

P6.013

Review of possibilities for a Collective Thomson Scattering diagnostic on tokamaks

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A focus of research for future fusion machines is fast ions dynamics: therefore the measurement of space and velocity distribution function of fast ions is a priority in diagnostics for a fusion reactor. Collective Thomson Scattering (CTS) is a technique for diagnosing plasma ions, planned for ITER in a configuration never tested. The present study analyses the possibilities to test an ITER-like CTS on FTU, JET and FAST proposal.

1. Introduction

CTS is a light scattering technique. A main radiation beam (momentum \mathbf{k}_i and frequency ν_i) is focused in the plasma. Scattered radiation (\mathbf{k}_s, ν_s) is collected at angle (θ_{sc}): its spectrum is proportional to the particle velocity distribution function $f(\omega/k)$, where $\mathbf{k}=\mathbf{k}_s-\mathbf{k}_i \approx 2\mathbf{k}_i \sin(\theta_{sc}/2)$ links, through $\omega=\mathbf{k}^* \mathbf{v}$, velocity and frequency. The space resolution is the dimension (L) of the intersection of the incident beam and the collecting line of sight: to get $L \approx 0.20$ m and to measure velocities from the alpha birth $V_{0\alpha}=1.3 \cdot 10^7$ m/s down to ion thermal $v_{thi}=7 \cdot 10^5$ m/s, light sources must be used with wavelength $\lambda_i > (4\pi\lambda_D) \sim 1$ mm (corresponding to ≈ 100 GHz gyrotrons) and $k \sim 6000 \text{ m}^{-1}$. In this frequency range, plasmas emit electron cyclotron (ECE) radiation, which is the source of background noise for the CTS measurements. This review starts from a study on CTS for ITER [1] where a frequency below the fundamental electron cyclotron frequency (60-70GHz), was demonstrated useful to achieve $L=a/10=0.28$ m, for $\theta_{sc} \sim 170^\circ$, to detect alpha particles. The designs of CTS systems on FTU [2,9], FAST [3] and the ITER CTS [4] have adopted this view, while the experiments done so far [5] use frequencies between the first and second ECE harmonic. Therefore, in principle, experiments on FTU (and possibly on JET), in ITER configuration, would provide a consolidation of the ITER CTS design. The paper is organized as follows : in sec. 2, the design parameters of CTS diagnostic on JET are presented ; in sec. 3, the CTS system built on FTU and the project for FAST proposal are summarized; in sec.4 conclusions are presented .

2. Design parameters of a CTS diagnostic for alpha particles measurements on JET.

The JET plasma parameters used are : electron density $n_e \leq 1 \text{ } 10^{20} \text{ m}^{-3}$, electron and ion temperatures $T_i \sim T_e \sim 5 - 15 \text{ keV}$, toroidal magnetic field $B_T = 3 - 3.4 \text{ T}$, plasma current $I_p = 2 - 3.4 \text{ MA}$, $0.3\% \leq n_\alpha/n_e \leq 1\%$ (alpha particle density n_α) for advanced modes of operation and $n_\alpha/n_e \sim 0.07\%$ for H-mode at high density. The scattering angle is $\theta_{sc} \sim 160 - 170^\circ$. The radiation scattered by a plasma contains information on electron and ion distribution functions. The Salpeter[6] parameter α_s is defined as $(n_{e20} \text{ electron density in units of } 10^{20} \text{ m}^{-3})$

$$\alpha_s = 1/k\lambda_D = \frac{1.015 \text{ } 10^3}{f_0(\text{GHz}) * \sin(\theta_{sc}/2)} \sqrt{\frac{n_{e20}}{T_e(\text{keV})}}$$

The condition $\alpha_s > 1$ determines the geometry where the contribution of ions is dominant. Assuming $\theta_{sc} \approx 175^\circ$, $\alpha_s = 2.3$ is reached for $f_0 = 50 - 70 \text{ GHz}$ and for $T_e \leq 40 \text{ keV}$. The alpha feature has spectral range $kV_{0\alpha}/2\pi \sim 10 \text{ GHz}$, of the order of the electron feature $kv_{the}/2\pi \sim 40 \text{ GHz}$. So the geometry (i.e. θ_{sc} and the angle ϕ between \mathbf{k} and perpendicular to \mathbf{B}) is determined suitable for the ratio of alphas to electron signal $R_{ae} \geq 2$. R_{ae} calculations for $n_\alpha/n_e = 0.003$ and 0.001 show that frequencies $f_0 = 60 - 80 \text{ GHz}$ can be used for $5^\circ \leq \phi \leq 20^\circ$. Moving to the calculation of the temperature of the scattered radiation (T_s), assuming a Maxwellian distribution of alpha particles, T_s is given by :

$$T_s (\text{keV}) = 1.35 \text{ } 10^4 * \Gamma * \varepsilon * Z_\alpha^2 * \frac{n_{e20}}{\sin(\theta_{sc}) * f_0(\text{GHz})^2} \frac{n_\alpha}{n_e} P(\text{MW})$$

