**ANNUAL PROGRESS REPORT ON
TFTR Experimental Data Analysis Collaboration**

Covering the period November 15, 1993 though November 14, 1994

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The research performed during the third year of this grant concentrated on a few key TFTR experimental data analysis issues: 1) characterization of MHD mode activity in TFTR; 2) comparison of low mode number MHD modes with neoclassical MHD theory; 3) further developments in local electron heat transient transport measurements; and 4) some other topics. Emphasis is placed on differences in these characteristics in DT and DD plasmas. Progress in these areas and activities undertaken in conjunction with this grant are summarized briefly in this report.

I. Introduction

This third annual progress report on the TFTR Experimental Data Analysis Collaboration DOE grant DE-FG02-92ER54139 to the University of Wisconsin-Madison covers work performed during the third year (November 15, 1993 through November 14, 1994) of the original three-year grant period. Because of the desirability of analyzing the DT data obtained from TFTR during the current campaign, which apparently may be extended 3 to 6 months beyond the presently mandated completion date of September 30, 1994, a supplemental extension is being proposed to extend this grant into a fourth year. The recent grant research activities summarized in this report involve work directed toward understanding (and hopefully reducing) key aspects of transport-limiting effects in DT plasmas in TFTR. It concentrates on the following four important issues for the DT experimental phase of TFTR: characterization and understanding of MHD phenomena; MHD effects on transport; transient transport; and other topics (miscellaneous, tritium inventory evolution and effects over the course of DT operations).

During this third grant year, Dr. Z. Chang (postdoc) has been in continuous residence at Princeton Plasma Physics Laboratory (PPPL). Professor J. D. Callen (Principal Investigator) and Dr. M. W. Kissick (postdoc) have each made approximately quarterly, week-long collaborative visits to PPPL during the year. Also, two of Professor Callen's UW-Madison graduate students [S. E. Kruger (MFE

Fellow) and C. Ren] are spending the summer of 1994 on assignment at PPPL working on issues related to this collaboration research grant.

Research during the current grant year is summarized in the succeeding sections. The last regular section (VI) provides a brief overall summary and is followed by a list of references. Appendix A lists the many open literature publications of this past year (total of 14, of which we were the lead authors on 5) and posters/talks that have resulted, at least in part, from support provided by this grant. Finally, Appendix B summarizes the personnel involved in this work and their degree of involvement during the current grant year.

II. MHD Mode Activity in TFTR [A.5, A.10, A.11, A.15, A.18-A.22, A.25, A.26, A.29, A.30, A.36]

The current grant year has been an important, historic period in plasma fusion research as TFTR has moved into DT operation. Dr. Chang has been an on-site participant [A.12-A.14] in TFTR experimental operations (primarily in HLDAS operation and MHD data analysis) for the entire 3 year duration of this grant. During the past year he has routinely taken 3 (or as many as 5) shifts per week as a control room operator of the HLDAS and MHD data systems. Scientifically his work has concentrated on exploring the differences in MHD mode activity (tearing-type modes, sawteeth, fishbones, etc.) and their confinement effects in DT as compared to DD high power TFTR plasmas. Preliminary results have been presented at many of the daily control room meetings of the TFTR group. Dr. Chang has participated in the taking of a significant fraction of the DT data and looks forward to analyzing it in detail over the next year. Some of the specific areas in which progress has been made in characterizing MHD mode activity and its effects on the confinement of plasma and energetic fusion products in TFTR are indicated in the following subsections. A more detailed discussion of the low mode number tearing-type MHD activity, whose analysis we have taken the lead role in, is deferred to the next major section.

IIA. Fishbone Instabilities in DT, DD Plasmas [A.19, A.25, A.30, A.36]

Fishbone activity is the most commonly observed MHD mode in high power TFTR DD and DT experiments. Through detailed comparison using the current DT data, Dr. Chang has found that the fishbone activity is enhanced in DT discharges – perhaps due to an alpha heating effect. Detailed analysis is continuing.

