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ALPHA PARTICLES IN FUSION RESEARCH

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ALPHA-PARTICLE EXPERIMENTS ON THE TOKAMAK FUSION TEST REACTOR AND THE COMPACT IGNITION TOKAMAK

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Plans for alpha-particle experiments on the Tokamak Fusion Test Reactor and Compact Ignition Tokamak are described. The main physics issue is whether alpha particles are confined long enough to be thermalized. Some of the diagnostic methods required to measure alpha-particle confinement are briefly described.

I. INTRODUCTION

This paper describes our present thinking about the appropriate alpha-particle experiments and diagnostic methods for the Tokamak Fusion Test Reactor (TFTR) and Compact Ignition Tokamak (CIT). One goal of these experiments is to determine plasma regimes in which the alpha-particle confinement will be good enough to ensure efficient alpha-particle heating in reactor-sized devices like the International Thermonuclear Experimental Reactor (ITER). Efficient alpha-particle heating typically requires that the alpha-particle confinement time τ_α be comparable to or larger than the alpha-particle thermalization time $\tau_{th} \approx 1$ s (for burning plasmas).

Our strategy is to use the deuterium-deuterium (D-D) stage of TFTR to evaluate the "single-particle" confinement of alpha-like 1-MeV tritons and 3-MeV protons, then proceed to the first tests of "collective" alpha-particle effects in TFTR's deuterium-tritium (D-T) stage, and finally to use CIT to test alpha-particle confinement under reactor-like D-T burning plasma conditions. Since each of these steps involves both new physics and new diagnostic developments, and since these experiments are quite difficult and costly, close coordination between experiment, modeling, and theory is necessary.

This paper briefly reviews this strategy according to the time frame of the experiments: Section II describes present and near-future alpha-particle simulation experiments on TFTR, Sec. III describes the prospects for the D-T experiments in TFTR, and Sec. IV describes the initial plans for alpha-particle experiments in the burning plasmas of CIT.

II. TFTR ALPHA-LIKE PARTICLE EXPERIMENTS

Alpha-particle simulation experiments can be performed on TFTR and other existing tokamaks without the use of D-T alpha particles. These experiments use either the small populations of alpha-like D-D (or D^3He) fusion products, or the large populations of energetic (but generally lower energy) ions created during ion cyclotron range of frequency (ICRF) minority or neutral beam injection (NBI) heating.

Several interesting results have been obtained from the TFTR fusion product studies.[1] Measurements of the 14-MeV neutron emission rate due to the burnup of 1-MeV tritons were lower than calculations for classical confinement and slowing down of tritons, although the time evolution of the burnup appears consistent with classical modeling. This contrasts with triton burnup measurements on Joint European Torus[2] (JET), and with measurements of ^{3}He burnup into 15-MeV protons on TFTR (Ref. 3), in which both the magnitude and time behavior of the tritons was consistent with the classical collisional slowing down of tritons by electrons (within the experimental uncertainties). Preliminary indications[4] are that this low TFTR burnup may be associated with the unusually long triton thermalization time in TFTR supershots, since the burnup ratio is nearly classical in L-mode discharges. This suggests that some tritons may be lost over a time scale $\tau_E \approx \tau_p \approx 0.2$ to 0.5 s.

Direct measurements of 1-MeV tritons escaping to the bottom of the TFTR vessel have measured anomalously large triton losses during strong magnetohydrodynamic (MHD) activity[5]; however, the observed increase in escaping triton loss (above the MHD quiescent level) is apparently not large enough to explain a factor of 2 reduction in triton burnup. In the absence of MHD activity, the escaping triton flux has generally varied as expected from the simple first-orbit loss model[6]; for example, the triton loss fraction (measured at the bottom) decreases by a factor of 6 between 0.8 and 1.6 MA, approximately as expected from the reduced banana width at the higher current.

One possible explanation for the apparently low triton burnup on TFTR is that the toroidal magnetic field (TF) ripple is causing significant loss of trapped tritons. Since this TF ripple loss is expected to occur near the outer midplane,[7] a new escaping triton detector probe has been installed at this location.[8] Work is in progress to obtain a poloidal profile of the escaping alpha-particle flux, and to compare this profile with loss models that include both first-orbit and ripple loss.

