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Design Proposal for a JFT-2M TV Thomson Scattering System

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A design for the optics of a TV Thomson scattering system for JFT-2M is presented, which will measure electron temperature and density profiles having up to 82 points, spanning the horizontal mid plane of the machine. A detailed design for the collecting optics is presented since it is critical to the success of the system. It is shown that the Bouwers type catadioptric collection optics can be color corrected allowing the system to be used over a wide wavelength range. The laser requirements are presented and are easily met with commercially available systems. Two sketches of spectrometer designs are presented for two different sizes of detector. The detector gating and readout requirements are presented and can be met in existing detector systems. The importance of developing larger area detectors is emphasized and a possible detector system is presented.

Keywords: TV, Thomson Scattering, JFT-2M, $T_e(r)$, $n_e(r)$

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JFT−2M用テレビトムソン散乱装置製作のための設計検討

日本原子力研究所那珂研究所核融合研究部
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（1988年6月23日受理）

JFT−2M用テレビトムソン散乱装置の光学系に関する設計を行った。この設計ではJFT−2M真空容器内水平方向の直径に渡る電子温度及び電子密度分布を，最大82点の測定点から得られる事とした。まず収集光学系は本装置の重点課題である為，その設計を詳細に行った。バウアーズ型二重ミラー光収集系は色補正され広い波長範囲で使用できる。レーザーに関する必要条件は市販品のレーザーで充分満足できる。2種類の検出器に対応した2種類の分光器の構成を示した。検出器のゲート動作やデータ読取り条件は，現存の検出器を組みあげる事で満足できる。本装置にとってさらに大きな光電面を持つ検出器の開発は特に重要であり，また，それ等の構成に関して述べた。

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1. Introduction

Many methods exist for measuring the electron temperature as a function of position and time in plasmas. Two methods are commonly used in Tokamak plasmas where reasonably precise values at well defined positions are required. The electron cyclotron emission (ECE) method is particularly effective when the time dependence of the temperature at a fixed position in the plasma is needed. Multichannel and frequency scanning ECE systems can provide radial profiles, however, where radial profiles at a single time or only a few times are needed, the method of choice is usually Thomson scattering.

Thomson scattering offers several advantages. It is independent of the magnetic field, allowing the experimenter to vary the field at will. It is independent of plasma phenomena, determining the temperature directly from the body of the electron distribution function. (In the case of nonthermal distributions this corresponds better to what we usually think of a temperature.)

Calibration is fairly direct and straightforward. In practice Thomson scattering has demonstrated excellent accuracy and reliability. In the past Thomson scattering has been limited to one or at most two times during a Tokamak shot. The recent development of large YAG laser rods has opened the possibility of using a 10 Hz laser to measure many profiles during a shot. The present design allows for this possibility, as well as the possibility of using a more conventional ruby laser.

The type of Thomson scattering system being considered here1-5) consists of a laser producing a short (10 to 50 nsec.) energetic (5 to 20 Joules) pulse of light with a low beam divergence ($\sim$0.2 mrad.). This beam is focussed over the measurement region to as small a diameter as possible. The light scattered by the electrons is imaged onto a set of fiber optic bundles the far end of which is imaged onto the entrance slit of a spectrometer. In the focal plane of the spectrometer one then has a two dimensional region with wavelength being one dimension and position in the plasma being the other.

The focal plane of the spectrometer is imaged onto an image intensifier system which is in turn imaged onto an array detector such as a charge coupled device (CCD). The output of the CCD can then be analyzed to give the Doppler broadening and total amount of scattering at each position. These data can then be interpreted in terms of electron temperature and electron density in the plasma.

The very small scattering cross-section of the electron requires that the laser energy be as large as practically possible. The aperture of the collecting optics must also be large, and the overall efficiency of the optics must be as good as possible. This results in a large optical throughput in the spectrometer which requires an image intensifier with a large area.

The principal problems encountered are the plasma light, and stray laser light. To make the signal large compared with the plasma light it is necessary that the laser power averaged over the detector gate time be large. This is accomplished by using a large laser energy and short gate. Large H alpha light can be blocked at the focal plane of the spectrometer.

The stray light is only at the laser wavelength and is minimized by careful baffling of the laser input tube, careful design of the laser dump, and getting the best possible rejection in the spectrometer. This involves careful selection of the grating and minimizing the reflected light. At the focal plane of the spectrometer a dump is placed at the position of the laser line.

Since the signal light is polarized, a polarizer at the input to the fiber optics reduces the plasma and stray laser light by a factor of two.

These precautions should be adequate for the present system.

2. JFT-2M Thomson scattering requirements

The JFT-2M Tokamak can be run in several modes. With no divertors it is possible to run a circular or somewhat elongated plasma with a horizontal minor radius of 350 mm. The plasma is more normally run with a smaller minor radius. It is undesirable, however, to have the Thomson scattering system unable to provide full profiles during exceptional discharges. The present design calls for measuring along the entire 700 mm length..

In some ways it would be easier to measure along a vertical profile, however, as discharge conditions change the center of the plasma moves significantly in the horizontal plane. Therefore, any system measuring vertical profiles must be able to measure along a number of different vertical lines. This considerably complicates the system. Also because the maximum vertical plasma dimension is appreciably greater than the maximum horizontal dimension, one must look at a larger area of the plasma and the optical throughput (the image area times the solid angle) would become greater. As we shall see TV type Thomson scattering systems are always in some sense throughput limited, either by detector size, or cost. A further disadvantage of measuring along a vertical line is that the necessary small size of the laser beam in the plasma means that the laser window must be located at a considerable distance from the plasma for the beam to be large enough not to damage the window. In the case of JFT-2M this distance is about 7 meters. One cannot go 7 m. below the machine. 7 m. above it would be difficult to mount sufficiently stable optics.

