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THERMOGRAPHIC AND POWER DEPOSITION MEASUREMENTS ON ALT-II BLADES

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Abstract

On the ALT-II toroidal belt pump-limiter in TEXTOR thermographic and thermocouple measurements have been performed. The heat distribution on the blades show some inhomogeneities which are attributed to different effects: a) The leading edges at the ends of the blades are heated more than the rest, partly due to alignment errors, b) poloidally there is an asymmetry because of differences in the directed particle fluxes, c) the magnetic field ripple causes a modulation of the power flux and d) finally the toroidal flatness of each tile generates non-uniformities toroidally. From the observed data the total energy flux to the limiter, the time resolved power flux to the limiter and the radial power decay length are derived.

1. Introduction

Operation with the toroidal belt pump limiter ALT-II has started on the TEXTOR - tokamak. ALT-I /1-4/, a modular pump limiter proceeding ALT-II, has demonstrated, as have other modular pump limiter systems /5,6/, good particle removal and density control capabilities. However, with higher heating power becoming available, the rather small surface area of a single modular pump limiter makes power handling difficult. Therefore limiter systems exposing larger surfaces to the plasma have to be devised, like the toroidal belt limiter ALT-II, which allows the deposited power density to remain low. One of the main objectives of the ALT-II programme, besides the investigations concerning particle removal and density and impurity control with this toroidal configuration, is to contribute to the data base on the heat load distribution over the toroidal belt limiter surface and on the neutralizer plate. For this purpose ALT-II is equipped with special diagnostics - I.R. cameras and thermocouples in selected limiter tiles. In the following, first results obtained for Ohmically heated discharges and for discharges with up to 2.6 MW ICR heating will be described and discussed. Higher heating powers will become available in the near future when the ICRH power is increased to 4 MW and NI, with powers 2.6 MW, is installed on TEXTOR.

2. Experimental Arrangement

ALT-II is a toroidal belt pump-limiter positioned outboard at 45° below the midplane of TEXTOR, a medium size tokamak with a major radius of 1.75 m, a minor radius of up to 48 cm and a pulse length of up to 4 s. The ALT-II /7,8/ belt consists of eight blades of 1.7 cm thickness which are individually movable in the radial direction. Scoops to enhance the particle removal from the discharge are mounted behind the limiter blades. Each blade is covered with 28 IG-110 graphite tiles in two rows; the size of the tiles is 10 cm * 14 cm and they have an average thickness of 8 mm. They are contoured to accept a constant power flux at the outer 1/3 in the poloidal direction for a power e-folding length of 1 cm. The rest of the tile should not be heated at proper plasma and blade alignment (a=44.5 cm).

The heat flux to the blades is measured 1) by two IR-cameras looking at two blades 180° apart and 2) by a set of thermocouples in each blade. The IR picture is passed through an imaging and through a field lens to the scanner. Both lenses are made of NaCl. By changing the positions of both field lens and scanner it is possible to vary the field of view of the blade from a full blade including the neighbouring blade tips to a few tiles with higher magnification. Each blade is equipped with at least two thermocouples in end tiles in order to check the toroidal uniformity. Additionally, in two blades thermocouples are also attached to tiles in the central part of the blades.

3. Temperature Distribution on the Blades

3a. Heat Load Pattern Derived from IR-Pictures

The pictures of the IR-camera give the temperature distribution on the blades and the time resolved surface temperature rise during a discharge. The initial temperature is mostly close to the liner temperature which is pre-selected typically in the range of 150 - 300° C. During an Ohmic discharge the temperature does not increase by more than about 20° C if all blades are aligned as a belt. If only one blade is exposed the temperature of the toroidal leading edges rises by about 200° C and the temperature of the rest of the blade by up to 40° C. The temperature rise is highest at low densities.

The detailed heating pattern of a blade is rather complex as can be seen in fig. 1, and this is attributed to different effects. The first of these is the different heating of the end tiles as compared to the rest. This is partially due to the gap of 12 cm between two neighbouring blades causing nearly twice the heat flux to those two end-tiles which are not shadowed by the neighbouring blade. Another contribution can result from an imperfect alignment of the belt; a 1 mm radial misalignment of a single blade is above the temperature resolution of the camera.

