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Review of D-T Experiments Relevant to Burning Plasma Issues

by

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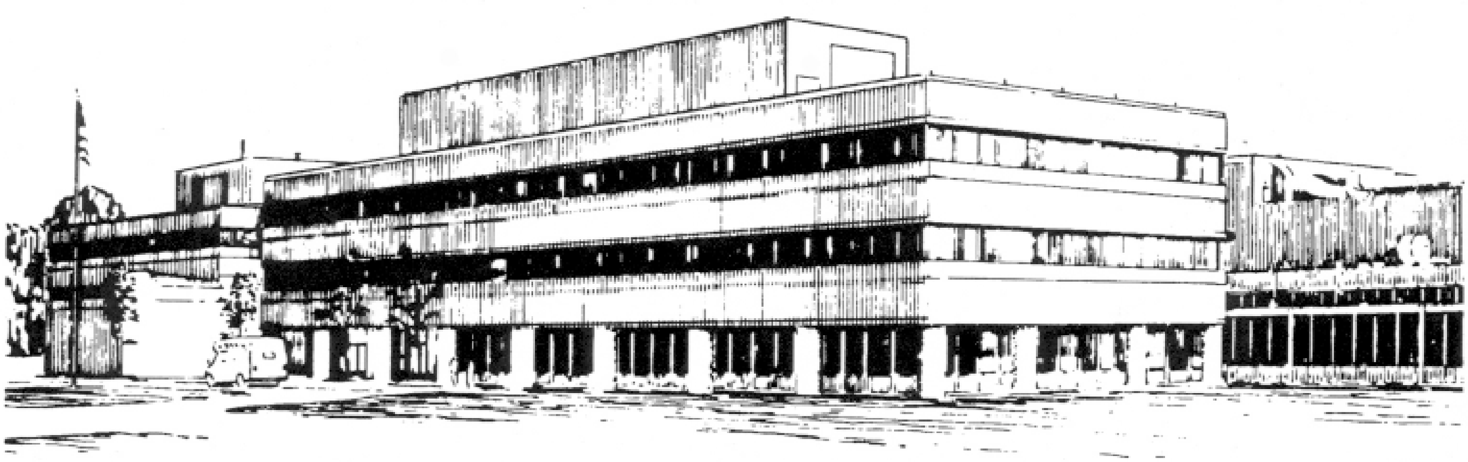

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Review of D-T Experiments Relevant to Burning Plasma Issues

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Abstract

Progress in the performance of tokamak devices has enabled not only the production of significant bursts of fusion energy from deuterium-tritium (D-T) plasmas in the Tokamak Fusion Test Reactor (TFTR) and the Joint European Torus (JET) but, more importantly, the initial study of the physics of burning magnetically confined plasmas. TFTR and JET, in conjunction with the worldwide fusion effort, have studied a broad range of topics including magnetohydrodynamic stability, transport, wave-particle interactions, the confinement of energetic particles, and plasma boundary interactions. D-T experiments differ in three principal ways from previous experiments: isotope effects associated with the use of deuterium-tritium fuel, the presence of fusion-generated alpha particles, and technology issues associated with tritium handling and increased activation. The effect of deuterium-tritium fuel and the presence of alpha particles is reviewed and placed in the perspective of the much larger worldwide database using deuterium fuel and theoretical understanding. Both devices have contributed substantially to addressing the scientific and technical issues associated with burning plasmas. However, future burning plasma experiments will operate with larger ratios of alpha heating power to auxiliary power and will be able to access additional alpha-particle physics issues. The scientific opportunities for extending our understanding of burning plasmas beyond that provided by current experiments is described.