The total temperature range desired is large. The present system is designed to cover the range from 50 ev. to 7 kev. This range is adequate to look at edge plasmas in some detail as well as to look at the hottest plasmas with reasonable accuracy. This range is pushing the optical throughput of the system to a very large value. Any further extension of the temperature range probably requires a separate system. If the full temperature range is necessary for all spatial positions, the present design calls for a detector with at least a 50 mm. diameter. If the spatial region can be separated into a central region and two outer regions, and the temperature ranges in the inner and outer regions can be reduced by a factor of four, then there is the possibility of using two smaller spectrometers each with a 25 mm. detector. This will be considered further when we discuss the spectrometer.

The density range required is also large being from $1 - 3 \times 10^{12}$ to 3×10^{14} cm^{-3}. This is well within the normal dynamic range of present detector systems and should pose no problems. The lower limit is limited only by the shot noise of the system and therefore depends on the laser energy, the spatial resolution required, and the light gathering power and efficiency of the optical and electro-optic systems. To achieve the specified lower limit a 10 Joule laser at the ruby wavelength or 5 Joule per pulse for frequency doubled YAG is probably necessary.

3. Laser requirements

For several reasons it is important to keep the diameter of the laser beam in the plasma as small as possible. By minimizing the area of the plasma seen by the collecting optics we minimize the optical throughput of the system and thereby its cost, and also minimize the amount of plasma light and of stray laser light that gets into the system.

Assuming a simple geometric optics focal spot, the smallest diameter that will contain a laser beam over a length L, is $(2LDd)^{1/2}$, where D is the initial beam diameter, at which it has a beam divergence d. Typically a 10 Joule laser will have a 25 mm. diameter D and the lowest beam divergence normally available is 0.0002 radians. This leads to a beam diameter of 2.65 mm. for JFT-2M. An additional 1 mm. is necessary to allow for any slight misalignment.

A typical laser of this energy and beam divergence will have four heads. There will be a diffraction limited oscillator, followed by three amplifiers. To minimize initial cost it is possible to start with a system with only two amplifiers and about 5 Joule output. This will limit the lowest densities at which the system will work, and increase the error bars by a factor of ~ 2.

In either case the additional heads will disturb the beam increasing the beam divergence from the diffraction limit of about 0.034 mrad. to about 0.2 mrad.

Another possibility to further reduce the beam diameter is to use a laser with a phase conjugate mirror. This makes it possible to get a diffraction limited output. This would reduce the beam diameter to about 1 mm. Not all of this reduction in diameter is practically realizable, since it would require the laser window to be 17 meters from the plasma center. Keeping the beam aligned over this distance would be difficult, and the very long vacuum pipe would be awkward. Used at 7 m. however a 32% reduction in optical throughput could be realized, so the system is worth considering. The present design does not assume this however.

The phase conjugate laser system would probably require only three heads since two of them would be double passed. Such a system works by firing the oscillator into a polarizing prism which reflects the beam at a right angle into a Faraday rotator. The rotator rotates the plane of polarization through 45°, the beam then passes through the two amplifiers and into the phase conjugate mirror. This mirror consists of a high pressure methane cell or possibly a tube filled with an organic liquid whose molecules are highly symmetric. The light returning from this mirror retraces its path exactly thus correcting any errors introduced by the laser rods. When it passes through the Faraday rotator it gains another 45° rotation in the focal plane. It then passes through the polarizing prism rather than being reflected back into the oscillator. The fraction which reaches the oscillator should be less than 10^{-4} of the output, and will require another small Faraday isolator in the oscillator beam. Such a system is being developed at PPPL, and it may be possible to use such a system on JFT-2M. Some of the additional cost would be offset by the reduction in the number of laser heads.

4. Viewing and laser dumps

There appears to be adequate space for a conventional stainless steel "razor blade" type of viewing dump. The divertor area may have to be left clear and considerable plasma light is expected from this area. Experience with a similar system on the Princeton PBX machine indicates that such light may be a nuisance but is not likely to be a serious problem. Stray laser light from this region is not likely to be serious.

The laser dump is a more serious problem because there is only 65 mm. between the vacuum wall and limiter edge. If the dump has a small hole (perhaps 5 or 6 mm.) and a number of internal apertures, with a carbon block at the back it should be adequate, but the stray laser light may be a somewhat greater problem in this system than in similar systems. It is not expected to be a large part of the signal except at the very lowest densities.

5. Collection optics

In order to get the best possible signal to noise ratio and be able to measure to low densities it is important to use the largest laser energy possible and to collect as much of the scattered light as possible. In the tradeoff generally more laser energy is less expensive than collecting more light up to the energy limit of commercially available lasers, because the collected light determines the size of the spectrometer, the output camera lens, and the necessary detector area. However, to increase the laser energy much beyond 10 to 20 Joules with low beam divergence involves getting into exotic laser systems which become very expensive and unreliable.

The overall quality of the system depends then on making the f number of the collection optics as low as possible, consistent with a reasonable spectrometer design, and with available detectors. A further restriction on the collection optics is that they must fit above or below the vacuum vessel between the coils.

The Bouwers concentric double mirror system, as developed for Thomson scattering by Edwin Tolnas at the Princeton Plasma Physics Laboratory, would seem to be the most suitable known system to use with JFT-2M. It has the advantages of placing the aperture at the window, being a compact folded system, and being well suited to imaging on a fiber optic output.

The fiber optics allow the spectrometer to be removed a considerable distance from the machine, and allow the transformation of the image shape to that of a suitable spectrometer input slit. The use of fiber optics also allows the use of focal planes that are not flat, greatly easing the requirements on the optical design of both the input optics and the spectrometer.

The wide temperature range required of this system and the desire that the system be adaptable to both ruby and frequency doubled YAG lasers means that the optics should be color corrected, which has not been necessary in past designs. The design of the input optics has therefore been carried out in detail to be sure that a suitable system is possible.

