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The Spectrometer of the High-Resolution Multiposition Thomson Scattering Diagnostic for TJ-II

J. Herranz
C J. Barth
F. Castejón
A. López-Sánchez
E. Mirones
I. Pastor
D. Pérez
C. Rodríguez

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CLASIFICACIÓN DOE Y DESCRIPTORES

S70

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Herranz J., Barth(*) C.J., Castejón F., López-Sánchez A.,
Mirones E., Pastor I., Pérez D. and Rodríguez C.

Asociación Euratom-Ciemat para Fusión
Avenida Complutense 22, 28040 Madrid, Spain
(*) FOM-Instituut voor Plasmafysica 'Rijnhuizen' Association Euratom-FOM,
Trilateral Euregio Cluster, P.O. Box 1201, 3430 BE Nieuwegein, The Netherlands

Abstract

Since 1998, a high-resolution multiposition Thomson scattering system is in operation at the stellarator TJ-II, combining high accuracy and excellent spatial resolution. A description of the diagnostic spectrometer is presented. The main characteristics of the spectrometer that allow TJ-II Thomson scattering diagnostic to have high spatial and spectral resolution are described in this paper.

Espectrómetro del diagnóstico de dispersión Thomson multiposición de alta resolución para TJ-II

Herranz J., Barth(*) C.J., Castejón F., López-Sánchez A.,
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Asociación Euratom-Ciemat para Fusión
Avenida Complutense 22, 28040 Madrid, Spain
(*) FOM-Instituto de Física de Plasmas 'Rijnhuizen' Asociación Euratom-FOM,
Trilateral Euregio Cluster, P.O. Box 1201, 3430 BE Nieuwegein, Los Países Bajos

Resumen

Desde 1998, está operativo el sistema de dispersión Thomson multiposición de alta resolución en el *stellarator* TJ-II, combinando una alta precisión en las medidas con una excelente resolución espacial. Presentamos una descripción del espectrómetro del diagnóstico. En el informe se describen las principales características del espectrómetro que determinan que el diagnóstico de dispersion Thomson de TJ-II tenga alta resolución espacial y espectral.

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22 pp. 6 figs. 6 refs.

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Avenida Complutense 22, 28040 Madrid, Spain
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The Spectrometer of the High-Resolution Multiposition Thomson Scattering Diagnostic for TJ-II

1. Introduction

A very high spatial resolution Thomson scattering system [1] (see Fig. 1) has been developed for the TJ-II facilities [2]. The system is able to determine electron temperature and density at 450 spatial positions of 0.8×10^{-3} m along a 0.360 m laser chord with a resolution of $\sim 2.3 \times 10^{-3}$ m (~1% of plasma radius). The spectrum is resolved at each position into 90 wavelength channels of 2.4 nm. These features characterize the TJ-II diagnostic amid the Thomson diagnostics with the highest spectral and spatial resolution. The high-resolution multiposition Thomson scattering system is used in TJ-II stellarator to routinely measure electron temperature and density profiles [3].

The special difficulties of TJ-II (see Fig. 1 item a) for the construction of the diagnostic are the magnetic flexibility and complex geometry. To be solved, the spectrometer (see Fig. 1 item b) and laser branch (see Fig. 1 item d, e, and f) are assembled on a 10 m height structure (see Fig. 1 item c). This frame allows a radial movement of the laser chord, making it possible for it to pass through the magnetic axis of the various TJ-II magnetic configurations.

In this report, the viewing optics and the detector branch, constituents that shape this powerful diagnostic, will be discussed.

The high spatial resolution allows the measurement of fine structures in the electron temperature and density profiles [4] so as to diagnose the appearance of radially localized phenomena, like improvement of transport [5], or the statistical behavior of those structures [6]. The wavelength resolution will be exploited to extract information of the electron distribution function.

Light of a Q-switched ruby laser (Lumonics PDS2) is injected vertically into TJ-II plasmas. The light scattered by the electrons is collected by means of a triplet after passing a BK7 vacuum window (see Fig. 1 item g, Fig. 2 item 2) and guided by conventional optics, a doublet field lens, to a Littrow spectrometer for dispersion and analysis.

Spectral analysis is carried out by a flat grating positioned in the Littrow configuration. The array of spectra is projected onto a split spherical mirror: wavelengths in horizontal direction, and scattering volume positions in vertical direction.

The two-dimensional image (0.200 m x 0.260 m) is detected by an image intensifier with GaAsP cathode, which is coupled by lenses and a beam splitter to a pair of Intensified CCD cameras.

The schematic layout of the spectrometer is shown in Fig. 2. The drawings (top view) of the spectrometer can be seen in Fig. 3.

This paper is organized as follows: The introduction is presented in Section 1, the viewing optics is described in Section 2, the detector branch of the spectrometer is shown in Section 3 and, finally, Section 4 contains the conclusions.

