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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 (JET). 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. Transport modelling of the relevant *D-T* and reference deuterium discharges is consistent with the alpha-particle heating observation.

Keywords: tokamak, D-T fusion, alpha-particles

The main source of heating in thermonuclear reactors will be alpha-particles (^4He-ions), which are born with an energy of E_α=3.5 MeV, resulting from the fusion reaction $D+T \rightarrow {}^4He+n$ between deuterium (D) and tritium (T). Providing the power for a self-sustained *D-T* plasma burning, the confined alpha-particles 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).

High-power experiments in TFTR [1] were carried out in plasma fuelled with equal densities of deuterium (n_D) and tritium (n_T). In such plasmas, the energy stored in the electron 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, the alpha-heating was claimed in the hot-ion H-mode [4] discharge. At the plasma mixture of ≈60% tritium, which was declared as optimal, the ratio of *D-T* fusion power to the absorbed power $P_{fusion}/P_{absorbed}$, reached 0.65 in the discharge. It was claimed that change in the core electron temperature produced by alpha-particle heating was ≈10%. Also, some effects of the heating were seen in the electron temperature and energy content.

In the recent *D-T* experiment at JET (DTE2), direct alpha-particle self-heating is identified in high-performance plasma discharges with power modulation of *D*- and *T*-NBI and no radio frequency heating.

It was found that alpha-particles continue transferring their kinetic energy to plasma electrons during slowing-down after the removal of applied NBI. During the NBI afterglow period, the total neutron rate (substantially *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 the reference high-performance deuterium discharges, in which both T_e and *D-D* neutron rate are decreasing during the NBI afterglow. The alpha-particle self-heating effect was observed in both the so-named hybrid scenario [5] discharges as well as in discharges with an internal transport barrier (ITB) [6]. A comparison of some *D-T* and deuterium discharges with NBI cuts are presented in figure 1. It is important to note that the *D-T* neutron profile measurements [7] show that alpha-particle source profiles are peaked on the plasma axis, so the main heating effect is expected in the plasma core.

