of the main plasma? Excessive ash buildup can compromise ignition.

VI.B. Technological Issues

The most important technology issue concerns the theta pinch formation method. The theta pinch required for a reactor is considerably larger than any built to date. Since the understanding of theta pinch formation of FRCs is still empirical in several respects, it is essential to gain an understanding of the limiting factors that may constrain the design of a scaled-up device. There are two other questions of technology that are perhaps less crucial, but nonetheless, must be answered satisfactorily. How severe are the technological and/or economic barriers to a 1-MeV neutral beam system, and what are the design difficulties in the direct conversion system, including both the "conventional" and traveling wave stages?

VI.C. Concept Merit Issues

The advancement of the D-^{3}He-fueled FRC depends on the perception by fusion researchers that it is an attractive concept. The "concept merit" is a vague concept and more quantitative merit indices are needed. Certainly, economics (e.g., the cost of electricity) is one factor, but one still open to question in a development program spanning a number of years. Other merit indices need to be quantified as well, including synchrotron loss and nuclear hazard. For synchrotron loss, it must be determined how the FRC concept can be compared quantitatively with other confinement concepts. In terms of nuclear hazard, how much is the nuclear hazard reduced for D-^{3}He-based FRC fusion compared with D-T or other D-^{3}He systems. Another merit issue concerns the use of polarized fuels: Does a significant increase in the reactivity (e.g., 30%) give enough of an economic advantage to justify the trouble of making a polarized fuel?

VI.D. Development Strategy Issues

Strategy issues concern the best path to a reactor from the present status of the FRC concept. The first question relates to the sensitivity of the design. Suppose the transport rate (or some other physics index) turns out to be twice (or half) the level assumed in the design. How would this affect the design? Moreover, expecting that changes will occur in the physical understanding, what is the best strategy for accommodating such changes? For example, if the transport rate were a factor of 2 lower, is the best strategy to reduce the magnetic field, to reduce the plasma size, or some other response? The second question relates to the fuel strategy. What is the best trade-off between removing tritium, which increases the tritium inventory and requires a specialized isotope separation system, and burning the tritium, which increases the radiation damage and radioactive waste problem. The third question concerns the FRC development path and the developmental steps from the present experiments to a reactor. The intervening devices should address essential physics issues not treated in previous work, e.g., energetic beam stabilization and steady-state sustainment.

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SUMMARY OF THE FIRST WORKSHOP ON ALPHA-PARTICLE PHYSICS IN TFTR, PRINCETON, NEW JERSEY, MARCH 28–29, 1991

I. INTRODUCTION

The First Workshop on Alpha-Particle Physics in TFTR was held March 28–29, 1991, at the Princeton University Plasma Physics Laboratory (PPPL) in Princeton, New Jersey. Approximately 35 scientists from outside PPPL attended the meeting, including representatives from major U.S. fusion laboratories and universities, as well as from Japan, Joint European Torus (JET), and the U.S. Department of Energy.

The motivation for this meeting was to clarify and strengthen the Tokamak Fusion Test Reactor (TFTR) alpha-particle physics program and to increase the involvement of the fusion community outside PPPL in the TFTR deuterium-tritium (D-T) experiments (which are currently planned for mid-1993 to mid-1994). Therefore, the meeting was sharply focused on alpha-particle physics relevant to the upcoming TFTR D-T run. Before the meeting, each participant was sent a baseline TFTR D-T simulation and was asked to devote half of his talk to specific TFTR issues.

The workshop consisted of 27 talks grouped into five major sessions: (a) experimental possibilities, (b) theoretical possibilities, (c) diagnostic possibilities, (d) relevance for future machines, and (e) discussion/summary. The present summary contains a brief sampling of the new results and ideas brought out during these talks, followed by two more general overviews of the status of experiment and theory. An independent summary of this meeting was recently published in Ref. 1.

