Collective Thomson scattering diagnostic for the GDT experiment

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In this paper, we propose a collective Thomson scattering diagnostic for fast ion measurements for the gas-dynamic trap (GDT) facility at the Budker Institute. The diagnostic utilizes 54.5 GHz gyrotron usually used for electron cyclotron resonance heating as a source of probe radiation and is aimed at reconstruction of distributions over transverse and longitudinal velocities of NBI-driven ions in the plasma core. Here we present a feasibility study of this concept.

I. INTRODUCTION

The use of microwave radiation for probing the ion velocity distribution with good spatial and temporal resolution has proven its capability for hot plasma confined in toroidal magnetic traps. Information about ion dynamics is recovered from the scattering of electromagnetic waves of the collective fluctuations of the plasma density and, potentially, magnetic field; such process is shortly referred as a collective Thomson scattering (CTS). Along with optical methods, such as spectroscopy of neutrons and gamma-quanta, the millimeter-wave CTS is one of the main ways of diagnosing the distribution function of fast ions in tokamaks. The possibilities of CTS were demonstrated experimentally at TFTR, JET, TEXTOR, ASDEX-Upgrade tokamaks for diagnosing the distribution function of fast ions, at W7-AS stellarator for diagnosing the temperature of thermal ions and the lower hybrid plasma instability at LHD stellarator for measurement of both fast and thermal ions, and, most recently, at the newest W7-X stellarator for diagnosing the temperature of thermal ions. CTS is considered as a main method for detecting the fusion alpha particles in ITER. Another fruitfully developing direction is active microwave diagnostics of small-scale plasma turbulence by measuring the scattering spectra on turbulent density fluctuations.

Based on this experience, it seems to be very attractive to exploit the same technique for measuring ion distributions in large open magnetic traps used in magnetic fusion research. Some of devices are already equipped with high-power ECRH systems that may be used a source of probe radiation for the CTS diagnostics. The bulk plasma parameters in the most advanced traps are comparable to those of toroidal machine, while the population of fast ions and their influence on the performance are usually much greater in open traps then in tokamaks and stellarators. However, microwave CTS diagnostic has not been realized for open traps. A close ideology based on CTS with a CO2-laser as a probing source was planned to be installed at the GAMMA-10 tandem trap for measuring the ion temperature as part of testing the diagnostic system developed for the LHD stellarator, however, as far as authors know, these experiments did not receive further development.

In this paper we report on the project of the CTS diagnostic for the running experiment at the gas-dynamic trap (GDT) facility at the Budker Institute.

II. WHY WE NEED CTS DIAGNOSTIC AT GDT

GDT is a fully axisymmetric linear magnetic device aimed at nuclear fusion applications. The main part of GDT is 7m-long central solenoid which is limited by high-field magnetic mirror coils; plasma absorbing end-plates are placed sufficiently far from the magnetic mirrors in a region with expanded magnetic field lines, see figure 1. The plasma heating system consists of eight neutral beam injectors (NBI) providing up to 5 MW of a total injected power and two 400 kW/54.5 GHz gyrotrons for the electron cyclotron resonance heating (ECRH). Combined ECRH and NBI heating allows reaching record plasma parameters for large open traps. Demonstrated significant progress in the confinement time of fast ions and in the neutron yield (up to 80%) due to the selective deposition of ECRH

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FIG. 1. Schematic of the GDT.
power into the electron component of the plasma have led to a noticeable revision of the prospects for using axially symmetric traps as a high-power source of fusion neutrons.\textsuperscript{30,32} In combination with a number of new theoretical ideas, progress in the field of confinement of hot plasma in a gas-dynamic trap led to a discussion of the possibilities of a fusion power reactor based on the open trap concept.\textsuperscript{30,31}

