Parallel transport induced tokamak thermal quench and its mitigation

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2[nd] Technical Meeting on Plasma Disruptions and Their mitigation

This work was supported by the Office of Fusion Energy Sciences and Office of Advanced Scientific Computing Research through the base theory and TDS SciDAC program.

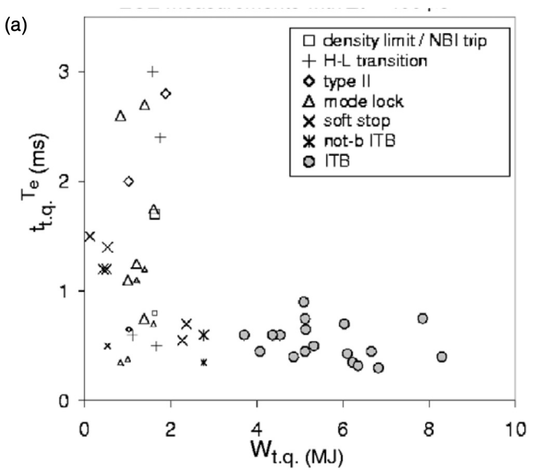
Outline

- Problem setup and physics issues
- Parallel transport induced thermal quench follows exotic kinetic physics and scaling laws
- ITER discussions on pellet assimilation, thermal load mitigation, and runaway avoidance

Thermal quench is the origin of all sins in tokamak disruption

- An ideal disruption mitigation scheme should *solve* the problem(s) at the TQ stage
  - Thermal load management → desires long TQ duration
  - Runaway avoidance → desires a not too cold Te

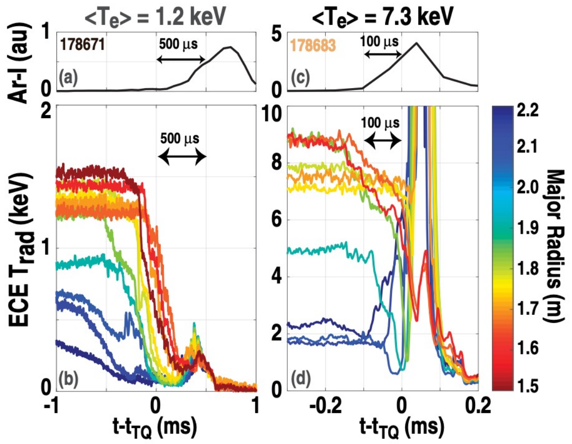
Riccardo V., *et al*., 2005



Experiments show that TQ duration can vary enormously

- 0.05-3ms for JET[1]
- Fast TQ ~100μs or shorter[2] observed on DIII-D for ITB-type disruptions with pellet injection

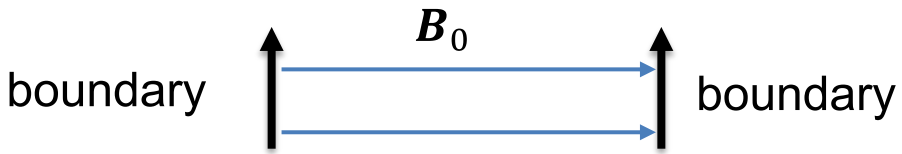
Paz-Soldan C., *et al*., 2020



[1] Riccardo V., *et al*., 2005; [2] Paz-Soldan C., *et al*., 2020

Problem setup for examining TQ physics

- Plasmas will undergo a thermal collapse when a localized cooling spot is introduced
  - In a tokamak disruption, the large-scale MHD activities turn the nested flux surfaces into globally stochastic field lines connecting core plasma directly onto divertor/first wall[1]
  - Solid pellet injection to tokamak reactor, especially with high-Z impurities to provide localized radiative cooling[2]
- Fastest TQ (worst case scenario) is tied to parallel transport with modest magnetic connection length (compared with plasma mean free path)
  - Critical parameter → $K_{n0}=\lambda_{mfp}/L_B$;
    - Worst case scenario: $K_{n0} > 1$, or K_{n0}>>1

