Staged cooling of a fusion-grade plasma in a tokamak thermal quench

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Plasma thermal quench (TQ) is a rapid cooling process occurring when hot plasmas are exposed to external cold energy sinks. The core of TQ is the fundamental transport physics which has broad appeal to plasma physicists with a variety of specializations. In tokamak fusion reactors like ITER where hot plamas (T~100 million Kelvin) are confined by strong magnetic fields, when the confinements are disrupted either intentionally or unintentionally, TQ occurs and marks the point of "no return" of the rapid energy release from hot plasmas to the cold reactor walls. This process can significantly bring thermal load management issue at the walls and potentially cause severely damage to the reactors.
Despite the crucial role of TQ and the broad interests of fundamental transport physics, previous understandings have been failed to predict or explain many TQ-relevant experimental measurements, in particular the broad variation of TQ times.
Here we present our theoretical and numerical study of TQ physics, in which we find surprising physics scalings and unique transport characteristics that will improve our understandings to the TQ physics and experimental results. Specifically, in tokamak disruptions where the magnetic connection length becomes comparable to or even shorter than the plasma mean-free-path, parallel transport can dominate the energy loss and the thermal quench of the core plasma goes through four phases (stages) that have distinct temperature ranges and durations [1]. The main temperature drop occurs while the core plasma remains nearly collisionless, with the parallel electron temperature $T_{e\|}$ dropping in time t as $T_{e\|} \propto t^{-2}$ and a cooling time that scales with the ion sound wave transit time over the length of the open magnetic field line [2]. These surprising physics scalings are the result of effective suppression of parallel electron thermal conduction in an otherwise bounded, quasineutral, and collisionless plasma, which is different from what are known to date on electron thermal conduction along the magnetic field in a nearly collisionless and quasineural plasma. We also find that $T_{e\|} \propto t^{-2/5}$ in the collisional stage. All the above theoretical results are supported by our fully-kinetic particle-in-cell simulations [Figure 1].
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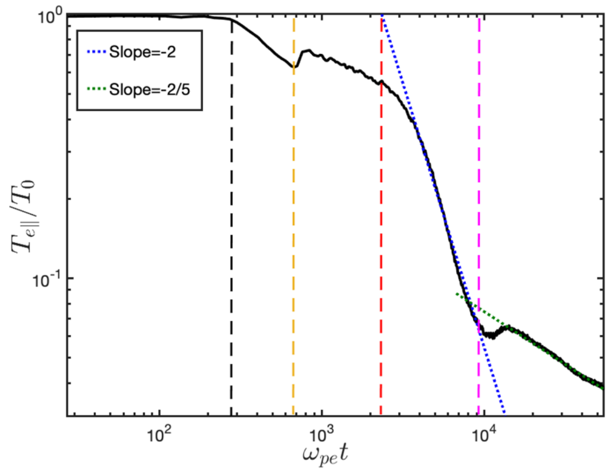

Figure 1. $T_{e\|}$ (x = 0, t) of a slab plasma ($x \in [-L_B, L_B]$) from a VPIC simulation with $L_B = 700\lambda_{De}$, where λ_{De} is the initial electron Debye length. The initial plasma is uniform with electron and ion mass ratio $m_e/m_i = 1/100$, ion charge state Z = 1 and Knudson number $K_{n,0} = 98$ and the thermobath boundary on two ends has temperature $T_w = 0.01T_0$, where T_0 is the initial plasma temperature. The vertical dashed lines mark the moments when the four fronts (two electron fronts followed by two ion fronts) reach the center, while the dotted lines with slopes of −2 (blue) and −2/5 (green) are marked for the collisionless cooling flow phase and collisional phase.

References

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[2] Li, J., Zhang, Y., & Tang, X.-Z. (2023). Staged cooling of a fusion-grade plasma in a tokamak thermal quench. Nuclear Fusion 63, 066030.