Max-Planck-Institut für Plasmaphysik

IAEA-PPPL
Alpha particle dynamics and Alfvénic instabilities in ITER post-disruption plasmas

[Lier et al, NF 2021]

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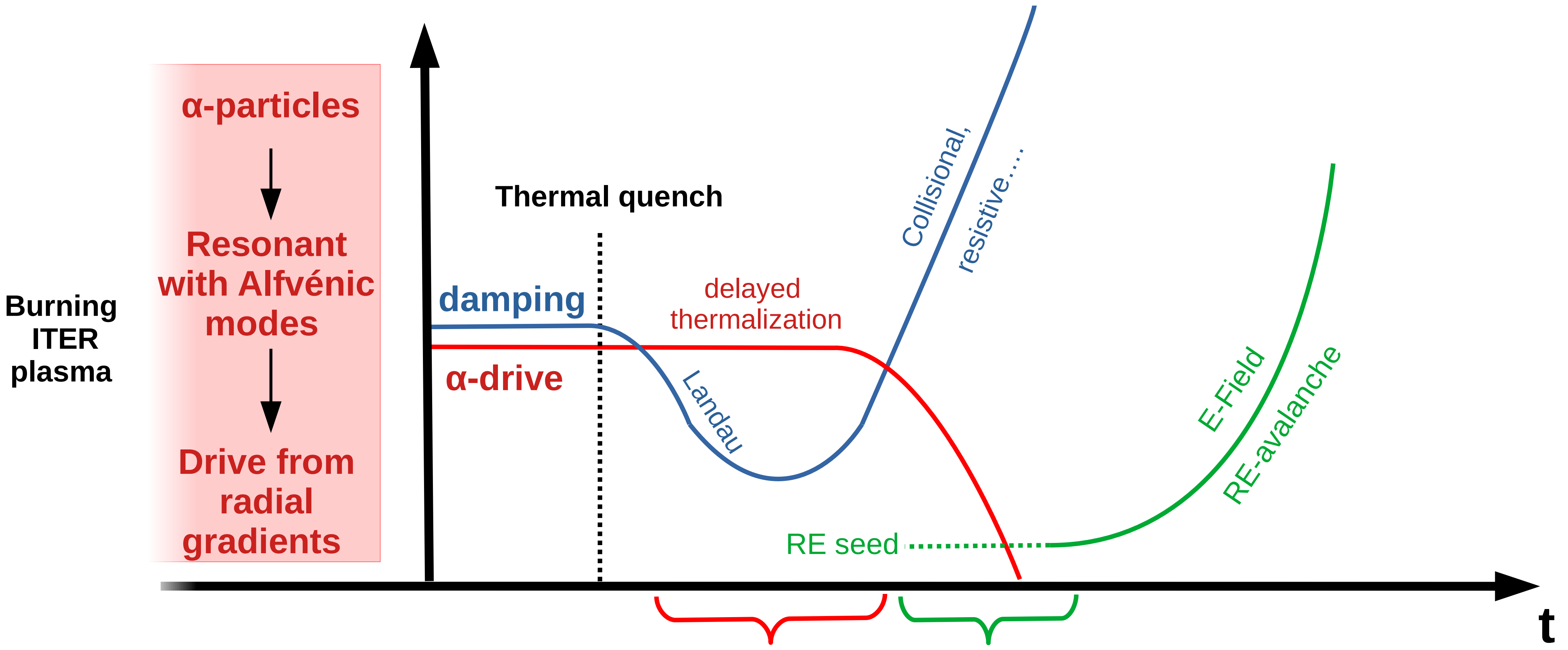
[2]Chalmers, Gothenburg
[3]PPPL, Princeton
[4]RWTH, Aachen

Physical Concept

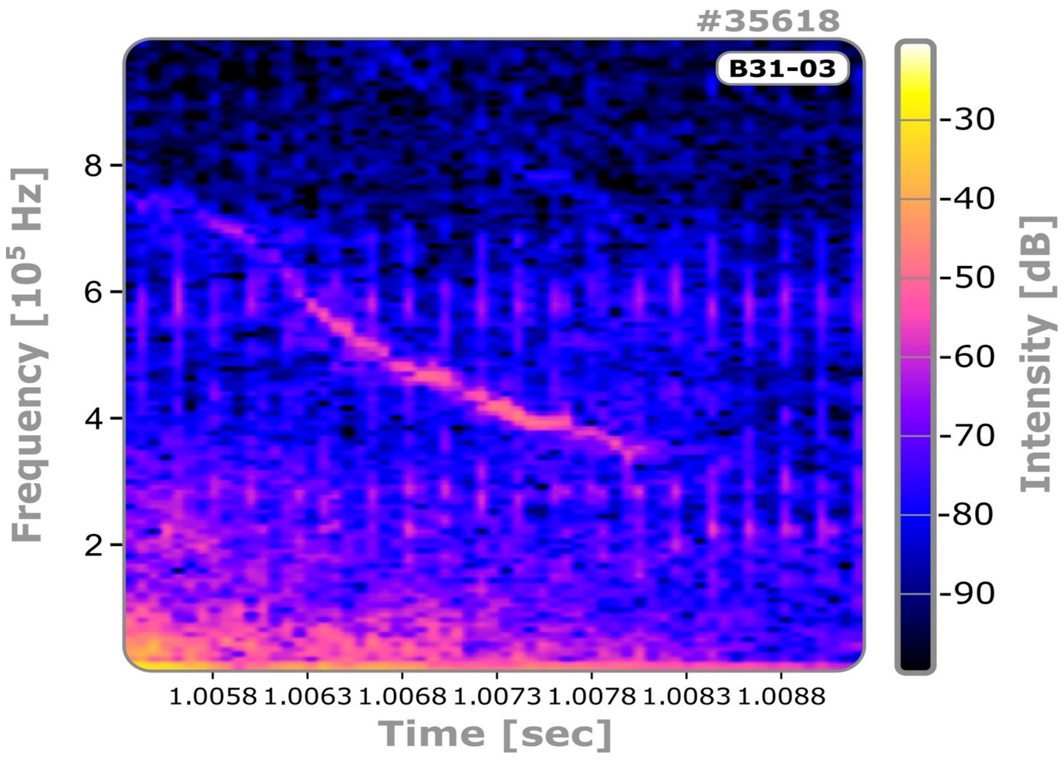


1. **Long enough to drive Alfvénic modes unstable?** → 2. **Instabilities strong enough to interact with RE seed?**

Context – Experimental observations (1/2)

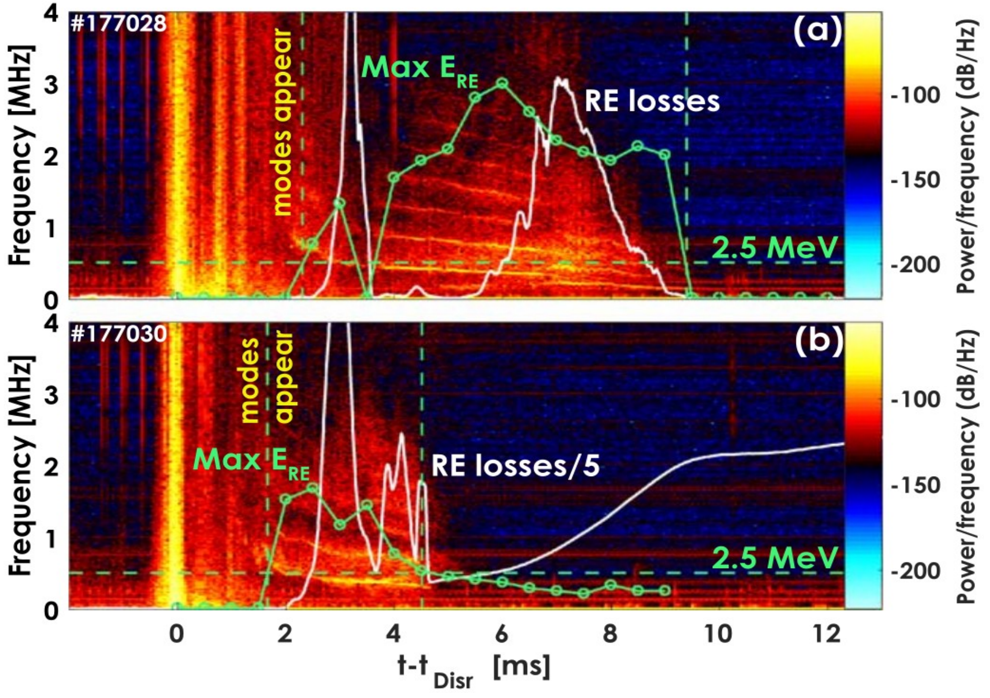
Present day tokamaks already observe post-disruption modes

AUG



Current quench spectogram AUG#35618 [P. Heinrich]

DIII-D

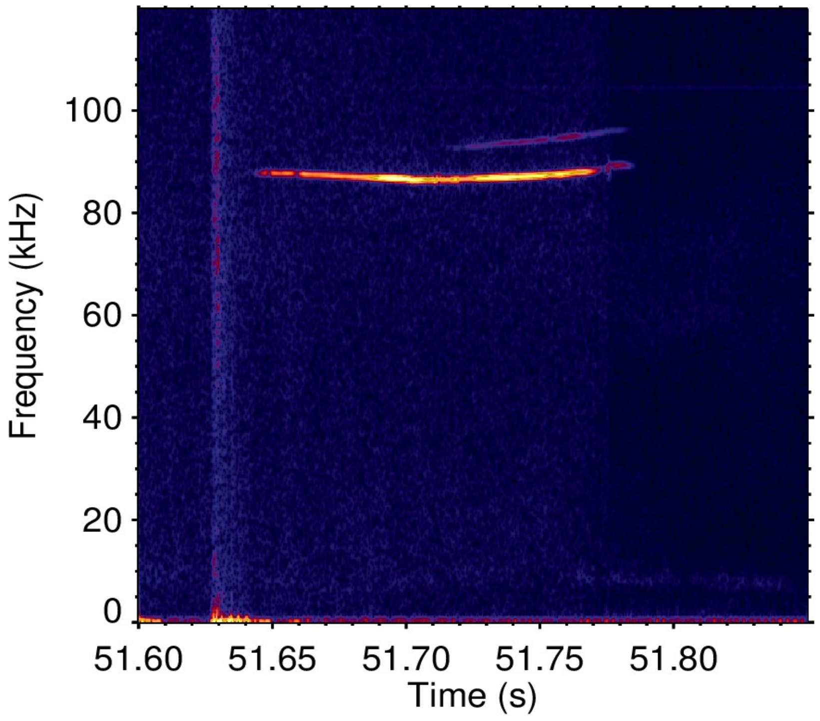


Spectograms of DIII-D [Lvovskiy, PPCF, 2018]

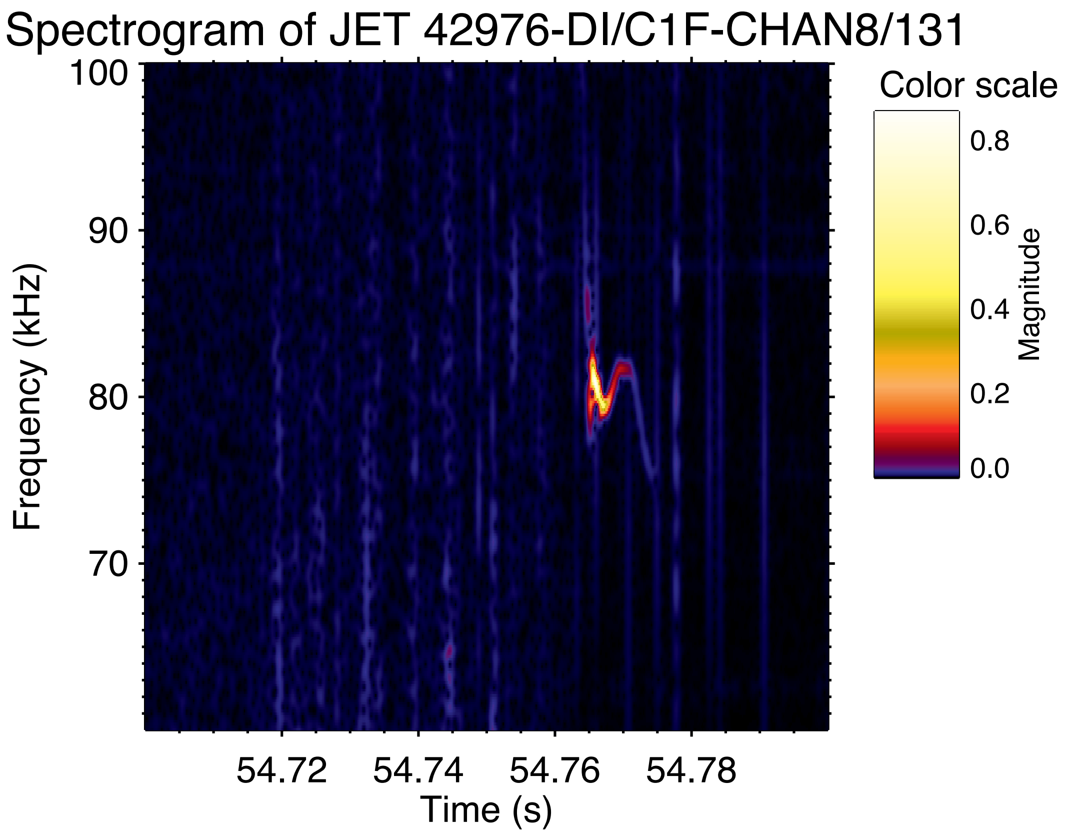
Context – Experimental observations (2/2)