Initial attempts to design a system with an f:5 aperture which would fit between the JFT-2M coils resulted in systems with large aberrations. The optical throughput of such a system is also very large and requires a very large spectrometer and detector.

A system has been successfully designed with an f:6 aperture. This system is shown, as mounted on the JFT-2M machine, in Fig. 1 and 2. It consists of a color correcting lens of zero power placed directly above the window, followed by a thick corrector for correcting the spherical aberrations of the mirrors. The light is then reflected by the primary mirror back to the secondary mirror which is a reflecting portion of the back of the corrector. The light then passes to a row of fiber optic bundles. Fig. 3 shows a ray trace of this system, Fig. 4 a spot diagram of the focal spots both on axis and at the extreme end of the focal plane, and Fig. 5 a ray trace of a transverse cross-section of the system.

The color correction is good which minimizes the focal spot size and the possibility of temperature errors from misalignments of the laser beam and the image of the fiber optic bundles in the plasma.

6. Fiber optics

To maximize the transmission of the fiber optics it is necessary that the ratio of core diameter to cladding thickness be as large as possible. Fiberguide Industries working with Richard Palladino of the Princeton Plasma Physics Laboratory has developed large core quartz fibers with a very thin silicone cladding. Palladino has found that these fibers are optimally filled at f:1.75. This large aperture is a balance between large absorption losses at lower f number, and greater fiber cost due to increased bundle area at larger f number.

To span the laser beam image with adequate clearance at f:1.75 the fiber optic focal plane will be 0.9 mm. wide and 193 mm. long. If we use a system with 82 points each bundle will be 2.35 mm. long, and will consist of 5 rows of 12 fibers of approximately 200 micron fiber.

The maximum length of these fiber bundles is limited by absorption losses and cost. Absorption losses in the blue region of the spectrum become significant in lengths above 10 m. The additional cost per meter is essentially the fiber cost. There are about 5000 fibers in the total bundle.

The individual bundles are rearranged to form a shorter wider array at the far end, having dimensions of 2.35 mm. × 74 mm. This provides the proper ratio to give the necessary number of spectral resolution elements at the spectrometer output when imaged onto a CCD with 4 : 3 width to height ratio.

7. Spectrometer

Fig. 6 and 7 show diagramatically two possible systems based on one 50 mm. or two 25 mm. detectors. In the latter case two spectrometers would be needed. It has the advantage that it will work with readily available 25 mm. detectors, also the spectrometers could be smaller. The basic design of the spectrometers would probably be the same.

The formatting of the spectrometer output must correspond to some existing array type of detector. Here we have assumed that we need to closely follow the 4 : 3 size ratio of standard TV CCDs. Depending on the orientation of the chip we can choose either 63 or 82 spatial elements giving about 11 mm. or 8.5 mm. spatial resolution. This is independent of whether we use the one or two spectrometer configurations.

Figs. 8 and 9 show the spectral distribution of the scattered light for a number of temperatures. Also shown are the regions which must be blocked to minimize stray laser light around 6943Å and to remove the H alpha light around 6561Å. Also shown are the 24 spectral resolution elements required to give the desired temperature range.

In the two spectrometer cases, the high temperature spectrometer would have half the number of spectral resolution elements but twice as wide, and the low temperature spectrometer would have only half the number of elements but with the same width as those in the single spectrometer, but covering only half the wavelength range.

Fig. 10 shows a sketch of a design for a spectrometer. It uses a hemiconcentric achromatic Littrow lens. On the scale of the single spectrometer system, the grating would have 900 groove / mm. and the distance from the slit to the lens is about 700 mm.

8. Detector requirements

To be shot noise limited an image intensifier is required between the focus of the camera lens and the CCD detector. High gain is required so it probably easiest to use a microchannel plate intensifier. These have the disadvantage that about 40% of the photoelectrons do not enter the holes in the microchannel plate and are lost. This is equivalent to throwing away 40% of our signal.

As we can see from Figs. 6 and 7, a lens of f number less than 0.8 is required to get all the light from the primary focal plane of the spectrometer onto a 50 mm. or two 25 mm. diameter image intensifiers. Such a lens will be expensive and probably somewhat lossy. Unfortunately the larger detectors mentioned in these figures don't exist. Even the 50 mm. size does not exist in a microchannel plate intensified version.

One solution to this problem is to use a 50 mm. proximity focussed diode type of intensifier and couple it with tapered fiber optics or with a lens to a smaller 25 or 16 mm. microchannel plate intensifier. This can then be coupled with tapered fiber optics to the CCD.

Several possible problems can arise with this system. One is getting good time response. In order to sample the plasma light at a time shortly before or after taking data during the laser pulse, it is necessary to be able to take two sets of data within a few milliseconds. The phosphors normally used in intensifier tubes (P20) have longer time constants than this. It is therefore necessary to have tubes made with fast phosphors.

Another potential problem is saturation of the microchannel plate. When an electron enters a hole in a microchannel plate, it discharges the voltage distributed along the tube wall. The tube is recharged through very high impedance so with our fast (20 nsec) pulse only one electron per hole is allowed. Great care must be exercised if this is not to limit the dynamic range of the system. It may be necessary to include corrections for non-linearity in the calibration procedure if a microchannel plate is used.

To minimize plasma light the laser pulse is made as short as practically possible and the first intensifier of the detector system is gated with a gate of about 50 nsec. If the intensifier photocathode does not have good conductance, it is difficult to drive this gate. It is always possible, however, by putting a conducting layer outside the photocathode and driving the cathode capacitively.

The CCD must be capable of storing two images, so that we can measure both the signal and background light with a few millisec.

