General Summary:

Radial currents have been used for generating plasma rotation. Particularly, oscillating torque experiments were performed. The resulting changes in the particle and heat transport were studied.

Controlled variation in the poloidal asymmetry as well as in the plasma potential were induced by biasing. The particle confinement appears to be related to the sign of the radial electric potential. This is connected to the radial electric field and the direction of rotation. The electron diamagnetic drift direction is better. This corresponds to negative electric fields and potential.

This was observed on Macrotor (1981) first, verified on CCT (1990), on TEXTOR (1991), and on TEXT, just during this summer (1992), by both the local operators (Ken Gentle) and by visitors (Bob Taylor).

The poloidal asymmetry was studied in relation to heat confinement. While, we made progress to diagnose the changes in distribution functions using mach probes, the heat transport appears to be related to a number of different issues: (1) particle convection, (2) stability of the contours of constant density and (3) wave transport. At least two of these effects were observed to be non-local.

The wave transport is the most critical item in here. Its excitation is believed to be related to the aspect ratio and its propagation to curvature. The excitation mechanism was identified to be the helical non-equilibrium in a tokamak, ultimately related to trapped particle physics. Instrumentation for determining the direct evidence for the effect of curvature was also developed. Some preliminary results have been obtained, by Brian Wells (graduate student).

DISCLAIMER

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

(1) Deep (7 cm) insertion on mach probes into TEXT have been achieved with boron nitrate carriers without disruptions or probe damage. Noticeable but soft ablation takes place on the electron side only.

(2) Detailed microscopic correlation functions have been measured down to 2 mm (not quite the ion gyro radius on TEXT).

(3) Probe data shows that the perpendicular correlation distance in TEXT is 0.2 cm. The poloidal correlation distance is > 0.5 cm, depending on plasma poloidal rotation.

(4) Radial E-fields have been measured on TEXT and CCT with the same probe and a large similarity exist in ohmic, biased and bifurcated discharges.

(5) Digital Langmuir probe sweepers were developed for TEXT after the CCT sweepers were destroyed on TEXT.
I. ACCOMPLISHMENTS

A. Pulsed radar design, construction, and testing

This diagnostic has great potential for density profile measurement in large fusion devices such as ITER. Its advantages include good time resolution, multiple single narrow-band frequency sources (instead of expensive wide-band sources), single port access requirements, no necessity of poloidal symmetry assumptions in the profile inversion, and the possibility of making fluctuation measurements with near simultaneity. The system works by sending very short pulses of electromagnetic radiation out to the plasma and timing the round-trip delay time. The plasma density profile is then obtained by using multiple frequencies and suitably inverting the data.

A first proof-of-principle pulsed radar system was constructed and tested at UCLA. Since it was intended to ultimately test this radar system at DIII-D, a full scale replica of a port box was used and the plasma simulated by a metal mirror. After several design tests a microwave circuit design was selected that gave maximum returned signal. Laboratory tests of the pulsed radar system were successfully completed by early April 1992 at UCLA. The system was judged to be working very well; measuring distance changes as small as 3 mm in the laboratory. The completed design was then transferred to Task VIIB to be installed and tested at DIII-D under plasma conditions. Work continued on Task IIIB on the technology developed required for a final system to be used on DIII-D and ITER.

B. Amplitude modulated radar design, construction, and tests

Amplitude modulated radar has many of the same advantages listed above for the pulsed radar. It operates in a similar manner, except that instead of very short pulses, it emits a modulated signal, that when suitably analyzed gives the plasma density profile (similar to the pulsed radar several microwave frequencies must be used).

Tests of this design are underway at UCLA. It has been found that it has a much larger sensitivity to spurious reflections than does the pulsed radar. This limits its usefulness at present. It is not known if these problems can be overcome and the design is still under study.

C. TEXT reflectometer design, construction, and tests

Design and tests for a TEXT reflectometer system have been initiated. The design selected used O-mode, and covered densities in the range $10^{12} - 4 \times 10^{12} \text{ cm}^{-3}$. This design
would then cover the interesting edge region of the TEXT tokamak and thus complement the planned H-mode studies and biased probe studies. The design also included protection of the microwave mixers and sources from large levels of radiation present at the start-up of each TEXT discharge. In the past, this radiation has been found to destroy mixers in the proposed frequency range.

D. Laboratory reflectometry experiments

An important part of the Task IIIA program is the fundamental investigation of the relation of the reflectometer signal to density fluctuations within a plasma. Questions have included spatial localization, wavenumber sensitivity, and relation of the measured phase and amplitude signals to the absolute density fluctuation level.

Significant progress has been made in this area and was reported at a number of conferences (1992 IAEA Workshop on Reflectometry, 1992 High Temperature Plasma Diagnostic Conference and 1992 EPS Meeting) as well a paper scheduled for publication in the November issue of Review of Scientific Instruments. Briefly, these results showed that a one dimensional code (described in the next section) is unable to correctly predict the laboratory plasma results. The laboratory findings indicate that the signal is very localized near the cutoff layer and this localization is independent of the plasma fluctuation wavenumber. This contradicts the predictions of the one-dimensional numerical code. Also, the size of the measured signal is from 10 to 20 times larger than predicted by the code and extends to a much higher fluctuation wavenumber.

These results are interpreted as indicating that one-dimensional effects are in fact dominated by 2 and 3 dimensional effects and that consequently one cannot use a 1D code in the presence of these higher dimensional effects. These results are quite controversial indicating that this is still a very active area of research. In particular, one argument against the UCLA results is that at least some of the current experimental systems are in fact, one dimensional and that the 1D code therefore is a good model for them. If the systems are truly one dimensional this would appear to be a sufficient argument, however, from the UCLA laboratory results it is clear that two dimensional (or 3D) effects can be quite important and can dominate the simple 1D effect. Therefore, it seems prudent to determine experimentally whether or not a given experimental system is 1D before applying a code that is known to not describe a system that has 2D effects. It should be noted that these problems generally only appear when one attempts to derive absolute values of the density fluctuation level ($\bar{n}$) from reflectometry data. This is an ongoing area of research that should provide further interesting and useful results in the future.

