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Evidence for a New Path to the Self-Sustainment of the Thermonuclear Fusion Reactions in Magnetically Confined Burning Plasma Experiments

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** See annex of F. Romanelli et al, "Overview of JET Results", (23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea (2010)).*

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ABSTRACT.
To achieve a sufficiently high energy gain to become commercially viable, thermonuclear fusion in magnetically confined plasmas relies on collisional heating provided by the MeV-energy, fusionborn alpha particles to replace the external heating initially applied to reach the ion temperature optimising the fusion reactivity. This process for plasma self-heating occurs over time scales five to ten times longer than the energy confinement time, thus can be seriously affected by the magnetohydrodynamic instabilities observed in current experiments. Here we provide the first explanation for observations made in 1997 of unexpected ion heating by fusion-born alpha particles occurring over time scales shorter than the energy confinement time. We demonstrate that non-thermal alpha particles above a critical concentration stabilize the turbulence in the ion-drift direction, therefore significantly reducing an ion energy loss channel. This result opens new perspectives on alternative paths for the self-sustainment of magnetically confined thermonuclear fusion plasmas.

1. INTRODUCTION

Experimental and theoretical progress in magnetically confined thermonuclear fusion plasmas has reached the level where ITER [1] is expected to obtain a net energy gain (Q) of around ten using a deuterium-tritium (DT) 50:50 fuel mixture ($Q_{DT} = 10$). To obtain this goal, the fusion-born alpha particles (αs), with birth energy = 3 .5MeV, must remain confined while thermalizing through Coulomb electro-static collisions. This provides the self-heating to the background plasma replacing the external, additional heating applied initially to reach the ion temperature optimizing the overall fusion reactivity, $T_i \approx 15$keV. As the birth energy of the αs by far exceeds the value where their collision frequency with the electrons equals that with the ions (~150keV in usual plasma conditions, about fifteen times the plasma temperature), the plasma self-heating process requires the αs first to slow-down on the electrons. This process occurs over a time scale ($\tau_{\alpha e}$) comparable to the energy confinement time (τ_E): the αs then loose ~95% of their energy while thermalizing onto the electrons, with only ~5% going directly to the ions at the end of their thermalization process. The electrons are then required to heat the bulk ions through energy equi-partition: this process occurs over a time scale (τ_{ei}) that is around five to ten times longer than τ_E.

This mechanism for plasma self-heating by fusion-born αs was experimentally verified in the three DT fusion experiments performed so far: on the Joint European Torus (JET) [2] in 1992 (reaching $Q_{DT} \approx 0.15$ [3]), in the Tokamak Fusion Test Reactor (TFTR) [4] from 1993 to 1997 (peak $Q_{DT} \approx 0.255$), and again on JET in 1997. This Deuterium-Tritium Experiment (DTE1) [6] produced the world record fusion power $P_{FUS} \approx 16$MW, with a record $Q_{DT} \approx 0.65$ maintained over about half τ_E.

However, it is also clear that any mechanism affecting this long two-step process (as $\tau_{\alpha e} + \tau_{ei} > 5\tau_E$) for plasma self-heating by fusion born αs, will have a detrimental impact on achieving a high QDT value, reducing the attractiveness of magnetically confined thermonuclear fusion as a commercially viable energy source. Examples are the magneto-hydrodynamic instabilities frequently observed in present day experiments [7,8,9], which are in most cases also predicted to occur in ITER [10,11].

A series of dedicated discharges were performed during DTE1 with plasma conditions optimised for the observation of the collisional bulk electron heating by the fusion-born αs (the alpha-heating experiment), and this process was found to follow the theoretical predictions [12,13]. However, at that time it was also noted that under certain experimental conditions a bulk ion heating was obtained that was much larger than expected, furthermore occurring over time scales shorter than τ_E. Despite much analysis of this data in the early 2000s [14], no convincing explanation has been so far put forward for those observations, which have then been somehow abandoned until now.