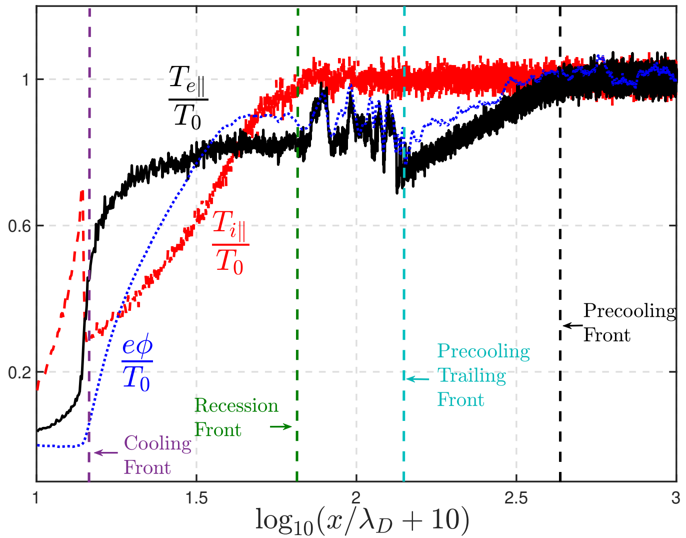


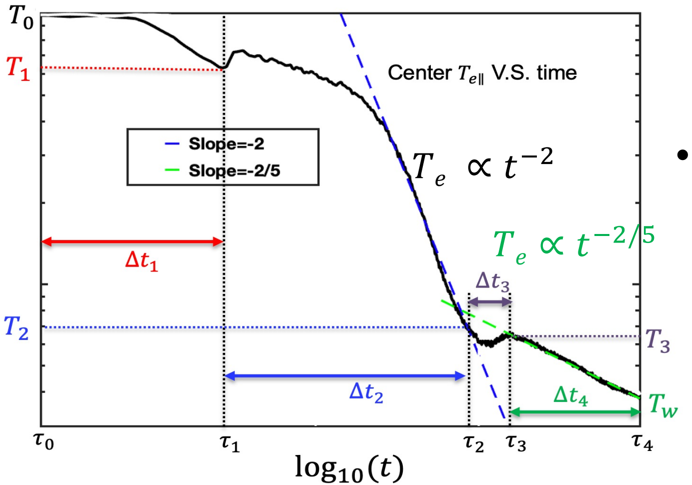
(a) Absorbing bdy
(b) Thermal bath bdy

[1] Sweeney, *et al,* 2018; [2] Bondeson A., *et al* 1991

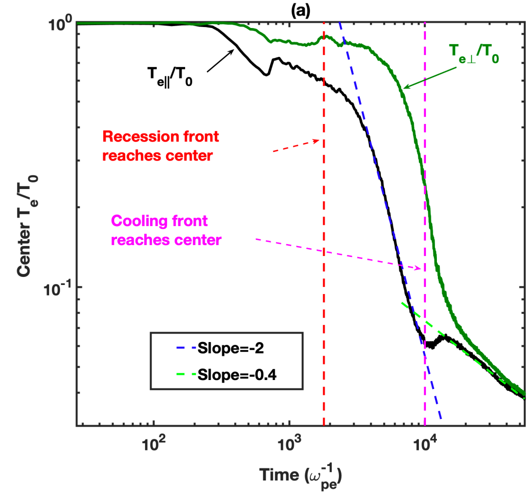
Main physics findings

- TQ is controlled by four propagating electron and ion fronts in a semi-infinite plasma
- These fronts turn core TQ of a bounded plasma into four phases with different durations and amounts of $T_{e\parallel}$ cooling





- Kinetic instabilities & associated wave-particle interaction drive collisionless cooling of core $T_{e\perp}$



