24-9405②
PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CHO-3073

PPPL-2987
UC-420,421

PPPL-2987

PREPARATIONS FOR DEUTERIUM TRITIUM EXPERIMENTS ON
THE TOKAMAK FUSION TEST REACTOR

BY

R.J. HAWRYLUK, H. ADLER, P. ALLING, ET AL.

APRIL, 1994

PPPL

PRINCETON
PLASMA PHYSICS
LABORATORY

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial produce, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

NOTICE

This report has been reproduced from the best available copy.
Available in paper copy and microfiche.

Number of pages in this report: 29

DOE and DOE contractors can obtain copies of this report from:

Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831;
(615) 576-8401.

This report is publicly available from the:

National Technical Information Service
Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
(703) 487-4650

Preparations for Deuterium Tritium Experiments on the Tokamak Fusion Test Reactor

R.J. Hawryluk, H. Adler, P. Alling, C. Ancher, H. Anderson, J.L. Anderson¹, J.W. Anderson, V. Arunasalam, G. Ascione, D. Ashcroft, C.W. Barnes¹, G. Barnes, D.B. Batchelor², G. Bateman, S. Batha³, L.A. Baylor², M. Beer, M.G. Bell, T.S. Biglow², M. Bitter, W. Blanchard, P. Bonoli⁴, N.L. Bretz, C. Brunkhorst, R. Budny, T. Burgess², H. Bush⁵, C.E. Bush², R. Camp, M. Caorlin, H. Carnevale, Z. Chang⁶, L. Chen, C.Z. Cheng, J. Chrzanowski, I. Collazo², J. Collins, G. Coward, S. Cowley⁷, M. Cropper, D.S. Darrow, R. Dautert, J. DeLooper, H. Duong⁸, L. Dudek, R. Durst⁶, P.C. Efthimion, D. Ernst⁴, J. Faunce, R.J. Fonck⁶, E. Fredd, E. Fredrickson, N. Fromm, G.Y. Fu, H.P. Furth, V. Garzotto, C. Gentile, G. Gettelfinger, J. Gilbert, J. Gioia, R.C. Goldfinger², T. Golian, N. Gorelenkov⁹, M.J. Gouge², B. Grek, L.R. Grisham, G. Hammett, G.R. Hanson², W. Heidbrink¹⁰, H.W. Herrmann, K.W. Hill, S. Hirshman², D.J. Hoffman², J. Hosea, R.A. Hulse, H. Hsuan, E.F. Jaeger², A. Janos, D.L. Jassby, F.C. Jobs, D.W. Johnson, L.C. Johnson, J. Kamperschroer, J. Kesner⁴, H. Kugel, S. Kwon⁵, G. Labik, N.T. Lam⁶, P.H. LaMarche, M.J. Laughlin¹¹, E. Lawson, B. LeBlanc, M. Leonard, J. Levine, F.M. Levinton³, D. Loesser, D. Long, J. Machuzak⁴, D.K. Mansfield, M. Marchlik⁵, E. S. Marmar⁴, R. Marsala, A. Martin, G. Martin, V. Mastrocola, E. Mazzucato, M.P. McCarthy, R. Majeski, M. Mauel¹², B. McCormack, D.C. McCune, K.M. McGuire, D.M. Meade, S.S. Medley, D.R. Mikkelsen, S.L. Milora², D. Monticello, D. Mueller, M. Murakami¹², J.A. Murphy, A. Nagy, G.A. Navratil¹², R. Nazikian, R. Newman, T. Nishitani¹³, M. Norris, T. O'Connor, M. Oldaker, J. Ongena¹⁴, M. Osakabe¹⁵, D.K. Owens, H. Park, W. Park, S.F. Paul, Yu.I. Pavlov¹⁶, G. Pearson, F. Perkins, E. Perry, R. Persing, M. Petrov¹⁷, C.K. Phillips, S. Pitcher¹⁸, S. Popovichev¹⁶, A.L. Qualls², S. Raftopoulos, R. Ramakrishnan, A. Ramsey, D.A. Rasmussen², M.H. Redi, G. Renda, G. Rewoldt, D. Roberts⁶, J. Rogers, R. Rossmassler, A.L. Roquemore, S.A. Sabbagh¹², M. Sasao¹⁵, J. Scharer⁶, G. Schilling, J. Schivell, G.L. Schmidt, R. Scillia, S.D. Scott, T. Senko, R. Sissingh, C. Skinner, J. Snipes⁴, P. Snook, J. Stencel, J. Stevens, T. Stevenson, B.C. Stratton, J.D. Strachan, W. Stodiek, J. Swanson⁵, E. Synakowski, W. Tang, G. Taylor, J. Terry⁴, M.E. Thompson, J.R. Timberlake, H.H. Towner, M. Ulrickson, A. von Halle, C. Vannoy, R. Wieland, J.B. Wilgen², M. Williams, J.R. Wilson, K. Wright, D. Wong¹⁸, K.L. Wong, P. Woskov⁴, G.A. Wurden¹, M. Yamada, A. Yeun¹⁸, S. Yoshikawa, K.M. Young, L. Zakharov, M.C. Zarnstorff and S.J. Zweben.

Plasma Physics Laboratory, Princeton University
P.O. Box 451 Princeton, N.J. 08543

¹ Los Alamos National Laboratory, Los Alamos, NM

² Oak Ridge National Laboratory, Oak Ridge, TN

³ Fusion Physics and Technology, Torrance, CA

⁴ Massachusetts Institute of Technology, Cambridge, MA

⁵ EBASCO

⁶ University of Wisconsin, Madison, WI

⁷ University of California, Los Angeles, CA

⁸ General Atomics, San Diego, CA

⁹ TRINITI, Moscow, Russia

¹⁰ University of California, Irvine, CA

¹¹ JET Joint Undertaking, Abingdon, U.K.

