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ABSTRACT

The surface temperature of a diagnostic probe and the target plate of the DITE bundle divertor, has been measured using an infra-red scanning camera. From the surface temperature measurements the incident energy flux on the surface is calculated.

The spatial distribution of energy on the divertor target plate is non-uniform and the maximum energy flux is received near the centre line and the inside edge of the plate. The energy input to the plate reaches a maximum near the end of the discharge pulse.

The energy flux to a probe has been obtained as a function of radial position in the shadow of a standard probe limiter. The diagnostic probe receives energy mainly at the beginning and end of the discharge for a normal pulse.

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INTRODUCTION

The measurement of surface temperatures during the discharge pulse of fusion experiments is a valuable aid in the study of the surface interactions. In particular, the quest for low z_{eff} plasmas makes it essential to identify the mechanisms responsible for the introduction of impurities into the plasma and surface temperatures must be known in order to distinguish between evaporation, desorption and sputtering. By making time and space resolved temperature measurements, the magnitude and distribution of the energy flux can also be calculated, which is an important factor in the overall energy balance of a plasma discharge. A method of reducing the plasma wall interactions in the torus is to use a magnetic divertor which allows the plasma to be guided out into a separately pumped chamber. A bundle divertor [1] has been incorporated in DITE [2] and measurements of the energy flux to the target plate of this divertor have been made as a function of time and space. The AGA infra-red scanning camera [3] has the required accuracy, spatial and temporal resolution for making such measurements, with the advantage of not disturbing the experimental environment and avoiding the problems associated with exposing sensors to regions of high energy flux. In this paper measurements of the temperature and energy flux to the divertor target plate and to a probe in the torus are described.

EXPERIMENTAL TECHNIQUE

The infra-red camera uses a mechanical scanning system, which in the normal scanning mode produces a 100 line raster every 60 ms. This time resolution can be improved by stopping the vertical scan prism and continuously traversing a selected line across the surface. From these continuous temperature profiles, individual profiles can be selected by the method previously described [4] which consists of counting line scans with a multi-channel timer. Surface temperatures can then be measured at the times pre-set by each channel. The present system with the camera in the continuous line profile mode allows a maximum of 14 temperature profiles to be stored at any time during the DITE discharge with individual point temperature measurements separated by a minimum of 0.6 ms.

Since the intensity of the radiation from the surface depends on the surface emissivity as well as its temperature, it is necessary to measure the emissivity preferably immediately before or after a discharge, since changes in the condition of the surface with time will occur. For both the divertor target plate and the probe measurements therefore, a heated reference cavity of known emissivity and temperature was provided near the region of interest. Thermocouples were also necessary for the steady state temperature measurement of the surfaces. The emissivity of the surface is given by:

$$\varepsilon_s = \frac{\Delta_{is} + \varepsilon_r(I_R - I_a)}{I_s - I_a} \qquad (1)$$

where Δ_{is} is the difference in radiation intensity between the surface and the reference, ε_r the reference emissivity and I_R, I_s and I_a the radiation intensity of the reference, surface and surroundings respectively, which are obtained from the camera calibration and the steady state temperatures.

THE ENERGY FLUX COMPUTATIONS

The surface temperature $\theta(t)$ for an energy flux $F(t)$ per unit time per unit area for a semi-infinite solid has been given by Carslaw and Jaeger [5]:

$$\theta(t) = \frac{\kappa^{\frac{1}{2}}}{K\pi^{\frac{1}{2}}} \int_0^t F(t-\tau) \exp\left(-\frac{x^2}{4Kt}\right) \frac{d_t}{\tau^{\frac{1}{2}}} \qquad (2)$$

For the surface temperature, x=o, (2) becomes:

$$\theta(t) = \frac{1}{C} \int_0^t F(t-\tau) \frac{d\tau}{\tau^{\frac{1}{2}}} \quad \text{where } C = \sqrt{K\pi\rho c}$$

where K is the thermal conductivity, ρ the density and c the specific heat of the material used. A computer program is then used to evaluate F(t), using a value of C for molybdenum of $3.24 \times 10^4 \mathrm{J m^{-2} K^{-1} s^{-\frac{1}{2}}}$.

THE DIVERTOR TARGET PLATE MEASUREMENTS

A schematic diagram of the DITE bundle divertor is shown in Figure 1. When the target is in its normal position orthogonal to the flux lines, it is not possible to view the plate with the I.R. camera. For the measurements described here a special pair of molybdenum plates each 273 x 130 x 1mm thermally isolated from each other were placed in the divertor chamber at 45° to the normal position, enabling the whole face of one plate to be viewed through a 50mm diameter sapphire window. The plate nearest the camera, plate B, was provided with a heated reference cavity thermally isolated from the plate itself and placed on the centre line near the outside edge. Small holes on the outside edge were provided to enable line scans to be located precisely in the vertical direction. In addition to the reference cavity thermocouple, three other thermocouples were connected to the plate for steady state measurements and one thermocouple was connected to plate A.