In the standard regime of operation, GDT plasma consists of two components. First one is the bulk plasma serving as a target for NBI. This component is confined in the gas-dynamic regime and has an isotropic equilibrium velocity distribution due to a high collision frequency. The second plasma component consists of fast ions produced as a result of oblique injection of hydrogen or deuterium atomic beams into the bulk plasma. The fast ions are confined in the adiabatic regime which means that their movement is governed by conservation of energy and magnetic moment (an adiabatic invariant). As a result, they are bouncing in a region between two turning points defined by the effective mirror ratio $R = 2$. The energy confinement time of fast ions is determined by the electron-ion collisions, namely, by the electron drag force; this time turns out to be much less than the angular scattering time. Due to this fact, the fast ions have a strongly non-Maxwellian anisotropic velocity distribution with a relatively small angular spread. Since the distribution function of fast ions is anisotropic in pitch angles, their density is strongly (up to 3 times) peaked near the turning points, what provides favorable conditions for fusion D-D and D-T reactions in subcritical plasma. Thus, the fast ion distribution over pitch angles becomes the main factor determining fusion efficiency, e.g., the neutron yield and the locality of a neutron source.\textsuperscript{33,34}

The ECRH suppresses the main channel of the fast ion loss (collisions with thermal electrons) and changes the anisotropy of the distribution function of fast ions. In this case, the problem of measuring the energy and pitch angle distribution function of fast ions becomes one of the primary ones. In particular, a direct measurement of the distribution function is necessary to clarify existing ideas about the adiabatic nature of fast ion confinement, about the influence on their distribution function of MHD instabilities, electromagnetic instabilities in the ion-cyclotron range, a radial electric field and Coulomb collisions in the new (just achieved for open traps) range of plasma parameters. The strategy of optimizing the GDT operation depends on solving these issues.

The CTS diagnostic with one of the ECRH gyrotrons used as a source of probe radiation seems to be a suitable tool to fulfill this demand.

Previously, the distribution of fast ions in the GDT plasma was investigated with a charge-exchange (CX) of a diagnostic neutral hydrogen beam.\textsuperscript{33,34} The 12-channel CX analyzer provided energy resolution of 0.4–1.3 keV and narrow angular resolution below 1° in the angular range of 32°–47°. The angle in such a system corresponds to the direction of detected ion velocity. Using CX diagnostics, it was possible to measure the time dependence of the distribution function of fast ions in the range of 3–18 keV. However, at each shot, CX energy spectra provide information on the ion distribution in a narrow range of pitch angles. Due to technical complexity, this method cannot be used as a regular diagnosis.

### III. CTS GEOMETRY

CTS is scattering of electromagnetic waves on plasma density fluctuations. A principle of CTS is sketched in figure 2. The measurements are done using a probe beam with the wave vector $k^i$ and angular frequency $\omega^i$, which is scattered in the plasma on fluctuations with $(k, \omega)$, and a receiving beam with the wave vector $k^s$ and frequency $\omega^s$. Three-wave synchronism implies

$$k = k^s - k^i, \quad \omega = \omega^s - \omega^i. \quad (1)$$

Salpeter showed that if $k\lambda_D < 1$, where $\lambda_D$ is the Debye length, the spectrum of the scattering radiation inherits signatures of collective plasma effects.\textsuperscript{35,36}

The CTS diagnostic measures a spectrum of scattered microwaves. Let $P^i$ and $P^s$ be the scattered and incident power. The received spectral power density is then given by\textsuperscript{36}

$$\frac{dP^s}{d\omega} = P^i \lambda^i s r^2 n_e O_b G \frac{S(k, \omega)}{2\pi}, \quad (2)$$

where $r_e$ is the classical electron radius, $\lambda^{i,s} = 2\pi c/\omega^{i,s}$ are the incident and scattered wavelengths, $n_e$ is the electron density, $O_b = \int I^i I^s dV$ is the beam overlap defined as the volume integral of the normalized incident and scattered beam intensities, $G$ is the geometrical form factor defined by polarization of the incident and scattered radiation, and $S(k, \omega)$ is the spectral density of plasma fluctuations.\textsuperscript{37,38} In the next sections, we will discuss each of these factors, $O_b$, $G$ and $S$, in more detail.