Keywords

Deuterium-tritium, alpha-particle physics, isotope scaling, ICRF heating, JET, TFTR

1. Introduction

The worldwide technical progress in tokamak experiments ranging from the pioneering experiments on T-3, to mid-scale experiments, such as PLT, PDX, ASDEX, DIII-D and Alcator C-Mod, to the largest experiments JT-60, JET, and TFTR has enabled not only the achievement of significant levels of fusion power in deuterium (D) experiments but has also provided detailed scientific understanding. This has set the stage for proceeding with deuterium-tritium (D-T) experiments on JET and TFTR, which began the study of burning plasmas. In going from the early tokamak experiments, to the mid-scale experiments to the largest ones, scientific issues associated with size scaling were very important and perhaps remain among the most important issues for future burning plasma experiments operating with even higher fusion power. An excellent review of this topic can be found by the ITER Team [1]. This paper will concentrate on what was learned when the transition from deuterium to D-T operation was made on TFTR and JET. The results from the TFTR and JET D-T experiments have been extensively published and summarized in other review and overview papers [2-24]. This paper will not attempt to reproduce that large body of work but will highlight some of the key results and identify some of the remaining scientific and technical issues for future D-T experiments.

Both JET and TFTR were designed to perform D-T experiments. JET is an elongated tokamak with a divertor, with a plasma current of 4MA and a toroidal field of 3.6T during the D-T campaign. JET produced 16.1MW of fusion power and the ratio of fusion power to heating power, which is often called Q_{DT}, was up to 0.64 [12,25]. For comparison, TFTR discharges had a circular cross-section defined by an inboard limiter. The plasma current during the D-T campaign was 2.7MA with a toroidal field of 5.6T, which produced 10.6MW of fusion power and a value of Q_{DT} of 0.27. In both machines, the plasma-facing components were composed of a combination of graphite and carbon-carbon composite tiles. The D-T experimental campaigns were performed after years of operation in deuterium, which established the high performance regimes. JET has produced 0.68GJ of fusion energy during their most recent campaign in 1997, whereas TFTR produced 1.7GJ during D-T operation from late 1993 to early 1997, when TFTR operation ceased. Both devices processed 99 grams of tritium to support operations. Since conducting their D-T campaign in 1997, the JET facility has continued to operate in deuterium and is preparing plans for another D-T campaign in 2006. The plan to have another extended deuterium campaign in JET limited the extent of the D-T campaign in 1997.

There are three principal ways in which D-T experiments differ from D experiments. First are differences associated with isotope effects and, in particular, those which affect transport and ICRF heating. Second, the production of fusion-generated alpha particles from the D-T reactions enables the study of alpha-particle physics issues, including the observation of alpha heating. Third, the technology associated with operation, maintenance and decommissioning addresses issues of contamination and activation never previously addressed at this scope within the fusion community. Only a brief discussion of this important topic will be given. However, in many ways this was a watershed issue, demonstrating that the fusion community could safely conduct these experiments, using the fuel needed for a reactor and successfully address the issues of activation, contamination, and waste disposal.

2. Isotope Effects in Confinement and Transport

A large number of different operating regimes have been studied on both JET and TFTR. JET has concentrated their confinement studies on H-mode plasmas both ELM free as well as with ELMs [14]. This is of particular relevance to ITER, since ELMy H-mode operation is the proposed baseline-operating scenario. In ELM free discharges, the confinement of D-T plasmas is slightly less than in D plasmas, whereas in ELMy discharges it is slightly higher. TFTR has studied isotope scaling in ohmic, ICRF L-mode [26], NBI L-mode [27], Supershot [28- 32], limiter H-mode [33] and reverse shear discharges [27]. The supershot regime was the highest performance operating regime in TFTR, though near the end of the operating period exploration of reverse shear discharges had begun. With the exception of reverse shear discharges, a favorable scaling with isotopic mass was observed. The focus of this paper will be on JET ELMy H-mode and TFTR supershot studies.

The JET and TFTR D-T experiments provide another test of our understanding of transport and turbulence. Theoretically, transport is usually believed to be governed by small-scale turbulent processes determined by local plasma physics parameters, which would imply gyro-Bohm scaling and a weak adverse scaling with mass, $\tau_E^{th} \propto \langle A \rangle^{-0.2}$ [14]. This scaling would have a favorable scaling with device size. However, the ITER energy confinement time database indicates a slightly favorable confinement scaling with isotope mass.

