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by A. Pochelon et al.

Content:

HIGH FREQUENCY MAGNETIC MEASUREMENTS IN J E T PLASMAS DURING AUXILIARY HEATING

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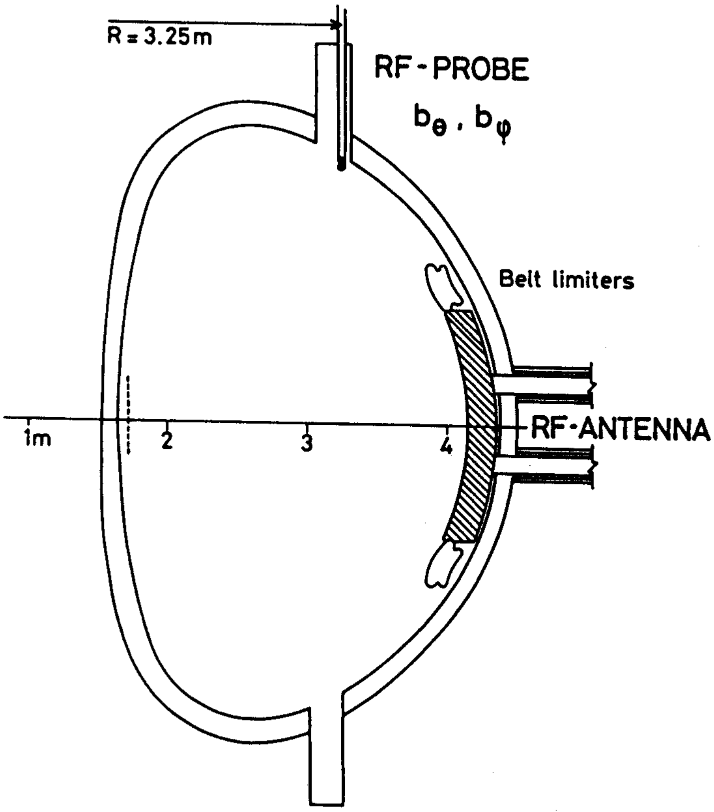
A high-frequency double magnetic probe has been installed on JET to study wave-fields from natural plasma emission (0.1-10 MHz) during auxiliary heating and to study wave-fields during ICRH (20-50 MHz).

With auxiliary heating, the emission of bursts of magnetic activity (0.1-10 MHz) is observed during internal disruptions. We describe the evolution of these bursts, the evolution of their spectra, and their temporal relation with both the fast instability leading to the internal disruption and with the fast transport phase which follows. These measurements suggest the role played by these magnetic bursts during the instability itself and during the fast transport phase.

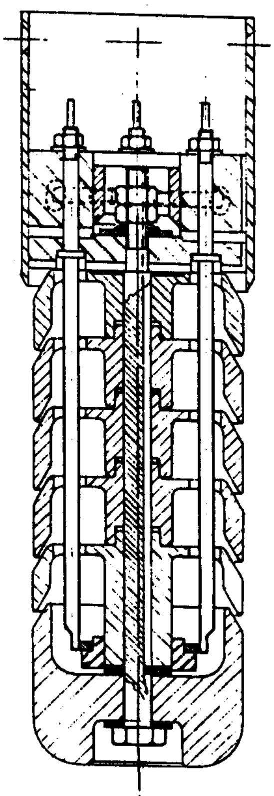
In the ICRH frequency range, the simultaneous measurement of b_Θ and b_ϕ gives access to the polarisation of the wave-fields at the edge. In particular, this measurement has indicated the presence of converted wave-fields with $b_\perp \gg b_\parallel$. In conditions favourable to the existence of eigenmodes, a double peak structure has been noticed on the wavefield modulus, strongly suggesting a double reflection of the fast wave on both the cut-off of the fast wave and on the high field side wall.

Experimental Details:



This RF-Probe has been designed for JET to measure RF-wavefields during ICRH-heating.

It uses the plasma boundary probe-shaft system to be inserted and positioned in the vacuum vessel.

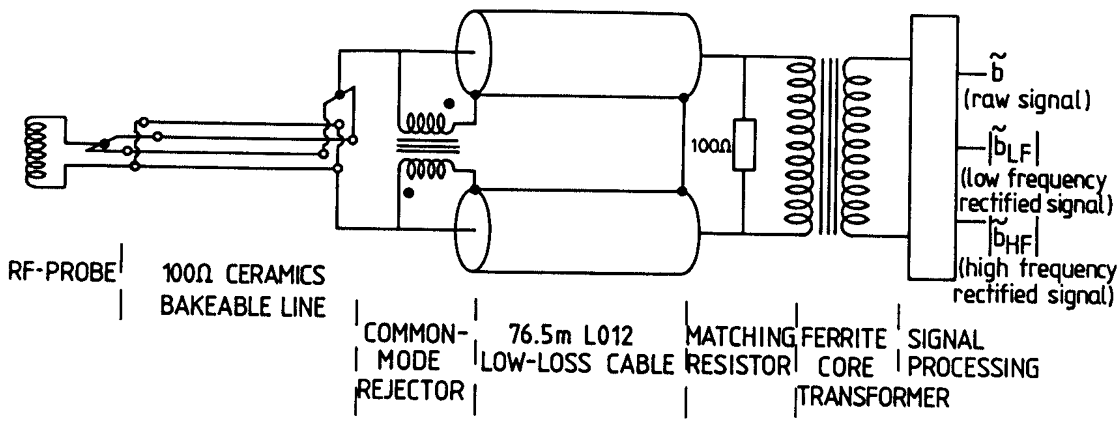


It consists of a slotted carbon particle- and Faraday-shield, and a double inconel rod frame yielding b_θ and b_ϕ (S ≅ 10 cm^2 at RF frequency). The two orthogonal probes allow us to reconstruct the wavefield vector parallel to the wall.

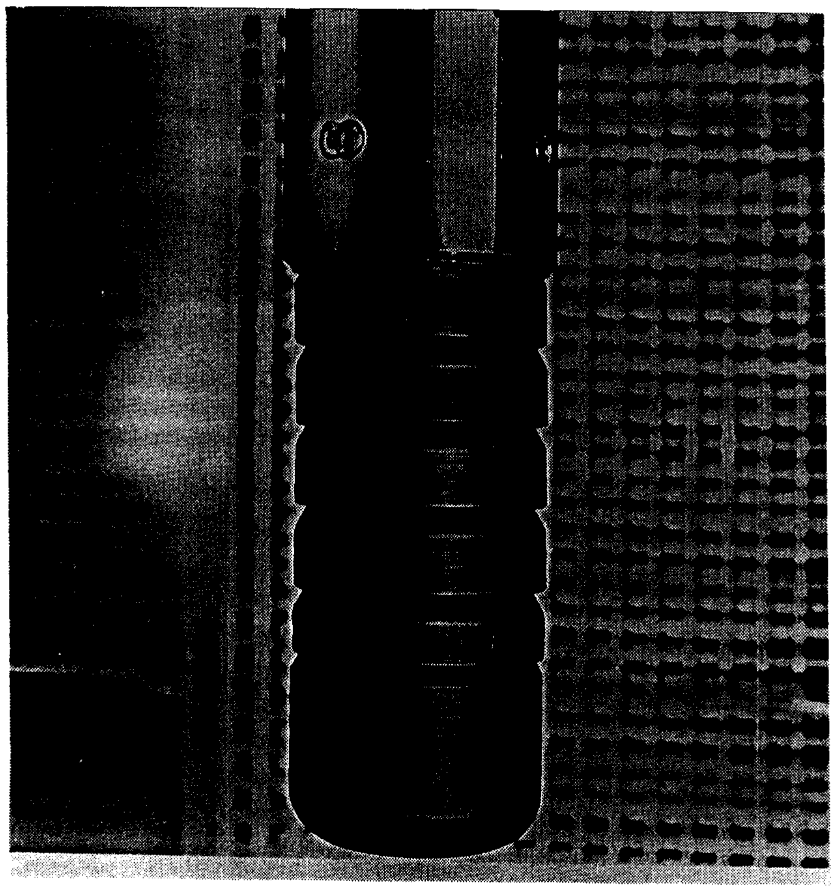
RF Probe Cabling Layout

The probe is followed by a 100 Ω bakeable quadrupole line, a common mode rejector, 100 meters of 4 low-loss cables properly terminated by an isolation transformer, and cut to the same electrical length, so as to ensure good phase information.

