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The impact of fusion-born alpha particles on runaway electron dynamics in ITER disruptions

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Post-disruption waves and runaway electrons

Several tokamaks reported/ing post-disruption waves. A few examples:

- AUG: post-disruption waves happen frequently, but no runaway electron impact [Heinrich]
- DIII-D: many dedicated experiments, waves with RE impact [Paz-Soldan, Lvovskiy, Liu ...]
- JET: lots of old data, including DT shots [Newton, Sharapov, ...]
- TEXTOR [Koslowski], ...

Two key considerations:

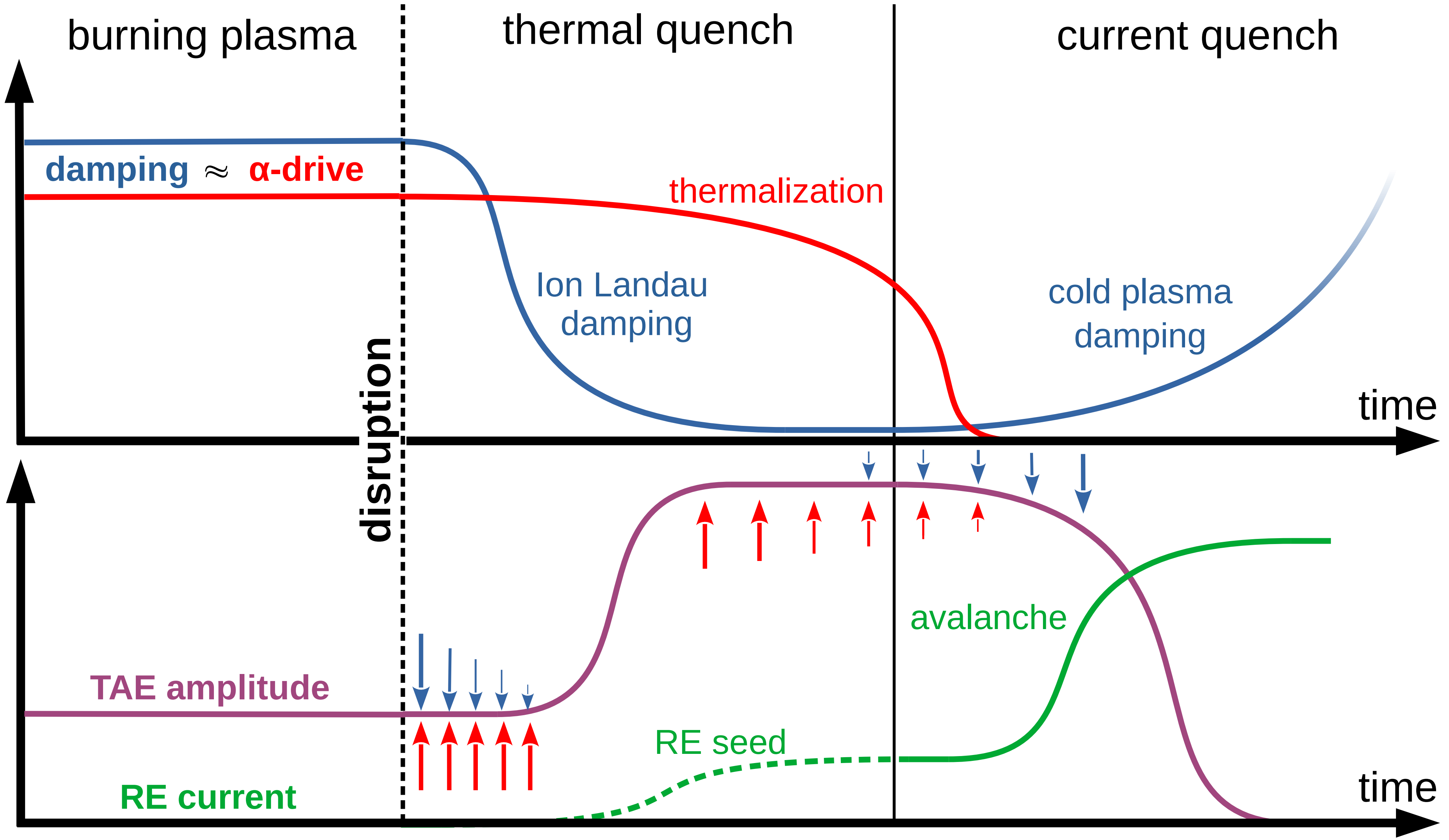
1. AUG low T_{th} scenario to study a "zoo" of modes ➡ key is the low damping at low temp [Lauber IAEA 2018, Horváth NF 2016]
2. On ITER there will also be DT alphas to provide mode drive

➡ Can we expect modes, and runaway suppression by them, at ITER?

For more details, see: Lier et al., NF 63 056018 (2023)

The core idea

[A. Lier, PhD Thesis (2023)]



We set out to understand the following:

- What happens to alpha particles in mitigated ITER disruptions? [CODION[1], analytical[2]]
- How does the equilibrium evolve, and what modes can it support? [VMEC[3], LIGKA[4]]
- What modes can be driven, considering the drive and damping? [LIGKA, CASTOR[5]]
- What will be the saturated mode structure & amplitudes? [HAGIS[6]]
- What RE transport can these modes cause? [ASCOT5[7]]
- What impact will this have on the RE dynamics? [DREAM[8]]

⬆ This list doubles as the outline

[1]CODION: Embreus PoP 22 052122 (2015)

[2]analytical: Lier NF 63 056018 (2023)

[3]VMEC: Hirshman CPC 43 143 (1986)

[4]LIGKA: Lauber JPCS 226 447 (2007)

[5]CASTOR: Kerner JCP 142 271 (1998)

