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POWER DEPOSITION TO THE FACING COMPONENTS IN TORE-SUPRA.

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Abstract

The modification of power scrape-off-length, λq, and power deposition are studied during various configurations in ohmic TORE-SUPRA plasmas. The plasma is either leaning on the horizontal limiter alone, on the full set of 6 pump limiters or on the inner bumper limiter, all configurations with and without the ergodic divertor system energised.

From comparison of the infrared images of the limiter we derived that the λq for power deposition was slightly less than 9mm (+/-1mm) in ohmic plasma which is in agreement with the predicted design value of 10mm.

Inserting the 6 limiters, instead of 1, does not modify significantly λq, but lead to small asymmetries. The power is shared by all the limiters and the maximum surface temperature on the horizontal limiter decreased. These λq values have been independently determined by calorymetric measurements done on 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.

In the presence of the ergodic divertor we observe a broadening of the scrape off layer, the e-folding length for power deposition reaching 2.5cm. Large asymmetries on power deposition can be seen on the front face of the limiter leading to the formation of hot spots at the leading edges.

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1. Introduction.

The experimental conditions [1] envisaged for Tore-Supra operation, i.e. large additional heating power to the plasma (25MW) for long pulse duration (30seconds or more) emphasized the need to find 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 (called "the Carbon bloom") when operating in an all graphite environement [2].

Tore-supra is a medium size machine (R=2.365 m ; a=0.8 m) aimed to tackle problems relevant to the next generation of tokamaks.

This tokamak is entirely designed for long pulse operation [3] 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 (25MW, 30s). We have large areas of plasma-wall interaction and at least 3 different regimes can be distinguished, figure 1:

- I) A discrete limiter regime where 7 limiters [4],[5] [6], [7], are used to control the plasma density and heat removal with external fuelling sources (gas, pellets and neutral beams). The set of limiters is designed to handle 8 MW (1 MW for each of the six vertical limiters and 2 MW for the horizontal limiter) and to remove between 50 and 100 $\mathrm{t.l.s}^{-1}$.

- II) An inner bumper limiter regime where the plasma is leaning on the toroidal bumper limiter capable of handling up to 13 MW in a D.C. regime. This large limiter is made of graphite tiles brased on an actively cooled stainless-steel structure. Its surface of 12 m^2 represents a large fraction of the 90 m^2 inner vessel area.

- III) A divertor regime [8],[9],[10] where the plasma is pushed on the ergodic divertor coils (6, equally spaced inside the machine). The aim of the ergodic divertor is to bring up externally driven modes which create an ergodic magnetic boundary layer. The role of the radial field perturbation is to connect "gently" the ergodic layer to the outer limiters and facing components. The goal to be achieved by this system is to enhance drastically the transport in the edge without destroying the bulk properties. The main effects expected are: 1) a lowering of the temperature at the edge and thus at the wall and limiters to reduce the production of impurities,

2) an increase of density at the plasma edge to facilitate particle removal by pumping ducts installed between the winding of the current bars. These channels lead particles to titanium pumps (for H_2 or D_2) installed on the 2 sides of each ergodic-divertor

coil.

3) to prevent impurity ions to backstream along the field lines to the bulk of the plasma . The ions are expected to be dragged out by friction and contained near the neutraliser plates.

Of course these 3 independent regimes can be mixed up by a proper choice of plasma position and radius and by moving the pump limiter positions.

2. Experimental conditions.

Different operating scenarios have been used so far on TORE-SUPRA, depending on the scientific program accomplished. Usually 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 horizontal pump limiter (R=238cm, a=75cm). A first comparison is made hereafter of the thermal load when the plasma is in contact either with the horizontal pump limiter alone or with the horizontal pump limiter and the vertical limiters. Secondly a comparison is made of the thermal load on the horizontal pump limiter, used alone to limit the plasma, with different shapes and magnitudes of plasma current and for different values of the ergodic divertor coils current.

3. Diagnostics.

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.

