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ABSTRACT

Localized alpha-particle velocity distribution and density, ion temperature, DT fuel ratio, and internal magnetic field pitch angle can all be potentially diagnosed by a collective Thomson scattering system. Relativistic electron cyclotron calculations and TORAY ray tracing for 6 tesla ITER parameters indicate that 90 GHz is an optimum frequency for this diagnostic. With 400 kW at the plasma and a 90° scattering angle, signal to noise ratios approaching 100 are possible for 0.5% n_e alpha-particle fractions and 100 ms integration times. A millimeter-wave system would be robust and adaptable to the ITER environment and access.

INTRODUCTION

The study of alpha-particle physics will be an important aspect of ITER's early operational phase. Also ITER's high fusion power output, large size, and limited access will present challenges to adapting many of the plasma diagnostic techniques currently in use on tokamaks. Innovative approaches are required to meet ITER's needs for new diagnostic capabilities for alpha-particle measurements and other plasma parameters. These diagnostics must be robust to the radiation environment, able to provide spatial coverage of the largest man-made fusion plasmas to date, and be adaptable to the limited access to the plasma.

Collective Thomson scattering (CTS) promises to be an effective technique for spatially resolved alpha-particle velocity distribution and fractional density measurements [1]. It has also been demonstrated to be capable of ion temperature measurements in tokamaks [2]. In addition, it has been pointed out that CTS has the potential for sensitive internal magnetic field pitch angle measurements which can be used to determine plasma current density [3]. Each of these plasma parameters that CTS can diagnose are among the highest priority ones for a successful experimental fusion program. Also a diagnostic that can provide multiple parameter measurement capability would be an attractive technology for ITER because it would make more efficient use of limited diagnostic access.

Collective Thomson scattering refers to electromagnetic scattering from correlated electron motions, i. e., from electron Debye shielding clouds moving with the plasma ions. The ions do not directly scatter detectable radiation because of their large mass. The condition for observing collective electron fluctuations is $(|k|\lambda_D)^{-1} \geq 1$, where λ_D is the electron Debye

length and $|k| = |k_o - k_s| \approx (4\pi n_r \sin^2 \theta / 2) / \lambda_o$, where k is the fluctuation wave number, k_o and k_s are the incident and scattered wavevectors, λ_o is the source wavelength, θ is the scattering angle and n_r is the refractive index. In other words, the scale length of the fluctuations being diagnosed must exceed the electron Debye length. For ITER plasmas the electron Debye length will be of the order of 50 μm , making necessary long diagnostic wavelengths of the order of 1 mm for meeting the CTS condition at large scattering angles of 90°.

Shorter wavelengths can be used at smaller scattering angles. It has been proposed that a 10 μm CO₂ laser be used for CTS alpha-particle diagnostics [4]. Such a wavelength would require a scattering angle of about 0.5° in ITER. The ITER diagnostic plan [5] has identified a wavelength of about 200 μm as the preferred diagnostic wavelength which would require a scattering angle of 10° or less. In this paper we advocate the consideration of a longer wavelength option for an ITER CTS diagnostic system at a wavelength of approximately 3 mm. This would make possible the use of 90° scattering angles and would provide an engineering advantage of not requiring optical techniques, tolerances, or line of sight access to the tokamak. We show here that earlier concerns about background plasma emission and beam refraction may not be inhibiting to millimeter-wave CTS diagnostics in ITER. It would also build on experience gained from millimeter-wave gyrotron CTS systems that are currently being implemented on JET [6] and TFTR [7].

ANALYTIC BASIS

The analytical basis of CTS for localized ion velocity distribution and density measurements is on a firm theoretical and experimental foundation. Extensive modeling of CTS for alpha-particle diagnostics has been carried out [8, 9] and recently the theory has been extended to include electromagnetic effects [10, 11] which are important for scattering geometries where k is near perpendicular to the magnetic field. Figure 1 illustrates the main features of a collective Thomson scattered spectrum calculated for ITER relevant plasma parameters.

