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**Final Progress Report
Thomson Scattering Diagnostic Analyses to Determine
the Energetic Particle Distributions in TFTR**

DE-FG02-92ER54169

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Progress Report on
Thomson Scattering Diagnostic Analyses
to Determine the Energetic Particle
Distributions in TFTR

DOE Grant No. DE-FG02-92ER54169

Lodestar Report LRC-95-48

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Abstract

This report summarizes the work performed under DOE grant titled *Thomson Scattering Diagnostic Analyses to Determine the Energetic Particle Distributions in TFTR*, grant # DE-FG02-92ER54169. Lodestar has been an active participant in the low power Collective Thomson Scattering (CTS) diagnostic at TFTR in collaboration with MIT. Extensive studies were conducted regarding the use of gyrotron scattering as a low cost diagnostic for both energetic ions and alpha particles on TFTR. Our numerical scattering code has been improved and compared with similar code developed at JET. We have participated and assisted in the CTS experiments through onsite visits and have successfully performed most of the data analysis tasks remotely. Through our analysis on the initial data base accumulated, we are able to understand qualitatively the general features of the anomalous large scattered signal, have proposed an explanation for its generation mechanism, and have suggested a potential new use of CTS as an edge diagnostic.

1 Introduction

This report summarizes the work performed under DOE grant titled *Thomson Scattering Diagnostic Analyses to Determine the Energetic Particle Distributions in TFTR*, grant # DE-FG02-92ER54169. Significant progress was made in the understanding of thermal scattering physics near resonance and in the analysis of data under complex experimental conditions. Lodestar has been an active participant in the low power Collective Thomson Scattering (CTS) diagnostic at TFTR in collaboration with MIT. The objectives of the experiment are to perform a "proof of principle" test of CTS in a high performance tokamak, to study the lower hybrid resonance, and to evaluate the performance of CTS as an energetic particle diagnostic. Extensive studies were conducted regarding the use of gyrotron scattering as a low cost diagnostic for both energetic ions and alpha particles on TFTR. In particular, the use of lower hybrid resonance for signal enhancement was carefully investigated. Calculations, numerical simulations and modeling were performed using realistic experimental parameters. Improvements were made of our scattering code, SKATR, and its results were checked with similar code developed by Henrik Bindslev at JET. Experimental data from TFTR shots were analyzed remotely at Lodestar and compared to our numerical results in close collaboration with the MIT gyrotron group (John Machuzak) and TFTR staff.

Our accomplishments can be summarized into three categories: i) preparation and development work, ii) experimental participation, and iii) preliminary data analysis and results.

2 Preparation and Development Work

In preparation of analyzing CTS data from TFTR, a comprehensive plan was carried out at Lodestar to understand the key physics issues relevant to thermal resonance (or near perpendicular) scattering at TFTR and to evaluate its performance as a "proof of principle" CTS diagnostic for the probing of the lower hybrid resonance and the detection of energetic particles. Our existing scattering code was updated and improved. The results of our code was then compared with theoretical predictions and was further cross checked with the results from a similar code developed at JET. Detailed numerical studies and experimental modeling were then performed.

2.1 Code Development and Comparison

Several improvements were made to our scattering code SKATR. First, through collaboration with MIT and JET, interpolation routines, first used by S. R. P. Smith at JET, were incorporated into our code. Such routines are used to speed up calculations of bessel and Z functions. Second, the code was modified for better efficiency, accuracy, and flexibility that allows easier comparison and bench-marking with similar scattering code at JET. Third, higher order thermal correction terms are added for a more complete description of thermal scattering physics near resonance. These terms were first pointed out by Aamodt and Russell [1] to be important near resonance and are now fully included in our scattering code. More details about these higher order terms will be discussed in the following sections.

The code was tested and compared rigorously with similar scattering code developed by Henrik Bindslev of JET. Henrik Bindslev spent two weeks at Lodestar where intensive efforts were made to bench-mark and compare both codes. Perfect agreement were obtained in the calculations of the unscreened current density correlation tensor, $\langle \tilde{j}^{(0)} \tilde{j}^{(0)} \rangle$, the susceptibility tensor, χ , the fluctuation operators, $\hat{S}_\alpha$, the dielectric form factor operators, $\hat{G}_\alpha$. A slightly different approach was used in calculating the scattering function, Σ , and a difference of 5 % was observed in the results. Agreement was also achieved in the calculation of signal to noise ratio and beam-integrated ($k_{||}$ -integrated) scattering function and our results were within 7 % of one another.

