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on
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Diagnostic in High Performance Tokamaks

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Abstract

This report summarizes the work performed under DOE grant titled *Collective Thomson Scattering Energetic Particle Diagnostic in High Performance Tokamaks*, grant # DE-FG03-95ER54334. Lodestar was an active participant in the low power Collective Thomson Scattering (CTS) diagnostic experiment at TFTR in collaboration with MIT. A simple and effective fitting technique was developed to extract key parameters from the scattered data. Utilizing this new technique, the concept of lower hybrid resonance scattering was adapted for a feasibility study of a low/medium power collective scattering diagnostic for ITER. The implementation and the testing of such a technique for actual parameter extraction using TFTR data, however, was severely limited due to experimental and instrumentation complications. Based on the studies we have performed up to date, it is believed that a combination of non-physics related effects such as multiple wall reflection of incident signal and spectral impurity problem of the gyrotron can account for the anomalous signal strength. A collaborative effort with GA was initiated and a feasibility study of developing and implementing a collective Thomson scattering (CTS) diagnostic for the detection of energetic particles at DIII-D was completed. Specifically, the process of selecting an optimum receiver location for the diagnostic is discussed in details. Results presented here include detailed signal to noise calculations and ray-tracing studies. Critical physics issues and selection criteria are discussed and a procedure to detect anisotropic energetic ion temperatures is also outlined. Favorable results, obtained in our feasibility study, indicate that it should be possible to develop and implement a CTS diagnostic at DIII-D.

1 Introduction

This report summarizes the yearly progress of work performed under DOE grant titled *Collective Thomson Scattering Energetic Particle Diagnostic in High Performance Tokamaks*, grant # DE-FG03-95ER54334. Lodestar was an active participant in the low power Collective Thomson Scattering (CTS) diagnostic experiment at TFTR in collaboration with MIT. A simple effective fitting technique was developed to extract key parameters from the scattered data. In particular, through numerical simulation, it was demonstrated that the alpha particle number density can be extracted rather easily using a few data channels clustered near the lower hybrid resonance frequency. This eliminates previous concern regarding the difficulty of extracting alpha parameters in resonance scattering. Utilizing this new technique, the concept of lower hybrid resonance scattering was adapted for a feasibility study of a low/medium power collective scattering diagnostic for ITER. Based on our preliminary study, such a system appears to be quite feasible and practical. For example, utilizing the low frequency X-mode transmission window of ITER, a 84 GHz gyrotron source with moderate output power of 20 - 30 KW is sufficient for a proof-of-principle test of such a diagnostic. These modest source requirements should provide tremendous cost savings and reduce lengthy source and hardware development and testing time. The implementation and the testing of such a technique for actual parameter extraction using TFTR data, however, was severely limited due to experimental and instrumentation complications. In particular, large broadband scattered signal, with signal strength typically 10 - 20 dB larger than predicted, was observed over a large frequency range. Nevertheless, through realistic numerical modeling and thorough data analysis, steady progress was made in the understanding of the source of this anomalous signal. Based on the studies we have performed up to date, it is believed that a combination of non-physics related effects such as multiple wall reflection of incident signal and spectral impurity problem of the gyrotron can account for the anomalous signal strength. A collaborative effort with GA was initiated and a feasibility study of developing and implementing a collective Thomson scattering (CTS) diagnostic for the detection of energetic particles at DIII-D was completed. Specifically, the process of selecting an optimum receiver location for the diagnostic is discussed in details. Results presented here include detailed signal to noise calculations and ray-tracing studies. Critical physics issues and selection criteria are discussed and a procedure to detect anisotropic energetic ion temperatures is also outlined. Favorable results, obtained in our feasibility study, indicate that it should be possible to develop and implement a CTS diagnostic at DIII-D.

In the remainder of this report, we will summarize our progress on: data extraction and numerical studies (Sec. 2), ITER study (Sec. 3), TFTR data analysis and modeling (Sec. 4), and GA feasibility study (Sec. 5).

2 Data Extraction and Numerical Studies

It is well known that in the off-resonance, electrostatic approximation, the scattering function, S_{es} , is proportional to the 1-D velocity distribution along the incident wavevector $\vec{k}_o$,

$$S_{es} \propto \frac{1}{|\epsilon|^2} \sum_i^n n_i f_i(v) \quad (1)$$

ϵ is the dielectric function of the plasma. The total scattering function S_{es} results from the summation of contributions from electrons and all ionic species. For energies much greater than thermal and for Salpeter parameter greater than 1, the energetic particles or the alphas give the dominant contribution and $S_{es} \propto n_\alpha f_\alpha$ and alpha parameters can easily be extracted from the scattering data.

Near resonance such as in the case when $\omega \sim \omega_{lh}$, the dielectric function approaches zero and the scattering function becomes

$$S_{es} \propto \Psi(\omega) \sum_i^n \frac{n_i f_i(v)}{n_i \partial f_i(v) / \partial v} \quad (2)$$

where $\Psi(\omega)$ is a Lorentzian shape factor of the form

$$\Psi(\omega) = \frac{1}{\pi} \frac{|\Gamma|}{(\omega - \omega_{lh})^2 + \Gamma^2} \quad (3)$$

Thus a simple one-to-one mapping of S_{es} to f_α cannot be made in general for near-resonance scattering and alpha parameters cannot be easily extracted as in the off-resonance case.