Present day tokamaks already observe post-disruption modes

JET



Current quench spectogram of JET #89141. [S. Newton, P. Pölöskei]



Current quench spectogram of JET DT shot #42976. [S. Sharapov]

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Alpha particles – velocity distribution

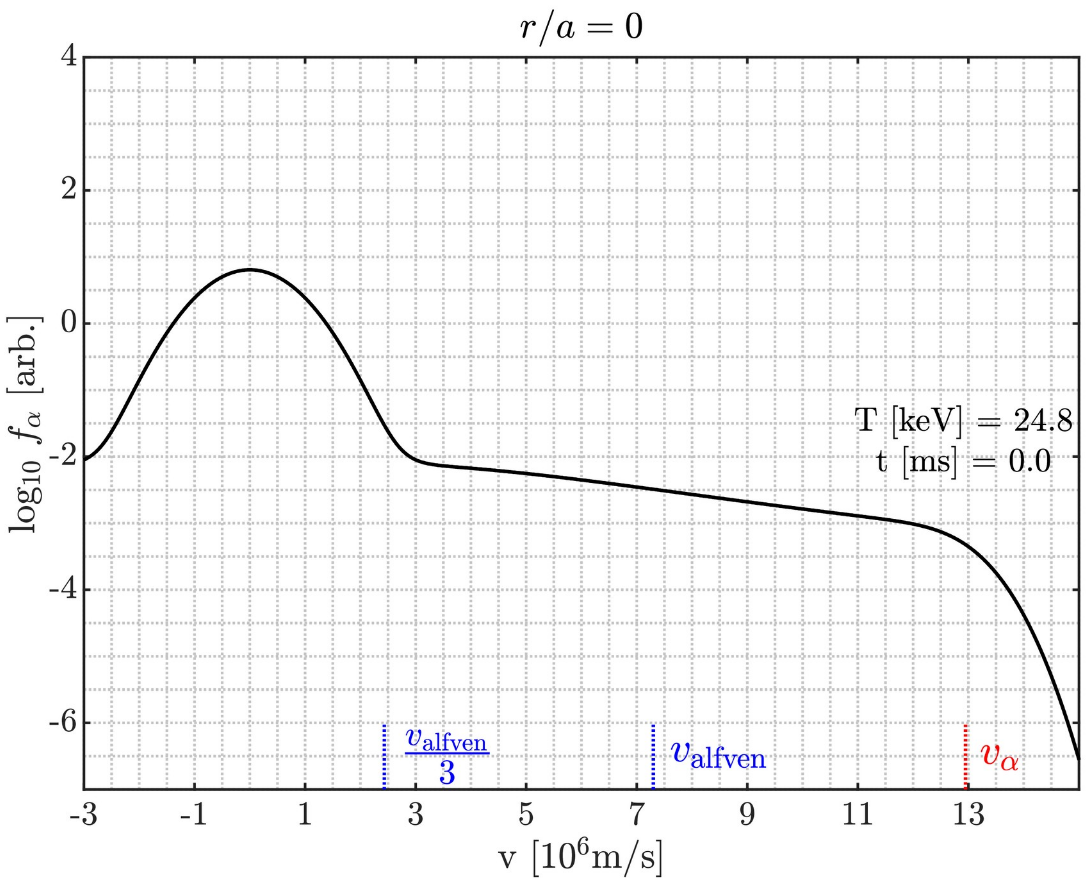


Fig. 1
CODION[1] simulation: Isotropic alpha particle velocity distribution for ITER 15MA scenario[2] #2

Fusion born alpha population is energetic by nature:

α birth velocity — Alfvén phase velocity

$$v_\alpha \approx 13 \cdot 10^6 m/s \quad > \quad v_{alfven} = B/\sqrt{\mu_0 m_i n_i}$$

↓

Simulations[3] show weakly unstable modes in ITER quiescent phase

↓

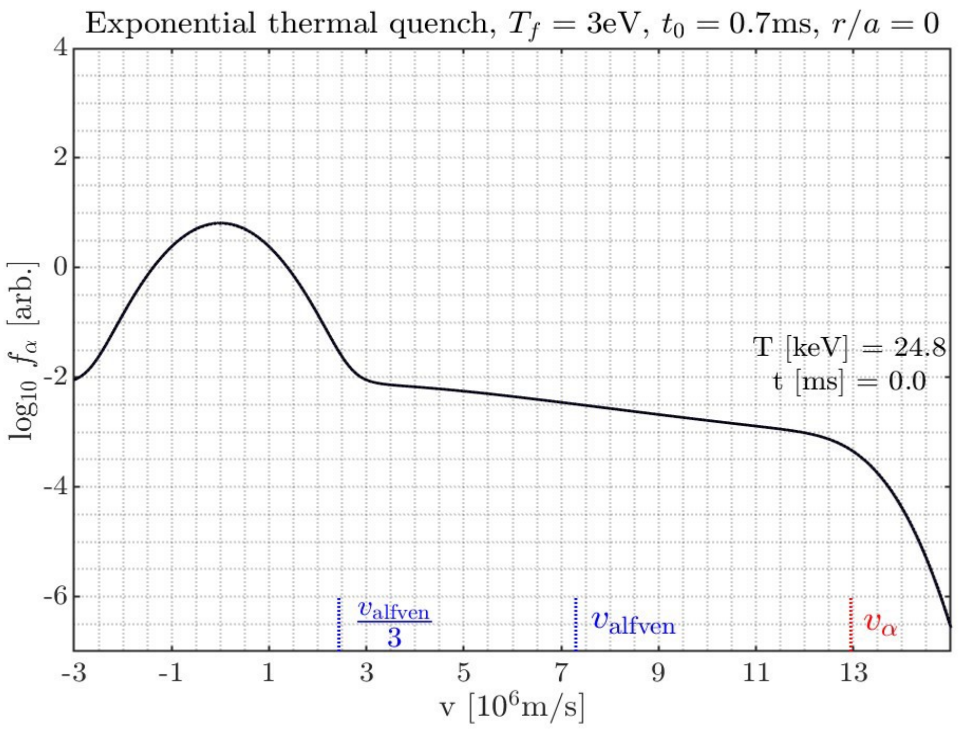
Hypothesis

Post-disruption damping* drops faster then post-disruption alpha drive

*damping dominated by Landau damping ~ exp(-T)

[1]Embreus, PoP, 2015 [2] Polevoi, IDM, 2002 [3] Pinches, PoP, 2015

Alpha particles – delayed thermalization



VIDEO
CODION[1] simulation: initial alpha distribution undergoing thermal quench.

Consider 'worst case', unmitigated disruption:

$$T(r,t) = T_f + [T(r,0) - T_f] \exp(-t/t_0)$$

with Fokker-Planck solver **CODION[1]**

Collisional cooling ineffective for energetic particles

↓

Resonances possible far into the thermal quench

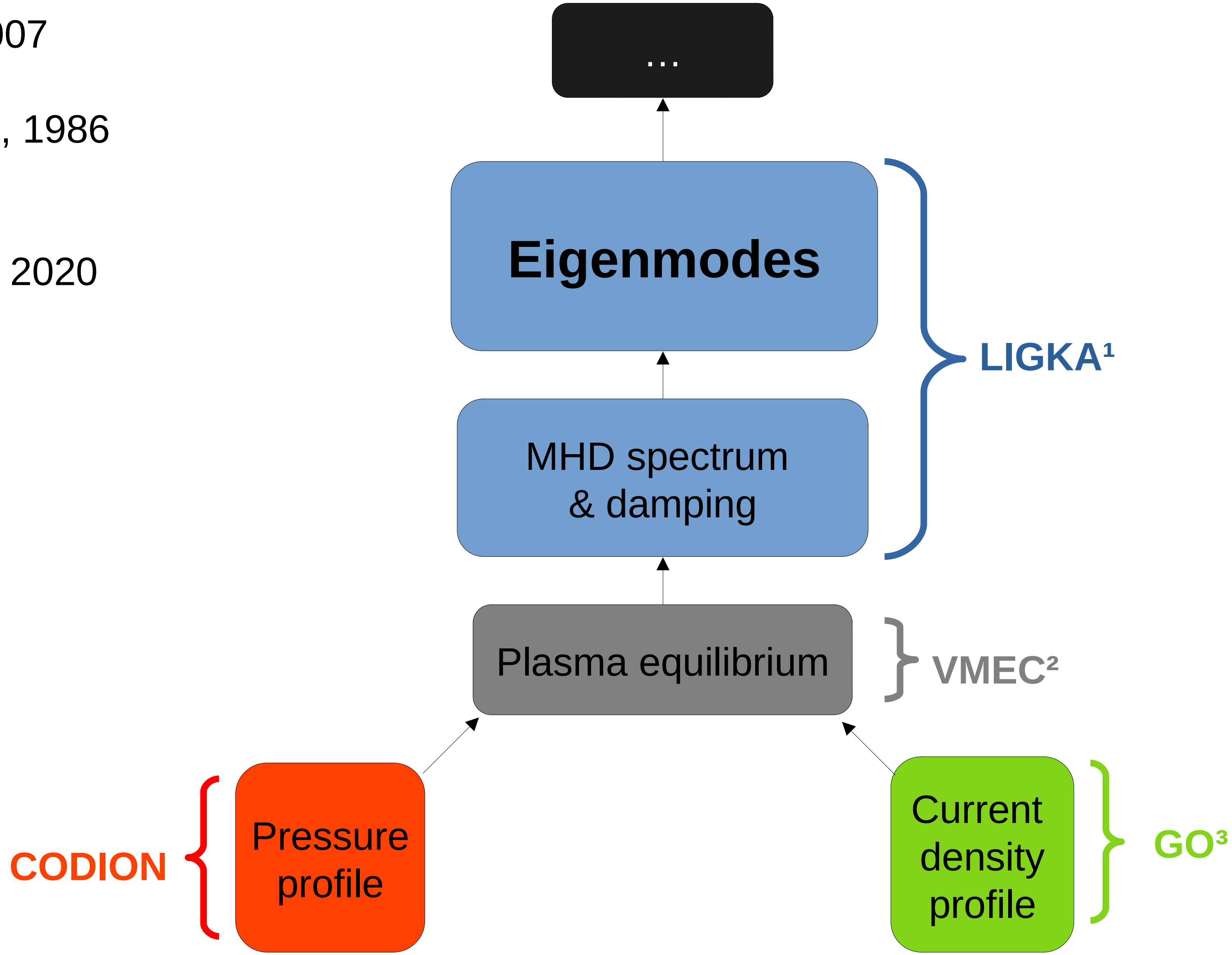
[1]Embreus, PoP, 2015

Workchain towards post-disruption Eigenmodes

[1]Lauber, JCP, 2007

[2]Hirshman, CPC, 1986

[3]Papp, NF, 2013
[3]Vallhagen, JPP, 2020



Workchain towards post-disruption Eigenmodes

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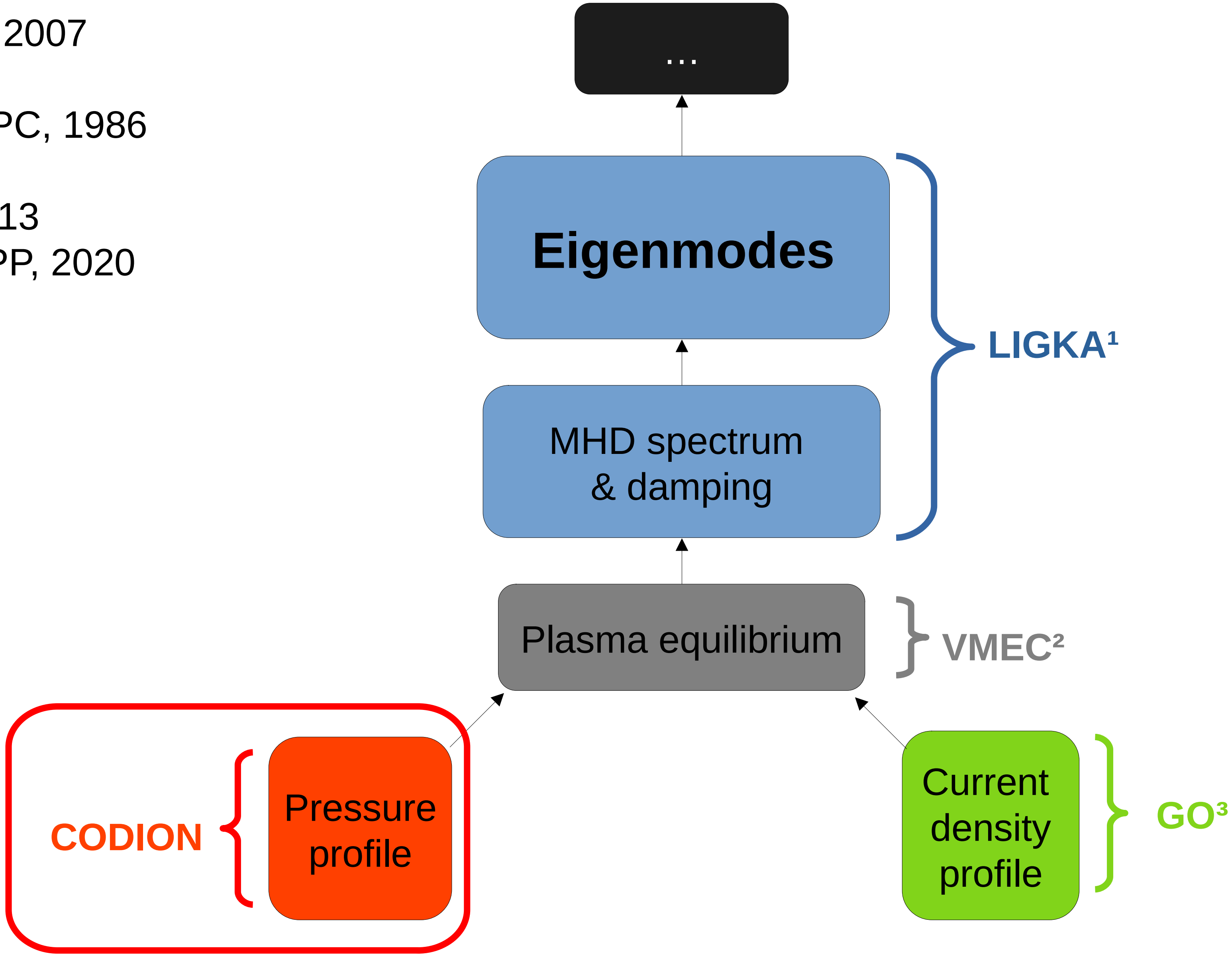