Experiments on alpha-particle simulation using fast ion populations created by ICRF and NBI are just beginning on TFTR. One recent result showed an unexpected loss of 0.5- to 1-MeV protons during 2- to 4-MW proton minority heating, possibly suggesting that the mega-electron-volt ion transport may increase in the presence of ICRF waves, as theoretically anticipated.[9] However, no unexpected bulk plasma transport was seen with minority ion heated discharges, as was also the case in JET (Ref. 10), suggesting that collective alpha-particle effects may have no significant effect on bulk plasma confinement. Since these ICRF tails are strongly anisotropic, they cannot fully simulate the isotropic alpha-particle effects, so other experiments using tangentially injected neutral beams are being designed to simulate the parallel alpha-particle population.[11]

A tentative conclusion that can be drawn from these alpha-particle simulations is that the single-particle confinement of alpha-like mega-electron-volt ions can indeed be worse than expected classically (as seen in the MHD-induced escaping triton flux and in the low triton burnup), but that these effects result in a loss of not more than ~50% of the fast triton population. These results apply specifically to TFTR plasmas at plasma currents of 0.8 to 1.6 MA and plasma confinement times $\tau_E \approx 0.2\tau_{th}$ (for tritons). Another tentative conclusion is that large populations of fast ions such as those generated by ICRF or NBI do not adversely affect plasma confinement, although the distribution functions are different from those expected for D-T alpha particles.

III. TFTR D-T ALPHA-PARTICLE EXPERIMENTS

With D-T fuel, the TFTR alpha-particle creation rate will be >100 times the present D-D creation rate, so that collective alpha-particle effects may appear for the first time. Therefore, one main goal of TFTR's D-T experiments is to compare alpha-particle confinement with D-D triton confinement, while specifically looking for new alpha-particle-induced instability effects.

Predictions for steady-state D-T alpha-particle populations in TFTR (Ref. 12) are in the range $n_\alpha(0)/n_e(0) \approx 0.3$ to 0.7% and $\beta_\alpha(0) \approx 0.25$ to 1.5% for plasmas with projected $Q_{\text{D-T}}$ in the range of 0.3 to 1.0. These alpha-particle parameters are nearly comparable to ignited plasma values,[13] particularly in the "alpha-particle storage mode" just after auxiliary heating is turned off. Since TFTR will have only a limited number of full-power D-T discharges, careful pretesting and preparation of operation scenarios and diagnostics is essential.

Three general types of diagnostic methods are currently being developed for D-T alpha-particle experiments in TFTR:

1. The 14-MeV neutron diagnostics measures the alpha-particle source rate and its radial profile (since one neutron is created for each alpha particle).

2. The confined alpha-particle diagnostics measures the alpha-particle distribution function inside the plasma.

3. The escaping alpha-particle diagnostics measures the time and spatial dependence of alpha-particle loss.

The alpha-particle source rate measurements will be used to calculate the classically expected confined alpha-particle populations and loss using the measured T_e and n_e profiles, and including alpha-particle orbit effects. These expectations can then be compared with the measured populations of confined and lost alpha particles. For example, the population of slow confined alpha particles should increase after about τ_{th} from the beginning of the auxiliary heating pulse, and, in the absence of significant alpha-particle transport, should retain a radial profile similar to the alpha-particle source profile.

Since descriptions of many of these diagnostics were previously given,[14,15] we are only summarizing their present status:

1. The neutron flux is measured with the existing epithermal neutron flux detection system, which has been working reliably and has been absolutely calibrated in D-D to within ~20% (Ref. 16). The same system can be used in D-T with some minor electronics changes.

2. The alpha-particle source profile will be measured with a multichannel neutron collimator, which has recently begun working with 10 channels of ZnS neutron detectors.[17] Preliminary measurements indicate that the 2.5-MeV neutron source profiles are similar to expectations based on the TRANSP transport code,

and sawtooth events and 14-MeV neutron profiles have been observed. The same system will be used for D-T.

3. Slow confined alpha particles (<500 keV) are measured with a relatively standard charge-exchange recombination spectroscopy (CHERS) system. Sensitivity tests of the existing CHERS system will soon be made with helium gas puffs, which can simulate alpha-particle ash transport. Further tests with helium NBI (70 keV) and ^{3}He minority tails ($\approx$1-MeV) ions are also possible. Hardware modifications for D-T alpha-particle measurements have not been started.

4. Fast confined alpha particles will be measured with a 60-GHz gyrotron-based collective ion scattering system, in collaboration with Massachusetts Institute of Technology.[18] After installation (which has not yet started), tests of its sensitivity and backgrounds can be made using energetic ion populations made by the heating beams or ICRF.

