MAGNETIC CONFINEMENT FUSION

Will the alphas abscond?

Richard D. Petrasso

WHEN Princeton University's Tokamak Fusion Test Reactor (TFTR) began burning a 50:50 deuterium–tritium mix last December, a key question was what would become of the energetic alpha particles (helium nuclei) generated in the fusion reaction. For a future reactor, losses of even a few per cent of the energetic alphas could have serious consequences. With losses of more than 15 per cent, the temperature needed for fusion ignition, about 250 million kelvin, would be difficult to sustain unless the thermal energy confinement was good. And the heat load of even 5 per cent of these particles could damage the vessel walls, especially if the heating was unevenly distributed over the surface. With the completion of an extensive sequence of deuterium–tritium (D–T) experiments, including one in which a record 6.2 MW of fusion power was achieved, an international workshop* gave researchers the chance to consider what had been learned.

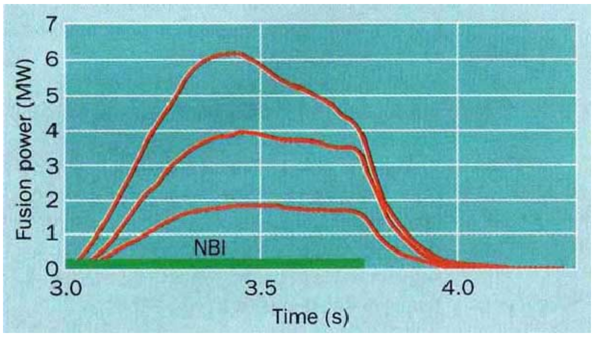

FIG. 1 Fusion power emitted from the burning of deuterium–tritium, for three discharges in which different proportions of tritium were injected via energetic heating beams into the plasma. Top trace, seven tritium sources (this set the record of 6.2 MW fusion power); middle, four sources; bottom, one source. NBI (neutral beam injection) indicates the duration of the heating beams. (From J. Strachan.)

As I described in a News and Views report three years ago[1], when the first such workshop was held, future fusion reactors are expected to run on a 50:50 D–T mix, as D–T fusion has a much higher reaction rate and requires a far lower temperature than other fuel combinations. The TFTR experiments are the first to try this mix, although the Joint European Torus (JET) ran two discharges using 13 per cent tritium in November 1991, setting the previous record of 1.8 MW fusion power. The end product of the D–T reaction is a 14.1-MeV neutron and a 3.5-MeV α. The neutrons, unlike the αs, are uncharged and therefore unconfined by the magnetic field of the tokamak (about 50 kG). In principle, these would be the heat source driving electric power generators.

When deuterium and tritium operations first started at TFTR, two scientific issues were paramount. First, would a large fraction of the αs unexpectedly abscond from the plasma without depositing their kinetic energy into the plasma? And second, would the plasma be able to store and retain its thermal energy as effectively as it did when running in pure deuterium? At TFTR, because fusion power was found to scale as the square of the stored plasma energy content, any diminution in the plasma's ability to hold its thermal energy, the efficacy of which is measured by the energy confinement time τ_E, would be directly reflected in a low level of fusion reactions.

Encouragingly, the main message from the TFTR workshop was that unexpected losses of energetic alphas did not occur, and τ_E actually improved by 20 per cent to 0.18 s (R. Hawryluk, Princeton Plasma Physics Laboratory (PPPL)). At present, the reasons for the improvement are not understood, but are being actively investigated (K. Itoh, National Institute for Fusion Science).

Figure 1 shows the fusion power generated when three different mixes of deuterium and tritium ions were injected into the plasma. These beam ions, with an energy of about 100 keV, both heat and fuse with the background plasma ions. In the top trace, representing 30 MW of beam power injected for 0.75 s, the fusion power was seen to peak at the new record of 6.2 MW, 0.4 s after beam heating was initiated (J. Strachan, PPPL). About 75 per cent of this power results from the heating beams fusing with background ions and with energetic, unthermalized ions originating from the beams. After the peak, the fusion power then smoothly declined by 30 per cent over the remaining duration of the beam heating (0.35 s). For other discharges (lower two traces of Fig. 1), the fractional decline was smaller (R. Budny, PPPL).

Compared with the proposed International Thermonuclear Experimental Reactor, ITER, the TFTR has a small plasma cross-section (minor radius 87 cm). So about 5 per cent of the αs, known as 'prompt losses', were expected to escape the plasma before depositing essentially any of their energy[2]. (They move downwards, in this instance; the direction depends on the magnetic field and its gradient). The signal from these escaping αs closely tracks the total production of fusion power as determined from the measurement of 14.1-MeV neutrons (S. Zweben, PPPL). In contrast, fully confined αs in TFTR take about 0.2 s to deposit roughly 60 per cent of their kinetic energy into the plasma, about the same as the energy confinement time τ_E. Ideally, future reactors will operate so that the α energy deposition time is comparable to τ_E or smaller.