In addition, new information on the dependence of the reflectometer signal on density scale length are emerging (this is part of the Ph.D. work of S. Baang). Initial results indicate a very different scaling of the signal with scale length than that predicted by simple 1D arguments. These results are being cross-checked and should be available by the APS meeting in November.

E. Final development of numerical full wave model for reflect/plasma interaction

As part of the UCLA effort in fundamental investigation of reflectometry a one-dimensional full wave numerical model has been developed. During the past year, the final development
of this code was completed (this is the master's thesis of Albert Chou). The code has been used in a detailed comparison with experimental work (reported in the section above). It solves the full wave equation in the presence of an arbitrary plasma density profile. It can be used to simulate a wide variety of plasma conditions, ranging from the laboratory to high density tokamak plasmas and including arbitrary density perturbations (e.g. ion acoustic waves).

F. Reflectometry Development and Measurements on the CCT Tokamak

The reflectometry work on CCT continued in the past year. This tokamak is an ideal testbed for several reflectometer experiments including: cross-correlation between Langmuir probes and reflectometer, in/out/top/bottom asymmetries in H-mode transition behavior of simultaneous measurement (via reflectometer/probes) of the effect of AC bias on $\bar{n}$. The significance and results of each of these are discussed below.

The probe/reflectometer comparison focuses on the spatial resolution and response to density fluctuations (in a highly turbulent plasma) of the reflectometer as compared to a Langmuir probe. This is an important and interesting experiment that will give valuable information especially as regards the measurement of absolute density fluctuation levels via reflectometry. The first cross-correlation between Langmuir probes and reflectometer has been accomplished producing a relatively high level of coherence (approximately 0.4). This occurred for what is thought to be a long radial wavelength fluctuation with frequencies in the MHD range. From this, it was estimated that the spatial resolution of the reflectometer was of order the vacuum wavelength or less. However, the radial coherence length of the fluctuation was not taken into account in this estimate so that this distance could be considerably shorter. These investigations are continuing. It is planned to compare the density fluctuation levels measured by the probes to that inferred from the reflectometer using various theoretical treatments (e.g. WKB and the one-dimensional full wave calculation).

In 1990 and under Task IIIA, the first in/out reflectometer system was installed on the CCT tokamak (here in=high magnetic field side and out=low magnetic field side). Significant asymmetries in the H-mode transition properties of the density fluctuations were observed with this system. In 1991 a full poloidal array of reflectometers (in/out and top/bottom) was installed. This system allowed simultaneous measurement of the H-mode transition properties and was the first reflectometer system of this kind. The results to date have shown that the inside does not transition in the same manner as the outside. The inside becomes somewhat unstable, sometimes showing no effect of the transition and sometimes showing a shifting of the fluctuation energy to higher or lower frequencies. The top and bottom channels show an approximately intermediate behavior as compared to the inside and outside positions. This is strong evidence of poloidal asymmetries which could be explained in several ways: a) the fluctuation suppression mechanism (possibly shear in the radial electric field) is poloidally asymmetric, b) the nature of the turbulence is different and so responds differently to the same suppression mechanism, c) there is a strong dependence on another unmeasured parameter, e.g. magnetic shear, or d) a combination of a)–c).

Finally, simultaneous measurements (using reflectometry and Langmuir probes) of the changes in fluctuation level as the plasma is subjected to an A.C. radial current (in an attempt to produce an A.C. H-mode) were made. These measurements showed unambiguously that the fluctuations were suppressed within the plasma and that it was not a simple movement of the plasma column.
II. DISSEMINATION OF INFORMATION

A. Papers and Proceedings Articles


B. Meetings and Presentations


4. 1992 Conference on High Temperature Plasma Diagnostics, Santa Fe, N.M.

(a) "Fundamental Investigation of Reflectometry as a Density Fluctuation Diagnostic," presented by T.L. Rhodes. Invited talk.


III. NEAR TERM PLANS AND GOALS

Amplitude modulated reflectometry is a very attractive method for the determination of density profiles but does have problems with spurious reflections. Other researchers have previously encountered this problem (notably in relation to measurements of the plasma sheath as the space shuttle reenters the atmosphere) and have suggested some possible resolutions. These will be investigated as well as the possibility of other solutions.

The laboratory plasma reflectometer experiments will be continued and expanded. These experiments will include the dependence of the reflectometer signal on the density gradient and microwave frequency and the question of determining the density fluctuation levels directly from reflectometry measurements. These questions are believed to be quite important, both for present and future reflectometer systems. Additionally, a correlation reflectometer will be constructed and tested in the controlled laboratory environment. The correlation reflectometer will then be transferred to CCT for use there. The goal with these tests is to determine the correlation lengths via the reflectometer and compare directly to measurements from Langmuir probes. These tests will be made in both the relatively quiescent laboratory plasma and the highly turbulent CCT plasma.

The measurements on the CCT tokamak have proven very fruitful, providing useful information on both the H-mode transition and on fundamentals of the reflectometer-plasma interaction. It is planned to continue these experiments, in particular the direct comparison of the reflectometer to Langmuir probes. The equipment necessary for these tests (Langmuir probes, bias and isolation electronics, reflectometer system, data acquisition, common port assembly) are mostly constructed and in place on the tokamak. The major goals here are to determine possible methods of measuring density fluctuations via reflectometry and to determine the response (e.g. spatial resolution, wavenumber sensitivity) of the reflectometer in a tokamak environment (one that can be easily diagnosed by probes). The combination of experiments on the controlled laboratory plasma and on CCT is highly complementary with distinct advantages that are not available to any other research group currently working in this area.
PROGRESS REPORT FY 1992
Task IIIB

I. ACCOMPLISHMENTS

A. Advanced Technology Development for Next Generation Reflectometer and Heterodyne ECE Systems

To effectively utilize reflectometry for density profile and fluctuation studies, next generation devices such as ITER require considerable developments in millimeter wave technology. While reflectometry systems would require operating frequencies in the 70-220 GHz range, commercially available millimeter wave devices and components are generally available only up to \( \approx 94 \) GHz. This problem is compounded in the case of heterodyne ECE measurements, which will require operating frequencies up to > 400 GHz. Therefore, a major focus of the Task IIIB program has been to directly satisfy the need for solid state sources and detector arrays as well as the related components to permit these essential diagnostics to be implemented on these machines.