2. Viewing optics

2.1 Viewing triplet and holographic filter

The viewing triplet (see Fig. 2 item 4) collects the scattered light in the plasma and images the scattering volume onto a narrow vertical slit. It is a system of symmetrical lenses, which consists of two identical converging elements with a third symmetrical diverging one.

A triplet, instead of a doublet, is needed in order to minimize coma, chromatic and spherical aberration, as well as field curvature and astigmatism. Having the object (laser chord, see Fig. 2 item 1) only one dimension, the distorsion is not significant.

The object distance, s=0.955 m, has been chosen to keep the viewing triplet as far as possible from the stellarator, and avoiding vignetting for the lower positions of the laser chord that would be generated by the flange of the window, when positioned further away. In addition, some space should be left between window and lens for the calibration ceramic plate.

The distance between the triplet and the scattering volume can be altered shifting the whole spectrometer with respect to its stand, the C-frame structure, by adjusting two coarse screws. The final position with minimum blur is performed via an axial movement of the triplet. Also, a lateral movement of the triplet is possible using a sliding.

To filter out the strong signal of the laser wavelength, a very narrow holographic filter (see Fig. 2 item 3) is placed in front of the viewing triplet and as far as possible from the laser chord, minimizing the incident angle of the extreme off-axis points.

The transmission curve, given by the supplier for an incidence angle of 0 deg, is shown in Fig. 4. In our configuration, the extreme scattering volumes are imaged under incidence angles of up to 11 deg. The holographic filter transmission, as a function of the incident angle, can be observed in Fig. 5.

2.2 Field lens doublet

The main purpose of the field lens doublet (see Fig. 2 item 5, Fig. 3 item a) is to reach conservation of étendue. The plano-convex field lens images the exit pupil of the viewing triplet onto the grating surface at 1.038 m apart from the last surface of the field lens, decreasing the loss of light for off-axis object points. Unfortunately, the field lens introduces an unwanted strong augmentation of the field curvature.

The double lens diameter is 0.280 m, which is large enough to cover the full length of the slit (0.260 m), and only 0.040 m wide because the lenses system is positioned at just 0.0085 m apart from the narrow slit. The doublet lenses are axially separated 0.002 m.

The material has a low dispersion and a high refraction index. Thus, chromatic aberrations and the lens thickness are kept as small as possible.

The optical material is relatively fragile and due to the difficulties getting the optical glass, also quite expensive. The doublet system can be shifted lengthwise and placed therefore at its best position.

2.3 Vertical slit

The entrance slit of the spectrometer (see Fig. 2 item 6, Fig. 3 item b) is located behind the spectral mirror (optical element described below).

The vertical (0.265 m) and narrow (0.0023 m) slit performs a double role. On the one hand, it lets the Thomson scattered light access the spectrometer. On the other hand, sources of noise such as light reflected by the inner wall of TJII and collected by the viewing triplet or background spectral lines generated by plasma emission (after múltiple reflections), are both considerably cut out or even completely stopped by the slit before breaking into the spectrometer.

A good balance between these two conflicting interests is to operate with a slit width of 0.0023 m. Due to its high quality, the triplet does not introduce significant aberrations in the laser image. Hence, being the laser chord width at the edges 0.0027 m and having its intensity a gaussian distribution, around 95% of the beam intensity enters the spectrometer, while background signal is kept at an acceptable intensity level.

A micrometer settles the required width, and an array of screws set the correct parallelism of the two vertical knives of the slit.

A pneumatic cylinder with double needle valves(*), which reduce the velocity of the cylinder, is used to open up to 0.01 m the slit and therefore making it possible to determine the relative position of the laser chord all over the slit. The two blades of the slit move at once. A microswitch confirms in which position, 0.0023 or 0.01 m, is operating the slit.

(*) A needle valve has a long tapered needle fitting in a tapered seat.

2.4 Littrow triplet

Due to the 0.26 m of slit length, a triplet instead of a cheaper and more simple doublet is needed as Littrow lens (see Fig. 2 item 7, Fig. 3 item d). The achromatic triplet (focal length: 0.945m, f/12.5) collimates the incoming ligh and images the previous element onto the spectral mirror (described below), which is 0.015 m before the slit, after having suffered a first order reflection in the grating surface.

The system is symmetrical, except for the diameter of the first lens that is larger to fully accommodate light paths in the whole spectral range considered. It can be shifted axially to focus on the correct position.

2.5 Blazed grating, laser diode and flat mirror

Spectral analysis is achieved by a blazed grating (blaze wavelength: 650 nm) with 900 grooves/mm in the Littrow configuration (see Fig. 2 item 8, Fig. 3 item e).

In this spectrometer, the blazed grating, two diffusor glasses (Fig. 3 item g) and also a mirror (Fig. 3 item f) are mounted on the same holder. This system allows to swap them when needed during alignment, calibration or plasma operation.