Current density profile j(r,t)

GO code solves the induction equation in 1D
→ Electric field diffusion
→ RE generation
} j(r,t)

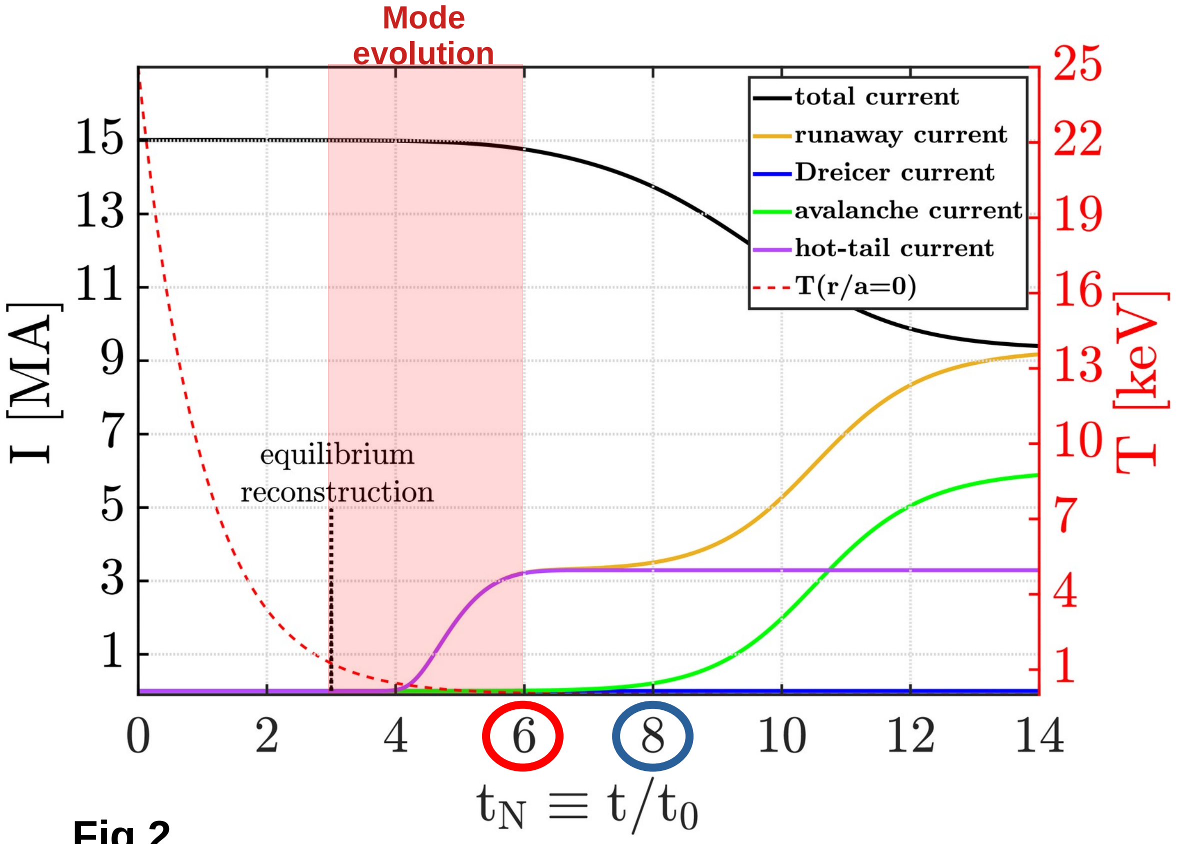


Fig.2
Currents of an unmitigated disruption identified by T_f=3eV and t_0=0.7ms and its background temperature

6 T ~ 100 eV: Alphas thermalize

8 T < 100 eV : Avalanching

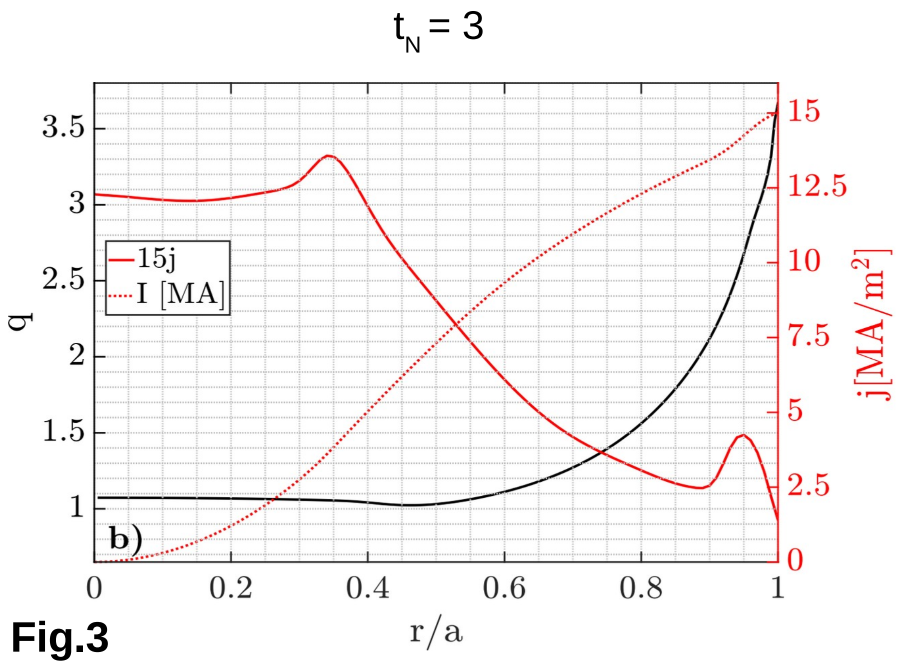
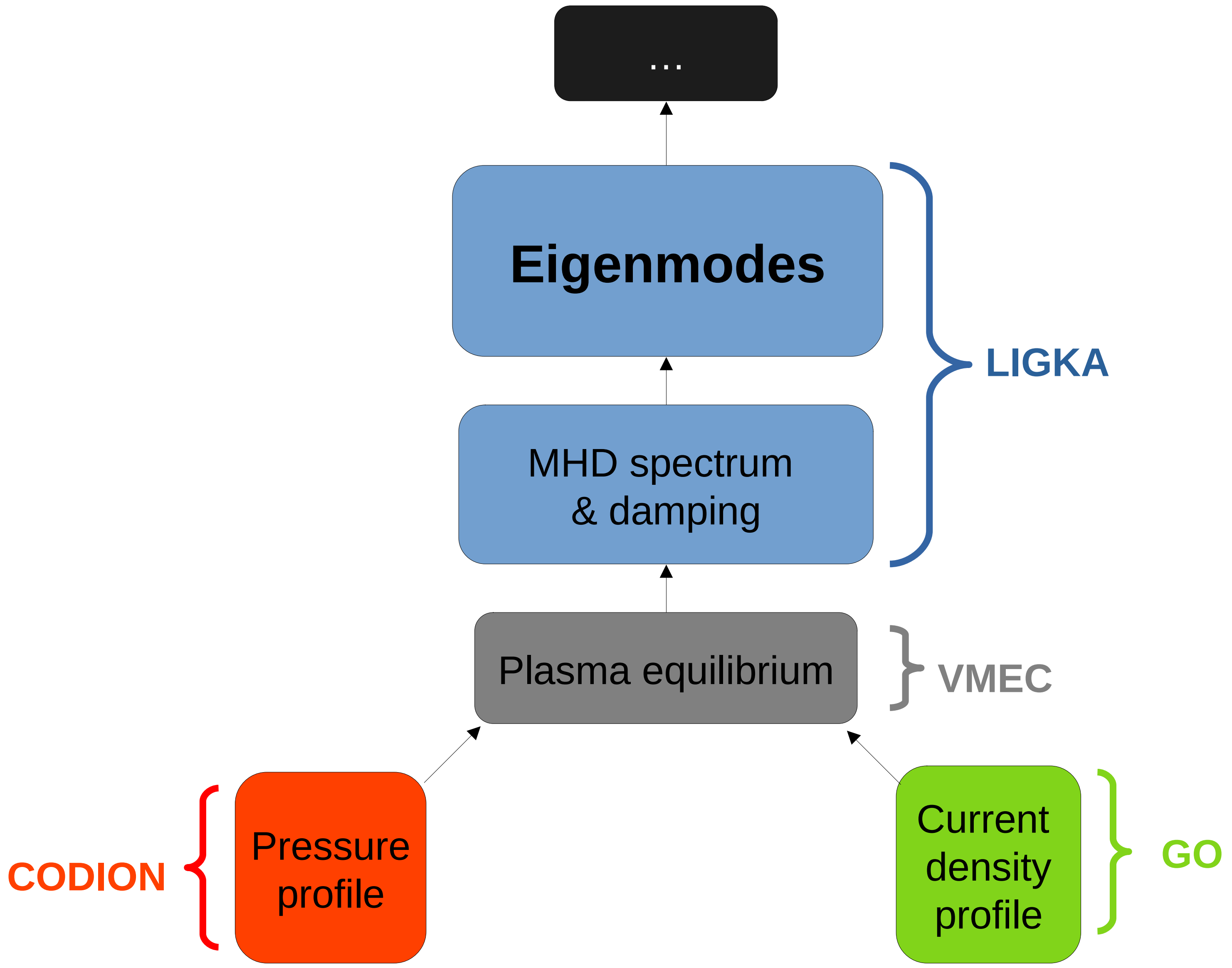


Fig.3
Resulting profiles of safety factor *q*, current density *j* and integrated current *I*.

Workchain towards post-disruption Eigenmodes



Eigenmodes in the ideal MHD spectrum

LIGKA tool employed:

- found frequency gaps for TAEs (and BAEs) in the ideal MHD spectrum
- scan over absolute scaling of q-profile (fig. 6a) shows vast availability irrespective of q_0