1. Monolithic Frequency Multiplier Arrays

The approach taken at UCLA to provide watt-level solid-state sources and devices for reflectometry and ECE imaging is to utilize quasi-optical spatial power combining of large scale monolithic frequency multiplier diode arrays. Fabricated monolithically on GaAs and InP substrates, the arrays offer a potentially low-cost way to achieve watt-level output power throughout the 60 to 400 GHz millimeter-wave region. The results achieved to date, obtained with a variety of different device structures, have been extremely positive. GaAs barrier NN\(^+\) (BNN) diodes, which are essentially Schottky diodes with a modified doping profile, have produced frequency doubled 2.4-2.6 W pulses at 66 GHz and efficiencies of 7.5\% (see Fig. 1). Using a back-to-back configuration of stacked GaAs Schottky-quantum-barrier varactors (SQBV) devices, whose symmetric C-V curve results in a natural frequency tripler arrays, have produced 4.8-5.2 W at 99 GHz with efficiencies of 2.0\% (see Fig. 2). Preliminary results with resonant tunneling diodes (RTD), whose negative resistance characteristics make them an exciting device for a range of applications from multipliers to millimeter-wave amplifiers and oscillators, have produced frequency-tripled pulses of 33 mW at 99 GHz. Table I provides a brief summary of frequency multiplier development work to date.
Figure 1. Output power and efficiency of a BNN doubler array at 66 GHz, as a function of input pumping power.

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Figure 2. Output power and efficiency of a SQBV tripler array at 99 GHz, as a function of input pumping power.
Table 1. UCLA Frequency Multiplier Results

<table>
<thead>
<tr>
<th></th>
<th># devices</th>
<th>$n \times f_0$ (GHz)</th>
<th>$P_{\text{max}}$ (W)</th>
<th>$\eta_{\text{max}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNN</td>
<td>720</td>
<td>2 $\times$ 33</td>
<td>2.4-2.6</td>
<td>7.5</td>
</tr>
<tr>
<td>Schottky</td>
<td>760</td>
<td>2 $\times$ 33</td>
<td>0.5</td>
<td>9.5</td>
</tr>
<tr>
<td>SQBV</td>
<td>3100</td>
<td>3 $\times$ 33</td>
<td>4.8-5.2</td>
<td>2.0</td>
</tr>
<tr>
<td>MQBV</td>
<td>3200</td>
<td>3 $\times$ 33</td>
<td>1.25</td>
<td>0.7</td>
</tr>
<tr>
<td>RTD</td>
<td>500</td>
<td>3 $\times$ 33</td>
<td>0.033</td>
<td>0.03</td>
</tr>
</tbody>
</table>

2. Electronic and Opto-Electronic Beam Control Arrays

Three Schottky varactor diode beam control arrays have been successfully fabricated. A small array (1.8 cm x 1.0 cm, 4800 diodes) has successfully demonstrated transmittance amplitude control throughout the W and D frequency bands (75-170 GHz); results at 99, 132, and 165 GHz are shown in Fig. 3. The array has furthermore demonstrated high frequency amplitude modulation of a transmitted 165 GHz beam (see Fig. 4), at a rate sufficiently fast for amplitude modulation (AM) reflectometry applications. Such an array is an essential component for a moderate pulse (≈100-300psec) radar reflectometer.

![Figure 3. Experimental beam transmittance as a function of DC bias; the basic form of the curves arises from the array being capacitive at 99 GHz, resonant at 132 GHz, and inductive at 165 GHz.](image_url)
Based upon these encouraging results, a project has been initiated to improve the modulation frequency response to the levels required for moderate pulse reflectometry. By the careful balancing of strip inductance with diode capacitance, a new beam control design has been developed which should be capable of switching short (50-200 ps) pulses of millimeter waves (see Fig. 5).

Figure 4. Transmitted power at 165 GHz as a function of modulation frequency.

Figure 5. SPICE simulation of an electronically controlled millimeter wave beam control array, switched between low transmission and high transmission states.
Replacement of the Schottky varactor diodes in the beam control array with high frequency photoconductors produces a device which can be switched optically rather than electrically. The main advantages of opto-electronic control are ultra short (< 5 ps) switching times, and better electrical noise immunity (control signals transported along fiber-optic cables). Work has now begun on the design and fabrication of a photoconductive diode beam control array on a GaAs substrate. This would be one way to produce the ultrashort pulse which would be used in a single source broadband reflectometer system.

3. ECE Imaging Arrays

Millimeter wave imaging detector/mixer arrays are required for the next generation of reflectometers (i.e. holographic reflectometry) and ECE measurement systems. In addition, these arrays may prove useful for scattering and interferometer systems. Under Task III B, we have two approaches under investigation. The first is a hybrid 16 channel array, using beam lead GaAs Schottky diodes bonded to Yagi-Uda antenna elements with an integrated balun. Single channel video responsivity measurements (see Fig. 6) show an approximate 15% 3 dB RF bandwidth, while single sideband heterodyne measurements yield an IF bandwidth of > 20 GHz. Hot/cold load measurements show a system noise temperature of \( \approx 10,000 \text{ K} \) (15 dB conversion loss) which would permit the imaging of low level MHD fluctuations. The second approach is a monolithic 16 channel array, utilizing planar, monolithically fabricated GaAs Schottky diodes and Bow-tie antenna elements which have been modified for an extended IF bandwidth (2-20 GHz). Scaled model video responsivity measurements (see Fig. 7), show that this structure has an approximate 30% 3 dB RF bandwidth. An appropriate doping profile for the Schottky diode has also been designed.