The flat grating and the mirror have micrometers that regulate the correct and precise horizontal orientation needed to calibrate or align. Due to the long distance grating-spectral mirror, these have a high precision thread.

A laser diode (Fig. 3 item h) has been positioned behind the holder. The aim of this device is manifold. First, once it has been correctly positioned, the laser beam determines the optical axis of the spectrometer and enables to carry out a proper alignment. Also, it illuminates the pupil at the grating position for various tests. To this end, two diffusor glasses –different sizes and positions- are also mounted in the holder and can be inserted into the laser path at the right moment.

Important optical tests, as correct positioning and centering of the scattering volumes all along the rather narrow slit, are easily done swapping the grating with the flat mirror. When used, a great deal of care must be taken not to damage the sensitive image intensifier.

Small screws at the rear part of mirror and grating allow correction the vertical leaning. If necessary, the multiple holder can be axially shifted to correct the distance between the triplet in Littrow set-up and the grating, preventing from touching the triplet lens with the grating surface, because both surfaces could be easily scratched.

A couple of microswitches are mounted to point out whether mirror, laser diode or grating is being used.

2.6 Spectral mirror

In the Littrow spectrometer, the spectral mirror (see Fig. 2 item 9, Fig. 3 item c) is applied to image the grating surface at the entrance pupil of the camera objective, as well as to lower the vignetting.

To image the grating surface, the mirror has been moulded in spherical shape. The two independent blocks of the spherical mirror, belong to a sector of the same thick sphere of glass of around 1.15 m radius, while the radius of the imaging sphere is ~ 0.78 m. The original disk has been cut into two pieces at the center, creating a gap of 0.011 m.

This gap filters out the very intense vessel stray light at the laser wavelength which, otherwise, would extend its tails over the whole mirror, and therefore, across the image of the spectra. However, the gap or physical distance between the two aluminized parts restricts the lowest temperature to be measured. The closer, the colder the temperature that is measurable.

The positioning of the two spherical blocks is done via an illuminated pinhole in the center of curvature of the mirror. In the correct position, a unique reflection has to be observed.

The mirror holder is horizontally rotated in such a way that it a ccommodates the detection and collecting branches and matches the surface of the grating on the camera objective.

To minimize light loss in the viewing branch, all lense surfaces have an anti-reflection broadband coating, while the mirror has a high reflectivity broadband coating.

In our working conditions, the intensity of H-alfa emission is not a significant problem. But, if the case arises, a mechanical blocking filter is available to prevent the spherical mirror from receiving the 656.3 nm spectral line from the grating.

2.7 Polarizer

The rejection of half of the plasma light and half of the vessel stray light is achieved by means of a broadband polarizer (see Fig. 2 item 15, Fig. 3 item i) just in front of the camera objective. The sheet is shifted into the optical path using a pneumatic cylinder and damped by needle valves.

This superfluous scattered light enters the spectrometer after having been reflected by the stellarator wall and therefore, partially lost its original polarization. This signal, scattered by other different volumes in the plasma, would be collected and mistakenly interpreted as coming from the very same one. In our configuration, the signal is orders of magnitude smaller.

Unfortunately, due to the wide spectral range considered, the correct Thomson scattering signal is also attenuated by the polarizer sheet. A positive collateral effect is a relative improvement of the signal-to-background ratio.

2.8 Camera objective

The demagnification of the spectral mirror is done by a commercial Canon EOS f=50 mm/1.0 camera objective (see Fig. 2 item 10, Fig. 3 item j). No ray tracing details has been supplied nor other optical properties of the objective by the manufacturer, except lens characteristics when focused at infinity (see Fig. 6).

On account of this lack of details, we measured four important optical parameters of the Canon camera objective: transmission for the wavelength range of 500 to 850 nm, resolution of the objective, the vignetting curve and the focal length.

The average transmission of the objective determined for a set-up with magnification M=0.09 is ~ 70 %, being 83 % the paraxial transmission with a laser diode (670 nm).

The tangential and sagital aberrations amount to 0.026 m, after applying the corresponding system demagnification of 0.45. The longitudinal chromatic aberrations correspond to a secondary spectrum: $\Delta f/f = 0.25$ %. The residual chromatic aberrations are nearly independent of wavelength. Chromatic aberrations can be corrected for by a rotation of the detection system. Therefore, it is expected that the image quality of the objective will be determined only by the geometrical aberrations.

The vignetting decreases the throughput at the edge of the spectrum to ~ 80%. The objective shows a vignetting down to 65 % for an image height of 0.0125 m, which corresponds to the edge of the specified image field.

Finally, the focal length calculated from the used object distance and the magnification gives (55.0 +/- 0.1) x 10^{-3} m.

The appropriate adjustement of image distance at 0.63 m has to be done using its camera body. Once the operation is accomplished, the camera body is removed.

3. Detector branch

3.1 Image intensifier

The operation of the image intensifier (see Fig. 2 item 11, Fig. 3 item k) is based on the photoelectric effect, which converts into photoelectrons, a percentage of the incident photons of the spectral image that is projected onto the active region of a photocathode.

