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A TRIPLE GRATING POLYCHROMATOR FOR THOMSON SCATTERING*

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Abstract

A high rejection, high transmission, triple grating polychromator with crossed dispersion has been designed and constructed for Thomson scattering plasma diagnostics. Identical gratings, collimating, and field lenses were used for all three stages. A mechanically convenient arrangement was made possible by using the field lenses to adjust the dispersion of the second stage to the required design value. The transmission in the pass band for light polarized perpendicular to the rulings of the grating was measured at 33% for the instrument itself, and at 15% through the instrument and six feet of attached fibre optics. With the 30 nm pass band set at 4 to 34 nm wavelength away from the ruby laser line, the order of 10^{-11} of 694 nm light incident in the input slit was present in each 3 nm wide output channel giving a relative rejection factor of 10^{-10}.

Introduction

In Thomson scattering measurements of plasma temperature only about 10^{-13} of the initial ruby laser beam carries information to each spectral channel of the detecting equipment.[1] A very high degree of discrimination

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is required against the unshifted 694 nm wavelength of the ruby laser. For example, the design of the Tormac plasma vessel[2] at the Lawrence Berkeley Laboratory is such that a high level of the 694 nm wavelength light is scattered from the apparatus and mixed with the Thomson signal at nearby wavelengths. A solution to a similar problem with the SCYLLAC fusion device has been reported.[3] Siemon's method uses a three-stage polychromator with extreme rejection of stray light based on the vario-illuminator,[4] and eliminates the necessity of critically designed laser beam optics and beam and viewing dumps. As shown by Van Cittert and by Siemon this arrangement highly discriminates (by a factor of 10^3 to 10^4 per stage) against the unwanted stray light, giving overall a rejection of between 10^9 and 10^{12}.

The high rejection is a consequence of the condition that only light which is correctly dispersed by the first stage of the polychromator through the wide intermediate slit is recombined (so-called cross dispersion) by the second grating through a narrow slit between stages 2 and 3. Stray light which passes the wide slit does not satisfy this required dispersion condition and is diffracted by the second grating so as not to enter stage 3. Siemon's arrangement is much more effective than a wide pass band double or triple polychromator in which each stage further redisperses the light, and where all slits following the entrance slit must be wide. For this case stray light adjacent to the pass band emerging from the first stage is only slightly shifted in relative position by subsequent stages but still mostly passes through the instrument, giving an overall rejection comparable with a single stage alone.

The instrument described below is based also on the varioilluminator principle. It possesses the considerable constructional advantage that all three stages are essentially identical. Each stage uses the same type of high efficiency replica reflection grating in conjunction with a collimating lens in a near Littrow mounting. A convenient layout of gratings and lenses is made possible by appropriate positioning of the interstage field lenses, which additional to their relay function are used to adjust the dispersion of the second stage to produce the requisite accurate spectral recombination at the narrow slit between stages (2) and (3). Without these field (relay) lenses, severe losses of light would occur by vignetting. The field lenses are placed close to the interstage slits and focus the collimating lens of stage (1) on that of stage (2) and similarly that of (2) on (3). They thus ensure that any light leaving one collimating lens and passing through the interstage slit is incident on the next collimating lens.

The layout of the polychromator is shown in Fig. 1. It should be noted that the field lenses are axially displaced 7.6 mm away from the slits to correct the dispersion of stage (2) to the required design value in a way which is analyzed in the next section.

Spectral Dispersion and Recombination

The relation (see Fig. 2) between the incident angle α, and the first order diffracted angle β, for light of wavelength λ nm striking a plane grating with g grooves per mm is given by

$$\sin \beta_1 = - \sin \alpha_1 + 10^{-6} \lambda g \tag{1}$$

The angular dispersion (for constant α) is

$$\frac{\partial\lambda}{\partial\beta_1} = 10^{6} g^{-1} \cos \beta_1 \text{ nm per radian} \tag{2}$$

If in the near Littrow mounting a collimating lens of focal length f_1 mm is used, we get to a close approximation a linear dispersion

$$\frac{1}{f_1}\ \frac{\partial\lambda}{\partial\beta_1} = \frac{\partial\lambda}{\partial x} = 10^6\ (g\ f_1)^{-1}\ \cos\ \beta_1 \text{ nm per mm} \qquad (3)$$

where $dx = f_1\ d\beta_1$ = linear displacement in the focal plane in mm.