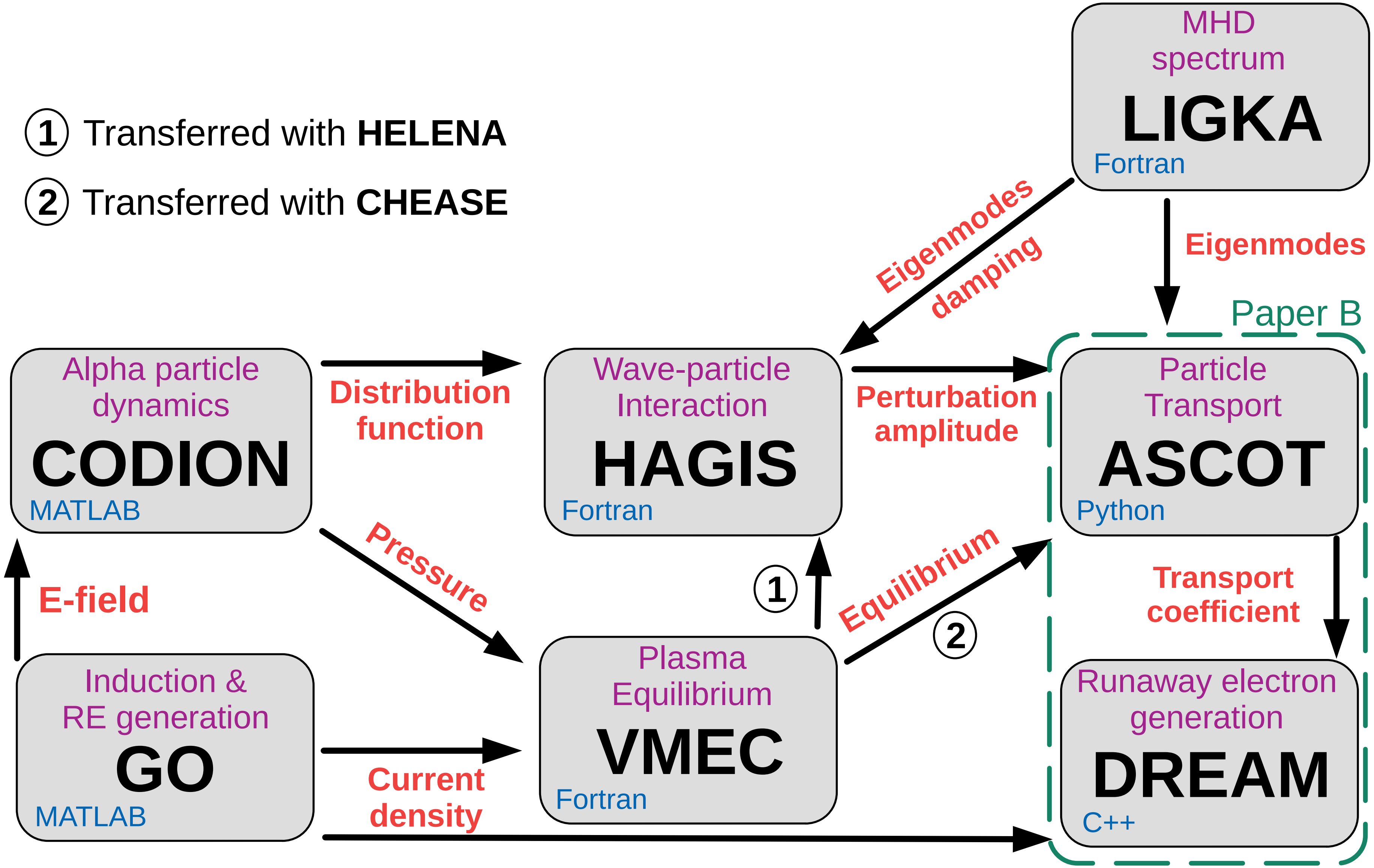
[6]HAGIS: Pinches PPCF 46 B187 (2004)

[7]ASCOT5: S. D. Scott JPP 86 865860508 (2020)

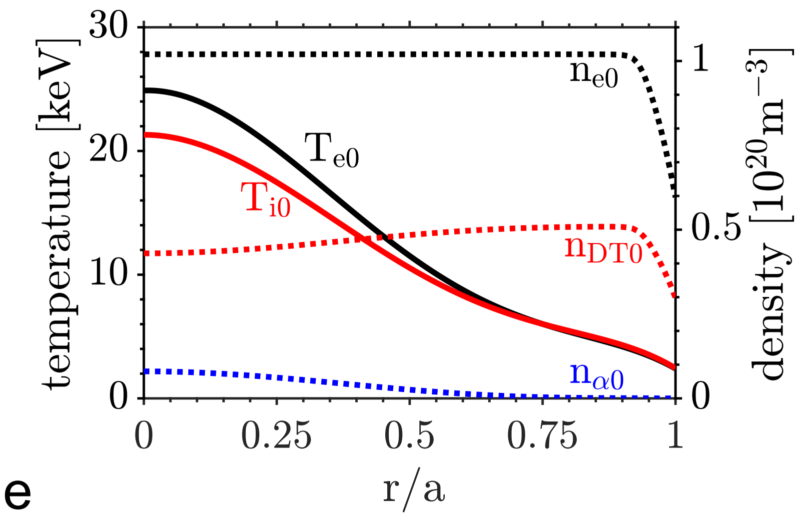
[8]DREAM: Hoppe CPC 268 108098 (2021)

The toolchain

[A. Lier, PhD Thesis (2023)]



Key assumptions



- **ITER 15 MA scenario #2 1:1 DT**
- Prescribed exponential temperature drop with t_{TQ} to T_f = 10 eV
  - ➡ Performed a scan for t_{TQ}, note $t_N = t / t_{TQ}$ normalisation
- Singly-ionised impurities appear instantaneously as a flat profile
  - ➡ Performed a scan for Ne + D2 mixtures
- We assume that there is good confinement of alphas - better than REs anyway
  - ➡ Performed a scan for intermittent transport (similar to ASTRA / AUG [Linder JPP 2021])
- On the interesting (TQ) time scale, the equilibrium is assumed fixed
  - ➡ Performed a scan for q_0
- HAGIS cannot treat alpha thermalisation during the mode evolution
  - ➡ I will discuss the timescales; but treat amplitudes as upper estimates

