A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

OFFPRINT

Evidence for a new path to the self-sustainment of thermonuclear fusion in magnetically confined plasmas

D. TESTA and M. ALBERGANTE

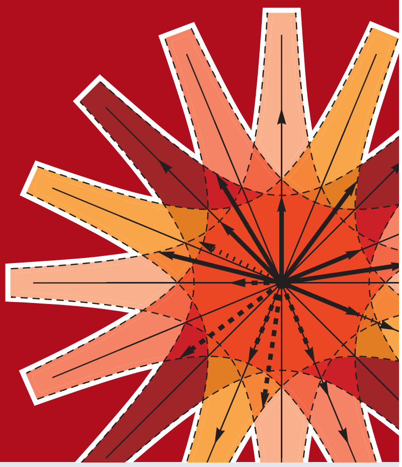
EPL, **97** (2012) 35003

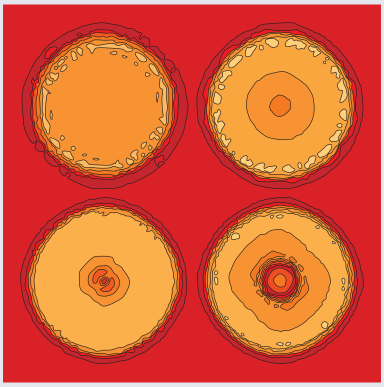
epl

A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

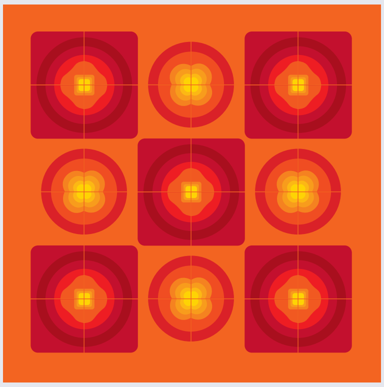
EPL Compilation Index

www.epljournal.org

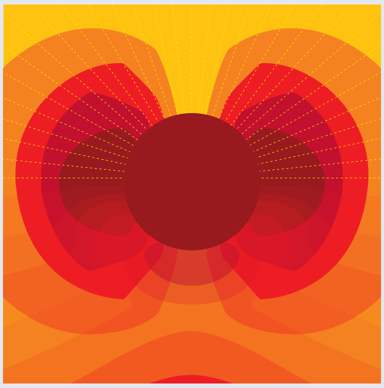




Biaxial strain on lens-shaped quantum rings of different inner radii, adapted from **Zhang *et al*** 2008 EPL **83** 67004.



Artistic impression of electrostatic particle–particle interactions in dielectrophoresis, adapted from **N Aubry and P Singh** 2006 *EPL* **74** 623.



Artistic impression of velocity and normal stress profiles around a sphere that moves through a polymer solution, adapted from **R Tuinier, J K G Dhont and T-H Fan** 2006 *EPL* **75** 929.

Visit the EPL website to read the latest articles published in cutting-edge fields of research from across the whole of physics.

Each compilation is led by its own Co-Editor, who is a leading scientist in that field, and who is responsible for overseeing the review process, selecting referees and making publication decisions for every manuscript.

- Graphene
- Liquid Crystals
- High Transition Temperature Superconductors
- Quantum Information Processing & Communication
- Biological & Soft Matter Physics
- Atomic, Molecular & Optical Physics
- Bose–Einstein Condensates & Ultracold Gases
- Metamaterials, Nanostructures & Magnetic Materials
- Mathematical Methods
- Physics of Gases, Plasmas & Electric Fields
- High Energy Nuclear Physics

If you are working on research in any of these areas, the Co-Editors would be delighted to receive your submission. Articles should be submitted via the automated manuscript system at **www.epletters.net**

If you would like further information about our author service or EPL in general, please visit **www.epljournal.org** or e-mail us at **info@epljournal.org**

EPS · Società Italiana di Fisica · EDP SCIENCES · IOP Publishing

Image: Ornamental multiplication of space-time figures of temperature transformation rules (adapted from T. S. Bíró and P. Ván 2010 *EPL* **89** 30001; artistic impression by Frédérique Swist).

A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

February 2012

EPL, **97** (2012) 35003
doi: 10.1209/0295-5075/97/35003

www.epljournal.org

Evidence for a new path to the self-sustainment of thermonuclear fusion in magnetically confined plasmas

D. TESTA[(a)] and M. ALBERGANTE

Ecole Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas, Association EURATOM-Confédération Suisse - 1015 Lausanne, Switzerland

received 16 September 2011; accepted in final form 2 January 2012
published online 3 February 2012

PACS 52.55.Pi – Fusion products effects (*e.g.*, alpha-particles, etc.), fast particle effects
PACS 52.35.Ra – Plasma turbulence
PACS 52.55.Fa – Tokamaks, spherical tokamaks

Abstract – In this work we provide the first explanation for observations made in 1997 on the Joint European Torus of unexpected ion heating with fusion-born alpha particles occurring over time scales much shorter than those theoretically foreseen. We demonstrate that non-thermal alpha particles above a critical concentration stabilize ion-drift-wave turbulence, therefore significantly reducing one of the main energy loss channels for thermal ions. As such ion heating occurs over times scales much shorter than those classically predicted, this mechanism opens new prospects on additional paths for the self-sustainment of thermonuclear fusion reactions in magnetically confined plasmas.