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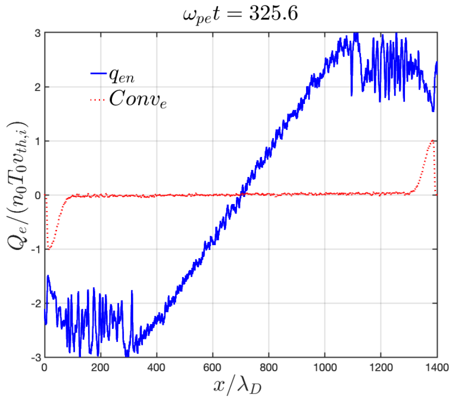
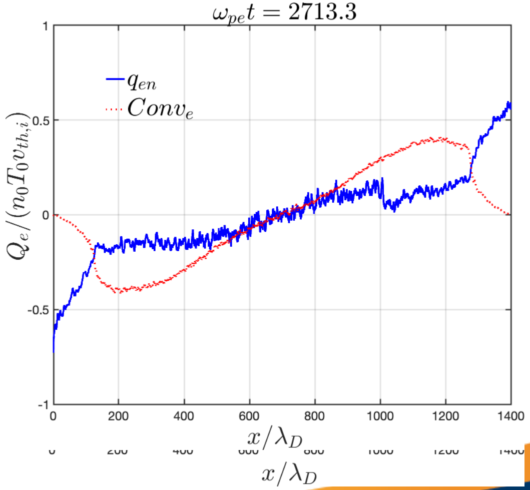
Novelty/Complication in electron thermal conduction

- In the short precursor phase (Δt_1):
  - Between the two electron fronts: $q_{e\parallel} \sim n_e T_{e\parallel} v_{th,e}$
  - In the recession layer:
    - Absorbing boundary: $q_{e\parallel} \sim n_e T_{e\parallel}\, V_{e\parallel} \approx\ n_e T_{e\parallel}\, V_{i\parallel}$
    - Thermobath boundary: $q_{e\parallel} \sim n_e T_{e\parallel} v_{th,e}$ but $\partial q_{e\parallel}/\ \partial x \approx n_e T_{e\parallel}\ V_{e\parallel}/L$
      - This is why a cooling flow forms!

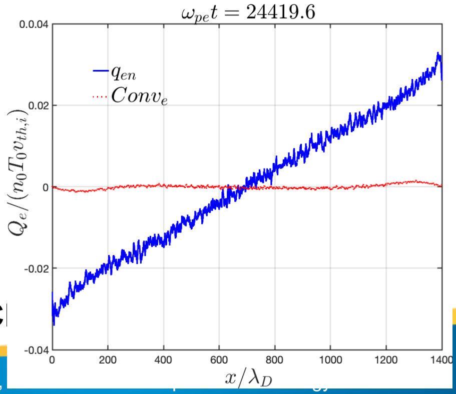


- Main collsionless cooling flow phase (Δt_2):
  - $q_{e\parallel} < T_{e\parallel}\ V_{e\parallel} \approx\ n_e T_{e\parallel}\ V_{i\parallel}$ for both absorbing and thermobath boundary

→ TQ of fusion-grade plasma is dominated by electron convection, not conduction.