The spectral density of fluctuations consists of two additive parts, $S = S_i + S_f$, where $S_i$ and $S_f$ are, respectively, contributions of a thermal bulk plasma and fast ions. In GDT, fast ions can be treated as non-magnetized when calculating the CTS spectra. Then its contribution is proportional to one-dimensional distribution function...
along the direction of resolved plasma fluctuations:

\[ S_f \propto F(\omega/k), \quad F(u) = \int f(v) \delta(u - kv/k) d^3v, \tag{3} \]

where \( f(v) \) is a local distribution of fast ions in a three-dimensional velocity space calculated inside the scattering volume. The energy of fast ions is much higher than those of the bulk particles, so the weight of fast ions in the total scattering would increase with increasing \( \omega \). Although recovering of full distribution function \( f(v) \) by combining \( F(u) \) along several different lines of sight is, in principle, possible, we do not consider such an option in the current GDT project. Thus, the one-dimensional distribution \( F(u) \) is an ultimate result of the CTS diagnostic considered in the present paper.

Nevertheless, to have a key to actual distributions of fast ions over perpendicular and longitudinal velocities (respected to an external magnetic field \( B \)) we consider two complimentary CTS geometries in which the wave vector \( k \) is aligned approximately along and across \( B \). Figure 3 illustrates the result of adjusting this idea to actual ports available at GDT and of further optimization described in the next sections. The probe gyrotron radiation is launched from the top of a vacuum chamber. The scattered signal is received either from the top or from the bottom. The first case characterized by approximately \( (k_i^* - k_f^*) \perp B \), thus resolves the fast ion distribution over perpendicular velocities. The second case characterized by approximately \( (k_i^* - k_f^*) \parallel B \), thus resolves the fast ion distribution over longitudinal velocities. Both geometries correspond to the scattering volume in a central part of the trap occupied by the fast ions. To improve coupling, the probe and receiving ports are shifted by 30° in azimuthal direction. Characteristics of the proposed scheme are listed in Table I. The CTS diagnostics implies some limitations on the bulk plasma density. For both CTS schemes, the on-axis density must be less then \( 1.5 \cdot 10^{13} \text{cm}^{-3} \) for the reliable operation at the O mode (see below). This is not a critical restriction since the normal on-axis density at GDT lies in the range of \( 0.9 - 1.3 \cdot 10^{13} \text{cm}^{-3} \).

**IV. CTS SPECTRUM**

In GDT conditions, a frequency spectrum of the CTS signal is determined by the spectral density of fluctuations \( S_i \); all other terms in Eq. (2) are slowly varying functions of frequency in a detection band. For the contribution of bulk plasma we assume isotropic Maxwellian distributions without drifts for both electrons and ions. Then the expression for the spectral density function for a magnetized plasma, in the electrostatic approximation, is given by

\[ S_i = \frac{k_i^2}{\omega_i^2 \epsilon_{ci}} \left\{ 1 + \frac{\omega_i}{\epsilon_i} \right\} \Im H_c + \frac{T_i}{T_s} \frac{H_i}{\epsilon_i} \Im H_i, \tag{4} \]

where \( \epsilon_i \) is the longitudinal dielectric constant, \( H_s \) denotes the electron \((\alpha = e)\) and the ion \((\alpha = i)\) susceptibilities,

\[ H_s = \frac{2 \omega_i^2}{k_i^2 v_s^2} \times \sum_{l=-\infty}^{+\infty} e^{-k_i^2 v_s^2} \left( 1 + \frac{\omega_i}{\epsilon_i} \frac{Z}{k_i \epsilon_i} \right), \tag{5} \]

\( \omega_{pe} = (4 \pi e^2 n_e/m_e)^{1/2} \) and \( \omega_{ci} \) denote the electron and ion plasma and cyclotron frequencies, respectively, \( n_e \) are electron and ion densities, \( v_s = \sqrt{2 T_s/m_e} \) are the electron and ion thermal velocities, \( \rho_s = v_s/\omega_{ci} \) denote the Larmor radii; the parallel and the perpendicular wave vectors are defined with respect to the direction of the magnetic field; \( I_l \) are the modified Bessel function of the first kind, and \( Z \) is the standard plasma dispersion function. Below we always assume H or D plasma without

