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Status and Prospects of RF Waves in Tokamaks

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Preprint of Course on Applications of RF Waves to Tokamak Plasmas,
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Preamble

This report is the text of the summary of the "Course on Application of RF waves to Tokomak plasmas" held in Varenna, Italy, 5-14 September 1985. As such it refers frequently to lectures made during the course and assumed to be available to the reader.

The author apologises for any inconvenience caused by the separate publication of this report.

COURSE ON APPLICATIONS OF RF WAVES TO TOKAMAK PLASMAS

VARENNA - SEPTEMBER 1985

Status and Prospects of RF Waves in Tokamaks

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Abstract

An attempt is made to summarize the status of the rf applications to tokamak as presented in this conference and to extract from it prospects for the use of rf waves in Tokamaks.

The major papers of the course on Applications of RF Waves to Tokamak plasmas have been reviews of the particular heating methods and my purpose is not to repeat here with different but almost certainly less appropriate words what has been so carefully written by the respective authors. Rather more my intention is to present the message of the course as I understood it.

The course was broadly divided into five groups of lectures:

(i) General physics of plasma waves interaction in Tokamak.

(ii) Reviews of rf heating methods used in Tokamak, themselves divided into Theory, Experiment and Modelling.

(iii) Specific points on the various uses of rf waves in Tokamak, including ways of getting more information on heat transfer.

(iv) Engineering and technical subjects related to the rf couplers and to the sources of rf waves.

(v) Plans for future rf experiments.

From groups (i) and (ii) the physical basis of the reviewed methods look firm, and numerous experimental results are fairly well described by the present theories. In a synthetic review Stix showed how wave heating and current drive mechanisms could be viewed as a diffusion process in velocity space without entering the phenomenology of each scheme /1/. While in some cases, like wave-plasma coupling, the agreement theory-experiment seems good enough to extend their use to diagnose the plasma, in other cases the situation seems clear only up to a point as in the Fish's description of lower hybrid current drive /2/. The crosses shown in Fig. 1 represent some 250 data points obtained in PLT during current ramp up experiments and plotted in a diagram Pel/Pin versus Vph/V_R. Pel/Pin represents the part of the rf power absorbed by the current carrying electrons which is eventually transferred to the poloidal field and Vph/V_R is the ratio between the parallel velocity of the wave and the runaway velocity defined by reference to the Dreicer electric field. The solid line represents the theoretical expectations which fit remarkably as long as two free parameters are adjusted once for all. The first one is the fraction of rf power absorbed (75%), and does not deserve special comments. The second parameter is the "upshift" in the wave phase velocity spectrum two possible but somehow controversed explanations of which were given by Sergeev and Canobbio, both based on non-linear effects /3/, /4/.

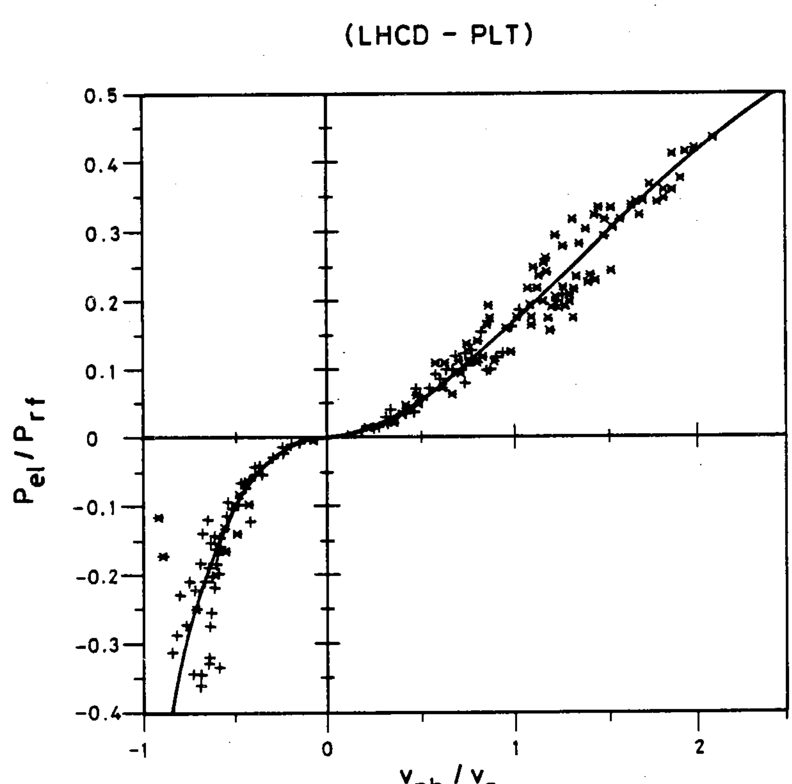


Fig 1. Comparison of Lower Hybrid Current Drive Theory with Experiment in PLT - From Ref /2/.