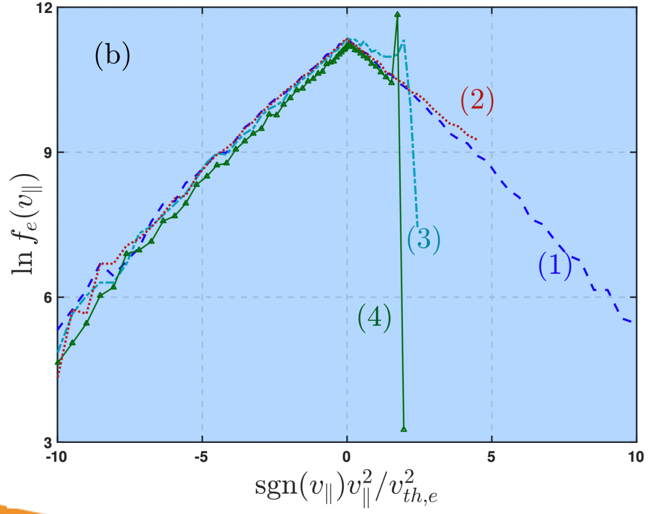


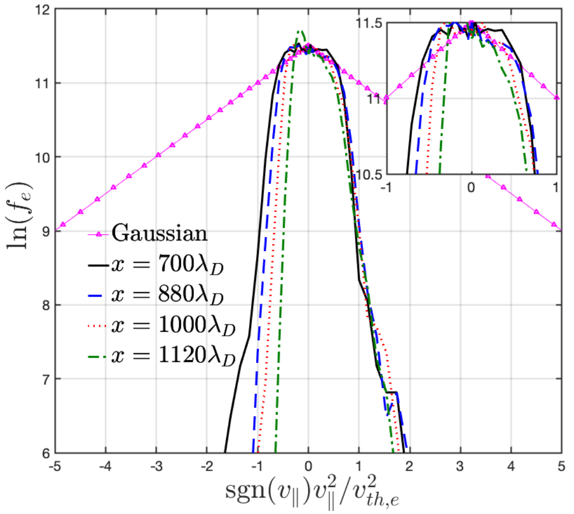
- Final collisional cooling phase (Δt_4) :
  - $q_{e\parallel}\ \approx n_e T_{e\parallel} v_{th,e}\ \lambda_{mfp}\ /LB$ Braginskii closure recovered when $\lambda_{mfp} \ll L_B$

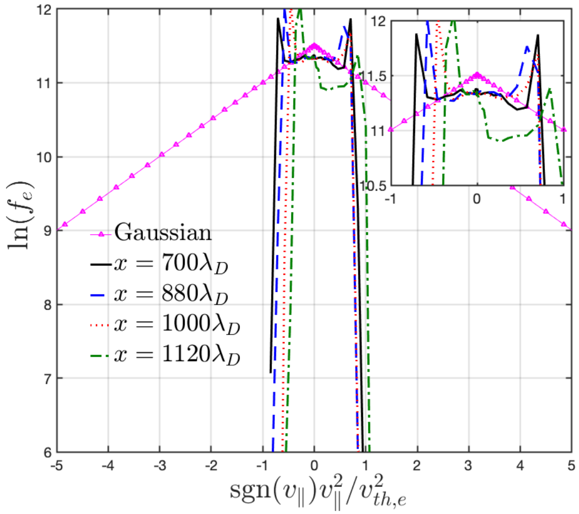


Electron distribution function in collisionless TQ

- In the short precursor phase (Δt_1):
  - High $v_{e\parallel}$ cuttoff, starts with one-sided cutoff





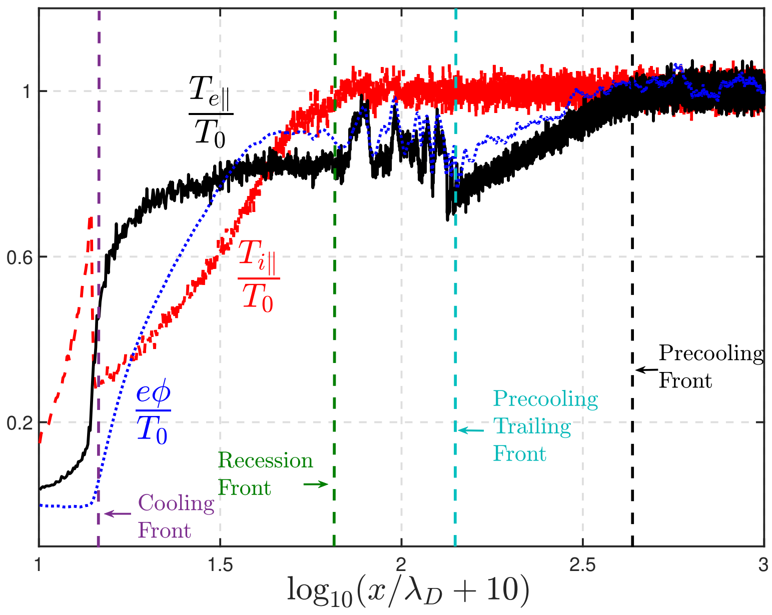


- Main collisionless cooling flow phase (Δt_2):
  - Low $v_{e\parallel}$ cutoff, also two-sided cutoff
  - Electromagnetic kinetic instability
    - Right: electrostatic simulation; left: electromagnetic simulation