For angles of k to $B < 80^\circ$ the spectrum is a direct representation of the ion distribution function along k that is integrated over velocity components transverse to k . The various ion species are distinguishable by their different velocity contributions to the Doppler shifted scattered spectrum. The thermalized bulk ions such as

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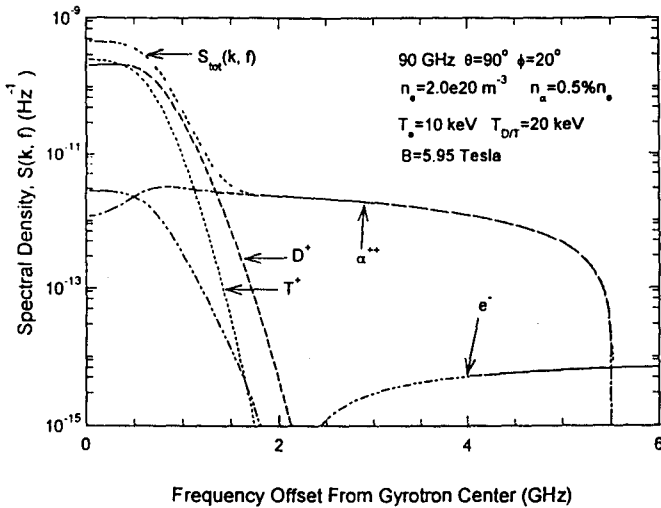


Figure 1. Calculated CTS spectrum for ITER using a 90 GHz gyrotron.

deuterium and tritium have different velocities because of their different masses. They contribute to the peaked part of the spectrum a low frequency offsets, up to 1.5 GHz in Figure 1 where they are assumed to have Maxwellian velocity distributions. Energetic ions such as alpha-particles contribute to the high frequency offset part of the spectrum. This part of the spectrum extends out to 5.5 GHz in Figure 1 where a beam slowing down velocity distribution function with a cutoff at the 3.5 MeV birth energy [8, 9] was assumed.

Computer simulations have shown that once a CTS spectrum is obtained it is possible to determine the bulk fuel temperature, fuel ratio, and fusion product alpha-particle temperature and fraction simultaneously [12]. Determination of the internal magnetic field direction is obtained by scattering orientations of \mathbf{k} near perpendicular to \mathbf{B} where a plasma resonance at lower hybrid frequencies enhances the scattered signal. The frequency of this resonance is a sensitive measure of the orientation of \mathbf{k} to \mathbf{B} [3]. Also this resonance can be exploited to reduce the power requirements for CTS [7], but with increased difficulty for quantitative interpretation of the spectrum for energetic ion velocity distributions and fractions.

PLASMA ACCESSIBILITY

Accessibility to the plasma at millimeter wavelengths is difficult because of electron cyclotron emission (ECE)/absorption and density cutoff limits. However, it is possible to find a window in millimeter-wave frequency space for diagnostics. A particularly good one at high magnetic fields (≥ 5 tesla) is for extraordinary mode (x-mode) propagation below the electron cyclotron resonance [1, 13]. The accessibility of this window for ITER parameters current at the time of this writing ($R=8.21$ m, $a=3.0$ m, $n_e=2.3e20$ m⁻³, and $B=5.95$ tesla) is evaluated in Figure 2.

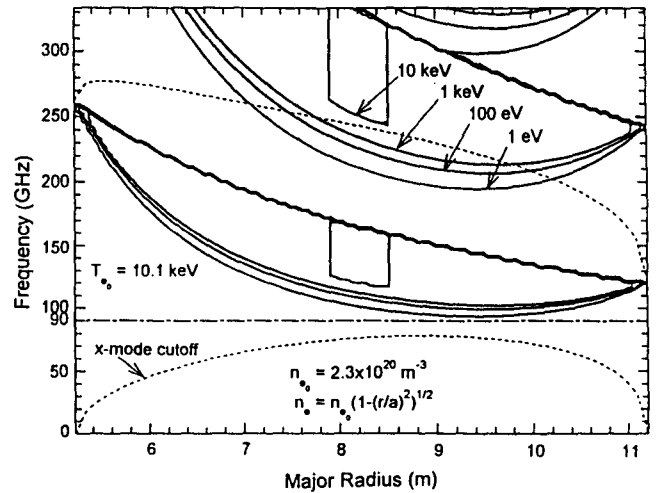


Figure 2. Contour plots of extraordinary mode ECE and cutoffs for propagation perpendicular to the magnetic field.

For propagation perpendicular or near perpendicular to the magnetic field the broadening of the electron cyclotron resonance and its harmonics is only due to relativistic down shifting. A simplified formulation for the calculation of relativistic ECE perpendicular to the magnetic field [14] was used to plot contours of ECE for the extraordinary mode in the frequency-major radius plane of ITER. Figure 2 shows these contours for 10 keV, 1 keV, 100 eV, and 1 eV levels for the fundamental (Ω_{ce}) and parts of the second ($2\Omega_{ce}$) and third ($3\Omega_{ce}$) harmonics. A peak electron temperature of 10.1 keV and a parabolic profile were assumed for this calculation. Overlaid on this contour plot, as dashed curves, are the x-mode cutoffs. A peak density of 2.3×10^{20} m⁻³ with a parabolic profile raised to the half power was assumed.

