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Overview of the First Workshop on Alpha Particle Physics in TFTR

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Abstract

An overview is presented of the" First Workshop on Alpha Particle Physics in TFTR" held at PPPL in March 1991. An brief summary of each talk is given, along with separate overviews of the experimental and theoretical status of alpha physics in TFTR.

1. Introduction

The "First Workshop on Alpha Physics in TFTR" was held at the Princeton Plasma Physics Lab March 28-29, 1991. Approximately 35 scientists from outside PPPL attended the meeting, including representatives from major U.S. fusion laboratories (General Atomics, MIT, LASL), U.S. universities (e.g. UCLA, Wisconsin, William & Mary), Japan, JET, and DOE.

The motivation for this meeting was to clarify and strengthen the TFTR alpha physics program, and to increase the involvement of the fusion community outside PPPL in the TFTR D-T experiments (which are presently planned for mid-'93 to mid-'94). Therefore the meeting was sharply focused on alpha 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 on: a) Experimental Possibilities, b) Theoretical Possibilities, c) Diagnostic Possibilities, d) Relevance for Future Machines and e) Discussion/Summary session. This summary contains a brief sampling of the new results and ideas brought out at by these talks, followed by two more general overviews of the status of experiment and theory. An independent summary of this meeting has recently been published in Nature [1].

2. Outline of talks at the meeting

a) Experimental Possibilities:

1) **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 presently consists of about 600-1200 D-T discharges over the two calendar years 1993-94 (the exact number of shots depends on the assumed neutron production per shot).

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

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

4) **Budny** (PPPL) presented an evaluation of the expected alpha particle parameters for a "baseline" neutral-beam-heated TFTR D-T "supershot" discharge (using TRANSP). For the conservative case, with an estimated $Q_{DT}\approx0.3$, the central alpha beta was $\beta_\alpha(0)\approx0.3\%$, and the volume average was $\langle\beta_\alpha\rangle\approx0.03\%$. The corresponding result for an extrapolated case was $\beta_\alpha(0) \approx 0.8\%$ (at $Q\approx0.4$). The profile of alpha beta was sharply peaked toward the center, and the classical first-orbit loss was small (<10% at

I=1.6 MA). A summary of this analysis will be published shortly [2].

5) **Mikkelsen** (PPPL) introduced a tritium pellet scenario for TFTR alpha studies, which allows more D-T discharges per gram of tritium than the standard tritium-NBI supershot scenario. He and Schmidt (PPPL) predicted $\beta_\alpha(0)$= 0.5%-0.8% for tritium-pellet-fuelled discharges operating at higher densities than for supershots, with 10x less use of tritium per shot. Mikkelsen also evaluated the effect of the planned 12 MW ICRF on alpha 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 x2, when compared with a NBI-only supershot.

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

7) **Wong** (PPPL) and **Heidbrink** (UC Irvine, GA) discussed recent experimental simulations of the Toroidal-Alfven Eigenmode (TAE) instability using parallel neutral-beam-injected ions. These two experiments seemed to give consistent results, namely, a strong TAE mode and large NBI losses at fast-ion betas of $<\beta_f>\approx 1\%$. The mode frequency scaled with the local Alfven frequency, and its amplitude increased with the fast-ion beta. The observed thresholds were considerably higher than simple (local) theoretical predictions.

8) **Marcus** (JET) discussed the simulation of alpha particles using ICRF minority tails in JET. These JET discharges had $\beta_f(0)$=12% 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 distributions

expected in D-T. Triton burnup measurements in JET are almost always classical, implying negligible diffusion of alpha-like fusion products.

b) Theoretical Possibilities:

1) **Cheng** (PPPL) showed that the TAE mode in TFTR to be marginally unstable for the "conservative" TFTR D-T case at $<\beta_\alpha>=0.03\%$ and $V_\alpha/V_A(0)=1.7$ (using the global eigenmode calculation). He also noted that the TAE $<\beta_\alpha>$ threshold is about 10x 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.

2) **Chen** (PPPL) discussed high-n TAE instabilities near β-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 $\theta=\pm\pi/2$.

3) **Spong** (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 which increased linearly with $\beta_\alpha(0)$ between 0.3-0.6%. He described work in progress to develop a 3-D nonlinear MHD fluid/particle code for alpha particle studies.

4) **Rewoldt** (PPPL) showed that the MHD ballooning limit may be reduced substantially by alphas. In the "optimistic" $Q\approx0.5$ case which he used, the threshold for the onset of high-n ballooning modes was $\beta_\alpha(q\approx1)<0.1\%$.

5) **Biglari** (PPPL) discussed a new resonant interaction between the fast precessional drift and bounce motion of fast ions, which allows energetic

trapped alphas to destabilize kinetic ballooning modes (KBM). This interaction depends on the shape of the fast particle distribution function, possibly explaining the absence of instability in JET ICRH simulations. It was pointed out that in general, both the KBM and TAE modes coexist in tokamaks.