Intoduction. – 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 ($Q_{\mathrm{DT}}=10$). To reach this goal, fusion-born alpha particles (αs), with their birth energy at $E_{\alpha\mathrm{BIRTH}}=3.5\,\mathrm{MeV}$, must remain confined while thermalizing through collisions with the background plasma. This provides the self-heating to the background plasma replacing the external, additional heating applied initially to reach the ion temperature (T_{i}) optimizing the overall fusion reactivity, $T_{\mathrm{i}}\approx 15\,\mathrm{keV}$. For the plasma conditions expected to reach a sufficiently high Q_{DT}, the birth energy of the αs by far exceeds the value ($E_{\alpha\mathrm{CRIT}}$ [2]) at which their collision frequency with thermal electrons ($1/\tau_{\alpha\mathrm{e}}$) equals that with thermal ions ($1/\tau_{\alpha\mathrm{i}}$). Thus, the plasma self-heating process requires the αs first to thermalize on the electrons. For the typical plasma conditions expected in ITER, this process occurs over a time scale comparable to the energy confinement time (τ_{E}). The electrons are then required to heat the ions through energy equipartition: this process occurs over a time scale (τ_{ei}) that is around five to ten times longer than τ_{E}. During their thermalization, the αs transfer in excess of $\sim$80% of their energy to the electrons, the exact value depending on the ratio $E_{\alpha\mathrm{BIRTH}}/E_{\alpha\mathrm{CRIT}}$, with the remaining fraction going directly to the ions only at the end of the αs' thermalization process, *i.e.* for $E_\alpha < 3E_{\alpha\mathrm{CRIT}}$.

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) [3] in 1992 (reaching $Q_{\mathrm{DT}}\approx 0.15$ [4]), in the Tokamak Fusion Test Reactor (TFTR) [5] from 1993 to 1997 (peak $Q_{\mathrm{DT}}\approx 0.25$ [6]), and again on JET in 1997. This Deuterium-Tritium Experiment (DTE1) [7] produced the world record fusion power $P_{\mathrm{FUS}}\approx 16\,\mathrm{MW}$, with a record $Q_{\mathrm{DT}}\approx 0.65$ maintained over about half τ_{E}.

However, from a theoretical point of view, it has also become clear that any mechanism affecting this long (as $\tau_{\alpha\mathrm{e}}+\tau_{\mathrm{ei}}>5\tau_{\mathrm{E}}$) two-step process 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 [8–10], which are in most cases also predicted to occur in ITER [11,12].

A series of dedicated discharges were performed during DTE1 with plasma conditions optimised for the observation of the collisional thermal electron heating by the fusion-born αs (the *alpha-heating* experiment): this

(a) E-mail: duccio.testa@epfl.ch

process was found to follow the theoretical predictions [13,14]. However, at that time it was also noted that under certain experimental conditions a thermal 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 [15], no real explanation has been so far put forward for those observations.

In the alpha-heating experiment the DT mixture ratio $n_{\mathrm{T}}/(n_{\mathrm{D}}+n_{\mathrm{T}})$, where n_{D} and n_{T} are the deuterium and tritium density, respectively, was varied in the range $0 \leqslant n_{\mathrm{T}}/(n_{\mathrm{D}}+n_{\mathrm{T}}) \leqslant 0.92$ 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 $P_{\mathrm{NBI}} = 10.5\,\mathrm{MW}$, using the same DT fuel mixture as the background plasma. The 140 keV (D-NBI) to 170 keV (T-NBI) injection energy range for the NBI ions was selected to maximise the direct collisional heating to the thermal ions, as for these discharges the collision frequency of the D-NBI and T-NBI ions with the electrons equals that with the ions at $E_{\mathrm{D,CRIT}} \sim 150\,\mathrm{keV}$ and $E_{\mathrm{T,CRIT}} \sim 240\,\mathrm{keV}$ in the plasma core, respectively. The value of P_{NBI} was then selected to match the predicted ion heat losses, to keep a constant T_{i}, thus facilitating the evaluation of the alpha-heating to the electrons. These discharges were very quiet in terms of coherent magneto-hydrodynamic activity, and showed very comparable levels of incoherent turbulence. A maximum in the alpha fusion power $P_{\alpha\mathrm{FUS}} \approx 1.3\,\mathrm{MW}$ was observed for $n_{\mathrm{T}}/(n_{\mathrm{D}}+n_{\mathrm{T}}) \approx 0.55 \pm 0.1$, with the ensuing increase in the core electron temperature $\Delta T_{\mathrm{e0}} \approx 1.3\,\mathrm{keV}$ in accordance with the theoretical predictions [7,13,14] of $\sim$95% of the αs' energy collisionally transferred to electrons over a time scale $\tau_{\alpha\mathrm{e}} \approx 1.2\,\mathrm{s}$, slightly longer than $\tau_{\mathrm{E}} \approx 0.7\,\mathrm{s}$.

