EUROPEAN FUSION DEVELOPMENT AGREEMENT

HEATING OF THERMAL IONS BY ALPHAS IN THE JET DT EXPERIMENT

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INTRODUCTION

The alpha heating experiment was performed in the autumn of 1997. It was apparent in early study of the data that the ion heating was surprisingly large and that analysis required a reduction of the ion thermal conductivity in the presence of alphas. This analysis was delayed because key personnel were involved in the change in organisation at JET. The CXS data has subsequently been thoroughly checked and the latest corrections incorporated. The result that there is unexpected ion heating holds good and is still unexplained. ***It is important to add that the published results on electron heating are unchanged by subsequent analysis.***

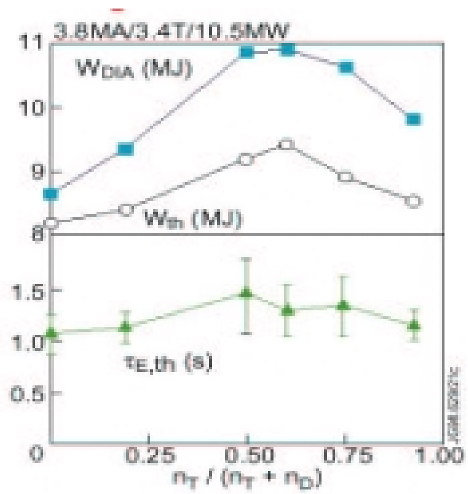

Figure 1: *The diamagnetic energy (Wdia), the thermal energy (Wth) and the thermal energy confinement time ($t_{E,th}$) versus the DT mixture.*

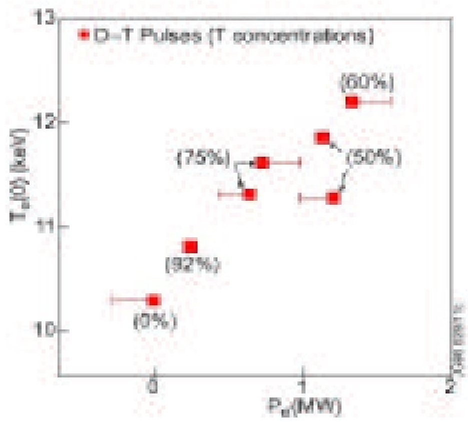

Figure 2: *The central electron temperature, measured with ECE ($T_e(0)$) versus the alpha power P_a. The bars represent the differences in NBI power relative to the 92% tritium case.*

THE ALPHA HEATING EXPERIMENT

[P Thomas et al.,PRL 80(1998)p5548]

The standard 3.8MA/3.4T ELM-free, hot ion, H-mode was used to maximise $P_\alpha/P_{NBI,abs}$. The mixture, $n_T/(n_D+n_T)$ was varied from 0 to 92% to separate heating from τ_E(A). This required that the wall be loaded with the DT mix; as was the NBI.Since only one box was operated in tritium, the maximum NBI power was 10-10.5MW.

A trial experiment was run with P_{ICRH}driven by Γ_{DD}. This showed that the electron temperature increase due to the anticipated alpha heating could be detected. P_{fusion}~ 5MW with DT was predicted with TRANSP analysis.In the event, with DT P_{fusion}=6.75MW was obtained, with P_{fusion}/P_{abs}=0.65 (pulse 42847).

Clear electron heating was observed. The temperature increase, of ~1keV/MW, was the same as that obtained with ICRH. Litle or no isotopic effect is seen in τ_E..There is, perhaps, a slight confinement enhancement with alpha heating. The increase in W_{fast} with T^0 NBI, apparent in W_{dia}-W_{th}, stabilises sawteeth [F Nave et al, to appear in NF(2001)].

STRONG ION HEATING WAS OBSERVED

The increase in T_i was larger than that of T_e even though the alpha power to the ions was around 15% of the total alpha power. The ion temperature is very similar in the 0% and 92% tritium plasmas. All the pulses show some turnover of $T_i(0)$ with time, as seen in figure 3. This is due to the density increase.

