FUSION RESEARCH CENTER

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Technical Progress Report

TEXAS EXPERIMENTAL TOKAMAK
A Plasma Research Facility

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Alan J. Wootton

Fusion Research Center
The University of Texas at Austin
P.O. Box 7726
Austin, TX 78713-7726
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THE UNIVERSITY OF TEXAS

Austin, Texas

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Progress Report for the Texas Experimental Tokamak A Plasma Research Facility

In the year just past, we made major progress in understanding turbulence and transport in both core and edge. Development of the capability for turbulence measurements throughout the poloidal cross section and intelligent consideration of the observed asymmetries, played a critical role in this work. In our confinement studies, a limited plasma with strong H-mode-like characteristics serendipitously appeared and received extensive study though a diverted H-mode remains elusive. In the plasma edge, we appear to be close to isolating a turbulence drive mechanism. These are major advances of benefit to the community at large, and they followed from incremental improvements in diagnostics, in the interpretation of the diagnostics, and in TEXT itself.

Our general philosophy is that the understanding of plasma physics *must* be part of any intelligent fusion program, and that basic experimental research is the most important part of any such program. The work here will demonstrate a continuing dedication to the problems of plasma transport which continue to plague the community and are an impediment to the design of future devices. We expect to show here that we approach this problem consistently, systematically, and effectively.

The Texas Experimental Tokamak

TEXT is a medium scale tokamak with

- auxiliary heating,
- diagnostics for complete turbulence and transport measurements,
- wall conditioning systems,
- systems for application of perturbations in electric field, rotation, impurity concentration, turbulence, and electron temperature
- diverted, poloidally limited, or toroidally limited configurations.

The basic physical parameters of the device are major radius of 1.05 m, minor radius ≤ 0.29 m, toroidal field ≤ 2.8 T, plasma current ≤ 400 kA and pulse length of 0.5 s.

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During the past year, the electron cyclotron resonance heating (ECRH) capability was increased to 600 kW at 56 and 60 GHz. The operating space for diverted discharges was explored and standard diverted discharges developed for confinement studies, divertor studies and SOL studies. Cold wall boronization techniques were developed for wall conditioning to reduce the impurity concentration. As a result of the boronization, limiter discharges with H-mode-like features serendipitously appeared, and the density limit in diverted discharges was increased to the Greenwald limit. To support the wide ranging program in the study of turbulence and transport in relevant regimes, the TEXT plasma repertoire now includes both diverted and limited configurations in a boronized or an unboronized vacuum vessel at densities to the Greenwald limit with 600 kW of ECRH available for auxiliary heating.

The effort expended in the installation of a 500 kW, 110 GHz gyrotron for high density ECRH, and in acquiring hardware for inside launch antennas for high density ECRH assures increased capabilities for experiments and increased power levels in the near future. All that separates us from realizing this potential is acceptance by DOE of our current proposal submission. With that, we can be sure of sufficient time for the FRC program to benefit from the additional effort required to complete the 110 GHz system with the expenditure of existing funds.

Core Turbulence and Transport

The potential of the HIBP for measuring turbulence throughout the poloidal cross section was realized, and the capability for these measurements was developed for the electron cyclotron emission diagnostic. As usual, new diagnostic capabilities led to new results. The turbulence was shown to have a ballooning character. The HIBP improvements also played a major role in the long-standing diagnostic controversy over the mean value of wave number in the core. Along with improved data interpretation which takes into account both the details of the plasma-diagnostic interaction and the 2D character of the turbulence, the increased energy in the HIBP and the addition of BES have brought us much closer to a consistent measurement of wave number in the plasma core.

Of course, we study turbulence as a means for understanding transport. The likelihood that magnetic turbulence plays a role in transport in the core was further reduced by a series of experiments employing electron cyclotron emission and ECRH. Recent perturbative transport experiments may have identified a non-linear transport mechanism in the core. Although the implications are not yet clear, these experiments and their confirmation on TFTR and JET may eventually lead to a change in the paradigm for transport or at least to the identification of a supplementary transport process selectively accessed by the perturbative experiments. In this latter case, the additional process may be an underlying transport mechanism that has confused the interpretation of past transport experiments.

Improved confinement

In March of 1995, we observed the first transitions to a state of improved tokamak particle and energy confinement in TEXT that were caused by the introduction of over 300kW of central ECRH. The transitions appeared following boronization in a poloidally limited configuration. The temporal phenomenology of the transitions is similar in many respects to L-H transitions. Initiated at the midplane by a sawtooth crash, the transition is identified by a sharp drop in the global edge $D\alpha$ emission and a simultaneous rise in the line-averaged electron density $\bar{n}_e$; thus indicating improved particle confinement. Though there is indication of improved energy confinement, little improvement in the confinement scaling with plasma density over L-mode is found. These transitions provide encouragement that auxiliary power and wall conditioning are adequate for L-H transition and that the continued elusiveness of the diverted H-mode is related to previously unidentified physics of the H-mode.

Edge Transport and Turbulence

A strong correlation between electrostatic turbulence and transport in the edge was recognized early. Extensive characterization of the SOL and edge turbulence provided clues to the drives, but the drives have so far remained unknown. During the last year, we made major progress in

understanding turbulence drives. Atomic drives were shown to be irrelevant to TEXT plasmas or simply non-existent. As a result of the use of novel Langmuir probes to look for conducting wall drives, enigmatic turbulence features were found and shown to be dependent upon conducting walls but not consistent with current theory. Both a new diagnostic and the new divertor configurations were required for the survey experiments that uncovered strong evidence for curvature drive that is consistent with current theory. An understanding of turbulence drives may lead to enlightened divertor design and perhaps to control of turbulence.

More direct means of turbulence control could employ feedback techniques. Using techniques that are appropriate and easy to implement on TEXT, we continued to explore the concept. These experiments previously identified local turbulence modification without transport modification and recently have turned to details of the probe coupling to the plasma in an attempt to induce the transport modification. To our surprise, we find that the coupling studies have challenged current understanding of the physics of diagnostic probes and plasma sheaths.

Future of TEXT

At present, the Fusion Research Center is awaiting DOE judgement of our grant applications. Two were submitted, one for a spherical tokamak and another for continued innovative turbulence and transport experiments in the well-diagnosed and well-understood configurations provided in TEXT. In the context of the TEXT proposal, we believe that these sort of experiments are essential to developing a fundamental understanding of the complex nonlinear physics of fusion plasmas, an understanding which will be necessary for development of the physics base required to go beyond an ignition demonstration machine. Should the TEXT program be allowed to continue, we look forward to an exciting year as evidenced by this list of priorities for FY1996.

- Continue studies of improved confinement transition physics (limiter H-mode, diverted H-mode: effect of fueling asymmetries and use of 2nd harmonic ECH).
- Identify relative roles of magnetic and electrostatic turbulence in the core.

- Continue exploration of non local transport effects.
- Explore the region of exceptionally good confinement near the magnetic axis .
- Initiate documentation of core turbulence asymmetries.
- Continue exploration of edge turbulence: role of curvature and wall conditioning, feedback control.
- Initiate studies of Alfven modes suitable for current drive.
- Complete measurements of current ramp phenomena (Ejima coefficient, resistivity).
- Initiate MHD feedback control via intra-island heating.
- Install, test, and document proposed TPX density diagnostic.
- Begin development of new techniques for turbulence analysis.

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FRC Engineering Upgrade

During the past year, the engineering group has been preparing for operation of the 110 GHz gyrotron. The motor generator, the high voltage rectifier and the inside launch system. Essential monitoring of the TF power supply was added to reduce down time. To support the newly developed wall conditioning regimen, a robust power supply of rather novel design was added to allow unattended operation of the glow cleaning system.

Generator

This year has seen a considerable effort put into bringing Generator No. 2 (13.8 KV 18.5 MVA) on line. This generator is required for both the 110GHz gyrotrons and/or the proposed USTX neutral beam injector. A sophisticated vibration monitoring, analysis and telemetry system was purchased from Bentley Nevada and installed on both Generators 1 and 2. With this system, Bentley Nevada is able to remotely (from Houston) access our vibration monitoring computer system. In this manner, interacting with Bentley Nevada we were able to mechanically balance the generator rotors in one day. This represents a major improvement in time, money, and convenience.

An updated version of the generator computerized control system software is now installed and is operational on both Generators 1 and 2.

A failsafe gravity fed emergency bearing oiling system has been installed. In the event of a power failure this provides ample time to shut down the generators which are usually operated and monitored remotely.

High Voltage Rectifier System (ADCAPS)

The computerized control system for this unit is now sufficiently advanced to allow for remote control. The 13800V 3 phase input wiring is completed and the 100KV DC wiring to the Tokamak hall is complete. We expect to test the system (Generator No. 2 and ADCAPS) by the end of August.

Engineering Diagnostics

A fast CAMAC 32 channel digitizer monitoring system has been purchased and interfaced to the torodial field power supply. This enables us to monitor the gate drive pulse to each of the several hundred SCRS in the T.F. power supply.

This has proved invaluable in diagnosing any faults that occur and has substantially decreased the power supply down time.

110 GHz Tank and Tube

The internal high voltage wiring of the 110 GHz tank is 90% complete. Inlet and outlet connections for the gyrotron tank oil pump have been installed and the high voltage and oil connections for the gyrotron socket have been completed.

The Varian 110 GHz gyrotron tube was successfully tested at General Atomics in February 1995. Successful testing was achieved after it was discovered that the electron beam of the gyrotron was off-center and focussed too tightly. Re-aligning the beam and increasing the beam size vastly increased the operating window of the gyrotron. Pulse lengths up to 500 ms at 250 kW output were obtained . Output power levels up to 375 kW were obtained at shorter pulse lengths.

56 -60 GHz Gyrotron System

Routine operation all three gyrotrons (two 60 GHz, one 56 GHz) in conjunction with the tokamak was achieved in July 1994. The complete system has demonstrated very good reliability, with all three tubes being available in excess of 90% of the time. Plans were implemented to install high field side X-mode launchers using equipment transferred from D-III-D. An inside launch assembly was obtained from General Atomics in March 1995, and a second unit will be shipped by August 1995.

