Presented at the American Physical Societe, Anaheim, USA, Nov. 1989

POWER DEPOSITION TO THE PUMP LIMITERS IN TORE-SUPRA WITH OHMIC PLASMAS.

D.GUILHEM[1], J.KOSKI[2], J.WATKINS[2], M.CHATELIER[1], C.KLEPPER[3], P.CHAPPUIS[1], I.FLEURY[1]

The modification of power scrape-off-length, λq, and power deposition are studied both with the horizontal limiter alone and with the full set of 7 pump limiters for 1MW ohmic plasmas in TORE-SUPRA. By making spatially resolved infrared surface temperature measurements during the plasma discharge, the magnitude and distribution of the energy flux can be derived. For comparison, the surface temperature of the horizontal pump limiter is calculated with a finite element code using a 3D description of the field lines, an exponential scrape-off-layer, and the pump limiter geometry. From comparison of the infrared images of the limiter we derived that the λq for power deposition was slightly less than 9mm (+/-1mm) which is in agreement with the predicted design value of 10mm. For an 8 seconds discharge, the maximum surface temperature on the horizontal limiter is 450°C. Inserting the 7 limiters does not modify λq (which becomes 10mm). The power is shared by all the limiters and the maximum surface temperature on the horizontal limiter decreased to 320°C. These λq values have been independently measured by the integrated energy deposition on the horizontal limiter and other internal structures 5cm into the scrape-off layer. These values agree with the infrared measurements in the two cases.

1-CEA/DRFC/CADARACHE 2-SNL-A 3-ORNL

* This work is jointly funded by the U.S. Department of Energy under contracts N°. DE-AC05-84OR21400, and DE-AC09- and the EUR/CEA association.

1. INTRODUCTION.

The experimental conditions [1],[2] envisaged for Tore-Supra operation, i.e. large additional heating power to the plasma (25MW steady state) for long pulse duration (30seconds) emphasized the need to find some methods to control the particle balance and to remove the heat losses at the plasma boundary without being overwhelmed by the impurity influx which is one of the most crucial problems that long pulse machines have to solve today. For example JET has already been confronted to this problem [3] ("the Carbon bloom").

Tore-Supra is entirely designed for long pulse operation of at least 30 seconds with a nominal plasma current of 1.7 MA and a magnetic field of 4.5 Teslas at 2.25 Metres. All the internal components are actively cooled (40 Bars, 200°C) for long operation at full power. Calorimetric measurements of the different components are made by extensive use of thermocouples enbeded in the structures of the machine.

We are reporting here experiments made when the plasma is either 1) leaning on the horizontal limiter only, 2) leaning on the full set of 6 discrete limiters available (1 Horizontal and 5 verticals) and 3) leaning on the horizontal limiter alone when the ergodic divertor is swiched on.

2. EXPERIMENTAL CONDITIONS.

The operation of TORE-SUPRA at full power (25MW, 30s) has led to the design of a full set of actively cooled pump carbon limiters to remove at least 8MW (2MW for the horizontal limiter and 1MW for each of the vertical limiters) and to partially control the particle balance [4] [6]. An interim version is now installed, composed of 5 vertical and one horizontal outboard (OPL) pump limiters, semi-inertially water cooled. The later is a result of a collaboration between the U.S.-DoE and the Association EUR-CEA, it is fully instrumented and therefore can serve as a reference for the final design. Ohmic discharges (1.85T, 740kA, 8.5s) in helium have been used to test the thermal load and the particle exhaust efficiency of the OPL. Figure 1 is a layout of a section of the machine (figure

2) showing the different water cooled components and their radial position.

The operating scenario is described in figure 3. The plasma is formed on the inner wall (R=232cm, a=76cm) and subsequently displaced 6cm outwards, early on the current plateau, to lean on the OPL (R=238cm, a=75 cm). In addition to the limiter above, a non pump outboard (ONLP) limiter of identical shape to the OPL served to produce similar discharges so that the effect of the OPL on particle control could be made. A comparison is made hereafter of the thermal load when the plasma is in contact either with the OPL alone or with the OPL and the vertical limiters together.

3. <u>CALORIMETRIC AND BOLOMETRIC MEASUREMENTS.</u>

Calorimetric measurements provide estimates of the time integrated balance of the energy flow at the plasma edge. Radiated and charge exchange energy losses (Wr) are deduced from the outer wall calorimetry (R=242cm, a=94cm), conductive/convective losses (WC) onto the OPL and vertical (top and bottom) limiters (TBL) are independently measured as well as the integrated energy flow on the ergodic divertors, which are located 5cm in the SOL (R=238cm, a=80cm) see figure 1. Table-I figure 4 shows up the different plasma facing components areas and the related energy for the calculation of the energy balance. For exemple the inner wall has an area of $12m^2$ on the $90m^2$ of the total area facing the plasma surface, so the fraction of the radiated power (W_R) to the inner wall is 12/90 W_R, plus a fraction of the total conducted energy αW_C, α being between 0 and 1.

Results are shown in table-II on figure 4, for a discharge (shot-1151) with the plasma on the TBL and on the OPL and a discharge (shot-1158) with the plasma leaning on the OPL only. Supposing that the radiated and the charge exchange losses are spatially uniform, edge components in the SOL should receive this energy in proportion to their surface area. This is not the case for the ergodic divertor nor for the vertical limiters which are 5cm behind the OPL location. The difference is interpreted as conductive-convective energy directly onto these components. The radiated energy contribution is observe to decrease (from 29% to 16%) when passing from the multilimiter to the single limiter configuration, while the conductive-convective power on the OPL is nearly tripled. In the later case, the mean power flux on the OPL is $2.4MW/m^2$.

The calorimetric results are compared with bolometric measurements of the radiated power as displayed in table-III on figure

4, together with ohmic power estimates. This compares well with the total energy values in table-I of figure 4, when considering the 7 seconds of the current plateau duration after the outward displacement of the plasma. Although the bolometric measurements are systematically larger (30% - 40%) than the inner wall calorimetric measurements, they also indicate the decrease of the radiated power when moving from the multilimiter to the single limiter configuration.

4. POWER LOAD CALCULATIONS OF THE HORIZONTAL PUMP LIMITER.

The surface temperature of the horizontal pump limiter is calculated with a finite element code using a 3D description of the field lines, an exponential scrape off layer, and the real pump limiter geometry. Figure 5 shows the base line concept used to perform cooling studies for the uncooled phase head (a tooled phase head is being prepared to be able to handle a total power of 2MW during steady state operation). The head is made of 3 different parts,

- an assembly of pyrolitic graphite blades,
- a stainless steel base plate with 180°C water cooling,
- a graphite shelf to protect the stainless steel structures of the limiter.

The limiter head face is 50cm wide, 60cm high and the maximum depth of the graphite at the centre of the face is 8 cm.

4.1 MODEL.

The following assumptions were used in the calculations:

- shot duration of 6s, with outputs at 2,4 and 6 seconds
- initial temperature of the limiter = 180°C
- power scrape off lengths λ_q=0.8, 1.0, 1.2 and 1.4 cm were assumed,
- major radius = 2.38cm, minor radius = 0.745cm,
- power to head = 0.7MW, based on the power going to a head of 5.5cm thickness and 65cm poloidal high. The heat flux in the toroidal direction at the limiter tangency point was scaled according to the power scrape-off length to get the 0.7MW on the head. This also assumes symmetry between the ion and electron sides, which is not exactly what we observe,
- the material properties were taken from our values for "as deposited" pyrolitic graphite (a-b plane values) and glidcop Al-25 copper. The tile was assumed to be well bonded to the copper, i.e. with no contact resistance.
- toroidal field coil current of 585 Amperes, with 2028 turns in each toroidal field coil. This gave a toroidal field of about

1.9 Tesla on the plasma centerline and about 1.3 tesla in the vicinity of the limiter.

- Plasma current of 0.75 MA used to estimate a poloidal field, with a poloidal beta of 1 and a plasma self inductance l_i=1. The plasma current was chosen to match shots 1387 and 1398, but since we are near the midplane of the limiter where the poloidal field is parallel to the limiter face, these plasma parameters do not really affect things as strongly as they do at the top and bottom of the limiter face.

4.2 RESULTS FROM THE CODE.

With the assumptions made above the code calculates the heat flux distribution on the head for different plasma geometries and positions. Figure 6 is one of these plots and shows the break in the shape of the tile. The shape has been calculated to have the same temperature at the tip and at the leading edge in the equatorial plane when the e-folding lenght for power deposition is assumed to be λ_q= 1.0cm. This can be seen as well on figure 7 representing the profile distribution of the heat flux along the central blade. The heat flux profile is flat on the central part of the blade and is equal to the heat flux at the leading edge. The shape of the part between the central part and the leading edge is just a straight line connection.

Knowing the heat flux distribution on the limiter face, which is supposed constant during the six seconds of the shot duration, one can estimate the temperature distribution at the surface of the graphite and deep into it, to the stainless steel water cooled base plate (supposed held constant at 180°C).

Figure 8 represents the isotherm lines in the blade at the end of the pulse (t=6s), for a scrape-off length of λ_q=1.0cm. The evolution of the surface temperature along the central blade is shown on figure 9, at 3 different times during the shot, t=0.97s, t=1.93s and t=3.05s, again for λ_q=1cm.

The shape of the central part of the blade is calculated so that the heat flux is almost constant and hence the temperature, for λ_q=1.0cm; the consequence of this design is that a small modification of the e-folding length for power deposition lead to a noticeable modification of the temperature profile along this central part of the blade as indicated in figure 10.

Another parameter is also very sensitive to the e-folding length; namely the ratio of the center temperature to the temperature of the leading edge, which is located 3.5 cm deep into the scrape-off layer. Figure 11 presents this ratio as a function of λ_q and for 3 different times t=2s, 4s and 6s during a shot. This ratio varies from 1.4 when λ_q=0.8cm down to 0.7 when λ_q=1.2cm. One can notice that it is almost independent of time .

The code calculates as well the time history of the surface temperature at different locations on the central blade in the equatorial plane, figure 12. These 7 locations are shown on figure 8, marked 1 at the tip of the head to 7 at the leading edge. The time dependence is not a square root of time like in the semi-infinite wall model and hence to deduce the time history of the heat flux to the limiter from the time history of the surface temperature is not straigtforward. A code is being developped to do this and will be presented elsewhere. The maximum temperature is encountered at locations 1 and 2 (same time dependence) during the first 2.5 seconds and subsequently location 7, the leading edge, reachs a maximum surface temperature of 470°C.

5. MEASURED SURFACE TEMPERATURE OF THE HORIZONTAL PUMP LIMITER.

5.1 EXPERIMENTAL SET-UP.

Figure 2 indicate the location of the discrete components (7 pump limiters, 2 lower hybrid antenae, 3 ion cyclotron resonnance heating antenae, 2 neutral injection ports and finally 6 ergodic Divertor coils). They are dissemined around the 360° of the machine. 3 endoscopes (figure 15) equally spaced, visualise 1/3 of the machine, each. Figure 13 shows the toroidal position of the 3 endoscopes E1, E2 and E3, and of six infra-red references presented figure 14. A surface temperature of 1000°C is obtained by passing 150 amperes into these references.

5.2 EXPERIMENTAL RESULTS.

Analysis of the recordings have been made in detail for several shots and for different experimental programs. The first programme was a study of power loading on the outboard pump limiter during ohmic plasma. The second one considered the modifications of the power loading of the internal structures of the machine when using all the limiters implemented at that time in the machine. Finally the third program addressed the modifications of the plasma when the ergodic divertor was energized in the single limiter configuration.

5.2.1 Plasma leaning on the horizontal pump limiter only.

The pictures of the infra-red camera give the temperature distribution on the blades and the time resolved surface temperature rise during a discharge. The initial temperature is the temperature of the cooling water flowing in the pump limiter structure. During these experiments this temperature was 180°C.