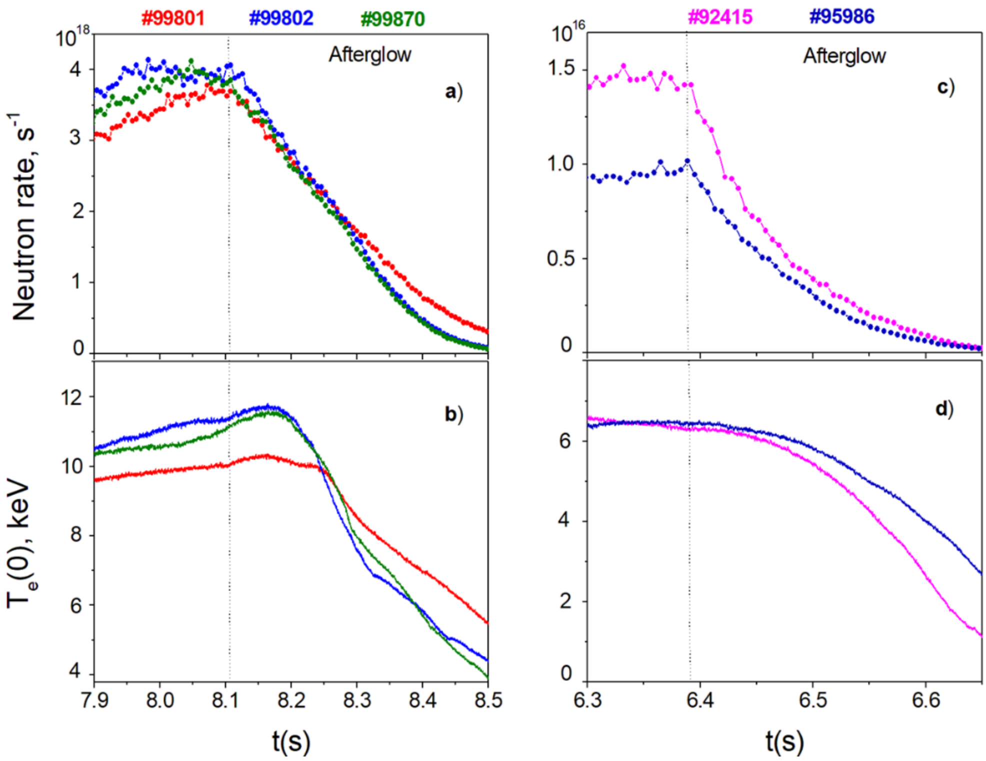

Figure 1. *(a) and (b) - waveforms of the D-T JET pulses; (c) and (d) – the deuterium JET pulses (the waveforms were shifted in time to align both NBI afterglow periods). The panels show waveforms of central electron temperatures, Te(0), and measured neutron rates, where the dash line is marking the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

A detailed analysis of the observed effect has been performed for the *D-T* discharge #99801 fuelled with approximately equal densities of deuterium and tritium, $n_D \approx n_T$, and the reference deuterium discharge #100793. Waveforms of NBI power, n_{e0}, $T_e(0)$ and neutron rate are presented in figure 2. Both discharges were delivered at the toroidal magnetic field B_0=3.45T on the magnetic axis, plasma current is I_p=2.3MA and the electron density $n_{e0} \approx 4.3\times10^{19}\,\mathrm{m}^{-3}$, a central line averaged density measured by far infrared diagnostic system (FIR interferometry). The neutral *D*- and *T*-beams with energies E_{NBI}≈105-115 keV were injected to heat the fuel ions. A maximum NBI heating power of P_{NBI}≈26 MW was injected by radial and tangential neutral beams; the NBI afterglow period was from *t*=8.105s to *t*=8.5s (see figure 2a) that is sufficient for thermalisation.

As can be seen from figure 2d, at the top performance of the *D-T* discharge, the core electron temperature gain is about 30% ($\Delta T_e(0) \approx 2.5$ keV) at same heating conditions with deuterium discharge. As it was declared in [1-3], this T_e increase happen 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

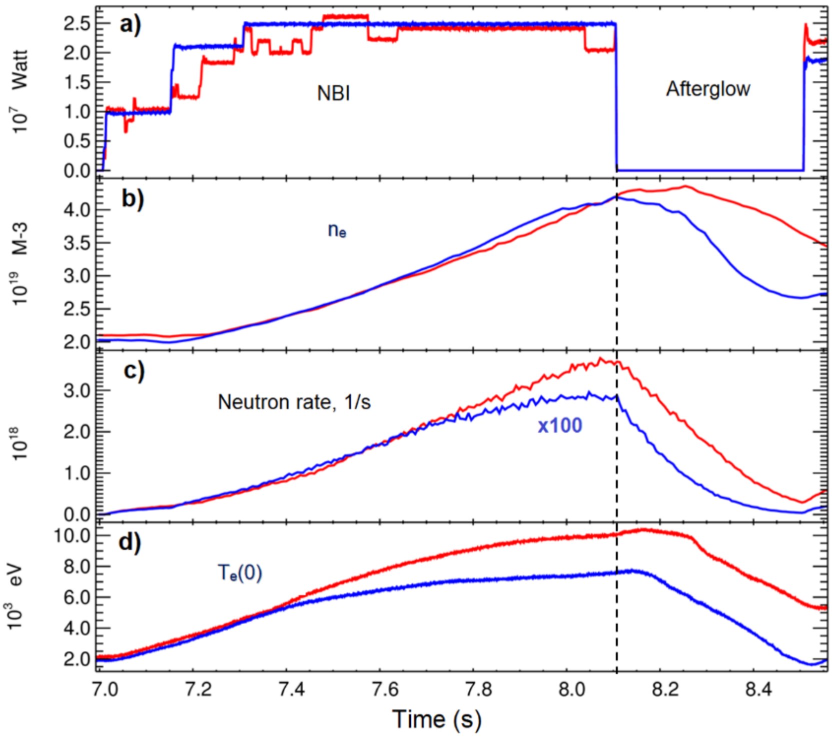

Figure 2. *Waveforms of the D-T JET pulse #99801 (red solid lines) vs the deuterium JET pulse #100793 (blue solid lines). Panels show waveforms of the NBI heating power, the central electron temperature, Te(0) and the measured neutron rate.*

