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A MINIATURE FIBRE OPTICTS OBSERVATION SYSTEM FOR ENCLOSED PLASMA MACHINES

D. E. EVANS
I. K. PASCO

Culham Laboratory
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I.K. PASCO

ABSTRACT

This paper describes an observation system consisting of a miniature lens and fibreglass image conduit assembly which permits the measurement of radial luminosity distributions in cylindrically symmetric plasmas, when the configurgation of current-carrying conductors makes the plasma inaccessible to conventional high speed photography techniques. Density profiles obtained with the assembly are indistinguishable from those measured by the usual method.

U.K.A.E.A. Research Group,
Culham Laboratory,
Abingdon,
Berks.

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1. INTRODUCTION

A technique for measuring the radial density distribution in an optically thin, cylindrically symmetric plasma, based on the observation of the visible continuum radiated, has been described by Dancy and Keilhacker (1965) and McLean (1967) and has been extensively employed in the study of theta-pinch discharges (Beach et al. 1969). It has been restricted to situations in which the plasma is capable of being viewed through a slot whose length is not less than the plasma diameter and whose orientation is perpendicular to the plasma axis. This paper describes an extension of the method to discharges where the current-carrying conductors that generate the magnetic field confining the plasma almost completely enclose the vessel containing the plasma. An observation system, consisting of a miniature lens and fibre-glass image conduit assembly, is inserted through a small diameter tunnel in the conductor so that the lens is adjacent to the transparent wall of the vacuum vessel, and the opposite end of the image conduit protrudes into the laboratory where its face can be observed. In this way, the luminosity distribution of the plasma becomes accessible to measurement while the perturbation to the confining magnetic field is minimized.

2. PRINCIPLE OF THE NEW SYSTEM

The method of operation of the new observation system can best be understood by comparison with the conventional method. Assume an optically thin, cylindrically symmetric plasma whose axis coincides with the z-axis of a rectangular coordinate system and let the visible continuum emitted in the x-direction be recorded. Then the observed intensity will be a function of y only, $I(y)$, and the dependence of the plasma luminosity on radius r can be recovered by performing an Abel transform on $I(y)$, see for example Griem, (1964), and Dancy and Keilhacker (1965).

In the conventional method, shown schematically in figure 1(a), a lens images the $y - z$ plane on to the photocathode of an image converter camera. The plasma, represented by the circle on the left of the diagram, can be thought of as divided by a system of chords parallel to the x-axis, and the light emitted in the x-direction from between a neighbouring pair located at y and $y + \Delta y$ reaches the image plane between ξ and $\xi + \Delta\xi$. The slot near the plasma through which this light passes, can thus be regarded as divided by the chords into a sequence of imaginary apertures, each aperture serving to transmit light only from between the pair of chords that define it. This is of course an idealization only realized when the lens is very far from the plasma. Our innovation consists in replacing the sequence of imaginary apertures which is the slot by a single real aperture, so that the set of parallel chords changes into a fan-like structure centred on the single aperture. This is shown in figure 1(b), where the small lens forms the only real aperture. Light emitted from the volume of plasma enclosed between pairs of chords like the pair shown, and parallel to them, converges in the focal plane of the lens at ρ. Just as in the conventional arrangement the raw observation consists of the distribution of projected intensity $I(y)$, so in this new system the raw observation is the focal plane intensity distribution $I(\rho)$. This can readily be transformed to a distribution in s, the distance from the pair of chords to the centre of the plasma, and the cylindrical symmetry of the plasma ensures that $I(s)$ is identical to $I(y)$.

In performing this transformation, allowance must be made for the reduction in illumination at ρ which occurs because the separation, t, between the pair of chords decreases as ρ increases. The measured intensity $I(\rho)$ is normalized to constant t by dividing it by $t = D\ (1 + \rho^2/f^2)^{-1/2}$, D being the diameter of the lens and f its focal length. The normalized distribution in ρ, $I_1(\rho)$, is converted to a distribution in s in the usual way by noting that

$$I(s)\ ds = I_1(\rho)\ d\rho$$

$$I(s) = I_1(\rho)\ \frac{d\rho}{ds}$$

where from $\rho = f \tan\varphi$ and $s = R\ \sin\varphi$ (R being the distance from the lens to the centre of the plasma) we have