ITER discussions

Pellet assimilation

- Pellet assimilation has two aspects:
  - Pellet mass ablation is proportional to the plasma power flux reaching the pellet
  - Spread of the high-Z impurities ions from the ablated pellet mass scales with the cooling front speed

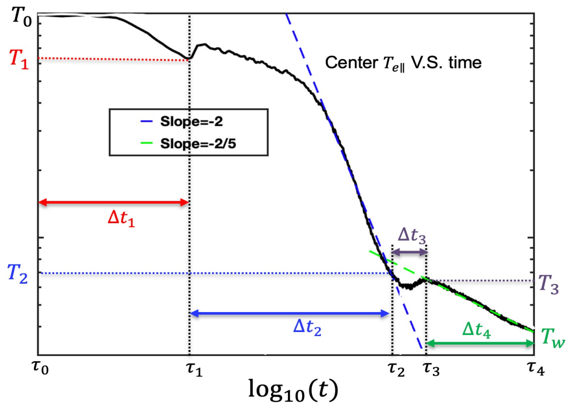


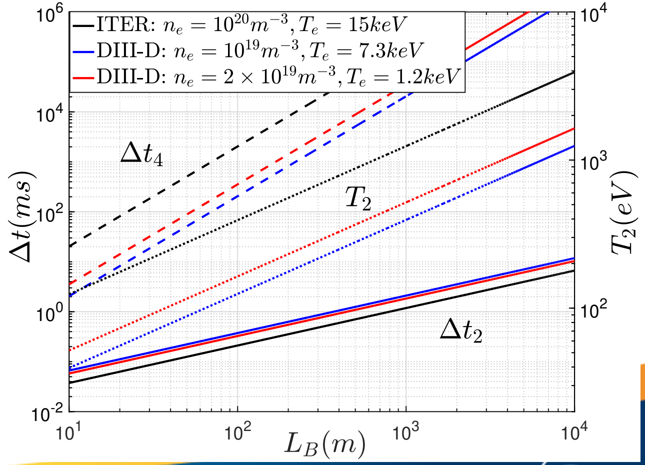
- To deposit more pellet mass locally, high Te in the collisionless precuror phase is favored.
- To deposit the pellet mass deeper into the plasma, pellet shielding by shattered pellet cloud is favorable. Same goes to staged pellet injection.

- To reduce radiation peaking factor, have pellet ablation at high T (collisionless cooling phase, recall cooling front speed). Staged pellet injection is unfavorable to spread the high-Z impurities.

TQ thermal load mitigation

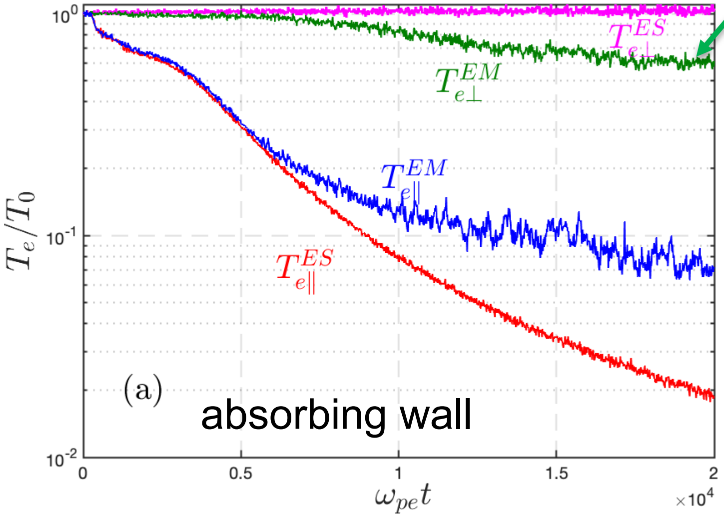
- In a naturally occurring disruption triggered by 3D B fields, thermal load is a bigger problem in the collisionless cooling phase, during which a significant fraction of the plasma thermal energy is taken out quickly.
- Two ways to mitigate:
  - MGI to shield the divertor/first wall, so the collisionless cooling of the core is against the dense/cold boundary plasma, and the edge/boundary plasma is always in the collisional cooling regime → heat pulse arrival follows the collisional cooling scaling (long hence favorable)
    - Unmitigated TQ does the similar thing with vapor shielding at the PFC → delayed heat pulse arrival at the PFC
  - Massive hydrogen injection to dilutionally cool the entire plasma (almost same pressure though) so it starts with collisional cooling
    - Has other benefit as well !