their energy $E_\alpha >> E_{crit} \approx 0.38$ MeV (according to [8], at the critical energy of ions , E_{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 $E_{T\text{-}NBI} < E_{crit} \approx 0.31$ MeV and $E_{D\text{-}NBI} < E_{crit} \approx 0.21$ MeV. Hence, the *D*- and *T*-beam ions are mostly heating the plasma fuel ions, merely 3.5-MeV *D-T* alpha-particles could heat electrons in the plasma core that shown in figure 2d. The ion-electron slowing down time of 3.5-MeV alphas, is $\tau_{s\alpha}$~910 ms [9]. As a result of electron friction during 400 ms, the average alpha-particle energy loss is ~1.8 MeV [8], so their energy will be $E_\alpha \sim 1.7$ MeV >> E_{crit}. Therefore, *D-T* alpha-particles can provide sustainable electron heating during slowing down in the afterglow lasting ≈400 ms. The NBI ion thermalisation time is less than 200 ms.

One can see that the *D-T* neutron rate (meaning the alpha-particle source rate) at the top of the discharge fusion performance is about 130 times higher than *D-D* neutron rate (see figure 2c). 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 one and the electron heating by the *D-D* fusion products during the afterglow is negligible.

It is important to note that n_e and T_e radial profiles related to the top of the *D-T* fusion performance and the afterglow are not changing in the plasma core. Hence, the convective heat loss mechanism observed in the JT-60U tokamak [10], when an electron temperature is increasing in the post-beam phase, does not play a role during the *D-T* afterglow compared with the alpha-particle heating. In the deuterium discharge the convective loss effect could take place since the n_e drop is observed in the NBI afterglow (see figure 2b).

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. The analysis of footprints of the alpha-particle losses recorded before the NBI power cut and in the afterglow shows that the pitch-angle and energy distributions are typical for the first-orbit losses in both periods. It is a confirmation that alpha-particles are unaffected by any anomalous transport, which could cause additional losses.

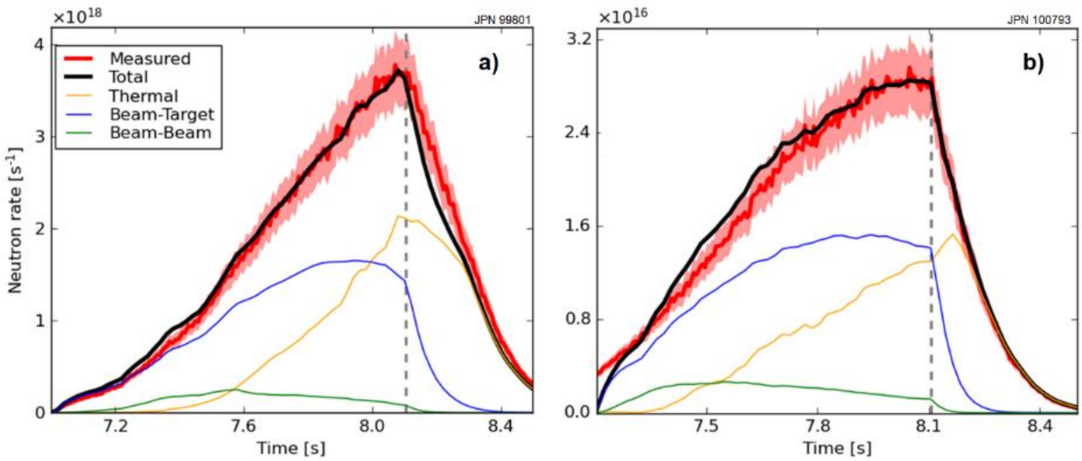

Figure 3. *TRANSP [12] neutron rate modelling of JET D-T discharge #99801 (a) and deuterium discharge #100793 (b). The thermal, beam-target and beam-beam neutron rate components are presented as well as the total calculated rate and measured one.*

The TRANSP [12] neutron rate calculations (see figure 3) show that in the analysed *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 discharge higher than the thermal one though it grows, exceeding the beam-target rate, for a while after switching off the NBI heating. 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 2-fold faster than in the *D-T* afterglow phase. The modelling 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.