![Figure 6. Yagi-Uda element video response.](image-url)
One application of these millimeter wave imaging arrays is in the area of advanced, holographic reflectometry. The first planned application of these imaging arrays, however, will be ECE thermal imaging on TEXT, in collaboration with Dr. G. Cima at the University of Texas at Austin. One possible experimental setup is sketched schematically in Fig. 8. Each channel of the line array collects thermal energy, radiated at harmonics of the local electron cyclotron frequency, along a line focus through the plasma. The in vacuum lens is a specially designed dichroic lens with the property that lower frequencies are imaged closer to the lens while higher frequencies are imaged farther from the lens, thus producing a near optimum imaging arrangement. The IF output of each channel of the mixer array is separated by frequency into a number of subchannels, each of which contains the thermal energy emitted at a different radial location along the line of sight of the mixer array channel. Hence, a wide bandwidth, one dimensional imaging array can thus produce a fairly detailed, two dimensional thermal image of the plasma. With a sufficiently low system noise temperature and a relatively short (< 100 μs) integration time, one would be able not only to visualize the shape of the thermal flux surfaces but also study the spatial and temporal evolution of the sawteething central area of the plasma.
4. Nonlinear Transmission Lines

Another promising monolithic configuration for both pulsed and continuous wave millimeter-wave source development for reflectometry is the periodic nonlinear transmission line (NLTL). Periodically loaded with high frequency varactor diodes, a NLTL is able to transform a slowly-rising input pulse into a steeply rising output pulse. In this manner, highly compressed solitons and fast rise-time soliton pulse trains may be generated in response to a large amplitude input pulse. When fed with a large amplitude sinusoidal input wave, efficient conversion of the input power into a large number of harmonics can be effected from a single, high power source. Such frequency "combs" may be used for instantaneous profile coverage as well as for reflectometer fluctuation studies.

Using back-to-back multiple barrier SQBV diodes, we expect to generate short, > 10 V pulses with high efficiency. While this should prove sufficient power for performing moderate pulse (50-250 ps) radar reflectometry, it falls far short of what would be required for ultrashort pulse (< 10 ps) reflectometry on a physically
large device such as ITER. In short/ultrashort pulse radar reflectometry, time-of-flight measurements performed on the reflected pulse are used to compute the distance to the reflecting layer. In the case of ultrashort pulses, however, the wave packet contains Fourier components that are considerably spread out in frequency space. Upon reflection, each component of the incident wave packet therefore reflects from a different spatial location (density) in the plasma thus spreading out the reflected wave packet in time. For the case of X-mode reflectometry in ITER, an incident ≈ 10 ps pulse is returned over ≈ 60 ns in time. As this translates into a reduction of approximately 6000 in the returned signal power, we would require a corresponding increase in transmitted power to maintain the same signal to noise ratio as in the moderate pulse radar reflectometry. We are therefore also examining alternate materials, as summarized in Table 2 below, for their applicability to NLTLs. Two such promising materials are silicon carbide (SiC) and diamond films, which in addition to having extremely high breakdown voltages have considerable resistance to heat and temperature effects as well. The difficulty with these newly emergent material technologies lies in processing; physical resolution and wafer uniformity are still quite poor at this moment in time.

Table 2. Comparison of Potential NLTL Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>( f_{\text{cutoff}} )</th>
<th>( \tau_{\text{width}} )</th>
<th>( V_{\text{break}} )</th>
<th>( P_{\text{out}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.2 THz</td>
<td>4.0 ps</td>
<td>20 V</td>
<td>0.8 W</td>
</tr>
<tr>
<td>GaAs</td>
<td>5.0 THz</td>
<td>1.0 ps</td>
<td>25 V</td>
<td>1.3 W</td>
</tr>
<tr>
<td>( \alpha )-SiC</td>
<td>0.8 THz</td>
<td>6.3 ps</td>
<td>( \approx 400 ) V</td>
<td>( \approx 400 ) W</td>
</tr>
<tr>
<td>( \beta )-SiC</td>
<td>1.8 THz</td>
<td>2.7 ps</td>
<td>( \approx 400 ) V</td>
<td>( \approx 400 ) W</td>
</tr>
<tr>
<td>Diamond</td>
<td>2.1 THz</td>
<td>2.4 ps</td>
<td>( \approx 1000 ) V</td>
<td>( \approx 1000 ) W</td>
</tr>
</tbody>
</table>

B. High Power \( \text{CO}_2/\text{FIR} \) Laser Development for Multichannel Scattering and Interferometry/Polarimetry

The operation of interferometry, polarimetry and collective scattering systems can potentially be considerably improved through recent far-infrared (FIR) laser development work at UCLA. Over the last year, this work has concentrated on improving the output power, stability, and frequency pulling resistance of the FIR laser.
1. Metallic-Waveguide Far-infrared Laser

In order to improve the overall output characteristics of optically-pumped FIR lasers, recent development at UCLA has concentrated on the use of overmoded cylindrical metallic waveguide (smooth bore and corrugated) instead of conventional smooth-bore dielectric waveguide. Laboratory results have shown that waveguide propagation losses, especially at longer wavelengths (i.e. 1.22 mm using $^{13}CH_3F$ isotopic methyl fluoride), can be significantly reduced by the use of such metallic waveguide in the laser resonator. Using a corrugated aluminum waveguide, the maximum output power at 1.22 mm has been increased by approximately a factor of 2. The free-space beam profile and polarization properties are comparable to that obtained using a dielectric waveguide. In the case of the smooth-bore copper waveguide, difficulties with tuning and maintaining the proper cavity mode made operation extremely difficult, thereby rendering the laser unsuitable for plasma diagnostics applications. The improved performance of the optically-pumped FIR corrugated metallic waveguide laser will permit operation of a multichannel 2-D FIR scattering/interferometry diagnostic on the TEXT-Upgrade tokamak.

2. FIR Ring Laser Development

Linear cavity twin-frequency optically pumped far-infrared (FIR) laser systems, such as those developed at UCLA for plasma diagnostics applications, have suffered from frequency pulling induced by feedback of FIR radiation. If the frequency is pulled by only one part in $10^6$, the heterodyne scattered signal is lost in the frequency pulled sidebands. We have now demonstrated that a ring FIR laser, operating in a unidirectional traveling wave mode, is much less affected by external feedback.

