Evidence for a New Path to the Self-Sustainment of the Thermonuclear Fusion Reactions in Magnetically Confined Burning Plasma Experiments
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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 15keV. 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 (τ_{ae}) comparable to the energy confinement time (τ_E): the αs then lose ~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 16MW, 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 τ_{ae} + τ_{ei} > 5τ_E) for plasma self-heating by fusion born αs, will have a detrimental impact on achieving a high Q_{DT} 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 \( \alpha \)s (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 observed that was much larger than expected, furthermore occurring over time scales shorter than \( \tau_E \). 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 \( n_\text{T}/(n_\text{D} + n_\text{T}) \), where \( n_\text{D} \) and \( n_\text{T} \) are the deuterium and tritium density, respectively, was varied in the range \( 0 \leq n_\text{T}/(n_\text{D} + n_\text{T}) \leq 0.92 \) while keeping constant the magnetic equilibrium and the plasma density. To achieve the required \( T_i \), these discharges were additionally heated using Neutral Beam Injection (NBI), with constant power \( P_{\text{NBI}} = 10.5 \text{MW}, \) 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 \( P_{\text{NBI}} \) 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 \( P_{\alpha\text{FUS}} = 1.3 \text{MW} \) was observed for \( n_\text{T}/(n_\text{D} + n_\text{T}) = 0.55 \pm 0.1 \), with the ensuing increase in the core electron temperature \( \Delta T_{e0} = 1.3 \text{keV} \) in accordance with the theoretical predictions [6,12,13] of \( \sim 95\% \) of the energy of the \( \alpha \)s collisionally transferred to electrons over a time scale \( \tau_{ae} = 1.2 \text{sec} \), slightly longer than \( \tau_E = 0.7 \text{sec} \).

Figure 1 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 \( n_\alpha/n_e \) \((n_\alpha \) is the density of fusion-born \( \alpha \)s at their birth energy of 3.5MeV and \( n_e \) the electron density, respectively) and \( P_{\alpha\text{FUS}} \). Focussing our attention on Pulse No: 42856 \((n_\text{T}/(n_\text{D} + n_\text{T}) = 0.53 \) and \( n_\alpha/n_e = 0.035) \), the peak \( T_{e0} \) is obtained at \( t = 14.10 \text{sec} \), within one \( \tau_{ae} \) after the peak \( P_{\alpha\text{FUS}} \), obtained at \( t = 13.75 \text{sec} \), whereas the peak \( T_{i0} \) is obtained slightly before the time of the peak in \( P_{\alpha\text{FUS}} \). Second, the \( T_{i0} \) rise is much larger and faster than the \( T_{e0} \) rise as a function of \( P_{\alpha\text{FUS}} \): we have \( \Delta T_{i0}/P_{\alpha\text{FUS}} = 1.7 \text{keV/MW} \) with a rise rate \( \tau_{\text{eR}} = T_{e0}/(\Delta T_{e0}/\Delta t) = 1.4 \text{sec} \), consistent with \( \tau_{ae} = 1.2 \text{sec} \). Conversely, \( \Delta T_{i0}/P_{\alpha\text{FUS}} = 5.9 \text{keV/MW} \), i.e. \( \Delta T_{i0}/P_{\alpha\text{FUS}} \times 3.5 = \Delta T_{e0}/P_{\alpha\text{FUS}} \), with a rise rate \( \tau_{\text{IR}} = 800 \text{msec} \), i.e. five times faster than the slowingdown of the \( \alpha \)s on thermal ions \((\tau_{\text{ei}} = 4 \text{sec}) \) and the electron-ion energy equipartition time \((\tau_{\text{ei}} = 5 \text{sec}) \).

Third, there is a clear \( \Delta T_{i0} = 3 \text{keV} \) excess in the core ion temperature for \( n_\text{T}/(n_\text{T} + n_\text{D}) = 0.53 \) at the time of the maximum in \( P_{\alpha\text{FUS}} \) 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 \( n_\text{T}/(n_\text{T} + n_\text{D}) = 0 \), even accounting for the residual \( \sim 5\% \) direct collisional heating by the \( \alpha \)s on the thermal ions. Finally, \( T_{i0} \) decays after the peak \( P_{\alpha\text{FUS}} \) on time scales comparable to \( \tau_E \), 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 \( \tau_E \) and \( \tau_{\text{ei}} \) time scales, and linked this
anomalous ion heating to an unexplained reduction by a factor ~2 of the ion thermal conductivity $\chi_i$ 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 than expected, 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 electron and 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 slowing down of the fusion-born $\alpha$s 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 $\alpha$s.

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 $\alpha$s, i.e. within a fraction of one slowing down-time of the $\alpha$s 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 \( P_{\alpha\text{FUS}} \). The second timepoint (T2) for the analysis is taken when there is a large fraction of fusion-born \( \alpha \)s that have had the time to fully thermalize, i.e. typically within one \( \tau_{\alpha\text{e}} \) after the time-point of the peak \( P_{\alpha\text{FUS}} \) value.

