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Evidence of Electron Heating by Alpha Particles in JET Deuterium-Tritium Plasmas

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The fusion-born alpha particle heating in magnetically confined fusion machines is a high priority subject for studies. The self-heating of thermonuclear fusion plasma by alpha particles was observed in recent deuterium-tritium (D-T) experiments on the joint European torus. This observation was possible by conducting so-called "afterglow" experiments where transient high fusion yield was achieved with neutral beam injection as the only external heating source, and then termination of the heating at peak performance. This allowed the first direct evidence for electron heating of plasmas by fusion-born alphas to be obtained. Interpretive transport modeling of the relevant D-T and reference deuterium discharges is consistent with the alpha particle heating observation.

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The main source of heating in thermonuclear reactors will be alpha particles (^{4}He nuclei), which are born with an energy of $E_\alpha = 3.5$ MeV, resulting from the fusion reaction $D + T \rightarrow {}^4\mathrm{He} + n$ between deuterium (D) and tritium (T). Providing the power for a self-sustained D-T burning plasma, the confined alpha particle must efficiently transfer their energy to the plasma particles during slowing-down in the plasma. The alpha particle heating in magnetically confined fusion machines is a high priority subject and has been studied in the largest tokamaks with D-T plasma capabilities, the tokamak fusion test reactor (TFTR) and the joint European torus (JET). Identification of the alpha particle heating in modern fusion devices is a big challenge since it is rather small relative to auxiliary heating effects. Therefore, results presented in this Letter are important in the perception of approaching burning plasma conditions.

High-power experiments in TFTR [1] were carried out in plasma fueled with equal densities of deuterium (n_D) and tritium (n_T). In such plasmas, the energy stored in the electrons and ions increased by ~20% compared to similar pure deuterium plasmas. It was claimed that the increase took place both due to improved confinement associated with the use of tritium, and probably heating of electrons by D-T fusion alpha particles.

Subsequent experiments at JET were performed with various D-T fuel mixtures, aiming to separate the effects of improved confinement and alpha particle heating [2,3]. Scanning the plasma and neutral beam injection (NBI) mixtures from pure deuterium to almost pure tritium, alpha heating was claimed in the hot-ion H-mode discharges [4]. At the plasma mixture of ≈60% tritium, which was declared as optimal, the ratio of D-T fusion power to the absorbed power $P_{\mathrm{fusion}}/P_{\mathrm{absorbed}}$, reached 0.65 in the discharge. It was claimed that change in the core electron-temperature produced by alpha particle heating was ≈10%. Also, it was found that the plasma energy confinement has no significant isotopic dependence in these discharges and the ion-temperature increase is mostly due to transfers of equipartition and NBI power from the electrons.

In the recent D-T experiment at JET (DTE2), direct alpha particle self-heating is identified in high-performance so-named "hybrid" discharges [5] with power modulation

