Feasibility study of collective Thomson scattering diagnostic of fast ion distribution function for the GDT experiments

E.D. Gospodchikov[1], A.G. Shalashov[1], L.V. Lubyako[1], A.L.Solomakhin[1,2], M.E. Viktorov[1], T.A. Khusainov[1], O.B. Smolyakova[1], V.V. Prikhodko[2], P.A. Bagryansky[2]

[1] *Institute of Applied Physics RAS, Nizhny Novgorod, Russia*

[2] *Budker Institute of Nuclear Physics, Novosibirsk, Russia*

Introduction

GDT (Gas Dynamic Trap) is a fully axisymmetric linear magnetic device aimed at nuclear fusion applications [1]. GDT plasma consists of two components: bulk plasma confined in the gas-dynamic regime and 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 and has an anisotropic distribution function. Measuring the energy and pitch angle distribution function of fast ions is one of the primary problems for GDT experiments. In particular, fast ion distribution over pitch angles is the main factor determining fusion efficiency, the neutron yield and the locality of a neutron source. 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.

CTS diagnostics development

Collective Thomson scattering (CTS) of high-power microwave radiation by the thermal fluctuations of electron density provides possibility of getting access to the fast ion velocity distribution. The scattering function in the collective regime depends on the ion composition and ion velocity distribution; this feature is widely used for probing these parameters in toroidal magnetic traps [2]. We propose to use the same technique for measuring the fast ion distribution in GDT [3]. This device is already equipped with a high-power ECRH system that is ready to be used as a source of probe radiation for CTS. Compared to tokamaks and stellarators, the following factors benefit the CTS experiment at GDT: (1) the relative population of fast ions and their influence on the overall performance are usually much greater in a large open trap than in toroidal fusion devices; (2) for the open magnetic configuration, the CTS and ECRH volumes may be well separated in space; this allows CTS operating with low electron cyclotron plasma emission, which is the main source of noise in case of toroidal traps; (3) modern ECRH systems of tokamaks and stellarators are operated at 110−170 GHz; the lower frequency of the probe radiation, determined by the available 54.5 GHz gyrotron at GDT, increases the scattering efficiency by a factor of 10 − 30 [3]. On the other hand, GDT discharges are essentially not stationary and short-time (5 − 10 ms); so there is a limited possibility to accumulate the CTS signal to improve sensitivity, a usual technique in large toroidal machines.

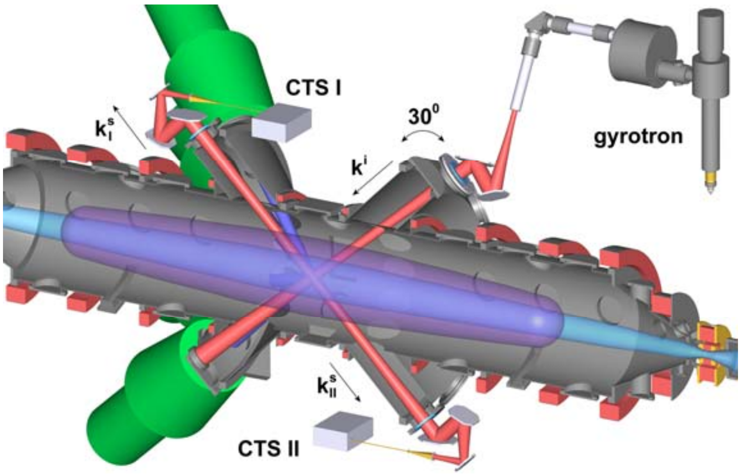

Figure 1. *CTS diagnostic at GDT.* $\mathbf{k}^i$ *denotes the incident gyrotron beam,* $\mathbf{k}_I^s$ *denotes the received CTS beam sensitive to fast ion distribution over perpendicular velocities,* $\mathbf{k}_{II}^s$ *denotes the received CTS beam sensitive to the distribution over longitudinal velocities.*

Figure 1 shows a general arrangement of the CTS diagnostic. The "east" 54.5 GHz/400 kW gyrotron of the ECRH system [4] is used as a source of probe radiation. For this purpose, the gyrotron radiation is rerouted from the ECRH port, located in the high magnetic field zone near the trap end, to the central part, where fast ions are generated and confined. The scattered signal is received either from the top or from the bottom of the vacuum chamber to resolve the fast ion distribution over perpendicular (CTS I) and longitudinal (CTS II) velocities. To improve coupling, the probe and receiving ports are shifted by 30° in the azimuthal direction, and the ordinary-mode polarization is used both for the probe and received waves (the O–O scattering). For more details see [5].

