FINAL PROGRESS REPORT ON

TFTR Experimental Data Analysis Collaboration

Principal Investigator: J. D. Callen, University of Wisconsin-Madison

Grant Period: November 15, 1994 through November 14, 1995

July, 1995

The research performed during the fourth (extension) year of this grant concentrated on a few key TFTR experimental data analysis issues: definitive identification that pressure-gradient-driven neoclassical MHD tearing modes are responsible for the low mode number magnetic islands in TFTR supershot plasmas; initiation of tearing-type locked mode physics activities; beginning attempts to determine the tearing mode parameter Δ' directly from electron fluctuation data; further studies of cool pulse propagation from the edge toward the center of TFTR discharges; investigation of tritium recycling in TFTR using the DT neutron rate; and some other topics. Progress in these areas and activities undertaken in conjunction with this grant are summarized briefly in this report.

I. Introduction

This fourth annual progress report on the TFTR Experimental Data Analysis Collaboration DOE grant DE-FG02-92ER54139 to the University of Wisconsin-Madison covers research performed during a fourth, extension year (November 15, 1994 through November 14, 1995) beyond the original three-year grant period. Dr. Zuoyang Chang, who had previously been on continuous assignment at PPPL during the 3 preceding grant years, was hired at PPPL just before the beginning of this grant extension year. A postdoctoral scientist (Dr. M. F. Zabiego) visited and collaborated with our group (on French foreign office funding) for the year (August 15, 1994 - September 27, 1995), mainly on issues concerning excitation and control of tearing-type modes in TFTR (see Section III below). We are now in the process of transferring this experimental data analysis collaboration from TFTR to DIII-D. The various laboratory collaborative visits undertaken in the pursuit of these activities under the auspices of this grant are listed in Appendix A.

Research progress on this grant during this past year (July 1994 - July 1995) is briefly summarized in Sections II - VII. The summaries are quite brief because so much of the work has already been (or is in the process of being) published in public forums - 3 journal articles or equivalent, 10 meeting abstracts/presentations, 8 other talks (see Appendix A). The last regular section (VIII) provides a very brief overall summary and is followed by a list of regular references (e.g., [1]). Appendix A lists publications and fusion program activities supported by this grant during the current period, and provides a list of project references (e.g., [A.1]). Appendix B summarizes the personnel who have been involved through this grant, and their degree of involvement this past year.

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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 product, 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.

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II. Bootstrap-Current-Driven Tearing Modes in TFTR [A.1, A.2, A.11, A.16, A.17, A.18, A.20]

Low mode number ($m/n = 3/2, 4/3, \text{ or } 5/4$) magnetic islands have been observed in TFTR supershot plasmas [A.1]. These tearing-type modes degrade plasma confinement and the neutron production rate significantly (up to 50% [A.1]) in both D-D and D-T plasmas. Previous attempts to correlate these modes with the standard resistive MHD [1] Δ' theory have been unsuccessful. We have proposed that these modes are due to perturbed bootstrap current effects via the more modern neoclassical MHD theory [2] pioneered by the PI on this grant about a decade ago. Thus, we have been intensively investigating many aspects of these new types of tearing-type modes [3] both theoretically [4,5] (as part of our APT Fusion Theory Grant) and through detailed analysis of many features of the modes observed in TFTR supershot plasmas on this grant. These intensive activities have now paid off in that these intrinsically new types of bootstrap-current-driven neoclassical MHD tearing modes have now been definitively identified [A.2] as being responsible for the low mode number magnetic islands observed in TFTR supershot plasmas. Since one prediction of the theory is that these modes should be stable in reversed shear tokamak plasmas, this identification play a role in the recent successful achievement of high performance discharges on TFTR via reversed shear. Over the past year we have given a number of talks [A.11, A.16, A.17, A.18, A.20] on this definitive correlation of the modes observed in the fusion grade plasmas in TFTR with the predictions for the new, modern neoclassical MHD theory [2], to alert the fusion community to this important new result and its implications, particularly for high bootstrap current fraction, long-pulse tokamak discharges.