A subsequent amplification of the photoelectric energy in the microchannel plate (MCP) occurs, and generation of light by the cathodeluminescent effect forms the output image. The degree of amplification is dependent on the magnitude of the voltage applied across the MCP.

Here, among the different characteristics of a tube, such as gain, Equivalent Background Noise, resolution, Modulation Transfer Function... the parameter of importance in the detection is the quantum efficiency (QE) or photocathode sensitivity at a specific wavelength. At the cathode, the signal-to-noise-ratio (SNR_i) and QE are related as

$SNR_i \alpha QE^{1/2}$

Other noises and distortions are also introduced in the subsequent electron multiplication and cathodeluminescent processes. The parameter that considers all these effects altogether is the noise figure (NF) of the MCP, or ratio of the MCP input SNR to the MCP output SNR, which is given by:

$NF= SNR_i / SNR_o$

where SNR_i is proportional to, as noted above, the square root of the number of photoelectrons released from the photocathode over unit area per unit time, and SNR_o is the signal to noise ratio at the output end or phosphor side. The noise figure is dominated by the noise figure characteristics of the MCP because the high gain of the latter reduces the significance of the noise sources, which follow the channel plate.

It should be stressed at this point that the SNR_o of a third generation tube, utilizing an MCP for current multiplication as well as an anti-ion-feedback layer, is clearly degraded by the noise figure of the MCP.

This wafer, a third generation image intensifier with high quantum efficiency, has a noise figure lesser than 1.8. This figure corresponds to the NF of the aluminum oxide ion barrier coated MCPs, which is in the range of 1.76 to 2.0.

The 25 mm Gen III wafer GaAS image intensifier tube installed has been supplied by Litton EOS with export license from the US Department of State. It is gateable to 5 ns and has glass input and non-inverting plano non-protuding (fiber optic) output.

The performance of the intensified charge-coupled device, ICCD, (item described below) is governed by the quantum efficiency of the photocathode of this image intensifier.

3.1.1 Power supply

A fast electronics device provides short image intensifier gate times in the order of 20 ns FWHM of the laser pulse duration.

The special high voltage power supply unit has been manufactured by Kentech Instr. Ltd., and it is intended to provide the correct gated voltages. The nominal pulses width ranges from 30 ns to 3 s, including a DC mode.

Basically, three parts form the gating power supply: HV bias supplies, cathode gate circuit and logic control.

The unit polarizes the phosphor to a voltage of + 6kV relative to MCP output, as well as the MCP output and the cathode gate circuit. The gate occurs in response to a rising edge at the trigger input. Rise and fall times are ~7 ns. The MCP output voltage determines the intensifier gain, ranging from 0 to +1400 V in response to the non-linear gain control potentiometer. The cathode is switched between +100 V (overload and off modes) and –800 V (gated mode).

3.2 Imaging lenses and beam splitter

A couple of low f-number, XR Heligon 1.6/95 mm and 1.2/64 mm camera objectives (see Fig. 2 item 12, Fig. 3 item l), with a very good resolution (MTF greater than 0.5 at 50 lp/mm and along the 25 mm view field), images the phosphor screen output onto the ICCD's cathode.

The phosphor output is demagnified a factor 0.67 onto the ICCD cathode (see below). Including the 50:50 beam splitter (see Fig. 2 item 13, Fig. 3 item n), the total collection efficiency is ~ 6%.

3.3 Intensified CCD cameras

The light emitted by the phosphor screen and projected by the imaging lenses, are finally detected and recorded by the intensified charge couple device, Oriel InstaSpec V ICCD camera (see Fig. 2 item 14, Fig. 3 item m).

The camera applies an image intensifier with improved S25 photocathode, with quartz window, and EEV CCD02-06 chip with 385x578 square pixels of 22 mm size (then the total area is 8.47x12.72 mm^2). The second Generation intensifier is a proximity focused tube gated down to 5 ns time scales and operates from 180 nm to 850 nm. The P46 phosphor screen is fiber optically coupled to CCD via taper 1.5:1. The taper restrains stray light and keeps away minimal distortion levels that are normally related to lenses.

Thomson and plasma light images are recorded in each plasma shot. To this end, two ICDD cameras are mounted because the read-out speed of the 16 bits high dynamic range, 13 ms/pixel, is not fast enough to read the full chip area and separate both images. So, even though the tube can be applied to intensify the spectral image, the device is just switched on and off as a very fast electronic shutter, discriminating and recording Thomson and plasma shots by two different cameras.

Cooling the CCD sensor improves its detectivity by plummeting down the shot noise created by the dark current. The three stage thermoelectric cooled system, controlled by software, achieves air cooling to –25 °C and down to –45 °C with 10 °C water, which can be flowed through a couple of connectors at the top of the head. Due to delamination and gel crack that generate decoupling between fiber optic taper and CCD, the sensor is not cooled below 5 °C.