It is important to note here that the plasma conditions of the JET alpha-heating experiment during the DTE1 campaign are rather different from those expected in ITER for two main reasons. First, the ratio between the width of the αs orbit and the machine size is different, being about $\sim$1/3 in JET compared to $\sim$1/6 to $\sim$1/10 as expected for ITER. Second, the volume-averaged value of $E_{\alpha\mathrm{BIRTH}}/E_{\alpha\mathrm{CRIT}}$ was around $\sim$30 for $n_{\mathrm{D}} = n_{\mathrm{T}} \sim 0.45 \times n_{\mathrm{e}}$ (n_{e} being the electron density) in JET, but is expected to be around $\sim$15 to $\sim$20 in ITER. Finally, in DTE1 αs and fusion power were essentially produced by beam-target reactions, and not by thermal DT reactions as expected for ITER. These differences indicate that extrapolations to ITER solely based on the JET DTE1 plasma conditions could be subject to large uncertainties, specifically with respect to predictions for the interaction of αs with coherent modes and incoherent turbulence driven by the background plasma.

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, αs' concentration $n_{\alpha}/n_{\mathrm{e}}$ (n_{α} is the density of fusion-born αs at their birth energy of 3.5 MeV) and $P_{\alpha\mathrm{FUS}}$.

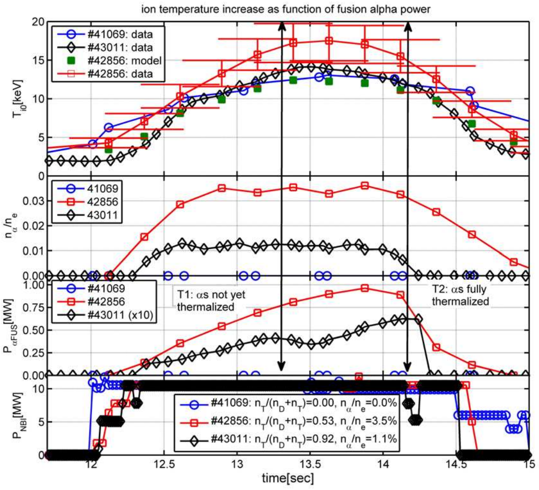


Fig. 1: (Colour on-line) Overview of the alpha-heating experiment. We show the ion temperature evolution for the three discharges corresponding to the extremes in the DT fuel ratio, $P_{\alpha\mathrm{FUS}}$ and $n_{\alpha}/n_{\mathrm{e}}$ experimental scan. The two time-points used for the turbulence analysis reported later are shown at $\mathrm{T1} = 13.35\,\mathrm{s}$ and $\mathrm{T2} = 14.10\,\mathrm{s}$.

Focussing our attention on #42856 ($n_{\mathrm{T}}/(n_{\mathrm{D}}+n_{\mathrm{T}}) = 0.53$ and $n_{\alpha}/n_{\mathrm{e}} \approx 0.035$), the peak T_{i0} is obtained slightly before the time of the peak in $P_{\alpha\mathrm{FUS}}$ at $t = 13.75\,\mathrm{s}$, whereas [13,14] the peak T_{e0} is obtained at $t = 14.10\,\mathrm{s}$, within one $\tau_{\alpha\mathrm{e}} \approx 1.2\,\mathrm{s}$ after the peak $P_{\alpha\mathrm{FUS}}$. Second, the T_{i0} rise is much larger and faster than the T_{e0} rise as a function of $P_{\alpha\mathrm{FUS}}$: we have [13,14] $\Delta T_{\mathrm{e0}}/P_{\alpha\mathrm{FUS}} \approx 1.7\,\mathrm{keV/MW}$ with a $\tau_{\mathrm{eR}} = T_{\mathrm{e0}}/(\Delta T_{\mathrm{e0}}/\Delta t) \approx 1.4\,\mathrm{s} \approx \tau_{\alpha\mathrm{e}}$ rise rate. Conversely, we have $\Delta T_{\mathrm{i0}}/P_{\alpha\mathrm{FUS}} \approx 5.9\,\mathrm{keV/MW}$, *i.e.* $\Delta T_{\mathrm{i0}}/P_{\alpha\mathrm{FUS}} \approx 3.5 \times \Delta T_{\mathrm{e0}}/P_{\alpha\mathrm{FUS}}$ with a rise rate $\tau_{\mathrm{iR}} \approx 800\,\mathrm{ms}$, at least five times faster than the slowing-down of the αs on thermal ions ($\tau_{\alpha\mathrm{i}} \approx 4\,\mathrm{s}$) and the electron-ion energy equipartition time ($\tau_{\mathrm{ei}} \approx 5\,\mathrm{s}$).