Inserting one blade on purpose by e.g. 1 mm and observing the poloidal heat symmetry at the toroidal leading edge is a sensitive method to check the correct plasma position relative to the belt. A deviation from the correct belt/plasma positioning is caused by an expansion of the liner due to external heating (ALT-II is attached to the liner) or by different plasma profiles produced by changes in the plasma parameters like density or toroidal magnetic field. The IR camera response is sensitive to changes in the radial plasma position of less than 5 mm.

In the poloidal direction it is expected that the tiles are heated only weakly at the center and roughly by one order of magnitude more in the outer flux contoured part. This large difference has never been observed. At most, a factor of three has been found. The discrepancy between the design value and the measured one can probably be explained by the effect of the ripple of the toroidal magnetic field. This effect has to be explored in more detail.

The temperature pattern along the flux shaped part of the tiles indicates that the e-folding length of the power flux is less than 1 cm for Ohmic discharges, that is the value which has been the basis for the design of the poloidal tile contour. In discharges with full additional heating a longer decay length is expected.

In most cases a top - bottom asymmetry is observed if the plasma is positioned correctly i.e. poloidally tangential to the central part of the blade. The higher heat flux is in the ion drift direction. The asymmetry inverts when reversing the plasma current direction but remains unchanged when reversing the toroidal field direction. The asymmetry factor depends on the plasma density; for $n_e = 1.*10^{19}\ m^{-3}$ it amounts to a factor of about two whereas at high densities $n_e = 3.*10^{19}\ m^{-3}$ it is nearly unity. Asymmetry factors of similar magnitude have earlier been observed with the modular pump limiter ALT-I in the equatorial plane/3/. The reason for the asymmetry is not yet understood and needs more investigation.

A third deviation from uniformity shows up in the toroidal direction and is attributed to the ripple of the toroidal magnetic field (in TEXTOR ≈1.5% at the blade position). The field line excursion of totally 1.8 mm results from the finite number of B_T coils (16). Under the field coils a minimum of the heat flux is found and in between two coils a maximum. It will be shown below, that the power decay length can be deduced from the heating pattern caused by the field ripple.

A fourth heating pattern has the extent of only a tile width. Different field configurations (inverted B_T and / or Ip) have confirmed that this flux non-uniformity has to be attributed to the fact that a tile is flat in toroidal direction. This flatness leads to a different angle of incidence of the composed magnetic field right and left from the axis of symmetry in a tile. Though the tile is only 10 cm wide the non-uniformity in heat deposition due to this effect amounts to about a factor of two.

3b. Thermocouple Measurements

In order to measure the toroidal power distribution, the total power to the limiter, and to detect misalignments, thermocouples have been placed around the belt. The IR camera

pictures show many details of the heat flux and how it is distributed over a blade. The thermocouples allow to extrapolate this information around the belt and even adjust the belt so that all blades share the power equally. A predicted thermocouple signal for a given power flux onto a tile is derived from a two dimensional heat conduction code /9/. The code predicts that the deposited heat will penetrate radially through a tile at about 1 second after a discharge; then surface and thermocouple values agree. However, the poloidal heat transport along a tile takes more than a minute and, because of intermittent liner heating during this time, there is only about 30 seconds of unperturbed thermal history. With the given thermocouple position and the observed heat distribution, it is estimated from the code that the temperature reading 30 seconds after the discharge is proportional to the overall heat flux. At that time, the measured value is about 30% higher than the final equilibrium one.
In addition, the thermocouples in the blades provide a simple and reliable method for the in situ calibration of the IR-camera system. The TEXTOR liner can be heated to temperatures of more than 400° C and then allowed to cool very slowly. In this case the thermocouple reading is identical with the surface temperature; by comparing both values the IR-system is calibrated without any assumptions about the surface emissivity or the window transmission.