Lectures from group (iv) showed the tremendous progress made in the last ten years in the know-how and in the technology associated with the use of powerful rf waves in Tokamaks. Most (if not all) the rf heating methods discussed during the course seem to be valuable candidates for delivering the power required in a Tokamak reactor even if eventually Economy will dictate the choice. Such progress is illustrated by the JT60 Lower Hybrid Grill, the gyrotrons for ECRH and an ICRF JET antenna, a picture of which is shown in Fig 2.

- Each JT60 Grill, as described by Nagashima will be fed by 8 klystrons delivering 1 MW for 20 seconds each at a frequency variable between 1.7 and 2.3 GHz /5/.

- 100 kW, 100-140 GHz gyrotrons were presented by Mourier, Felch and Mathews /6/, /7/, /8/. Their efficiency is above 30% and further progress is expected, such as multicavity gyrotrons, which will close their efficiency gap with the lower frequency rf tubes.

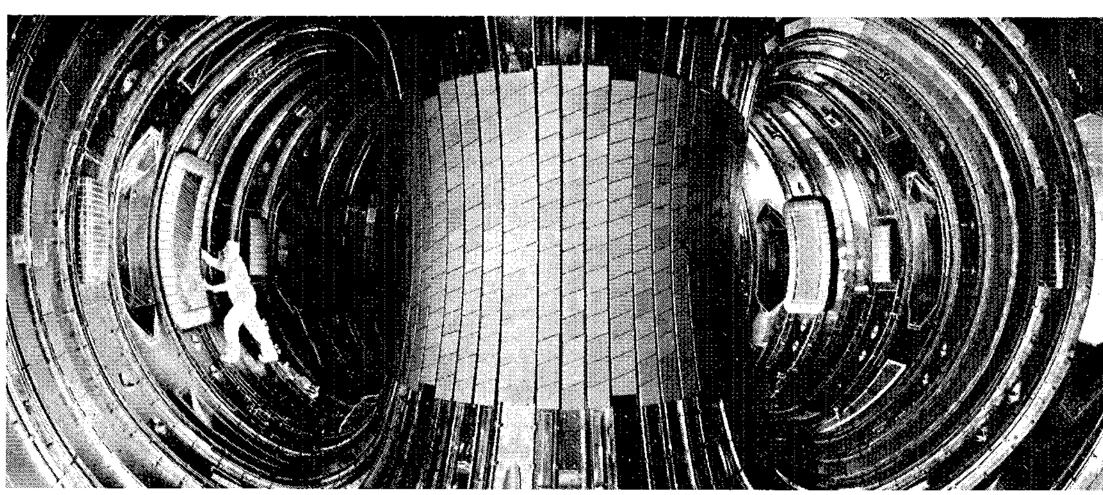


Fig 2. Inner view of the JET vacuum vessel showing one of the ICRF antenna

- The ICRF JET antenna has been used in a frequency range from 25 to 47 MHz and has successfully delivered to the plasma up to 2.5 MW for 2 seconds. It has experienced 5 months of plasma operation and survived very well in a harsh environment including plasma disruptions /9/.

To illustrate the present achievements, and to introduce my next point, let me show you the time evolution of some key parameters during application of

ICRF to a 4 MA JET plasma. During this pulse a record rf power of around 5 MW and an energy of 10 MJ were delivered to the plasma. The discharge is initiated at t = 40 s and the plateau of current is established at 45 s up to t = 50 s. Figs 3, 4 and 5 show the time evolution of respectively the plasma current and rf power, the near axis and volume averaged electron temperature, the peak ion temperature from neutron flux measurement, the total input and radiated powers. The most striking features are

- the increased sawteeth activity on electron temperature. Actually the peak electron temperature varies by around 1.5 keV during a sawtooth.
- the increase by some 800 eV of the peak ion temperature when averaged over the much smaller sawteeth, approaching 4 keV at the top.
- the unchanged ratio Pradiated/Pinput, consistent with an unchanged value of Zeff $\simeq$ 3 as measured from bremsstrahlung.
- the rather small increase, by some 10% of the volume averaged electron temperature.