Third, there is a clear $\Delta T_{\mathrm{i0}} \approx 3\,\mathrm{keV}$ excess in the core ion temperature for $n_{\mathrm{T}}/(n_{\mathrm{D}}+n_{\mathrm{T}}) = 0.53$ at the time of the maximum in $P_{\alpha\mathrm{FUS}}$ compared to the value expected using the same transport model that correctly predicted the T_{e} [7,13,14] and the T_{i} evolution [15] for $n_{\mathrm{T}}/(n_{\mathrm{D}}+n_{\mathrm{T}}) = 0$, even accounting for the residual $\sim$5% direct collisional heating by the αs on the thermal ions. Finally, T_{i0} decays after the peak $P_{\alpha\mathrm{FUS}}$ on time scales comparable to τ_{E}, despite a constant source from collisions with the injected NBI ions. Ensuing transport analyses [15] performed with TRANSP [16] validated the T_{i} data, excluded isotopic effects on the τ_{E}, $\tau_{\alpha\mathrm{e}}$ and τ_{ei} time scales, and linked this *anomalous* ion heating to an unexplained factor $\sim$2 reduction of the ion thermal conductivity χ_{i} in the plasma core.

Hence, it is phenomenologically intuitive that some mechanisms other than classical collisional heating and energy equipartition must be at play not only to produce this much larger and much faster than expected, but also to saturate the increase of T_{i}. As the collisional slowing-down of the fusion-born αs on the electrons, and the ensuing energy equipartition with the ions, are essential ingredients for the self-sustainment of the fusion reactivity in magnetically confined plasmas, we must understand whether these observations of an *anomalous* ion heating can be linked to physical mechanisms that could be used to optimize the operational scenario of forthcoming devices such as ITER. To this aim, we start from the ansatz that there is a direct link between electron and ion-drift-wave micro-instabilities, such as Trapped Electron Modes (TEM), Electron and Ion Temperature Gradient (ETG and ITG, respectively) turbulence, and the temporal evolution of the thermal-electron and -ion temperatures through modifications to the electron and ion diffusivity and thermal conductivity [17]. In [18–20] and more recently in [21], it has been shown that turbulence could negatively affect ITER operation by worsening energy confinement through increased heat and particle transport. Hence, it is important to assess whether this 1997 JET DTE1 data indicate that αs can contribute to turbulence suppression and the ensuing reduction in thermal-ion heat transport.

Analysis of the electron and ion drift-wave turbulence measurements. – The spectral decomposition of the turbulence measurements was originally performed [15] using the phase-slope [22] and Singular Value Decomposition [23] techniques. These methods suffered at that time from severe limitations: numerical (CPU and RAM resources) and mathematical (deconvolution of a spectrum made up of a large number of components whose number and amplitude is unknown *a priori*). Powerful methods based on the sparse representation of signals [24–28] have recently become available for spectral decomposition in fusion plasmas. Moreover, we can now use codes such as GENE [29] to study the effect of a minority population of high-energy ions on the predicted turbulence spectrum. Hence, it is really advantageous to re-analyse the same turbulence measurements to try to provide an explanation for the reduction in χ_i in the presence of a population of fusion-born αs.

We evaluate the drift-wave turbulence spectra using data from magnetic pick-up coils mounted on the vessel walls, providing measurements of the radial component of the fluctuating magnetic field (δB_r) at the plasma edge, and Electron Cyclotron Emission (ECE) measurements of the electron temperature fluctuations (δT_e), covering most of 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 thermalization phase of the αs, well before the time-point corresponding to the peak value of $P_{\alpha\mathrm{FUS}}$. The second time-point (T2) is taken when there is a large fraction of αs that have had the time to fully thermalize, typically within one $\tau_{\alpha e}$ after the time-point of the peak $P_{\alpha\mathrm{FUS}}$.

Figure 2 shows the eigenfunction for ion-drift-wave turbulence measured at the time-point T2 for the discharge #42856, which had the highest value of $P_{\alpha\mathrm{FUS}}$

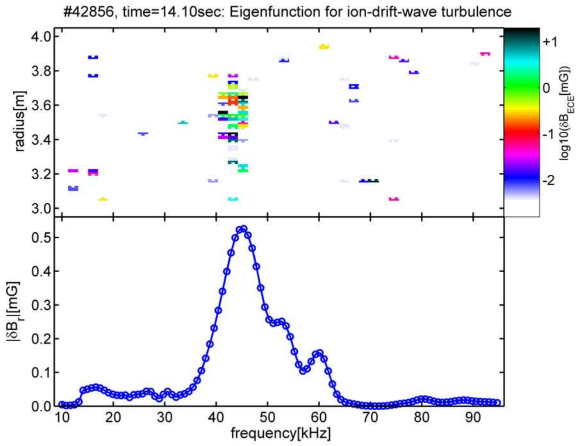


Fig. 2: (Colour on-line) Eigenfunction for ion-drift-wave turbulence, measured using cross-correlation between the edge magnetic (δB_r) and the radial profile of the electron temperature ($\delta T_e(R)$) fluctuation signals. The data are shown for the discharge #42856 at the time-point T2, when there is a large fraction of fusion-born αs that have fully thermalized (main plasma parameters at this time-point: $n_T/(n_D+n_T)=0.53$, $n_\alpha/n_e=0.032$, $T_{e0}=9.6\,\mathrm{keV}$, $T_{i0}=15.5\,\mathrm{keV}$, $P_{\alpha\mathrm{FUS}}=0.96\,\mathrm{MW}$).

