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TV Thomson Scattering System on JFT-2M

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A higher spatial resolution TV Thomson scattering system was constructed on JFT-2M tokamak This system has been providing complete profiles of Te and ne at a single time during a plasma discharge. New detector system was developed composed of two stages of image intensifier tubes coupled to a CCD. The extinction ratio of image intensifier was improved to 1.4×10^{7} at least.
Keywords:Thomson scattering, Ruby laser, CCD, image intensifier, plasma, JFT-2M

1. Introduction

Electron temperature(Te) and density(ne) are the essential parameters to investigate the physics of tokamak plasma. There are several ways to measure Te and/or ne in plasma. The representative diagnostic systems on Te are the electron cyclotron emission (ECE)[1], X-ray pulse height spectrometer(SX)[2] and Thomson scattering[3-]. The systems on ne are the microwave interferometry[4] and Thomson scattering. Each system has some advantages. ECE and SX are passive methods for Te measurement, and are simple systems. But ECE system gives the arbitrary temperature from the intensity, and SX system gives the monitor Te because of the impurity lines on the energy spectrum. On the other hand, the microwave interferometry gives the line-integrated electron density, and several chords through plasma is necessary to get the ne profile with the abel-inversion at least. The ne and Te profiles measured with these methods have not enough spatial resolution, especially at edge. It is difficult to determine the slope of Te, ne and pressure(Pe) at edge with a high resolution of below 1cm. However, Thomson scattering system measures the local Te and ne with the e-folding width of doppler-broadened profile of scattered spectrum and total scattered intensity, respectively[5]. Thomson scattering has some advantages as follows; Laser beam does not disturb the plasma, and the measured point is definite. But, Thomson scattering cross-section is so small ($6.6\times10^{-25}cm^2$) that laser power, sensitivity of detector and transmittance of optics should be made as high as possible.

Initial TV Thomson scattering system(TVTS) was developed to measure Te and ne profiles of plasma diameter in Princeton University Plasma Physics Laboratory (PPPL)[6-8]. This system has the following characteristics;a wide-angle lens was used for collecting the scattered light, and the micro-channel plate intensifier(40mm in diameter was available at maximum) with a gating pulse system and the intensified silicon diode target vidicon tube were used as a detector. This detector had to be improved for a low sensitivity and a serious limitation of input diameter of MCP. ICCD(Intensified CCD) tube has been developed soon. ICCD has an anode consisted of CCD and an electron emitted from cathode surface hits on CCD to produce ~10^6 electrons. However, it is impossible to buy ICCD anymore. Then, the new detector for TVTS was designed and fabricated in collaboration with PPPL[9]. This detector consists of two stages of image intensifier tubes with a large input surface(80mm in diameter) coupled to a CCD fiber-optically. By the way,TVTS on JFT-2M tokamak is composed of six subsystems; optical, electro-optical, control and data acquisition, laser[10], software and vacuum component[11] subsystems[12].

Not only ruby laser power is high ($1.5x10^{10}$W/cm^2) in plasma, but also quartz image fibers and Littrow type spectrometer are applied to produce the high optical transmittance. The characteristics of this system is as follows; total measuring length of 70cm, spatial points of 81, spatial resolution of 0.86cm, measured temperature range of 50eV<Te<7~8keV and measured density range of ~$3x10^{12}$<ne<$5x10^{14}$cm^{-3}.

The Te and ne profiles give the physical informations on JFT-2M plasma; The increase of central temperature and density and the pedestal of Te at edge were observed in H-mode. In this paper we describe TVTS, especially about new detector, and the Te and ne measured in JFT-2M plasma.