When the gain is set high in the first intensifier and the CCD sensor is cooled, single photons can be easily discerned above the CCD readout noise.

TTL pulses are used for ensuring synchronized operation of the ICCD with laser and first image intensifier gating.

3.3.1 InstaSpec IV GPIB system

The camera can be handled by any host computer that has a General Purpose Interface Bus (GPIB) interface. The InstaSpec IV GPIB system, which consists of the detector head and the controller box, conforms to this standard.

The detector head, as already described, contains the CCD sensor and its pre-amplifier. It also contains the temperature sensor and thermoelectric cooler.

The controller box, based on an IBM AT 80386 computer holds, basically, an InstaSpec IV interface card and a NI GPIB card. The interface card has a 16-bit A/D converter that gives true 16-bit accuracy and dynamic range.

Conclusions

In this work the spectrometer of the multiposition high-resolution Thomson Scattering diagnostic for TJ-II is presented. This element plays a key role in order that the TS system of TJ-II can achieve high spatial and spectral resolution. These characteristics are basic in present Plasma Physics experiments.

The single elements that the spectrometer consists of are described in the paper. The viewing optics is designed in order to give high spatial resolution, low aberration and distortions. These characteristics are accomplished using the following elements: notch filter, viewing triplet, field lens doublet, vertical slit, Littrow triplet, blazed grating, spectral mirror, polarizer, and camera objective.

The detector branch acts during a short pulse and its electronics allows the proper light intensification and the perfect synchronization with the laser beam. This element is made up of the following items that have been described in the text: image intensifier, imaging lenses, beam splitter, and double ICCD cameras.

Acknowledgements

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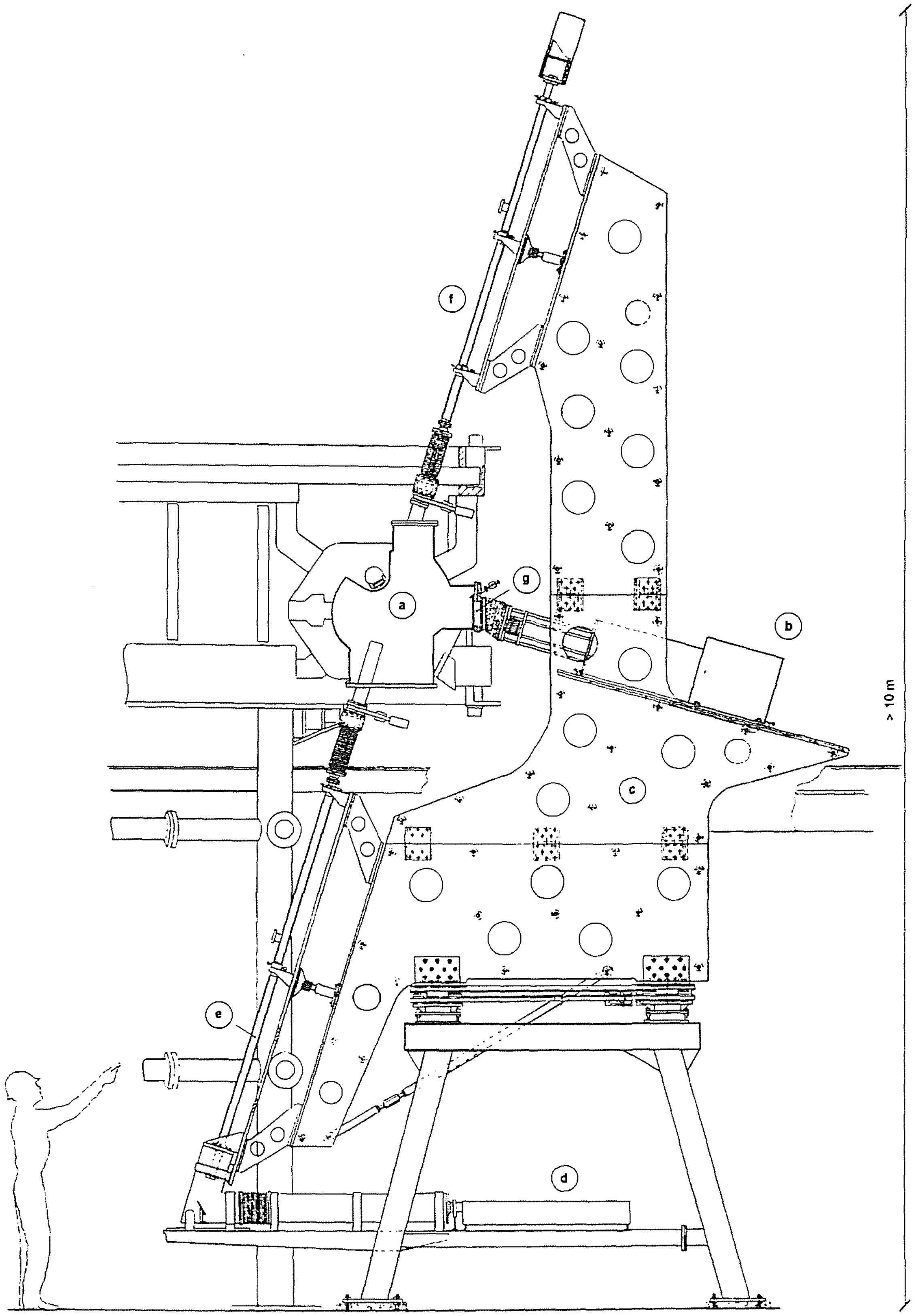

