FAST ION DIAGNOSTICS IN JT-60U
(γ-ray and Collective Thomson Scattering Measurements)

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Introduction

Measurement of confined high-energy alpha particles is one of the important diagnostics in ITER because the alpha particles play significant role in heating the plasma. Collective Thomson scattering (CTS) based on pulsed CO_2 laser (λ = 10.6μm) and γ-ray measurements have been developed to measure the fast or bulk ion in JT-60U and to demonstrate feasibility of measurements in ITER. In section 1, we propose γ-ray measurements with neon gas puffing for MeV ion diagnostics, and test result of LiH neutron plug to improve neutron shielding ability is described. In section 2, we describe feasibility of the CTS as ion temperature measurement and as fast ion diagnostics in negative-ion based NB heated plasmas and minority ion ICRF heated plasmas.

1. Gamma-ray measurements

Objective of the γ-ray measurements is to investigate behavior of confined MeV-energy ions. In JT-60U, hydrogen ions were accelerated by second harmonic ICRF heating up to several MeV. Gamma-ray spectra in an energy range of 1 to 20 MeV were measured by 5"×5" NaI(Tl) scintillator surrounded by 50 cm polyethylene and 30 cm lead shield.

(1) Neon gas puffing method

The observed γ-ray lines at energies of 2.1 and 4.4 MeV were originated from inelastic collisions between fast protons and impurity nuclei (^{11}B and ^{12}C). Since the impurity species are originated from the first wall, the concentration depends on wall condition. It has been found that neon gas puffing is a useful method to measure confined MeV-proton behavior using 1.63 MeV gamma-ray originated from inelastic collision between protons and ^{20}Ne nuclei: threshold proton energy is 2 MeV. Intense line γ-ray of the neon was observed as shown in Fig. 1. Neon gas puff method for fast ion diagnostics has following characteristics: (i) large cross-section (≈ 1 barn), (ii) relatively low γ-ray energy (1.6 MeV) , (iii) concentration is independent of the wall condition. Energy distribution of ions in a range of 2-6 MeV was

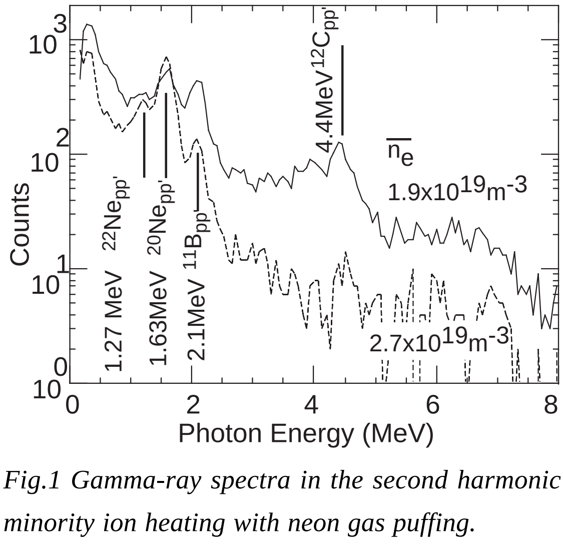


Fig.1 Gamma-ray spectra in the second harmonic minority ion heating with neon gas puffing.

estimated from intensity ratio of the γ-ray lines and the tail density was evaluated from intensity of the γ-rays[1].

(2) ^{6}LiH neutron plug

In JT-60U, γ-ray measurement of deuterium NB heated plasma is difficult because of large amount of secondary γ-rays from structures around the torus and detector. To measure γ-ray spectra during NB heated plasma, it is necessary to reduce background γ-rays. The ^{6}LiH neutron plug was designed and fabricated for γ-ray detector "GAMMACELL" for ITER [2, 3]. In the plug, ^{6}LiH powder is filled in aluminum cylinder of 3 cm in diameter and 30 cm in length. The plug absorbs neutrons by ^{6}Li +n → ^{4}He + T reaction and has large neutron attenuation coefficient, K ≈ 900, for 2.8 MeV neutrons [3]. Shielding ability of the ^{6}LiH neutron plug, has been tested in NB heated plasmas in JT-60U for neutron yield of 5×10^{14} s^{-1}. The plug was installed in the collimator made of polyethylene to reduce the secondary γ-rays around the detector; the plug does not reduce the secondary γ-rays from the structure around the torus. Figure 2 shows that the plug reduced secondary γ-rays by a factor of 10, comparing the spectra with and without the plug. This result shows an improvement of diagnostic capability during deuterium NB heating.

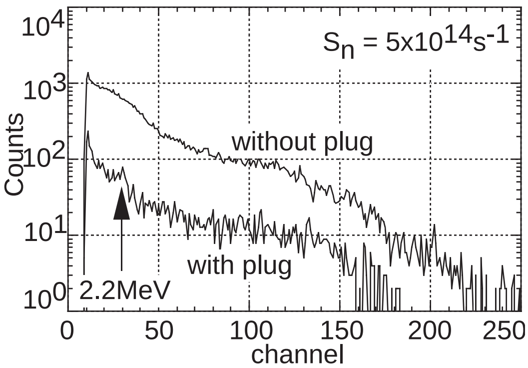


Fig.2 Gamma-ray spectra in NB heated plasma with and without the LiH plug.