¹² Columbia University, New York, NY

¹³ JAERI Naka Fusion Research Establishment, Naka, Japan

¹⁴ Ecole Royale Militaire, Brussels, Belgium

¹⁵ National Institute of Fusion Studies, Nagoya, Japan

¹⁶ RRC Kurchatov Institute, Moscow, Russia

¹⁷ Ioffe Physical-Technical Institute, Russia

¹⁸ Canadian Fusion Fuels Technology Project, Toronto, Canada

MASTER

Abstract

The final hardware modifications for tritium operation have been completed for the Tokamak Fusion Test Reactor (TFTR) [Fusion Technology, **21** (1992) 1324]. These activities include preparation of the tritium gas handling system, installation of additional neutron shielding, conversion of the toroidal field coil cooling system from water to a Fluorinert™ system, modification of the vacuum system to handle tritium, preparation and testing of the neutral beam system for tritium operation and a final deuterium- deuterium (D-D) run to simulate expected deuterium-tritium (D-T) operation. Testing of the tritium system with low concentration tritium has successfully begun. Simulation of trace and high power D-T experiments using D-D have been performed. The physics objectives of D-T operation are production of ≈ 10 megawatts (MW) of fusion power, evaluation of confinement and heating in deuterium-tritium plasmas, evaluation of α -particle heating of electrons, and collective effects driven by alpha particles and testing of diagnostics for confined α -particles. Experimental results and theoretical modeling in support of the D-T experiments are reviewed.

PACS Numbers: 28.52.Cx, 52.25.Fi, 52.55.Fa

I. INTRODUCTION

The design of the International Thermonuclear Experimental Reactor (ITER)¹ is based upon the experimental results from a large number of tokamak experiments conducted principally with hydrogen and deuterium as the fuel. In the world tokamak fusion program two major facilities, the Tokamak Fusion Test Reactor (TFTR)² and the Joint European Torus (JET)³, plan to study the burning plasma physics associated with the use of deuterium-tritium fuel in support of ITER. A limited scope, "Preliminary Tritium Experiment (PTE)" has been performed on Joint European Torus (JET) in 1991³ with a more extensive program planned to begin in 1996. TFTR has been modified for tritium operation and will begin an extensive series of experiments in December 1993.

The principal goals of the TFTR deuterium-tritium experiments are:

1. Safe operation of the tritium handling and processing systems, and successful machine and diagnostic operation in a high radiation environment with 14 MeV neutrons;
2. Documenting changes in confinement and heating going from deuterium to tritium plasmas;
3. Evaluating the confinement of α -particles, including the effect of α -induced instabilities, and obtaining initial indications of α -heating, and helium ash accumulation;
4. Demonstrating the production of ≈ 10 MW of fusion power.

These goals not only individually support the technical and physics research and development objectives of ITER but their integration does as well. The achievement of ≈ 10 MW of fusion power entails not only successful technical performance but more importantly the development and extension of reliable operating regimes which address plasma stability issues associated with the increase in the stored plasma energy going from deuterium to tritium. In present plasma experiments, these effects are predicted to be relatively modest. However, in future ignited or near-ignited experiments, these effects are large and impact fundamental design considerations. Thus confirmation of our understanding in present tokamaks by performing experiments which integrate all of the goals is an important objective.

In this paper, a brief description will be given of the principal modifications to the TFTR device for D-T operations and the status of the facility. A more extensive discussion will be given of the planned experiments on TFTR and how they will address key design considerations of a tokamak reactor utilizing deuterium-tritium fuel.

II. MACHINE CONFIGURATION

The hardware modifications for tritium operation on TFTR have been completed. These activities include preparation of the tritium gas handling system (shown in Fig. 1) which has been successfully tested with low concentrations of tritium ($\approx 0.5\%$) and is capable of handling up to 5g of tritium (50 kCi)⁴. The tritium gas is brought on-site in an approved shipping canister and transferred to a uranium bed where it is stored. The uranium bed is heated to transfer the gas to the neutral beam or torus injection systems. The gas is then injected into the torus or neutral beams and pumped by the cryo-panels in the beam boxes. During plasma operation, some of the gas will be retained in the graphite limiter tiles in the vacuum vessel. The quantity of tritium in the vacuum vessel is restricted by regulatory requirements to 20 kCi . The gas on the cryo-panels is transferred to the Gas Holding Tank.

During initial operation, the gas in the Gas Holding Tank will be oxidized by the Torus Cleanup System and absorbed onto molecular sieve beds. These beds will be shipped off-site for reprocessing or burial prior to the receipt of a replacement canister of tritium gas. Next year, a cryo-distillation system will be commissioned to re-purify the tritium on-site and decrease the number of off-site shipments required.

Modifications to the tokamak include: supplemental diagnostic and personnel shielding, tritium stack and area monitoring, remote control for components in high radiation fields, and upgrades to the vacuum and neutral beam pumping system for tritium operation⁵. For components and systems in high radiation fields, modifications have been made to increase reliability. The toroidal field coil cooling system has been converted from water to Fluorinert™ (a fully fluorinated compound), bolts on the TF coil casings have been tightened using remotely operated tools for bolts in areas difficult to access, and graphite tiles in high heat flux regions on the bumper limiter have been replaced by carbon/carbon-fiber composite tiles.

Changing the fuel from deuterium to tritium engenders a change in the rigor and formality of operation as the TFTR device becomes, according to Department of Energy (DOE) regulations, a Category 3 (low hazard) nuclear facility⁶. The site boundary dose due to normal operation will be limited to <10 mrem/year. Safety analysis has been performed which demonstrate that the maximum design basis accident would result in a 140 mrem dose at the site boundary. An Environmental Assessment has been conducted which resulted in a "Finding of No Significant Impact" to the environment due to the low inventory of tritium on-site. The Laboratory and the Department of Energy recognize the importance of demonstrating safe operation with tritium and have implemented detailed procedures used to process tritium, rigorous qualification and training programs for operators and engineers, extensive safety reviews by internal and outside experts, and a

formal program for control of operations. At the present time, a final review of the operations and test procedures used for tritium processing is occurring prior to continued testing with low concentrations of tritium.

III. MACHINE STATUS

Upon the completion of the outage to modify the machine for deuterium-tritium experiments, operations resumed in deuterium. Besides qualifying the machine for tritium experiments, the focus of these deuterium experiments was to simulate the initial planned deuterium-tritium experiments utilizing deuterium. The objective of the initial high-power deuterium-tritium experiments will be to achieve 5 MW of fusion power. With further operational experience and the resolution of the physics issues identified above, it is projected that ≈ 10 MW will be produced.