and n_α/n_e. When there is a large fraction of fusion-born αs that have thermalized, the largest turbulent components are found around 45 kHz. This value is slightly above the ITG frequency range (20 kHz to 40 kHz) calculated by GENE for a zero-flow plasma: this upshift is consistent with the measured toroidal plasma flow being between ∼5 kHz at the plasma edge and ∼25 kHz in the plasma centre. The time evolution of the ECE fluctuation signal $\delta T_e(t,R)$ correlates very well with the time evolution of $\delta B_r(t)$ measured at the plasma edge, corroborating our choice to use the more routinely available δB_r as a proxy to evaluate drift-wave turbulence. The ITG eigenfunction sits in the region $3.35 < R$ [m] < 3.65, with peak amplitude $\max(|\delta B_{\mathrm{ECE}}|) \approx 20\,\mathrm{mG}$, evaluated using [30,31]. This eigenfunction overlaps with the plasma volume where TRANSP indicated that a χ_i reduction was needed to explain the T_i increase [15]. Conversely, no such eigenfunction can be measured at the time-point T1, when the αs have not yet thermalized. This is due to the signal-to-noise ratio for $\delta T_e(R)$ being too small, giving an equivalent $\max(|\delta B_{\mathrm{ECE}}|) < 3\,\mathrm{mG}$. This indicates that ion-drift-wave turbulence has been reduced to below measureable levels in the plasma core when there is a sufficiently large population of fusion-born αs close to their birth energy.

Figure 3 shows the δB_r spectrum measured at the plasma edge in the drift-wave frequency range at the two time-points T1 and T2 for all discharges in the alpha-heating experiment. For $n_\alpha/n_e > 1.5\%$, the amplitude of ITG turbulence, evaluated (in line with the GENE's results) for all components with positive toroidal mode numbers $n > 20$ as $|\delta B_r(\mathrm{ITG})| = (\Sigma_{n>20}|\delta B_r(n)|^2)^{1/2}$,

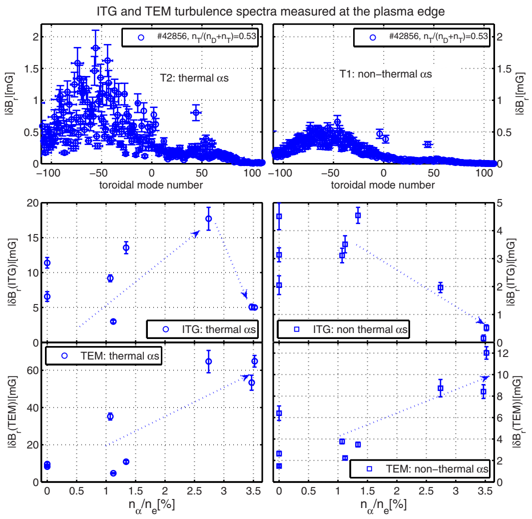


Fig. 3: (Colour on-line) Measured δB_r for the alpha-heating experiment. Bottom frames: auto-power spectrum, separated into electron (TEM) and ion (ITG) drift-wave components. Top frames: spectral decomposition in toroidal mode number (n) components for the discharge with the maximum $P_{\alpha FUS}$: TEM turbulence is associated to negative $n < -20$, ITG turbulence to positive $n > 20$.

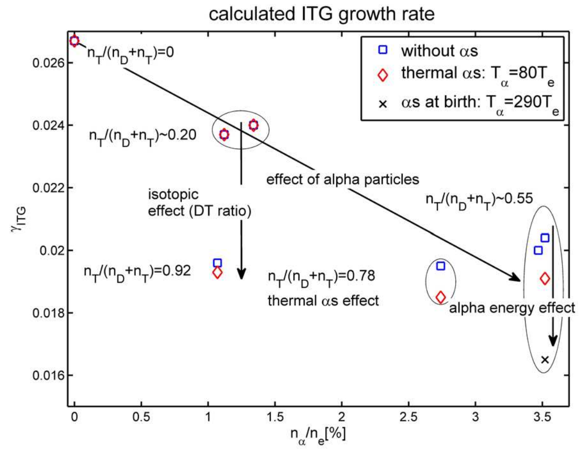


Fig. 4: (Colour on-line) The maximum ITG growth rate as a function of the concentration of αs. The calculation uses the value of $n_T/(n_D + n_T)$ and the actual background plasma data at $R = 3.5$ m at the time-point T1 for all the discharges in the alpha-heating experiment.

decreases significantly when the αs have not yet thermalized (time-point T1). This result is consistent with theoretical predictions [32] and experimental observations [33]. For the data taken at the time-point T2, with fully thermalized αs, ITG turbulence has around four times larger amplitudes, decreasing only for $n_\alpha/n_e > 2.8\%$. The amplitude of TEM turbulence (components with negative toroidal mode numbers $n < -20$, as per the GENE's results) is around two times larger than the ITG one with non-thermal αs, becomes much larger with thermal αs, and always increases as a function of n_α/n_e, hence $P_{\alpha FUS}$.

