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Design of the Collective Thomson Scattering Diagnostics for Large Helical Device Using a Quasi-optical Frequency Tunable Gyrotron as a Radiation Source

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Abstract

Development of the collective Thomson scattering (CTS) diagnostic system for LHD is presented. High frequency, tunable (87–97 GHz), medium power (~100 kW) quasi-optical gyrotron will be used as a radiation source. We will show the detailed description of the system as well as initial calculations of the scattered microwave power from the LHD plasma. Using the quasi-optical gyrotron as a radiation source was inspired by the fact that this particular evice has the ability of tuning of the operational frequency. Which is made it very attractive for using under the various scenarios for LHD plasmas.

Keywords:

collective Thomson scattering, sma diagnostics, ion temperature, LHD, quasi-optical gyrotron

1. Introduction

Collective Thomson scattering (CTS) has been traditionally used for measuring the electron and ion temperature in laboratory plasmas. The detected signal is the one that originate due to the scattering of the electromagnetic radiation by the Debye cloud of electrons, which effectively surround each ion. These clouds of electrons move with the ions and impart a Doppler shift to the scattered radiation.

Theory shows that the net scattered power is dependent on the amplitude of fluctuations in electron density [1-3]. The scattered radiation power $P_s(\omega)$ per frequency interval dω into solid angle interval dΩ is:

$$P_s(\omega)\,\mathrm{d}\Omega\mathrm{d}\omega = P_i \Psi r_0^2 n_e L_{pl} S(\boldsymbol{k},\omega)\,\mathrm{d}\Omega\mathrm{d}\omega\,, \quad (1)$$

where P_i is source power, r_0^2 is classical electron radius, Ψ and L_{pl} are geometrical factors. $S(\boldsymbol{k}, \omega)$ is the scattering form factor, containing the information about the frequency spectrum at the selected wave vector.

For a plasma containing several ion species the scattering form factor can be written in terms of G_e and G_i, the dielectric susceptibilities of the of the electrons and of the ions of species i,

$$S(\boldsymbol{k},\omega) = \frac{\left|1-\sum G_i\right|^2 F_e + n_e^{-1}\left|G_e\right|^2 \sum Z_i^2 N_i F_i}{\left|1-G_e-\sum G_i\right|^2} \quad (2)$$

F_e and F_i are the velocity Maxwellian distribution, of electrons and ions of species i, N_i the number density of ions of type i, and Z_i is their charge. The dielectric susceptibilities G_e and G_i are related to the plasma dispersion function $W(\xi)$ by:

$$G_e = -W(\xi)\alpha^2, \text{ and } G_i = -Z_i \frac{T_e}{T_i} W(\xi)\alpha^2\,. \quad (3)$$

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$$W(\xi) = 1 - 2\xi \exp\left(-\xi^2 \int_0^{\xi} \exp t^2 dt\right) - i\sqrt{\pi}\,\xi \exp t^2 \qquad (4)$$

with $\xi = (\omega/kv)$, $v = \sqrt{2KT/m}$ is the thermal velocity and Salpeter parameter $\alpha = 1/k\lambda_D$ [4] – the usual scale length to Debye length ratio.

The form of $S(\boldsymbol{k}, \omega)$ depends on α. For small scale fluctuations ($\alpha \ll 1$) the electrons become uncorrelated. This is the case of incoherent Thomson scattering, for which $S(\boldsymbol{k}, \omega)$ is simple Gaussian. In opposite case ($\alpha \geq 1$), collective scattering fluctuations occur. $S(\boldsymbol{k}, \omega)$ consist of a low frequency part, called *ion feature* at $\omega_i = kvT_i$, and high frequency part near electron plasma wave frequency.