Calorimetric measurements of the different components are made by extensive use of thermocouples enbeded in the structures of the machine. These measurements provide estimates of the time integrated balance of the energy flow at the plasma edge. Radiated and charge exchange energy losses are deduced from the vessel calorimetry (R=242cm, a=94cm), conductive/convective losses onto the horizontal pump limiter and vertical (top and bottom) limiters are independently measured as well as the integrated energy flow on the ergodic divertors, which are located 5cm in the scrape-off layer (R=238cm, a=80cm) figure 1. An infra-red camera placed on the top of the machine is wieving the pump limiter head through an endoscope. The infra-red camera has been absolutely calibrated by means of absolutely calibrated infra-red references placed under vacuum in the machine.

4. Experimental results.

4.1 Plasma leaning on the horizontal pump limiter only.

The pictures of the infra-red camera give the temperature distribution on the horizontal pump limiter face 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 or 200°C. The detailed heating pattern of the face is rather complex as can be seen on figure 2. This figure presents a map of the temperature on the pump limiter face. The temperature profile is almost symmetric with respect to the tip . The maximum temperature of the central blade is 370°C near the end (t=8s) of the current plateau (Ip=750kA) in an ohmic plasma. From the temperature profiles and the synthetic profiles from a numerical model [13], [14] we can unfold that the e-folding length for power deposition λ_q is 9mm 1mm. The e-folding length unfolded by calorimetric measurements is 10mm 1mm. The latter is an averaged value all around the torus. The power load of the pump limiter reached a maximum value of 2.4MW.m^{-2} .

4.2 Plasma leaning on all pump limiters.

When inserting at the same radius r=75.5cm, the full set of 6 limiters, using the same plasma parameters, one finds that the maximum temperature decreases to 305°C at the center of the pump limiter. From the profiles and from the outputs from the code, we can unfold an e-folding length larger than in the single limiter configuration: 10mm 1mm. 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 dependent on the safety factor q at the edge.

4.3 Effects associated to the ergodic divertor.

The plasma is leaning on the horizontal limiter acting as the only limiter in the machine and used to visualise the effects of the ergodic divertor on the thermal and particle fluxes in the scrape-off layer. The detailed heating pattern of the face is complex as can be seen on figure 3. This figure presents a map of the temperature of the pump limiter face. The temperature profile is no longer symmetric with respect to the tip. The largest power deposition is on the upper half of the ion drift side and on the lower half of the electron drift side. The leading edges experiences large asymmetries on each sides in the poloidal direction. The maximum temperature of the center of the face is 320°C (instead of 480°C) on the flat top (t=7s) of the current plateau (Ip=1.4MA). An important feature is that we have created a hot spot on each of the leading edges. For exemple on the ion drift side the temperature at the end of the current plateau (t=7s) is 430°C when the ergodic divertor is on and 370°C without. All these effects can be seen on figure 4 showing the time history of 3 points (see location on figure 3) on the upper part of the ion drift side. As soon as the ergodic divertor is switched on, a striking temperature decrease can be observed on points located at the center of the pump limiter and near the tip whereas the leadding edge heats up even faster. These local structures on the front face of the limiter are being modelled in reference [14]. This relative temperature increase of the leading edges compared to the tip, corresponds to an increase of the e-folding length for power deposition at the edge. This is confirmed by calorimetric measurements which show a large increase of the ratio of energy deposition onto the ergodic divertor structures (5cm deep in the scrape-off layer) to the energy deposition on the limiter (λq=2.5cm). So far we have been using a provisional inertially cooled limiter. This situation will be improved by replacing it by a limiter head designed to be actively cooled so that 3kW/cm^2 can be removed permanently even at the leading edges.

Some more features and results can be found in reference [11] on thermal load on the first wall and on particle exhaust, in reference [12] and [13] for plasma modifications, in reference [14] on the power deposition modifications in the scrape-off-layer and [15],[16] on modeling of the power deposition on facing components.

5. Conclusion.

The insertion of 6 limiters do not modify significantly the e-folding length for power deposition which is 9mm in the single limiter experiment and 10mm in the multi-limiter configuration. The temperature profiles are almost symmetric in the single limiter configuration and slightly asymmetric in the multi limiter configuration, depending on q at the edge (shadowing effect).