Previous experiments in the supershot regime with deuterium neutral-beam injection (NBI) have identified the conditions under which ≥ 5 MW of fusion power can be produced in D-T plasmas in TFTR. Wall coating, using lithium pellet injection, has significantly improved supershot performance and reliability^{7,8}. With this technique, $n_e \tau_E T_i = 5.8 \times 10^{20} \text{m}^{-3} \text{ a s}$, keV, $n_e(0) = 1.0 \times 10^{20} \text{m}^{-3}$, $T_i = 29$ keV, $\tau_E = 205 \text{ms}$ and a D-D fusion neutron rate $S_{DD} = 5.6 \times 10^{16} \text{n/sec}$ have been achieved. This corresponds to a fusion power, P_{DD} , of 65kW and $Q_{DD} \equiv P_{DD} / (P_{NBI} + P_{OH})$ of 2.1×10^{-3} . One dimensional transport code simulations of a 50/50 D-T plasma using the same electron and ion temperature and density profiles predict that $P_{DT} \approx 11$ MW and a Q_{DT} of 0.38 would have been achieved. At modest powers, $P_{NBI} = 15$ MW, the energy confinement time has increased transiently to 240 ms (corresponding to $\tau_E / \tau_E^{(L\text{-mode})} \approx 3$ which is typical of the best supershots) with the injection of two lithium pellets prior to NBI and one lithium pellet in the post-NBI phase of the previous shot. The DD fusion performance of NBI supershots is shown in Fig. 2 as a function of the total heating power.

At low power TFTR supershots smoothly approach an asymptotic stored energy during the pulse, but at high power they often reach a peak in stored energy after 300 – 500 ms into beam injection, then suffer a deterioration of as much as a factor of two (the so-called "beta collapse") over the subsequent several hundred milliseconds. At a major radius $R = 2.45\text{m}$, the plasma beta collapses are coincident with or follow the growth of internal MHD ($m/n = 3/2, 2/1, 4/3, \dots$) modes as recorded by Mirnov loops. In some cases the MHD can cause a flattening of the $T_e(R)$ profile which is observed in the vicinity of the rational q -surfaces at which the MHD modes are observed. Analysis indicates that the decrease in plasma energy content is consistent with a model for which transport is increased only within the islands⁹.

Reliable high performance operation entails reproducible low recycling wall conditions along with disruption avoidance and minimization of adverse MHD effects. To achieve $P_{DT} > 5\text{ MW}$ in TFTR supershots requires $I_p = 2.0\text{ MA}$, $P_{NBI} = 30\text{ MW}$, composed of a 50:50 D:T mix, and $\tau_E = 140\text{ ms}$ which produces a Troyon-normalized beta, $\beta_N \equiv \beta_T(\%) \cdot a(m) \cdot B_T(T) / I_p(\text{MA})$ of 1.5. The modest value of β_N allows for increased stored energy due to the injection of energetic tritons (which have a longer slowing-down time than deuterons), the presence of fusion α -particles and the heating of the electrons by the α -particles. The parameter of relevance for fusion yield, $\beta_N^* \equiv 2\mu_0 \cdot \langle p \rangle \cdot a(m) / B_T(T) \cdot I_p(\text{MA})$, where $\langle p \rangle$ is the root-mean-square plasma pressure, reaches 2.4 in prototypical high performance plasmas as a result of the highly peaked pressure profile. To achieve the required confinement reliably, Li pellet injection is used to condition the walls and improve reproducibility. The reproducibility of confinement achievable with Li-pellet conditioning is illustrated in Fig. 3. During a dry-run of the planned 5 MW D-T experiment, 13 of 16 simulated D-T discharges with Li pellets would have achieved $> 5\text{ MW}$ of fusion power.

An operating strategy for achieving higher fusion power has been developed using multiple Li pellets to condition the walls, high power neutral beam injection of about 35 MW, and high plasma current (~ 2.5 MA). In deuterium operation, 34 MW of neutral injection has been achieved and the power is projected to increase in tritium due to improved equilibration in the neutralizer cell. During recent experiments, as a result of aggressive wall conditioning with Li pellets, supershots have been produced at $I_p = 2.5$ MA corresponding to $q_\psi = 3.8$ which represents a significant extension of the operating regime.

IV. α -CONFINEMENT

The confinement of α -particles is very important in a reactor for two reasons. First, if a small unanticipated fraction (a few percent) of the α -particles is lost, and the resulting heat flux is localized, damage to first wall components could result. Second, if a significant fraction of the α -particles are not confined then the $nT\tau$ requirements for ignition would increase.

The loss of fusion products during deuterium experiments has been extensively studied and is reported on in a companion paper by S. Zweben¹⁰. An array of detectors in the TFTR vacuum vessel has been used to measure the energy and pitch angle of the escaping α 's. The conclusions of these studies are as follows:

1. Good agreement has been obtained as a function of plasma current with the prediction of the losses due to unconfined "first orbits". For the fusion products, an upper bound of $D < 0.1 \text{ m}^2/\text{s}$ has been deduced for their radial transport coefficient in MHD-quiescent plasma.
2. The predictions of stochastic ripple diffusion are in good qualitative agreement with experimental observations near the outer midplane.

3. MHD instabilities, in particular low m/n modes, are observed to be responsible for increased loss of fusion products. A theoretical model based on magnetic perturbations affecting α drift orbits is in qualitative agreement with the observations.
4. ICRF waves can interact with fusion products and result in increased particle loss. The mechanism is not fully understood but may be related to velocity space diffusion across the passing-trapped boundary for particles due to resonances with fusion product ions.
5. Loss of fusion particles which is delayed in time and is not associated with first-orbit loss has been observed. Qualitatively, it appears as a collisional and/or TF-ripple induced loss process; however, it is larger than predicted and not fully understood.

