PROGRESS REPORT
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**"APPLICATION OF OPTICAL FLUCTUATION DIAGNOSTICS TO TRANSPORT STUDIES
IN HIGH TEMPERATURE TOKAMAK PLASMAS"**

by the

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through the

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University of Wisconsin System
750 University Avenue
Madison, WI 53706**

**Raymond J. Fonck
Principal Investigator
S.S. No. 357-44-7464
Phone: (608) 263-7799**

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Progress to date: April 1990 thru May 1991

First data was obtained from the TFTR BES system in May 1990, after the prototype 4-channel system with photomultiplier detectors from PBX-M was transferred to the TFTR Hot Cell. The system was expanded to 16 spatial channels during the Summer 1990 run period, and data of interest was obtained near the end of the run in October, 1990. The most attention has been given to a radial profile data set obtained for an L-mode plasma condition in TFTR, where we characterized the nature of the long-wavelength turbulence seen by the BES diagnostic. We summarize here highlights of the initial run with BES on TFTR. We also give a progress report on support activities at UW.

TFTR BES Experimental Results

The success of the initial BES experiments was paced by overall system development including hardware and analysis software and by the availability of the advanced detector technology constructed at UW. As new higher-sensitivity avalanche photodiodes (APD) became available, they were retrofitted into the existing photomultiplier detector housings. The APD's provided a decrease in the photon statistical baseline of 2-4 times less than the photomultiplier detectors, which allowed us to reduce the lower limit of detectable $\tilde{n}/n$ to 0.2 % or so. By the end of the 1990 experimental campaign on TFTR in October 1990, we had 7 channels fitted with low-noise small-aperture APD's which gave best signal-to-noise ratio (SNR), and 4 channels with larger aperture APD's. While the larger APD's had better SNR than the photomultiplier detectors, calibration drifts have so far precluded their use for low amplitude fluctuations.

The best BES data was obtained in dedicated TFTR experimental runs which provided several reproducible discharges with long flat-top times to allow long integration times for BES and provide enough shots for a detailed radial scan. Only two such runs were accorded the BES experiment in the 1990 campaign, and these runs were used to accumulate initial data from a standard L-mode discharge and a similar supershot condition. The supershot run was done early in the summer, and the BES data was of marginal quality due to the fact that only two of the detectors had been converted to the APD's. The L-mode scan provided a radial profile of $\tilde{n}/n$, radial coherence length measurements from $r/a = 0.5$ to 1.0 , and poloidal coherence lengths at $r/a = 0.7$ (in the confinement region of the plasma) and $r/a = 0.96$ (at the edge). In addition, a controlled variation of injected beam power provided a power scan, and hence effectively a scan in global confinement time. Most of the quantitative BES results come from this L-mode scan sequence, but observations were also made of the supershot condition, a low-field low-current discharge, high β -pol plasmas, and limiter H-mode plasmas.

We note here that each run during this first campaign required hand adjustments of the fiber-detector assemblies in the TFTR Hot Cell to scan the plasma, and hence were very manpower-intensive. The need for Test-Cell access to change poloidal array locations restricted our data sets to poloidal scans at two radii in any given experiment.

The first and one of the more striking findings of the BES measurements is that the power spectrum is concentrated at low frequencies, less than 50 KHz or so, for these long wavelength fluctuations, where $k_{\perp} < 1 \text{ cm}^{-1}$, as indicated in Fig. 1. Higher frequencies are evident in the high-amplitude edge fluctuations and in some other special cases, but the dominance of low frequency turbulence in the plasma core region appears to be an almost universal feature. In the L-mode, $\bar{n}/n$ (integrated over all frequencies) is high at the plasma edge, where $\bar{n}/n \approx 10\%$, and drops rapidly to $< 1\%$ in the confined plasma region, as indicated in Fig. 2. The potential relevance of these fluctuations to the plasma confinement and transport was indicated by the observation that $\bar{n}/n$ rose as P_{inj} increased and concurrently τ_E decreased (Fig. 3).

A sequence of two-point cross-correlations of nearby sightlines allowed a characterization of these low-frequency fluctuations in the hot plasma core region. While they appear to propagate in the plasma ion diamagnetic drift direction in the lab frame, corrections for the Doppler shift in frequency due to the residual plasma toroidal rotation in these balanced injection discharges indicate that the phase velocity of the waves in the plasma frame was very close to zero. That is, the data is consistent with no propagation in the plasma frame. There is strong evidence for a mode propagating in the electron drift direction in the plasma edge region, but it does not appear in the hotter plasma core region.

