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SCRAPEOFF LAYER STUDIES WITH AN INSTRUMENTED LIMITER*

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ABSTRACT

An instrumented limiter was used as a diagnostic to measure energy deposition and power fluxes in the scrapeoff layer. The limiter consisted of an array of 12 tiles, each equipped with a thermocouple. This arrangement represented a calorimeter array that yielded the total limiter energy and decay length of the power flux in the scrapeoff layer. Energy deposition and decay lengths are discussed for various plasma parameters.

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1. Introduction

Measurements of power fluxes to limiters and divertor plates are necessary for the design of these components and the determination of the energy loss channels of the plasma. Infrared cameras are very useful tools for measuring the surface temperature as a function of space and time and inferring corresponding heat fluxes. This technique is very powerful but also expensive, and it requires extensive data processing. A much simpler method for measuring power flux distributions on the limiter was explored during the beryllium limiter experiment in ISX-B [1]. In this experiment the limiter was fabricated of individual sections (tiles) that were separately bolted to a temperature-controlled ground plate. Each tile had a thermocouple embedded in its center to measure the bulk temperature. Thus the limiter represented an array of calorimeters. This arrangement did not allow for any time resolution of the power flux during the discharge, but it gave fairly accurate measurements of the distribution of the energy deposition on the limiters. Combining this method with infrared measurements of the surface temperature to obtain time resolution should result in a very reliable system to determine limiter loads and temperatures.

2. Experiment arrangement

Details of the limiter design have been described in a previous paper [2]. The horizontal rail limiter consisted of 12 tiles, each 2.5 cm wide, 10 cm long in the toroidal direction, and about 7 cm high in the radial direction. The front face was shaped to spread the plasma heat flow over a larger surface area. Figure 1 shows the configuration of the limiter and the shape of one tile [1]. The tiles were bolted to a 1.27-cm-thick stainless steel plate that was temperature controlled with an organic liquid [2]. The purpose was to keep the tile temperature at levels at which the ductility of beryllium was sufficiently high. In the present case, the coolant temperature was normally set at 200°C. For good thermal contact to the base plate, the tiles were bolted down with a spring loading of 440 N of force each.

The sheathed thermocouples had an outer diameter of about 1.5 mm and were located approximately in the center of the tile, 4 cm from the front surface. The thermocouple voltages were amplified with an array of isolation amplifiers and fed via transient recorders into a computer. Alternatively, for longer term observations, the amplified signals were recorded with strip chart recorders.

3. Thermal analysis

At the beginning of a day's operation, the temperature of the limiter tiles was uniform and at about 200°C, as determined by the coolant temperature. In contrast, at the end of a day's operation, the bulk temperature of the central tile could be as high as 300°C while the outermost and innermost tiles were still at about 220°C and very close to the base plate temperature. For a nominal load case of 2.5 kW/cm² for 200 ms, the surface temperature increased from 200°C to 800°C. For this case, thermal properties were temperature averaged and taken at 500°C. In table I the thermal properties of beryllium are given at the relevant temperatures.

Table I
Thermal properties of beryllium

	Temperature (°C)			
	200	300	500	1200
Specific heat, c (J/g K)	2.35	2.55	2.80	3.80
Thermal conductivity, K (W/cm K)	1.45	1.30	1.05	0.60
Thermal diffusivity, κ (cm ² /s)	0.35	0.30	0.20	0.10

The total pulse length of the plasma discharges was nominally 300 ms with the neutral beam injection lasting for 200 ms, starting 100 ms into the discharge. Compared to the thermal diffusion time in the tile of about 40 s, the heat deposition was instantaneous. For this case the proper solution of the heat conduction equation would correspond to the slab solution with an instantaneous heat source on the front surface and heat removal at the back surface. The solutions are complicated and not very transparent. If complete temperature profiles as function of time are required, numerical methods are more appropriate. Figure 2 shows the temperature of one tile at the thermocouple location as obtained with a finite-element code for a 200-ms pulse of 2 kW/cm². For the present purpose, it can be shown that the "lumped thermal capacity" approach is sufficient to model the thermocouple measurements, and the "semi-infinite body" approach to compute surface temperatures.