Discharge Cleaning

The glow discharge cleaning system has been upgraded to allow higher current glow discharge for boronization.

Wall Conditioning

Four techniques are used for wall conditioning: pulsed discharge cleaning, glow discharge cleaning, boronization, and tokamak shots. Through trial and error, we have assigned wall conditioning roles to each of these. We plan a series of experiments with the goal of completely understanding the relation between the boronization technique that we currently use and the resulting plasma properties that it affects, recycling and impurity concentration. This will allow us to improve conditioning techniques.

From the inception of operations on TEXT through 1994, it was the custom to use pulsed discharge cleaning in H or D for 12 hours each evening. On occasion, the pulse rate, or D/H pressure, and Ohmic heating current were reoptimized for the production of water vapor. During 1994, experiments demonstrated that glow discharge cleaning resulted in more rapid reduction of water vapor following vents. In early 1995, boronization using trimethyl boron was added.

The present conditioning regimen was optimized primarily by comparing several characteristics of the tokamak discharges after the particular technique was applied. These include loop voltage V_L , recycling at the vacuum vessel wall and the ratio of radiated power to chord averaged electron density. The lowest values of loop voltage and radiated power are achieved following boronization. The effects of boronization last for about 300 shots. Typical shot by shot progressions of V_L between boronizations is shown in Figure II.10. Immediately after boronization, V_L is approximately 1.2. The range for V_L before boronization was used on TEXT was 1.8 to 2.2. The hatched region in Figure II.10. V_L is allowed to increase to a value near 2 before the next boronization session. Between boronizations, glow cleaning in He is used to reduce water vapor that may result from changing of vacuum hardware or minor vacuum accidents. Pulsed discharge cleaning is now used only immediately after a vent or in those cases when it is necessary to completely strip the vacuum vessel walls after a failed boronization experiment.

Figure II.10. V_L versus tokamak discharge number following boronization. Prior to boronization the normal range for V_L was the hatched region

We plan to conduct experiments in wall conditioning. The goal is to understand the wall conditioning in TEXT and perhaps contribute to its understanding at large. In this study, we will characterize the glow discharge plasma to improve the boronization, attempt to accelerate recovery of density control following boronization, and determine the limits of impurity control due to this cold wall boronization technique.

Computation

There are three major components to the FRC computation facilities. The data acquisition system is CAMAC based and the data is archived and maintained via a cluster of DEC VAX computers. These computers are also used for data analysis. Desktop Macintosh computers are provided for use as terminals in connecting to the vaxes, and they are becoming more widely used for analysis of data. Finally, there are several RISC based IBM computers that are used for specialized, computation-intensive purposes such as EFIT and EIRENE. During the last year, we have emphasized improvements in data acquisition, the vaxes, and the desktop macs.

Two central processor cards have been added to the VAX 6400, making a total of three processors in this computer. This more than doubled the amount of general computation power available on the VAX Cluster. 128 MB of memory have been added to the VAX 6400 to support the new processors. 7 GB of disk space have been added to the VAX Cluster, making a total of more than 17 GB. 128 MB of memory have been added to one of the IBM RS6000 workstations.

Four Power Macintosh personal computer systems have been obtained for the staff. A total of 160 MB of Macintosh memory has been purchased during the year. All Macintosh II class machines now have at least 9 MB of memory, and several machines have 16 MB or 24 MB of memory. A total of 9.1 GB of Macintosh disk storage has been purchased during the year. Some of the disk drives were required to provide increased storage capacity and some were required to replace broken drives. Ethernet cards have been obtained for all Macintosh II class machines. Macintosh printer performance has been increased by the addition of an Apple LaserWriter 16/600 PS printer and a HP DeskJet 1200C/PS color printer. An Apple Scanner has also been purchased.

Three more CAMAC crates with fiber-optic U-Port adapters have been obtained. An additional 3 Megasamples of memory for existing CAMAC digitizers have been obtained.

Ballooning in Density Fluctuations

During the past year, ballooning characteristics in density fluctuation power spectra have been observed on TEXT-U tokamak using a 2 MeV Heavy Ion Beam Probe (HIBP) [FRC report # 466]. The density fluctuation power spectra exhibit clear peaks in the frequency range 70-150 kHz in the low-field side region of the plasma only. This structure is not present in the core region of the high-field side [fig. 1a and 1b]. The observed mode amplitude [fig.2] and its average frequency are modified when additional heating power (ECH) is applied. Preliminary analysis of the experimental data and comparisons with theoretical predictions indicate that this structure may be related to trapped electron modes. Initial results have been submitted to Nuclear Fusion Journal for publication and additional experiments to further characterize the observed structure are underway.

Fig.1 a) location of the measurements and b) density fluctuation power spectra

Fig.2 Change of mode amplitude with ECH 1gyro=150kW, 2gyros=300kW, and 3gyros=410kW

Beam Emission Spectroscopy

Since the last progress report (July, 1994), performance of the BES system has been dramatically improved using new cryogenically cooled detectors and hydrogen as the neutralizer gas in the diagnostic neutral beam. has been dramatically improved using new cryogenically cooled detectors and hydrogen as the neutralizer gas in the diagnostic neutral beam. The improved signal-to-noise ratio allows measurements from the plasma edge in to $r/a \approx 0.5$.

A special experiment was devoted to comparison of fluctuation data measured by different fluctuation diagnostics in the standard TEXT-U regime 2 T / 200 kA / $2 \times 10^{19} \text{ m}^{-3}$ / H (D). Although a direct comparison is hampered by the fact that different diagnostics observe different locations in the plasma, initial results may be presented assuming poloidal symmetry of $\langle k_\theta \rangle$ and $\langle V_{ph} \rangle$. Figures 1(a) and 1(b) show radial profiles of $\langle k_\theta \rangle$ and $\langle V_{ph} \rangle$, respectively, measured by BES, the HIBP, and Langmuir probes for $0.5 \leq r/a \leq 1.1$ in the same experimental run. Results of FIR scattering are taken from Ref. [1]. HIBP data for this experiment are shown as the shaded region in Fig. 1, while the filled circles refer to results from TEXT [2,3]. The value of the phase velocity at $r/a = 0.6$ in Ref. [2] was 13.3 km/s. Interpretation of the HIBP measurements is complicated by the oblique orientation of the sample volume with respect to the poloidal direction. The lower boundary for $\langle V_{ph} \rangle$ and the upper boundary for $\langle k_\theta \rangle$ are obtained assuming no propagation in the radial direction and taking the shortest poloidal distance between sample volumes as the sample-volume separation.

In the SOL, BES measurements are consistent with Langmuir probes. In the interior, all of the diagnostics observe a broad spectrum centered around 100 - 150 kHz, with fluctuations propagating in the electron diamagnetic drift direction. Measured poloidal wave numbers and phase velocities are in good agreement. The data is consistent with a drift-wave model [2]. HIBP phase velocities are consistent with those measured by FIR scattering and BES assuming $\langle k_r \rangle \sim 0$. Low $\langle k_r \rangle$ was confirmed by BES (although the emission-volume orientation was not optimal). The ion feature seen by BES near the edge is similar to an ion feature reported by

FIR scattering and has similar characteristics and plasma-parameter scalings as measured by FIR scattering [1]. The clear propagation of the low-frequency mode in the ion diamagnetic drift direction is not evident in HIBP data and this difference is a subject of future studies.

References

1. D.L. Brower et al. Nucl. Fusion **27** (12) 2055 (1987).
2. R.V. Bravenec et al., Phys. Fluids B **4** (7) 2127 (1992).
3. T.P. Crowley et al., Nucl. Fusion **32** (8) 1295 (1992).

Fig. 1. Radial distributions of a) poloidal phase velocity, b) poloidal wave number of the density fluctuations measured by BES, FIR, HIBP, and Langmuir probes in TEXT-U.

ECE Correlation Radiometry

Tremendous progress has been made during the past twelve months in measuring electron temperature fluctuations using the CRECE system in the core of the TEXT-U tokamak. The measurement technique has been proven,¹ and work has begun to more fully characterize the measured turbulence. As of April, 1994, the relative amplitude of these fluctuations, $\tilde{T}_{e,rms}/T_e$, and the associated power spectrum over most of the plasma minor radius had been measured. The relevance of these fluctuations to electrostatic heat transport had been investigated, with the conclusion that long wavelength modes do not significantly contribute to anomalous heat conduction.^{2,1} During the past year this work has been further extended to include measurements of ℓ_r and fluctuations off the equatorial midplane. This work necessitates a thorough understanding of both the spatial and minimum signal level resolution capabilities of the CRECE diagnostic.

Poloidal asymmetry of electron temperature fluctuations

Spectra of the turbulent electron temperature fluctuations have now been measured on both the top of the plasma and the inside midplane in addition to the outside midplane. Measurements at the top of plasma are accomplished by shifting the entire CRECE antenna system vertically. The ECE resonance is placed on the vertical plane through the plasma magnetic axis, and the plasma is shifted vertically to scan the minor radius. This configuration has the additional benefit that the CRECE sample volumes are aligned such that maximum resolution is obtained in the poloidal direction.

As is clear from Fig. 1, there is considerable asymmetry in the spatial distribution of the temperature fluctuations. Plotted are the power spectra of the turbulent electron temperature fluctuations for three different locations in the plasma, with the sample volumes at roughly the same minor radius. Data from the outside equatorial plane show the largest power in these fluctuations, while the inside midplane shows almost an order of magnitude less. Some of this attenuation is due to the larger emission volumes on the inside as a consequence of being beyond the focus of the lens; however, experiments have shown that defocusing affects only the

FIG. 1. Power spectra of electron temperature fluctuations for a "standard" TEXT-U limiter discharge indicating the poloidal asymmetry in the turbulence.

high frequencies.¹ The spectrum from the plasma top is intermediate in intensity. The data presented refer to a "reference" limiter discharge of 27-cm minor radius, toroidal field of ~ 2 T, plasma current of ~ 200 kA, and chord-averaged electron density of $\sim 2 \times 10^{19} \text{ m}^{-3}$.