The JET team has determined a weak isotope scaling for ELMy H-mode discharges in good agreement with the ITER scaling. In particular, they have concluded that $\tau_E^{th} \propto \langle A \rangle^{0.16\pm0.06}$ [14]. For comparison, the current ITER scaling (ITER98pby2) is that $\tau_E^{th} \propto \langle A \rangle^{0.19}$. To develop an understanding of the source for the weak isotope scaling, Cordey *et al.* [14] studied the scaling of the pedestal compared to the core. Many transport models are sensitive to the edge conditions and the question here is the favorable isotope scaling associated with changes in the pedestal or the core.

The JET Team has found that the stored energy associated with the pedestal increases with isotopic mass, nearly linearly [14]. In addition, the power loss associated with ELMs decreases [14]. Thus, part of the effect of the isotope effect is associated with changes in pedestal parameters. In the core region, the thermal confinement excluding the energy associated with the pedestal has a weak adverse scaling with isotopic mass, $\tau_{thcore} \propto \langle A \rangle^{-0.16\pm0.1}$, very similar to gyro-Bohm scaling [14]. When the ion heat conductivity is evaluated in the core taking into account changes in power deposition, the ion heat conductivity is found to be significantly higher in tritium experiments compared with deuterium. $\chi_I \propto \langle A \rangle^{0.73\pm0.4}$, which is slightly higher than that given by gyro-Bohm ($\chi_I \propto \langle A \rangle^{0.5}$); though within the error bars. Modeling studies by Bateman *et al.* [34] further support that the core transport is consistent with a gyro-Bohm turbulence model. This study found good agreement with the experimental data when the pedestal height from experimental studies was used to define the edge conditions. Recently, Budny *et al.* [35] has fit the confinement time from the JET experiments in terms of dimensionless parameters. The authors have inferred a more positive scaling with isotopic mass $\langle A \rangle^{0.41}$ and have concluded that the scaling for the ion heat conductivity is between Bohm and gyro-Bohm, though large relative errors were inferred in their fitting procedure. Perhaps more interestingly, these authors suggest that a power law fit may not be adequate to describe the variations in isotopic mass and collisionality.

Righi *et al.* [15] has found that the power required to obtain an H-mode transition is less in tritium experiments than in deuterium, scaling inversely with hydrogenic mass. This may also be influenced by the behavior of ELMs in which the frequency of ELMs decreases with isotopic mass. The power required to obtain an H-mode transition is an important consideration for the design of future burning plasma experiments.

The results on TFTR show some marked differences from those on JET, which will be important for both projecting the performance of future experiments as well as understanding the alpha heating experiments. With the benefit of hindsight, it appears that the TFTR supershot plasmas had many signatures of a transitionless internal transport barrier [36]. Steep density and ion temperature gradients in the core, low recycling at the edge, and improved core and global confinement characterized these discharges. In TFTR supershot discharges, a significant increase in the ion temperature, a modest increase in the electron temperature, and a correspondingly significant increase in the confinement time was observed [28-32]. This was a very reproducible effect conducted in a large number of conditions. The triple product, $n_i(o)T_i(o)\tau_E$, increased up to ~80% going from deuterium to D-T. The thermal confinement, $\tau_E^{th} \propto \langle A \rangle^{0.89\pm0.1}$ and the ion heat conductivity decreased substantially in the core by a factor of ~2 and had a strong adverse scaling with mass, $\chi_i^{tot} \propto$

$<A>^{-1.8 \pm 0.2}$ for fixed plasma parameters (T_i) and, $\chi_i^{tot} \propto <A>^{-2.6 \pm 0.3}$ for fixed engineering parameters (P_b).

Ernst *et al.* [36] developed an interesting and successful model to understand the isotope effect in TFTR. In particular, these authors observed that there is a competition between the linear growth rate from a gyro-Bohm transport model, which decreases with ion mass, and the shearing rate, which increases with ion temperature gradient. On TFTR, the sharp density and ion temperature gradients contributed to a large component of the radial electric field, which was not offset by toroidal rotation, since balanced injection was largely employed. By including the radial electric field shear, they were able to model the strong isotope effect observed in TFTR supershots. The implications of this work is that isotope effects depend strongly on operating regimes with differences in pressure gradients, current or rotation profiles. However, more work is required to apply this model to the various operating regimes and for different devices and, in particular, to reversed shear discharges.