The results from fusion product experiments in present deuterium experiments show that the particles can interact with magnetohydrodynamics (MHD) instabilities and plasma waves. The theoretical calculations indicate that when the values of β_α and n_α are sufficiently high, α -particles themselves can induce instabilities which can, in turn, eject the α -particles from the plasma. The present theoretical understanding of the role of α -collective effects in TFTR is that α -particles will not stabilize sawteeth and are not expected to cause α -driven fishbones, but will drive Toroidal Alfvén Eigenmodes (TAE) unstable in some conditions, are not expected to reduce the β -limits due to Kinetic Ballooning Modes (KBM) and may drive the Beta Alfvén Eigenmodes (BAE) unstable at high- β . One of the instabilities with the lowest predicted threshold is the Toroidal Alfvén Eigenmode (TAE). Experiments in deuterium plasmas have been conducted on TFTR¹¹ and DIII-D¹² using neutral beams and on TFTR with ICRF¹³ to simulate these instabilities. The threshold for instability is in good agreement (within a factor of 2) with the predicted threshold¹⁴. The frequency of the mode scales with the Alfvén frequency and the mode can

be destabilized either by passing particles from neutral beam injection or by trapped particles due to ICRF heating as shown in Fig. 4. Very recent experiments have shown that the TAE instability is observed in some high field (5T) neutral beam heated discharges in which $V_f/V_A > 0.2$. V_f is the fast ion velocity and V_A is the Alfvén velocity. Detailed analysis for these new experimental results are in progress. Measurements of the mode structure using Beam Emission Spectroscopy in low-field (1 – 1.5 T) neutral beam simulations indicate the presence of a large global mode. Very sensitive reflectometry measurements have been used to determine the mode number in ICRF simulations. Up to about 50% of the fast beam ions in low toroidal field neutral beam heated experiments are observed to be lost due to these instabilities in TFTR. In ICRF experiments, significant loss (~10%) of the energetic minority ion tail has been measured in high power L-mode experiments. The fractional loss increases with the mode amplitude of the instability (as shown in Fig. 5).

Projected α -parameters ($\beta_\alpha(0)$, $R\nabla\beta_\alpha$, V_α/V_A) on TFTR are close to those on ITER because the electron temperature is similar and the non-thermal ion distribution increases the plasma reactivity. The theoretical models predict the operating regimes in which the instability should occur^{14,15}. Furthermore, they provide predictions regarding how the threshold should vary with ion temperature, shear length, and density profile shape. Experiments are planned during the D-T phase of TFTR to test these predictions. Recent theoretical work has developed the techniques to predict the mode amplitude¹⁶ and the effect of these instabilities on the α -particle loss rate¹⁷. Comparison of theory and experiment will improve the estimates of heat flux to first wall components in the ITER due to α -particles.

In support of the α -particle experiments, a comprehensive set of diagnostics has been implemented. The α -birth profile will be measured using a 10-channel neutron collimator,

and the α -loss rate by detectors mounted on the wall and a moveable probe. Four new techniques will be used to determine the α -distribution function and radial profile. Charge-exchange recombination spectroscopy using a high throughput optical system will be used to measure the energy distribution to ~ 1 MeV at 10 radial points¹⁸. Injected Li pellets will be used to increase the charge-exchange rate and enable charge-exchange measurements from 0.2 keV to 4.0 MeV¹⁹. Both of these techniques have been tested in deuterium experiments using ICRF to produce a ^3He tail. In addition, spectroscopic measurements of the Doppler spectrum of He^+ light emitted from the pellet cloud will be used to measure the distribution function. Another approach entailing collective scattering of a 60 GHz wave will be used to characterize the α -distribution function²⁰. Increased scattering associated with the lower hybrid resonance will be employed to reduce the power requirements for the gyrotron. The onset of the instabilities and their mode structure will be measured using a 4-channel reflectometer, beam emission spectroscopy, ECE grating polychromator, Mirnov coils and microwave scattering. The α -particle diagnostics will provide measurements of the instability itself, its effect on the α -distribution function and, together with the standard profile diagnostics, its effect on the background plasma.

V. α -HEATING

It is planned to evaluate α -heating of the electrons by operating in a reliable quiescent regime with a minimum of plasma performance degradation with time. This can be accomplished by decreasing the power and the value of β_N . In TFTR, α -heating is a relatively small fraction of the heating power²¹ ($P_\alpha \approx 2$ MW when $P_{\text{NBI}} \approx 30$ MW); however, the heating is projected to be well localized in the plasma core as shown in Fig. 6a. The predicted increase in electron temperature is shown in Fig. 6b, assuming that the thermal conductivity of the bulk plasma does not change with isotope mix and does not change with the heat deposition profile. Experiments are planned to vary the isotope mix to

evaluate the effects on plasma confinement. Low power ICRF experiments at 1.6 MW combined with high power neutral beam heating have simulated α -heating resulting in a measurable increase in the electron temperature of ~ 1 keV indicating that electron heating with modest power is measurable.

VI. α -ASH ACCUMULATION

The production, transport, and removal of helium ash is an issue that has a large impact in determining the size and cost of ITER. The experiments on TFTR will provide the first opportunity to measure helium ash buildup, assess helium transport coefficients, and examine the effects of edge helium pumping on central ash densities in D-T plasmas. In addition, the importance of the central helium source in determining the helium profile shape and amplitude will be examined. Ash concentrations are expected to reach 1 – 2% of the electron density in high-performance supershots. Using the α -CHERS, and CHERS diagnostics, central ash concentrations greater than 0.1% should be measurable. Helium ash density profiles, measured as a function of time, will be compared to predictions based on the helium diffusivity D_{He} and convective pinch V_{He} inferred from helium gas puffs²² and central helium source measurements made by α -CHERS and the neutron collimator. The influence of edge pumping will be explored by comparing ash buildup with a low-recycling limiter in a Supershot plasma to that in a high-current, high-recycling L-Mode plasma.