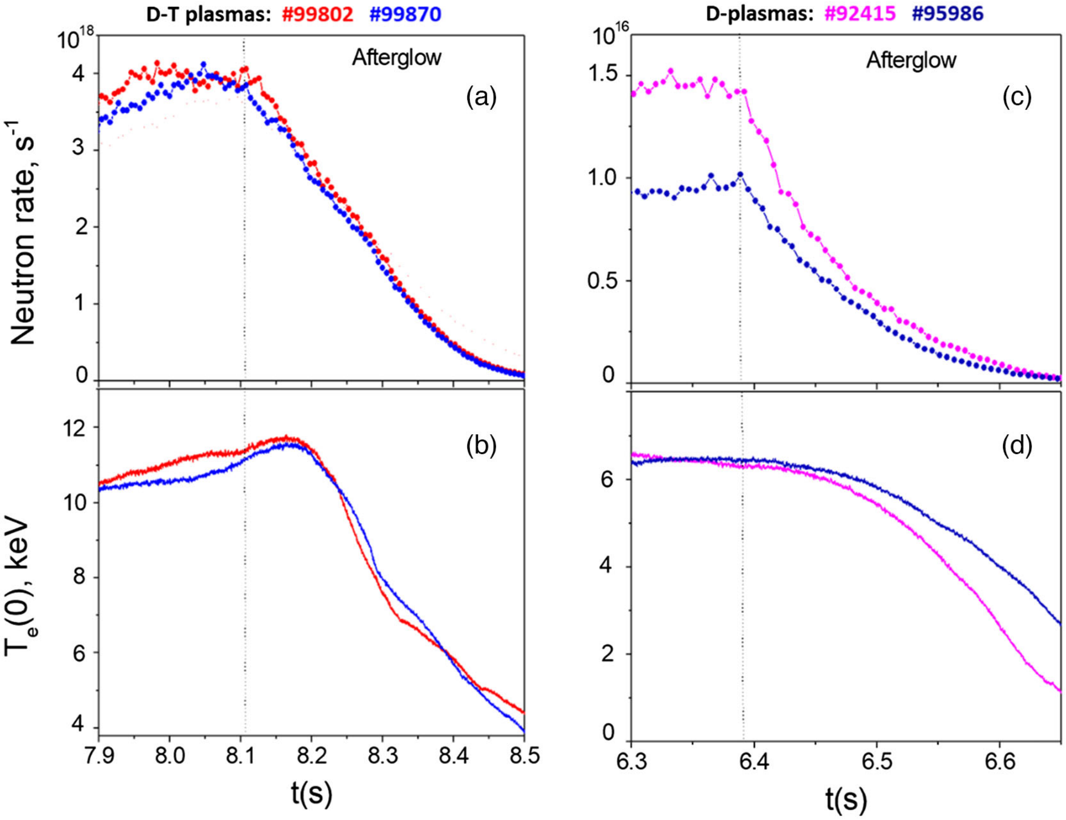

FIG. 1. (a) and (b) Waveforms of the *D-T* JET pulses; (c) and (d) The deuterium JET pulses (the waveforms were shifted in time to align both NBI afterglow periods). The panels show waveforms of central electron temperatures, $T_e(0)$, and measured neutron rates, where the dashed line is marking the start of the NBI afterglow period.

of *D*- and *T*-NBI and no radio frequency heating. It was expected that in hybrids, which are characterized by a reduced plasma current and the safety factor profile (*q* profile) with a broad region of low magnetic shear, the alpha particle impact on fusion plasma performance could be enhanced.

Indeed, we found that alpha particles continue transferring their kinetic energy to plasma electrons during slowing-down after the removal of applied NBI. During the afterglow period (defined as a 400 ms period during which the NBI heating is switched off), the total neutron rate (dominantly *D-T* neutrons) is decreasing, while the plasma core electron temperature, $T_e(0)$, measured by the electron cyclotron emission (ECE) diagnostics, is still increasing for a short period. This evolution is in a contrast to reference high-performance deuterium discharges, in which both the T_e and *D-D* neutron rate are basically decreasing during the NBI afterglow. The alpha particle self-heating effect was observed in several hybrid scenario *D-T* discharges. To demonstrate this effect, a comparison of some *D-T* and deuterium discharges with NBI afterglow are presented in Fig. 1. These high-performance hybrid *D-T* discharges that reached maximal fusion power $P_{\mathrm{DT}}^{\max} \approx 12$ MW with NBI-only plasma heating, have been performed at the toroidal magnetic field $B_0 = 3.45$ T on the magnetic axis, plasma current is $I_p = 2.3$ MA and tritium concentration 53%–55%. Due to lack of reference deuterium discharges, we selected pulse No. 92415 (3.4 T/2.5 MA), which is also a hybrid, and the discharge No. 95986 (3.4 T/2.7 MA) is a different plasma scenario, with an internal transport barrier and elevated *q* profile [6].