III. Nonlinear Dynamics, Control of Tearing, Locked Modes [A.12, A.13, A.15, A.19]

While the neoclassical MHD tearing-type modes have been definitively identified as being responsible (in their nonlinear saturation phase) for the low mode number magnetic islands in TFTR supershots, there are still a number of open questions, primarily regarding their initial (nonlinear) excitation above an apparent (both theoretically and experimentally) threshold. We have been exploring [A.12, A.13, A.15, A.19] the bifurcation behavior at low mode amplitude which leads to these modes, and the use of a control parameter (mainly through ICRF current-profile and hence Δ' control) through which these deleterious modes could be manipulated into damped or stable regimes. Alternatively, it has been suggested [6] that the competition between parallel and perpendicular transport in the formation of the island structure provides the threshold conditions for these modes. We have been seeking to develop experimental data analysis procedures for distinguishing between these two mechanisms.

More generally, since tearing-type modes often evolve into locked modes and since the bootstrap-current neoclassical MHD drive could significantly influence locked modes, particularly at high β , we have been involved in promoting a broader community dialogue on these issues. In particular, we co-organized (with R.

Fitzpatrick, U. Texas) locked mode physics discussions at the DPP-APS Minneapolis meeting, and in an afternoon-long workshop at the recent Sherwood Theory meeting in Incline Village, NV. The objective of these discussions is to bring together theorists and experimentalists to develop a complete theory-based, experimentally verified picture of the physics involved in the initiation and subsequent growth of locked modes, and to seek ways to ameliorate the deleterious effects of these modes on long pulse, high β plasma confinement.

IV. Direct Determination of Key Tearing Mode Stability Parameter [A.6]

As an outgrowth of our group's earlier theoretical investigations of the temperature perturbations induced by isolated magnetic islands [7], and of the very high quality electron temperature fluctuation data available from the TFTR "jog experiments" [8], we have been seeking to determine directly the key tearing mode parameter Δ' from the data. Namely, we are seeking to use (via formulas that we have developed) the differences in magnetic island half-width and maximum temperature fluctuation level on the two sides of the magnetic island to determine the jump in the slope of the magnetic flux function across the island, and hence Δ' . Initial attempts [A.6] and more recent work have obtained a Δ' in agreement (for a 3/2 mode) with the negative (stable) value deduced from both our analytically derived formula [4] and a shooting-code analysis by Z. Chang. We are currently developing more sophisticated techniques for extracting the island-induced coherent fluctuations out of these noisy data signals (with help and suggestions from R. J. Fonck and R. D. Durst at UW-Madison), and developing a wider database of shots so analyzed to determine Δ' under a range of plasma conditions. We then hope to publish a Physical Review Letter on this work.

V. Cool Pulse Transport Studies [A.5, A.8, A.14]

In previous work [9] we invented a new technique for probing anomalous electron heat transport in TFTR -- by following the inward propagation of cool pulses induced by injection of trace impurities (and their radiation) into the edge of tokamak plasmas. Subsequent studies by K. W. Gentle et al. on TEXT [10] have uncovered a mysterious, small "instantaneous" increase in central electron temperature even as the cool pulse propagates inward for ohmically heated plasmas. We have found [A.5, A.8, A.14] that this anti-causal effect (central T_e increase while cooling the edge?) also occurs in TFTR ohmic plasmas, but that it goes away as the auxiliary heating power exceeds the ohmic heating power level. We are continuing these studies and planning to publish a paper on this work in the future.

VI. Tritium Recycling in TFTR [A.4]

During the summer of 1994 we sent a DOE/MFE fellowship graduate student (S. E. Kruger) in our group at UW-Madison to PPPL for his practicum. We arranged for him to work in collaboration with TFTR scientists (R. V. Budny, Z. Chang, J. A. Strachan, C. H. Skinner) on analyzing the D-T neutron signals from a sequence of nominally D-D plasmas so as to determine the degree of retention of tritium in the wall and its recycling back into the plasma on subsequent shots [A.4]. A PPPL report entitled "Investigations of the Tritium Recycling in TFTR using the DT Neutron Rate" has been written and is currently being reviewed and slightly revised in preparation for publication in the near future.