The detailed heating pattern of the blades is rather complex as can be seen on figure 16. This figure presents a map of the temperature of the central part of the pump limiter. The extension of the view is 7cm apart from the tip in toroidal direction and 5cm apart from the equatorial plane in poloidal direction. One can recognize the different tiles which have a 19mm poloidal extension with a gap of 1mm between 2 adjacent tiles. The temperature profile is rather symmetric with respect to the tip; this can be seen on figure 17 which represents the temperature profile on the tile situated in the equatorial plane (the hotest one). The maximum temperature of the central blade (from where the profile on figure 17 is taken) is 370°C (saturation of the camera) near the end (t=8s) of the current plateau (Ip=750kA). Figure 18 represents the time evolution of the surface temperature at 3 different locations on the central blade (see figure 16 for localisation). One can notice the symmetry of the temperature on the electron and ion drift sides. The time history of the temperatures has not a time square root dependence so one cannot use a semi-infinite model to unfold local fluxes. From the profile on figure 17 and from the synthetic profiles given by the numerical model (figure 9), one can deduce that the e-folding length for power deposition λ_q is 9mm 1mm. This value is a local value since the measurement is made at the pump limiter. Nevertheless it is almost equal to the value measured by calorimetry on the facing components.

5.2.2 Plasma leaning on all the pump limiters.

When insertting at the same radius r=75.5cm, the full set of the 6 limiters, using the same plasma parameters i.e. Ip=750kA, Vl=1v, we find that the maximum temperature decreases to 305°C at the center of the pump limiter figure 19, which represents the temperature profile along the central blade. We can now notice on this figure a small asymmetry between the ion and the electron drift sides, the latter being the hotest. From this profile and from the outputs from the code (figure 10), one conclude that the e-folding length is slightly larger in that case than in the single limiter configuration: around 10mm. The fact that the temperature profiles are no longer symmetric suggests a shadowing effect of the observed limiter by at least one other limiter. This effect is dependant on the safety factor q at the edge. A systematic study of the shadowing effect has not been made in these experiments but will be carried out extensively in the future.

The time history of the temperature at the centre of the limiter on the electron and ion drift sides is shown on figure 20. Now the maximum temperature at the center of the blade is 305°C (to be compared to the 370°C in the single limiter configuration). The asymmetry is visible figure 19 between the electron and ion sides.

<u>5.2.3 Effects associated to the ergodic divertor.</u>

The current flowing in the ergodic divertor coils I_{div}=40KA is very small i.e. 4%, compared to the plasma current I_p=1MA. This is not the case for axisymmetric divertors like the JET pump divertor where a fraction of 20% of the plasma current is requested to achieve a single nul X point.

The plasma is leaning on the horizontal limiter acting as the only limiter in the machine and used to visualise the thermal and particle flux effects of the ergodic divertor on the scrape-off layer. The aim of the ergodic divertor is to bring up externally driven modes which create an ergodic magnetic boundary layer. A radial field perturbation figure 21, connects "gently" the ergodic layer to the outer limiters and facing components, lowering the boundary temperature and increasing the boundary layer density. In these experiments we have the possibility to study two free parameters associated with the ergodic divertor, namely:

- The value of the current in the ergodic divertor coils is tuned to modify the strength of the perturbed field at the edge of the plasma. The modification of the radial field leads to a change in the magnetic island size and hence to a change in temperature structures as seen on the pump limiter infra-red images.

- The modification of the plasma current modifies the value of the safety factor at the edge. Since the magnetic perturbations are resonant on discrete q-surfaces (figure 21), a modification of the plasma current brings resonant surfaces from the inside of the plasma to the pump limiter face where they are visualised. These effects can be seen on figure 22, where the temperature of the center of the pump limiter is shown during a ramp up of the plasma current.

* <u>Size of the islands.</u>

The plasma current is ramped up to 800kA and squared wave current with different amplitudes are used for the divertor coils. This can be seen on figure 25, where has also been plotted the surface temperature of the horizontal pump limiter for 3 different locations in the equatorial plane.

After 3.5 seconds when the plasma current has reached its plateau value, even a small current in divertor coil has an effect on the surface temperature of the tip, but has no effect at all on the temperature of the ion and electron side. This means that the island size is small and does not reach the 2 side points 1cm deep in the scrape-off layer. When we increase the current in the ergodic coils then at a certain level there is a temperature response of the side points similar to the response of the tip. The infra-red images show that a modification of the ergodic coil current modifies only the size of the island

* Pump limiter temperature increase.

During these experiments the plasma current was increased rapidly to 600kA and then a slow ramp up of the current was used to reach a value of I_p=1MA at t=6.5 seconds after the beginning of the shot (figure 23). The current in the divertor coils I_{div} was applied only at t=2.5 seconds with a constant value which was changed from shot to shot. In these experiments the plasma was always limited by the horizontal limiter alone, from the beginning to the end of the shot. The temperature of the hottest part of the limiter was monitored. Figure 23 presents the temperature increase from the beginning of the shot up to the time when the plasma current is maximum i.e. t=6.5s, as a fonction of the current in the divertor coils. We can note a striking decrease of the limiter surface temperature as we increase the divertor currênt. Small I_{div} current lead to a large decrease of the temperature which tend to the temperature of the cooling water flowing in the limiter.

A fraction of the power which was going to the pump limiter is now going somewhere else. This can be seen on figure 24 where we have plotted the time integrated energy during a shot, on the various facing components, as a fonction of the divertor current I_{div}. Increasing the divertor current lead to a decrease of the energy flowing to the pump limiter, and a corelative increase of the power flowing on the other facing components far beyond the limiter at Ied=0. In this experiment the ergodic divertor structures and neutralisers are 5cm behind the limiter and the first outer wall is almost 10cm behind the limiter. Now the energy which was primarily conducted to the main horizontal limiter, can reach structures far away from the LCFS and placed all around the machine, which proves that the principal effect of the ergodic divertor is to largely increase the e-folding length for heat deposition. This can be quantified using the calorimetric measurements of the various facing components of the machine figure 26 and 27.

7. CONCLUSION.

The modification of power scrape-off-length, λq, and power deposition are studied both with the horizontal limiter alone and with the full set of 7 pump limiters for 1MW ohmic plasmas in TORE-SUPRA.

By making spatially resolved infrared surface temperature measurements during the plasma discharge, the magnitude and distribution of the energy flux can be derived. For comparison, the surface temperature of the horizontal pump limiter is calculated with a finite element code using a 3D description of the field lines, an exponential scrape-off-layer, and the pump limiter geometry. From comparison of the infrared images of the limiter we derived that the λq for power deposition was slightly less than 9mm (+/-1mm) which is in agreement with the predicted design value of 10mm. For an 8 seconds discharge, the maximum surface temperature on the horizontal limiter is 450°C. Inserting the 7 limiters does not modify λq (which becomes 10mm). The power is shared by all the limiters and the maximum surface temperature on the horizontal limiter decreased to 320°C. These λq values have been independently measured by the integrated energy deposition on the horizontal limiter and other internal structures 5cm into the scrape-off layer. These values agree with the infrared measurements in the two cases.

REFERENCES.

[1] TORE-SUPRA: Basic design of tokamak system
Report EUR-CEA-FC 1021 (1979)

[2] TORE-SUPRA: Basic design of tokamak system
Report EUR-CEA-FC 1068 (1980)

[3] M. KEILHACKER, "JET RESULTS WITH BERYLIUM" Workshop on the new phase for JET: The Pumped Divertor Proposal (25/26 Sept. 1989)

[4] R. Aymar, B. Bertrand, J.L. Bondil, F. Cappiello, P. Chappuis, C. Deck, P. Deschamps, A. Grosman, M. Lipa, G Mayaux, A. Samain, Z. Sledziewski, C. Hertout, J. Letuve; "Implementation of the plasma wall interaction in TORE-SUPRA".

[5] G. Claudet, G. Bon Mardion, B. Jager and G. Gistau
"Design of the cryogenic system for the TORE-SUPRA tokamak"
Cryogenics 1986 Vol.26, August/September P.443

[6] P. Deschamps and al. "Power exhaust and plasma surface interaction control in TORE-SUPRA"

[7] P. Chappuis, R. Aymar, P. Deshamps, M. Gabriel, 15th SOFT Conference, Utrecht (1988).

[8] T. Uckan, C.C. klepper, P. Mioduszewski, R.T. McGrath, Fusion Technology, Vol.13 (Jan. 1988).

[9] N. Ohyabu, J.S. de Grassie et al. Report GA A-17786 (1984)

[10] A. Samain, A Grosman and W. Feneberg, JN.Mat. 111-112 (1982) 408

[11] A. Samain, Ph. Ghendrih, A. Grosman, C. Passeron
"Ergodic Divertor" Tokamak workshop contribution
GUT-ISING Dec. 1989

[12] J. Koski Private communication

[13] M. Chatelier, C.C. Klepper, J.L. Bruneau, P. Chappuis, C. Gill, D. Guilhem, M. Lipa, L. Rodriguez, J.C. Vallet, D. Van-Houtte
"First pump limiter experiments in TORE-SUPRA"
EPS conference, VENISE 1988.

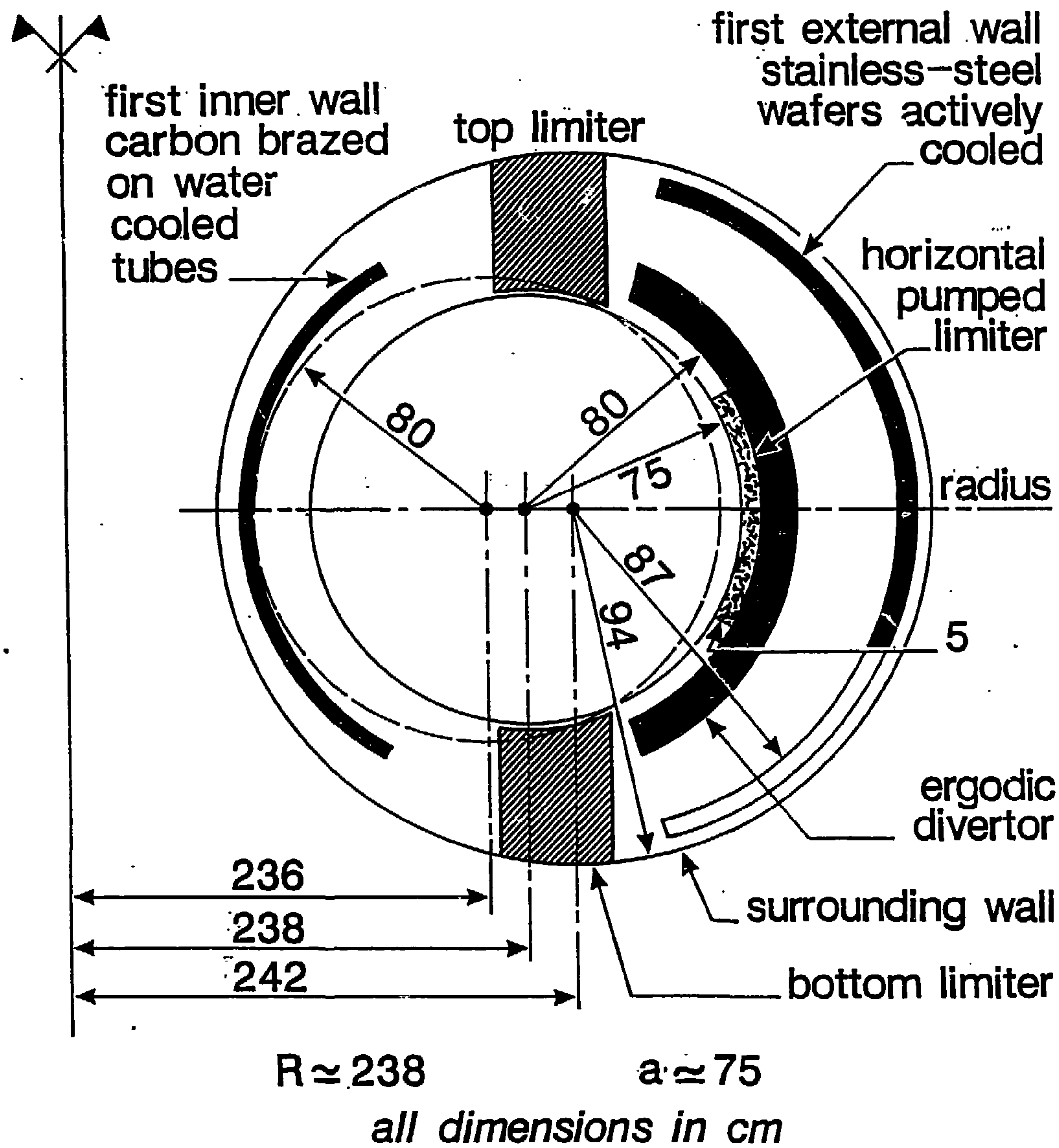


FIGURE 1: Layout of a section of Tore-Supra showing the different radial position and poloidal extentions of the water cooled facing components.

