TIME-RESOLVED MEASUREMENTS OF THERMAL LOADS ON THE FTU LIMITER

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ABSTRACT

A methodology for measuring instantaneous thermal loads on a portion of the Frascati Tokamak Upgrade (FTU) poloidal limiter was developed; such a methodology is based upon the processing of experimental data recorded by thermocouples and an infra red detector. By a proper calibration procedure, the instantaneous surface temperature of a portion of the limiter can be obtained; the de-convolution of the time-resolved limiter surface temperature provides time-resolved thermal loads. In this paper the apparatus is described and some examples of elaborated data are given.

INTRODUCTION

Many aspects of tokamak operation are strongly related to physical phenomena occurring in the edge plasma region [1]. Here, the presence of a high temperature plasma directly facing material structures (limiter, first wall) also points out important questions about the life and the behaviour of materials used at present in tokamaks and tested for a future tokamak reactor. High power fluxes (tipically 1- 10 MW/m2) deposited onto plasma facing components can lead to local melting or sublimation. In any case the direct measurement of thermal fluxes and surface temperatures is important to define the stresses in the materials and to get information about phenomena of impurity production mechanisms (sputtering, evaporation) which influence the plasma discharge. Surface temperature and thermal flux measurements by means of infrared detectors have been already performed on several limiter tokamaks; on FTU, because of its compact design, the difficulty to set up a thermography has lead first to measure thermal fluxes and surface temperatures by means of thermocouples embedded in the limiter material or flush mounted. Embedded thermocouples cannot provide time-resolved measurements, since their global time response depends on the thermal inertia of the surrounding material; flush mounted fast response thermocouples provide data with a good time resolution (generally tens or hundreds of ms), which anyway cannot be sufficient to study fast heat transients; moreover they are rapidly damaged by local high fluxes during hard plasma disruptions.

I. EXPERIMENTAL APPARATUS

The FTU limiter is composed of two AISI-316 austenitic half rings (inner and outer limiter, 2 cm radial thickness; 3.5 cm toroidal thickness); 22 inconel 'mushrooms' (diameter ranging between 3.4 and 6.8 cm; 1 cm radial thickness) are assembled upon the two half rings and face the plasma directly; 8 thermocouples are placed inside 8 different limiter mushrooms in order to measure the temperature increase after a plasma discharge. An infrared detector was placed on the limiter vertical port in order to measure the average surface temperature of the lowest inner limiter mushroom during a plasma discharge (Fig. 1); this was the only possible choice according to the machine compact design and the limited number of ports (12) already

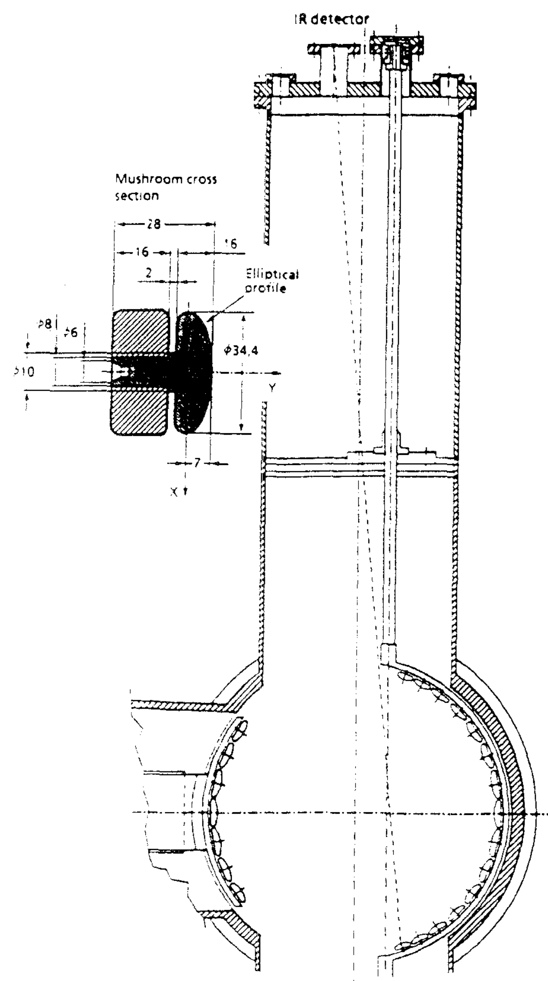

Fig. 1 FTU poloidal section in correspondance of the limiter; poloidal cross section of the lowest inner mushroom

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used for other diagnostics.We used a HgTeCd photoconductive probe with a time response of about 0.01 ms and working in the range 2-5 mm wave length. The optical system is made of one 1" diameter, 1" focal length lens. The measurement chain is composed of a preamplifier, a low-pass filter and a data acquisition system (DAS). The preamplifier was placed very close to the detector in order to reduce the electronic noise due to the high stray magnetic field (up to 1 T) of the tokamak magnets; the signal is sampled every 30 ms from t= -5 s to t=+25 s (the shot starts at t=0).

