Peripheral-plasma diagnostics in a tokamak by limiter thermography

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The limiter in a tokamak draws significant particle and energy fluxes from the plasma and sharply reduces the interaction between the plasma and the wall, thereby protecting the wall from damage and protecting the plasma from catastrophic contamination. The temperature of a movable limiter in the T-10 tokamak has been measured using the IR emission from the surface of the limiter. When the results of these measurements are interpreted with reference to certain models for the boundary layer at the wall it becomes possible to calculate the heat flux to the limiter. This heat flux is 2–3 kW/cm^2 in normal discharges and ranges up to 10 kW/cm^2 in discharges with disruptions. The total power drawn by the limiter is thus comparable to the power deposited in the discharge under these conditions. The measurements reveal that the radial decay of the longitudinal energy flux in the peripheral layer of the plasma column is exponential. The results also yield the constant of this decay. During discharges with disruptions, in the initial and final stages of normal discharges and also when microwave power is injected into a plasma, there is a highly nonuniform heating of the limiter surface. This nonuniformity indicates a definite structure for the peripheral plasma. An overall result of this study is that the limiter can be used successfully in a role in addition to its primary role. Specifically, it can be used as a diagnostic probe in a close contact with the plasma which is not achievable by other means.

§1. INTRODUCTION

Reducing the interaction of hot plasma with the wall of the vacuum chamber is presently one of the central problems in controlled fusion research. In tokamaks, this purpose is served by a limiter. A limiter is essentially a narrow region of the inner surface of the toroidal discharge chamber which protrudes into the chamber and which serves to separate the hot plasma column from the wall by reducing the dimensions of the column. The dimensions of the plasma column are reduced, and the interaction of the plasma with the wall is sharply reduced, because the limiter draws part of the particle and energy fluxes from the plasma which would otherwise go to the wall.

Part of the limiter in a tokamak is usually movable. By moving this part along the minor radius of the torus one can adjust the diameter of the plasma column, adjust the dimension of the plasma layer beyond the limiter over a broad range, and redistribute the particle and energy fluxes from the plasma between the wall of the vacuum chamnber and the limiter.

The heat flux drawn by the surface of the limiter is a significant fraction of the overall energy balance in a fusion device. This heat flux to the limiter must be measured directly in order to reach an understanding of the operation of existing tokamaks and to design tokamaks of the next generation.

Because of the limited dimensions of the limiter, the energy flux density to the surface of the limiter is extremely large even in the existing devices, where it reaches several kilowatts per square centimeter. Consequently, the heating and erosion of the limiter are extremely significant. As a result, there is a need for a careful study of the thermal operating regimes of a limiter for the purpose of optimizing the surface shape of the limiter and finding the optimum limiter material. Such studies are the more important because limiters are expected to be used in tokamaks of the next generation, where the energy load on the working elements will be even greater.

Let us examine the operation of a limiter from a different standpoint. Since it is in close contact with the plasma, the limiter draws energy fluxes which are propagating in the outer part of the plasma column. In response to the arrival of these fluxes, the temperature increases at the corresponding parts of the limiter surface. By measuring the temperature of sufficiently small surface regions at each instant we can obtain information on the intensity of the fluxes and on the role of external factors involved in their formation. A limiter may thus be thought of as a diagnostic tool which furnishes information on the peripheral plasma. In this case we do not have to deal with the customary unpleasant question of distortion of the experimental results by the effects of the probe on the plasma; the presence of the limiter and the consequences of its presence are part of the normal operating conditions of the plasma device and are not affected by the intention to make use of the limiter as a probe.

The most suitable method for measuring the temperature fields at the surface of a limiter is to measure the thermal radiation of various parts of the limiter during the working pulse of the tokamak. These measurements can be carried out by conventional IR techniques. Although IR apparatus has been used in fusion research for a long time now, its use has been extremely infrequent.[1–5] In the present paper we report the results of such measurements carried out in the T-10 tokamak during operation of this tokamak in a purely ohmic heating regime and also in regimes in which auxiliary plasma heating by the electron-cyclotron-resonance method was studied.

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§2. EXPERIMENTAL ARRANGEMENT AND PROCEDURE

The T-10 tokamak, in which the experiments are carried out, has a minor radius of 39 cm, a major radius of 150 cm, a toroidal magnetic field of usually $\sim 3\ T$, and a working pulse length ~ 0.7 s. The typical characteristics of the plasma in the working regime are an average electron density $\bar{n}_e = (1-4)\cdot 10^{13}\ \mathrm{cm}^{-3}$, an axial electron temperature $T_e(0) \sim 1500$ eV, an axial ion temperature $T_i(0) \sim 700$ eV, a discharge current between 200 and 400 kA, and a toroidal loop voltage ~ 2V.