↓

q_0=1.07 chosen

↓

$$n=[7-15,22-26]$$

$$m=[\{(n-2)-(n+4)\},\{(n-2)-(n+6)\}]$$

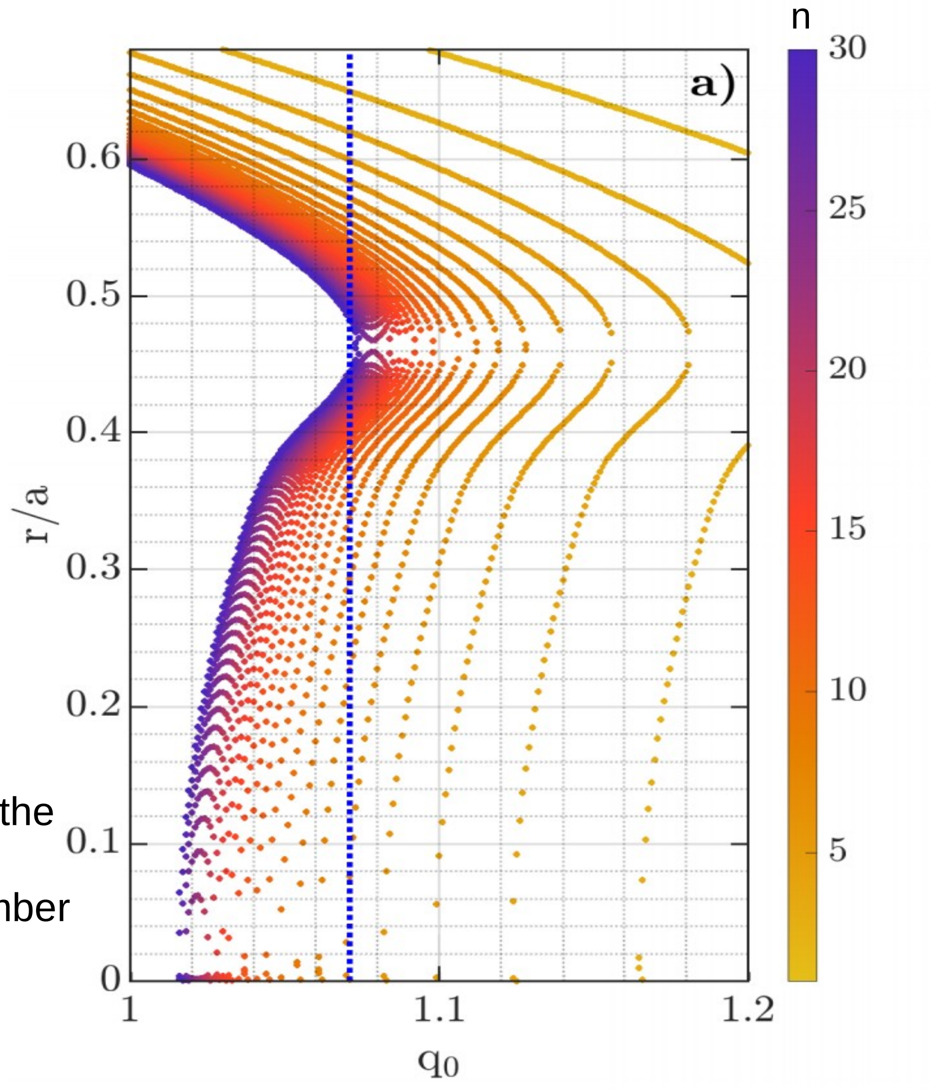
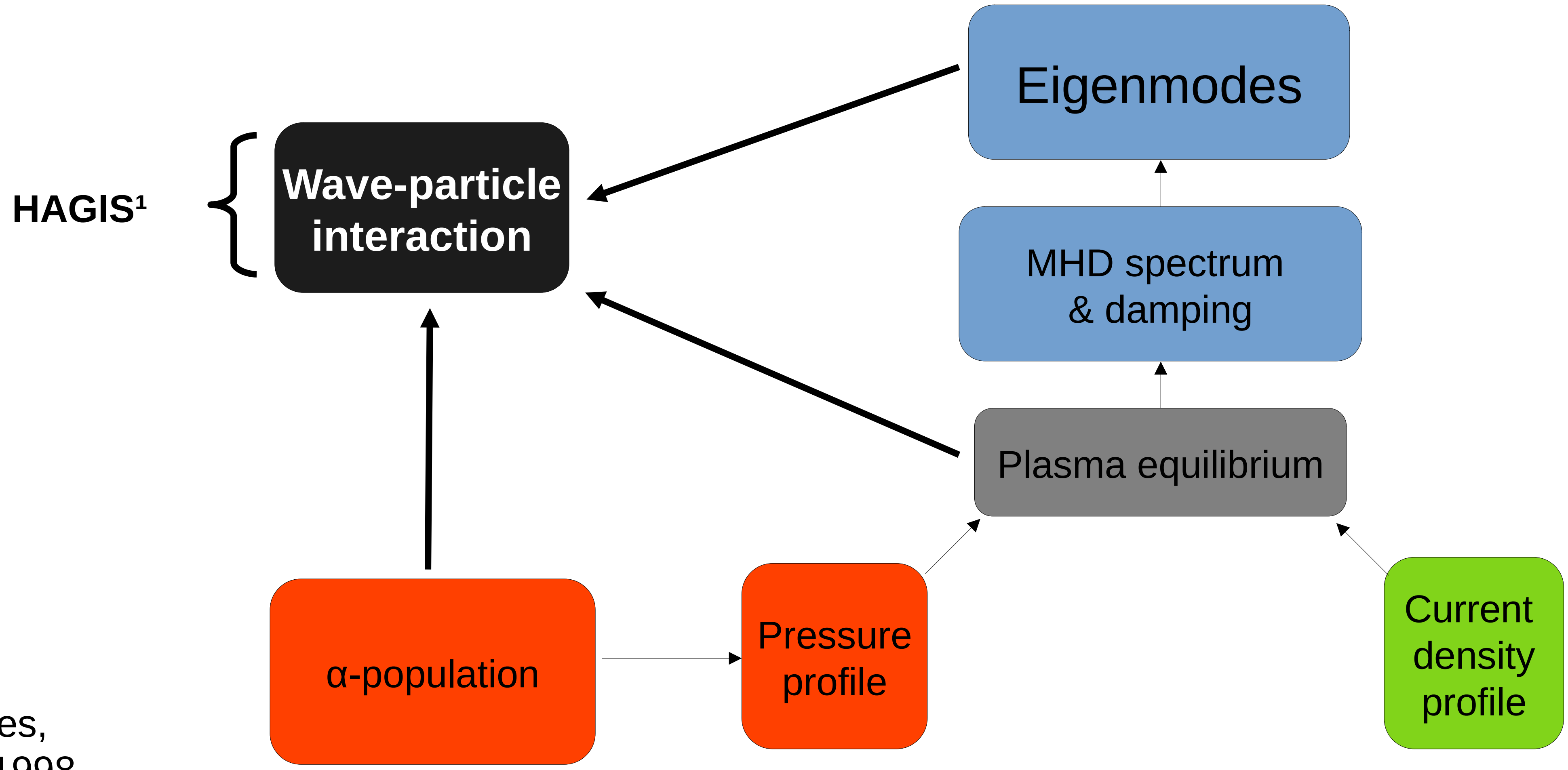


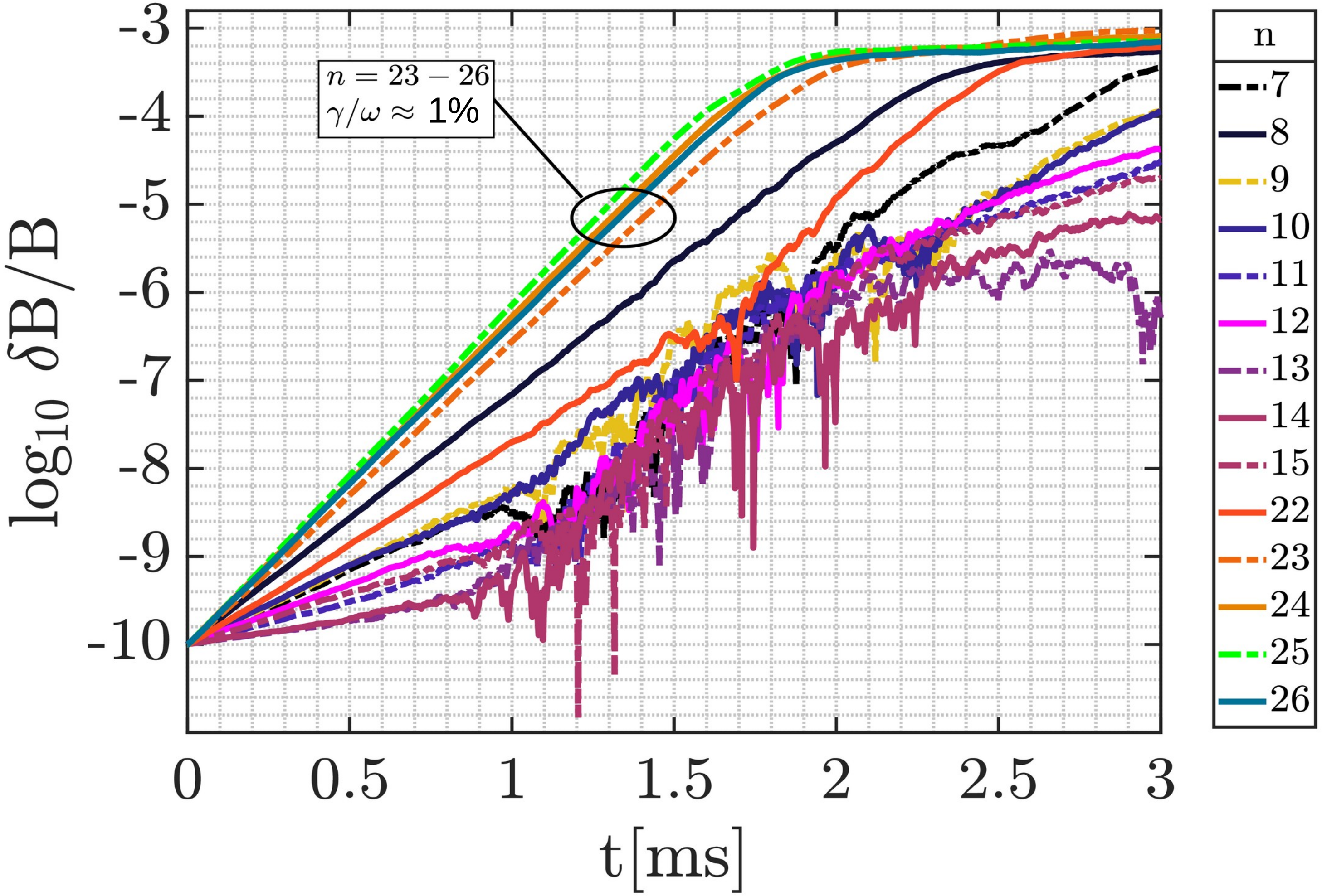
Fig.4
Radial location of the frequency gaps of toroidal mode number n=m TAEs as a function of q_0.



[1]Pinches, CPC, 1998

Active mode evolution

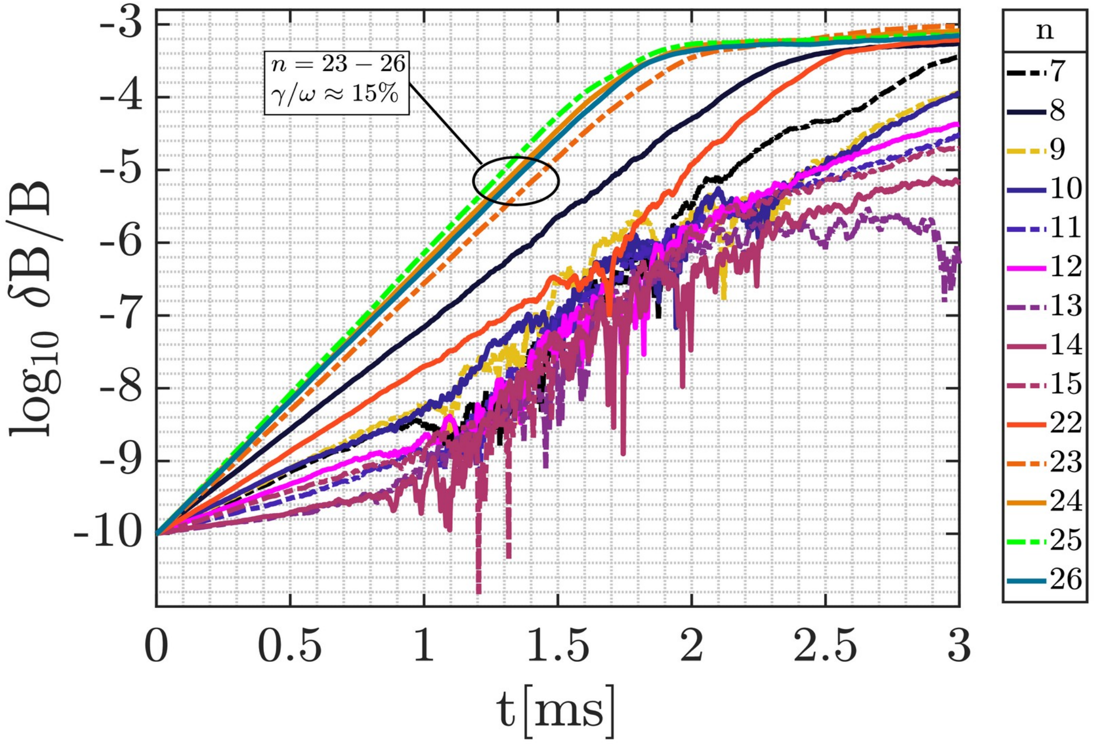
HAGIS calculates non-linear wave-particle interaction → evolves mode through EPs and redistributes EPs through modes



max(δB/B) ~ 0.1%
before RE avalanching

Fig.5
Evolution of mode amplitude δB/B as caused by resonant interaction with f_{SD} in multi-mode simulation.

Mode effects on RE dynamics



max(δB/B) ~ 0.1%
before RE avalanching

→effects on RE dynamics?

- HAGIS simulation indicating RE radial transport[1]
- Study[2] found (stochastic) mag. Perturb (~0.05%) sufficient for RE avalanche suppression
- Further study: use ASCOT[3] to determine transport coefficients as a function of (E,ƛ,r) for REs

[1][Lier, NF, 2021]
[2][Svensson, JPP, 2021]
[3][Schneider, NF, 2019]

Outlook – Limiting assumptions

Proof of principle stage[1]:

- Unmitigated disruptions
- Perfect alpha particle confinement

Ongoing work:

- (simple) mitigated scenarios
- Alpha particle transport

[1][Lier et al, NF 2021]

Ongoing work – Addressing limiting assumptions

1. Mitigated disruptions

To assess the increased parameter space:

Alpha distribution now calculated by analytical model (O. Embreus)

$$f_\alpha(r,t,v)$$

↑

$$T(r,t),\ n_e(r,t)$$

Ion composition secondary to collision dynamics
→ use ions to tune v_A?