Through extensive numerical studies, a simple fitting procedure has been identified where this complication can not only be circumvented, but also be taken advantage of for parameter extraction. This procedure relies on several characteristic of near-resonance scattering at TFTR:

- the lower hybrid spectral peak frequency is sensitive to bulk plasma density.
- the signal strength of the peak is insensitive to alpha particle density.
- the finite spatial beam width of the incident radiation leads to finite $k_{||}$ or off-resonance contribution to the scattering function S_{es} .

The procedure involves several steps. First, the receiver channel where the lower hybrid feature is captured is identified and the center frequency is recorded. Since the resonance peak amplitude is large (see Equation 2, this channel should easily be identified. In general,

this is the first channel where sharp rise of signal away from the bulk is detected. Second, given that the peak amplitude is insensitive to alpha number density (see Equation equation:res, the peak amplitude is used as a calibration point. This is the first data point or the pivot point used for the fitting procedure. Third, the signal amplitudes of successive channels in the high frequency side are then recorded. Away from the lower hybrid peak, resonance contribution decreases rapidly as illustrated by the Lorentzian factor given in Equation 3 as finite $k_{\parallel}$ contributions result in increasing Γ or damping. This serves to effectively broadens or weakens the resonance and results in the transition of non-resonance scattering as described by Equation 1. Numerical simulations indicate that the logarithmic signal power of successive channels decreases linearly as a function of frequency. As a result, the data can be compared with code prediction and alpha parameters can be extracted quickly by simple least square fitting technique.

Figure 1 illustrates this technique where the simulated scattered spectra are shown for 3 different values of alpha densities of 0.02, 0.2, and 2 % respectively. The histograms simulates the discrete receiver channel data with finite frequency resolution and the solid line is the fitted straight line with the lower hybrid channel as the pivot point. Projected parameters for the TFTR-ERS regime were used and slowing down velocity distribution for alphas was assumed for this simulation. While the power of the lower hybrid resonance peak remains relatively unchanged over the changes in alpha density, the slopes of the fitted lines over the successive channels has changed systematically. This is shown more clearly in the next figure where only the fitted lines are plotted (Figure 2a). Given the magnetics information from other diagnostics, the bulk density information from the frequency of the lower hybrid peak, the alpha particle density can be obtained. Similarly, various velocity distributions may perhaps be differentiated using the same technique. This is illustrated in Figure 2b where maxwellian distribution was used instead of slowing down distribution. For the same alpha particle density used, the slopes of the fitted lines for the two distributions are sufficiently different.

The accuracy of the fitting procedure depends on the number of channels used. Clearly, only channels with signal to noise ratio of greater than one can be used and the number of usable channels is then limited by the incident pump power, integration time, and alpha particle number density. For TFTR, a minimum of 3 channels can be achieved for a modest input power of 1 KW. This is near the limit of the output power range of the MIT 60 GHz gyrotron tube employed for the low power CTS diagnostic currently online at TFTR.

3 ITER Study

The feasibility of implementing a high power CTS diagnostic for ITER is usually studied under the consideration of several important criteria. These criteria include:

- accessibility issues – avoidance of cutoffs and resonances.
- signal to noise issues – maximizing source power output and minimizing plasma or ECE noise.
- hardware and source availability – development time and cost constraints.
- physics and propagation issues – minimizing refraction, Faraday rotation, and ellipticity complications.

The result of such studies usually point to the need for very high source power in off-resonance scattering. For example, for operation within the low frequency X-mode transmission window, the typical power requirement is about 1 MW or higher and long pulse (≤ 1 sec) operation. Depending on the source frequency, this requires possibly lengthy and costly hardware development. The use of lower hybrid resonance for signal enhancement, on the other hand, can eliminate the need for such hardware development.

Utilizing the new results described in Section 2, the concept of resonance scattering was adapted for a feasibility study of a low/medium power collective scattering diagnostic for ITER and the characteristics and features of such a system are summarized below.

3.1 Accessibility and Frequency Requirements

Given the latest ITER operating parameters, the low frequency X-mode transmission window is still available and lies in the frequency range of 50 - 90 GHz. A source frequency of 84 GHz was chosen for our study. Such a frequency can operate for densities up to $n_e \leq 2.4 \times 10^{14} \text{ cm}^{-3}$ for 6 T field and up to $n_e \leq 2 \times 10^{14} \text{ cm}^{-3}$ for 5 T field.

3.2 Signal to Noise and Source Power Requirements

Even at elevated electron temperature of 20 - 25 keV range projected for ITER, ECE noise near 84 GHz (below the electron cyclotron frequency) is small and is not expected to be greater than 100 eV. Signal to noise ratio of greater than 1 can be achieved for adjacent channels away from the lower hybrid resonance with modest source power of 20 - 25 kW and integration time of 50 msec.

3.3 Source and Hardware Availability Requirements

The modest power output can easily be accomplished with present technology and requires no lengthy and costly development. Hardware, receivers, and various components are standard off the shelf items at these power level and frequency. It is noteworthy to point out that the selected frequency of 84 GHz falls within the frequency transmission window for atmospheric sensing and a quick survey indicates that gyrotrons and gyro-amplifiers with similar specifications are already in operation in this area.

3.4 Physics and Propagation Issues Requirements

At near-resonance scattering geometry, propagation distances and refraction effects are minimized. Moreover, at frequencies near 84 GHz, the two propagation modes, O and X-modes, are not degenerate and are distinct from one another, thus reducing Faraday rotation and ellipticity effects.

3.5 Data Analysis and Parameter Extraction Requirements

The technique developed and described in Section 2 can easily be adapted for extraction of alpha parameters.