The toroidal vacuum chamber of the tokamak is made of bellows ~ 80 cm in diameter. At four points on the torus, at 90° intervals, there are diagnostic branch pipes, whose installation is shown clearly in Fig. 1. Each branch pipe has one vertical flange and two horizontal flanges, through which diagnostic apparatus is inserted into the chamber. The waveguides of a gyrotron complex intended for auxiliary plasma heating enter the chamber through a vertical flange of the branch pipe in which the experiments are carred out (i.e., in the horizontal direction in Fig. 1). The gyrotrons operate at a frequency of 87 GHz; the length of the working pulse is ~ 100 ms with a rise time of a few microseconds; and the power deposited in the chamber is 400 kW. The gyrotrons are triggered 400 ms after the beginning of the discharge.

In the same cross section of the torus, near the vertical walls of the branch pipe, on the inner surface of the toroidal chamber, there are eight stationary limiters, four on each side of the branch pipe. These limiters are made of graphite; overlapping each other, they form a solid ring ~ 40 mm high.

The movable limiter behind which the observations are made is inserted through the lower horizontal flange of the

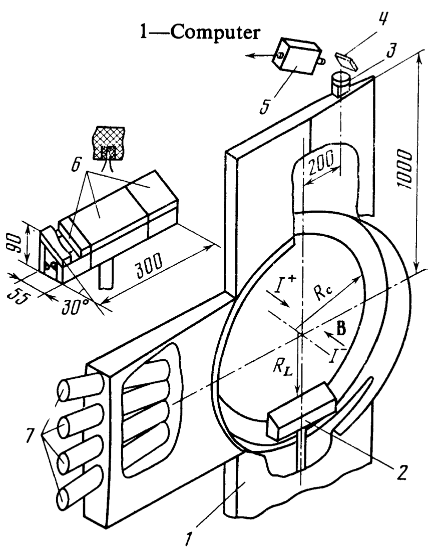

FIG. 1. Arrangement of the apparatus in the diagnostic branch pipe of the tokamak. 1) Diagnostic branch pipe; 2) movable limiter; 3) sapphire window; 4) mirror; 5) receiver camera of the infrared apparatus; 6) positions of the thermocouples in the limiter; 7) input ports for microwave power from the gyrotron complex; R_c) "liner" radius (the inside radius of the tokamak vacuum chamber); R_L) limiter radius, equal to the distance from the center of the tokamak vacuum chamber to the upper edge of the movable limiter. The dimensions are in millimeters.

diagnostic branch pipe (Fig. 1). This limiter is a rectangular brick of stainless steel with a facing of parallel plates of MPG-8 graphite. This is an anisotropic material, produced by compressing powdered graphite. The typical thermal properties of this material corresponding to a temperature ~ 250 °C are $k = \lambda / c\rho = 0.52\ \mathrm{cm^2/s}$ and $\varkappa = (\lambda c \rho)^{1/2} = 1.3 J/(\mathrm{cm^2 \cdot s^{1/2} \cdot deg})$ in the direction perpendicular to the surface of the plates; here λ is the thermal conductivity, c the specific heat, and ρ the density of the limiter material. The plates are 15 mm thick. The character time for heat to spread in the direction across the plate is ~ 3 s. The limiter is mounted on a vertical shaft; by moving this shaft one can change the position of the limiter along the minor radius. Most of the measurements were carried out with the limiter in a position such that its upper edge was at a radius $r = 32$ cm from the axis.

The limiter is monitored through a sapphire window in the upper horizontal flange of the diagnostic branch pipe, 1.3 m from the surface of the limiter. Only the upper face of the limiter, facing the axis of the plasma column, is in the field of view of the apparatus; the vertical faces of the limiter are not seen. For measurements of the radial profile of the heat flux density, the upper (working) face of the limiter is tilted to an angle of 30° from the tangent to the axis of the plasma column. The limiter can be positioned in such a manner that its upper face tilts toward either the "electron side" or the "ion side" of the discharge. In the experiments described below, the tilt was on the electron side in all cases.

For the measurements we use standard commercial infrared apparatus: a model 750 heat-radiation visualizer manufactured by the Swedish company AGA. The camera of the visualizer uses a single IR detector, of liquid-nitrogen cooled indium antimonide. The radiation is detected in the spectral interval from 3 to 5.6 μm; the sensitivity of the apparatus (without filters) is 0.1° C at 30°C. The thermal picture of the object is obtained by means of an optomechanical system which scans the image formed by the objective over the sensitive area of the detector. The output signal from the detector is fed to the monitor of the visualizer system, forming a television image of the object on its screen. The frame frequency is 25 Hz, and the line frequency is 2500 Hz.