2. Overview of TVTS

It is described in ref.[12,13] in detail, then is written here in brief. Figure.1 shows the overview of TVTS. A ruby laser beam with 20J (or usually 15J) in 20ns and 0.25 milliradian beam divergence is focussed to below 3mm diameter over the 70cm measurement region in the horizontal mid-plane of the plasma. The beam is terminated in a beam dump designated to minimize stray laser light. A 6m long beam tube in vacuum places the window at a point where the beam size(25mm in diameter) is large enough to keep laser damage to the window(threshold power of breakdown:~$6x10^9$W/cm^2) at a tolerable level. The light scattered from the beam is collected from an f:6 cone and imaged at f:1.75, using a Bouwers concentric catadioptric mirror system on the top flange, onto an array of 81 fiber optic bundles each of which measures 0.9x2.25mm. These bundles are then rearranged from the 0.9x191mm input to 2.25x72.9mm at the input to the spectrometer. A relay lens expands this image onto the input slit of the spectrometer. A simple Littrow spectrometer is used to minimize the scattering of stray laser light and the formation of secondary images by reflections. A field lens at the image plane focuses the light onto a camera lens which images the spatially resolved spectra onto the face of an 80mm diameter gateable image intensifier tube. This tube demagnifies the image from 80mm to 18mm. A second image intensifier tube provides further gain and further demagnifies the image from 18 to 11mm. Output image of second image intensifier is fiber-optically coupled to a cooled CCD. The data from the CCD are digitized and temporarily stored in the personal computer used to control the camera. The data are then sent to a Vax station 3500 for calculation of Te and ne.

3. Image intensifier coupled to CCD detector system

The detector consists of two stages of image intensifier tubes coupled to a CCD as shown in Fig.2. Both of the intensifier tubes have fast phosphors. The first tube, made by DEP in Holland (type:PP0050), has an 80mm diameter fiber optic faceplate with a red enhanced S25 photocathode, and a P47 blue phosphor with a decay time of about 80ns with a fiber optic output. It demagnifies from 80 to 18mm and has appreciable pincushion distortion. On the other hand, the second tube(type:XX1600) has a fiber optic input with 18mm diameter, a blue sensitive S20 photocathode and a P46 green phosphor with about 160ns decay time. It demagnifies from 18 to 11 mm and adds some additional pincushion distortion.

The CCD is made by EEV and is their type CCD02-06-1-014 as shown in Table I. It is a 385 by 288 pixel, frame transfer type which makes it possible to transfer a frame in about 2ms. It is also possible to compress frames into the storage register. This is coupled to the output of the second image intensifier through a long(50mm) fiber optic coupler. The CCD is housed in a polyethylene foam filled cannister which can be cooled by a flow of cold nitrogen gas to below -30^{o}C. This results in negligible dark current during the readout time of about 1s.

The CCD is controlled by a Princeton Scientific Instruments Inc. camera controller. This controller provides all the clocking signals for CCD, and digitizes and stores the output. Using the IBM type personal computer which is an integral part of this controller, it is also possible to do some preliminary analysis of the data which is very useful for alignment problem with the system.

3.1 Extinction ratio

Plasma background lights, such as a bremsstrahlung emission and a spectral line emission , are always incident on the input surface of image intensifier tube. In the case of (scattered signal)/(background signal)=10~20 estimated from experiments, duration of plasma discharge=1s and gated duration=100ns, a high extinction ratio is necessary to get the signal-to-noise ratio S/N >10. That is, the S/N is represented as (scattered signalxextinction ratio)/{(scattered signal/10)x(duration of discharge/gated duration)}. The extinction ratio should be (5~10)x10^7.

The PP0050 tube has four electrodes. They are the cathode, the focus electrode, the zoom electrode and the anode shown in Fig.3. The tube is normally gated by biasing the focus electrode sufficiently negative. This is expected not to provide an adequate extinction ratio. We expected that it would be necessary to gate the zoom electrode. The tube was operated at -10kV cathode voltage and grounded anode. The zoom pulse is generated by changing a cable (delay line) to ~20kV. It is discharged by a spark gap which drives a 50 ohm terminating divider. Measurement of the voltages for different magnifications are shown in Fig.4. The extinction measurements were carried out at the nominal voltages for the 0.192 magnification. Biasing the focus electrode from 250 to 700 V negative with respect to the cathode gave about the same extinction of ~3x10^3. It was found that the zoom electrode had to be biased to 480V negative with respect to cathode to give good extinction. The extinction at 480V was 8.5x10^6. If the signal remained even when the high voltage supply was turned completely off is subtracted from the total signal at extinction, one obtains an extinction factor of 1.4x10^7. At its' full operating voltage of 20kV the tube would have higher gain and the extinction factor including the direct shine through should exceed 10^7. The effect of voltage on the tube gain was measured and found to be linear and follow the law g=k(v-4300) above 5000V(k=const, v is the voltage). A gate pulse is flat to about 4% during the laser pulse shown in Fig.5.