II. DETECTOR CALIBRATION

The apparatus was tested in the lab, where we reproduced the same geometry of the FTU apparatus but we replaced the mushroom with a black body. A calibration curve, i.e., a relationship between the blackbody temperature and the detector output voltage was found; to get the FTU calibration curve we combined together the detector signal, the temperature signal measured by the thermocouple embedded in the mushroom and the results of a simulation of heat transfer in the limiter mushroom obtained by a 2-D finite element code [2]. Simple edge plasma modelling [1] shows that the thermal flux on the surface of the limiter mushroom during the plasma shot (1 s roughly) is given by

$$P(y) = P \exp(-y/\lambda_E) \qquad (1)$$

where P is a normalisation factor, y is radial depth in the edge plasma region measured from y=0 at the last closed magnetic surface and λ_E (energy decay length) characterises the spatial shape of the thermal flux. The simulation shows that 25 s after the discharge start the mushroom surface temperature is uniform and practically the same as the one measured at the thermocouple location. Therefore the detector signal measured at t = 25 s corresponds to the temperature of the embedded thermocouple; then the calibration curve obtained with the black body is scaled until the experimental points fit the curve itself; in this way we get that experimental points fit the curve within an uncertainty of about $\pm$ 20 K. This procedure allows to overcome the non avalaibility of a limiter mushroom in the lab and allows to check the global reliability of the measurement chain, since a unique calibration curve is obtained for different shots.

III. DATA ELABORATION

A. Temperature measurements during a shot

The spatially-averaged surface temperature can be determined by taking into account that the thermal flux onto the limiter mushroom is not spatially uniform. By means of eq. (1), the spatial profile of the thermal load can be obtained for a given P value and for different λ_E values (Fig. 2 a). In the figure x=0 corresponds to the mushroom top, x=1.72 is the leading edge. For expected λ_E-values the maximum thermal load is near the mushroom leading edge. From a given spatial profile one gets, by means of the heat transfer code, the time-evolution of the surface temperature profile during the shot (Fig. 2 b); then, by taking into account that the detector signal is roughly proportional to the fourth power of the absolute temperature and to the corresponding surface element area, one gets the spatial profile of the thermal energy radiated by the mushroom surface; this is proportional to the amplitude of the detected signal (Fig. 2 c). Finally, one can estimate the surface portion from which the radiated energy comes (Fig. 2 d).

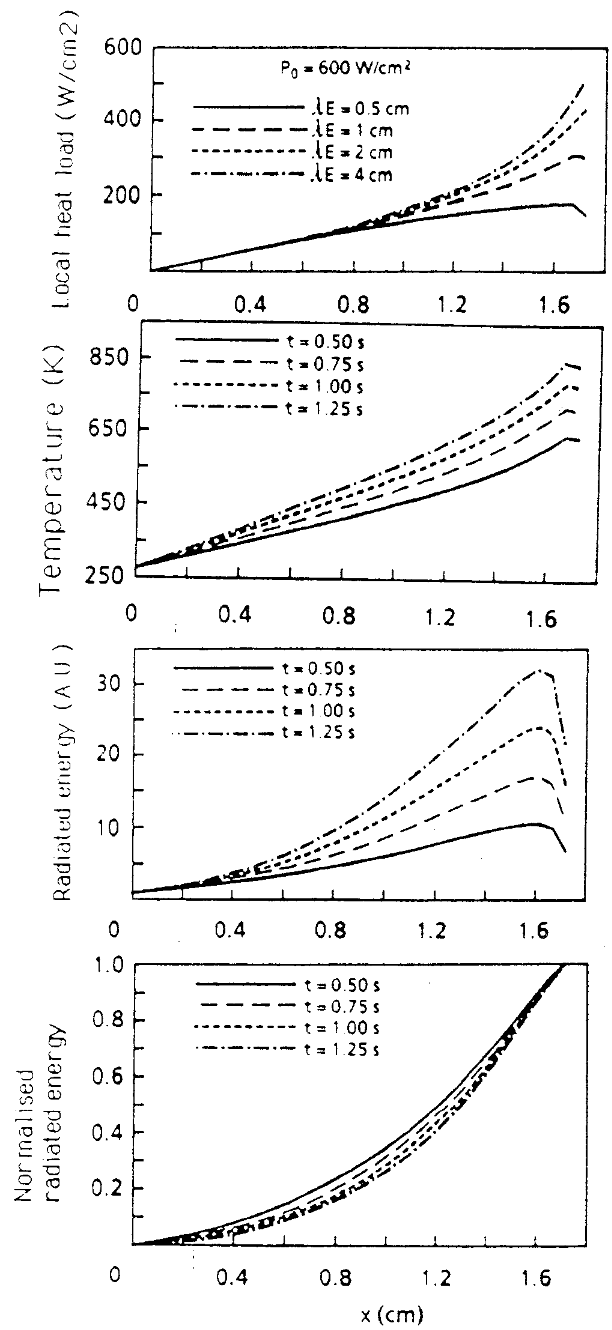

Fig. 2 From the top: Mushroom thermal load profiles; time evolution of surface temperature profile; radiated energy profiles at different times; normalised energy radiated at different times. x=0 is the mushroom top and x=1.72 the leading edge.