As well as these 'prompt-loss' αs, a similar fraction of αs is theoretically predicted to escape and hit the outer vacuum walls of the TFTR at slightly below the midplane (M. Redi, PPPL). Unlike the prompt losses, these escapees, known in the lexicon of the field as 'stochastic-toroidal-field-ripple losses'[3], are expected to occur in large fusion reactors such as ITER (S. Putvinski, ITER team, San Diego). The loss occurs because of a sensitive interaction between small perturbations (~1 per cent) in the toroidal magnetic field (a consequence of the finite number of the toroidal magnetic field windings, 20 for the TFTR) and a class of αs for which the toroidal velocity component oscillates through zero[4]. Hints of these losses were obtained during the tritium experiments by particle detectors (S. Zweben, PPPL), but additional measurements and analysis are under way to assess whether these losses have the

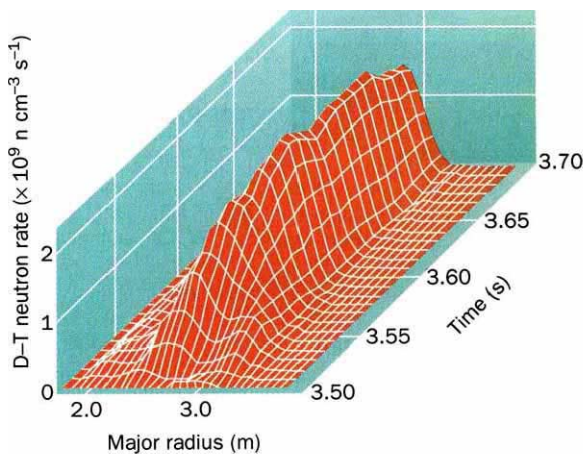

FIG. 2 Imaging of the 14.1-MeV neutrons produced in deuterium–tritium fusion allows mapping of the inflow and transport of trace amounts of tritium, injected at time $t = 3.50$ s into a deuterium plasma. The transport of both tritium and deuterium is crucial to sustaining the fusion burn. (From L. Johnson.)

* *IEA US–Japan Workshop on D–T Experiments*, Princeton, New Jersey, USA, 2–4 March 1994.

expected magnitude and scaling. For example, do they decrease with increasing plasma current? As this loss mechanism is directly germane to future reactors, it is especially important to check the theoretical predictions at TFTR.

An entirely different genre of α-loss mechanisms involves the interaction between coherent magnetohydrodynamic oscillations ('collective' oscillations) and the αs. Like Proteus, these oscillations can manifest themselves in different guises, as 'fishbones,' 'snakes' or 'sharkteeth'[5], to name but a few, and if they grow large enough they can eject energetic particles, such as the heating beam ions or the αs, from the plasma (B. Coppi, Massachusetts Institute of Technology). At high concentrations (about 1 per cent), the αs themselves can drive these instabilities (unlikely in TFTR, but possible in future reactors).

The chosen operating parameters for TFTR kept these collective modes to a minimum, and for these levels there were no associated α losses (H. Hsuan, PPPL; and L. Zakharov, PPPL). But the discharge with maximum fusion power may have been affected — one school of thought attributes the droop in fusion power, at least in part, to a coherent mode that appeared just after the peak.

One collective oscillation that could be a particular problem in future machines is the α-driven Alfvén mode (H. Kimura, Japanese Atomic Energy Research Institute; C. T. Hsu, Massachusetts Institute of Technology). Amongst other conditions, this instability occurs when the average α velocity (1.3×10^7 m s^{-1} at birth) is higher than the Alfvén velocity ($v_A = B/\sqrt{4\pi m_i n_i}$, where B is magnetic field and m_i, n_i the mass and number density of the ions). The good news is that it was not observed in the TFTR experiments (E. Fredrickson, PPPL; and R. Nazikian, PPPL), as indeed theoretical calculations had indicated. The ratio of α pressure (the product of number density, n_α, and kinetic energy, E_α) to magnetic field pressure ($B^2/8\pi \approx 100$ atm) would need to be roughly 5 times greater than it typically was in the TFTR (C. Z. Chang, PPPL). But because the conditions are far more likely to be satisfied in future machines, efforts are being made to push the TFTR over the excitation threshold. One way that has been suggested is to drive a larger fraction of the plasma current off-axis (D. Spong, Oak Ridge National Laboratory).