II. OUTLINE OF TALKS

II.A. Experimental Possibilities

Meade (PPPL) described the TFTR D-T program, which aims to (a) study the confinement and heating of D-T plasmas, (b) determine the effects of alpha particles, (c) demonstrate D-T technical capabilities, and (d) demonstrate D-T power production. The D-T run currently consists of ~600 to 1200 D-T discharges over calendar years 1993-1994 (the exact number of shots depends on the assumed neutron production per shot).

Furth (PPPL) described the history of the TFTR D-T objectives—from vague engineering goals of 1976 to explicit alpha-particle goals discussed at this workshop. He emphasized the importance of beam-target reactions for creating reactorlike β_α values in TFTR.

Zweben (PPPL) described the general philosophy for alpha-particle physics experiments in TFTR: to maximize potential alpha-particle collective instabilities to clarify potential problems in future D-T tokamaks. The choice of D-T experiments will be based on deuterium-deuterium (D-D) simulation results and on relevant theory.

Budny (PPPL) presented an evaluation of the expected alpha-particle parameters for a baseline neutral beam-heated TFTR D-T "supershot" discharge (using the TRANSP code). For the conservative case, with an estimated $Q_{\text{D-T}} \approx 0.3$, the central alpha-particle beta was $\beta_\alpha(0) \approx 0.3\%$, and the volume average was $\langle\beta_\alpha\rangle \approx 0.03\%$. The corresponding result for an extrapolated case was $\beta_\alpha(0) \approx 0.8\%$ (at $Q \approx 0.4$). The profile of β_α was sharply peaked toward the center, and the classical first-orbit loss was small (<10% at $I \geq 1.6$ MA). A summary of this analysis will be published shortly.[2]

Mikkelsen (PPPL) introduced a tritium pellet scenario for TFTR alpha-particle studies, which allows more D-T discharges per gram of tritium than the standard tritium-neutral beam injection (NBI) supershot scenario. He and Schmidt (PPPL) predicted $\beta_\alpha(0) = 0.5$ to 0.8% for tritium pellet-fueled discharges operating at higher densities than for supershots, with ten times less use of tritium per shot. Mikkelsen also evaluated the effect of the planned 12-MW ion cyclotron resonance frequency (ICRF) on alpha-particle parameters of the baseline NBI-heated supershot. This extra heating power (and the expected increase in central electron temperature) can increase $\beta_\alpha(0)$ by about two times when compared with an NBI-only supershot.

Boivin (PPPL) discussed his TFTR measurements of toroidal field (TF) ripple-induced diffusion of trapped alpha-particle-like ions. The observations roughly agree with the Goldston-White-Boozer theory of stochastic ripple diffusion. Complementary measurements implying very slow diffusion of passing mega-electron-volt ions were also discussed.

Wong (PPPL) and Heidbrink [University of California-Irvine, General Atomics (GA)] discussed recent experimental simulations of the toroidal Alfvén eigenmode (TAE) instability using parallel NBI ions. These two experiments seemed to give consistent results, i.e., a strong beam-driven mode and large NBI losses at fast ion betas of $\langle\beta_f\rangle \approx 1\%$. The mode frequency scaled with the local Alfvén frequency, and its amplitude increased with the fast ion beta. The observed thresholds were considerably higher than simple (local) theoretical predictions for TAE modes.

Marcus (JET) discussed the simulation of alpha particles using ICRF minority tails in JET. These JET discharges had $\beta_f(0) = 8\%$ with no sign of instability and with nearly classical confinement and thermalization of the fast ions. However, these ion tails are dominated by trapped particles and may not fully simulate the isotropic alpha-particle distributions expected in D-T. Triton burnup measurements in JET are almost always classical, implying negligible diffusion of alpha-particle-like fusion products.

II.B. Theoretical Possibilities

Cheng (PPPL) showed the TAE mode in TFTR to be marginally unstable for the conservative TFTR D-T case at $\langle\beta_\alpha\rangle = 0.03\%$ and $V_\alpha/V_A(0) = 1.7$ (using the global eigenmode calculation). He also noted that the TAE $\langle\beta_\alpha\rangle$ threshold is about ten times *lower* at $V_\alpha/V_A = 1.0$, so that perhaps the mode can be more clearly seen at lower densities (higher V_A) than the standard case.