A detailed analysis of the observed effect has been performed for the hybrid *D-T* discharge No. 99801 fueled with approximately equal densities of deuterium and tritium, $n_T \approx 48\%$ ($P_{\mathrm{DT}}^{\max} \approx 11$ MW), and the reference deuterium discharge No. 100793. Waveforms of NBI power, n_{e0}, $T_e(0)$ and neutron rate are presented in Fig. 2. Both discharges were operated at the toroidal magnetic field $B_0 = 3.45$ T on the magnetic axis, plasma current is $I_p = 2.3$ MA and the electron density $n_{e0} \approx 4.3 \times 10^{19}$ m^{-3}, a central line averaged density measured by far infrared diagnostic system (FIR interferometry). The neutral *D* and *T* beams with energies $E_{\mathrm{NBI}} \approx 105 - 115$ keV were injected to heat the fuel ions. A maximum NBI heating power of $P_{\mathrm{NBI}} \approx 26$ MW was injected by radial and tangential neutral beams; the NBI afterglow period was from $t = 8.105$ to $t = 8.5$ s [see Fig. 2(a)] that is sufficient for thermalization.

As can be seen from Fig. 2(d), at the peak performance of the *D-T* discharge, the core electron temperature is about

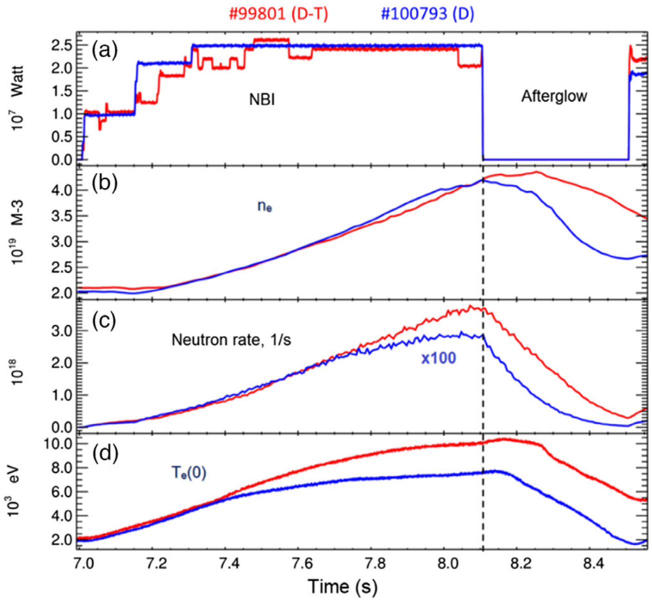

FIG. 2. Waveforms of the *D-T* JET pulse No. 99801 (red lines) vs the deuterium JET pulse No. 100793 (blue lines); panels show waveforms of the NBI heating power, the central electron temperature, $T_e(0)$ and the measured neutron rate; dashed line marks the NBI power cut.

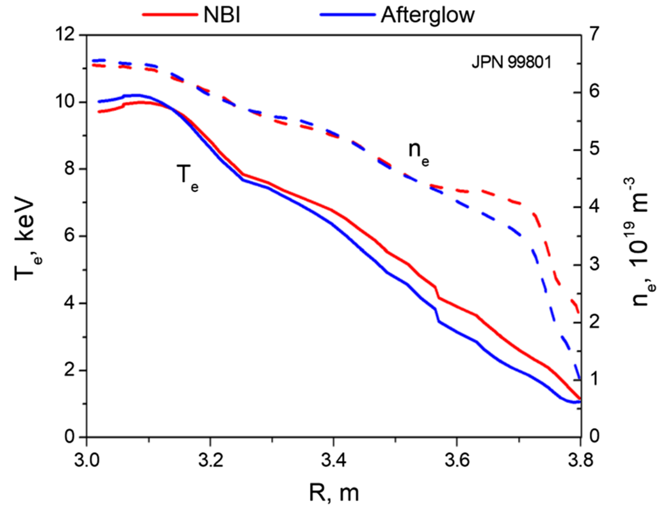

FIG. 3. ECE measurements of the electron temperature profile (T_e) and high-resolution Thomson scattering measurements of the electron density profiles (n_e): red lines—smoothed profiles during NBI heating ($t \approx 8.09$ s); blue lines—smoothed profiles in the afterglow ($t \approx 8.15$ s).