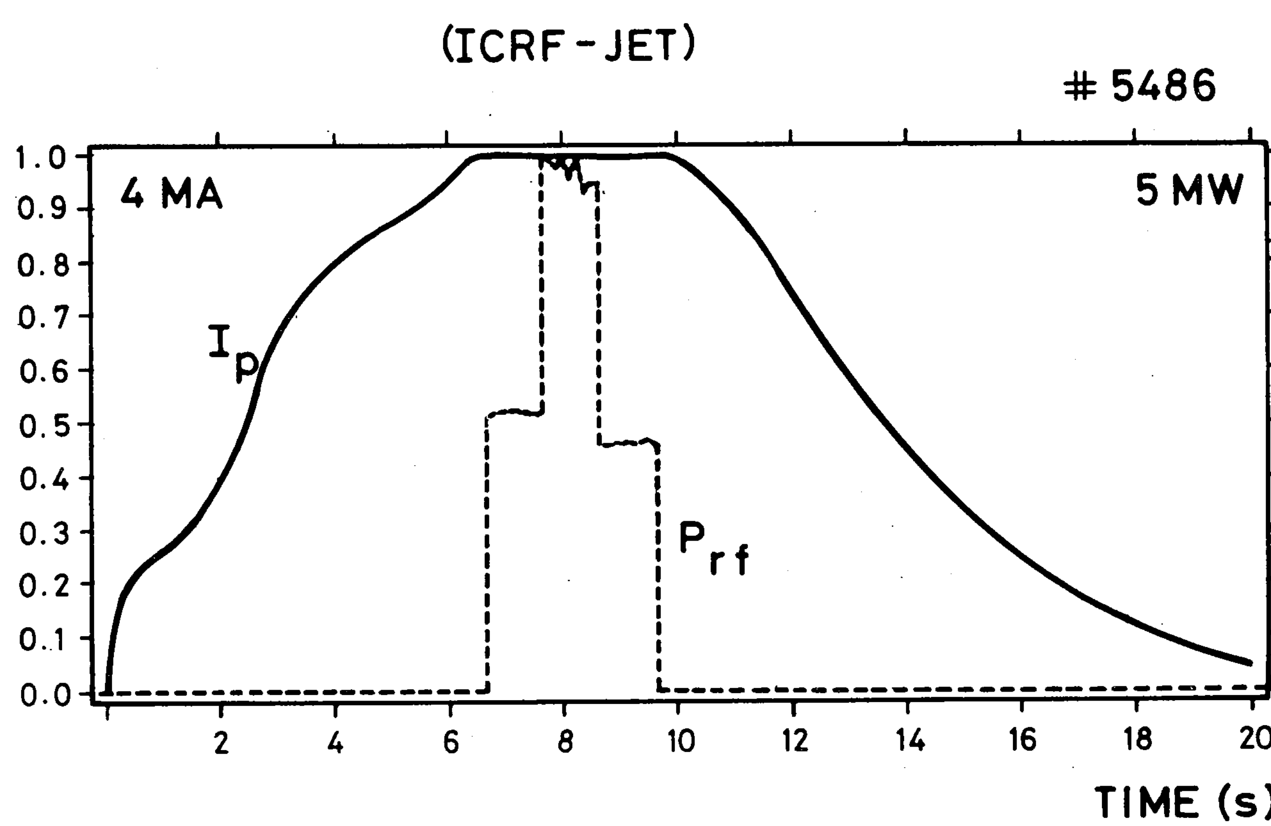


Fig 3. Time evolution of the plasma current and the ICRF power in JET during pulse 5486