The net result, we believe, after such an collaborative effort between Lodestar and JET, is a better understanding of the underlying physics and leads to a much improved thermal scattering code for TFTR, JET, and ITER that is fully functional, efficient, fast, and accurate. A portion of this work was reported in the past APS-DPP meeting at St. Louis [1].

2.2 Scattering Physics

We have made progress in the understanding of the physics of near perpendicular and near resonance scattering off thermal plasmas. The behavior of the total scattering cross section, Σ , at near perpendicular scattering, has been investigated numerically. Based on the original higher order thermal expansion treatment by Aamodt and Russell [2, 3], the fully electromagnetic scattering cross section can be written as

$$\Sigma = \underbrace{\Sigma_{nn}}_{\text{T term}} + \underbrace{\Sigma_{bb}}_{\text{B term}} + \underbrace{\Sigma_{ee}}_{\text{E term}} + \underbrace{\Sigma_{vv}}_{\text{V term}} + \underbrace{\Sigma_{cross}}_{\text{cross term}} \quad (1)$$

The various cross section terms are the Thomson (density fluctuation) term Σ_{nn} , the magnetic field fluctuation term Σ_{bb} , the electric field fluctuation term Σ_{ee} , the velocity fluctuation term Σ_{vv} , and the sum of all the cross coupling term Σ_{cross} respectively. Σ_{vv} contains second order expansion terms that were not included in the first version of our code.

Using our updated and improved code, we have made detailed numerical studies of thermal resonance scattering over the relevant parameter range of TFTR plasmas. Several important phenomena related to the behavior of these terms and their consequences discovered in the course of our investigation will be summarized in the following paragraphs. Although we have performed these studies with various alpha (energetic) particle distribution functions, such as maxwellian, bi-maxwellian, and slowing down distributions, only selected results from using slowing down distributions will be shown here.

First, the various scattering terms such as Σ_{bb} and Σ_{ee} are non-negligible as compared to the Thomson term Σ_{nn} near resonance and must be retained. This was first pointed out by Aamodt and Russell [2] and was confirmed numerically. The importance of non-Thomson terms is particularly important for high density supershot plasmas ($n_e \sim 10^{14} \text{ cm}^{-3}$) at TFTR. An example of this effect is illustrated in Figure 1 where Σ_{nn} , Σ_{bb} , and Σ_{ee} are shown for typical supershot conditions in TFTR. Second, the strength of the various terms depend sensitively on plasma conditions. For example, for lower density cooling down plasmas conditions that are typical of TFTR plasmas after the neutral beams are turned off, the non-Thomson terms are in general weaker as compared to Σ_{nn} . Figure 2 illustrates this point.

Third, the cross terms contribute significantly to the total scattering cross section. As a matter of fact, the sum of the cross terms is in general negative in value which tends to reduce the net cross section. This effect was first pointed out by Henrik Bindslev at JET [9]. This reduction effect is most prominent under TFTR supershot conditions. Figure 3 compares Σ to Σ_{sum} which is the summation of all the terms except the cross terms. It is clear from the figure that the cross terms significantly reduce the amplitude of Σ . This reduction is partially due to the cancellation of two dominant, comparable terms, Σ_{nn} and Σ_{bb} , as a result of their large negative cross product Σ_{nb} (see Figure 1). For lower density plasmas such as that for cooling down plasma conditions, the effect of the cross terms is less prominent and Σ and Σ_{sum} are almost identical. This is illustrated in Figure 4. Under these conditions, Σ_{nn} is in general the most prominent term and its cross products with all other terms are small. As a result, the sum of all the cross terms, although still negative, is much

Figure 1: Plot of Σ_{nn} (dark curve), Σ_{bb} (medium light curve), and Σ_{ee} (light curve) for typical supershot conditions. The scattering angle θ is 20° and the wavevector makes an angle ϕ of 89.7° with B_0

Figure 2: Plot of Σ_{nn} (dark curve), Σ_{bb} (medium light curve), and Σ_{ee} (light curve) for typical cooling down conditions. The scattering geometry and the plasma conditions are the same as that of Figure 1.

Figure 3: Plot of Σ (dark curve) and Σ_{sum} (light curve) for typical supershot plasma conditions. The scattering geometry and the plasma conditions are the same as that of Figure 1.

smaller in value, and the reduction effect is small.