During the tokamak pulse, an analog signal from the monitor of the visualizer is fed to a small computer with an internal memory of 36 k bytes through an eight-digit analog-to-digital converter with a conversion frequency of 0.5 MHz. After the conversion of the analog signal into a digital signal, each frame of the thermal image consists of 100 rows, each of 200 elements. The image of the limiter fills only a small part of the frame, with a "height" of 37 rows and a "width" of 13 columns. The direction of the rows is the toroidal direction in the tokamak. The first row corresponds to the outer edge of the limiter, while the 37th corresponds to the inner edge, toward the axis of the device. The first point of each row (the first column of points) corresponds to a short, steep slope of the upper plate, facing the ion side of the discharge. The second row of points should be associated with the intensity of the emission from elements at the limiter crest, and all the other points, beginning with the third row, should be associated with elements on the long, gently sloping part of the limiter, facing the electron side of the discharge (see Fig. 1 regarding the directions of the ion and electron currents).

The distance between the points along a row (i.e., in the toroidal direction), referred to the surface of the actual limiter, is 4.6 mm. The distance between rows (along a column, i.e., in the poloidal direction), again referred to the surface of the real limiter, is 8.3 mm. Going from one point to another along a row corresponds to a radial shift of 2.8 mm. The calibration data are entered in the computer in the calculation of the absolute value of the limiter temperature and of the power drawn by the limiter's surface. Before carrying out the basic measurements, we ensured that the signal from the infrared emission of the plasma was negligible in comparison with that from the limiter and that the errors associated with the presence of an aperture, which cuts off the lateral rays, are also completely negligible.

After each tokamak pulse, the raw data stored in the small computer are transferred to a large computer for processing and assignment to appropriate files. The major part of this processing is to take into account the effect of the instrumental function of the apparatus, which has a significant width and which was carefully measured beforehand. In analyzing the experimental data we also took into account the corrections found as a result of the calibration measurements. The calibration measurements were taken in the same geometry as the working measurements. The calibration process is essentially one of determining the component of the resulting radiation signal which comes from the various parts of the apparatus surrounding the limiter, primarily, the inner surface of the liner, and finding the transmittance of the sapphire window. The calibration measurements were carried out at various limiter temperatures from 100 to 700 °C; these temperatures were measured by thermocouples inside the limiter, a few millimeters below the working surface.

In each discharge in the tokamak, we recorded 50 frames each 40 ms long, in continuous succession, on the screen of the visualizing system. The apparatus was triggered slightly before the beginning of the discharge so that the temperature field at the surface of the limiter was measured just before the discharge, during the discharge, and after the discharge, as the limiter cooled down in the plasma-free chamber. The triggering of the measurement apparatus was closely synchronized with the discharge in the tokamak, and each result from the temperature measurements at a given point on the surface could be assigned a definite time.

§3. EXPERIMENTAL RESULTS

After the processing of the experimental data by the scheme described above, the computer generates three-dimensional temperature distributions corresponding to each frame recorded. Figure 2 illustrates the results with the distribution found from the processing of a frame recorded at the end of the current plateau (at 603 ms) during a typical discharge pulse with ohmic heating of the plasma. We see that the region of maximum heating is small and falls in the central part of the limiter, at its left edge, where it touches the plasma and where the energy evolution is at a maximum.

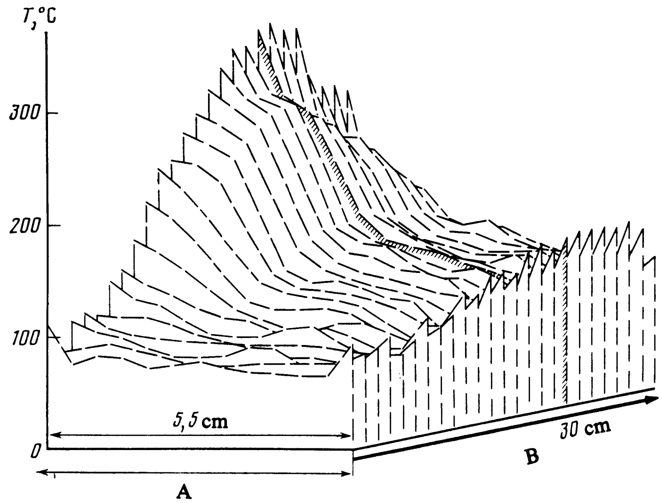

FIG. 2. Limiter temperature field during the plateau in the discharge current at 603 ms. Each curve corresponds to a single line on the screen of the heat visualizer. The hatching shows the "hottest line" (near the middle of the limiter). A) Toroidal direction; B) poloidal direction (individual lines).

Simple geometric considerations based on the limitation of thermal conductivity explain the slight increase in the temperature near the opposite edge of the limiter. The distributions of this type are extremely easy to interpret and are convenient for quickly seeing the overall picture of the heat evolution over the surface of the limiter during the brief exposure time corresponding to the given frame.