For spectral recombination in the second stage of the instrument we require a constant value of the diffracted angle β_2 for the dispersed light having varying angles of incidence α_2. Thus for a collimating system of focal length f_2 mm in the second stage we have for the required dispersion at the input slit to stage 2

$$\frac{\partial\lambda}{\partial x} = \frac{1}{f_2}\ \frac{\partial\lambda}{\partial\alpha_2} = 10^6\ (g\ f_2)^{-1}\ \cos\ \alpha_2 \qquad (4)$$

Matching these dispersions (3) and (4) we get the condition

$$\frac{f_2}{f_1} = \frac{\cos\ \alpha_2}{\cos\ \beta_1} = \frac{\cos\ 28.60}{\cos\ 20.76} = 0.939 \qquad (5)$$

where α and β are given the values used in our instrument. Thus for f_1 = 260 mm we require f_2 = 244.1 mm.

Adjustment of the Dispersion by Use of a Field Lens

As a much less expensive and more convenient alternative to obtaining the collimating lens of precisely 244.1 mm focal length required to satisfy equation (5), we have used in our instrument the same readily obtainable 260 mm focal lens as in stages (1) and (3), and displaced the field lenses adjacent to slits (2) and (3) to give an equivalent condition. With the arrangement shown in Fig. (3) consider a light ray travelling back from grating 2 through the collimating lens and field lens to slit (2). The optical transfer matrix M from the grating to the slit is given by

$$(M) = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \begin{pmatrix} 1 & a \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -S & 1 \end{pmatrix} \begin{pmatrix} 1 & b \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -P & 1 \end{pmatrix}$$

$$= \begin{pmatrix} 1 - aS - bP - aP + abPs & a + b - abS \\ -S - P + bSP & 1 - bS \end{pmatrix} \tag{6}$$

Where a and b are the distances shown in Fig. 3 and P and S are the powers at the collimating and field lenses. A ray with displacement y mm and angled at ϕ radians to the optic axis at the collimating lens will arrive at the plane of the slit with a displacement x mm and an angle θ radians where

$$\begin{pmatrix} x \\ \theta \end{pmatrix} = (M) \begin{pmatrix} y \\ \phi \end{pmatrix} = \begin{pmatrix} m_{11}\, y + m_{12}\, \phi \\ m_{21}\, y + m_{22}\, \phi \end{pmatrix}$$

A parallel beam of light (constant ϕ, variable y) incident on the collimating lens will focus to the point $x = m_{12}\phi$ in the plane of the slit if $m_{11} = 0$ that is if

$$m_{12} = a + b - abS = \frac{1 - aS}{P} \tag{7}$$

Using the condition in eqn. (7) we then have

$$x = m_{12}\phi = \frac{1 - aS}{P}\,\phi = f_2\phi$$

where f_2 is the ratio between the angular and linear dispersion as used in euqations (4) and (5). We thus obtain

$$a = \frac{1}{S} - \frac{Pf_2}{S} = 7.64 \text{ mm}$$

$$b = \frac{1}{P} + \frac{1}{S} - \frac{1}{PSf_2} = 251.86 \text{ mm}$$

$$a + b = 259.50 \text{ mm}$$

where $\frac{1}{P}$ = 260 mm, $\frac{1}{S}$ = 125 mm and f_2 = 244.1 mm as used in our design.

Input Mirrors and Output Fibre Optics

The ruby laser beam travels horizontally through the TORMAC plasma vessel where a plasma volume 30 mm long, 3 mm diameter scatters light by 90° in the horizontal plane into the polychromator. A collection lens system forms an image of the scattering volume 10 mm high 1 mm wide after a double reflection from two mirrors each at 45° to the vertical which are immediately before the entrance slit. The two reflections combine to give a 90° reflection in the horizontal plane and to rotate the image and the light polarization by 90° to match the polychromator input slit.

The diffraction gratings are blazed to have an efficiency of over 80% in first order for light horizontally polarized (that is perpendicular to the rulings), and an efficiency of about 50% for vertical polarization. The efficiency is expressed as a percentage of the reflection from an aluminum mirror (90% reflectivity). Overall the polarization properties of the polychromator are an advantage as they effectively halve the unpolarized background plasma light without the introduction of a separate polarizer into the system.

The polychromator output light focusses onto a 10 mm x 10 mm close packed array of plastic light guide fibres, each approximately 1 mm diameter, set in a black epoxy resin. The fibres are separated at their output ends to give 10 bundles each of 10 fibres, and thus 10 channels each 3 nm wavelength wide, appropriate to the measurement of electron temperatures from 30 to 300 eV.