RF - PROBE : SIMPLIFIED LAYOUT



The Magnetic Probe (double probe)

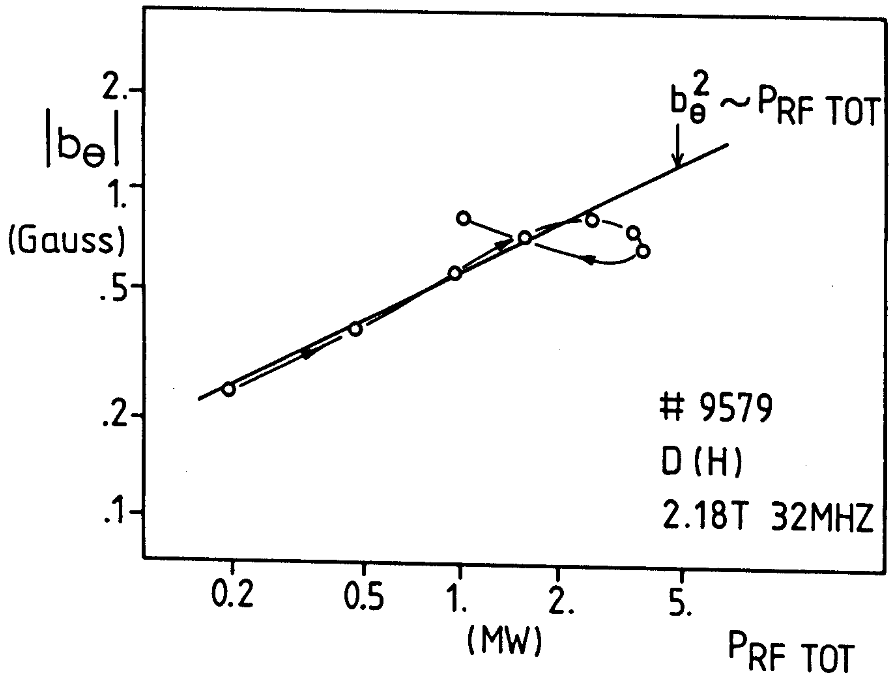


RESULTS

I) WAVEFIELDS DURING ICRH

1) Introduction

The wavefield measured at the probe position depends strongly on the RF heating conditions (B_T, minority concentration, etc.). In the absence of eigenmodes, the wavefield at the probe has been verified to be proportional to $b_\Theta \sim \sqrt{P_{RF}}$, as expected. This is shown to be true so long as there is no variation in the antenna-plasma distance. The departure from the straight line in this figure is correlated with a change in this distance.



A time averaging has been used to plot the above Figure, because the wavefields are strongly fluctuating quantities. Sawtooth and particularly Mirnov mode activity modulate the wavefield by more than $|\Delta b|/\langle|b|\rangle \sim 100\%$, with $|b_\Theta|$ and $|b_\phi|$ having similar variations on this fast scale.

2) Wavefield Polarisation

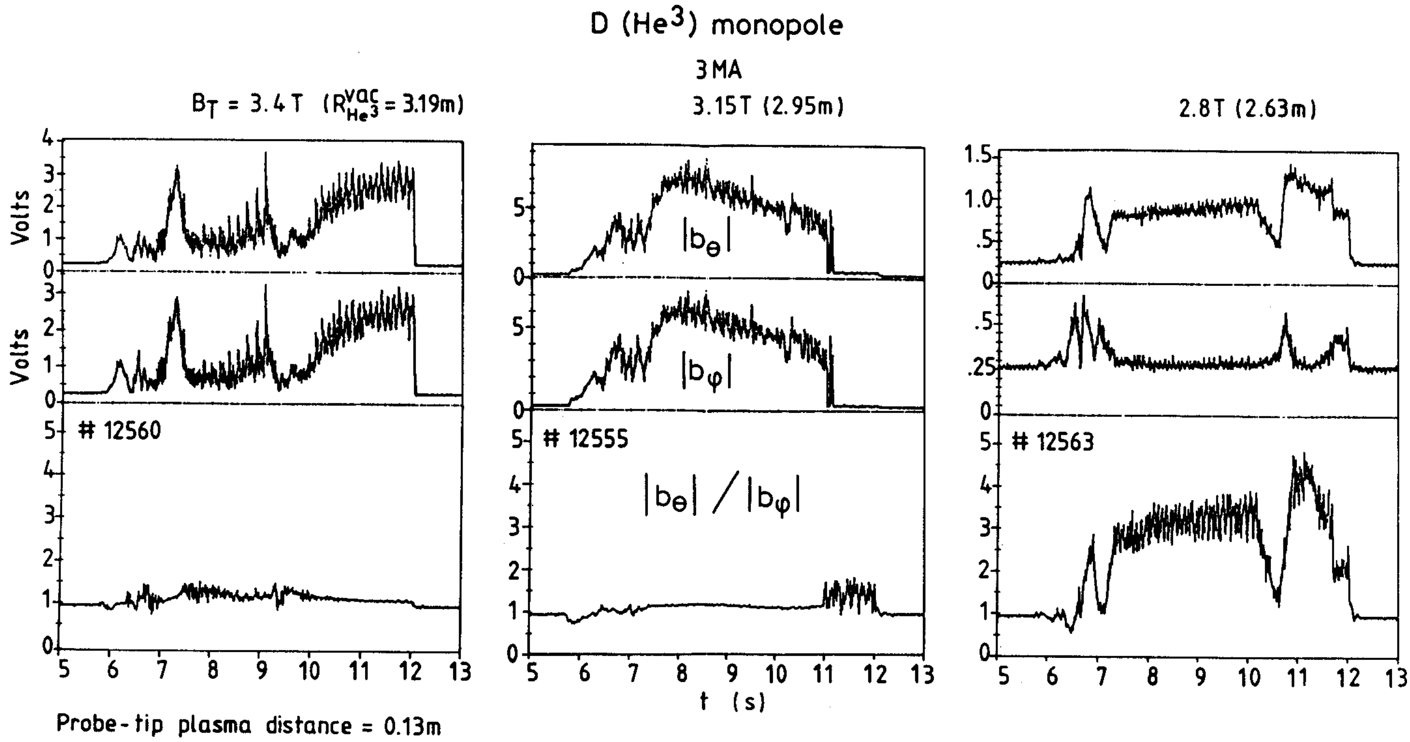
The wavefield polarisation $|b_\Theta|/|b_\phi|$ has been observed to vary over a wide range

$$0.6 \lesssim |b_\Theta|/b_\phi| \lesssim 7$$

depending on the chosen RF conditions.

In the following decreasing toroidal field scan in $D(He^3)$, monopole antennae, the resonance layer is displaced inwards, whilst the minority concentration conditions, the density and RF-power are maintained identical.