A cohesive understanding of these results has yet to emerge. The most obvious interpretation is that the fluctuations have a ballooning character. However, several details still need to be investigated:

- Is the ballooning due to a shift of the turbulence to shorter wavelengths beyond the resolution of the CRECE diagnostic? One might expect somewhat larger wave numbers on the high-field side for two reasons: $k_\theta \sim 1/\rho_s \sim B_T \sim 1/R$; and $k_\theta \sim \omega/v_\theta$, where ω is poloidally constant but $v_\theta = v_\theta(\text{plasma frame}) + |E_r/B_T|$ is smaller on the high-field side. However, the amplitude on the inside is reduced over the entire frequency band, rendering this explanation at best incomplete.
- Is the attenuation at the top relative to the outside due to the poorer radial resolution on top, implying a significant mean radial wave number (or wave-number spread) at the top?
- It is notable that the power in the fluctuations at the top is significant out to the Nyquist frequency of the acquisition system. Is this additional

power due to enhanced k_θ resolution when the tall-but-thin emission volumes are located at the plasma top?

- Measurements to date have only been made on the midplane and in the upper plasma. What is the nature of the change in the fluctuation spectra as one progresses around the plasma at the same minor radius?

An intensive investigation is underway and planned for the next grant period to answer these questions.

Correlation lengths, propagation, and emission-layer thickness

As a next step in understanding the temperature fluctuations, considerable effort has been made in measuring both ℓ_r and ℓ_θ . We have been particularly successful in measuring ℓ_r .³

For the same reference discharge condition, the cross correlation of a 200-MHz wide fixed-frequency filter in conjunction with a 200-MHz wide YIG filter was measured for separations ranging from 3 to 30 mm. The measured cross coherence as a function of radial separation for each of the 32 frequency bands was fit to a smoothly decreasing function. The lower frequency data were best fit by a Lorentzian, while the higher frequencies were best fit by a Gaussian. The half-width at half-maximum, which characterizes the radial correlation length of the temperature fluctuations, is plotted as a function of frequency in Fig. 2 at three radial locations on the outer midplane.

There appears to be a frequency band (highlighted by open symbols in the figure) that exhibit longer correlation lengths (~ 2 cm) than the remainder (~ 1 cm). (For $r/a = 0.4$, the longer correlation lengths and large scatter at the lower frequencies are caused by the persistent sawtooth activity. Data above 170 kHz are in the noise region of the spectrum and show a random distribution.) In addition, this longer correlation length increases with decreasing radius. The frequency band corresponds to the persistent feature seen in the temperature fluctuation spectra,^{2,1} which is localized to the gradient region of the electron temperature profile. Results of these measurements may seem counter-intuitive, since one might expect high frequencies to have shorter correlation lengths. The results, however, are consistent with similar measurements of density fluctuations by BES.

FIG. 2. Measured radial correlation length of electron temperature fluctuations.

These data have provided an unexpected result. The measured ~ 1 cm correlation length can only be taken as an upper-limit estimate of the true ℓ_r , since the calculated width of the emission volume of the ECE radiation is of this order.⁴ Conversely, this measurement can be viewed as an upper limit on the true emission volume width, and represents the first experimental determination of the ECE resonance layer width.

The mean phase shift between the signals from the two emission volumes provides information on the radial propagation of the turbulence. For the data above, no phase shift was seen over the entire frequency band, i.e. $\bar{k}_r \approx 0$.

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- 3 C. Watts, G. Cima, R. Bravenec, R. Gandy, T. D. Rempel and A. J. Wootton, Rev. Sci. Instrum. **66**, 451 (1995).
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The q-Diagnostic

Introduction and theory

The q-diagnostic is a new diagnostic that was installed on TEXT in the fall of 1993 after the successful upgrade of TEXT. The diagnostic, as its name suggests, is used to reconstruct the q-profile in TEXT. This is accomplished by measuring the local pitch angle profile along a line of sight that runs perpendicular to the horizontal midplane of the plasma.

The method is based on detecting fast neutrals injected along a vertical chord, by a 35-40 KeV diagnostic neutral beam. The neutrals' velocity is thus largely perpendicular to the magnetic field. These fast neutrals while in flight may undergo a charge exchange reaction and so have their trajectory altered, due to gyration around the local magnetic field. The charge exchange reaction is, to all purposes, momentum conserving. A second charge exchange reaction converts these particles back to their neutral state. No longer under the influence of the magnetic field, these neutrals stream across the plasma ; their direction of flight altered due to prior interaction with the magnetic field. A detection of these particles will then allow one to infer the direction of the local magnetic field at the beam column.

A toroidally spaced array of neutral particle energy detectors is used to detect these neutrals streaming across the plasma. The system is set to detect only those fast neutrals originating from the beam column, through collimation and energy filters. The toroidal location of the peak in the signal is then related through a simple geometrical relationship to the local pitch angle.

The pitch angle profile along the beam column is constructed by scanning the vertical column with the diagnostic on a shot to shot basis. That is for each plasma discharge the diagnostic is set to detect the pitch angle at a certain position along the vertical column. In this fashion a profile is constructed. This of course relies on the consistency of the plasma discharge on a shot to shot basis, for a nominal set of conditions.

The status of the Diagnostic

The initial runs in the fall of 1993 to the spring of 1994 yielded data that showed hints of a pitch angle profile. The data was marginal, in that it was able to demonstrate that the diagnostic had established proof of principle of the physics behind the diagnostic. The data collected during the months of January to April 1994 led to a paper[1] being presented at the Tenth Topical Conference On High Temperature Plasma Diagnostics.

In May 1994 work was started on two fronts; design of new electronics for the amplification and discrimination of the detected signals, and the construction of a "Faraday" cage for the electrostatic analyzer plates, that are used for the energy selection of the incoming fast neutrals.

Previously the electronics for the discrimination of signals, for accurate signal counting, came from the old Charge-Exchange diagnostic (measurement of ion temperature profiles). This was an old system and there was no provision for setting the discrimination levels for individual channels. Thus one could not be sure whether each channel was accurately discriminating signals. A new discrimination system was designed and built, based on fast ECL logic. The system now is capable of discriminating and counting at well over 10 MHz.

The existing electronics used for the amplification of current pulses ,emitted by the detectors (channel electron multipliers), were replaced. It was thought that the old Charge Exchange amplifier system would suffice and so a system was built, based directly on the old system. However it was discovered that there was a noticeable impedance mismatch between the detector output and amplifier input. The current amplifier system resolves this issue and is now able to perform its job at over 3 MHz.

The current limitation of the overall system is at around 3 MHz. The signal to noise ratio is well over 50. As of December 1994 all data taken was sampled at 0.05ms.

A "Faraday" cage was also designed and constructed for the electrostatic analyzer plates. This was done to prevent any stray electric fields from any potential sources from penetrating the region between the plates. The cage was constructed from high mu-metal thus ensuring that magnetic fields also do not enter into play.

Another improvement to the diagnostic was to design a feedback voltage signal to the electrostatic analyzer plates from the diagnostic neutral beam. In this manner one is able to constantly monitor the voltage on the analyzer plates. This is important for the plates have to be correctly biased in order to select the incoming neutrals at any given time. Thus the worry of the beam (DNB) voltage fluctuating in time is erased.

The combined effects of all these improvements to the diagnostic were significant. The data now is of a quality that is worthy of rigorous analysis. A oral qualifier, based on the data, was presented by the graduate student working on the diagnostic, in February 1994.

The diagnostic is at a stage where the "hardware" problems have been worked out. Data has been acquired for several discharge conditions: high q discharges, fast and slow plasma current ramp discharges, discharges with significant sawteeth and low q discharges. Work is now largely focused on data analysis. The objective now is to yield reliable pitch angle profiles from the data in a consistent and straightforward manner.

The above graph shows typical data from this diagnostic. The angle (x-axis is in degrees. The yaxis shows vertical location in meters with respect to the plasma midplane. The data is compared to a prediction

(thick line) based on Spitzer conductivity with the effects of finite beam width and ripple trapping omitted. Both of these omissions will be remedied in future analysis.

The potential of this diagnostic is very promising. The spatial resolution is of the order of 1 cm. The time resolution is found to be very high. The count rate is of the order of 1 Mhz and the system is clearly able to handle it. Thus one can resolve the pitch angle profile during a single sawteeth period. The end output of this diagnostic will be time resolved pitch angle profiles that may reveal information about sawteeth phenomena. Another objective is to make these profiles a staple input to an equilibrium code such as EFIT.

Reference

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Phase Contrast Interferometry (PCI)

Development of the TEXT-U phase contrast imaging (PCI) diagnostic has been completed and will be installed on the tokamak in August 1995. The system, a CO₂ laser based internal reference interferometer, will be used to measure density fluctuations in both the plasma core and edge. Major work completed this year includes:

- Design and fabrication of the optical system.
- Construction and operation of the 16 channel detector amplifiers with the HgCdTe detector array and CAMAC digitizers.
- Completion of the tokamak flange that allows PCI and the TEXT-U interferometer to share the same port.
- Control system design.
- Development of a calibration facility that uses acoustic waves
- Computer simulations indicating that a drift wave mode having a mean $k\theta = 3 \text{ cm}^{-1}$ can be resolved with our initial configuration.

We are presently doing final operation and testing of the system in a side-lab with the exact optical configuration that will be used on TEXT-U. The initial tokamak operation will consist of a 3.2 cm wide CO₂ beam to measure $k\theta$ in the core. This beam size with our detector configuration will allow measurements from $2 \text{ cm}^{-1} < k\theta < 12 \text{ cm}^{-1}$ with 500 kHz analog bandwidth.

In operation, the output of a 25 W Synrad CO₂ laser is expanded by a set of reflective optics to form a Gaussian beam waist in the equatorial plane of the plasma. A similar arrangement images this waist on to the groove of a quarter wave phase plate. The phase plate is a key component of the PCI system. It changes the relative phase between the scattered and unscattered (internal reference) beam components by 90 degrees. This phase change converts the phase modulation of the beam to an intensity variation that can be detected with a square law power detector.