The light channels are detected singly or in pairs by photomultiplier tubes at the end of the fibre optics.

Performance of the Polychromator

The focussing settings of the collimating lenses, and lateral positioning of the field lenses were first adjusted with the gratings replaced by aluminized mirrors set at appropriate angles, using a high intensity white light source. Under these conditions it is also easy to locate the images of the slit formed by reflections from the front and back surfaces of the collimating lenses (together with the field lenses) and to block this stray light by positioning thin black wires. The image in white light at the final slit after the third stage was blurred to less than 0.1 mm, which is consistent with the measured 3 seconds of arc resolution of the main lenses.

With the gratings in place and adjusted in angle to transmit 694 nm, light of this wavelength was made incident on the input slit by the use of a 2 nm wide spike filter and a white light source. The measured transmission through the instrument plus six feet of fibre optics was 15%. We estimated the fibre optics packing fraction as 0.9, a transmission of 0.9 per foot, and an input and output factor due to reflection losses of 0.9, thus an overall factor of $(.9)^8$ = 43% as the fibre optics transmission. If we take the transmission to first order of each grating as 74%, and of each lens surface as 99% we get the transmission of the polychromator itself as $(0.73)^3 \times (.99)^{16}$ = 33%, and including the fibre optics as 0.33 x 0.43 = 14% in close agreement with the measurements.

For the rejection measurements the polychromator was adjusted to transmit a band from 690 to 660 nm and to reject 694 nm. A free running ruby laser suitably diffused by a ground glass screen was fired into the monochromator. The output was then compared to the input after it was attenuated by a neutral density N.D 10 filter. After allowance for the filter transmission at 694 nm, and the polychromator transmission factor (15%) these measurements showed a relative stray light reduction of between 10^{10} and 2×10^{10} for all channels. It has been pointed out to us by R. E. Siemon that it would further reduce stray light if the second field lens was placed on the other side of the slit between stages 2 and 3. As this slit is narrow, no effective change in dispersion would result, and the effect of scattering from-the surfaces of this lens would be reduced.

The transmission of the polychromator for light polarized parallel to the rulings was less than 2%. Thus the instrument also performs as a polarizer, reducing the background plasma light by a factor close to 2.

Possible Developments

Some improvement in performance would still appear possible. Holographic gratings exist which have considerably less scattered light than the replicas of machined ruled ones, together with high efficiency in a wide pass band.[5] All collimating and field lenses could be coated to give less than ½% reflectivity. Overall it would appear that a three grating instrument could be constructed with over 50% transmission in the pass band for favorable polarization, and a rejection factor approaching 10^{12} for light outside this band. Although our instrument has a 3 nm wavelength resolution defined by the fibre optics, the final image is blurred to less than 0.1 mm, giving a resolution capability of 0.3 nm wavelength with suitable fibre optics. This could no doubt be improved by more careful optical design. It would be simple to add two or more stages of similar design to our device and thus improve the rejection to 10^{16} or more and still retain a reasonably high transmission.

Acknowledgements

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Figure Captions

Fig. 1. Diagrammatic layout of the polychromator showing the relative positions of the input mirror system, slits, collimating and field lenses, gratings and the output fibre optics.

Fig. 2. Crossed dispersion with angles of incidence α and angles of diffraction β, with collimating lenses of focal length f_1 and f_2. The focal (slit) plane displacement is x.

Fig. 3. The use of a field lens (Power S) to control the dispersion produced by the collimating lens (Power P). The lens power is defined as the reciprocal of its focal length.