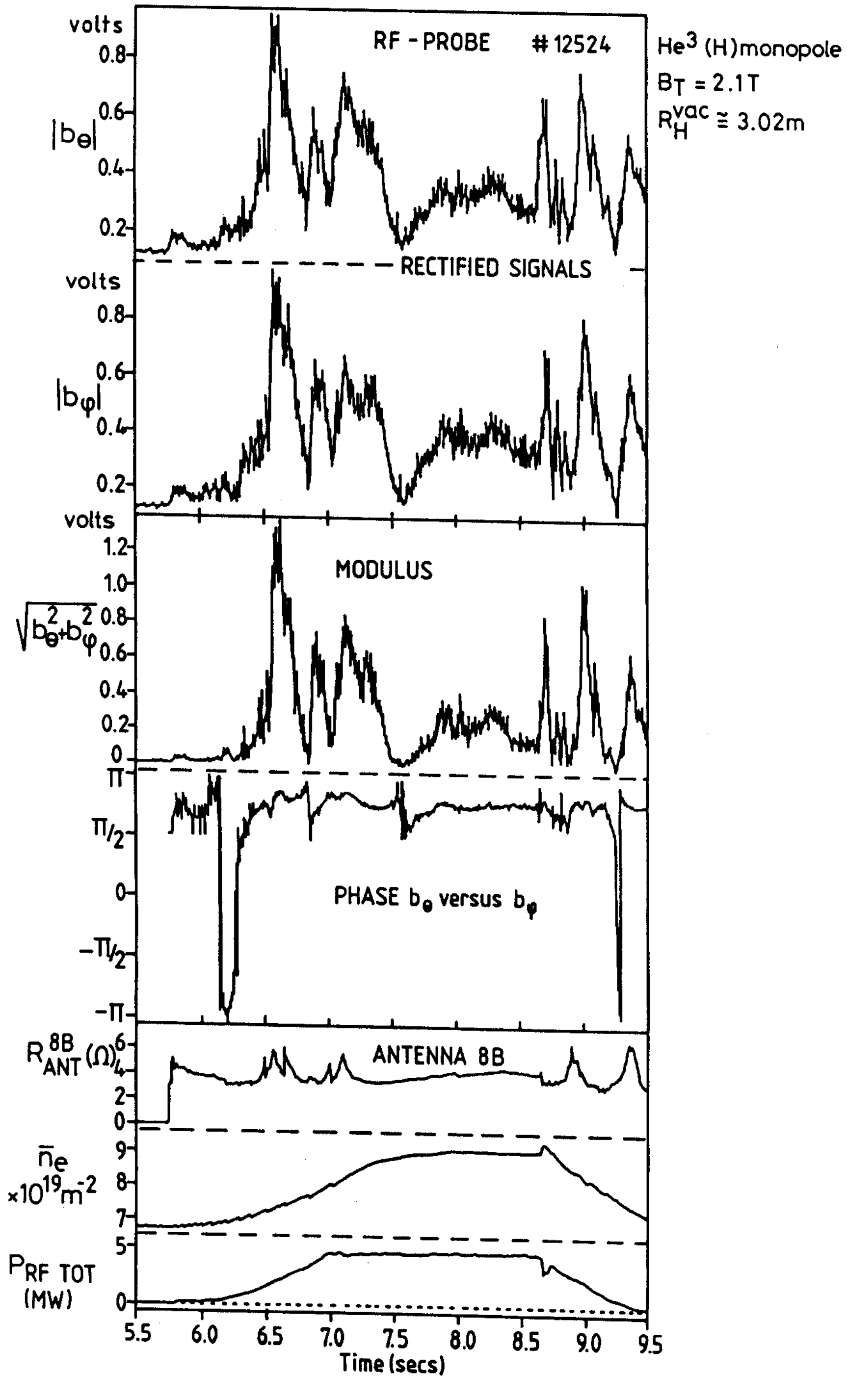
The ratio is close to unity for the two high field cases and is shown to increase to about 5 for the low field case. In this low field case, a new H-cyclotron layer has been introduced in the plasma, in front of the antennae (R_H^{vac}=3.94m), so that the probe sees the "converted" waves or ion-ion hybrid wave, which would explain the high ratio $|b_\Theta|/|b_\phi|$, typical of the slow wave.



3) Global Eigenmodes

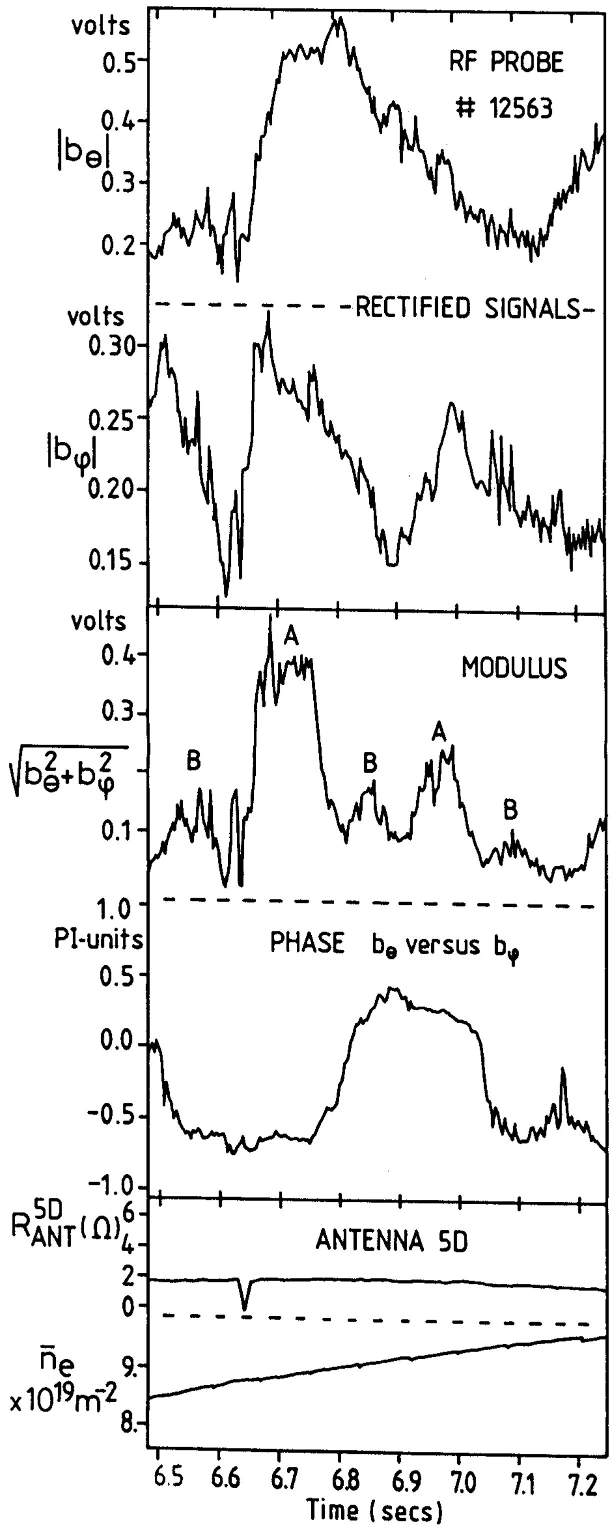
Whilst maintaining the generator frequency constant, the density increase produced by the applied RF power allows us to sweep through various plasma eigenmodes [1,2].

In the following example (He^3(H) monopole, 32 MHz, 2.15T) peaks are observed on the rectified $|b_\Theta|$ and $|b_\phi|$ wavefields. More detailed information is obtained using the complex wavefield and calculating the modulus $\sqrt{b_\Theta^2 + b_\phi^2}$ and phase (probe b_ϕ versus b_Θ) of the complex wavefield parallel to the wall.



Stationary wavefield structure

In the next example ($D(He^3)$ monopole, 32 MHz, 2.8 T) the density sweep allows us to see a double peak structure A-B, where the A-peaks are large and followed by the smaller amplitude B-peaks. The phase groups the peaks A and B in pairs, separated each time by a π jump, typical of stationary waves. In this example, the decreased toroidal field has introduced a new H-layer located at R_H^{vac} = 3.94m, in supplement to the already existing He^3 layer ($R_{He^3}^{vac}$ = 2.63 m).