The ergodic divertor has proved its efficiency in spreading the heat flux deep in the scrape-off layer, with a decrease by 3 of the averaged temperature on the whole head when the current in the ergodic divertor is maximum (45kA). The e-folding length for power deposition, estimated by calorimetry, is 25mm. The heat load of the limiter face is asymmetric between top/bottom and ion/electron side.

A drawback is that the ergodic divertor has created hot spots on the leading edges of the pump limiter. So far, no tentative has been made to prevent the formation of these hot spots by a proper choice of experimental conditions (specially plasma current).

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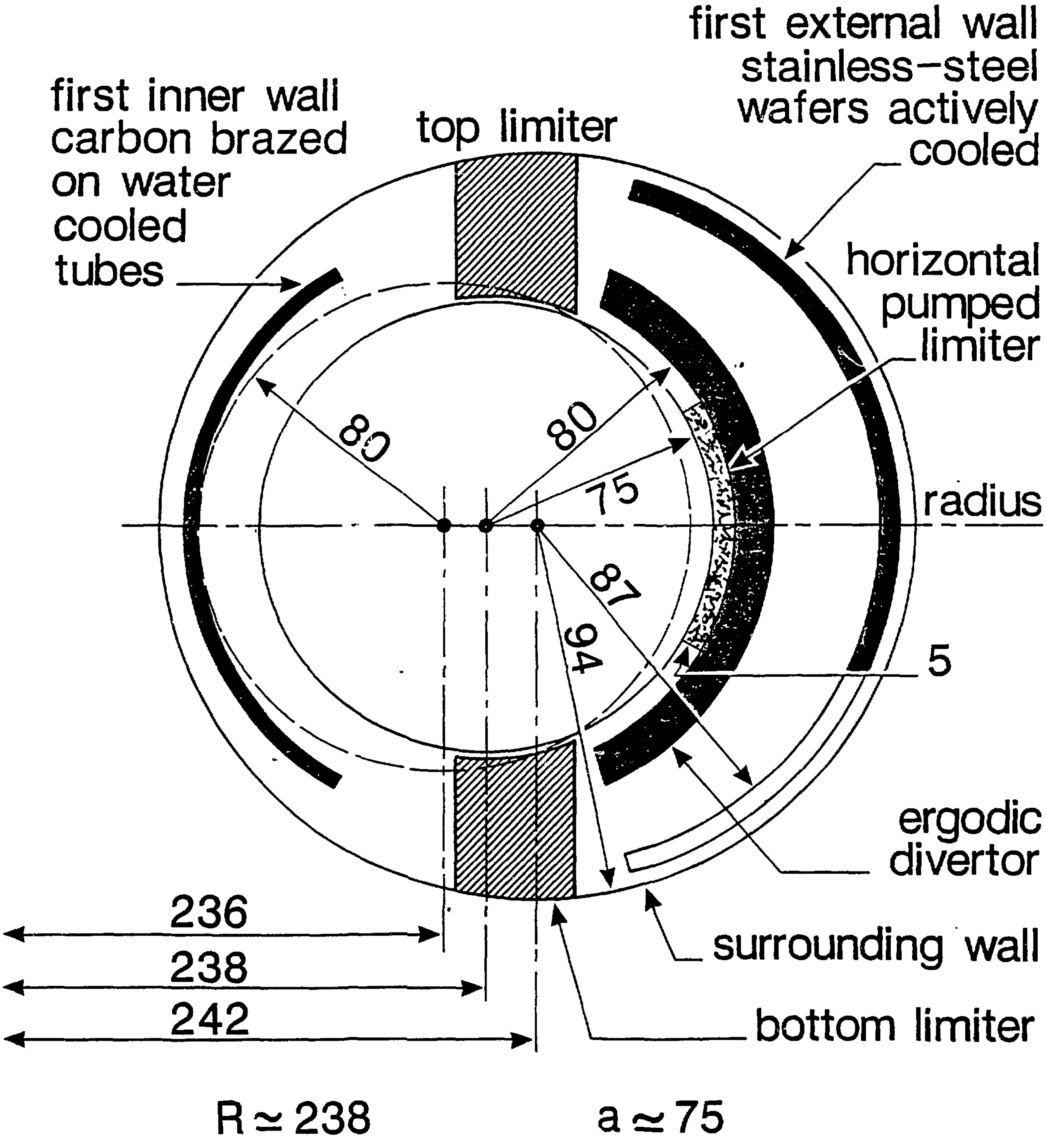
Figure captions:

Figure 1 : Section of TORE-SUPRA showing the respective positions of the limiters, the inner vessel where the plasma can be pushed on, the ergodic divertor and the external first wall. All these components are actively cooled (200°C, 40bars).

