FUSION RESEARCH CENTER

DOE/ER/54241-1

Technical Progress Report

TEXAS EXPERIMENTAL TOKAMAK

A Plasma Research Facility

GRANT DE-FG03 94ER 54241
November 1, 1993 - October 31, 1994
Alan J. Wootton

Fusion Research Center
The University of Texas at Austin
P.O. Box 7726
Austin, TX 78713-7726
July 1994

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY
OFFICE OF ENERGY RESEARCH

THE UNIVERSITY OF TEXAS

Austin, Texas

MASTER

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Summary

Introduction

Our purpose is to operate and maintain TEXT Upgrade as a complete facility for applied tokamak physics in order to elucidate the mechanisms of working gas, impurity, and thermal transport in tokamaks and in particular to understand the role of turbulence. So that we can continue to study the physics that is most relevant to the fusion program, TEXT completed a significant device upgrade this year. The new capabilities of the device and new and innovative diagnostics were exploited in all main program areas including

Configuration Studies
Electron Cyclotron Heating Physics
Improved Confinement Modes
Edge Physics/Impurity Studies
Central Turbulence and Transport
Transient Transport

The research originally proposed in these areas is substantially unchanged. In addition to the proposed research, we have begun to think about the next machine at Texas. Specifically, which device will allow us to pursue new physics of relevance to the fusion program.

Highlights

During the past year, the operating regime of TEXT was extended beyond Ohmically heated circular discharges to include auxiliary heating and diverted discharges.

- up to 600 kW of ECH heating is now commonly available
- diverted discharges can be produced with any of four x-point configurations

Details of the progress in each of the research areas are described in the subsequent sections. These are the highlights

Configuration Studies

- Stable discharges were achieved in all four of the promised diverted configurations

Electron Cyclotron Heating Physics

- The three gyrotrons fundamental to the success of the TEXT-U program were brought into operation
- Magnetic turbulence levels were deduced from the transport of ECH generated superthermals and shown to be too small to cause the *thermal* transport observed in the core of TEXT-U.

Improved Confinement

- Embarked on a systematic search for H-mode
- Tantalizing evidence for H-mode in isolated discharges

Edge Physics/Impurity Studies

- Initial experiments demonstrated that the TEXT divertor can support studies of divertor physics and code validation
- Experiment is consistent with a prediction that turbulence can be driven by the shear in the parallel mass flow

Central Turbulence and Transport

- Improved diagnostics including a more energetic heavy ion beam probe, a unique temperature fluctuation diagnostic and a BES diagnostic are providing new data on interior turbulence

Transient Transport

- In a cold wave propagation experiment, the electron thermal transport was found to greatly exceed that deduced from power balance. This reproducible result is not in agreement with other experiments or standard models of transport.

The Next Machine

- A spherical tokamak with current drive, a divertor, and neutral beam heating was proposed for a serious test of the device concept.

Progress in each of the program areas is described in greater detail in the following sections. Plans for next year are also included. This section concludes with a summary of the publications.

FUSION RESEARCH CENTER
JOURNAL PUBLICATIONS
1993-94

1. Catto, P., J. R. Myra and A. J. Wootton, "Analytic model for the runaway distribution function in the presence of spatial diffusion," *Phys. Plasmas* 1:684-690 (1994).

2. Catto, P. J., J. R. Myra, R. D. Bengtson and A. J. Wootton, "Modeling and simultaneous sawtooth measurements of the thermal and energetic electron diffusivities from the Texas Experimental Tokamak," *Phys. Fluids B* 5:125-137 (1993).

3. Rempel, T. D., R. F. Gandy and A. J. Wootton, "Density fluctuation effects on electron cyclotron emission correlation measurements in optically gray plasmas," *Rev. Sci. Instrum.* **65 (6)**:2044-2048 (1994).

4. Rhodes, T. L., C. P. Ritz and R. D. Bengtson, "Scaling of Far Edge Plasma Turbulence and Fluctuation induced Particle Transport in the Text Tokamak," *Nuclear Fusion* **33**:1147-1163 (1993).

5. Richards, B., T. Uckan, A. J. Wootton, B. A. Carreras, R. D. Bengtson, P. Hurwitz, G. X. Li, H. Lin, W. L. Rowan, H. Y. W. Tsui, A. K. Sen and J. Uglum, "Modification of tokamak edge turbulence using feedback," *Phys. Plasmas* 1:1606-1611 (1994).

6. Roberts, D. R., D. C. Sing and R. F. Steimle, "Refraction and Absorption Measurements of a Focused ECH Beam," *Nucl. Fusion* **33**:1707-1713 (1993).

7. Rowan, W. L., "Applications of Atomic Data in the Study of Transport in Tokamaks," *Physica Scripta* **T47**:96-101 (1993).

8. Rowan, W. L., A. G. Meigs, E. R. Solano, P. M. Valanju, M. D. Calvin and R. D. Hazeltine, "Rotation in Ohmically heated tokamaks: Experiment and theory," *Phys. Fluids B* **5**:2485-2490 (1993).

9. Simcic, V. J., T. P. Crowley, P. M. Schoch, A. Y. Aydemir, X. Z. Yang, K. A. Connor, R. L. Hickok, A. J. Wootton and S. C. McCool, "Internal magnetic and electrostatic fluctuation measurements of magnetohydrodynamic modes in the Texas Experimental Tokamak (TEXT)," *Phys. Fluids B* **5**:1576-1579 (1993).

10. Sugar, 2., Victor, Kaufman and W. L. Rowan, "Rh I isoelectronic sequence observed from Er23+ to Pt 33+," *Optical Society of America* 1977 (1993).

11. Sugar, J., V. Kaufman and W. L. Rowan, "Observation of Pd-like resonance lines through Pt^{32+} and Zn like resonance lines of Er^{38+} and Hf^{42+}," *Journ. Optical Soc. of Amer.* **B**:799-801 (1993).

12. Sugar, J., V. Kaufman and W. L. Rowan, "Spectra of Ag I isoelectronic suquence observed from Er^{21+} to Au^{32+}," *Journal of Optical Society of Amer. B* **10**:1321-1325 (1993).

13. Tsui, H. Y. W., "Formation of a velocity shear layer in confined plasmas," *Phys. Fluids B* **4**:4057-4061 (1993).

14. Tsui, H. Y. W., K. Rypdal, Ch.P. Ritz and A. J. Wootton, "Coherent Nonlinear Coupling between a Long-Wavelength Mode and Small-Scale Turbulence in the TEXT Tokamak," *Phys Review Ltrs.* **70**:2565-2568 (1993).

15. Tsui, H. Y. W., P. M. Schoch and A. J. Wootton, "Observation of a quasicoherent mode in the Texas Experimental Tokamak," *Phys. Fluids B 5* **4**:1274-1280 (1993).

16. Tsui, H. Y. W., A. J. Wootton, J. D. Bell, R. D. Bengston, D. Diebold, J. H. Harris, N. Hershkowitz, C. Hidalgo, J. C. Ingraham, S. J. Kilpatrick, G. X. Li, H. Lin, D. M. Manos, M. A. Meier, G. M. Miller, C. P. Munson, J. Pew, S. C. Prager, T. Uckan and P. G. Weber, "A comparison of edge turbulence in tokakamks, stelarators, and reversed-filed pinches," *Physics of Fluids B* **5**:2491-2497 (1993).

FUSION RESEARCH CENTER
CONFERENCE PROCEEDINGS
1993-94

1. Gentle, K. W., G. Cima, H. Gasquet, G. A. Hallock, P. E. Phillips, W. L. Rowan and C. Catts, "Characteristics of Equilibrium and Perturbed Transport Coefficients in Tokamaks," Transport in Fusion Plasmas, (1994).

2. Gentle, K. W., G. Cima, H. Gasquet, G. A. Hallock, P. E. Phillips, W. L. Rowan and C. Watts, "Observation of Non-Standard Propagation of Temperature Perturbations in a Tokamak," Europhysics Conference Series, (1994).

3. Gentle, K. W., T. Group, O.Gehre and A.-U. Group, "Particle Transport in Equilibrium, Transients, and Transitions," Local Transport Studies in Fusion Plasmas, (1994).

4. Karzhavin, Y., H. Y. W. Tsui, R. d. Bengtson, R. V. Bravenec, D. L. Brower, Y. Jiang, G. Hallock, P. Hurwitz, J. S. Mao, P. E. Phillips, W. L. Rowan, S. R. Shin and Y. Wan, "Effect of neon injection on turbulence in TEXT-U," 20th EPS Confrence on Controlled Fusion and Plasma Physics, Lisbon, Portugal, (1993).

5. Rowan, W. L., R. D. Bengtson, X. Bonnin, K. W. Gentle, P. H. Edmonds, P. D. Hurwitz, P. E. Phillips, K. Schroder, E. R. Solano, D. J. Storek and J. R. Uglum, "Particle and Energy Balance in Diverted Plasmas in TEXT-U," 21st European Conference on Controlled Fusion and Plasma Physics, Montpellier, France, (1994).

6. Rowan, W. L., R. D. Bengtson, X.Bonnin, K. W. Gentle, P. H. Edmonds, P. D. Hurwitz, P. E. Phillips, K. Schroder, E. R. Solano, D. J. Storek and J. R. Uglum, (1994).

7. Solano, E. R. and R. d. Hazeltine, "X-point effect on neoclassical kinetic theory," 20th EPS Conference on Controlled Fusion and Plasma Physics, Lisbon, Portugal, (1993).

8. Uckan, T., B. Richards, R. D. Bengtson, B. A. Carreras, D. B. Crockett, K. W. Gentle, G. X. Li, P. D. Hurwitz, W. L. Rowan, H. Y. W. Tsui and A. J. Wootton, "Active probing of plasma edge turbulence and feedback studies on the Texas experimental tokamak," 20th EPS Conference on Controlled Fusion and Plasma Physics, Lisbon, Portugal, (1993).

9. Uckan, T., B. Richards, A. J. Wootton, R. D. Bengtson, R. Bravenec, B. A. Carreras, G. X. Li, P. D. Hurwitz, P. E. Phillips, W. L. Rowan, H. Y. w. Tsui, J. R. Uglum, Y. Wen and D. Winslow, "Feedback Control and Stabilization Experiments on the Texas Experimental Tokamak (TEXT)," 11th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Ibaraki-ken, Japan, (1994).

10. Wootton, A. J., "The Effects of magnetic Perturbations on Plasma Transport or is Magnetic Turbulence Important in Tokamaks?," Transport, Chaos and Plasma Physics Conference, Marseille, France, (1993).

FUSION RESEARCH CENTER
INVITED TALKS
1993-94

1. McCool, S., "A report on our preconceptual design study," Workshop on Establishing the Physics Basis Needed to Access the Potential of Compact Toroidal Reactors, Oak Ridge, Tennessee, (1994).

2. Wootton, A. J., "The Effects of Magnetic Perturbations on Plasma Transport or is Magnetic Turbulence important in Tokamaks?," Transport, Chaos and Plasma Physics, Marseille, France, (1993).

3. Wootton, A. J., "Fluctuations and Local Transport-Latest Developments," Local Transport Studies in a Fusion Plasmas, Varenna, Italy, (1993).

FUSION RESEARCH CENTER
BOOKS
1993-94

1. Horton, W., R. D. Bengtson and P. J. Morrison. "Space-Time Statistics of Drift Wave Turbulence with Coherent Structures." Transport, Chaos and Plasma Physics. Benkadda, Doveil and Elskens ed. 1994 World Scientific.

2. Wootton, A. J. "The Effects of Magnetic Perturbation on Plasma Transport or is Mangetic Turbulence Important in Tokamaks?" Transport, Chaos and Plasma Physics. Benkadda, Doveil and Elskens ed. 1994 World Scientific.

FUSION RESEARCH CENTER
ABSTRACTS
1993-94

1. Bengtson, R., G. X. Li, H. Y. W. Tsui and A. J. Wootton, "Mach Probe Measurements on TEXT-U," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

2. Bravenec, R. V. and A. J. Wootton, "Modeling of HIBP and FIR-Scattering Density Fluctuation Spectra," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

3. Castle, G. G. and S. C. McCool, "Impurity Pellet Ablation Dynamics in TEXT-U.," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

4. Chen, J. Y., M. Foster, S. McCool, M. Austin, D. Brower, H. Lin, P. Phillips, P. Schoch and X. Z. Yang, "Stochasticity Due to Interaction between Intrinsic and Extrinsic Magnetic Island in TEXT and TEXT-U," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

5. Cima, G., T. Rempel, M. Kwon, R. F. GAndy, R. V. Bravenec, P. Phillips, D. Patterson, A. J. Wootton and C. E. Thomas, "Core Electron Temperature Fluctuations in TEXT-U," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

6. Collins, R. A. and W. L. Rowan, "Impurity Emission Asymmetries in the TEXT-U.," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

7. Craig, J. L., P. E. Phillips and E. R. Solano, "Magnetic Sensors for Determining Last Closed Magnetic Flux Surface Shape," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

8. Craven, W. A., S. C. McCool and A. J. Wootton, "Stochastic Field Experiments (SFX) on TEXT-U.," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

9. Crowley, T. P., A. Ouroua, P. M. Schoch, P. E. McLaren, B. Z. Zhang and J. W. Heard, " The 2 MEV Heavy Ion Beam Probe Diagnostic on TEXT-Upgrade," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

10. Demers, D. R., P. M. Schoch and A. Ouroua, "Computer Control of the Heavy Ion Beam Probe and Data Acquisition System," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

11. Duraiappah, L., R. D. Bengtson, Y. Karzhavin and P. M. Valanju, "New Measurements of the Magnetic Field Direction in TEXT-U," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

12. Edmonds, P. H., "First Results with Divertor Operation in TEXT Upgrade," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

13. Filippas, A. V., R. D. Bengtson, C. W. Horton and E. J. Powers, "Conditional Statistical Analysis of Plasma Fluctuations in the Edge of TEXT-U," 35th Annual

Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

14. Foster, M. S., J. L. Craig, P. E. Phillips and P. K. Landers, "A Magnetic Pickup Coil Diagnostic Set for Feedback Control of Plasma Position in TEXT-U.," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

15. Gentle, K. W., G. Cima, G. Hallock, P. E. Phillips, B. Richards, W. L. Rowan, D. Sing and A. J. Wootton, "Particle Transport Coefficients from Perturbations," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

16. Hallock, G. A., R. Chatterjee, K. Chiang, A. Darbar, M. L. Gartman, A. S. Rahman, S. Reedy and S. R. Shin, "The TEXT Upgrade Fir and Phase Contrast Interferometers," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

17. Hurwitz, P. D., W. L. Rowan and G. X. Li, "Path Effects in Optical Measurements of Turbulent Fluctuations in TEXT," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

18. Jagger, J., P. Edmonds, D. Foster, H. Huang, J. Herbst, Y. Hu, J. Kitzmiller, J. Mao, S.McCool, W. K. Naumann, D. Pavlovsky, H. Reyes, B. Richards, D. Sing, D. Terry, J. Uglum, M. Bell, J. W. Bryan, K. Carter, M. Gartman, F. Hall, W. Henry, S. Hilsberg, D. Dobday, M. Howse, D. Hungerford, J. Key, P. Landers, N. Lemma, W. Morris, R. Ramirez, N. Sloan, I. Sterzing and R. White, "The Text Upgrade Program: A Status Report," 35th Annual Meeting, American Physical Society. Division of Plasma Physics, St. Louis, Missouri, (1993).