In essence, based on our numerical studies, near-resonance CTS diagnostic is observed to be a viable and practical diagnostic for energetic and alpha particle measurements. It is a good and economical alternative to the high power off-resonance CTS system. The theoretical and physics issues have been well studied and understood. The system requires very modest source power of 20 - 30 kW and thus requires no major hardware and source development. The issues of data analysis and parameter extraction are taken care of. Such modest power output will also reduce potential possibility of interference with other diagnostics. As ITER operation parameters evolve and change, such a system can be upgraded, modified, or replaced economically.

4 TFTR Data Analysis and Modeling

A significant portion of time and effort were devoted to the understanding and analysis of TFTR collective Thomson scattering (CTS) data. The characteristics of the data, based on the limited CTS data gathered so far, are very different than those of code predictions and can be summarized as follow:

- the signal is extremely broadband, with bandwidth typically greater than 1 GHz.
- the signal strength is typically 10 - 20 dB larger than prediction.
- the data do not show clear evidence of the lower hybrid resonance feature.
- the signal strength appears to correlate with neutral beam injection power and frequently exhibits non-stationary behavior.
- there is little observable difference between DD and DT shots and the presence of alphas has not been positively identified.

To make sense of the observed data and to explain the anomalous broadband signal, a series of numerical studies, which incorporate various experimental effects and physics issues, were performed. Some of the effects simulated are summarized below and more details of the studies were presented in last year APS-DPP meeting [1] at Saint Louis, Missouri, and in a recent review of CTS experiment at TFTR [2]. It is fair to point out that while the lower hybrid resonance feature has not been confirmed definitely at TFTR, recent results from Wendelstein-7 [3] high power CTS experiment has clearly identified the spectral feature. The application of the Lodestar full electromagnetic code to the published results give reasonable good qualitative agreement.

4.1 Effects of Nonthermal Beam Ions

Given the fact that the signal strength scales with the neutral beam injection power, one possibility is that the presence of nonthermal beam ions may cause enhance scattering. To simulate this effect, an inverted beam distribution function was used in the scattering code:

$$f_o = \frac{1}{\pi^{3/2} v_{T\perp} v_{T\parallel}^{1/2} (1 + \gamma \lambda \tau)} \left(e^{-v_{\perp}^2/v_{T\perp}^2} e^{-v_{\parallel}^2/v_{T\parallel}^2} - \gamma e^{-v_{\perp}^2/(\lambda v_{T\perp}^2)} e^{-v_{\parallel}^2/(\tau v_{T\parallel}^2)} \right) \quad (4)$$

$v_{T\parallel}$ and $v_{T\perp}$ are the parallel and perpendicular (with respect to the magnetic field) thermal velocities; γ , λ , and τ are parameters that determine the width and depth of the hollowness

of the distribution. The result of one such simulation is shown in Figures 3a and 3b where a comparison is made between slowing down beam and inverted beam distribution in fitting to actual data from shot # 81874. The dots shown in the figures represent experimental data points. The simulation results, based on thermal scattering physics, indicate that such inverted distributions do tend to smear out the lower hybrid resonance spectral feature. However, it is also clear from Figure 3b that such distributions, if stable, cannot account for the anomalous signal strength observed.

4.2 Effects of Energetic Electrons

The presence of energetic electrons can give broadband signal in the frequency of interest. Such energetic electrons are commonly observed during the initial ohmic phase build up of the plasma but are normally quenched at later times. To account for the signal strength observed requires a few percents of MeV range electrons during the neutron beam injection phase. Such abundance of energetic electrons appear to be unlikely and details of the study [1, 2] will not be presented here.

4.3 Effects of Finite Gyrotron Linewidths – Direct Stray Light Pickup and Scattering

In most CTS studies, assumptions were typically made that the incident radiation frequency is discrete and spectrally pure. In reality, all incident radiation sources have finite spectral linewidths. Although the halfwidths can be quite narrow, typically in the range of few kilohertz to tens of kilohertz, the effects are non-negligible. For example, consider a Lorentzian lineshape given as

$$P_o(f) \sim \frac{\Delta f}{f - f_o)^2 + \Delta f^2} \quad (5)$$

P_o is the incident power, f_o is the incident frequency, and Δf is the halfwidth. For f_o of 60 GHz, Δf of 50 KHz, and a frequency offset of 1 GHz gives a power reduction of over 90 dB. Although this is an insignificant amount of power for most applications, it is nonetheless non-negligible as compared to scattered signal. For example, stray light level of a milliwatt will corresponds to a power level of picowatt at a frequency offset of 1 GHz and is comparable to typical predicted scattered signal level strength. The finite linewidth also alters the spectral details of the scattered signal. Based on recent gyrotron linewidth measurements by the MIT group, the finite linewidth could indeed be a serious experimental limitation and the use of 50 KHz as halfwidth is not unreasonable. Since most of this study

involves detail comparison between numerical results and non-plasma (vacuum) shot data, details of the results [1, 2] will not be presented here.

4.4 Effects of Multiple Wall Reflections and Scattering

Due to cost constraint, the present TFTR-CTS experimental configuration does not include either beam or viewing dumps for proper termination of incident beam and the reduction of stray light. Moreover, at the gyrotron operating frequency that lies within the low frequency X-mode transmission window, the plasma is transparent to the radiation and absorption is negligible. Although every attempt was made to reduce the pickup of stray light, it remains to be a serious concern. A combination of finite gyrotron linewidth and multiple wall reflections of incident light and signal may account for the data observed. Such effects were simulated numerically and Figures 4a and 4b show the result of one of this study. Again, shot # 81874 was used to compare with the numerical result. Good agreement was observed in terms of signal level and spectral feature up to about 900 MHz.