2. Determination of the Scattered Angles

Using of 90 GHz range radiation allow to achieve larger α values. For the typical LHD plasma parameters ($B_0 = 2.75$ T, $n_e \approx n_i = 5 \times 10^{13}$ cm^{-3}, and $T_e \approx T_i = 3$ keV) we conduct the calculation of the possible scattered angles. Those estimation shows that almost any kind of the scattering experiment is possible. The scattered angles vary from near very small angles ~ 0–5° (quasi-forward scattering) to almost backward scattering values ~ 180°. From the expression of Salpeter parameter $\alpha = 1/k\lambda_D$:

$$\sin\frac{\theta_{Br}}{2} = \frac{1.08 \times 10^{-4} \lambda_i}{\alpha} \left(\frac{n_e [\mathrm{cm}^{-3}]}{T_e [\mathrm{eV}]}\right)^{1/2} \qquad (5)$$

one can see that utilization of lasers (for instance CO_2 laser) is possible for a very small angles only. This fact will be make separation of insident and scattered beams more difficult. A plot of condition $\alpha = 1.5$ for 92 GHz quasi-optical gyrotron and CO_2 laser radiation as function of density and temperature for LHD plasmas (see Fig. 1).

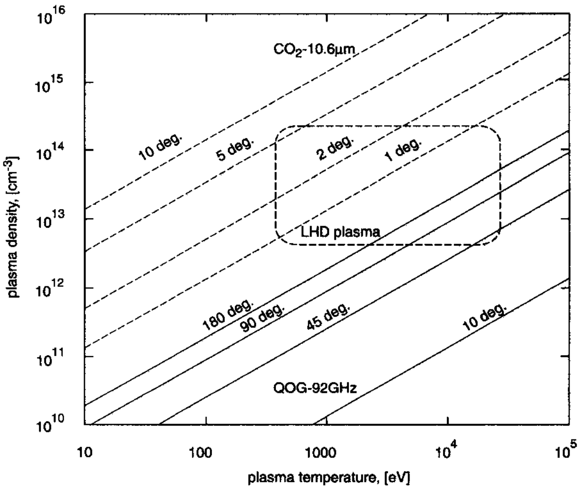

Fig. 1 Plot of condition $\alpha = 1/k\lambda_D = 1.5$ for 92 GHz quasi-optical gyrotron and CO_2 laser radiation as function of density and temperature for LHD plasmas. Density and temperature for collective type of scattering are located over each line.

3. Description of the System

Gyrotron and MOU: The proposed system for LHD will utilize the quasi-optical (Q. O.) gyrotron as a power source. The Q. O. gyrotron designed for operation at the fundamental frequency ($\omega = \Omega_{ce}$) in the range of 92 ± 5 GHz and in the range of 2 × (92 ± 5) GHz at the second harmonic ($\omega = 2\Omega_{ce}$)[1] In Q. O. gyrotron the resonant structure is a Fabry-Pérot resonator placed transversely to electron beam and operating in the pure Gaussian TEM_{00q} mode. The advantages of Q. O. concept are the frequency tunability and the geometric separation between the spent electron beam and the microwave output. Above mentioned characteristics offers flexibility for experiments on fusion devices, where it may be advantageous to change the localization of power deposition zone (even for diagnostic usage) without changing the magnetic field and therefore affecting the plasma properties.

For coupling the output gyrotron radiation to a corrugated circular waveguide matched optical unit (MOU) is used. MOU mirrors (mirrors A and B at the Fig. 2) are designed to reshape beam profile from gyrotron output so that the radiation smoothly couples with HE_{11} waveguide transmission mode.

Transmission line: At present time for the delivery microwave radiation to the plasma we are planned to use one of the present ECH transmission line[2] [5]. CTS transmission line (Fig. 2) is using 31.75 mm evacuated corrugated waveguides. The full path will have 10 miter bends and about 100 m in length. This transmission system was optimized for delivering of 70–90 GHz microwave radiation. The probing microwave beam, according present plans, will be injected through the downside 1.5 L port. The detection part will be placed at corresponding upper side port. The investigation of the possi-

[1]At present time the gyrotron under conditioning at FIR, Fukui University.