The dependence of Σ , Σ_{nn} , Σ_{bb} , and Σ_{ee} on plasma density can further be illustrated in Figure 5 where the various terms are plotted against density for the same scattering geometry as that of Figure 1. Both Σ_{nn} and Σ_{bb} increase with density but the total cross section, Σ , remains almost relatively the same over a factor of ten changes in density. At high densities ($n_e \geq 6 \times 10^{13} \text{ cm}^{-3}$), Σ_{nn} and Σ_{bb} are large but the reduction from the cross terms are also large. At medium densities ($n_e \sim 5 \times 10^{13} \text{ cm}^{-3}$), Σ and Σ_{nn} are approximately equal. At low densities ($n_e \leq 3 \times 10^{13} \text{ cm}^{-3}$), an interesting phenomenon occurs whereby Σ_{nn} is at a minimum and Σ_{ee} is actually the dominant terms. In this regime, reduction due to cross terms are negligible and Σ is larger than the individual terms.

The behavior of Σ_{nn} at low densities can be understood from the ordering of the various scattering terms as outlined in Aamodt and Russell [2]. Using equation 17a in their paper, the electron density fluctuation, δn^e , as defined in their paper:

$$\delta n^e = \sum_s \delta n^s(0) + \frac{1 - \sum_s \omega_{ps}^2 / \omega^2}{\mathcal{D} / \eta^4} \{ \dots \} \quad (2)$$

ω_{ps} is the ion plasma frequency, $\mathcal{D}$ is the dielectric function, η is the wave dispersion

Figure 4: Plot of Σ (dark curve) and Σ_{sum} (medium curve) for typical cooling down plasma conditions. The scattering geometry and the plasma conditions are the same as that of Figure 2.

Figure 5: Plot of Σ , Σ_{nn} , Σ_{bb} , and Σ_{ee} versus plasma density. The scattering geometry is the same as that of Figure 1.

Figure 6: Plot of Σ , Σ_{nn} , Σ_{bb} , and Σ_{ee} versus the ion frequency factor for supershot condition with the density is fixed at $n_e = 1 \times 10^{14} \text{ cm}^{-3}$ and $\theta = 20^\circ$.

function, the summation is over the ion species, and the expression inside the curly braces $\{\dots\}$ are not shown here. Near resonance, $\mathcal{D}$ approaches zero and the second term dominates. Thus δn^e reaches a minimum when $(1 - \sum_s \omega_{ps}^2 / \omega^2) \rightarrow 0$ or when $\sum_s \omega_{ps}^2 = \omega^2$. The ion frequency factor $(1 - \sum_s \omega_{ps}^2 / \omega^2)$ depends not only on the plasma density but also on the scattered frequency or the angle ϕ that the wavevector makes with the magnetic field B_0 . As ϕ moves away from exact perpendicular or 90° , the scattered frequency ω increases and the factor will also change. This is important in the TFTR configuration where the incident gyrotron beam has a finite beam width that causes ϕ to have an angular spread. We have studied the dependence of the various cross section terms on the ion frequency factor when either the density is changing or when ϕ is changing. The dependence on ϕ for supershot conditions is shown in Figure 6. As the ion frequency factor approaches zero, Σ_{nn} drops sharply as compared to all the terms

2.3 Scaling Studies and Experimental Modeling

The possibility of extracting alpha particles and bulk plasma parameters was studied systematically including resonance and magnetic field effects. Although the presence of the lower hybrid resonance can boost the scattered signal strength by several orders of magnitude, it also complicates the extraction of useful parameters from the antic-

ipated data. The scattering cross section can be written as $\Sigma \propto \mathcal{N}/\mathcal{D}$, where $\mathcal{N}$ and $\mathcal{D}$ are the numerator and the denominator portions of the scattering cross section. For off-resonance and off-perpendicular scattering, $\mathcal{D}$ is approximately constant and Σ depends only on $\mathcal{N}$ which is proportional to the one-dimensional alpha particle velocity distribution function, $f_{\alpha}^{(1)}(\omega/k)$. At near perpendicular scattering, $\mathcal{D}$ is no longer constant and changes rapidly near a resonance and the simple relationship of $\Sigma \propto f_{\alpha}^{(1)}(\omega/k)$ no longer holds.