GENE simulations of the drift-wave turbulence spectra section heading. – Turbulence simulations were performed with the GENE code, using the magnetic equilibrium and background plasma data at mid-radius, $R = 3.5$ m, consistently with the measured Eigenfunction shown in fig. 2. The αs were modelled with an isotropic Maxwellian distribution function [34], and an equivalent temperature was used to set the correspondence with the energy stored by the αs. The non-linear evolution of small-scale turbulence, such as TEM, ETG and ITG, consistently reflects the linear behaviour of the micro-instabilities [35–37]. Hence, as larger linear growth rates (γ) always induce stronger non-linear heat fluxes, we use the numerically obtained linear growth rate as a proxy to evaluate the strength of the saturated turbulence. As we are interested in the time evolution of the ion temperature, we study primarily ITG turbulence.

A first set of simulations is needed to identify the key features of the ITG turbulence characterizing the reference plasma scenario with $n_T/(n_D + n_T) = 0$, where neither tritium (possible isotopic effects) nor αs (to isolate their contribution) were present. We find that the ITG instability lies in the range $n > 25$, with the largest components for $65 < n < 120$, and is associated to the short wavelengths that drive the strongest ion heat transport [17,35–37]. We then include the isotopic effect due to tritium and the role of αs at different equivalent temperature: fig. 4 shows these results.

First, note that for low $n_\alpha/n_e \approx 1\%$, there is an isotopic effect on the ITG growth rate γ_{ITG}, as $\gamma_{ITG} \approx 0.024$ with $n_T/(n_D + n_T) \approx 0$, whereas $\gamma_{ITG} < 0.020$ for $n_T/(n_D + n_T) \approx 0.9$, but practically no difference when including the αs in the calculation. Second, for $n_\alpha/n_e > 2.5\%$, there is a small, but clearly systematic reduction in γ_{ITG} when thermal αs are included in the calculations. Third, we have increased the temperature of the αs for the case $n_\alpha/n_e = 3.5\%$ (discharge #42856) from $T_\alpha = 80T_e$, corresponding to thermalized αs (as expected at the time-point T2), to $T_\alpha = 290T_e$, corresponding to αs at their birth energy (as expected at the time-point T1). We find that the lowest value of γ_{ITG} is obtained with $T_\alpha = 290T_e$, indicating that non-thermal αs contribute most to the stabilization of ITG turbulence.

These simulations corroborate the analysis of the ion-drift-wave turbulence measurements. The observed reduction in the *linearly calculated* γ_{ITG}, together with the *experimental evidence* that the amplitude of ITG turbulence reduces to below measureable levels in the presence of enough αs close to their birth energy, suggests a weaker turbulent transport, in line with the χ_i reduction implied by the earlier TRANSP analyses.

In a second set of simulations, we study the time evolution of the core T_{i0} as function of the ITG turbulence characteristics for the discharge #42856: the results are shown in fig. 5. The intensity of ITG turbulence ($|\delta B_r(ITG)|$) and

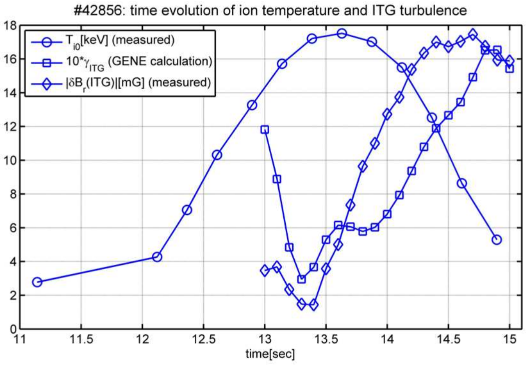


Fig. 5: (Colour on-line) Time evolution of the core ion temperature (T_{i0}) and the ITG turbulence characteristics for the discharge #42856. The ITG turbulence amplitudes is measured at the plasma edge (data only available from $t = 13$ s onwards), and the growth rate is calculated by GENE.

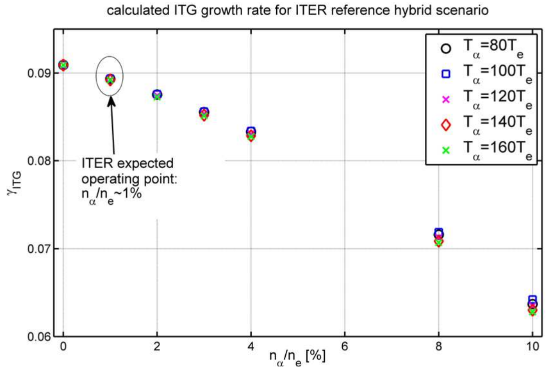


Fig. 6: (Colour on-line) Predicted ITG growth rates for the ITER reference steady-state hybrid scenario. The ITG growth rate is calculated by GENE as function of n_α/n_e for different values of T_α.