Figure 2 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 \( P_{\alpha\text{FUS}} \) and \( n_{\alpha}/n_e \). When there is a large fraction of fusion-born \( \alpha \)s 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 \( R \approx 3.5\text{m} \pm 15\text{cm} \), with peak amplitude \( |\delta B_{\text{ECE}}| \approx 20\text{mG} \) 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 odd parity), therefore do not cause radial transport and stochastic loss of the \( \alpha \)s. This Eigenfunction overlaps with the plasma volume where TRANSP indicated that a \( \chi_i \) 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 \( \alpha \)s have not yet thermalized. This is due to S/N ratio being too small in the plasma core, \( |\delta B_{\text{ECE}}| < 5\text{mG} \), indicating that ion-drift turbulence has been reduced to below measureable levels when there is a sufficiently large population of fusion-born \( \alpha \)s close to their birth energy.

Figure 3 shows the spectrum of the magnetic field amplitude \( |\delta B_{\text{MEAS}}| \) measured at the plasma edge in the drift-wave frequency range at the two time points T1 and T2. For \( n_{\alpha}/n_e > 1.5\% \), the amplitude of ITG turbulence (components with positive toroidal mode numbers \( n > 20 \)) decreases significantly when the \( \alpha \)s 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 \( \alpha \)s have fully thermalized, ITG turbulence has around four times larger amplitudes, which decreases only for \( n_{\alpha}/n_e > 2.8\% \). 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 \( n_{\alpha}/n_e \), which is consistent with the corresponding increase in \( T_e \) as function of \( P_{\alpha\text{FUS}} \).

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, \( R = 3.5\text{m} \), consistently with the measured Eigenfunction shown in Fig. 2. The \( \alpha \)s were modelled with an isotropic Maxwellian distribution function \([36]\), 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 \( \gamma \) 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 \( \alpha \)s (to isolate their contribution) were present, and then include the isotopic effect due to tritium and the role of \( \alpha \)s at different equivalent temperature, as shown in Fig. 4. First, note the
isotopic effect on the ITG growth rate \( \gamma/\omega_{ITG} \) without \( \alpha \)s, as \( \gamma/\omega_{ITG} \approx 0.020 \) for \( n_{\alpha}/(n_T + n_D) \approx 0.9 \). Second, for \( n_{\alpha}/n_e > 2\% \) there is a small, but clearly systematic, reduction in \( \gamma_{ITG} \) when the \( \alpha \)s 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 \( \alpha \)s (the situation expected at the time-point T2), to \( T_\alpha = 290T_e \), corresponding to \( \alpha \)s 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 \( \alpha \)s 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 \( \chi_i \) 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 \( \alpha_{ITG} \) both decrease as the \( \alpha \)s start to thermalize over the bulk plasma, from \( t = 13\sec \) to \( t = 13.5\sec \). This then allows \( T_{i0} \) to increase over a time scale \( \tau_{ir} \approx 0.86\sec \) comparable to the energy confinement time \( \tau_E \approx 0.7\sec \), which is much faster than the alpha particle slowing-down time on the ions (\( \tau_{\alpha i} \approx 4\sec \)) and the electron-ion energy equi-partition time (\( \tau_{ei} \approx 5\sec \)). An increase in \( \gamma_{ITG} \) and in the ITG instability strength is then observed to occur from \( t=13.5\sec \) onwards, i.e. after around one alpha particle slowing-down time on the electrons (\( \tau_{\alpha e} \approx 1.2\sec \)), as the fusion born \( \alpha \)s 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 \( \gamma_{TEM} \) 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 \( \gamma_{ITG} \) as the \( n_{\alpha}/n_e \) and \( T_\alpha \) increase, as in JET.

It is now important to understand why the effect of \( \alpha \)s on \( \gamma_{ITG} \) 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 \( \eta_i = L_e/L_{Te} > \eta_{IC} = (4/3)(1 + \eta^{-1})(1 + 2s/q)\varepsilon_n \) for \( \varepsilon_n > \varepsilon_{nC} \) with \( \varepsilon_{nC} = 0.9/(1 + \eta^{-1})(1 + 2s/q) \). Here \( \tau = T_e/T_i, L_X = (\log(X)/d)_{r}^{-1}, \varepsilon_X = LX/R \) 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 \( \alpha \)s can have a substantial effect on \( \gamma_{\text{ITG}} \). 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 \( \gamma_{\text{ITG}} \) 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 \( \alpha \)s 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 \( \alpha \)s 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 \( \alpha \)s 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 alpha heating phase for the three discharges corresponding to the extremes in the DT ratio, $P_{\text{afUS}}$ and $n_\alpha/n_e$ experimental scan. The two time points for the turbulence analysis are also indicated at $T_1 = 13.35\text{sec}$ and $T_2 = 14.10\text{sec}$.

Figure 2: Eigenfunction for ion-drift-wave turbulence for Pulse No: 42856 at the time-point $T_2$, when there is a large fraction of fusionborn $\alpha$s that have fully thermalized (main plasma parameters at this time point: $n_T/(n_T+n_D) = 0.53$, $n_\alpha/n_e = 0.032$, $P_{\text{afUS}} = 0.96\text{MW}$, $T_{e0} = 9.6\text{keV}$, $T_{i0} = 15.5\text{keV}$).

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 $P_{\text{afUS}}$: 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 $\gamma_{\text{ITG}}$ as a function of $n_e/n_a$ and $n_{T}/(n_{T}+n_{D})$ for the JET alpha-heating experiment. The ITG frequency is in the range $20<\gamma_{\text{ITG}}/2\pi\text{kHz}<40$, 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 $n_a/n_e$: there is a clear reduction in $\gamma_{\text{ITG}}$ as $n_a/n_e$ increases, whereas $\gamma_{\text{TEM}}$ increases.