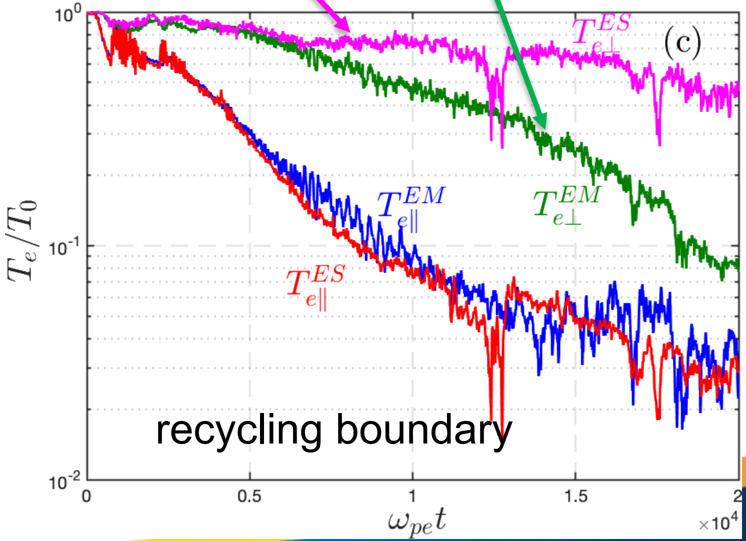




Mechanisms for collisionless core $T_{e\perp}$ cooling: runaway seeding

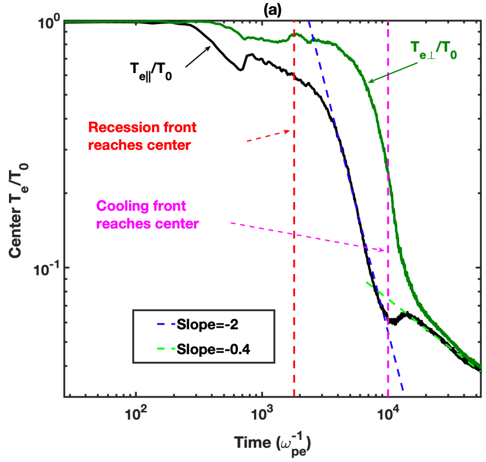
- Collisionless core $T_{e\perp}$ cooling can be
  - Through the electromagnetic instabilities & the associated wave-particle interaction that contributes to temperature isotropization: for both absorbing and recycling walls
  - Through penetrated cold recycled electrons: for recycling boundary only