3.2 Distortion and modulation transfer function (MTF)

Spatial resolution depends on the design of collecting optics, Littrow spectrometer and CCD camera. We show the good image on the output of spectrometer in Fig.6. The 81points clearly seen and it goes to CCD through camera lens and the intensifier tube. However the distortion of tube was measured and is shown in Fig.7. The optical design of the camera lens corrects for this distortion and that of the second stage intensifier. The distortion for this tube is about 6.8% at 40mm input radius.

The resolution of PP0050 is 86lp/mm on axis and XX1600 is 75lp/mm, which are sufficient for 81points. By the way, MTF of XX1600 is 95% at 2.5lp/mm on axis based on DPE data sheet.

4. Te and ne profiles

TVTS was installed on JFT-2M tokamak and tested for the detector on the condition of -30°C. The temperature fluctuation is below 1°C. As CCD and fiberoptic coupler contract with cold, every test was done under the condition of -30°C. The standard lamp was set inside of vacuum vessel to calibrate TVTS totally. The software was modified based on the PPPL's, and also the Oak Ridge national laboratory's was combined in JAERI. Te and ne profiles are obtained at a real time. The representative profiles measured with TVTS in H-mode plasma are shown in Fig.8. Te profile shows the pedestal at edge and ne profile shows the sharp gradient at edge and also flat profile. In addition, Pe profile shows the sharper slope at edge compared to L-mode.

5. Summary

TVTS is completed in the collaboration with PPPL. Almost components was fabricated in JAERI, and tested. The advanced technique which PPPL has was applied for JFT-2M TVTS.

1.International collaboration of TVTS project was terminated successfully.

2.New detector system was fabricated and its characteristics are as follows;
extinction ratio >1.4x10^7, MTF~95% at 2.5lp/mm on axis,
gate duration ~100ns, uniformity of gate pulse <4%.

3.Characteristics of TVTS are;
compact and high transmittance system, spatial resolution of 0.86cm, spatial point of 81, measured length of 70cm.

4.Te and ne are measured on JFT-2M, and the representative results are;
Te: pedestal formation on H-mode plasma. ne:sharp gradient at edge on H-mode plasma and flat profile. Pe:sharp slope at edge on H-mode.

Acknowledgement

The highest spatial resolution TVTS was developed in a collaboration with PPPL for two years. And it has been measuring Te and ne profiles on JFT-2M. Through these research, I would like to express my gratitude to Dr.K.Young in PPPL, Dr.Maeda in JAERI for their continuous support.

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Table I Characteristics of frame transfer CCD

CCD model	CCD02-06-1-014(EEV)
Spectral response range	350-1000nm
number of pixel	385x576pixels
image area	385x288pixels, 6.3x8.5mm
1channel	4x9pixels
dynamic range	~4000/pixel
cooling	cooled nitrogen gas flow, -30~-40°C
exposure control	gated duration of image intensifier, ~100ns