Most CCDs have sufficient dynamic range since each data point will come from summing 160 pixels. Since the noise adds only as the square root of the number of pixels, this increases the dynamic range to about 12 times the individual pixel range which is normally at least several hundred. For ease of operation a dynamic range of 2000 or more is desirable.

9. Data collection and analysis

Data is normally collected by reading out the two images stored in the CCD after a shot, digitizing the individual pixels to 10 bit accuracy, and storing the output in CAMAC memory. Since accurate digitizing is fairly slow, it may be necessary to refrigerate the CCD to avoid leakage problems.

The data can be summed as it is read into the computer. There the background can be subtracted and the data corrected for spatial or wavelength variations in gain, using calibration data.

If the JT-2M data computer is already overloaded, the cost of a small dedicated computer is only a small part of the total system cost, and is well worth having, to provide profiles between shots.

There is little value in archiving the data from each pixel, but it is valuable to archive the summed raw data, so that later corrections in calibration (from window coating etc.) can be applied. If archiving even this much data is difficult, new calibration data can usually be converted to temperature and density corrections, with only a small loss in accuracy.

10. Calibration and alignment

Precise alignment of the laser beam with the image of the fiber optic bundles is essential. This can usually be accomplished by using a probe which can be inserted into the region of the laser beam, and simultaneously illuminated with a helium neon laser beam which is exactly congruent to the ruby laser beam, and with light shining backwards through the fiber optic bundles. The laser beam must also be accurately centered in the laser dump so that it may be necessary to adjust the input optics as well as the laser beam.

For stability it is very desirable that the input optics be mounted solidly to the floor as close to the floor as possible. Mounting under the machine strongly preferred to mounting above it. Barriers to carbon dust can probably eliminate that problem. Some study of this on the machine would be very valuable.

Calibration can be done by using lamps of known spectral output to uniformly illuminate a white plate. Placed in front of the input optics this can provide both the necessary spectral sensitivity information, and information of spatial variations in gain. Rayliegh scattering should also be used to give more accurate spatial gain information. Having a known light source which can be inserted into the machine and which covers the spectral range can be very useful in correcting the calibration data for any coating of the viewing window.

The presence of microchannel plates and/or phosphors in the detector system can give rise to non-linear signals. This must be carefully checked initially and if the effect is significant, the calibration procedure must include determining the non-linearity so that suitable corrections can be applied during analysis.

11. Summary

A system for making Thomson scattering measurements at 82 points along a horizontal mid plane of the JFT-2M machine appears to be practical. All the necessary elements exist, but it would be very desirable to develop large area image intensifier tubes, as this would allow less expensive optics and the development of very high optical throughput systems.

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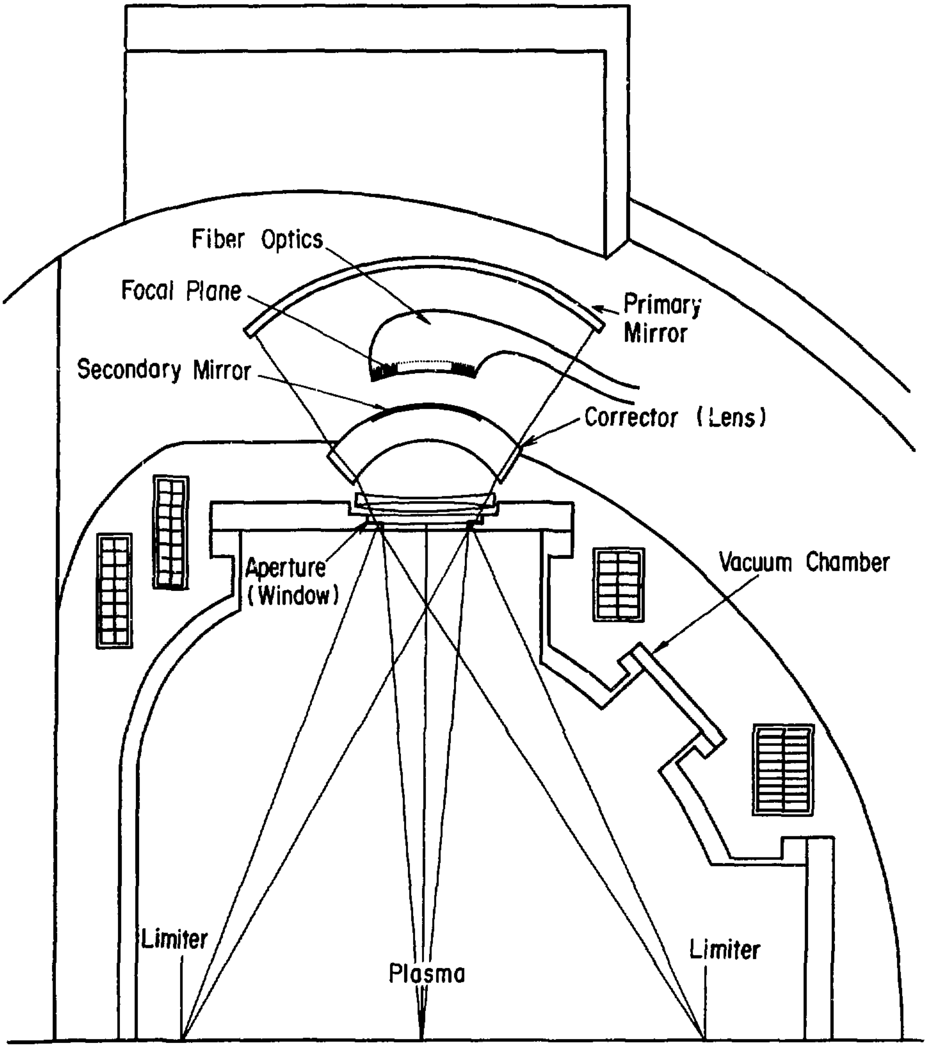

Fig. 1 Cross-section of JFT-2M showing the proposed Thomson scattering collecting optics.