Figure 2 : Temperature distribution of the front face of the horizontal limiter in the single limiter configuration, at the end of an ohmic shot. The temperature is almost symmetic with respect of the tip.

Figure 3 : Temperature distribution of the front face of the horizontal limiter in the single limiter configuration and in the presence of the ergodic divertor (Idiv=35kA). The temperature distribution is no longer symmetric and structures can be seen.

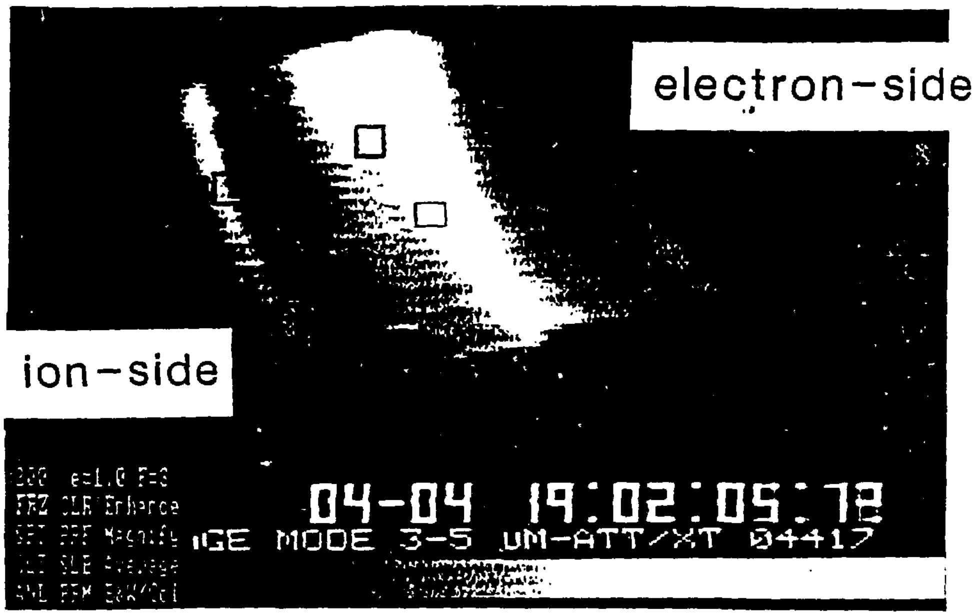
Figure 4 : Time evolution of 3 points (see figure 3) on the ion drift side when the ergodic divertor is switch on. Note the striking decrease of the temperature near the tip whereas the leading edge heats up faster.