With h being the heat transfer coefficient between the tile and the cooled base plate, L the length in the direction of heat conduction, and K the thermal conductivity, the Biot

number is defined as $Bi = h \cdot L / K$. When the Biot number is small enough, the problem can be treated by the "lumped thermal capacity" approach in which the object is considered to have a single mass-averaged temperature. For $Bi \leq 0.1$ the resulting error will be less than 5%. In the present case, a typical value for the heat transfer coefficient h was $1.8 \times 10^{-2} \text{ W/cm}^2 \text{ K}$, resulting in a Biot number smaller than 0.1. Hence, the "lumped thermal capacity" approach was applicable.

For a "semi-infinite body" the surface temperature at given heat flux q_0 and a thermal diffusivity κ is given by [3]

$$T(t) = (2q_0/K)\sqrt{\kappa t/\pi} . \quad (1)$$

An object of length L can be considered as semi-infinite if the dimensionless expression $L^2/\kappa t$ is larger than unity. This condition is fulfilled for the beryllium tile with $L = 7 \text{ cm}$ and a heat pulse of 300 ms.

A prerequisite for the method described here was that the temperature distribution across the limiter, measured 30–50 s after the discharge, was still representative of the initial power flux distribution on the limiter surface. It could be shown that (1) the lateral heat conduction on the limiter surface was negligible during the pulse, and (2) the heat transfer between tiles was negligible during the observation time of 100 s.

To examine the first requirement, one has to compare the temperature gradients along the limiter surface and perpendicular into the surface. If x is the coordinate along the limiter surface in the direction of the major radius, the power flux distribution across the limiter for a circular plasma with minor radius a and exponential decay with the characteristic length λ_q is

$$q(x) = q_0 \exp[-(\sqrt{a^2 + x^2} - a)/\lambda_q] , \quad (2)$$

where q_0 is the maximum flux at the center of the limiter. The corresponding surface temperature distribution is obtained by combining Eq. (2) with Eq. (1). Differentiation with respect to x yields the temperature gradient parallel to the limiter surface (assuming a

continuous surface). The temperature distribution perpendicular to the surface (z -direction) is given by [3]

$$T(z,t) = (2q/K)\sqrt{\kappa t} \operatorname{ierfc}(z/\sqrt{4\kappa t}) . \quad (3)$$

Differentiation with respect to z yields the temperature gradient into the surface. The ratio of parallel gradient to perpendicular gradient is

$$\frac{\operatorname{grad}_{\parallel} T}{\operatorname{grad}_{\perp} T} = \frac{2x}{K\sqrt{a^2 + x^2}} \sqrt{\frac{\kappa t}{\pi}} . \quad (4)$$

For a pulse length of 300 ms and x between 0 and ± 15 cm (outermost tiles), this ratio is small; that is, the temperature distribution at the end of the pulse is representative of the power flux distribution, and solutions for one-dimensional heat conduction can be applied.

To apply one-dimensional heat conduction through the observation time of 100 s, the second condition stated above has to be fulfilled, that is, heat transfer between tiles must be negligible. Comparing the temperature profile at 30 s after the discharge with the distribution taken at 100 s shows that the profile did not change. This indicates negligible heat transfers between tiles during the observation time. Figure 3 shows the measured profiles 30 s and 100 s after the deposition.

Assuming heat transfer from the tiles to the base plate only, the temperature decay can be described by

$$mc\dot{T} = -hA(T - T_p) , \quad (5)$$

with the solution

$$T(t) = T_p + (T_i - T_p)e^{-\alpha t} , \quad (6)$$

where $T(t)$ is the bulk temperature at time t and T_i is the maximum tile temperature at $t = 0$. T_p is the base plate temperature, and α is the ratio hA/mc with heat transfer coefficient h , contact area A , and heat capacity mc . In the present case, the contact area

was $A = 25 \text{ cm}^2$, and the heat capacity was 615 J/K at 200°C . From the temperature decay after a pulse, the time constant has been determined to be $\alpha = 7.3 \times 10^{-4} \text{ s}^{-1}$, resulting in a heat transfer coefficient of $h = 1.8 \times 10^{-2} \text{ W/cm}^2 \text{ K}$.

Since α is very small, the loss rate during the observation time of 100 s is small. Hence, the exponential in Eq. (6) can be linearized, and the temperature is $T(t) = T_p + (T_i - T_p)(1 - \alpha t)$. This yields a constant temperature derivative in time, and the energy loss rate can simply be determined by $Q = mc\Delta T/\Delta t$.