The independent measurements of W_{dia} and Γ_{14MeV} are in good accord with TRANSP output, which uses the CXS $T_i(r)$. Analysis on sensitivity to Z_{eff} has to be completed.

The ion heating with alphas is three times that of the electrons. This ion heating is not observed with ICRH substituting for alphas, although these plasmas show the same level of electron heating!

**As seen in figure 6, the ion thermal conductivity is minimised(albeit at different minor radii) in the presence of alphas.
The TRANSP analysis shows that the power input to the ions, eg at 3.5m, changes by less than 5%.**

The classical alpha heating is negligible. Also, the equipartition power, in the confinement region, hardly changes across the mixture scan.

In contrast to the pulses with alpha heating, the ICRH pulses show ion temperature rises comparable to those of the electrons, as expected due to equipartition.

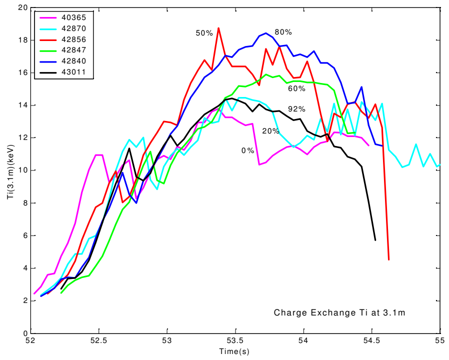

Figure 3: *The central ion temperature, measured with charge exchange spectroscopy, versus time, for the six pulses of the DT mixture scan. The traces are marked with the mixtures*

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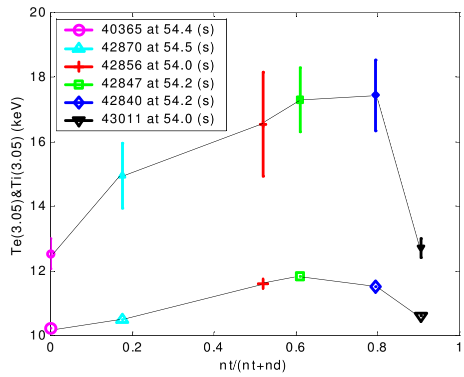

Figure 4: *The central ion(CXS) and central electron temperature(ECE) versus DT mixture, determined from Z_{eff} and DT neutron emission.* ***The selected time points are at maximum $T_e(0)$.***

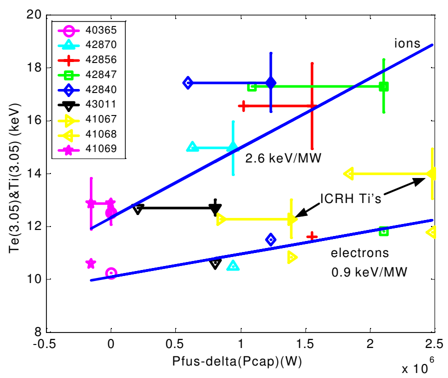

Figure 5: *The central ion and central electron temperatures for the DT mixture scan and the ICRH emulation series. The bars indicate the change in NBI power relative to the 0%T pulse 40365 (note difference with figure 2). The fitted lines are to DT data only.*

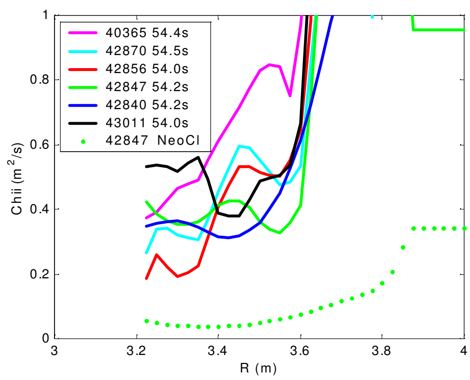

Figure 6: *The ion thermal conductivity, from TRANSP, versus major radius. The Chang-Hinton neoclassical value for the 60% case is shown to set a scale.*

WHAT IS THE EXPLANATION FOR THIS ION HEATING?