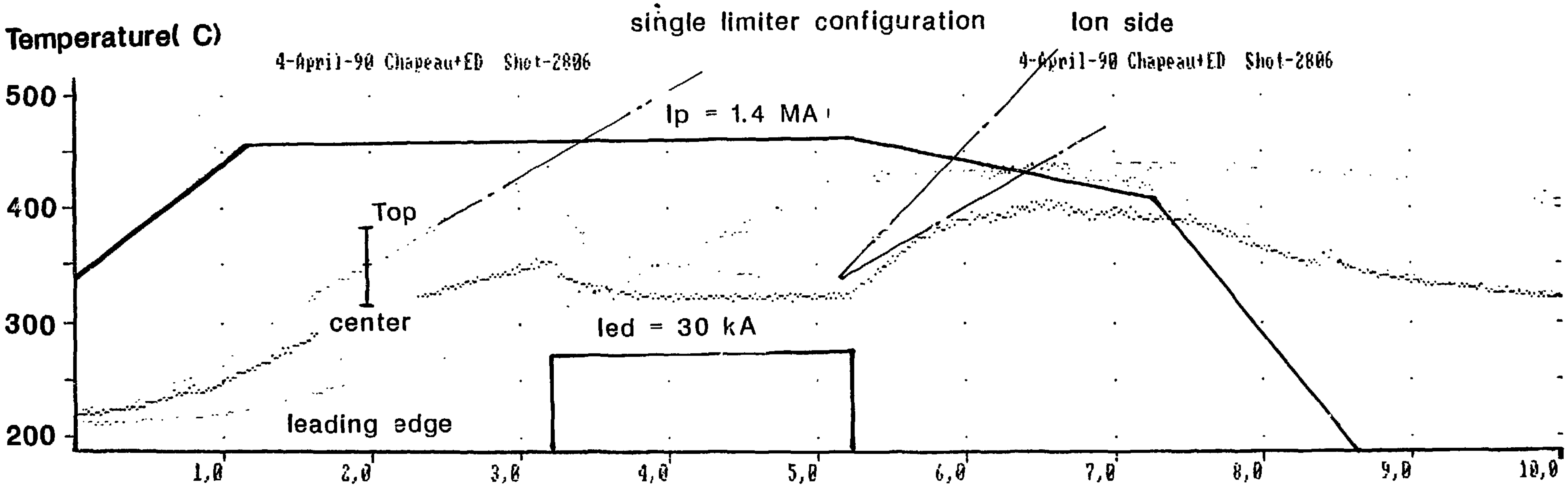
R ≃ 238 a ≃ 75

all dimensions in cm

SINGLE LIMITER CONFIGURATION



Effects of the ergodic divertor:



Temperature(C)
single limiter configuration
Ion side
4-April-90 Chapeau+ED Shot-2806
4-April-90 Chapeau+ED Shot-2806
Ip = 1.4 MA
Top
center
Ied = 30 kA
leading edge
500
400
300
200
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
9,0
10,0

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ERGODIC DIVERTOR IMPACT ON TORE SUPRA PLASMA EDGE*

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Abstract:

Present ergodic divertor experiments in TORE SUPRA have been devoted to benchmarking the operational regimes of the apparatus. Two major effects are reported ; on one hand, strong changes occur in the ergodized boundary layer (up to 20% of the minor radius), and on the other hand, the central plasma and especially the confinement is not directly affected, i.e. the observed modifications are induced by edge effects. The basic trends, which are recorded are a decrease of both the edge electronic temperature and the edge density gradient while the radiated power is increased at the very edge of the ergodic region. The latter feature is in agreement with the impurity line emission characterized by an increase of the peripheral lines with a strong decrease of the central lines.

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1 - Introduction

The ergodic divertor (E.D.) experiment which is a major part of the TORE SUPRA program, aims at the control of the plasma- wall interaction, namely the control of recycling, of power loading and of both the impurity generation and transport [1]. Although the present experiments are devoted to benchmarking the operational regime of the apparatus, significant results on power load control have been achieved.

This paper reports the basic phenomena observed during the initial experiments [2,3] for which the toroidal field was limited to 1.8 T and new experiments at 3.1 T. In the latter case, plasma currents ranging from 1 to 1.6 MA and line average densities from 1 to 3.10^{19} m^{-3} were achieved. Helium and Hydrogenic (H and D) plasmas were studied in the two following configurations.

- an "OUTBOARD" configuration (R=2.37m, a=0.77 m) where the plasma is limited by an outboard graphite pump limiter(scoop operation), in the midplane, some 0.05 m ahead of the E.D. modules.
- an "INBOARD" configuration (R= 2.32 m, a=0.76 m) where the plasma is limited by the inner wall, i.e. a graphite axisymmetric limiter.

The design of the ergodic divertor module is reported in reference [4] and the overall description of plasma-wall components on TORE SUPRA is to be found in [1].

Experimental results are analyzed in view of the theoretical work, see Ref. [5]. The main observations are summarized in section 2. Section 3 is devoted to a more detailed analysis of the heat and particle diffusion modifications. The general trends of these results are reviewed in section 4.