[2]Designed at NIFS

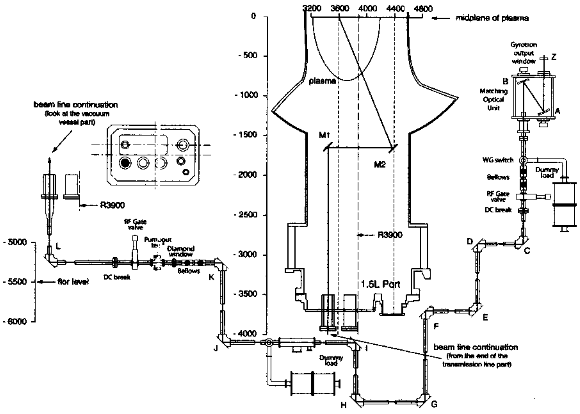

Fig. 2 Schematic diagram of CTS transmission line.

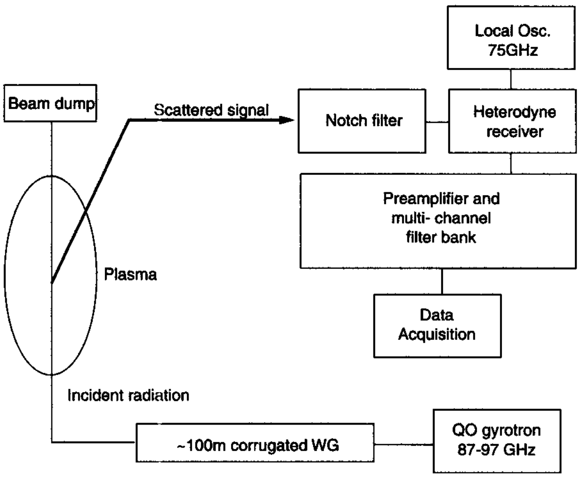

Fig. 3 Schematic diagram of the heterodyne detection system.

bility of using horisontal port for scattered radiation is under way now.

Detection system: Use of middle power gyrotron require good signal-to-noise ratio. Thus, a heterodyne type detection system will be used (Fig. 3). The scattered radiation from LHD plasma, which consist of the incident carrier and Doppler shifted parts, will be mixed with 75 GHz local oscillator (LO) signal. To suppress high radiation from the incident beam the tunable band-reject filter have to be inserted in front of detector. To obtain frequency spectra at post detection stage the signal will be split into several parts. To evaluate detailed spectrum of the scattered radiation each channel has its own intermediate frequency range that depends on corresponding part of microwave spectrum.

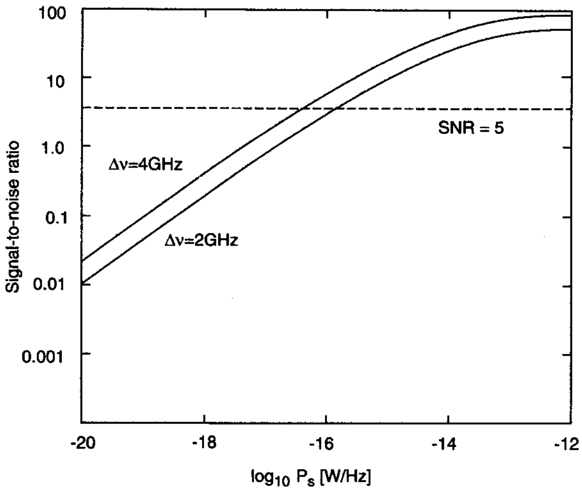

Fig. 4 Estimated SNR of the heterodyne detection system.

In the real plasma experiment, measurable spectral width is constrained to lie within the bandwidth capability of heterodyne detector and conventional electronics, typically about of several GHz. In the case when both temperatures, for electrons and ions, are practically the same ($T_e \simeq T_i$) the spectral width could be given by $kv_i/2\pi = \sqrt{2}\omega_{pi}/2\pi\alpha$. This condition can be easily met by using a sufficiently high α. If heterodyne detector noise dominates, the parameters of frequency analyzing circuit can be derived from the signal-to-noise level at the detector $s = P_s^{\Delta\nu}/NEP$ ($NEP = 8.6 \times 10^{-17}$ WHz$^{-1/2}$) and the output of frequency analyzer $S = \sqrt{1 + \Delta\nu\tau s}/(1 + s)$, where $P_s^{\Delta\nu}$ is power of scattered radiation delivered into heterodyne detector per Hz bandwidth, $\Delta\nu$ is the bandwidth of resolution interval and τ is integration time (which equal to gyrotron pulse length). Estimated SNR is shown on the Fig. 4.