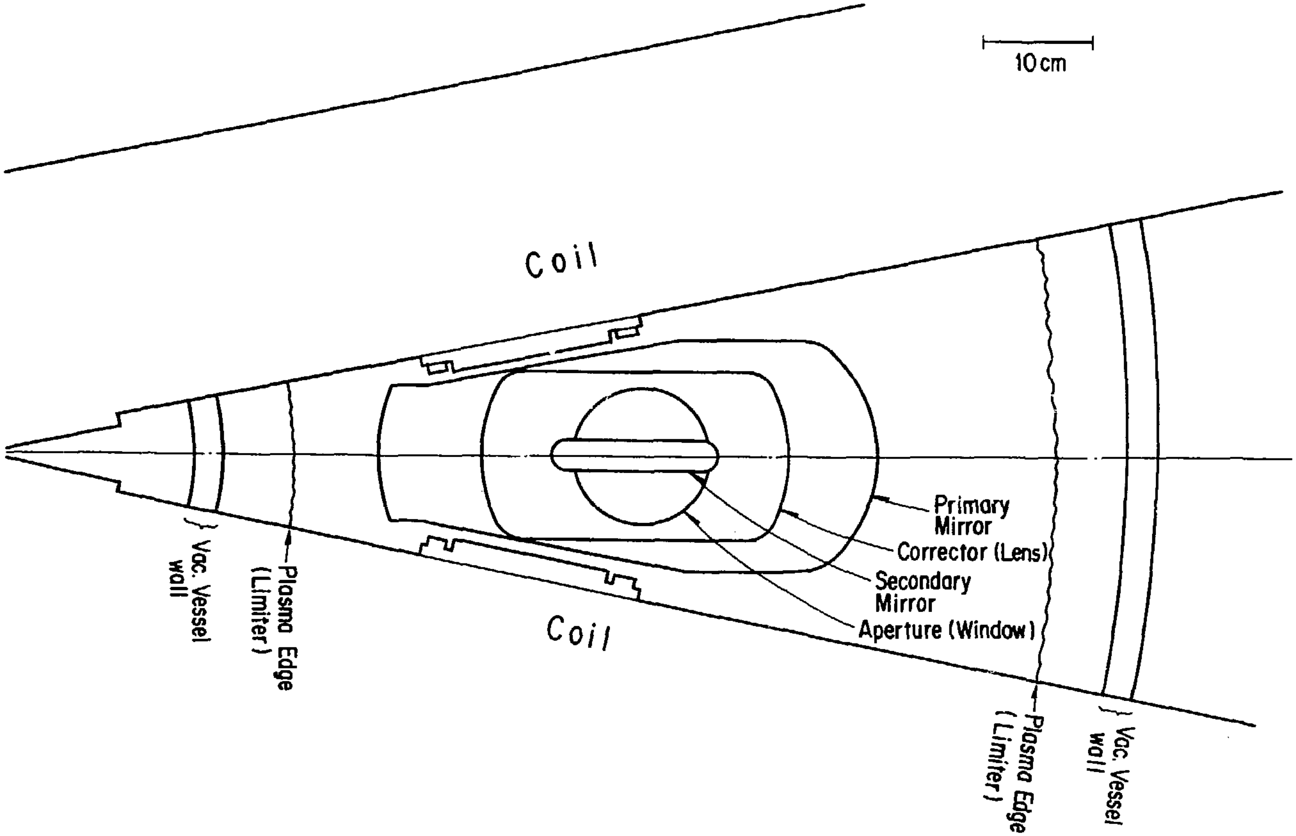

Fig. 2 Top view of a JFT-2M port, and the proposed Thomson scattering collecting optics.

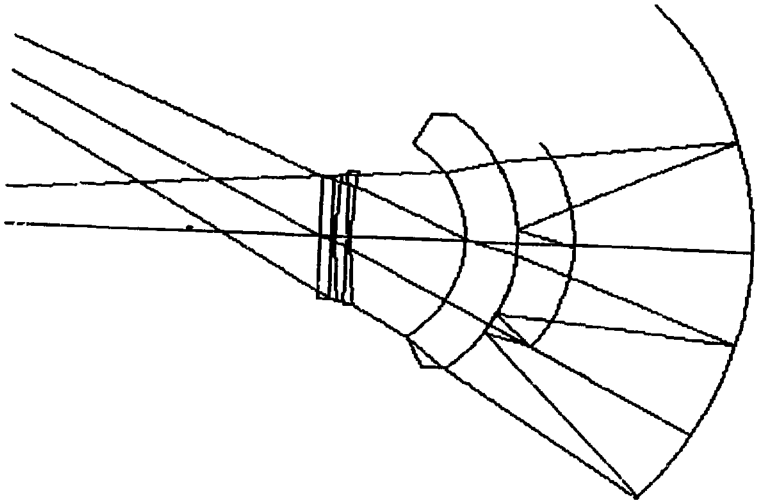

Fig. 3 Ray trace diagram of the collecting optics. (Side view).

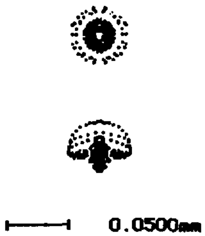

Fig. 4 Spot diagrams of the focus on the axis, and at the extreme end of the focal plane.

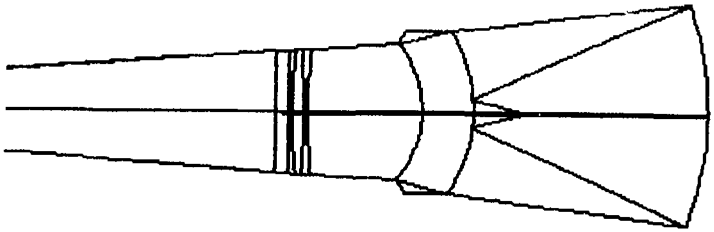

Fig. 5 Ray trace diagram of the collecting optics. (Cross-section).

