EFDA–JET–CP(13)03/10

F.P. Orsitto, G. Giruzzi, A. Bruschi, W. Bin
and JET EFDA contributors

Review of Possibilities for a Collective Thomson Scattering Diagnostic on Tokamaks

Review of Possibilities for a Collective Thomson Scattering Diagnostic on Tokamaks

F.P. Orsitto[1], G. Giruzzi[2], A. Bruschi[3], W. Bin[3]
and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Associazione ENEA-Euratom sulla Fusione, Frascati (Italy)
[2]CEA, IRFM, Saint Paul-lez-Durance (France)
[3]Istituto di Fisica del Plasma CNR-EURATOM-ENEA Association, Milano, Italy
** See annex of F. Romanelli et al, "Overview of JET Results",*
(24th IAEA Fusion Energy Conference, San Diego, USA (2012)).

Preprint of Paper to be submitted for publication in Proceedings of the
40th EPS Conference on Plasma Physics, Espoo, Finland.
1st July 2013 – 5th July 2013

ABSTRACT

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 ki and frequency νi) is focused in the plasma. Scattered radiation (ks,νs) is collected at angle (θ_{sc}): its spectrum is proportional to the particle velocity distribution function f(□/k), where **k = ks–ki ≈ 2ki** $\sin(\theta_{sc}/2)$ links, through $\boldsymbol{\omega} = \mathbf{k*v}$, 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 ≈ 0.20m and to measure velocities from the alpha birth $V_{0\alpha} = 1.3\times10^7$ m/s down to ion thermal $v_{thi} = 7\times10^5$ m/s, light sources must be used with wavelength $\lambda_i >(4\lambda\pi D) \sim$ 1mm (corresponding to ≈ 100GHz gyrotrons) and k ~ $6000m^{-1}$. 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 = 0.28m, for θ_{sc}~170°, 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 $n_e \leq 1\times10^{20}$ m^{-3}, electron and ion temperatures $T_i \sim T_e \sim$ 5–15keV, toroidal magnetic field B_T = 3–3.4T, plasma current I_p = 2–3.4MA, $0.3\% \leq n_\alpha/n_e \leq 1\%$ (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 θ_{sc} ~160–170°. The radiation scattered by a plasma contains information on electron and ion distribution functions. The Salpeter[6] parameters α_s is defined as (n_{e20} $\alpha_s = 1/k\lambda_D = \dfrac{1.015\ 10^3}{f_0(GHz) * \sin(\vartheta_{sc}/2)} \sqrt{\dfrac{n_{e20}}{T_e(keV)}}$ electron density in units of 10^{20} m^{-3}).

The condition $\alpha_s > 1$ determines the geometry where the contribution of ions is dominant. Assuming $\theta_{sc} \approx 175°$, $\alpha_s = 2.3$ is reached for f_0 = 50–70GHz and for $T_e \leq$ 40keV. The alpha feature has spectral range $kV_{0\alpha}/2\pi$ ~10GHz, of the order of the electron feature $kv_{the}/2\pi \sim$ 40GHz. So the geometry (i.e.

θ_{sc} and the angle φ between **k** and perpendicular to **B**) is determined suitable for the ratio of alphas to electron signal $R_{\alpha e} \geq 2$. $R_{\alpha e}$ calculations for $n_\alpha/n_e = 0.003$ and 0.001 show that frequencies $f_0 =$ 60–80GHz can be used for $5^o \leq \varphi \leq 20^o$. Moving to the calculation of the temperature of the scattered radiation (T_s) , assuming a maxwellian distribution of alpha particles, Ts is given by :

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

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 $\theta_{sc} = 170^o$, $n_{e20} = 1$, $n_\alpha/n_e = 0.3\%$, $T_s(\text{keV}) \sim 0.03$, 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 = 3.4T, 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 $n_e < 9\times10^{19}\ m^{-3}$***. This point is investigated by ray-tracing at a frequency $f_0 = 60$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 $\phi_{tor} = 12^o$) , for poloidal angles in the range $\phi_{pol} = -3^o$ to -16^o, (scattered waves), for $\phi_{pol} = +21^o$ (incident wave). Launching and collecting mirrors are located at R = 432cm, Z = ± 35cm, in JET equatorial port sketched in Fig.1. The choice of the toroidal angle is determined by refraction. A scan of the toroidal angle was performed: for $\phi_{pol} = +21^o$, the toroidal launching angle is $\phi_{tor} \leq 17^o$, to get a ray to the plasma centre. ECE temperature ($T_{rad} = T_N$) at $f_0 = 60$GHz, is $T_N < 1$keV (Fig.2), assuming channel bandwidth of a spectrum analyzer B = 1GHz, $T_{NEP} \approx 10$eV receiver noise, integration time $\tau = 10$ms , S/N>10 is obtained[11].

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 $B_T < 8$T. The extraordinary (X) and ordinary (O) modes can propagate at plasma densities up to 2.4–4.8 (O-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 $\theta_{sc} \approx 55^o$, when aligned with the scattering volume at plasma centre. The receiving line is coupled to a hetherodyne radiometer (a single sideband 32 channel spectrometer, 1.2GHz bandwidth centered at the gyrotron frequency). The ECE background is $T_N \approx 50$eV .