19. Jiang, Y. and D. L. Brower, "Density Profile Evolution During Tearing Modes, Locked Modes and Disruptions on the TEXT Upgrade Tokamak," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

20. Karzhavin, Y., H. Y. W. Tsui and R. D. Bengtson, "Improved Ohmic Confinement Regimes on TEXT-U.," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

21. Li, G. X., R. D. Bengtson, H. Lin, M. Meier, H. Y. W. Tsui and A. J. Wootton, "The Effects of Connection Length on Edge Velocity Shear Layer and SOL Fluctuations on TEXT-U Tokamak," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

22. Lierzer, K. W., K. W. Wenzel, R. D. Petrasso, S. C. McCool, G. G. Castle, P. H. Edmonds, M. S. Foster and J. R. Uglum, "Soft X-ray Emission Measurements in TEXT-U," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

23. McCool, S. C., A. J. Wootton, R. D. Bengtson, G. G. Castle, W. A. Craven, W. E. Drummond and B. Z. Zhang, "An Assessment of the Role of Magnetic Turbulence in Tokamak Transport.," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

24. McLaren, P. E., T. P. Crowley, P. M. Schoch, A. Ouroua, R. L. Hickok, K. A. Connor, J. F. Lewis and J. G. Schatz, "The 2 MeV Electrostatic Energy Analyzer for TEXT-Upgrade," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

25. Meier, M. A., G. A. Hallock, H. Y. W. Tsui, R. D. Bengtson and G. X. Li, "The Time Domain Triple Probe Method," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

26. Meigs, A. G., W. L. Rowan, M. D. Calvin, P. M. Valanju, E. R. Solano and D. Crockett, "Impurity flow during electrode biasing on TEXT-U," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

27. Ouroua, A., T. P. Crowley, P. M. Schoch, R. L. Hickok, K. Connor, J. G. Schwelberger, R. R. White, P. E. McLaren and J. Heard, "Experimental Analysis of the Effect of Beam Attenuation Modulation on Fluctuation Measurements by a Heavy Ion Beam Probe," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

28. Rempel, T., G. Cima, M. Kwon, R. F. Gandy, R. V. Bravenec, A. J. Wootton and C. E. Thomas, "Density Effects on Correlated ECE and Temperature Fluctuations in TEXT-U," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

29. Roberts, D. R., S. Santosa, D. C. Sing and R. F. Steimle, "In Search of Magnetic fluctuations Using Microwaves in TEXT-U," 35th Annual Meetng, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

30. Ross, D. W., "Atomic Physics Instability Mechanisms: A Critique.," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

31. Schwelberger, J. G., T. P. Crowley, K. A. Connor, A. Ouroua, R. L. Hickok, B. Z. Zhang and E. R. Solano, "Q - Profile Measurements with a Heavy Ion Beam Probe on TEXT," 35th Annual Meeting, American Physical Society, Division of Plamsa Physics, St. Louis, Missouri, (1993).

32. Shin, S. R., G. A. Hallock, K. Chiang, A. Darbar, M. L. Gartman, A. Rahman, S.Reedy and H. Y. W. Tsui, "Inversion of Electron Density Data from the TEXT Fir Interferometer," 35th Annual Meeting, American Physical Society Division of Plasma Physics, St. Louis, Missouri, (1993).

33. Solano, E. R., J. R. Uglum, P. H. Edmonds and J. L. Craig, "Plasma Position Stability in TEXT-Upgrade," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

34. Steimle, R. F., D. R. Roberts, S. Santosa, G. Cima and D. C. Sing, "Suprathermal Electron Transport Studies using Vertically-Viewing ECE in TEXT-U," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

35. Storek, D., K. W. Gentle and R. Bravenec, "Heat Flux Measurements at the TEXT Boundary," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

36. Tsui, H. Y. W., B. Richards, T. Uckan, A. J. Wootton, B. A. Carreras, R. D. Bengtson, G. X. Li and M. Meier, "Active Probing of Turbulence Dynamics in TEXT-U," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

37. Uckan, T., B. Richards, R. D. Bengtson, B. A. Carreras, G. X. Li, H. Lin, P. Hurwitz, W. L. Rowan, H. Y. W. Tsui and A. J. Wootton, "Effects of the Edge Feedback on the TExas Experimental Tokamak (TEXT)," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

38. Vannucci, A. and S. C. McCool, "Major Disruptions in TEXT-U Tokamak," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

39. W. H. Miner, J., H. Y. W. Tsui, J. C. Wiley and A. J. Wootton, "The Edge Database," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

40. W.H. Miner, J., J. Y. W. Tsui, J. C. Wiley and A. J. Wootton, "The Edge Database," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

41. Wen, Y. and R. Bravenec, "Comparison of Radiated Power Measurements on TEXT and TEXT-U.," 35th Annual Meeting,, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

42. WOOTTON, A. J., "Magnetic Perturbations and Plasma Transport," Transport, Chaos & Plasma Physics Conference, Marseille, France, (1993).

43. Zhang, B. Z. and A. J. Wootton, "Magnetic Fluctuations with Biased Electrode in TEXT," 35th Annual Meeting, American Physical Society, Division of Plasma Physics, St. Louis, Missouri, (1993).

FUSION RESEARCH CENTER
ACCEPTED FOR PUBLICATION
1993-94

1. William L. Rowan, R. D. Bengtson, X. Bonnin, P.H. Edmonds, P.D. Hurwitz, E.R. Solano, H..W. Tsui, J.R. Uglum, and A. J. Wootton, *"Particle Balance in diverted plasmas in TEXT-U."* accepted by J. Nucl. Matl.

2. T. Uckan, B. Richards, A. J. Wootton, R. D. Bengtson, B.A. Carreras, G.X. Li, P. Hurwitz, W. L. Rowan, H.Y.W. Tsui, J.R. Uglum and D. Winslow, *"Feedback control and stabilization experiments on the Texas Experimental tokamak (TEXT)."* accepted by J. Nucl. Matl.

3. H.Y.W. Tsui, R. D. Bengtson, G.X. Li, B. Richards, T. Uckan, J. Uglum and A. J. Wootton, *"Wave launching as a diagnostic tool to investigate plasma turbulence",* accepted by Rev. Sci. Instrum.

4. G. Cima, *"Correlation Properties of Black Body Radiation In The Context of the Electron Cyclotron Emission of Magnetized Plasmas",* accepted by Nuovo Cimento D, 1994.

5. C. Watts, G. Cima, R. Gandy, T. Tempel, a. Wootton, *"Measurements of Tempertature Fluctuations from Electron-Cyclotron Emission,"* accepted by Rev. Scient. Inst.

6. G. X. Li, R. D. Bengtson, H. Lin, M. Meier, H.Y.W. Tsui, and A. J. Wootton, *"The plasma potential asymmetry and steady state radial convection in TEXT-U tokamak",* accepted by Nuclear Fusion.

7. A. Yu. Dnestrovskij, R. D. Bengtson, Yu. Karzhavin, and A. Ouroua, *"A method for neutral spectra analysis taking ripple-trapped particle losses into account",* accepted by Rev. Sci. Instrum.

8. P.M. Valanju, L. Durriapah, R. D. Bengtson, Y. Karzhavin, A. Nitikin, *"Initial results from a charge exchange q-diagnostic on TEXT-U",* accepted by Rev. Sci. Instrum.

9. J. Q. Dong, W. Horton, R. D. Bengtson, G.X. Li, *"Momentum-Energy transport from turbulence driven by parallel flow shear,"* accepted by Phys. Fluids.

10. D.R. Roberts, R.F. Steimle, G. Giruzzi, G. Cima, and C. Watts, *"Vertical Viewing of Elkectron-Cyclotron Emissions for Diagnosing Fast Electrons in TEXT-U",* accepted by Rev. Sci. Instrum.

11. G. Cima, C. Watts, R. Gandy, *"Correlation Radiometry of Electron Cyclotron Radiation in TEXT-U",* accepted by Rev. Scient. Inst.

FUSION RESEARCH CENTER
SUBMITTED FOR PUBLICATION
1993-94

1. M.S. Foster, S.C. McCool, A.J. Wootton, "*The AC Response of a Tokamak Plasma toDriven Helically Resonant Radial Magnetic Perturbations*," submitted to Nuclear Fusion, 1994.

2. A.J. Wootton, "*Core Temperature Fluctuation and Related Heat Transport in The Texas Experimental Torus - Upgrade*," submitted for publication, Physics of Plasmas (1994).

3. M.A. Meier, G. A. Hallock, H.Y.W. Tsui, R.D. Bengtson, "*The time domain riple probe method,*" submitted to Rev. Sci. Instrum.

Configuration Studies

The configuration studies program is directed to a study of the TEXT-Upgrade plasma equilibrium, shape, position control, and stability.

Equilibria

The primary diagnostic tools for this study are the complete set of B(z) and B(r) magnetic loops installed inside the vacuum vessel, combined with the tokamak PF coil current monitors. The primary theoretical modeling tools used are EFIT[1], an equilibrium code modified at Texas to include an iron core and more efficient routines for more rapid computation and portability[2] and PSICONT, a code that implements a single filament model. Additional diagnostics can also be in the models, such as the position sensing coils, the diamagnetic loops, density and temperature diagnostics. Figure 1 a) through c) shows the PSICONT equilibria and Figure 1 d) shows a preliminary EFIT reconstruction of a single null D-shaped discharge. These represent the four discharges in the TEXT Upgrade baseline configuration. Comparisons of plasma shape and position with other diagnostics, particularly H(alpha) camera imaging, soft x-ray array profile and FIR density measurements generally indicate good agreement.

Shape and Position Control

Plasma shape and position control is via a feedback system built around a high speed digital signal processor. The feedback sensors are moment coil sets located both inside and outside the vacuum vessel and the tokamak PF coil current sensors. The moment coil sets have of order 2 cm gaps in coverage at the corners of the vessel. During divertor operation some poloidal flux escapes detection and this introduces position errors. First order correction by summing the divertor coil current has reduced the size of this problem. A similar problem exists for the bias winding. The magnetic data is frequently and successfully benchmarked against the soft x-ray and FIR density profile data to ensure reliability.

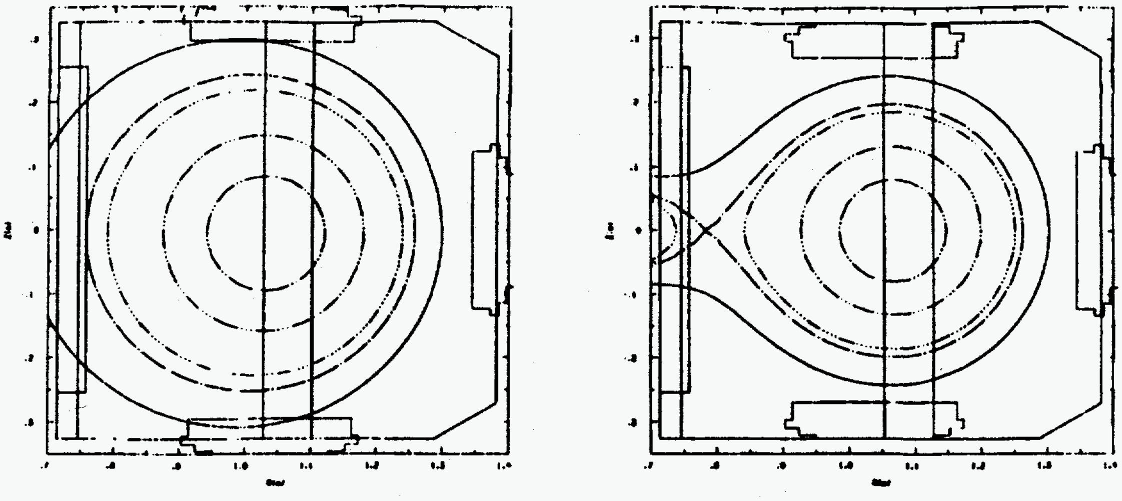
Stability

At best performance the system works extremely well, however control is limited by the response speed of the SCR controlled power supplies and by the vessel penetration times. As a consequence of these limitations position stability is marginal for certain diverted configurations. For circular limited discharges the plasma is both up-down and in-out unstable, the growth rate is hundreds of milliseconds and position control can be held to a few millimeters. Equatorial single null discharges are in-out unstable and up-down stable, the vertical field power supply has a response time of about 5 to 10 milliseconds and no serious control problems have been experienced. The single null D-shaped discharges are the most unstable, the problem is compounded by the requirement for a four quadrant radial field power supply. In recent studies, a chopper stabilized supply (on loan from General Atomics) was used to energize the divertor bias winding starting from before breakdown. The resulting asymmetric 'error field' allows the use of a simpler two quadrant radial field supply. This technique has the potential to greatly alleviate the radial field power supply requirements. At present, the response time of the HF supply (25 ms) severely limits the operating envelope available for single null D-shaped discharges. In spite of limitations, the single null D-shaped discharges have been used in successful experiments.

References

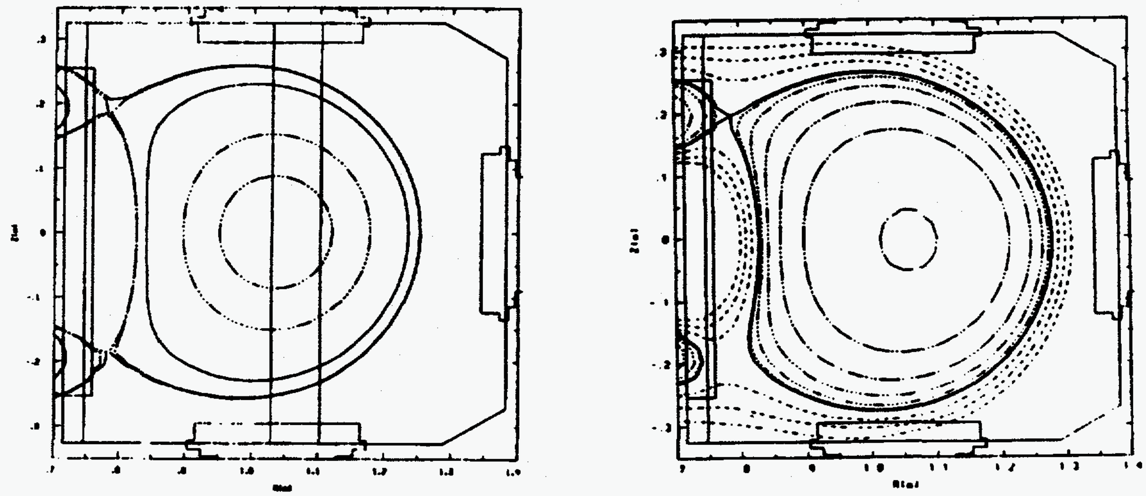
1 L. L. Lao, H. St. John, R. D. Stambaugh, et al., Nuclear Fusion 25, 1611 (1985).

2 E. R. Solano, G. H. Neilson, and L. L. Lao, Nuclear Fusion 30, 1107 (1990).



a) Limited Circular Discharge.

b) Equatorial Single Null Discharge.



c) Double Null D-Shaped Discharge.

d) Single Null D-Shaped Discharge.

Figure 1. Experimental Equilibria for Baseline TEXT-Upgrade Discharges

Improved Confinement in Tokamaks

Improved confinement modes, among which the H-mode is probably the most important, are essential to a tokamak fusion reactor as well as to intermediate experiments. The physics of these modes is therefore of great practical importance. Improved confinement modes also offer an invaluable contrast to the normal confinement regime that can indicate which factors are important in driving transport, the elucidation of which is the fundamental objective of TEXT. An H-mode on TEXT-U would then be a valuable asset that would immediately impact our entire program.