The effect of feedback on the frequency stability of linear and ring FIR laser cavities has been investigated quantitatively for the 1.22 mm FIR line obtained by pumping $^{13}CH_3F$. It has been demonstrated that the ring laser operates in a dominantly unidirectional traveling wave mode. In contrast, the linear cavity operates with a standing wave mode and was shown to exhibit the transferred Lamb dip and associated two-photon light shift. The ring laser has been demonstrated to be much less influenced by feedback than the linear cavity, as the feedback radiation interacts weakly with the unidirectional mode of the ring laser cavity. In addition, the two-photon light shift is not present in the ring laser and so leads to further frequency stability compared to the linear laser. Feedback radiation of approximately 2% of the output power resulted in frequency pulling of $\approx$100 kHz in the linear cavity, whereas the effect on the ring laser was negligible.

Prior to application of ring laser cavities to fusion diagnostics, improvements in output power will have to be made as these preliminary studies indicate a lower than expected output power for the ring laser. However, this should be possible with the appropriate optical design. For example, the current system employed four mirrors in the ring cavity which increases coupling losses to and from the dielectric
waveguide. Future designs will utilize only three optical components together with corrugated metallic waveguide which has substantially lower insertion losses than dielectric waveguide at the relevant frequencies.

3. **Stacked CO**₂** Laser System**

Considerable effort has been devoted toward the development of new stacked/tandem CO₂ laser system. A major motivation for this work has been the TEXT 2-D interferometer/scattering system. The new laser will have increased power as well as the ability to serve as the pump source for simultaneous FIR scattering and interferometry.

C. **Amplitude Modulated (AM) Reflectometry Design, Construction, and Testing**

A high frequency sinusoidal amplitude modulation V-band reflectometer system was constructed and tested at UCLA on the same DIII-D mock-up port as the pulse radar reflectometer system. The primary advantage of the AM reflectometry over the pulsed radar reflectometry is that complicated time delay measurements are replaced with much simpler phase delay measurements. In addition, the use of narrowband bandpass filters centered at the modulation frequency can considerably enhance the signal-to-noise of the overall system. Upon testing, however, the system was found to be highly sensitive to spurious reflections, limiting the system resolution to ≈ 5 cm. Further study is underway to attempt to overcome this serious problem.

D. **Holographic Reflectometry and Scattering**

The advanced holographic reflectometry and scattering development has thus far been limited to a study of how Bayesian and maximum entropy methods can be applied to an advanced, holographic, density fluctuation system. Actual laboratory experiments will proceed once the imaging arrays mentioned previously have been completed and fully characterized.

E. **Advanced Phase Locking Techniques for Reflectometry and Scattering**

The goal of this study was to develop a stable and reliable phase locked loop, capable of significantly decreasing the phase noise and improving the coherency of carcinotron backward wave oscillator tubes so that they become suitable as local oscillators (offset in frequency by 0.01%) for heterodyne detection. It had been determined previously that the response time of the 260-295 GHz Thomson CSF carcinotron tube proved to be insufficiently short to overcome the intrinsic
incoherency of the tube to directly phase lock it to a highly stable reference. The approach we had undertaken was to apply the phase locked loop to a 140 GHz reflex klystron, frequency doubled to 280 GHz, to maintain a stable difference frequency with the carcinotron of 200 MHz. The initial system proved unreliable as spurious signals from the carcinotron would frequently knock the klystron out of lock. This problem has now been rectified by first frequency locking the carcinotron to a highly stable 17.4 GHz reference, and then phase locking the klystron to the now frequency stabilized tube.
II. DISSEMINATION OF INFORMATION

A. Papers and Proceedings Articles


B. Meetings and Presentations

1. 1991 APS meeting, Tampa, FL.

(a) "Millimeter and Submillimeter Wave Technology Developments for the Next Generation of Fusion Devices," H-X. King, L.B. Sjogren, N.C. Luhmann, Jr., and D.B. Rutledge. (Poster Presentation)

(b) "Improved Performance of an Optically Pumped FIR Laser Using Metallic Corrugated Waveguide," Y. Jiang, C. Jing, and W.A. Peebles. (Poster Presentation)

2. 1992 International Symposium on Space Terahertz Technology, Ann Arbor, MI.

(a) "Monolithic Millimeter-Wave Diode Array Beam Controllers: Theory and Experiment," presented by L.B. Sjogren.

(b) "Monolithic Millimeter-Wave Diode Grid Frequency Multiplier Arrays," presented by H-X.L. Liu.

3. 1992 Conference on High Temperature Plasma Diagnostics, Santa Fe, NM.


4. 1992 Device Research Conference, Boston, MA.

(a) "Monolithic High-Power Millimeter Wave Quasi-Optical Frequency Multiplier Arrays Using Quantum Barrier Devices," presented by Hong-Xia L. Liu.
TASK VIIA PROGRESS REPORT

FY 1992

Transport Studies on TEXT-Upgrade
Using FIR Scattering-Interferometry and Reflectometry

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CO-PRINCIPAL INVESTIGATORS:
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TASK VIIA: Transport Studies on TEXT-Upgrade
Using FIR Scattering-Interferometry and Reflectometry

Progress made in TASK VIIA with the UCLA FIRSIS [Far-Infrared Scattering-Interferometry System] during the past year can be observed in three specific areas which include; (i) diagnostic installation, upgrades, testing and operation, (ii) first experimental results on the TEXT-Upgrade tokamak, and (iii) physics studies, consisting of data analysis from TEXT and TEXT-Upgrade, which have resulted in journal publications (see bibliography).

UCLA FIRSIS measurements and physics investigations have been performed in support of the overall TEXT-Upgrade program of the Fusion Research Center [FRC] at the University of Texas. This research consists of activities pursued primarily by UCLA with the support of the FRC and, conversely, research activities where UCLA provides diagnostic support for projects initiated by members of the TEXT-U staff. The bibliography provided indicates the major contributions over the past year to the fusion program. These numerous contributions to the TEXT-U program involved a major UCLA commitment of manpower for hardware design, fabrication, installation, testing and maintenance, as well as diagnostic operation, data analysis and generation of publications.

As mentioned in the first paragraph, progress of the UCLA FIRSIS program on TEXT-Upgrade can be measured in three different areas which will now be outlined.