4.5 Effects of O-mode Leakage and Cross Mode Scattering

Although universal polarizer was used to select the desire polarization (X-mode) and the results were checked, small amount of mode leakage (O-mode), typically -30 dB down, does persist. Under typical TFTR operating parameters, the leaked O-mode are either cutoff or near cutoff and are strongly refracted. Depending on the location of the receivers (bottom-inside or bottom-outside), it may be possible for the leaked O-mode to be picked up by the receivers by direct refraction. A series of raytracing studies were conducted to check such a possibility. For the typical bottom-inside location of the receiver, refraction was observed to bend the incident beam away from the receiver. The only possibility of leaked O-mode to reach the receiver is by a combination of refraction and reflection. There is also the possibility for cross mode (O-X) scattering but numerical studies showed that this would not be sufficient to account for the observed signal level.

4.6 Effects of Finite Beam and Scattering Volume

The incident gyrotron beam is a focus gaussian beam with a finite spatial extent. To a good approximation, the beam shape in vacuum can be described by a beam function W

$$W(k_{\parallel}, k_{\perp}) = \frac{\pi w_o^2}{2 \cos \theta/2} e^{-\frac{w_o^2}{8} \left(k_{\parallel}^2 + \frac{k_{\perp}^2}{\cos^2 \theta/2} \right)} \quad (6)$$

($k_{\parallel}$ and $k_{\perp}$ are the parallel and perpendicular wavenumbers, w_o is the beam waist and θ is the scattering angle. The resultant scattering cross section, Σ_{tot} , is then given by

$$\Sigma_{tot} = \frac{\int \int W(k_{\parallel}, k_{\perp}) \Sigma(k_{\parallel}, k_{\perp}) dk_{\parallel} dk_{\perp}}{\int \int W(k_{\parallel}, k_{\perp}) dk_{\parallel} dk_{\perp}} \quad (7)$$

The beam waist for TFTR is 10 cm in diameter. As the waist narrows, perhaps due to anomalous focusing by localized plasma turbulence, the lower hybrid resonance feature can be smeared out. Details of this study have been reported [1, 2].

4.7 Summary

In summary, the low power TFTR-CTS diagnostic has yielded inconclusive results so far regarding the detection of alpha particle and the lower hybrid resonance features. As described in the numerical modeling and data analysis results above, this is probably due to a combination of non-physics related limitations such as finite gyrotron linewidths and multiple wall reflections. If such limitations can be eliminated or reduced, a medium CTS system is still a viable and excellent option for consideration for ITER implementation. This is supported by the numerical studies conducted at Lodestar that demonstrates the ease of extracting key alpha particle parameters via fitting technique and the feasibility, advantages, and flexibility of such a system in the 84 GHz model study.

5 GA feasibility study

This section summarizes some of the results of a feasibility study of developing and implementing a collective Thomson scattering (CTS) diagnostic for the detection of energetic particles at DIII-D. Specifically, the process of selecting an optimum receiver location for the diagnostic is discussed in details. Results presented here include detailed signal to noise calculations and ray-tracing studies. Critical physics issues and selection criteria are discussed and a procedure to detect anisotropic energetic ion temperatures is also outlined.

The feasibility study was motivated by the potential of the CTS diagnostic and its unique feature of diagnosing energetic particles, the availability of high power microwave hardware resources and operation expertise, and favorable experimental configurations at DIII-D. Such potential, unique capabilities, and desirable features include:

- Potential of diagnosing energetic particle velocity distribution during neutral beam injection (NBI) and fast wave heating (FWH) experiments. This is illustrated in Figure 5 where the difference in scattered spectra with and without energetic ions are shown.
- CTS can provide number density and velocity distribution information of energetic ions by standard analysis and curve fitting techniques. This is illustrated in Figures 6 and 7 where the effects of energetic ion density and temperature on the scattered spectra are shown.
- CTS can provide localized measurement with resolution limited by the overlapping incident and scattered beam widths.
- Availability of both high power gyrotron (scattering) source and high power RF heating source at DIII-D.
- Potential of diagnosing bulk plasma parameters. This is illustrated in Figures 8 and 9 where the effects of carbon impurities and ion temperatures on the scattered bulk spectra are shown.
- DIII-D has expertise in both high power RF and gyrotron operation and also in scattering theory.
- There are no ongoing nor planned high power CTS experiments within the United States.
- Experimental implementation of CTS at DIII-D can generate useful data base for potential CTS diagnostic for ITER.

In the following sections, the criteria used in this study, scientific justification, and some of the results obtained are summarized.