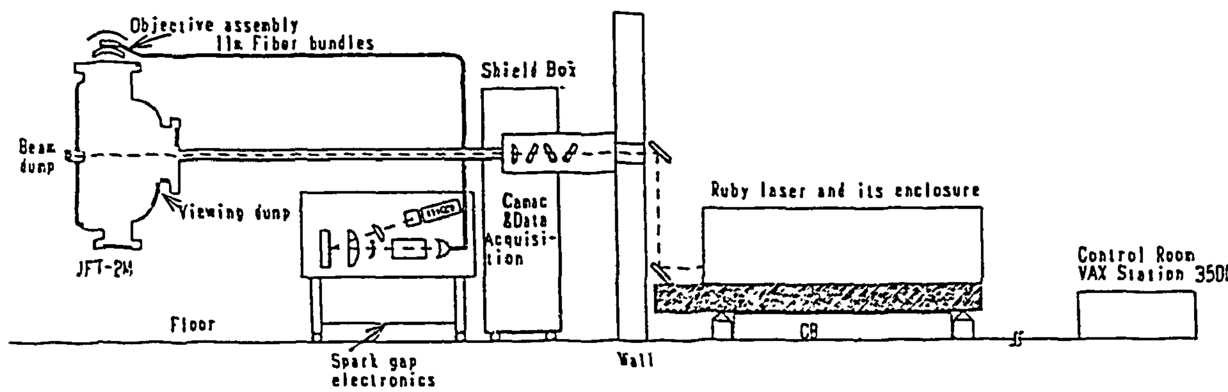

Fig.1 Elevation view of TV Thomson scattering system on JFT-2M.
(Spark gap electronics:laser triggered spark gap using a sample from the laser pulse and spark gap using a pair of electrodes near the gap)

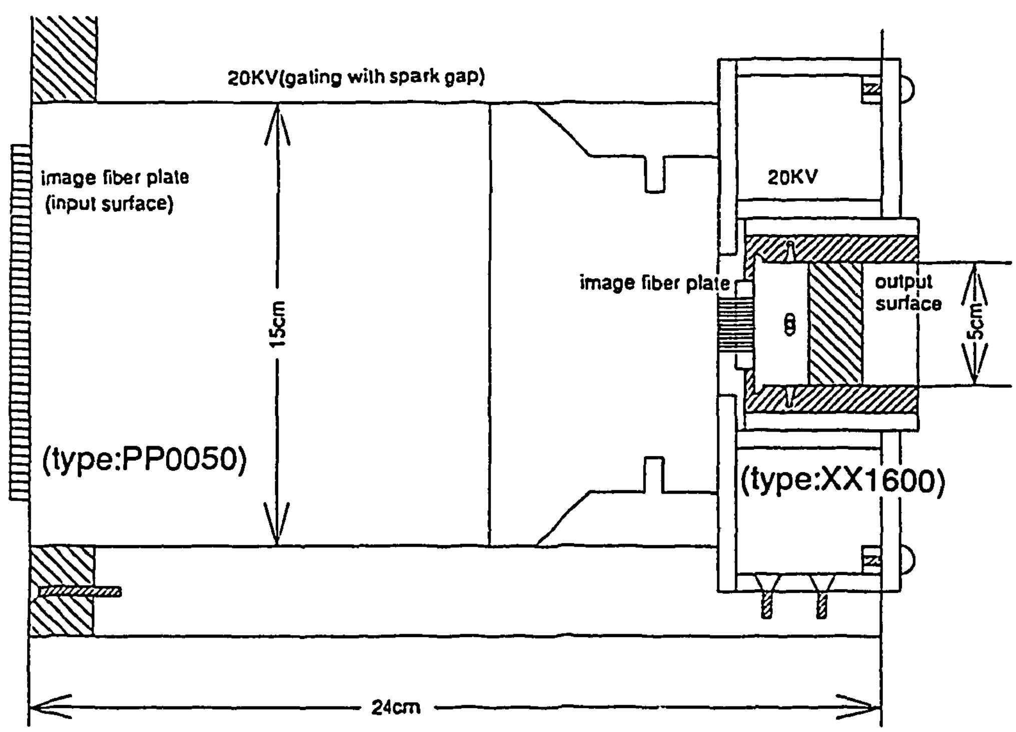

Fig.2 Two stage of image intensifier tubes.
(type PP0050 electrodes from left side; cathodes;ground, focus;~1000V, zoom bias;~-1000V, and zoom pulse voltage;~5kV, anodes;20kV)

