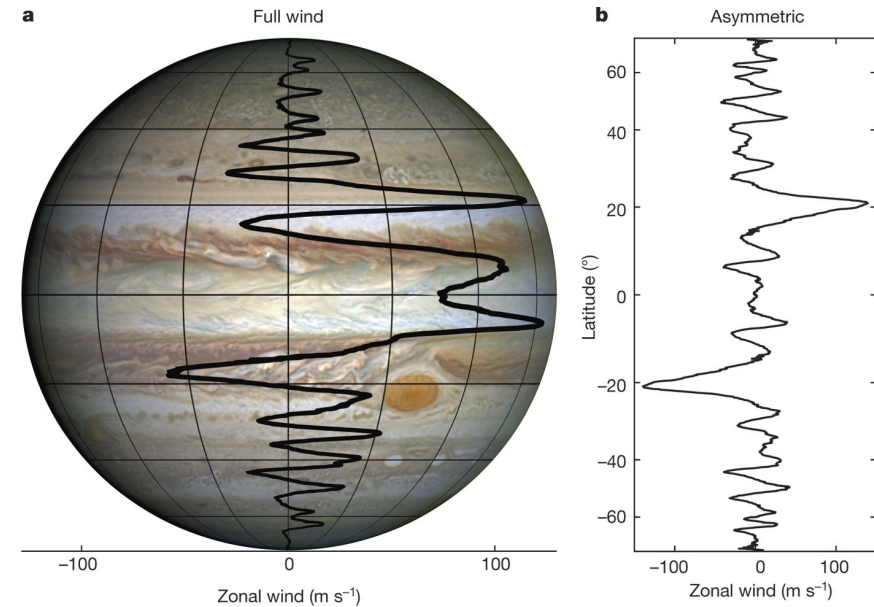
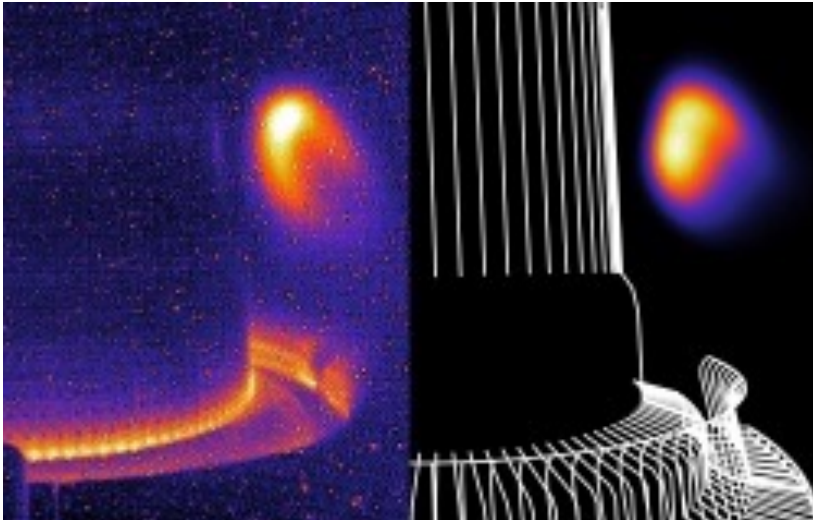