IIB. Sawteeth and Disruptions [A.11, A.18, A.36]

So far the effects of sawteeth on alpha particles seem similar to those on other energetic fusion products and the alpha component effects on sawteeth seem to be negligible. Further, disruptions seem similar in DD and DT plasmas, except for the fact that the stored energies are higher in DT plasmas.

IIC. TAE Instability Studies [A.10, A.30, A.36]

Last year Dr. Chang developed computer software analysis tools for exploring high frequency magnetic fluctuation on TFTR and discovered significant TAE mode

activity in "regular" ICRF-heated discharges. These same analysis tools have been used to study TAE modes [or Alfvén range of frequency (ARF) modes in general] and their effects on energetic fusion products in greater detail in NBI and/or ICRF heated TFTR plasmas this past year. Also, these modes have been searched for in DT plasmas. As a key member of the TFTR MHD group, Dr. Chang has played an active role in characterizing these modes and working with theorists at PPPL to compare the TFTR experimental results with theoretical models.

IID. International MHD Database [A.36]

Dr. Manickam of the PPPL theory group is leading the development of an international MHD database – to serve the needs of the TPX and ITER projects. Dr. Chang has provided a paradigm description of such data from TFTR and presented a framework for how such a database could be constructed at the national MHD group meeting in Dallas on March 13 [A.36].

III. Low Mode Number Modes, Effects [A.4, A.5, A.11, A.15, A.17, A.21, A.25, A.26, A.29, A.30., A.33, A.34, A.36]

Single-helicity magnetic islands have been observed in a significant fraction of TFTR high power supershot plasmas [A.5] with mode numbers $m/n = 3/2, 4/3, 5/4$ or even $6/5$. When these single-helicity modes occur they degrade plasma confinement in approximate agreement with theoretical predictions for the effect of a magnetic island in a plasma [1]. This degradation in the performance of TFTR supershots limits the relatively slow alpha heating in DT shots. We have taken the lead in characterizing and attempting to understand these low mode number modes and their effects in TFTR plasmas, and in quantifying the frequency of occurrence of these modes in DT and DD supershots in TFTR.

IIIA. Tearing type Identification [A.4, A.15, A.29]

For the large poloidal numbers ($m \gg 1$) observed in TFTR supershots, the standard cylindrical linear resistive MHD parameter Δ' is usually negative, and hence indicates stable standard tearing-type modes. Recent theoretical work we have performed [2] has generalized previous work [3] and shown that the small effects due to toroidal metric elements and finite β , and finite island width effects are typically stabilizing (i.e., make Δ' more negative). While the standard resistive MHD tearing-type modes are predicted to be stable, single-helicity neoclassical MHD [4] pressure-gradient tearing-type modes [5] are predicted to be unstable and grow into the nonlinear Rutherford regime [6] where they saturate quasilinearly. Comparisons of the experimental data with these low collisionality regime neoclassical MHD modes indicates encouraging agreement on the temporal growth and saturation of the externally measured magnetic fluctuations, and the scaling with plasma pressure and other plasma parameters. More detailed comparisons are being pursued and a paper is being written on this very encouraging comparison of theory and experiment in low collisionality TFTR plasmas. Presuming the neoclassical MHD tearing-type modes are indeed responsible for these low mode

number magnetic islands, the theory [4,5] of these instabilities points to a means for stabilization: arrange for reversed shear ($dq/dr < 0$) in the radial region where these modes occur.

IIIB. Internal temperature Fluctuations Induced by Low Mode Number Magnetic Islands [A.4, A.17].

In order to facilitate more detailed comparisons with theory, in our related theoretical developments we have calculated [A.4, A.17], within a simple slab-type model, fluctuations in electron temperature (and other plasma parameters) caused by a magnetic island imbedded in toroidally flowing TFTR plasmas. Initial indications are that the observed [7] radial structure and levels of the fluctuations are in reasonable agreement with the theoretical predictions. C. Ren is working with Drs. Chang, Zarnstorff et al. to add cylindrical and toroidal mode-coupling effects. We hope to be able to extract the radial structure of the magnetic perturbations in the plasma that create the low mode number magnetic islands from these detailed experiment-theory comparisons.