VII. ICRF HEATING

ICRF heating is one of the primary techniques under consideration for ITER. Ion cyclotron resonance heating (ICRF) utilizing either hydrogen or ^3He minorities has been successfully demonstrated at high power on PLT²³, JET²⁴ and TFTR²⁵. In addition, low power experiments on DIII-D have shown evidence for fast wave current drive²⁶. ICRF wave

physics in deuterium-tritium plasmas is complicated by the presence of additional resonances and by α -damping which, due to the large $k_{\perp}\rho_i$, can compete with electron absorption in the fast wave current drive regime. A promising scenario for D-T plasmas is heating at the second harmonic of the tritium cyclotron frequency, which is degenerate with the ^3He fundamental. By selectively heating a majority ion species rather than a minority ion species, potential difficulties with rf driven fast ion excitation of instabilities such as TAE modes should be avoided. Though the core damping is predicted to be acceptable, off-axis absorption at the deuterium fundamental can compete with the second harmonic tritium core damping in tokamaks with moderate aspect ratio. Modeling indicates that deuterium fundamental heating occurs off the midplane in regions where the shear Alfvén mode conversion layer ($n_{\parallel}^2 = S$ resonance) approaches the deuterium fundamental layer. In TFTR superset plasmas with the $2\Omega_T$ layer coincident with the Shafranov-shifted axis at 2.82m (assuming an 0.2m shift), the $2\Omega_D$ layer is out of the plasma on the low field side, but the Ω_D layer is in the plasma on the high field side at 5.66T, or $R \approx 2.1\text{m}$. For the present range of TFTR magnetic fields and ICRF frequencies, the $n_{\parallel}^2 = S$ resonance can be positioned in the core region only by adding a relatively high concentration of ^3He minority to the D-T plasma. Under these conditions, significant mode conversion of the launched fast waves to slow Alfvén waves is predicted to occur, resulting in significant direct electron heating²⁷. Experiments planned on TFTR will be able to document the effectiveness of second harmonic tritium heating and to explore the regimes in which damping associated with the $n_{\parallel}^2 = S$ mode conversion layer is expected to be important.

VIII. FUTURE DIRECTIONS

Several new and novel concepts have been suggested which, though speculative, could improve the tokamak concept. Several of these concepts require deuterium-tritium fuel to evaluate their feasibility.

Recently R. Majeski *et al.*²⁷ have suggested that the mode-converted slow wave excited at the $n_{||}^2 = S$ mode conversion layer in a D-T plasma could be used to drive localized electron currents. This is an attractive alternative to fast-wave damping because the effective single-pass absorption on electrons can approach 80% in TFTR, well in excess of fast-wave single-pass absorption. Furthermore, the driven current is localized to the mode conversion layer, which may be placed on or off axis in order to modify the current profile.

Experiments on TFTR as well as on DIII-D and JET have shown that it is possible to achieve high values of β_P ($\epsilon\beta_P \sim 1.5$) with improved energy confinement ($\tau_E/\tau_E^{(L-mode)} \sim 3$) by modifying the plasma current profile. Recent experiments, discussed in a companion paper by S. Sabbagh *et al.*²⁸, have shown that in some TFTR discharges, the core plasma has a direct access path to the second stable region. The question then arises whether this altered magnetic configuration affects the threshold for α -collective effects. Zonca and Chen²⁹ and Cowley and Furth have suggested that the second stability region will also make the α -driven modes stable by reducing the fraction of trapped α -particles and inducing drift reversal for sufficiently high β .

Fisch and Rax³⁰ have proposed coupling the energy in the fast α -particles to RF waves which in turn could either drive currents or heat the ion channel. It is possible that such coupling of the α -particles to thermal fuel ions could increase the fusion power density by up to 50% and reduce the $nT\tau$ product required for ignition by 10 – 30 %. If, furthermore, an appropriate non-thermal distribution of fuel ions can be produced by selective coupling, additional gains in fusion power density and reductions in $nT\tau$ could be achieved. Both the high- β_P regime and the interaction of energetic α -particles with plasma waves could be of great physics interest in a D-T plasma.

Experiments to study mode conversion in D-T plasmas, and high β_p effects in D-T plasma have been proposed for TFTR. The collective scattering diagnostic may be able to evaluate the effect of the α -particles on the background lower hybrid waves.

IX. SUMMARY

The modifications to the TFTR facility have been completed. The final checkout and testing is in progress prior to performing the D-T experiments safely. The deuterium-tritium experiments on TFTR will not only enable confirming some of the key design assumptions in ITER but also explore new and novel physics operating regimes which could improve the tokamak concept.

ACKNOWLEDGMENTS

Preparation for the deuterium-tritium experiments have entailed a tremendous effort by the technical, engineering and research staff of the Princeton Plasma Physics Laboratory and by participants from national and international laboratories, universities, and industry. Their effort and support is very gratefully acknowledged.

Work supported by U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

References

- ¹ D. E. Post, Plasma Physics and Controlled Nuclear Fusion Research (Proc. 13th Int. Conf., Washington, 1990) (*International Atomic Energy Agency, Vienna 1991*), Vol.3, p.239
- ² R.J. Hawryluk, D. Mueller, J. Hosea, C.W. Barnes, M. Beer, M.G. Bell, R. Bell, H. Biglari, M. Bitter, R. Boivin, N.L. Bretz, R. Budny, C.E. Bush, L. Chen, C.Z. Cheng, S. Cowley, D.S. Darrow, P.C. Efthimion, R.J. Fonck, E. Fredrickson, H.P. Furth, G. Greene, B. Grek, L.R. Grisham, G. Hammett, W. Heidbrink, K.W. Hill, D. Hoffman, R.A. Hulse, H. Hsuan, A. Janos, D.L. Jassby, F.C. Jobes, D.W. Johnson, L.C. Johnson, J. Kamperschroer, J. Kesner, C.K. Phillips, S.J. Kilpatrick, H. Kugel, P.H. LaMarche, B. LeBlanc, D.M. Manos, D.K. Mansfield, E.S. Marmor, E. Mazzucato, M.P. McCarthy, J. Machuzak, M. Mauel, D.C. McCune, K.M. McGuire, S.S. Medley, D.R. Mikkelsen, D. Monticello, Y. Nagayama, G.A. Navratil, R. Nazikian, D.K. Owens, H. Park, W. Park, S. Paul, F. Perkins, S. Pitcher, D. Rasmussen, M.H. Redi, G. Rewoldt, D. Roberts, A.L. Roquemore, S. Sabbagh, G. Schilling, J. Schivell, G.L. Schmidt, S.D. Scott, J. Snipes, J. Stevens, B.C. Stratton, J.D. Strachan, W. Stodiek, E. Synakowski, W. Tang, G. Taylor, J. Terry, J.R. Timberlake, H.H. Towner, M. Ulrickson, S. von Goeler, R. Wieland, J.R. Wilson, K.L. Wong, P. Woskov, M. Yamada, K.M. Young, M.C. Zarnstorff, S.J. Zweben, *Fusion Technology*, **21** (1992) 1324
- ³ The JET Team, *Nuclear Fusion*, **32** (1992) 187