Though the largest isotope effect was observed in supershot discharges, it was prevalent in other operating regimes, with the exception of reversed shear discharges. Many of the characteristics of the reverse shear discharges were similar to supershot discharges, with the exception of the current profile. The stored energy in D-T and deuterium reversed shear discharges was similar and the favorable isotope scaling was not observed [27]. More significantly the power threshold for internal transport barrier formation increased with isotopic mass. The reason for this difference remains to be understood and may be important to understand how future advanced performance regimes behave.

3. Isotope Effects in ICRF Heating

ICRF heating is one of the heating options for ITER and a preferred heating option for compact high field burning plasma experiments, such as FIRE and Ignitor. ICRF heating of D-T discharges has been studied first on TFTR and then on JET. Second harmonic tritium heating successfully increased the ion temperature on TFTR and a combination of direct electron heating and ^{3}He minority heating was observed to increase the core electron temperature. In these experiments, the ICRF power was applied to a neutral beam heated discharge [37-38]. Measurements of the power deposition were found to be in good agreement with theoretical models [39]. Near the end of the D-T campaign on TFTR, mode conversion heating with the mode conversion layer in the plasma core, where the ion temperatures were in excess of 30keV, was studied. Ion heating was clearly observed [40-41].

JET routinely used ICRF heating during their D-T campaign and in their highest performance discharges [12]. A tritium plasma was heated by deuterium minority heating resulting in a record Q_{DT} for steady operation, of 0.22 [13,16,17]. This was accomplished by optimizing the energy of the energetic deuterium tail. Tritium minority heating was also studied on JET. Strong ion heating was observed with ^{3}He minority heating. The wave absorption was weaker in second harmonic tritium heating, as would be expected, and the orbit loss associated with acceleration of the ions to high energy reduced the efficiency. ^{3}He minority scenario was recommended for ITER during the heating phase on the way to ignition, since the ^{3}He concentration could be small and an optimized mix of D and T could be maintained, unlike with either deuterium or tritium minority heating [16]. In conclusion, ICRF heating was both successful and well understood in D-T discharges, though technology issues associated with the antenna remain for future burning plasma experiments.

4. Alpha-Particle Studies

The behavior of alpha particles was studied in both MHD quiescent discharges and in discharges with MHD activity [24]. MHD quiescent discharges facilitated the study of the confinement and slowing down of the alpha particles, since the interaction with MHD activity can be important. The effect of alpha particles on MHD stability was also studied.

Finally, the first experiments of alpha particle heating were performed. A key ingredient in these experiments was the successful development of new diagnostics to study the fusion-generated alpha particles. Many of these diagnostics were tested during the D-T experiments for the first time and were in their own right a major technical accomplishment.

To benchmark the models for the alpha-birth profile, neutron-emission measurements were used. The chord integrated radial profile measurements for the D-T neutron emission as well as the time dependence was in good agreement with TRANSP calculations based on plasma parameters in high performance discharges on both TFTR and JET [12,42,43]. Thus, the TRANSP calculations provide a good model for the alpha birth profile.

The alpha heating power density in the core of the highest performance TFTR and JET discharges is comparable to the projected values in ITER, despite the large difference in fusion power [44]. In addition, $\beta_\alpha(0)$ and $-R\bullet\nabla(\beta_\alpha)$, which is a measure of instability drive term for TAE modes, is also comparable, as shown in Table 1. Thus on both TFTR and JET, it was possible to study many important issues associated with alpha-particle physics. However, there is one important difference between current machines and future higher performance burning plasma experiments. The ratio of P_{alpha}/P_{heat} is considerably less in JET and TFTR compared with ITER or other future burning plasma experiments, and limits the range of alpha-particle heating studies.

5. Confinement and Slowing-down of Alpha Particles in MHD Quiescent Discharges

The escaping alpha particles were measured in TFTR by means of detectors inside the TFTR vacuum vessel near the first wall [45]. The escaping alpha flux to the detector near the bottom of the vacuum vessel decreased with plasma current in agreement with classical first orbit loss calculations. At 2.5MA, the first orbit loss was about 3% in supershot discharges.

