BREAKING OF THE ION TEMPERATURE CLAMPING IN ELECTRON HEATED PLASMAS WITH TURBULENCE STABILIZATION

[1]P. MANAS, [2]J. RUIZ RUIZ, [1]J. GARCIA, [1]J.F. ARTAUD, [1]C. BOURDELLE, [3]Y. KAZAKOV, [1]J. MORALES, [1]V. OSTUNI, [4]J. CITRIN AND THE WEST TEAM*

[1]CEA, IRFM, Saint-Paul-les-Durance, France
[2]Rudolf Peierls Centre for Theoretical Physics, University of Oxford, OX1 3NP, UK
[3]Laboratory for Plasma Physics, ERM/KMS, TEC Partner, 1000 Brussels, Belgium
[4]Google Deepmind, London, UK
*see http://west.cea.fr/WESTteam

Email: pierre.manas@cea.fr

The achievable central ion temperature is observed to be limited in current magnetic fusion machines (tokamaks [1,2] or stellarators [3]) in the case where electron heating is dominant, resulting in significantly high ratios of electron to ion central temperatures, which is known to destabilize turbulence. This raises questions on the achievable fusion performance of a future reactor since the fusion reaction rate from thermal deuterium and tritium fuel significantly depends on the ion temperature. Furthermore, highly energetic alpha particles will mainly drive electron heating, the fuel ions being heated only partly from these alphas and from collisional equipartition with thermal electrons, resulting in an overall dominant electron heating. To understand if this limitation in current machines is or can be alleviated in future machines two approaches are followed. An experimental database of WEST plasmas, heated by lower hybrid waves, is studied and compared to JET ICRH heated plasmas [4] where the three-ion heating scheme is used [5] and MeV ions are generated, transferring their energy by more than 90% on the electron population. In the case of WEST, it is found that the central electron to ion temperature ratio directly correlates with global quantities, namely the global energy confinement time (τ_E) and the volume averaged electron-ion collisional heat exchange time (τ_{ei}) [2]. This correlation is recovered by the modelling using QuaLiKiz-NN10D [6] in METIS [7] for turbulent transport and temperature profile predictions. In the absence of a central Internal Transport Barrier (ITB), JET and WEST plasmas (and ITER modelling) follow the same global trend of decreasing central T_i/T_e with increasing τ_{ei}/τ_E. However, the global scaling is also shown to be broken in JET cases where a central ITB form due to turbulence stabilisation via fast ion driven modes [4]. In this case, higher central ion temperature can be achieved despite dominant central electron heating.

The WEST database used in this work consists of ~560 shots including plasma currents of 0.5 MA, magnetic field 3.7 T, line averaged densities ranging from 2.5 to 6×10^{19} m^{-3} and LHCD injected power between 1 and 5.5 MW. The electron temperature is measured from Electron Cyclotron Emission, the ion temperature from the neutron rate (provided additional information on the plasma composition) and the electron density from interferometry. Similar saturation of T_i as found in AUG and W7-X is observed around 1.5 keV (figure 1). Performing integrated modelling from a reference case and scanning the LHCD injected power from 1 to 3.8 MW results in quantitatively similar saturation. The role of the increased electron to ion temperature ratio in turbulence destabilisation has been investigated with QLKNN-10D and found to have limited impact on such achievable central T_i. Due to the

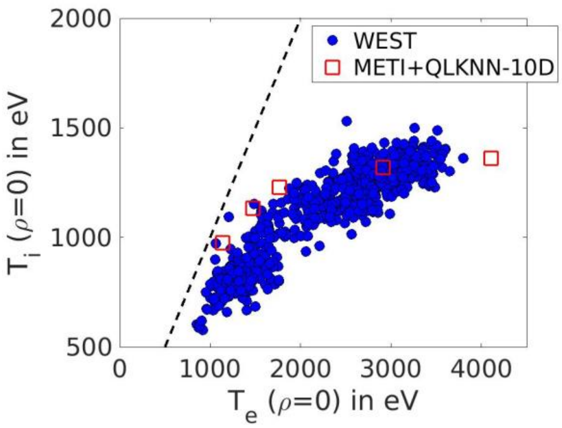

Figure 1: WEST experimental database including LHCD heated plasmas only, up to 5.5 MW. Predictions of temperature profiles using METIS and QLKNN-10D for a range of LHCD is also shown.

observed strong correlation between the T_i/T_e and the ratio of the two characteristic times τ_{ei}/τ_E (figure 2) in the modelling and experimental data, ways to improve the highest achievable central ion temperature are explored from simulations, either by decreasing the volume averaged electron-ion collisional heat exchange time or by increasing the energy confinement time. Increasing the density allows to increase the collisional coupling between electrons and ions while also impacting the energy confinement time. This results in larger T_i/T_e at low τ_{ei}/τ_E. In a different way, increasing the machine size at constant aspect ratio, q_{95}, magnetic field and external power density results in higher T_i/T_e ratios due to larger energy confinement times at higher major radius.