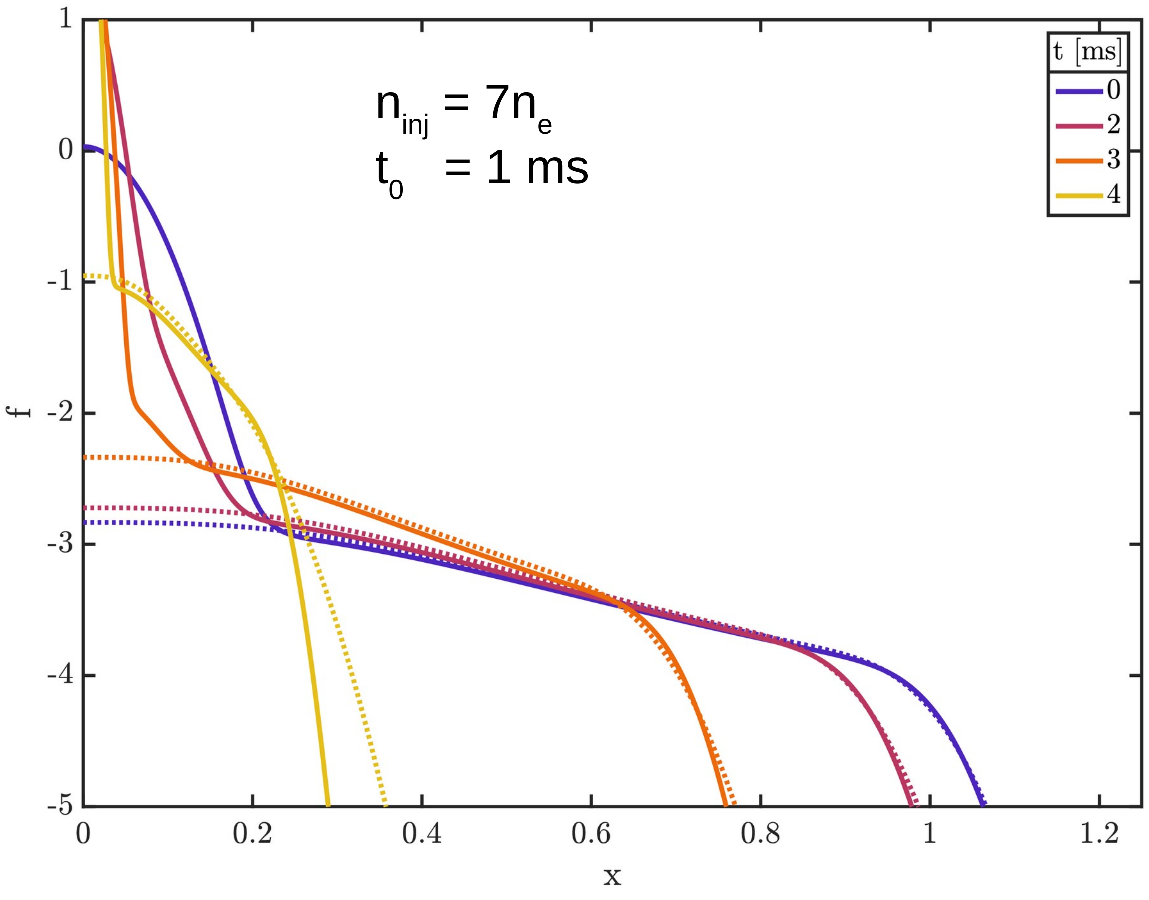


Fig
Analytical (dashed) vs CODION (dashed) results for alpha population in mitigated disruption

Ongoing work – Addressing limiting assumptions

2. Alpha particle transport

Avoid MHD simulations for the entire parameter space:

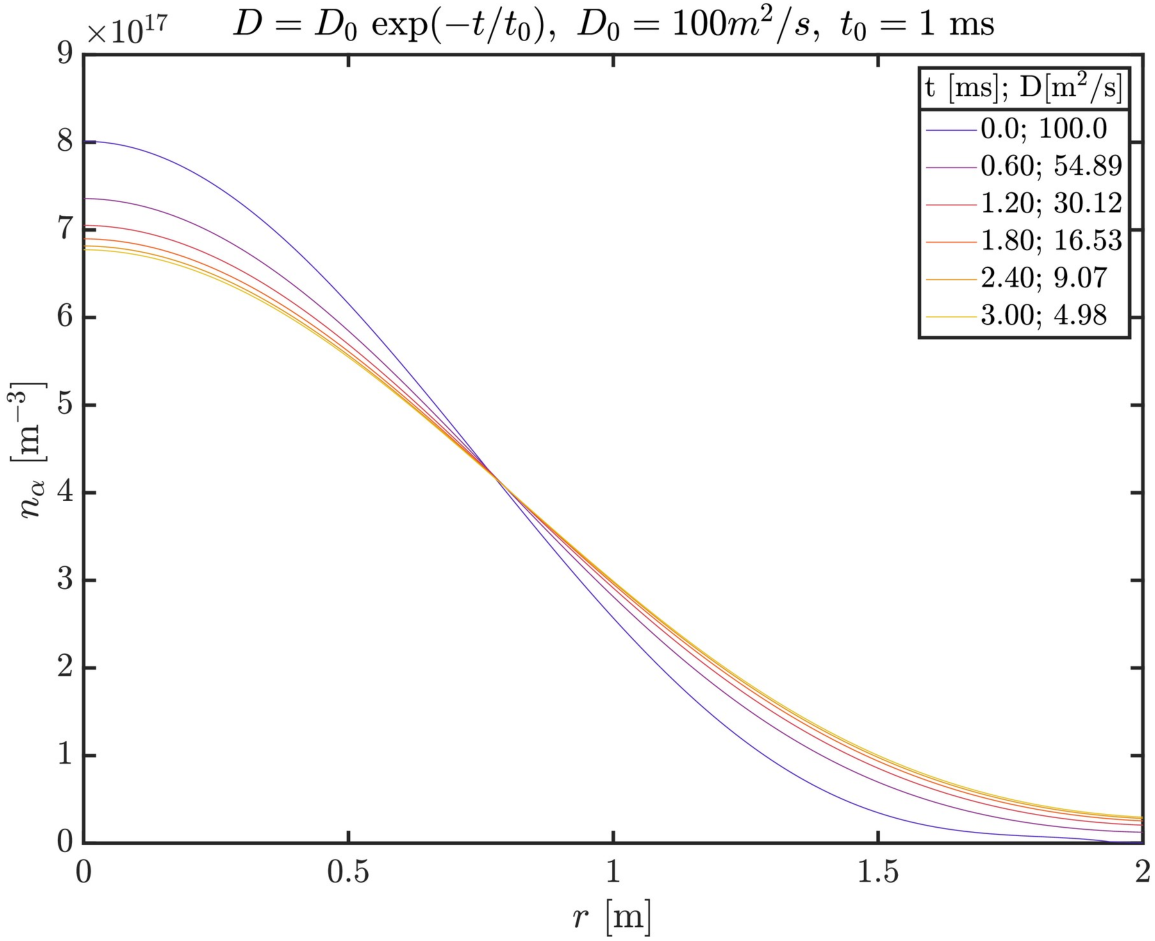
Solve diffusion equation

$$\frac{\partial u(r,t)}{\partial t} = D(t)\frac{\partial^2 u(r,t)}{\partial r^2}$$

with

$$D(t) = D_0 \exp(-t/t_0)^1$$

and scan D_0 for stochasticity

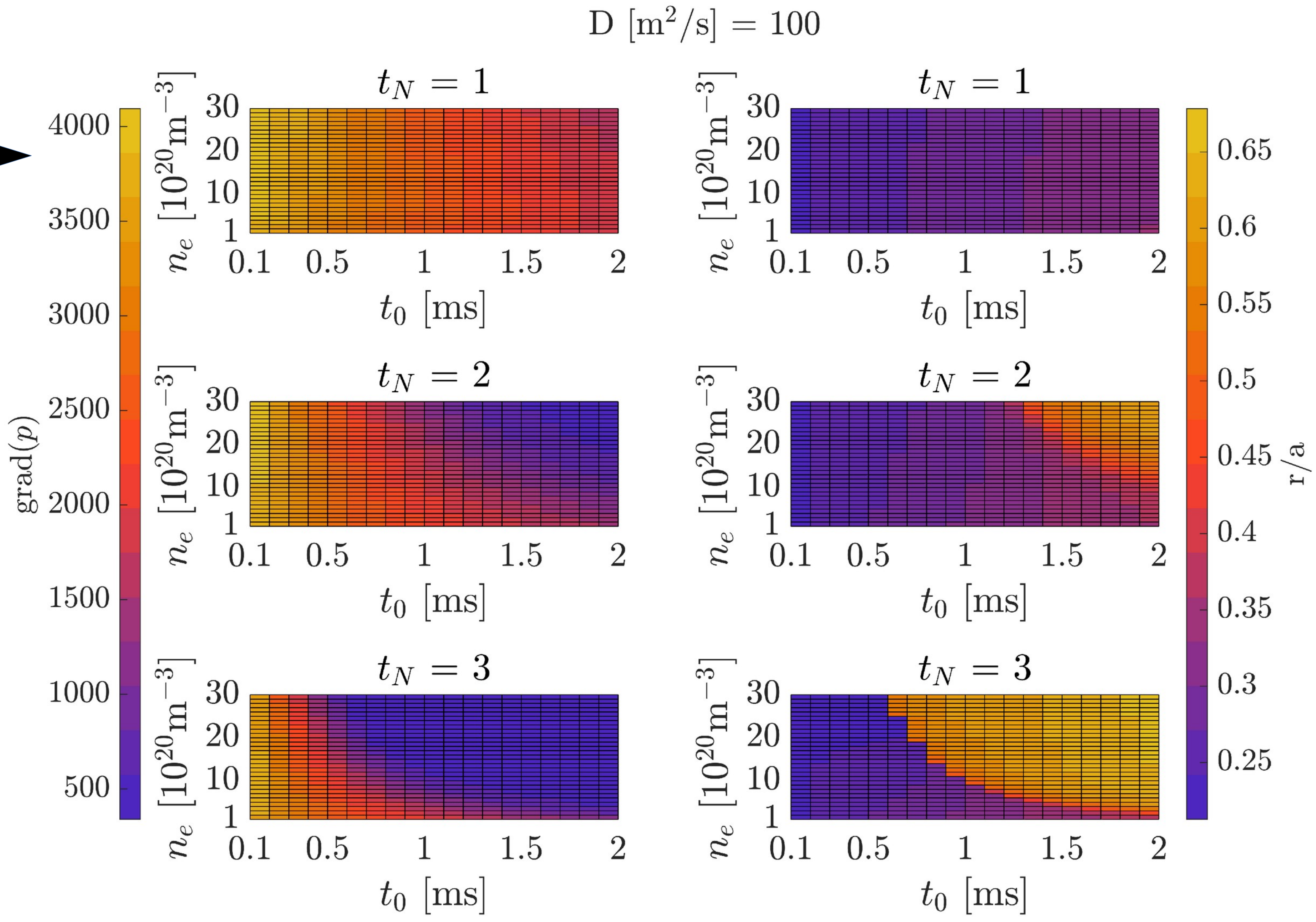


1[Linder, 2020, NF]

Ongoing work

Scanning over
t_0
n_e
D_0
and evaluate pressure gradients (strength, location)

→ Is there an optimal mitigation scenario? A strongest mode we can drive?



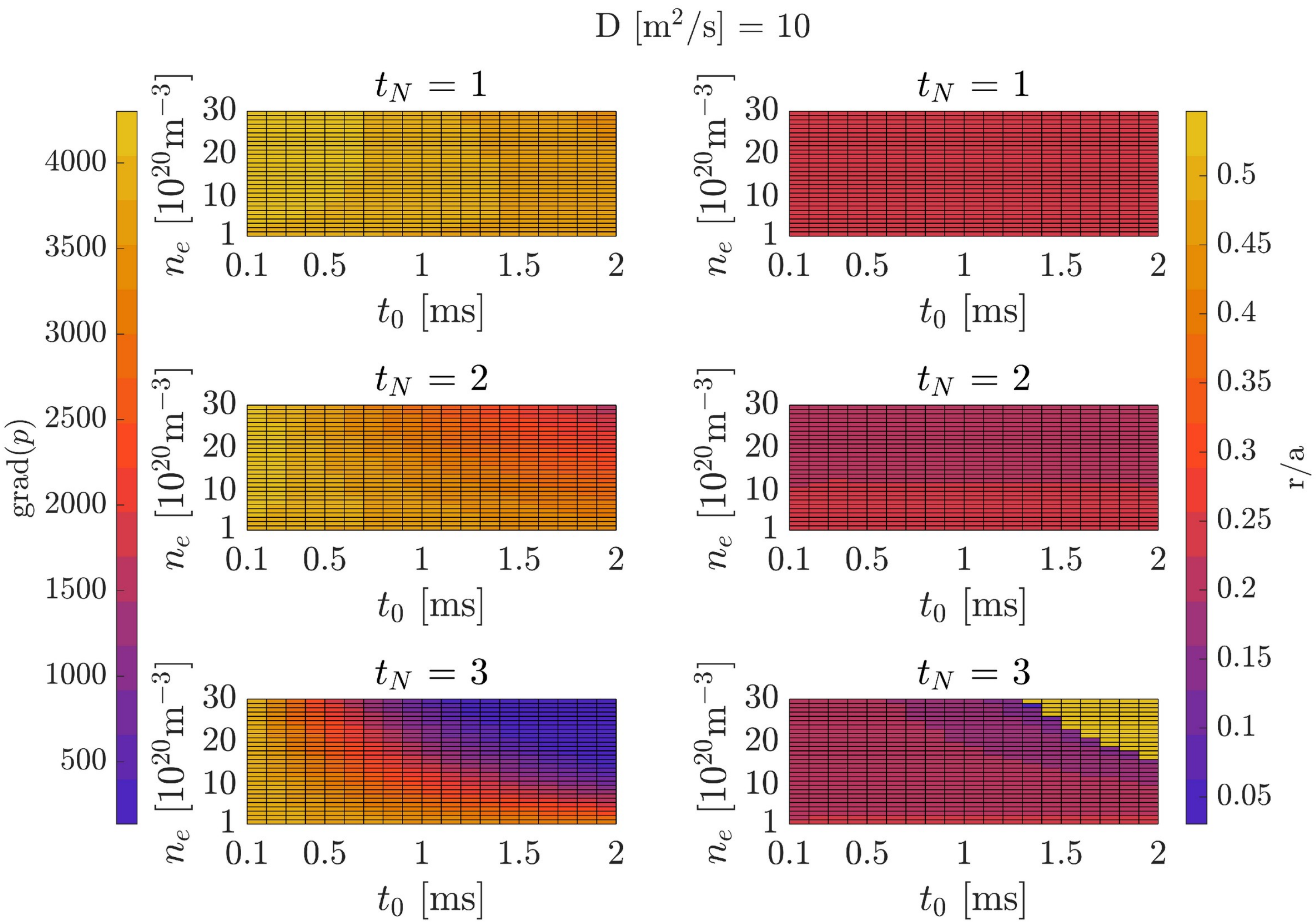
Summary & Outlook

- **Showed survivability of the energetic tail of a fusion-born alpha population far into the thermal quench**
- **The post-disruption MHD spectrum shows availability of a wide range of Toroidal Alfvén Eigenmodes which experience low damping**
- **Wave-particle interaction showed those TAEs to be driven unstable by the alpha population up to amplitudes of $\delta B/B$ = 0.1%**
- **The modes driven indicate a capability to enhance RE transport → effect on RE dynamics (suppression?)**
- **Ongoing work: Analytical model to scan big parameter space (mitigated disruptions) and search for optimum for this mechanic**