The study of the confined alphas was a major experimental challenge due to the low concentration and large range in energies spanning from thermal particles to 3.5MeV. The high-energy alpha particles (0.5-3.5MeV) were measured by means of a double charge exchange technique on TFTR [46,47]. A lithium pellet was injected into the discharge. From the cloud of singly ionized lithium ions, two electrons were transferred to the alpha particles. The neutralized alpha particles were then detected by a charge exchange diagnostic, which detected deeply trapped alpha particles. To model this narrow range of the distribution function, a Fokker Planck calculation was used to overcome the limited statistics in the Monte Carlo treatment used in TRANSP. The energy spectrum of the alpha particles near the axis of the discharge is in good agreement with TRANSP and Fokker Planck calculations [46,48.49].

Since this diagnostic measured the deeply trapped alpha particles, the effects of stochastic ripple diffusion were evaluated on the confined alphas. Stochastic ripple diffusion predicts that particles at larger major radii, where the effect of the toroidal field ripple is greater, should exhibit greater loss as was clearly measured [50]. In high performance supershot discharges, stochastic ripple diffusion was only a couple of percent; however, in reversed shear plasmas, which were located outboard in major radius in a higher toroidal field ripple region, the stochastic ripple diffusion was about 20% [51,52]. Experiments on JT-60U measured the heat deposition due to ripple loss of fast ions to the plasma-facing components using an infrared camera, extending the work on TFTR [53].

The intermediate energy alpha particles, 150 to 600 keV were measured by charge exchange recombination spectroscopy [54]. This technique relies upon charge exchange from neutral beam particles to provide an electron to an excited energy state of alpha particles, which then undergo a transition. The absolute intensity of the emitted light provides an absolute measurement of particles in this energy range. A very high throughput optical system was developed for this task. This diagnostic on TFTR provided a sensitive measure of the radial transport of the alpha particles. The absolute intensity and the radial distribution showed that the alpha particles were very well confined with $D_{alpha} < 0.03 m^2/s$ [55,56].

The thermal helium ash was measured with a conventional charge exchange recombination system. The helium density profile is determined by radial diffusion and recycling from the limiter and walls. For these supershot discharges, the radial diffusivity is comparable to the ion thermal diffusivity and the ratio of $\tau_p{}^*/\tau_E$ =8, which would be acceptable for a reactor, operating under similar conditions [57]. The issue for future machines will be the ability to pump particles on the edge and on the details of impurity transport compared with that of the heat [58]. In particular, will transport barriers affect the relative confinement of alpha ash?

On TFTR, the evolution of alpha particles from their birth energies all the way to thermal energies was measured and found to be in accord with expectations in MHD quiescent discharges with positive shear and q(0) ~1. This is consistent with other studies of energetic particles, which has been reviewed by Heidbrink and Sadler [59]. Discharges with reversed shear or high central shear were less intensively studied in TFTR. The loss due to stochastic ripple diffusion was greater but other possible loss mechanisms were not fully excluded.

6. Effect of MHD Instabilities on Alpha-particle Confinement

MHD activity can affect the confinement of energetic particles and also alpha particles. Sawteeth were observed to redistribute the intermediate energy alpha particles (in the range of 150-600keV) in minor radius [60]. Though this effect was quite pronounced on TFTR, the effect of such a distribution may be more modest in a high performance burning plasma. In such plasmas, the heating dynamics would be affected transiently. Since the alpha slowing down time would be short compared to the energy confinement time and the sawtooth period, the impact may be modest.

In addition to the redistribution due to sawteeth, other MHD instabilities can cause enhanced loss of alpha particles. On TFTR, neoclassical tearing modes resulted in enhanced loss to the probes at the vacuum vessel wall [9]. A strong toroidal anisotropy is observed as the mode rotates. Enhanced loss is also observed due to major and minor disruptions and kinetic ballooning modes [61,62]. Because the loss is localized, it can place additional requirements on plasma-facing components.