- 4 J.L. Anderson, R.A.P. Sissingh, C.A. Gentile, R.L. Rossmassler, R.T. Walters, D.R. Voorhees, Proc. 15th IEEE/NPSS Symposium on Fusion Engineering, Hyannis, October 1993, *to be published*
- 5 E.D. Perry and L.E. Dudek, Proc. 15th IEEE/NPSS Symposium on Fusion Engineering, Hyannis, October 1993, *to be published*
- 6 C.A. Gentile, J. Levine, M. Norris, F. Rehill, C. Such, Proc. 15th IEEE/NPSS Symposium on Fusion Engineering, Hyannis, October 1993, *to be published*
- 7 J.L. Terry, E.S. Marmor, R.B. Howell, J. Snipes, D.K. Owens, G.L. Schmidt, D.K. Mansfield, D.M. Meade, J.D. Strachan, M.G. Bell, M. Bitter, A. Cavallo, P.L. Colestock, P.C. Efthimion, E.D. Fredrickson, R.J. Goldston, B. Grek, R.J. Hawryluk, K.W. Hill, J.C. Hosea, H. Hsuan, A.C. Janos, D.L. Jassby, D.W. Johnson, D.C. McCune, K.M. McGuire, D. Mueller, Y. Nagayama, H.K. Park, A.T. Ramsey, J. Schivell, J.E. Stevens, B.C. Stratton, E.J. Synakowski, G. Taylor, R. Wilson, M.C. Zarnstorff, Plasma Physics and Controlled Nuclear Fusion Research (Proc. 13th Int. Conf., Washington, 1990) (*International Atomic Energy Agency, Vienna 1991*), Vol.1, p.393
- 8 D.L. Jassby, D.K. Mansfield, M.G. Bell, R.V. Budny, D.R. Ernst, J.D. Strachan, E.S. Marmor, J.A. Snipes, J.L. Terry, C.E. Bush, E.D. Fredrickson, K.W. Hill, L.C. Johnson, H.K. Park, A.T. Ramsey, E.J. Synakowski, G. Taylor, *High-Performance Supershots in TFTR with Lithium Pellet Injection*, PPPL-2940 (October 1993), *to be submitted to Nuclear Fusion*
- 9 Z. Chang, E.D. Fredrickson, J.D. Callen, K.M. McGuire, M.G. Bell, R.V. Budny, C.E. Bush, D.S. Darrow, A.C. Janos, L.C. Johnson, H. Park,

- S.D. Scott, J.D. Strachan, E.J. Synakowski, G. Taylor, R.M. Wieland, M.C. Zarnstorff, S.J. Zweben, *Transport Effects of Low (m,n) MHD Modes on TFTR Supershots*, PPPL-2941 (October 1993), *submitted to Nuclear Fusion*
- 10 S.J. Zweben *et al.*, *this conference*
 - 11 K-L. Wong, R. Durst, R.J. Fonck, S.F. Paul, D.R. Roberts, E.D. Fredrickson, R. Nazikian, H.K. Park, M. Bell, N.L. Bretz, R. Budny, C.Z. Cheng, S. Cohen, G.W. Hammett, F.C. Jobs, L. Johnson D.M. Meade, S.S. Medley, D. Mueller, Y. Nagayama, D.K. Owens, S. Sabbagh, E.J. Synakowski, *Phys. Rev. Lett.* **66** (1991) 1874
 - 12 W.W. Heidbrink, E.J. Strait, E. Doyle, G. Sager, R.T. Snider, *Nuclear Fusion* **31** (1991) 1635
 - 13 J.R. Wilson, M.G. Bell, H. Biglari, M. Bitter, N.L. Bretz, R.V. Budny, C.E. Bush, Z. Chang, L. Chen, D.S. Darrow, P.C. Efthimion, E.D. Fredrickson, G.Y. Fu, R.C. Goldfinger, B. Grek, L.R. Grisham, G.W. Hammett, R.J. Hawryluk, D.J. Hoffman, J.C. Hosea, A.C. Janos, D.L. Jassby, F.C. Jobs, D.W. Johnson, L.C. Johnson, J.S. Machuzak, R. Majeski, D.K. Mansfield, E. Mazzucato, K.M. McGuire, S.S. Medley, D. Mueller, M. Murakami, R. Nazikian, D.K. Owens, H.K. Park, S.F. Paul, C.K. Phillips, A.T. Ramsey, D.A. Rasmussen, F. Rimini, J.H. Rogers, A.L. Roquemore, G. Schilling, J. Schivell, G.L. Schmidt, J.E. Stevens, J.D. Strachan, B.C. Stratton, E.J. Synakowski, G. Taylor, M. Ulrickson, K.L. Wong, M. Yamada, K.M. Young, M.C. Zarnstorff, S.J. Zweben, *Plasma Physics and Controlled Nuclear Fusion Research (Proc. 14th Int. Conf., Würzburg, 1992) (International Atomic Eenergy Agency , Vienna, 1993), Vol.1, p.661*

- 14 G.Y.Fu, C.Z. Cheng and K.L. Wong, Phys. Fluids B **5** (1993) 4040
- 15 C.Z. Cheng, G.Y. Fu, H.E. Mynick, R. Budny, R.B. White, S.J. Zweben, C.T. Hsu, D.J. Sigmar, D.A. Spong, B.A. Carreras, C.L. Hedrick, Plasma Physics and Controlled Nuclear Fusion Research (Proc. 14th Int. Conf., Würzburg, 1992), Vol. II, p51
- 16 D. Spong, *this conference*
- 17 C.T. Hsu, D.J. Sigmar, Phys. Fluids B **4** (1992) 1492
- 18 B.C. Stratton, R.J. Fonck, Y.J. Kim, G. McKee, T. Thorson, Rev. of Sci. Instr. **63** (1992) 5179
- 19 R. K. Fisher, J.M. McChesney, A.W. Howald, P.B. Parks, J.A. Snipes, J.L. Terry, E.S. Marmor, S.J. Zweben, S.S. Medley, Rev. of Sci. Instr. **63** (1992) 4499
- 20 D.Y. Rhee, D.R. Cohn, J.S. Machuzak, P. Woskov, N. Bretz, R. Budny, P.C. Efthimion, H.K. Park, Rev. of Sci. Instr. **63** (1992) 4644
- 21 R.V. Budny, M.G. Bell, H. Biglari, M. Bitter, C.E. Bush, C.Z. Cheng, E.D. Fredrickson, B. Grek, K.W. Hill, H. Hsuan, A.C. Janos, D.L. Jassby, D.W. Johnson, L.C. Johnson, B. LeBlanc, D.C. McCune, D.R. Mikkelsen, H.K. Park, A.T. Ramsey, S.A. Sabbagh, S.D. Scott, J.F. Schivell, J.D. Strachan, B.C. Stratton, E.J. Synakowski, G. Taylor, M.C. Zarnstorff, S.J. Zweben, Nuclear Fusion **32** (1992) 429