30% higher [$\Delta T_e(0) \approx 2.5$ keV] at similar heating conditions compared with the deuterium discharge. Note, the T_e experimental uncertainty is ~10% or less. As it was declared in [1–3], this T_e increase happens both due to improved confinement associated with the use of tritium and heating of electrons by *D-T* fusion alpha particles. In the afterglow period, the *D-T* core electron temperature has a trend with $dT_e/dt \geq 0$ during the first $t \approx 60$ ms of the *D-T* afterglow, reaching $T_e(0) \approx 10.3$ keV. In the next ~70 ms the core temperature is slightly decreasing to ~10 keV and then, it is falling rather rapidly, but not so fast as in the reference deuterium discharge. Thus, during the first ~130 ms of the afterglow, the core electron temperature of the *D-T* plasma remained in the range in the range 10–10.3 keV without any auxiliary heating. We should note that slowing down of the 3.5-MeV alpha particles is predominantly due to electron friction since their energy $E_\alpha \gg E_{\rm crit} \approx 0.38$ MeV (according to [7], at the critical energy of ions, $E_{\rm crit}$, the rate of loss of energy to the plasma electrons and to the ions equal). At the same time, thermalisation of NBI ions occurs mainly due to interaction with fuel ions because of $E_{\rm T\text{-}NBI} < E_{\rm crit} \approx 0.31$ MeV and $E_{\rm D\text{-}NBI} < E_{\rm crit} \approx 0.21$ MeV. Hence, the *D* and *T* beam ions are mostly heating the plasma fuel ions, merely, 3.5 MeV *D-T* alpha particles could cause the heating of electrons in the plasma core as shown in Fig. 2(d). The ion-electron slowing-down time of 3.5-MeV alphas, is $\tau_{s\alpha} \sim 910$ ms [8]. As a result of electron friction during 400 ms, the average alpha particle energy loss is ~1.8 MeV [7], so their energy will be $E_\alpha \sim 1.7$ MeV $\gg E_{\rm crit}$. Therefore, *D-T* alpha particles can provide sustainable electron heating during slowing down in the afterglow lasting ≈400 ms. The NBI ion thermalization time is less than 200 ms.

One can see that the *D-T* neutron rate (meaning the alpha particle source rate) at the peak of the discharge fusion performance is about 130 times higher than *D-D* neutron rate [see Fig. 2(c)]. Therefore, the core density of charged *D-D* fusion products, 3-MeV protons, 1-MeV tritons, and 0.82-MeV ^{3}He, is considerably lower than the alpha particle density in the *D-T* plasma and the electron heating by the *D-D* fusion products during the afterglow is negligible.

It is important to note that measured n_e and T_e radial profiles at the peak of the *D-T* fusion performance and in the afterglow are changing coherently (see Fig. 3). We found that in similar pulses without afterglow, the n_e density in the plasma core is still rising at around 8.1–8.3 s as a result of the transition to H mode at around 7.2 s. It is therefore to be expected that the n_e density rise would still be observed in the initial 100–200 ms of the afterglow since the plasma is still in the end of the H-mode transition phase and heating power is still effectively being supplied by the energetic alpha particle population. The equivalent deuterium reference pulse, also with afterglow, did not exhibit this persistent rise in the core density during the initial afterglow phase.

