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# 13-POINT THOMSON SCATTERING SYSTEM FOR 13-POINT THOMSON SCATTERING SYSTEM FOR JFT-2M PLASMA JFT-2M PLASMA

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A 13-point Thomson scattering system mounted on the JFT-2M tokamak A 13-point Thomson scattering system mounted on the JFT-2M tokamak routinely provides reproducible electron temperature and density data. Good performance has been achieved with the help of a large collecting Good performance has been achieved with the he1p of a 1arge co11ecting lens (capable of gathering data over a vertical 60-cm long plasma volume), 1ens (capab1e of gathering data over a vertica1 60-cm 10ng p1asma vo1ume), the automatic transfer of data from a 180-channel attenuator into the CPU, the automatic transfer of data from a 180-channe1 attenuator into the CPU, the use of high-pass optical filters and a large polarizer plate to reduce stray light, and a better matching of LED calibration signal inten-duce stray 1ight, and a better matching of LED ca1ibration signal intensities to those of the scattered signals. sities to those of the scattered signa1s.

Peaked density profiles are measured in improved L-mode (1L) Peaked density profiles are measured in improved L-mode (lL) plasmas, in contrast to those observed during the H-mode phase. IL-mode plasmas, in contrast to those observed during the H-mode phase. IL-mode is caused by the broad and high electron temperature. With pellet is caused by the broad and high electrcn temperature. With pellet injection, peaked density profiles are again observed. injection, peaked density profi1es are again observed.

Keywords: Thomson Scattering, Glass Fiber Bundle, JFT-2M, 13-point Keywords: Thomson Scattering, G1ass Fiber Bund1e, JFT-2M, 13-point Measurement, Ruby Laser, Peaked Ne Profile, Broad Te Profile, Measurement, Ruby Laser, Peaked Ne Profi1e, Broad Te Profi1e, IL-mode, H-mode IL-mode, H-mode

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TFT-2Mフラズマ用13点トムソン散乱装置

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JFT-2Mトカマクに取付けられた13点トムソン散乱装置は、 定常的かつ再現性良く電 子温度及び密度のデータを供給している。大きな集光レンズ(垂直方向60cm長に渡るプラズ マのデータを収集). 180チャンネルの減衰率を計算機メモリへ自動転送、迷光を除去する為 に高エネルギー帯を通す光学フィルター及び大偏光板の適用、LED較正信号と散乱信号の 対応を良くしたこと等により、良い性能が得られて来ている。

尖った電子密度の分布が改善されたしモード(IL·モード)ブラズマで測定され、それ は日モード領域で観測されたものと対照的である。ペレット注入時、同様に尖った密度分布 が観測された。

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#### Contents Contents



# $\mathbf H$

次



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## *1. Introduction*

Several tokamak experiments have been equipped with Several tokamak experiments have been equipped with multi-point Thomson scattering systems [1-8]. A TV Thomson multi-point Thomson scattering systems [1-8]. A TV Thomson scattering system(TVTS) has been developed at the Princeton scattering system(TVTS) has been developed at the Princeton Plasma Physics Laboratory(PPPL) and installed on PLT, PBX and Plasma Physics Laboratory(PPPL} and installed on PLT, PBX and TFTR [1-3], as well as on Dili and DIII-D [4,5]. A light TFTR [1-3], as well as on D111 and D111-D [4 5]. A light detection and ranging (LIDAR) system has been developed for the detection and ranging (L1DAR) system has been developed for the Joint European Torus (JET) [6]. The spatial resolution of the Joint European Torus (JET) [6]. The spatial resolution of the former system is about 1cm and that of the latter about 10cm. In order to obtain the temporal evolution of the profiles, further order to obtain the temporal evolution of the profiles, further development of the TVTS would be required. One complete profile development of the TVTS would be required. One complete profile is usually obtained with each tokamak discharge, except in the case of scattering systems using YAG lasers [7]. For a small case of scattering systems using YAG lasers [7]. For a small tokamak like JFT-2M, a TVTS system would be suitable for tokamak like JFT-2M, a TVTS system would be suitable for measuring electron temperature and density profiles. measuring electron temperature and density profiles.