Where the factor $\Gamma = 1/2$ for the extraordinary mode, and $\Gamma = 1$ for the ordinary mode. The term ε is the overlapping efficiency of the incident and antenna beams. For the JET parameters and $f_0(\text{GHz}) = 60$, $P(\text{MW}) = 0.5$, extraordinary mode, scattering angle $\theta_{sc} = 170^\circ$, $n_{e20} = 1$, $n_\alpha/n_e = 0.3\%$, $T_s(\text{keV}) \sim 0.03$, for $\varepsilon = 50\%$. To model the propagation of the gyrotron beam, ray tracing calculations were carried out taking the reference shot 73344. In the calculations the magnetic field and current are rescaled to $B = 3.4 \text{ T}$, parameter for DT experiments. Calculating the characteristic frequencies determining the wave propagation properties for electron cyclotron waves it is found that the window between the lower cutoff and the cyclotron frequency is very narrow. **This limits the plasma density for which these measurements are possible to $n_e < 9 \text{ } 10^{19} \text{ m}^{-3}$.** This point is investigated by ray-tracing at a frequency $f_0 = 60 \text{ GHz}$, using a toroidal, fully relativistic ray-tracing code [7] in magnetic equilibria reconstructed by the CRONOS code [8]. Figure 1 shows ray-tracing (at fixed launching toroidal angle $\phi_{tor} = 12^\circ$), for poloidal angles in the range $\phi_{pol} = -3^\circ$ to -16° , (scattered

waves), for $\phi_{\text{pol}} = +21^\circ$ (incident wave). Launching and collecting mirrors are located at $R = 432$ cm, $Z = \pm 35$ cm, in JET equatorial port sketched in Fig. 1.

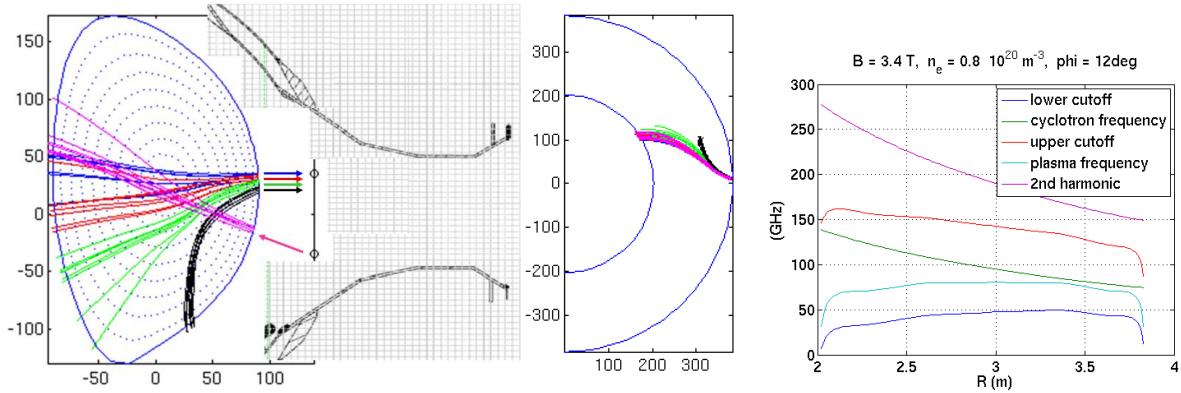


Fig.1 Ray tracing calculations for $f_0=60\text{GHz}$: (a) poloidal projections of the incident and scattered ray trajectories at various angles ϕ_{pol} at fixed toroidal angle $\phi_{\text{tor}}=12^\circ$; a sketch of a JET equatorial port is also shown, on scale, in order to show the compatibility of the system with the port geometry. (b) toroidal projection of the same rays. Plasma Parameters : $B_T = 3.4$ T, $n_e = 0.8 \cdot 10^{20} \text{ m}^{-3}$. Color Code for the ray tracing varying the poloidal angle of the ray $\phi_{\text{pol}} = -3^\circ, -5^\circ, -10^\circ, -16^\circ, +21^\circ$. (c) Calculations of upper and lower cut-off for X-mode. The plasma spatial profiles are rescaled from those of the JET shot 73344.