For a detailed analysis of the results of these measurements, a more elaborate procedure is necessary: 1) construct poloidal and toroidal temperature profiles for a series of frames and 2) determine the time evolution of the surface temperature in the various parts of the limiter on the basis of the entire sequence of frames obtained during the given discharge pulse.

The poloidal profiles (Fig. 3) are usually smooth bell-shaped curves with a half-width ~50 mm, with a height which falls off rapidly with distance from the crest of the limiter down its slope. The peaks of these curves are roughly

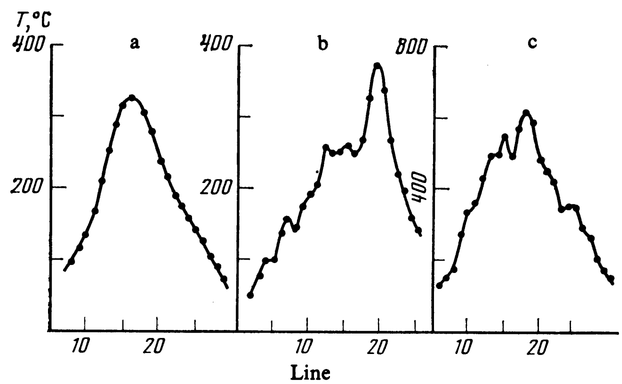

FIG. 3. Poloidal temperature profiles. a) In a discharge without disruptions, during the current plateau; b) in a discharge with a disruption, in the initial stage of the disruption; c) in a discharge without a disruption, during the current growth.

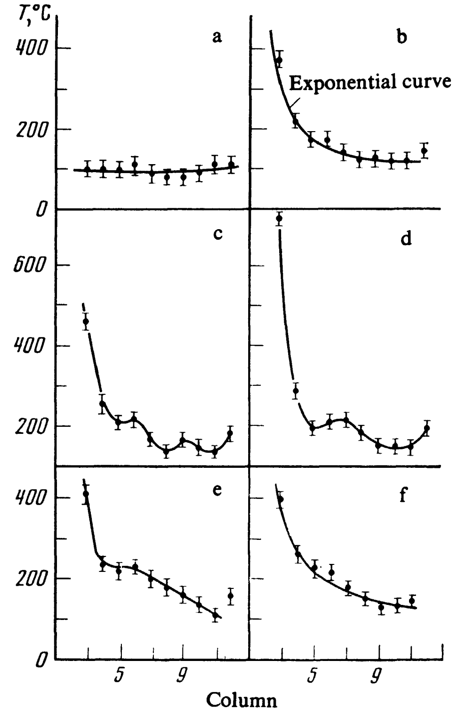

FIG. 4. Toroidal temperature profiles (averaged over lines 15–19). a) During the linear current increase; b) in the current plateau (358 ms into the discharge); c, d) during the microwave pulse (438 and 477 ms into the discharge); e) after the gyrotrons are turned off (557 ms into the discharge); f) after the discharge has ended (at 636 ms).

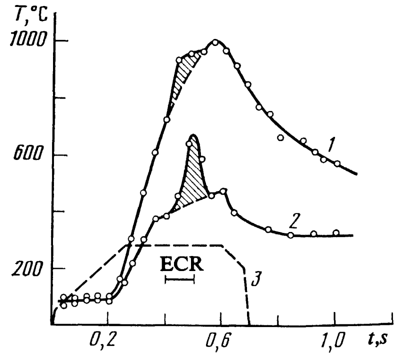

FIG. 5. Time evolution of the temperature of the central part of the limiter.

coincident and usually fall in rows 16 and 17, not in row 19, which corresponds to the center of the limiter. The erosion marks on the surface of the limiter are also displaced into the tokamak chamber, according to a subsequent visual inspection.

In most cases the toroidal profiles (Fig. 4) are also smooth curves. Because of the slope of the upper limiter plate, these profiles essentially describe the radial profile of the longitudinal energy flux in the peripheral part of the plasma column. Before the beginning of the discharge, the toroidal profiles are horizontal straight lines, indicating that the upper plate of the limiter has a completely uniform temperature during the time interval between discharge pulses. [The initial temperature level varies only slightly over the course of a day since the energy accumulated in the limiter in one pulse, $\sim 10^4$ J (discussed below), is small in comparison with the total heat capacity of the limiter.]

The profiles retain this shape in the early stages of the discharge, up to about 200 ms, indicating that essentially no heat is drawn by the limiter over this entire time. The heating of the limiter begins at about 220–250 ms (Fig. 5), and the profiles are smooth, rapidly descending curves up to the point at which the gyrotrons are turned on at 400 ms (in the discharges with auxiliary heating). On a logarithmic scale, these curves become straight lines, indicating exponential decay of the heat flux density along the minor radius of the torus. The maximum limiter temperature in our experiments was 1100 °C.

