Measurements of Fast Confined Alphas on TFTR

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This Letter reports the first measurements of the fast confined α-particle energy distribution in a fusion plasma. The pellet charge exchange technique shows the fusion generated α's in the core of the Tokamak Fusion Test Reactor plasma slow down classically, and appear to be well confined. Preliminary indications are that stochastic ripple effects are responsible for steepening the energy distribution outside the plasma core ($r/a \gtrsim 0.35$). Sawteeth mixing of fast α's is suggested in data during the post-beam-heating plasma decay.

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First generation fusion reactors will operate using deuterium and tritium (D-T) fuel. The 3.5 MeV α particles generated by D-T fusion reactions must be well confined by the magnetic fields in order to deposit a large fraction of their energy in the reacting plasma via collisions before they are lost to the tokamak walls. It then becomes possible to heat the plasma ions to fusion ignition, where α's are being created and confined in sufficient quantity to maintain the plamsa temperature. If the α's are not well confined, achieving fusion ignition will require higher plasma temperatures and densities than presently assumed. If α's are lost due to instabilities or toroidal magnetic field ripple, they can result in localized heating and possible damage to the tokamak outer wall. Next generation fusion devices such as the International Thermonuclear Experimental Reactor (ITER) must be designed to limit these α losses to a few percent. For a review of α-particle physics in burning plasmas, see Furth *et al.* [1].

The ongoing D-T experiments [2] in the Tokamak Fusion Test Reactor (TFTR) represent the first opportunity to study α-particle confinement and heating. Previous tokamak experiments using only deuterium have shown that the fast ions created by fusion reactions lose their energy to the plasma consistent with classical Coulomb collisions [3]. The slowing down of α's from D-T reactions is expected to exhibit similar behavior. However, in the presence of certain magnetohydrodynamic activity, anomalous losses of fusion product ions have been observed [3]. The energy distribution of the confined α particles in a tokamak will reflect whether they are confined on a time scale that is long or short in comparison to their slowing-down times. This Letter describes the first experimental measurements of the energy distribution of fast confined α's in a fusion plasma. The results show the α's in the core of the TFTR plasma are well confined and are slowing down classically. Outside the core ($r/a \gtrsim 0.35$), there are indications that stochastic ripple effects are steepening the observed energy spectra. During the plasma decay, after the neutral beam heating is turned off, large sawtooth instabilities appear to be causing radial transport of the fast α's.

Because of the importance of α particles in fusion research, a number of diagnostic techniques are under development [4]. Thomson scattering from the electron cloud surrounding the alphas has been proposed using microwave [5] and laser [6] radiation. Based on the original proposal of Post *et al.* [7] using high-energy beams, charge exchange recombination spectroscopy [8] and charge exchange neutral measurements [9] are being developed using injected neutral heating beams. A charge exchange spectroscopy measurement using the low-energy heating beams is operational on TFTR, and this diagnostic measures the α particles in the energy range below ~600 keV [10]. Ion cyclotron emission near the harmonics of the α's [11] may provide information. The pellet charge exchange approach [12] discussed in this paper has also been under development for several years. Initial operation of this diagnostic to measure energetic ion cyclotron resonance frequency driven minority ion distributions has been reported [13].

A small lithium pellet (volume ~7 mm^3) is injected radially into TFTR. Upon entering the plasma, the pellet ablates, forming an ionized plasma ablation cloud which travels along with the pellet and is elongated in the direction of the tokamak magnetic field. A small fraction

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of the α particles incident on the cloud are neutralized by sequential single electron capture; $He^{2+} + Li^{+} \rightarrow He^{+} + Li^{2+}$ followed by $He^{+} + Li^{+} \rightarrow He^{0} + Li^{2+}$, and also by double capture $He^{2+} + Li^{+} \rightarrow He^{0} + Li^{3+}$. By measuring the energy distribution dn_{He^0}/dE of the resultant helium neutrals escaping from the plasma using a mass and energy resolved neutral particle analyzer (NPA), the energy distribution of the incident α particles $dn_{He^{2+}}/dE$ can be determined using