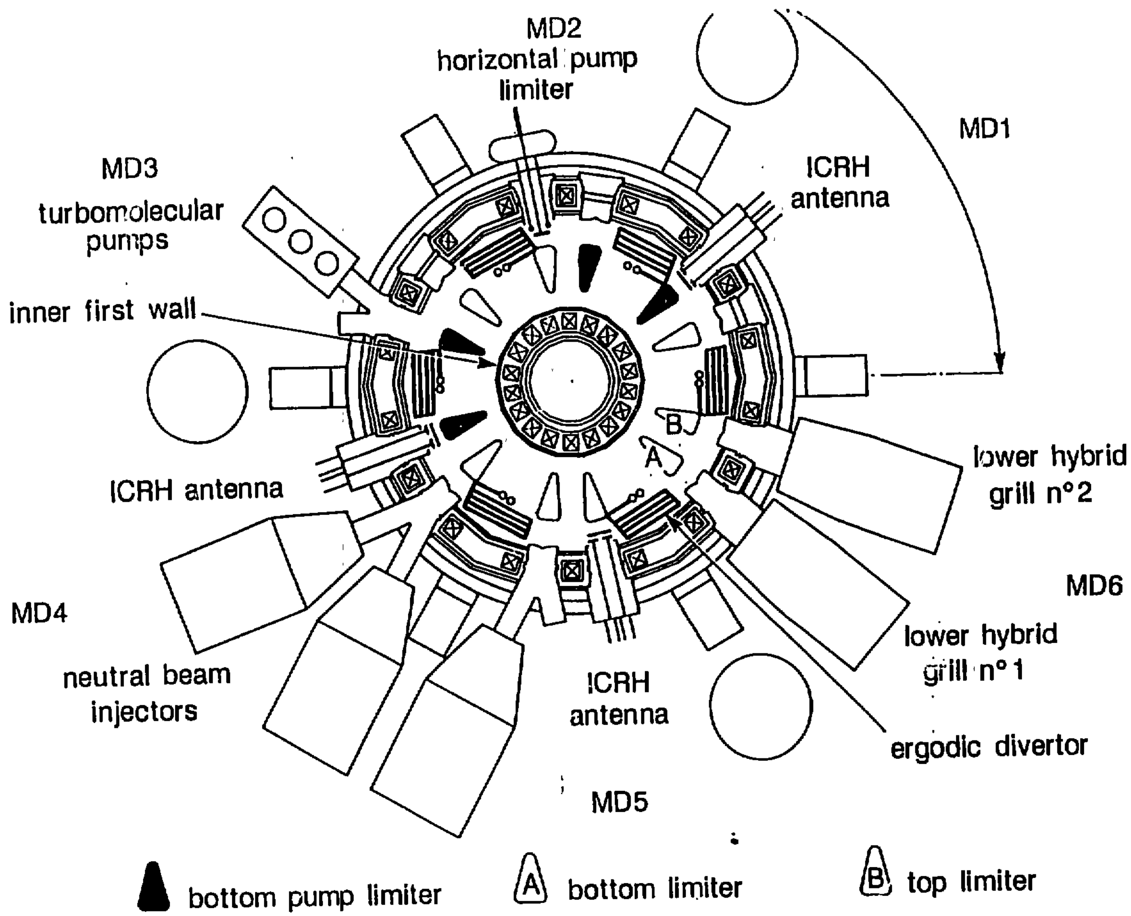


FIGURE 2: Layout of the machine showing the place of the different pump limiters, antennae, neutral injection boxes, divertor coils and turbomolecular pumps.

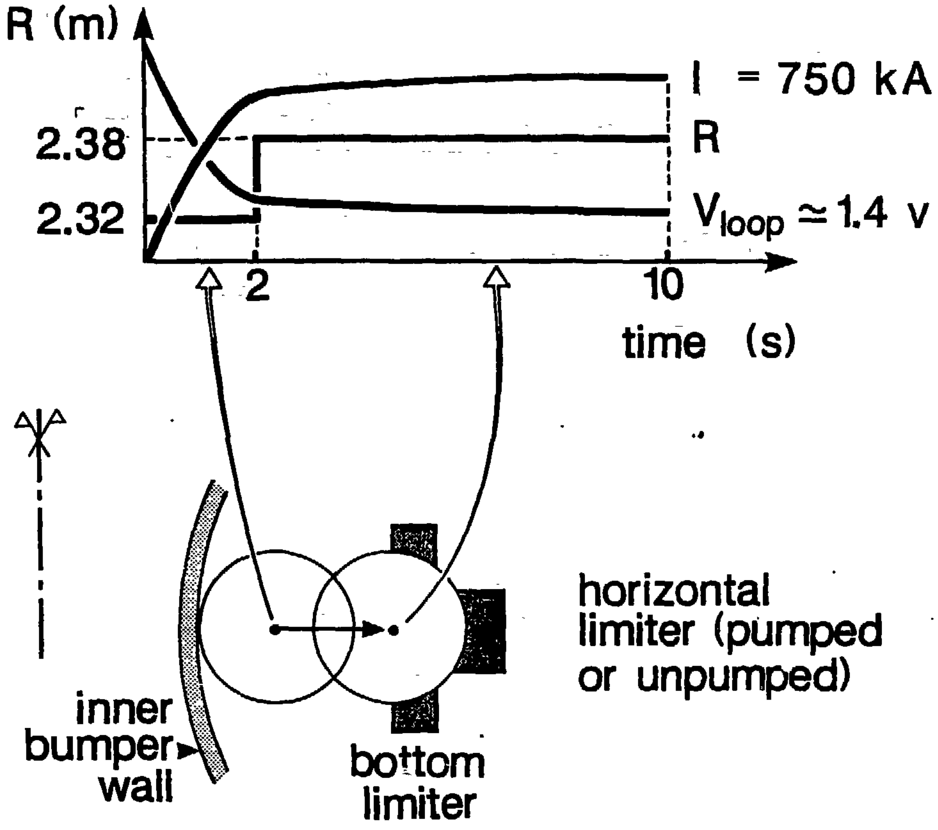
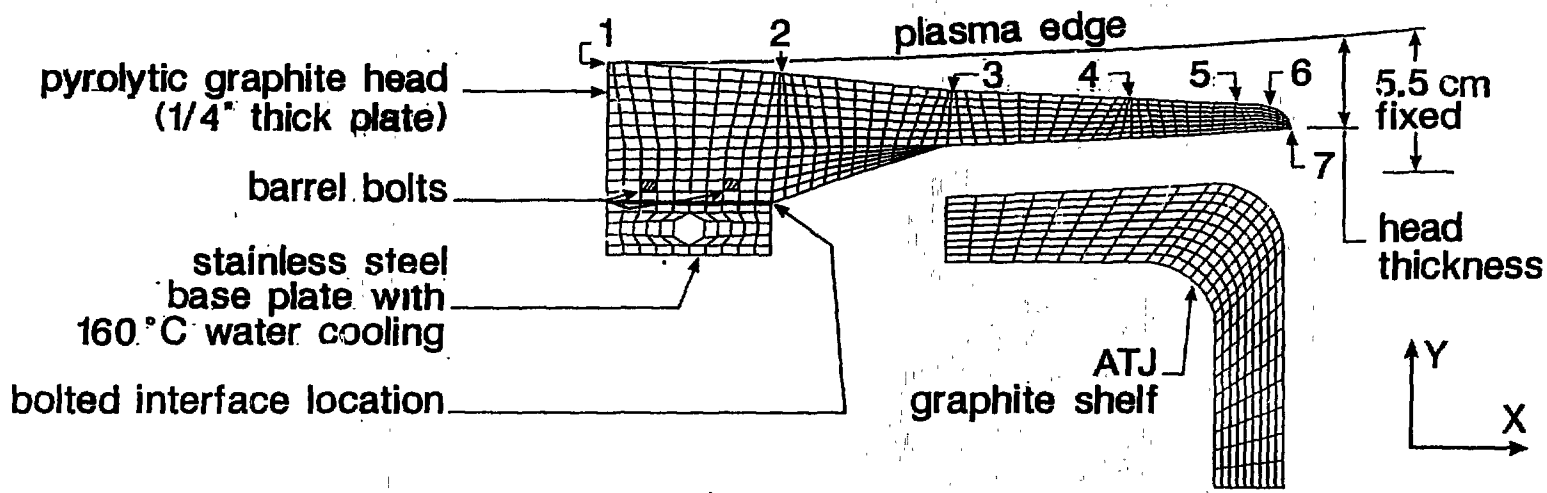


FIGURE 3: Operating experimental scenario used.



BASE LINE CONCEPT USED TO PERFORM COOLING STUDIES FOR THE UNCOOLED PHASE HEAD

FIGURE 4: Base line concept used to perform cooling studies for the "uncooled phase" head.

PIECE	AREAS (m^2)	PHYSICAL PARAMETER
VACUUM CHAMBER	90	
OUTER WALL (OW)	62	$W_{OW} \simeq \frac{62}{90} W_R$
INNER WALL (IW)	12	$W_{IW} \simeq \alpha W_C + \frac{12}{90} W_R$ $(0 \leqslant \alpha \leqslant 1)$
OUT BOARD PUMP LIMITER (OPL)	0.3	$W_{OPL} + W_{TBL} = W_C$ (when $\alpha = 0$)
TOP LIMITERS BOTTOM (TBL)	6x0.16 1	
ERGODIC DIVERTOR (EDS) STRUCTURES	3	$W_{EDS} = \beta W_C$ $(0 \leqslant \beta < 1)$
ERGODIC DIVERTOR (EDN) NEUTRALISERS	0.25	$W_{EDN} \simeq \gamma W_C$
PORTS	10	

W_R : radiated energy

W_C : conducted–convected energy **TABLE 1**

FIGURE 5: Calorimetric and bolometric measurements. TABLE-I

P(kW)	all limiters shot 1151	horizontal limiter only shot 1158
P_{Ω}	1020	970
$P_B(t = 2\ s)$	325	225
$P_B(t = 6\ s)$	375	275
$P_B/P_{\Omega}\ (t = 2\ s)$	0.32	0.23
$P_B/P_{\Omega}\ (t = 6\ s)$	0.37	0.28

OHMIC (P_{Ω}) AND BOLOMETRIC (P_B) POWER EARLY (t = 2 s) AND LATE (t = 6 s) IN THE CURRENT PLATEAU THE RATIO PB/P_{Ω} IS INDICATED.

FIGURE 5: Calorimetric and bolometric measurements. TABLE-II

W (kJ)	all limiters shot 1151	horizontal limiter only shot 1158
W_C^{OPL}	1750	5180
W_C^{TBL}	2400	540
W_{ED}	660	750
W_C	4600	6330
W_R	1710	1050
W_T	6520	7520
W_R / W_T	0.29	0.16

CALORIMETRIC DETERMINATION OF RADIATED W_R AND CONDUCTED OR CONVECTED W_C ENERGY ONTO THE OUTBOARD (OPL) TOP AND BOTTOM LIMITERS (TBL) ERGODIC DIVERTORS(ED THE RATIO OF RADIATED TO TOTAL ENERGY (W_T) IS GIVEN.