$$\frac{d\rho}{ds} = \frac{f/R}{[1 - s^2/R^2]^{3/2}} \ .$$

3. <u>LENS AND IMAGE CONDUIT SYSTEM</u>

The hardware of the new system consists of a cylinder of coherent glass fibre light guide (image conduit) which will convey a light pattern imaged on one end to the other end with only a small loss in resolution and intensity. In the experimental arrangement used to investigate the feasibility of the method, the image conduit was 10 cm long and 3 mm in diameter and there were 75 individual quartz-clad fibres across the diameter. A simple converging lens whose focal length f and diameter D were each approximately equal to 3 mm was mounted in a collar which held it in such a position that the entrance face of the image conduit coincided with its focal plane. These parameters gave our system an overall acceptance angle of $\pm 25^{\circ}$, which meant that with the lens located a distance $R = 7$ cm from the centre of a theta-pinch plasma tube, a plasma 6 cm in diameter would be fully visible. The experimental layout was completed by imaging the back face of the image conduit onto the photocathode of an image converter camera by means of a lens which gave a magnification of 10. The photocathode was masked by a slit whose length was parallel to the y-axis and whose width served to determine the time resoltuion.

Distortion of the light distribution on the face of the image conduit is inevitable when a simple bi-convex element instead of a fully compensated lens is used in an F/1 situation, as it was here. The extent of the distortion could be observed and measured by observing a test card through the assembly. This was placed so far from the lens that the image and the focal plane virtually coincided. Test card photographs taken directly as well as through the lens and image conduit assembly are displayed in figure 2. The distortion which is revealed by this comparison could in principle be corrected by the addition of a second element to the lens, but here we have attemped to allow for its by multiplying the measured intensity distribution across the diameter of the image, $I(\rho)$, by a numerical factor which varies as ρ^2. This factor was arrived at by noticing that constant areas on the test card were reduced as the radius ρ was increased, thereby increasing the intensity of light per unit area of the image. The correction factor we applied had the form $(1 - \varepsilon \cdot \rho^2)$ where ε was constant which depended upon the details of our arrangement. Its effect was to reduce the observed intensity $I(\rho)$ by about 8% at the edge of the image.

4. EXPERIMENTAL COMPARISON

Two experiments have been carried out to compare the performance of the lens and image conduit assembly with that of the conventional optical system. In the first of these, an optically thin, cylindrically symmetric luminous plasma was simulated by a glass pipe filled with water in which a little white ink was suspended. This was flash-illuminated from one end and light scattered sideways through the cylindrical wall was photographed by each technique, and "plasma density" profiles were computed. The resulting "density" profiles are show in figure 3.

The second experiment made use of a real theta-pinch plasma in a single turn coil 20 cm long by 10 cm diameter which had a peak axial field of 10 kG. Here streak photographs were made with the image converter camera, using both the new and the conventional methods, and density profiles were computed. The results are displayed in figure 4.

The error bars ordinarily displayed on density distributions measured by this technique, for example, by Beach et al (1969), are composed of two independent parts, namely one part which expresses the uncertainty in normalizing the data to a specific plasma density, and one part which describes the fluctuation of the points about a mean curve. That the former is much the larger of the two is shown by the presence of large error bars attached to points whose deviation from a mean curve is nevertheless relatively trivial. In making a comparison between our technique and the conventional one, we considered that only the statistical or shape determining errors were significant, and we ignored the normalization error. In fact, statistical errors are very small, and we forbore to plot them at all. On the other hand, some difficulty in assigning a precise radius scale to the density profile was encountered, and we accordingly show a measure of uncertainty in the value of the abscissa which stems from this.

In both figures, the points in the distribution measured by the lens and image conduit assembly preserve to a high degree the profile defined by the conventional technique. That the distribution shape is not determined by instrumental effects is shown by the fact that a flat distribution with a sharp edge is reproduced just as accurately as a distribution which peaks in the middle and falls monotonically with increasing radius.

5. CONCLUSION

The lens and image conduit assembly described in this paper makes it possible to take streak photographs of a plasma, which, owing to the arrangement of surrounding coils and shells, would otherwise be inaccessible to conventional streak photography. It has been demonstrated that the resulting luminosity distributions can be analysed to obtain density profiles of the plasma which are indistinguishable from those obtained by the usual method.