During the last year, one of the objectives of TEXT-U was the pursuit of H-mode. In preparation for this work, auxiliary heating systems were brought into operation, diverted configurations were developed, additional impurity control measures including graphite tiling, helium glow cleaning, solid target boronization and Li pellet injection were added to the customary pulsed discharge cleaning. By 23 July, we had failed to reproducibly obtain the "H" mode, although indications of improved confinement exist in some discharges. We are now embarked on a systematic search for the H-mode, and have begun by constructing a data base of results obtained with Ohmic, and electron cyclotron (ECRH) together with Ohmic, heated plasmas. The objective is to catalog the parameter space in which we operate TEXT-U, and to compare various parameters with existing scaling laws and theoretical predictions. We are especially interested in cataloging our "L" mode confinement properties in preparation for renewed "H" mode exploration. Only discharges with 400 kW ECRH are included, although 600 kW are routinely available.

Plasma shape

Figure 1 shows typical reconstructions for the poloidal cross sections for the two discharges in which H-mode was sought, together with the vacuum vessel, the TiC coated C limiters (discrete poloidal rails at top, bottom and outside, a segmented toroidal belt at the inside) and the toroidal field corresponding to the ECRH deposition locations.

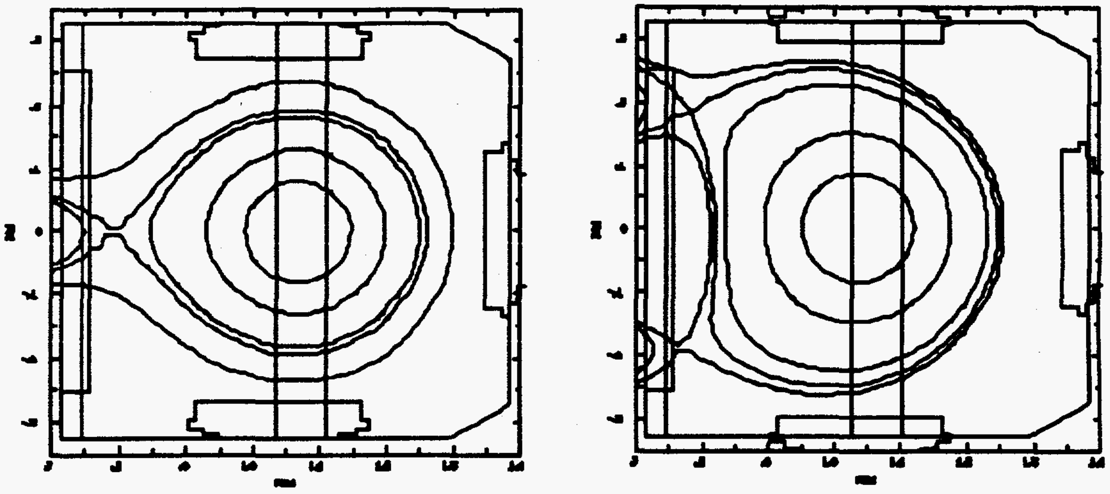


Figure 1. On the left is a reconstruction of a plasma with an inner X-point. On the right is a reconstruction of a plasma with an upper X-point, in the grad B direction. Only those flux surfaces at and outside the separatrix are accurate. The vertical lines show the location of the toroidal field corresponding to the ECRH deposition locations for 56 (larger major radius) and 60 GHz (smaller major radius) ECRH.

External control parameters

The quantities varied in this study include plasma position, toroidal field, plasma current, and density. The ranges and implications of each in TEXT-U are described in this section.

Plasma position. Quantified as the current centroid position, XC and YC in the usual x-y coordinates used for the poloidal cross section. Position partly determines plasma shape, and together with toroidal field B_ϕ the ECRH deposition placement with respect to the plasma center. Variation of XC must be interpreted with with care as values XC < 0 increase the separatrix to top, outer and bottom limiter and wall separation (conducive to H-mode) but decrease the X-point to wall separation (deleterious to H-mode).

Toroidal field. This determines the ECRH deposition location within the vessel. The value generally quoted is at R = 1.05 m. The toroidal field for experiments cluster about two values with variations for edge or central heating.

$\approx$ 1 T (for second harmonic X-mode heating).
$\approx$ 2 T (for first harmonic O-mode heating).

Plasma Current. This is restricted by the safety factor. Smaller values increase the separation between the separatrix and the top, bottom and outer limiters. Typical values for experiments are

$\approx$ 100 kA at $\approx$ 1 T
$\approx$ 200 kA at $\approx$ 2 T

Density. This is restricted to ensure that cut off of the ECRH waves does not occur. Typical values used are

$<\approx 1\times10^{19}m^{-3}$ at $\approx$ 1 T
$<\approx 2\times10^{19}m^{-3}$ at $\approx$ 2 T

Larger values have been attempted, particularly when edge heating at the outer equator is attempted. To date all discharges studies have been produced in deuterium.

Operational Space.

In terms of the current H-mode scaling laws (for example, H-mode Database Working Group, 20th EPS, Part 1, I-15 (1993).), the operational space studied is described in figure 2. This figure shows that the power per unit surface area is well above that thought to provide, under optimum condition, the H mode, although we have not yet consistently observed this mode.

Improved confinement discharges

Some indications of improved confinement have been observed. During the ECRH pulse in these isolated discharges, the stored energy increases along with the electon density while the D_α signal decreases. At this time, the discharges cannot be consistently produced.

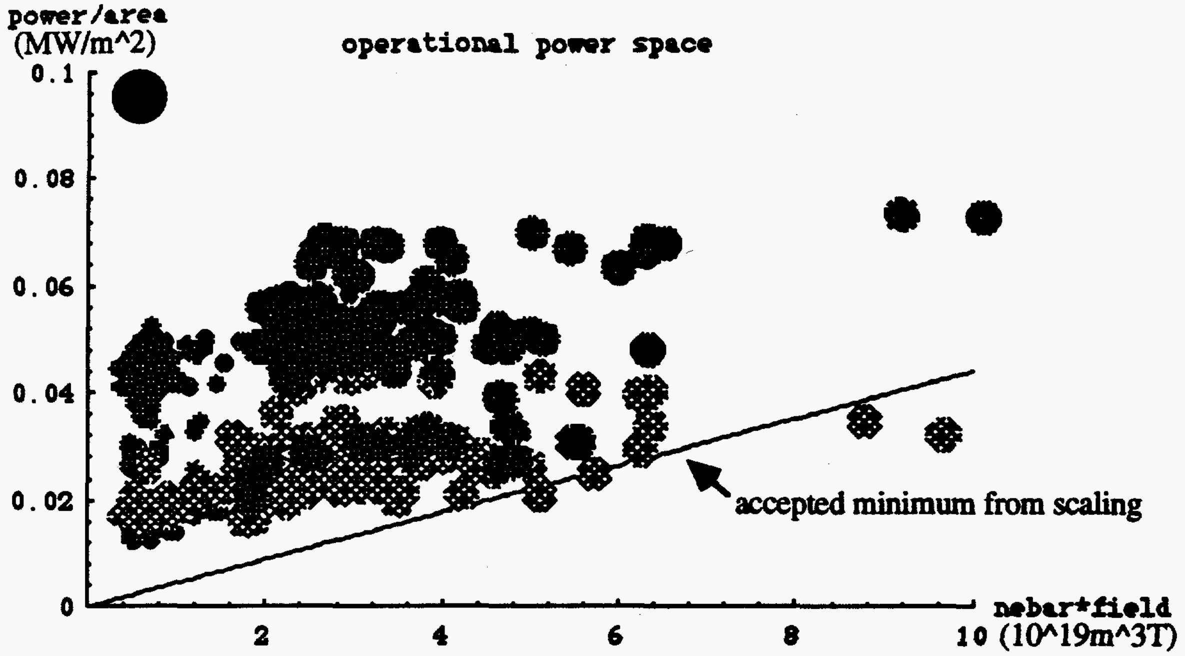


Figure 2. The operational space of power per unit toroidal surface area (MW/m^2) and density (units of 10^{19} m^{-3}) times toroidal field (T). The straight line represents the value found to be the minimum necessary to obtain H mode in other tokamaks. Only data with up to 2 gyrotron operation is shown.

Plans for the coming year

- Seek a consistent improved confinement regime with ECRH
- Explore discharges with a larger separatrix to material surface distance
- Develop a consistent, effective vessel wall preparation
- Analyze 3 gyrotron data and add to the data base
- Develop the diamagnetic loop as a standard diagnostic

Electron-Cyclotron Heating Physics

The aims of this program are to exploit the localized heating capability of electron cyclotron waves to study turbulence and transport. Most of the effort this year was spent in bringing all three of our gyrotrons into operation. That work is at least recorded in earlier sections. The research topics described in the proposal are being pursued with one exception. Based upon these findings and our limited resources, we no longer plan to pursue high-power microwave scattering as a method for measuring internal magnetic fluctuations. Scattering of the waves by density fluctuations will still be investigated as part of our ongoing efforts to maximize localization of the ECH power deposition.

All of our milestones have been achieved in the development of a new use of ECH for transport diagnosis.

1) 170 kW of ECH was used to locally generate a population of superthermal electrons in the core. These superthermals could be grossly characterized by $n_e' = 0.002 n_e(0)$ and $T_e' \sim 10 T_e(0)$, where $n_e(0) = 1.5\times10^{13}\,\mathrm{cm}^{-3}$ and $T_e(0) = 1.5\,\mathrm{keV}$ are the parameters of the thermal population. The superthermal population was observed from the spectrum of its electron-cyclotron emissions, as viewed vertically through the tokamak volume and as shown in Figure 1.

2) In accordance with Fokker-Planck modeling, the superthermal distribution has been confirmed to have strong dependencies on the parameters of the thermal distribution, the ECH power deposition, the inductive drive, and radial diffusive processes.

3) By measuring all parameters of the experiment exclusive of the diffusion, we have been able to determine the diffusion upon comparison of the measured spectra with the spectra based upon the Fokker-Planck simulations. Furthermore, when assuming a diffusion coefficient $D \propto v_{\|} (\delta b/B)$ due to magnetic turbulence, we find agreement between the measured and simulated spectra for $(\delta b/B) \sim 3\text{-}5\times10^{-5}$. This level of magnetic turbulence, although within the range expected, is too small to cause the *thermal* transport observed in TEXT-U. This result is consistent with

previous investigations which showed that electrostatic transport could account for most of the thermal transport.

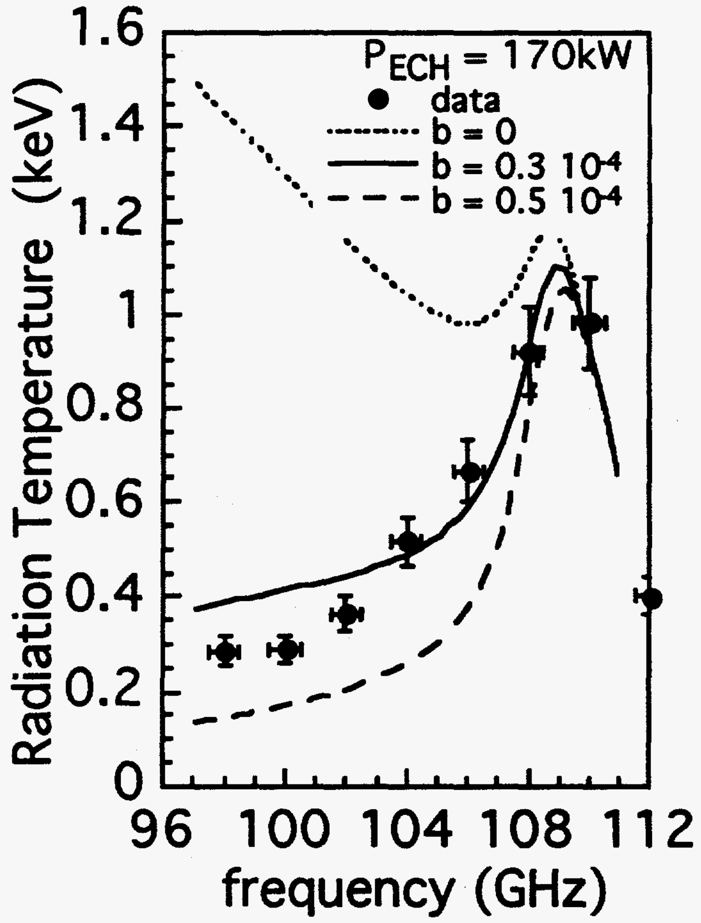


Figure 1: A comparison of the experimental and simulated ECE spectra that shows the strong spectral dependence on the level of magnetic turbulence.

Plans for the coming year

- Conduct studies of turbulence modification, MHD suppression, and startup assistance with ECH as described in the grant renewal.

Studies of turbulence modification will be emphasized during the coming year, with milestones including:

- A description of the ECH-related mechanisms for turbulence modification; including both local and non-local mechanisms.
- A determination of whether there is a heat pinch during ECH in TEXT, and it's relationship (if any) to turbulence-induced transport.

Publications

1. *Refraction and Absorption Measurements of a Focused ECH Beam*, D.R. Roberts, D.C. Sing, and R.F. Steimle, Nuclear Fusion 33, 11 (1993) 1707.
2. *Vertical Viewing of Electron-Cyclotron Emissions for Diagnosing Fast Electrons in TEXT-U,* D.R. Roberts, R.F. Steimle, G. Giruzzi, G. Cima, and C. Watts, *to be published in* The Review of Scientific Instruments.

Edge Physics and Impurity Studies

The edge physics/impurity studies program is intended to investigate the properties of turbulence and transport in the plasma periphery and to improve the physics understanding of them. Impurity transport studies will concentrate on the periphery but not to the exclusion of the confinement region.

While the goals and most of the activities of the program are unchanged, there is one major addition. At the time of submission of the three year proposal, the TEXT divertor was not operating, it was not clear what our degree of success would be, and we were conservative in proposing divertor experiments. The TEXT divertor has been a great success. Some preliminary experiments were interpolated into our program to lay a foundation for future divertor experiments in the SOL.

This part of the report covers progress in these areas

Divertor studies including code validation
Turbulence drives
Active turbulence control
Improved analysis techniques
Asymmetries in the SOL
Diagnostics including familiar Langmuir probes, tile probes, and spectroscopic diagnostics for fluctuation measurements

Divertor Studies

The goal of these initial experiments was simply to determine whether the TEXT divertor displays typical divertor behavior and whether it can be used for code validation. In the first divertor experiments,[1,2] particle balance in diverted discharges was compared with that in limited discharges. The plasma parameters $n_e(r)$, $\phi(r)$, $T_e(r)$ were measured in the scrape-off layer and in the plasma periphery at one poloidal location and mapped onto the rest of the plasma by assuming constancy on flux surfaces. Emission from neutral hydrogen was measured throughout the plasma. The particle source and then the global particle confinement were inferred from these measurements using a 3-D neutral transport simulation.

When compared with the limited discharge, recycling is clearly moved outside the last closed flux surface by the divertor. At least by this measure, the TEXT-U diverted plasmas behave as expected. The diverted plasma displays better particle confinement and steeper edge gradients (see figure 1) than the toroidally limited plasma. This may be due to modified recycling, though experiments will continue to understand the impact of recycling on confinement.