➡ Uncertain parameters (t_{TQ}, D2:Ne, α transport, q_0) are scanned

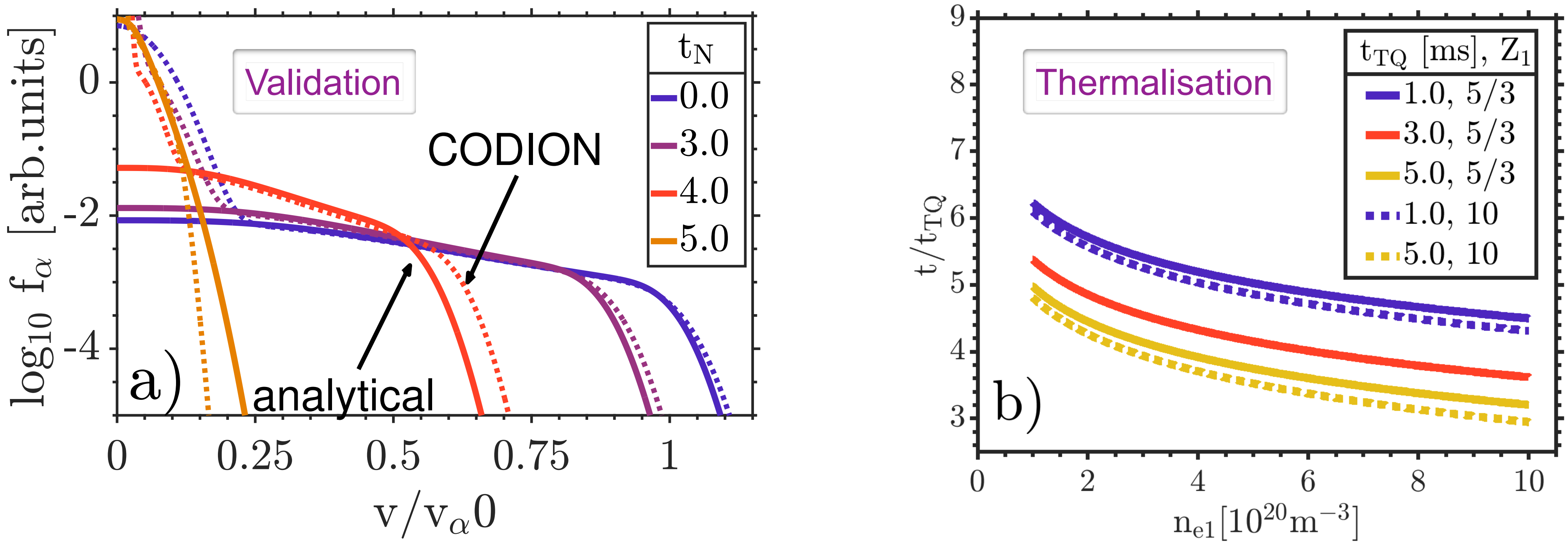
Alpha particle dynamics

We can calculate the evolution of the alpha distribution in a disruption

- CODION is not the cheapest for doing large parameter scans

➡ Developed a fast analytical cooling alpha model (for equations, see [Lier NF 2023])

(a) Validation of analytical model with CODION (b) 5-25 ms window for mode drive

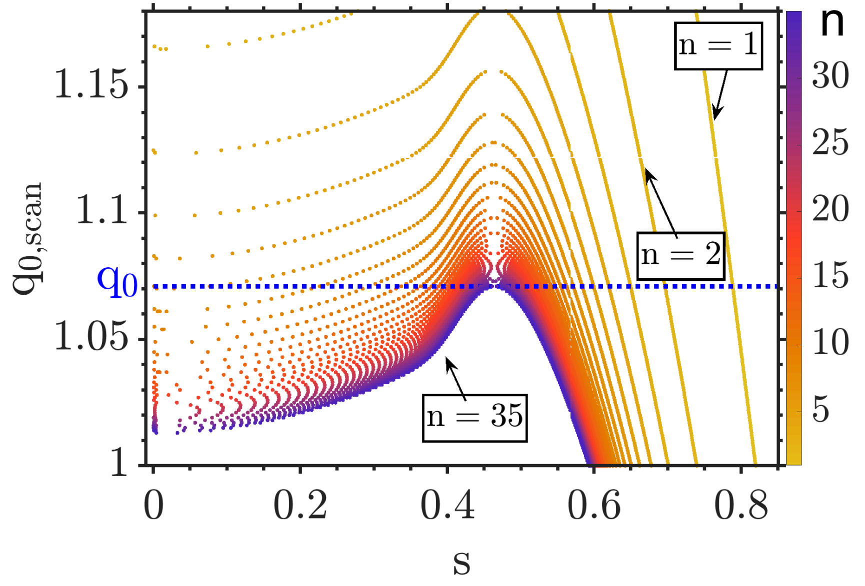


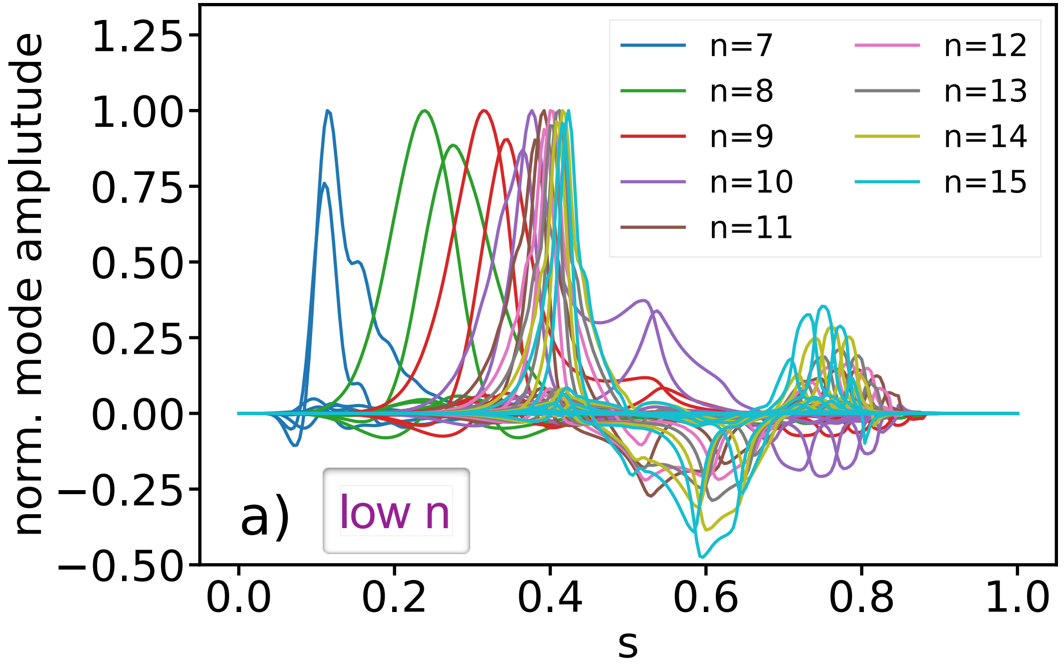
Mode structures (LIGKA)