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**TABLE I. Characteristics of GDT CTS (preliminary design).**

| Characteristic | CTS I (top) | CTS II (bottom) |
|---------------|-------------|-----------------|
| Scattering angle  | 65°–87° | 93°–110° |
| Parallel wavevector \( k_{||} \) | -0.5–0.5 cm \(^{-1} \) | 12–15 cm \(^{-1} \) |
| Transverse wavevector \( k_{\perp} \) | 11–14 cm \(^{-1} \) | 2–3.5 cm \(^{-1} \) |
| Scattering volume, \( V_{\text{CTS}} \) | 900 cm \(^3 \) | 900 cm \(^3 \) |
| Radial position of \( V_{\text{CTS}} \) | 5–10 cm | 0–5 cm |
| Axial position of \( V_{\text{CTS}} \) | -5–5 cm | -5–5 cm |
| Radial size of \( V_{\text{CTS}} \) | 4 cm | 4 cm |
FIG. 4. Contour plots of fast ion distribution function \( f(v_{\perp}, v_{\parallel}) \) for different positions along the trap axis labeled with the mirror ratios \( R = B(z)/B_{\text{min}} \). Maximum velocity in the plot range correspond to 30 keV. Results obtained with DOL code with parameters typical of GDT experiment with pure NBI heating (no ECRH): NBI energy 25 keV, NBI launching angle 45° to trap axis, \( B_{\text{min}} = 0.35 \) T, \( T_e = T_i = 180 \) eV, \( n_e = 8 \times 10^{12} \) cm\(^{-3} \), \( n_i = 2.6 \times 10^{12} \) cm\(^{-3} \), \( n_f = 2.6 \times 10^{12} \) cm\(^{-3} \) at \( R = 1 \). Note that these distributions are far from being stationary; calculations stop at time of 4.2 ms just before the real NBI switch-off.

In GDT conditions, fast ions can be treated as non-magnetized. This essentially simplifies calculation of its contribution to the scattering function and the dielectric constant. Then one obtains

\[
S_f = \frac{2\pi n_f}{n_e} \left| \frac{H_e}{\epsilon_l} \right|^2 F(\omega/k) \tag{6}
\]

and \( \epsilon_l = 1 + H_e + H_i + G_f \) with

\[
G_f = \frac{4\pi e^2 n_f}{m_i k} \int \frac{dF}{du} \frac{du}{\omega - ku + i0} \tag{7}
\]

Here we assume a unit norm for the distribution function, \( \int F du = 1 \), and \( n_f \) is a volumetric density of fast ions inside the scattering zone. The term \( G_f \), i.e. the contribution of fast ions to the plasma shielding, is always small in the frequency range important for the CTS diagnostic (including range where \( S_f \gg S_i \)).

In this paper we perform forward CTS modeling, i.e., we calculate the scattering function for a given distribution function. The fast ion distribution function is calculated with the bounce-averaged Fokker–Planck code DOL, a nonstationary model intended to describe kinetic plasma processes in axisymmetric magnetic mirror traps. The output of the code is two-dimensional (axially symmetric in a velocity space) distribution \( f(v_{\perp}, v_{\parallel}) \) of collisionally slowed-down NBI-born ions at the magnetic field minimum (corresponded to the trap center). Using invariants of collisionless ion motion along a magnetic field line, \( v_{\perp}^2/B \) and \( v_{\perp}^2 + v_{\parallel}^2 \), we map the distribution function to other positions along the trap axis. An example relevant to actual GTD experiments is shown in figure 4. Corresponding density of fast ions along the trap axis is plotted figure 5. One can see that maximum density is reached near the mirror ratio \( R = 2 \) which corresponds to the turning point of an ion born with the 45° pitch-angle at the trap center. In physical space this point is about 1.8 m far from the center.

Then we calculate the scattering function \( S(k, \omega) \) using one-dimensional distributions of fast ions obtained as numerical integrals,

\[
F(u) = \int f(v_{\perp}, v_{\parallel}) \times \delta \left( u - \frac{k}{k} v_{\parallel} + \frac{k}{k} v_{\perp}\cos \phi \right) v_{\perp} dv_{\perp} dv_{\parallel} d\phi. \tag{8}
\]

The results for the CTS geometries I (sensitive to perpendicular velocities) and II (sensitive to longitudinal velocities) are presented in figures 6 and 7. Figure 6 allows comparing different channels of the scattering. One see that the fast ions are totally dominating in the CTS spectrum in the frequency range of 100–300 MHz. For

FIG. 5. Distribution of fast ion density along the trap axis. Density is normalized over its value in the trap center, plasma conditions are the same as in figure 4. Colored points indicate cases shown in figure 7.

 imposturities, so all ions are singly ionized and \( n_e = n_i \).
anisotropic fast ions, the signals of CTS I and II are rather different, while the thermal component results in more or less the same signal in both cases. This is a natural consequence of two facts: the scattering angle is similar in both cases and the magnetic field effect on CTS are weak in our geometry. Some oscillations of CTS I spectrum are due to limitations of our numerical model.