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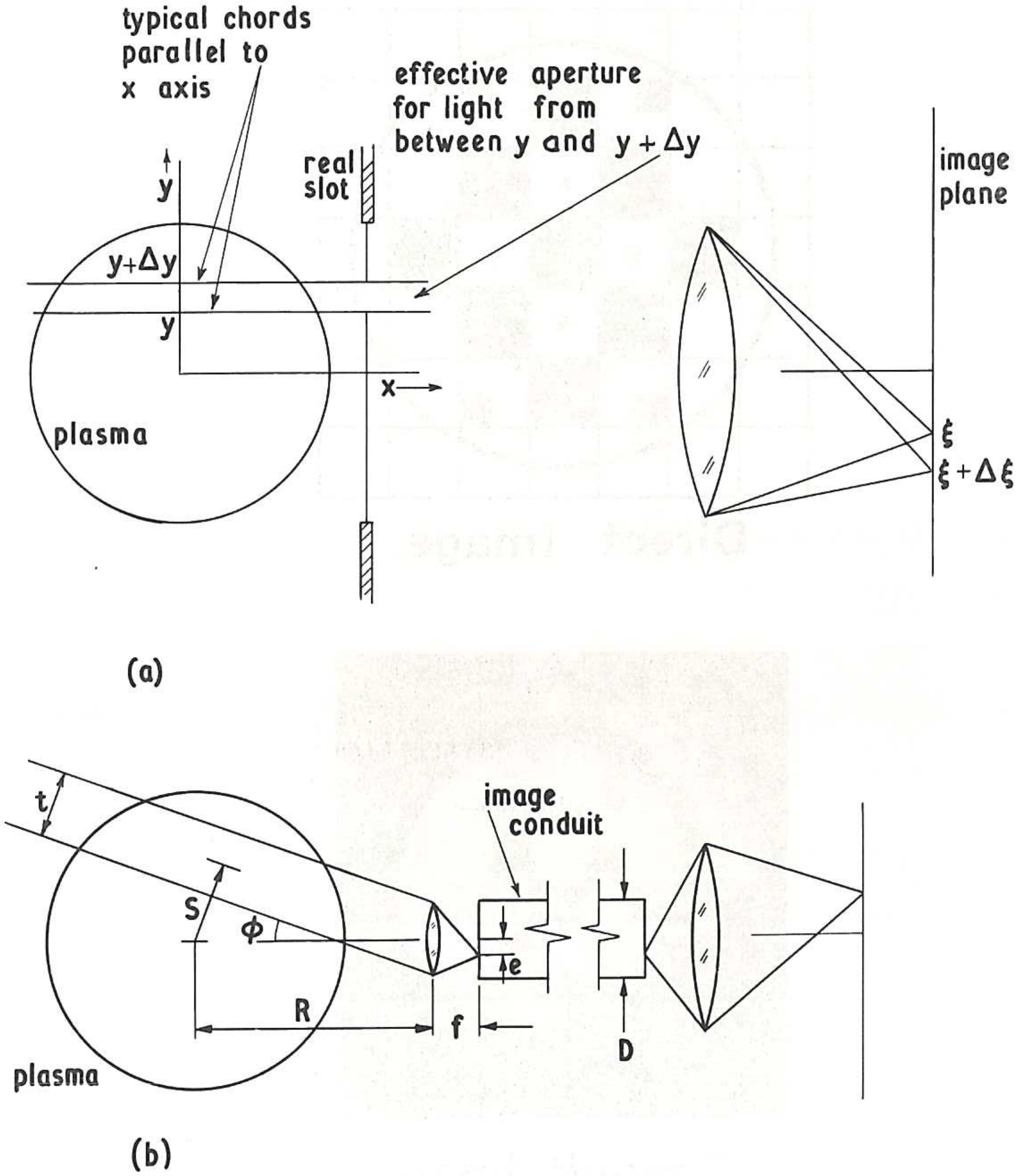

Fig.1.(a) Optical arrangement conventionally employed in making streak photographs of cylindrically symmetric plasma. The mid-plane (y-axis) of the plasma is imaged by the lens. The separation between the lens and the plasma is so great that a point on the image is illuminated by light travelling effectively parallel to the x-axis.

(b) Lens and image conduit assembly. Face of image conduit is a focal plane of the lens and light brought to a focus a distance ρ from the centre of the conduit comes from a plasma region enclosed between parallel chords making angle ϕ with the x-axis.

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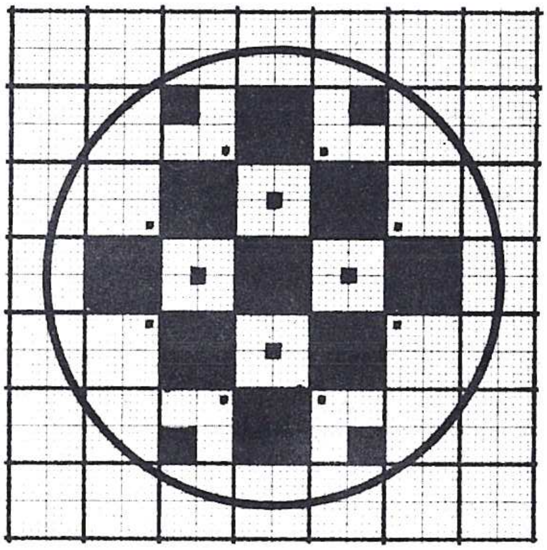