$$dn_{He^{2+}}/dE = (dn_{He^0}/dE)/F_0(E), \quad (1)$$

where $F_0(E)$ is the fraction of incident α's neutralized in the cloud as a function of incident α energy. Based on modeling studies [14] and pellet injection experiments [15], we conclude that the cloud density should be large enough to produce an equilibrium fraction $F_0^\infty(E)$ of neutrals. A detailed calculation of $F_0^\infty(E)$ shows that its magnitude depends on the lithium ionization state distribution in the pellet cloud, but that the energy dependence of $F_0^\infty(E)$ is sensitive to the ionization state mix. This can be understood by realizing that, at these high α-particle energies, the α's are primarily capturing the inner shell electrons of the lithium ions. These results, together with the results of a Monte Carlo code calculation which includes the helical nature of the incident α orbits, will be the subject of a more detailed paper [16]. The code results show a neutralization probability very close to the calculated single-pass equilibrium fraction.

On TFTR the pellet is injected radially, and the NPA views the cloud from behind. Hence the time dependence of the observed helium neutral signals, combined with the measured radial position of the pellet, yields the α energy spectrum as a function of the radial position in the plasma as illustrated in Fig. 1. The pellet was injected 200–500 msec after the beams were turned off. This timing delay had the advantage of allowing the plasma temperature to decay from its peak value, which facilitated deeper pellet penetration and a lower neutron background signal. It also allows us not to perturb other measurements during the neutral beam heated phase.

Figure 2 shows the measured α-particle energy spectrum at the center of a 1.0 MA D-T discharge on TFTR with the pellet injected 220 msec after 20 MW of neutral beam (NB) heating. The eight discrete points, corresponding to the eight energy channels in the NPA, show the measured α spectrum using Eq. (1). The solid line in Fig. 4 below shows the predicted α energy spectrum based on the Monte Carlo code TRANSP [17] which follows the orbits of the α particles as they slow down and scatter by Coulomb collisions with the background plasma. TRANSP assumes the α's are well confined, i.e., confined for a long time compared to their slowing-down time scale, and takes into account the spatial and temporal dependence of the α production and slowing down.

Above 1.5 MeV, which is the energy an α born at 3.5 MeV would slow down to 220 msec after its birth,

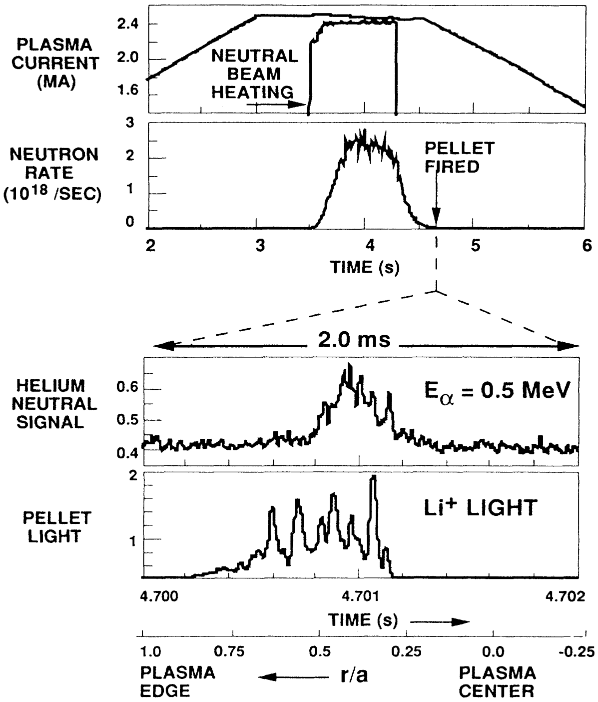

FIG. 1. Time behavior of selected plasma wave forms (long time scale) and charge exchange neutral and pellet light signal wave form (expanded time scale) for lithium pellet injection into a 30 MW D-T plasma on TFTR.

the time dependence of the α production affects the calculated α energy distribution. Below this energy, the TRANSP result is essentially a classical steady-state E^{-1} slowing-down distribution [3]. The excellent agreement between the measured α spectra and TRANSP shows that the α's in the center of TFTR are well confined and slowing down classically. This result represents the first experimental verification that D-T fusion-generated α