For typical P and λ_E values about 90% of the thermal energy collected by the detector comes from 1/4 of the overall surface of the mushroom (approximately from x=0.6 to x=1.72); hence one assumes that the detected signal corresponds to the average surface temperature of this portion, thus neglecting the signal contribution due to the remaining mushroom surface.

B. Time-resolved thermal flux

It can be shown that during the shot the surface portion radiating most of the thermal energy can be approximated by a one-dimensional semi-infinite solid hit by a spatially uniform thermal flux; therefore, given the experimental surface temperature T(t) measured by the detector, the corresponding time-dependent thermal flux F(t) is given by the following convolution integral [3]:

$$F(t) = \frac{k}{(4\pi a)^{1/2}}\left(\int_0^t \frac{T(t)-T(\tau)}{(t-\tau)^{3/2}}d\tau + 2\frac{T(t)-T(0)}{t^{1/2}}\right) \qquad (2)$$

where k and a are the thermal conductivity and diffusivity of inconel respectively.

C. Examples of data

We show in Fig. 3 the result of a signal elaboration as above described: from raw data, by applying the calibration procedure and the de-convolution integral we get the spatially-averaged surface temperature and the corresponding thermal flux; surface temperature and thermal flux signals are compared with the signal of plasma

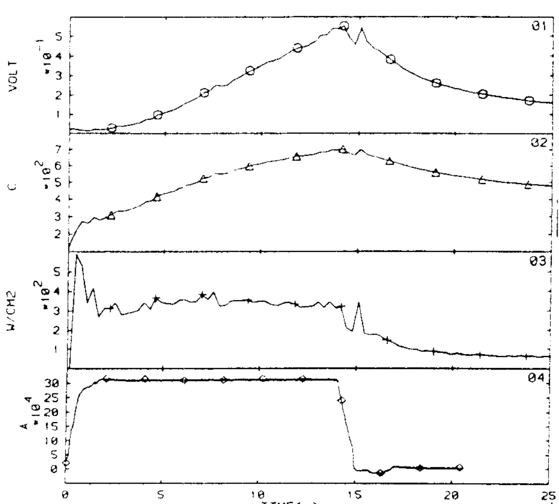

Fig.3 From the top: detector signal; time resolved mushroom surface temperature; time resolved thermal flux; plasma current.

current measured by means of a Rogowski coil: as expected, the surface temperature increases for the whole shot duration and suddenly decreases as soon as plasma current is shut down. During the current ramp-up (first 50 - 100 ms) one gets a peak in the measured thermal flux which is due both to the sudden mushroom heating because of the higher power injected in the plasma at the beginning of the discharge, and due to signal noises which cannot be completely eliminated and whose magnitude cannot be easily determined. One has to take into account that the detector is influenced by the induced magnetic field generated by the fast current variation in the central tokamak transformer during the first discharge phase; in this phase, being the mushroom relatively cold, the detector receives the minimum signal, so that the signal to noise ratio has the minimum value. As far as the measurement uncertainty is concerned, one can observe that during the current plateau phase the detected signal is much greater (tipically by a factor 1000) than the voltage fluctuations due to the electronic noise, and in this phase there are no current variations in the machine transformer which can noticeably perturb the detector signal; therefore the uncertainty is practically due to the corresponding uncertainties in evaluating the emitting area and the surface emissivity. Assuming that the relative error in evaluating the emitting area is 20% and the relative variation in the surface emissivity is around 30% in the whole temperature range, the relative uncertainty on the detected signal is around 50%; since the signal is proportional to the fourth power of the absolute temperature, the relative error on the latter can be assumed around 15%; this is also the uncertainty on the thermal flux measurement, since the relationship between temperature and thermal flux is linear. For the example given, the time-averaged thermal flux is around 4 MW/m2; in the first set of experiments we found time-averaged fluxes in the range 1-10 MW/m2, depending mainly on the power injected in the discharge, the radiated power and the relative distance between the inner limiter mushroom and the last magnetic closed surface; the results are consistent with those obtained by elaborating, in an independent way, the temperature signals of the embedded thermocouples. Fig. 4 shows the correlation between time fluctuations of surface temperature, thermal flux and the Nickel impurity content in the discharge measured by means of UV spectroscopy in the edge plasma region facing the lowest sector of the inner limiter. A detailed analysis (here not reported) of metallic impurities of different elements (Fe, Cr, Mn) which are present in the limiter alloy shows a similar result. This correspondence is general, that is the thermal flux time fluctuations always correlate to the fluctuations of metallic impurities. The phenomenon can be explained by assuming that if for any reason the metallic impurity content increases (as for example due to the sudden detachment of a metallic fragment from limiter or due to plasma displacement) the bulk plasma radiates more energy and therefore the power onto the limiter or onto a portion of it has to decrease. Moreover, by observing that the mushroom average temperature is too low to cause a surface melting, and that the duration of the phenomenon is about tens of ms, one can suppose that the