VII. Other Topics [A.3, A.7, A.9, A. 10, A.21]

Our heavy involvement in TFTR experimental data analysis is evidenced by inclusion of some of our staff in many of the TFTR IAEA Seville meetings papers [A.3] Further diverse collaboration activities have included Z. Change exploring kinetic-ballooning-mode (KBM) type instabilities in TFTR, M. F. Zabiego reporting on magnetic fluctuation data from Tore Supra [A.9], and transport related talks given by the PI [A.10, A.12].

VIII. Summary

As discussed in the preceding text, notable scientific progress has been achieved during this grant year on: a) definitively identifying the neoclassical MHD tearing-type modes as being responsible for the low mode number magnetic islands in TFTR (see Section II); b) developing additional details of tearing-type modes on reactor relevant tokamak plasmas and initiating locked mode physics activities (see sections III, IV); c) quantifying the tritium recycling from the walls of TFTR on subsequent D-D shots (see Section VI); and d) other, mostly plasma-transport-related areas (see Sections V and VII). Details of this work can be found in the references given in Appendix A, which also notes various fusion programmatic activities the PI has engaged in over the past year.

References

- [1] H. P. Furth, J. Killeen, M. N. Rosenbluth, Phys. Fluids 6, 459 (1963); H. P. Furth, P. H. Rutherford, H. Selberg, Phys. Fluids 16, 1054 (1973); P. H. Rutherford, Phys. Fluids 16, 1903 (1973); R. B. White et al., Phys. Fluids 20, 800 (1977); B. A. Carreras, B. V. Waddell, H. R. Hicks, Nuclear Fusion 19, 1423 (1979).

- [2] J. D. Callen, W. X. Qu, K. D. Siebert, B. A. Carreras, K. C. Shaing and D. A. Spong, "Neoclassical MHD Equations, Instabilities, and Transport in Tokamaks," in Plasma Physics and Controlled Nuclear Fusion Research 1986 (IAEA, Vienna, 1987), Vol. II, p. 157.
- [3] W. X. Qu and J. D. Callen, Univ. of Wisconsin Report UWPR 85-5 (1985) (unpublished); R. Carrera, R. D. Hazeltine, and M. Kotschenreuther, Phys. Fluids 29, 899 (1986).
- [4] C. C. Hegna and J. D. Callen, "Stability of Tearing Modes in Tokamak Plasmas," Phys. Plasmas 1, 2308 (1994).
- [5] H. R. Wilson, J. W. Connor, R. J. Hastie and C. C. Hegna, "Threshold for Neoclassical Magnetic Islands In A Low Collision Frequency Tokamak," UKAEA Culham Fusion Report UKAEA FUS 302 (June 1995). -- to be published.
- [6] R. Fitzpatrick, "Helical Temperature Perturbations Associated With Tearing Modes In Tokamak Plasmas," Phys. Plasmas 2, 825 (1995).
- [7] J. D. Callen, Z. Chang, R. L. Coffey, T. A. Gianakon, C. C. Hegna, A. I. Smolyakov, W. X. Qu and J. P. Wang, "Magnetic Island Effects, Interactions In Tokamaks," in Proceedings of Workshop on Local Transport Studies in Fusion Plasmas, Varenna, Italy, 30 August - 3 September 1993, J. D. Callen, G. Gorini and E. Sindoni Editors (Soc. Italiana di Fisica, Bologna, Italy, 1993), p. 243-250.
- [8] M. C. Zarnstorff and the TFTR Group, "Search for Radial Structures and T_e Fluctuations in TFTR," talks presented at: Newport TTF Meeting, 23 February 1993; St. Louis DPP-APS meeting, 1-5 November 1993; and Dallas TTF Meeting, 9-12 March 1994 (to be published). See also M. C. Zarnstorff, S. Batha, A. Janos, F. L. Levinton and the TFTR Group, "Search for Radial Structures on TFTR," in Ref. 7, p. 257-262.
- [9] 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. Schivell, 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).
- [10] K. W. Gentle et al., "An Experimental Counter-Example to the Local Transport Paradigm," Phys. Plasmas 2, 2292 (1995); K. W. Gentle, W. R. Rowan et al., "Strong Nonlocal Effects in a Tokamak Perturbative Transport Experiment," Phys. Rev. Letters 74, 3620 (1995).