Figure 2 shows the plate mounted in the divertor chamber during a discharge, the reference cavity and the location holes can be seen. The inset Figure 2b shows an infra-red picture of the plate obtained with the current in an anti-clockwise direction using the camera in the framing mode. Figure 3 shows two line scans across the target plate in the line profile mode. Figure 3a is on the centre line with the plasma current clockwise and Figure 3b 17mm above the centre line with the current reversed. Each profile represents a scan across the divertor plate at the times given, where t=o is the start of the plasma current pulse. The edges of the plate are indicated at the bottom of each series. The large signal on the right side of Figure 3b indicates the location hole 17mm above the centre line and is due to a difference in emissivity and not temperature. It is evident from these two examples that the energy is arriving late in the discharge pulse and that the anti-clockwise case, where the plate is facing the ion drift direction, has a more uniform temperature distribution.

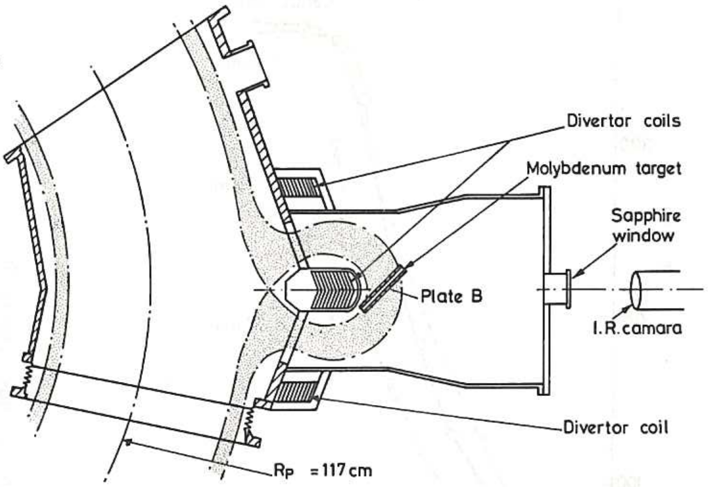

Fig.1 A schematic diagram of the DITE divertor

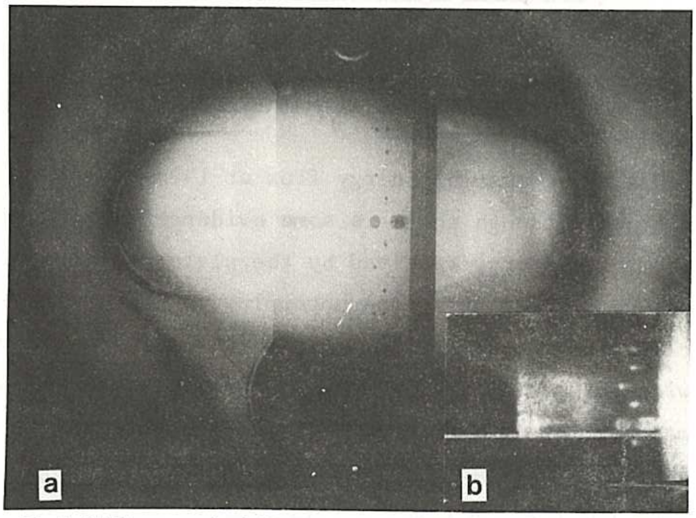

Fig.2 (a) Photograph of the divertor target plate during the discharged viewed through the sapphire window. (b) An infra-red video recording of the plate during the discharge

Figure 4 shows the time dependence of the maximum surface temperatures measured along a horizontal line, for several different vertical positions, from 51mm below the centre line to 17mm above. These temperatures are used to compute the energy flux shown in Figure 5. The energy deposition is very localised and the flux reaches a maximum late in the discharge. Since each position represents a different discharge, the time of this maximum does not vary appreciably. Figure 6 shows a similar energy flux vs time plot for plasma current in the anti-clockwise direction computed from the temperature profile scans. The energy flux is however lower than in Figure 5 and with a more uniform distribution. A similar late arrival of the energy is however still present.