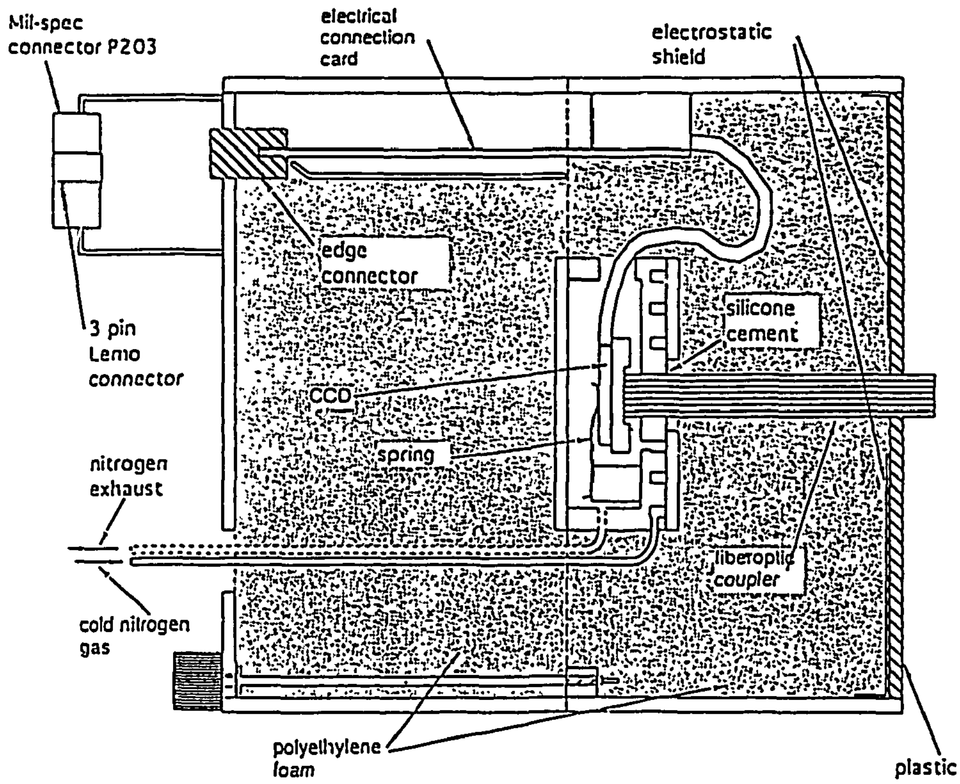

Fig.3 CCD detector housing including CCD chip.
(fiberoptic coupler touches on CCD chip)

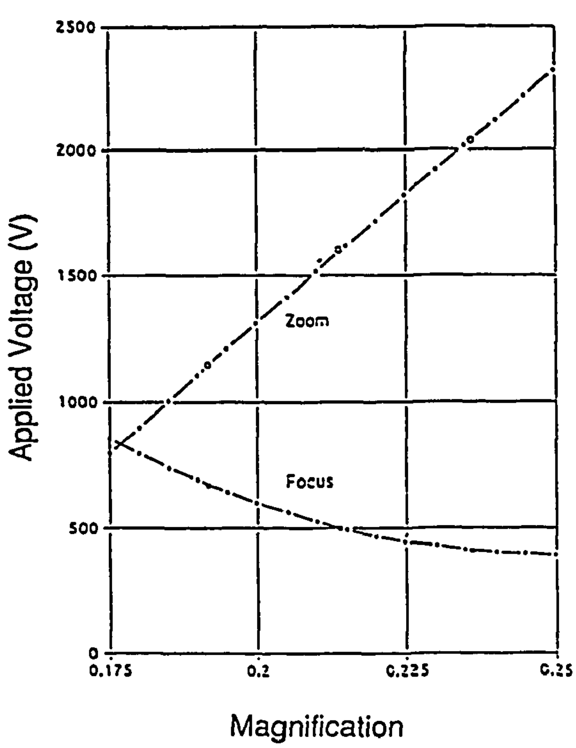

Fig.4 Zoom and focus voltages vs. magnification for anode-cathode voltage of 10kV.