For comparison, one can see that $T_e(0)$ in the deuterium discharge is marginally increasing though n_e decreasing in the post-NBI phase [see Fig. 2(b)]. The similar effect has been observed in some JT-60U tokamak discharges [9]. It was established that a convective heat transport mechanism is responsible for this effect. Our TRANSP [10] calculations confirm that the convective fraction in the electron power-density balance is sustaining during the deuterium afterglow. In contrast, this fraction is constantly decreasing

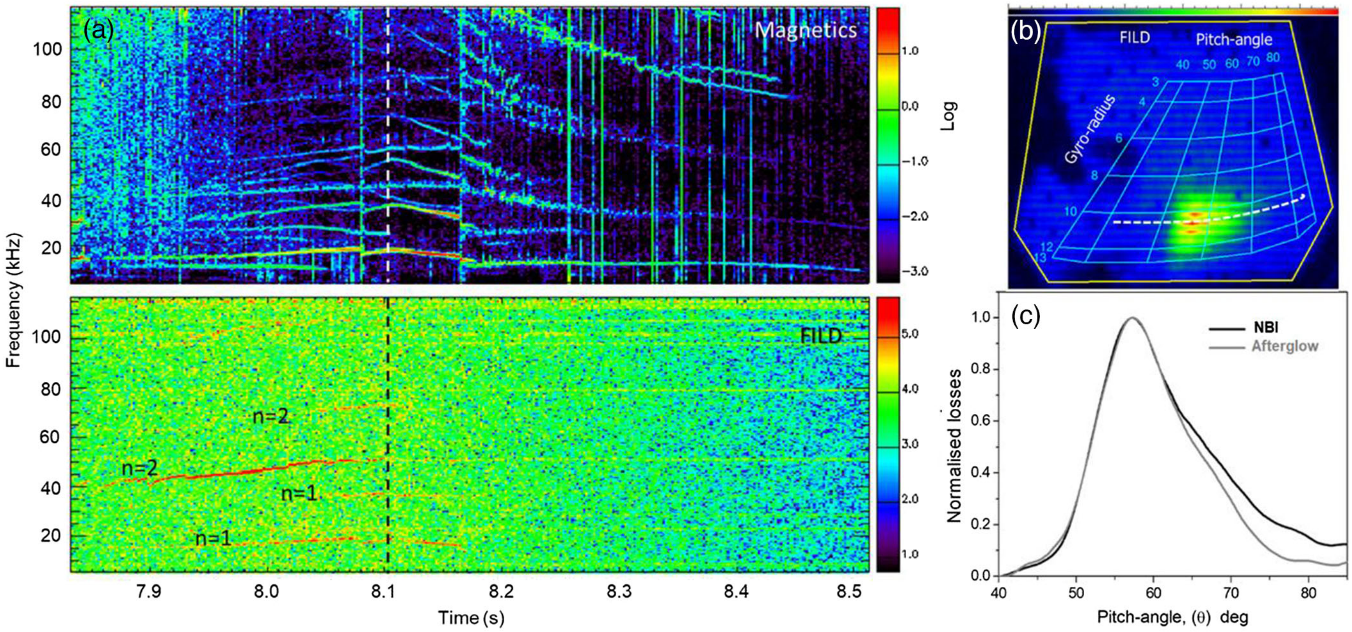

FIG. 4. (a) Fourier spectrogram of an in-vessel magnetic pickup coil (upper box) and FILD (bottom box) signals detected in JET discharge No. 99801; dashed line marks the NBI power cut. (b) Typical footprint of alpha particle losses recorded with FILD in the afterglow ($t = 8.15$–8.20 s). Grid—gyroradius (cm) and pitch angle (degree); white dashed line indicates the gyroradius related to the smoothed pitch-angle distributions ($t = 8.0$–8.1 s and 8.15–8.20 s) presented in Fig. 4(c).

in the high-performance and afterglow periods of the *D-T* discharge.

During the *D-T* experiments, alpha particle losses were routinely measured with the scintillator probe [11], which is a fast ion loss detector (FILD) with energy and pitch-angle resolution and an array of multichannel thin-foil charge collectors, Faraday cups, with poloidal, radial, and energy resolution [12,13]. Footprints of alpha particle losses in the FILD [see Fig. 4(b)] reveal typical first-orbit losses in both periods of the *D-T* discharge. Figure 4(a) shows the MHD activity and coherent alpha particle losses detected with FILD. One can see that the impact of MHD instabilities on losses is prominent during the NBI phase, however coherent losses are weak in the afterglow. Thus, an extra MHD induced transport does not occur in the afterglow. Note, pitch-angle distributions of prompt losses presented in Fig. 4(c) shows that they are more peaked in the afterglow period due to the longer slowing down time of the NBI ions expected in the plasma core. These observations confirm that most alpha particles are apparently unaffected by MHD induced transport in the afterglow, which could otherwise cause additional losses.