There are three possibilities:
1] The CXS data or the measurements of P_{nbi} are defective
2] The alphas produce an electric field, which triggers a transport barrier. Alternatively, these plasmas could already have been close to having a barrier and the alpha heating pushed them over.
3] The alphas couple to the thermal ions - eg by ion cyclotron instability or Alfvén waves.

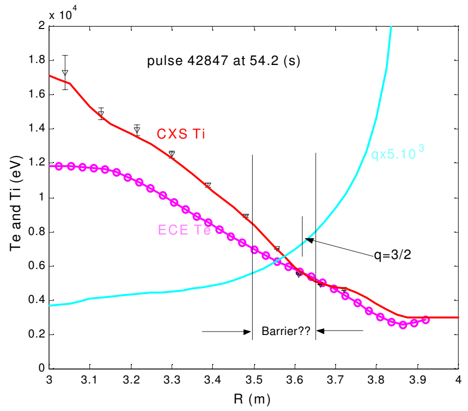

Figure 7: *Evidence for ion transport barier at q=3/2?*

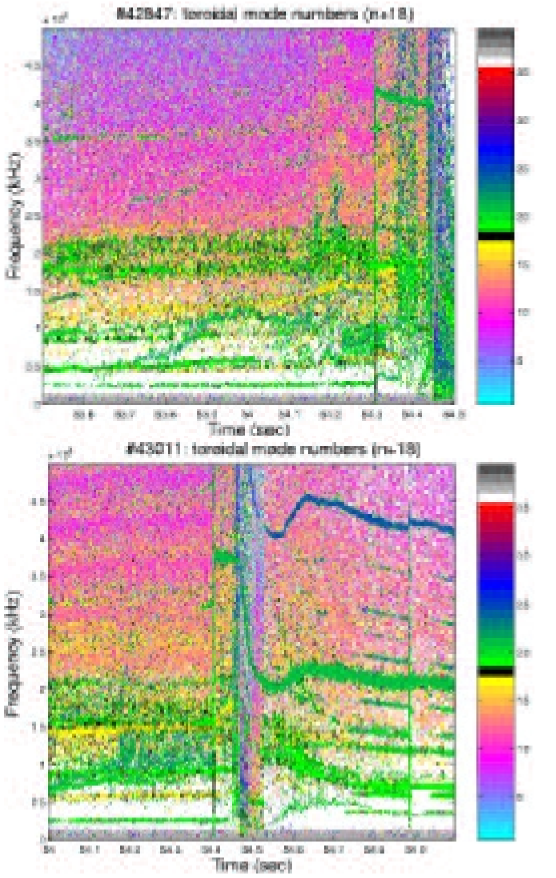

Figure 8: *Mode number spectra versus time, showing that the plasma rotation velocity does not vary significantly across the mixture scan.*

DATA DEFECTS?

It is possible that either the CXS T_i or the NBI power measurements are at fault. However, this does not seem very likely:

(a) All the data validation using CXS T_i holds up very well. The magnetic energy contents and 14MeV neutron yields are reproduced well by the profile data.
(b)Some of the measured P_{nbi} variation, across the scan, is of the same order as the alpha heating power. Good quality fits to the electron temperature data result, if this variation is included (see figure 2). Thus the NBI power measurements seem consistent with the ECE data.

INTERNAL TRANSPORT BARRIERS?

The T_i profiles(see figure 7) give an impression of barrier formation (increased dT_i/dr). The ion thermal conductivity decreases but to nothing like the neoclassical value.

In principle, alpha losses could produce enormous electric fields. However, simple estimates show that all the αs, produced in these plasmas, would have had to have been lost to produce fields of order E_α/a.

The measured variation of the toroidal rotation frequency is of order 4.10^5 m/s (not shown). Also the correlation with ion heating is very poor! As seen in figure 8, the relationship between mode number and frequency does not change, so any change in electric field, in the plasma frame, is insignificant.

THUS, THERE IS NO EVIDENCE OF AN ALPHA SPECIFIC MECHANISM FOR BARRIER FORMATION.