Requirements to the CTS receiver

The scattered signal has a narrow-band noise spectrum, the useful part carrying information about the fast ions is localized in the symmetric band of ±300 MHz with respect to the probe frequency of 54.5 GHz (fig. 2). So the frequency resolution of 10 MHz allows measuring of 20 − 30 points of the fast ion CTS feature, which seems to be a reasonable lower limit for reliable diagnostic of the ion distribution function. The expected value of the effective radiation temperature of the scattered signal lies in the range of 100 − 500 eV which is noticeably higher than the level of spontaneous plasma emission measured at the GDT; this corresponds to the power of 5 − 25 nW coming to the receiving antenna input and the power scattering

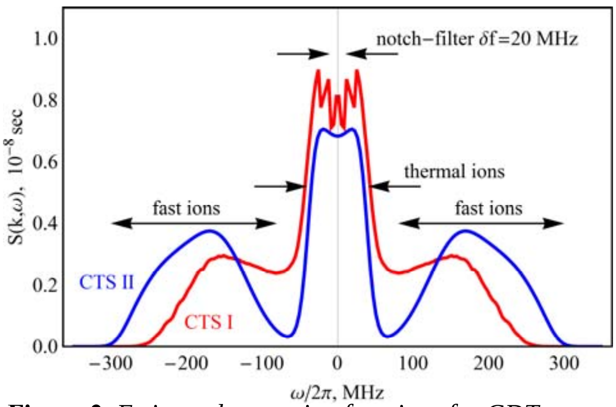

Figure 2. *Estimated scattering functions for GDT*

efficiency of 10^{-14}. Typical evolution time of GTD plasma discharge is about 1 ms; correspondingly, we set that the CTS receiver must provide a time resolution no worse than 100 μs. To ensure spectrum measurements with the required time and frequency resolution, the CTS receiver must have a sensitivity of at least 0.1 eV.

Preliminary experiments

To understand possible noise and hazard sources in CTS measurements, we performed a series of dedicated experiments with actual GDT plasma discharge and running gyrotron. The gyrotron radiation used for plasma probing is inevitably distributed over the vacuum chamber forming a so-called stray-radiation backlight. When the stray-radiation gets into the unprotected receiver input, it may cause malfunction of the receiver. The stray-radiation was measured during the plasma discharge using two independent techniques: by a calorimeter placed near the CTS port and by direct detecting a signal with the high-performance digital oscilloscope, protected by a filter system and equipped with a broadband antenna. Calorimeter measurements showed a level of energy-flux density of 0.7 W/cm^2/srad, which for a horn antenna for a wavelength of 5.5 mm gives a power level of 0.2 W. Direct recording of the antenna signal in the band of 54.47 ± 0.01 GHz showed a power level of 5×10^{-7} W with −55 dB attenuation of the filter system, which gives a power of 0.15 W, see fig. 3 (a,b). Approximating for other experimental conditions, we conclude that the stray-radiation level measured at the CTS receiving antenna during the GDT plasma discharge does not exceed 1 W. Although this power is by 5 orders of magnitude less than the probe signal, it significantly exceeds the admissible level of 1 mW at the antenna input for the CTS receiver. Thus, the input signal must be attenuated by at least 30 dB in a narrow band around the gyrotron frequency.