This simple picture disappears, however, under certain special experimental conditions—primarily in discharges with a disruption and also during electron-cyclotron heating of the plasma. The smooth temperature profiles become distorted; a clearly defined structure of alternating maxima and minima is imposed on them. The appearance of this structure is by no means simply fortuitous.

Let us first consider the description of the structures which are observed on the poloidal profiles during discharges with a current disruption. In this case there are maxima and minima of a wide variety of sizes, ranging from shallow but sharp bends to isolated, clearly expressed peaks of substantial width. These peaks are typically distributed in a random way over the profile, and there is no correlation along the columns of the positions of the maxima and minima taken on some particular row. The most obvious and best-developed structure is observed on those frames which are recorded just before the time of a current disruption. However, even the profiles obtained in the earliest stages of a discharge interrupted by a disruption already have the embryonic features of this structure: sharp and frequent changes in slope and isolated small peaks. This situation is not typical of the initial stage of discharges without a disruption. We might also note that the total width of the temperature profile in discharges with a disruption is far greater than that in discharges without a disruption.

A structure is also observed on frames taken in "quiet" discharges, without a disruption, at certain special times in the pulse: in the initial stage of the discharge, in the final stage of the discharge, during the current decay, and during the operation of the gyrotrons. A structure is also observed at times near the end of the gyrotron pulse.

Finally, we note that there are temperature rises on some parts of the poloidal profile, which sometimes lead to the formation of small peaks, which are detected 100–200 ms after the discharge current stops flowing. These peaks arise on the smooth temperature distributions of the cooling limiter and are accompanied by nothing in the way of a significant change in the total width of the temperature profile.

The toroidal profiles undergo pronounced changes during the operation of the gyrotrons. A sharp increase in the temperature occurs, from 400 to 800 °C; this change is localized in a small region (~ 10 mm in size) near the crest of the limiter (Fig. 4). Elsewhere on the limiter along its slope the

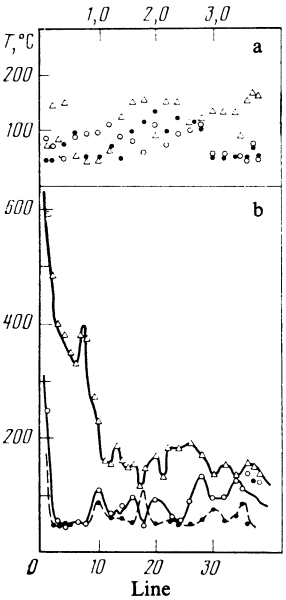

FIG. 6. Heating of the limiter during the injection of microwave power into a chamber without a plasma. Poloidal temperature profiles: a) Before the microwave pulse; b) during the microwave pulse, 85 ms after the beginning of this pulse. △—First column of points, "ion side" of the limiter; ●—second column of points, crest of limiter; ○—third column of points, "electron side" of limiter.

smoothness of the temperature profile is disrupted, and a structure consisting of maxima and minima appears. After the gyrotrons are turned off, this structure spreads out and disappears over a thermal time. By the end of the discharge, a smooth profile, nearly exponential, has formed again.

The surface of the limiter is observed by means of the IR apparatus not only during the working discharges in the tokamak, i.e., with a plasma in the chamber, but also during the injection of microwave power into a chamber without a plasma. These experiments are carried out in the time intervals between discharges, at the same power and length of the microwave pulse. The heating of the limiter surface in these experiments is of a completely different nature. As can be seen from Fig. 6, the region of maximum heating is at the very edge of the upper plate of the limiter, in a very narrow band adjacent to the outer end of the limiter. The heating of the limiter surface is extremely nonuniform; regions with an elevated temperature are found predominantly along the edges of the limiter. We typically observe the appearance of extremely local and brief bursts of radiation.

§4. CALCULATION OF THE ENERGY FLUX DENSITY DRAWN BY THE LIMITER

The experimental data reported above show that we have reliable information on the temperature distribution over the limiter surface at various times during the discharge pulse. Nevertheless, it is not possible to directly calculate the energy which reaches the limiter, since we are not able to take into account the distorting effect of heat fluxes from the lateral sides of the limiter, where the temperature was not measured. Analysis shows, however, that there is a region in the central part of the surface where the effect of these laterial heat fluxes can be ignored. The surface temperature gradients in the vicinity of this region are also quite small; the net result is that we can use the solution of the one-dimensional heat-conduction problem to describe the relationship between the temperature increment at the surface, $\Delta T(t)$, and the heat flux density across the surface, $q(t)$:

$$\Delta T(t)=k^{1/2}\pi^{-1/2}\lambda^{-1}\int_0^t dt'q(t')/(t-t')^{1/2}. \qquad (1)$$

This integral equation is solved under the assumption that over a time interval $\Delta t = 40$ ms, i.e., over the time interval between two successive measurements of the temperature at a given point on the surface, the heat flux remains constant. The heat flux density through the surface at the point m, $q(t)$, is thus obtained as a histogram over time. The corresponding values of q_m^j are calculated in succession from

$$q_m^j=\frac{\varkappa}{2}\left(\frac{\pi}{\Delta t}\right)^{1/2}\Delta T_m(t_j)-\sum_{i=1}^{j-1}\frac{q_m^i}{(j-i+1)^{1/2}+(j-i)^{1/2}}, \qquad (2)$$

which follows from (1).