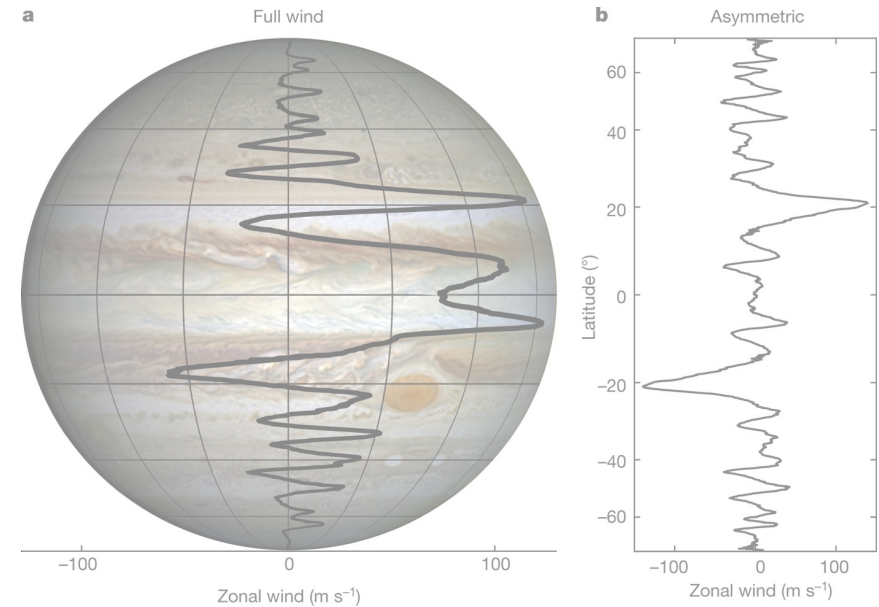
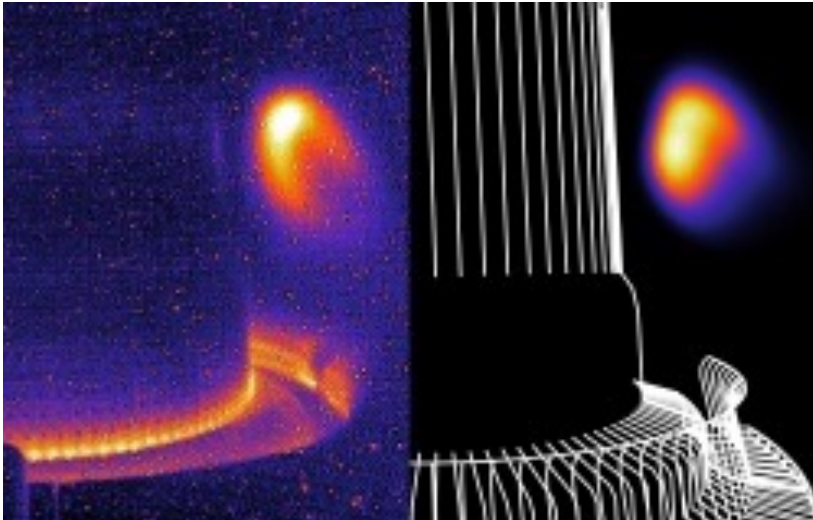
# Possible synergies

- **Kinetic physics:** Interaction between waves and relativistic electrons in tokamaks
- **Turbulence:** Turbulence self-organization into zonal flows and associated transport

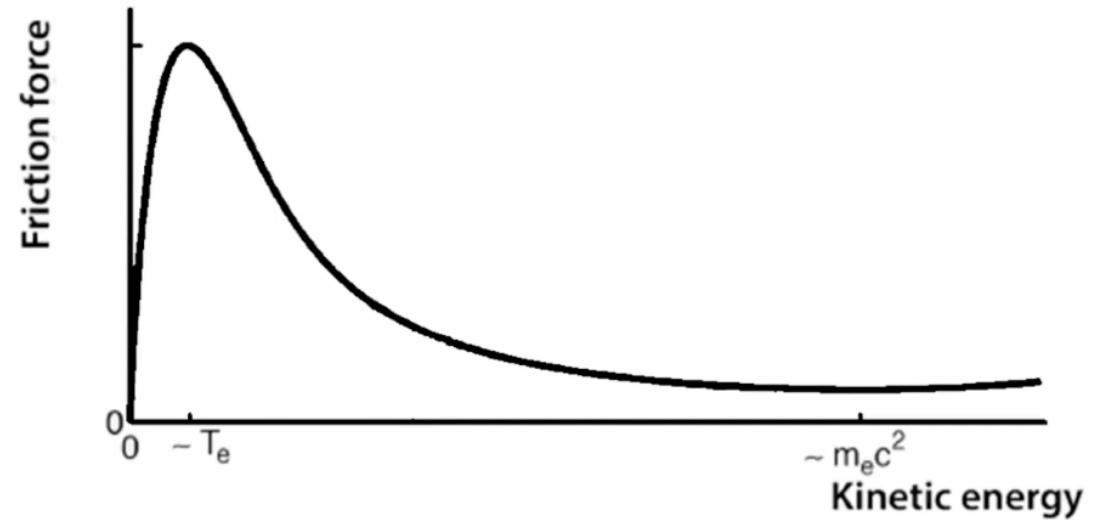


# Possible synergies

- **Kinetic physics:** Interaction between waves and relativistic electrons in tokamaks
- **Turbulence:** Turbulence self-organization into zonal flows and associated transport