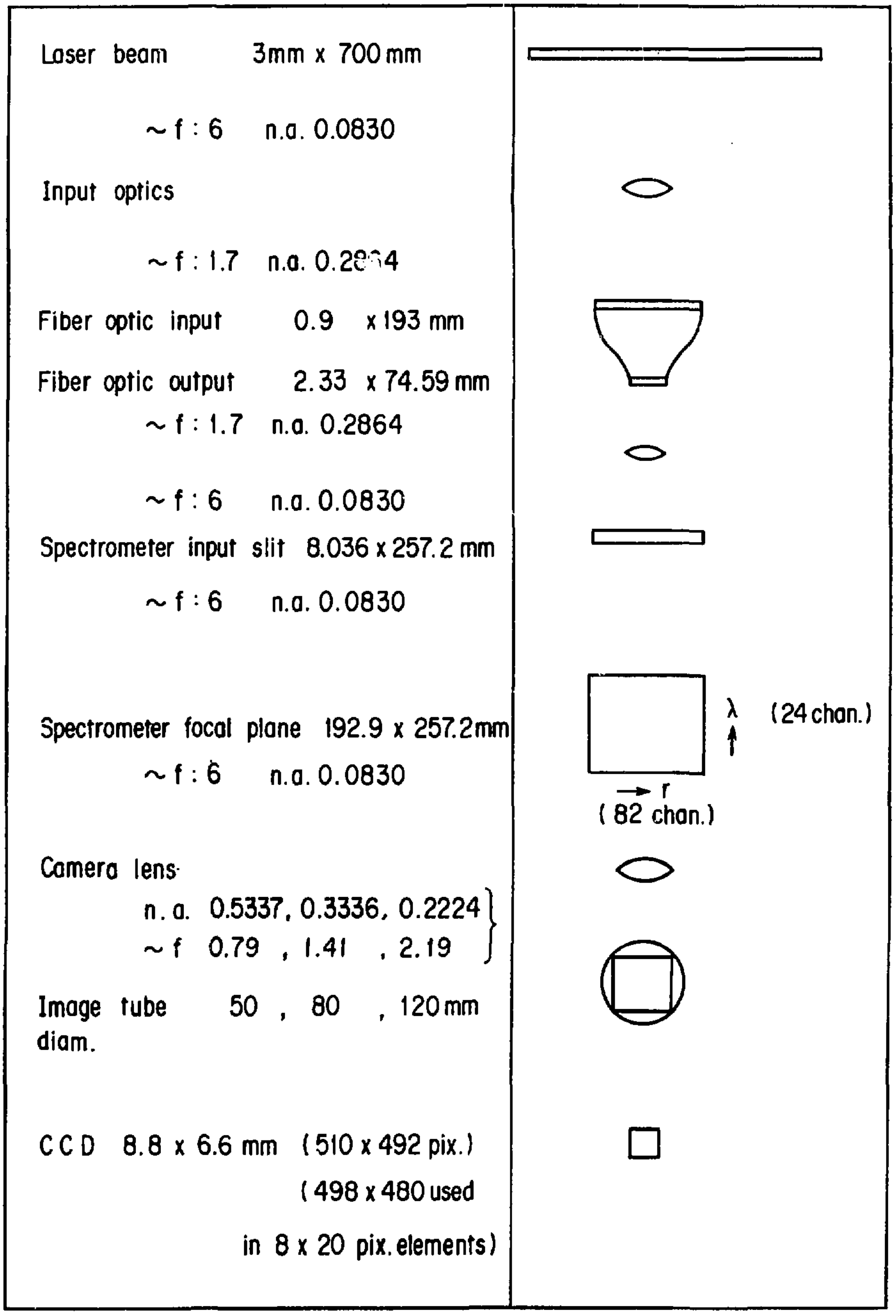

Fig. 6 Areas and solid angles through the one spectrometer system.