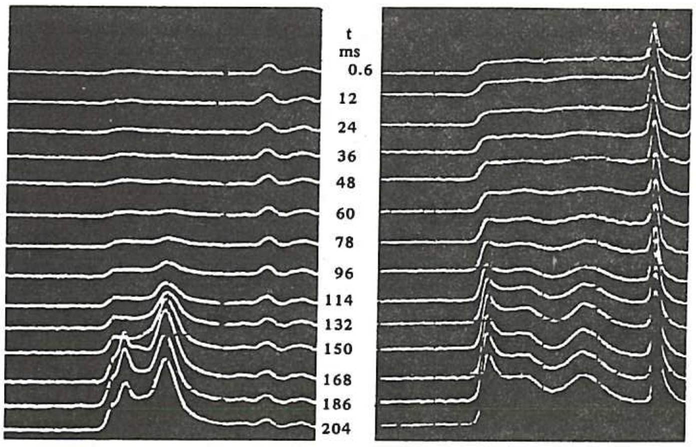

Fig.3 Radiation profile scans across the divertor plate at the times specified. (a) Plasma current clockwise. (b) Plasma current anti-clockwise

For all these results the plasma current remained substantially constant for 200 ms with a constant divertor coil current from the start of the discharge for

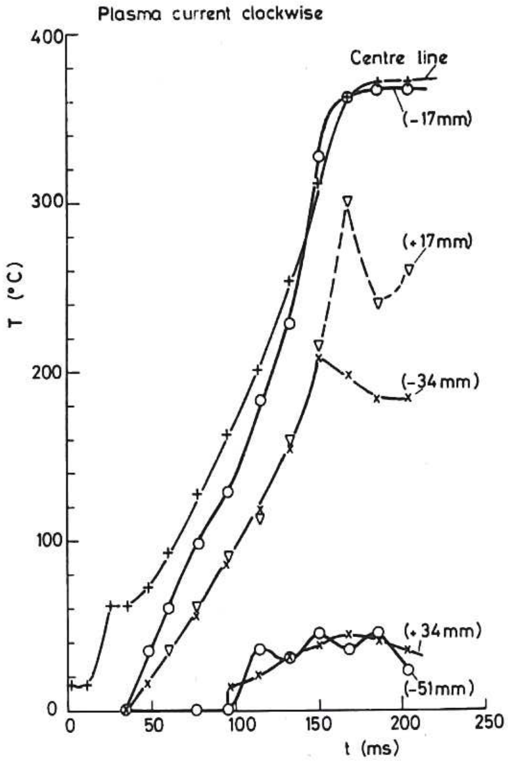

Fig.4 The maximum surface temperature across the plate at different vertical positions with respect to the centre of the plate, plasma current clockwise

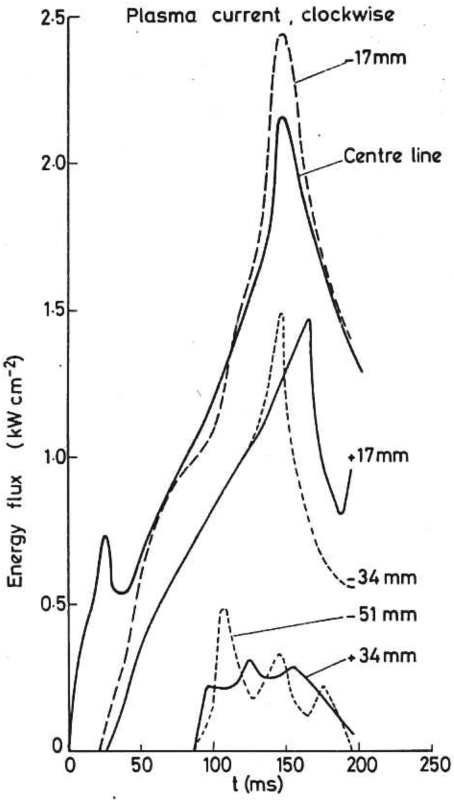

Fig.5 The energy flux to the target plate at different vertical positions obtained from the data in Fig.4. Plasma current clockwise

190ms. The maximum energy flux at 150ms for both current directions has not yet been explained although there is some evidence that runaway electrons may be partly responsible. The total energy received by the plates was 15% of the I^2R power of the DITE discharge. This was determined using thermocouples to measure the bulk temperature rise of the plates with clockwise plasma current. This is less than the value of 50% determined using thermocouples with the plates in the normal position, since at 45° the plate intercepts fewer divertor magnetic field lines and energy flux contours plotted for this position show that high energy flux regions terminate on the inside edge of the plate. Integration of the energy flux for plate B gives a total energy in good agreement with the value obtained from thermocouple measurements.