γ_{ITG} decrease as the αs start thermalizing on the background plasma, from $t = 13$ s to $t = 13.5$ s. This allows T_{i0} to increase over a time scale $\tau_{iR} \sim 0.8$ s: this is comparable to the energy confinement time $\tau_E \sim 0.7$ s, but is much faster than the αs slowing-down time on the ions ($\tau_{\alpha i} \sim 4$ s) and the electron-ion energy equipartition time ($\tau_{ei} \sim 5$ s). An increase in γ_{ITG} and $|\delta B_r(\text{ITG})|$) then occurs from $t = 13.5$ s onwards, after around one slowing-down time of the αs on the electrons ($\tau_{\alpha e} \sim 1.2$ s), as the fusion born αs have had the time to fully thermalize so that their mean energy has decreased sufficiently. This first prevents a further increase in T_{i0}, and then causes its reduction despite the continuous injections of NBI ions collisionally transferring their energy to thermal ions. Again, the results of these 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 fusion-born αs contribute to suppressing ITG turbulence, with a positive effect on the heat transport of thermal ions in magnetically confined fusion experiments: it is then important to assess whether this mechanism could also apply to ITER. As indicated in the Introduction, the physics of energetic ions in ITER will be different with respect to the JET DTE1 campaign of 1997. Moreover, the micro-turbulent spectrum can importantly interact with Alfvén turbulence [38–40].

The successful achievement of steady-state operation is a major objective for ITER and, despite more thorough analyses clearly being required, we perform initial GENE linear simulations for the ITER reference steady-state scenario [41,42] to deduce whether αs could play a role in ITG suppression. The results, shown in fig. 6, show a clear reduction in γ_{ITG} as n_α/n_e and T_α increase, but not as strong as in the JET case.

It is now important to understand why the effect of the αs on γ_{ITG} is much smaller for the simulated ITER plasmas, and also why no anomalous ion heating was observed in the TFTR DT experiments [6]. A very simple, if only heuristic, answer to these questions is obtained using [43,44].

A fluid treatment of ITG turbulence predicts that it becomes locally unstable when the ratio of the density to the ion temperature scale lengths L_n/L_{Ti} is above the marginal stability value $(L_n/L_{Ti})_C = (4/3)(1 + T_i/T_e)(1 + r(\mathrm{d}q/\mathrm{d}r)/q^2)(L_n/R)$ when the density scale length is above a critical value $(L_n/R)_C = 0.9/(1 + T_i/T_e)/(1 + r(\mathrm{d}q/\mathrm{d}r)/q^2)$, q being the safety factor profile and r the radial coordinate across the plasma cross-section. The plasma profiles for the JET alpha-heating experiment have $(L_n/R) > (L_n/R)_C$ and $\eta_i \sim 1.15\eta_{iC}$: a small contribution from the αs can then have a substantial effect on γ_{ITG}. The TFTR DT experiments [6] also had $(L_n/R) > (L_n/R)_C$ but $\eta_i > 5\eta_{iC}$, too far away from the ITG marginal stability limit to notice any anomalous ion heating with a ∼1% concentration of αs. Finally, the ITER reference steady-state scenario [41] has $(L_n/R) > (L_n/R)_C$ and $\eta_i \sim 2\eta_{iC}$: this explains why the predicted γ_{ITG} reduction is not as strong as that observed in JET, and indicates at the same time that slight modifications to the background plasma should allow ameliorating the local stabilizing effect of the αs on the ITG turbulence in ITER. Further, time-dependent non-linear simulations are being planned to optimize this operational scenario so as to improve the predictions for the efficiency of this mechanism for ITG turbulence stabilization in ITER.

Summary and conclusions. – In summary, we find that a sufficient concentration of fusion-born αs that have not yet thermalized stabilizes ITG turbulence, reducing an energy losses for the thermal ions. This mechanism explains phenomenologically the (at that time) unexpected and so far unexplained increase in the ion temperature observed in the JET alpha-heating experiment of 1997. These results open additional possibilities for optimizing the path to the self-sustainment of the thermonuclear fusion reactions in magnetically confined plasmas. 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 local significant reduction in the ion heat transport by suppressing ion-drift-wave turbulence, as observed in JET.

* * *

This work was partly supported by EURATOM under the contract of Association with CRPP-EPFL. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was also partly supported by the Swiss National Science Foundation. The authors would like to acknowledge useful discussions with S. Brunner, S. Coda, A. Fasoli, J. Graves, J. B. Lister, L. Villard and D. Wagner (all at CRPP), P. Thomas at the ITER organization, and L. Garzotti and P. C. deVries at the JET organization. The authors would also like to thank the Reviewer for the suggestions made to the first draft of this paper.