A more realistic approach, then, is to understand the scaling relationship between Σ and various alpha parameters such as alpha particle density. This study has been carried out over the relevant parameter range for TFTR. An example of the result is shown in Figure 7 where the relationship between Σ and alpha particle density is shown under supershot conditions for $\phi = 88.5^{\circ}$ (dark curve) and $\phi = 87.1^{\circ}$ (light curve). For this particular plot, Σ is integrated over a frequency width of 80 MHz. This frequency width corresponds to the bandwidth of a typical receiver channel used at TFTR. A simple one-to-one relationship between Σ and alpha density n_{α} is observed only at low alpha density ($n_{\alpha} \leq 0.5\%$). At larger n_{α} , Σ appears to saturate and actually decrease in value at further increase in n_{α} . This saturation is partially due to the change in the dielectric function $\mathcal{D}$ at large n_{α} .

Thus given the maximum achieved fusion power at TFTR so far to be about 10 MW and the predicted n_{α} to be about 0.2 % or less in the core of the plasma, the use of lower hybrid resonance for scattered signal enhancement should provide useful information regarding the alpha particle density in the plasma. It should be pointed out here that in general, the relationship between Σ and n_{α} is complicated and can only be evaluated by careful numerical studies over the desired parameter range. Moreover, non-thermal distributions can easily alter the simple correlation between Σ and n_{α} . For example, we have performed numerical studies which indicates that the presence of a small population of energetic electrons commonly found in tokamak discharges will improve the dynamic range of linear dependence of Σ on n_{α} .

The effect of finite gaussian beam width on the scattering cross section has been studied. Due to the scattering geometry where both incident and scattered beams are near perpendicular with respect to B_0 , the scattering cross section, Σ is most sensitive to changes in the parallel wave number $k_{\parallel}$. As a result, our scattering code SKATR was modified to incorporate the effects of finite gaussian beams by numerically integrating Σ over the finite width in the parallel wavenumber $\delta k_{\parallel}$.

Signal to Noise calculations were performed including the effects of finite beam width and also finite receiver channel widths. Actual vacuum beam width, receiver

Figure 7: Plot of Σ versus the alpha particle density n_α for $\phi = 88.5^\circ$ (dark curve) and $\phi = 87.1^\circ$ (light curve).

bandwidths, and measured ECE noise levels were used. For an expected gyrotron output power of 100 W or more and an integration time of 100 - 500 msec, signal to noise ratio of 10 or higher can be obtained through resonance enhancement of signal strength. We believe such calculations are accurate and simulate the expected experimental data realistically. An example of our signal to noise calculation for supershot conditions is shown in Figure 8.

Refraction effects were studied using TORAY, the ray tracing program at Princeton Plasma Physics Laboratory. Existing super-shot data base of TFTR was used for such ray tracing studies. Taken into account experimental constraints such as existing antenna ports and focusing elements, and the desire to center the scattering volume in the plasma core, the optimum antenna launching and receiving angles, and the scattering angles volumes can be determined with minimum refraction. With a cutoff density for X-mode at $n_e = 1.4 \times 10^{14} \text{ cm}^{-3}$ and typical peak super-shot density at $n_e = 9 \times 10^{13} \text{ cm}^{-3}$, refraction effects are important but not detrimental.

We have also explored the possibility of cross-mode scattering (O-X and X-O) at TFTR. Cross-mode scattering has an advantage in that the reduction effect in Σ discussed earlier is reduced. This is due to the fact that in cross mode scattering, Σ_{nn} is weak, the only dominant term is Σ_{bb} , and the resultant cross terms are small. This is similar to the situation for like-mode scattering at low plasma density where Σ_{nn} is the only dominant term. Good signal enhancement can be maintained in cross-

Figure 8: Plot of signal to noise ratio of beam-integrated spectrum for supershot plasma conditions.

mode scattering for ϕ away from 90° over the entire beam-integrated spectrum. This allows good signal to noise ratio to be maintained over a wide frequency range (or the corresponding energy range), thus providing the possibility of extracting useful alpha particle information over an extended energy range. The disadvantage of cross-mode scattering is that the scheme is only useful at low plasma density below the O-mode cutoff. At an operating frequency of 60 GHz, this corresponds to a critical density of $n_e \leq 4.4 \times 10^{13} \text{ cm}^{-3}$. This precludes its use for most TFTR discharges and can be use only selectively such as for probing the edge plasma. Moreover, ray refraction, which complicates data analysis, can be significant even at below critical density. At present, the possibility of cross-mode scattering at TFTR is still under further studied and reviewed.