2. THE ANOMALOUS ION HEATING OBSERVED IN THE JET DTE1 EXPERIMENT.

In the alpha-heating experiment the DT mixture ratio $n_T/(n_D + n_T)$, where n_D and n_T are the deuterium and tritium density, respectively, was varied in the range $0 \leq n_T/(n_D + n_T) \leq 0.92$ while keeping constant the magnetic equilibrium and the plasma density. To achieve the required Ti, these discharges were additionally heated using Neutral Beam Injection (NBI), with constant power $P_{NBI} = 10.5$MW, using the same DT fuel mixture as the background plasma. The 150keV injection energy of the NBI ions was selected to maximise the direct collisional heating to the thermal ions. The value of P_{NBI} was selected to match the predicted ion heat losses, to keep a constant T_i, facilitating the evaluation of the alpha heating to the electrons. These discharges were very quiet in terms of coherent magnetohydrodynamic activity, and showed comparable levels of incoherent turbulence. A maximum in the alpha fusion power $P_{\alpha FUS} \approx 1.3$MW was observed for $n_T/(n_D + n_T) \approx 0.55 \pm 0.1$, with the ensuing increase in the core electron temperature $\Delta T_{e0} \approx 1.3$keV in accordance with the theoretical predictions [6,12,13] of ~95% of the energy of the αs collisionally transferred to electrons over a time scale $\tau_{\alpha e} \approx 1.2$sec, slightly longer than $\tau_E \approx 0.7$sec.

Figure1 shows the main plasma parameters for three discharges in the alpha-heating experiment, illustrating the full range of variation in the DT ratio, alpha particle concentration n_α/n_e (n_α is the density of fusion-born αs at their birth energy of 3.5MeV and ne the electron density, respectively) and $P_{\alpha FUS}$. Focussing our attention on Pulse No: 42856 ($n_T/(n_D + n_T) = 0.53$ and $n_\alpha/n_e \approx 0.035$), the peak T_{e0} is obtained at t = 14.10sec, within one $\tau_{\alpha e}$ after the peak $P_{\alpha FUS}$, obtained at t = 13.75sec, whereas the peak T_{i0} is obtained slightly before the time of the peak in $P_{\alpha FUS}$. Second, the T_{i0} rise is much larger and faster than the T_{e0} rise as a function of $P_{\alpha FUS}$: we have $\Delta T_{e0}/P_{\alpha FUS} \approx 1.7$keV/MW with a rise rate $\tau_{eR} = T_{e0}/(\Delta T_{e0}/\Delta t) \approx 1.4$sec, consistent with $\tau_{\alpha e} \approx 1.2$sec. Conversely, $\Delta T_{i0}/P_{\alpha FUS} \approx 5.9$keV/MW, i.e. $\Delta T_{i0}/P_{\alpha FUS} \times 3.5 \approx \Delta T_{e0}/P_{\alpha FUS}$, with a rise rate $\tau_{iR} \approx 800$msec, i.e. five times faster than the slowingdown of the αs on thermal ions ($\tau_{\alpha i} \approx 4$sec) and the electron-ion energy equipartition time ($\tau_{ei} \approx 5$sec).

Third, there is a clear $\Delta T_{i0} \approx 3$keV excess in the core ion temperature for $n_T/(n_T + n_D) = 0.53$ at the time of the maximum in $P_{\alpha FUS}$ compared to the value expected using the same transport model that correctly predicted the T_e evolution [6,12,13] and the T_i evolution for $n_T/(n_T + n_D) = 0$, even accounting for the residual ~5% direct collisional heating by the αs on the thermal ions. Finally, T_{i0} decays after the peak $P_{\alpha FUS}$ on time scales comparable to τ_E, even with a constant source from collisions with the injected NBI ions. Ensuing transport analyses performed with TRANSP [15] validated the T_i data, excluded isotopic effects on the τ_E and τ_{ei} time scales, and linked this anomalous ion heating to an unexplained reduction by a factor ~2 of the ion thermal conductivity χ_i in the plasma core [14]. Hence, it is phenomenologically intuitive that some mechanisms other than classical collisional heating and energy equi-partition must be at play not only to produce this much-larger and much-faster thanexpected, but also to saturate the increase of the ion temperature.