This picture shows analogies to a case where two types of global eigenmodes, which are excited by LFS antennae [1], may form standing waves over different regions of the plasma. A detailed comparison with numerical calculations would be required to understand which is the adequate picture to describe these measurements.

In this particular case one should note that the probe, due to its radial position, is able to observe eigenmodes which are not observable from the antenna.

It is always questionable whether the probe, which is located at the top of octant 5D, would only be sensitive to the antenna in this octant (Antenna 5D).

In fact, we have switched on and off various antennae in the same $D(He^3)$ conditions as above (like # 12563) but with the resonance close to the core (B_T = 3.15 T). For example, switching on the antenna located at 180° toroidally (1D) is equally well observed to decrease or increase the RF wavefield measured at the probe. Reciprocally, the antenna 5D, located just below the probe, does not significantly increase the probe signal.

This fact leads to the conclusion that in this eigenmode situation the probe signals result from interferences of all antennae.

II) NATURAL WAVEFIELD EMISSION AT THE INTERNAL DISRUPTION

With NBI, the RF-probe measures bursts of high frequency activity. We report here on some of these measurements and investigate the time correlation with the Gong-mode (≡ the magnetic perturbation of the internal disruption measured at the edge, due to toroidal and shape coupling [4,5]).

The bursts of wavefield emission are observed on $|b_\phi|$ with NBI and between typically 0.1 and 10 MHz. They are observed just following the growth of the Gong (or internal disruption instability) and the sawtooth crash, not before. It seems therefore that this emission, probably of magnetosonic origin (b_ϕ), is linked with the reorganisation phase just following the sawtooth pressure collapse.

The duration of this emission is observed to last longer after a monster sawtooth crash:

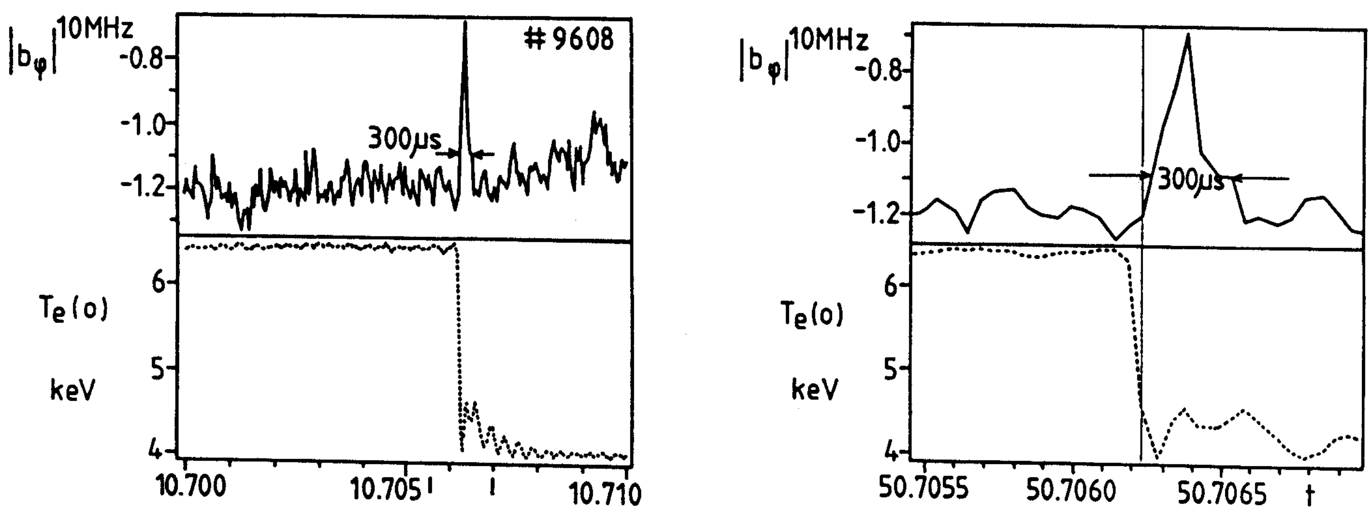
$$\tau_{1MHz} \begin{cases} = 10 \text{ ms after a monster sawtooth} \\ = 1 \text{ ms after a normal sawtooth} \end{cases}$$

It is also shorter at higher frequencies :

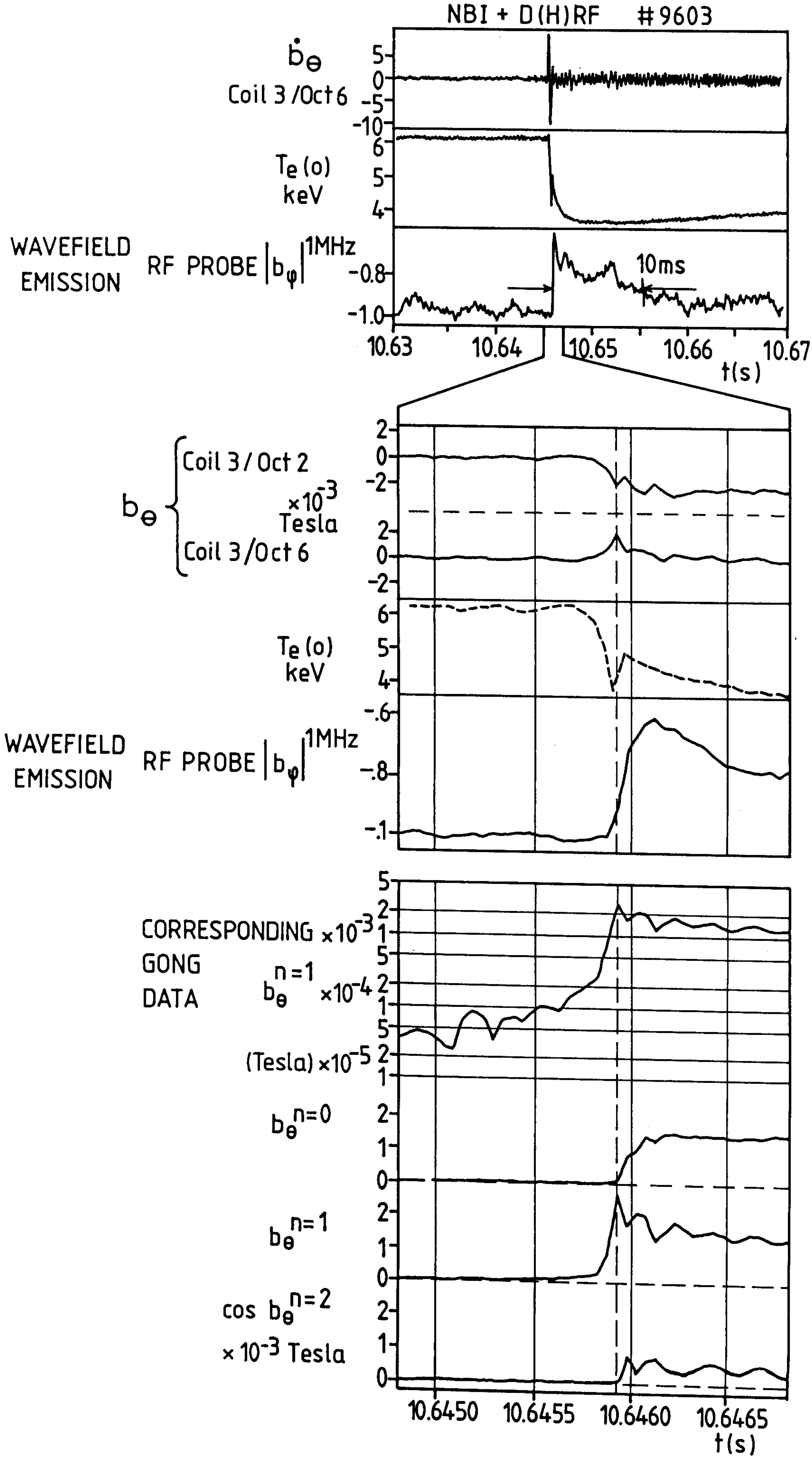
$$\tau_{10MHz} = 0{,}3 \text{ ms after a normal sawtooth}$$

This emission presumably allows us to measure the time of fast pressure changes in the core and is to be compared with the high frequency density fluctuation burst measured on TFR [6]. The magnetic high frequency perturbation starts when the growth of the internal disruption instability begins to saturate, as indicated by the saturation of the Gong-motion.