This region in which the energy flux can be calculated directly from the data of the temperature measurements is only a small part of the limiter surface. To determine the total energy flux drawn by the limiter we need to know how this flux density is distributed over the entire surface. The experimental data (Ref. 4) indicate that the temperature falls off exponentially in the radial direction. Let us assume that the longitudinal heat flux falls off by the same law along the minor radius α over the entire region in which the plasma column makes contact with the limiter:

$$P(r)=P_0\exp[-(r-a)/\delta], \qquad (3)$$

where P is the power of the longitudinal energy flux. The quantity P_0 is determined from

$$P_0=q_m\exp(\Delta r/\delta)\sin\alpha, \qquad (3')$$

where Δr is the position of point m in the shadow of the limiter, measured from the crest of the limiter, while the factor sin α takes into account the slope of the surface to which the flux density q_m corresponds. The integration is carried out over the entire projection of the limiter onto the minor cross section of the plasma column. In the approximation of small values of δ ($\delta \ll \alpha$) the final result is

$$P(t)=(2/\sin\alpha)\,(2\pi a\delta)^{1/2}\delta\exp(\Delta r/\delta)P_m(t), \qquad (4)$$

where the factor of 2 reflects the fact that heat arrives on both sides of the limiter. Since $P(t)$ and $q_m(t)$ are proportional, a calculation of the time evolution of the total power is quite reliable, while the absolute values of $P(t)$ depend on the applicability of Eq. (3) to the entire surface of the limiter.

The results of the power calculation for one of the typical cases are shown in Fig. 7, which also shows values of the energy which has accumulated in the limiter over the time from the beginning of the discharge up to the time t. Also shown here are data on the decay constant δ at various times.

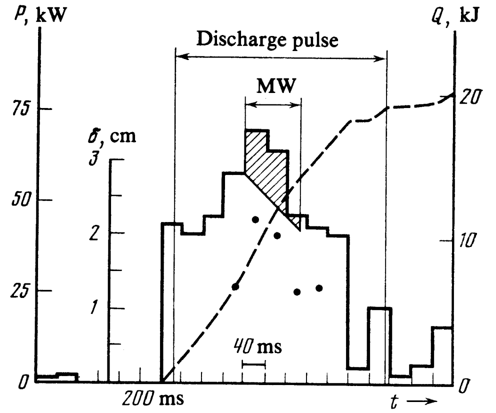

FIG. 7. Results of a calculation of the power P (solid line) dissipated at the limiter, of the decay constant δ (●), and of the energy Q (dashed line) accumulated in the limiter for pulse No. 28565. The microwave heating power is 450 kW; there is essentially no soft x-ray emission; the plasma density is decaying. The hatching shows the additional power increase caused by the operation of the gyrotrons.

A significant power dissipation begins in the discharges without disruptions at about 200 ms, i.e., on the plateau of the discharge current. At this time the power in the ohmic-heating regime is 30–40 kW, i.e., $\sim 10\%$ of the power supplied to the discharge. Higher power levels, up to 75–100 kW, are detected in cases in which the plasma density increases during the discharge. Under these conditions the constant δ has its maximum value (2 cm); i.e., the decay of the energy flux density is extremely smooth. In regimes with a decreasing plasma density, in contrast, we observe a sharper decay of the density and the value of δ is 1.2–1.5 cm.

The energy accumulated in the limiter over the entire discharge is usually $\sim$20–30 kJ. In discharges with an increasing plasma density, this energy reaches 40 kJ, while in discharges with a decreasing density it is 15–18 kJ. A high value of the energy accumulated at the limiter is always accompanied by lower readings of the wide-angle radiation-loss detector in the adjacent branch pipe.

In discharges with disruptions, $P(t)$ is far higher, ranging up to 200–300 kW. The maximum power density reaches 10 kW/cm^2 in certain discharges. A high but brief power peak is always observed at the beginning of the plateau, well before the time of the disruption.

The additional power increment caused by the operation of the gyrotrons is calculated by the same method. The magnitude of this increase varies markedly from pulse to pulse, and there is an obvious correlation between the magnitude of this power increment and the intensity of the soft x radiation from the central regions of the plasma column. If a large signal is observed from the soft x-ray detector, indicating an effective auxiliary heating of the plasma, the power increment at the limiter is small. Conversely, a significant (up to 10–20 kW) power increase during the operation of the gyrotrons is observed in those pulses in which the intensity of the soft x radiation increases only slightly during the microwave pulse.