In Science16, Nature17,18 and recently in Scientific American19, it has been shown that turbulence could negatively affect ITER by worsening energy confinement through increased heat and particle transport: could it be that JET data from 1997 indicate that suppressing turbulence actually reduces thermal ion heat transport?

3. ANALYSIS OF THE TURBULENCE MEASUREMENTS IN THE ELECTRON- AND ION-DRIFT DIRECTION IN THE IONACOUSTIC FREQUENCY RANGE.

We start from the ansatz that there is a direct link between drift-wave turbulence in the electronand ion-drift direction and the temporal evolution of the thermal electron and ion temperatures through modifications to the electron and ion diffusivity and thermal conductivity [20]. The nonlinear evolution of small scale turbulence, such as Trapped Electron Modes (TEMs) and Ion Temperature Gradient (ITG) modes, consistently reflects the linear behaviour of the micro-instabilities: hence, larger linear growth rates induce stronger nonlinear heat fluxes [21, 22, 23].

Here we present a new analysis of the measurements of the incoherent electro-magnetic turbulence spectra at drift-wave frequencies for the alpha-heating experiment. The spectral decomposition of the incoherent turbulence measurements was performed in14 using the phase-slope [24] and Singular Value Decomposition [25] techniques. Both methods suffered in the early 2000s from severe limitations, both numerical (available CPU and RAM resources) and mathematical (de-convolution of a spectrum made up of different components whose number and amplitude ratio is unknown).
More powerful analysis methods based on the Sparse Representation of signals [26-30] have recently become available for spectral decomposition in fusion plasmas (see also the Methods section), and also very sophisticated codes such as GENE [31] can now be used to analyse the effect of a minority population of high-energy ions on the predicted turbulence spectrum. As the collisional slowingdown of the fusion-born αs on the electrons, and the ensuing energy equi-partition with the ions, are essential ingredients for the self-sustainment of the fusion reactivity in burning plasmas, we must understand whether the of an anomalous ion heating can be linked to physical mechanisms that, in turn, could be used to optimize the operational scenario of forthcoming devices such as ITER. Hence, it is really advantageous to re-analyse the very same turbulence measurements using these new tools to try to provide a convincing, even if phenomenological, explanation for the reduction in the thermal ion conductivity in the presence of a minority population of fusion-born αs.

We evaluate the turbulence spectra using data from magnetic pick-up coils mounted on the low- and high-field side vessel walls and electron-cyclotron emission (ECE) measurements covering the plasma cross-section. As shown in Fig.1, two time-points are selected for turbulence analysis. The first time-point (T1) corresponds to the early phase of the thermalization of the αs, i.e. within a fraction of one slowing down-time of the αs on the electrons ($\tau_{\alpha e} \approx 1.2$sec at the birth energy of 3.5MeV), much before the time-point corresponding to the peak value of $P_{\alpha FUS}$. The second timepoint (T2) for the analysis is taken when there is a large fraction of fusion-born αs that have had the time to fully thermalize, i.e. typically within one $\tau_{\alpha e}$ after the time-point of the peak $P_{\alpha FUS}$ value.

Figure2 shows the measured Eigenfunction for turbulence in the ion-drift direction at the time-point T2 for the Pulse No: 42856, which had the highest value of $P_{\alpha FUS}$ and n_α/n_e. When there is a large fraction of fusion-born αs that have thermalized, the largest turbulent component is found around 40kHz, i.e. exactly in the ion-drift-wave range.