The width of the probing beam is adjustable from 3 cm to 15 cm with replacement and translation of one cylindrical optic on an optical rail, as shown in Fig. 1. A variable beam width is an important and novel aspect of the TEXT-U PCI system. A small beam size is used for high spatial resolution and a large maximum k . The larger beam sizes are used

to allow measurements at very low k . The optical system which has been designed provides very low aberrations over the entire range of operation.

We have operated the TEXT-U PCI system in a sidelab for testing and calibration. Using acoustic waves, we have verified its sensitivity in the wavelength range of 0.5-12 cm. Using a calibrated microphone, we have verified the sensitivity to be 10^{-6} radians at a wavelength of 3 cm. This is equivalent to a density fluctuation of $4.8 \times 10^{10} \text{ cm}^{-3}$. This sensitivity was limited by noise in the RF oscillator in the laser, and is expected to improve when this problem is corrected.

Simulation work to verify whether PCI will be able to detect several fluctuation modes in the plasma has also been done. Gaussian models of the spectra $S(k, \omega)$ that match the experimentally observed modes in TEXT are used as input to the simulation. Initial results have been obtained with a spatially homogeneous model of the turbulence. The expected PCI signals were obtained by performing an FFT of the input spectra and using appropriately spaced autocorrelation lags in space as the time series from the detector. These expected spectra are seen to closely match the input spectra. It was found that the spatial resolution afforded by a large number of detectors is necessary to detect a drift wave feature and a wide beam is necessary to resolve a long wavelength mode. Future work on the simulations will include an inhomogeneous plasma model and the addition of noise to the signals.

PHASE COMPACT INTERFEROMETER

Flux Surface Destruction as a Mechanism for Anomalous Transport

One possible theory for anomalous transport invokes a mechanism by which confinement is locally degraded on a flux surface. One mechanism frequently called the "bubbling island" model proposes that bootstrap current driven magnetic islands destroy the confinement on rational surfaces for short periods of time. In this model neighboring islands grow until interactions between islands reduce the pressure gradient turning off the bootstrap current driving the island formation. The flux surfaces then heal until the pressure gradient and bootstrap current can again produce magnetic islands. Any loss of confinement should reduce the T_e gradient. The above mechanism should manifest itself on a radial scale of the order of 1 cm and on time scales on the order of a few ms. [T.A. Gianakon, J.D. Callen and C.C. Hegna, Phys. Plasmas 1, 2245 (1994).]. By making measurements on small radial scales, looking for local reductions in the T_e gradient, it is possible to put an upper bound on the size and duration of such a disturbance.

On TEXT-U, two 8 channel, high resolution heterodyne ECE radiometers were used to measure the electron temperature with sample volumes that reside in a 25 cm range along the major radius on the equatorial plane. The radial resolution is 1 cm and the spot size is not more than 2 cm at any location in the plasma. The toroidal field is adjusted to allow for sampling of the high and low field side of the plasma column in separate experiments. Three channels have tunable filters that allow us to adjust the location of their sample volumes independently of the other channels. The spacing between channels was in the range of 0-2 cm with a sample frequency of 200 kHz. During the flat top of the discharge the plasma column was displaced in the major radial direction by a distance of 3 cm. Each position sweep is 75 ms in duration and four sweeps were performed during each shot. This technique is similar to one used on TFTR [M.C. Zarnstorff, et. al., Proceedings of the International School of Plasma Physics, "Local Transport Studies in Fusion Plasmas", Villa Monastero-Varenna, Italy 1993]. A detailed discussion of the experiments

on Text-U was presented at the EC-9 conference, Borrego Springs, CA. Jan. 22-26, 1995.

With information from the plasma position diagnostic, it is possible to map the temperature samples to their respective minor radial location in the plasma frame. In this calculation, we neglect the effects from the poloidal magnetic field and beta. These effects should produce an error of no more than 5 mm in the true radial location of the sample volume. A piecewise continuous profile can be used to derive relative calibration factors for the 16 ECE channels. Scaling factors between neighboring channels are derived by computing the matching factors needed to make the piecewise profile smooth and continuous (Fig. 1). These profiles clearly show three distinct confinement zones for low magnetic fields. For higher fields the T_e profile looks more gaussian and the evidence for three confinement zones disappears. At this time we have no explanation for this phenomena. We intend to look into sawtooth activity and possible dependencies on q .

Following the technique used by Zarnstorff et. al.(see reference above), we attempt to fit a curve to the T_e profile in order to then compute an inverse T_e gradient scale length given by the expression $1/L_{T_e} = 1/T_e (dT_e/dr)$. We chose to fit a line to a 1 cm section of the profile corresponding to the radial resolution of the ECE diagnostic. The slope of this line is then extracted as a measure of the gradient which is then normalized by the local temperature to compute the inverse T_e gradient scale length.

Since our ECE diagnostics have many channels close together it was possible to make an independent measure of the inverse T_e gradient scale length by using the relative calibration factors to estimate L_{T_e} using the expression

$$1/L_{T_e} = \frac{2(S_1 - c_{21}S_2)}{d(S_1 + c_{21}S_2)}$$

From these measurements of the inverse T_e gradient scale length it can be seen that for the majority of the profile there is no indication of local T_e flattening (Fig. 2). We are working on a prediction for the scatter of points from the two channel method. This scatter is dominated by the signal to noise ratio of the diagnostic and the spacing between channels.

With smaller spacing the scatter gets larger making interpretation more difficult. This can be improved by sacrificing time resolution. We wanted to have the highest possible time resolution to verify that there is no destruction of confinement on very short time scales. The resulting measurements indicate that there is no evidence of T_e flattening down to a radial resolution of 1 cm and a time resolution of 5 μ s.

If we assume classical diffusion with a step size equal to the island width every time an island "turns on" then we can use the expression $D \propto W^2/\tau$ where $D=1 \text{ m}^2/\text{s}$, W is the maximum radial island width and τ is the average period in which the islands "turn on". This idea should be valid for any mechanism that destroys confinement on a flux surface. Solving for τ and using the minimum resolution of the experiments discussed below of 1 cm gives us an estimate of $\tau \sim 100 \mu$ s for the time between subsequent "turn on's."

Figure 1a. T_e profile with $B_\phi=1.86 \text{ T}$. Compare figure 2a.

Figure 1b. T_e profile with $B_\phi=1.96$ T. Compare Figure 2b.

Figure 2a. Inverse T_e gradient scale length with $B_\phi=1.86$ T. Compare figure 1a.

Figure 2b. Inverse T_e gradient scale length with $B_\phi=1.96$ T. Compare Figure 1b.

Transient Transport

Perturbative transport experiments on TEXT-U have proved to be most productive. The 'cold-pulse' experiments using impurity ablation have revealed significant non-local behavior in electron thermal transport that poses a great challenge to our understanding of thermal conductivity. The reduction in core transport associated with rapid edge cooling¹ is not anticipated in any present theory or model of tokamak transport. The critical data that led to this conclusion is shown in figure 1. The figure

demonstrates that after injection of an impurity at 301 ms, the edge temperature decreases immediately, but the core temperature begins to rise. The subsequent finding of similar behavior on TFTR and the observation of non-local effects in JET confirms the generality of this novel aspect of transport. More generally, these results confirm the utility of perturbations as a technique for exploring transport with the potential for continued surprises! Since we do not even have a conceptual model for the state of turbulence (e.g. a stationary nonlinear saturated state vs. intermittent turbulence near marginal stability), it is essential to search for behavior experimentally which might suggest the dominant physical mechanisms.

Cold Pulse. The $T_e(t)$ at various $\rho = r/a$ are shown in heavy lines. The fit from a nonlocal model is shown dashed.

1 K.W. Gentle, *et al.*, Phys. Rev. Lett. **74**, 3620, 1995

Transitions to Enhanced-Confinement in Limiter Discharges Caused by ECRH

In March of 1995, we observed the first transitions to a state of improved tokamak particle and energy confinement in TEXT that were caused by the introduction of over 300kW of central ECRH. The high-current ($q_a \approx 3$) target discharges were solely limited on either boronized limiter at the top or bottom of the vessel. The temporal phenomenology of the transitions is similar in many respects to L-H transitions. They are initiated at the midplane by a sawtooth crash, then show a sharp drop in the global edge D_α emissions (proportional to the particle source) and a simultaneous rise in the line-averaged electron density $\bar{n}_e$; thus indicating improved particle confinement. The central electron-cyclotron emission (proportional to electron temperature) and diamagnetic energy (proportional to total plasma energy) start to rise, indicating improved energy confinement. However, little improvement in the confinement scaling with plasma density over L-mode is found. The largest fraction of the density increase occurs outside of $q=1$, while the electron-temperature profile increases more uniformly. There is also no clear development of sharp (1-2cm scale-length) edge pedestals in either the density or electron temperature. The radiated power from the core rises slowly following the transition, indicating a more gradual accumulation of impurities. ELMs are not routinely observed in the D_α emission, although sharp spikes in the radiated power from the edge are sometimes observed.

After the transition the plasma potential becomes more negative with respect to L-mode throughout the interior on the plasma high-field side, as measured by the Heavy-Ion Beam Probe (HIBP). In contrast, the interior potential profile on the low-field side does not change observably. The diagnostic has not yet been calibrated to yield values of absolute potential. The broadband interior density fluctuations measured by the HIBP are also found to increase for points measured outside of the approximate $q=1$ surface on either the low- or high-field sides. These novel results are shown in Figure 1. Measurements were performed by holding the HIBP beam stationary at points near $\rho=0.85$ on the low-field side, and by

sweeping the beam along a central chord. These locations are shown on the cartoon of the plasma cross section in Figure 1.

In contrast, a Langmuir probe observing the scrape-off layer (SOL) fluctuations at the top of the plasma sees a significant decrease of turbulent electron temperature T_e and floating potential Φ_{fl} fluctuations during the transition state. The average temperature also decreases, so that $\tilde{T}_e/T_e$ is not much changed. Less of a decrease is observed in the measured average density and density fluctuation levels.