§5. DISCUSSION AND CONCLUSIONS

The results found in this study vary widely in nature. Some of the results are of essentially technical interest, e.g., the value of the power drawn by the limiter or the maximum limiter temperatures. Other results reflect the experience which has been acquired in the use of infrared apparatus in a large tokamak and provides a basis for recommendations on the use of this apparatus in future devices. Finally, there are some results, such as the measurements of the radial decay in the limiter temperature field and the discovery of a clearly defined structure in this field, which are results of physical interest and which are linked with the particular behavior of the plasma in other tokamaks.

That such clearly different questions are being presented and discussed in a single paper reflects the present stage of research on controlled fusion, where our task is to concentrate the knowledge which has been acquired and the technical facilities available on the development of large devices of the prereactor generation. Success here requires not only an understanding of the physics invovled but also definite information on the behavior of various structural materials and parts under extremely specific conditions and data on the capabilities of various types of apparatus.

We regard the observation of a structure in the temperature field of the limiter under certain conditions as a key and unexpected result of this set of experiments. We have made a careful study of the possibility that these structures result from experimental errors, but we were forced to reject all these sources of error since even the raw data, processed by hand, without the help of a computer, reveal similar structures.

It is not difficult to explain the structure consisting of local temperature bursts which is observed as the limiter cools after the discharge. This structure is undoubtedly due to short-lived arcs between the limiter surface and the decaying plasma. That such a plasma exists in a tokamak a significant time after the end of the discharge is proved by the signals from Langmuir probes positioned near the wall in the tokamak vacuum chamber. We recall that the toroidal magnetic field of a tokamak decays over a time of about 1 s after the end of the discharge.

The random structure which is observed in discharges with disruptions can be explained in a first approximation on the basis that as the plasma column decays various magnetic surfaces carrying plasma of various densities and temperatures pass in succession through the surface of the limiter. This process apparently explains the wide, flat limiter temperature profile observed in discharges with disruptions.

It is more difficult to explain the origin of the structure which is observed on the temperature profiles during the input of microwave power and also in the initial and final stages of the discharge. We attempted to link this structure with either the presence and rotation of the low-mode perturbations which are usually present in the plasma or rapid oscillations of the amplitude of these perturbations. However, analysis of the data obtained from the magnetic probes measuring these perturbations revealed no correlation of any sort between the probe readings and the appearance of the structural features on the profiles of the temperature field. Furthermore, there is a strong argument against that explanation: the fact that the temperature patterns at given times on the electron and ion sides of the limiter are completely different. We might add that the presence of structure on both sides of the limiter rules out the possibility that this structure is due to the appearance of runaway electrons.

We thus cannot yet offer a satisfactory explanation of the effects which give rise to the structure in the temperature field of the limiter surface in all cases. Surprisingly, certain features of this strange effect, e.g., the particular conditions under which it is observed, correlate with features of (so far unexplained) events which are observed in other tokamaks by completely different methods. This comment also applies to the several "structural" events which have been observed in tokamaks by high-speed visible-light photography.[6] In the ASDEX tokamak, for example, a filamentary structure was discovered in the peripheral plasma near the point at which the gas is admitted. In the DITE tokamak, a structure consisting of radially oriented cells was observed in the peripheral plasma. This structure appeared in the initial stage of the discharge, disappeared as the current was raised, and then reappeared and disappeared several times again. The number of cells decreased with increasing current and correlated with the value of the safety factor q. During the plateau in the plasma current, this structure was generally not found. In the ASDEX, emission brightness spots were observed near the limiter surface, stretching out to a distance of 10–20 mm from it. The limiter there was a multisection limiter, so that it was difficult for the temperature to become uniform over the limiter surface. The area of the bright spot thus coincided with the area of a section. The emission was produced by fast neutrals desorbed from hot parts of the limiter surface and then excited by plasma electrons.

We are thus talking about the existence of general features in the behavior of different entities: structural plasma formations, fluxes of neutrals desorbed from hot parts of the limiter, and structures in the limiter temperature field. The limiter can play a twofold role in this set of events. It may either serve as a passive detector of existing plasma structures, without introducing any new features in these structures, or it may play a definite role in the genesis and development of these structures. Uniform heating of the limiter surface will result in the desorption of substantial amounts of gas and in the formation of plasma structures, as has been observed during pulsed gas injection in the ASDEX. On the other hand, the interaction of the limiter even with a homogeneous plasma can give rise to regions of evaluated temperature on the surface, by the mechanism proposed in Ref. 7, for example. By analogy with the multisection structure of the limiter in the ASDEX, which hindered heat transfer there, heat transfer over the surface of the limiter in the T-10 tokamak is restricted by the low thermal conductivity of graphite. This circumstance may have contributed to the formation of hot spots. The existence of hot spots and the enhanced desorption of neutrals from these spots might in turn promote the formation of plasma structures. Pertinent in this regard is the fact that the cellular structure of the peripheral plasma layer was observed in the DITE in discharges with a limiter which restricted the diameter of the plasma column. This cellular structure was not observed in discharges with a diverter, in which cases the limiter was removed.