The ITG Eigenfunction is localised at $R \approx 3.5m \pm 15cm$, with peak amplitude $|\delta B_{ECE}| \approx 20mG$ in the plasma core (evaluated using the formalism [32,33]), and has even parity, corresponding to kink type turbulent modes that do not induce magnetic islands (associated to tearing-type modes, with oddparity), therefore do not cause radial transport and stochastic loss of the αs. This Eigenfunction overlaps with the plasma volume where TRANSP indicated that a χ_i reduction was needed to explain the T_i increase [12,13,14]. Conversely, no such Eigenfunction can be measured at the time-point T1, when the αs have not yet thermalized. This is due to S/N ratio being too small in the plasma core, $|\delta B_{ECE}| < 5mG$, indicating that ion-drift turbulence has been reduced to below measureable levels when there is a sufficiently large population of fusion-born αs close to their birth energy.

Figure3 shows the spectrum of the magnetic field amplitude $|\delta B_{MEAS}|$ measured at the plasma edge in the drift-wave frequency range at the two time points T1 and T2. For n_α/n_e>1.5%, the amplitude of ITG turbulence (components with positive toroidal mode numbers $n > 20$) decreases significantly when the αs have not yet thermalized (time-point T1). This result is consistent with theoretical predictions by Angioni [34], and experimental observations by Tardini [35]. For the data taken at the time-point T2, when the αs have fully thermalized, ITG turbulence has around four times larger amplitudes, which decreases only for n_α/n_e>2.8%. The amplitude of TEM turbulence (components with negative toroidal mode numbers n<–20) is much larger than the ITG one, and increases as function of n_α/n_e, which is consistent with the corresponding increase in Te as function of $P_{\alpha FUS}$.

3. GENE SIMULATIONS OF THE TURBULENCE SPECTRA IN THE ELECTRON- AND ION-DRIFT DIRECTION IN THE IONACOUSTIC FREQUENCY RANGE.

Turbulence simulations were performed with the GENE [31] code, using the magnetic equilibrium and background plasma data at mid-radius, R = 3.5m, consistently with the measured Eigenfunction shown in Fig.2. The αs were modelled with an isotropic Maxwellian distribution function36, and an equivalent temperature is used to set the correspondence with the energy stored by the fusion products. Finally, we take the numerically obtained growth rate γ to give an approximate estimate of the strength of the saturated turbulence.

A first set of simulations is needed to identify the key features of the turbulence characterizing the reference plasma scenario with $n_T/(n_T + n_D) = 0$, i.e. where neither tritium (possible isotopic effects) nor αs (to isolate their contribution) were present, and then include the isotopic effect due to tritium and the role of αs at different equivalent temperature, as shown in Fig.4. First, note the isotopic effect on the ITG growth rate $(\gamma/\omega)_{ITG}$ without αs, as $(\gamma/\omega)_{ITG} \approx 0.02$ for $n_T/(n_T + n_D) \approx 0.2$ whereas $(\gamma/\omega)_{ITG} \approx 0.020$ for $n_T/(n_T + n_D) \approx 0.9$. Second, for $n_\alpha/n_e > 2\%$ there is a small, but clearly systematic, reduction in γ_{ITG} when the αs are included in the calculations.

Third, we have increased the temperature of the alpha particle population for the specific case $n_\alpha/n_e = 3.5\%$ (Pulse No: 42856) from $T_\alpha = 80T_e$, corresponding to fully-thermalized αs (the situation expected at the time-point T2), to $T_\alpha = 290T_e$, corresponding to αs at their birth energy (the situation expected at the time-point T1). We find that the lowest value of $(\gamma/\omega)_{ITG}$ corresponds to $T_\alpha = 290T_e$, indicating that indeed αs that have not yet thermalized contribute most to the stabilization of ITG modes. Overall, the results of this set of GENE simulations are in quantitative agreement with the analysis of the ion-drift-wave turbulence measurement. As ITG modes contribute significantly to ion heat and transport, then the link between mode suppression and χ_i reduction with the measured time evolution of T_i is established.