4. Quantities Deduced from the Thermal Measurements

4a. Energy Sharing of the Limiter

From the development of the temperature pattern of the blades during one discharge several quantities can be derived. In a simple way the total energy deposited on a blade is calculated. The heat transport calculations show that the temperature has equalized radially through a tile in about 1 s and therefore the total energy flowing to a blade can be written as

$$E = m * c * \langle \Delta T \rangle,$$

where $\langle \Delta T \rangle$ is the temperature rise over the whole discharge; the bracket represents the average over all tiles and takes care of the fact that the blade is not heated uniformly. The energy flux to the blades depends on their radial position(s), and on the plasma parameters n_e and Z_{eff}. Fig 2 shows the average temperature rise, the absolute and the relative (as compared to the input) energy as a function of the electron density for a set of discharges. Within the range of the radial position of ALT-II between 44 cm and 46 cm the global temperature rise of the blades is independent of its position. This indicates that nearly all the convective flux goes to ALT-II and is not shared with other limiting elements in TEXTOR. The blades are, as expected, more strongly heated if only a reduced number is inserted.
Fig. 2 shows that the energy flux to the blades is decaying with increasing plasma density. This dependence is easy to understand because there are two competing processes for the energy transport in the boundary. One is the convection to limiters and the other one is

radiation. The radiation scales as $Z_{eff}^p * n_e^q$, where the exponents p and q are between one and two depending on whether the emission is predominantly line or continuum radiation. At low densities about 50% of the energy flux to the plasma edge is convective while at high densities and sufficiently high oxygen concentrations more than 90% is radiative loss from the boundary layer.

4b. The Power Flux

The determination of the power flux during a discharge requires a more refined analysis than the derivation of the total energy. The reason for that is the fact that on the one hand for the time scale which is well resolved by the IR system ($\Delta t \approx$ 10-100 ms) the tiles are not thin enough so that the temperature rise can be interpreted as a calorimetric signal. On the other hand the graphite is so thin that after about half a second the heat front has penetrated into it. It has been found to be adequate for the analysis of the thermographic data to apply a twodimensional heat code /9/ to the tile geometry. One option in this code is to use the time dependent temperature pattern of the tiles as an input and to derive from that the heat flux density as a function of time along a poloidal arc. Fig. 3 gives an example of this application to a discharge where starting at t=0.8 s an ICR heating pulse of 2.5 MW is switched on for 1.5 s. It is found that during Ohmic discharges 5-10 W/cm^2 are impinging on the blade while during the additional heating the power flux increases to 35 W/cm^2. In fig. 3 the time response of the power flux is slow because of IR - noise problems during ICRH which requires some averaging of the input data. Therefore long ICRH pulses are necessary for the evaluation of the data.

Assuming that the heat flow at the plasma boundary follows the magnetic field lines it is possible to transform the tile-surface heat flux to a value flowing to a plane perpendicular to the field lines. This transformation shows that the power flux of 35 W/cm^2 at the tile-surface corresponds to about 2.5 kW/cm^2 in the plane normal to the field lines.

From the heat flux along the magnetic field local plasma properties can be derived. The power flux can be related to electron density and temperature by

$$P = \gamma * j_{sat} * k * T = \gamma * \alpha * n_e * T^{3/2}$$

With the energy transmission factor γ of 8 /10/ it follows

$$\tilde{n}_e * \tilde{T}^{3/2} = 2.21 * 10^3 * \tilde{P}$$

Here the different quantities are normalized: $\tilde{n}_e$ to 10^{12} cm^{-3}, $\tilde{T}$ to eV and $\tilde{P}$ to kW/cm^2. The scanning probe /7,8/ data give a value of n_e at the tangency point of typically $4*10^{12}$ cm^{-3} for Ohmic discharges. With $\tilde{P} = 2.5$ for ICR-heated discharges a value of about kT = 100 eV and with $\tilde{P} = .35$ for Ohmic discharges a value of kT = 28 eV are obtained. The Ohmic value agrees fairly well with data from other diagnostics /7/. The ICRH value has to be reduced since the density at the tangency point, which has not yet been measured under these conditions, increases as compared to the Ohmic case at high ICRH power levels.