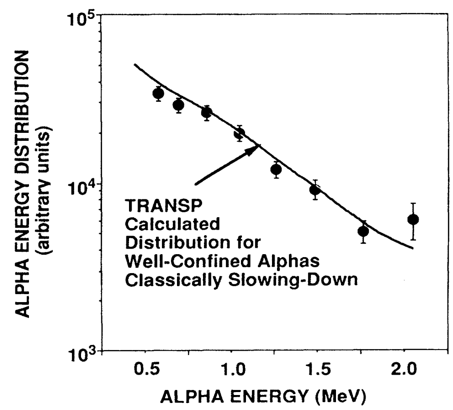

FIG. 2. Measured α-particle energy distribution in the plasma core for a 1.0 MA TFTR plasma with 20 MW of neutral beam heating.

particles are behaving as expected in a tokamak plasma, and is a very encouraging result for the prospects for magnetic fusion.

Outside the plasma core, the measured local α distributions begin to show what are possibly the effects of toroidal magnetic field ripple. Figure 3 shows the measured α energy spectra as a function of radial position in the plasma for the 2.5 MA D-T discharge shown in Fig. 1. The pellet was injected 500 msec after 30 MW of neutral beam heating. At $r/a = 0.25$, the measured spectrum is close to that predicted by TRANSP. But at $r/a = 0.35$ and 0.45, the measured α populations at higher energies fall below the TRANSP predictions, which do not include ripple effects. Because the line-of-sight observation angle on TFTR is only 2.75 deg from radial, the NPA is measuring α's on banana-trapped orbits. Trapped particles are known to be susceptible to rapid losses caused by toroidal field ripple [18]. Except at the edge of a tokamak, the ripple loss is due mainly to stochastic ripple diffusion of the trapped banana orbits [19]. Stochastic ripple diffusion affects ions with $v > v_s = (\Omega/2\delta)(\varepsilon/\pi N q)^{3/2}(dq/dr)^{-1}$, the critical velocity for the onset of stochastic behavior [20], where $\Omega = eB/m$, $\delta \equiv \delta B/B$ is the ripple at the tip of the banana orbit, $\varepsilon = r/R$, N is the number of toroidal field coils, and q is the safety factor. The pellet penetrated to within 20 cm of the magnetic axis ($R_{\text{axis}} = 2.59$ m), and the helium neutral signal was only observed for the last 20 cm of the pellet travel. In the signal region, $E_s = \frac{1}{2}\, m v_s^2$ lies between 3.5 and 1.5 MeV so that birth energy α particles at $E_0 = 3.5$ MeV were susceptible to rapid stochastic ripple losses. Since the classical slowing-down time is at least two orders of magnitude longer than the 1 to 5 msec stochastic ripple loss time [20], birth energy α particles will be lost from the plasma before they can slow down classically and hence cannot be the source of lower-energy α's observed in Fig. 3. We suggest two processes which could explain the observed spectra.

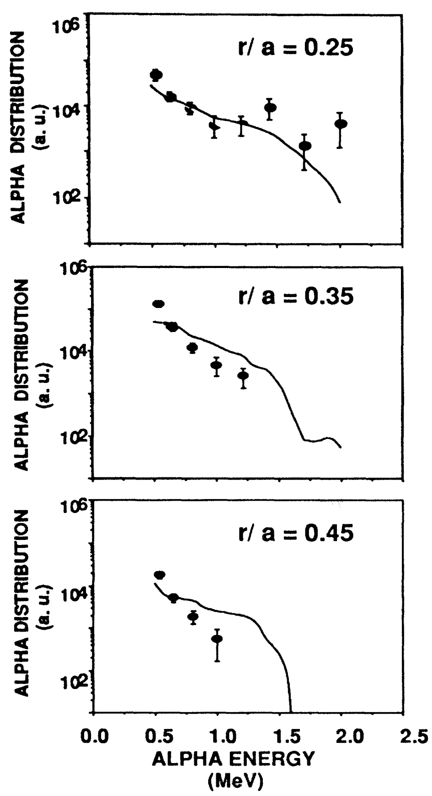

FIG. 3. Measured α-particle energy distributions as a function of plasma radial position for TFTR plasma discharge shown in Fig. 1. Disagreement with TRANSP code (solid lines) at $r/a = 0.35$ and 0.45 is possibly due to toroidal magnetic field ripple loss effects.