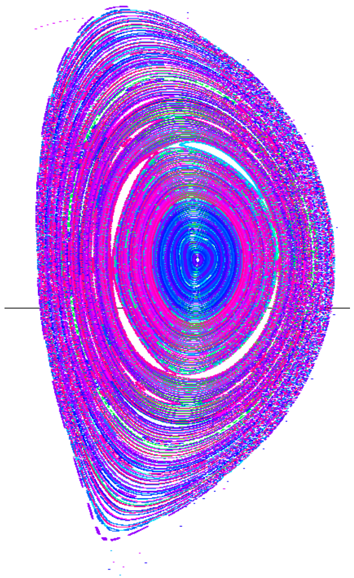
Runaway avoidance

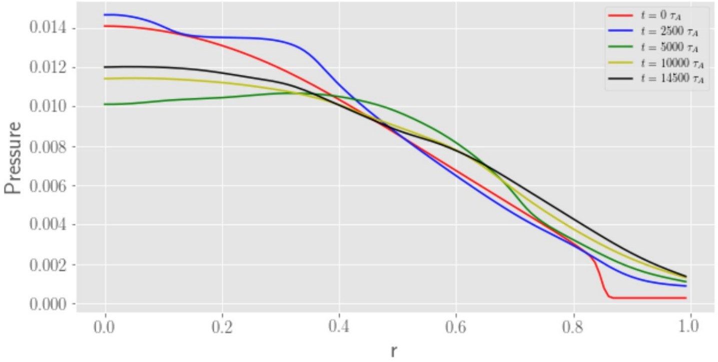
- In a naturally occurring disruption, runaways come about because Te gets too low so E becomes too large
  - Impurity production due to PMI in the collisionless cooling phase is most likely the culprit for the more rapid radiative cooling in an otherwise collisional cooling phase, which by itself should sustain a reasonable Te for a long period.



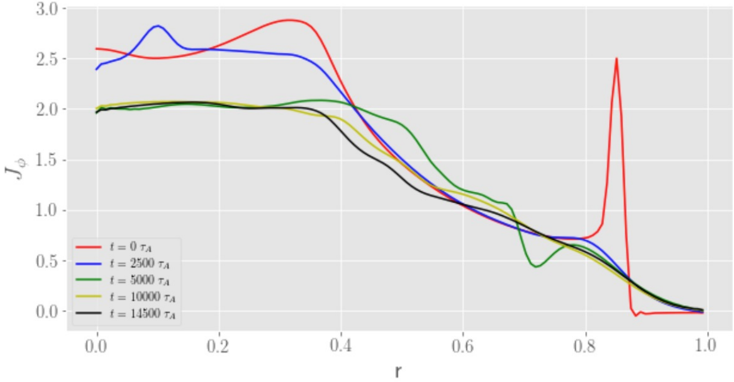
- The most promising approach to avoid runaways is to suppress PMI-induced impurity production and their inward penetration, both greatly enhanced in the collisionless cooling phase, by removing the collisionless cooling phase altogether
  - Back to massive hydrogen injection: dilutionally cool the plasma so TQ starts with the collisional cooling phase → suppress impurity production by PMI.
    - Bonus points: 3D fields + collisional cooling of $T_{e\perp}$ further suppress runaway seeding.

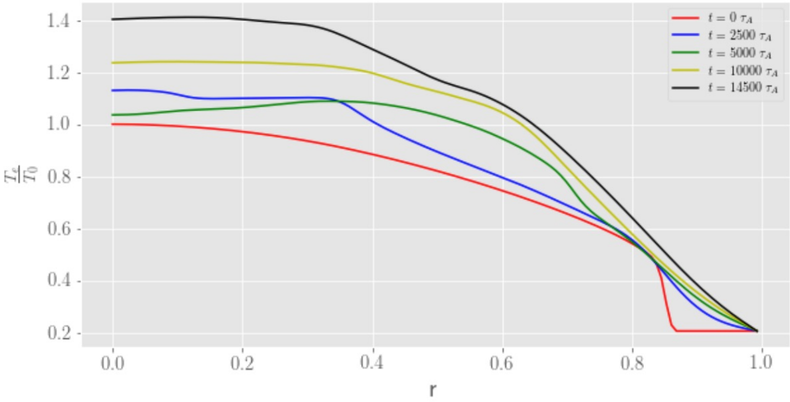
Dilutional cooling into collisional regime produces overlaid TQ and CQ that avoids runaways