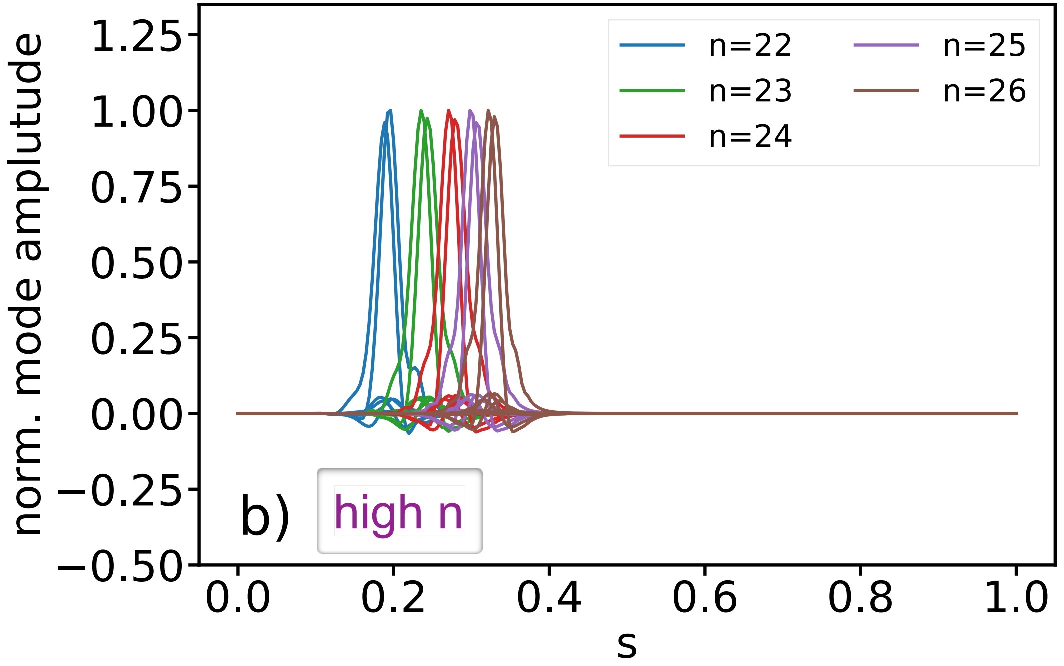
Large number of TAE modes found for all q_0 scanned

- VMEC thermal quench equilibrium
- Up to 13 poloidal harmonics, f ~ 80 kHz
- **Core localised modes + lot of overlap (flat core q)**

  ➡ Beneficial for transport







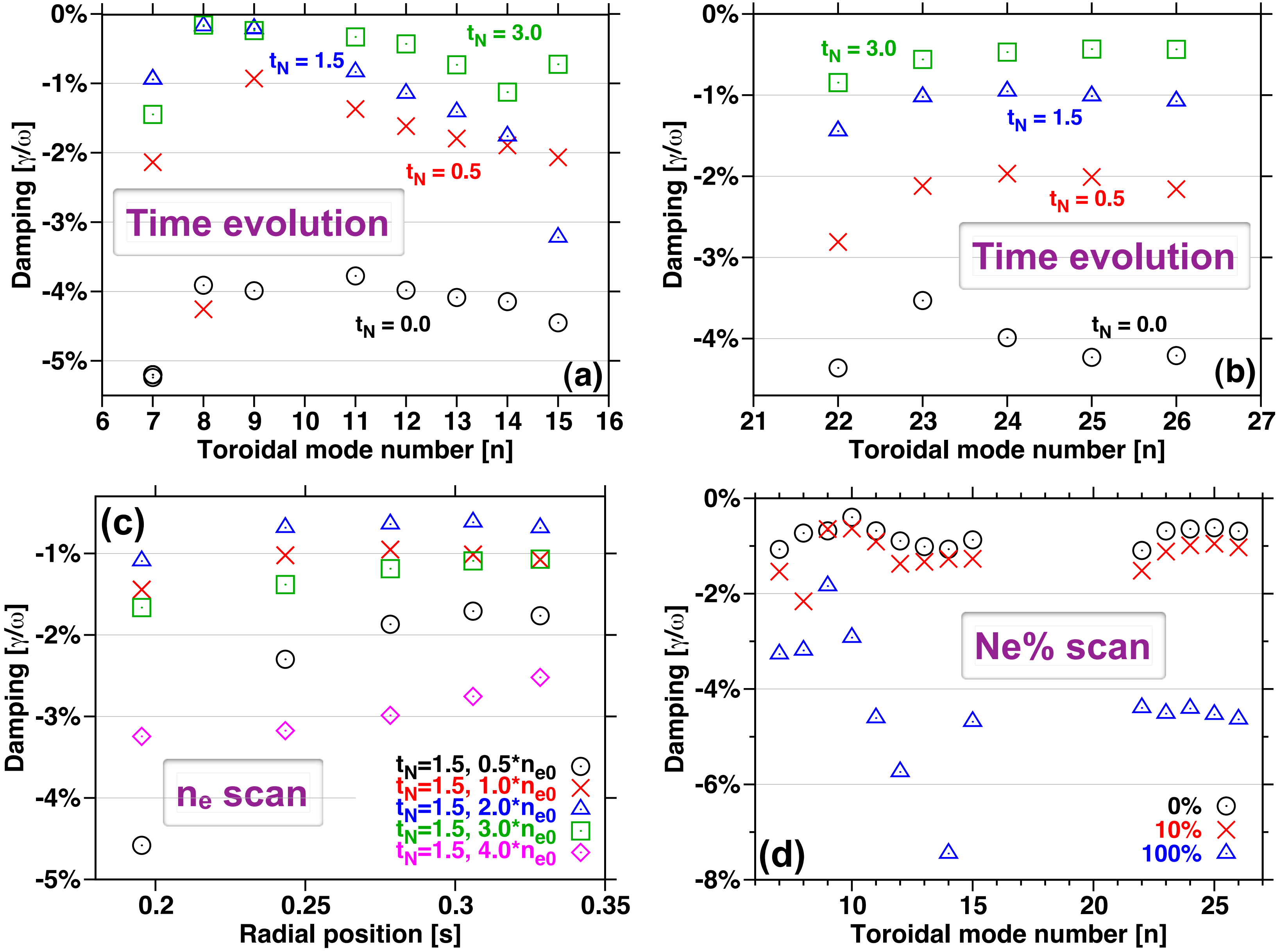
Mode damping

LIGKA-calculated damping, includes

- Nonlocal continuum damping, ion & electron Landau damping, radiative damping
- Negligible collisional damping on trapped electrons and resistive fluid damping if $t < 8t_{TQ}$
- **Ion Landau damping is dominant, but decays exponentially with temperature**
- Electron Landau damping is proportional to pressure, which also drops
- Negligible continuum damping for TAEs
- Radiative damping (FLR effect) - drops with decreasing Larmor radius (TQ)
- **Once the temperature reaches ~eV, cold plasma damping becomes important**