Given the radial variations and poloidal asymmetries that have been observed in these and other TEXT-U discharges, more comprehensive measurements throughout the interior and edge are needed before results from the HIBP, probes, and other TEXT-U diagnostics can be incorporated into a global model of the transition. Such a model will likely require that we determine the spatial and temporal relationship between changes in the radial electric field, the fluctuations, the deuterium and impurity fueling, the rotational velocity shear, and the transport at the transition.

Figure 1

An Improved Ohmic Confinement Regime

Improved Ohmic confinement studies are continuing on TEXT-U ¹. In previous experiments the spontaneous transition to an improved confinement mode has been investigated. The transition occurred in shots with a high level of impurities. A sharp decrease in H_{α} and drop of the SOL electron temperature were detected simultaneously during the transition indicating a possible temperature or neutral flux dependent trigger for the mode. The density was increasing at the edge at the time of transition, thus the drop in H_{α} may indicate a decrease in the peripheral neutral influx. A factor of two to three reduction in the fluctuation-driven particle flux and a 30% reduction in the density fluctuation level observed by Langmuir probes indicates a reduction in edge turbulence leading to improved confinement.

The goals of recent experiments were to achieve a controlled transition to this mode and then make detailed, reproducible measurements of the plasma parameters for comparison with fluctuation analysis results. Plasma conditions were very different than in previous experiments. Boronization efforts to clean the vacuum chamber led to very low levels of residual impurities and a low Z_{eff} . Initially attempts were made to reproduce the controlled transition via neon injection. Density profiles were measured by FIR scattering while profiles of radiation loss were measured by both photodiode detectors and conventional bolometers. It was found that in clean plasma conditions, a moderate injection of neon caused the formation of a MARFE at the high-field side of the tokamak which moved to the top limiter causing a disruption. Diamagnetic measurements showed no increase in the internal stored energy. A strong increase in density fluctuations was measured by the HIBP at the edge of the high-field side of the tokamak during MARFE formation. Thus, this behavior was unrelated to previously measured transitions to improved confinement.¹

It was found in the new series of experiments that the transition to higher confinement occurs in operating regimes with a high toroidal field ($B_t = 25 - 26$ kG) low current ($I_p = 130 - 150$ kA), and high density (n_e close to the density limit of $\sim 5 \times 10^{13} \text{ cm}^{-3}$) achieved by slow constant gas

puffing. Detailed measurements of the density profile (see Fig. 1) shows the formation of a MARFE on the high-field side of the tokamak. However, in this case, the MARFE is suppressed after formation and strong peaking of the density is observed. In general, the behavior of plasma parameters is similar to that seen in the previous transition¹ to improved confinement.

Figure 1. Chord averaged density showing the transition near 200 ms. The units for the vertical axis are arbitrary.

Fluctuations were studied in similar regimes² and variations of the amplitude of the fluctuations seen by FIR, BES and probes were used to explain the changes in the diffusion coefficient during this transition. It was shown by a computation using the ASTRA code³ and a model⁴ that the strong density peaking measured could be described by a reduction of the particle diffusion coefficient (Fig. 2, solid line is diffusion coefficient before transition, dashed line is the coefficient after transition) and that the

reduction is proportional to the measured reduction in the fluctuation power.

Fig. 2. Result of numerical calculation via the ASTRA code³ and the model⁴. Diffusion coefficient before (upper solid line) and after (lower dashed line) transition to improved confinement mode. Also shown are particle diffusion coefficients inferred from fluctuations measured with FIR, BES, and Langmuir probes (normalized to the solid curve).

Future Plans

Further experiments are planned to obtain detailed measurements of the radial distribution of fluctuations. The full array of TEXT equilibrium and fluctuation diagnostics will continue to be applied to this discharge. In particular, we will determine the spatial and temporal relationship between changes in the radial electric field, the fluctuations, the rotational velocity shear, and the transport at the transition.

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Core Transport due to Magnetic Fluctuations

The spatial diffusion of fast electrons created by electron cyclotron resonant heating (ECRH) has been examined using electron cyclotron emissions viewed along nearly vertical chords in the TEXT-U tokamak.^{1,2,3} Enhanced emission at frequencies downshifted from the cold cyclotron frequency is attributed to non-thermal electrons. The emission spectra during ECRH are consistent with the presence of low density suprathermal electrons. Measurements of the radial structure of the emission have confirmed that during ECRH the fast electrons are strongly peaked in the plasma center. By comparing the experimentally measured ECE spectrum with the results of a comprehensive Fokker-Planck calculation, the diffusion of fast electrons has been measured in the plasma core of TEXT-U during electron cyclotron heating. The simulation includes the effects of both magnetic and electrostatic fluctuations on the transport of fast electrons. The experimental spectra are best fit by spectra that include magnetic fluctuations with $\tilde{b} = (2.5-5) \times 10^{-5}$ (Fig. 1). The fluctuation levels appear to weakly increase when comparing discharges with 1, 2 or 3 gyrotrons following the general trend of confinement degrading with increasing auxiliary power. Addition of an electrostatic fluctuation term does not significantly change the results and the electrostatic term by itself cannot explain the experimentally measured data. Uncertainties in the level of RF power, internal toroidal electric field and Z_{eff} profile limit the accuracy of this measurement. However, this measurement indicates that an upper limit can be placed on $\tilde{b}$ in the core of between 3×10^{-5} and 5×10^{-5} . This is in fair agreement with measurements made outside of the TEXT limiter using magnetic probes and with measurements of runaway electron diffusivity in the outer edge of the plasma. Furthermore, this result seems to fit with other experimental observations of fast electron diffusion during lower hybrid current drive using hard X-ray emissions, where the fast electrons are typically better confined than the thermal population. Since a magnetic fluctuation level of 10^{-4} would be necessary in order to explain transport in the core plasma, the magnetic fluctuation levels inferred here are unlikely to be the dominant cause of the transport of thermal electrons in TEXT-U.

Figure 1 VECE data from a discharge heated by three gyrotrons compared to the Fokker-Planck simulation using different levels of magnetic turbulence.

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MHD Suppression

Experiments were initiated using modulated ECH to attempt to stabilize $m=2$ MHD instabilities. An internal pick-up coil was used to provide a timing signal to the ECH system, which then produced microwave pulse synchronous to the rotation frequency of #d. A schematic of the system is shown below:

Initial results using modulated ECH to attempt to stabilize MHD were not successful, the gyrotron system was able to produce ECH pulses synchronized with the MHD rotation frequency, but the ECH beam was heating too far inside the the $q=2$ surface. Data from the initial experiment is shown below:

The application of the synchronized ECH caused the frequency of the MHD to drop, which is an indication of an increase in the magnetic island size. The MHD failed to drop because the Ohmic mode discharge was a significantly lower q compared to the earlier experiments on TEXT, causing the $q=2$ surface to be further outside than was anticipated.

Turbulence Drives

Cross field transport in the SOL is well correlated with the transport due to electrostatic turbulence. The source of the turbulence remains elusive, but the turbulence properties have been identified. One of these may be particularly valuable. The magnitude of $k_{\parallel}$ relative to k_{θ} may suggest a spatial location for the drives. Since parallel wave numbers for the turbulence are small, the turbulence drives may be well separated from the point of observation -- as far away as the divertor plates or the limiter. Hence, turbulence may be due to atomic drives resulting from ionization [1] or radiation [2] near the divertor plates or limiter or due to curvature drives [3] that depend on unfavorable magnetic curvature along only one limited region of a magnetic field line.

Ionization Drive

To understand the ionization drive, simply consider the electron source, $n_e S n_0$, due to the ionization of neutrals. Clearly, a density fluctuation will act through this term to increase the level of fluctuations. The theory of the drive is described in ref 1. In TEXT-U experiments, the ionization drive was sought by comparing regions of different ionization rate within a single tokamak discharge and by varying the ionization rate over a series of discharges. These experiments did not indicate strong evidence for ionization drive, and the predicted transport was more than an order of magnitude smaller than the measured transport. It is concluded that the ionization drive does not play a role in TEXT-U and may not exist at all. The latter point is consistent with a recent critique [4] of the original theory.

Radiation Drive

The growth rate for the radiation drive is [2]

$$\gamma = \frac{2 n_z}{3} \left(\frac{2 I_z}{T_e} - \frac{\partial I_z}{\partial T_e} \right)$$

where n_z is the impurity density, I_z is the cooling rate, and T_e is the electron temperature. In TEXT-U experiments, the effects of the second term were sought. Were the cooling rate to decrease with increasing T_e (as

suggested in the original work on this drive [2]), then the instability would grow. In TEXT-U experiments, T_e in the plasma periphery was modulated with ECRH. The plasma radiation appeared to be in phase with the temperature at the plasma edge, hence the second term of the above equation is not destabilizing. At least in the discharges studied, radiation drive does not have a role in TEXT-U.

Curvature Drive

The toroidal curvature of the magnetic field lines may be a source for turbulence in tokamaks [3]. On the open field lines in the SOL, some fluid modes may be unstable for the appropriate average curvature of the magnetic field lines with respect to the pressure gradient. In a tokamak, curvature is stabilizing on the inner side of the torus (on the high field side of the poloidal cross section) and destabilizing on the outer side (on the low field side).

Figure 1. Curvature drive in a DN discharge

On TEXT-U, curvature drives can be studied by comparing turbulence measurements in two different configurations, poloidally limited and double null (DN). In the double null configuration (see figure 1), the SOL on the high field side (favorable curvature) is effectively isolated from that on the low field side (unfavorable curvature). The growth rate, γ , for the curvature instability at $k_{||}=0$ in each of the two configurations can be estimated using a simple model [3] due to Garbet. The results are shown in Figure 1 where R is major radius, and V_{thi} is ion thermal velocity. For the poloidally limited configuration, $\gamma = 2.5 \frac{R}{V_{thi}}$ for the entire SOL. As shown in figure 2, the turbulence level is as predicted, higher on the low field side (LFS) than on the high field side (HFS). This is consistent with previous findings [5]. A similar experiment in a limited configuration in TEXT-U gave essentially the same fluctuations on both the HFS and on the LFS.