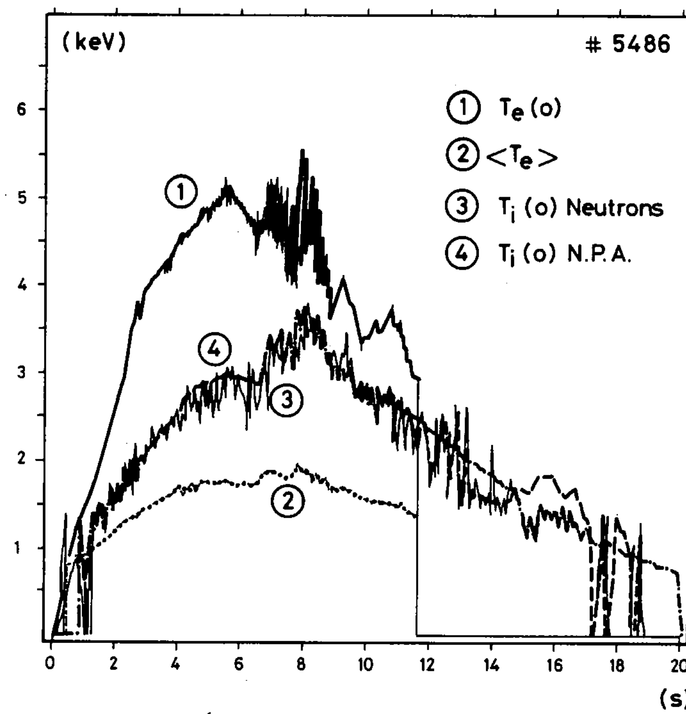


Fig 4. Time evolution of various temperatures in JET during pulse 5486

1) Peak electron temperature from ECE
2) Volume averaged electron temperature
3) Axial D temperature from Neutron Flux Measurement
4) Axial D temperature from charge Exchange Measurement

Note added in proof: Electron temperatures are overestimated by 25% in this figure.

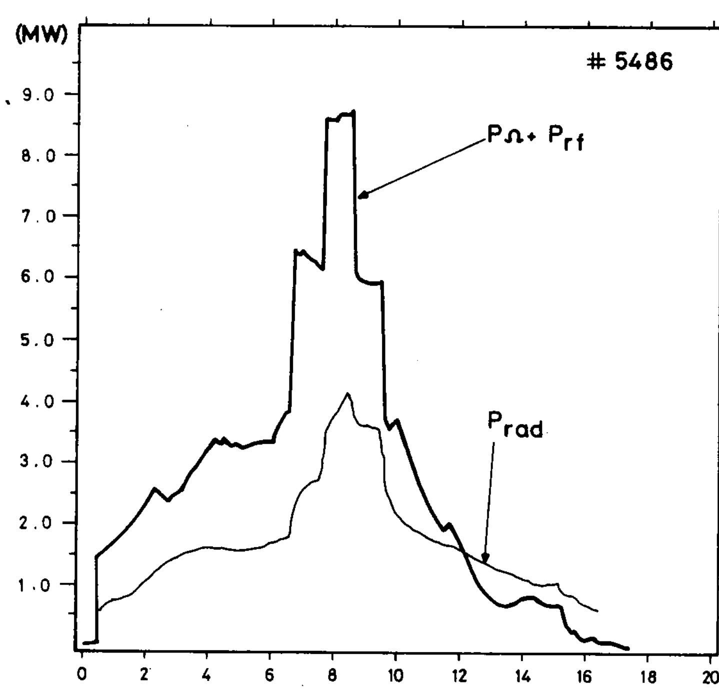


Fig 5. Time evolution of the total input power and of the radiated power deduced from bolometric measurements in JET during pulse 5486

During the pulse the peak density, as deduced from multi-channel interferometry, increased from 3 to 4 10^{19} m^{-3}. The energy content of the plasma was increased by 1 MJ, but the global energy confinement time decreased by 40% relatively to its value before the rf pulse. More data on confinement in JET are given in Figs 6a and 6b which shows the variation of the plasma energy and of the confinement time respectively versus the total input power $Pt = P\Omega + Prf$. The three sets of points correspond to different conditions of plasma current and magnetic field, the series around 1 MJ is for (H)D heating while the others are for (^{3}He)D heating. The solid and dotted lines represent the two following fits, independent of the minority species:

"L Mode" $\tau_E = 0.34 \sqrt{\frac{Ip}{Ptot} \sqrt{B\phi}}$: (S,MA,T,MW)

"Saturating L Mode" $\tau_E = (0.095 + \frac{0.29}{Ptot}) \sqrt{Ip \sqrt{B\phi}}$: (S,MA,T,MW)