5.1 System Parameters, Experimental Configuration, and Key Issues

Numerical results presented in the following sections are obtained based on realistic system parameters, hardware characteristics, and experimental limitations. Several of the key criteria or parameters are:

1. High power gyrotron source characteristics – the gyrotron is assumed to operate at 110 GHz, with output power of 1 MW and a pulse duration of 250 msec.
2. Discharge parameters – bulk plasma parameters used are: $n_e = 3 \times 10^{13} \text{ cm}^{-3}$, $T_e = T_i = 5 \text{ keV}$, and $B_o = 1.8 \text{ T}$. This gives a core plasma frequency of $\omega_p = 49 \text{ GHz}$ and electron cyclotron frequency of $\Omega_c = 50.4 \text{ GHz}$ ($2\Omega_c = 100.8 \text{ GHz}$). T_e and T_i are the electron and ion temperatures respectively, and ω_p and Ω_c are the electron plasma and cyclotron frequencies.
3. Incident source location – The incident source is located at R+1 255 (ie, upper quadrant) and with an injection angle of 19° with respect to the toroidal plane.
4. Energetic particles parameters – ICRH generated fast ions are assumed to have anisotropic distributions with $T_\perp > T_\parallel$, where $T_\perp$ and $T_\parallel$ are the perpendicular and parallel temperatures of the fast ions. Typically, bi-maxwellian distributions are used for the simulations. Typical fast ion density parameters are $n_{fast}/n_e = 2 - 4 \%$ where n_e and n_{fast} are the electron and fast ion densities.
5. Receiver characteristics – a multi-channel, heterodyned receiver system is considered. The bandwidth of each channel is assumed to be 100 MHz and the dominant noise source is assumed to be from ECE with $T_{ece} = 1 \text{ keV}$.

The above criteria are further supplemented by several critical scientific physics issues and experimental constraints. These include:

1. Accessibility and mode selection – given the operating parameters of DIII-D, a transmission window exists for the gyrotron frequency of 110 GHz operating in either O or

X mode polarizations ($2\Omega_c \leq \omega_o \leq 4\Omega_c$). However, due to signal to noise (SNR) and beam termination considerations to be discussed below, X mode is preferred.

2. Termination of the incident gyrotron radiation – the presence of a plasma resonance surface inside the plasma core is needed to absorb the incident radiation. For typical DIII-D operation with $B_o \sim 1.8$ T, this requires the presence of a second cyclotron harmonic surface on the high field side where the incident X-mode radiation are absorbed. This reduces the need for an expensive beam dump.
3. Optimizing scattering geometry – for typical DIII-D operating conditions and limited port access, the scattering geometry is determined to maximize the signal to noise ratio (SNR) of the scattered signal. In particular, the scattering should be less than 70° for DIII-D. This will be discussed in more details in the next section.
4. Minimizing propagation and magnetic effects – propagation effects such as ray refraction should be minimized. This reduces uncertainty in determining precisely the scattering volume and scattering angle and reduces complications in data interpretation. Scattering off plasma resonances are also to be avoided.

5.2 Mode Selection

For typical DIII-D operation parameters with $B_o \sim 1.8$ T, both O or X mode polarizations can be used for the CTS diagnostic. The gyrotron operating frequency of 110 GHz is above the cutoff frequencies of both O (49 GHz for $n_e = 3 \times 10^{13} \text{ cm}^{-3}$) and X (80 GHz) modes.

X mode polarization is preferred and selected based on the following reasons:

1. Incident X mode radiation is absorbed efficiently by the second cyclotron harmonic layer while the absorption of O mode radiation is less efficient. The selection of O mode polarization will then require the installation of expensive beam dumps for the proper termination of incident radiation.
2. X mode polarization gives better signal to noise ratio (SNR). This is illustrated in Figure 10 where the scattered power spectra for O and X modes are compared. A gain of about a factor of 3 in SNR is observed for X mode. Thus when SNR is the critical deciding factor, then X mode is preferable. Also, for a given incident power, the same SNR can be achieved with smaller integration times, resulting in better temporal resolution, for X mode than O mode.

3. The incident radiation hardware currently in used at DIII-D is designed for X mode launching for ECH. The selection of X mode polarization for CTS diagnostic allows the direct adaptation of existing hardware configuration without any modification, does not interfere with the ECH experimental setup, and eliminates the need to redesign launching components.

5.3 Selection of Receiver Port Location

Given the incident gyrotron radiation entry location is fixed at R+1 255 (+/- indicates locations above/below the horizontal plane), a number of access port locations are evaluated as possible receiver ports. The key criteria used in the selection process are:

1. Proper termination of the incident beam and minimizing absorption of the scattered beam.
2. Minimizing refractive effects.
3. Maximizing SNR and minimizing the scattering angle.
4. Avoidance of magnetic effects and resonance scattering.

5.3.1 Termination and Absorption Issues

Figure 11 gives a top view of the right half of the DIII-D torus with ports at R 165, 180, and 195. The second harmonic surface and the surface that represents the center of the plasma are indicated. For $B_o = 1.8$ T, the second harmonic surface is situated on the high field side of the plasma core. The proper implementation of CTS requires the incident beam be terminated and absorbed completely after it passes inward through the plasma center, while the scattered beam be detected as it propagates outward with minimal absorption loss without hitting the second harmonic surface. The proper termination of the incident radiation reduces multiple wall reflections and minimizes stray radiation that can interfere with the scattered signal that can degrade the performance of the diagnostic. It also eliminates the need for the installation of expensive beam dumps inside the torus. On the other hand, the minimizing of absorption loss of the scattered beam improves SNR of the received signal. For $B_o = 1.8$ T, ports at R 165 are not suitable as the straight line path of the scattered beam cuts through the second harmonic surface.