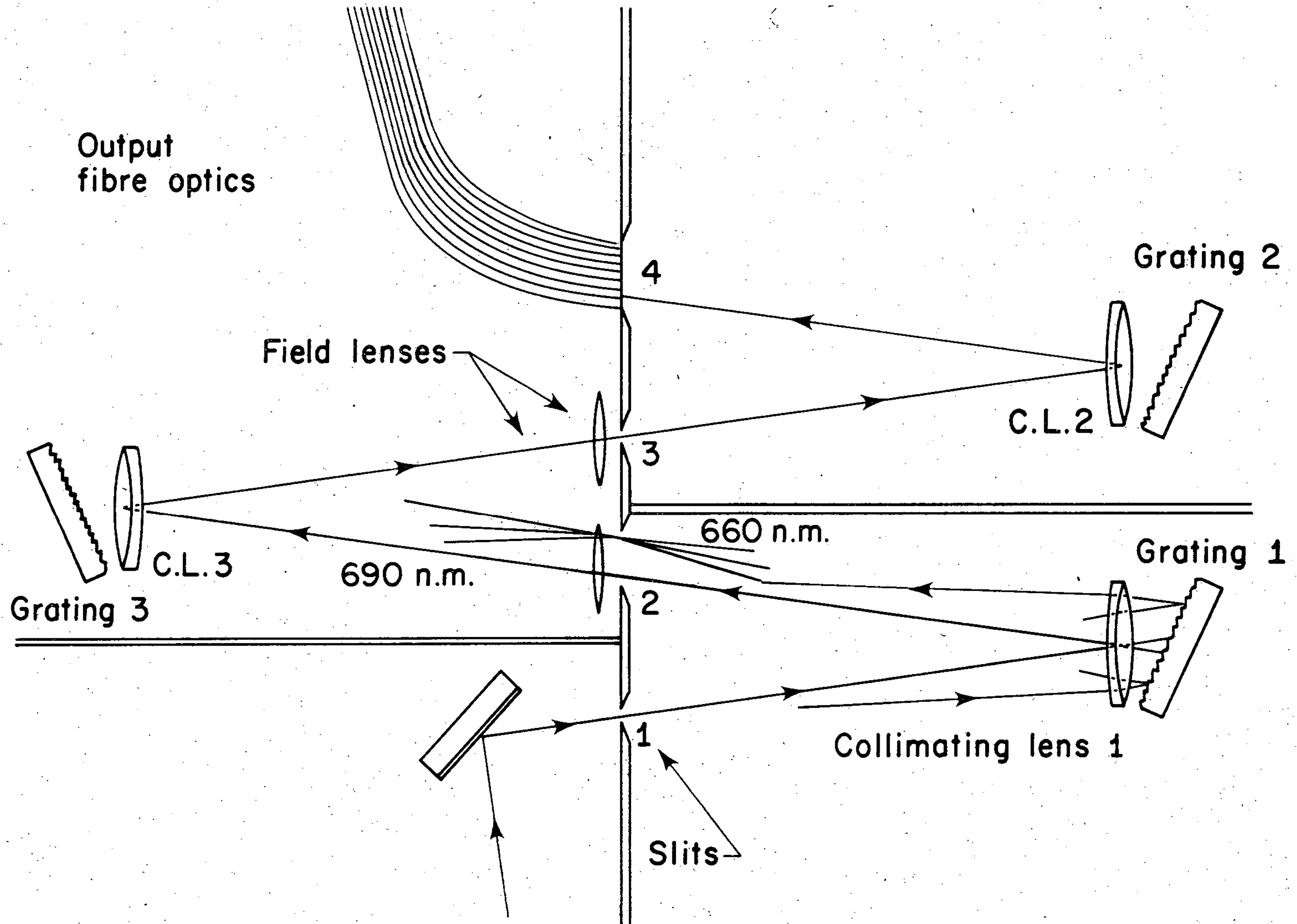

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Figure 1

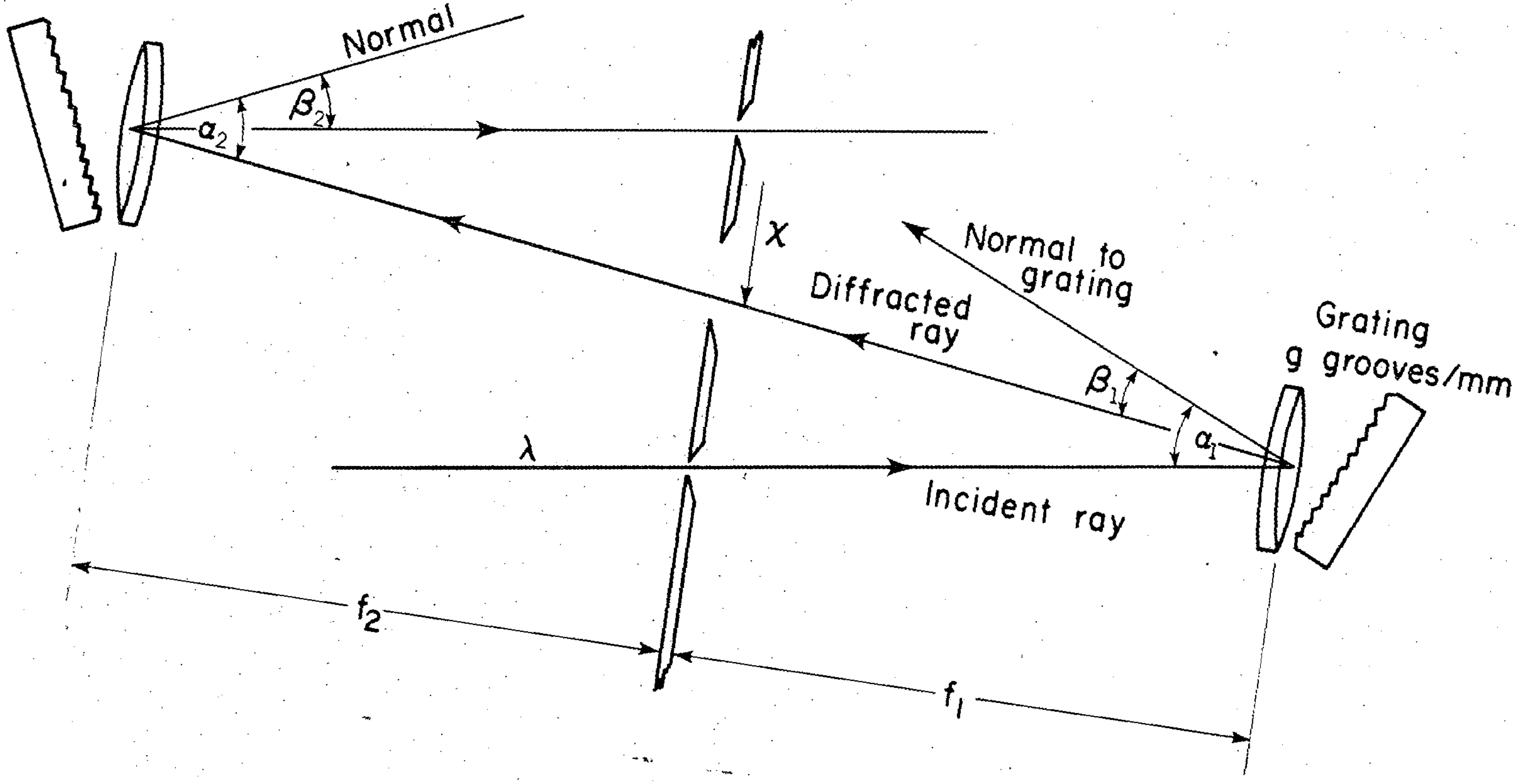

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Figure 2