Figure 7 illustrates sensitivity of the CTS spectrum to the shape of the distribution function—different colors correspond to the different positions of the scattering volume along the trap axis (labeled by points with the same colors in figure 5). As expected, the CTS signal follows the shape of one-dimensional distribution function.

V. CTS RESOLUTION

To estimate the influence of radiation refraction in inhomogeneous plasma, we use the ray-tracing code previously developed for the ECRH modeling in GDT. Some results are illustrated in figure 8. The ray-tracing treats independently the O and X modes propagating in the magnetized plasma. Top plots show how the refraction increases with the plasma density: the same ray is launched at a fixed angle for a set of congruent density profiles. One see that plasma cutoffs implies rather strong limitations on operational plasma density: it should be below approximately $10^{13}$ cm$^{-3}$ (on-axis) to avoid the X-mode cutoff and below approximately $1.5 \cdot 10^{13}$ cm$^{-3}$ to avoid the O-mode cutoff. Based on similar considerations and after checking through all typical GDT conditions, we conclude that O-mode is the only acceptable option for the reliable CTS diagnostic.

The incident and scattered microwave beams are modeled as a sum over a three-dimensional set of rays with wave intensities, $I_i$ and $I_s$, distributed according to the antenna pattern. The intensity along each ray can be calculated from the trivial radiation transfer equation with no losses, $d(I \cos \delta / N^2) / dl = 0$, where $N$ is a refractive index, $\delta$ is an angle between the group velocity $\partial \omega / \partial k$ and the wave vector, and $l$ is a coordinate along the ray. Bottom plots in figure 8 shows two-dimensional cuts of two crossing three-dimensional beams. Initial conditions for these beams are set with taking into account restrictions of physical ports at GDT. In particular, we find that on-axis position of the scattering volume is possible.
FIG. 8. Results of ray-tracing. Top plots: refraction of O and X mode rays as on-axis plasma density varies from (a) \(0.8 \times 10^{13}\) cm\(^{-3}\) to (b) \(1.5 \times 10^{13}\) cm\(^{-3}\). Bottom plots: axial cross-section of CTS I and II scattering geometry for the O-mode. Plasma density and temperature profiles correspond to pure NBI discharges in GDT and similar to those reported in Ref. [33].

only for the CTS II geometry. By iterating of such calculations for different options available at GDT, we find the restrictions on parameters listed in Table [11]. It is interesting to note, that the beam overlapping, calculated as a three-dimensional integral, is practically constant, \(O_b = \int I^i I^s dV \approx 0.2\) cm\(^{-1}\), for all cases of interest. The characteristic size of the scattering volume is about 4 cm what makes 10% of the actual plasma radius in the central cross-section.

The geometrical form factor is given by the following expression [44]:

\[
G_{\mu\nu} = \left(\frac{\omega_s^s \omega_i^i}{\omega_{pe}^i}\right)^2 \frac{2 N_s^i N_i^j}{\omega_{pe}^i} \left(\hat{e}^s \cdot \hat{e}^s \cdot (\hat{I} - \hat{\epsilon}^i) \cdot \hat{e}_{j\mu}^i \cos \delta_s^i \cos \delta_{i\mu}^j \right) \left(\hat{e}_{s\nu}^i \cdot \hat{e}_{s\nu}^i \right) \left(\hat{e}_{i\mu}^s \cdot \hat{e}_{i\mu}^s \right),
\]

where the subscripts \(\nu\) and \(\mu\) specify the wave mode (O or X), the superscripts refer to the incident or scattered waves (\(i\) or \(s\)), \(e\) denotes the polarization vector, \(N\) and \(\delta\) are the cold plasma dielectric tensor and corresponding refractive index, respectively. The results of calculating \(G\) are presented in figure [9]. Note that using of the O–O scattering would reduce the CTS signal by a factor of 2–5 compared to the most strong X–X scattering; however this is a reasonable pay for the reduced role of refraction when using the O wave polarization. Black curves correspond to a planar scattering geometry when \(k^i, k^i\) and \(B\) lie in the same plane. To improve coupling in the O–O case, one of the ports (probe or receiving) may be rotated in the plane transverse to the trap axis. Red curves in the figure [9] show the case when the probe and receiving ports are shifted by 30° in azimuthal direction. One can see that this trick, physically possible at GDT, may moderately improve the O–O coupling.