Figure 4 demonstrates results of TRANSP interpretive modelling 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 $\rho \equiv \sqrt{\psi_{tor}^{norm}} < 0.05$, where ψ_{tor}^{norm} is a normalized toroidal magnetic flux. Also, electron temperature on axis and a difference between the ion and electron temperatures, $T_i - T_e$, in the plasma core are shown. The ion-temperature and toroidal rotation profiles are determined from charge exchange emission spectroscopy [13], utilising NeX-CX emission from low-level neon injected for this measurement.

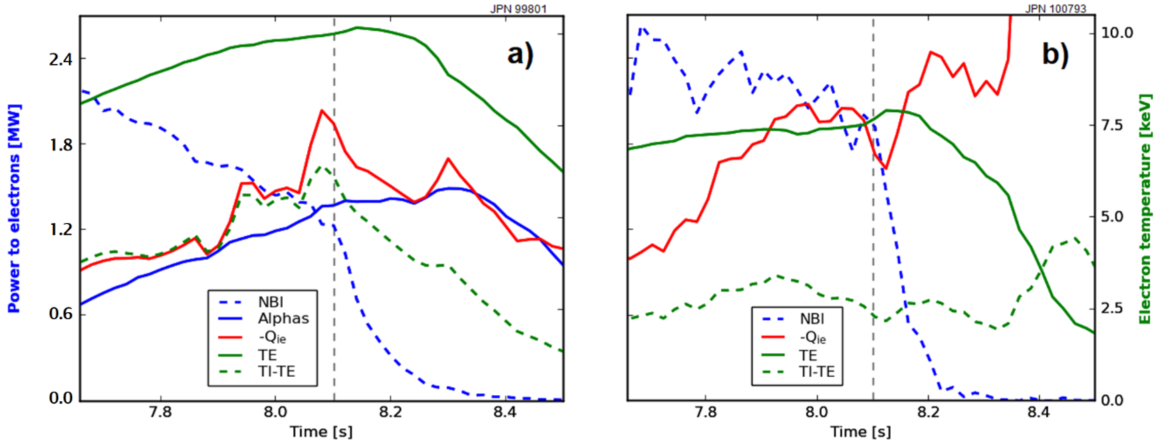

Figure 4. TRANSP analysis of electron heating in JET D-T discharge #99801(a) and deuterium discharge #100793 (b). The power transferred to electrons (left scale) by alphas, NBI and thermal ions (-Q_{ie}) are presented as well as electron temperature on axis (TE) and a difference between the ion and electron temperatures (TI-TE) in the plasma core (right scale).

The *D-T* discharge modelling (see figure 4a) shows that the alpha-particle power transfer grows during the NBI heating phase and keep 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 $\Delta T \equiv T_i - T_e > 0$, 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. On other hand, in the deuterium afterglow (see figure 4b), the electron heating due to the power exchange between bulk ions and electrons is proved by the calculated Q_{ie} . We need to note that an assessed Q_{ie} uncertainty is about 30% as far as measured and extrapolated T_i errors are rather high in the plasma core.

In conclusion, we can state that in the recent JET *D-T* plasma experiments the alpha-particle self-heating effects were observed in the high-performance 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 turned off, alpha-particles continue 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 modelling of the *D-T* and deuterium discharges is consistent with experimental measurements despite large error bars of the input data. The direct evidence of alpha-particle heating presented in this paper, which confirms conclusions of former *D-T* experiments, is crucial for developments of burning plasma reactors.

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