7. Alpha-particle Effect on MHD Behavior

While MHD can affect the behavior of energetic particles, energetic particles can also affect MHD instabilities. A review of previous experiments was given by Heidbrink and Sadler [59]. During the past decade, motivated by experiments on JET and TFTR and also future burning plasma experiments, there has been extensive theoretical and experimental work on energetic particle-wave interactions. One of the instabilities, which have been extensively studied is the toroidal Alfvén eigenmode (TAE) instability, which is destabilized by energetic particles resonant with the Alfvén velocity. This instability is predicted to be among the most dangerous instabilities for burning plasmas. Neutral beam and ICRF experiments on TFTR and also on the other large facilities have shown that a large fraction of the particles can be ejected from the plasma at sufficiently high power. Compared with the high power neutral beam and ICRF experiments used to excite the toroidal Alfvén eigenmode instability, the alpha power was relatively low and this was not a violent instability in either TFTR or JET D-T experiments [11,20,24]. In particular, in the highest fusion power discharges, this instability was not driven by alpha particles and did not have a deleterious effect. The relatively modest alpha-particle density together with a large damping rate from the beam ions stabilized this instability in high performance TFTR discharges.

Subsequent theoretical calculations showed that the predicted alpha-driven toroidal Alfvén eigenmode threshold is sensitive to the q-profile [63-66]. Reversed shear discharges and discharges with high q(0) on axis were predicted to be favorable to the onset of the instability. The phase after beam turn-off, when the alpha particle drive was still present but ion damping was reduced was predicted to offer an opportunity to observe the instability.

TFTR experiments, with high q(0) after beam turn-off, observed the onset of the alpha-driven instabilities and confirmed theoretical predictions for the onset of the instability [67,68]. By means of microwave reflectometry, the radial eigenmode of the n=4 TAE was seen to be in approximate agreement with linear theory, though issues remain for some modes. These experiments confirmed that the onset condition for the toroidal Alfvén eigenmodes was relatively well understood. Future work on nonlinear consequences of alpha-driven toroidal Alfvén eigenmodes remains, especially under conditions when many modes would be destabilized and higher amplitude instabilities are developed, which may occur in future burning plasma experiments.

Though the alpha-driven toroidal Alfvén eigenmodes on TFTR were very weak, evidence exists that these modes spatially redistributed part of the alpha particles. The pellet charge exchange diagnostic measured the radial profile of .53MeV and 1.7MeV particles. Compared with a discharge which did not have an observable toroidal Alfvén eigenmode instability, the alpha particles are redistributed radially and the low energy particles are depleted from the core. This was observed when the central q(0) was ~2 but not for lower values of q(0) [50]. These were very interesting results near the end of the TFTR D-T campaign. Further experiments and more theoretical modeling is required to understand the alpha-particle redistribution in detail. Since these experiments on TFTR, strong radial redistribution of energetic beam ions has also been observed during negative-ion neutral beam experiments on JT-60U [69-70].

One of the potential benefits of alpha particles is that they might help to stabilize the sawtooth instability, as has been observed with ICRF energetic particle formation. An interesting experiment was performed on JET which showed that the sawtooth period increased with tritium concentration but did not peak with maximum fusion power production [71]. A detailed analysis of these experiments indicated the effect was due to the increase in slowing down time of the tritium ions compared with deuterium ions and the resulting increase in perpendicular energy density in the fast beam ions. The same analysis suggests that for the highest performance D-T discharge in JET the alpha particles had a significant stabilizing effect and may have contributed to the increased sawtooth period. Thus, it may be possible that future higher power D-T experiments on JET will be able to demonstrate this effect.

8. Alpha-particle Heating

Experiments on JET and TFTR have begun the study of alpha-particle heating [72,73]. On TFTR, the alpha heating power was about 3% of the heating power, though about 15% of the power through the electron channel, enabling a measurement of electron heating. In these supershot experiments, the sawteeth were stabilized and there was no detectable adverse MHD. In TFTR deuterium experiments, the central electron temperature was observed to scale as the square root of the energy confinement time. Since the isotope effect was significant on TFTR, plasmas were matched with similar energy confinement time to account for the isotope effect on the central electron temperature. A measurable increase in electron temperature (ΔT_e~0.8±0.3keV for P_{fusion} = 4.5MW) was observed, in reasonable accord with expectations both in terms of the magnitude of the increase and the radial dependence [72]. The increase in central electron temperature was observed to be greater in discharges with higher fusion power (ΔT_e~2keV for P_{fusion} up to 7.5MW); though, there were few shots at these higher values of fusion power with comparable D shots for a baseline.