Figure 2. Comparison of HFS and LFS turbulence in a diverted discharge

Conducting Wall Drives

The conducting wall drive arises on open field lines.^{3 2} Fundamentally, it is due to a cross field gradient in the difference in electrostatic potential between the plasma and a conducting end wall in conjunction with end loss and polarization drift. The drive is expected to disappear in the presence of an insulating end surface. To look for the drive, a set of Langmuir/Mach probes was constructed in a probe body that was insulating on one side, and conductive on the other side. There were four probes mounted on each side of the probe body. Two probes on each side were biased to collect ion saturation current and two probes measured floating potential. In the plasma edge, with the magnetic field line terminated on an insulator, a feature was observed at about 100 kHz in the power spectrum of both the floating potential and ion saturation current signal. The data shows that under all circumstances there is a background turbulence (i.e. there is always an instability), but that under conditions apparently associated with an insulating boundary an additional feature appears. Whether this is contradiction to the theory is not clear at this point. The experiment is quite suggestive, but it must be repeated with better control before a conclusion can be drawn. We are not satisfied that the experiments performed were rigorous, because a) the density was

changing, and b) the insulating/conducting boundary was very small. Concerning the density changes, we know from HIBP measurements that a similar feature in the interior (the ballooning feature) is very sensitive to density, and we may simply be observing that the interior ballooning feature extends into the SOL, and that it is very density dependent. Concerning the size of the boundaries, we think it is important that the poloidal extent of the conductor or insulator exceed the product
 (turbulence coherence time) $\times$ (poloidal rotation velocity)

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The Perpendicular Electron Energy Flux Driven by Magnetic Fluctuations in the Edge of TEXT-U

A series of experiments performed on TEXT-U¹ and on other machines² demonstrated that electrostatic turbulence could account for particle transport. The situation concerning energy fluxes is less clear. The edge total energy flux, comprised of both conduction and convection, is more difficult to measure than the total particle flux because of significant losses from other mechanisms such as radiation, charge exchange, and ionization. Separating electron and ion fluxes is difficult because of uncertainties in the edge ion temperature and thus uncertainties in the power transfer between electrons and ions. Similarly the energy flux associated with electrostatic turbulence is more difficult to measure than the electrostatically driven particle flux because of the requirement for precise details of temperature fluctuations. Nevertheless attempts to compare total and electrostatic turbulence driven energy fluxes have been made, and within large error bars, the electrostatic turbulence can explain electron energy flux³.

Another mechanism to explain the anomalous large edge conducted energy flux across the magnetic field is the destruction of magnetic surfaces by magnetic fluctuations. In tokamaks the associated conducted energy flux due to the turbulent magnetic structure has not been measured directly; rather the turbulent magnetic fluctuation amplitude is measured and then a model used to estimate the energy flux. In this work, the link between magnetic fluctuations and cross magnetic field energy transport was measured in TEXT.

Experiment

The ensemble-averaged radial energy flux⁴ is

$$Q_r = \frac{\langle \tilde{Q}_{\parallel} \tilde{B}_r \rangle}{B}$$

where $\tilde{Q}_{\parallel}$ is the fluctuating electron heat flux parallel to the equilibrium magnetic field, $\tilde{B}_r$ is the fluctuating radial magnetic field, and B is the equilibrium field. The ensemble average $\langle \rangle$ is realized experimentally by averaging many time records. Since the phase of the fluctuations is

assumed random over a magnetic surface, the ensemble average approximates a magnetic surface average.

Fig. 1. Low frequency component (averaged over 1 ms) of the parallel heat flux. The repeller gating pulse shows the time window of the measurements. The radial position of the bolometer was $r = 0.283$ m.

The key to measuring the energy flux from fluctuating magnetic field is to obtain $\tilde{Q}_{||}$ and $\tilde{B}_r$ locally within the plasma. For that purpose we have developed a fast, insertable pyrobolometer^{5,6}. The bolometer incorporates pyrocrystals of LiNbO_3 for parallel heat flux measurements and a small magnetic coil for radial magnetic field measurements. The waveform of the parallel heat flux with 1 ms averaging is shown in Fig.1. Due to a high level of electrostatic pickup we were unable to resolve high frequency components of the heat flux; therefore, only low frequency components of the parallel heat flux are available for the analysis. The rms. amplitude of the low frequency parallel heat flux is $Q_{||0} = 80 \times 10^{-4}$

W/m². The spectral power of the radial magnetic field fluctuation is shown in Fig. 2.

Fig. 2. Spectral power of the radial magnetic field fluctuations. The radial position of the bolometer was $r = 0.283$ m.

We estimate an upper limit on the magnetic fluctuation induced heat transport by the following procedure. The above equation for the radial heat flux can be spectrally decomposed as

$$Q_r = B^{-1} \sum_{\omega} |\tilde{Q}_{||}(\omega)| |\tilde{B}_r(\omega)| \gamma(\omega) \cos[\phi(\omega)]$$

where $|\tilde{Q}_{||}(\omega)|$ and $|\tilde{B}_r(\omega)|$ are the spectral amplitudes of the two fluctuating quantities, $\gamma(\omega)$ is the coherence, and $\phi(\omega)$ is the phase shift between the fluctuating electron heat flux and the fluctuating radial magnetic field. First, we assume the spectral amplitudes $|\tilde{Q}_{||}(\omega)|$ are less than $Q_{||0}$. Measurements on MST RFP⁷ as well as the CCT tokamak⁸ show this assumption to be valid. Second, we assume that $\gamma(\omega) = 1$, and a zero phase shift, $\phi(\omega) = 0$, for all modes. Third, we replace the $\tilde{B}_r$ amplitude by its rms value $\tilde{B}_r^{\text{rms}}$. After that, the upper limit for Q_r is

$$Q_{r\text{max}} = Q_{||0} \tilde{B}_r^{\text{rms}} / B$$

For $B = 2.0$ T, $Q_{||0} = 80 \times 10^{-4}$ W/m², and $\tilde{B}_r^{\text{rms}} = 2 \times 10^{-5}$ T, $Q_{\text{rmax}} = 8 \times 10^{-8}$ W/m². This is much less than the actual loss rate at the last closed flux surface, $P_{\text{Ohm}}/A_S = 1 \times 10^{-4}$ W/m². However, Q_{rmax} was measured 13 mm behind the limiter so that the total perpendicular energy flux is reduced from the 10^{-4} W/m² by parallel flow to the limiters. Correcting the loss rate, for the measured scale length for the power loss, results in a total perpendicular energy flux at the location of the pyrobolometer of 0.3×10^{-4} W/m². This is still about a factor of 400 larger than the maximum electron thermal flux associated with magnetic fluctuations. Thus by direct measurement of parallel heat flux and magnetic fluctuations, it has been demonstrated that magnetic fluctuations cannot account for the observed thermal transport in the edge of TEXT.

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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. In a larger sense, our experiments should be considered as a means of developing a concept with the technique which was most appropriate and easiest to implement on TEXT. 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. [[refs - B. Richards, et al., Phys. Plasmas 1, 1606 (1994); Uckan, T., Richards, B., et al., Nucl. Fusion 35 (1995) 487; Uckan, T., Richards, B., et al., J. Nucl. Mater. 220-222 (1995) 663]] The modification of the turbulence should affect the local particle and heat transport; global transport effects will be explored.

Results

Some feedback experiments have been performed during the last year. Signals from the magnetic pickup coils suggest a large degree of broadening of naturally occurring modes in the background turbulence due to the feedback driven power; however, this was not observed on the probe diagnostics. In general, large-scale (global) changes in the core plasma parameters have not been observed to date, and changes in edge parameters were mostly at the 20% or less level and confined to the region near the field lines which connect to the driver probe.

The majority of the effort in the Active Probe work for the year has been spent on studying the coupling of the probe to the plasma and the resulting waves (or signals) which are launched. This was performed by driving a single frequency (30 kHz) signal which is easier to diagnose than the feedback-driven signals. It is felt that if the coupling to the plasma can be improved, it will increase the magnitude of the effects on the edge plasma, with the possibility of then affecting the core parameters.

The results of the work with a single-frequency drive challenge current understanding of the physics of diagnostic probes and plasma sheaths. The size and structure of perturbations generated by the driven probe is different from that predicted with standard probe theory. [[refs - I. H. Hutchinson, Principles of Plasma Diagnostics, Cambridge University Press, Cambridge, (1987); P. C. Stangeby, Phys. Fluids 27, 682 (1984)]] Specifically, we have detected currents driven by the probe tens of meters away from the driver along a field line, and have seen changes in the floating potential (due to a bias which is also applied to the probe) within a small region near the connecting field line (see figure 1). Measurements of the phase of the detected signals using high-speed digitizers indicate that the signal travels at approximately the Alfvén velocity. A large effort is underway to understand the theory behind the coupling of our electrostatic probes to what, therefore, appear to be shear Alfvén waves.

Figure 1: *Potential perturbation 12.6 m away from the Active probe.*

The structure of the probe-induced potential perturbation measured at a triple probe 12.6 m away from the Active Probe along a field line extends about 2 cm radially and 3 cm (10 kA) poloidally. Only the peak at the lower plasma current (on the left) is predicted by field line tracing codes; the second peak appears to occur on the $q=4$ rational surface. A

similar perturbation to the ion saturation current and to the DC floating potential occurs over the same region.

Divertor Modeling for TEXT

In order to achieve a better understanding of our divertor discharges, some effort has been focused on edge plasma modeling in such geometries. A student (X. Bonnin) has been sent for five months at IPP-Garching in Germany to learn how to operate the B2-Eirene code developed there [1, 2], and which has already been used to successfully model the ASDEX-U [3] and TEXTOR machines, as well as being used by the ITER European team [4]. At the end of his stay, the code will be transferred to Texas and runned locally.

The B2-Eirene code consists of the B2 plasma simulation package [5] and the Eirene Monte-Carlo neutral transport program [6; 7]. In B2-Eirene, these are coupled in a fully internal time-dependent [8] fashion requiring no outside user intervention during execution. The features of B2 include solving for the continuity, 3-momentum and energy equations for the electrons as well as all ionization stages of multiple ionic species (i.e. main fuel gas, He ash, intrinsic and/or puffed impurities) on a curvilinear quadrangular mesh following the magnetic field lines. The modular construction of the code allows for simple and rapid modification of the transport laws and coefficients as well as providing run diagnostics and parameter change opportunities during code execution. The code also includes a gradTxB drift term, already operational, and a full neoclassical drift description [9] is being implemented.

