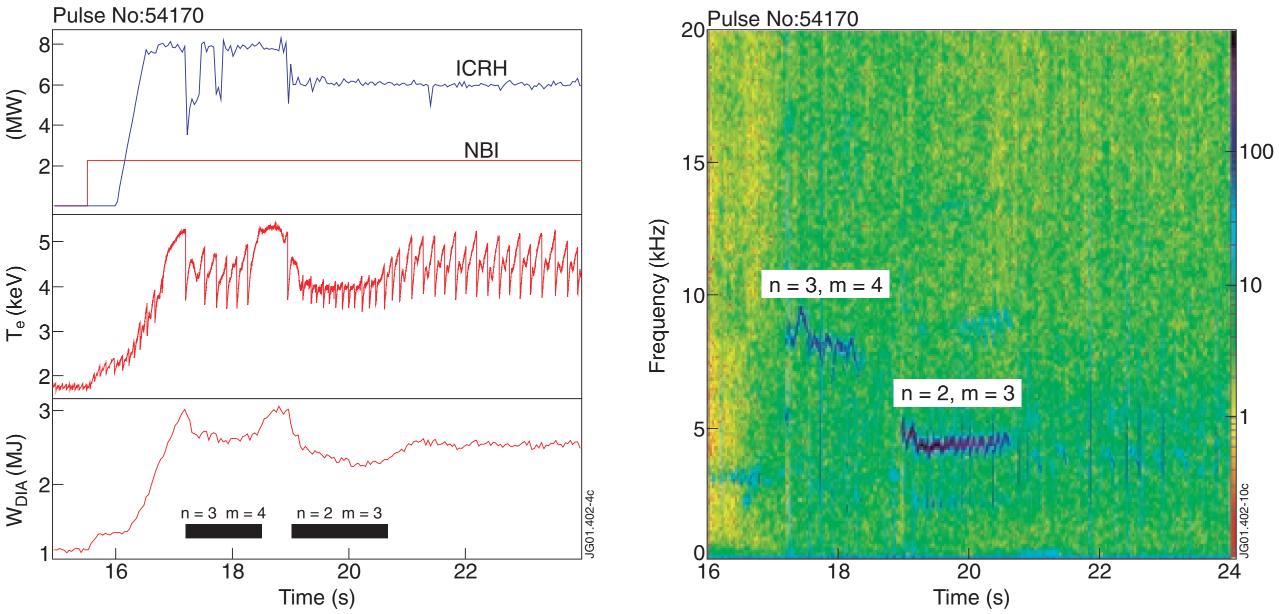


Fig. 3: Traces on the left-hand side show comparison of two similar ELMy H-mode discharges at 2.4T, 2.4MA with 4.5 MW of ICRH and the same pre-programmed NBI power ramp. In the discharge with +π/2 ICRH phasing, a (3,2) NTM is triggered by the first large sawtooth crash. This leads to disruption and termination of the pulse. The right hand side traces of central Soft X-ray (SXR) emission show that the sawtooth period is increased (improved stabilisation) by the +π/2 phasing of the ICRH.


a)

b)

Fig. 4: (a)Application of 3rd harmonic ICRH to accelerate injected ^{4}He ions from NBI (power waveforms shown in the top graph). The accelerated ^{4}He ions temporarily stabilise the sawteeth if the power level is high enough (> 6 MW) as shown on the electron temperature (middle graph), and the crashes after these monster sawteeth lead to destabilisation of the NTMs. The presence of NTMs has a clear degrading effect on the plasma stored energy (bottom graph). (b) Time traces of the frequency spectrum of magnetic perturbations picked up by the JET sense coils, showing the presence of NTMs in the same discharge as (a). The right hand colour scale indicates the relative signal amplitudes.