FIG. 1. TJ-II Thomson scattering system.
(a) TJ-II vessel, (b) spectrometer system, (c) structure, (d) ruby laser, (e) entrance tube, (f) exit tube, and (g) vacuum window.

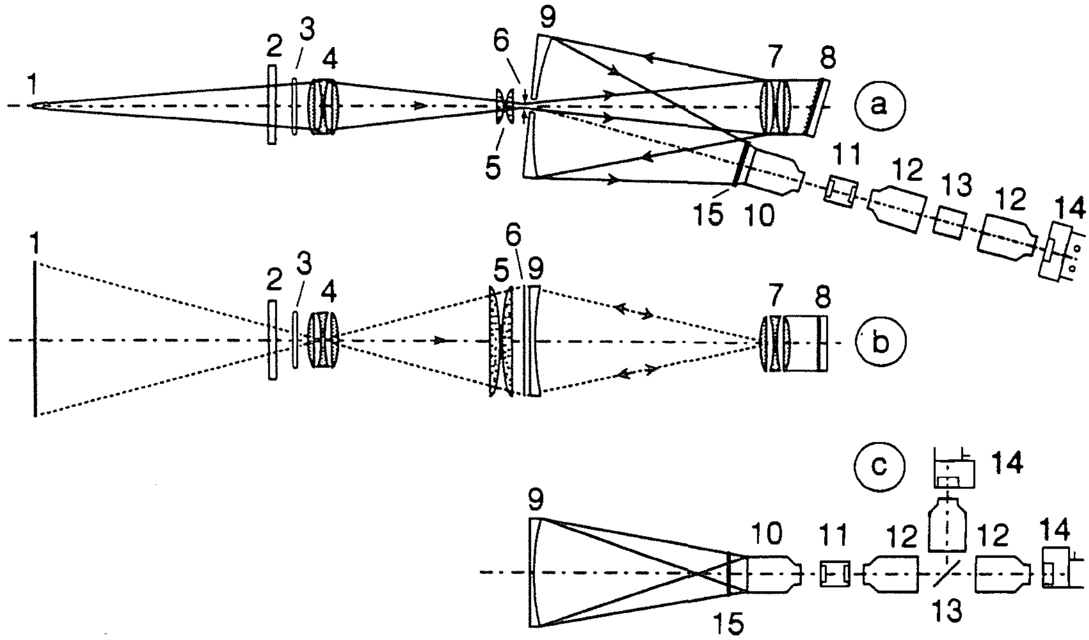

FIG. 2. Layout of the high-resolution multiposition Thomson scattering system.
(a) horizontal cross section,
(b) vertical cross section along the scattering plane,
(c) vertical cross section of the detector branch.
(1) laser beam, (2) window, (3) notch filter, (4) viewing triplet, (5) field lens doublet, (6) vertical slit, (7) Littrow triplet, (8) blazed grating, (9) spectral mirror, (10) camera objective, (11) image intensifier, (12) imaging lenses, (13) beam splitter, (14) ICCD cameras and (15) polarizer.