FIGURE 5: Calorimetric and bolometric measurements. TABLE-III

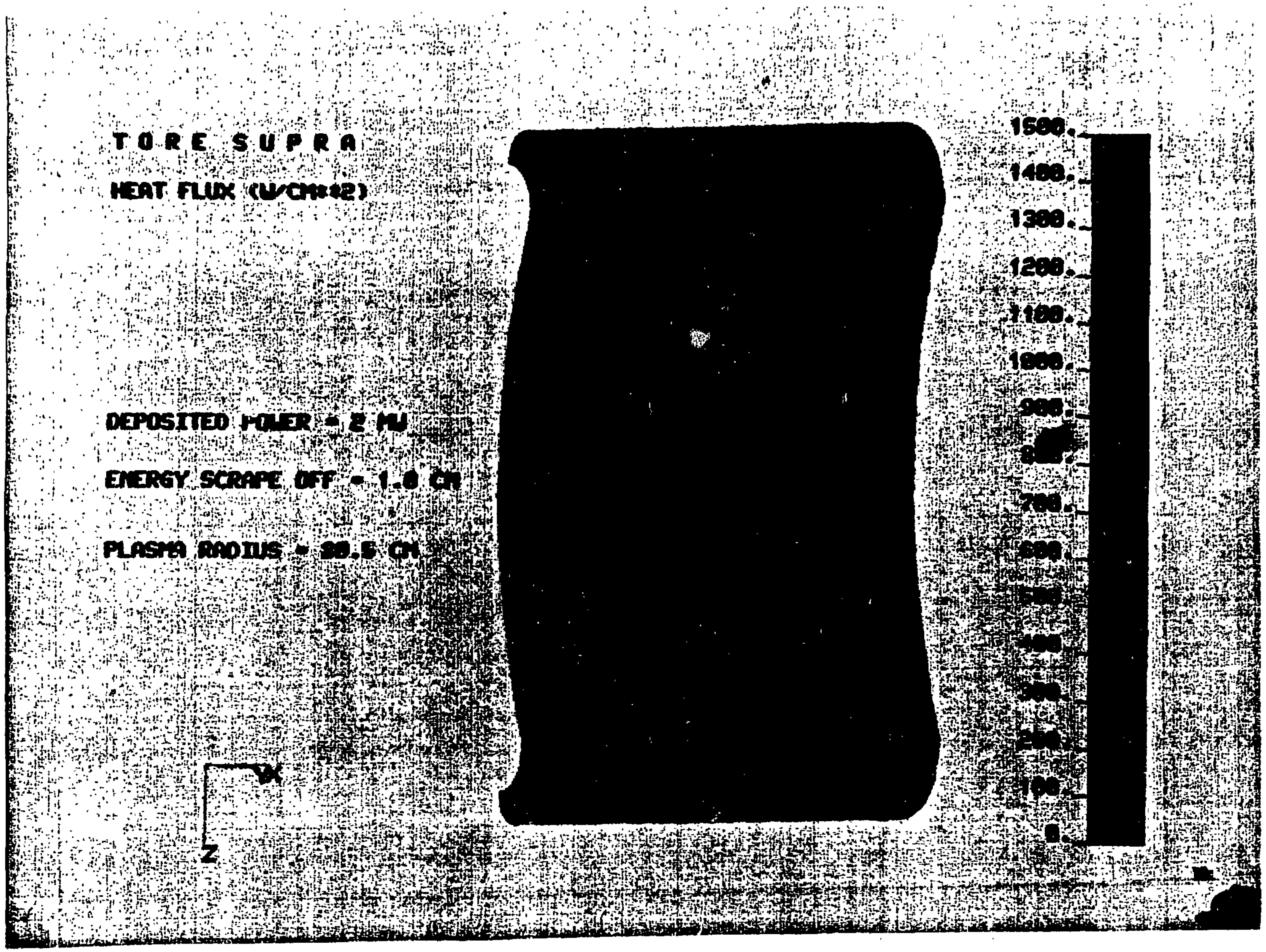
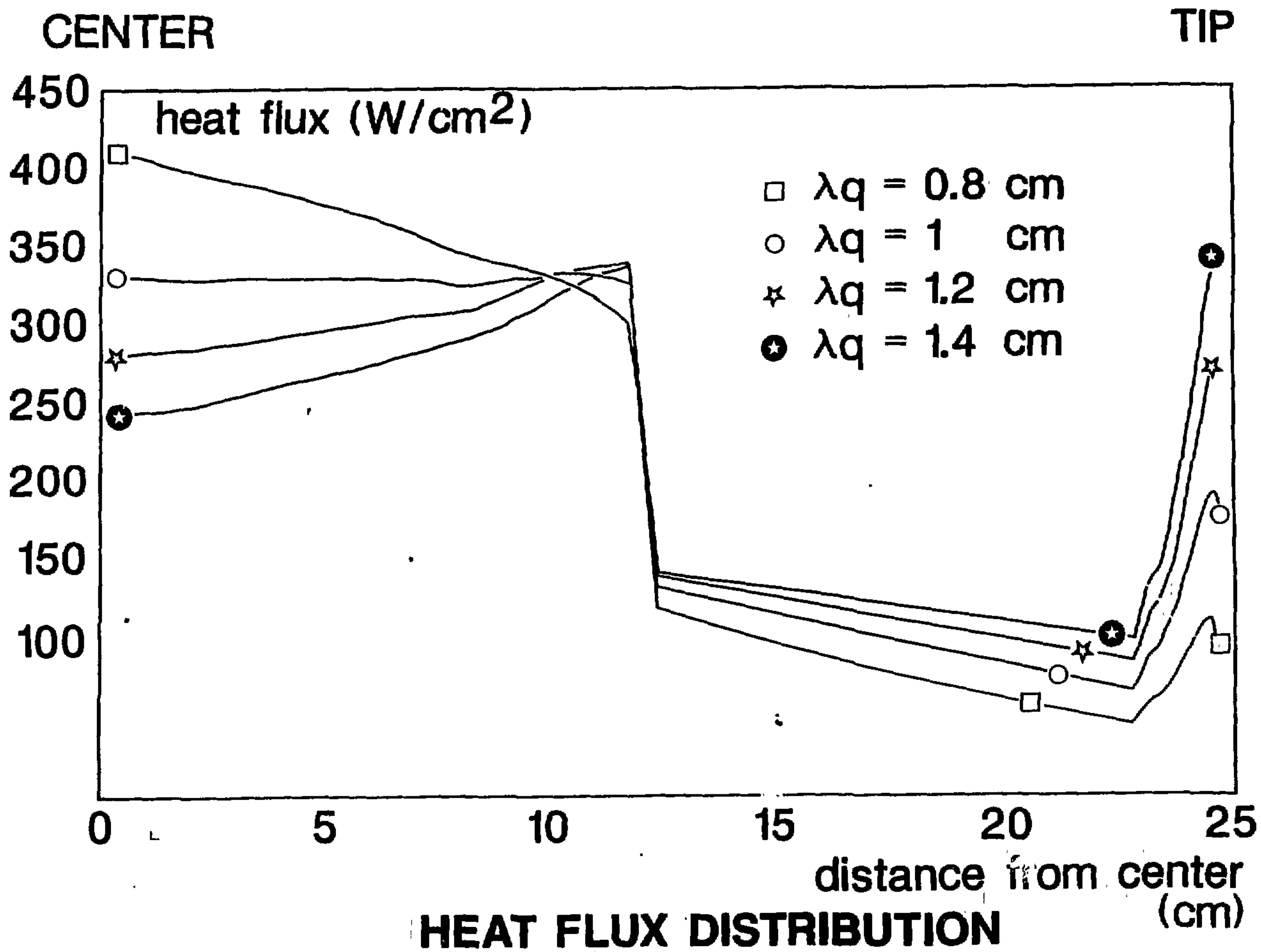
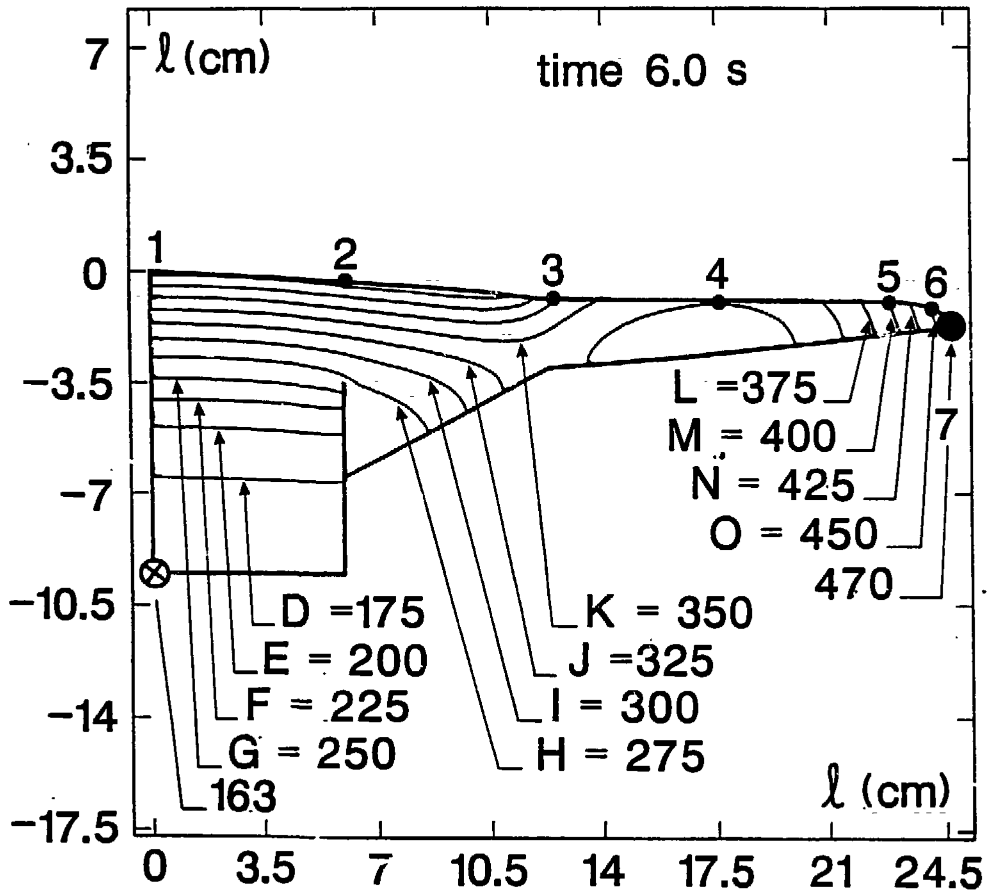


FIGURE 6: Simulation of fluxes received by the pump limiter taking into account the real geometry of the limiter head and an e-folding length for power deposition of 1cm.

FIGURE 7: Heat flux distribution falling on a blade situated in the equatorial plane for different e-folding lengths.





2D IR COMPARISON (1 cm SCRAPE OFF)

FIGURE 8: Section of the blade situated in the equatorial plane showing the isotherm contours assuming an 1cm e-folding length for power deposition, a 750kW total power flowing to the limiter head, at a time t=6 seconds after the beginning of the shot. Note the locations 1,2,...7 used in figure 12

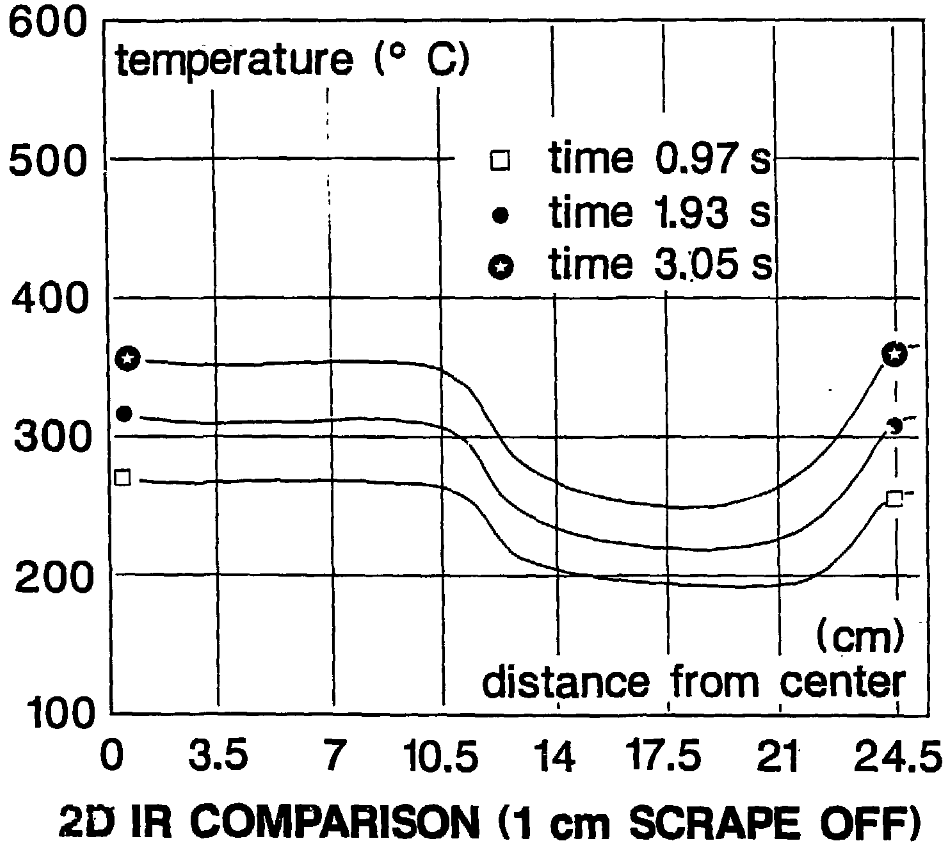


FIGURE 9: Temperature profiles at 3 different times during a shot, of the central blade along the equatorial plane. Th e-folding length for power deposition is 1 cm and the total power flowing to the limiter head is 750kW.