where $Ptot = P\Omega + Prf$

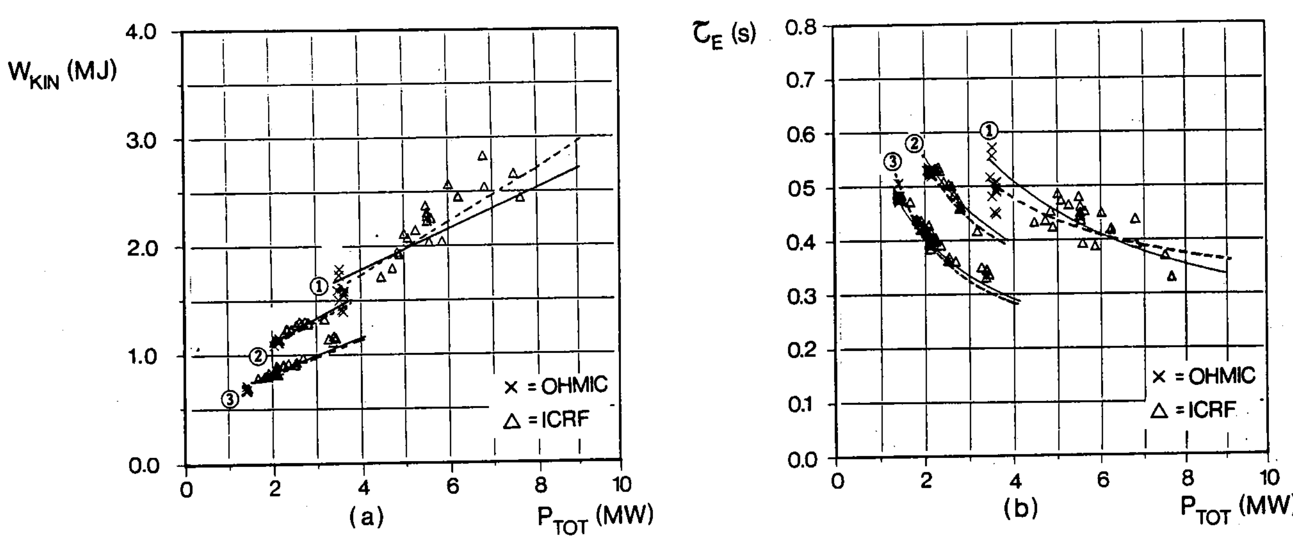


Fig 6. Stored kinetic energy (a) and energy confinement time (b) in JET versus the total input power $P_{tot} = P_{RF} + P_{\Omega}$

1 : 3.4 T ; 4.0 MA (^{3}He)D

2 : 3.1 T ; 2.7 MA (^{3}He)D

3 : 2.0 T ; 2.0 MA (H)D

X ohmic values before RF pulses.

Δ during RF

Such a degradation of the confinement time with any additional heating seem to be universally observed as stressed in the conclusions of the previous course on "Basic Physical Processes of Toroidal Fusion Plasmas" by Rutherford and shown in Fig 7.

Extracted from the "Summary of the course and workshop "Basic Physical Processes of Toroidal Fusion Plasmas" by P.H. RUTHERFORD

TOPIC	Tokamak experiments on confinement and stability	Auxiliary Heating of Tokamaks
DISCOURAGING	Deterioration of τ_E with P_{aux} confirmed in large Tokamaks	Deterioration of τ_E with P_{aux} approximately the same as with Neutral beam
ENCOURAGING	Good confinement does exist, depending on profiles and edge conditions	ICRH, ECRH and LHRH (?) work just as well as Neutral beam. More opportunities for profile optimization

Fig 7.

Confirmation of those statements were reported during the course by Wesner on Asdex /10/, Wilson on PLT /11/, Porkolab on Alcator /12/ and Prater on Doublet III /13/ in such a way that it was a surprise for most of us when in certain and rare occasions no degradation was indicated.

At this stage it may be useful here to mention a difference between physicists over the meaning of "degradation". For most of the Tokamaks around the world, experimental data of ohmic discharges have been statistically found to follow scaling laws where the plasma temperature does not appear while on T10 the used energy confinement time scaling has a $T_e^{-\frac{1}{2}}$ dependence. For instance Fig 8 which show the plasma energy content versus the total input power would likely be interpreted at Princeton as a degradation while it would not necessarily be at the Kurchatov, since the temperature has increased.