Appendix A

Grant-Related Publications and Fusion Programs Activities

Journal Articles, Conference Proceedings Papers:

- [A.1] Z. Chang, E. D. Fredrickson, J. D. Callen, K. M. McGuire, M. G. Bell et al., "Transport Effects on Low (m,n) MHD Modes on TFTR Supershots," Nuclear Fusion 34, 1309 (1994).
- [A.2] Z. Chang, J. D. Callen, E. D. Fredrickson, R. V. Budny, C. C. Hegna, K. M. McGuire, M. C. Zarnstorff and TFTR Group, "Observation of Nonlinear Neoclassical Pressure-Gradient-Driven Tearing Modes in TFTR," Phys. Rev. Letters 74, 4663 (1995); PPPL-2988, September 1994.
- [A.3] Contributions/co-authorship of the following papers to be published in the Proceedings of the IAEA Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Seville, SPAIN, 26 September - 1 October:
- a) R. J. Hawryluk et al. (including Z. Chang), "Review of Recent D-T Experiments from TFTR," paper A-1-I-1.
 - b) M. G. Bell et al. (including Z. Chang), "Fusion Power Production in TFTR," paper A-2-I-1.
 - c) M. C. Zarnstorff et al. (including Z. Chang), "Heating and Transport in TFTR D-T Plasmas," paper A-2-I-2.
 - d) E. Fredrickson et al. (including Z. Chang), "TAE Modes and MHD Activity in TFTR D-T plasmas," paper A-2-II-5.
 - e) P. C. Efthimion et al. (including S. E. Kruger), "Tritium Transport, Influx, and Helium as Measured on TFTR During D-T Operation," paper A-2-II-6.
 - f) G. Taylor et al. (including Z. Chang), "ICRF Heating of Deuterium-Tritium Plasmas in TFTR," paper A-3-I-3.

Meeting Abstracts, Summaries, or Papers:

DPP-APS Annual Meeting in Minneapolis, MN, 7-11 November 1994

- [A.4] S. E. Kruger, R. V. Budny, J. D. Strachan, C. H. Skinner, Z. Chang, J. D. Callen, L. C. Johnson, D. L. Jassby and TFTR Team, "Modelling of the

DT Neutron Rate and Recycling in TFTR," Bull. Am. Phys. Soc. 39, 1678 (1994).

- [A.5] M. W. Kissick, E. D. Fredrickson, J. D. Callen, "Refined Transient Electron Heat Diffusivity Results from TFTR," Bull. Am. Phys. Soc. 39, 1678 (1994).
- [A.6] C. Ren, J. D. Callen, Z. Chang, E. D. Fredrickson, S. Paul, A. Janos, K. M. McGuire and M. Zarnstorff, "Study of Magnetic Island Structures in TFTR," Bull. Am. Phys. Soc. 39, 1681 (1994).
- [A.7] Z. Chang, E. D. Fredrickson, R. V. Budny, J. D. Callen, A. Janos, K. M. McGuire, R. Nazikian, E. Mazzucato, G. Taylor and TFTR Team, "Observation of KBM-like Modes in TFTR DD and DT Experiments," Bull. Am. Phys. Soc. 39, 1697 (1994).

Eighth Transport Task Force Meeting, Marina del Rey, CA, 6-9 March

- [A.8] M. W. Kissick, "Discussion of A Nonlocal χ_e Observation on TFTR and Implications."
- [A.9] M. F. Zabiego, "Magnetic Fluctuations and Anomalous Transport: Comparison Between Theory and Experiment on Tore Supra."
- [A.10] J. D. Callen, Summary of "Transient Transport and Magnetic-Fluctuation-Induced Transport and Plasma Structures."

International Sherwood Fusion Theory Conference, Incline Village, NV, 3-5 April

- [A.11] Z. Chang, E. D. Fredrickson, R. V. Budny, A. Janos, K. M. McGuire, M. C. Zarnstorff and TFTR Team, J. D. Callen, C. C. Hegna, M. Zabiego, "Investigation of Neoclassical Tearing Instability in TFTR," paper 1C15.
- [A.12] M. Zabiego, J. D. Callen and Z. Chang, "Tearing Mode Bifurcation: A Way to Control MHD Activity In Tokamak Plasmas," paper 3C46.

IEEE International Conference on Plasma Science, Madison, WI, 5-8 June.