2.4 Experimental Participation

Many trips were made to TFTR in the course of this contract and research program. The purpose of the trips were to assist in preparation and setup of the experiment and in calibrating and testing the receiver system; to familiarize ourselves with all aspects of the diagnostics, and to be knowledgeable of its capability and its limitations; to participate in the actual experiments and data acquisitions; and to engage in discussion with resident physicists regarding the diagnostics. For example, we have

assisted in the measurement of the noise temperature of each receiver channel and its calibration in collaboration of John Machuzak of MIT. We have participated in the initial testing of the diagnostic and its receiver system using a low power 60 GHz EIO source that was shared with Norton Bretz of PPPL. Although we do not expect to see significant scattered signal with such a low power source, such an exercise did help us to tackle and debug some of experimental issues and concern in anticipation of the eventual operation of the gyrotron. Such issues include the operation and debugging of the multi-channel receiver system, the setting of proper receiver gain levels, and the accuracy of the hardware noise subtraction technique; the proper operation of the chopper and its timing; the level of background ECE noise and its temporal fluctuations; the concern of stray light and its effects on the receiver system; and the process of remote data transfer and analysis.

3 Preliminary Data Analysis and Results

The low power CTS diagnostic at TFTR is maintained and operated by the MIT group headed by Paul Woskov and John Machuzak citeMachuzak. It was original designed for operation at 140 GHz and was modified to operate at 60 GHz. At this incident frequency and with typical TFTR toroidal field at 5 T, the incident gyrotron radiation couples to the second branch of X mode and thus the diagnostic is set for X-X scattering. The gyrotron power was chopped or modulated by a mechanical chopper at a rate of 1 KHz. Raw time series acquired is pre-processed and integrated by a hardware integrator over the chopper open/close time of 0.5 msec to reduce the amount of raw data. Thus the the "raw" data actually stored on the TFTR data system have an effective time resolution of 1 msec (1 complete open/close cycle) and the effective signal to noise ratio is also increased by the factor of $\sqrt{\tau Bw}$ or 200. (τ is 0.5 msec and Bw is the bandwidth of each receiver channel of 80 MHz). When the chopper is closed, the signal detected by each channel is the background ECE noise centered at each channel's frequency band. When the chopper is opened, assuming stray is minimal, the signal detected is the sum of scattered signal plus ECE noise. The difference between the signal detected during each on/off chopper cycle is then the scattered signal. At the design input power of 200 W and integration time of 100 msec, the normal scattered signal level is less than the ECE noise level. As a result, post-integration of the difference of the signal is necessary to enhance the signal to noise ratio of the data. The term "normal" here refers to thermal scattering off stable particle distributions. As will be shown later, the observed signal strength

in many cases was much higher than predicted. Extensive tests were conducted to verify that the enhanced signal level was not due to the direct pickup of stray light.

The diagnostic became operational in November 1994 and we are still in the initial stage of experiment and data analysis. Thus our data base is limited at this time and only preliminary results of analysis and conclusions will be presented here. The data base is further limited by temporary experimental limitations. Most of the data acquired so far are restricted to scattering near the edge. This is due to a malfunction in one of the antenna steering motor, thus restricting the scattering region to be near the outer edge of the plasma, typical at a major radius of about 3.3 m with the center of the plasma to be near 2.6 m. This problem has recently been fixed. Second, the output of the gyrotron deteriorates in time, from an initial output of up to 1 kW to a typical output of 100 W during shots. Given the 6 dB loss through the transmission waveguide, the actual incident power into the plasma is typically about 20 W and not the 200 W as expected. This problem has also been fixed recently by the excellent work of the MIT group. As a result, most of the sample results presented here were acquired under the above mentioned limitations. Nevertheless, through our initial analysis, we are able to draw some preliminary conclusions, to correlate the data with the results of other diagnostic, and to identify a few key physics issues that are crucial to the understanding of the scattering data.

In the remainder of this section, we will first state our initial findings and then illustrates them with sample data and analysis.

Based on the existing data base, several preliminary conclusions can be drawn:

- Good quality or statistically significant data were obtained in only medium to high power neutral beam shots. This has been verified by comparing shots with and without neutral beam heating. In general, the scattered power scales with the neutral beam power.
- The signal level was clearly above what is expected from thermal scattering off stable distributions. This is particularly true for most of the data gathered near the edge. In many cases, the difference can be as large as 2 orders of magnitude. This enhancement of scattered signal appears in both the low frequency end of the spectrum where bulk scattering occurs and in the higher frequency range where energetic particles or charged fusion products are expected.
- The time signature of the data is non stationary in many cases and non-gaussian variations are common. In several shots, time dependent features in the scattered signal near the edge can be correlated with MHD activities in the plasma

core.