Burst of wavefield emission following a normal sawtooth crash:



Burst of wavefield emission following a Monster sawtooth crash, correlation with the "Gong" instability:



Conclusions

- We have shown the presence of RF wavefield eigenmodes and demonstrated that the complex wavefield (modulus and phase) yields detailed information about the wavefield spectrum even in regions that the antenna does not necessarily "see".

- In addition, in conditions favourable to the existence of eigenmodes, a double peak structure has been found on the modulus and on the phase, strongly suggesting a double reflection of the fast wave on both the cut-off of the fast wave and on the opposite HFS wall, in agreement with numerical model calculations.

- The polarisation of the wavefield varies over a wide range : $0.6 < |b_\Theta|/|b_\phi| < 7$, depending on the place of the ion-cyclotron layer, showing the presence of "converted" wavefields.

- High frequency magnetic bursts have been detected following internal disruptions. The emission starts when the internal disruption (as measured by the "Gong") saturates. The duration of these bursts presumably indicates the duration of the MHD reorganisation phenomena following a sawtooth crash.

Acknowledgements

It is a pleasure to acknowledge discussions with Drs. K. Appert, M. Bures, T. Hellsten, J. Jacquinot and L. Villard. We are particularly indebted to Mr. Ph. Marmillod, A. Stevens and J. Vince for their support and to Dr. J. Snipes for his help. This work has been supported by the Ass. Euratom-Confédération Suisse and the Fonds National Suisse de la Recherche Scientifique.

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HEAT PULSE PROPAGATION FROM SAWTEETH AND FROM TRANSIENT PROFILE MODIFICATIONS WITH AND WITHOUT SHEAR ALFVEN WAVE HEATING

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Heat pulse propagation is a well-established means of studying electron heat conduction. Here we study heat pulses produced by two different mechanisms. First, we consider pulses released periodically by the central sawtooth activity which indicate the expected χ^{HP} degradation during additional heating. Secondly, the transient response of the soft X-ray profile to switching the RF heating power also produces a pulse propagating outwards which moves at a reduced speed. This second type of response is studied as a function of plasma parameters and shows a strong q-profile dependence. These two profile reorganisation phenomena, which are measured at the same time and at the same place, lead to an apparent contradiction between two different electron heat conductions measured simultaneously in the same discharge. Therefore, these measurements pose in a new way the question of the validity of a local χ_e model.

This work was supported by the Fonds National Suisse.

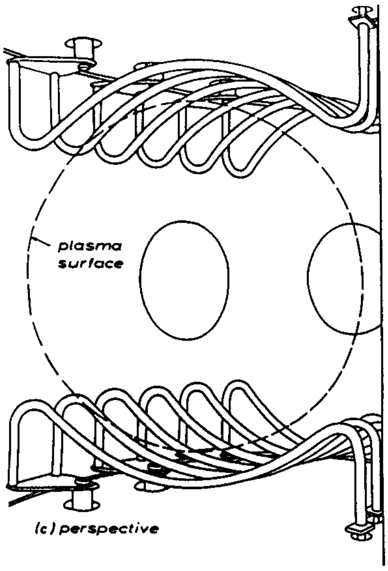
EXPERIMENTAL DETAILS

$R/a = 0.61/0.18$ m

TCA Parameters

$B_T = 1.5$ T

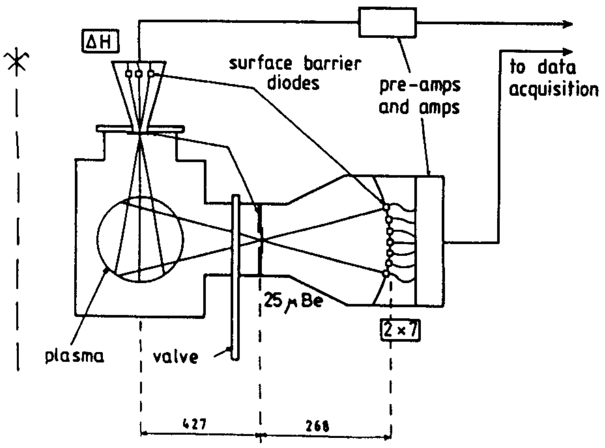
$I_p < 175$ kA



Shear Alfvén Wave Heating

$f = 2.5$ MHz (ω/ω_{ci} ~10-20%)

4 antenna groups in the 4 quadrants

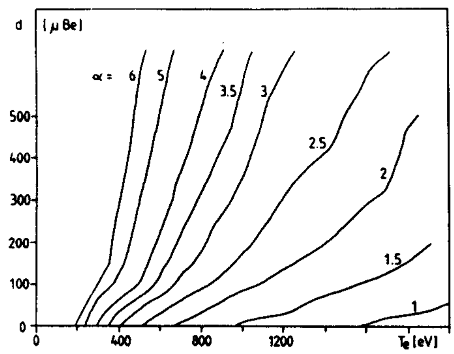


Soft X-ray camera

15 diodes each $r/a = 0.10$

Soft X-ray flux

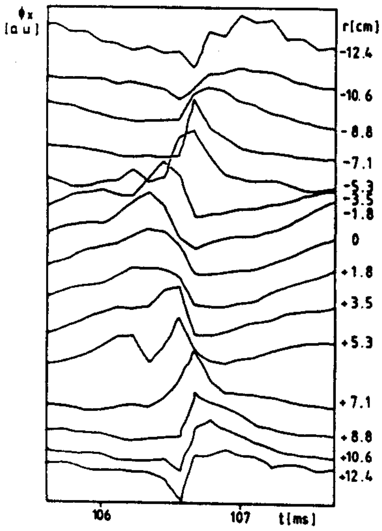
$$\phi \sim n_e^2 \, T_e^{\alpha(T_e)} \cdot f(Z_{eff}, Z_i)$$



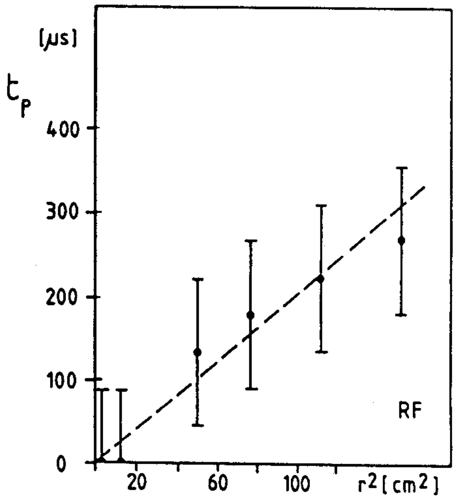
I. HEAT PULSE PROPAGATION

A) PROPAGATION OF HEAT PULSE RELEASED BY SAWTEETH

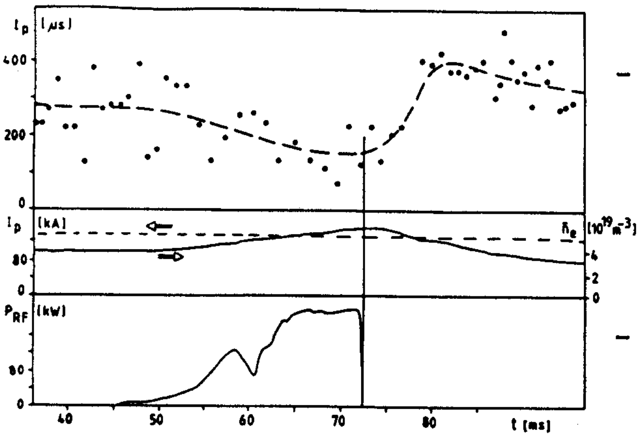
1) the propagation is of diffusive nature :