Going onto the "technical" results, we first note that the maximum temperatures, the surface power density, and the fraction of the power drawn by the limiter according to the measurements in the T-10 experiments are not greatly different from the corresponding values found in other tokamaks, and they are characteristic for devices of this class. In the TFR, for example, the maximum limiter temperature, also measured with an IR camera, was 1500 °C; the power drawn by the limiter was 10–15% of the power supplied to the discharge; and the power density over the surface of the limiter was typically 2–3 kW/cm^2. This fact reflects the circumstance that at the plasma parameters with which we are presently dealing there is no particular difficulty in finding a limiter shape which will reduce the specific load to an acceptable level. Infrared limiter thermography is absolutely necessary for this optimization. Infrared limiter thermography will undoubtedly take on a much greater role in devices of the next generation, where lowering the heat load on the structural parts of the devices will become a very serious problem.

In discussing the T-10 measurements we might note that since the radial decay constant was less than 1.5–2 cm it would have been advisable to reduce the angle of the upper limiter plate to spread out the incident load over a larger area. Here, however, we must immediately deal with the question of a possible mutual relationship between δ and the shape of the limiter surface; despite the obvious importance of this question, it has not yet been studied, to the best of our knowledge. The very possibility of measuring δ by means of limiter thermography appears to us to be very important, since it will provide real-time information on transverse heat diffusion in the plasma near the tokamak wall.

Whatever their causes, the structural features in the temperature field mean that there are extremely large temperature gradients, ranging up to 50 K/mm, along the smallest dimension of the limiter. The existence of these structural features, on the one hand, and the pronounced poloidal temperature asymmetry during discharges with disruptions, on the other, may lead to microscopic cracks on the limiter surface, which have in fact been discovered by visual inspection.

The existence of an early peak in the heat flux to the limiter in discharges terminating with a disruption can be exploited in tokamaks of later generations in feed back circuits for providing automatic warning of a sharp disruption.

It is also important to note that the influx of neutral gas, used to change the plasma density in certain regimes, has a strong effect on the heat load on the limiter. Further research is required to determine whether this effect can be exploited to protect the limiter from heat overloads.

In precisely the same way, we need further research on the effects which are observed during the operation of gyrotrons. When the gyrotrons operate, additional heating of the limiter takes place. In general, this is a completely natural result, since the energy content of the plasma increases at this time. However, as can be seen clearly from the toroidal profiles, the region on the limiter surface where the additional heating is caused by the operation of the gyrotrons is far smaller than the region corresponding to ohmic heating. During electron-cyclotron heating of the plasma, the energy of the rf radiation is pumped into the electrons. In the T-10 tokamak, the time for energy transfer from electrons to ions through Coulomb collisions is longer than the energy lifetime of the plasma, and there is a significant deviation of the electrons from the ions in terms of energy. Accordingly, the smaller dimension of the heating region in the toroidal direction (i.e., in the radial direction, by virtue of the slope of the upper limiter plate) is evidence that the radial decay constant for these electrons is quite different from that for the other plasma particles.

The clearly defined relationship between the soft x-ray signals and the increment in the power drawn by the limiter during the microwave pulse is evidence that there are two classes are regimes, which differ markedly in terms of the conditions under which the microwave power is deposited in the plasma. One class of regimes is favorable for depositing microwave power in the inner plasma regions, while in the other class of regimes the radiation is absorbed in the outer plasma; there the radiation disrupts the structure of the outer plasma layer and causes a pronounced increase in the limited temperature.

The nature of the IR emission from the limiter when gyrotrons are operated in a chamber without a plasma, during the time intervals between pulses, is evidence for the appearance of a multitude of short-lived arcs on the limiter surface. This arcing causes a serious erosion of the surface of the graphite facing and the formation of hydrocarbon compounds, which deposit on the inner surface of the chamber.

Let us summarize the results of this study. The limiter in a tokamak is an excellent research probe in extremely intimate contact with the tokamak plasma. Thermography of the surface of this probe provides a unique opportunity for studying the physical properties of the peripheral layer and its interaction with the limiter surface. It has been found that the properties of this peripheral layer are closely related to features of the behavior of the tokamak plasma as a whole, e.g., the conditions for the deposition of microwave power in the interior of the plasma, and also the stability of the plasma (a global characteristic). The fact that the information is obtained from this probe extremely rapidly means that it can be exploited in feedback circuits in large tokamaks. Limiter thermography in these systems appears to be an absolutely mandatory procedure for optimizing the shape of limiters because of the exceedingly high heat loads.

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