PFC/JA-91-14

Fusion Energy -- The Moment of Truth Nears

Richard D. Petrasso
Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

The generation of copious, energetic, charged fusion products (α-particles) and the deposition of their energy within the fusing plasma are pivotal issues for the achievement of fusion energy. With less than nearly perfect α energy input, the plasma cannot sustain the high temperatures (250 million K) needed to maintain deuterium-tritium fusion reactions. In preparation for the first ever experiments on deuterium-tritium plasmas in July 1993 -- to occur in the U.S. Tokamak Fusion Test Reactor (TFTR) -- a workshop* was held last month to debate the critical issues regarding the plasma physics of α-particles and tritium operations.

Since the first fusion experiments in the early 1950s -- conducted mainly with devices called pinches, mirrors and stellarators -- all magnetically confined plasmas have been principally composed of weakly fusing, nonradioactive hydrogen isotopes, either hydrogen (mass 1) or deuterium (mass 2). But it was understood that with the eventual attainment of high-quality fusion plasmas, experiments would switch to a mixture of deuterium and tritium (mass 3), the latter being a radioactive β-emitter. Despite the special care required in handling tritium, the overriding reasons for its choice are, first, that the deuterium(d)-tritium(t) reaction

$$d + t \rightarrow \alpha \, (3.5 \text{ MeV}) + n \, (14.1 \text{ MeV})$$

has by far the largest reaction rate and, second, that it occurs at the lowest temperature (n is an energetic neutron, which in principle would be used to power conventional generators, and α is an energetic He^{2+} nucleus).

The large kinetic energy of the α and neutron results from the strong nuclear interaction which converts 0.4 per cent of the deuteron and triton mass into energy. In contrast ordinary chemical reactions are a million times

less energetic, though they too derive their energy by converting mass (as in $mc^2 = E$). But it is precisely because of this million-fold enhancement that, on the one hand, the frightful power of the hydrogen bomb has been realized and, on the other, two generations of physicists and engineers have pursued the goal of fusion energy. One of the principal results of this effort has been the tokamak, a toroidal plasma-containment device in which a large magnetic field (about 50 kilogauss) and plasma current (around 3 megamp) thread the torus, thereby inhibiting the loss of energetic plasma particles.

A figure of merit that represents the quality of any fusion plasma, be it the Sun's core or a tokamak, is $Tn\tau$, where T is the central ion temperature, n the central ion density, and τ the overall energy confinement time (the duration for which the plasma thermal energy can be effectively contained). For a deuterium-tritium plasma to ignite -- that is, for the α-energy input to sustain the 250×10^6 K temperature against thermal and radiative losses -- $Tn\tau \approx 6 \times 10^{22}$ K cm^{-3} s (the value in the hydrogen-burning solar core, by contrast, is a staggering 5×10^{47} K cm^{-3} s: $T = 15 \times 10^6$ K; n $\sim 10^{26}$ cm^{-3}; and $\tau \sim 3 \times 10^{14}$ s = 10 million years). The fusion plasma experiments of the 1950s were a factor of 10^7 below this ignition threshold. In the past few years TFTR[1] and JET[2] (Joint European Torus) obtained plasma conditions which, had they been operating with deuterium-tritium under identical conditions, would have momentarily achieved a $Tn\tau$ a factor of 20 and 6 below this threshold. (For JET, $T = 250 \times 10^6$ K; $n = 3.7 \times 10^{13}$ cm^{-3}; and $\tau = 1.1$s.) Thus although neither tokamak will achieve ignition -- nor were they designed to -- each can be expected to produce measurable amounts of α power (2 megawatts) and α-particles (3×10^{18}s^{-1}) if using deuterium-tritium fuel. But most of all, several critical issues can be experimentally addressed for the first time.

One such issue is the energy and particle transport in a deuterium-tritium plasma (D. Post, TFTR). Although one might not expect that changing from one hydrogen isotope to another would notably affect the transport, experience teaches otherwise. For example, plasmas of pure deuterium typically run hotter than those of pure hydrogen, and this is partly reflected in a larger value of τ. A corollary is, however, that impurities are also better confined in a deuterium plasma[3]; if inadvertently injected in too large quantities, these could radiatively quench the plasma, as occurred on the record JET discharge[2,4]. Thus it will be important to investigate whether the empirical scaling for the energy confinement, $\tau \sim m_i^{1/2}/P^{1/2}$, still holds ($m_i$ is the ion mass and P the total absorbed power), and whether impurities are more likely to reside within the plasma precluding a significant and sustained value of $Tn\tau$.