➡ All main damping effects are considered, or are negligible

Mode damping scans

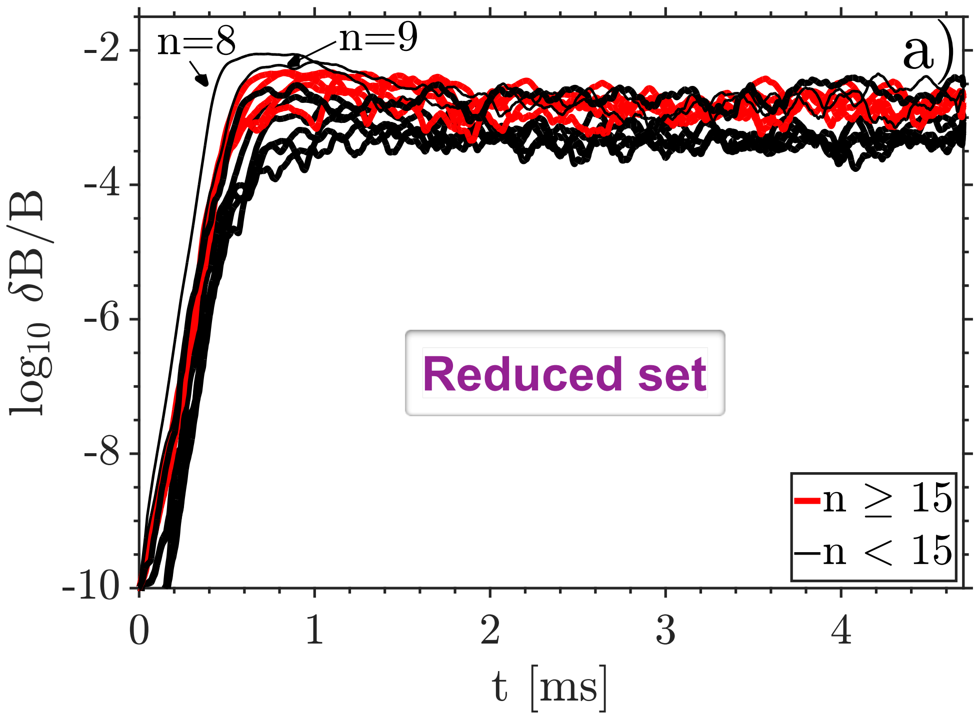


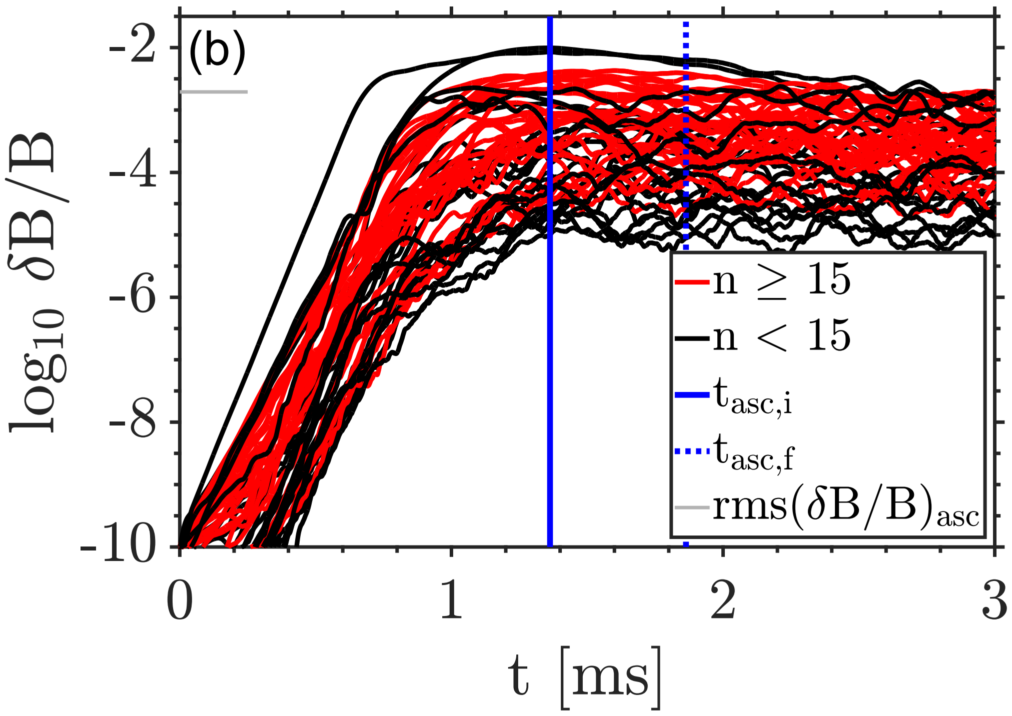
Mode amplitudes (HAGIS)

First shown: time evolution of unmitigated case t_{TQ} = 1 ms

- Simulations started at t = 1.5 t_{TQ} (low damping) and run until thermalisation
- Linear growth is γ/ω ~ 1.8%, saturation at ≤1 ms

➡ Significant amplitudes (dB/B ~ 0.1% - 1%) reached well before α thermalisation!