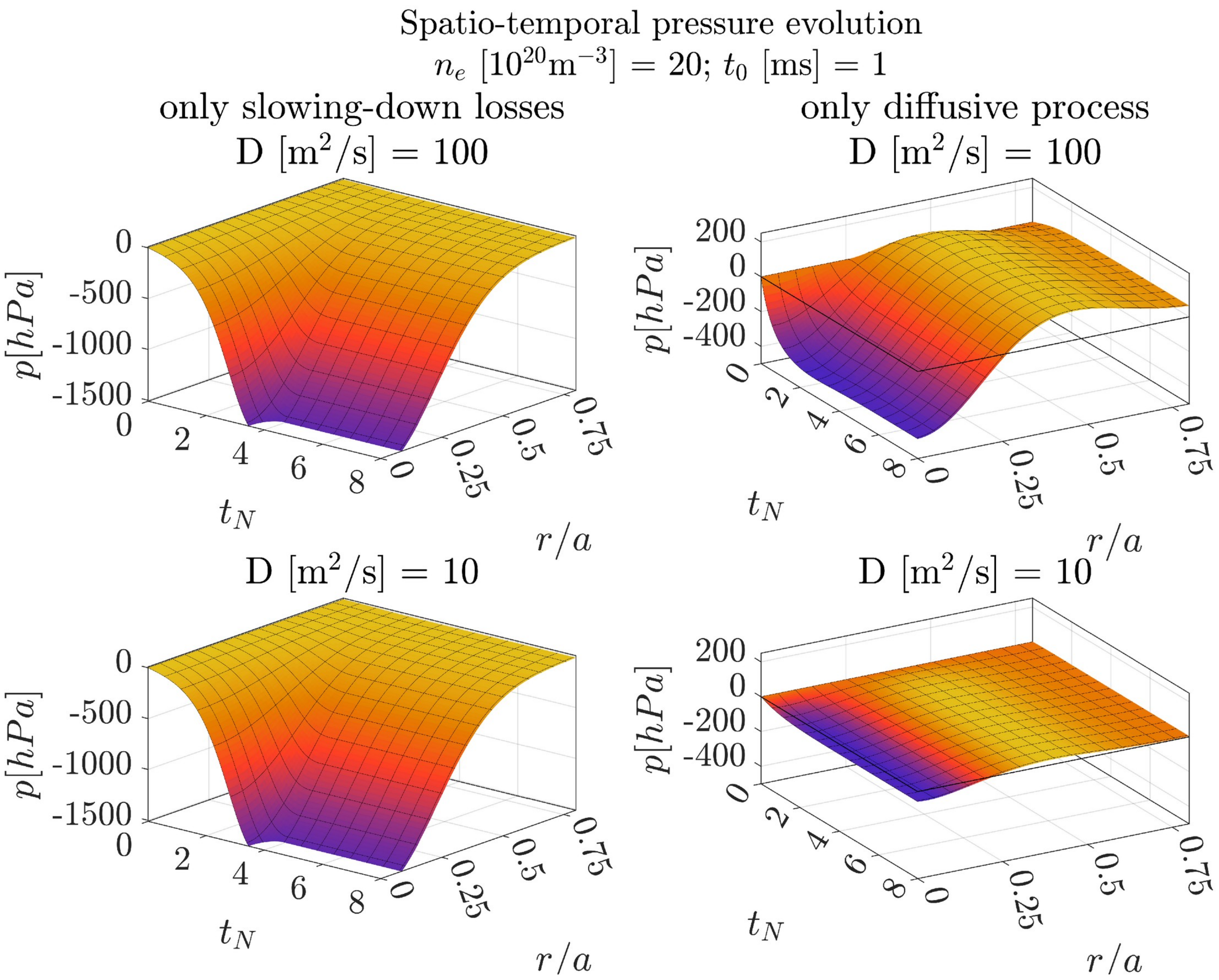
Backup – Ongoing work

Scanning over
t_0
n_e
D_0
and evaluate pressure gradients (strength, location)

→ Is there an optimal mitigation scenario?
A strongest mode we can drive?



Backup – Ongoing work



Backup - Mode effects on a RE seed

Which mode amplitudes to choose?
We are already $3t_N$ into the disruption and at $6t_N$ damping and avalanching becomes significant.

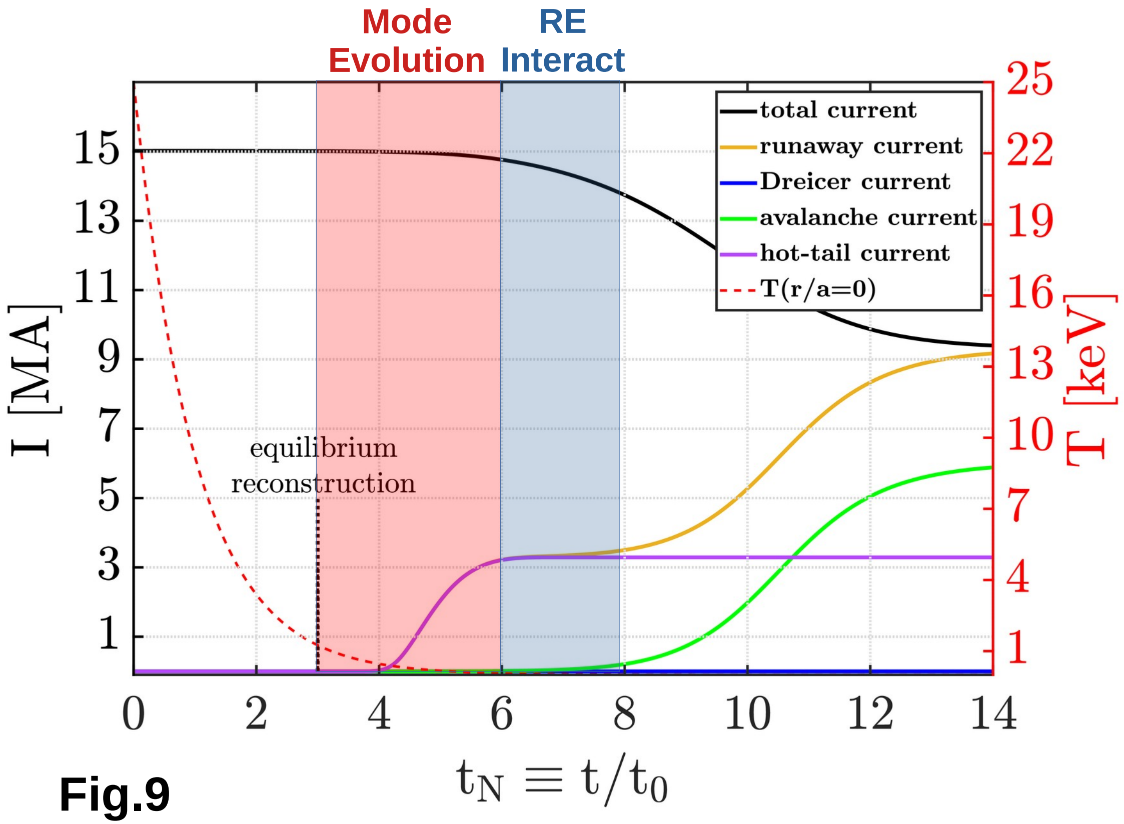
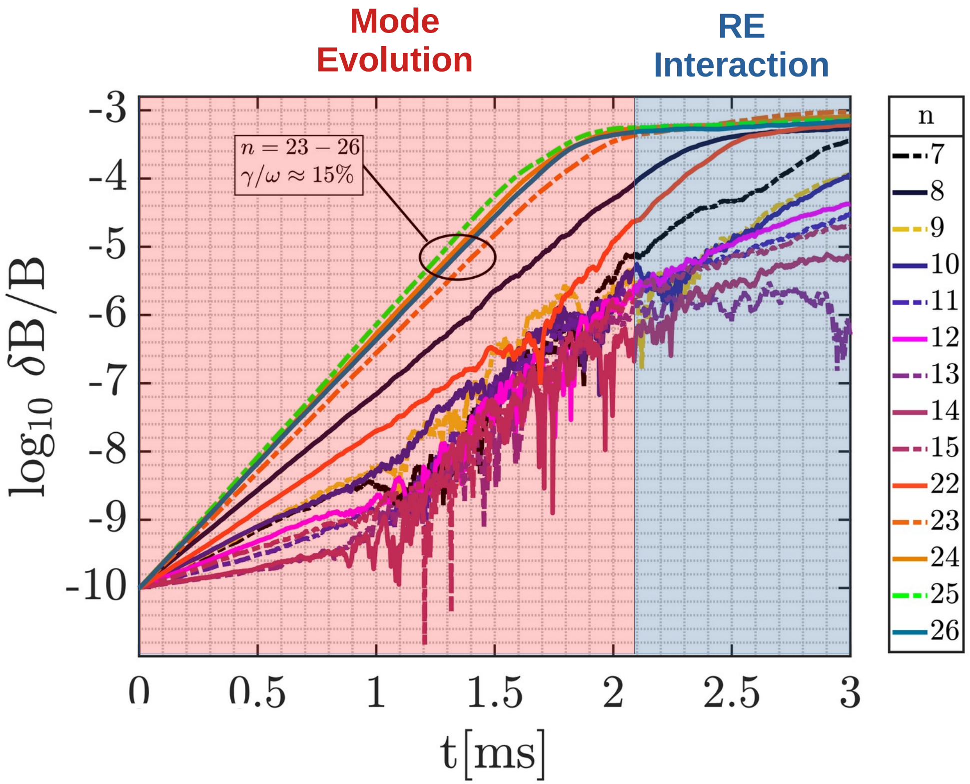


Fig.9
Currents of an unmitigated disruption identified by T_f=3eV and t_0=0.7ms and its background temperature



Backup - Mode effects on a RE seed

RE seed initialized:

$$E_{kin} = [10\,keV - 30\,MeV]$$
$$\lambda \equiv v_{\parallel}/v = [0 - 1]$$
$$r/a = [0.05 - 0.45]$$

Each triple combination represented by 25 REs, uniformly distributed along torus.
Σ#REs = 10000

Throughout interaction measure changes to the *toroidal angular momentum*

$$P_{\phi}(p_{||}, \Psi_p)$$

as indication to changes of radial position.