An important point to recognize is that the entire spectral distribution and spectral characteristics as observed in the lab frame are determined by rotation. Without a systematic scan in rotation speed, we can characterize the properties of these perturbations only by the measured coherence lengths in the radial and poloidal directions. These correlation lengths were found to increase from 1 cm or less in the plasma edge region to values of 5-10 cm in the $r/a = 0.5$ core plasma region. A picture radically different from the usual idea of propagating waves in the plasma thus emerges from the data. Rather, the lab-frame fluctuations appear to arise from relatively large perturbed structures in the plasma frame which rapidly pass by our observation points in the lab frame due to rotation. A check with a time-delayed coherence measurement indicates that these perturbed density structures do not survive a single rotational transit around the torus, and hence have lifetimes of 600 μsec or less.

Qualitatively similar results were found in the low-frequency turbulence observations in the supersonic plasma, but the data quality and quantity is less due to the fewer APD detectors available for that run. Likewise, low-field low-current plasmas used for the TAE mode experiments were studied for their low-frequency turbulence characteristics, and similar results were found.

There may be quantitative differences in the levels of $\tilde{n}/n$ and the absolute coherence lengths between these different regimes, but the variations are more in the range of a factor of two rather than an order of magnitude.

Considerable attention was given to the possibility of beam density fluctuations induced by the high amplitude edge plasma turbulence. Downstream along the beam, this would manifest itself as a very long coherence length fluctuation in the plasma core region. We have found that plasma-induced beam fluctuations are detectable, especially when an interior channel is cross-correlated with a very strong edge channel with high amplitude fluctuations. However, it does not appear in local cross-correlations in the plasma interior, as indicated in Fig. 4, and does not strongly influence the determination of radial coherence lengths. In practice, each data set must be carefully examined to discount this troublesome source of false radial coherence.

The present emphasis in the data analysis effort is concentrating on examining any correlations between the local $\tilde{n}/n$, coherence lengths, and the plasma density and temperature gradients lengths. These relations are of most interest to the theoretical community.

As indicated from the PBX-M prototype experiments, the BES diagnostic is quite efficient in observing local MHD structures in the plasma core region. This capability was used to provide crucial internal observations of the recently discovered TAE mode in TFTR. In particular, BES allowed determination of the radial mode structure and the radially varying poloidal mode number of the TAE mode, thus confirming its identification (cf. Fig. 5). In a similar vein, BES was used to observe radially localized MHD turbulence in the Columbia University high beta-pol experiments on TFTR. There, a clear correlation between the localized turbulence as seen by BES and increased local transport derived from kinetic transport analysis was observed, as shown in Fig. 6.

Detector and Optics Developments

After the TFTR run, visual inspection showed a significant deterioration of the vacuum-vessel optical components of the TFTR BES system. In particular, the internal mirror suffered a degradation in reflectivity by factors of 3 or more, while the vacuum window was coated with an as yet undetermined material which reduced its transmission at 0.5 or less. Both components are to be replaced, and much more selective exposure of the optical system to machine vacuum will ensure longer lifetimes of these components.

After initial tests with cooled photoconductive photodiodes indicated that considerable effort may be required to turn these into viable BES detectors, the BES detector development effort at UW turned its attention to avalanche photodiodes. A low-noise circuit board for the APD and

associated preamplifiers was constructed and retrofitted into the BES detector housings. As mentioned earlier, a total of 7 channels were converted to the small aperture (1.5 mm dia.) APD, while 4 others were fitted with the larger (3.0 mm dia.) APD. This conversion also required the replacement of some collimator lenses with low f-number aspheric lenses. Bench tests showed these detectors to be very sensitive to thermal drifts and self-heating, so a gated high voltage switch was fabricated and sent to PPPL to allow stabilized APD operation. In spite of these efforts, instability in the calibration of the response of the large aperture APD's persists, and is presently under scrutiny. Overall, the introduction of the PAD's reduced the photon statistical noise by a factor of 4 below that of the photomultipliers.

Bench tests at UW confirmed the presence of the excess noise factor in the APD performance (associated with noise in the internal diode gain), and indicated an additional increase in effective quantum efficiency of 2-3 can still be obtained by eliminating the avalanche gain. Since the data showed all relevant fluctuations occurring at low frequencies, we revisited the potential of photoconductive diodes for these experiments. We used a suggestion from a PPPL engineer to develop a very low noise frequency-compensated preamplifier with reactive feedback to allow photon noise limited detection in the 0 -200 KHz frequency range for the intensity levels expected on TFTR. We also found one type of photodiode from EG&G which had a much lower than advertised leakage current. Selection of good diodes from a given lot of diodes allows us to avoid extreme cooling to eliminate leakage current noise. These developments, coupled with a low-noise circuit board layout, have allowed us to produce at UW a prototype next-generation BES detector which is at least two time less noisy than the present BES detectors. This translates directly into an increase in the SNR by at least a factor of two.