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

7) **White** (PPPL) evaluated the alpha 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 fishbone threshold.

8) **Tani** (JAERI) evaluated the global TF ripple-induced alpha loss in the baseline TFTR D-T case to be about 4%. This was in good agreement with a simpler PPPL code (Boivin).

9) **Miley** (Illinois) 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 transport during NBI-induced fishbones would be interesting for TFTR.

c) Diagnostic Possibilities:

1) **Fonck** (Wisconsin) evaluated the possibility of a fast-alpha 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 due to visible bremmstrahlung, which will need to be carefully subtracted out by using, for example, asymmetries in the line emission profile.

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

3) **Fisher** (GA) found that by using lithium pellets instead of carbon pellets the signal from double charge-exchange on alphas increases by 1-5 orders of magnitude in the alpha energy range 3.5-0.5 MeV. Therefore this measurement of n_α in the pellet cloud may be feasible using alphas from D-^{3}He in present TFTR ICRH plasmas

4) **Marcus** (JET) described the status of alpha particle diagnostics in JET. The main systems planned were neutron spectrometers, escaping alpha detectors, collective scattering, ^{3}He NBI (for simulation experiments), neutral charge exchange analyzers, a 2-D neutron profile monitor, and CXRS.

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

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

7) **Vahala** 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.

d) Relevance for the Future:

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

2) **Post** (PPPL) described what TFTR could do for the alpha physics phase of ITER. Among these were clarifying the isotope effect (for T ions), verifying the classical ripple loss theory, finding the effects of alpha instabilities on alpha confinement and on beta limits, investigating He ash transport, and developing alpha diagnostics.

e) Discussion/Summary Sessions:

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

2) **McGuire** (PPPL) described the relationship between the TFTR alpha 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 APS meeting, and a TFTR Experimental Proposal Handbook should be available shortly. Hamid Biglari will coordinate interactions

between TFTR and the theoretical community.

3) **Furth** (PPPL) challenged the audience to create a database plot of the total fusion power vs input pc :or large tokamaks (and its fraction contributed by beam-target reactions).

4) **Jassby** (PPPL) discussed the possible advantages of compression scenarios for TFTR D-T experiments. Adiabatic compression could increase the central electron temperature and central alpha beta and alpha 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.

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

6) **Strachan** (PPPL) discussed priorities for alpha physics in the upcoming D-D and D-T runs. The main emphasis should be on a comparison of TFTR alpha 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 existing D-D database, and made several suggestions for possible TFTR Experimental Proposals.

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

3. Overview of Experimental Status

By the end of this workshop it was clear that there are several interesting alpha physics issues which can be studied in the D-T phase of TFTR. However, it was equally clear that there aren't yet any detailed shot-by-shot experimental proposals for these studies. Such specific proposals should be formulated during the next year in order to test the desired shot sequences during the 1992 DD run.

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 velocity and V_A is defined here as the central Alfven speed. This was projected to be about $V_\alpha/V_A \approx 1.4$-1.7 in the plasma core for a standard D-T supershot, at which point the predicted TAE β_α threshold is about 10 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+RF 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 in order to locate regimes of maximum instability in the available TFTR supershots parameter space.

Another parameter of increasing interest is the background plasma β, which can change the character of alpha instability near the usual MHD-beta limit (see below). The standard TFTR D-T supershot has plasma β values near this limit (Sabbagh, Columbia). In theory, there may be a transition to higher-n modes near the β limit. This has possibly been seen already in the D-III-D TAE mode simulation experiments, which are at higher β 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 instability diagnostics.

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

4. Overview of the Theoretical Status

The theoretical consensus at the meeting was that two classes of modes afford the most serious potential for collective α-particle induced losses: α-destabilized Alfven waves and kinetic ballooning modes. 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 DT 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 Alfven gap across the plasma. On the first point, analytical differences between various workers need to be sorted out in order to provide a consensus formula and parametric dependencies which 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 what 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 3-D 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 MIT-ORNL collaboration.

Finally, the nonlinear stage of these instabilities remains largely virgin territory. Existing calculations of collective α-particle induced losses are either non-self-consistent or based on single-wave, coherent trapping. A self-consistent treatment of turbulent α-particle-induced fluctuations, their possible saturation mechanisms, fluctuation amplitudes, and their implication for both background and α-particle transport has just recently been started (e.g. as reported at the Sherwood Theory Conference '91).

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[1] R. Petrasso, Nature 350, 661(1991)
[2] R.V. Budny, et al, Proc. 18th European Physical Society Conference, Berlin (1991)

Note: Conference Proceedings (i.e. copies of the viewgraphs) may be obtained by contacting S. Zweben at PPPL.