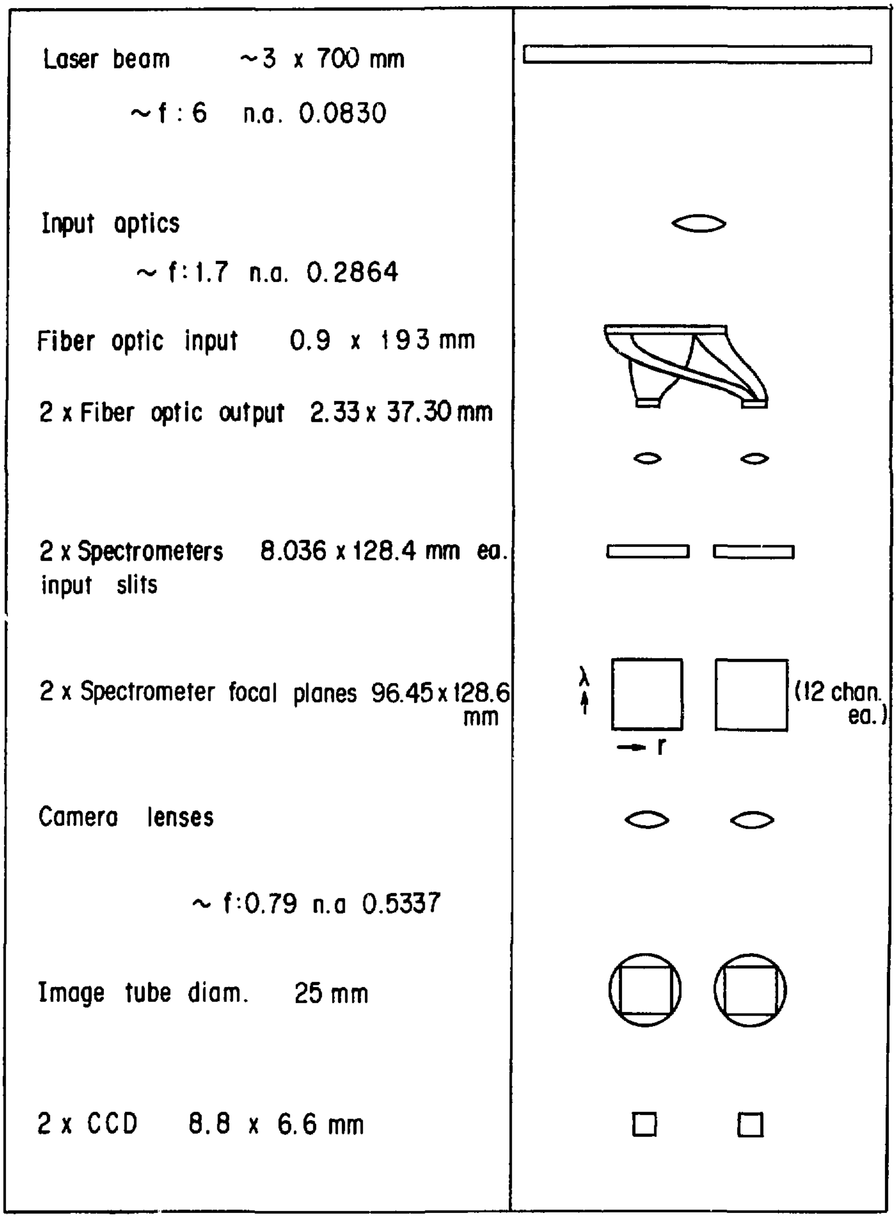

Fig. 7 Areas and solid angles through the two spectrometer system.

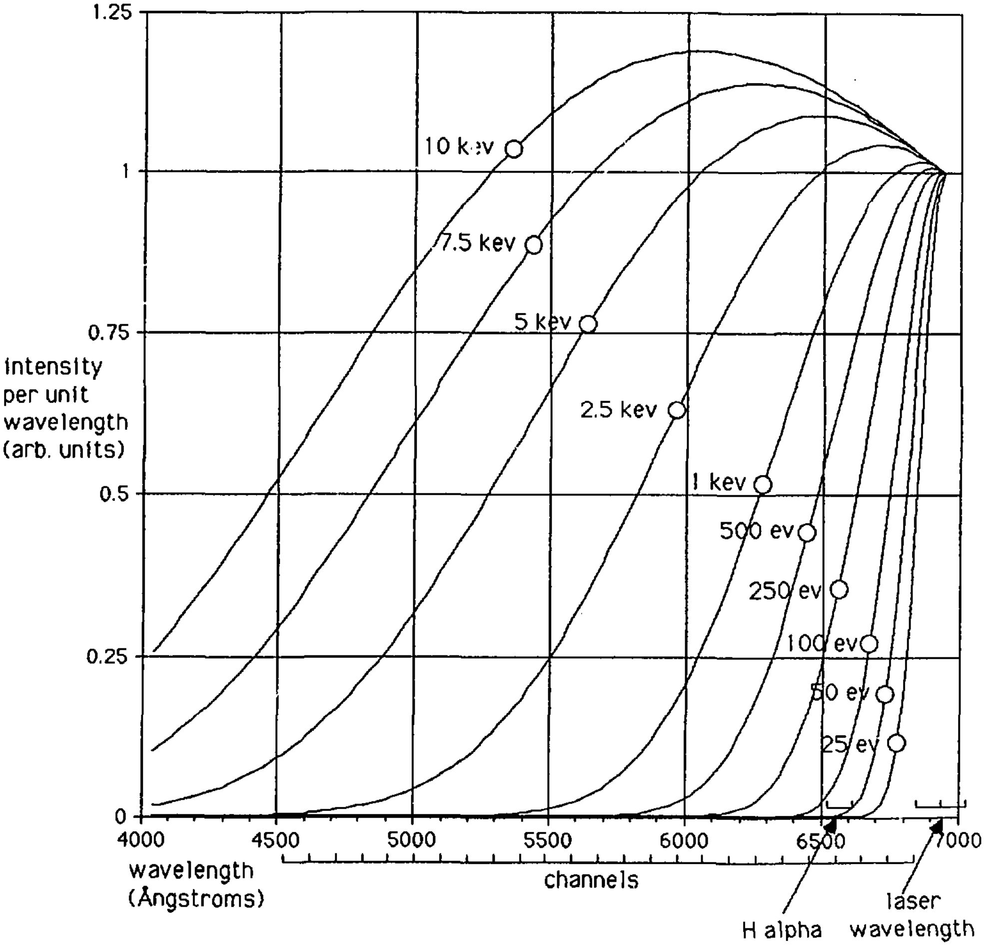

Fig. 8 The spectral distribution of right angle scattered light at a number of electron temperatures, showing the proposed spectral channels, and the ruby light and H alpha blocking regions (4000 to 7000 Å).