- The observed bulk portion of the spectrum appears to be non-thermal and correlates with fluctuations involved with Ion Cyclotron Emissions (ICE) observed at both TFTR and JET near the edge. The bulk signal is also enhanced during the neutral beam pulse as compared to that in the afterglow of the neutral beam pulse.
- Possible identification of alpha particles cannot be concluded at this time due to a limited data base of DT shots in the plasma core. While the signal strength appears to be stronger for DT shots as compared to DD shots in the core, we do not have enough statistics to conclude the alphas has been positively identified.

Shot # 81964 was a high power neutral beam shot (28 MW, beam on from 3 - 4 sec during the discharge). The gyrotron power was pulsed on for a period of 50 msec near the end of the neutral beam pulse from 3.9 - 3.95 sec. The scattering volume was near the edge of the plasma at a density of about $n_e \sim 10^{13} \text{ cm}^{-3}$. The spectrum integrated over the time-period from 3.929 - 3.947 sec is shown in Figure 9. A well defined "shoulder" near 1 GHz is clearly noticeable. Note that each receiver channel is actually at discrete frequencies with bandwidth of 80 MHz each (see Figure 10. For plotting purpose, the discrete data points are joint together to form a continuous curve. the spectrum is shown The corresponding signal to noise ratio (S/N), obtained by dividing the signal over its standard deviation and integrated over the time period from 3.929 - 3.947 sec, is shown in Figure 10. The histogram indicates the location of each receiver channel (80 MHz bandwidth) and the resultant S/N of each channel. Note that above 600 MHz, gaps exist between the receiver channels. Thus this plot is a more realistic representation of the data shown previously in Figure 9. Significant S/N is observed for receiver channels up to 1 GHz. As a matter of fact, S/N remains above 1 up to 2 GHz. As pointed out earlier, this signal strength is much higher than expected from predictions of our numerical thermal scattering code. To fully appreciate the level of signal strength discussed here, the raw data of one of the receiver channel, channel # 10, which is centered at 1.020 GHz, is shown in Figure 11. The graph compares the signal received when the chopper was opened and the gyrotron radiation entered the plasma to the signal received when the chopper was closed and the radiation was blocked from entering the plasma. The difference in the signal level is large and clearly visible even without any post-integration and noise reduction. For comparison, the prediction of our thermal scattering code is shown in Figure 12. Plasma and scattering parameters, appropriate

Figure 9: Time-integrated scattered spectrum for shot #81964.

Figure 10: Time-integrated signal to noise ratio for shot #81964.

Figure 11: Raw data of receiver channel # 10 (centered at 1.020 GHz) for shot #81964. The light curve is for signal detected during chopper-open and the dark curve is for signal detected during chopper-close.

Figure 12: Numerically generated spectrum to simulate the shot # 81964.

for shot # 81964, were used. To simulate the large signal observed beyond the bulk frequency range and into the high frequency channels, two sources of energetic ions with isotropic, slowing down distributions, 120 kV deuterium neutral beam particles and 1 MeV tritons were included. The MeV tritons were included to simulate the presence of DD fusion products (0.8 MeV He^3 , 1 MeV tritons, and 3 MeV protons). For illustrative purpose, only tritons are included here as the birth velocity of He^3 is close to the tritons and the birth velocity of protons is too high for the frequency range of the receivers. It is interesting to point out here that both TFTR and JET have reported on indirect evidence of DD fusion products via the detection of edge Ion Cyclotron Emissions (ICE) [6, 7, 8]. The subject will be discussed in more details later. Qualitatively, the code generated spectrum reproduces the shoulder-like feature near 1.1 GHz (see Figure 9) that represents the birth velocity of the 1 MeV tritons given the particular scattering geometry for this shot. However, the spectrum does not fill in the frequency range from 400 - 600 MHz as shown in the experimental data and that the predicted power level is much lower as compared to the experimental data. For example, near the shoulder region of 1.1 GHz, the code prediction is 2 orders of magnitude lower. This is a major discrepancy and the signal level detected indicates that the scattering process is highly non-thermal. One possibility is that the energetic particles involved in the scattering have anisotropic distributions. This will be discussed in more details below regarding the enhancement of bulk signal.