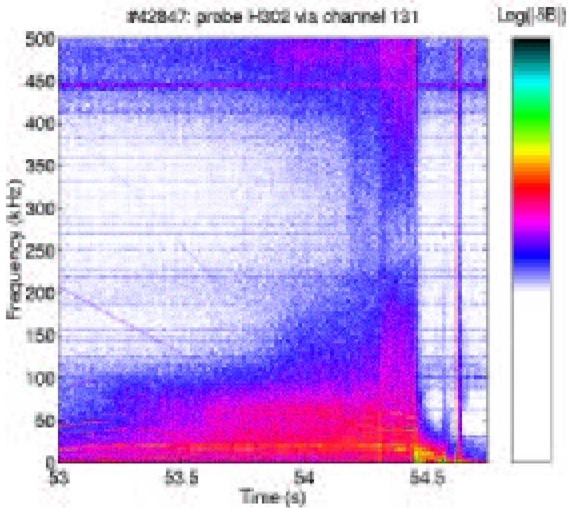

Figure 9: *A magnetic spectrogram for the highest yield pulse. No TAEs or EAEs are discernable.*

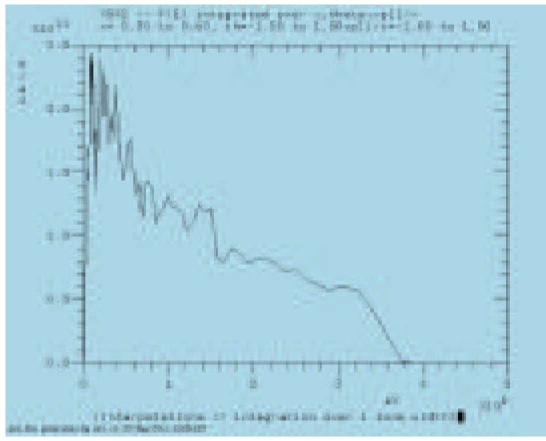

Figure 10 : *Monte-Carlo alpha distribution function. Shows no bump-on-tail due to growing DT yield.*

ANOMALOUS ION HEATING?

TAEs and EAEs are not present, as shown in figure 9. It is possible that Compressional Alfvén waves[N.N.Gorelenkov, C.Z.Chang, Phys. Plas. 2 (1995)p1961 and D.Gates et al., submitted to PRL] are present, as proposed for anomalous ion heating in NSTX. ICE monitors were not available during this experiment.

The increasing alpha source rate might produce +ve df/dv as might finite ρ_α. The Monte-Carlo distribution from TRANSP shows no signs of +ve df/dv anywhere and is similar in magnitude and shape to the Spitzer distribution. Thus, bump-on-tail instability, arising from the transient nature of the alpha source, is unlikely. Finite Larmor radius effects have yet to be checked.

CONCLUSIONS

- **THE ION HEATING WAS STRONGER THAN THAT OF THE ELECTRONS IN THE DTE1 ALPHA HEATING EXPERIMENT.**
- **THE CXS DATA HAS BEEN THOROUGHLY CHECKED AND TRANSP VALIDATION LOOKS VERY GOOD.**
- **EMULATION PULSES, USING ICRH, SHOW THE SAME ELECTRON HEATING BUT VERY MUCH REDUCED ION HEATING.**
- **THE ION THERMAL CONDUCTIVITY IS MINIMISED IN THE PRESENCE OF ALPHAS.**
- **THE REASON FOR THE ION HEATING REMAINS A MYSTERY. IT SEEMS THAT AN ION TRANSPORT BARRIER MIGHT BE RESPONSIBLE BUT THE EVIDENCE IS WEAK.** ***HOWEVER, THERE IS NO EVIDENCE FOR ANY ALPHA SPECIFIC EFFECT CAUSING A BARRIER.***
- **IT IS IMPORTANT TO RESTATE THAT THE PUBLISHED RESULTS ON ELECTRON HEATING STAND.**

§DTE1 EXPERIMENTAL TEAM FOR THE ALPHA HEATING EXPERIMENT

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