5.3.2 Refractive Effects

The toroidal path of a scattered ray originating from the scattering volume to a particular receiving port can be quite long and refractive effects are therefore non-negligible in such a situation. This is especially true for ports at R 180 and 195, which are farthest away toroidally from the incident gyrotron port at R 255. Figures 12a and 12b give the poloidal and toroidal views of the beam paths for the simulated receiver location at R 195. The raytracing calculations are performed assuming only circular cross section plasmas with no elongation nor triangularity. While the incident beam suffers minimal refraction because of its small toroidal tilt of only 19° , the refraction and bending of the scattered rays are significant even when the X mode cutoff frequency is $\omega_R > 1.5\Omega_c$ at the plasma center. These refractive effects can be understood by considering the angle, θ_n , that the radiation wavevectors, $\vec{k}_o$ ($\vec{k}_s$), make with the density gradient, ∇n . For the incident beam, the angle is small at 19° (assuming $\nabla n \perp \mathbf{B}_o$). Thus the parallel component of the refractive index η ($= ck/\omega$) with respect to $\mathbf{B}_o$, $\eta_{\parallel}$, is small and the effective cutoff frequency remains almost relatively unchanged. The scattered beam, however, sustains a much larger angle with respect to ∇n because of the toroidal location of the receiver port. This corresponds to a large value of $\eta_{\parallel}$ and the cutoff frequency is now substantially reduced by the geometric factor of $\cos \theta_n$.

An intuitive way to visualize the dependence of the effective cutoff frequency on the angle θ_n or $\eta_{\parallel}$ is demonstrated in Figure 13 where the X-mode Pöeverlein diagram is constructed for DIII-D in the approximation of horizontally launched rays and $\mathbf{B}_o \perp \nabla n$ (the diagram for non-horizontal launch is similar but slightly more complicated). The Pöeverlein construction is a graphical method for finding the general shape of a ray in a stratified plasma. The diagram is drawn with $\eta_{\parallel}$ (and $\mathbf{B}_o$), $\eta_{\perp}$ (and ∇n) parallel to the x, y axes respectively. The circles and ellipses are cross sections of refractive index surfaces with a plane parallel to the plane of incidence. These refractive index curves are generated by the Booker's quartic or by solving the 4th order cold dispersion relation. In vacuum, the parameter $X = \omega_p^2/\omega_o^2 = 0$ and the cross section of the refractive index surface is a circle (the outermost curve). As density increases, the curves get smaller and become elliptical, with the major axis along the y axis or the direction of ∇n . At the critical density where X mode is cutoff ($X = 1 - Y$ where $Y = \Omega_c/\omega_o$), the refractive index curve shrinks to a point at the origin O . The vertical lines represent rays with various angles θ_n and $\eta_{\parallel}$ and are at distances of $S = \sin \theta_n$ from the origin. For a given value of $\eta_{\parallel}$, the corresponding vertical line intersects a refractive index curve at two different points, yielding the two roots of the dispersion relation. There are two other roots for O mode, giving the total of four roots for the quartic. This is the normal

situation with no cutoffs. For example, the $\eta_{\parallel} = 0.51$ line $L1$ intersects the refractive index curve of $X = 0.4$ at two points C and D . Then the line OC , which makes an angle θ_{oc} with $\eta_{\parallel}$, gives the refractive index η for a wave whose normal is in the direction of OC and $OC \sin \theta_{oc} = \eta \sin \theta_{oc} = S$ which is simply Snell's law. Also, at the intersection point C , the normal to the curve gives the ray direction (which is in general different than the wavevector direction in an anisotropic plasma considered here). As the ray travels inwards into a plasma of increasing density (i.e., moving along the same vertical line on the diagram), a critical density will be reached when line $L1$ just touches the corresponding refractive index curve at a single point E . At this point, the two roots C and D coalesce, the ray is parallel to $\eta_{\parallel}$, and the ray is cutoff.

The selection of receiver locations at large toroidal separations from the gyrotron injection point will result in long toroidal path lengths and large θ_n . As demonstrated from the Poverlein construction, this in turn leads to large refractive effects, uncertainties in the determination of scattering parameters, premature cutoff of rays, and degradation of the performance of the CTS diagnostic. For $n_e = 3 \times 10^{13} \text{ cm}^{-3}$, $X = 0.2$ and the cutoff occurs for $\theta_n \sim 53^\circ$. Thus only toroidal locations that results in $\theta_n < 53^\circ$ are desirable. This eliminates port locations at R 180 and 190 as possible choices for receiver locations.

This leaves port locations at R 210 and 225 as the only remaining choices. As expected, both locations produce relatively short toroidal path lengths with minimal refractive effects. Figures 14a and 14b show the poloidal and toroidal ray paths for R 225 and the bending of the scatter rays is minimal as compared to the bending for R 190 shown in Figures 12a and 12b. Again, the raytracing calculations are performed assuming only circular cross section plasmas with no elongation nor triangularity.

5.3.3 Scattering Angle Issue

Another important criterion is that the signal to noise ratio SNR be maximized at the selected receiver location. This can be accomplished by a two-step procedure. First, the scattering angles are obtained from ray-tracing calculations via the intersection of the incident and scattered ray bundles for each receiver location. This is necessary since SNR depends on θ_s . Second, given this information, simulated CTS spectra can now be generated numerically and SNR can be calculated using realistic system and discharge parameters. The results, after extensive simulations, indicate that for DIII-D the best SNR are obtained for small θ_s . This is to be expected since the Salpeter parameter, α , which determines whether the scattering process is dominated by collective or incoherent processes, is largest at small θ_s . This can be seen from the simple relationship between α and θ_s :

$$\alpha = \frac{1}{(k_s \lambda_D)^2} \sim \frac{1}{(2k_o \lambda_D \sin \theta_s)^2} \quad (8)$$