In a second set of turbulence simulations, show in Fig.5, we then study the time evolution of the core T_{i0} and T_{e0} as function of the ITG and TEM turbulence characteristics for the Pulse No: 42856. The intensity of ITG modes, evaluated from the $|\delta B|_{ITG}$ measured at the plasma edge, and α_{ITG} both decrease as the αs start to thermalize over the bulk plasma, from t = 13sec to t = 13.5sec. This then allows T_{i0} to increase over a time scale $\tau_{iR} \sim 0.8$sec comparable to the energy confinement time $\tau_E \sim 0.7$sec, which is much faster than the alpha particle slowing-down time on the ions ($\tau_{\alpha i} \sim$ 4sec) and the electron-ion energy equi-partition time ($\tau_{ei} \sim 5$sec). An increase in γ_{ITG} and in the ITG instability strength is then observed to occur from t=13.5sec onwards, i.e. after around one alpha particle slowing-down time on the electrons ($\tau_{\alpha e} \sim 1.2$sec), as the fusion born αs have had the time to fully thermalize so that their mean energy has decreased sufficiently. This, in turn, first stops the increase in T_{i0} and then causes its reduction despite the continuous NBI ions transferring their energy to the bulk ions through collisions. Conversely, the behaviour of TEM modes, as deduced from the time evolution of γ_{TEM} and $|\delta B|_{TEM}$, remains essentially unaffected throughout the alpha particle thermalization process, hence TEM micro-instabilities do not play any role on the time evolution of Ti0. Again, the results of this third set of GENE simulations very well match the various features observed in the discharge evolution and the turbulence measurements.

Therefore, there is evidence from JET data of 1997 that suppressing ITG turbulence has a positive effect on the heat transport of thermal ions in tokamak fusion experiments: could this result also apply to plasma self-heating in ITER? Initial simulations have been performed with GENE using the ITER reference steady state scenario [37,38], with the results shown in Fig.6. This operational scenario for ITER has not yet been optimized for ITG or TEM stabilization: still we find a clear reduction in γ_{ITG} as the n_α/n_e and T_α increase, as in JET.

It is now important to understand why the effect of αs on γ_{ITG} and T_i has not been observed in the TFTR DT experiments, as well as why the effect is much smaller for the simulated ITER plasmas shown in Fig.6. A simple answer is obtained from [39,40], where one can find that a fluid treatment of ITG turbulence predicts that it becomes unstable for $\eta_i = L_n/L_{Ti} > \eta_{iC} = (4/3)(1 + \eta^{-1})(1 + 2s/q)\varepsilon_n$ for $\varepsilon_n > \varepsilon_{nC}$ with $\varepsilon_{nC} = 0.9/(1 + \eta^{-1})/(1 + 2s/q)$. Here $\tau = T_e/T_i$, $L_X = -(d\log(X)/dr)^{-1}$, $\varepsilon_X = LX/R$ and

$s = (r/q)(dq/dr)$: the JET DTE1 profiles for the alpha-heating discharges have $\eta_i \sim 1.15\times\eta_{i\,C}$, hence even a small contribution from the αs can have a substantial effect on γ_{ITG}. Conversely, the TFTR DT supershots [5] had $\eta_i \sim 5\eta_{i\,C}$, explaining why the anomalous ion heating effect was not observed in TFTR.

Finally, the ITER profiles analyzed here have $\eta_i \sim 2\eta_{i\,C}$: this explains why the γ_{ITG} reduction is not as strong as in the JET data, and indicates that slight modifications of the background plasma should allow ameliorating the effect of the αs on the ITG turbulence. Further, time-dependent non-linear simulations will be performed to optimize this operational scenario so as to improve the efficiency of this mechanism for turbulence stabilization in ITER.

CONCLUSIONS.