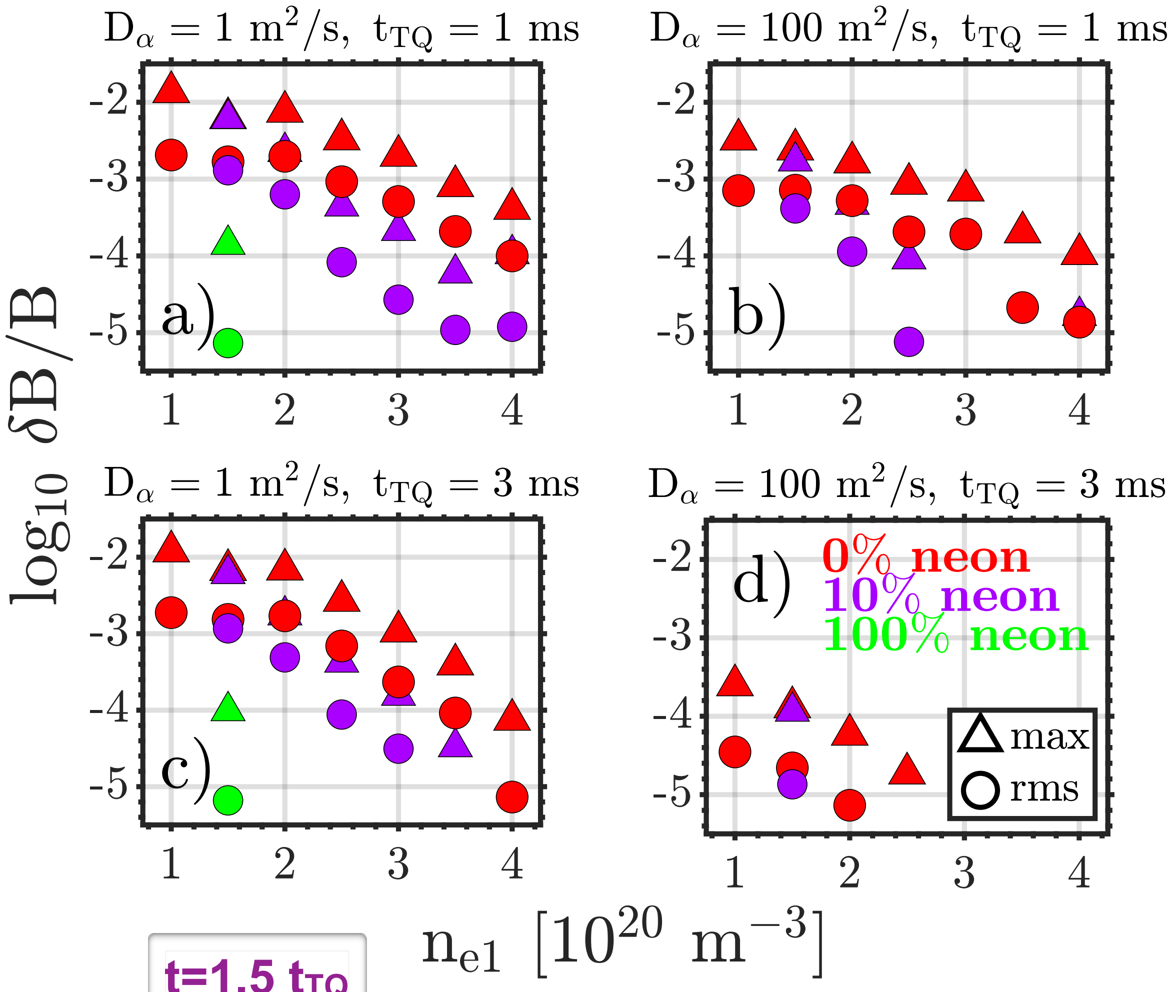


Mode amplitude parameter scan

Diffusion (exp decay) 1-100 m²/s, t_{TQ} = 1-3 ms, n_{e1} = 1-4 n_{e0}, n_{Ne}/n_D = 0-1.

- **Drop of amplitude with n_e**
  - ➡ Increased damping and alpha thermalisation
- **Drop of amplitude with t_{TQ}**
  - ➡ More time for alphas to thermalise
- **Drop of amplitude with Ne%**
  - ➡ Change of Alfvén speed ➡ resonance
- **Drop of amplitude with transport**
  - ➡ Lower alpha pressure gradient for drive
- **Drop of amplitude with time point chosen**
  - ➡ More time for alphas to thermalise