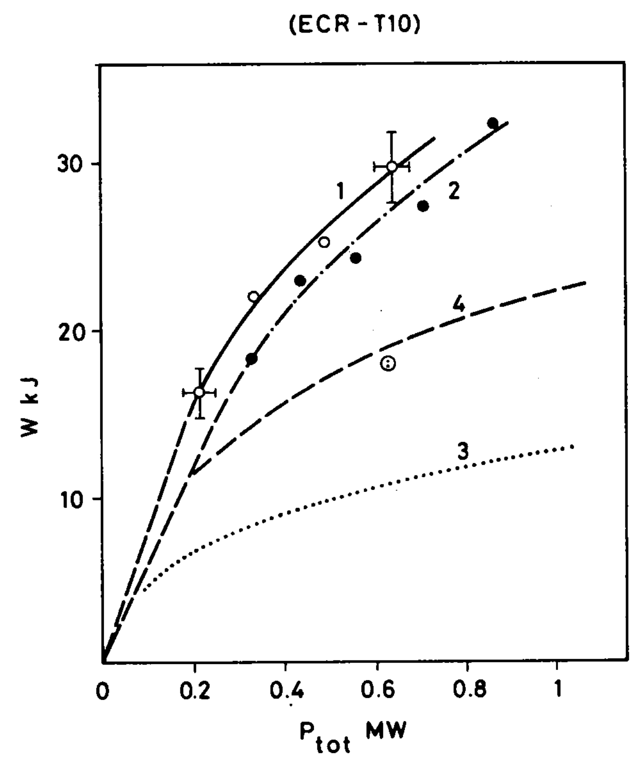
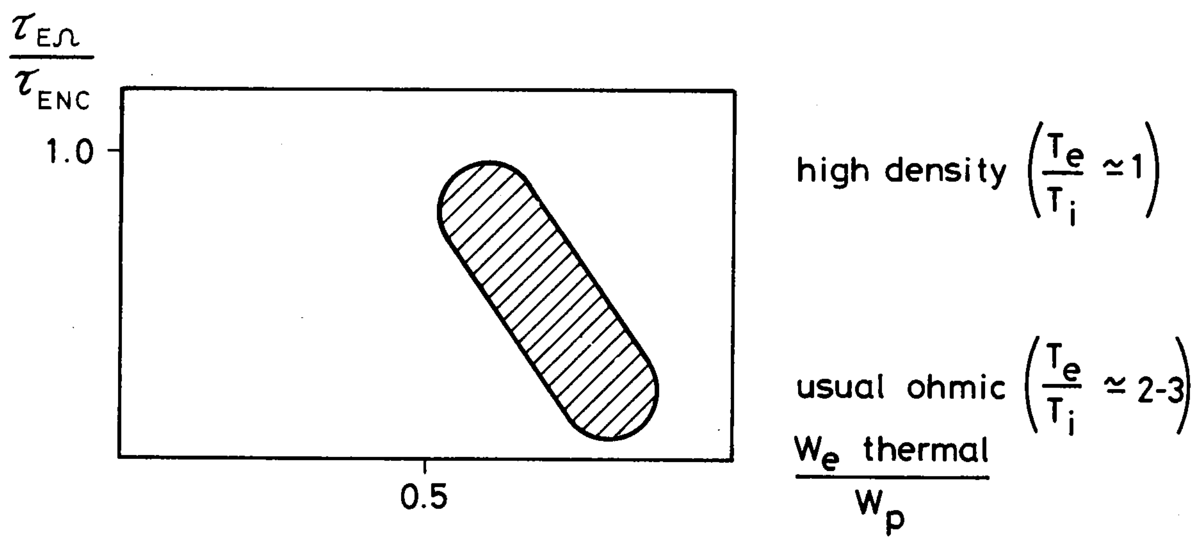


Fig 8. Energy content vs. the total input power, $P_{tot} = P_{OH} + P_{aux}$ at two I_p values, 180 kA (1) and 270 kA (2) under on-axis ECRH, $\bar{n}_e = 3.10^{13}$ cm^{-3}. The point ϕ - the off-axis ECR heating of the 180 kA plasma (12.5 cm outward shift, at the end of the HF pulse). 3 and 4 - the Kaye-Goldston scaling for 180 and 270-kA discharges, respectively. - From Ref /14/ -

We should also notice that we have been accustomed in the past fifteen years to a degradation of the confinement time in ohmic regime alone relative to the neoclassical predictions. If we write the kinetic energy content of the plasma as the sum of

$$Wp = Wi(tail) + Wi(thermal) + We(tail) + We(thermal)$$

Fig 9 shows qualitatively the evolution of $\tau_{E\Omega}/\tau_{ENC}$ versus We(thermal)/Wp and illustrates the well known anomalous electron transport in ohmic regime.



$$W_p = W_i \text{ tail} + W_i \text{ thermal} + W_e \text{ thermal} + W_e \text{ tail}$$

$$\tau_E = W_p \,/\, P \text{ input}$$

Fig 9. Qualitative dependence of the observed energy confinement time normalized to the Neoclassical one in Tokamaks versus the contribution of the thermal electrons to the total plasma energy.