The Eirene package, which has already been up and running at TEXT for more than a year [10], allows for a Monte-Carlo description of the neutral species (hydrogen atoms and molecules as well as neutral impurities). The code had already been used in its stand-alone version to obtain relative neutral source intensities and particle confinement times in TEXT-U discharges. It takes care of computing sputtering fluxes at the divertor plates, ionization sources, H-alpha emissivities, and the like.

The two codes, both useful in their own right, provide a complementary picture of divertor edge plasmas. By coupling them, a full description can be obtained. The codes communicate with each other by variable arrays, B2 providing the plasma background quantities on which

the Monte-Carlo neutrals evolve, and Eirene returning particle, momentum and energy sources and sinks due to plasma-neutral and wall interactions. The time-dependent description allows for the study of transient plasma phenomena like Edge Localized Modes (ELMs) [11], radiative instabilities (MARFEs) [12] and short impurity gas puffs.

From the code development point of view, TEXT-U provides new cases exploring corners of parameter space not yet covered by the German activities. Our machine functions in a low-recycling regime, with open divertors and a deep neutral penetration in the main plasma, while ASDEX-U works with a closed divertor and in high to very high recycling conditions. Also, the code had to be generalized to be able to work with connected and disconnected double-null geometries and a new interface with the grid generator Carre [13] was written. Some effort in upgrading the mesh generator itself was also needed. In particular, for biased double-null discharges with high plasma current, the bottom X-point (also called outer or passive X-point) is pushed towards the high field side and can even lie directly on the bottom divertor plates themselves (within positioning errors). In experiment, such discharges are recognizable by a single strike point on the lower divertor plates. These types of geometries, especially with the possibility of varying the X-point to plate distance will provide for valuable recycling studies.

In equatorial single-null discharges (see figure 1a), there is an up-down asymmetry in D_α and impurity emission from the vicinity of the divertor plate. The spectroscopic viewing chords are shown in figure 1a. The radiance measurements and simulations are in figure 1b. The tangent radius of 1b is measured with respect to the center of the magnetic configuration. The degree of asymmetry is independent of plasma current direction, but decreases and eventually reverses with increasing n_e . The divertor plate construction and the magnetic configuration are up-down symmetric, so this configuration is ideal for study of the plasma drives for up-down asymmetries. In a first attempt to understand the measured asymmetry, the B2-Eirene [1] plasma simulation code was used to examine the impact of the $\nabla T \times B$ drift on D_α emission at the divertor plate. The inclusion of the drift correctly predicts the sign of the asymmetry. Addition of carbon impurities (drift + C of Fig. 1b) further enhances the asymmetry and improves agreement with the experimental data. The

increased effect of the $\nabla T \times B$ drift with carbon may simply be due to enhancement of the temperature gradient via radiative losses. However, the dependence on density is not yet understood.

Figure 1. $D\alpha$ emission: simulation and experiment.

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Infrared Imaging on TEXT-U

The main purpose of the infrared television camera diagnostic is to measure the heat flux to the divertor tiles in the tokamak. Present activities include power balance, vertical and toroidal SOL lengths, toroidal and vertical asymmetries. The camera views radially into the machine, imaging the inside back wall of the tokamak.

The development of this diagnostic can be divided into two parts: Automation of the data acquisition process and the development and automation of the temperature measurement and heat flux calculation.

Before this year, data from the infrared television camera was recorded on a VHS VCR and digitized later with a frame grabber on a different computer. The raw temperature data was averaged over an area, and the average heat flux was calculated over that area. The output from the camera was 7-bit, but the VHS format degraded the data to about 6-bit. Due to poor dynamic resolution, this method did not give consistent results when one tried to account for the power into the tokamak. Our camera has been upgraded to 8-bits, and a digital data capture board was built with enough memory to capture video for the entire tokamak shot (≈ 0.5 sec). This digital format allows one to immediately process the temperature data without any degradation.

One assumption commonly made is that the emissivity of the tiles inside the tokamak is spatially uniform. In general, this is not true. Our digital format allows us to map the emissivity and overlay this onto the temperature data to extract the true temperature distribution. This spatial emissivity compensation coupled with the increased dynamic resolution of the camera and the data collection process allows us to quantitatively calculate the heat flux to the divertor tiles inside the tokamak. Since spatial information has not been lost, we have been able to measure the SOL lengths in diverted plasmas. This ability has also allowed us to observe toroidal asymmetries in the heat flux in the tokamak. Since the input power is low in this machine, traditional methods were not able to account for the input power. Our procedure allows us to account for 30-35% of the input power due to the heat flux.

Since thermocouples were not yet installed on the tokamak tiles, we developed several all-optical methods for calculating the emissivity (which changes in time) of the tiles in situ.

Our temperature compensation is different than that which is traditionally employed. The blackbody power falling on our camera detector does not scale as T^4 , because the camera does not have an infinite bandwidth. The integral of the blackbody power distribution function over the bandwidth of our camera (8-14 μ) for our temperature range can be fit to a quadratic. This calibration curve is essential for accurate heat flux measurements.

The heat flux calculation is performed for each pixel and can be processed immediately after the tokamak shot. The calculation is performed in one dimension and can be calculated only seconds after each shot. Currently, the computer which calculates the heat flux is the same one which collects the data, so temperature data is usually viewed during run time.

A 10X telescope was also purchased for the camera, which allows one to observe the heat flux pattern with sub-millimeter resolution. This will allow a more accurate determination of the SOL lengths in the tokamak.

A typical heat flux pattern for a single null diverted plasma is shown in Figure 1. Since, our divertor tiles are located at discrete locations in the tokamak, their curvature varies toroidally. Thus, one observes two discrete strikepoints at each bank of tiles, instead of two toroidally symmetric bands. Immediately, one can see that the strike point on the electron drift direction (upper right spot of Figure 1.) is brighter (by about 50%) than the ion drift direction side. This effect is not yet fully understood but the observation is consistent with other diagnostics on the machine.

Figure 1. Typical heat flux pattern from a single null diverted plasma on TEXT-U.

H_α Fluctuations

On any tokamak, probes are limited to a few fixed locations due to size considerations and their need for direct contact with the plasma. Spectroscopic measurement of line emission provides an alternative to probes that does not suffer from this specific limitation. For example, we have made studies of H_α intensity fluctuations the edge of TEXT-U using a photodiode array (PDA) detector[1]. The optics for the PDA consists of a simple lens and an interference filter to image line emission from the plasma edge onto a 32 element linear photodiode array with unity magnification. Each diode's amplifier provides a constant transimpedance gain in the range of 10^5 - 10^6 V/A up to 100 kHz. The poloidal separation between sample volumes in the plasma is equal to the 1 mm separation between diode centers on the array. The radial distribution of H_α emission, peaked strongly near the last closed flux surface, provides natural radial discrimination in a tokamak. The PDA signal is a chord average over both the focussed and defocussed edges of the plasma, but because the transverse dimension of the viewing chords on the defocussed side, about 20 cm, is much larger than the fluctuation scale lengths, spatial averaging greatly attenuates this contribution.

In previous years, spectroscopic imaging of turbulence has been used in two novel experiments on TEXT-U:

- *A search for ionization-driven turbulence[4].* The SOL is made unique in part by the presence of working gas atoms. A considerable effort has therefore been made to develop the theory of neutral ionization as an instability mechanism which might drive the strong edge and scrape-off layer (SOL) turbulence[5]. Using the PDA, we have made measurements of relative H_α fluctuation levels in regions of varying neutral density. We have seen no evidence of ionization driven turbulence in these experiments.
- *Development of a three sample volume estimate of the spectral density function $S(k,\omega)$ [6]* We have developed an estimate for the spectral density function $S(k,\omega)$ which utilizes data from just three diodes and models the PDA signal as a sum of two modes in k -space corresponding

to the contributions from inside and outside the naturally occurring poloidal velocity shear layer. This method aids in the radial localization of the PDA measurements and may be applied to other TEXT-U diagnostics such as CRECE[7], which has seen evidence of a bimodal wavenumber spectrum in the core.

More recently, spectroscopic imaging has been used to compare fluctuations on the high-field and low-field edges of TEXT-U circular and diverted discharges[8]. Here, a long focal length ($f = 40$ cm) lens was used to view from the outboard midplane, and the entire diagnostic was mounted on an optical rail so that its focal plane could be translated from the inboard to the outboard edge of the plasma.

Cross section of the TEXT-U diverted discharge showing the regions where the PDA was focussed for the inboard/outboard comparison experiments. Also shown are the H_{α} fluctuation power spectra on the two sides of the plasma

The fluctuation levels and correlation lengths were found to be nearly the same on both the high-field and low-field sides of the circular discharge we studied. This is in sharp contrast to the results from a diverted D-shaped plasma, where the fluctuation levels on the high-field side were too low to be measured with this imaging technique. The figure shows the TEXT-U diverted geometry as well as the power spectra derived from the inboard and outboard measurements. The lack of observable turbulence on the inboard edge indicates that curvature-driven instabilities may be important in the SOL, as suggested by Garbet[9]

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Education

The FRC has graduated 70 PhD students since 1966. Currently, we support 25 graduate students. Our graduates are employed at the major fusion labs in the US including, Princeton Plasma Physics Labs, Oak Ridge National Labs, General Atomics, and MIT. As direct employees or in extended-stay collaborations, our graduates have participated in programs in Germany (ASDEX), France (ToreSupra), and the EEC (JET).

Students make a major contribution to our program and are one of the major reasons for the efficiency of the TEXT operation. This year they will contribute approximately half of the FRC posters that will be presented at the 1995 APS-DPP meeting.