Chen (PPPL) discussed high-n TAE instabilities near the beta limit. A new formula was presented for continuum damping of TAE modes, which is an order of magnitude larger than electron Landau damping. The TAE mode persists as one approaches the beta limit and moves from $\theta = 0$ to $\theta = \pm\pi/2$.

Spong [Oak Ridge National Laboratory (ORNL)] evaluated (independently of Cheng) the TAE instability for TFTR D-T and found instability for the baseline case at $\beta_\alpha(0) = 0.3\%$, with a growth rate that increased linearly with $\beta_\alpha(0)$ between 0.3 and 0.6%. He described work in progress to develop a three-dimensional nonlinear magnetohydrodynamic (MHD) fluid/particle code for alpha-particle studies.

Rewoldt (PPPL) showed that the MHD ballooning limit may be reduced substantially by alpha particles. He used the optimistic $Q \approx 0.5$ case and found that the threshold for the onset of high-n ballooning modes was $\beta_\alpha(q \approx 1) < 0.1\%$.

Biglari (PPPL) discussed a new resonant interaction between the fast precessional drift and bounce motion of fast ions, which allows energetic trapped alpha particles to destabilize kinetic ballooning modes (KBMs). This interaction depends on the shape of the fast particle distribution function, possibly explaining the absence of instability in JET ion cyclotron resonance heating (ICRH) simulations. It was pointed out that, in general, the KBM and TAE modes coexist in tokamaks.

Berk (University of Texas at Austin) described work in progress on a unified theory of the TAE mode for the entire m spectrum. For low n, the dissipation from Alfvén resonance is significant and competitive with the alpha-particle drive.

White (PPPL) evaluated the alpha-particle fishbone threshold for TFTR D-T to be $\beta_\alpha(0) = 1\%$, which is apparently above the accessible $\beta_\alpha(0)$ in TFTR. He also described the physics of the alpha-particle fishbone threshold.

Tani (Japan Atomic Energy Research Institute) evaluated the global TF ripple-induced alpha-particle loss in the baseline TFTR D-T case to be ~4%. This was in good agreement with a simpler PPPL code (Boivin).

Miley (University of Illinois–Urbana) described several ideas and experimental concepts for ash control experiments on TFTR. Controlled instabilities (e.g., fishbones) are potentially useful for ash removal; experiments on alpha-particle transport during NBI-induced fishbones would be interesting for TFTR.

II.C. Diagnostic Possibilities

Fonck (University of Wisconsin) evaluated the possibility of a fast alpha-particle charge-exchange recombination spectroscopy (CHERS) system using the existing heating beams in TFTR. Measurements of $n_\alpha(r)$ with 5-cm spatial resolution for energies up to 0.8 MeV are possible. There is a large background caused by visible bremsstrahlung, which must be carefully subtracted out, e.g., by using asymmetries in the line emission profile.

Woskov [Massachusetts Institute of Technology (MIT)] evaluated the possibility of a fast alpha-particle gyrotron scattering system for TFTR. With suitable time averaging, he concluded that a useful alpha-particle density and velocity distribution measurement can be made in TFTR. The spatial localization for $n_\alpha(r)$ is estimated to be ~10 cm.

Fisher (GA) found that by using lithium pellets instead of carbon pellets the signal from double charge-exchange on alpha particles increases by one to five orders of magnitude in the alpha-particle energy range of 3.5 to 0.5 MeV. Therefore, this measurement of n_α in the pellet cloud may be feasible using alpha particles from D-^{3}He in present TFTR ICRH plasmas.

Marcus (JET) described the status of alpha-particle diagnostics in JET. The main systems planned were neutron spectrometers, escaping alpha-particle detectors, collective scattering, ^{3}He NBI (for simulation experiments), neutral charge-exchange analyzers, a two-dimensional neutron profile monitor, and CHERS.

Bindslev (JET) described a relativistic theory of the dielectric effects in collective Thomson scattering for alpha-particle diagnostics. For JET the relativistic effects are important, while for TFTR they are not.