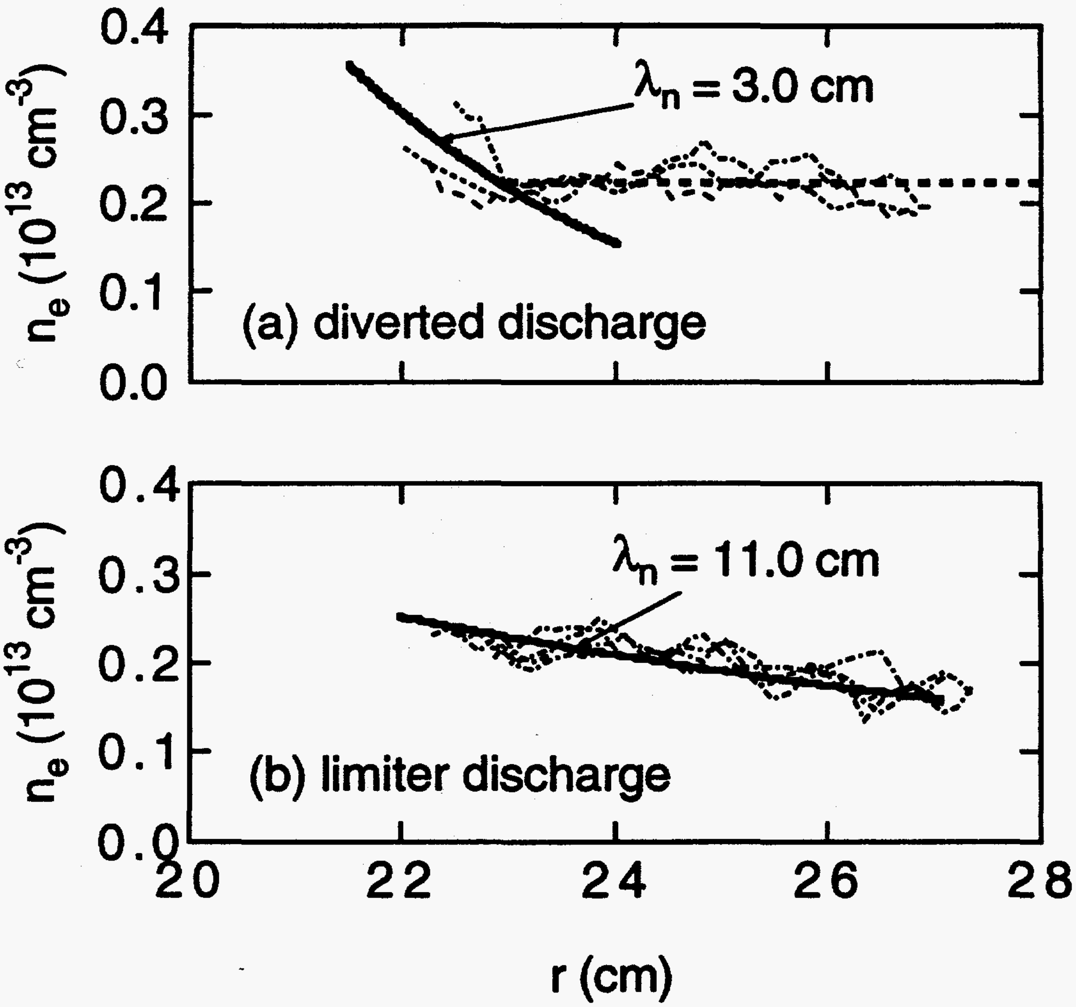


Figure 1. Example of SOL data taken in diverted and limiter discharges.

Attempts to simulate neutral measurements with the EIRENE[3] neutral transport code were successful. EIRENE was chosen for use here because it is used for divertor studies in present day machines and for projections to ITER. An example of comparison of simulation and measurement is in figure 2. Some details such as an electron-ion side asymmetry were not reproduced. These could be due to inadequate spatial resolution in the $n_e(r)$, $T_e(r)$, or $T_i(r)$ data used in the simulation or the asymmetry could indicate a deficiency in the simulation model. The fact that we can say this much demonstrates that we can do code validation on the TEXT divertor provided we improve our diagnostics. Diagnostics improvement is underway as indicated below. So that we can move beyond neutral transport simulation to combined neutral transport simulation and plasma simulation, we are acquiring access to the B2/EIRENE code.

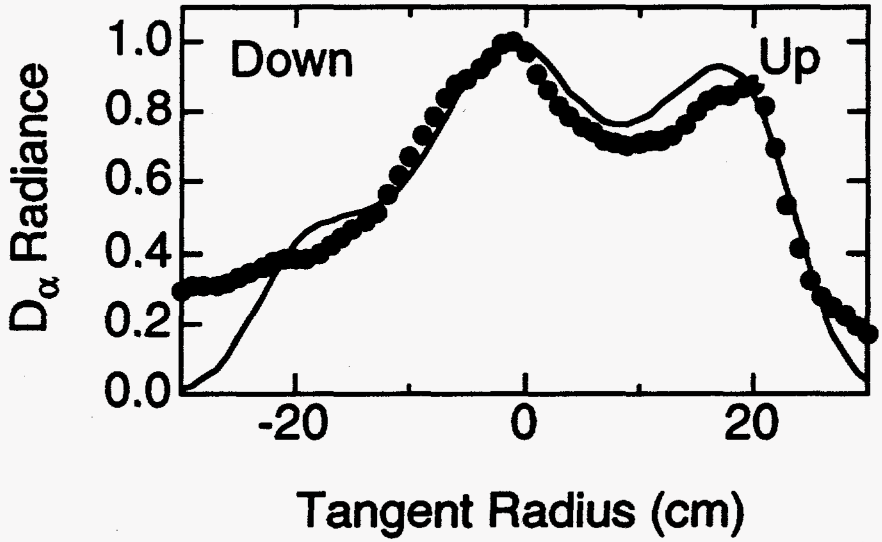


Figure 2. Comparison of simulation and measurement of D_α Radiance for a single null discharge as shown in Fig. 1a of the Improved Confinement section.

<u>Plans for the next year</u>

- Improve SOL diagnostics via tile probes and spectroscopic measurements of T_i
- Acquire B2/EIRENE for simulation of the plasma edge.
- Begin studies of impurity behavior in the divertor SOL

References

1. William L. Rowan, Roger D. Bengtson, X. Bonnin, K. W. Gentle, P. H. Edmonds, P. D. Hurwitz, P. E. Phillips, K. Schroder, E. R. Solano, D. J. Storek, and J. R. Uglum, Proceedings of the 21st European Conference on Controlled Fusion and Plasma Physics, Montpellier, France, June 1994.
2. William L. Rowan, R. D. Bengtson, X. Bonnin, P. H. Edmonds, P. D. Hurwitz, E. R. Solano, H. Y. W. Tsui, J. R. Uglum, and A. J. Wootton, to be published in Journal of Nuclear Materials.
3. D. Reiter, The EIRENE Code; User's Manual, KFA Julich Report 1947 (1984)

Turbulence drives

Earlier work[1] demonstrated that the scaling of turbulence and turbulence induced transport in the edge plasma of TEXT did not depend linearly upon the usually assumed free energy sources such as the local density and temperature gradients. Neither the fluctuation levels $\tilde{n}_e/n_e$ and $\tilde{\phi}_f/T_e$ nor the fluctuation driven transport $\Gamma_{\tilde{n}\tilde{\phi}}$ depend in a strong manner on the gradient drives ρ_s/L_n and ρ_s/L_T alone. There is insufficient evidence to rule out a pressure gradient drive. However, the radial variations of these parameters do not appear to support a pressure drive without additional parameters. There was some agreement with drift wave turbulence theory in that the fluctuation level $\tilde{n}_e/n_e \approx B_{\Phi}^{-(0.5-1)}$, $\bar{k}_\theta \approx \rho_s$, the inverse gyro frequency, and $\Gamma_{\tilde{n}\tilde{\phi}} \approx B_{\Phi}^{-2\pm1}$

With the obvious deficiencies of local gradient models as indicated above, we have looked at the importance of radiation and sheath instabilities as turbulence drives. Initial experiments which changed the boundary conditions at the plasma/sheath/limiter interface from a conducting to insulating boundary indicated a change in floating potential turbulence level by a factor of order 2. These results are preliminary, but strongly indicate the importance of a sheath instability in driving plasma turbulence. The physics of the sheath instability in the SOL of TEXT-U should be very similar to that on the divertor strike plate in large tokamaks.

We have attempted to detect a thermal instability drive in the edge plasma by comparing local probe measurements of temperature fluctuations with chord integrated measurements of radiated power. Cross correlation techniques were used to extract the portion of the radiation signal from the probe location. Initial experiments demonstrated a high coherence between the temperature fluctuations and radiated power at frequencies below 50 kHz. Future work will use improved circuitry with a frequency response up to 350kHz and will avoid low order rational q-surfaces.

We have, in collaboration with J. Q. Dong and C. W. Horton of the IFS, looked at turbulence driven by the shear in mass flow velocity parallel to the magnetic field. Figure 1 shows radial profiles of the parallel flow Mach number, the normalized velocity shear, and the poloidal phase velocity. The experimental results support the interpretation that the poloidal shear flow is generated through the turbulence driven by parallel sheared plasma flow.

Plans for the coming year

- Look for evidence of the thermal instability with improved frequency response for the radiated power measurement.
- Look for evidence of the thermal instability after simplifying the radiated power spatial structure in the edge by enhancing one impurity either by adjusting the edge temperature with ECH or by selective addition of impurities

References

1. T. L. Rhodes, et al. Nuclear Fusion 33, 1147 (1993).

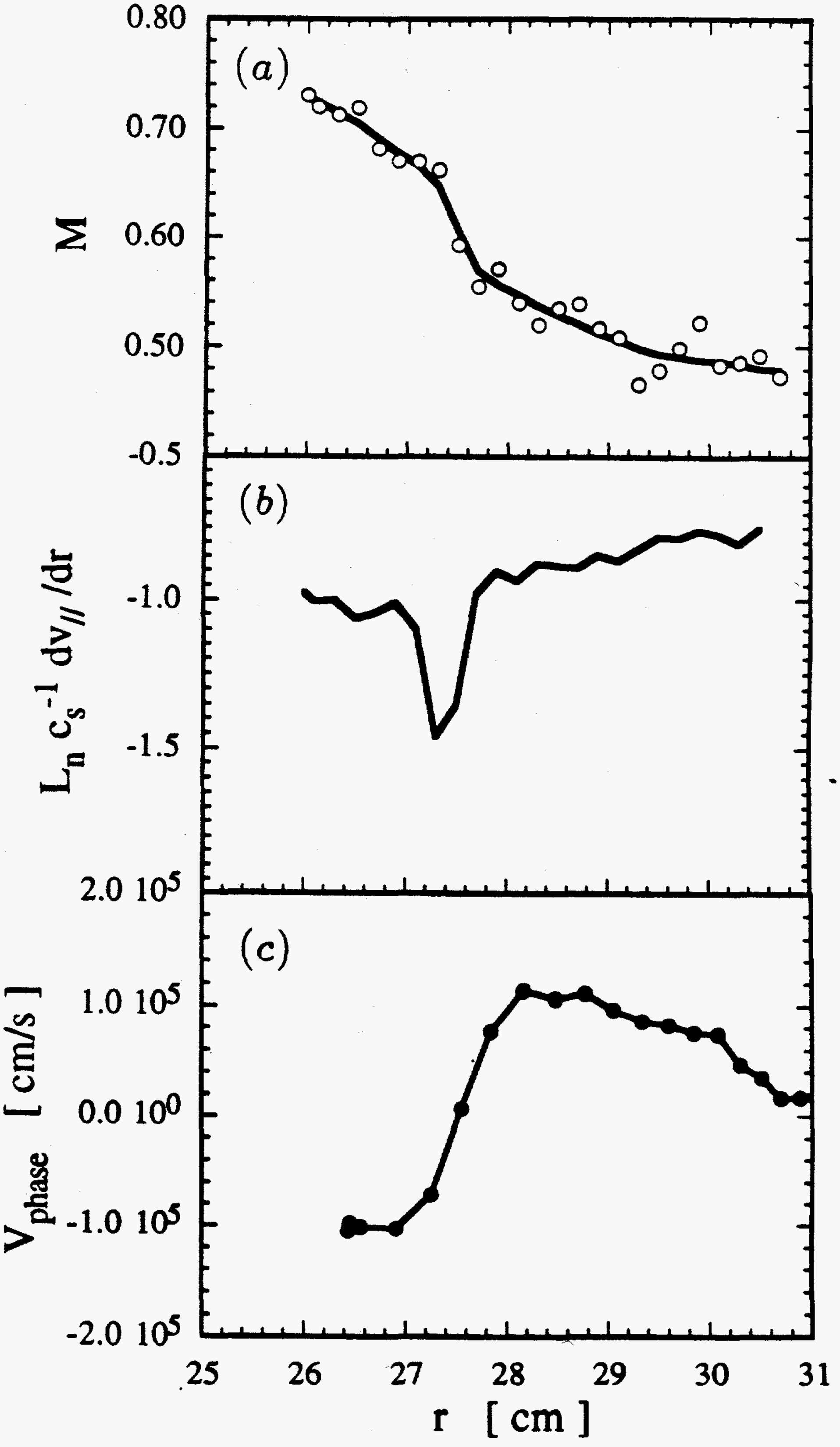

(a)
M
0.80
0.70
0.60
0.50
-0.5
(b)
$L_n c_s^{-1} dv_{//}/dr$
-1.0
-1.5
2.0 10^5
(c)
V_{phase} [cm/s]
1.0 10^5
0.0 10^0
-1.0 10^5
-2.0 10^5
25
26
27
28
29
30
31
r [cm]

Fig. 1

Improved analysis techniques

We have coupled the Khoros visual programming environment to the TEXT data archive. The Khoros system was chosen because it is publicly available; it is specifically designed for digital signal processing and data visualization; and because the Khoros environment is programmable. It is expected that this advanced software environment will greatly increase the ease of incorporating new analysis techniques into our data reduction.

A bispectral analysis technique has been used as a diagnostic tool with our wave launching experiments to investigate the turbulent plasma dynamics. Waves were driven in the plasma with a launcher and detected 10 m down a flux tube on a Langmuir probe. The experimental results show that the launched waves interact with the intrinsic fluctuations both linearly and non linearly.

Asymmetries in the SOL

We have analyzed the up-down asymmetry in the plasma potential of TEXT-U. The presence of this asymmetry suggests that the related steady state convection could be significant. However, the dependence of this asymmetry on density suggests that the flux surface averaged particle transport is not important except a low densities.

Probe development and understanding

With the motivation of understanding Langmuir probe characteristics in a flowing, magnetized, bounded plasma with gradients, we are analyzing IV characteristics of a Langmuir probe taken in the SOL at a low frequency ($f < 50$ kHz). Improvements in electronics should allow complete IV probe curves at frequencies high compared to turbulence in the plasma. In addition a new Langmuir probe technique based on the triple probe method has been developed to provide simultaneous measurement of plasma temperature, potential, and density with the temporal and spatial resolution required to accurately characterize plasma turbulence.

Diagnostic: Tile Probes

Probes are sometimes installed in the divertor tiles to measure the parameters of the plasma flowing onto the divertor tiles. This is a particularly important complement to existing SOL measurements measurement as it provides a boundary value for the spatially varying SOL parameters such as density and temperature. Tile probes will significantly enhance our knowledge of the SOL in diverted discharges. The challenges of probe tile design are to produce a probe that is resistant to high heat flux inherent in its location and that provides signals that are susceptible to straightforward interpretation.