The experimental data presented in this Letter was analyzed using TRANSP interpretive simulations based on carefully validated plasma diagnostic data (n_e, T_e, etc.) with combined experimental and computational uncertainty evaluated to be $\pm 10\%$. TRANSP simulations were performed for most high-performance DTE2 discharges [14], providing a reliable scientific basis of the *D-T* predictive modeling [15].

Neutron rate calculations presented in Fig. 5 show that in the analyzed *D-T* discharge the thermal neutron rate dominates during both the high-performance and the afterglow periods, exceeding the beam-target neutron rate component. In contrast, the beam-target component in the reference deuterium discharge is higher than the thermal one throughout the NBI heated phase though it grows for a short period after switching off the NBI heating, exceeding the beam-target rate. One can see that neutron rates in both discharges are decreasing during the afterglow periods. However, in the deuterium afterglow, the neutron rate decays about twofold faster than in the *D-T* afterglow phase. The modeling demonstrates that a sluggish decay of the neutron rate observed in the *D-T* discharge is mostly defined by the thermal neutron rate component. Thus, the alpha particle generation is sustaining for longer in the afterglow, providing an efficient heating of electrons in the core. Also, the *D-T* neutron profile measurements [16] show that the alpha particle source profiles are peaked on the plasma axis, so the main heating effect should be in the plasma core as expected.

Figure 6 presents results of TRANSP interpretive modeling of electron heating in both *D-T* and the reference deuterium discharges. The power transferred to electrons by alphas, NBI, and the equipartition power exchange between ions and electrons, Q_{ie}, were obtained for the plasma core, in the range of the dimensionless radius $\rho \equiv \sqrt{\psi_{\rm tor}^{\rm norm}} < 0.05$, where $\psi_{\rm tor}^{\rm norm}$ is a normalized toroidal magnetic flux. We need to note that the assessed Q_{ie} uncertainty is about 30% since measured and extrapolated

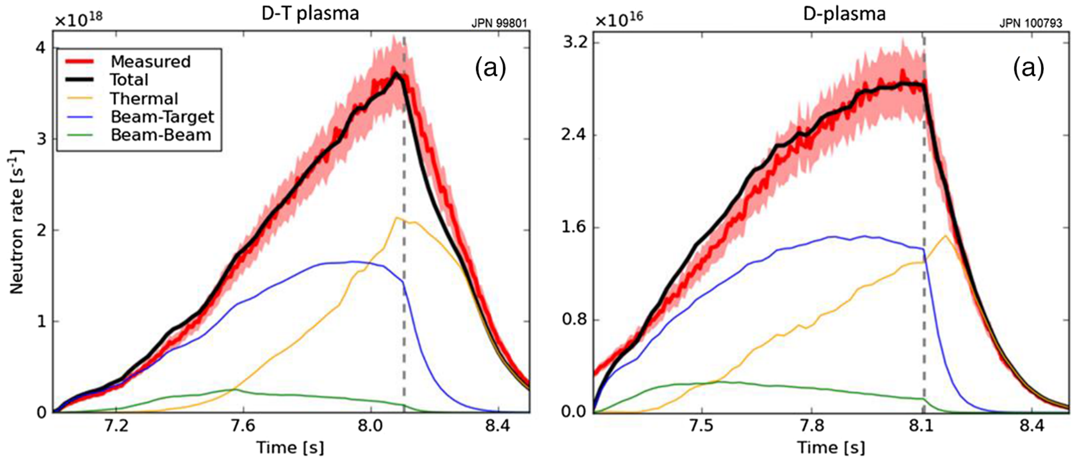

FIG. 5. TRANSP [10] neutron rate modeling of JET *D-T* discharge No. 99801 (a) and deuterium discharge No. 100793 (b). The thermal, beam-target, and beam-beam neutron rate components are presented as well as the total calculated rate and measured one; dashed line marks the NBI power cut.