$t_p \sim r^2$



2) the propagation time varies with the applied power :



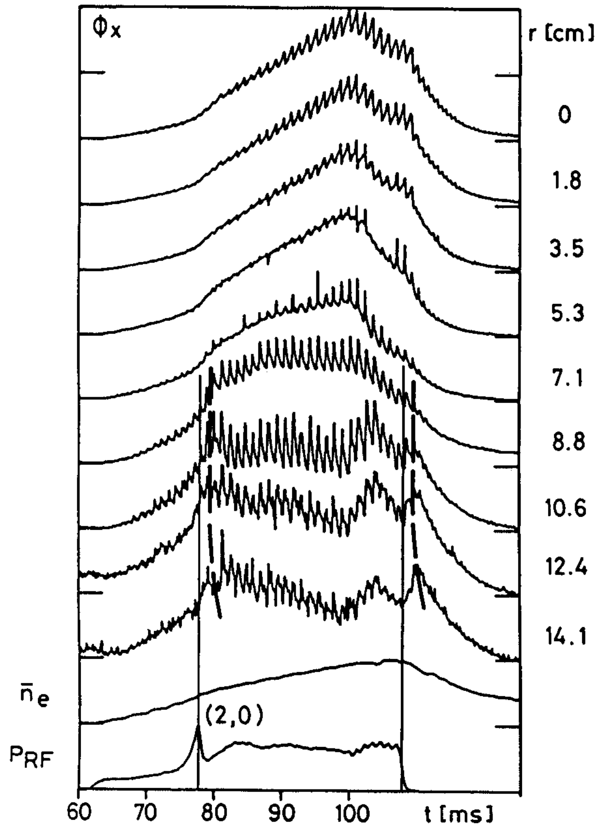
- the heat pulse propagation time is decreased with increased AW applied power (unlike JET [1])
- the propagation time seems to respond to the stored energy rather than to the RF-power or wavefield.

Calculating $\chi_e = c\frac{r^2}{t_p}$ with $c = \frac{1}{8}$ [2]

yields typically
$$\begin{cases} \chi_e^{OH} = 4\ m^2/s & \text{(about 5 times the power balance value} \\ \chi_e^{RF} = 8\ m^2/s & \text{(with 140 kW of add. power)} \end{cases}$$

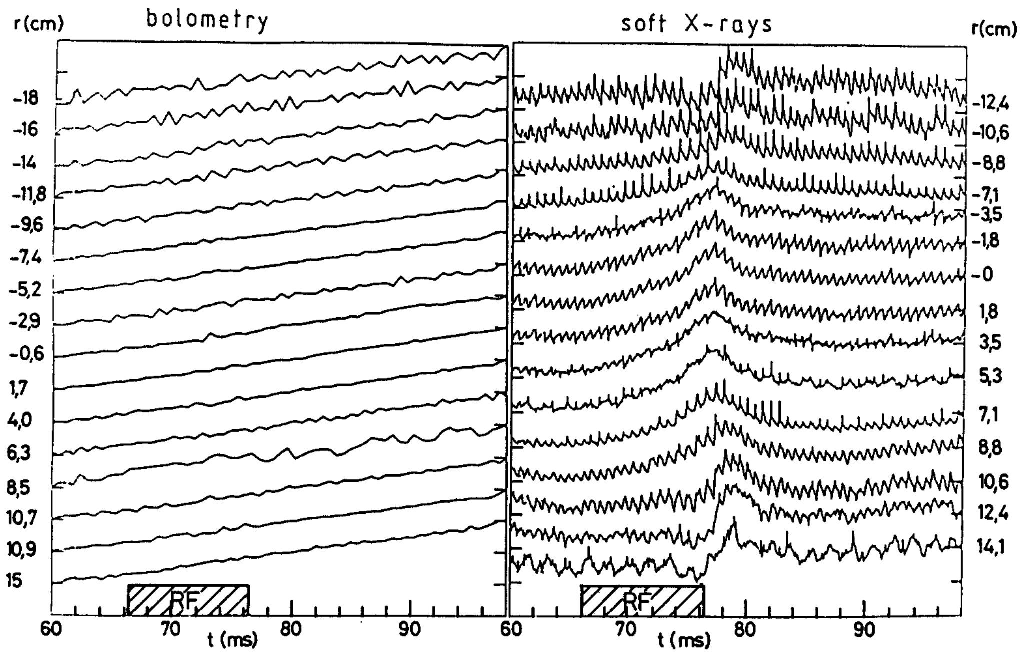
B) MAXIMUM OF X-RAY FLUX (≡ MXF) or PROFILE RESPONSE TO TRANSIENTS

We study the response of soft X-ray profiles to switching the Alfvén power on and off.



This example shows the maximum of the soft X-ray flux (MXF) moving out radially when the RF power is switched off, or when crossing a loading peak, which is shown up as a peak of delivered power.

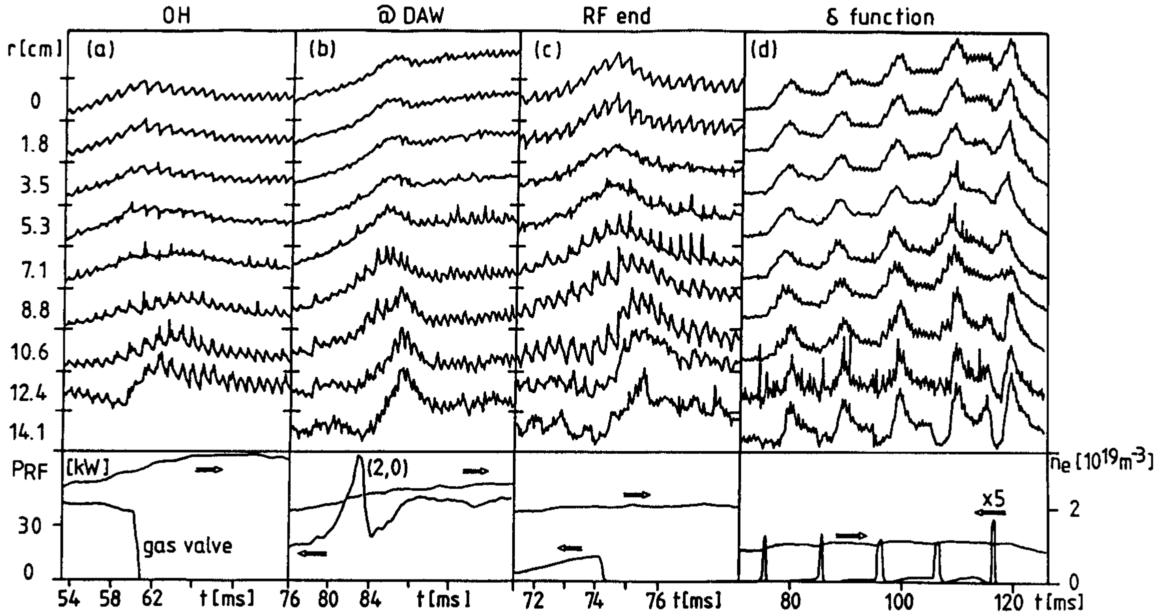
The MXF is not seen on the corresponding bolometric signals, nor on the 8-channel interferometer, supporting the argument that we are measuring a temperature perturbation.