It is evident from this evaluation that there is a gap in frequency space across the whole plasma cross-section between the lower extent of the ECE (~ 100 GHz) and the upper extent of the lower x-mode cutoff (~ 80 GHz). Suprathermal electrons and much higher electron temperatures would reduce this gap. However, measurements on TFTR for fusion burning relevant plasma conditions with neutral beam heating and ion cyclotron resonance heating (ICRH) confirm low emission background levels (~ 20 eV) in this x-mode window [7].

It would be possible to consider ordinary mode (o-mode) propagation for this diagnostic. In that case the plasma frequency cutoff would block off the frequencies below the ECE resonance. The diagnostic beams would need to go into the plasma vertically to access the plasma between Ω_{ce} and $2\Omega_{ce}$ at about 180 GHz, but strong ECE from regions of the plasma not in the propagation paths of the diagnostic beams would be a problem via wall reflections unless viewing dumps were used. Also, the plasma emission would be affected by absorption of the diagnostic beam making extraction of a weak signal difficult. The x-mode window therefore has reduced

problems with background emission and has more flexibility as to horizontal or vertical access.

RAY TRACING

Beam refraction must be considered when propagating near a plasma cutoff. The ray tracing code TORAY [15] was modified for elongated, triangular plasmas and used to evaluate beam refraction for 90 GHz x-mode propagation in ITER as presently defined at 5.95 tesla. The results are shown in Figures 3 and 4 for a conceptual 90° scattering geometry in the poloidal plane. The density profile assumed is the same as in Figure 2. A set of 90 GHz rays are shown entering the plasma vertically from the top and another set horizontally from the outside. The high power diagnostic beam and receiver field-of-view could be represented by a ray in either set.

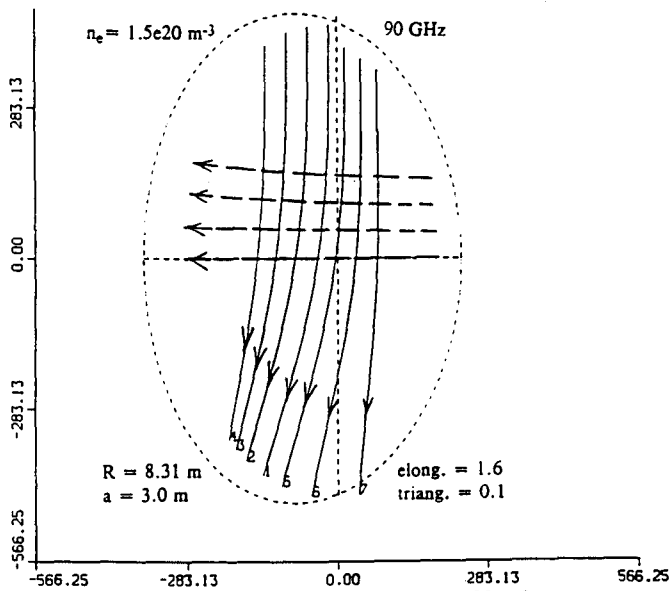


Figure 3. Ray tracing in ITER for peak density $1.5 \times 10^{20} \text{ m}^{-3}$.

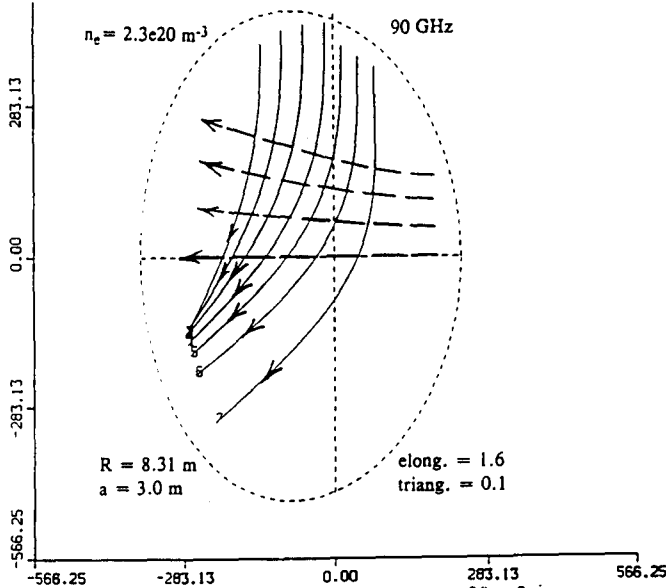


Figure 4. Ray tracing in ITER for peak density $2.3 \times 10^{20} \text{ m}^{-3}$.