A small set of tile probes was installed in March 1994 to test our tile probe design and to determine whether tile probes would be useful. The probes tips are pyrolytic graphite and have hemispherical tips that extend above the surface of the TiC coated graphite tiles. These have performed well and have provided the opportunity to develop biasing schemes and to look at frequency response. Based on these experiences, a complete set will be installed in late September.

Plans for the coming year

- Install a complete set of tile probes, learn to analyze the data, and incorporate into divertor studies

Diagnostic: H_α fluctuations

We have continued to develop H_α fluctuation diagnostics to complement the Langmuir probe diagnostic by extending fluctuation measurements to otherwise inaccessible regions of the plasma. These diagnostics may be especially important in next-generation devices such as TPX if high edge temperatures and densities prevent the use of probes. As noted repeatedly, this diagnostic is intended as an ELM diagnostic. It was developed using available high frequency signals (turbulence). The advances in analysis will improve our ability to do elm work, have resulted in a new turbulence diagnostic, and have allowed examination of analysis techniques for diagnostics.

The H_α emission is detected with high frequency imaging arrays.[1] The most interesting turbulence information is extracted by statistical comparisons among the signals from the image elements. In initial studies, the observed high frequency H_α emission was simulated using direct measurements of the turbulence with probes.[2] We found generally good agreement between the simulated and measured turbulence characteristics. In these studies, we verified that there is significant spatial localization as we had initially suspected. Even so, this diagnostic requires the use of analysis techniques for chord integrated turbulence measurements in regions where the turbulence has strong spatial nonuniformities, such as near the shear layer . In the most recent work,[3,4] we obtained a spatial Fourier transform of the turbulence which shows both positive and negative features in k-space. In this way, the contributions from each side of the shear layer can be considered separately. The Fourier technique requires that the imaging array have many closely elements. So, we have developed a method which uses the data from just 3 elements to model the S(k) spectrum as a sum of two modes (Gaussian features) in k-space. This can also be used to estimate the relative importance of the shear layer in H_α measurements and directly addresses the chord integration problem that occurs in other diagnostics such as HIBP.

Plans for the next year

- Compare turbulence on the low field side (LFS) and on the high field side (HFS) of a double null discharge. In other devices, the characteristic lengths differ on the LFS and the HFS. Is this due to differences in turbulence? This is a stringent test for this diagnostic. The physics is interesting too.

References

1. P. D. Hurwitz, B. F. Hall and William L. Rowan, Rev. Sci. Instrum. 63 (10), 4614 (1992).
2. P. D. Hurwitz, William L. Rowan and G. X. Li, presented at the 9th APS Topical Conference on Atomic Processes in Plasmas, September 1993, San Antonio, Texas.

3. P. D. Hurwitz, William L. Rowan and G. X. Li presented at the 35th Annual Meeting, APS Division of Plasma Physics, November 1993, St. Louis, Missouri.
4. P. D. Hurwitz and William L. Rowan, to be published in Rev. Sci. Instrum.

Impurity transport

We have found correlations between radial impurity transport and turbulence,[1] but impurity flows within flux surfaces were found to be neoclassical.[2] Before continuing studies of turbulence and impurity transport, it is reasonable to determine whether other impurity behavior might be neoclassical. One notable impurity phenomenon in the SOL and in the plasma periphery is the poloidal asymmetry. In TEXT, the asymmetries were measured for CII-CV and OII-OV.[3] In a series of experiments, the impurity source was modified so that the source driven asymmetry could be separated. The part of the asymmetry not due to sources has a shape as predicted by neoclassical theory, but the magnitude is too small. It appears that this discrepancy can be made up by asymmetries in density and temperature. Thus, except for rather small effects, it is in fact only the radial component of the impurity transport that might be due to turbulence.

Plans for next year

See Divertor Studies (above)

References

1. W. Horton, and W. Rowan, Physics of Plasmas 1, 901 (1994).
2. William L. Rowan, A. G. Meigs, E. R. Solano, and P. M. Valanju, Phys. Fluids 5, 2485 (1993).
3. R. A. Collins, *An Investigation of the Impurity Emission Asymmetries in TEXT-U*, Ph.D. Dissertation 1994, The University of Texas.

Active Probe

Specific aims: The primary purpose of the Active Probe experiment is to explore means of modifying (both increasing and decreasing) tokamak edge turbulence by use of driven Langmuir probes. The principle technique used is feedback control in which fluctuations in the plasma edge are sampled and amplified, a controlled phase shift and bias are added, and this signal is used to drive a second ("driver") edge probe. The modification of the turbulence should affect the local particle and heat transport; global transport effects will be explored. This primary goal has not been changed. Results described below point to a secondary, diagnostic use of the Active Probe experiment in tracing magnetic field lines. This could prove useful in determining the magnetic surface structure near the separatrix or in island structures.

Results: Active probe research in the past year has focused on three areas

1. characterization of the propagation mode for the signal generated at the probe. In the proposal, this was explicitly described as the distinction between field line and non-field line propagation.
2. determination of the importance of the dc bias which was used to linearize the driver probe V-I characteristic. This was required to remove uncertainties in interpretation of previous data
3. measurement of non-linear coupling of the drive signal to the background turbulence as a possible key to improved physical understanding of both turbulence and the active probe.

Characteristics of Signal Propagation

In order to explore the physics of the coupling of the Active Probe to the plasma, we launch a single frequency at 30 kHz without feedback. We find that the probe is, in fact, driving a current which travels down field lines. This current has been observed to be collected on the limiters. During a plasma current scan, we find a signal on poloidally-aligned magnetic pickup coils that is consistent with the current flowing down field lines as defined with field-line tracing codes.

The fact that the current follows a field line suggests a possible diagnostic application of the active probe. The signals driven by a probe (e.g., in a divertor tile) can tag a given field line and magnetic coils can then be used to find the position of the field line in a non-perturbing fashion. This could find application in tracing a field line through an ergodic region or through a divertor x-point (locating the x-point experimentally) in a non-perturbing way.

Effects of Probe Bias

During previous feedback experiments, the probes were dc biased in order to drive more current from the probes and in order to operate the driving probe in a relatively linear region of its V-I curve. It was believed from our previous results on biased electrode experiments that the 50V bias was insufficient to alter the fluctuations without the application of feedback. However, those experiments were done with a significantly different biased probe. Recent comparisons of fluctuation spectra taken with and without bias on the probe used for the active probe experiments have shown that in some cases up to a 40% decrease in amplitude at frequencies less than 30 kHz has been seen near the driver due to bias alone. Although this is of the same order as the feedback effect, the previous results showing decreases of fluctuations with feedback were not entirely due to bias.

Figure 1a shows the floating potential on a sensor probe located 12 meters away (along a field line) during a current ramp, which sweeps the field line past the sensor probe. For a 50V bias applied to the driver, we see a change of 15 V in bias from the background floating potential during the ramp, which occurs over a distance comparable to a poloidal correlation width. In figure 1b, we see a change in the fluctuations also (not as large as with the near sensor probes), with a minimum fluctuation level occurring at the time of maximum bias and larger fluctuation amplitude both before (~30% over a 30 kHz band) and after (broadband smaller change) Ip has swept the connecting field line past the sensor probe.

The similarity of conditions under which the bias only experiments decrease the local fluctuations to conditions found in a biased electrode H-mode (i.e., potential gradients, current flows) suggests the possibility of a common origin. If this is the case, research on this "mini-H mode" could shed additional light on the H-mode transition and H-mode transport.

Non-Linear Coupling

A conditional sampling technique has been used in conjunction with standard correlation analyses to investigate the coupling of a launched 30 kHz wave with naturally occurring waves in the plasma. Significant coupling has been found to MHD at 8 kHz and to high frequency turbulence at 200 - 500 kHz. This will allow us to probe into the dynamics of the edge turbulence (cascading, etc.).

References

1) T. Uckan, et al., in *Proceedings of the 20th EPS Conference on Controlled Fusion and Plasma Physics, 1993,* (European Physical Society, 1993), Vol. 17C, Part II, p. 635;

2) B. Richards, et al., Phys. Plasmas **1**, 1606 (1994)

3) P.E. Phillips, et al., J. Nucl. Mater. **145-147**, 807 (1987); Taylor R.J. et al., in *Plasma Physics and Controlled Nuclear Fusion Research 1990,* Washington, D.C. (IAEA, Vienna, 1991) Vol. 1 4634

4) Tsui, J.Y.W. et al., to be published.

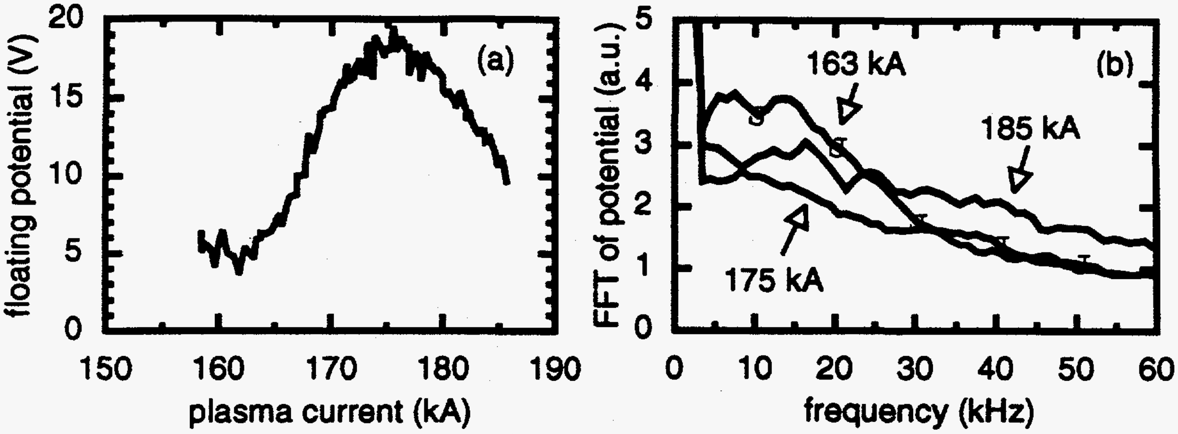


Figure 1 a) Floating potential on far sensor probe as a function of plasma current during a current ramp. b) Floating potential fluctuations at three times during the ramp showing the lowest fluctuation level at the time of maximum potential.

<u>Plans for the coming year:</u>

- Optimize feedback effects through variation of phase shift and gain and look for global changes in particle confinement
- Test utility as a diagnostic by mapping field lines in a diverted discharge

Edge Physics/Impurity Studies Publications

R. A. Collins, An Investigation of the Impurity Emission Asymmetries in TEXT-U, Ph.D. Dissertation 1994, The University of Texas.

G. X. Li, R. D. Bengtson, H. Lin, M. Meier, H. Y. W. Tsui, and A. J. Wootton, " The plasma potential asymmetry and steady state radial convection in TEXT-U tokamak," To be published Nuclear Fusion.

P. J. Catto, J. R. Myra, R. D. Bengtson, and A. J. Wootton, "Modeling and simultaneous sawtooth measurements of the thermal and energetic electron diffusivities from the Texas experimental tokamak," Phys. Fluids B 5, 125 (1993).

A. Yu. Dnestrovskij, R. D. Bengtson, Yu. Karzhavin, and A. Ouroua, "A method for neutral spectra analysis taking ripple-trapped particle losses into accoutnt," To be published, Rev. Sci Instrum.

J. Q. Dong, W. Horton, R. D. Bengtson, G. X. Li, "Momentum-Energy transport from turbulence driven by parallel flow shear," To be published Phys. Fluids.

P. D. Hurwitz and William L. Rowan, to be published in Rev. Sci. Instrum.

M. A. Meier, G. A. Hallock, H. Y. W. Tsui, R. D. Bengtson, "The time domain triple probe method," Submitted to Rev. Sci. Instrum.

T. L. Rhodes, Ch. P. Ritz, R. D. Bengtson, "Scaling of far edge plasma turbulence and fluctuation induced particle transport in the TEXT tokamak," Nuclear Fusion **33**, 1147 (1993).

B. Richards, T. Uckan, A. J. Wootton, B. A. Carreras, R. D. Bengtson, P. Hurwitz, G. X. Li, H. Lin, W. L. Rowan, H. Y. W. Tsui, A. K. Sen, J. Uglam, "Modification of tokamak edge turbulence using feedback," Phys. Plasmas, 1, 1616 (1994).

B. Richards, et al., in Proceedings of the 21th EPS Conference on Controlled Fusion and Plasma Physics, 1993, Montpellier, (European Physical Society, 1994).

William L. Rowan, R. D. Bengtson, X. Bonnin, P. H. Edmonds, P. D. Hurwitz, E. R Solano, H. Y. W. Tsui, J. R. Uglum, and A. J. Wootton. "Particle Balance i diverted plasmas in TEXT-U," to be published J. Nucl. Matl.

William L. Rowan, Roger D. Bengtson, X. Bonnin, K. W. Gentle, P. H. Edmonds, P. D. Hurwitz, P. E. Phillips, K. Schroder, E. R. Solano, D. J. Storek, and J. R. Uglum, Proceedings of the 21st European Conference on Controlled Fusion and Plasma Physics, Montpellier, France, June 1994.

H. Y. W. Tsui, R. D. Bengtson, G. X. Li, B. Richards, T. Uckan, J. Uglum, and A. J Wootton, "Wave launching as a diagnostic tool to investigate plasm turbulence," To be Published Rev. Sci. Instrum.

H. Y. W. Tsui, A. J. Wootton, J. D. Bell, R. D. Bengtson, D. Diebold, J. H. Harris N. Hershkowitz, C. Hidalgo, J. C. Ingraham, S. J. Kilpatrick, G. X. Li, H. Lin, D M. Manos, M. A. Meier, G. M. Miller, C. P. Munson, J. Pew, S. C. Prager, Ch. P Ritz, A. Rudyj, K. F. Schoenberg, J. Sorensen, T. Tanaka, T. Uckan, and P. G Weber, "A comparison of edge turbulence in tokamaks, stellarators, an reversed-field pinches," Phys. Fluids B 5, 2485 (1993).

T. Uckan, B. Richards, A. J. Wootton, R. D. Bengtson, B. A. Carreras, G. X. Li, P Hurwitz, W. L. Rowan, H. Y. W. Tsui, J. R. Uglum, and D. Winslow, "Feedbac control and stabilization experiments on the Texas Experimental tokama (TEXT)." to be published J. Nucl. Matl.

P. M. Valanju. L. Durriapah, R. D. Bengtson, Y. Karzhavin, A. Nitikin, "Initia results from a charge exchange q-diagnostic on TEXT-U," To be published Rev. Sci. Instrum.

Central Turbulence and Transport

Experiments involving "Central Turbulence and Transport" were categorized in our grant renewal document (April, 1993) under the headings "Mode Identification, "Electrostatic Transport," "Electromagnetic Transport," and "Turbulent Drive Studies." Results from last year will now be presented following this organizational structure.

I. Mode Identification –

Most of the past year was spent commissioning the various interior turbulence diagnostics, now including beam-emission spectroscopy (BES) and electron cyclotron emission (ECE) correlation radiometry in addition to the upgraded heavy-ion beam probe (HIBP) (FIR scattering and phase-contrast imaging were not operational during this period). Initial data from these diagnostics will be addressed individually below, and then the implications of the totality of the data will be summarized.