JET was able to operate at higher ratios of P_{alpha}/P_{heat} = 0.12 with 30-40% of the power input to the core electrons than TFTR and conducted an experiment to measure alpha heating by varying the tritium concentration over a wider range than TFTR [73]. This was done to isolate the isotope effect, which as discussed above was inferred to be weak on JET. The effect of differences in heating power from shot to shot was taken into account. A significant systematic effect in this experiment was the variability due to sawteeth, which changed with tritium concentration, as noted above [71]. Though there were only a limited number (5) of pulses used in these experiments, clear indications of alpha heating (ΔT_e~1.3±0.23keV for P_{fusion} = 5-6MW) were observed on JET. Future higher power experiments are required to do a comprehensive study of alpha heating. In historical context, the early neutral beam and rf heating experiments in the early 70's demonstrated that it was possible to heat a tokamak; however, subsequent experiments at much higher power enabled the detailed scientific study of confinement and stability. In many ways, the experiments on TFTR and JET made the first step by obtaining clear indications of alpha heating. The next round of higher performance experiments is required to exploit this new heating technique and evaluate its effect on confinement and stability.

9. Potential for Utilizing Alpha Particles to Further Improve the Prospects for a Reactor

Theoretical work on alpha channeling [74-78], frequency sweeping of waves [79], and stochastic ion heating [80,81] raise the tantalizing prospects of: increased ion heating, alpha ash control, modifications of the alpha heating profile, reductions in alpha pressure to decrease instability drive, and current drive. While it is unlikely that any technique would simultaneously provide all of these potential benefits, the attainment of one or more of these objectives could be beneficial. This is an area in need of further experimental study, first in hydrogen or deuterium discharges and then in D-T discharges. Fundamental wave-particle physics studies of alpha channeling were begun on TFTR near the end of operations [82-85] and showed some encouraging results but raised some important theoretical issues [86-87]. Recently, Thomas *et al.* [88] suggested that the increased ion heating accompanying the alpha-particle heating experiments is not well explained and raised the question as to whether unexplained transfer of alpha heating to the ion channel occurred. The data for this is limited and further analysis is underway. Gates *et al.* [81] have predicted that stochastic ion heating from compression Alfvén instabilities driven by neutral beam ions may contribute to enhanced ion heating. Experiments on NSTX are underway to investigate this. This is an area awaiting further experimental results to determine the viability of these techniques for future burning plasma experiments. While a demonstration of the impact of these concepts will require a burning plasma, experiments to develop an understanding of these concepts can be performed in current experiments.

10. Technology Associated with Deuterium-Tritium Experiments.

Both JET and TFTR successfully used on-site tritium processing, a key technology for future experiments. Both machines observed that tritium retention in graphite is a serious concern. After extensive efforts to remove the tritium, 16% of the tritium, which went into the torus, remained inside the TFTR vacuum chamber and 12% in JET [89-93]. This is an unacceptable retention rate for future-burning plasma experiments and has motivated the development of novel in-situ techniques. A recent collaboration between PPPL and JAERI has studied the removal of tritium from TFTR limiter tiles used during the D-T experiments. The tiles were scanned with a laser to heat the surface and release the tritium from the co-deposited layers [94-95]. Initial results look promising and the possibility of using this technique on future JET experiments is being discussed. This also motivates the search for alternative plasma facing component materials as recognized by the design teams for future burning plasma experiments. This remains an active area of research.

JET has demonstrated that it is possible to maintain in-vessel components with a remotely operated manipulator [96-97]. After the conclusion of the D-T campaign, they used this technique to replace their divertor tiles. This is a critical technology for future experiments. However, it is important to realize that in ITER the fluence will be up to 10^4 greater, which places even greater requirements on this technology and the ability to remotely repair all components, which was not possible in JET. Nonetheless, the JET results are a very significant demonstration of this important technology.

TFTR is in the process of being decommissioned [98-99]. This is a three-year effort and all of the external structure around the vacuum vessel and toroidal field coils has been removed, though the neutral beam boxes are being retained for future experiments. At this time, the vessel is being cut apart using a diamond wire cutting technique and already three of the ten vessel sectors have been removed. On TFTR, contamination control is the largest radiological issue along with waste disposal and handling. In future machines, activation will be much greater and disassembly will have to be performed remotely.