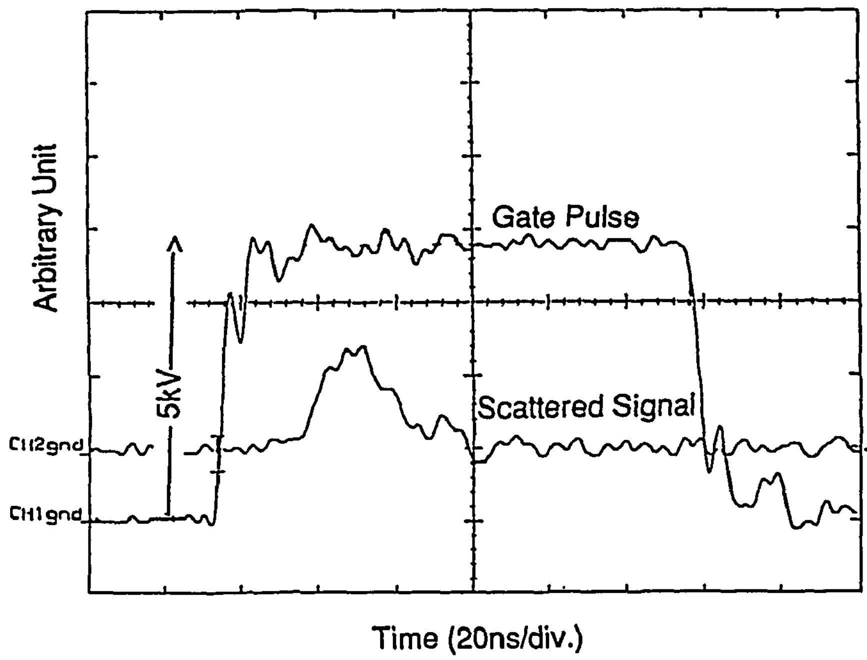

Fig.5 Gate pulse waveform triggered by the sample laser pulse from oscillator.

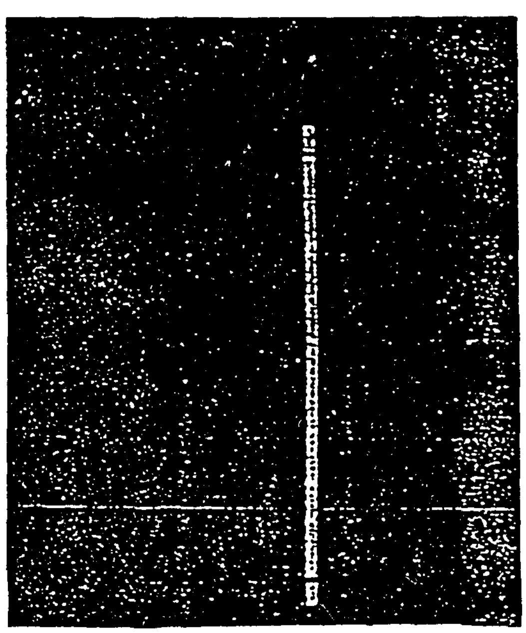

Fig.6 Spectral line emitted from Hg-lamp. (wavelength; 5460.7A, this image represents the spatial position; from top, 5 points for plasma light, 1 point for reference channel, 81 points for scattered light and plasma light, 1 point for reference channel and 5 points for plasma light)

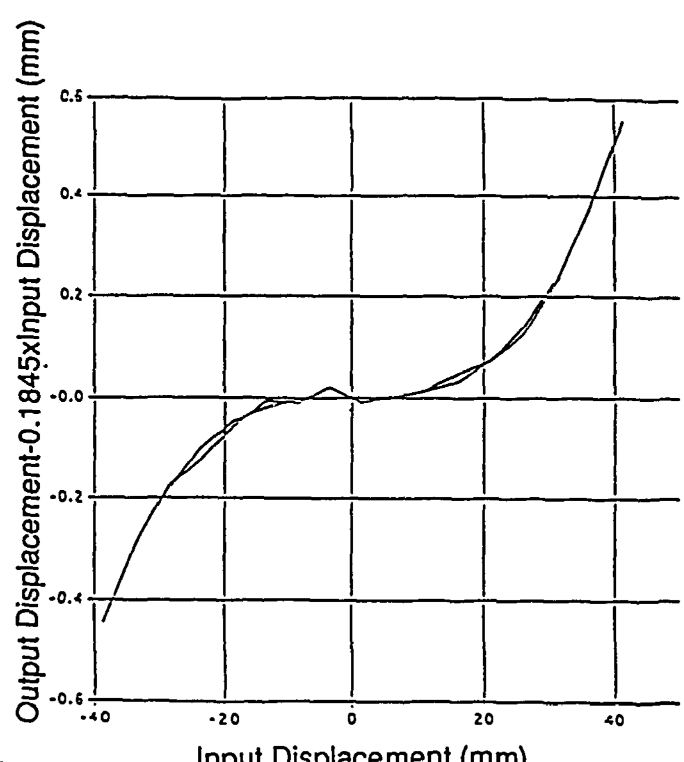

Fig7. Distortion of DEP tube type PP0050. Output displacement vs.input displacement