Another example of the enhanced level of signal strength detected is shown in Figure 13 where the raw data of receiver channel # 1 is shown. This was a DD shot with medium neutral beam power (13 MW). The scattering volume was near the outer edge (~ 3.4 m) of the plasma with a plasma density of about $1.5 \times 10^{13} \text{ cm}^{-3}$. Similar to shot # 81964, the differences in signal levels between when the chopper is opened and when the chopper is closed is large. This example also illustrates the non-stationary signature of the data. A jump in the signal levels was registered near 3.950 sec for both curves.

Fluctuations in ECE are commonly observed as a result of MHD activities in the plasma core. For example, a sawtooth crash in the plasma core will lead to a jump in ECE outside the mixing length of where the crash occurred after a small time delay. For this particular shot, a sawtooth event did occur near 3.946 sec and is shown in Figure 14. The bottom panel indicates the temperature data near our scattering volume on the outside edge while the top panel shows the ECE temperature data near the center of the plasma registered by the ECE multi-channel polychromator diagnostic at TFTR. The diagnostic records noise temperatures at the first harmonic

Figure 13: Raw data of receiver channel # 1 (centered at 60 MHz) for shot #81705. The light curve is for signal detected during chopper-open and the dark curve is for signal detected during chopper-close.

Figure 14: ECE multi-channel polychromator data for shot #81705. The top panel is the ECE temperature data (209.072 GHz) near the scattering volume and the bottom panel is the ECE temperature data (255.424 GHz) near the plasma core. The horizontal scale is time in sec.

of local electron cyclotron frequency. The sawtooth event at the core at 3.946 sec triggered a rise in ECE on the edge at a delayed time of 3.950 sec. The modulation on the curves was artificial and was a result of the chopped gyrotron radiation that interfered with the ECE receivers.

The observation of a sudden jump in signal for both when the chopper was opened and when the chopper was closed (Figure 13) is consistent with the jump in the ECE background. What is interesting for shot # 81705 and quite a few other shots we have analyzed, is that after the jump occurred at 3.950 sec, the chopper-open signal remained non-stationary for another 15 msec or so, registering a second jump in signal near 3.962 sec. The chopper-close signal (or the ECE background), however, did not register similar changes and was quite stationary in time. Thus the enhanced difference in signal observed from 3.654 - 3.966 sec appears to be due to real variability in scattered signal and not a result of fluctuations in background ECE noise level.

The effect of the non-stationary nature of the data can further be analyzed by selective integration and averaging of data. This is illustrated in Figure 15 where time-averaged spectra for two different time segments are shown and compared. The light curve is the integrated spectrum over the time period from 3.925 - 3.948 sec, the period before the first jump in signal was registered. Note that the level 10^{-21} W/Hz is about the detection threshold of the receivers and the scatters of the data from channel to channel shown below this level is due to poor signal to noise ratio. The dark curve is the integrated spectrum from 3.954 - 3.968 sec, the period where non-stationary data occurred and where the ECE background is stationary in time after the first jump. This integration period precludes any effect of background ECE fluctuations. The difference in the spectra is significant, with the largest difference in the high frequency channels, hinting at the possibility that scattering off energetic particles were responsible for the signal detected at these high frequency channels. It has been reported that during a MHD or sawtooth event, energetic particles are expelled from the plasma core. If a small percentage of these energetic particles that reaches the edge has a highly anisotropic velocity distribution, then it is possible that they can cause enhance scattering. This scenario, albeit speculative, is consistent with our observations and results:

- Trigger – an sawtooth crash in the plasma core.
- Source – delayed arrival of bursts of energetic particles.
- Result – enhanced scattered signal in the high frequency channels.

Figure 15: Comparison of time-average spectra for shot #81705. The light curve is the integrated spectrum over the time period from 3.925 - 3.948 sec and the dark curve is the integrated spectrum from 3.954 - 3.968 sec

In conjunction with the multi-channel receiver system, detailed spectra centered on the gyrotron frequency were also obtained using a 200 MHz digitizer. The data gave fine spectral details of the scattered signal in the bulk frequency range (0 - 100 MHz). The spectra were obtained via FFT of 1 msec long segments of time series. For shot # 81705, a spectral peak near 78 MHz that corresponded to the second harmonic of deuterium cyclotron frequency (26 MHz) near the scattering volume was observed. For this particular shot, A notch filter was installed in the front end of the receiver and the first 50 MHz of the data was blocked off. The signal strength was much larger than expected and was consistent with the enhanced bulk signal detected by the multi-channel receiver system.