IIIC. Studies of Internal Structures [A.15, A.25, A.30, A.34, A.36]

The detailed investigation of the coherent (tearing-type) MHD modes in TFTR has shown that they are often a combination of say 4/3 and 3/3 modes – due to toroidal mode coupling? We are currently taking advantage of the advanced diagnostic systems on TFTR (particularly the ECE, Mirnov, BES and MSE diagnostics) and the innovative "jog" experiments [7] to resolve the fine structure of the coherent MHD modes on TFTR. Further analysis and comparison with ideal and tearing-type MHD mode theories should help us resolve many important nonlinear MHD theoretical issues.

IV. Transient Electron Heat Transport in TFTR [A.1, A.3, A.8, A.27, A.28]

The new "cold pulse" method [A.3] that we developed for determining a transient electron heat diffusivity in the "confinement" radial region $0.38 < r/a < 0.56$ from the response to the injection of impurities in the edge of TFTR L-mode discharges has been extended [A.27] and has led to related studies by both us and other groups (JET, TEXT – see below).

IVA. Extensions of Transient Electron Heat Transport Studies [A.27]

The radial range over which the transient electron heat diffusivity is determined has been extended inward to $r/a < 0.31$ by considering cases between sawteeth. The inferred heat diffusivity ($\leq 1 \text{ m}^2/\text{s}$) in the central region is much smaller than that in the usual confinement region ($\sim 6 \text{ m}^2/\text{s}$). Also, the electron heat diffusivity in the confinement region inferred from sawtooth-induced heat pulse propagation in the same discharge ensemble was shown to be in good agreement with the cold pulse values [A.27]. In addition, within the same discharge ensemble, variations in the injected impurity concentration (and therefore cooling power) over a factor of three were shown to not influence the inferred heat diffusivity [A.27]. Finally, an accidental double injection of impurities (100 ms apart)

was found to exhibit different behavior in the electron temperature perturbation in the outer source-affected region, but to yield the same transient electron heat diffusivity in the confinement region. All these additional studies have been in accord with the basic cold pulse model [A.3], and have served to increase both our and other groups confidence in the use of this new method to measure the transient electron heat diffusivity in hot tokamak plasmas.

IVB. Cold Pulse Propagation Studies by Others

Other labs and researchers are beginning to use the cold pulse measurements to probe transient electron heat transport. Cold-pulse propagation results in JET [8] are generally consistent with those we have obtained in TFTR, although they have used a nonlinear heat flux functional of the temperature gradient in analyzing their data. Very large ($\Delta T_e/T_e > 0.5$) cold pulses induced by strong impurity injection at the edge of TEXT have been found [9] to propagate inward diffusively but initially with very large diffusion coefficients (up to $1000 \text{ m}^2/\text{s}$) -- until the temperature perturbations become small and normal transient diffusivity values are obtained. This would seem to indicate a nonlinear response for large perturbations. In addition, the central electron temperature inexplicably rises slowly even as the nonlinear cold pulse propagates in from the edge of TEXT. Thus, our new cold pulse method of measuring transient electron heat transport has clearly opened up a new avenue of research and offers the promise of providing new information for understanding the central conundrum of anomalous electron heat transport in tokamaks.

V. Other Topics [A.2, A.6, A.7, A.9, A.16, A.24, A.31, A.32]

In addition to the primary topics covered above in which we have played a major role, other studies which we have also been involved in this past year or which we are just beginning work on are described in the following subsections. Because of funding support limitations we have stopped the development [A.27] of more refined models of the subtle fast ion effects on currents and flows in low collisionality tokamak plasmas.

VA. Miscellaneous TFTR Experimental Issues

Because of his central role in helping to take and analyze TFTR data, particularly that having to do with MHD modes and their effects, Dr. Chang has contributed to a number of other TFTR experiments and thus been a coauthor on a number of TFTR group publications. Specifically, he has contributed to the ICRF heating studies [A.6, A.9, A.16], to studies of toroidal rotation and velocity shear effects on supershots and transitions to H-modes [A.24, A.32] and between the center and edge plasmas [A.7], and most generally to the search for tritium isotope effects in DT plasmas [A.31].