4c. The Power Decay Length

The power decay length of the edge plasma flux can be determined in several ways. The first one is to move one of the blades in the shadow of the rest of the belt. Under the assumption that the scrape-off length is not changed by this movement it is straightforward to derive the e-folding length from the decrease of the temperature jump during a discharge by moving the blade stepwise radially outwards. From the six thermocouples arranged in blade two the decay lengths for different locations have been determined. On the average the value λp amounts to 5-7 mm.

A second way of getting the power decay length is based on the analysis of the magnetic field ripple effect. As mentioned above the full excursion of a field line amounts to 1.8 mm. Under the assumption that 1) the power flux on a distorted magnetic surface is constant and that 2) the radial dependence of the power flux is described by an exponential equation the variation of the heat flux in the toroidal direction can be described by

$$I(\varphi)/I(0) = I_0(\Delta r/\lambda p) - 2*I_1(\Delta r/\lambda p)*\sin(\varphi*16) + 2*I_2(\Delta r/\lambda p)*\cos(2*\varphi*16) + \ldots$$

Since the modified Bessel functions $I_\nu(x)$ converge fast for $\Delta r/\lambda p \leq 1$, only the two first terms of the series expansion have to be taken into account. The number 16 in the trigonometric functions corresponds to the number of toroidal field coils. The power decay length is evaluated from temperature data points at the maxima and minima because there the angle between the tile surface normal vector and the magnetic field direction has the same value. Fig. 4 gives λp obtained from this procedure as a function of the central line averaged electron density. The value is consistent with that obtained from the radial scan.

Finally a last method for determining λp follows from the temperature distribution of the tiles in the poloidal direction. The power at the tile surface is given by

$$P_s = P_0 * e^{-\Delta r/\lambda_p} * (n_s*b)$$

i.e. it is given by an exponential function times the scalar product of the surface normal vector times a unit vector in the magnetic field direction. Code calculations solving this problem show again values of $\lambda p < 1$ cm in agreement with the results obtained with the other two methods. It should be mentioned, however, that the correct plasma positioning with respect to the blades enters critically into the last method.

Conclusions

The IR thermography has shown that the heat distribution on the toroidal belt limiter ALT-II is complex and it has been discussed that several effects contribute to this structure. Even at future power levels of 6 - 7 MW this non-uniformity of heat load distribution is not expected to cause problems since the blades are designed for power fluxes and operation well away from limiting material properties. However, in future machines operating closer to the material limits, non-uniformities of heat distribution may lead to local temperature values in excess of the tolerable value. The plasma contacting surfaces of a toroidal belt limiter should be contoured and adjusted radially as good as possible e.g. better than within 0.1 to 0.2 of the power decay length. Careful attention should be paid to the effects of the magnetic field ripple. Finally we note that poloidal and poloidal shaping of the plasma contacting surface is very important. Whether top - bottom asymmetries have to be taken into account in the limiter design needs further investigations.