➡ Unmitigated cases have higher amplitudes

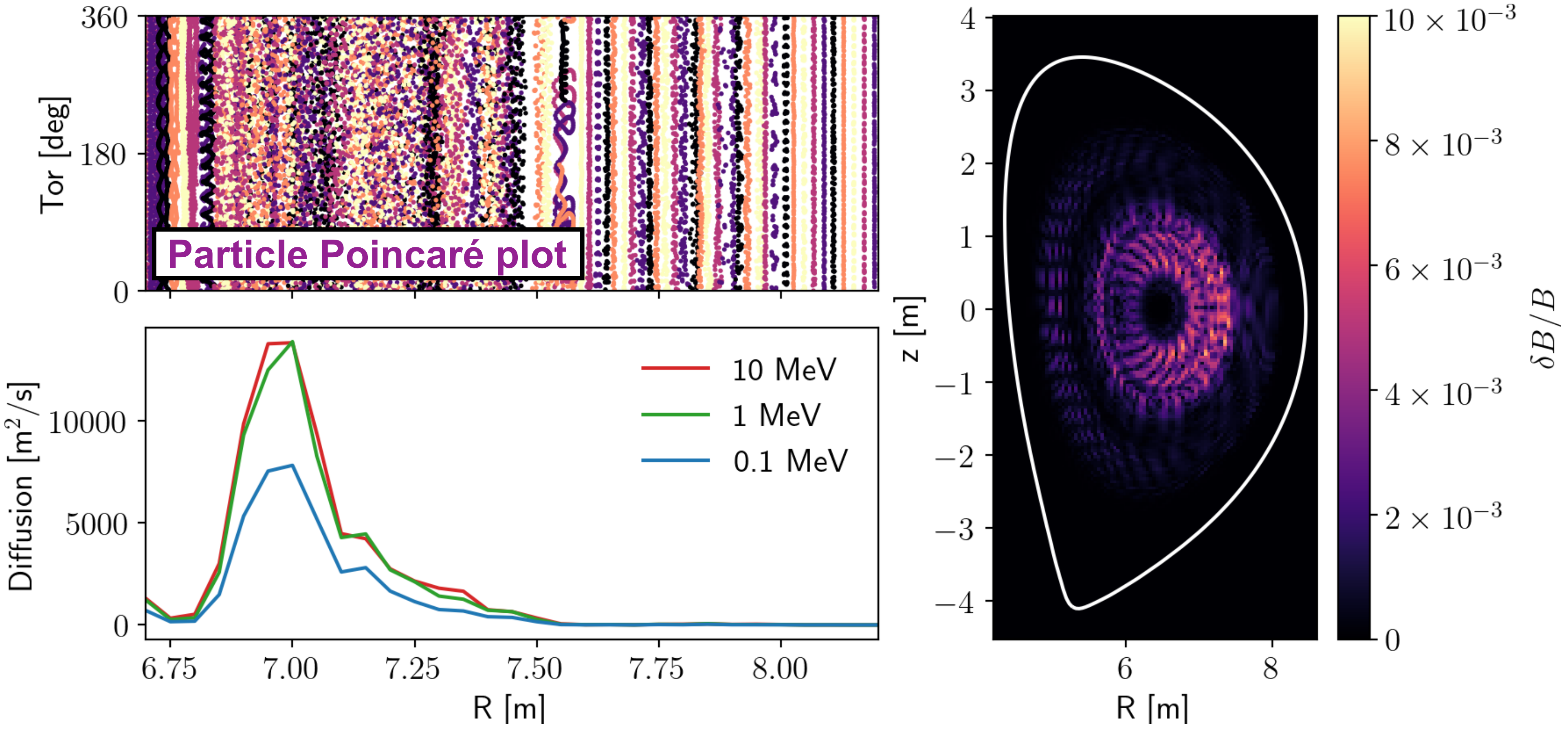


t=1.5 t_{TQ}

Runaway transport

Calculated using ASCOT5 test particle tracing

- Using the highest amplitude case, full mode set, RMS amplitude over 0.5 ms
- Maximum diffusion is **~1.4·10^4 m^2/s**, comparable to Rechester-Rosenbluth value

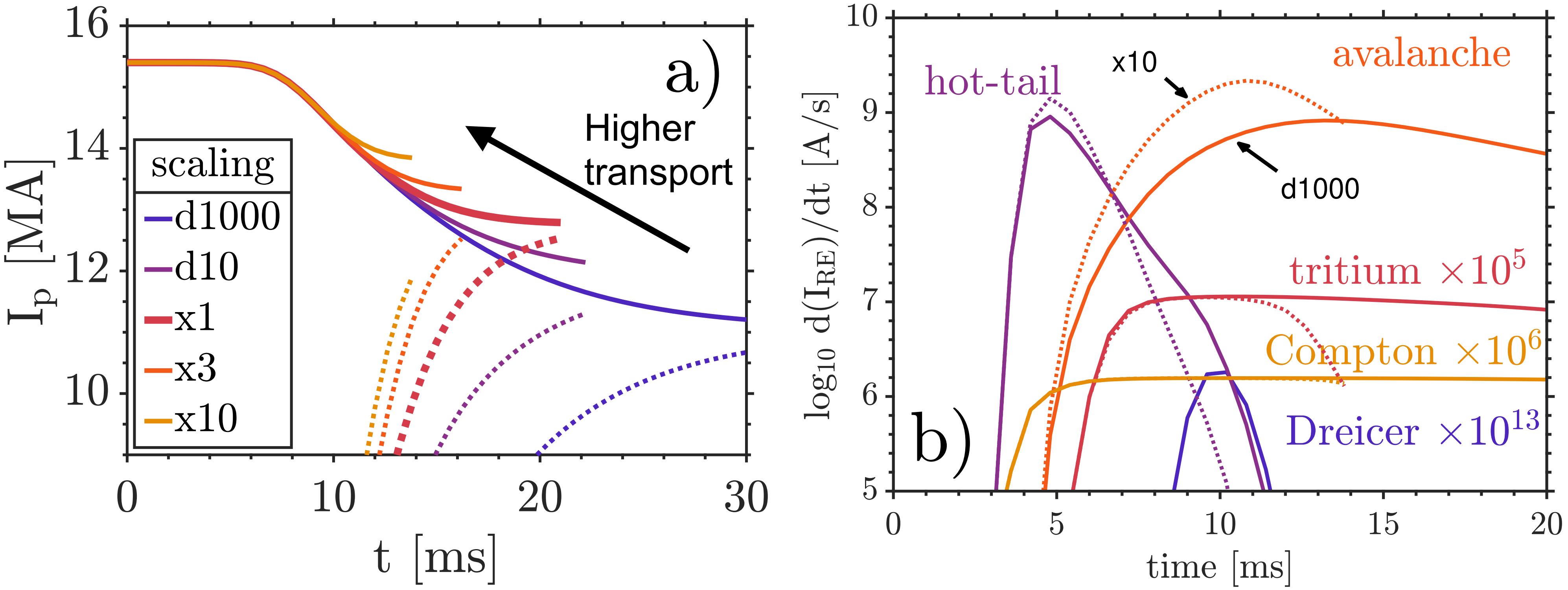


Runaway dynamics

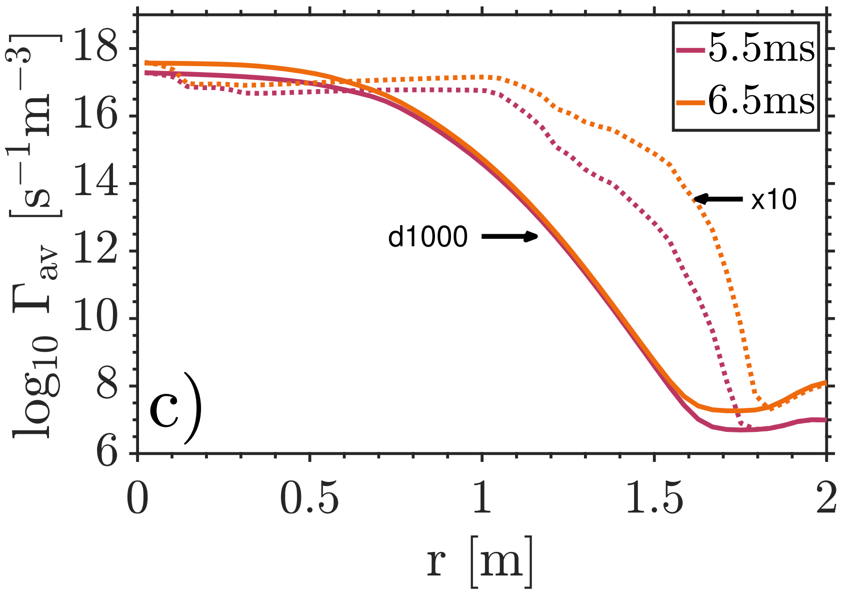
Self-consistent dynamics calculated with DREAM

- Transport from ASCOT5, strongest (no MMI) case
- Scaling scan for transport from x1e-4 to x1e2

➡ Perturbation leads to an **increase** in runaway current!