The cutoff density is $2.9 \times 10^{20} \text{ m}^{-3}$. In Figure 3 the peak density is $1.5 \times 10^{20} \text{ m}^{-3}$ which corresponds to ITER's present low power operation phase. The refraction in this case is not significant. Well defined horizontal and vertical profiles of CTS data can be obtained without the need for significant corrections for position or scattering angle. In Figure 4 the peak density is $2.3 \times 10^{20} \text{ m}^{-3}$, corresponding to ITER's high power phase. Refraction in this case is significant. Corrections for position and scattering angle would be necessary, however well defined horizontal and vertical profiles are still possible for CTS data. Therefore, these ray tracing results along with the prediction of low ECE background in Figure 2 demonstrate the viability of considering a 90 GHz CTS diagnostic option for ITER.

CONCEPTUAL SYSTEM DESIGN

A 90 GHz CTS diagnostic system would make use of a high power gyrotron and a sensitive heterodyne receiver. Megawatt 110 GHz gyrotrons are currently under development for electron cyclotron heating and will be readily available on the ITER time scale. Such a tube could be adapted to the lower frequency CTS diagnostic application without significant development. The gyrotron output would be rapidly modulated to help facilitated the detection of a weak signal in noise. The gyrotron system would be located in a remote area well shielded from ITER's radiation environment. Similar to CTS systems on JET and TFTR [6, 7] a corrugated HE_{11} transmission line would bring the gyrotron beam to ITER.

The challenging engineering would be at the ITER tokamak vessel. The last section of the waveguide run to ITER would become a part of the vacuum vessel. One or more miter bends would prevent direct line of sight of the radiation to the waveguide vacuum window and its backups. An advantage of millimeter waves is that the miter mirror exposed to the radiation could be made of almost any conductor from molybdenum to graphite and still be better than 99% efficient. Millimeter waves would also be more tolerant than infrared beams to mirror surface deposition and degradation. The waveguide at the tokamak could also be made from a robust material since propagation in the HE_{11} mode does require a very good conductor. The use of radiation tolerant waveguides would make this diagnostic very accommodating to enter the tokamak where possible and launch where needed.

In the tokamak a series of fixed waveguides would be installed with views where needed for profile measurements. Scanning antenna systems such as currently used on JET and TFTR would be avoided to increase robustness of the CTS system. Beam and viewing dumps would also be desirable and could be implemented with high density silicon carbide materials which have been tested to be very effective millimeter-wave dumps [16].

The receiver side of the CTS system would make use of similar HE₁₁ waveguides as the gyrotron. The receiver vacuum window(s) could be of a simpler design since they would not need to handle high power beams. The receiver itself would have a noise temperature less than the lowest expected plasma emission (> 1 eV), wide bandwidth (~12 GHz) and many channels (> 20) to resolve both sidebands of the scattered spectrum. A notch filter would also be employed to reject stray gyrotron radiation not scattered by the plasma.

CALCULATED PERFORMANCE

The expected performance of a CTS diagnostic system can be estimated by first calculating the scattered signal levels and then using these levels in a formula for determining the signal to noise ratio. The scattered signal levels are given by

$$P_s = P_o n_e r_e^2 L d\Omega G S(k, f)$$

where P_o is the gyrotron power at the plasma, n_e is the electron density, $r_e = 2.8 \times 10^{-13}$ cm is the classical electron radius, L is the length of the scattering volume along the gyrotron beam, $d\Omega$ is the solid angle of signal collection, G is a geometrical form factor for the coupling between the incident and scattered beams, and $S(k, f)$ is the spectral density function shown in Figure 2. For the present calculation we assume: $P_o = 400$ kW, $n_e = 1.8 \times 10^{20}$ m⁻³, $L d\Omega = 0.022$ cm for a launch antenna aperture of 20 cm, and $G = 0.257$ as determined by the results in [17]. This corresponds to scattered signal levels of $P_s = 1.9 \times 10^{-18}$ W/Hz for the bulk ions at an offset frequency of 0.6 GHz and $P_s = 1.6 \times 10^{-20}$ W/Hz for a 0.5% n_e fraction of alpha-particles at an offset of 4.2 GHz.