During the first discharges of a day, the temperature difference $(T_i - T_p)$ was small and so were the loss rates. During operation, the limiter temperature was building up according to the energy deposition profiles; that is, $(T_i - T_p)$ and the corresponding energy loss rates increased faster at the limiter center than at the outer tiles. After 100 discharges, the bulk temperature of the central tiles could be as much as 100°C higher than that of the outermost tiles. The resulting differences in the heat loss rates progressively distorted the energy deposition profile and had to be accounted for at higher shot numbers. In most cases considered here, the error was around 10%.

The bulk temperature distribution follows the power flux distribution of Eq. (2) and is given by the equation

$$T_b(x) = T_b(0)\exp[-(\sqrt{a^2 + x^2} - a)/\lambda_q] , \quad (7)$$

where $T_b(0)$ is the temperature of the central tile (at $x = 0$). The e-folding length of the power flux can be obtained from x_{HWHM} :

$$\lambda_q = -(\sqrt{a^2 + x_{\text{HWHM}}^2} - a)/\ln 0.5 . \quad (8)$$

During neutral beam injection, the limiter power was determined by the beam power. Since the beam power was a square wave pulse of duration $\Delta t = 200 \text{ ms}$, one could assume to get a fair measure of the power flux by simply dividing the total energy by the pulse duration. The energy on the central tile is then $mc\Delta T_b$, and

$$mc\Delta T_b = 2wq_0\lambda_q \Delta t , \quad (9)$$

where q_0 is the maximum power flux perpendicular to the flow, w is the tile width, and the factor 2 accounts for the fact that energy is deposited on both sides of the limiter. The power flux at the plasma boundary in a plane perpendicular to the flow is then

$$q_0 = \frac{mc\Delta T_b}{2w\lambda_q\Delta t} \quad (10)$$

where ΔT_b is the temperature rise of the central tile and λ_q follows with Eq. (8) from the temperature distribution. Due to the oblique angle of incidence, the projected power flux at the limiter tip was lower by a factor of 2.7. Knowing q_0 and λ_q , the surface temperature on the limiter can be computed with Eqs. (1) and (2). The considerations above are based on the assumption that the power fluxes are equal on the ion and electron drift sides. There is experimental evidence, however, that the particle fluxes are not equal. Hence, the measured power fluxes are likely to be an average between the ion and electron sides of the limiter.

4. Scrapeoff layer studies

4.1 Particle and power flux

The power flux q to the limiter is given by

$$q = \gamma n v_{\parallel} k T_e \quad (11)$$

where γ is the energy transfer coefficient, $n v_{\parallel}$ the parallel particle flux, and T_e the electron temperature of the edge plasma. The flow velocity is assumed to be a fraction of the sound speed $v_{\parallel} = \alpha c_s$, with $c_s = \sqrt{2kT_e/m_i}$ and $T_i \sim T_e$. The energy transfer coefficient γ is a function for the secondary electron emission coefficient δ and the mass ratio $\mu = m_e/m_i$ [4]:

$$\gamma = 2 + \frac{2}{1-\delta} - \frac{1}{2} \ln \left[\frac{4\pi\mu}{(1-\delta)^2} \right] \quad (12)$$

Thus, for a deuterium plasma, $\gamma = 6.8$ for $\delta = 0$, and $\gamma = 17$ for space charge limited secondary electron emission with $\delta = 0.86$ [5]. If n_e , T_e at the plasma boundary are known, Eq. (11) can be compared with q_0 determined by Eq. (10). At $I_p = 117$ kA, $B_t = 1.3$ T, $P_t = 0.9$ MW, and $\bar{n}_e = 4 \times 10^{13} \text{ cm}^{-3}$, Thomson scattering data indicated $n_e = 2.4 \times 10^{13} \text{ cm}^{-3}$, and $T_e = 87$ eV at the plasma boundary. The corrected bulk temperature rise of the central tile was 12°C and $\lambda_q = 1.3$ cm (see fig. 3). According to Eq. (10) we calculate $q_0 = 5.8 \text{ kW/cm}^2$. The secondary electron emission coefficient of beryllium is about 0.5 at the given electron temperature [6]. This yields $\gamma = 8$ for a deuterium plasma. Using the Thomson scattering data for plasma density and temperature and the measured power flux, we can estimate the parallel particle flow. For the given case we obtain $v_{||} = 0.24 c_s$. The accuracy of the used data and assumptions is not high enough for a precise calculation of the flow velocity, but this consistency check shows that the assumptions are justified within reasonable limits.