On JFT-2M, a 13-point Thomson scattering system using On JFT-2M, a 13-point Thomson scattering system using photomultiplier(PM) detection has been taking data for 2 years photomultiplier(PM} detection has been taking data for 2 years [9]. Although measurements are presently being made at 13 [9]. Although measure ents are presently being made at 13 spatial positions, this number could be increased to 38 or more. spatial positions, this number could be increased to 38 or more. The present configuration represents a compromise as concerns The present configuration represents a compromise as concerns the physical size of the enclosure containing the PM tubes. The the physical size of the enclosure containing the PM tubes. The separation in the plasma between adjacent measuring points is separation in the plasma between adjacent measuring points is approximately 5cm. approximately 5cm.

PM tubes have been chosen because of their wide dynamic PM tubes have been chosen because of their wide dynamic range, high gain, high quantum efficiency and range, high gain, high quantum efficiency and highly-reproducible gating action during data acquisition. highly-reproducible gating action during data acquisition. Because of variations in quantum efficiency over the surface of Because of variations in quantum efficiency over the surface of the photocathodes, as well as sample-to sample variations in the the photocathodes, as well as sample-to sample variations in the tubes themselves, careful calibration of each tube is necessary tubes themselves, careful calibration of each tube is necessary in order to obtain accurate data. Rather than a in order to obtain accurate data. Rather than a tungsten-filament lamp, LED's have been used for this calibration [10]. calibration [10].

This paper describes the components of the 13-point Thomson This paper describes the components of the 13-point Thomson scattering system, with emphasis on the glass fiber optic scattering system, with emphasis on the glass fiber optic bundle. Electron temperature (Te) and density (ne) profiles for bundle. Electron temperature (Te) and density (ne) profiles for plasmas showing good confinement (improved L-mode and other plasmas showing good confinement (improved L-mode and other modes) are also presented and discussed. modes) are also presented and discussed.

#### 2. Thomson Scattering System

The Thomson scattering system described here, shown in Fig.l, The Thomson scattering system described here. shown in Fig.1. represents an upgrade of a 6-point system described previously represents an upgrade of a 6-point system described previously [8]. A typical optical path is shown in Fig.2. The collecting [8]. A typical optical path is shown in Fig.2. The co1lecting lens is designed for gathering light from a 110cm long vertical plasma volume. The lens is of Gaussian type, as was also the plasma volume. The lens is of Gaussian type. as was also the case in the previous design. Vignetting from the observation case in the previous design. Vignetting from the observation window limits the vertical field of view to a length of 60cm. window limits the vertica1 field of view to a length of 60cm. The optical axis of the lens is 10cm below the plasma mid-plane. The optical axis of the lens is 10cm below the plasma mid-plane. A motor-driven vertical adjustment of 5cm is provided. The A motor-driven vertical adjustment of 5cm is provided. The diameter of the collecting lens is approximately twice that of diameter of the collecting lens is approximately twice that of the 6-point Thomson scattering system [8]. The lowest observation point in the plasma(position 1) is 10cm below the observation point in the plasma(position 1) is 10cm below the plasma mid-plane, for which the scattering angle is 80 $^{\sf o}$ . The scattering angle for the highest observation point, at position 13, is 131°. The spatial resolution is 1.6cm at the plasma <sup>13</sup>, is 1310. The spatial reso1ution is 1.6cm at the plasma mid-plane. A polarizer plate mounted behind the collecting lens mid-p1ane. A polarizer p1ate mounted behind the co11ecting lens reduces plasma radiation and stray light by half. Each fiber bundle is mounted with its input face perpendicular to the bundle is mounted with its input face perpendicular to the optical axis. The fiber bundles depolarize the scattered light. optica1 axis. The fiber bundles depolarize the scattered light. This effect simplifies the calibration procedure by removing the This effect simp1ifies the calibration procedure by removing the differences in polarization between the scattered light and the differences in polarization between the scattered li'ght and the unpolarized LED radiation used for calibration. (The unpolarized LED radiation used for calibration. (The reflectivities of the diffraction grating and of other optical surfaces in the beam path are polarization-dependent.) High-pass surfaces in the beam path are polarization-dependent.) High-pass optical filters are mounted at the input end of the first optical filters are mounted at the input end of the first optical fiber bundle in order to decrease the stray light. The output end of the fiber bundle is divided into 2 sections, each going to the input slit of a separate spectrometer. The going to the input slit of a separate spectrometer. The spectrometers are again of the Littrow type, but with a larger spectrometers are again of the Littrow type. but with a larger wavelength range: 5200-7000A. A second fiber bundle runs from the output slits of each spectrometer to the PM tubes(48 in all). output slits of each spectrometer to the PM tubes(48 in all). The optical transmission of the system is similar to that of the The optical transmission of the system is similar to that of the previous one. The PM tubes are gated on for 3-8 sec for previous one. The PM tubes are gated on for 3-8 sec for detection of scattered light, and again after 10 sec for the detection of scattered light. and again after 10 sec for the same time interval in order to measure the plasma light. The same time interval in order to measure the plasma light. The output signals are amplified tenfold and then attenuated as output signa1s are amplified tenfo1d and then attenuated as required to accommodate the dynamic range of 500 counts of the