<u>The MXF is not only the response of the profile to AWH transients</u>

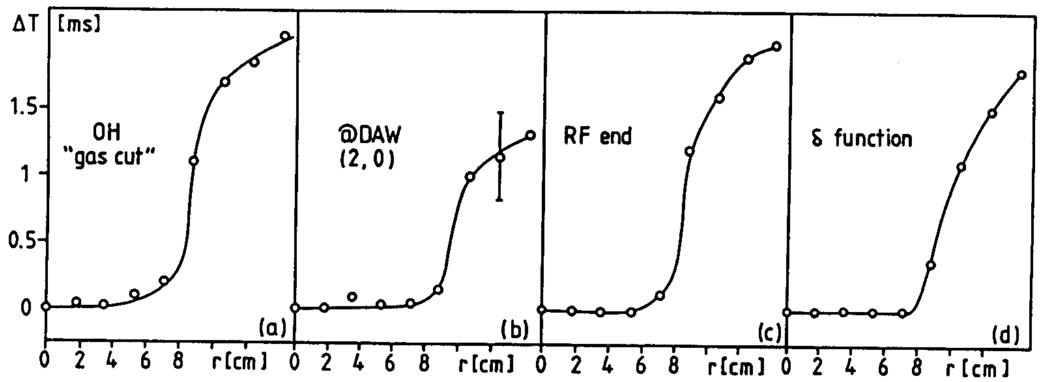
but also manifests itself as the response of the soft X-ray profile to

- transients of gas puffing
- power peaks due to the crossing of a DAW (Discrete Alfvén Wave)
- step or δ-functions of AW-power, anywhere in the Alfvén Spectrum.



The MXF seems to be the response to any perturbation. Its propagation shows the same characteristic delay curve in all cases :

- fast or instantaneous propagation in the core
- very slow propagation in the intermediate (therefore insulating) region
- faster propagation further out

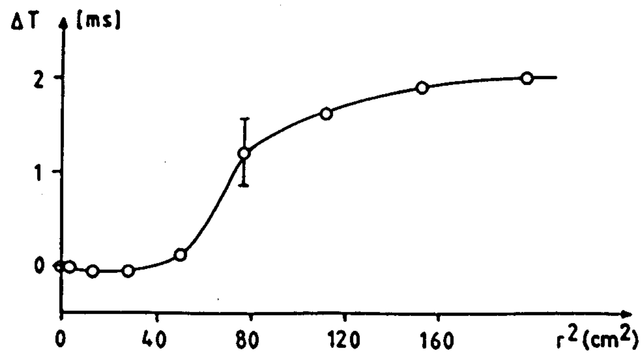


From now on there are two possibilities :

1) either we have a non-linear heat conduction

2) or the two "conductions" are of different nature, both affecting the temperature profile.

We already notice that the MXF "heat pulse" does not correspond to constant diffusion, as revealed by the following delay curve, plotted against r^2.



Paradox ?

It is surprising and instructive to observe that both

the MXF and
the Heat Pulse released by the sawtooth

occur at the same time and at the same place.

This leads to the paradox of a bivalent electron heat conduction :

$$\chi_e^{MXF} = 1.5 \text{ m}^2/\text{s}$$

$$\chi_e^{HP} = 8 \text{ m}^2/\text{s} \quad \text{(RF)}$$

II. MODULATION EXPERIMENTS or THE RESPONSE TO HARMONIC EXCITATION

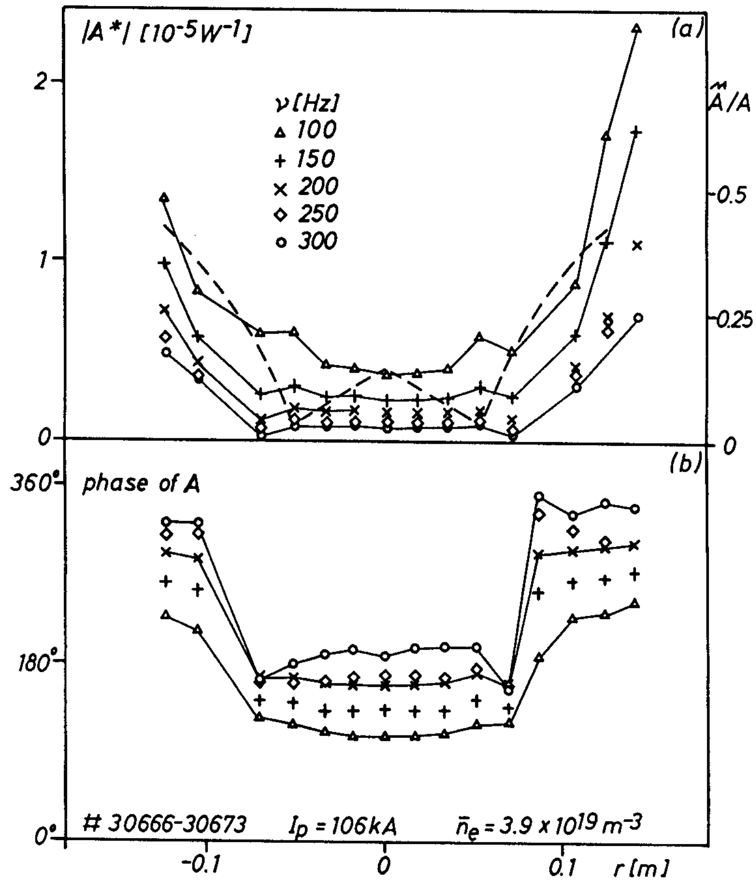
1) Soft X-ray amplitude and phase profiles

sinusoidal Alfvén wave heating modulations

modulation frequencies used $20\ \text{Hz} < f < 500\ \text{Hz}$

$(1/2\ \pi f < \tau_{Ee})$

The next figure shows the relative modulation amplitude A^* (normalised to the heating power) and the phase of the soft X-ray flux, as a function of radius for various modulation frequencies.



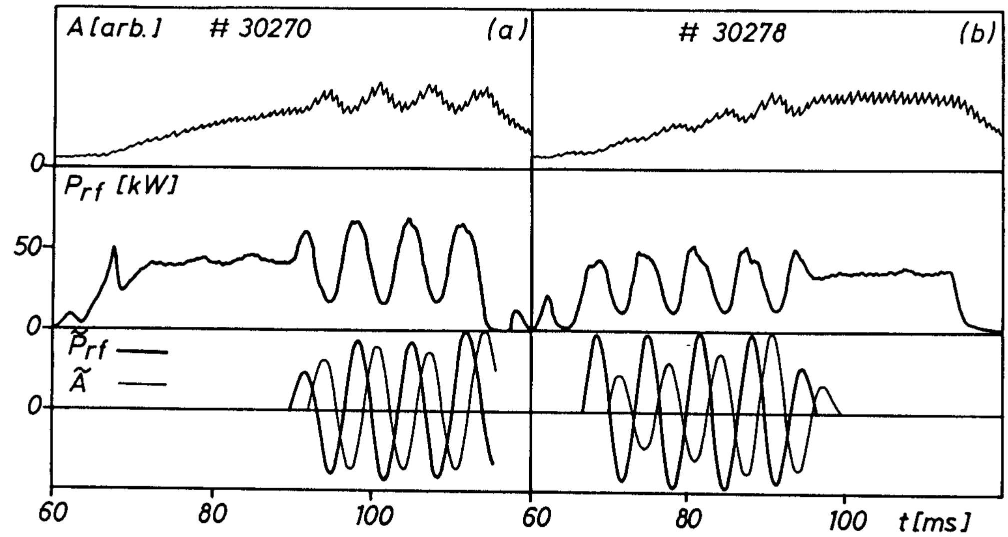
To be noted :

- The striking similarity between phase profiles and MXF time delay curve

- The phase is always larger than 90°. This implies that we have nowhere a directly thermalised heat source: there is some intermediate storage (indirect heating mechanism) or a variable power "acceptance".