And what about the αs that are well confined, which make up about 90 per cent of those born in the TFTR? As the α heating effects are only a few per cent, can we directly detect them through sensitive α-particle diagnostics? In fact, diagnostic methods are being developed that, for example, determine the density of the αs through their elastic collisions with plasma tritons. Some of these energy-boosted tritons, known as knock-ons, then fuse with deuterons generating neutrons that have an energy up to 20.7 MeV. To detect these high-energy neutrons, and to avoid being swamped by the 14.1-MeV neutrons from the background D–T reaction, an energy threshold detector is to be used: based on a threshold nuclear reaction in beryllium, it is sensitive only to neutrons with energies above 16.5 MeV (R. Fisher, General Atomics, San Diego).

A further important element of the deuterium–tritium experiments has been the study of tritium transport itself. Rather than adding a high proportion of tritium, the essence of this experimental programme has been to inject trace quantities (~1 per cent) of tritium into deuterium plasma, either in the energetic heating beams (D. Jassby, PPPL), or by introducing neutral (cold) tritium gas at the plasma edge (P. Efthimion, PPPL).

In the latter case, the inflow and on-axis peaking of the tritons can be observed by imaging the emission of the 14.1-MeV neutrons produced in D–T fusion (Fig. 2). The indications are that trace tritium diffuses into the plasma core at about the same rate as trace helium. (Trace helium injections can assist our understanding of the transport of spent αs.) Both tritium and deuterium transport are known to be of great importance in sustaining the fusion power. In fact, it has been suggested that part of the decline in fusion rate (Fig. 1, top trace) may be due to an increased inflow of cold deuterium from the plasma edge (C. Skinner, PPPL), a process known as enhanced recycling.

And what happens to the 'ash' of spent αs? For a future machine in which α heating dominates over all other forms, might the ash accumulate in the plasma core, diluting the fusion fuel and quenching the fusion burn? Before the TFTR ceases operations this autumn, experiments currently under way should detect the small quantities of α ash within the machine, giving us our first glimpse of this transport (E. Synakowski, PPPL).

So what is this future machine? Given the TFTR's encouraging evidence that the αs did not abscond and that the energy confinement improved, the next logical scientific step is a device in which the α-heating is substantial or even dominant, and for which instabilities, either driven or possibly suppressed by the αs, can be readily studied. Will the αs then abscond, or instead heat the plasma? □

Richard D. Petrasso is at the Plasma Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA.

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DAEDALUS

Dilute pleasure

ADDICTIVE drugs owe their market not to the pleasure of using them, but to the pain of giving them up. Their withdrawal symptoms are so unpleasant that addicts will commit any crime to get more drug. So Daedalus wants to alleviate withdrawal. He recalls the traditional French alcoholic, who sips wine all day and much of the night. His blood-alcohol never drops to zero, so he never has a hangover. If cocaine and heroin could be sustained like this, instead of giving a brief rush of pleasure followed by hideous withdrawal pains, they would be less of a menace.

Many modern pharmaceuticals can be injected as a subcutaneous fatty 'depot', from which they leach out slowly into the patient's bloodstream. DREADCO's biochemists are now devising a blank, rechargeable depot. It will act as an internal buffer for addictive drugs. Most of them, such as amphetamines, cocaine and heroin, are nitrogen bases; they can combine reversibly with acids. So the new drug buffer is an inert fatty polymer with many acidic groupings. It will seize any drug that gets into the user's bloodstream, and slowly release it again. This equilibrium will need careful tuning. The buffer must absorb drug from the blood in levels much above the desired value, and feed it out again to stop the level dropping much below.

When perfected, DREADCO's 'Drugstat' will simply be injected into the addict — either as treatment or as part of the punishment for drug-related crime. His next dose will be a strangely muted experience. There will be no sudden rush of pleasure; as fast as he takes in the drug, the Drugstat depot inside him will seize it. The low equilibrium dose in his bloodstream will give him only a mild mental alleviation. Yet this alleviation will persist wonderfully. Drugstat will maintain the defined concentration in his blood, leaking out just enough drug to avoid withdrawal symptoms. Many days may pass before he has to repeat the dose.

Drugstat will calm the wild roller coaster of the addict's life. It will meter his drug so efficiently that he will need far less of it. His new mental stability may even let him hold down a job and buy his reduced dose without resorting to crime. Furthermore, the pallid, diluted pleasure of Drugstatted addiction will no longer antagonize the respectable masses. Their puritanical envy and outrage at people who get pleasure without working for it, is the basic reason why drugs are illegal in the first place. Once Drugstat is in wide use, public opinion may at last permit drugs to be legalized, thus solving the whole problem. David Jones