Gerdin (Old Dominion) described a model for impurity-pellet alpha-particle diagnostics on TFTR. The model agrees fairly well with experimental data on carbon and lithium pellets in TFTR and Texas Experimental Tokamak (TEXT) and predicts a 10-cm-long target for alpha-particle diagnostics near the end of the pellet flight.

Vahala (William and Mary) described a new way to use a scattering diagnostic for measurements of internal magnetic fluctuations, such as may be produced by TAE modes. This method involves the conversion of O to X mode in perpendicular scattering. An example for TFTR showed the possibility of measuring magnetic fluctuations in the region $a/2 - a$.

II.D. Relevance for the Future

Sigmar (MIT) suggested several specific alpha-particle effects suitable for Burning Plasma Experiment (BPX)-relevant experiments that could be pursued by TFTR. He emphasized the possible interactions among various alpha-particle effects (e.g., the alpha-particle fishbone and alpha-particle TF ripple losses) and suggested an interactive study of experiment and theory to decide which alpha-particle physics could best be done with the limited number of D-T shots.

Post (PPPL) described what TFTR could do for the alpha-particle physics phase of the International Thermonuclear Experimental Reactor (ITER). Among these were clarifying the isotope effect (for tritium), verifying the classical ripple loss theory, finding the effects of alpha-particle instabilities on alpha-particle confinement and on beta limits, investigating helium ash transport, and developing alpha-particle diagnostics.

II.E. Discussion/Summary

Meade (PPPL) led a discussion of the diagnostic hardware options for the TFTR D-T run. The existing alpha-particle diagnostics are the multichannel neutron collimator (for alpha-particle source profile) and the lost alpha-particle array. Possible alpha-particle diagnostics not discussed explicitly at this workshop were ion cyclotron emission and gamma diagnostics of direct alpha-particle reactions. Various fluctuation diagnostics already exist on TFTR and most will be available for D-T. Rosenbluth (University of California–San Diego) suggested a new confined alpha-particle diagnostic based on measuring ultrahigh-energy neutrons produced by knock-on reactions between alpha particles and D-T fuel ions.

McGuire (PPPL) described the relationship between the TFTR alpha-particle physics effort and the new Transport Task Force Group on Fast Particle Transport, to be led by R. White (PPPL). There will be a TFTR D-T session at the 1991 American Physics Society meeting, and a TFTR Experimental Proposal Handbook should be available shortly. Biglari will coordinate interactions between TFTR and the theoretical community.

Furth (PPPL) challenged the audience to create a data base plot of the total fusion power compared with input power for large tokamaks (and its fraction contributed by beam-target reactions).

Jassby (PPPL) discussed the possible advantages of compression scenarios for TFTR D-T experiments. Adiabatic compression could increase the central electron temperature and central β_α and alpha-particle heating rate without additional injected power; however, the TFTR compression hardware would have to be recommissioned. Compression also allows variations in V_α/V_A, $V_{\alpha\parallel}/V_{\alpha\perp}$, and TF ripple.

Zweben (PPPL) discussed the question of how to scale the observed NBI TAE mode $\langle\beta_f\rangle$ thresholds to β_α thresholds in future D-T machines. Since the fast ion orbit confinement and thermalization times are different, the fast alpha-particle transport effects should be different for the same β_f.

Strachan (PPPL) discussed priorities for alpha-particle physics in the upcoming D-D and D-T runs. The main emphasis should be on a comparison of TFTR alpha-particle results with theory, which can then be used for designing future machines. This interaction would be optimized by selecting a few conditions for well-documented scans. He presented several examples of such scans using an existing D-D data base and made several suggestions for possible TFTR experimental proposals.

Young (PPPL) discussed the role of "outside" collaborations in the development of diagnostic systems for TFTR D-T. Present examples of such collaborations are those with MIT, University of Wisconsin, and GA.

III. OVERVIEW OF EXPERIMENTAL STATUS

By the end of this workshop, it was clear that there are several interesting alpha-particle physics issues that can be studied in the D-T phase of TFTR. However, it was equally clear that, as yet, there are no detailed shot-by-shot experimental proposals for these studies. Such specific proposals should be formulated during the 1992 D-D run to test the desired shot sequences.