2 - 2

A/D converter. The attenuation is adjusted from the control room, the attenuation values and the scattered signals being recorded together. The signals are integrated during the 100nsec gate duration. Graphic display of electron temperature and density profiles follows immediately. In addition, untreated data is stored in a memory module in the CAMAC crate for subsequent transfer to the central computer (Mitsubishi Ltd [11]). Software has been developed for calculating Te and ne from the experimental data [10]. Automatic recording and display of the 180 attenuation values increases system reliability.

The Q-switched laser system [8], producing about 4J, has been in operation since 1977.

#### *3.FJber Bundle Construction*  3.F.fber BundJe Construct.fon

Recent improvements in the reliability of optical fibers have Recent improvements in the reliability of optical fibers have motivated their use between the collecting lens and the motivated their use between the collecting lens and the spectrometers, and also at the output of each spectrometer. This modification has reduced the optical path between the collecting modification has reduced the optical path between the collecting lens and the spectrometers from about 2m to less than lm, thus lens and the spectrometers from about 2m to less than 1m, thus reducing the size of the optical system. Figure 2 shows a typical path through the complete optical system. When a large lens with a large solid angle is used for collecting scattered lens with a large solid angle is used for collecting scattered light, correct matching requires the use of a fiber of small light, correct matching requires the use of a fiber of small numerical aperture. The field lens transmits light from the numerical aperture. The field lens transmits light from the fiber bundle to the Littrow lenses in each of the two spectrometers used for analyzing the radiation scattered from the 13 vertically-arranged points. Here a flexible fiber bundle is used, in contrast to the systems developed for PLT and DIII-D, where small-diameter (50 micron) flexible glass fibers D111-D, where small-diaeter (50 micron) flexible glass fibers are used. The flexible type used here allows easy modification are used. The flexible type used here allows easy modification of measuring positions and spectral channels by interchanging of measuring positions and spectral channels by interchanging fibers or moving the collecting lens vertically. Except for the fibers or moving the collecting lens vertically. Except for the number of channels, the fiber bundles used here are similar to number of channels, the fiber bundles used here are siailar to those previously employed. Each bundle in the first has an input those previously employed. Each bundle in the first has an input end of rectangular cross-section, while two output faces are curved, with dimensions 70mm by 3mm. The dimensions of height is curved, with dimensions 70mm by 3mm. The diaensions of height is larger than that of the bundle used previously [8]. The 13 larger than that of the bundle used previously [8]. The 13 measuring points are separated into 2 groups for spectral measuring points are separated into 2 groups for spectral analysis-the 7 points from the central (high temperature) region. and the 6 from the edge (low temperature) region. In order to and the 6 from the edge (low temperature) region. 1n order to reduce losses, the fibers are kept as short as possible.

# 4*. Profile Measurements*

Density calibration is performed using Raman scattering and Density calibration is performed using Raman scattering and the spectral calibration is performed using LED's [12]. The the spectral calibration is performed using LED's [12J. The average electron density determined from Thomson scattering average electron density determined from Thomson scattering correlates well with values obtained from HCN interferometer correlates well with values obtained from HCN interferometer measurements, as shown in Fig.3. measurements, as shown in Fig.3.