4.2 Energy deposition at various plasma conditions

At fixed plasma current of 117 kA and beam power of 0.85 MW, the line-averaged density was varied between $7.1 \times 10^{13} \text{ cm}^{-3}$ and $8.8 \times 10^{13} \text{ cm}^{-3}$ while the energy deposited at the limiter remained roughly constant at 44 kJ. This corresponded to an average limiter power of 220 kW. According to Eq. (11), the power flux is proportional to $nT^{3/2}$. Langmuir probe data of density scans taken during the pump limiter experiment showed that the edge density strongly increased with $\bar{n}_e$ while the edge temperature decreased with $\bar{n}_e$ so that the product $nT^{3/2}$ was approximately constant. Thus, the energy deposition at the limiter was largely independent of the line-averaged density.

At fixed line-average density and plasma current, the limiter power increased with increasing neutral beam injection. This was due to two effects: the edge temperature increased and, because of deteriorating confinement, the edge density also went up with beam power.

Most interesting was the dependence of the limiter power on the plasma current. This is shown in fig. 4 for ohmic discharges. The scan was performed at constant density. The vessel was gettered by beryllium evaporation [1], and the radiated power remained constant at about 110 kW while the density was kept at $3 \times 10^{13} \text{ cm}^{-3}$. With increasing

current, the energy deposition became more peaked, and λ_q decreased from 1.6 cm at 116 kA to 0.7 cm at 176 kA. This was due to improved confinement with increasing current. Unexplained remains the fact that the total limiter power increased by 72% while the input power increased by only 40%. A similar observation was made in beam heated discharges. Here, the input power was essentially constant, because it was dominated by the beam power while the limiter power increased with current. This dependence was observed at higher currents because the limiter power was high enough to melt and evaporate beryllium from the limiter, causing gettering at the vessel walls. The energy profiles in fig. 4 show a systematic asymmetry, that is, more energy is deposited towards the inside. This amount of energy corresponds to about one half of the plasma energy content, and it is conceivable that it is deposited at the end of the discharge with the plasma collapsing towards the inboard wall.

The effect of gettering on the limiter power was observed during a series of shots taken at higher plasma currents of 145 kA. At this current, the limiter power flux was above the design load of 2.5 kW/cm², and the surface became progressively hotter. The resulting evaporation and gettering changed the radiated power from 300 kW at the beginning to 150 kW at the end of the series. With decreasing radiation, the limiter energy increased as demonstrated in fig. 5. The distribution was distorted because of strong surface melting and altered heat transport.

The effect of plasma edge cooling by neon puffing could also be demonstrated with this method. Figure 6 shows the energy distribution on the limiter at high currents with and without neon puffing. For a neutral beam pulse of 0.25 s, the limiter power was 344 kW without puffing and reduced to 224 kW with puffing. The radiation increased correspondingly from 180 kW to 300 kW.

5. Summary and future plans

An instrumented limiter, designed as a calorimeter array, has been used in ISX-B as a diagnostic tool for power flux measurements in the plasma edge. It has been proven to be a very simple and rugged diagnostic. Total limiter power, decay length of the power flux, and inferred maximum surface temperature could be obtained routinely between shots. The method has been used as a tool to study energy transport to the limiter under various plasma conditions.

For the Advanced Toroidal Facility (ATF), top and bottom instrumented rail limiters are being built. Additional features are that the central tile has Langmuir probes incorporated to measure particle fluxes and a gas puff nozzle for fueling studies. Furthermore, the limiters can be biased. Analysis of the energy profiles will be automated to provide the total limiter power, decay length, particle flux, and surface temperature between discharges. The Langmuir probes will provide time resolution of the particle flux for comparison with the power flux.

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Figure captions

Fig. 1. Configuration of the limiter and tile. (Every other tile is tessellated to test thermal stress relief).

Fig. 2. Temperature as function of time at the location of the thermocouple calculated with a finite-element code. The heat pulse is 2 kW/cm^2 for 200 ms.

Fig. 3. Typical temperature distributions at $t_0 = 30 \text{ s}$ and $t_1 = 100 \text{ s}$ after the heat deposition.

Fig. 4. Energy distribution on the limiter as function of plasma current for ohmic discharges.

Fig. 5. Energy distribution on the limiter as function of shot numbers at fixed plasma parameters. The increasing energies indicate the transition to the gettered state.

Fig. 6. Reduction of the limiter energy by edge cooling with neon puffing.

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1-D HEAT TRANSFER CODE

Fig.6

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