Acknowledgments

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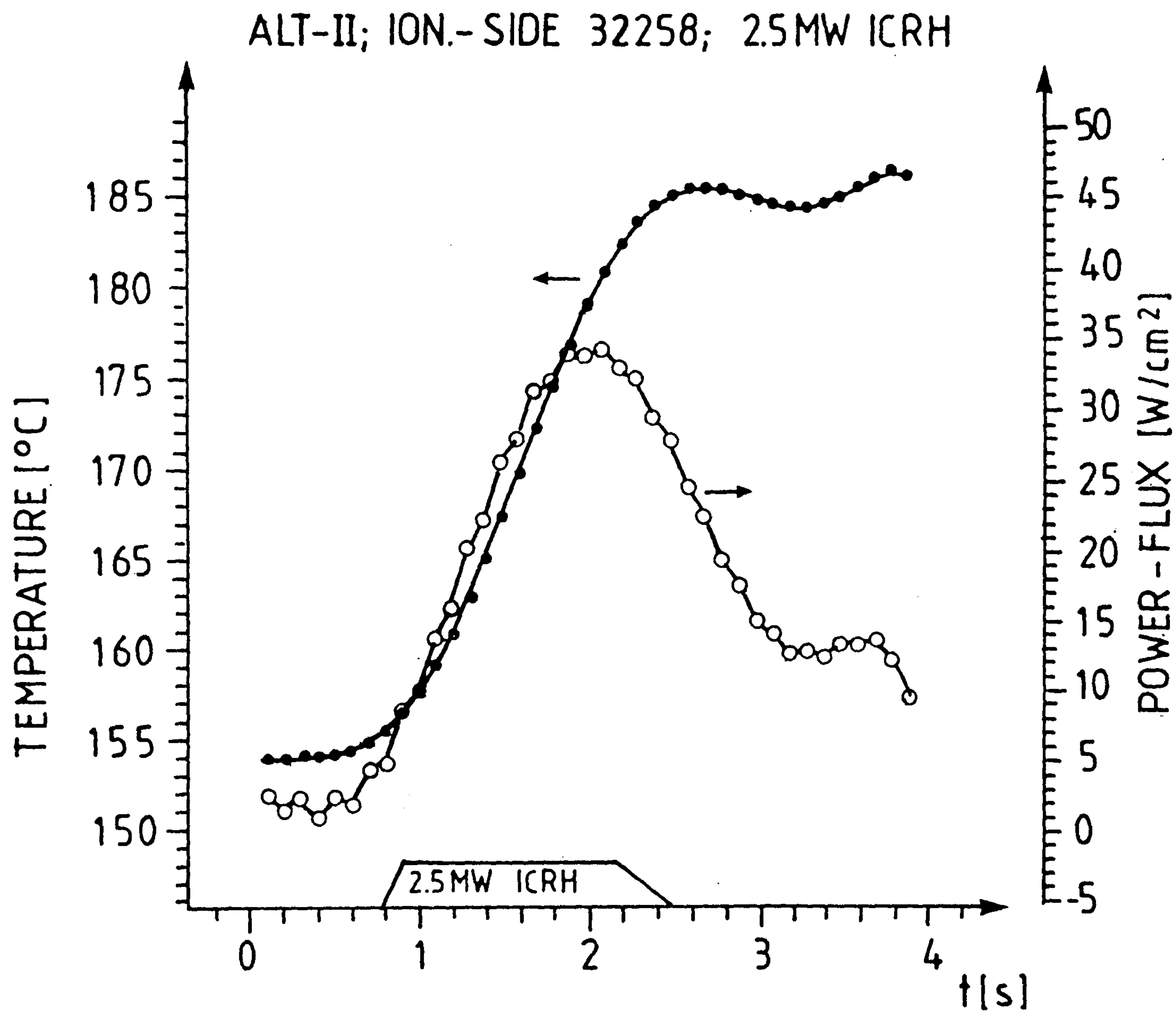
Figure captions

Fig.1 Temperature distribution on the major part of blade 2 and the edge of blade 3. The image shows different non-uniform heating effects such as: a) the leading edges in toroidal direction, b) a top - bottom asymmetry, c) differences due to field ripple and d) effect of tile flatness.