- 22 E.J. Synakowski, P.C. Efthimion, G. Rewoldt, B.C. Stratton, W.M. Tang, B. Grek, K.W. Hill, R.A. Hulse, D.W. Johnson, M.W. Kissick, D.K. Mansfield, D. McCune, D.R. Mikkelsen, H.K. Park, A.T. Ramsey, M.H. Redi, S.D. Scott, G. Taylor, J. Timberlake, M.C. Zarnstorff, *Phys. Fluids B* **5** (1993) 2215

- 23 J. Hosea, R. Bell, M. Bitter, A. Cavallo, S. Cohen, P. Colestock, G. Greene, G. Hammett, E. Hinnov, H. Hsuan, D. Hwang, R. Kaita, E. Mazzucato, D. McNeill, M. Ono, D. Schuresko, C. Skinner, S. Suckewer, and J. Wilson *Proceedings 12th European Conference on Heating, Confinement, and Stability During High Power ICRF Experiments on PLT (Budapest, 1985, Eds L. Pács and A. Montvai)* European Physical Society, Vol II, p120

- 24 The JET Team, *Plasma Physics and Controlled Nuclear Fusion Research (Proc. 14th Int. Conf., Würzburg, 1992) (International Atomic Energy Agency, Vienna, 1993), Vol.1, p.15*

- 25 G. Taylor, M.G. Bell, H. Biglari, M. Bitter, N.L. Bretz, R. Budny, L. Chen, D. Darrow, P.C. Efthimion, D. Ernst, E. Fredrickson, G.Y. Fu, B. Grek, L. Grisham, G. Hammett, J.C. Hosea, A. Janos, D.L. Jassby, F.C. Jobes, D.W. Johnson, L.C. Johnson, R. Majeski, D.K. Mansfield, E. Mazzucato, S.S. Medley, D. Mueller, R. Nazikian, D.K. Owens, S. Paul, H. Park, C.K. Phillisp, J.H. Rogers, G. Schilling, J. Schivell, G.L. Schmidt, J.E. Stevens, B.C. Stratton, J.D. Strachan, E. Synakowski, E. Synakowski, J.R. Wilson, K.L. Wong, S.J. Zweben, *Phys. Fluids B* **5** (1993) 2437

- 26 R.I. Pinsky, C.C. Petty, M. Porkolab, F.W. Baity, P.T. Bonoli, R.W. Callis, W.P. Cary, S.C. Chiu, R.L. Freeman, R.H. Goulding, J.S. Degraessie, R.W. Harvey, D.J. Hoffman, R.A. James, H. Kawashima, T.C. Luce, M.J. Mayberry, R. Prater, Plasma Physics and Controlled Nuclear Fusion Research (Proc. 14th Int. Conf., Würzburg, 1992) (*International Atomic Energy Agency, Vienna, 1993*), Vol.1, p.683
- 27 R. Majeski, J.C. Hosea, C.K. Phillips, J.H. Rogers, G. Schilling, J.E. Stevens, J.R. Wilson, Radiofrequency Power in Plasmas (Proc. 10th Topical Conf., Boston, 1993) American Institute of Physics, New York, 1994, p401
- 28 S. Sabbagh, *this conference*
- 29 F. Zonca and L. Chen, *Theory of Continuum Damping of Toroidal Alfvén Eigenmodes in Finite- β Tokamaks*, Phys. Fluids B 5 (1993) 3668
- 30 N. Fisch, J.-M. Rax, Plasma Physics and Controlled Nuclear Fusion Research (Proc. 14th Int. Conf., Würzburg, 1992) (*International Atomic Energy Agency, Vienna, 1993*), Vol.1, p.769

Figure Captions

- Fig. 1 Schematic of the tritium processing system.
- Fig. 2 Fusion power in deuterium supersonic neutral beam heated discharges as a function of total heating power. The projected fusion power for a 50:50 mixture of deuterium and tritium is shown using a value of $Q_{DT}/Q_{DD} = 180$.
- Fig. 3 Comparison of five high power neutral beam heated discharges which employed Li pellets to condition the wall. Good reproducibility is achieved.
- Fig. 4 The predicted frequency of the toroidal Alfvén eigenmodes is compared with the measured frequency for a wide variety of plasma conditions. The low field neutral beam experiments were reported by Wong *et al.*¹⁰ and the ICRF experiments by Wilson *et al.*¹² The recent high field experiments are shown for comparison.
- Fig. 5 The power loss by the tail particles heated by ICRF and the neutral beam ions in low field experiments increases with the magnetic field perturbation at the vacuum vessel wall. In the ICRF experiments, the measurements of $\tilde{n}_e/n_e$ by reflectometry are also observed to scale with the magnetic field amplitude.
- Fig. 6 a) The electron heating from α -particles in a 50/50 deuterium-tritium plasma is projected to be significant in the plasma core.
- b) The variation in electron temperature for a projected deuterium-tritium as well as tritium plasma is shown. In these conditions, the heat conductivity is assumed not to vary with species mix or heat deposition profile.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Figure 6