2) <u>The effect of transients (RF switching on) on modulation experiments</u>

or the necessity to wait many confinement times to establish a stationary response



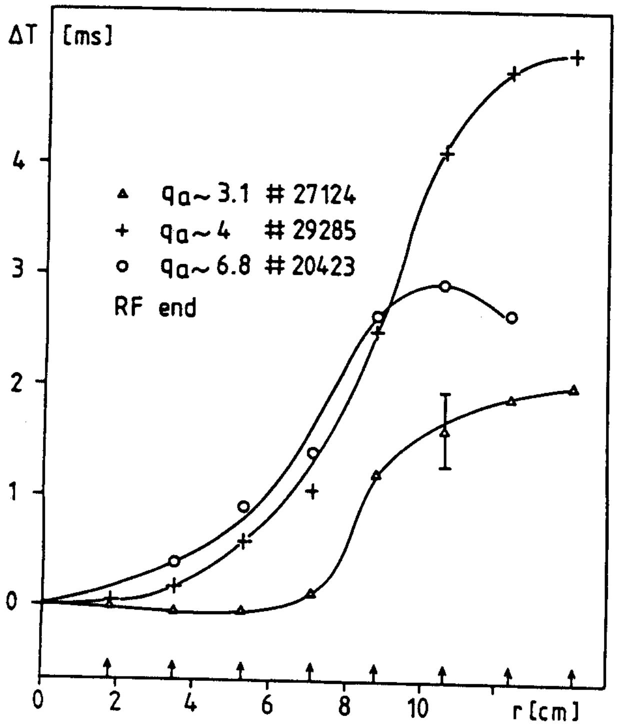
The delay to establish stationarity could also be considered as a manifestation of this "intermediate storage".

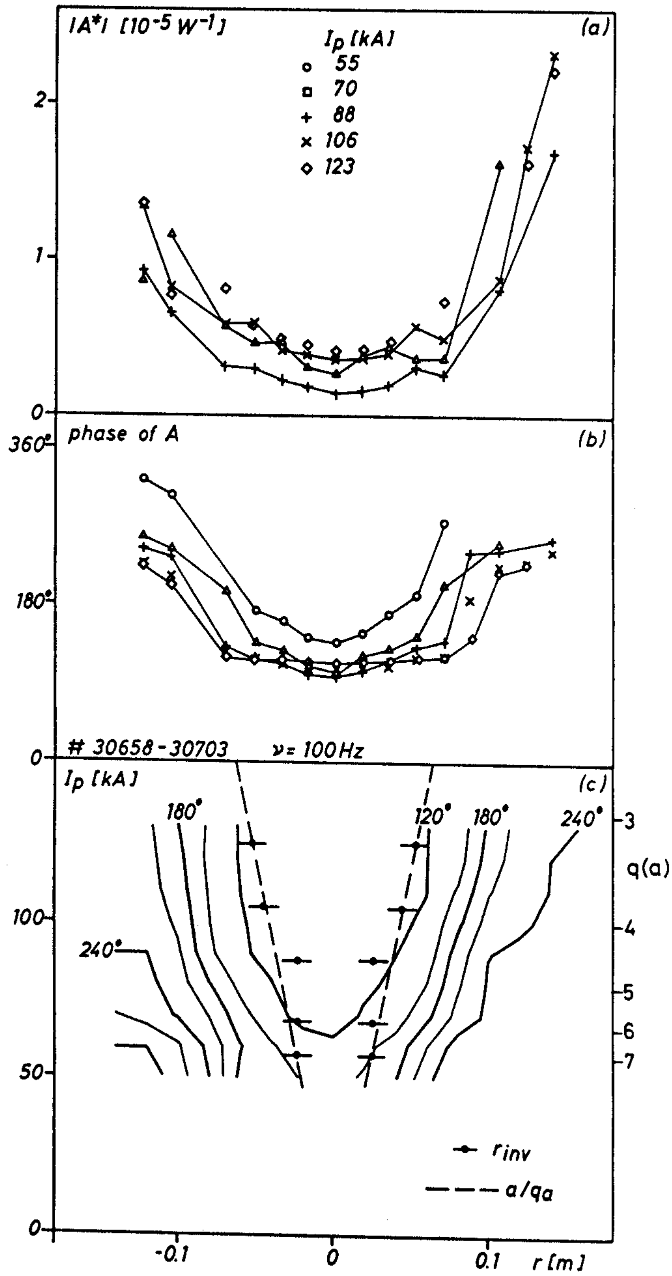
This long delay requires that we look for a phenomenon with a large time constant, for instance a current diffusion.

The phase on the contrary is directly established.

III) **EFFECT OF THE CURRENT PROFILE** on both

MXF and MODULATION EXP.





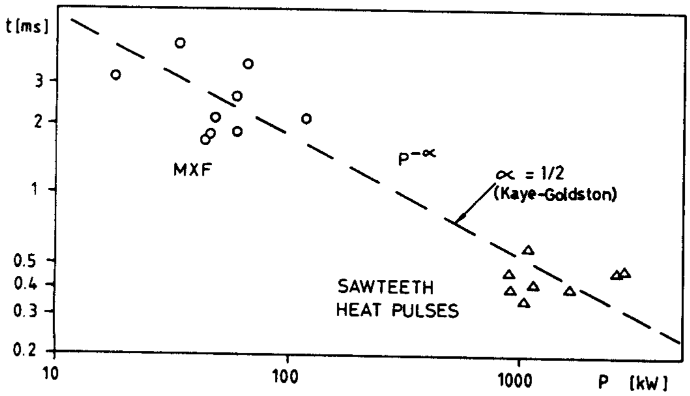
Both MXF and MODULATION experiments show a shrinking of the central rapid propagation zone at high q(a).

This shows dramatically the crucial role played by the current profile, and particularly by the central q ≲ 1 region

IV DISCUSSION :

Different ways of interpreting:

1) Same phenomenon, different powers



The MXF and the sawtooth HP obey the same physics, only the powers differ in magnitude:

$$\text{MXF:} \quad P = P_{OH} + P_{RF}$$

$$\text{HP:} \quad P = \Delta t \left(\underbrace{\frac{P_{OH}(o) + P_{RF}}{\delta t}} \right)$$

~ stored energy

This would be a power dependent (non-linear) conduction

2) Different phenomena

- The phase $\phi > 90°$ in the modulation exp. and
- the long delay ($\tau > 3\tau_E$) to establish stationarity in modulation experiments

both would imply intermediate storage mechanism.

The non-constant diffusion nature of the MXF forbids us to assimilate it to the usual sawtooth heat pulse conduction.

3) We suspect the current profile to be a good candidate for this intermediate storage because

a) of the long delay to establish stationarity (skin times)

b) the MXF is not linked with $n_e(r)$ or $P_{rad}(r)$ changes

c) the current profile effects have already determined the zone width of phase profiles (modulation exp) and delay curve profiles (MXF).

Conclusions

- The MXF is the response of the profile to various perturbations in OH and SAWH conditions

- The role of the current profile (particularly the central $q = 1$ region) in the dynamic response of the plasma is demonstrated
  - by the shape of the soft X-ray harmonic response profile
  - by the MXF delay curve

  suspected
  - from the need to resolve a heat conduction paradox in a larger frame
  - the different nature of the MXF and the sawtooth HP
  - from the need of finding and intermediate storage mechanism ($\phi > 90^o$)
  - from the long times ($\tau > 3\ \tau_E$} to establish stationary modulation conditions, pointing to skin times. The $n_e(r)$ profile is not affected.

- Therefore, the dynamic response of the temperature profile to any attempt of perturbing the plasma is strongly linked to the current profile. This could be a manifestation of profile consistency.

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Much of this material is to appear in Plasma Physics.