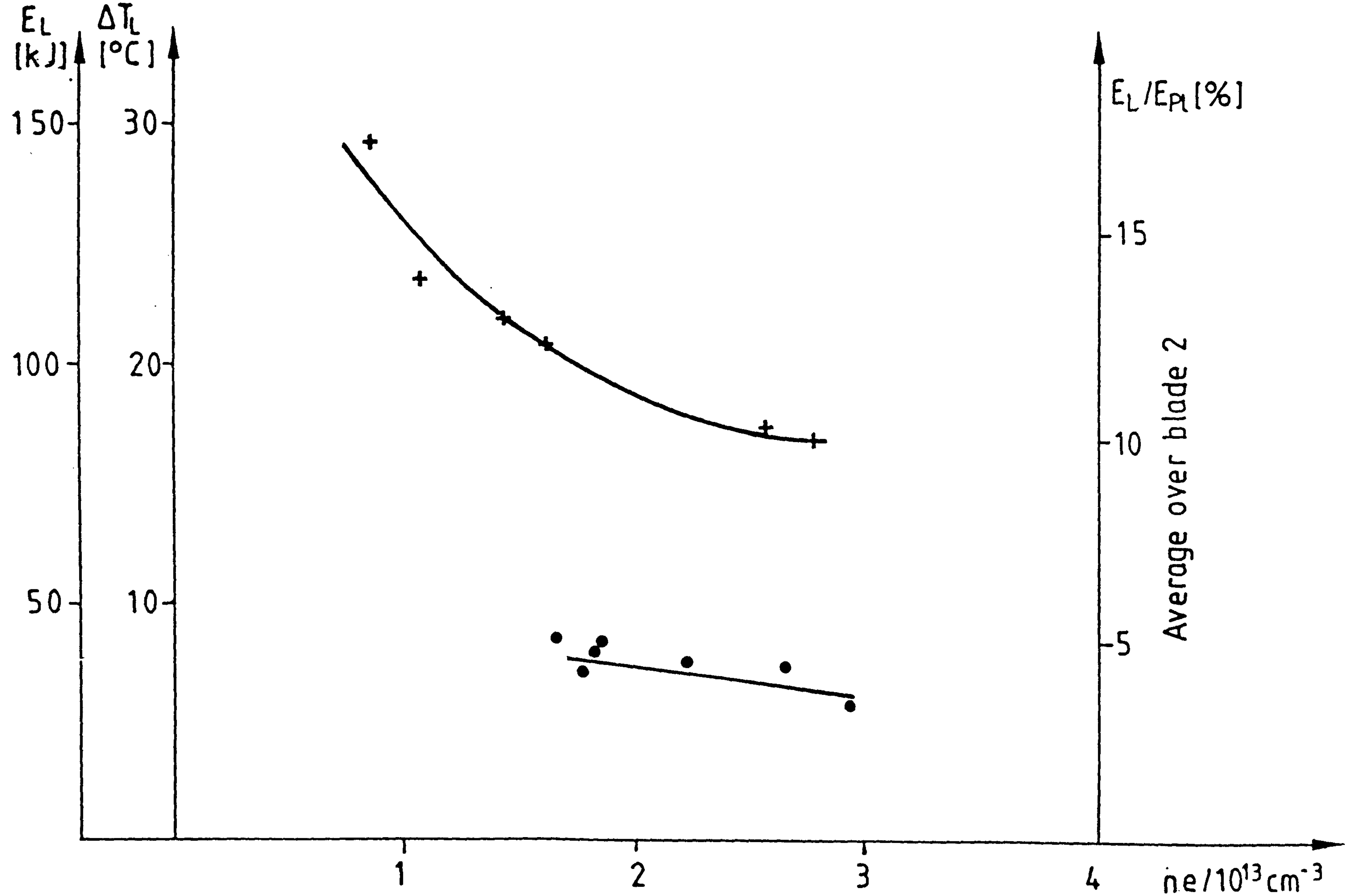
Fig.2 Average temperature rise, average energy and average relative energy on a blade exposed to the plasma as a function of central line averaged density. In this figure two curves are shown. The one with the crosses represents the case where two blades are at 46 cm and the others at 47.5 cm. For the lower curve six blades are positioned at a = 46 cm and two blades are at a = 47.5 cm. The heating of the toroidal leading edges is not included.

Fig.3 Temperature rise and power flux as a function of time for an ICR - heated discharge.