I. Diagnostic Installation, Upgrades, Testing and Operation:

In September and October of 1991, the first scheduled time-period for diagnostic installation on TEXT-Upgrade occurred. During this time, the vertically-viewing UCLA FIRSIS was installed. This system was similar to that which previously existed on the TEXT device. Major changes included (i) a new FIR laser system designed to improve power output and mode quality, and (ii) an optical table mounted at the midplane for the yet to be installed horizontal view.

From November 1991 to April 1992, the UCLA FIRSIS operated in the high-resolution multichannel interferometer mode during TEXT-Upgrade operations. The interferometry mode of operation was chosen over scattering since there was a need, on the part of the TEXT-U group, to know the density profile during machine operations as the dedicated TEXT-U interferometers were not functional. The position of the density profile with respect to the limiters and new vacuum vessel was used to verify and calibrate the magnetic coil positioning loops used in the TEXT-U control system. The centroid of the line-averaged density profile was matched quite well by the magnetic coil monitors throughout the discharge. Details of the
measured density profiles, particle transport estimates from perturbation experiments and investigations of MHD and disruptive effects will be discussed further in the experimental results section.

In April, the UCLA FIRSIS was reconfigured to perform fluctuation measurements via multichannel collective scattering which was continued through June for the vertical view. Features previously observed on TEXT were re-examined in the Upgrade device. In addition, new results were obtained for machine operation with a biased electrode in the plasma edge. The intent was to induce H-mode operation and investigate the transition.

In addition, during the May-June time period, installation of the horizontal view [i.e. a view through the midplane port] was completed. This included alignment of the optical elements and receiver. Initial diagnostic shakedown and operation as a single channel interferometer took place in June-July. By scanning vertically on a shot-to-shot basis, complete up-down density profiles were measured. This permitted examination of the vertical symmetry in the density profiles for the first time. During July-August, the horizontal view was operated in the scattering configuration, as well. Simultaneous operation of both the horizontal and vertical views, in order to perform orthogonal-view cross-beam correlation measurements, was accomplished at this time. The TEXT-Upgrade device is scheduled for shutdown at the end of August, 1992 for a period of at least 6 months for divertor coil installation.

II. First Experimental Results on TEXT-Upgrade with UCLA FIRSIS:

The first major milestone achieved with the UCLA FIRSIS on TEXT-Upgrade during FY92 was the high-resolution measurement of the electron density profile. The vertical view interferometer typically operated with 15 chords which could then be remotely scanned on a shot-to-shot basis. A 60 chord line-averaged profile and its inversion are shown in the paper entitled “Application of High-Resolution Interferometry to Plasma Density Measurements on TEXT-Upgrade” by D.L. Brower et al., Review of Scientific Instruments 63, October 1992. Investigation of the sawtooth-induced density perturbation also permitted an estimate of electron particle transport in the confinement region of the TEXT-Upgrade plasma.

Detailed information on the evolution of the electron density profile has been obtained during large-amplitude tearing instabilities, locked modes and disruptions on TEXT-Upgrade. For tearing instabilities, density islands which can be directly correlated with magnetic islands are observed as a localized flattening about the mode rational surface. As a precursor to a major disruption, the density island rotation is slowed as the amplitude increases even-
ultimately leading to a locked mode, in a fashion analogous to that for magnetic islands. The resulting distorted density profile can persist for several milliseconds prior to the actual disruption. Previously, the effect of tearing instabilities on the plasma magnetic surfaces and temperature profiles has been well documented. Here, for the first time, similar information is available for the electron particle distribution providing further insight into the nature of the instabilities. From this data, a real-time 2-D view of the plasma electron distribution can be generated as the island rotation frequency slows approaching the locked-mode phase and subsequent disruption. Results from this work will be presented at the IAEA meeting in Wurzburg, Germany this fall.

A second milestone involved operation of the horizontal view in the interferometry configuration. By scanning the single channel system on a shot-to-shot basis for reproducible TEXT-Upgrade discharges, a 28 channel line-averaged profile was obtained. Inversion of this data indicated that the profile was symmetric up-down for Ohmic, limiter operation of TEXT-U and that the density profile center matched the magnetic coil position monitors calculation for plasma center. The horizontal view was operated in this mode for various tokamak plasma conditions.

Fluctuation measurements have also been made with the UCLA FIRSIS using both the vertical and horizontal views. Observations of both the ubiquitous broadband turbulence and the quasi-coherent mode on the high-field side have been made and the results appear similar to those previously made on TEXT. The first attempt to perform orthogonal-view cross-beam correlation measurements has been made. This requires simultaneous operation of both views of the FIRSIS during a single plasma discharge at a particular wavenumber. Initial measurements at low k indicate an appreciable cross-coherence for frequencies less than 30 kHz. Results at higher wavenumbers are under active investigation. These measurements are being made to improve the spatial localization of the scattering system.

III. Physics Results:

The major physics results for FY92 can most easily be reviewed by examining the papers listed in the bibliography. These papers include investigations lead by UCLA group members as well as those initiated by members of the TEXT-U group. Two important and active areas of research are briefly described below.

Recent work has concentrated primarily on the studies of disruptions, tearing instabilities and their relation to turbulence and anomalous transport. For example, the physical relationship between naturally-occurring large-scale \((m=2)\) Mirnov oscillations and small-scale
turbulence in TEXT is described. Dependences on plasma profiles (e.g. density and potential), which are strongly perturbed in the vicinity of the magnetic islands, are unfolded. Theoretical expectations for tearing modes and electron drift waves are compared to the characteristics of the measured mode amplitudes and frequency spectra. The dispersion relation for the turbulent density fluctuations, which propagate in the electron diamagnetic drift direction, is observed to be consistent with that of electron drift wave theory when a Doppler shift due to $\mathbf{E}\times\mathbf{B}$ plasma rotation is included. The fluctuation magnitude is found to correlate with the electron density scale length in a manner following mixing length estimates. [see C.X. Yu et al., Physics of Fluids B: Plasma Physics 4, 381-385(1992) and Nuclear Fusion, September 1992]