A. Beam-Emission Spectroscopy (BES)

An eight-channel BES system has been installed and operated to measure density fluctuations in the edge and outer core. The system images the TEXT-U diagnostic neutral beam (DNB) operated in He to distinguish beam emission from the strong edge hydrogen emission. The system has a poloidal spatial resolution of ~ 0.6 cm (FWHM) and a radial resolution of ~ 1.5 cm. Due to the available viewing geometry, only the lower, central region of the plasma (r/a $\gtrsim$ 0.7) can be accessed at present.

Interior to the outermost closed flux surface, the fluctuation spectra are observed to be bimodal with a low-k feature ($\langle k_\theta \rangle \rho_S \approx 0.1$) propagating in the ion diamagnetic direction and a high-k feature ($\langle k_\theta \rangle \rho_S \approx 0.2\text{-}0.3$) propagating in the electron diamagnetic direction, as in Fig. 1. The average phase velocity in the laboratory frame, $2\pi \langle f \rangle / \langle k_\theta \rangle$, of the ion mode is ~ -1.5 km/s while that of the electron mode is ~ 3 km/s.

The amplitude of the low-k ion mode is found to be a strong function of the plasma density. The mode is virtually absent below

$\bar{n}_e \approx 1.5 \times 10^{19}$ m^{-3} and becomes increasingly prominent at higher densities. In addition, it is strongest near the plasma edge. This observation, along with the fact that the turbulence in the scrape-off layer (SOL) also propagates in the ion diamagnetic direction (due to reversed E × B Doppler rotation) initially raised concern that this ion mode was the residue (i.e., carried in via beam attenuation/modulation) of the SOL fluctuations. This was found *not* to be the case because of the absence of any correlation between the emission from an interior volume and that from a volume in the SOL.

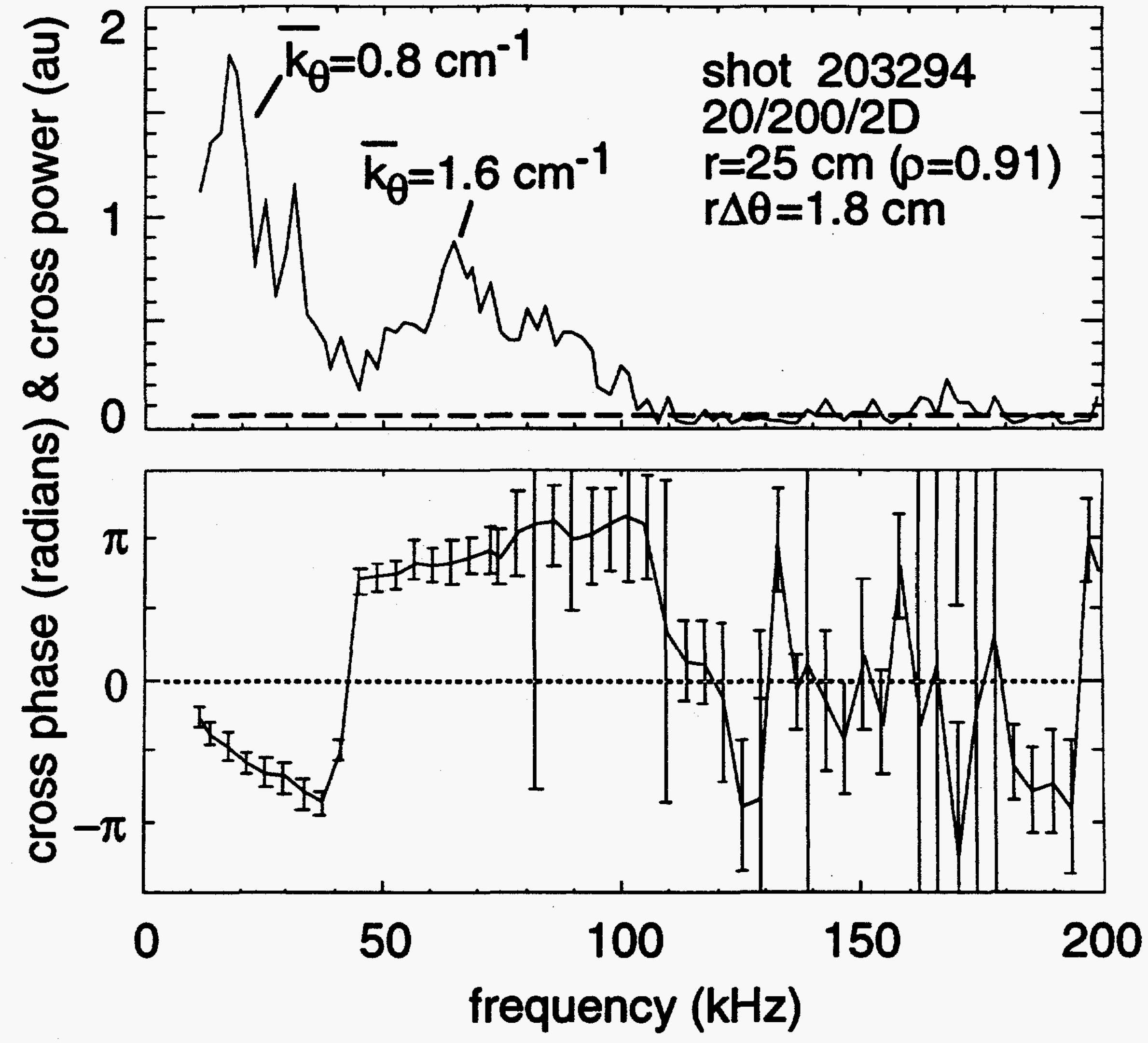


FIG. 1. Cross-power and cross-phase of emission (density) fluctuations measured by BES from two emission volumes at r/a ~ 0.91 and separated poloidally by 1.8 cm. Plasma condition: 2.0 T / 200 kA / 2 × 10^{19} m^{-3} / D.

B. 2-MeV Heavy-Ion Beam Probe (HIBP)

During the past year, the heavy-ion beam probe research team has succeeded in running a beam up to 1.8 MeV and installed and begun to calibrate the new 2-MeV electrostatic energy analyzer. During this calibration phase, preliminary measurements have been conducted during a variety of limiter and diverted discharges. Initial measurements of density fluctuation level $\tilde{n}/n$, electrostatic potential ϕ, and interior density fluctuation correlation measurements have been made using the new analyzer. We must stress that these results are preliminary.

Examples of phase and crosspower measurements are shown in Fig. 2. These measurements are from a two-point correlation in a 2.11 T / 160 kA / 1.5×10^{19} m^{-3} deuterium upper-X-point diverted discharge on TEXT-U. The sample volumes are estimated to be poloidally aligned at $r/a \sim 0.25$, with a sample volume separation of 1.3 ± 0.1 cm.

The phase is observed not to alias until the crosspower drops to below noise level at ~ 200 kHz. Correlation time analysis (as does the simple estimate $2\pi\langle f\rangle_{rms}/\langle k_\theta\rangle_{rms}$) yields a mean phase velocity of 4.2 ± 0.3 km/s. The calculated power-weighted (above 60 kHz) average poloidal wave number $\langle k_\theta\rangle_{rms}$ is 1.4 ± 0.1 cm^{-1}. Previous measurements with the original 500-keV HIBP on non-diverted TEXT discharges yielded values of $\langle k_\theta\rangle_{rms}$ a factor of four lower.[1,2] However, the old measurements were made on the low-field side of a limiter discharge while these new measurements are made on the *high-field side* of a *diverted* plasma. One might expect somewhat larger wave numbers on the high-field side for three reasons - i) $k_\theta \sim 1/\rho_s \sim B_T$ scaling, ii) $k_\theta \sim \omega/v_{ph}$, with ω poloidally constant but $v_{ph} = v_{ph}$ (plasma frame) + $|E_r/B_T|$ smaller on the high-field side,

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[1] J.W. Heard, Ph.D. dissertation, RPI, 1993.

[2] D.W. Ross, et al., Nucl. Fusion **31**, 1355 (1991); D.W. Ross, et al., Rev. Sci. Instrum. **63**, 2232 (1992); J. W. Heard, et al., Rev. Sci. Instrum. **64**, 1001 (1993).

and iii) effects of a quasi-coherent mode of high wave number previously observed (by FIR scattering) only on the inside midplane.[3]

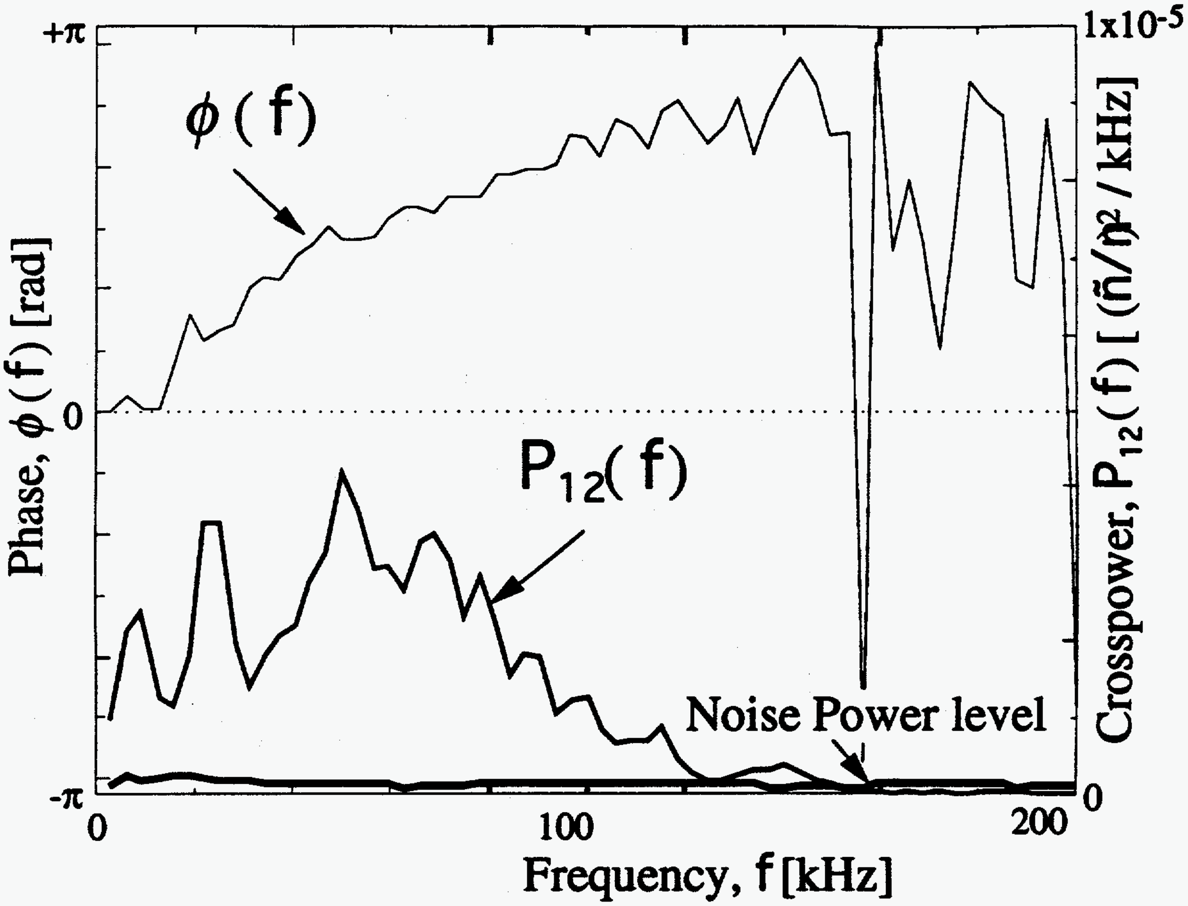

FIG. 2. Cross-power and cross-phase of density fluctuations measured by the 2-MeV HIBP from two sample volumes at r/a ~ 0.25 and separated poloidally by 1.3 cm. Plasma condition: 2.11 T / 160 kA / 1.5 × 10^{19} m^{-3} / D / upper X-point divertor. The noise power level is that with the beam turned off.

Of course, some of the differences between the wave number measurements of the 500-keV and 2-MeV systems might be instrumental in origin. The 2-MeV HIBP has better beam focussing, resulting in smaller sample volumes, and therefore higher

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[3] D.L. Brower, W.A. Peebles, and N.C. Luhmann, Jr., Phys. Rev. Lett. 55, 2579 (1985).

measurable wave numbers. The higher beam energies also reduce any beam attenuation/modulation effects which tend to lower the apparent wave numbers.[2] However, it should be stated that the instrumental limitations of the 500-keV system were investigated and found not to be serious enough to account for such a substantial difference in wave numbers.[2] Understanding the source of this difference is of high priority for future experiments.

Other interior density fluctuation correlation measurements have been made during different levels of electron cyclotron resonance heating (ECH). These measurements were made in the same discharge as the measurements in Fig. 2. We have observed changes in fluctuation level, frequency spectra, and average wave number with ECRH, but not enough data has been obtained to know how consistent these changes are. In some cases, the spectral averaged wave number $\langle k \rangle_{rms}$ decreases, as is consistent with a $\langle k \rangle_{rms}\rho_s$ scaling of the fluctuations. The mean velocity increases are consistent with the drop in $\langle k \rangle_{rms}$.

C. ECE Correlation Radiometry

By cross-correlating two outputs of a radiometer, tuned to second harmonic, X-mode, electron cyclotron emission (ECE), one can extract the average of the electron temperature fluctuations from the larger thermal fluctuations of the radiation itself.[4] In TEXT-U we have adopted this technique which is also the one that allows for the best possible resolution in conjunction with large collecting optics. Poloidal resolution is the most critical limit of ECE correlation radiometry in measuring turbulent temperature fluctuations.

On TEXT-U we have performed these kind of measurements starting in the summer of 1992, culminating with radial profiles of the spectral characteristics of the electron temperature fluctuations. Figure 3 shows the temperature fluctuation frequency spectra at various locations along the outer major radius. The fact that the spectra reach the statistical noise level above 200 kHz is a good indication that the method employed to decorrelate thermal

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[4] G. Cima, Rev. Sci. Instrum. 63, 4630 (1992).

fluctuations is adequate. Typical measurements at r/a = 0.5, integrated from 20 to 200 kHz, result in a rms value for the temperature fluctuation level $\tilde{T}_e/T_e$ of roughly 0.7%. The results shown have been obtained with about one second of averaging time, for which the overall sensitivity of the method is of the order of $\tilde{T}_e/T_e \sim 0.1\%$ over a band of 200 kHz.