A second crucial question is what fraction of α-particles will be either kicked out by intrinsic plasma instabilities -- such as by sawtooth oscillations and higher-frequency magnetic perturbations (S. Zweben, TFTR; see figure) -- or execute a process known as stochastic diffusion whereby they make a rapid random-walk out of the plasma before depositing their energy in the plasma, which takes 0.3 s according to classical calculations (R. Boivin, TFTR). In principle, each of these effects has been observed at TFTR through energetic protons (p) and tritons (t) created in the fusion reaction

$$d + d \rightarrow p \,(3\ \text{MeV}) + t \,(1.0\ \text{MeV})$$

And in closely related work at JET (F. Marcus), 14.7-MeV protons from deuterium-helium-3 reactions were poorly confined with a 1.5 MA plasma current, but well confined with a 4.5 MA current unless sawtooth oscillations

occurred. For deuterium-tritium plasmas, the crux of the issue will be quantitative: what fraction of the α–particles will be so affected, and how often?

A conceptually related issue is whether the large population of α-particles will themselves generate and drive formerly benign or unknown collective oscillations in the plasma that would again result in their 'self ejection'. Of the class of such instabilities that physicists theorize, none was more widely discussed than the α-driven Alfvén mode[5-7]. This instability should occur if a sufficient number of α-particles have, along the direction of the magnetic field, a component of velocity greater than a critical velocity called the Alfvén velocity, V_A (D. Sigmar, MIT). (The tokamak's confining magnetic field includes a toroidal component and a smaller poloidal field created by the plasma current.)

The Alfvén velocity, which depends on the field strength (B) and central ion density ($V_A = B/\sqrt{4\pi m_i n}$), is around 0.8×10^9 cm s^{-1} (with a field of 50 kilogauss and central ion density of 6×10^{13} cm^{-3}). The initial velocity of the 3.5-MeV α-particles is 1.3×10^9 cm s^{-1}, and about 40 per cent will have a 'parallel' velocity component exceeding the Alfvén velocity.

But it is also becoming apparent that two other conditions need to be satisfied if the Alfvén mode is to be excited. First, the number density of α-particles at the centre must not be less than about 0.3 per cent of the electron density. And second, the α-particles' gas-kinetic pressure must exceed 0.003 times the magnetic pressure they experience ($B^2/8\pi$, about 100 atmospheres).

Simulations of TFTR deuterium-tritium plasmas (R. Bundy) find all three thresholds likely to be exceeded. But recent "α-simulation experiments" (K. Wong) on TFTR using energetic neutral beams and deuterium plasmas indicate that the pressure threshold may be larger by about an order of magnitude[7]. If so,

then TFTR deuterium-tritium plasmas may be spared this particular α-particle loss channel.

The best method of injecting tritium into TFTR is also of pressing importance. The most frequently discussed methods are injecting it either with high-power heating beams, or firing in tiny frozen tritium pellets. Among other compelling arguments for using pellets (each less than 0.01 g in mass, equivalent to 100 curies of radioactivity), one is that it will tend to place the tritium mostly on the tokamak axis where it can be more effectively burned (D. Mikkelsen, TFTR). Another not inconsequential benefit is that pellet injection reduces by an order of magnitude the total amount of tritium injected into the machine (D. Meade, TFTR).

Making maximum use of the limited number of deuterium-tritium discharges is another concern (J. Strachan, TFTR); only 1,000 or so are feasible, whereas TFTR has already had about 50,000 hydrogen, deuterium and helium discharges. For example, should new diagnostic methods be developed that in principle could, with some spatial and temporal resolution, measure aspects of the α-particles' energy distribution? Although highly desirable, the means to measure these parameters are at present untested, although serious efforts to do just that are underway (P. Woskov, MIT). And even if not immediately applicable to TFTR, they might prove invaluable for the next generation of experiments.

An approach that addresses the immediate needs of TFTR is to place greater emphasis on proven methods that could measure the escaping α-particles (as with tritons as shown in the figure). Largely in combination with the α-particle birth profile (from 14.1-MeV neutron imaging), such measurements should reveal a clear picture of the overall α-particle transport.

Furthermore, it will be essential to establish experimentally for each diagnostic technique -- such as those used to measure the ion-temperature profile or the plasma impurity content -- its ability to operate reliably in the intense neutron and γ-ray fluxes resulting from the fusion neutrons. None of the tokamak diagnostic techniques has yet operated in such a severe environment, so that there is concern that, despite careful shielding and other precautions, some measurements might give false or unintelligible signals owing to the background radiations.

Finally, assuming that most of the α-particles do deposit their energy in the plasma, what is to be done with the thermalized He^{2+} 'ash' which would certainly dilute the deuterium-tritium fuel and so extinguish high-temperature ignition? One proposed solution (G. Miley, University of Illinois) is that suitable plasma instabilities should be periodically triggered so as to expel the ash. However, from this and previous considerations it is clear that a fine line has to be walked: on the one hand energetic α-particles must deposit their energy in the plasma; on the other, having done so, they must be transported out. TFTR should give us our very first glimpse of this delicate balance.