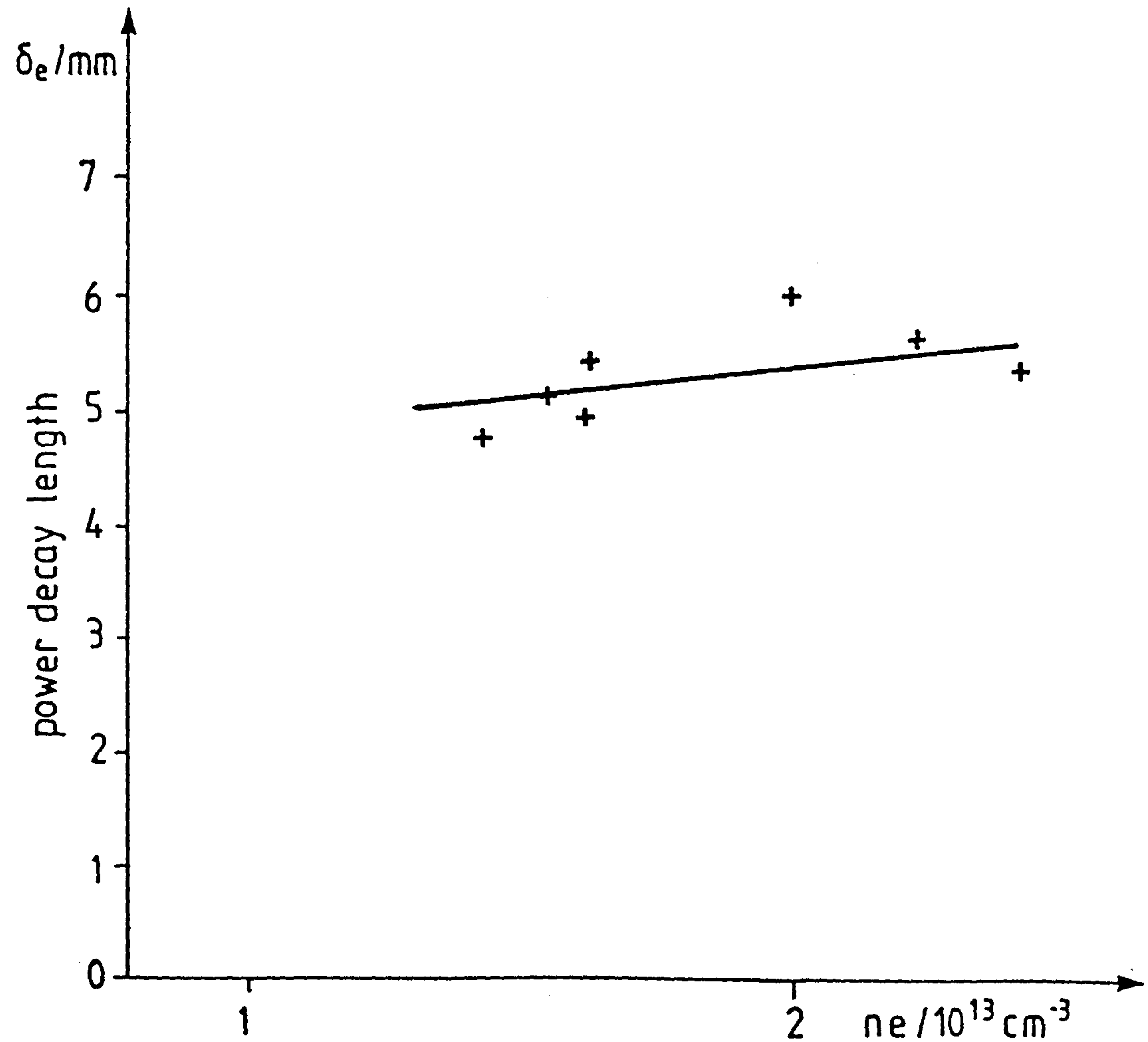
Fig.4 Power decay length as a function of plasma density derived from the power modulation due to the magnetic field ripple.



ALT-II; ION.-SIDE 32258; 2.5MW ICRH
TEMPERATURE [°C]
185
180
175
170
165
160
155
150
POWER-FLUX [W/cm²]
50
45
40
35
30
25
20
15
10
5
0
-5
2.5MW ICRH
0
1
2
3
4
t [s]



E_L [kJ]
ΔT_L [°C]
150
30
100
20
50
10
E_L/E_Pl [%]
15
10
5
Average over blade 2
1
2
3
4
ne/10^13 cm^-3



δe/mm
power decay length
0
1
2
3
4
5
6
7
1
2
ne/10¹³cm⁻³