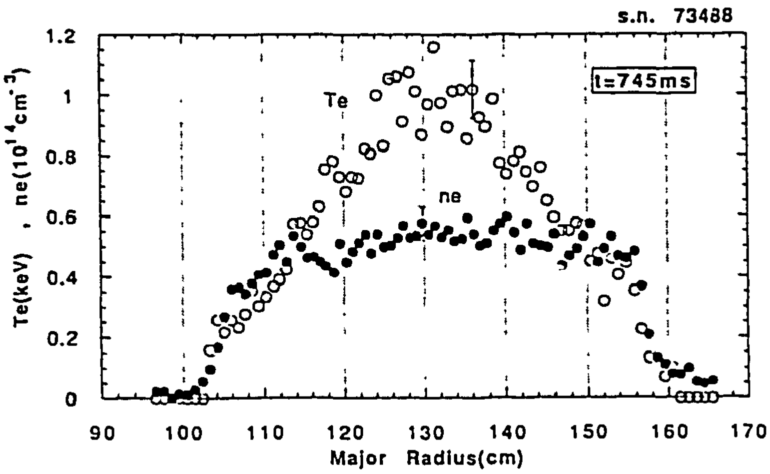

Fig.8 (a)Te and ne profiles in H-mode phase. (745ms, error bar is shown in figure)

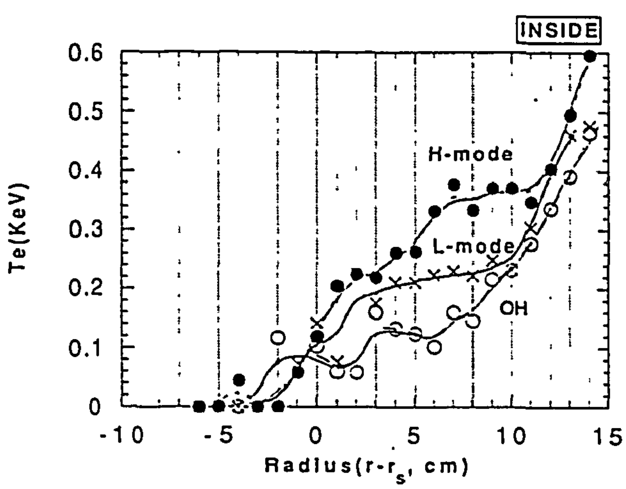

Fig.8 (b)Te profiles inside of plasma. (OH;joule heating phase, L-mode and H-mode phase ;neutral beam injection heating, r_S;plasma radius)

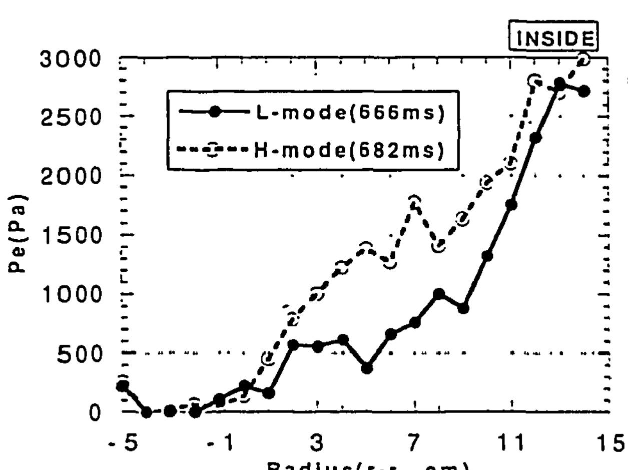

Fig.8 (c)Pe profiles inside of plasma.