VB. Evolution of Tritium Inventory in TFTR

During the summer of 1994 we have arranged for an MFE fellow (Scott E. Kruger), who is a graduate student of Professor Callen at UW-Madison, to do his

practicum at PPPL with Dr. R. V. Budny as his supervisor. Dr. Chang will help to supervise his activities as well. The project chosen for him is to develop a database on the inventory of tritium in the edge of TFTR DT and DD plasmas over the duration of the DT operations, and determine its effect on total (DD + DT) neutron production. The objective is to begin to develop a characterization and understanding of how much tritium is held in the carbon limiters and walls during the various phases of DT operation -- ohmic, high power beam injection, Lithium pellets, intervening DD shots. This information should also provide new information on recycling in the edge of tokamak plasmas.

VI. Summary

As discussed in the preceding text, significant progress has been achieved (and a number of papers published) in the areas that were proposed to be investigated in this grant. The most notable progress this past year has been in: a) characterizing the various types of MHD activity in TFTR plasmas, particularly as they differ in DT, DD supershots; b) beginning to demonstrate that the low m,n modes observed in TFTR supershots may indeed be due to neoclassical MHD pressure-gradient driven tearing-type modes; and c) further developing the cold pulse method for exploring transient electron heat transport that we pioneered, and cross-comparing the results with other methods. These activities plus the other ones discussed in the body of this report provide a firm basis for even more productive collaborations on the analysis of TFTR DT experimental data over the next year.

References

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- [6] P. H. Rutherford, Phys. Fluids 16, 1903 (1973).

- [7] M. C. Zarnstorff, "Search for Radial Structure in the T_e and q profiles in TFTR," M. C. Zarnstorff, S. Batha, A. Janos, F. L. Levinton and the TFTR Group, "Search for Radial Structures on TFTR," in Proceedings of Workshop on Local Transport Studies in Fusion Plasmas, Varenna, Italy, 30 August - 3 September 1993 (Società Italiana di Fisica, Bologna, Italy, 1993), p. 257.
- [8] J. J. O'Rourke and R. Giannella, "Measurements of Electron Thermal Diffusivity in Laser-Ablated Injection Experiments," Bull. Am. Phys. Soc. 38, 2056 (1993).
- [9] K. W. Gentle, "Cold Pulse Propagation in TEXT," talk at 7th TTF Workshop, Dallas, TX, 9-12 March 1994.

Appendix A

Grant-related Publications and Fusion Programs Activities

Journal Articles or Equivalent:

- [A.1] M. W. Kissick, P. C. Efthimion, D. K. Mansfield, J. D. Callen, C. E. Bush, H. K. Park, J. Schivell, E. J. Synakowski, and G. Taylor, "Dominance of Convective Heat Transport in the Core of TFTR Supershot Plasmas," *Phys. Fluids B* 5, 3618 (1993).
- [A.2] J. P. Wang, M. Azumi, K. Tani, J. D. Callen, "Momentum and Heat Friction Forces between Fast Ions and Thermal Plasma Species," *Nuclear Fusion* 34, 231 (1994).
- [A.3] M. W. Kissick, E. D. Fredrickson, J. D. Callen, C. E. Bush, Z. Chang, P. C. Efthimion, R. A. Hulse, D. K. Mansfield, H. K. Park, J. F. Shivell, S. D. Scott, E. J. Synakowski, G. Taylor, M. C. Zarnstorff, "Transient Electron Heat Diffusivity Obtained from Trace Impurity Injection on TFTR," *Nuclear Fusion* 34, 349 (1994); PPPL - 2936, August 1993.
- [A.4] J. D. Callen, Z. Chang, R. L. Coffey, T. A. Gianakon, C. C. Hegna, A. I. Smolyakov, W. X. Qu, J. P. Wang, "Magnetic Island Effects, Interactions in Tokamaks," in *Proceedings of Workshop on Local Transport Studies in Fusion Plasmas held at Varenna, Italy, 30 August - 3 September 1993*, p. 243.
- [A.5] Z. Chang, E. D. Fredrickson, J. D. Callen, K. M. McGuire, M. G. Bell, B. V. Budny, C. E. Bush, D. S. Darrow, A. C. Janos, L. C. Johnson, H. K. Park, S. D. Scott, J. D. Strachan, E. J. Synakowski, G. Taylor, M. C. Zarnstorff, and S. J. Zweben, "Transport Effects of Low (m,n) MHD Modes on TFTR Supershots," *Nuclear Fusion* 34, . . . (1994); PPPL - 2941, October 1993.
- [A.6] G. Taylor, . . . , Z. Chang, "Ion Cyclotron Range of Frequency Heating on TFTR," *Phys. Fluids B* 5, 2437 (1993).
- [A.7] R. D. Durst, . . . , Z. Chang and R. Hulse, "Observation of a Localized Transition from Edge to Core Density Turbulence in the TFTR Tokamak," *Phys. Rev. Lett.* 71, 3135 (1993).
- [A.8] E. D. Fredrickson, A. C. Janos, K. M. McGuire, S. D. Scott, G. Taylor, Z. Chang, "Study of Local Electron Heat Transport on TFTR," *Nuclear Fusion* 33, 1759 (1993).