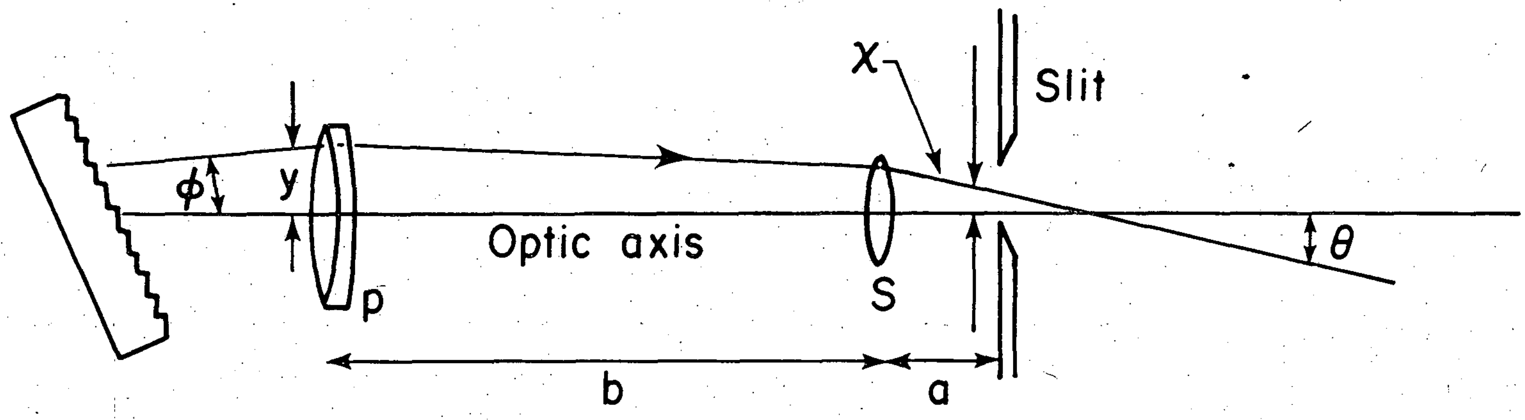

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Figure 3

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