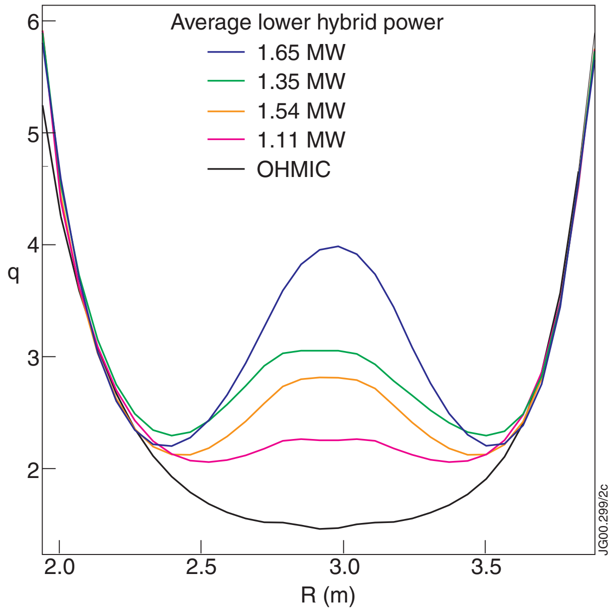
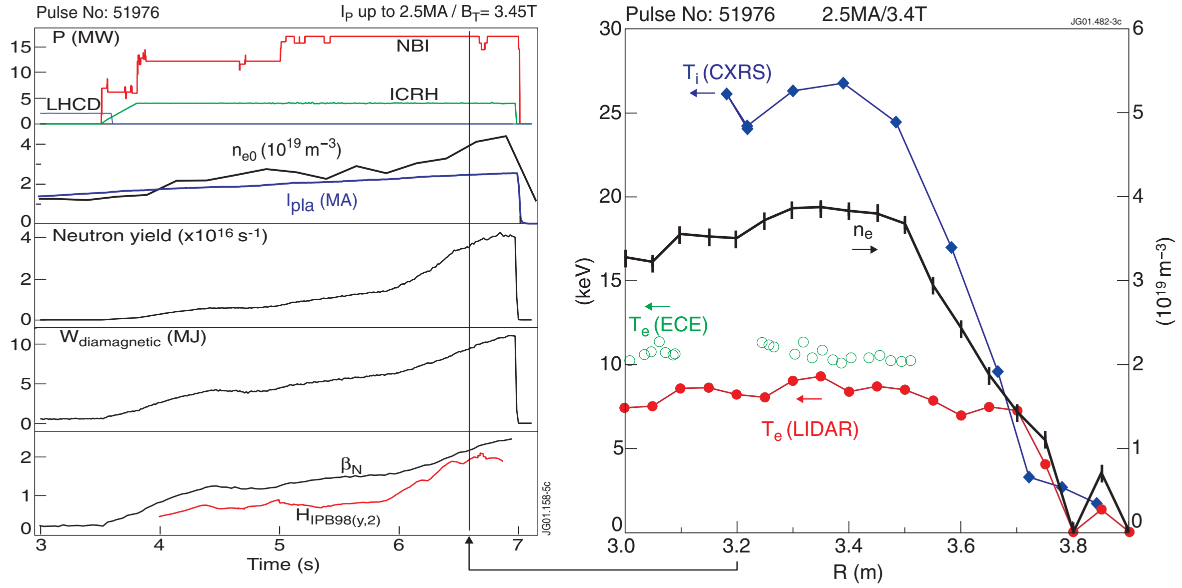


Fig. 5: Comparison of q profiles for target plasmas in ITB experiments prepared with and without LHCD power in the preheat (or early current ramp) phase of the discharge (i.e., the phase prior to the application of high power NBI/ ICRH). The degree of shear reversal is seen clearly to be proportional to the LHCD power. The profiles are derived from pitch angle measurements using the Motional Stark Effect (MSE) diagnostic.


a)

b)

Fig. 6: (a)Time evolution of a pulse (51976) with high fusion performance following an LHCD heating prelude (~2-3 MW, top graph) early in the current ramp, showing: additional heating power; central plasma density ($n_e(0)$) and plasma current; 2.5 MeV neutron yield; plasma stored energy (W_{DIA});β_N (= $\beta_{Toroidal}$ B_T a/I_p); and confinement enhancement with respect to IPB98(y,2) scaling ($H_{IPB98y,2}$). (b) Plasma ion temperature, electron temperature and electron density profiles measured at t=6.5s in the development of shot 51976. The formation of the ITB can be seen clearly.