Profiles obtained during the H-mode phase have already been Profiles obtained during the H-mode phase have already been presented previously [13,14]. Here we present profiles obtained presented previously [13 14J. Here we present profiles obtained during the improved L-mode(IL-mode) phase. The IL-mode plasma is during the improved L-mode(IL-mode) phase. The IL-mode plasma is described elsewhere [15]. The global plasma energy is higher described elsewhere [15J. The global plasma energy is higher than in the H-mode, as shown in Fig.4. Their profiles are shown than in the H-mode, as shown in Fig.4. Their profiles are shown in Fig.5(a) and (b), the latter showing the peaked profiles in Fig.5(a) and (b), the latter showing the peaked profiles observed during the IL-mode phase. The edge electron density observed during the IL-mode phase. The edge electron density decreases by about 5095 through the disappearance of the electron decreases by about 50% through the disappearance of the electron temperature pedestal which is the resulting increase in the diffusion coefficient D=0.2\*xe, as derived from the relation diffusion coefficient D=0.2 xe as derived from the relation xe=const/(ne\*dTe/dr). A steepened gradient is measured during the early phase of the H-mode, while the L-mode phase is characterized by greater decay lengths of profiles at the plasma characterized by greater decay lengths of profiles at the plasma edge for both the electron density and the plasma emission [16]. edge for both the electron density and the plasma emission [16).

The peaking ratio of electron density, neo/<ne>, neo and <ne> being the central electron density and the volume-averaged value being the central electron density and the volume-averaged value of electron density respectively, is high in the IL-mode phase, of electrοn density respectively, is high in the IL-mode phase, as shown in Fig.6. The IL-mode can be characterized by a as shown in Fig.6. The IL-mode can be characterized by a specific electron behavior, namely a larger value of Te due to specific electron behavior, namely a larger value of Te due to the peaked, narrow ne profile. Such conditions are favorable for the peaked, narrow ne profile. Such conditions are favorable for central energy deposition using neutral beam injection to central energy deposition using neutral beam injection to produce a high and broad electron temperature profiles. We next produce a high and broad electron temperature profiles. We next present results obtained during pellet injection. In many present results obtained during pellet injection. In many discharges, pellet injection causes profile changes. Higher discharges, pellet injection causes profile changes. Higher central density and peaked profile, as shown in Fig.7, results, central density and peaked profile, as shown in Fig.7, results. ne profile is similar to those of the IL-mode phase. ne profile is similar to those of the IL-mode phase.

## *5. Summary*

A 13-point Thomson scattering system for measuring Te and ne A 13-point Thomson scattering system for measuring Te and ne has been collecting data reproducibly since 1987. The following has been co11ecting data reproducib1y since 1987. The fo11owing points should be noted. points should be noted.

- 1)A large collecting lens collects the light scattered from a 1)A large collecting lens collects the light scattered from a 60cm long plasma volume. 60cm 10ng p1asma volume.
- 2)Attenuation values from 180-channel attenuator are 2)Attenuation values from 180-channel attenuator are automatically transfered into the CPU memory. automatically transfered into the CPU memory.
- 3)High-pass optical filters and polarizer plate are used to 3)High-pass optical filters and polarizer plate are used to reduce stray light. reduce stray light.
- 4)The fiber bundles used minimize the polarization differences 4)The fiber bundles used minimize the polarization differences between the scattered light and that used for calibration. between the scattered light and that used for ca1ibration.
- 5)The system operates reliably for electron densities above 5)The system operates re1iably for electron densities above  $(4-5)x10^{12}$  cm<sup>-3</sup>.
- 6)Peaked density profiles are measured in the IL-mode, in 6)Peaked density profi1es are measured in the IL-mode, in contrast to those of the H-mode. contrast to those of the H-mode.
- 7)Broad temperature profiles are measured in the IL-mode, which 7)Broad temperature profiles are measured in the IL-mode, which will lead to good confined plasmas. wi11 1ead to good confined p1asmas.
- 8)The electron energy in the IL-mode is higher than in the H-mode, due to the increase of electron temperature. H-mode, due to the increase of e1ectron temperature.
- 9)The density peaking ratio is highest in the IL-mode, which is 9)The density peaking ratio is highest in the IL-mode, which is similar to that of pellect injection. similar to that of pellect injection.

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### *References*  Keferences