T_i errors are rather high in the plasma core. Electron temperature on axis and a difference between the ion and electron temperatures, $T_i - T_e$, in the plasma core are also shown in Fig. 6. In these TRANSP calculations, the ion-temperature and toroidal rotation profiles are determined from charge exchange emission spectroscopy [17], utilizing NeX-CX emission from trace concentrations of neon injected for this measurement.

The *D-T* discharge modeling [see Fig. 6(a)] shows that the alpha particle power transfer grows during the NBI heating phase and keeps growing ≈200 ms in afterglow up to ≈1.5 MW. At the same time, the NBI power transfer to electrons is dropping down in both afterglows though in the deuterium discharge it is going faster. One can see that in both discharges $\Delta T = T_i\text{-}T_e > 0$, however, in *D-T* afterglow ΔT decreasing in contrast to the alpha particle power transfer that grows during ≈200 ms. There is not a credible change of ΔT in the deuterium case. Also, TRANSP shows that in the *D-T* discharge Q_{ie}, the equipartition power exchange between ions and electrons, in the core is comparable to the alpha particle power transfer contribution. In the deuterium afterglow, the electron heating due to the power exchange between bulk ions and electrons is demonstrated in Fig. 6(b). Note, in the *D-T* discharge the electron-ion heat exchange time, which is averaged over the period 7.95–8.25 s within $\rho < 0.05$, is ≈0.2 s, however, for the deuterium reference pulse this characteristic time-scale is ≈0.1 s.

It is known that energetic particles, which stabilize ion-temperature-gradient-driven microturbulence, could improve energy confinement [18–22]. Indeed, our TRANSP calculation reveals that the energy confinement

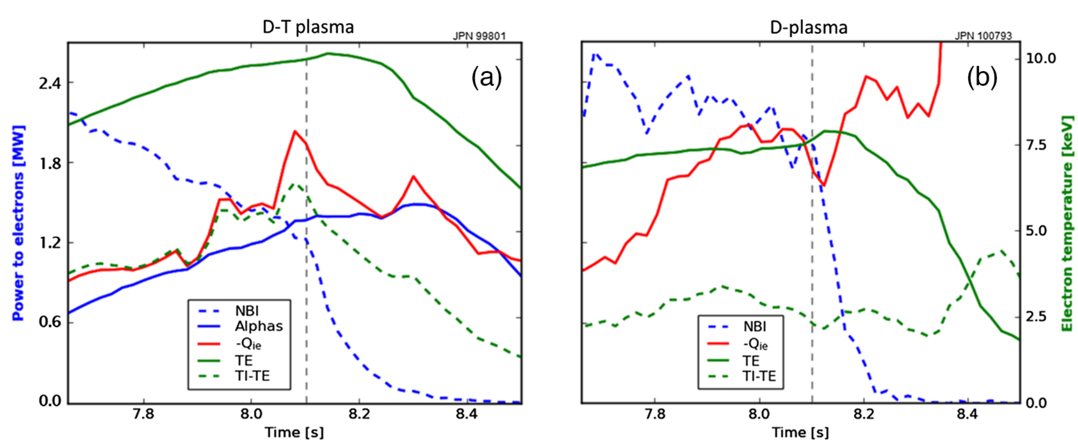

FIG. 6. TRANSP [10] analysis of electron heating in JET *D-T* discharge No. 99801(a) and deuterium discharge No. 100793 (b). The power transferred to electrons (left scale) by alphas, NBI, and thermal ions (-Qie) are presented as well as electron temperature on axis (TE) and a difference between the ion and electron temperatures (TI-TE) in the plasma core (right scale); dashed line marks the NBI power cut.