Two students received the PhD from the University of Texas based on experimental work on TEXT-U. George Castle completed a study of impurity pellet injection. His thesis was entitled, "The Dynamics of Plasma-Pellet Interaction in TEXT," and he received his PhD in December 1994. He is now employed at Culham Laboratory, Abingdon, UK to do experimental work on Compass. Paul Hurwitz completed the development and benchmarking of a new fluctuation diagnostic and used it to look for evidence of atomic and curvature drives in the SOL of TEXT-U. His thesis was entitled, "Optical Imaging of Turbulence Fluctuations in the Texas Experimental Tokamak-Upgrade," and he received his PhD in May 1994. He is now employed by Cypress Semiconductor in a job commensurate with his PhD. He is the first FRC student to find employment in an industrial job immediately after completing the PhD in the Physics Department though this is a common occurrence for the few FRC students who have completed their PhD in the Engineering Department. We are encouraging our students to broaden their education while at Texas so that they can pursue opportunities of this sort.

The thesis abstracts for both follow.

The Dynamics of Plasma-Pellet Interaction in TEXT

George Castle

PhD, December 1994

Thesis Abstract

The ablation of impurity pellets is studied in the TEXT tokamak. A variety of means are used to diagnose the interaction of the pellets (mostly carbon and lithium) with the plasma. The penetration depths of the pellets are found to agree well with standard pellet ablation models, except for those that burn out in the outer region of the plasma, where it was found that there appears to be an anomalously high heat flux that cannot be accounted for by the standard ablation model. It was also observed that the pellets accelerated in the toroidal direction, opposite to the sense of the plasma current. A model was developed to try to explain the excess pellet ablation and pellet acceleration in terms of an energetic suprathermal electron population. It was found that the data could be self-consistently explained in terms of such a model. Filamentary structures, or striations, were observed in both CCD and 35 millimeter visible light images of the pellet ablation trail. A model for these striations based on finite connection length effects is developed and is shown to be consistent with the data. The theory for several potential diagnostic applications using impurity pellets as a moving probe is developed. A theory is also constructed that describes the pellet as an ablating probe.

Optical Imaging of Turbulence Fluctuations in the Texas Experimental Tokamak-Upgrade

Paul Hurwitz

PhD, May 1994

Thesis Abstract

We have studied scrape off layer turbulence in the Texas Experimental Tokamak - Upgrade using a photodiode array diagnostic (PDA). The device consists of an optical system, an interference filter for selecting appropriate emission, a linear detector array, and a set of electronic amplifiers. Line emission from the main ion species, here H_α or

D_{α} , provides a convenient measure of electron density fluctuations and a natural radial localization to the measurement. We present a detailed comparison of the PDA results with those from a Langmuir probe in the same discharge using a Monte-Carlo simulation of the turbulent phases. While the predicted poloidal correlation length and wavenumbers of the turbulence agree well with the measurements, the predicted fluctuation power is too large and is broader in frequency space than the actual power. The discrepancy is probably the result of a lack of an adequate model for the radial scale lengths of the turbulence. We also developed a three sample volume estimate for the spectral density function designed to detect the presence of two features in wavenumber space. The method is applied to PDA data in the which the two features are the result of contributions from opposite sides of the naturally occurring velocity shear layer near the last closed flux surface. Finally, we used optical imaging to compare the turbulence characteristics on the high-field and low-field edges of circular and diverted discharges. In the circular discharge the fluctuation amplitudes and scale lengths are comparable in both regions. In contrast, the fluctuation levels in the inboard edge of the diverted discharge were too low to be measured with the PDA diagnostic, demonstrating that the source of the turbulence may be localized to the outboard edge.

University Spherical Tokamak Experiment (USTX)

Goal of the experiment

The Fusion Research Center at the University of Texas proposes to design, build, and operate the University Spherical Tokamak Experiment (USTX), a low-aspect-ratio tokamak with major radius $R_0 \approx 0.7$ m, aspect ratio $A = R_0/a \approx 1.25$, where a is the minor radius, and a toroidal plasma current $I_p \approx 1$ MA. USTX is intended to access high beta, high normalized beta, and low collisionality, with plasma properties dominated by the physics of low aspect ratio. It will be devoted to the study of stability, global confinement, local confinement and turbulence properties, and current initiation and current drive. The research will be carried out in collaboration with other laboratories and universities.

Synopsis of the experimental program plan

The flexible design of USTX allows for replacement of the vessel inner cylinder, toroidal-field inner leg and ohmic solenoid, so that arbitrarily small A can be investigated (even including a spheromak configuration). The flexible poloidal field system allows for large variations in plasma shape. A divertor option is included. Should a suitable current drive scheme be found, the toroidal and poloidal field systems will allow a pulse length exceeding two seconds.

Phase I. Build USTX with $A = 1.43$, $I_p \approx 1$ MA (earliest operation in Spring 1998).

- Commission basic diagnostics, control systems, vessel wall preparation techniques.
- Determine OH operating regimes and global confinement properties.
- Explore current initiation schemes with ECH assist and low BT breakdown.
- Investigate scrape-off layer (SOL) parameters.

Phase II. Add 1.25 MW of neutral-beam injection (earliest operation in Fall 1998).

- Perform experiments to determine which $A = 1.25$ option to build for Phase III.

- Design and build new solenoid, TF post and vacuum vessel inner cylinder.
- Determine operational regime limits with $A = 1.43$.
- Categorize at low A phenomena which induce disruptions in a normal- A tokamak.
- Determine confinement properties.
- Compare bootstrap current with theoretical predictions.
- Evaluate whether a subsidiary outer wall is required to obtain maximum beta
- Provide a test bed for non-inductive current-drive studies, e.g., by Univ. of Wisc.
- Determine if the SOL parameters lend themselves to a divertor option.

Phase III. Build and operate $A = 1.25$ option with non-inductive start-up and current drive, and auxiliary heating. Possibly install helicity injection hardware (earliest operation in late 1999).

- Repeat with $A = 1.25$, experiments outlined for Phase II ($A = 1.43$).
- Seek a regime with simultaneous low q , high confinement, high bootstrap fraction, and high current-drive efficiency.
- Add a divertor option.

Deliverable results expected

USTX is designed to be the smallest, least expensive machine capable of:

1. assessing the viability of building and operating a 1 MA inductive-current, neutral-beam heated, low-aspect-ratio tokamak;
2. providing a comparison between physics phenomena occurring at dominantly low aspect ratio and those found at normal aspect ratio;
3. assessing the possible operating regimes of a 1 MA inductive-current, auxiliary heated low-aspect-ratio tokamak;
4. providing scalings for global confinement times in a plasma dominated by low- A physics, especially at high beta, high normalized beta, and low collisionality;
5. comparing beta limits achieved with those expected theoretically;
6. comparing local confinement properties and turbulence properties;
7. assessing different techniques of non-ohmic current initiation;
8. assessing different current-drive techniques;
9. assessing the possibility of producing a very low- $A \approx 1.25$, non-inductive current-driven, auxiliary heated, scaled version of a prototypical low-aspect-ratio reactor;
10. assessing the possibility of divertor operation at low A .

Adequacy of the facilities and staff

The space occupied by the present TEXT-U device can house the USTX device together with two neutral beams (only one is planned and costed in this proposal). The only power supply required but not presently available on site is the specialized high-current OH solenoid supply. All existing TEXT-U and collaborators' major diagnostics, except those based on ECE, can be used on USTX with minor modifications. The engineering and physics team at the Fusion Research Center are capable of operating the proposed USTX. This team currently operates TEXT-U which, with its divertor, three gyrotron systems, diagnostic neutral beam, stochastic-field coil set, and full diagnostic set, is of approximately equivalent complexity. That the team is capable of producing results is demonstrated by its publication record. Training of students and collaboration with colleagues in the Institute for Fusion Studies will be a major part of the research effort.

Adequacy of the budget

USTX, a device suitable for investigating low-A current initiation and ramp-up, equilibria, operational regimes, stability, beta limits, and confinement properties can be constructed for under \$6.28M. This includes a neutral-beam line and ORNL engineering supervision and quality control. Without NBI, the cost is \$5.53M. Initial plasma operation is expected approximately 30 months from initiation of funding, assuming a satisfactory funding profile. Routine operation of USTX will cost \$4M per year.

Items	FY 1996	FY 1997	FY 1998
Total Base Level	\$4,254,875	\$4,018,926	\$4,091,401
USTX Construction	\$2,813,667	\$2,893,333	\$575,000
Total (with NBI & OH P/S)	\$7,068,542	\$6,912,259	\$4,666,401

The impact of this research

The principal gain of low A is that a smaller device can be built to achieve a given fusion power. The predicted loss in confinement at low A

must be offset by the larger plasma current which can in principle be utilized. Assuming the implied hollow current densities can be maintained (by current drive and bootstrap current), then tokamaks with $A \approx 1.25$ reduce the overall machine volume to less than one half that at normal A . In the short term a driven (non-ignited) low- A tokamak is envisioned as a neutron source. D-T reactors of Low- A are also under consideration, but on a longer time scale than those of normal A because of engineering difficulties. These include the design of a toroidal-field-coil inner leg that can withstand the neutron fluxes from D-T reactions without a neutron shield. One proposed solution is to use D-He³, which has a much reduced neutron flux, with $A \approx 2$. This solution is also long term, because of the necessity to produce He³.

Without experimental data, especially on confinement and operational regimes (e.g. the lowest q value which can be maintained) the possible advantages of low A , now seen as $1.25 < A < 2$, cannot be assessed. There are no data in which the physics of low aspect ratio dominates confinement. There are no data in which reactor-relevant dimensionless parameters have been reached. There are no accepted non-inductive current initiation or drive schemes. Therefore the next step in low- A tokamak research should be a flexible, minimum-size, minimum-cost device to address physics issues. USTX is this step.

Elucidation of physics principles

The existing TEXT diagnostics, applied to the plasmas expected in USTX, will permit comparisons between experiment and theory as presented in the 'Deliverables' section. This comparison will be made for equilibrium, stability, confinement, turbulence, etc. Agreement between experiment and theory implies understanding. Dimensionless parameters in USTX are similar to those of a reactor, except for the normalized gyro-radius. Understanding the role of normalized gyro-radius can be performed within USTX itself, or by comparison of the data with that from other machines. USTX directly addresses OFE's interest in research leading to improved fusion power plants, and aims to elucidate the physics principles of such a system.

USTX