These scattered signals, for one receiver channel, are well approximated by white noise which is a manifestation of the random thermal motions of the ions. When we make measurements of this scattered noise we are interested in determining its root mean square (rms) level. The signal to noise ratio is therefore defined as the precision with which this rms level can be determined in the presence of unwanted background noise due to the plasma emission and/or receiver noise temperature, P_n . It is given by

$$S/N = \frac{P_s}{P_s + P_n} \sqrt{\Delta f \tau + 1}$$

where Δf is the receiver channel bandwidth and τ is the signal integration time. This result is reduced by a factor $\sqrt{2}$ if P_n is not known. If we assume: $P_n = 20$ eV, $\Delta f = 100$ MHz for the bulk ions and 600 MHz for the alpha-particles, and $\tau = 100$ ms, then the signal to noise ratio for bulk ion measurements would be 1700 and for alpha-particles 77. These are high values with significant margin due to conservative assumptions on gyrotron power and alpha-particle fraction. It has been shown that estimating the performance of a CTS system in this way agrees very well with computer simulations [12].

Therefore, a 90 GHz CTS system on ITER would be a very effective localized alpha-particle and fuel ion diagnostic.

REFERENCES

- [1] P. P. Woskov, D. R. Cohn, J. S. Machuzak, and R. C. Myer, "Fusion alpha particle diagnostics with gyrotrons," Proceedings 12th Symp. on Fusion Eng., Monterey, Calif., p. 1544, 1987.
- [2] R. Behn, D. Dicken, J. Hackmann, S. A. Salito, M. R. Siegrist, P. A. Krug, I. Kjelberg, B. Duval, B. Jove, and A. Pocheleon, "Ion temperature measurement of tokamak plasmas by collective Thomson scattering," Phys. Rev. Let., vol. 62, pp. 2833-2836, 1989.
- [3] P. P. Woskov and D. Y. Rhee, "Localized magnetic pitch angle measurements by collective Thomson scattering," Rev. Sci. Instrum., vol. 63, pp. 4641-4643, October 1992.
- [4] R. K. Richards, C. A. Bennet, L. K. Fletcher, H. T. Hunter, and D. P. Hutchinson, "CO₂ laser Thomson scattering diagnostic for fusion product alpha particle measurements," Rev. Sci. Instrum., vol. 59, pp. 1556-1558, 1988.
- [5] V. Mukhovatov et al, "ITER Diagnostics," ITER Docum. Series, No. 33, IAEA, Vienna, 1990.
- [6] A. E. Costely, J. A. Hoekzema, T. P. Hughes, P. E. Stott, and M. L. Watkins, "A Thomson scattering diagnostic to measure fast ion and α -particle distributions in JET," JET-R(88), JET Joint Undertaking, Abingdon, UK, 1988.
- [7] J. S. Machuzak et al, "Alpha particle collective Thomson scattering in TFTR," Proceeding 6th Symp. on Laser-Aided Plasma Diagnostics, Bar Harbor, ME, pp. 124-129, 1993.
- [8] L. Vahala, G. Vahalla, and D. J. Sigmar, "Effect of electrostatic scattering parameters of the direct detection of fusion alphas," Nuclear Fusion, vol. 28 pp. 1595-1602, 1988.
- [9] T. P. Hughes and S. R. P. Smith, "Calculation of Thomson scattering functions for alpha particle diagnostics in JET plasmas," Nuclear Fusion, vol. 28, pp. 1451-1457, 1988.
- [10] S. C. Chiu, "Electromagnetic effects in fluctuations of nonequilibrium plasmas and applications to alpha diagnostics," Phys. Fluids B, vol. 3, pp. 1374-1380, 1991.
- [11] R. E. Aamodt and D. A. Russell, "Alpha particle detection by electromagnetic scattering off of plasma fluctuations," Nuclear Fusion, vol. 32, pp. 745-755, 1992.
- [12] D. Y. Rhee, "High power gyrotron and far infrared laser collective Thomson scattering diagnostics in burning tokamak plasmas," Ph.D. Thesis, MIT, Cambridge, MA, 1993.
- [13] P. Woskoboinikow, "Development of gyrotrons for plasma diagnostics," Rev. Sci. Instrum., vol. 57, pp. 2113-2118, 1986.
- [14] A. Nassri and M. Heindler, "A new formulation for aynchrotron absorption-emission coefficient in plasmas," Phys. Fluids, vol. 29, pp. 3275-3280, 1986.
- [15] A. H. Kritz, H. Hsuan, R. C. Goldfinger, and D. B. Batchelor, "Ray tracing study of electron cyclotron heating in toroidal geometry," Heating in Toroidal Plasmas, Grenoble, vol. II, pp. 707-723, 1982.
- [16] H. K. Park et al, "Status of the scattering system in TFTR," Bull. of Amer. Phys. Soc., vol. 37, p. 1490, 1992.
- [17] N. Bretz, "Geometrical effects in x-mode scattering," J. Plasma Physics, vol. 38, pp. 79-86, 1987.