In developing these experimental proposals, several theoretical parameters seem to be important. Foremost is the ratio V_α/V_A, where V_α is the initial (birth) alpha-particle velocity and V_A is defined here as the central Alfvén speed. This was projected to be $V_\alpha/V_A \approx 1.4$ to 1.7 in the plasma core for a standard D-T supershot, at which point the predicted TAE β_α threshold is about ten times higher than its value at $V_\alpha/V_A \approx 1$. Therefore, experiments should be designed to *increase* V_A, which can only be done in practice by *decreasing* the electron density. This is difficult to do with the present NBI heating scenario without also decreasing the experimental β_α, although pellet + radio-frequency heating scenarios are possible. A systematic theoretical search of the $n(r)$ and $q(r)$ profile dependencies of the TAE mode (for various mode numbers) should be made to locate regimes of maximum instability in the available TFTR supershot's parameter space.

Another parameter of increasing interest is the background plasma beta, which can change the character of alpha-particle instability near the usual MHD beta limit (see Sec. IV). The standard TFTR D-T supershot has plasma beta values near this limit (Sabbagh, Columbia). In theory, there may be a transition to higher n modes near the beta limit. This has possibly been seen already in the Doublet III-D (GA) TAE mode simulation experiments, which are at higher beta and higher n than the TFTR experiments. Ideally, this transition could be studied in TFTR D-T using both high-n and low-n alpha-particle instability diagnostics.

The status of confined alpha-particle diagnostics has been clarified by this workshop. Plans are being developed for the implementation of the TFTR fast alpha-particle CHERS and gyrotron scattering diagnostics, and for the testing of the pellet-based alpha-article diagnostic during the next TFTR run.

IV. OVERVIEW OF THE THEORETICAL STATUS

The theoretical consensus at the meeting was that two classes of modes afford the most serious potential for collective alpha-particle-induced losses: alpha-particle destabilized Alfvén waves and KBMs. Both analytical investigations (which physically identify and provide key insight into the nature of the modes) and numerical studies (which provide quantitative results geared to realistic geometries and operating conditions) were presented. In spite of this general consensus, the theory for both classes of modes is still evolving even at the linear stage, and further work is warranted in these areas before definitive projections can be made about D-T experiments.

The theoretical part of the workshop was instrumental in identifying the key difficulties that remain to be sorted out. In particular, two outstanding issues with respect to the TAE mode are (a) the precise nature of continuum damping and (b) the structure and survival of the Alfvén gap across the plasma. On the first point, analytical differences among various workers need to be sorted out to provide a consensus formula and parametric dependencies that can then be tested by experimentalists. Similarly, the radial profile of the gap needs to be numerically investigated for a variety of different experimentally relevant plasma profiles. The most pessimistic scenario corresponds to the case where the gap structure extends from the plasma center to the edge, thus allowing loss of alpha particles from the plasma center. It is critical to determine under which circumstances such a scenario can be obtained, and how profiles can be tailored to avoid it. More generally, greater theoretical attention needs to be paid to (a) the dynamic stabilization of these modes and (b) harnessing these and other (e.g., fishbone) instabilities in a controlled manner for the purpose of ash removal.

An exciting development on the numerical front is the development of a new class of three-dimensional hybrid fluid/kinetic codes. Such codes, which treat the energetic particles kinetically and the background plasma using fluid theory, are perfectly geared to study both the linear and nonlinear dynamics of energetic alpha-particle destabilized MHD modes. Such codes are under development at PPPL and through an ORNL-MIT collaboration.

Finally, the nonlinear stage of these instabilities remains largely virgin territory. Existing calculations of collective alpha-particle induced losses are either non-self-consistent or based on single-wave, coherent trapping. A self-consistent treatment of turbulent alpha-particle-induced fluctuations, their possible saturation mechanisms, fluctuation amplitudes, and their implication for both background and alpha-particle transport has just recently been started (e.g., as reported at the Sherwood Theory Conference).

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