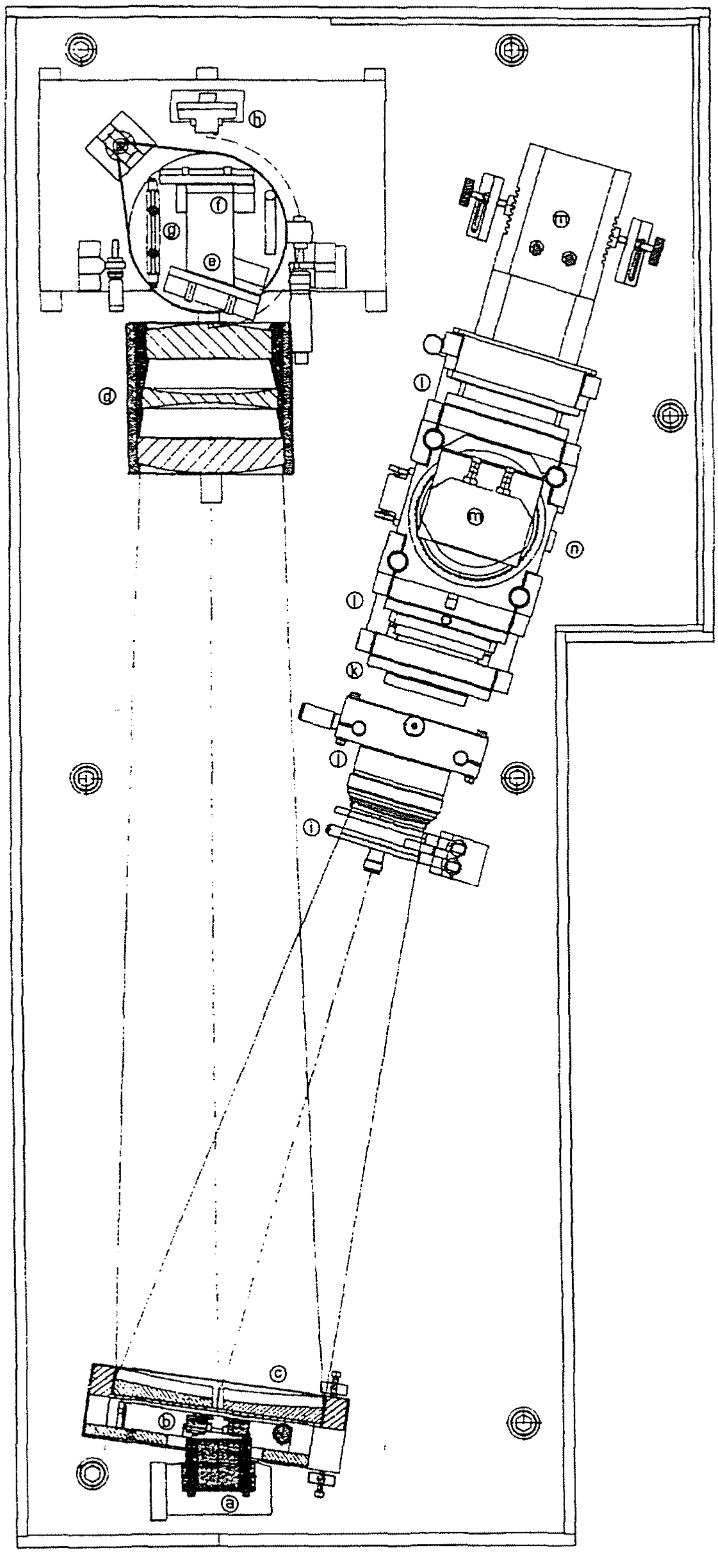

Fig 3. Topview of the spectrometer, without viewing triplet and notch filter.
(a) Field lens doublet, (b) vertical slit, (c) spectral mirror, (d) Littrow triplet, (e) blazed grating, (f) flat mirrot, (g) diffusor, (h) diode laser, (i) polarizer, (j) camera objective, (k) image intensifier, (l) imaging lenses, (m) ICCD cameras and (n) beam splitter.

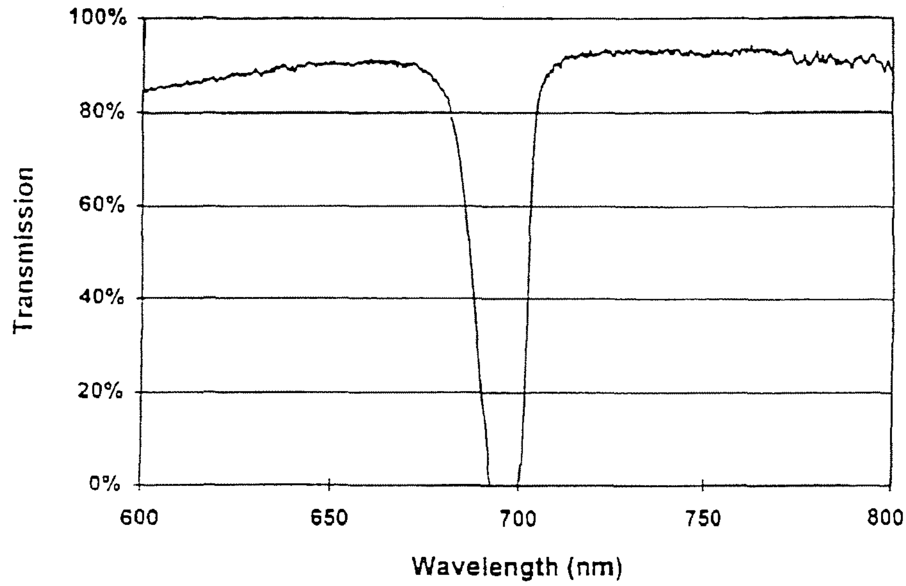

Fig 4. Notch filter transmission curve, given by the supplier (Kaiser Optical Systems Inc.), for an incidence angle of 0 deg.