- [A.13] M. Zabiego, J. D. Callen and Z. Chang, "Control of Tearing Modes in Tokamak Plasmas By Means of a Bifurcation Behavior," paper 4EP11.

Additional Meetings and Workshops Attended. Talks Given:

- [A.14] M. W. Kissick, "Further Studies of Cold Pulse Propagation in TFTR," Transient Transport Workshop at DPP-APS Minneapolis Meeting, November 8.

- [A.15] M. F. Zabiego, "Nonlinear Magnetic Islands in Tokamaks: Theory and Applications to TFTR Supershots, " Theory Seminar, PPPL, January 12.
- [A.16] C. C. Hegna, "Observation of Bootstrap-Current-Driven Magnetic Islands in TFTR," Culham Theory Seminar, Abingdon, UK, January 24.
- [A.17] J. D. Callen, "Pressure-Gradient-Driven Neoclassical MHD Tearing Modes in TFTR," MHD Meeting, General Atomics, February 22.
- [A.18] C. C. Hegna, "Bootstrap Current Driven Magnetic Islands in TFTR," Department of Plasma Physics, Imperial College, London, England, February 27.
- [A.19] M. Zabiego, "Inertial Effects On Tearing Instability Threshold; Bifurcation," Locked Mode Physics Workshop at Sherwood Theory Conference, Incline Village, NV, April 4.
- [A.20] J. D. Callen, "Nonlinear Evolution of Tearing Modes in Tokamaks," MHD Meeting, General Atomics, June 23.
- [A.21] J. D. Callen, "Some Theoretical Models of Pinch-Type Transport Effects," Transport Meeting, General Atomics, June 23.

Collaboration Visits

S. E. Kruger, C. Ren, to PPPL, summer of 1994.
 M. W. Kissick, September 12-16.
 J. D. Callen, to PPPL, December 19-21.
 M. W. Kissick, S. E. Kruger, M. F. Zabiego, to PPPL, January 9-13.
 M. W. Kissick, February 20-24.
 C. Ren, to PPPL, March 13-18.
 J. D. Callen, to General Atomics, February 20-22.
 J. D. Callen, to General Atomics, May 30 - June 23.

Other Relevant Meetings Attended: OFE and Programmatic Activities (J. D. Callen)

International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Seville, SPAIN, September 26 - October 1 -- chaired a theory oral session, participated in Nuclear Fusion Board of Editors meeting.

Leader of Transient Transport and Plasma Structures Working Group of TTF:
 Organized Transient Transport workshops at

DPP-APS meeting, Minneapolis, MN, November 8
8th TTF meeting, Marina Del Rey, CA, March 6-9 (and gave a summary
talk on current Working Group activities)
EPS Bournemouth, ENGLAND meeting, July 4.
Attended TTF Working Group Leaders and Steering Comm. meetings in
Minneapolis (November 6) and Marina del Rey (March 6).

Participated in MHD Working Group meetings in Minneapolis (November 6) and
Incline Village, NV, (April 2).

Organized (with R. Fitzpatrick, U. Texas) and hosted a locked mode physics
discussion at the DPP-APS Minneapolis meeting (November 7) and a Locked
Mode Physics Workshop, Incline Village, NV (April 4).

TFTR Program Advisory Committee.

APPENDIX B

GRANT MODALITIES

During the current grant period (11/15/94 - 11/14/95 – \$121,120) the participating personnel and their approximate degree of grant-supported involvement in this research program has been as follows:

Faculty: J. D. Callen (PI: average of 5% during academic year plus one summer month)

Postdocs: C. C. Hegna (25% time for 8 months, 4 months on assignment and supported by Culham Laboratory, ENGLAND, 11/94 - 3/95)
M. W. Kissick (50% time for 12 months)
M. F. Zabiego (8/94 - 9/95 visitor from Cadarache, FRANCE totally supported by French foreign office)

Graduate Students:

C. Ren (50% Research Assistant for 10 months; 50% Teaching Assistant for 2 months)
E. Held (50% Research Assistant for 3 months; Applied Math NSF Traineeship for 4 months; DOE Computational Science Fellowship for 3.5 months, beginning 9/95)
S. E. Kruger (DOE MFE Fellow)