THE DIAGNOSTIC PROBE MEASUREMENTS

The surface temperatures of a 38mm diameter molybdenum probe as a function of its radial distance from the centre of the plasma, have already been reported[4]. Figure 7 shows a schematic diagram of the experimental arrangement used for making these measurements. From these surface temperatures the energy flux has been calculated. Figure 8 shows the energy flux as a function of radius with a standard probe type limiter at a radius of 18cm. These measurements can be compared with the energy flux $\frac{1}{2}\ n_e\ V_s E$ (Table 1), where n_e, the electron density, is obtained from microwave interferometer measurements, E the electron energy is obtained from Thompson scattering, and V_s is the ion sound speed. In order to maintain an ambipolar flow to the limiter a sheath will form in front of the limiter which will repel the electrons and accelerate ions. This ambipolar flux will have a velocity of the order of the ion sound speed and $V_s = (\frac{2kTe}{Mi})^{\frac{1}{2}}$. Although such good numerical agreement between the measured flux values and those calculated by this simple model may be fortuitous, it does show the expected agreement in the radial dependence.

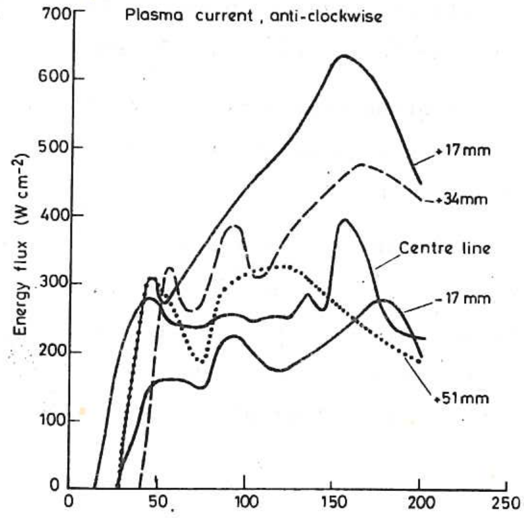

Fig.6 The energy flux to the target plate at different vertical positions with respect to the centre, plasma current anti-clockwise

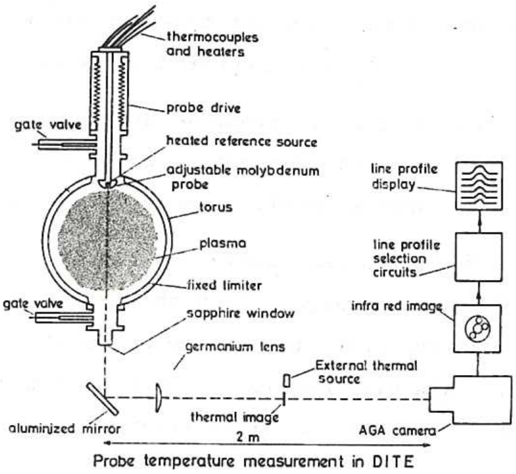

Fig.7 A schematic diagram of the arrangement for measuring the surface temperature of the diagnostic probe

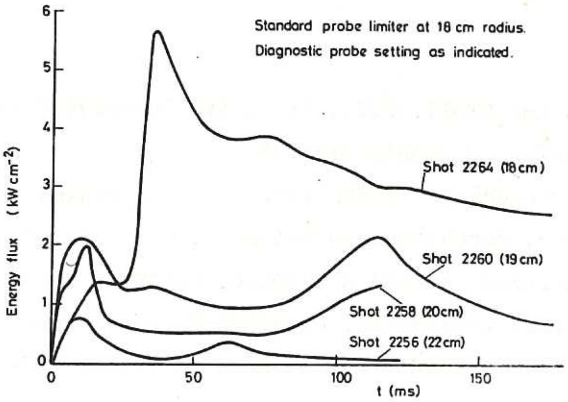

Fig.8 The maximum energy flux to a probe during a discharge. The curves correspond to different radial positions of the probe behind a standard probe limiter

Table 1

Radius (cm)	$n_e(10^{18}$ $m^{-3})$	T_e(ev)	$\frac{1}{2}nV_sE$ watt cm^2	Measured flux watt cm^{-2}
18	6.2*	110	1750	3870
19	5.5	85	875	950
20	4.5	65	475	500
22	2.4	35	100	150

*Disruption for this particular discharge makes density measurements difficult.

CONCLUSIONS

The divertor target plate measurements show a non-uniform energy deposition with an energy flux exceeding 2.5 kW cm^{-2}. With the target plate in the inclined position, high energy regions reach the edge of the plate. It is therefore desirable to repeat the measurements with a wider target plate which intercepts all the diverted plasma. Further investigation is also required to determine the cause of the late arrival of the energy.

The diagnostic probe measurements in the shadow of a probe type limiter show an energy flux with a radial dependence which is consistent with particle flux calculations. A scrape off layer approximately 5 cm thick was observed behind the probe limiter.

The infra-red camera has proved to be a useful method for surface temperature measurement although analysis from photographically recorded waveforms is time consuming. It is intended therefore to develop a computer data acquisition system to store and process the data. This will enable the number of measurements during the discharge to be increased, resulting in more accurate energy flux calculations and energy contour plotting.

ACKNOWLEDGEMENTS

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