Figure 16 gives two examples of these ion cyclotron spectra. Shot # 82846 is a DD shot with about 20 MW of neutral beam power and shot # 82847 is a DT shot with similar beam power. The spectra were obtained near the end of the neutral beam pulse for both shots at 4.93 sec. The notch filter was removed for these shots. Both spectra have similar features with peaks at both the fundamental, first, and second harmonics of the deuterium cyclotron frequency near the scattering volume (26 MHz). There is no evidence of any tritium cyclotron peaks in the spectrum for the DT shot (# 82847). The only noticeable difference between the two shots is that

the spectral peaks are slightly weaker in the DT shot. This appears to be a general trend in the limited number of DT shots we have analyzed. In some instances, there are also very low frequency peaks, in the range of few megahertz, such as the ones near 5 MHz present in both of the shots.

The strength of these ion cyclotron harmonic peaks appears to maximize for scattering near the edge. The spectral peaks have well defined center frequencies and the source region for these fluctuations appears to be well localized. This is consistent with similar non-thermal Ion Cyclotron Emissions (ICE) observations at both TFTR and JET [6, 7, 8]. The emissions were typically observed to be localized near the outside edge of the plasma, and were believed to be caused by energetic particles with large banana orbits that intersect the edge region. At TFTR, ICE due to both energetic neutral beam particles and charged fusion products from DD and DT fusion reactions have been reported. It is worthwhile to point out that tests were performed where the gyrotron radiation was blocked from entering the plasma during both the entire chopper open/close cycles to ensure that the signal detected was indeed scattered signal and not direct emissions pickup. Our observations of scattered signal with non-thermal spectral peaks at the ion cyclotron frequencies indicate that there may be density and/or field fluctuations associated with ICE. If this is indeed confirmed with further experiments and analysis, CTS would provide an alternate and powerful diagnostic to study these anisotropic particles and edge localized phenomena.

Although we cannot conclude definitively at this time the positive identification of alpha particles, there are preliminary evidence that alphas were detected. Figure 17 displays the raw data of receiver channel # 1 of shot # 82853 which was a DT shot with about 18 MW of neutral beam power. The neutral beam pulse was on till 5 sec of the discharge and the gyrotron was on from 4.9 - 5.1 sec. The scattering volume was near the center of the plasma at about 2.6 m and the plasma density was about $6 \times 10^{13} \text{ cm}^{-3}$. Near 4.951 sec, both chopper-open and chopper-close signals registered a transient increase, indicating a jump in ECE background, probably due to MHD event in the core. The difference of the two signal levels decreased gradually after the neutral beam was turned off at 5.0 sec. Since we do not have a comparison DD shot for shot # 82853 as a reference to check for evidence of alphas, we have resorted to looking at the difference of the integrated spectra between when the neutral beam was on and when the beam was off. The result is shown in Figure 18. The dark curve is the result of integration over the time period of 4.96 - 5.00 sec and the light curve is the result of integration over the period 5.005 - 5.065 sec. Signal to noise ratio of larger than 1 is observed during beam on up to about 1 GHz while after beam off, signal

Figure 16: Detailed bulk spectra for DD shot #82846 (top panel) and DT shot # 82847 (bottom panel). The horizontal scale is frequency in MHz.

Figure 17: Raw data of receiver channel # 1 (centered at 60 MHz) for shot #82853. The light curve is for signal detected during chopper-open and the dark curve is for signal detected during chopper-close.

Figure 18: Comparison of signal to noise ratios for shot # 82853. The dark curve is the result integrated from 4.960 - 5.000 sec and the light curve is the result integrated from 5.005 - 5.065 sec.

to noise ratio begins to fall below 1 right after 500 MHz. This comparison indicates that, during neutral beam on, there appears to be some evidence of the presence of energetic particles (with energy higher than the neutral beam particles), possibly alphas, that have caused scattered signal in the frequency range from 500 MHz - 1 GHz.

4 Summary and Discussion

In summary, we have investigated in details the subject of low power Collective Thomson Scattering Experiment at TFTR. We have identified the critical physics issues regarding thermal scattering near the lower hybrid resonance and have conducted detailed numerical studies to evaluate its performance and potential as an energetic particle diagnostic at TFTR. We have participated and assisted in the CTS experiments through onsite visits and have successfully performed most of the data analysis tasks remotely. Through our analysis on the initial data base accumulated, we are able to understand qualitatively the general features of the anomalous large scattered signal, have proposed an explanation for its generation mechanism, and have suggested a potential new use of CTS as an edge diagnostic.

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