2. Collective Thomson scattering

(1) Scattered spectrum

A Collective Thomson Scattering which is nominated as a candidate in ITER has been designed for the measurement of bulk-ion temperature and density in JT-60U.

The scattered power into the solid angle dΩ and frequency dω is given by [4]

$$P_s d\Omega d\omega = P_i r_0 n_e L d\Omega \frac{d\omega}{2\pi} S(k,\omega), \quad (1)$$

$$S(k,\omega) = \frac{2\pi}{k}\left|1-\frac{G_e}{\varepsilon}\right|^2 f_e(\omega/k) + \frac{2\pi}{k}\left|\frac{G_e}{\varepsilon}\right|^2 \sum_i Z_i^2 \frac{n_i}{n_e} f_i(\omega/k), \quad (2)$$

where ω is the frequency shift from the injection beam, k is the change in wave vector, r_0 is the classical electron radius, L is the scattering length, n_e is electron density, n_i is ion density, $S(k,\omega)$ is the spectral density function, ε is the dielectric function, G is dielectric susceptibilities, and f is velocity distribution, where i refers to the specific ion species, e to the electrons.

(2) Design of CTS for JT-60U

Specification of the injection laser and the receiver which is designed and produced in ORNL to be used in JT-60U is summarized in table 1.

The unstable resonator pulsed CO_2 laser is tuned with a cw CO_2 laser to select the pulsed laser wave length and polarization. Pulse length of the pulsed laser is stretched to nominally 1 μs.

Table 1. Specification of the collective Thomson scattering system

CO_2 Laser		Receiver		Scattering	
Wave length	10µm	Detector	QWIP	Scattering angle	0.5 deg.
Energy	10 J	Notch filter	Hot CO2 cell	Solid angle	1×10^{-5} sr
Power	10MW	NEP	9×10^{-19}W/Hz	Scattering length	46 cm
Pulse length	1 µs	Bandwidth	> 3GHz		
Repetition rate	> 1pulse/2sec				

The laser beam path is vertical through the plasma using top and bottom vertical ports 14.3 cm in diameter. Scattered angle must be very small angle ($\theta_s \approx 0.5$ deg.), because the Salpeter parameter $\alpha = 1/[2\lambda_D k_{laser} \sin(\theta_s/2)]$ must be greater than unity. Where, λ_D is the Debye length, k_{laser} is the input wave number.

Since scattering angle is very small, stray light must be reduced. A hot CO_2 absorber cell which has been developed for the ATF torsatron is used as a stray light notch filter [5].

Signal to noise ratio, S/N, after heterodyne detection is given by

$$S/N = \frac{P_N}{P_S + P_N}\sqrt{B\tau + 1}\,, \qquad (3)$$

where B is the receiver bandwidth, τ is the integration time, P_S is the scattered power, and P_N is system noise (= Noise Equivalent Power (NEP)). A quantum-well infrared photodetector (QWIP) which has a wide bandwidth (typically 20 - 30 GHz, NEP $\approx 9\times10^{-19}$W/Hz) has become available. To obtain a good S/N value ($\approx$ 5) requires a P_S of 3×10^{-19} W/Hz with a receiver bandwidth of 0.5 GHz, and a laser pulse length of 1 µs.

(3) CTS for diagnostics of bulk ion

Scattered power spectrum expected for high performance reversed shear plasma was calculated using equation (1), (2) with laser and receiver condition of Table1, electron density, and deuterium ion density, $n_e = n_D = 10^{20}$ m^{-3}, electron temperature of T_e=9keV, ion temperature of T_i = 15keV. The calculation shows that the contribution from electron is small and a good S/N value is expected up to 2 GHz for the bulk ion temperature measurement (Fig. 3).

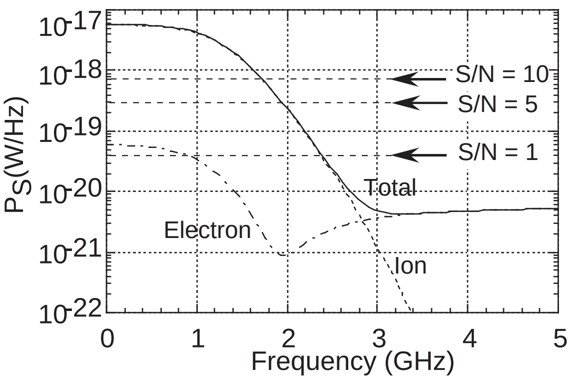


Fig.3 Calculated spectrum for reversed shear plasma. T_i=15keV, T_e=9keV, n_D=n_e=10^{20}m^{-3}

The presence of small proportions of impurities has important effects on the scattered spectrum. The effects of varying the concentration of fully-ionized oxygen atoms are shown in Fig. 4. The enhancement of the total scattering power is expected in low frequency (f < 1GHz) region. However, that increase at high frequencies (f > 1GHz), which is important for bulk ion temperature measurements, can be neglected.