Experiments on FTU showed that the gyrotron beam can interact with the resonace $\omega_c/2\pi =$ 140GHz 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 = 1.82m, a = 0.64m, B ≤ 8.5T, $I_p \leq 8$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 ^{3}He) via ICRH in the minority scheme. The launching system considered is very similar to the CTS for ITER[4,1] . Two backscattering geometries share the main beam and measure velocity distribution function of fast ions parallel and perpendicular to the magnetic field: anisotropic tails 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 in the range 100-120GHz, calculated TN≤100eV. Signal to noise ratio (S/N) is enough for integration times $\tau \geq 50$ms,using probe modulation .

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(θ_{sc} = 170_o) is obtained using Gyrotrons f_0 = 60GHz in plasmas B_T = 3.4T , $n_e < 9\times10^{20} m^{-3}$. Problems to be faced are: risk of back-reflection of the beam power injected; spurious absorbtion on resonances close to the launching system.

ACKNOWLEDGEMENTS

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[1]. F. Orsitto and G Giruzzi., Nuclear Fusion **37**(1997) 915

[2]. F. Orsitto et al., Review of Scientific Instruments **70**(1999)1158

[3]. M. Tardocchi et al., Nuclear Fusion **52**(2012)023002

[4]. F. Meo et al., Review of Scientific Instruments **75** (2004)3585

[5]. H. Bindslev et al., Physical Review Letters **97** (2006) 205005

[6]. E.E. Salpeter Physical Review Letters **122**(1961) 1663

[7]. V. Krivenski et al., Nuclear Fusion **25** (1985) 127.

[8]. J.F. Artaud et al., Nuclear Fusion **50**, 043001 (2010).

[9]. A. Bruschi, W Bin et al., Fusion Science and Technology, **55** (2009) 94

[10]. A. Pizzuto et al., Nuclear Fusion **50**(2010) 095005

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

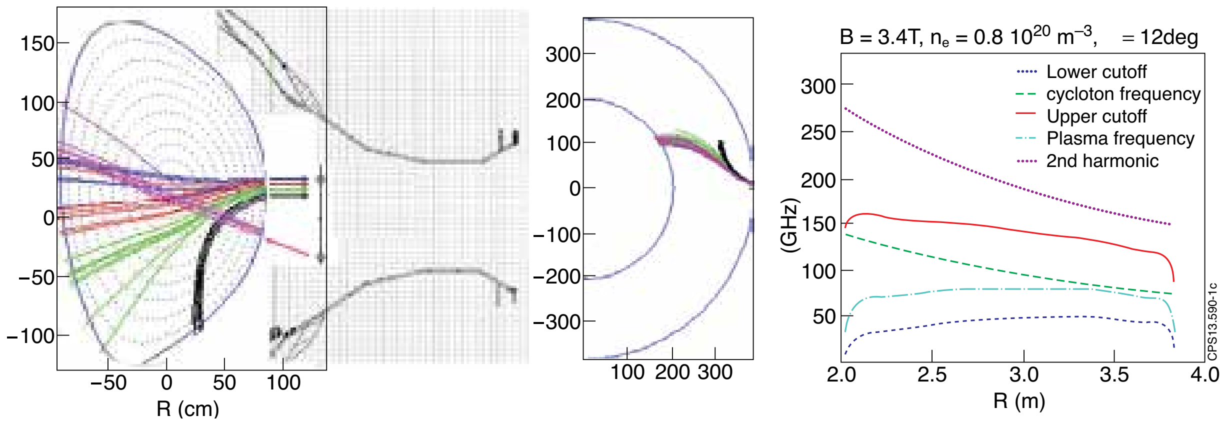

Figure 1: Ray tracing calculations for $f_0 = 60$GHz: (a) poloidal projections of the incident and scattered ray trajectories at various angles ϕ_{pol} at fixed toroidal angle $\phi_{tor} = 12^o$; a sketch of a JET equatorial port is also shown, on scale, in order to show the compatibility of the system with the port geometry. (b) toroidal projection of the same rays. Plasma Parameters: $B_T = 3.4$ T, $n_{e0} = 0.8\times10^{20}$ m^{-3}. Color Code for the ray tracing varying the poloidal angle of the ray $\phi_{pol} = -3^o, -5^o, -10^o, -16^o, +21^o$. (c) Calculations of upper and lower cut-off for X- mode. The plasma spatial profiles are rescaled from those of the JET Pulse No: 73344.

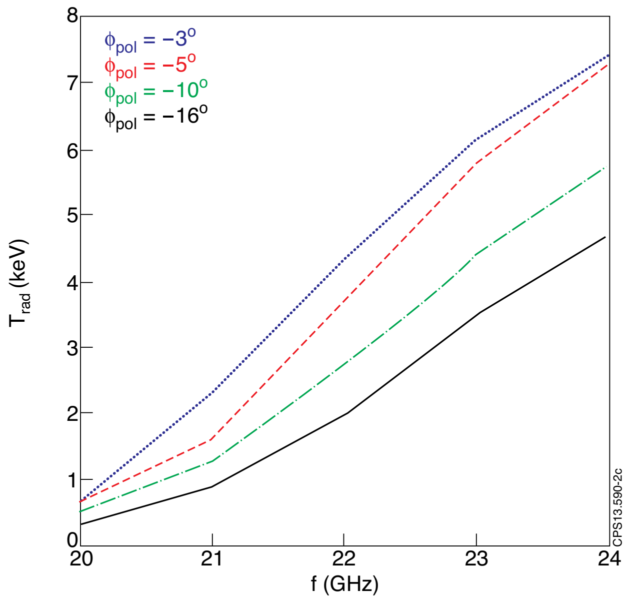

Figure 2: Temperatures of plasma radiation.