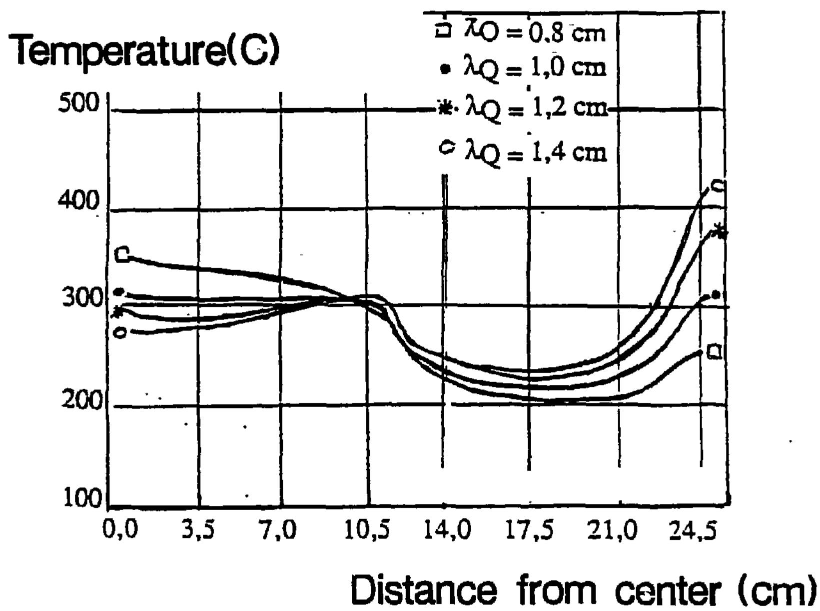


FIGURE 10: Temperature distribution of the central blade along the equatorial plane, for a total power of 750kW flowing on the limiter head and for different power deposition e-folding lengths.

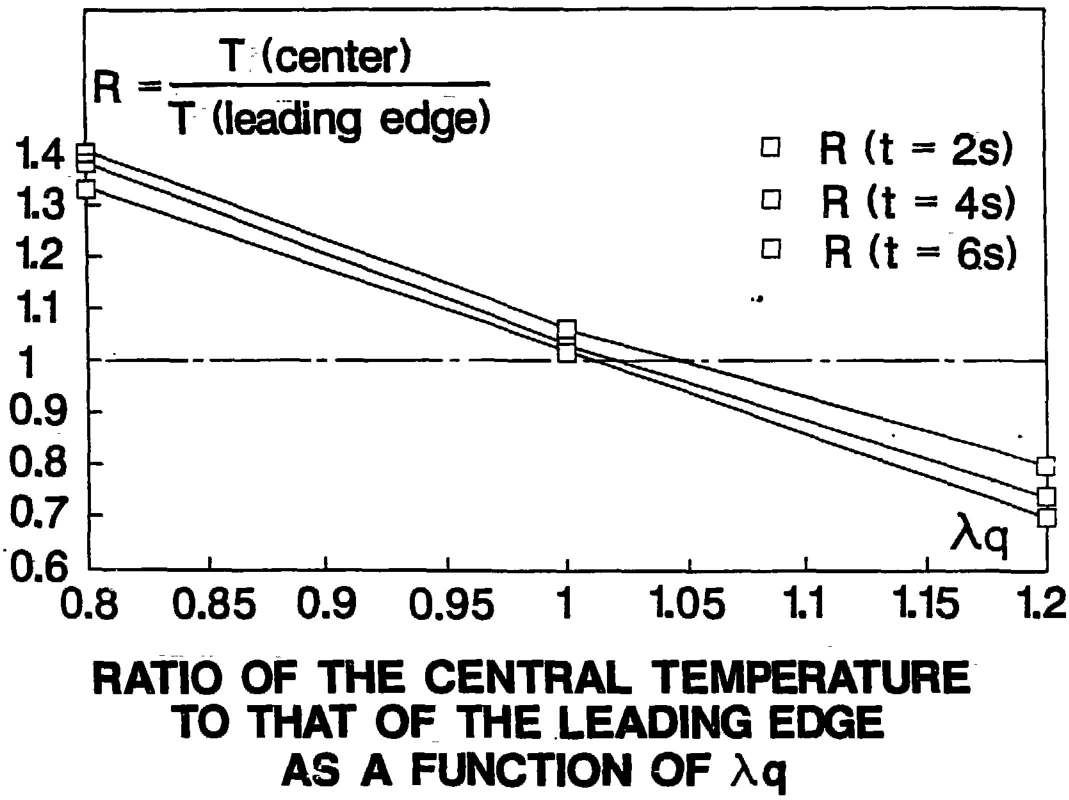


FIGURE 11: Ratio of the central temperature to that of the leading edge as a function of the e-folding length for power deposition.

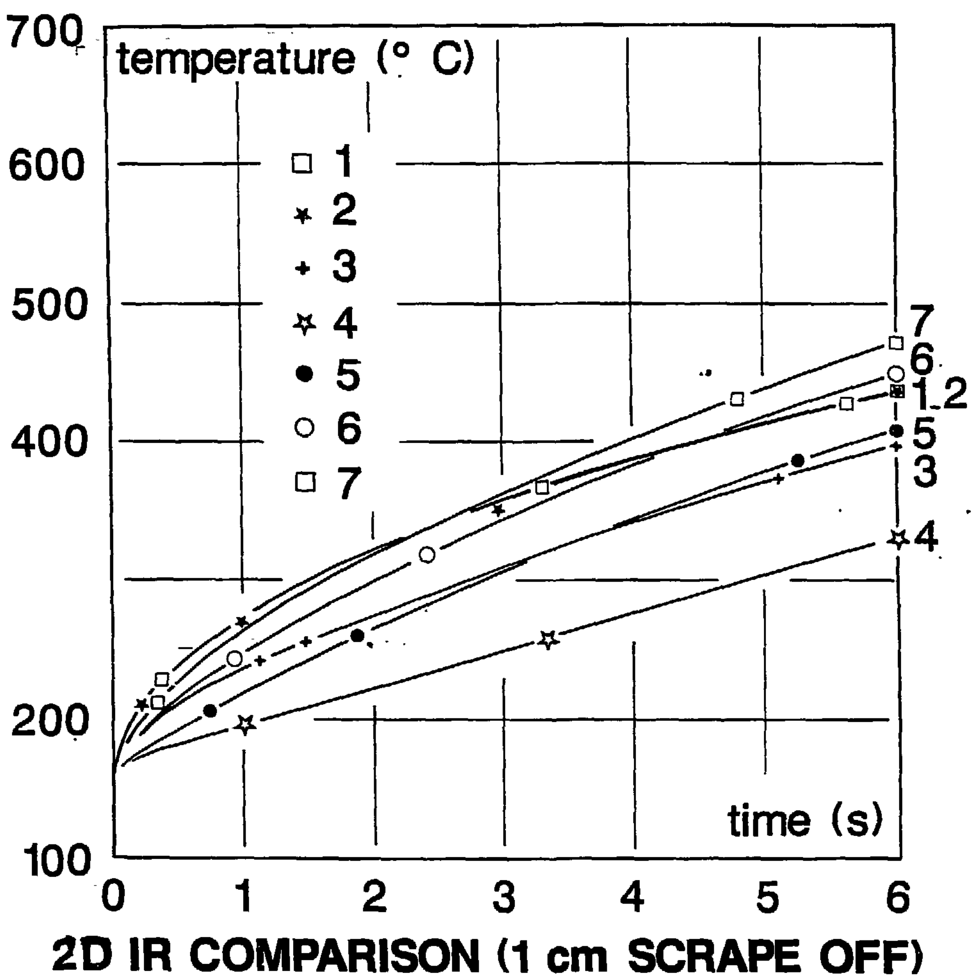


FIGURE 12: Temperature time history for different locations situated on the central blade along the equatorial plane, see figure 4 for localisation of these points marked

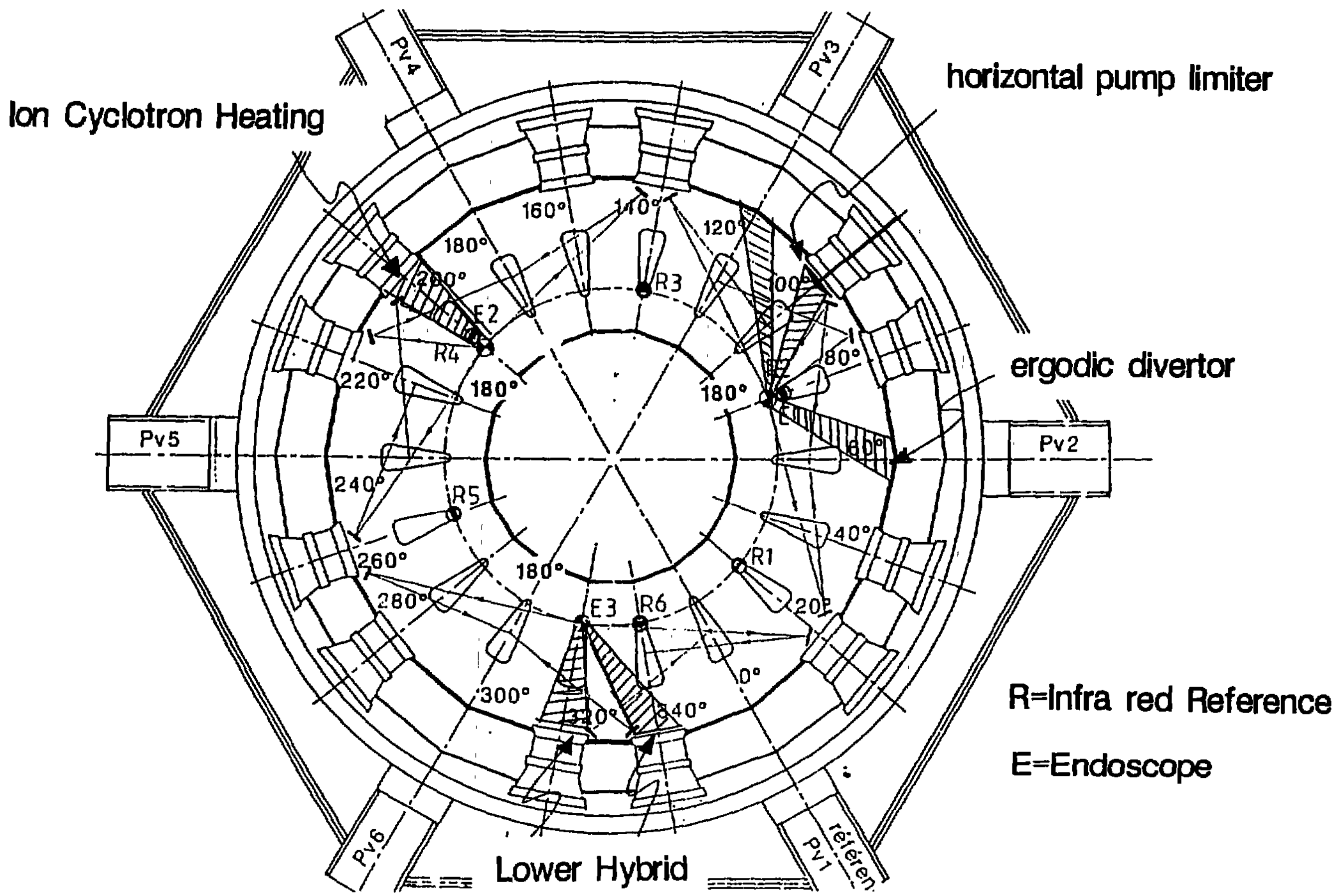


FIGURE 13: Equatorial view of the machine showing the position of the endoscopes and the references.