In summary, we find that a sufficient concentration of high-energy, fusion-born αs that have not thermalized stabilizes the ITG turbulence, reducing one energy loss channel for the thermal ions. This mechanism provides a convincing phenomenological explanation for the unexpected and so far unexplained increase in the ion temperature observed in the JET alpha-heating experiment of 1997. These results may open additional possibilities for future experiments that aim at optimizing the path to self-sustainment of the fusion reactions. This can be achieved by tailoring the plasma background so that the fusion born αs not only collisionally heat the background plasma, but also cause a significant reduction in the ion heat transport by suppressing ion-drift-wave turbulence.

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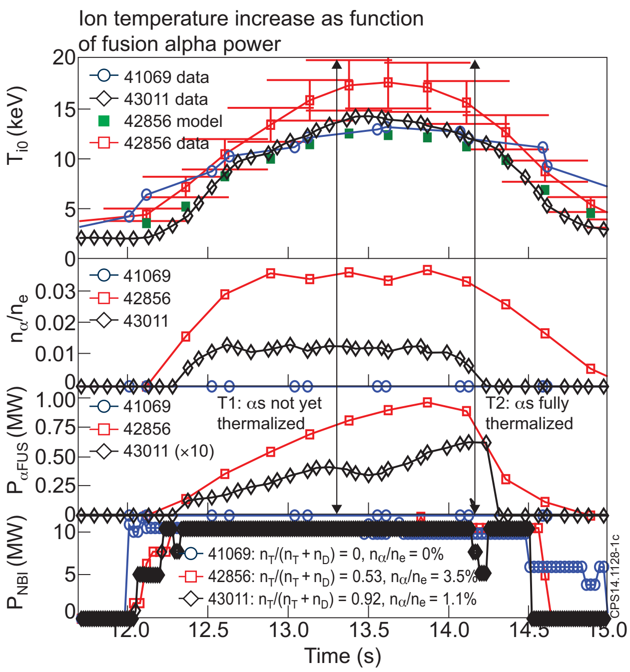

Figure 1: Main plasma parameters over the time window of the alphaheating phase for the three discharges corresponding to the extremes in the DT ratio, $P_{\alpha FUS}$ and n_α/n_e experimental scan. The two time points for the turbulence analysis are also indicated at T1 = 13.35sec and T2 = 14.10sec.

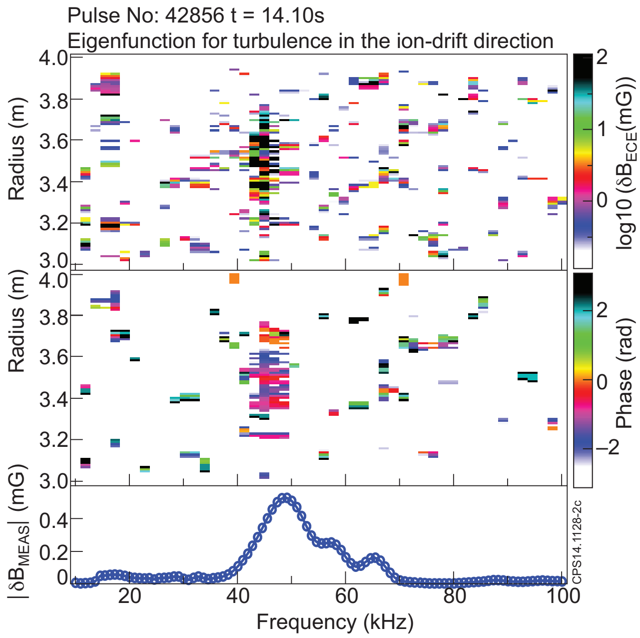

Figure 2: Eigenfunction for ion-drift-wave turbulence for Pulse No: 42856 at the time-point T2, when there is a large fraction of fusionborn αs that have fully thermalized (main plasma parameters at this time point: $n_T/(n_T+n_D)$ = 0.53, n_α/n_e = 0.032, $P_{\alpha FUS}$ = 0.96MW, T_{e0} = 9.6keV, T_{i0} = 15.5keV).