The first possibility is that the trapped α's first slow down in the well-confined core region of the plasma and then are radially transported into the outer radial region ($r/a \geq 0.3$). This radial transport may be a result of large sawtooth instabilities that occurred prior to the pellet injection measurement on this discharge. Fast-ion redistribution at sawtooth crashes has been inferred from triton burnup measurement in JET [21]. Sawtooth instabilities often occur during the plasma decay after the neutral beam heating is turned off on TFTR. Figure 3 would indicate that the sawteeth instabilities are redistributing fast α's with a fairly large mixing radius ($r/a \geq 0.45$). The sawtooth inversion radius from electron cyclotron emission measurements was at $r/a \sim 0.3$. Additional experiments and modeling are being planned to determine if sawtooth mixing can explain the observations. Note that the classical slowing-down result of Fig. 2 was for a TFTR discharge which did not have any large sawteeth instabilities prior to the pellet measurement time.

A second possibility is that a small fraction of the well-confined passing α's is pitch angle scattered into the trapped particle region near 2.75 deg as it is slowing down. Once below the threshold energy E_s it is no longer susceptible to stochastic ripple loss and can contribute to the observed α spectrum. A preliminary bounce-averaged Fokker-Planck model [22] shows promise in terms of explaining the measured spectra of Fig. 3. TRANSP is being modified to include ripple effects to better address this issue. It is also possible that the sawtooth instabilities are redistributing the α's from the passing region into our trapped particle observation region.

The effects of large post-beam-injection sawteeth have also been observed in the measured α distribution near the plasma center. Sawteeth mixing is an important issue because it can enhance α-particle losses by redistributing a fraction of the α's onto first orbit loss or ripple-loss orbits, thus reducing the α heating available for fusion ignition, and possibly producing unacceptable wall heat loads. Figure 4 shows the observed α energy spectrum

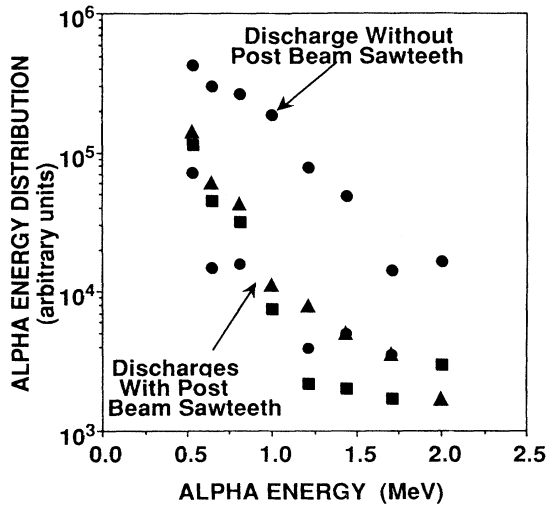

FIG. 4. Measured α-particle energy distributions in the plasma core of 1.0 to 1.2 MA TFTR discharges with and without post-neutral-beam-heating sawtooth instabilities.

at the plasma core of four TFTR discharges at plasma currents of 1.0 to 1.2 MA. These are all at lower electron temperature and density so that the lithium pellet was able to penetrate to the plasma center. Only one of the discharges did not exhibit large post-beam-injection sawteeth and it had a 5 to 10 times larger α-particle signal level. Whether the sawteeth are redistributing fast α's or other sawtooth effects are causing the drop in signal is not totally clear. One of the goals of our future experiments will be to obtain more data on this important issue to allow a more definitive conclusion.

In conclusion, we report the first experimental measurements of the energy distribution of fast confined α particles in a fusion plasma. The measured energy distribution in the TFTR plasma core shows the α's are well confined and slowing down classically. We also observe what appear to be the effects of stochastic toroidal field ripple losses and sawtooth instabilities on the α's, which are two important issues for next generation fusion experiments.

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