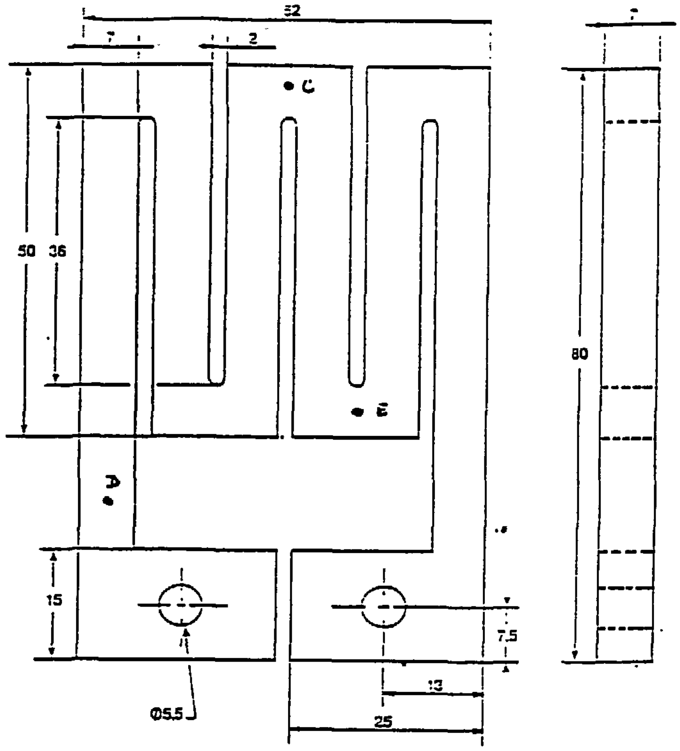


FIGURE 14: Infra-red reference made by graphite resistor in which up to 150 Amperes are flowing. In this case the surface temperature is 1000°C.

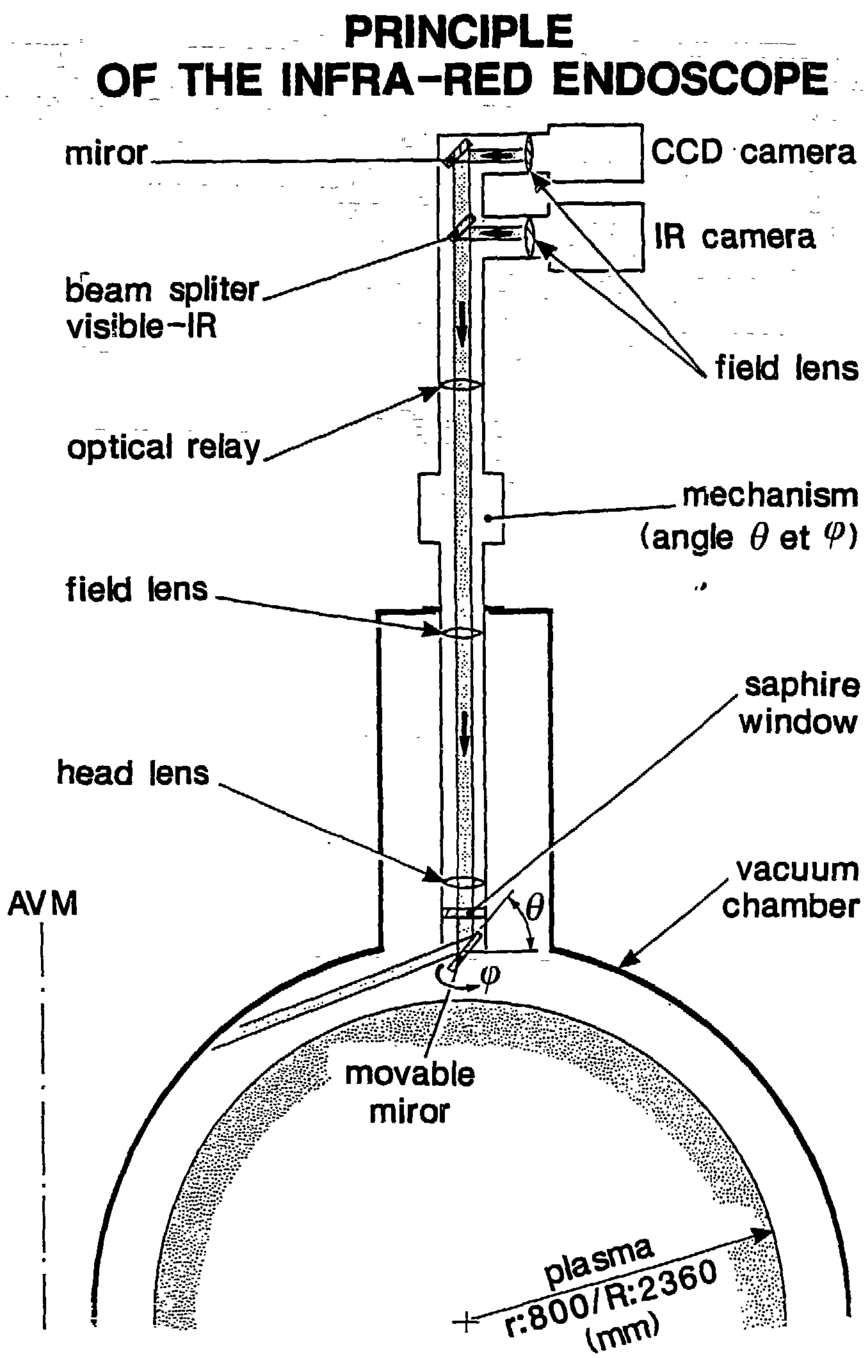


FIGURE 15: Layout of one endoscope showing the infra-red camera, CCD camera, optical relays, field lenses, saphire window, movable miror to change the view and finally the mechanism to rotate the mirror.

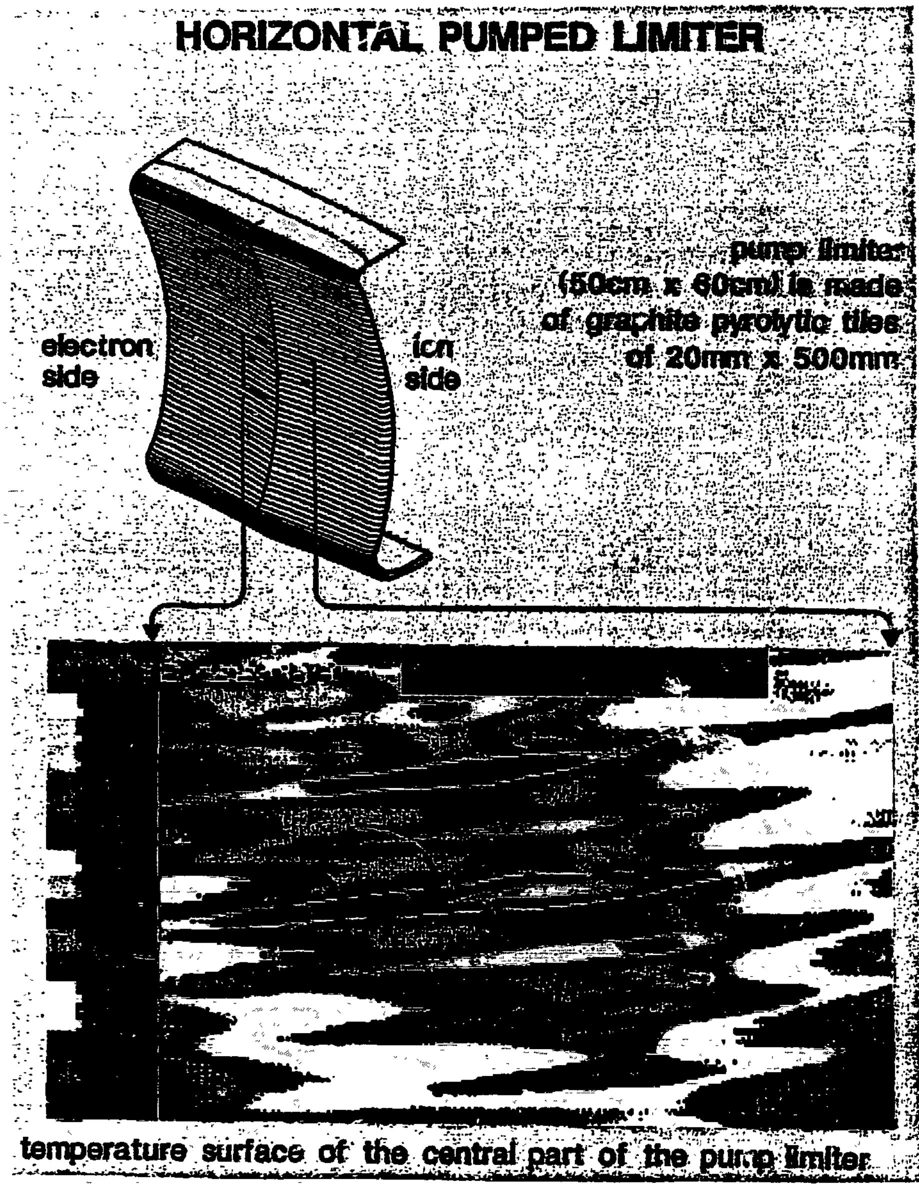
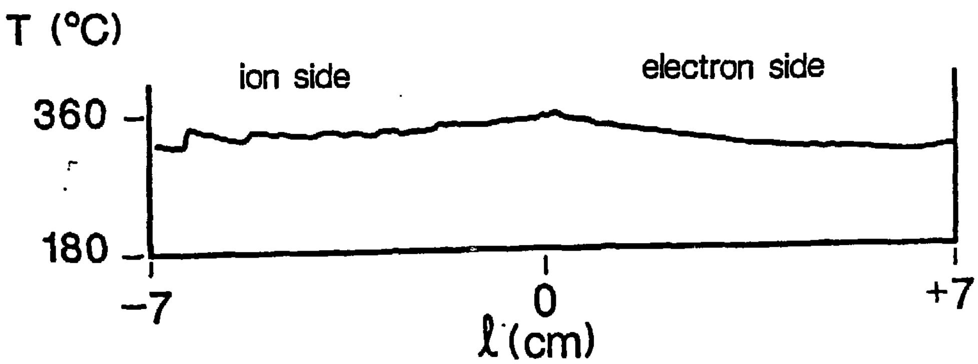


FIGURE 16: Temperature surface of the central part of the horizontal pump limiter (14cm horizontal field of view and 10cm vertical field of view) in an ohmic discharge.



temperature profile using the horizontal limiter as the only limiter in TORE-SUPRA :

Ip = 750kA , t = 8s

- Tmax = 370°C
- λq = 9mm ±1mm
- Symmetric profiles

FIGURE 17: Temperature profile of a central blade in the equatorial plane in an ohmic discharge using the horizontal pump limiter as the only limiter in the machine. I_p=750kA, t=8s, T_{max}=360°C, λ_q=9mm 1mm, symetric profile on each side of the tip.