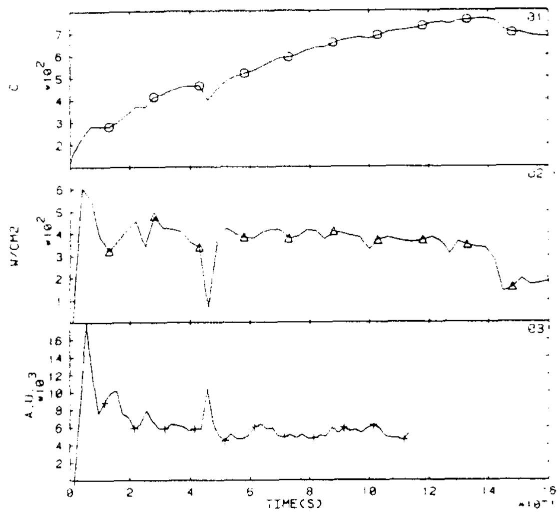

Fig. 4 From the top: mushroom surface temperature; thermal flux; Nichel XVIII line emission intensity.

most relevant mechanism for metallic impurities production is sputtering: in fact, in correspondence with a fast increase of impurity production, the bulk plasma radiates more energy so that the plasma edge temperature decreases; this leads to a lower sputtering yield and consequently to a decrease in the production of metallic impurities.

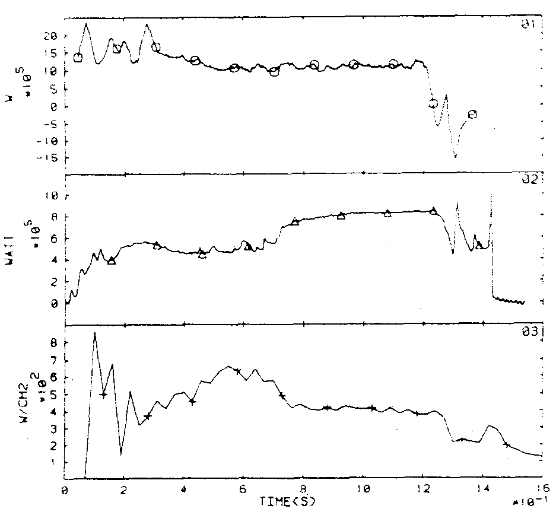

Fig. 5 From the top: total ohmic power; radiated power; thermal flux

The characteristic time of this feedback depends on the particle confinement time (1-10 ms) and is comparable with the duration of the observed phenomenon.
Finally, Fig. 5 shows on the same time scale the signals of the total ohmic power in the discharge, the power radiated from the bulk plasma measured by means of bolometry and the thermal flux on the limiter for an Argon injection experiment during the discharge; at t= 0.6 s from the beginning of the discharge the gas is puffed into the machine. A detailed analysis [4] shows that the effect of Argon is to recycle in the discharge and to enhance the radiation losses so that the thermal flux onto the limiter decreases; the decrease in the observed thermal flux is in good agreement with that predicted by an edge plasma model which fits the FTU parameters [5].

IV. CONCLUSIONS

A methodology for measuring time-resolved surface temperature and thermal flux onto a portion of the FTU limiter has been set up; this methodology is routinely used to infer time-resolved thermal flux data for FTU plasma discharges; it will also represent a valid bench-mark for the set up of a more complex thermography experience which is planned to get time and spatially resolved measurements of thermal fluxes over a wider portion of the limiter.

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References

[1] P.C. Stangeby and G.M. McCracken, Plasma boundary phenomena in tokamaks, *Nucl. Fusion* 30 (1990) 1225.
[2] G. Sewell, Analysis of a finite element method: PDE Protran, Springer Verlag, New York, 1985.
[3] H.S. Carlslaw, J.C. Jaeger, Conduction oh heat in solids, University Press,Oxford, 1973.
[4] I. Condrea, G. Franzoni, L. Pieroni, Effect of argon injection on the high Z impurity generation from the poloidal inconel limiter in FTU, *Nucl. Fusion* 35 (1995) 787.
[5] L. Pieroni, private communication.