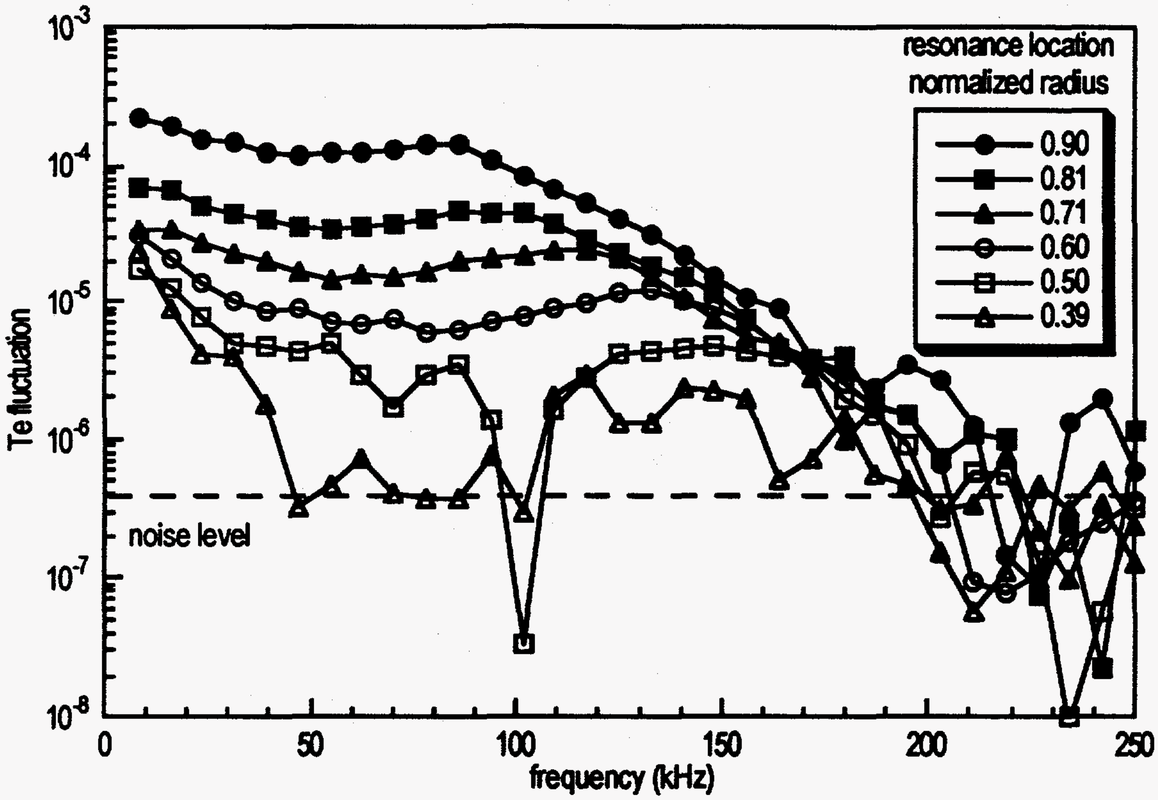

FIG. 3. Frequency spectra of electron temperature fluctuations at various locations along the outer major radius. Plasma condition: 2.0 T / 200 kA / 2×10^{19} m^{-3} / H.

Experiments were also performed at r/a ~ 0.5 separating the two emission volumes along the major radius by up to 4 cm. A radial correlation length of 1-2 cm, depending on frequency, has been observed, the lower bound being close to the theoretical radial resolution. The average phase between the two signals was found not to change, indicating an average radial wave number near zero.

Similar data will be sought from *poloidally* separated emission volumes in the near future.

D. Summary

The power spectra obtained by BES, the 500-keV HIBP, and correlation ECE in the "outer core" or "near edge" region are qualitatively similar. All typically indicate a bimodal structure, with a peak in the cross-power spectra at low frequency ($\lesssim 50$ kHz), and another at higher frequency ($\gtrsim 50$ kHz). (For far interior data, most of the power at very low frequency ($\lesssim 20$ kHz) can be due to sawteeth.)

The bimodal structure seen by BES, i.e., with the low-frequency mode propagating in the ion diamagnetic direction, is similar to the spectra seen in the far edge ($r/a \gtrsim 0.9$) of TFTR.[5] However, there are indications (from correlation ECE data in TEXT-U and BES in similar discharges in Phaedrus-T) that this bimodal structure persists much deeper into the core plasma of TEXT-U than is typically seen in TFTR. In TFTR there is a localized transition to a different, unimodal ion spectrum in the core. A similar transition may also exist in the deep core of TEXT-U but it has not yet been observed by any of the TEXT-U core fluctuation diagnostics. The ion mode seen by BES and its density scaling are similar to the ion feature which was observed at higher wave numbers by FIR scattering on TEXT.[6] In fact, they may be the same mode; future work will investigate this conjecture.

However, the clear propagation of the low-frequency mode in the ion diamagnetic direction seen by BES is not evident in HIBP data. Understanding this difference is a subject of future work, as is obtaining independent data from correlation ECE with poloidally separated emission volumes.

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[5] R.D. Durst, R.J. Fonck, J.S. Kim, S.F. Paul, N. Bretz, C. Bush, Z. Chang, and R. Hulse, Phys. Rev. Lett. **71**, 3135 (1993).

[6] D.L. Brower, W.A. Peebles, S.K. Kim, N.C. Luhmann, Jr., W.M. Tang, and P.E. Phillips, Phys. Rev. Lett. **59**, 48 (1987).

As for the electron mode, estimates of the power-weighted average poloidal wave number $\langle k_\theta \rangle$ seen by BES at its innermost locations (r/a ~ 0.7) are significantly larger (by at least a factor of two) than have been inferred previously from 500-keV HIBP data on similar discharges. The average k_θ observed by BES is comparable to that observed earlier by FIR scattering ($\langle k_\theta \rangle \rho_s \approx 0.3$). New data from the 2-MeV HIBP appears to be more consistent with BES and FIR scattering measurements of $\langle k_\theta \rangle$ and phase velocity for the electron mode, but as pointed out earlier, the data were taken on different discharge conditions and plasma locations. Clearly, this question need to be revisited with a coordinated effort by all the diagnostics (including correlation ECE) on the same discharge condition in as close to the same plasma location as possible.

II. Electrostatic Transport -

The particle and electron energy fluxes due to electrostatic fluctuations are given respectively by

$$\Gamma_e^{ES} = \langle \tilde{n}_e \tilde{v}_E \rangle = \langle \tilde{n}_e \tilde{E}_\theta \rangle / B, \qquad (1)$$

$$Q_e^{ES} = \frac{3}{2} \langle \tilde{p}_e \tilde{v}_E \rangle = \frac{3}{2} n_e \langle \tilde{T}_e \tilde{E}_\theta \rangle / B + \frac{3}{2} T_e \Gamma_e, \qquad (2)$$

where $\tilde{n}_e$, $\tilde{T}_e$ (in energy units), and $\tilde{p}_e$ are the fluctuating parts of the electron density, temperature, and pressure, respectively, and $\tilde{v}_E = \tilde{E}_\theta / B = -\nabla_\theta \tilde{\phi} / B$ is the radial component of the fluctuating E × B velocity. The brackets indicate ensemble (time) averages. Until recently, only $\tilde{n}_e$ spectra were measured routinely in the plasma interior (by FIR scattering and the HIBP). Therefore, past work was limited to quasilinear *calculations* of $\tilde{E}_\theta$ and $\tilde{T}_e$, including phase relationships, in terms of the measured $\tilde{n}_e$ spectra.[7]

Although HIBP measurements of $\tilde{E}_\theta$ have yet to be fully realized, progress has been made in measuring $\tilde{T}_e$, as presented earlier. Shown in Fig. 4 is the conducted electron heat flux (first

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[7] R.V. Bravenec, D.W. Ross, P.M. Schoch, D.L. Brower, J.W. Heard, R.L. Hickok, P.W. Terry, A.J. Wootton, and X. Yang, Nucl. Fusion 31, 687 (1991).

term on the RHS of Eq. (2)) estimated using the $\tilde{T}_e$ measured by correlation ECE, along with the heat flux deduced from power and particle balance for a standard TEXT discharge. As a worst case (maximal transport), we have assumed $\tilde{T}_e$ and $\tilde{E}_\theta = - ik_\theta\tilde{\phi}$ are in phase and perfectly correlated. We have further assumed the Boltzmann relationship $e\tilde{\phi}/T_e \sim \tilde{n}_e/n_e$, with the latter (and $\langle k_\theta \rangle$) measured earlier by the 500-keV HIBP[8] (having similar k-resolution as the correlation ECE and on the low-field side of the plasma).

We see the maximal measured heat flux falls well short of the actual heat flux, indicating that electrostatic heat transport is not a player *at the lower wave numbers measured by the ECE and 500-keV HIBP*. However, using the higher poloidal wave numbers recently measured by BES (for the electron mode) and the 2-MeV HIBP, and accounting for the attenuation of the higher-k fluctuations by the larger sample volumes of the correlation ECE system, the estimated maximal heat flux may be within the error bars of the measured heat flux. This conjecture of course needs to be examined carefully in future experiments.

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[8] J.W. Heard, Ph.D. dissertation, RPI, ?, 1993.

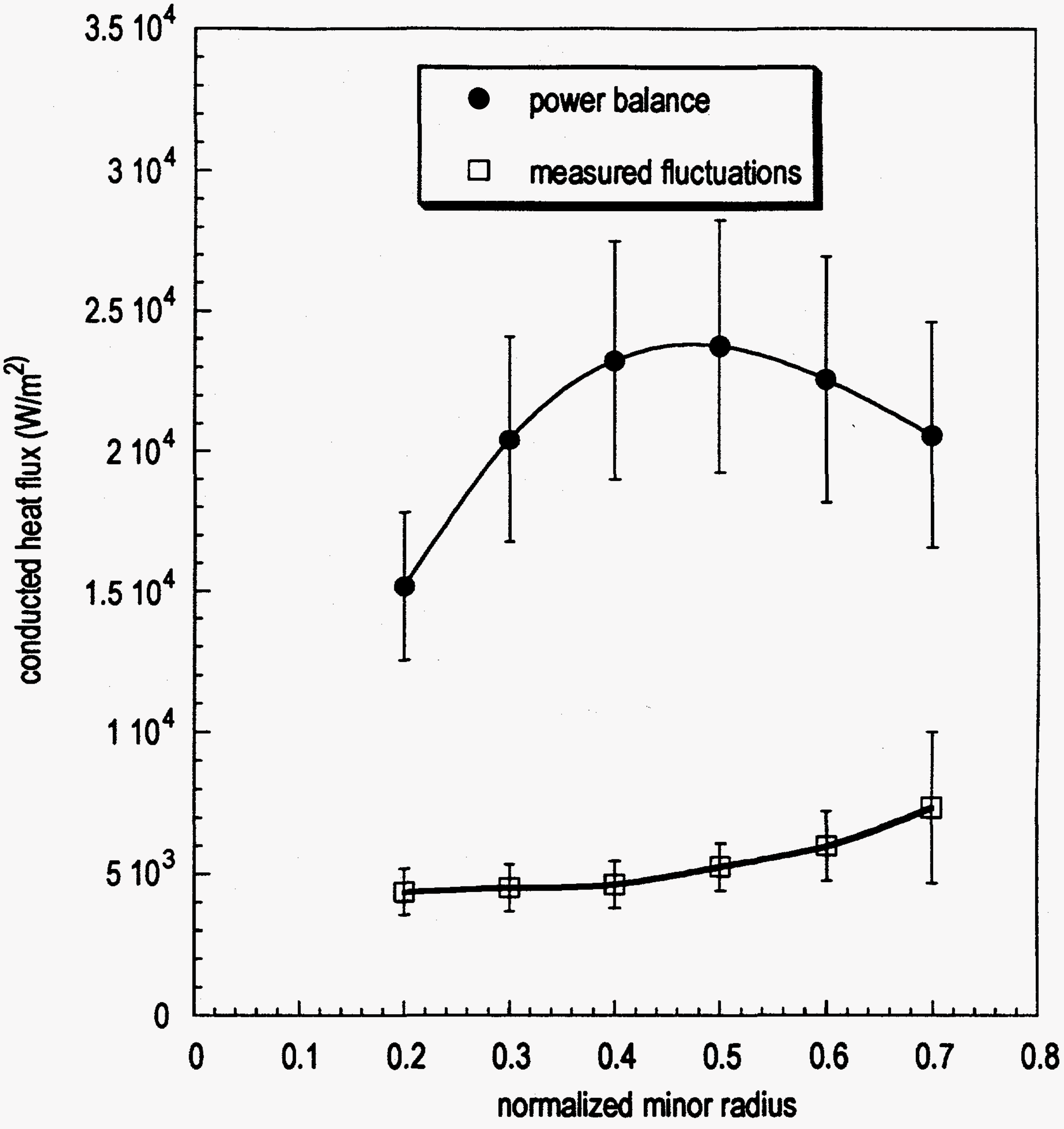

FIG. 4. The maximum (assuming optimal phase and unity correlation between $\tilde{T}_e/T_e$ and $e\tilde{\varphi}/T_e \sim \tilde{n}_e/n_e$) fluctuation-induced electron heat flux (open squares), computed from the correlation ECE measurements and those of the 500-keV HIBP on the low-field side of a standard (20 kG / 200 kA / 2×10^{19} m^{-3}) TEXT plasma. Also shown is the measured electron heat flux from power and particle balance (solid circles).

III. Electromagnetic Transport -

Past work on TEXT has suggested that magnetic fluctuations are not important to transport (at least at low β).[9] This work involved a series of perturbative experiments in which changes in the flux of hard x-rays from runaway electrons were monitored. The results can be interpreted in terms of runaway electron diffusivities, which in turn can be interpreted in terms of magnetic fluctuation levels from which electron thermal diffusivities (χ_e's) for thermal electrons can be inferred. These are summarized for the various techniques in Fig. 5, including the results of two new techniques, one analyzing the x-ray steady-state energy spectrum,[10] the other utilizing ECRH to create non-thermal electrons whose relativistically downshifted ECE emission is observed vertically (along a constant B trajectory).[11]

We observe that for all the techniques considered, the χ_e's inferred from magnetic fluctuations are much too small to account for the actual χ_e. The totality of the data provide convincing support to the conclusion that magnetic fluctuations are not relevant to electron thermal transport in the interior of TEXT. With the recent successful commissioning of three gyrotrons, this conclusion can be examined at higher β .

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[9] Roger D. Bengtson, M.R. Freeman, G.G. Castle, K.W. Gentle, S.C. McCool, A.J. Wootton, Peter J. Catto, J.R. Myra, H.E. Mynick, P.-W. Wang, to be published in *Proceedings of the 14th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Würzburg, 1992*(IAEA, Vienna, 1993).

[10] A.J. Wootton, FRCR #437, Aug., 1993.

[11] D.R. Roberts, R.F. Steimle, G. Giruzzi, G. Cima, C. Watts, FRCR #446.

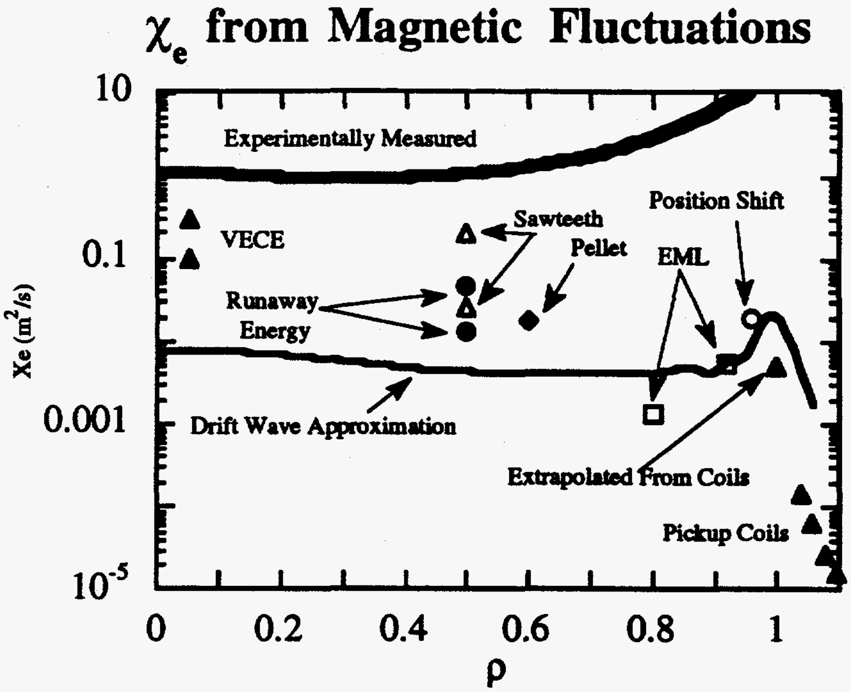

FIG. 5. Various estimates of electron thermal diffusivity χ_e from experimental inferences of magnetic fluctuation level (data points) and theory ("Drift Wave Approximation"). The actual χ_e from power balance is shown for comparison.