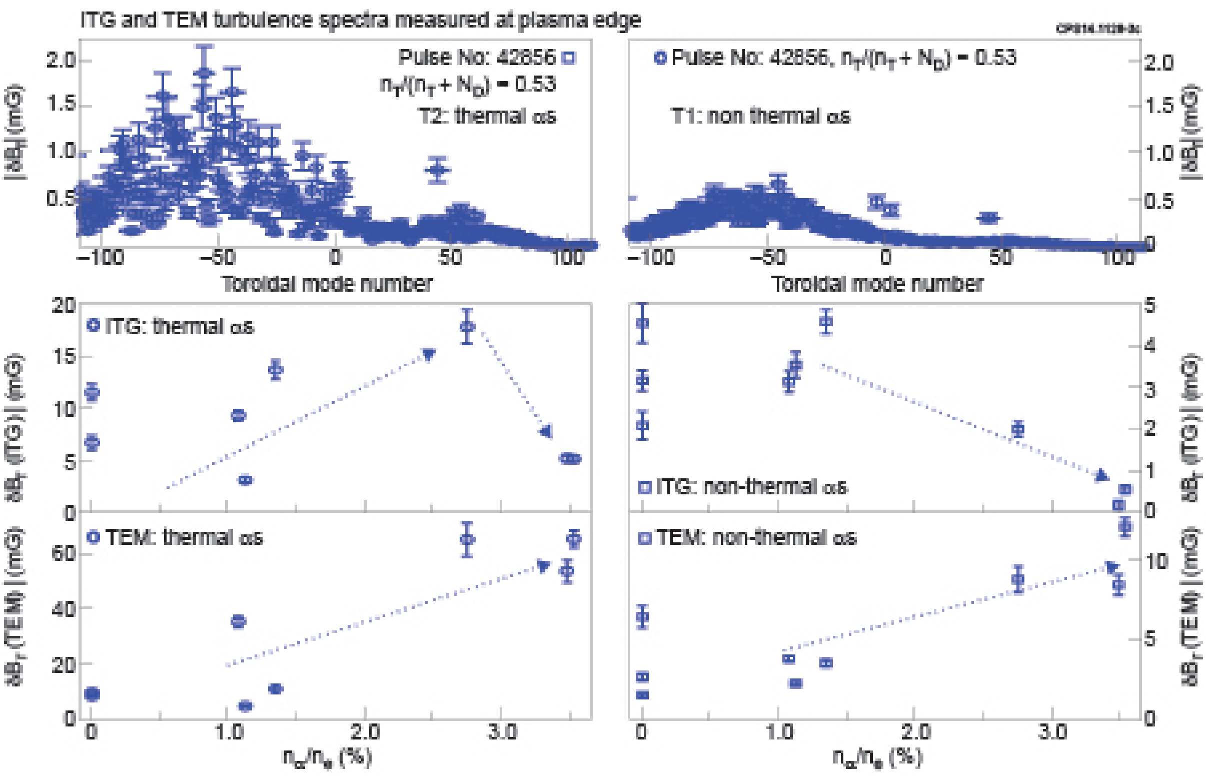

Figure 3: Bottom frames: auto-power spectrum for the measured magnetic fluctuation data for all the discharges in the alpha-heating experiment, separated into the TEM and ITG components. Top frames: the spectral decomposition in toroidal mode number components for the discharge with the maximum $P_{\alpha FUS}$: TEM turbulence is associated to negative toroidal mode numbers n<–20, ITG turbulence to positive toroidal mode numbers n>20.