- [A.9] G. Taylor, . . . , Z. Chang et al., "ICRF Heating of TFTR Deuterium Supershot Plasmas in the ^3He Minority Regime," *Plasma Phys. Control. Fusion* 36, 523 (1994).
- [A.10] K. L. Wong, J. R. Wilson, Z. Y. Chang et al., "Expansion of Parameter Space for Toroidal Alfrén Eigenmode Experiments in TFTR," *Plasma Phys. Control. Fusion* 36, 879 (1994).
- [A.11] S. J. Zweben, C. E. Bush, C. S. Chang, Z. Chang et al., "Anomalous Losses of Deuterium-Deuterium Fusion Products in TFTR," *Phys. Plasmas* 1, 1469 (1994).
- [A.12] R. J. Hawryluk, . . . , Z. Chang et al., "Preparations for Deuterium-Tritium Experiments on TFTR," *Phys. Plasmas* 1, 1560 (1994).
- [A.13] J. D. Strachan, . . . , Z. Chang et al., "Fusion Power Production from TFTR Plasmas Fueled with Deuterium and Tritium," *Phys. Rev. Lett.* 72, 3526 (1994); PPPL - 2978, February 1994.
- [A.14] R.J. Hawryluk, . . . , Z. Chang et al., "Confinement and Heating of a Deuterium-Tritium Plasma," *Phys. Rev. Lett.* 72, 3530 (1994); PPPL - 2977, February 1994.

Meeting Abstracts, Summaries or Papers:

DPP-APS Annual Meeting in St. Louis, MO, 1-5 November 1993

- [A.15] Z. Chang, J. D. Callen, E. D. Fredrickson, R. V. Budny, K. M. McGuire, and TFTR Team, "Study of Tearing-Type Instabilities in TFTR Supershots," *Bull. Am. Phys. Soc.* 38, 1906 (1993).
- [A.16] G. Taylor, . . . , Z. Chang, et al., "ICRF Heating of TFTR Supershot Plasmas," *Bull. Am. Phys. Soc.* 38, 1907 (1993).
- [A.17] J. D. Callen and R. L. Coffey, "Magnetic-Island-Induced Temperature Fluctuations and Their Measurement in Tokamaks," *Bull. Am. Phys. Soc.* 38, 2031 (1993).
- [A.18] E. D. Fredrickson, Z. Chang, A. Janos, and K. M. McGuire, "The Effect of α Fusion Products on Sawtooth Stability," *Bull. Am. Phys. Soc.* 38, 2031 (1993).
- [A.19] H. Hsuan, R. Budny, Z. Chang et al., "Low Frequency Fishbone Models in the TFTR NBI and ICRF Discharges," *Bull. Am. Phys. Soc.* 38, 2031 (1993).