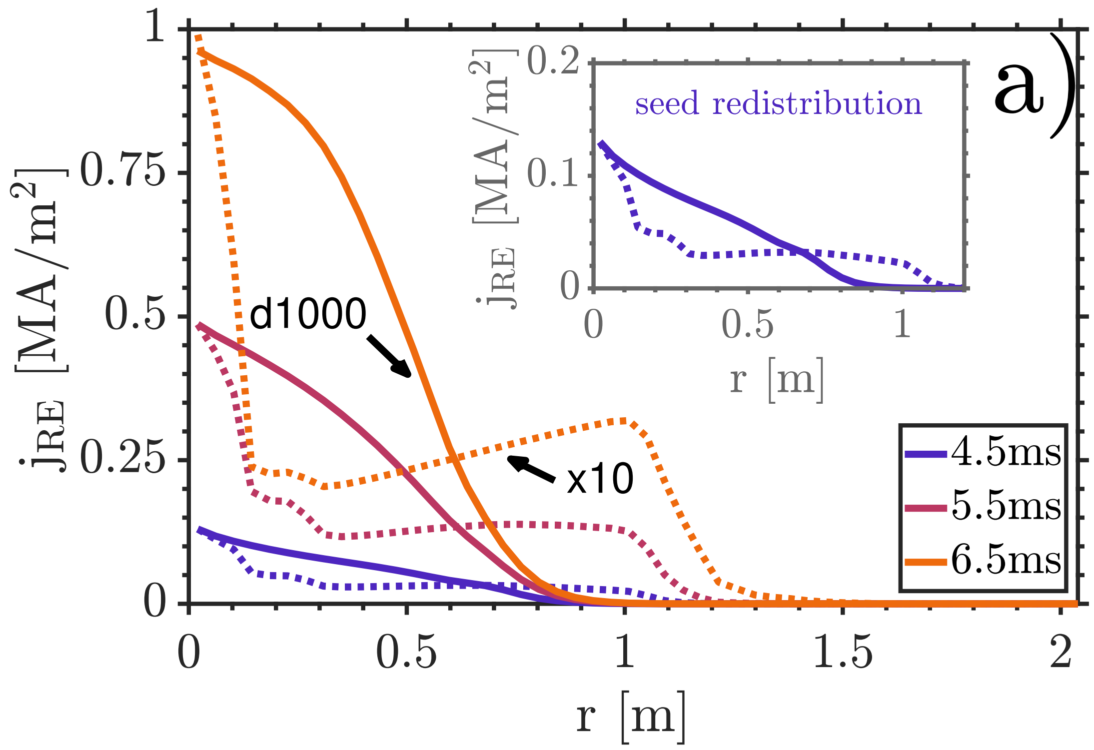
Did you say *INCREASE* in runaway current?!

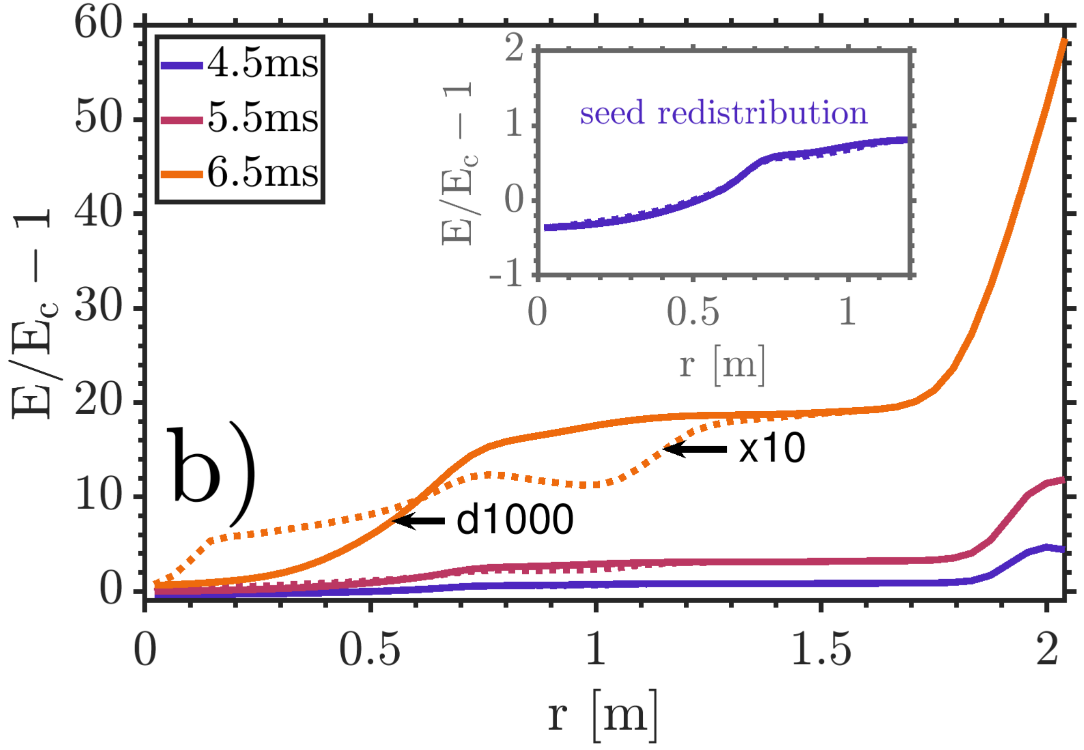


Avalanche increased due to seed redistribution!

- We have seen before, that perturbations can do this to REs
- Perturbation threshold for full RE suppression not reached

BUT! combined with other (edge) perturbation sources...?





Summary

The impact of alpha particles on runaway electron dynamics in ITER
Lier et al., NF 63 056018 (2023)

- Alphas take several milliseconds to thermalise in an ITER TQ
- During this time the damping drops faster than the alpha pressure gradient
- The equilibrium can sustain many (partially overlapping) TAEs at < 1% max amplitudes
- TAEs cause significant core RE transport, but
- **This alone would lead to an increase in RE current!**

  ➡ **Can this be combined with off-axis transport (MHD, RMP, REMC, etc)?**

- **This is still an intrinsic core RE transport mechanism!**

  ➡ Most effective in unmitigated scenarios - when we need natural mitigation the most!