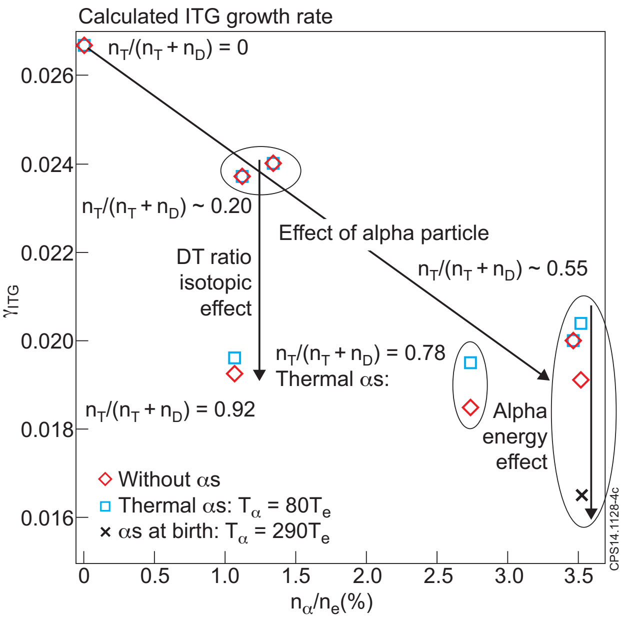

Figure 4: Dependence of the maximum γ_{ITG} as a function of n_α/n_e and $n_T/(n_T+n_D)$ for the JET alpha-heating experiment. The ITG frequency is in the range 20<γ_{ITG}/2π(kHz(<40, and the largest instability lies in the range 85<n<120, in agreement with the turbulence measurements.

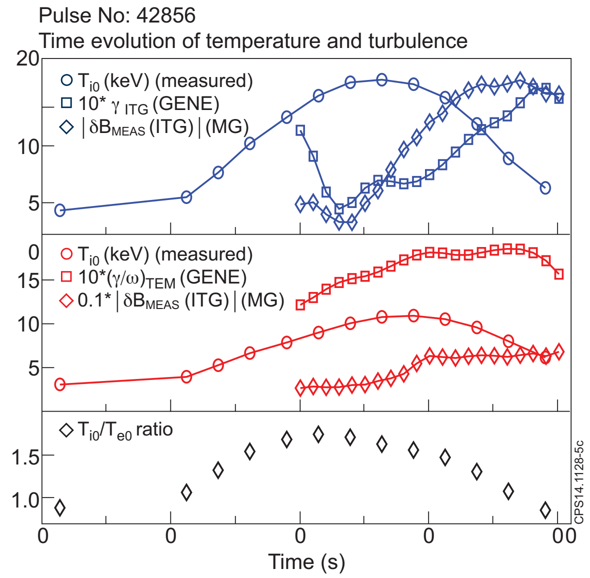

Figure 5: Time evolution of the ITG and TEM growth rates and turbulence amplitudes measured at the plasma edge, to be compared with the time evolution of the ion and electron core temperatures for Pulse No: 42856.

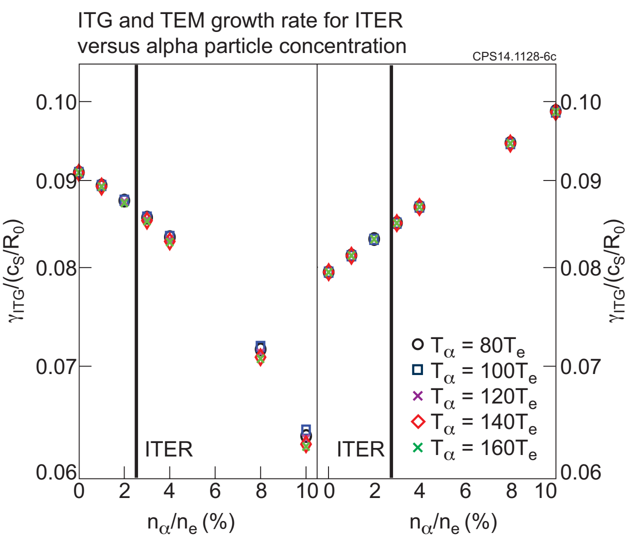

Figure 6: Predicted ITG and TEM growth rates for the ITER reference steady state scenario, as function of n_α/n_e: there is a clear reduction in γ_{ITG} as n_α/n_e increases, whereas γ_{TEM} increases.