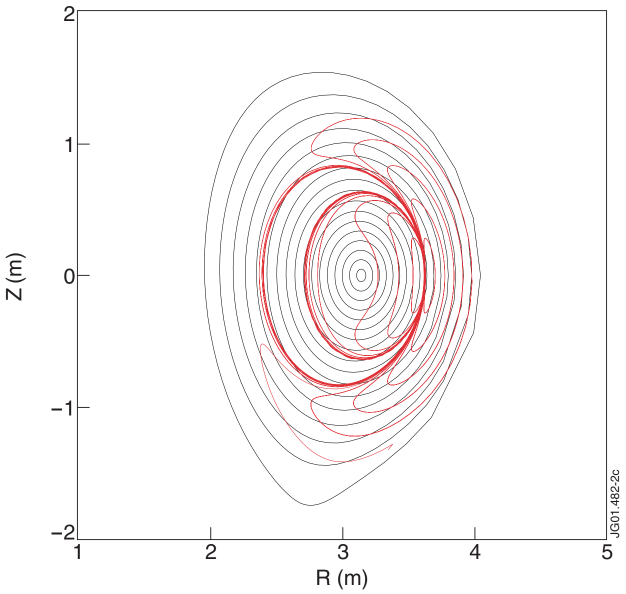


Fig. 7: Poloidal projection of the orbits of 3.5 MeV α-particles (red) plotted over the flux contour plot (black) for the equilibrium of the Optimised Shear (OS) Pulse No: 47413 (3.4MA/3.4T) at 8.3s. The waveforms for this discharge are shown in Fig 11. The flux contours are plotted in steps of 0.06 in $s = \sqrt{(\psi / \psi(a))}$, where ψ is the poloidal flux function. The α-particles are launched equally distributed in pitch angle ($v_{/\!/} / v$) and the launch point corresponds approximately to the foot of the ITB on the low field side in Pulse No: 47413.

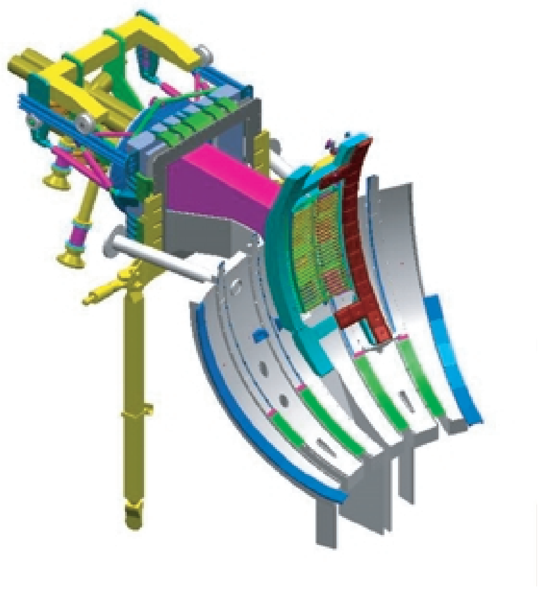


Fig. 8: Cutaway iso-drawing of the proposed JET-EP ICRH antenna, and its location in the JET vacuum vessel.