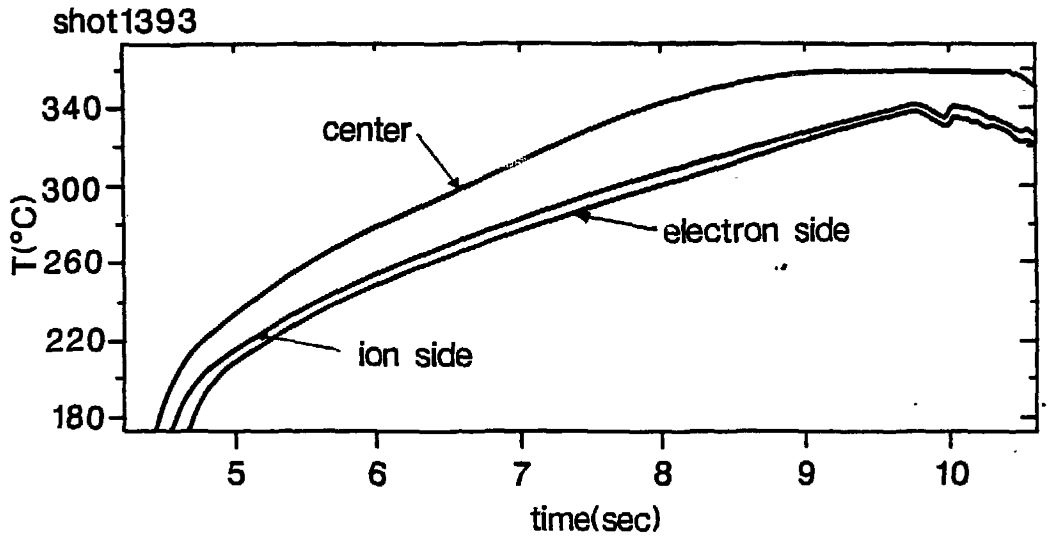
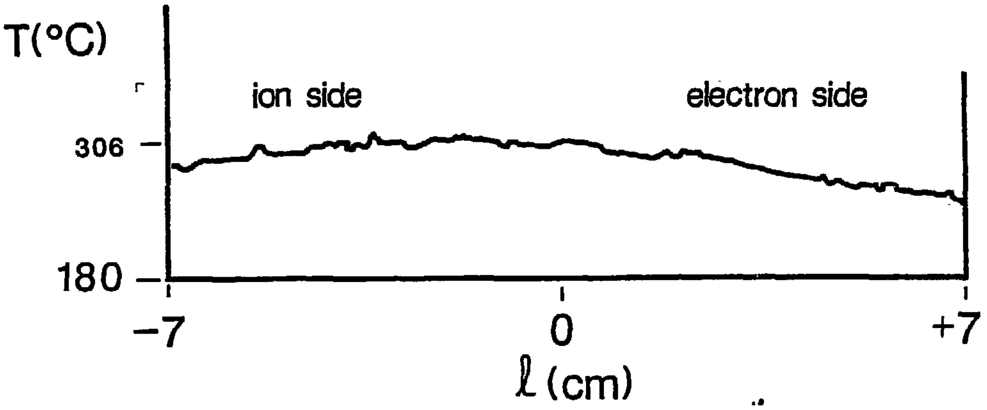


FIGURE 18: Time history of the surface temperature at the tip and on the ion and electron drift sides (see locations of these points on figure 16). The maximum temperature reached is 360°C (note here the saturation of the infra-red camera).



temperature profile using the full set of 7 limiters available in the machine : Ip = 750kA , t = 8s .

- Tmax = 305°C
- $\lambda q \simeq$ 10 mm on average
- asymmetric profile ⟹ shadowing effect with the other 6 limiters

FIGURE 19: Temperature profile of a central blade in the equatorial plane in an ohmic discharge using all the pump limiters in the machine. I_p=750kA, t=8s, T_{max}=306°C, λ_q=9mm 1mm, asymetric profile.

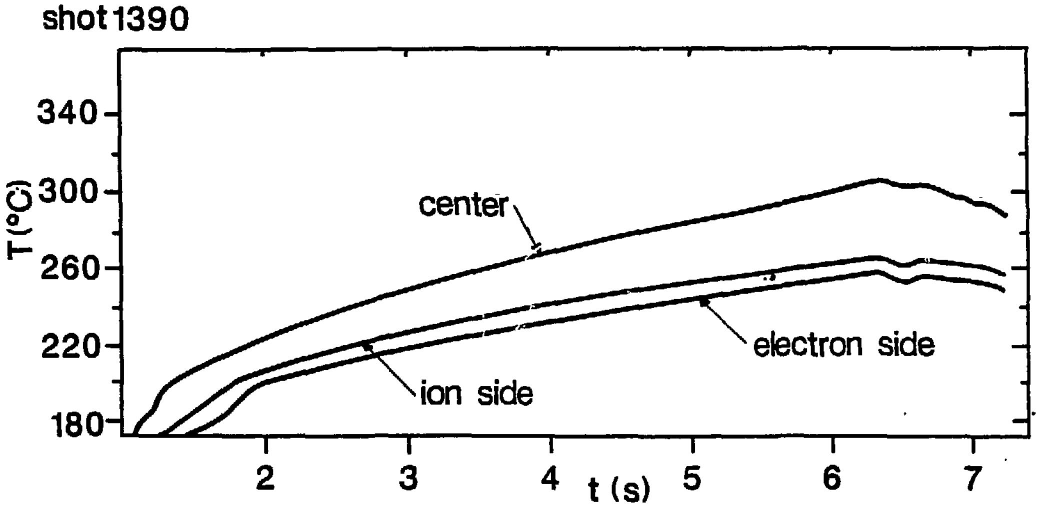
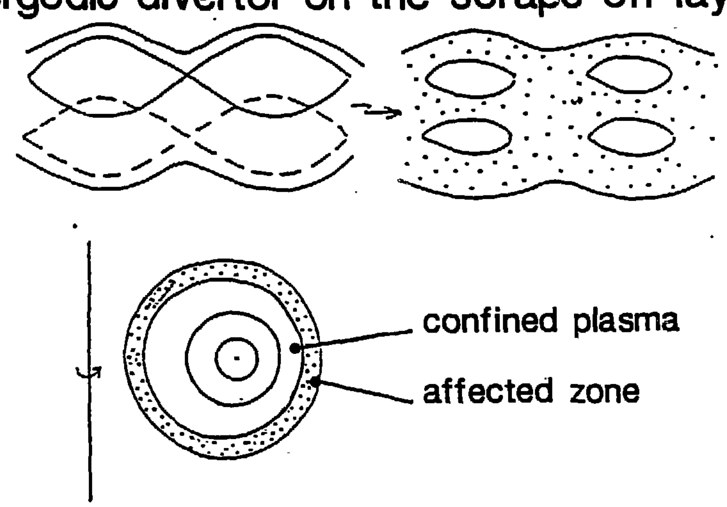


FIGURE 20: Time history of the surface temperature at the tip and on the ion and electron side (see locations of these points on figure 16). The maximum temperature reached is 306°C (note here the asymmetry of the temperature).

EFFECTS OF THE ERGODIC DIVERTOR ON THE PUMP LIMITER

the plasma is leaning on the outboard pump limiter used to visualise the effects of the ergodic divertor on the scrape off layer



study of two free parameters associated with the ergodic divertor

- current in the divertor → size of the structures
- plasma current → q -EDGE → mapping of the structures

FIGURE 21: Effect of the Ergodic divertor on the magnetic topology at the boundary of the plasma.

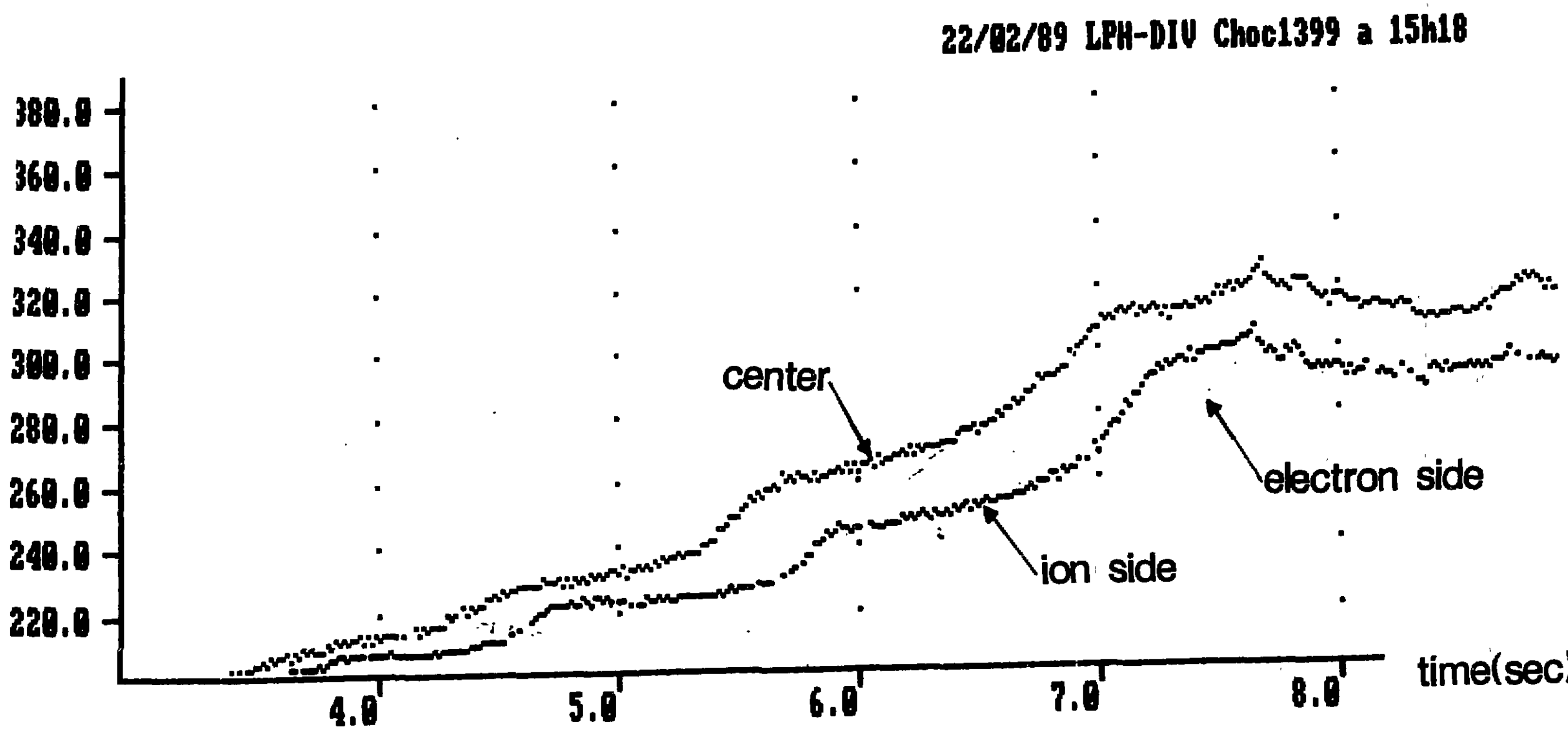


FIGURE 22: Variation of the surface temperature of the pump li[illegible] when the plasma current is ramped up at a constant [illegible] in the ergodic divertor. The modulation of the temperature due to the magnetic island, passing trough the limiter head is clearly seen