To determine this band, we perform precision measurements of the actual operating frequency of the probing gyrotron. This frequency oscillates during plasma shots with an amplitude of about 3 MHz relative to the stable average value of 54.47 GHz, see fig. 3(c). The frequency modulation is caused by the existing power supply. The generation line width is about 250 kHz. The spectrum contains no constituents, indicating the presence of frequency or amplitude modulation by a parasitic lower frequency signal excited inside a gyrotron cavity. The average frequency does not change in the course of one shot but varies from shot to shot with the maximum spread of 50 MHz. The gyrotron frequency statistic is presented in fig. 3(d); shot-to-shot reproducibility of the gyrotron frequency is $54.47^{+0.03}_{-0.02}$ GHz. Taking these results into account, we develop a band-stop notch filter with the transmission of at least −40 dB in 25 MHz band with the adjustable central frequency (of the probe radiation) in the range of ±50 MHz. The notch filter is placed at the receiver input to ensure receiver protection when operating together with the high-power gyrotron. This option does not exclude the operation with two gyrotrons, one for the probing and one for the plasma heating.

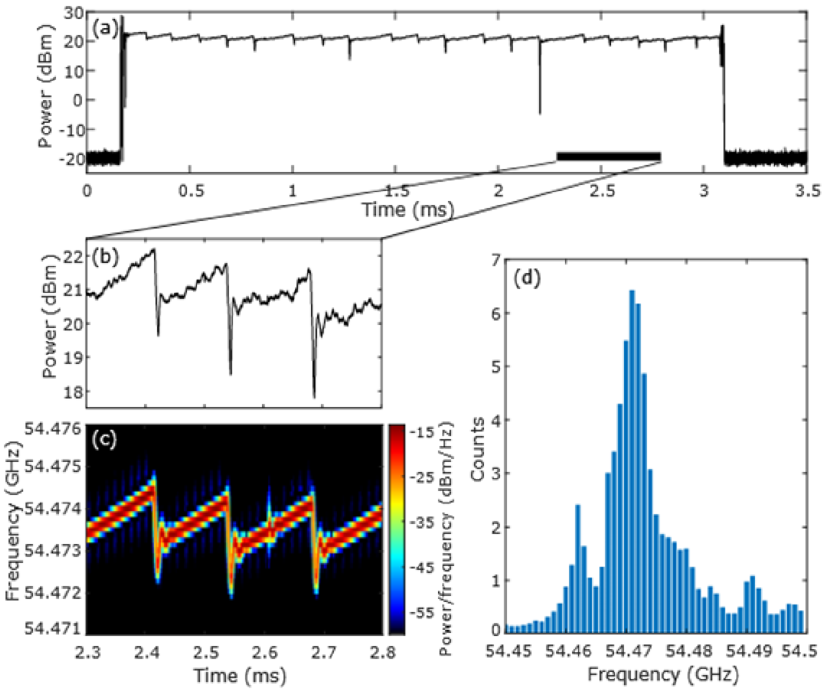

Figure 3. *The power and frequency modulation of the gyrotron stray-radiation received near the CTS port (a-c), and histogram showing the gyrotron frequency shot-to-shot distribution for 5 experimental days (d). Fractional heights in plot (d) correspond to frequency variation during a short phase after the gyrotron switching-on. Authors thank Scientific devices and systems, LLC for the technical support during preliminary GDT experiments.*

A receiving system that meets the requirements listed above and consists of two independent high-sensitivity radiometers protected by notch filters has been developed and now this system is being installed on the GDT. The receiving complex consists of two independent highly sensitive radiometers adapted to the expected characteristics of the measured signal equipped with analog spectrum analyzers (24-channel filterbank), matched outputs to digital oscilloscopes (Tektronix MS054, analysis bandwidth 500 MHz) and protection systems for the input RF circuits from a backlight of powerful gyrotron radiation [5].

The work has been supported by Russian Science Foundation (project No. 19-72-20139).

References

[1] P. A. Bagryansky *et al.*, Plasma Fusion Res. **14,** 2402030 (2019).

[2] H. Bindslev, Rev. Sci. Instr. **70**, 1093 (1999).

[3] A. G. Shalashov *et al.*, Plasma Phys. Cont. Fus. **62**, 065010 (2020).

[4] P. A. Bagryansky *et al.*, Nuclear Fusion **55** (5), 053009 (2015).

[5] A. G. Shalashov *et al.*, accepted in JINST (2021).