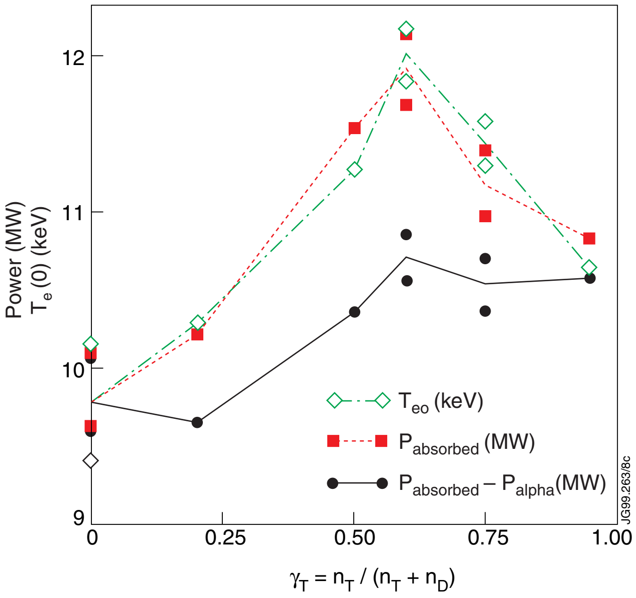


Fig 9 Central electron temperature ($T_e(0)$) and absorbed power in the plasma ($P_{absorbed}$) plotted against tritium fraction (γ_T) for a series of D-T ELM-free H-modes at 3.8MA/3.4T with approximately constant NBI power (10-10.5 MW). The D:T mix in the NBI power was chosen to equal that of the target plasma in each discharge. The absorbed power is calculated from the sum of the NBI power and the inferred α-particle heating power ($P_{absorbed} = P_{NBI} + P_\alpha$). The value of P_α is derived from the measured 14 MeV neutron yield assuming no losses of fast α-particles in the discharge. The proportionality of the extra electron heating and the inferred α-particle power can be seen clearly. The data come from the DTE1 experiment [39].