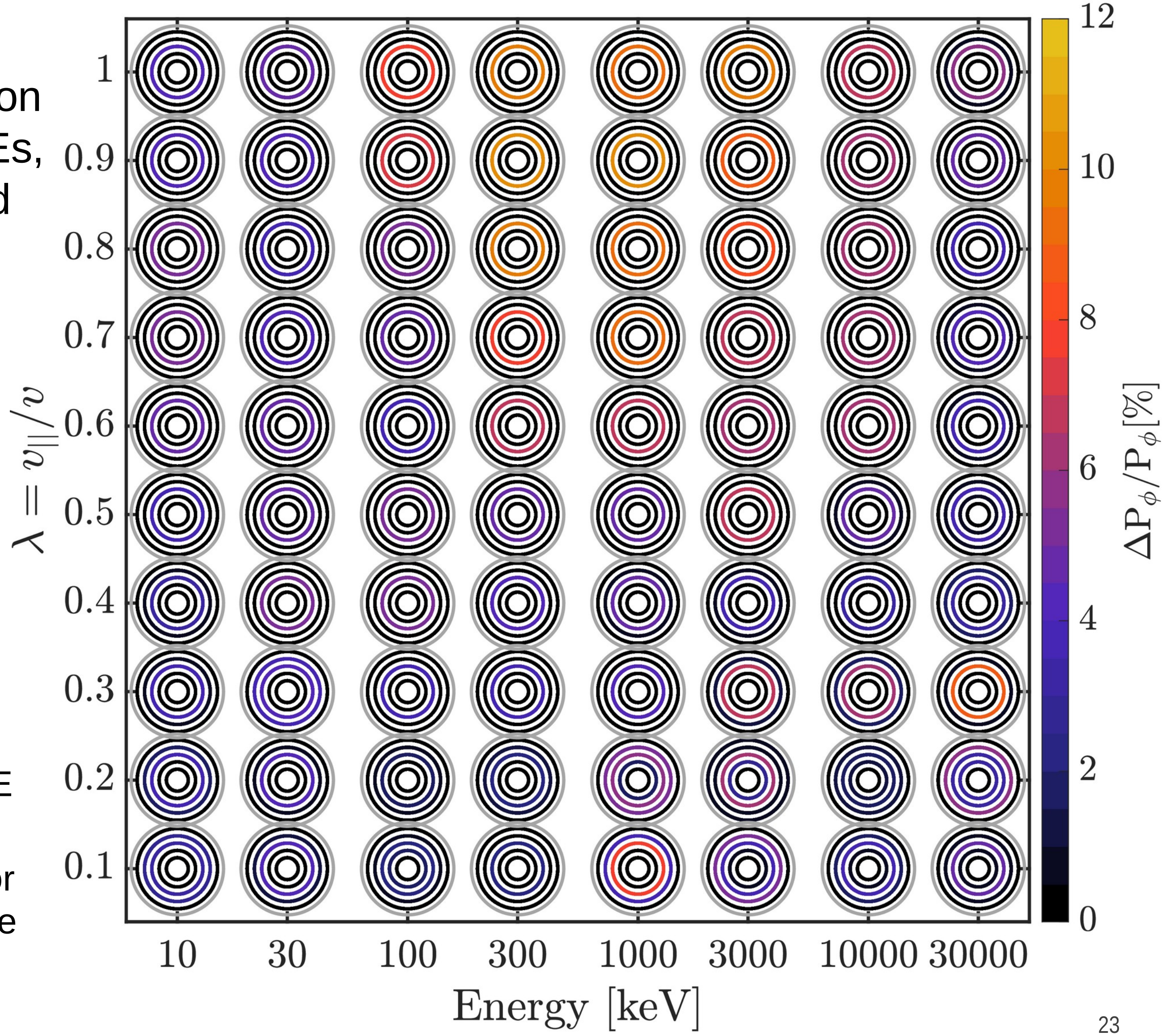
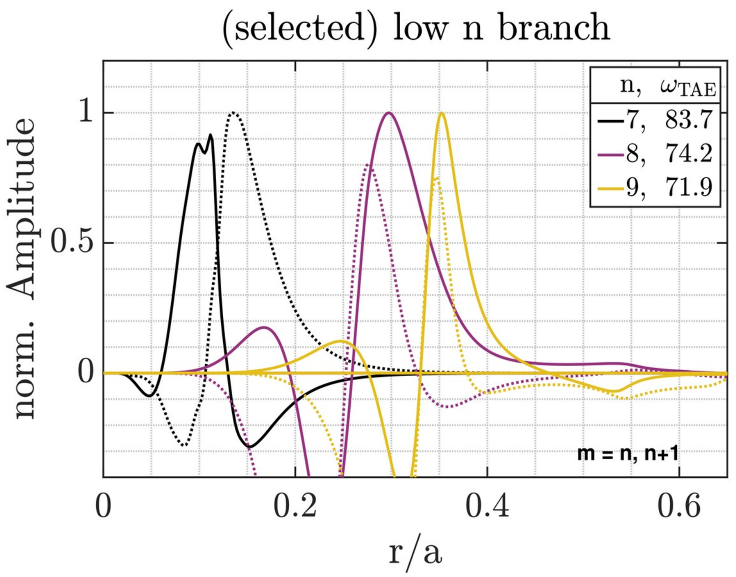
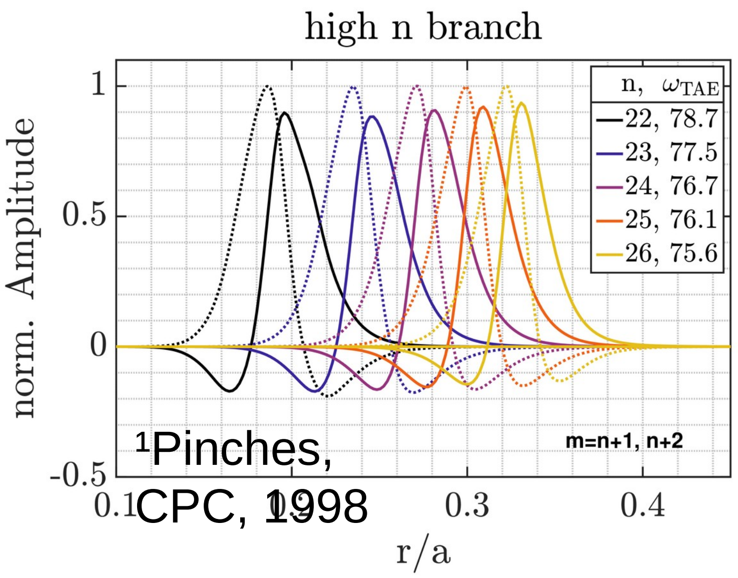


Fig.10
Ensemble-averaged change to P_{Φ} of the RE seed as caused by the TAEs.
X and y-axis show initial RE attributes, color indicates change after t_N=2. The Radii of the circles are the initial radial position of the particle in r/a=[0.05-0.45] in steps of 0.1.

Backup – mode structures





[1]Pinches, CPC, 1998

Mode structures for q_0 = 1.07

→ total structure is **core localized** along flat shear

- α-pressure core-peaked
- RE-generation core-localized

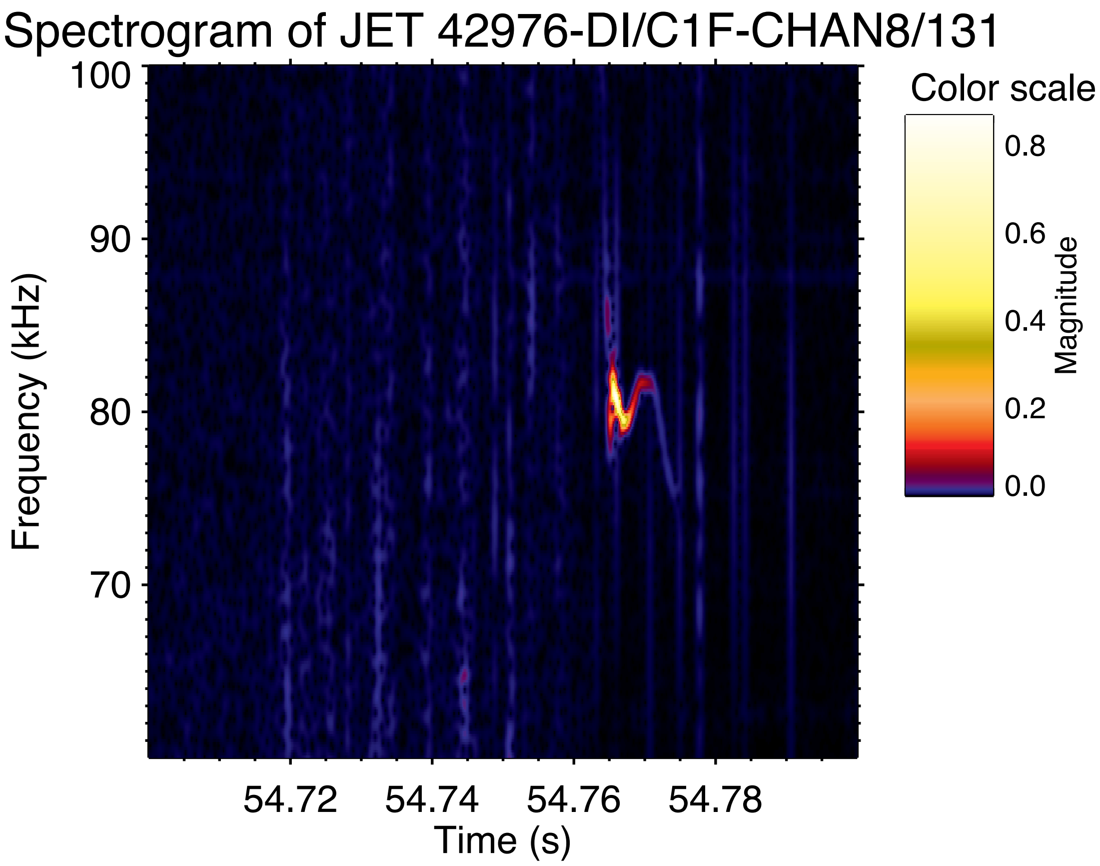
Fig.6
Selected TAE modestructures for q_0=1.07. Normalized amplitude of the real part with respective frequencies ω_{TAE} [kHz]. b) shows m=n,n+1 coupling and c) shows m=n+1,n+2 coupling.

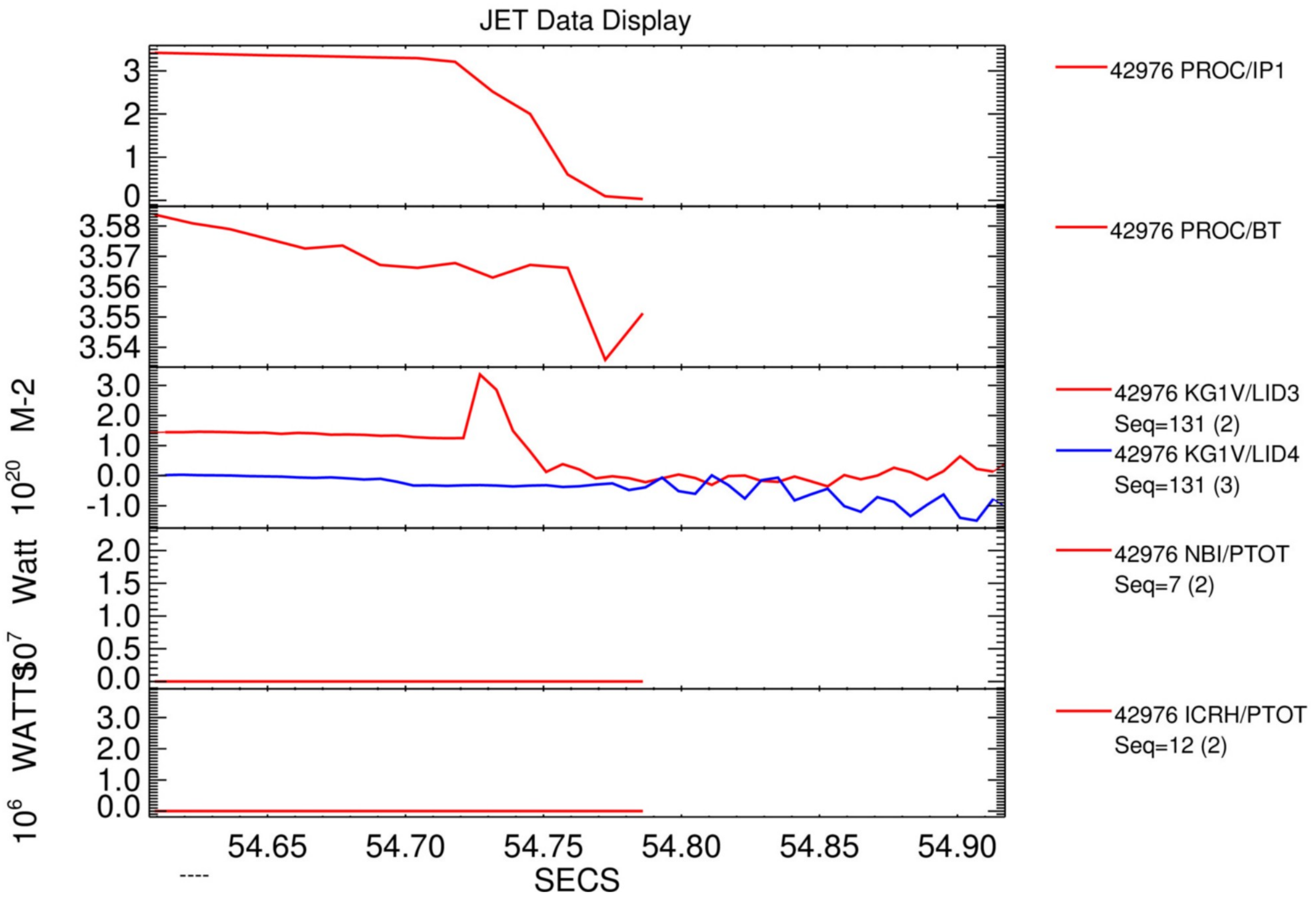
Damping strengths ɣ/ω [s^{-1}/s^{-1}]:

- Landau+radiative (LIGKA) ~ 0.1% (t_N = 3)
- Fluid damping (CASTOR[1]) ~ 1% (t_N = 8)
- Collisional damping[2] ~1% (t_N = 6)

[1][Kerner, JCP, 1998]
[2][Gorelenkov, PS, 1992]