BES Tests on Phaedrus-T

A relatively simple two-channel BES diagnostic test stand has been installed on the Phaedrus-T tokamak at UW using the low-power diagnostic beam and very high-throughput optics. In spite of the low beam power (< 30 kW), signal levels comparable to the TFTR BES system are obtained. The main use of the system is presently for tests of the new detectors, as mentioned above, and use of this test data to develop the appropriate analysis algorithm to handle the different noise characteristics of this detector. The Phaedrus-T system has also allowed comparison of $\tilde{n}/n$ observations in the Phaedrus-T edge plasma from both BES and a Langmuir probe. Such measurements are useful for verifying the ability of BES to measure local density fluctuations and to confirm the validity of our atomic models used in converting our intensity fluctuation measurements to local plasma density fluctuation levels. As indicated in the attached presentation on these efforts at the latest TTF meeting, we find very good qualitative agreement in the spectral features of $\tilde{n}/n$ from BES and the probe. Likewise the amplitude of $\tilde{n}/n$ from both measurements appear to agree with each other although more detailed modeling is still in progress. It is

particularly interesting that the probe and BES agree so well since the probe tip was only 3 mm in diameter while the BES sampled volume was 1 cm or more. This again indicates that the majority of fluctuation power is in the long-wavelength range accessible to BES.

We have started a study of the stationarity of the measured turbulence in the Phaedrus-T plasma. That is, we wish to determine if the measured BES spectrum is constant in time or due to bursts of turbulence which is simply averaged over the long sample times on the BES diagnostic. We are developing statistical means of evaluating the large amplitude ($\tilde{n}/n \approx 10\%$) fluctuations in Phaedrus-T to search for variations in the fluctuation spectra. If interesting results are found, the analysis technique will be refined to apply to the smaller scale fluctuations seen on TFTR.

Software Development and Remote Access Project

During the past year, an extensive suite of analysis software modules have been developed by the BES collaboration to allow auto- and cross-correlations and associated power spectra to be calculated with the BES data. Special attention has been paid to the influence of the white photon noise in the spectra and its influence on detectable fluctuation levels and coherence lengths. Complete with graphics displays capabilities, these modules access the BES archived data, and allow power spectra or multiple two-point coherence functions to be derived from the data. Recent activity has centered on fitting of the coherence functions to derive coherence decay lengths and on using time-delayed cross-correlations to explore the effects of rotation on the measured spectra.

The UW-PPPL collaboration on BES has served as the alpha test project for developing a means of participating in large-scale fusion experiments from off-site locations. In the Fall 1990 run, we had a simple program developed at PPPL to allow us to monitor in real time the TFTR shot clock. This, plus the on-line TFTR operator's log and our BES analysis and control software, allowed us to participate and even drive some of the TFTR BES experiments from our UW computer room. This effort has generated considerable interest, and is presently being expanded by extensive software development at PPPL to provide to remote sites the complete flow of information available to on-site investigators in the TFTR control room. Details are available in the attached poster presentation.

Fig. 1. Density fluctuation power spectra at different radii in TFTR L-mode. The horizontal line indicates the zero level due to photon statistics.

Fig. 2. Radial profile of rms density fluctuation amplitude in TFTR L-mode discharge. The limiter is at $R = 325$ cm.

Fig. 3. Local density fluctuation amplitude as function of total confinement time for locations in plasma core and at plasma edge.

Beam Density Fluctuations Induced by Strong Edge Turbulence

Shot = 156348, time = 3.700–3.956sec,
REF CH = CH 6(R= 307.1cm, Z= 0.0cm)

Fig. 4. Radial coherence spectra showing the local decrease in radial coherence, but a long range increase when the strong edge turbulence id used as the reference signal.

TAE Mode: Radial Structure from BES

Fig. 5. Radial structure of Toroidal Alfvén Eigenmode in plasma interior.

BES Observation of Internal MHD Fluctuations

High β -pol: No β collapse; Large Internal Island $\Rightarrow$ Flattening of T_e profile

Fig. 6. Correlation of localized density turbulence in plasma core with local transport increase in presence of large internal magnetic island

Fig. 7. Optical schematic of a conceptual high-throughput spectrometer system.

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