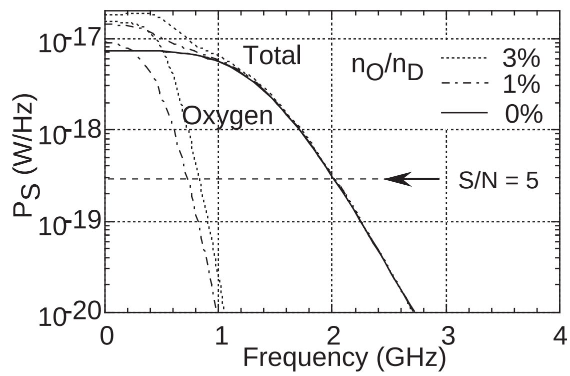
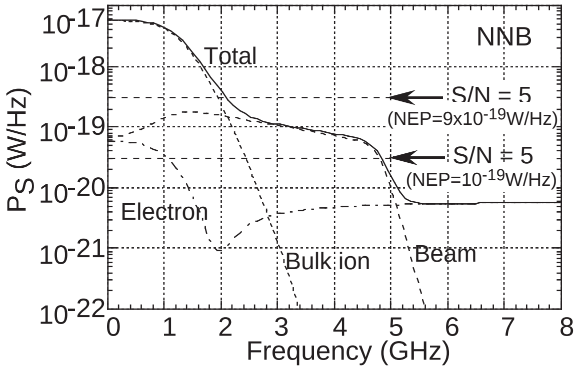


Fig.4 *Effect of oxygen concentration. T_i=15keV, T_e=9keV, n_D=10^{20}m^{-3} , n_O/n_D=0, 0.01, 0.03.*

(4) CTS for diagnostics of fast ion



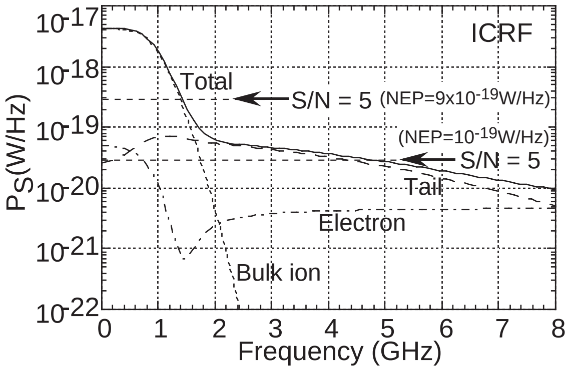


Fig.5 Spectra for negative-ion-based neutral beam injection. T_i*=15keV,* T_e*=8keV,* $n_e = 8\times10^{19}\ m^{-3}$*,* E_{beam} *= 400 keV,* $n_{beam} = 2\times10^{18} m^{-3}$*.*

Fig. 6 Spectra for minority hydrogen ICRF heating. T_i*=8keV,* T_e*=5keV,* $n_e = 5\times10^{19}\ m^{-3}$*,* T_{tail}*=200 keV,* $n_{tail} = 2\times10^{18} m^{-3}$*.*

Negative-ion-based neutral beam (NNB) system has been developed and applied to JT-60U experiments. Design values are beam energy of E_b = 500 keV, beam power of 10 MW, and the pulse length of 10 s. Figure 5 shows calculated scattered spectra for flat distribution of injected ions of E_b = 400 keV, $n_b = 2\times10^{18} m^{-3}$. Figure 6 shows calculated scattered spectra in the second harmonic minority ion (hydrogen) ICRF heating experiments, for T_{tail} = 200 keV, $n_{tail} = 2\times10^{18} m^{-3}$. Good Signal-to-Noise ratio for ion tail is not expected for the both cases by use of the present detector (NEP = 9×10^{-19} W/Hz). However, if a detector which has a lower NEP value (1×10^{-19} W/Hz) becomes available, the fast ion tail can be identified with a scattered power of 3×10^{-20} W/Hz.

Conclusions

Bulk-ion temperature and density measurement are feasible by the pulsed CO_2 laser (10J/pulse, 1μsec, 0.5 Hz) and the heterodyne receiver system. Measurement of the fast ions in NNB or ICRF heated plasmas will be available if low NEP detector (1×10^{-19} W/Hz) is developed. The pulsed laser and the receiver system will be installed and tested in diagnostic room in this year, and measurement on the JT-60U plasma will start in 2000.

For γ-ray measurement, it is found that neon gas puff is useful method for MeV ion diagnostics and the ^{6}LiH neutron plug improves neutron shielding ability a factor of ten.

Acknowledgments

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References

[1] T. Kondoh et al., J. Nucl. Mat. **241-243**, 564 (1997)
[2] V. Kiptily et al., "Diagnostics for Experimental Thermonuclear Fusion Reactors", p.463 (Edited by P.E. Stott et al.,Plenum Press, New York, 1996)
[3] V. Kiptily, ISTC annual report, project #161 (St.Petersburg, 1996)
[4] J. Sheffield, Plasma Scattering of Electromagnetic Radiation (Academic, New York, 1975)
[5] R. K. Richards et al., Appl. Phys. Lett. **62**, 28 (1993)