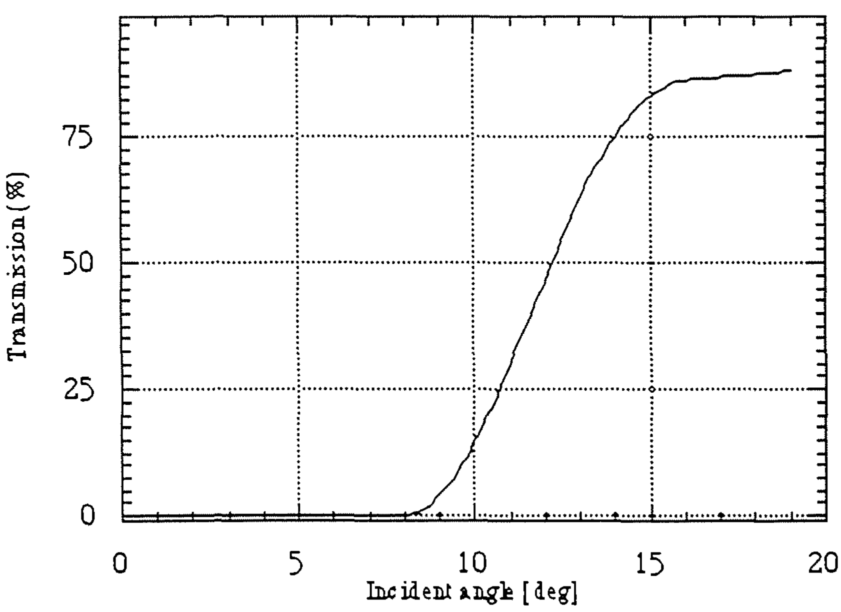

Fig. 5. Holographic notch filter transmission for the central wavelength, as a function of the incident angle.

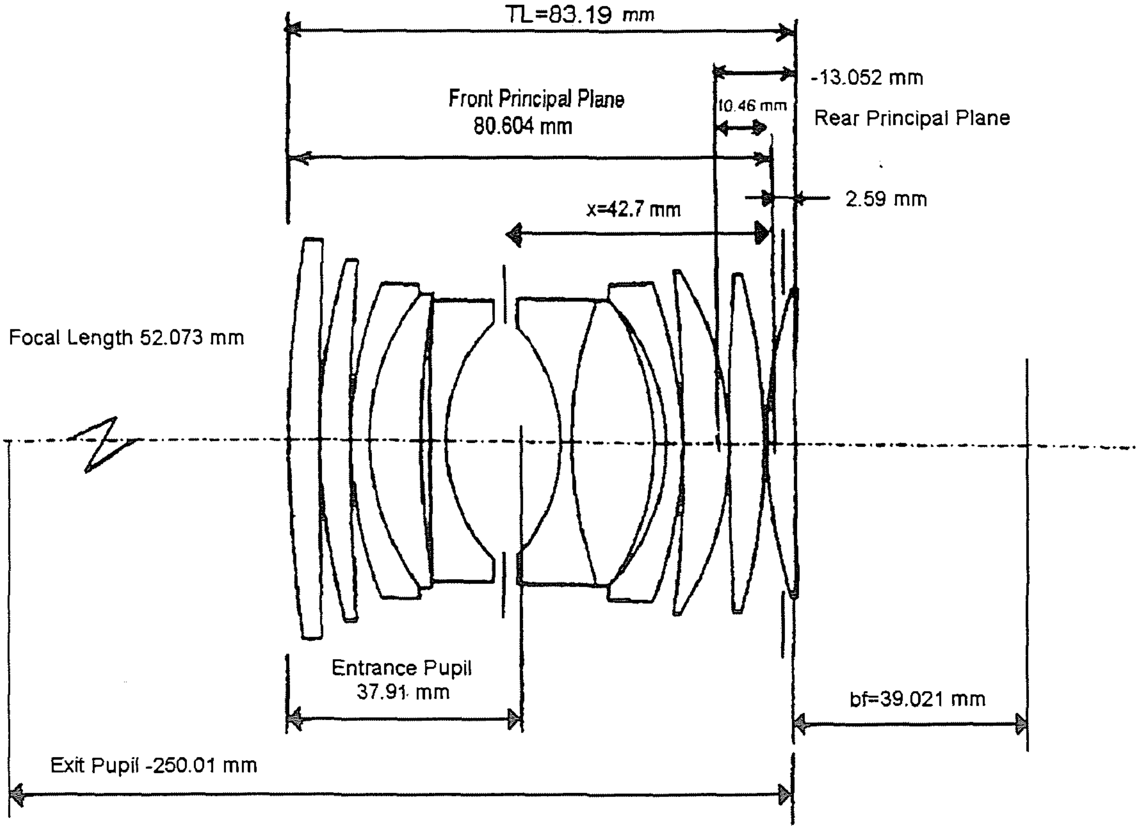

Fig 6. Canon camera objective. Lens characteristics given by manufacturer.