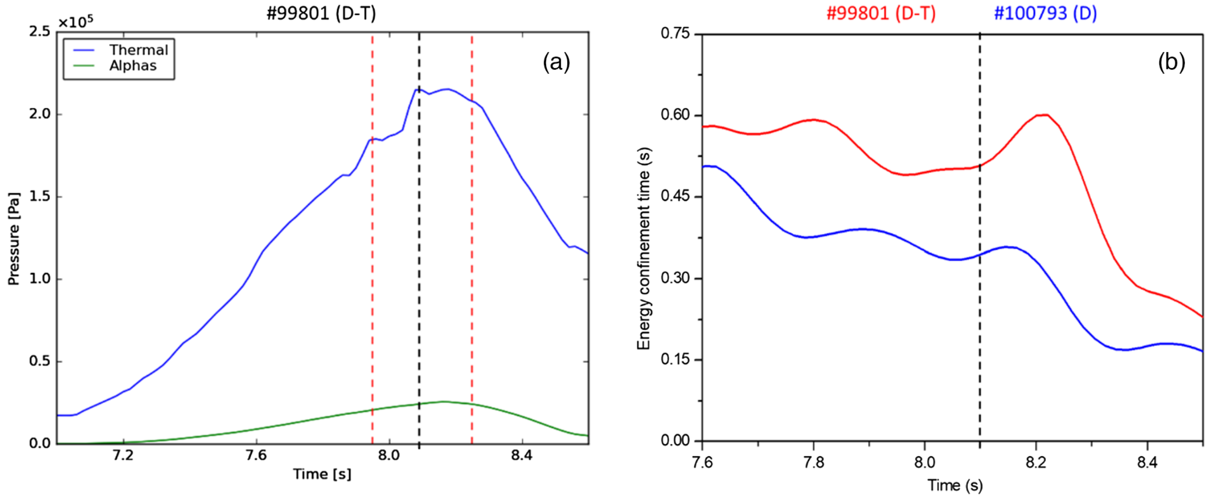

FIG. 7. TRANSP analysis related to the plasma centre, $\rho < 0.05$; (a) comparison of the thermal and alpha particle pressure in No. 99801; (b) evolution of the total energy confinement time (smoothed) in No. 99801 and No. 100793 discharges; red dashed lines denote the time slot for calculation of the averaged pressure and energy confinement time parameters (red); black dashed line marks the NBI power cut.

time (τ_E) of the *D-T* discharge is higher than in the reference deuterium one. Note, the alpha particle pressure is growing up in the heating period and beginning of the afterglow. This is clearly seen in Fig. 7(a), which shows both thermal and alpha particle pressures related to the plasma center, $\rho < 0.05$. The alpha particle pressure is reaching ≈12% of the thermal in the high-performance and afterglow period, 7.95–8.25 s. Figure 7(b) presents evolution of τ_E of both *D-T* and deuterium discharges in the high-performance phase and afterglow periods that depicts a potential alpha particle impact on energy confinement (note, the assessed τ_E uncertainty is ≈0.1 s). Certainly, extra studies are needed to explain the observed energy confinement enhancement in the *D-T* discharge.

In conclusion, we can state that in the recent JET *D-T* plasma experiments the alpha particle self-heating effects were observed in high-performance hybrid discharges with power modulation of the neutral *D* and *T* beams. In the *D-T* discharge the core electron temperature is about 30% higher than in the reference deuterium discharge. After the NBI power is turned off, alpha particles continue to transfer their kinetic energy to plasma electrons during slowing down. In this afterglow phase the *D-T* neutron rate is decreasing while the plasma core electron temperature is still increasing for a while. In contrast, in the high-performance deuterium discharges both T_e and *D-D* neutron rate are decreasing during afterglow. The transport modeling of both *D-T* and deuterium discharges is consistent with experimental measurements despite large computational error bars. Therefore, the direct evidence of the alpha particle heating as well as observation of the energy confinement improvement in the *D-T* discharge are essential scientific basis for predictive modelling and developments of burning plasma reactors.

Further information on the data and models underlying this Letter is available at [23].

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