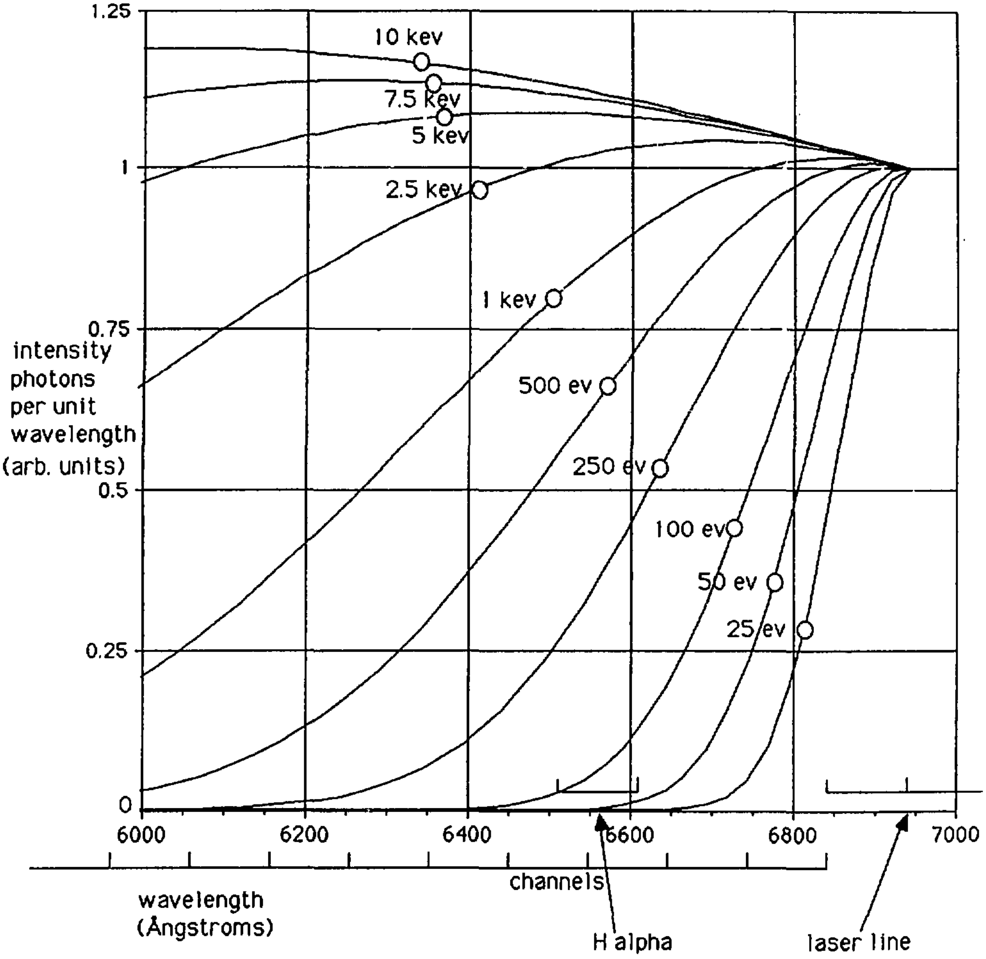

Fig. 9 The spectral distribution of right angle scattered light at a number of electron temperatures, showing the proposed spectral channels, and the ruby light and H alpha blocking regions (6000 to 7000 Å).

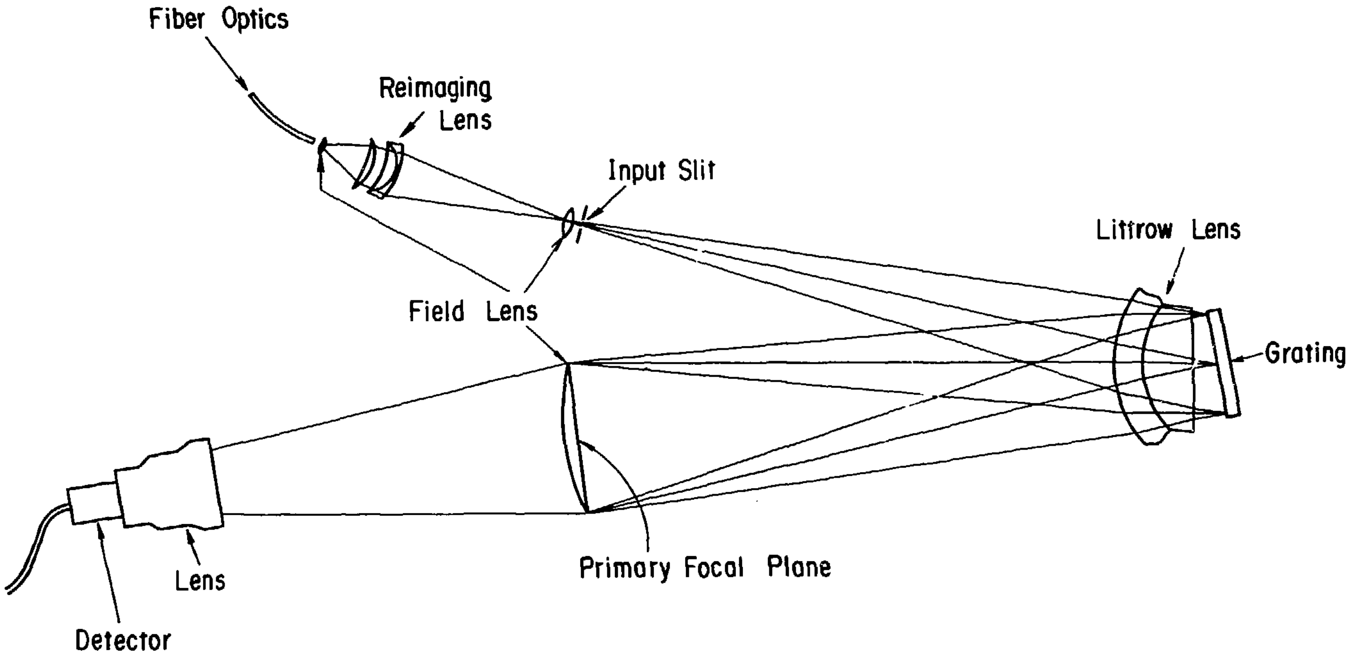

Fig. 10 A possible spectrometer design, using a hemi-concentric achromatic Littrow lens.