2 - Majors effects of the ergodic divertor

2.1. Resonance

A specific feature of the TORE SUPRA Ergodic Divertor experiment is that the effects of the ergodic divertor are maximized for a specific value of the safety factor at the edge. This global "resonance" is due to a balance between two effects. On one hand the spectrum of the magnetic perturbation determines on which rational surfaces the island chains are created, and thus determines the interaction distances between these island chains. On the other hand the perturbation, and hence the island widths, decreases exponentially towards the plasma center. Therefore, the overlapping of several neighbouring island chains can only occur when the modes in the vicinity of the maximum of the spectrum resonate at the very edge of the plasma. In the θ^*,φ^* space of intrinsic coordinates [5], the Fourier expansion of the magnetic perturbation,

$$\delta B_r = \sum_{m,n} \delta Br_{m,n} \; [\exp i\,(m\theta^*+n\varphi^*) + \text{Complex Conjugate}] \quad (1)$$

exhibits a maximum for $m=18\pm3$. The main toroidal mode number $n=6$ is determined by the toroidal spacing of the modules. This ensures the overlapping of the magnetic islands in a large domain at the edge and a significant fall-off of the perturbation far from the modules : the safety factor for which a maximum harmonic of the perturbation is located at the edge thus ranges from $q=15/6$ (2.5) to $q= 21/6$ (3.5). In agreement with these numerical results on the magnetic topology, the plasma response, described hereinafter, is significant over a wide range of plasma currents $I_p = 1.2 \div 1.6$ MA at $B_T = 3.1$ T. Resonant effects (extrema) are found for $q(a) = 2.9 \div 3$ in both configurations, this is readily expected since the magnetic equilibria are similar ($\beta p + li/2 \sim 0.7$).

Fig.1 shows, as an example, the relative variation of the Hα signal measured on the inner wall in the "outboard" configuration, as a function of the quasi-linear diffusion coefficient D of the perturbed field lines [3]. This coefficient is taken here as representative of the global effects of the ergodic divertor.

2.2. Recycling changes

The "inboard" and "outboard" configurations exhibit quite different recycling changes as the E. D. is turned on. In the inboard configuration recycling diminishes at the inner wall (i.e. the main limiter) whereas the density increases up to 25%. This effect increases with the magnetic pertubation strength, and is now under analysis : note that the studied shots were in Helium.

In the outboard configuration, recycling increases at the inner wall. The density either does not change (Helium shots) or decreases down to 30% (Hydrogen and Deuterium shots) as a possible consequence of wall pumping. The graphite area in contact with the plasma increases which is consistent with the Hα signal increase on chords viewing the inner wall.

In some cases the pressure in the pumping chamber (with no pumping) increases by 40%. However this does not account for the change in n_e (there is a factor 10 deficiency). In other cases, the pressure decreases. The plasma flux deduced from the Langmuir probes data, in the pump limiter throat is in rough agreement with the pressure results.

2.3. Heat flux deposition

Various thermal effects have been observed :

.the spatially averaged heat flux measured by I.R. thermography diminishes by a factor of up to 4 on the main limiter (outboard configuration),

.the calorimetry measurement of the cooling water system indicates that most of this heat deposition is transferred 0.05 m radially outward to the neutralizer plates of the ergodic divertor (located between the bars of the E.D. modules).

These effects appear above a threshold of the magnetic pertubation and are clearly resonant, i.e. they nearly disappear for values the safety factor which lie out of the so called resonant range (from 2.5 to 3.5 in present experiments).

The radiative power losses do not exhibit dramatic changes. In the outboard configuration, these losses remain proportional to n_e. The radiation is enhanced at the very edge but this region is too narrow to modify the power balance.

The average heat load changes quoted above is accompanied by heat load pattern, a theoretical analysis of these asymmetries is given in [6]. More details on heat flux deposition can be found in [7].

2.4. Impurity content .

In the inboard configuration, and during the first set of experiments, an increase by a factor of up to 7 has been observed in the brightness of several metallic lines measured by a grazing incidence V-U.V spectrometer [8]. This is never observed in the outboard configuration where metallic lines remain below the detection limit. The main impurities are then carbon, oxygen and chlorine. In Helium plasmas, C VI appears to be reduced by a factor of two, O VIII remaining unchanged. In deuterium plasmas both lines strongly