The choice of the toroidal angle is determined by refraction. A scan of the toroidal angle was

performed: for $\phi_{\text{pol}}=+21^\circ$, the toroidal launching angle is $\phi_{\text{tor}} \leq 17^\circ$, to get a ray to the plasma centre. ECE temperature ($T_{\text{rad}}=T_N$) at $f_0=60\text{GHz}$, is $T_N < 1\text{keV}$ (Fig.2), assuming channel bandwidth of a spectrum analyzer $B=1\text{GHz}$, $T_{\text{NEP}} \approx 10\text{eV}$ receiver noise, integration time $\tau=10\text{ms}$, $\text{S/N} > 10$ is obtained[11].

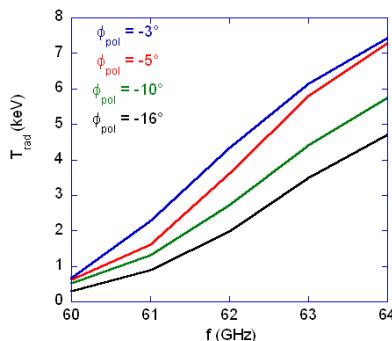


Fig.2 temperatures of plasma radiation

3. CTS diagnostic on FTU and FAST proposal.

The CTS system installed on FTU[9] has a $f_0=140$ GHz wave propagating below the electron cyclotron (EC) resonance for magnetic fields $B_T < 8\text{T}$. The extraordinary (X) and ordinary (O) modes can propagate at plasma densities up to $2.4\text{-}4.8$ ($O\text{-}X$) 10^{20} m^{-3} . Probe and scattered beams are launched and received using the same Equatorial Port of FTU. The launcher has two symmetrical mirrors with respect to the equatorial plane allowing a scattering angle $\theta_{\text{sc}} \approx 55^\circ$, when aligned with the scattering volume at plasma centre. The receiving line is coupled to a heterodyne radiometer (a single sideband 32 channel spectrometer, 1.2 GHz bandwidth centered at the gyrotron frequency). The measurement of ECE background at high

field is $T_N \approx 50\text{eV}$. Experiments on FTU showed that the gyrotron beam can interact with the resonance $\omega_c/2\pi = 140\text{GHz}$ located close to the mirrors of the launcher placed in proximity of the plasma edge. This point has relevance for ITER, because the launching geometry (*and X-mode polarization*) used on FTU is similar to that adopted for ITER CTS. FAST proposal[10] is a compact tokamak ($R = 1.82\text{ m}$, $a = 0.64\text{ m}$, $B \leq 8.5\text{ T}$, $I_p \leq 8\text{ MA}$), equipped with 30MW of additional heating in the form of ion cyclotron resonance heating (ICRH). FAST can produce a fast-ion population (H or 3He) via ICRH in the minority scheme. The launching system considered is very similar to the CTS for ITER[4,1]. The layout consists of two backscattering geometries, sharing the main beam, and measure the velocity distribution function of fast ions parallel and perpendicular to the magnetic field since anisotropic tails of fast ions are expected from ICRH. The transmitting and receiving antennas are accommodated in a single equatorial port. Strong beam refraction effects are expected, so gyrotron frequencies are considered in the range 100-120GHz (at level of 1MW power). The calculated ECE background radiation temperature is of the order of $T_N \leq 100\text{eV}$, and it is not depending much upon the toroidal launching angle. The evaluation of the signal to noise ratio (S/N) is enough for measurements at integration times $\tau \geq 50\text{ms}$, using probe modulation.

4. Conclusions

CTS is a diagnostics for fast ions, alpha particles, measuring also bulk ions. CTS below the fundamental ECE is important for achieving good signal to noise ratio, because of low ECE background: this configuration is chosen for ITER CTS, FTU and FAST and it will be tested on FTU and possibly on JET(in the case of an extended use of the machine). In the analysis for JET-CTS, a $S/N > 10$ in backscattering($\theta_{sc} = 170^\circ$) is obtained using Gyrotrons $f_0 = 60\text{GHz}$ in plasmas $B_T = 3.4\text{T}$, $n_e < 9 \cdot 10^{20} \text{m}^{-3}$. Problems to be faced are: risk of back-reflection of the beam power injected; spurious absorption on resonances close to the launching system.

*See the Appendix of F. Romanelli et al., Proceedings of the 24th IAEA FEC 2012, San Diego, USA.

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11. $S/N = [T_s/(T_s + T_{NEP}/\varepsilon + T_N)]^* (B\tau)^{1/2}$.	