Long-time precursors of order five times the global energy confinement time are observed for disrupting plasmas at the high-density limit on TEXT. These precursors, occurring well in advance of any change in the plasma MHD activity, are reflected in the electron particle and heat transport along with the density fluctuation level. Enhanced microturbulence is proposed as the physical mechanism for the confinement degradation and subsequent disruption. [see D.L. Brower et al., Physical Review Letters 67,200-203(1991) and Physical Review Letters 68,892(1992)]
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I. INTRODUCTION

In recent years the Task VIIB Program at UCLA has focussed on two primary research activities: (1) The development and demonstration of advanced diagnostic systems essential for both existing and planned fusion devices (2) The utilization of these systems to perform physics R&D necessary for extrapolation to future fusion plasmas. In addition to these technical goals, a third important ingredient in the Task VIIB Program is the training and education of graduate students on a major fusion device, such as DIII-D. In future years, the Task VIIB Program will be focussed solely on the development and demonstration of advanced diagnostic techniques. Continued support for physics R&D will be sought from the DIII-D group and, when applicable, from other sources. I would stress that continued support for utilization of demonstrated advanced diagnostic systems to address important physics R&D issues is crucial for a number of reasons. First, the development of advanced diagnostic systems is of little consequence unless they are utilized. Second, the physics R&D needs motivate further diagnostic development and vice-versa - the interplay has proved essential to the success of the Task VIIB Program.

The Task VIIB Program currently has two full-time research staff permanently located at the DIII-D site - Ed Doyle and Terry Rhodes. The program has already successfully graduated Tom Lehecka in 1989, and currently has one graduate student (Curt Rettig) permanently located at DIII-D. It is expected that Mr Rettig will graduate by the end of the year. In addition, there are two additional graduate students (Mr Kim and Mr Lee) participating in the Task VIIB Program. They will permanently relocate to DIII-D within the next year. Finally, there is an experienced offsite technical support group (S.R. Burns, L. Cardenas, X. Nguyen) who participate on a part-time basis in the design, fabrication, maintenance and installation of diagnostic systems onto DIII-D.

The original goals of the Task VIIB Program were the development and demonstration of two advanced diagnostic techniques on the DIII-D tokamak - (1) FIR heterodyne collective scattering and (2) Correlation reflectometry and reflectometry techniques in general. UCLA currently occupies three radial ports on DIII-D - one for FIR scattering; one for correlation reflectometry and additional fluctuation reflectometer measurements; and one for inside launch reflectometry and density profile measurement. The project has made outstanding progress in the few years since its inception. This progress has been recognized by a number of Invited Talks. For example, in the Fall, Ed Doyle will present an oral paper at the IAEA meeting in Wurzburg and Curt Rettig an Invited paper at the APS Meeting in Seattle.

II. DIAGNOSTIC SYSTEM PROGRESS & PROJECT ACCOMPLISHMENTS

1. Multichannel O-mode Reflectometer.

This system consists of seven, fixed frequency, Gunn oscillators and utilizes homodyne detection. It has primarily been used to simultaneously monitor changes in edge density fluctuations which occur at the L-H transition, near ELMs etc. However, it has also been demonstrated to be useful in monitoring MHD phenomena, and recently has been involved in the identification of toroidal Alfvén eigenmodes on DIII-D (collaborative research with Bill Heidbrink, Irvine). This system has become the workhorse of the L-H transition program and is utilized regularly to support a wide range of the DIII-D Research goals.

2. Broadband X-Mode System.

This system consists of a 50-75GHz BWO which is swept broadband in ~400μs to obtain the density profile on DIII-D. It has also been used as a tunable source to provide complementary fluctuation data to the above O-mode system. In the swept mode, profiles have been obtained
During Ohmic, L and H-mode plasmas, and excellent agreement has been obtained with interferometry and Thomson scattering. However, the system has limited spatial coverage and has not been operated routinely. In addition, in this initial demonstration, remote operation was not employed and data analysis was slow. It is the intention to significantly upgrade this system during the current Grant period to demonstrate routine (day-in/day-out), remote determination of density profiles via reflectometry. This has important consequences for future machines with limited port access, such as ITER and SSAT.

During the last year a new reflectometer system, operating between 33-75GHz has already been installed on the R255 mid-plane port. It utilizes Q and V-band BWOs together with overmoded WR-90 waveguide propagation. The primary initial goal will be to compare and contrast different reflectometer profile measurement techniques and hardware. For example, techniques such as broadband FM radar, AM modulation, and pulsed radar will be investigated. In addition, the launch and receive antenna configurations will be studied to arrive at the optimum design.

The previous profile measurements on DIII-D measured phase to a resolution of only one fringe (2\pi), and this quantization inherently limited the accuracy of the profile inversion. Standard high-resolution techniques, such as heterodyne detection or quadrature detection, are difficult to apply to a broadband swept system. Therefore, during the last year we have focussed attention on the development of advanced software analysis techniques such as complex demodulation and digital filtering. Initial laboratory tests (performed by Mr. Kim) look promising. The intention is to incorporate the necessary software into the DIII-D environment over the summer, perform system tests using the metal shutter on the R255 port as a mirror, and then perform full plasma tests when DIII-D returns to operation early next year. During the last year broadband FM calibration data has already been obtained and so the FM radar system should be ready to go.