τ_A=3.2μs





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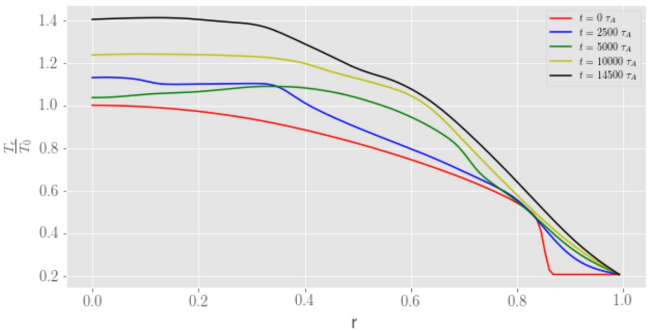
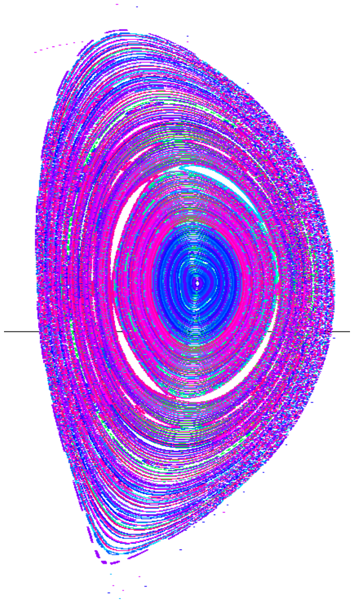
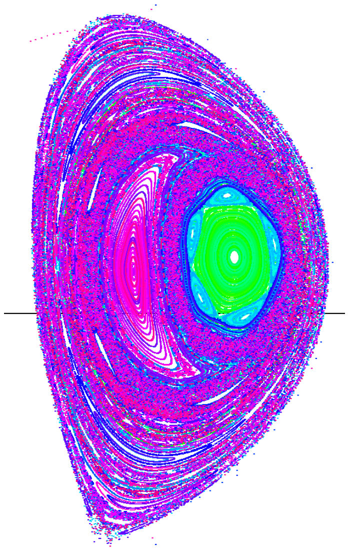
Self-consistent 3D B fields with Braginskii thermal conduction: Te heating from CQ despite B stochasticity



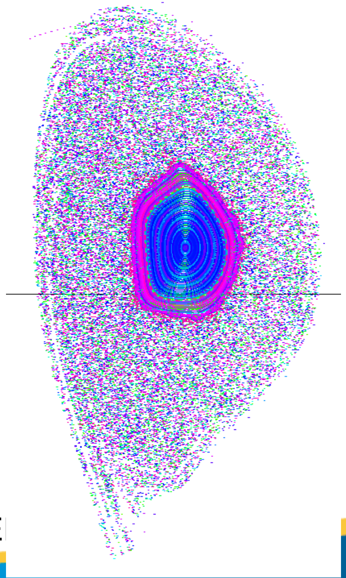
$t=2500\ \tau_A$



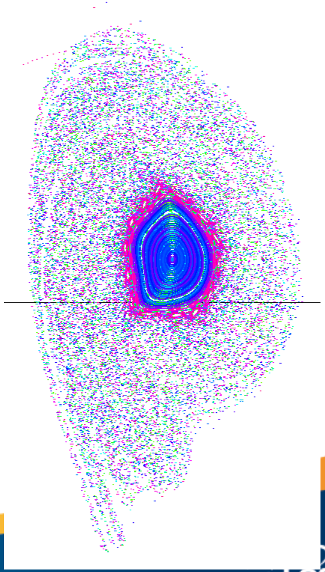
$t=4749\ \tau_A$



$t=9996\ \tau_A$



$t=14500\ \tau_A$



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Conclusions

- Parallel transport induced TQ has four phases with different electron heat flux physics scalings, durations, and amounts of $T_{e\parallel}$ cooling
  → inform strategies for pellet assimilation, radiation peaking factor control, thermal load management at the wall, and control of impurity production by PMI

- Fast electromagnetic kinetic instabilities & the associated wave-particle interaction provide collisionless cooling of core $T_{e\perp}$ and the draining of runaway seeds

- Integrated solution to disruption mitigation: Trading T for n for a slow pressure quench in the collisional regime appears to align the TQ and CQ over the same time period → avoid/minimize runaways + improve thermal load management + reduce impurity production/radiation