EXTERNAL DISTRIBUTION IN ADDITION TO UC-420

Dr. F. Paoloni, Univ. of Wollongong, AUSTRALIA	Dr. H. Yamato, Toshiba Res & Devel Center, JAPAN
Prof. M.H. Brennan, Univ. of Sydney, AUSTRALIA	Prof. I. Kawakami, Hiroshima Univ., JAPAN
Plasma Research Lab., Australian Nat. Univ., AUSTRALIA	Prof. K. Nishikawa, Hiroshima Univ., JAPAN
Prof. I.R. Jones, Flinders Univ, AUSTRALIA	Librarian, Naka Fusion Research Establishment, JAERI, JAPAN
Prof. F. Cap, Inst. for Theoretical Physics, AUSTRIA	Director, Japan Atomic Energy Research Inst., JAPAN
Prof. M. Heindler, Institut für Theoretische Physik, AUSTRIA	Prof. S. Itoh, Kyushu Univ., JAPAN
Prof. M. Goossens, Astronomisch Instituut, BELGIUM	Research Info. Ctr., National Instit. for Fusion Science, JAPAN
Ecole Royale Militaire, Lab. de Phy. Plasmas, BELGIUM	Prof. S. Tanaka, Kyoto Univ., JAPAN
Commission-European, DG. XII-Fusion Prog., BELGIUM	Library, Kyoto Univ., JAPAN
Prof. R. Bouciqué, Rijksuniversiteit Gent, BELGIUM	Prof. N. Inoue, Univ. of Tokyo, JAPAN
Dr. P.H. Sakanaka, Instituto Fisica, BRAZIL	Secretary, Plasma Section, Electrotechnical Lab., JAPAN
Prof. Dr. I.C. Nascimento, Instituto Fisica, Sao Paulo, BRAZIL	S. Mori, Technical Advisor, JAERI, JAPAN
Instituto Nacional De Pesquisas Espaciais-INPE, BRAZIL	Dr. O. Mitarai, Kumamoto Inst. of Technology, JAPAN
Documents Office, Atomic Energy of Canada Ltd., CANADA	Dr. G.S. Lee, Korea Basic Sci. Ctr., KOREA
Ms. M. Morin, CCFM/Tokamak de Varennes, CANADA	J. Hyeon-Sook, Korea Atomic Energy Research Inst., KOREA
Dr. M.P. Bachynski, MPB Technologies, Inc., CANADA	D.I. Choi, The Korea Adv. Inst. of Sci. & Tech., KOREA
Dr. H.M. Skarsgard, Univ. of Saskatchewan, CANADA	Prof. B.S. Liley, Univ. of Waikato, NEW ZEALAND
Prof. J. Teichmann, Univ. of Montreal, CANADA	Inst of Physics, Chinese Acad Sci PEOPLE'S REP. OF CHINA
Prof. S.R. Sreenivasan, Univ. of Calgary, CANADA	Library, Inst. of Plasma Physics, PEOPLE'S REP. OF CHINA
Prof. T.W. Johnston, INRS-Energie, CANADA	Tsinghua Univ. Library, PEOPLE'S REPUBLIC OF CHINA
Dr. R. Bolton, Centre canadien de fusion magnétique, CANADA	Z. Li, S.W. Inst Physics, PEOPLE'S REPUBLIC OF CHINA
Dr. C.R. James,, Univ. of Alberta, CANADA	Prof. J.A.C. Cabral, Instituto Superior Tecnico, PORTUGAL
Dr. P. Lukác, Komenského Universzita, CZECHO-SLOVAKIA	Prof. M.A. Hellberg, Univ. of Natal, S. AFRICA
The Librarian, Culham Laboratory, ENGLAND	Prof. D.E. Kim, Pohang Inst. of Sci. & Tech., SO. KOREA
Library, R61, Rutherford Appleton Laboratory, ENGLAND	Prof. C.I.E.M.A.T, Fusion Division Library, SPAIN
Mrs. S.A. Hutchinson, JET Library, ENGLAND	Dr. L. Stenflo, Univ. of UMEA, SWEDEN
Dr. S.C. Sharma, Univ. of South Pacific, FIJI ISLANDS	Library, Royal Inst. of Technology, SWEDEN
P. Mähönen, Univ. of Helsinki, FINLAND	Prof. H. Wilhelmson, Chalmers Univ. of Tech., SWEDEN
Prof. M.N. Bussac, Ecole Polytechnique,, FRANCE	Centre Phys. Des Plasmas, Ecole Polytech, SWITZERLAND
C. Mouttet, Lab. de Physique des Milieux Ionisés, FRANCE	Bibliotheek, Inst. Voor Plasma-Fysica, THE NETHERLANDS
J. Radet, CEN/CADARACHE - Bat 506, FRANCE	Asst. Prof. Dr. S. Cakir, Middle East Tech. Univ., TURKEY
Prof. E. Economou, Univ. of Crete, GREECE	Dr. V.A. Glukhikh, Sci. Res. Inst. Electrophys. Apparatus, USSR
Ms. C. Rinni, Univ. of Ioannina, GREECE	Dr. D.D. Ryutov, Siberian Branch of Academy of Sci., USSR
Preprint Library, Hungarian Academy of Sci., HUNGARY	Dr. G.A. Eliseev, I.V. Kurchatov Inst., USSR
Dr. B. DasGupta, Saha Inst. of Nuclear Physics, INDIA	Librarian, The Ukr.SSR Academy of Sciences, USSR
Dr. P. Kaw, Inst. for Plasma Research, INDIA	Dr. L.M. Kovrizhnykh, Inst. of General Physics, USSR
Dr. P. Rosenau, Israel Inst. of Technology, ISRAEL	Kernforschungsanlage GmbH, Zentralbibliothek, W. GERMANY
Librarian, International Center for Theo Physics, ITALY	Bibliothek, Inst. Für Plasmaforschung, W. GERMANY
Miss C. De Palo, Associazione EURATOM-ENEA , ITALY	Prof. K. Schindler, Ruhr-Universität Bochum, W. GERMANY
Dr. G. Grosso, Istituto di Fisica del Plasma, ITALY	Dr. F. Wagner, (ASDEX), Max-Planck-Institut, W. GERMANY
Prof. G. Rostangni, Istituto Gas Ionizzati Del Cnr, ITALY	Librarian, Max-Planck-Institut, W. GERMANY

DATE

FILMED

5/23/94

END