During the last year a preliminary investigation of the pulsed radar technique was also performed. This diagnostic technique has great potential for density profile measurement in large fusion plasmas such as ITER. As part of the Task IIIA Program a full-scale laboratory prototype experiment was performed. A mixer/modulator was utilized to generate 250 ps radar pulses which were passed through a mockup of the DIII-D port assembly and reflected from a simple mirror. The system was determined to be working well and was capable of sensing mirror movements as small as 3mm. Installation of the radar system on DIII-D was accomplished in mid-April 1992. This included installation of special high frequency coaxial cables, the mixer/modulator, pulse generator and sampling oscilloscope. The system was initially tested without a plasma. Reflections from both a near-field shutter and from the inside wall of the tokamak were obtained. Results indicated that the system was operating in a similar manner to that envisaged from the prototype tests. Remote computer control of the sampling oscilloscope was accomplished using a Mac IICl and GPIB control providing the ability to sample and store the data. This was important since the DIII-D data system does not currently permit this type of data acquisition. First plasma data was attempted in late April and early May. These initial plasma experiments did not show a clear pulse return from the plasma, although there was some indication of a small return signal. The primary problem was thought to be a result of the averaging algorithm associated with the sampling oscilloscope which causes acquisition of the 250 ps pulse to be accomplished over a timescale of milliseconds. During this time density fluctuations cause the reflecting later to move and therefore spread the reflected return pulse in time thereby reducing the overall signal to noise. A secondary effect was thought to result from non-optimized alignment associated with the duo-static antenna arrangement. In the next run period it is intended to modify the antenna system to operate in a mono-static arrangement. In addition the sampling oscilloscope will either be upgraded or replaced by a timer/counter system to avoid the time averaging problem associated with density fluctuations.

3. Correlation Reflectometer.

An X-mode correlation reflectometer was recently installed onto DIII-D and preliminary data has been recently obtained. The system consists of two, frequency tunable, 50-75GHz BWO
tubes, a common microwave circuit to ensure that the probing beams in the plasma have the same optical path, and a common microwave mixer. The mixer has two output signals, separated by the frequency difference of the two BWOs. A tracking receiver system is utilized to downconvert the high frequency (200MHz-10GHz) component. Using this system the radial correlation length of density fluctuations within the plasma can be inferred by varying the spatial separation of the two reflection layers (by varying the BWO frequencies), while monitoring the cross-coherence of the fluctuation signals from the two channels. Recently correlation lengths have been inferred for fluctuations residing in the plasma core during Ohmic and L-mode operation. The correlation length was found to increase by approximately a factor of four from Ohmic to L-mode. In the coming year the system will be upgraded to allow correlation length measurement in the interior of high density VH-mode plasmas.

4. Inside Launch Reflectometer System.

During the last year a prototype inside launch reflectometer system was successfully developed, installed and operated on the DIII-D tokamak. This work has built upon the first successful demonstration of an inside launch reflectometer system on the CCT tokamak at UCLA. The system will allow the investigation of in/out asymmetries relevant to the understanding of the L-H transition, ELM phenomena, ballooning modes, etc. Currently, the system takes advantage of an existing 60GHz ECH corrugated waveguide system that allows propagation of radiation from the high-field inside region. The reflectometer operates in O-mode and utilizes a 33-50 GHz BWO source. The output radiation from the BWO is coupled quasi-optically into the corrugated guide. Since the existing corrugated guide is designed for operation at 60GHz there are significant insertion losses, especially at the lower frequencies. However, the system operated satisfactorily above~40GHz which allowed comparison with the outside launch O-mode system. Preliminary results indicate that although fluctuations are always suppressed in the outside edge plasma at the L-H transition, this is not observed at the high-field inside edge plasma. It appears that fluctuation levels are virtually unchanged at the L-H transition. This result has great significance for recent theoretical models of fluctuation suppression based on ExB sheared flow. It should allow the different theories to be easily discriminated based on the observed variation in electric field shear and fluctuation suppression.

5. Multichannel Far-infrared Scattering System.

Initially the FIR scattering system on DIII-D consisted of a twin-frequency laser system possessing modest beam power (~5mW), but a well established heterodyne detection technique. The system is similar to that installed at TEXT, except for the radial geometry and much increased propagation distances. This system suffered from frequency pulling effects caused by feedback of radiation to the laser cavity. This has reduced frequency resolution and introduced uncertainty into the measurement. This is of particular relevance in terms of identifying the existence (or not) of ITGD turbulence in DIII-D. Recently the above scattering system was modified by the introduction of a new radiation source. A 280GHz carcinotron tube delivering up to 300mW of power has been integrated into the system together with a feed forward tracking receiver. This combination has resulted in a much improved IF stability and the system has already produced important physics information regarding interior fluctuation levels during H and VH-mode operation. It is capable of monitoring density fluctuations along the entire mid-plane of the DIII-D device. The system is currently limited to poloidal wavenumbers in the range 0.2≤k⊥ρs≤2. The beam geometry dictates a wavenumber resolution (confirmed in the laboratory) Δk ~ 0.7cm⁻¹ and a radial spatial resolution of ±20 cm at k=10cm⁻¹. Heterodyne detection enables propagation of the fluctuations to be determined in the laboratory frame of reference. A new technique has been demonstrated where spatial resolution is enhanced through knowledge of the radial electric field which Doppler shifts the measured spectrum by an amount dependent on location.

The scattering system has confirmed the rapid edge suppression of turbulence first observed via reflectometry on DIII-D. It has also established that interior turbulence levels are
also reduced on a longer timescale following the L-H transition. This reduction appears correlated with flattening of the density profile in the region r/a ~0.8 although it also possible that increased electric field shear plays a role. Finally, it has recently been confirmed that application of a magnetic field produced by an n=1 coil is able to reduce toroidal plasma flow and thereby reduce the \textit{interior electric field}. This reduction in electric field and the associated electric field shear has been shown to correlate with increased interior turbulence levels, as expected qualitatively from the shear decorrelation models. In addition the increase in turbulence was accompanied by spectral broadening and shifts consistent with the CER observed changes in electric field. This is the first clear demonstration of the ability to control turbulence levels in the interior of tokamak fusion plasmas.

\textbf{III. RECOGNITION OF PROJECT ACCOMPLISHMENTS}

As was mentioned briefly in the introduction, the progress of the Task VIIB Program over the last year was recently recognized at both the national and international level. First, Edward Doyle was chosen to deliver an oral talk at the upcoming IAEA meeting in Wurzburg on the topic of "Turbulence & Transport Mechanisms in the Edge and Interior of DIII-D H-Mode Plasmas". Second, Curt Rettig has been selected as an Invited Speaker at the APS Divisional Meeting to be held in Seattle, Washington this Fall. The title of his talk is "Microturbulence Drive/Suppression Mechanisms in DIII-D". We are particularly proud of the achievement of Mr. Rettig since he has achieved this honor while still a graduate student.
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