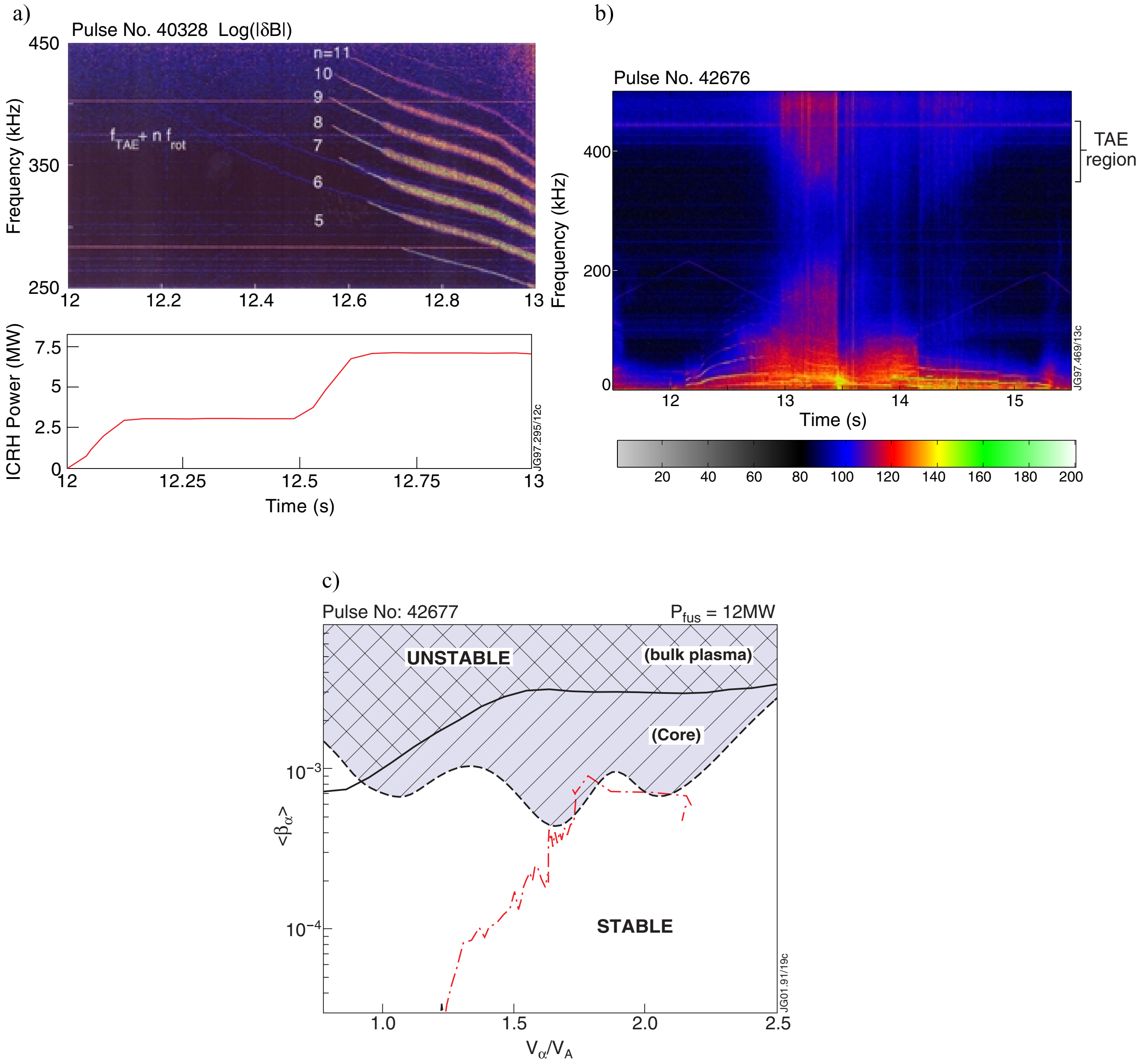


Fig. 10: (a) Magnetic fluctuation spectra showing TAE activity above 5 MW of hydrogen minority ICRH. (b)Magnetic fluctuation spectra indicating absence of TAE activity during the high performance DT ELM-free H-mode shot 42676 (I_P = 3.6 MA; B_T = 3.4T; 12.9 MW fusion power, peaking at 13.4s). (c) Instability zones for α-particle driven non-ideal Kinetic TAEs for the conditions of the high fusion yield pulse 42677 (similar to 42676 but with 12.1 MW fusion power peaking at 13.35s). The zones for instability in the bulk plasma and the core are indicated separately. The description of modes as *core-localised* refers to modes existing within the volume such that the minor radius r is given by r≤ 0.1R, R being the major radius. The bulk plasma unstable zone is calculated including the stabilising effect of the NBI, which is present throughout the high performance phase. The actual trajectory of discharge 42677 in $\langle\beta_\alpha\rangle$ vs v_α/v_A space is shown by the red dot-dashed curve.

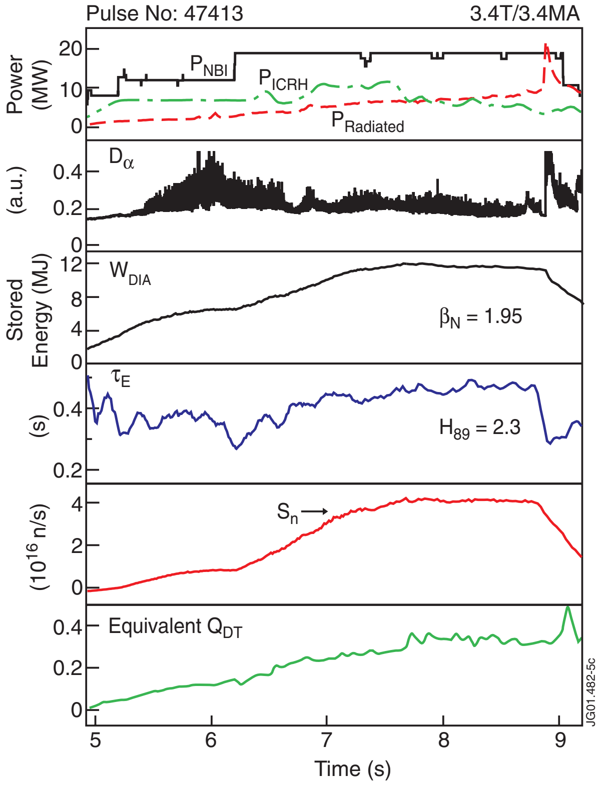


Fig. 11: Waveforms for a high performance quasi-steady state Optimised Shear (OS) pulse in JET. The equivalent Q_{DT} is calculated from the TRANSP code as described in the text.