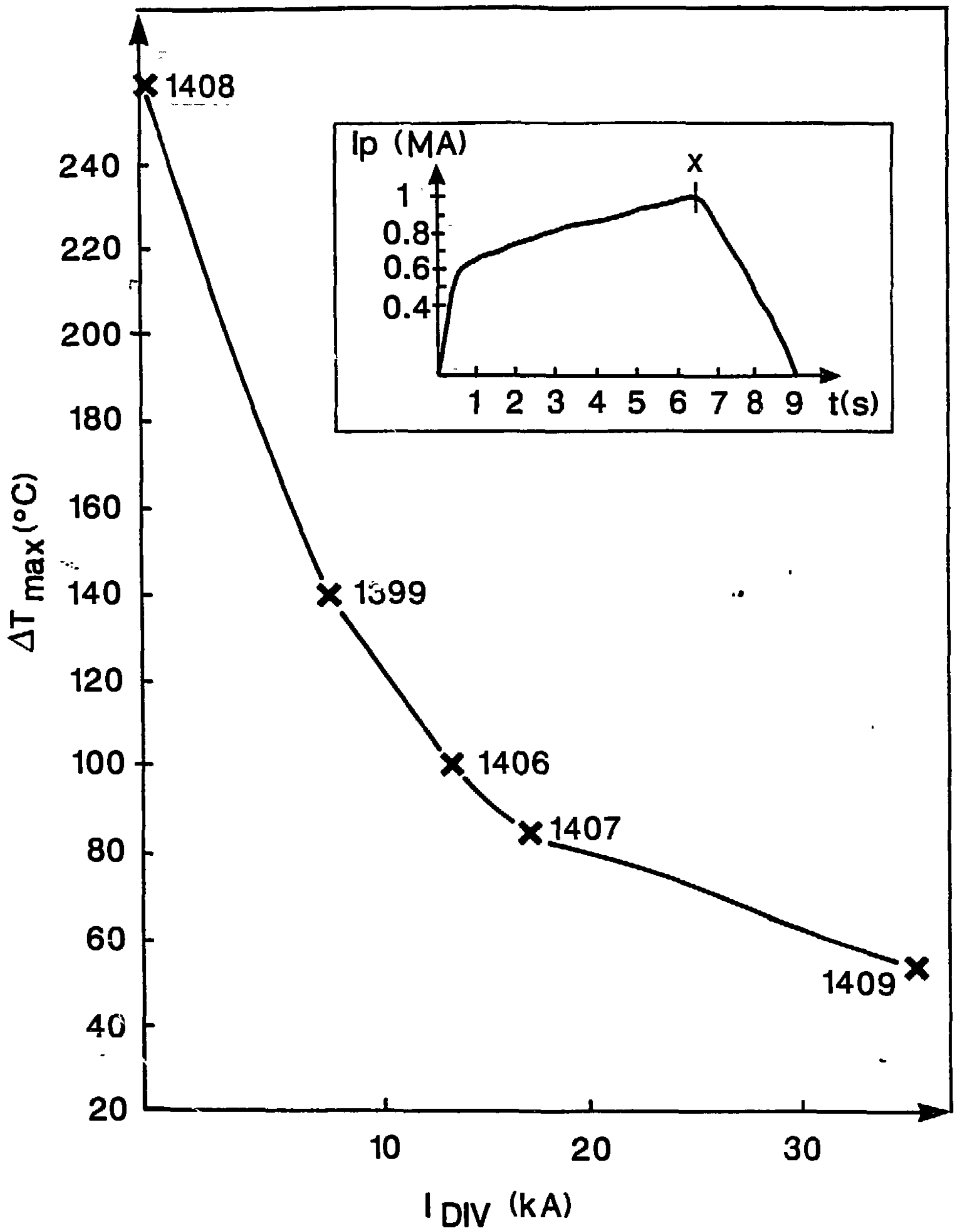


FIGURE 23: Drop of the maximum increase of the surface temperature on the horizontal pump limiter, when ergodic divertor current is increased.

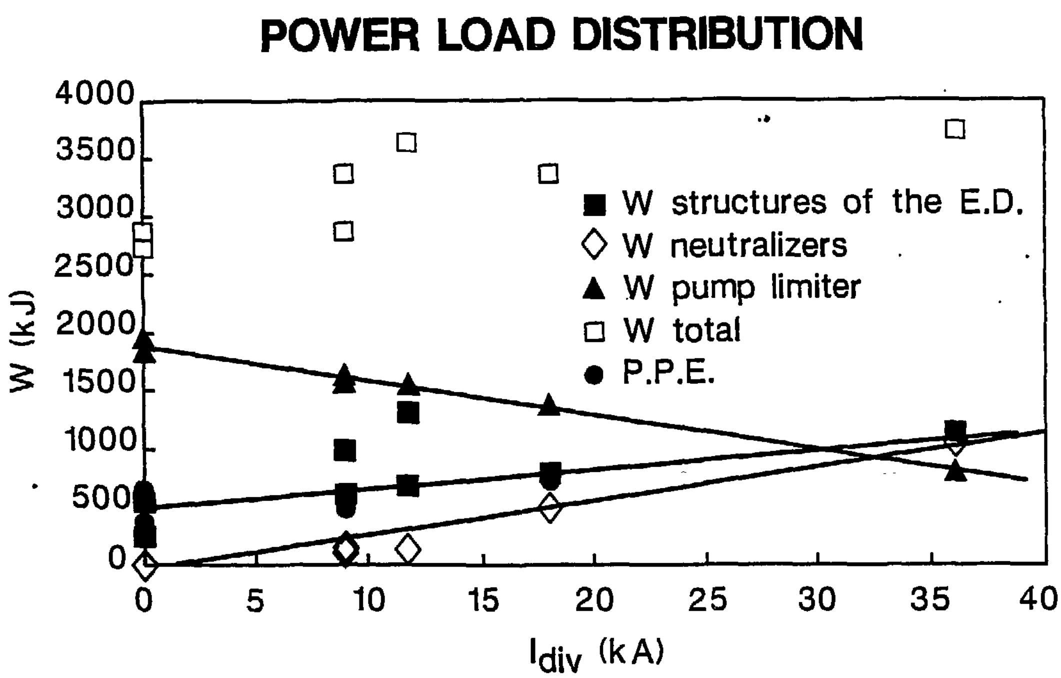


FIGURE 24: Energy deposited on the principal plasma facing components as a fonction of the Ergodic Divertor current. Note the decrease of the energy deposited on the pump limiter and the equivalent increase on all the other structures.

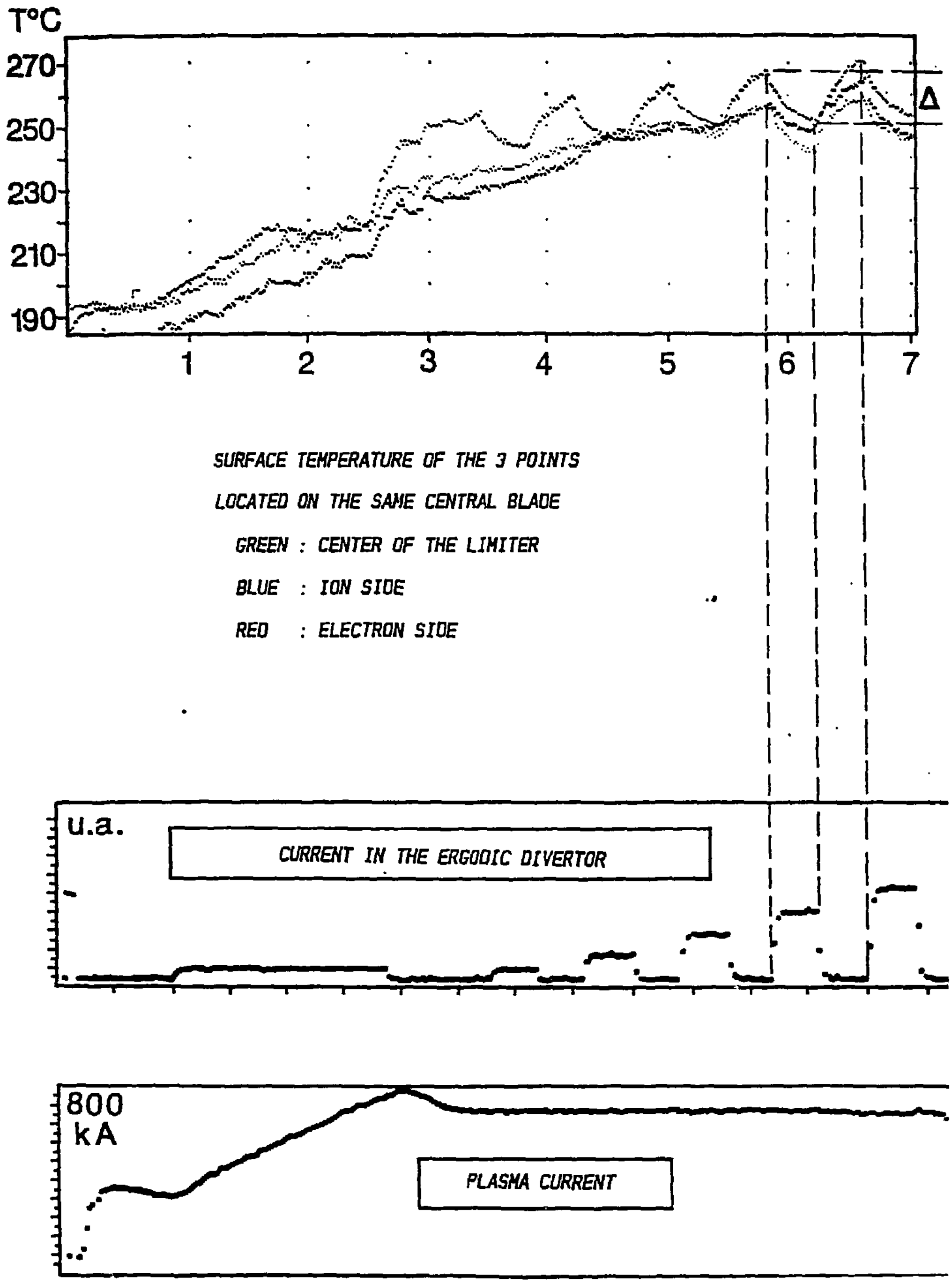
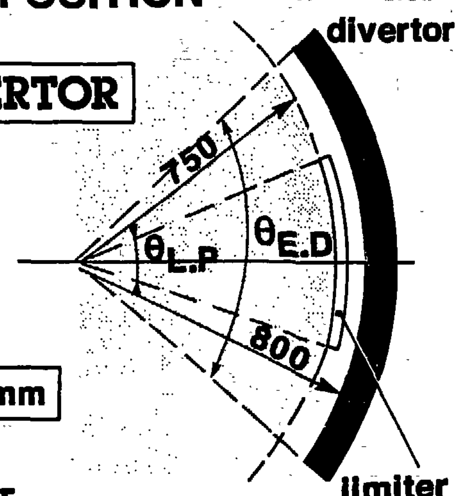


FIGURE 25: Temperature surface modifications as we increase the Ergodic Divertor current at a constant plasma current. The size of the islands are modified.

DETERMINATION OF THE λq FOR POWER DEPOSITION



* WITHOUT DIVERTOR

CALORIMETRIC MEASUREMENT

$$\frac{W_{D.E.}}{W_{P.L.}} = \frac{720\ kW}{5200\ kW} = \frac{R_{D.E}}{R_{L.P.}} \frac{\theta_{D.E.}}{\theta_{L.P.}}$$

$$\frac{EXP(-5/\lambda q) - 0}{1 - EXP(-2.5/\lambda q)} \rightarrow \boxed{\lambda q = 9\ mm}$$

THERMOGRAPHIC MEASUREMENT

by comparing the measured temperature on the pump limiter with the predicted one for the real geometry of the limiter and the magnetic field line including the ripple we can unfold that :

$$\boxed{\lambda q = 9\ mm \pm 1 mm}$$

These two measurements are independent and gives confidence in averaged calorimetrics measurements.

* WITH ERGODIC DIVERTOR

CALORIMETRIC MEASUREMENT : $\boxed{\lambda q = 25\ mm}$ AVERAGED VALUE

THERMOGRAPHIC MEASUREMENT : STRUCTURES → LOCAL VALUES

FIGURE 26: Determination of the e-folding length for power deposition at the plasma edge using the calorimetric measurements.

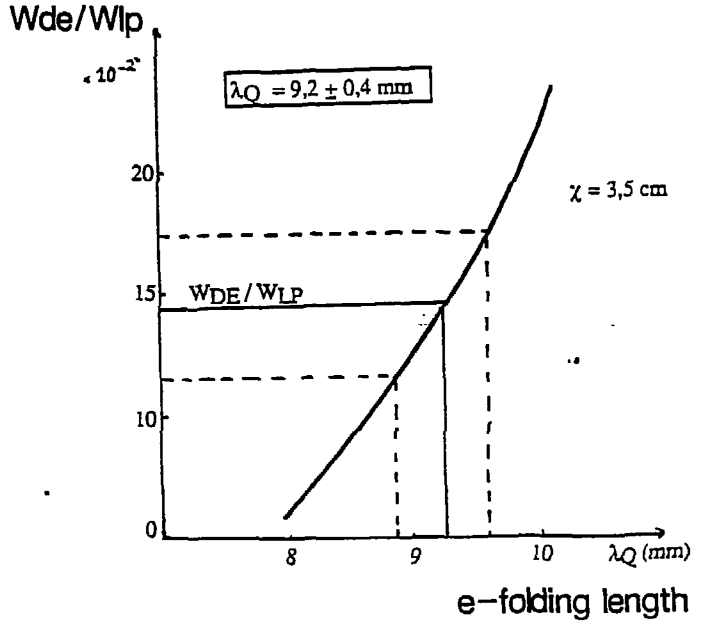


FIGURE 27: Ratio of the energy deposited on the ergodic divertor (5cm in the scrape-off layer) to the energy deposited on the pump limiter, as a fonction of the e-folding length λ_q for power deposition. No current in ergodic divertor lead to λ_q=9.2mm 0.5mm and for the maximum current in the E.D. coils leads to λ_q=25mm 3mm.