IV. Turbulent Drive Studies

The question here is what drives or stablizes the observed turbulence. An efficient means to investigate this question involves perturbing the plasma by some means and monitoring both the turbulence and plasma profiles (plasma density, temperature, electric field, current density, etc.) The transient transport experiments will be described in the following section.

Two plasma profiles that appear to be major players in the confinement issue are the radial electric field E_r, gradients in which are believed to stabilize turbulence,[12] and the current density j, the peakedness of which determines the internal inductance ℓ_i which has

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[12] K.H. Burrell, P. Gohill, R.J. Groebner, R.P. Seraydarian, Bull. Am. Phys. Soc. 37, 1410 (1992).

been shown to be correlated with confinement.[13] The 2-MeV HIBP has recently begun acquiring plasma potential data (from which E_r may be inferred) and the FIR polarimeter has likewise succeeded in obtaining fairly routine measurements of $B_p(r)$ (and therefore $j(r)$, $q(r)$). Therefore, experiments concerning the relative importance of E_r and ℓ_i can soon commence.

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[13] T. Taylor, U.S./Japan DIII-D/JT-60U/JFT-2M Workshop, January, 1993.

Transient Transport

Among the most powerful techniques for exploring transport processes and their connection with turbulence is the dynamic plasma response to transients. In previous years, we have used modulated ECH, gas modulation, and impurity ablation, among others, to analyze energy, particle, and impurity transport. Some of this work is reported in the Proceedings of the Varenna Workshop on Local Transport Studies in Fusion Plasmas. The principal application of the past year has been the implementation of the impurity ablation technique as a powerful probe of thermal transport.

The installation of new multichannel heterodyne ECE systems with ~1 cm localization and simultaneous coverage of most of the plasma cross-section provides excellent data for the response of electron temperature to a perturbation. We were thus able to explore some old, puzzling results of strong impurity injection experiments with superior instrumentation. The injection of carbon by laser ablation provides a strong radiative loss localized to the periphery ($r/a \geq 0.9$), because the carbon is ionized to weakly-radiating states before it penetrates further. The plasma response, shown in the Figure in heavy lines, shows several remarkable features. First, the cold pulse propagates through the outer plasma ($r/a \geq 0.75$) at a remarkably high rate, $\chi_e^{CP} > 10\ \chi_e^{PB}$, compared with power balance or sawtooth predictions. The rapid propagation is independent of pulse amplitude. However, the pulse slows and shrinks markedly thereafter, disappearing near $r/a \sim 0.5$. Within $r/a \sim 0.3$, the temperature <u>rises</u> promptly; the simplest interpretation is that the core transport decreases in less than 500 μs after the edge onset, allowing the constant ohmic input to raise the temperature. The result of a phenomenological model incorporating these features is shown in the Figure in light lines. Although the simple model does not fit every detail, it provides a good explanation of all the key features -- amplitudes and timing.

The significance of these results is the challenge they pose to the standard paradigm of local transport. A $\chi_e^{CP} > 10\ \chi_e^{PB}$ *exceeds* any reasonable nonlinearity in χ_e^{PB}, and in fact the experiment shows no indication of nonlinearity. Most important, the temperature rise in the core begins before any change occurs in local parameters; it implies a significant nonlocal effect on χ_e^{PB}.

The principal plans for transient transport experiments next year comprise:

- Measurement of the changes in turbulence associated with the cold pulse, especially local measurements with the HIBP.
- Measurement of particle transport with modulated gas feed. (The gas feed hardware has been modified to avoid earlier problems, and such experiments are now possible on TEXT-U.)
- Measurement of energy transport with modulated ECH, at least for high-q discharges with weak sawteeth.

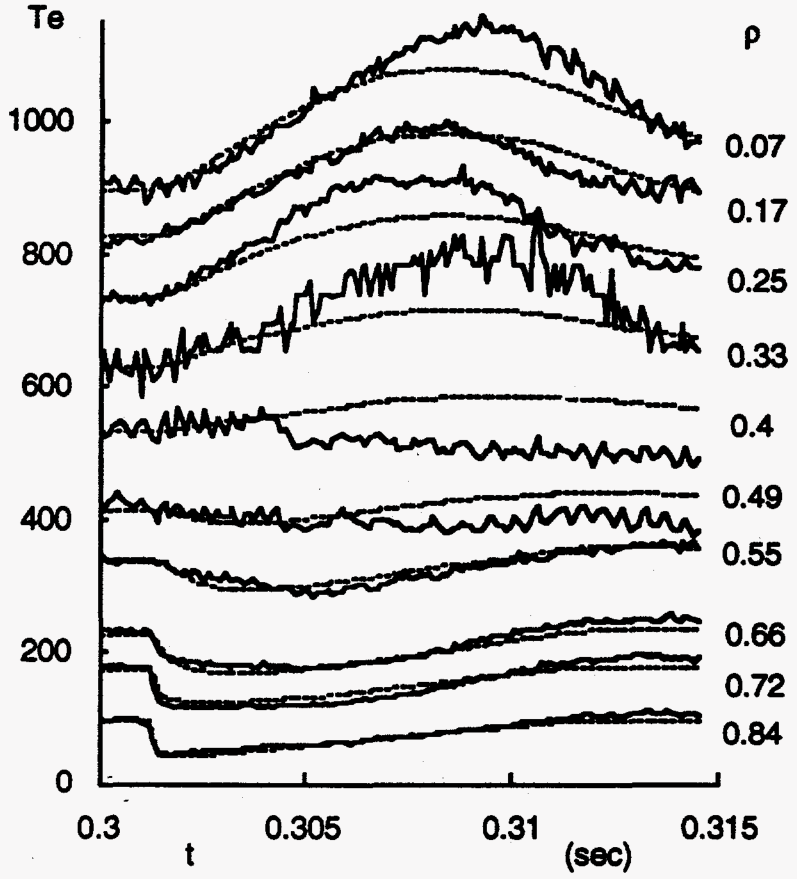


Fig. 2. Model fit to cold pulse

Publications:

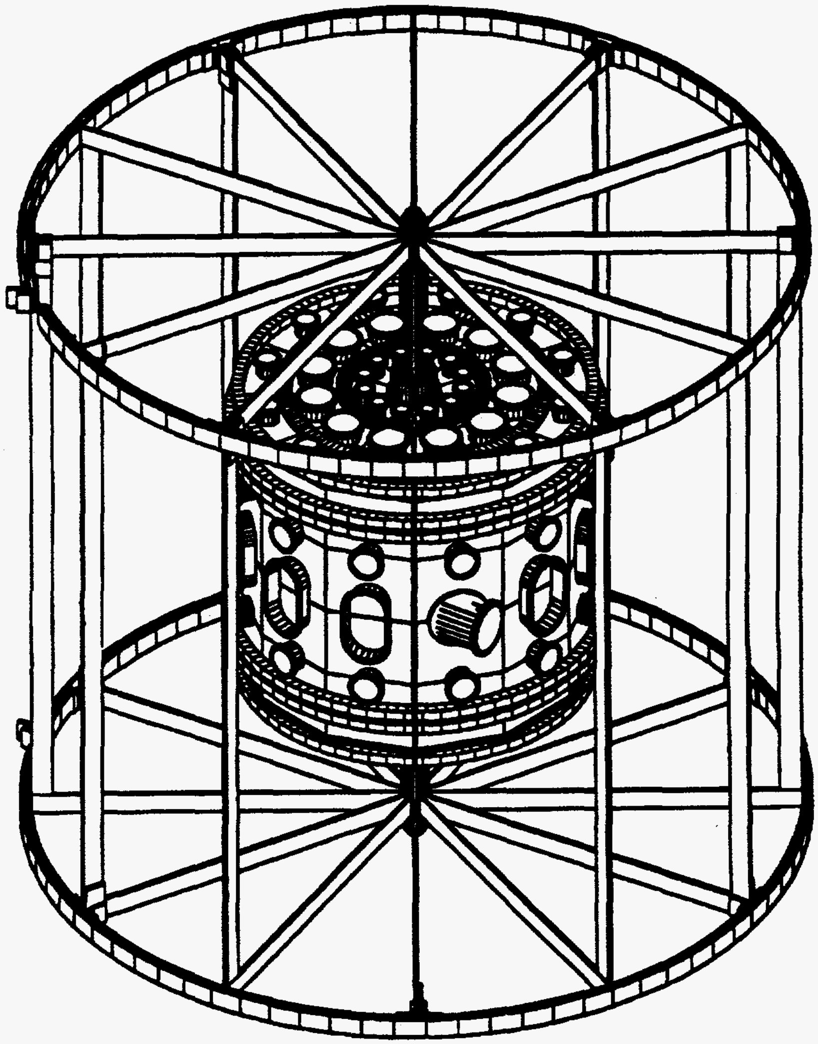
K.W. Gentle, "Particle Transport in Equilibrium, Transients, and Transitions," in *Local Transport Studies in Fusion Plasmas*, 181-5 (Societa Italiana di Fisica, 1994). (In press)

K.W. Gentle, G. Cima, H. Gasquet, G.A. Hallock, P.E. Phillips, W.L. Rowan, C. Watts, O. Gehre, and the ASDEX-U Team, "Characteristics of Equilibrium and Perturbed Transport Coefficients in Tokamaks," Proceedings of "Transport in Fusion Plasmas" (1994).

K.W. Gentle, G. Cima, H. Gasquet, G.A. Hallock, P.E. Phillips, W.L. Rowan, and C. Watts, "Observation of Non-Standard Propagation of Temperature Perturbations in a Tokamak," Europhysics Conference Series (1994)

The Next Machine at Texas?

In response to a Department of Energy initiative, the Fusion Research Center has performed a preconceptual design study of a one megamp class spherical tokamak. The proposed device would be a national facility sited at the University of Texas replacing the existing TEXT-U tokamak. In light of the extremely encouraging recent results of START at Culham, and HIT at the University of Washington, it seems advisable for the U.S. to undertake the construction of a next-step spherical tokamak at the earliest possible date.



A report on our preconceptual design study (the device is shown above) was presented at the "Workshop on Establishing the Physics Basis Needed to Access the Potential of Compact Toroidal Reactors" held at Oak Ridge National Laboratory July 19-21, 1994. The preconceptual design encompassed a study of relevant physics goals, equilibrium fields, plasma facing component power loading, OH solenoid, TF and PF coils, vacuum chamber, and heating and current drive scenarios. It also included an analysis of required diagnostics, power supplies and site considerations. The parameters of the device envisioned in our design study are as follows:

El Toro Gordo (nominal values in parentheses)

$A = 1.2 - 2.0\ (1.4)$ - widest possible range

$R_0 = 0.6 - 0.8$ m (0.7), $a = 0.3 - 0.7$ m (0.5)

$\kappa = 1.5 - 2\ (1.7)$, $\delta \approx 0.35$

$I_p < 1.2$ MA OH initially w/ RF breakdown, later NBCD, Helicity Inj.

$B_T = 0.5 - 0.8$ T (0.7), $B_\theta < 0.4$ T, $q_\psi(95) = < 3 - 10\ (4)$

$\bar{n}_e = 0.5 - 1\times10^{20}\ \mathrm{m}^{-3}$, $T_e(0) = 1 - 2$ keV, $T_i(0) = 0.6 - 1.2$ keV

$\tau_{Ee} = 20 - 90$ ms (40 ms) from scaling law study

Pulse = 200 - 500 ms

Current Drive / Heating

- Ω_{ce} breakdown (14 GHz, 40 kW) - U.Wisc
- 2 Ω_{ce} ECH T_e ramp (600 kW, 60 GHz), resonant $r/a \approx -0.6$ ($|B| = 1$ T), n_e cutoff $\approx 2\times10^{19}\ \mathrm{m}^{-3}$, also profile modification / modulated heat pulse
- 2.5 MW NB heating (40 keV) – (ORNL) co-injection, 2 e-fold penetration ≈ 50 keV, shine through not a problem at normal n_e
- NBCD $I_p \approx 100$ kA possible (Cox EPS talk)
- Helicity Inj. $I_p \approx 500$ kA (Brown, CalTech) has design funding. If $\varepsilon = 0.25$ (HIT $\varepsilon = 0.4$) ≈8 MW for 45 ms from existing OH caps
- Comp. Alfven CD - 4 MW, 2-4 MHz for 100 ms (ORNL), 4 phased toroidal antennas ≈0.2 A/W (Phaedrus 0.1 - 0.25 A/W) $I_p \approx 500$ kA, or Shear-wave heating— Mahajan
- Plasma compression possible if necessary

ETG Physics Goals

- Demonstrate 1 MA low R/a device
- Determine confinement scaling in such a device. Many scalings ∝ q or I_p. Use q_ψ or q_{cyl} ? $q_y \approx (1-\varepsilon^2)^{-3/2} q_{cyl} \leq 5\, q_{cyl}$! This bears on Bohm vs. gyro-Bohm etc.
- How does turbulence change at low R/a? If $\kappa_\perp \propto B_T$, then $k_\perp \approx 0.5 - 1.0\ \mathrm{cm}^{-1}$. If $\tilde{n}/n \propto 1/kL_n$, expect $\tilde{n}/n \approx 3 - 4\%$ (both easy to measure). What about E_r & E_r' ?
- Existing 2 MeV HIBP (RPI) will be ideal for ETG to measure $\phi(r)$ for $E_r(r)$ and $E_r'(r)$, and $\tilde{n}$, $\tilde{\phi}$ to study transport. 2 MeV Na penetrates to r=0 in an $n_e(0) = 2\times10^{20}\ \mathrm{m}^{-3}$ plasma;
- Neoclassical effects and MHD are major factors in ST's - have strong theory support in these areas with the IFS: Aydemir, Berk, Fitzpatrick, Hazeltine, Kotschenreuther, Mahajan, Waelbroeck, etc.

Conclusions

- A 1 MA Spherical Tok. could be built in a joint partnership and operated economically as a national facility at the Univ. of Texas

- TAERF has committed $0.5 M toward this device if built at UT. Negotiating with the Univ. of Texas for a similar commitment
- We have the necessary primary power
- We either have, or have identified, all necessary power supplies & heating systems
- We have the necessary floor space
- We have the fundamental diagnostics necessary, together with some unique collaborative diagnostics
- We have an existing staff of physicists, engineers, and technicians to provide basic operation

Future Work

Although we do not have sufficient manpower to extend our preconceptual spherical tokamak design to a full-fledged conceptual design, we will continue to refine our present design. We will also establish firm ties with suitable collaborative partners to explore options for auxiliary heating, non-inductive current drive (helicity injection, neutral beams compressional Alfven waves, etc.), and diagnostics. We are in the process of collecting and organizing information from the various studies that were carried out as part of the preconceptual design activity. This information will be published as a Fusion Research Center report.