Backup – JET supershot





Backup – TEXTOR case

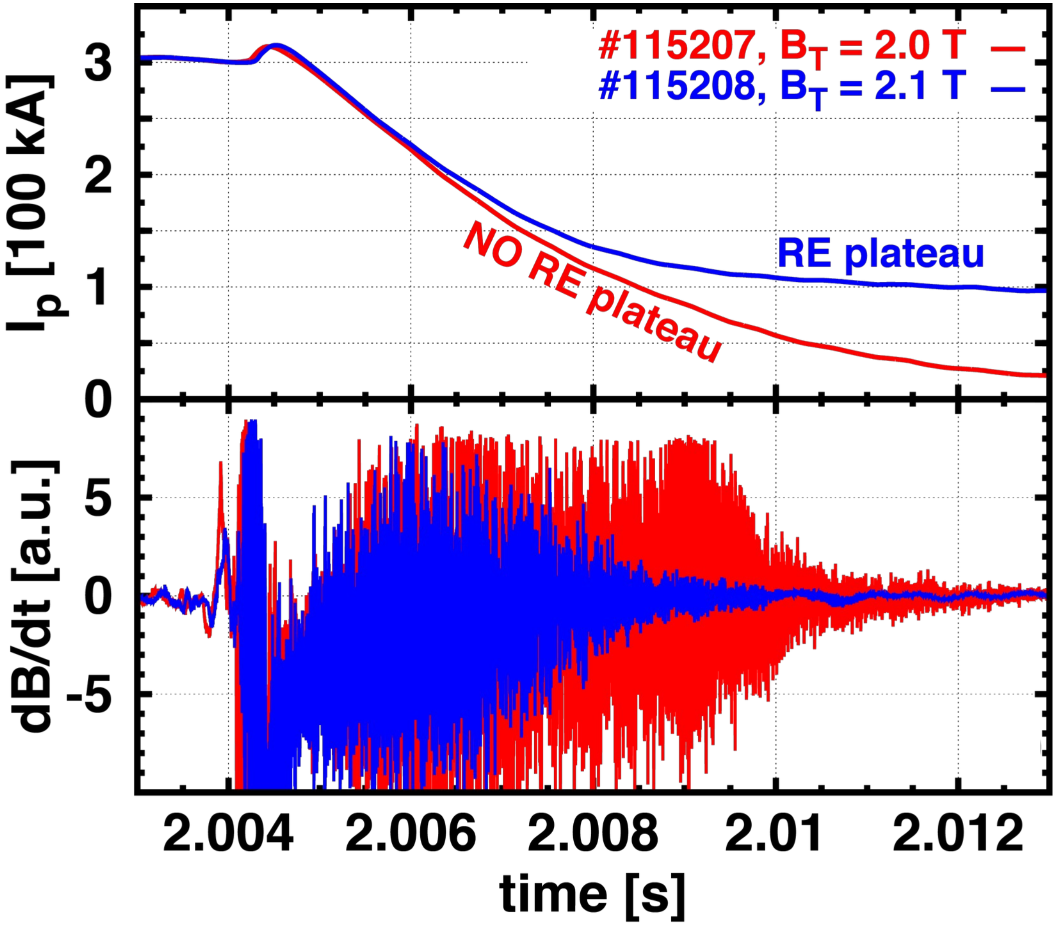


Fig.1: Plasma current evolution and Mirnov coil signals from TEXTOR shots #115207-8 (2013)

- Case of lower B_T shows strong coherent magnetic oscillations:
  - Toroidal Alfvén Eigenmode (TAE) identified as the cause of runaway electron suppression
  - Studies [1] estimated turbulence threshold level dB/B ~ 0.1% for suppression

ITER: could alpha particles provide drive for RE-suppressing modes?

[1] Zeng, PRL, 2013

Backup – pressure profile

$$p(r,t)=n_e T_e(r,t)+n_{D,T} T_i(r,t)+p_\alpha(r,t)$$

with

$$n_e=n_{D,T}=10^{20}\left[m^{-3}\right]$$

and

$$T(r,t)=T_f+\left[T(r,0)-T_f\right]\exp\left(-t/t_0\right)$$

$$p_\alpha(r,t)=\frac{m_\alpha}{3}\int v^4 f_\alpha(v,r,t)\,dv$$

↓

CODION is 0D in space: Each of the 100 radial points is populated by velocity distributions $f_\alpha(v,r,t)$ advancing independently in time

↓

Assumes case of good post-disruption confinement, as is also necessary for RE beam

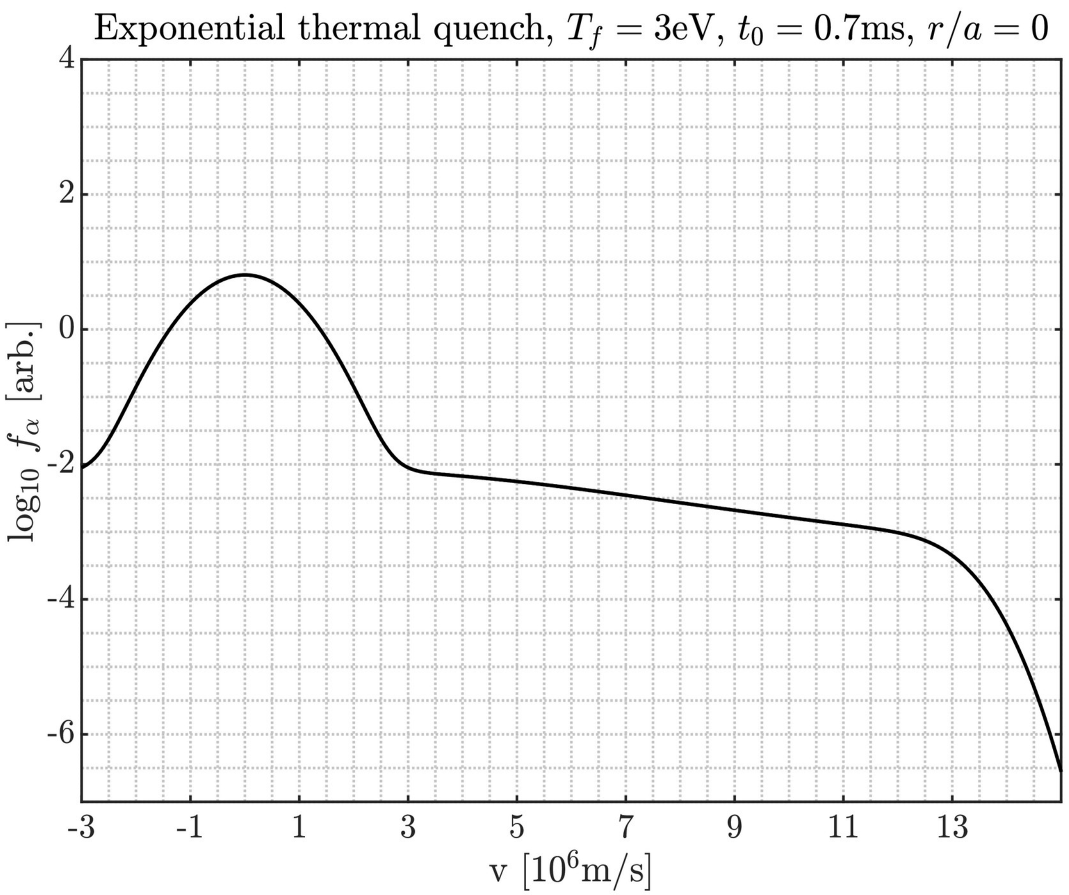
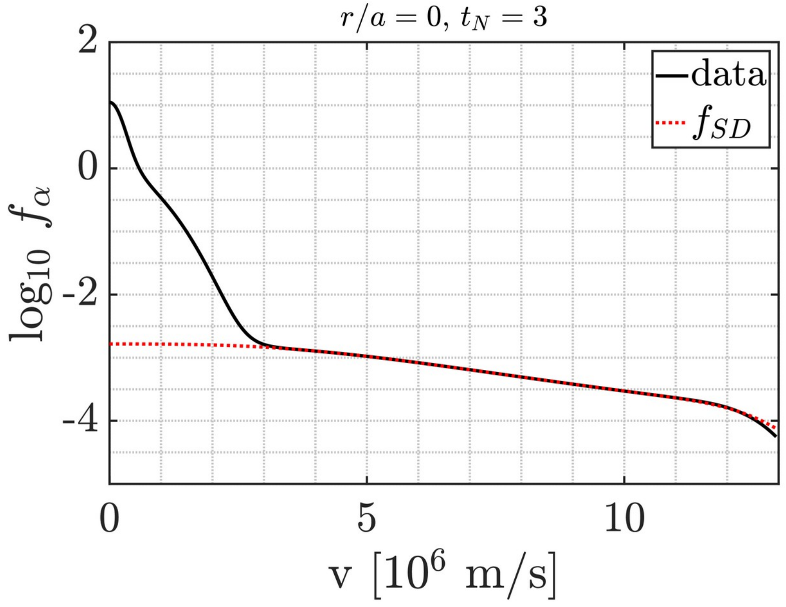


Fig.2
CODION simulation: Initial fusion born alpha particle population on axis $f_\alpha(v,0,0)$

Backup - active mode evolution



Energetic part of CODION obtained data is fitted with the analytic slowing down formula[1] f_{SD}

$$f_{SD}(r, v, t_N = 3) = \frac{C(r)}{v_c^3(r) + v^3} \, Erfc\left(\frac{v - v_\alpha}{\Delta v(r)}\right)$$

[1]Gaffey, JPP, 76

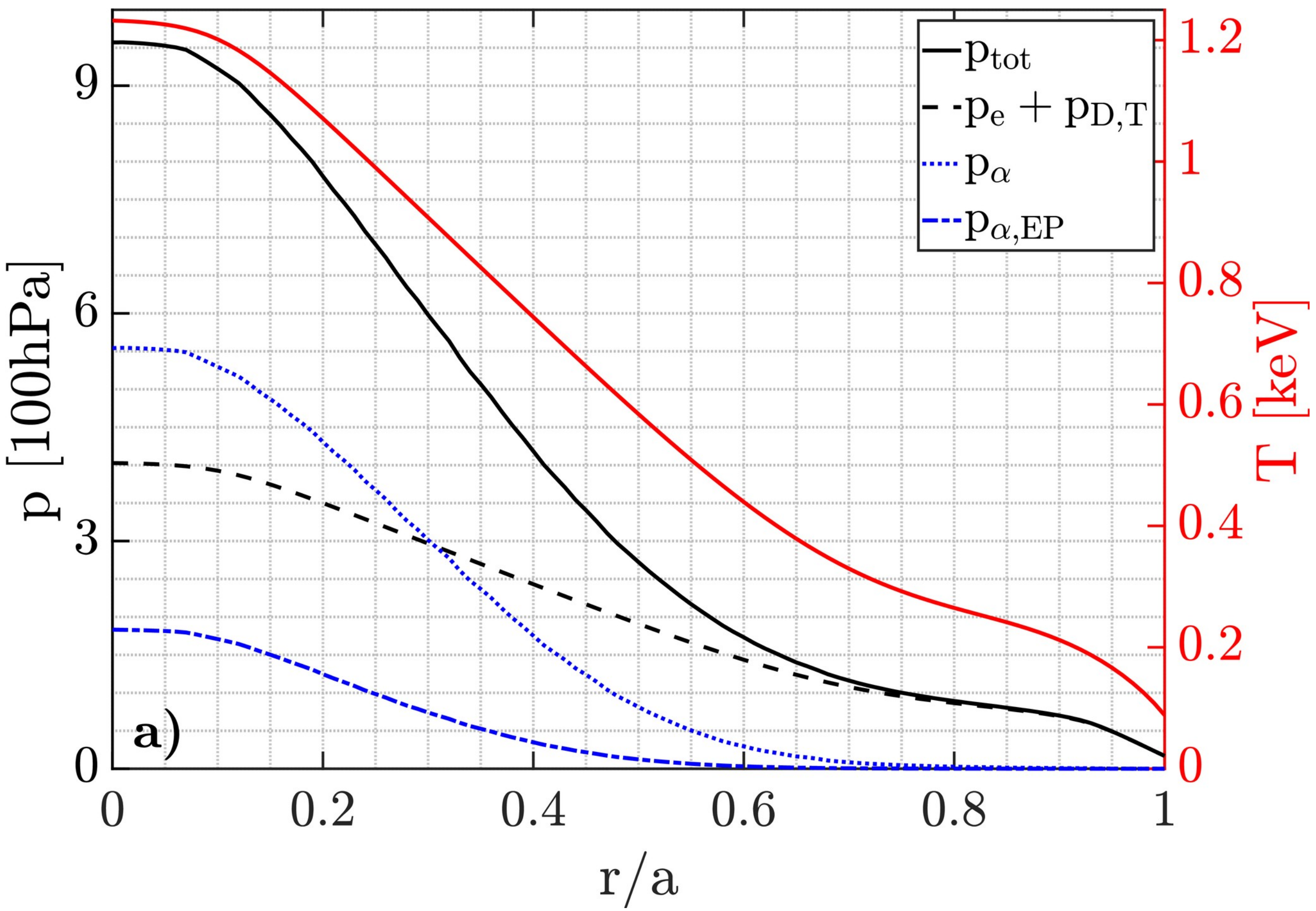


Fig.7
Pressure and temperature profiles for t_N=3. Note that $p_{\alpha,EP}$ is used for mode drive, not p_α, since the latter is misleading (due to CODION particle conservation)

Backup plots