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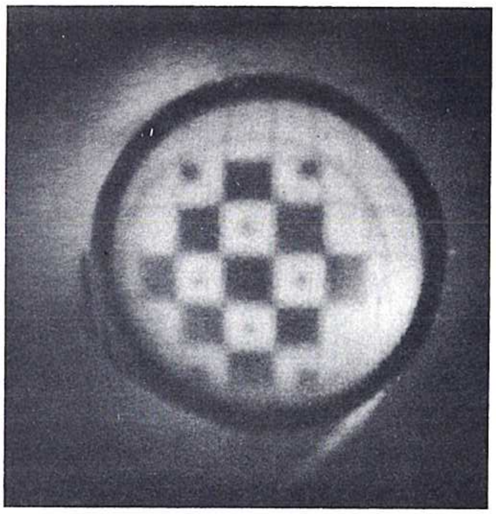

Conduit Image.

Fig.2 Resolution and distortion in image conduit. A test card photographed directly, and through lens and conduit assembly.

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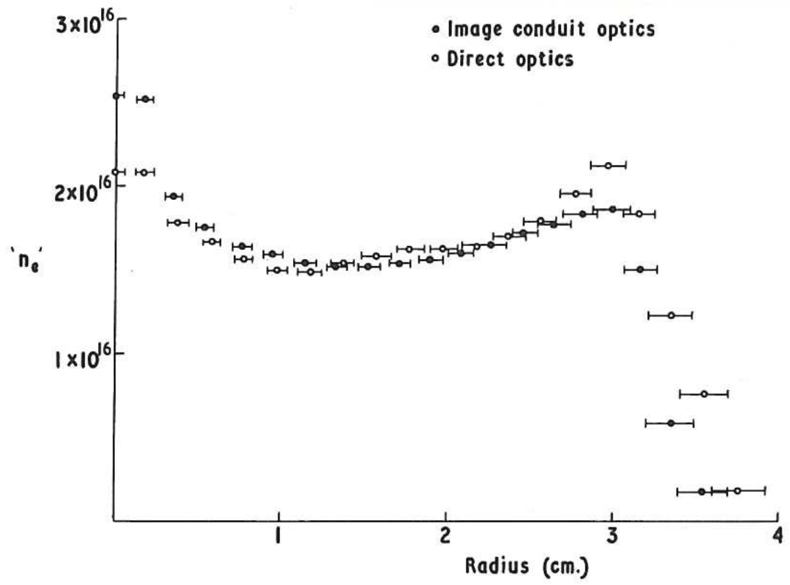

Fig.3 Mock plasma 'density' profile obtained by conventional technique (open circles) is compared with the same profile obtained through lens and image conduit assembly (full circles).

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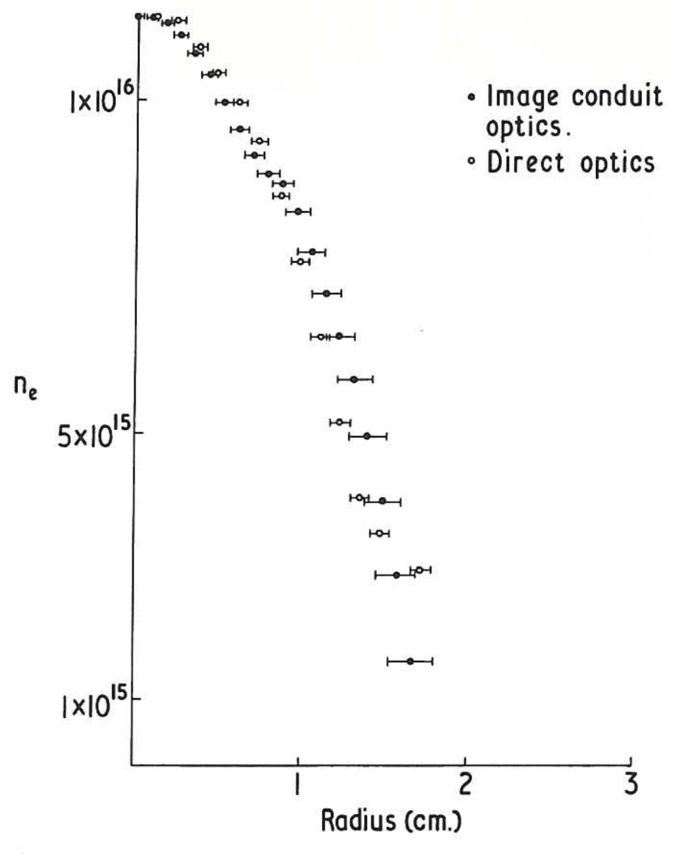

Fig.4 Theta-pinch plasma density profile observed by conventional technique (open circles), compared with profile observed through lens and image conduit device (full circles).

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