It may be that the same trend i.e. an increase of the energy confinement abnormality with We(thermal)/Wp, applies also during additional heating at least in Tokomaks where the fast populations can be expected to be neoclassically confined, especially the ions, namely with a plasma current $\geqslant$ 300 kA,

Arguments pointing to the thermal electrons as the culprits of anomalous heat transport with additional heating, as well as in ohmic regime can be found in several lectures:

- The local measurements of heat transport in T10. (ECRF - Razumova) /14/,
- The saturated degradation in PLT when the major part of the thermal energy is supported by the ions (ICRF - Hosea) /15/, (Fig 10),
- The improved confinement in Asdex in low density when a large amount of energy is supported by the electron tails (LHR - Söldner) /16/.
- Possibly no degradation in PLT when the rf power is deposited on thermal

ions. (IBW - Ono) /17/.

- The absence of discontinuity in the relationship between turbulence and confinement time when auxiliary heating is applied in TFR (NBI/ICRF - Olivain) /18/.

ENERGY CONFINEMENT VERSUS TOTAL POWER

(ICRF - PLT)

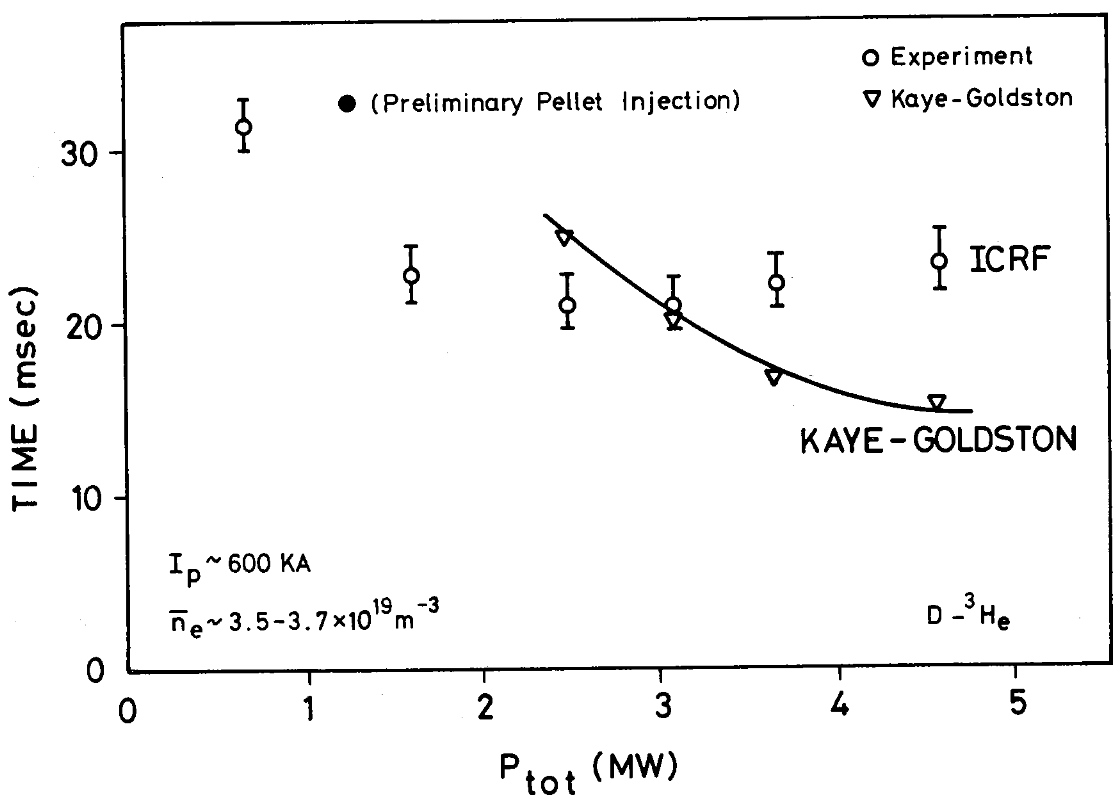


Fig 10. This curve shows a saturation in the degradation of the energy confinement time in PLT when the total input power reaches 2 MW, i.e. when $P_{RF}/P_{\Omega} \simeq 5$. The contribution of the ion energy content (deuterium and minority) to the total plasma energy is dominant when $P_{tot} \simeq 4$ MW. (From Ref /15/).

Even if this trend appears to be true it is not more than a trend and certainly not an explanation. At least it leads to a classification of the various rf heating methods according to which component of the plasma directly absorbs the rf power, as shown in Table 1.