VI. ABSOLUTE VALUE OF CTS SIGNAL

We characterize an absolute value of the CTS signal in terms of the effective noise temperature, \(T_{CTS}/2\pi = dP^e/d\omega\), where the r.h.s. is given by Eq. (3). The most variable part in this equation comes from the spectral density of plasma density fluctuations. Plots in figure [7]
FIG. 9. Geometrical form factors $G_{\text{O-O}}$, $G_{\text{X-X}}$, and $G_{\text{X-O}} = G_{\text{O-X}}$ as a function of the launching angle $\alpha$ respected to the trap axis for pure NBI discharges in GDT. Set of similar curves corresponds to different on-axis plasma densities that varies from $0.8 \cdot 10^{13}$ cm$^{-3}$ to $1.4 \cdot 10^{13}$ cm$^{-3}$. Red curves correspond to the probe and receiving ports shifted by 30 deg in azimuthal direction as shown in figure [3], black curves correspond to the probing and receiving at the same azimuthal position (plain geometry). Physically allowed ranges of $\alpha$ are $30^\circ - 50^\circ$ for the O–O scattering, $20^\circ - 45^\circ$ for the X–X scattering, and $20^\circ - 50^\circ$ for the X–O scattering.

suggest a characteristic value $S(k, \omega) \approx 5 \cdot 10^{-9}$ s which we shall use for estimations. All other terms in Eq. (3) may be calculated with ray-tracing. Figure [10] presents the final result of searching in the allowed parameter range.

Thus, the expected level of the CTS signal is of 100–500 eV in 300 MHz frequency band or, equivalently, power of 5–25 nW at the receiver input. These are rather high values compared to toroidal fusion experiments; the reasons of such difference will be discussed in the Summary. Note that the CTS volume is located far from the electron cyclotron-resonance at the fundamental harmonic, approximately near the 6-th cyclotron harmonic. With the electron temperature of 200–600 eV, the electron-cyclotron emission is virtually negligible, about $10^{-6}T_{\text{CTS}}$ due to transport of radiation at the fundamental harmonic. The main sources of noise in the proposed diagnostic come from the receiver itself and from, possibly, spurious spectrum (out of the main generation line) of the gyrotron used as a source of probe radiation. The latter issue requires additional experimental investigation.

VII. SUMMARY

The aim of this work is to identify the conditions under which a collective Thomson scattering experiment with available 54.5 GHz gyrotron source can, in principle, provide useful information about the fast ion particle velocity distribution in GDT. We find that it is possible with quite modest hardware requirements when operating in central regions of the trap characterized by low cyclotron plasma emission. The design of components for the CTS diagnostic is now in progress. Compared to well developed experiment in toroidal devices, we have two factors that eventually simplify the diagnostic: much higher relative density of explored fast ions and lower frequency of the probe radiation that increases the scattering as $T_{\text{CTS}} \propto (\omega_i)^{-3}$. Main ECRH systems of tokamaks and stellarators are usually operated at 110–170 GHz, thus any frequency below requires a dedicated gyrotron. On the other hand, GDT discharge is short-time (5–10 ms) and essentially nonstationary; so there is a limited possibility to collect the CTS signal in order to improve sensitivity, a usual technique in big toroidal machines.

Although we do not present here a comparison to only competing radiation source based on CO$_2$-laser, a similar research for ITER shows the preference for the gyrotron source[16]. At 10.6 nm, the CTS spectrum changes very rapidly with angle, only small-angle scattering can be used. In contrast, at gyrotron frequencies, much larger scattering angles are available, the spectra change slowly with angle, and reasonably large collection solid angles granting the Salpeter condition can be used. These benefits are fully exploited in our project.
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