k_s and k_o are the scattered and incident wavenumbers and λ_D is the Debye length. Typically for α large ($\alpha > 2$), scattering is in the collective regime and the diagnostic can be used to detect energetic ions. For $\alpha < 2$, incoherent scattering from electrons begins to dominate and SNR is severely degraded. For DIII-D, θ_s should be less than 70° to maintain $\alpha > 2$. Since the incident radiation is injected from the upper quadrant, R+1, θ_s can be reduced for a given toroidal location by selecting the receiver port at the lower quadrant. For DIII-D, a R-2 port will be better than a R-1 or a R+1 port in terms of having smaller θ_s . An example of the difference in signal to noise ratio is shown in Figures 15a and 11b where $\theta_s = 73^\circ$ and 53° respectively for simulated receiver locations at 210 R-1 and 210 R-2 respectively. The background signal in the frequency range of 1 to 2 GHz has increased over a factor of two from $\theta_s = 53^\circ$ to $\theta_s = 73^\circ$. This broadband increase in background level is equivalent to an increase in the noise floor of the total signal received, thus reducing the sensitivity of the detection system and degrading the effective SNR. The additive effect of enhanced incoherent scattering and high noise floor at large scattering angles also distort the shape of the scattered spectra, thus complicating the process of data inversion and extraction of fast ion velocity distribution information.

5.3.4 Magnetic Field Effects Issue

To minimize complications from magnetic field effects and enhance scattering off plasma resonance, near perpendicular scattering has to be avoided. This requires limiting the angle ψ that $\Delta \vec{k} (= \vec{k}_s - \vec{k}_o)$ makes with $\mathbf{B}_o$ to be 80° or less. Table 1 lists the various angles for several receiver toroidal location.

Toroidal location	φ_o	φ_s	ψ	θ_s	α
195 R-2	19°	-72°	51°	56°	3.3
210 R-2	19°	-68°	54°	53°	3.5
225 R-2	19°	-55°	68°	52°	3.6
240 R-2	19°	-32°	85°	50°	3.8
255 R-2	19°	-41°	80°	59°	3.2

φ_o and φ_s are the angles that the incident and scattered rays make with $\mathbf{B}_o$, ψ is the angle that $\vec{k}_s - \vec{k}_o$ makes with $\mathbf{B}_o$, θ_s is the scattering angle, and α is the Salpeter parameter. Given the experimental configuration at DIII-D, $\psi > 80^\circ$ occurs only for very small toroidal separation between the incident and the receiving ports. As a result, magnetic field effects

can be avoided by eliminating port locations at 240 R and 255 R from considerations. This again leaves port locations 210 R and 225 R as possible receiver locations. Note that in this report only ports at toroidal locations of 255 R or less are analyzed. Similar analysis can be performed for port locations greater than 255 R but port availability and access are probably limited due to the existence of the ICRH antenna at 285 R to 300 R.

In summary, after careful consideration of various critical issues, locations 210 R-2 and 225 R-2 appear to be good candidates as possible receiver locations. There is another significant advantage in choosing the two locations is that although the angles ψ are different for the two locations, the angles θ_s are almost identical nonetheless. This means signals received at both locations are the result of scattering at similar wavenumber ($|\vec{k}_s - \vec{k}_o|$) but at different orientation with respect to $\mathbf{B}_o$ or different θ_s . As will be shown in the following section, this may be used to full advantage to measure the anisotropic distribution of the energetic ions.

5.4 Measurement of Anisotropic Distributions

ICRH generated energetic ions are in general anisotropic with $T_\perp > T_\parallel$, where $T_\perp$ and $T_\parallel$ are the perpendicular and parallel temperatures respectively. As a result, the challenge of any CTS based diagnostic is whether it can resolve and measure such anisotropy in the energetic ion distribution. To a first approximation, the energetic ion can be assumed to be bi-maxwellian with the following distribution function,

$$f(v_\parallel, v_\perp) \propto \exp - \frac{M v_\parallel^2}{2T_\parallel} \exp - \frac{M v_\perp^2}{T_\perp} \quad (9)$$

For a given scattering geometry with fixed scattering angle, the CTS diagnostic measures only the one dimensional velocity distribution along $\vec{k}_s - \vec{k}_o$. The effective one dimensional velocity distribution unfolded from the scattered spectrum can be written as:

$$f^{(1)}(v^{(1)}) \propto \exp - \frac{M v^{(1)2}}{T^{(1)}} \quad (10)$$

where the relationship between the effective one dimensional temperature, $T^{(1)}$, and $T_\parallel$ and $T_\perp$ can be written as:

$$T^{(1)} = T_\parallel \cos^2 \psi + \frac{1}{2} T_\perp \sin^2 \psi \quad (11)$$

For a given scattering geometry with fixed angles ϕ_o , ϕ_s , ψ , $T_\parallel$ and $T_\perp$ cannot be determined uniquely from $T^{(1)}$ measured at a fixed θ_s . The situation improves, however, if

measurements can be made at two different receiver locations, say at R 210 and R 225. Two independent values of effective one dimensional temperatures can then be measured along two different line of sight:

$$\begin{aligned} T_{210}^{(1)} &= T_{\parallel} \cos^2 \psi_{210} + \frac{T_{\perp}}{2} \sin^2 \psi_{210} \\ T_{225}^{(1)} &= T_{\perp} \cos^2 \psi_{225} + \frac{T_{\perp}}{2} \sin^2 \psi_{225} \end{aligned} \quad (12)$$