4. Calculation of Expected Scattered Spectrum from LHD Plasma

Upon the inspection of the form factor it was found that a wide low part of the spectrum coming from the first term in Eq.(2), and tall narrow part coming from the second term of the same equation. The latter stems from the collective motion of the electrons with the ions, which is what we are concern to measure. Our calculations have been confined near the values of angular frequency ω for which second term makes a substantial contribution to the whole spectrum, i.e. $\omega \leq 3\ kv_i$.

The expected scattered spectrum from LHD neutral

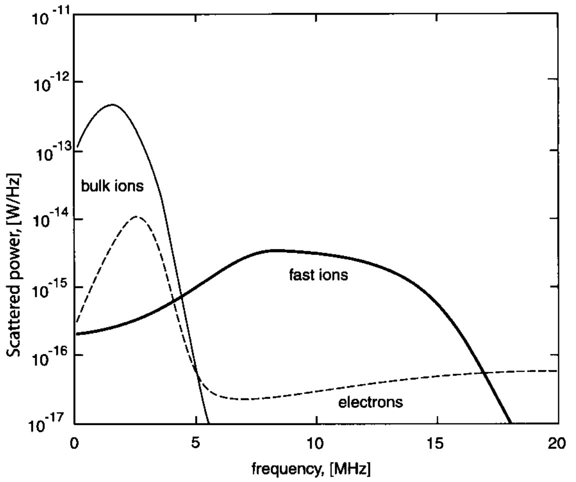

Fig. 5 The expected scattered spectrum from LHD plasma as a function of a Doppler shifted frequency from the gyrotron centered frequency. Plasma parameters : B_0 = 2.75 T, $n_e \approx n_i = 5 \times 10^{13}$ cm^{-3}, $T_e \approx T_i$ = 3 keV, E_{NBI} = 150 keV. We assume that electrons and bulk ions velocity distribution functions of the plasma are Maxwellian and that a high energetic ions have an isotropically $1/v^3$ slow-down distribution.

heated plasma as a function of a Doppler shifted frequency from the gyrotron centered frequency is shown on the Fig. 5. For spectrum simulation the following plasma parameters are chosen: B_0 = 2.75 T, $n_e \approx n_i = 5 \times 10^{13}$ cm^{-3}, and $T_e \approx T_i$ = 3 keV, E_{beam} = 150 keV. We assume that electron and bulk ion velocity distribution functions of the plasma are Maxwellian and (alphas) have an isotropic $1/v^3$ 'slow-down' distribution. For evaluating of the scattered form factor, so-called Salpeter approximation has been used.

The calculation was done for vertically elongated plasma. As a receiver 20 dB gain conical horn antenna was used. The position of antenna was changed according to the values of scattered angle. The results shows (see Fig. 5) that for the wide frequency range, there is sufficient scattered power, expected from bulk ions, and the contribution from electrons is three orders lower.

5. Summary

We have performed initial design of the LHD CTS system based on the Q. O. gyrotron as a radiation source. The main advantage of the using gyrotron as a radiation source instead CO_2 laser is as follows. In the case of lasers, the spectrum changes very rapidly with angle, only small-angle scattering can be used. This complicates obtaining high spatial resolution Δr. In contrast, at gyrotron frequencies, much larger scattering angles are available. ($\Delta r_{las} \simeq 43$ cm, $\Delta r_{gyr} \simeq 2.7$ cm). The spectra change on slowly with angle, and reasonably large collection solid angles can be used - limited only by coherence requirements for heterodyne detection. The choice of the scattered angle will depend primarily on effects of plasma refraction. For the significant part of the expected spectrum the fast ions component is dominant.It will be encouraging fact for the successful evaluation of the α-particles temperature directly from the total scattering signal.

Preliminary estimates show that middle-power gyrotron with power of up to hundred watts, and pulse duration about 1–2 msec is well suited for ion feature evaluation.

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