11. Conclusions

Results from TFTR and JET enhanced the technical and scientific basis for proceeding with a burning plasma experiment. These experiments reduced the risk for a future experiment by exploring the effects associated with the use of a tritium, by studying the confinement and heating of alpha particles and by demonstrating that D-T experiments can be safely performed. These experiments also identified scientific and technical opportunities in a future burning plasma experiment.

H-mode isotope scaling studies on JET, together with the worldwide physics database, provide a good technical basis for the baseline operation of a burning plasma experiment. The JET ELMy H-mode experiments support the confinement time and power threshold projections with respect to isotope mass. Analysis of the core transport indicates that the confinement in the core is in reasonable accord with gyro-Bohm scaling, though the overall energy confinement time has a weak positive isotopic dependence. An important observation was that the energy associated with the pedestal increased and the ELM frequency and power loss by ELMs decreased. Nonetheless, the understanding of isotope scaling is incomplete. The dimensionless scaling studies are not in full accord with gyro-Bohm scaling in the core. There is a clear variation in scaling results in different operating regimes. The radial electric field shear in TFTR appears to play a significant role in supershot discharges, in which the confinement time has a strong positive scaling with isotopic mass. Further work is required to understand the isotope scaling in other operating regimes and in particular, discharges with reversed shear.

The physics of ICRF heating is well established. Second harmonic tritium, He^3 minority, mode conversion to ion Bernstein wave, deuterium minority and tritium minority heating were all explored. He^3 minority and second harmonic tritium heating have been identified as the preferred approach for ITER and FIRE. Deuterium minority heating produced the highest values of Q_{DT} in steady state JET discharges. For future burning plasma experiments, the technology challenges associated with ICRF antenna remain due to the higher neutron fluence.

Alpha-particle confinement, transport, and slowing down are well understood in MHD quiescent discharges, though not as extensively studied in reversed shear experiments. Alpha particles can be expelled from the discharge and radially redistributed by MHD instabilities. Alpha particle driven instability was studied. In the highest performance discharges on both TFTR and JET, the alpha-particle pressure was insufficient to destabilize the toroidal Alfvén eigenmode. This motivated the construction of experiments on TFTR with high central values of the safety factor and reduced beam ion damping, which confirmed that the onset of the instability is in reasonable accord with theory. Even these weak toroidal Alfvén eigenmode instabilities redistributed the deeply trapped alpha particles. Future experiments with larger amplitude modes will focus on the nonlinear consequences of these instabilities. Alpha particle heating was observed on both TFTR and JET, setting the stage for future higher power and performance experiments in which the ratio of P_{alpha}/P_{heat} will be higher.

Critical aspects of the technologies for a burning plasma experiment were utilized for the first time, demonstrating that it is possible to operate, maintain and decommission a device operating with D-T fuels. The technological requirements will be far more demanding in future burning plasma experiments due to the higher neutron fluence and tritium processing requirements and potential tritium retention in the vacuum vessel.

The TFTR and JET experiments, together with the scientific and technical results from the worldwide fusion effort, have developed the basis for proceeding with higher performance burning plasma experiments. Those experiments will enable not only a comprehensive study of alpha-particle physics but also the assessment of the scientific issues associated with alpha-particle heating on stability and confinement. Furthermore, a burning plasma experiment will further the development of the technology required for fusion energy development.

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Table 1

	TFTR	JET	ITER
P_{fusion}(MW)	10.6	16.1	400
$p_{\alpha}(0)(MW/m^3)$	0.28	0.08	0.43
$\beta_{\alpha}(0)$%	0.30	0.4	0.8
$-R\bullet\nabla(\beta_{\alpha})$%	2.0	2.3	4.0
$V_{\alpha}(0/V_{Alfvén}(0)$	1.72	2.52	1.76
P_{α}/P_{heat}	0.03	0.09	0.66

Comparison of the parameters for the highest performance discharges on TFTR and JET with the predicted performance on ITER [44].

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