Turning to a larger device, JET, discharge 97090, with dominant electron heating [4], features increase in the confinement factor and deep-core ion temperature in combination with the presence of unstable Alfvénic activity. This is an L-mode with a plasma current of $I_p = 2.4$ MA, toroidal magnetic field $B_0 = 3.2$ T and electron density of $n_e \approx 3.5\text{-}4 \times 10^{19}$ m^{-3} kept approximately constant throughout the discharge. The plasma includes phases with increasing ICRH power of $P_{ICRH} = 2$ MW (low), 4 MW (medium) and 7 MW (high). A trace population of ^3He ions of density $n_{3He}/n_e \approx 0.2\text{-}0.3$ % was introduced into the plasma to absorb the ICRH power [5], and was accelerated to energies of $E_{3He} \approx 1.4$, 4, and 5 MeV respectively in the low-, medium-, and high-P_{ICRH} phases, and consequently heating mostly the electron population. That resulted in a clear increase in the electron temperature. Unexpectedly, the deep-core ion temperature was also shown to increase, which could not be explained by means of electron-ion collisional coupling or by linear effects of the energetic particles on the linear ITG microinstability [4]. The global energy confinement for the L-mode H_{89P} experienced a slight decrease from the Ohmic to the low- P_{ICRH} phase, but increased from the low- to the high-P_{ICRH} phase with a formation of an ITB. This improvement in confinement was attributed experimentally [4] to the presence of a zero-frequency zonal flow that was nonlinearly generated by the unstable Alfvénic modes driven by the energetic ^3He in this discharge. The presence of dominant electron heating, MeV energetic particles, and the absence of rotation (no neutral beam injection was used in the plasma for heating purposes) makes this plasma a suitable candidate for studying burning plasma physics in JET as well as investigating means of maximising the central ion temperature via local turbulence stabilisation in contrast to global mechanisms observed from WEST data analysis and modelling (figure 2).

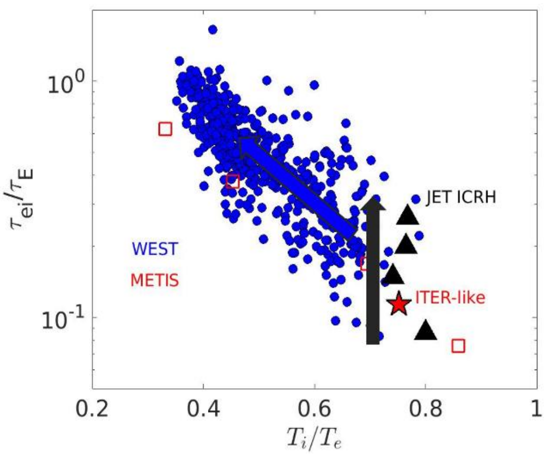

Figure 2: Characteristic collisional energy exchange time between electrons and ions over the global energy confinement time versus the central ion to electron temperature ratio for dominant electron heated plasmas. JET cases with the formation of an ITB are highlighted and break the global scaling of T_i/T_e decreasing with increasing τ_{ei}/τ_E denoted by the blue arrow.

Finally, using the same integrated modelling framework as the one used in figure 1, modelling of an ITER-like 15 MA scenario also result in a high ratio of T_i/T_e due to both, higher energy confinement time together with decreased collisional electron-ion energy exchange time (high density). Additional fast ion driven effect on core turbulence stabilisation could also be an additional mechanism further alleviating the limitation of the central ion temperature in dominant electron heated fusion plasmas as demonstrated in JET.

REFERENCES

[1] M. Beurskens *et al*, Nuclear Fusion **61** (2021) 016015

[2] P. Manas *et al*, Nuclear Fusion **64** (2024) 036011

[3] M. Beurskens *et al*, Nuclear Fusion **61** (2021) 116072

[4] J. Ruiz Ruiz *et al*, Physical Review Letters (2025)

[5] Y. Kazakov *et al*, Nuclear Fusion **55** (2015) 032001

[6] J.F. Artaud *et al*, Nuclear Fusion **58** (2018) 105001

[7] K. van de Plassche *et al*, Physics of Plasmas **27** (2020) 022310