1. Meade, D. et al., IAEA, Washington, D. C. (Proc. to be published, 1990).
2. Keilhacker, M. et al, Phys. Fluids 2, 1291 (1990).
3. Marmar, E. et al., Nucl. Fus. 22, 1567 (1982).
4. Petrasso, R. D., Nature 343, 21-22 (1990).
5. Fu, G. Y. and Van Dam, J., Phys. Fluids B1, 1949 (1989),
6. Sigmar, D. S., Hsu, C., White, R., and Cheng, C. Z., MIT Plasma Fusion Center, Rep. No. PFC/JA-89-58 (1989).
7. Wong, K. L. et al., Phys. Rev. Lett. 66, 1874-1877 (1991).
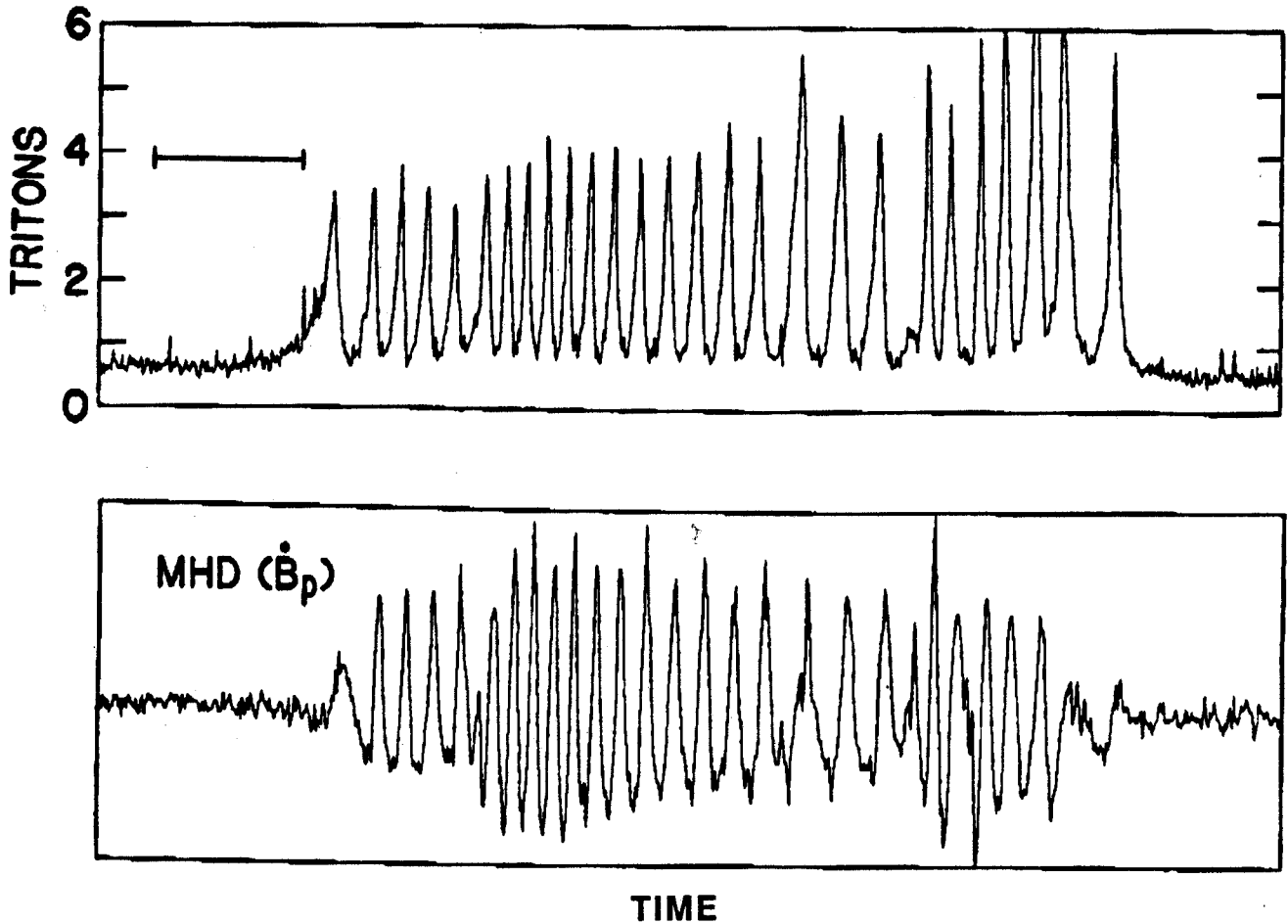
Escaping 1-MeV tritons (upper) resulting from magnetic perturbations $\dot{B}$ (lower) associated with magnetohydrodynamic modes. The energetic tritons are detected by particle detectors just outside the plasma boundary. An important issue is whether these perturbations or others, such as those associated with the α-driven Alfven mode, will eject a large fraction of the energetic α-particles generated in TFTR deuterium-tritium plasmas. (Scale bar, 1 ms.) (Courtesy of S. Zweben, TFTR.)