- [lJN.Bretz et al., Appl. Opt. 17 (1978) 192. [l]N.Bretz et al., Appl. Opt. 17 (1978) 192.
- [2]D.Johnson et al.. Rev. Sci. Instrum. 57 (1986) 1810. [2]D.Johnson et al., Rev. Sci. 1nstrum. 57 (1986) 1810.
- [3]D.Johnson et al., Rev. Sci. Instrum. 57 (1986) 1856. [3]D.Johnson et al., Rev. Sci. 1nstrum. 57 (1986) 1856.
- [4]D.Vaslow, General Atom. Rep. GA-A16378(1981) [4]D.Vaslow, General Atom. Rep. GA-A16378(1981)
- [5]C.L.Hsieh et al., General Atom. Rep. GA-A19192 (1988). [5]C.L.Hsieh et al., General Atom. Rep. GA-A19192 (1988).
- [6]H.Salzmann et al.. Joint Eur. Tok. Rep. JET-P(87)16 (1987). [6]H.Salzmann et al., Joint Eur. Tok. Rep. JET-P(87)16 (1987).
- [7]H.Rohr et al., Max Planck Inst.Rep. IPP III/121 B (1987). [7]H.Rohr et al., Max Planck Inst.Rep. IPP 111/121 B (1987).
- [8]T.Yamauchi et al., Japan J. Appl. Phys. 21 (1982) 347. [8]T.Yamauchi et al., Japan J. Appl. Phys. 21 (1982) 347.
- [9]T.Yamauchi et al., Japan At.Energ. Res. Inst. Rep. JAERI-M 87- [9]T.Yamauchi et al., Japan At.Energ. Res. Inst. Rep. JAER1-M 87 196 (1987). 196 (1987).
- [10]T.Yamauchi and I.Yanagisawa, Japan J. Appl. Phys. 25 (1986) 2 [10]T.Yamauchi and I.Yanagisawa, Japan J. Appl. Phys. 25 (1986) 2 63. 63.
- [ll]T.Matsuda et al., Japan At. Energ. Res. Inst. Rep. JAERI-M 87 [ll]T.Matsuda et al., Japan At. Energ. Res. Inst. Rep. JAERI-M 87 -129 (1987). -129 (1987).
- [12*1*T.Yamauchi and I.Yanagisawa, Appl.Opt. 2 4 (1985) 700. [12]T.Yamauchi and I.Yanagisawa, Appl.Opt. 24 (1985) 700.
- [13]T.Yamauchi et al., Phys. Lett. A 131 (1988) 301. [13]T.Yamauchi et al., Phys. Lett. A 131 (1988) 301.
- [14]T.Yamauchi and JFT-2M Group, Japan J. Appl. Phys. 27 (1988) L 924. 924.
- [15]M.Mori et al., Nucl. Fusion Lett. 28 (1988) 1891. [15]M.Mori et al., Nucl. Fusion Lett. 28 (1988) 1891.
- [16]T.Yamauchi and JFT-2M Group, Japan J. Appl. Phys. 28 (1989) L [16]T.Yaaauchi and JFT-2M Group, Japan J. Appl. Phys. 28 (1989) L 365. 365.



Fig. 1 Physical arrangement of laser, JFT-2M tokamak plasma, spectrometers and central processing unit (CPU).



Fig. 2 Optical path of the 13-point Thomson scattering system.



Fig. 3 Comparison of average electron density Comparison of average electron density Fig. 3 obtained from Thomson scattering and obtained from Thomson scattering and from HCN-laser interferometer measurements. from HCN-laser interferometer measurements.

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8



Fig. 4 Time evolution of plasma current,  $\boldsymbol{\mathrm{I}}_{\boldsymbol{\mathrm{p}}}$ , loop voltage, Vj, and global energy, W for a *He++*  plasma. Pnbi =  $0.36$ MW (He beam), Bt =  $l.34T$ , Ip = 250kA, lower single-null divertor = 250kA, lower single-null divertor configuration. configuration. Time evolution of plasma current,  $I_p$ , loop voltage,  $V_1$ , and global energy, W for a He<sup>++</sup> plasma. Pnbi =  $0.36$ MW (He beam), Bt =  $1.34$ T, I Fig. 4



Fig. 5 (a) Electron density and temperature profiles in the H-mode phase.



Fig. 5 (b) Electron density and temperature profiles in the IL-mode phase. Electron density and temperature profiles in the IL-mode phase. Fig. 5 (b)



Fig. 6 Electron energy as a function of electron density peaking ratio, neo/<ne>.



Electron density and temperature profiles during pellet Electron density and temperature profiles during pellet Fig. 7 injection, Pnbi = 0.8MW (from 700ms), Bt = 1.34T, Ip = 290kA, injection, Pnbi = o.8MW (from 700ms), Bt = 1. 34T, Ip = 290kA, D <sup>+</sup> plasma, three deutrium pellets and lower single-null D+ plasma, three deutrium pellets and lower single-null divertor configuration. divertor configuration.