REFERENCES

[1] Ikeda K. *et al.*, *Progress in the ITER Physics Basis, Nucl. Fusion*, **47** (2007).
[2] Sivukhin D. V., in *Reviews of Plasma Physics*, edited by Leontovich M. A., Vol. **4** (Consultants Bureau New York) 1966, p. 93.
[3] Wesson J., *Tokamaks* (Oxford Science Publication) 2003, pp. 617–644.
[4] Rebut P. H. (for the JET team), *Plasma Phys. Control. Fusion*, **34** (1992) 1749.
[5] Wesson J., *Tokamaks* (Oxford Science Publication) 2003, pp. 597–616.
[6] Zweben S. J. *et al.* (for the TFTR team), *Nucl. Fusion*, **40** (2000) 91.
[7] Keilhacker M. (for the JET team), *Nucl. Fusion*, **39** (1999) 209.
[8] Evans T. E. *et al.*, *Nat. Phys.*, **2** (2006) 419.
[9] Sauter O. *et al.*, *Phys. Rev. Lett.*, **88** (2002) 105001.
[10] Nave M. F. F. *et al.*, *Nucl. Fusion*, **42** (2002) 281.
[11] Vlad G. *et al.*, *Nucl. Fusion*, **46** (2006) 1.
[12] Chapman I. T., *Nucl. Fusion*, **50** (2010) 102001.
[13] Thomas P. R. (for the JET team), *Nucl. Fusion*, **39** (1999) 1619.
[14] Thomas P. R. *et al.*, *Phys. Rev. Lett.*, **80** (1998) 5548.
[15] Thomas P. R. *et al.*, *Alpha-heating of thermal ions in JET*, in *Proceedings of the 28th EPS Conference, Madeira (Portugal), 18–22 June 2001*, Vol. **254** (ECA) 2001, paper P3.001.
[16] Goldston R. *et al.*, *J. Comput. Phys.*, **43** (1981) 61.
[17] Garbet X. *et al.*, *Plasma Phys. Control. Fusion*, **46** (2004) B557.
[18] Glanz J., *Science*, **274** (1996) 1600.
[19] Carreras B. A., *Nature*, **385** (1997) 300.
[20] Macilwain C., *Nature*, **388** (1997) 115.
[21] Moyer M., *Sci. Am.*, March issue (2010) 50.
[22] Testa D., Fasoli A. and Solano E., *Rev. Sci. Instrum.*, **74** (2003) 1694.
[23] Kim J. S. *et al.*, *Plasma Phys. Control. Fusion*, **41** (1999) 1399.
[24] Bourguignon S., Carfantan H. and Böhm T., *Astron. Astrophys.*, **462** (2007) 379.
[25] Bourguignon S., Carfantan H. and Idier J., *IEEE Signal Process*, **1** (2007) 4.
[26] Klein A., *Plasma Phys. Control. Fusion*, **50** (2008) 125005.
[27] Testa D. *et al.*, *Fusion Sci. Technol.*, **57** (2010) 208; 238.
[28] Testa D. *et al.*, *EPL*, **92** (2010) 50001.
[29] Jenko F. *et al.*, *Phys. Plasmas*, **7** (2000) 1904.
[30] Akhiezer A. I. *et al.*, *Plasma Electrodynamics*, Vol. **2** (Pergamon Press, Oxford) 1975.
[31] Piliya A. D. and Popov A. Yu., *Plasma Phys. Control. Fusion*, **44** (2002) 2051.
[32] Angioni C. and Peeters A. G., *Phys. Plasmas*, **15** (2008) 052307.
[33] Tardini G. *et al.*, *Nucl. Fusion*, **47** (2007) 280.
[34] Estrada-Mila C., Candy J. and Waltz R. E., *Phys. Plasmas*, **13** (2006) 112303.
[35] Waltz R. E. and Miller R. L., *Phys. Plasmas*, **6** (1999) 4265.
[36] Lapillonne X. *et al.*, *Phys. Plasmas*, **16** (2009) 032308.
[37] Merz F. and Jenko F., *Nucl. Fusion*, **50** (2010) 054005.
[38] Bass E. and Waltz R. E., *Phys. Plasmas*, **17** (2010) 112319.
[39] Zonca F., Chen L., Dong J. Q. and Santoro R. A., *Phys. Plasmas*, **6** (1999) 1917.
[40] Zonca F. *et al.*, *Physics challenges and open issues of burning plasma physics in ITER*, in *15th European Fusion Physics Workshop, Praha (Czech Republic), December 3–5, 2007*, `www.afs.enea.it/zonca/references/seminars/zonca_efpw07.pdf`.
[41] Gormezano C. *et al.*, *Nucl. Fusion*, **47** (2007) S285.
[42] Albergante M. *et al.*, *Plasma Phys. Control. Fusion*, **53** (2011) 054002.
[43] Biglari H., Diamond P. H. and Rosenbluth M. N., *Phys. Fluids*, **B1** (1989) 109.
[44] Wesson J., *Tokamaks* (Oxford Science Publication) 2003, pp. 428–429.