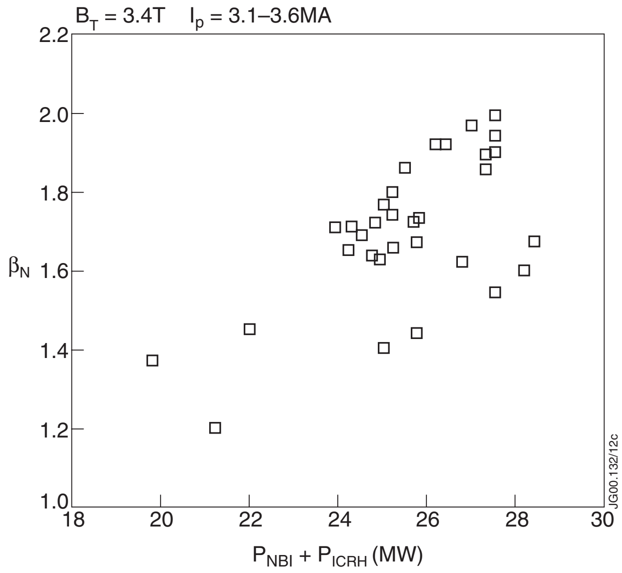


Fig. 12: Normalised β (β_N) as a function of additional heating power during the quasi-steady phases ($\tau > 4\tau_E$) of JET high performance OS plasmas at 3.4T. The data are all taken after an ITB has formed.

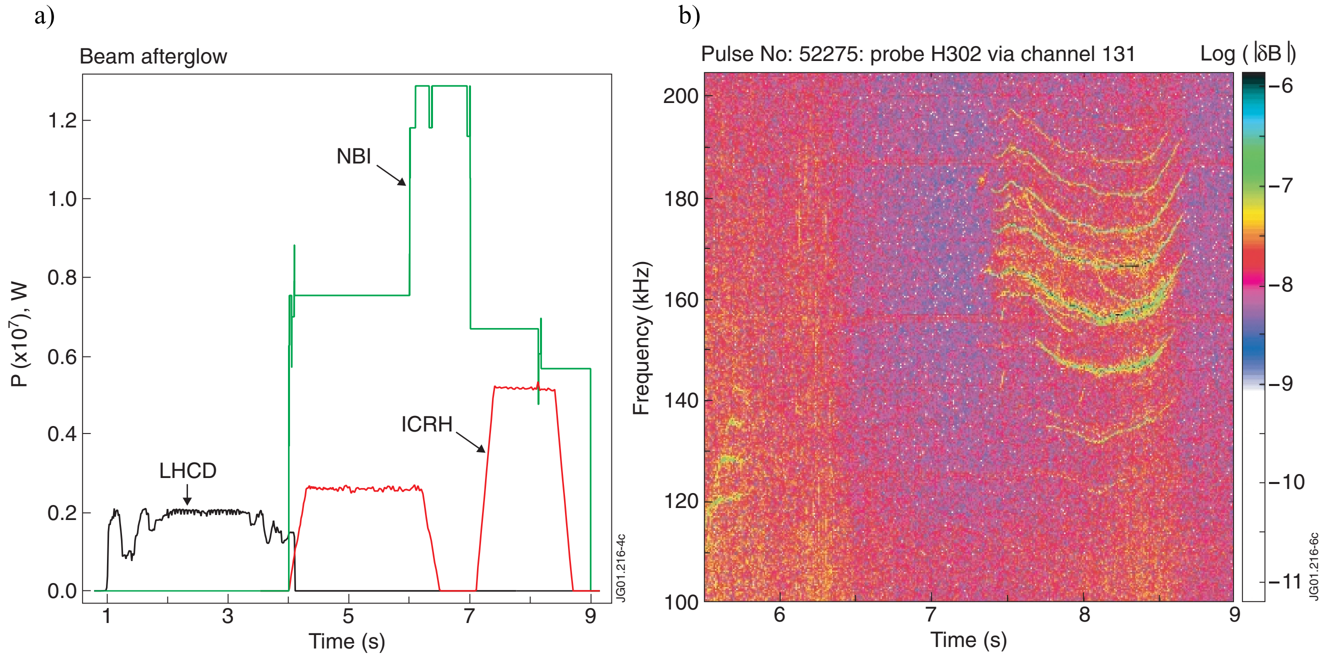


Fig 13: (a) Temporal evolution of LHCD, ICRH and NBI powers in the discharge pulse 52275, with B_T=2.6T and I_p=2.2MA. A non-monotonic q profile is measured by the MSE diagnostic at the start of the NBI power. The afterglow phase of the RS ITB plasma begins at the NBI power step down at 7s. (b) Spectrogram of the magnetic perturbations in pulse 52275 with non-monotonic q(r).