5. Fast confined alpha particles will also be measured with high-frequency magnetic probes intended to monitor their ion cyclotron emission. An array of such probes has been mounted on TFTR, and preliminary indications of D-D fusion product emission have been obtained.[19] A novel interpretation of the ion cyclotron harmonic emission in terms of D-D fusion product distribution functions has been proposed at JET (Ref. 20).

6. Fast confined alpha particles can also be measured by a fusion gamma diagnostic, such as the one recently installed on TFTR for measuring D-^{3}He reactions.[21] However, the expected signals from alpha-particle reactions on impurities are small[22] and may be visible only after the auxiliary heating in the alpha storage mode, or with injected carbon pellets.[23]

7. The escaping alpha particles will be measured with the same triton/proton scintillation detectors array that have been operating on TFTR (Ref. 6). The main problem anticipated for D-T is possible overheating or damage to the detectors, which need to be located very near to the edge of the limiters. Modified carbon-composite armor for these probes is being designed.

8. A similar but remote-controlled escaping triton probe was recently installed to measure the triton/proton losses just below the outer midplane where TF ripple loss is expected.[8] The same probe can be used for D-T alpha particles, perhaps with a double-bellows seal for fail-safe tritium containment.

9. Escaping alpha particles can also be measured with time-integrated sample deposition diagnostics located at various places around the first wall. Tests of 1-MeV-triton deposition were recently made with silicon samples located on the escaping alpha-particle probes. Subsequent secondary ion mass spectrometry depth profiling by Sandia National Laboratories[24] showed $\approx$1-MeV tritons at a depth of $\sim$10 μm with about the expected integrated flux.

In addition to these specific alpha-particle diagnostics, information about alpha particles and their collective instability effects can possibly be obtained from other more routine TFTR measurements.

1. The confined alpha-particle energy can be determined from the difference between magnetic and kinetic (i.e., thermal) measurements of plasma stored energy. However, the accuracy of this estimate will be poor due to the relatively small fraction of alpha-particle stored energy (<10%). Such estimates also need to take into account nonthermal particles from any auxiliary heating sources. However, sudden alpha-particle losses might be more easily measured, particularly after NBI turnoff, analogously to NBI "fishbones" seen in Princeton Beta Experiment by drops in the diamagnetic stored energy.

2. The escaping alpha-particle-energy flux can be determined from surface temperature measurements at the limiter, particularly near the outer midplane where TF ripple loss is expected. Up to 30% of the alpha-particle energy (or $\approx$2 MW) could be deposited there if all the trapped alpha particles were lost. Identification of alpha-particle losses could be simplified if the plasma were detached from direct limiter contact, as has already been done with lower power plasmas.

3. The stability of the alpha-particle population can be determined from the external magnetic loops (including frequencies to $\approx$100 MHz with the ion cyclotron emission diagnostic), and from the usual internal fluctuation diagnostics (microwave scattering, soft X ray, and electron cyclotron emission, etc). Both new instability phenomena (such as alpha-induced Alfvén waves) and modifications to familiar instabilities (such as sawteeth and low-frequency MHD near the beta limit) should be monitored. Preliminary assessments of the frequency and magnitude of these instabilities for TFTR and JET have been made.[13,25]

4. Alpha-particle heating effects could possibly be measured by the standard electron temperature diagnostics, although even at $Q = 1$, the alpha-particle heating contributes only $\sim$20% of the total plasma heating.

These diagnostics provide a characterization of alpha-particle confinement in TFTR. After the TFTR D-T experiments, we expect to have a preliminary evaluation of alpha-particle heating efficiency, a set of tested alpha-particle diagnostics, an indication of the effects of alpha-particle-induced instabilities and alpha-particle-induced modifications to MHD instabilities, and an assessment of the magnitude of anomalous alpha-particle losses. These results will benefit the fusion community by helping to prepare for subsequent ignition experiments.

IV. STRATEGY FOR ALPHA-PARTICLE EXPERIMENTS ON CIT

We expect that the identification of important alpha-particle-related phenomena on TFTR will focus fusion community ideas on techniques that could be tested on CIT for alpha-particle instability control, burn control, and ash removal. Such control might be obtained through externally applied fields or through an appropriate choice of the plasma operation regimes.