- [A.20] A. Janos, Z. Y. Chang, E. Fredrickson, K. McGuire, J. Mannickam and the TFTR Group, "MHD Stability of Supershot Plasmas in TFTR," Bull. Am. Phys. Soc. 38, 2032 (1993).
- [A.21] L. C. Johnson, M. G. Bell, R. V. Budny, Z. Chang et al., "The Effect of Low (m, n) MHD Modes on Neutron Profiles in TFTR Supershots," Bull. Am. Phys. Soc. 38, 2032 (1993).
- [A.22] K. M. McGuire, Z. Chang, D. Ernst, E. D. Fredrickson, A. Janos, "The Beta Limit during Supershots on TFTR," Bull. Am. Phys. Soc. 38, 2034 (1993).
- [A.23] D. S. Darrow, C. S. Chang, Z. Chang et al., "ICRF-Induced Fast Ion Loss in TFTR," Bull. Am. Phys. Soc. 38, 2034 (1993).
- [A.24] C. E. Bush, . . . , Z. Chang et al., "The Supershot to H-mode Transition in TFTR," Bull. Am. Phys. Soc. 38, 2037 (1993).

Workshop on DT Experiments PPPL, 2-4 March

- [A.25] Z. Chang, "Coherent MHD Related Performance Degradation in TFTR" (poster).

Seventh Transport Task Force Workshop, Dallas, TX, 9-12 March

- [A.26] Z. Chang, "Temperature Degradation Induced by Low (m, n) MHD & Its Effects on TFTR Plasmas."
- [A.27] M. W. Kissick, "Transient Electron Heat Diffusivity Using 'Cold Pulse' Method."
- [A.28] J. D. Callen, "Transient Transport."

International Sherwood Fusion Theory Conference, Dallas, TX, 14-16 March

- [A.29] Z. Chang, J. D. Callen, E. Fredrickson, R. Budny, K. McGuire, S. Scott, and TFTR Team, "Neoclassical V_p - Driven MHD Instability in TFTR Supershots," paper 3C45.

EPS Meeting, Montpellier, FRANCE, 26-30 June

- [A.30] E. D. Fredrickson, Z. Y. Chang et al., "Coherent Fluctuations in the Initial TFTR D-T Experiments."

- [A.31] R. V. Budny, . . . , Z. Chang et al., "Initial Investigations of Isotopic Mass Scaling and Alpha Heating in TFTR DT Plasmas."
- [A.32] C.E. Bush, . . . , Z. Chang et al., "Toroidal Velocity Profiles in DT Plasmas on TFTR."

Additional Talks Given

- [A.33] Z. Chang, "Termination of High Performance in TFTR Supershots," at Trilateral Workshop on Termination of High Performance Regimes held at JET project, Abingdon, England, 2 - 4 August.
- [A.34] Z. Chang, "Transport Effects of Low (m,n) MHD Modes on TFTR Supershots," Hefei Summer School and Workshop sponsored by ICSC - World Lab, Hefei, China, 4-8 October.
- [A.35] M. W. Kissick, "Automatic Transient Transport Communication: Simplicity and Security are Virtues," at Transient Transport workshop (November 2) held in conjunction with DPP-APS meeting, St. Louis, MO, 1-5 November.
- [A.36] Z. Chang, "TFTR MHD Activity in TFTR DD and DT Supershots" and "International MHD Database," at MHD Working Group Meeting (March 13) held in conjunction with Sherwood Theory meeting, Dallas, TX, 14-16 March.

Appendix B

GRANT MODALITIES

During the current grant period (11/15/93 - 11/14/94 – \$111,285) the participating personnel and their approximate degree of grant-funded involvement has been as follows:

Faculty: J. D. Callen (Principal Investigator: 5% during academic year, 0.3 months during summer)

Postdocs: Z. Chang (100% time for 12 months, on assignment at PPPL)
M. W. Kissick (50% time for 12 months)

Graduate Students:

S. E. Kruger, (MFE Fellow, 1994 summer practicum at PPPL)
C. Ren (50% Research Assistant on assignment at PPPL for 3 months during summer of 1994)