Given two equations and two unknowns, $T_{\parallel}$ and $T_{\perp}$ can now be solved uniquely as:

$$\begin{aligned} T_{\parallel} &= \frac{T_{210}^{(1)} \sin^2 \psi_{225} - T_{225}^{(1)} \sin^2 \psi_{210}}{2D} \\ T_{\perp} &= \frac{T_{225}^{(1)} \cos^2 \psi_{210} - T_{210}^{(1)} \cos^2 \psi_{225}}{D} \end{aligned} \quad (13)$$

where

$$D = \frac{1}{2} \cos^2 \psi_{210} \sin^2 \psi_{225} - \frac{1}{2} \sin^2 \psi_{210} \cos^2 \psi_{225} \quad (14)$$

The two receiver setup of measuring distribution anisotropy works best if ψ_{210} and ψ_{225} are very different while the scattering angles θ_s are almost identical. For DIII-D, the two locations at 210 R-2 and 225 R-2 are suitable candidates for the measurement. This procedure has been tested successfully with numerically generated spectra.

5.5 Summary

In summary, detailed results have been presented from our feasibility study of developing and implementing a collective Thomson scattering (CTS) diagnostic for the detection of energetic particles at DIII-D. Favorable results, obtained in our feasibility study, indicate that it should be possible to develop and implement a CTS diagnostic at DIII-D.

References

- [1] P. Y. Cheung et al., Bull. Amer. Phys. Soc. **40**, 1869 (1995).
- [2] P. Y. Cheung, presented at the TFTR-CTS diagnostic review, Princeton, N. J., October (1995).
- [3] E. V. Suvorov et al., Plasma Physics and Controlled Fusion, **37** 1207 (1995).

Figure Captions

- Figure 1. Simulated spectra and fitted results for relative alpha densities of a) 2.0 %, b) 0.2 %, and c) 0.02 %. The histograms represent the discrete receiver channels with finite bandwidth of 80 MHz. The Projected TFTR-ERS parameters and slowing down alpha velocity distribution were used for this simulation.
- Figure 2. Least square fitted results for a) slowing down velocity distribution and b) maxwellian velocity distribution. All parameters are same as that shown in Figure 1. The different lines in a given plot represent the fitted curve for the various alpha densities of 2.0, 0.2, and 0.02 % respectively.
- Figure 3. Comparison of numerical results with experimental data for shot #81874. a) The solid curve represents numerical result of using 0.1 % alphas with slowing down velocity distribution plus a 120 kV beam ions. The dots are actual experimental data. b) Comparison done with numerical result using an inverted bi-maxwellian beam distribution with parameters of $\gamma = 0.9$, $\lambda = 0.5$, $\tau = 0.5$, and parallel and perpendicular temperatures of 160 and 320 keV.
- Figure 4. Comparison of numerical results with experimental data for shot #81874. a) The solid curve represents numerical results of using 1 % of MeV protons with slowing down velocity distribution as energetic ions. b) The same parameters and distribution are used and the effects of multiple wall reflections or random scattering are also included.
- Figure 5. Detection of energetic ions ($n_{fast}/n_e = 2$ %) in scattered spectra. Top figure has logarithmic vertical scale and bottom figure has linear vertical scale.
- Figure 6. Illustration of the effects of energetic ion densities on scattered spectra. Top figure has logarithmic vertical scale and bottom figure has linear vertical scale.
- Figure 7. Illustration of the effects of energetic ion temperatures on scattered spectra. The perpendicular tail ion temperatures are varied. Top figure has logarithmic vertical scale and bottom figure has linear vertical scale.
- Figure 8. Top figure illustrates the effects of impurity carbon concentration on bulk scattered spectra. Bottom figure shows the dependence of the total bulk scattering cross section on Z_{eff} .
- Figure 9. Illustration of the effects of bulk ion temperatures on scattered bulk spectra. Top figure has logarithmic vertical scale and bottom figure has linear vertical scale.
- Figure 10. Comparison between X and O mode scattering. All parameters are the same for both polarizations.
- Figure 11. Top view of the right half of the DIII-D tokamak. Straight line paths from port locations at 165, 180, and 195 are shown. Half circles representing the minor radius at 1.7 m and the second harmonic surface for $B_o = 1.8$ T are also shown.

Figure 12. Ray tracing plots for simulated receiver location at 195 R-2 showing both incident and scattered rays and the intersection volume in both: a) poloidal view and b) toroidal view. The raytracing calculations are performed assuming only circular cross section plasmas with no elongation nor triangularity.

Figure 13. Poeverlein diagram for X mode polarization and horizontal launch. The diagram is drawn with $\eta_{\parallel}$ (and B_o), $\eta_{\perp}$ (and ∇n) parallel to the x, y axes respectively. The circles and ellipses are cross sections of refractive index surfaces with a plane parallel to the plane of incidence. The vertical lines represent rays with various angles θ_n and $\eta_{\parallel}$ and are at distances of $S = \sin \theta_n$ from the origin.

Figure 14. Ray tracing plots for simulated receiver location at 225 R-2 showing both incident and scattered rays and the intersection volume in both: a) poloidal view and b) toroidal view. The raytracing calculations are performed assuming only circular cross section plasmas with no elongation nor triangularity.

Figure 15. Comparison of SNR for simulated receiver locations at 210 R-1 and 210 R-2. The scattering angle for the two locations are $\theta_s = 73^\circ$ and 53° respectively.