Currently, the main goals of the proposed CIT machine are to investigate collective alpha-particle instability and alpha-particle heating in reactor-like plasmas.[26] In contrast to TFTR's D-T phase, CIT will operate in regimes where the plasma heating is mainly from alpha particles, as it would be in tokamak reactors. The pulse length of CIT is long enough to study thermal excursions due to alpha-particle heating (ignition and "burn control").

Alpha-particle studies in CIT will in some sense be easier than in TFTR, since the alpha-particle effects are much more dominant. For example, the primary diagnostics of alpha-particle heating efficiency are the conventional thermal plasma measurements of $T_{e,i}(r)$ and plasma stored energy, supplemented by the neutron measurements of alpha-particle source rate. Similarly, the escaping alpha-particle measurements will be looking for relatively large fluxes, e.g., a 10% loss of the total alpha-particle heating power is 2 to 4 MW.

On the other hand, CIT will be a very difficult machine for diagnostic hardware, since the port access is limited by the compact design, and since the radiation fluence (≈3000 D-T discharges) prevents the use of some familiar diagnostic components such as quartz lenses and fiber optics. The strategy for alpha-particle diagnostics is the same as for TFTR, namely, to have measurements of the alpha-particle source, the confined alpha-particle population, and the escaping alpha-particle flux.

The alpha-particle source will be measured with neutron diagnostics similar to those used on TFTR. The most challenging aspects of these measurements will be the *in situ* D-T calibration and the design of a multichannel collimator for this compact environment.

The fast confined alpha-particle measurement will most likely come from microwave scattering, which presumably is being tested on TFTR. Microwave diagnostics has a natural advantage on high-fluence D-T devices in that its sources and detectors can be located far from the machine. The proposed 200-GHz gyrotron system[18] requires a vertical launcher and at least two outside horizontal receivers for vertical spatial resolution. Note that the high density of CIT requires that microwave refraction effects be carefully taken into account.

The slow confined alpha-particle measurement will most likely be CHERS using a hydrogen diagnostic neutral beam of a few hundred kilo-electron-volt energy. Due to the limited access, both the diagnostic neutral beam (DNB) and the spectroscopic sightlines are perpendicular to the toroidal field, allowing measurement of the perpendicular alpha-particle energy distribution to ~2 MeV. The ultraviolet line of helium is used, with mirror-based optical coupling to detectors outside the radiation shield. The high density of CIT limits the penetration of the DNB in some circumstances.

The escaping alpha-particle measurement is made with scintillator detectors similar to those used in TFTR, although with detectors that operate at higher temperatures (e.g., P_{46} instead of P_{11} phosphors). The limited lifetime of these scintillators requires that they be replaced periodically, so that they would probably be inserted through ports at the outer midplane and divertor regions. Supplementary measurements with some type of time-integrating deposition surface also seems to be feasible. Infrared and visible inspection cameras should be used to monitor the wall for hot spots potentially caused by the escaping alpha particles.

Some new alpha diagnostic methods might also be tested in CIT for implementation on ITER-sized devices, especially those that do not require complex machine interfaces. An example is a new lower hybrid emission diagnostic method that requires only a receiving horn.[27] Scoping studies for more complex diagnostics can also be made, but planning must be done very early in the design of the machine to accommodate any additional access.

We anticipate that by the completion of CIT, the fusion community has observed all of the relevant alpha-particle stability, confinement, and heating phenomena and has identified the microscopic and macroscopic effects of alpha-particle behavior. At that point the need for additional alpha-particle control can be assessed, and the design of subsequent control techniques can be implemented and tested in an ITER-class device.

V. CONCLUSION

The planned D-T experiments in TFTR aim to quantify the magnitude of alpha-particle-induced instability effects and the possible anomalous alpha-particle losses. They also provide an initial test of several new alpha-particle diagnostics.

Experiments to demonstrate the efficiency of alpha-particle heating have a high priority on CIT. Planning for CIT alpha-particle physics studies should also emphasize those issues that are important for ITER-class devices. Thus, alpha-particle stability experiments on CIT should be designed to explore the relevant region of dimensionless parameter space (n_α/n_e, β_α, $v_\alpha/V_{\text{Alfvén}}$, etc.), even if this requires temporary "derating" of the machine parameters (e.g., toroidal field). Experiments that test some schemes for long-pulse burn control and/or ash removal could be tried on CIT for later implementation on ITER.

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