Table 1

Plasma Component	ion tail	ion thermal	electron thermal	electron tail
Wave absorption mechanism	ICR (minority) ICR (harmonic) LHR (ion heating)	ion-TTMP IBW	electron-TTMP Alfven ICR (wave conv)	ECR LHR (e-heat)
Other heatings	NBI α part. heat		ohmic	
Degradation of tail energy	E < 15 Te → ion thermal E > 15 Te → electron thermal	↑	↑	→ electron thermal

Then and depending on the plasma condition the energy of the heated component will obviously relax on the thermal components and in particular on the thermal electrons as shown by the arrows on Table 1. To extend Table 1 we could list the ohmic heating itself in the thermal electron column. At first glance, and if the trend mentioned above has some meaning, it could lead to preference being given to the heating schemes not acting on electrons and to avoid the creation of ions of too high energy. Actually this could be done up to a certain extent with ICRF by "defocussing" the power deposition from the plasma centre.

But in the long term the problem of confining all the plasma components should be solved. It seems to me like a "new frontier" for the wave plasma physicists. Beside discussing the respective merits of each rf method and since the technical tools now exist, we must use them to help the understanding of the confinement. We can do that either by heating itself (localised heating, modulation) or by diagnosing (scattering). Then possibly we will have to cure the confinement degradation and ways of doing so have been already proposed.

P.H. Rutherford suggested to stabilize the most dangerous MHD modes by using rf current drive in a process of feedback control /19/. Action of rf on MHD activity has been reported in T10 (ECR), PLT (LHR) /20/ and in JET (ICR) /21/ where by changing the cyclotron resonance from outside to inside the q = 1 surface the electron temperature oscillations were strongly affected in period and in amplitude as shown by Fig 11. A more radical way of action on the Tokamak was proposed by P.H. Rebut at the London conference /22/: to open

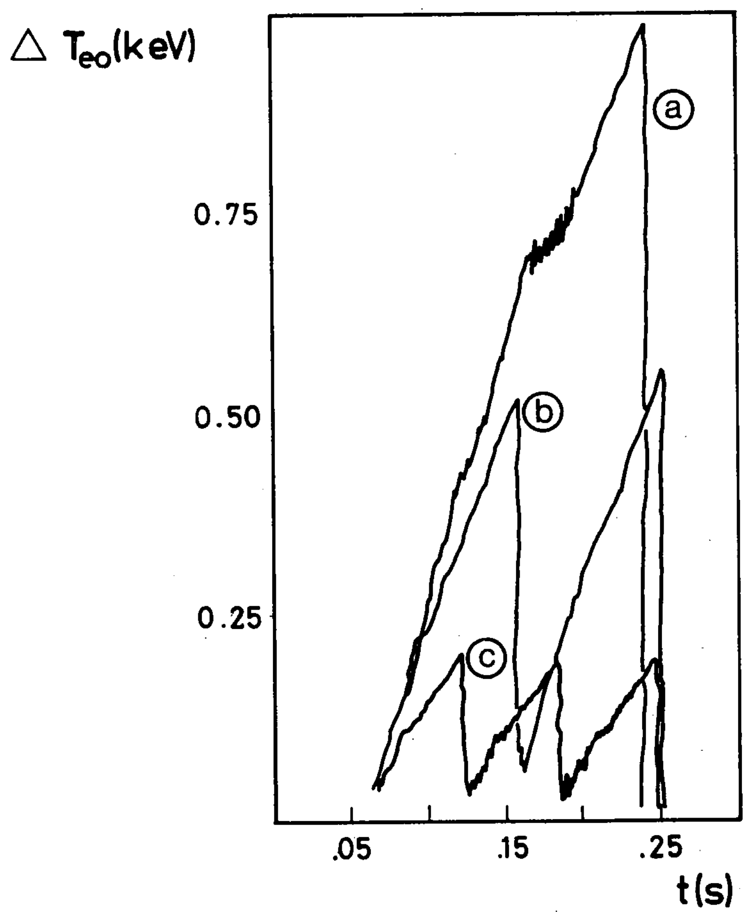


Fig 11. Variation in the sawtooth activity observed in JET during ICRF when the minority cyclotron layer is inside (curve a) at the edge (curve b) or outside (curve c) the volume defined by the q = 1 surface.

the feedback loop between electron temperature and current density profiles by using slide away electrons to support the plasma current and rf to heat the bulk plasma.

The present course has shown that the physics basis of wave heating and the techniques to do it seem now rather solid. But the Tokamak, at least as used presently, seems allergic to any heating and we know that homeopathic doses will not be sufficient. To recommend using our improved expertise in wave propagation and absorption in Tokamaks to understand and cure the heat transport will be my conclusion.

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