- ☞ Friction force of suprathermal electrons decreases with velocity



☞ Friction force of suprathermal electrons decreases with velocity

→ electrons accelerated by a toroidal electric field can enter a **runaway regime (1-30MeV)**

Large electric fields: [Breizman 2019]

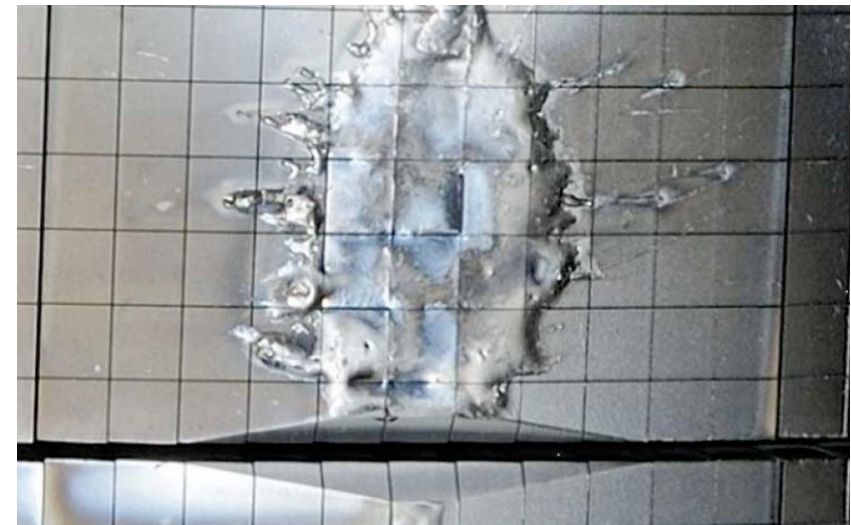
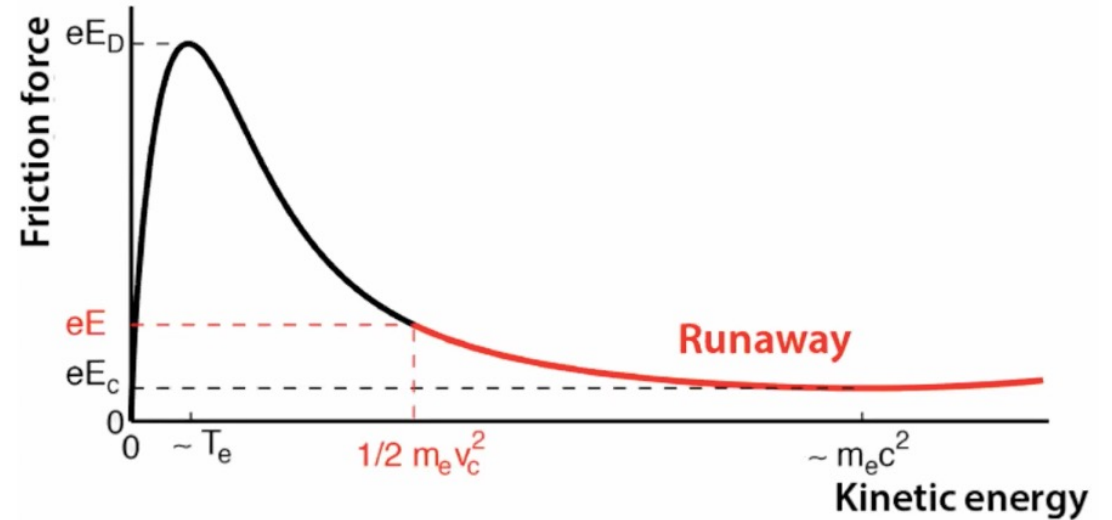
- Plasma startup
- Disruptions (loss of magnetic confinement)

☞ Disruption → runaway beams might collide with plasma facing components (PFC)

[Matthews 2016]

☞ Major threat for tokamaks  
→ design of a disruption mitigation system

[Hollman 2015]



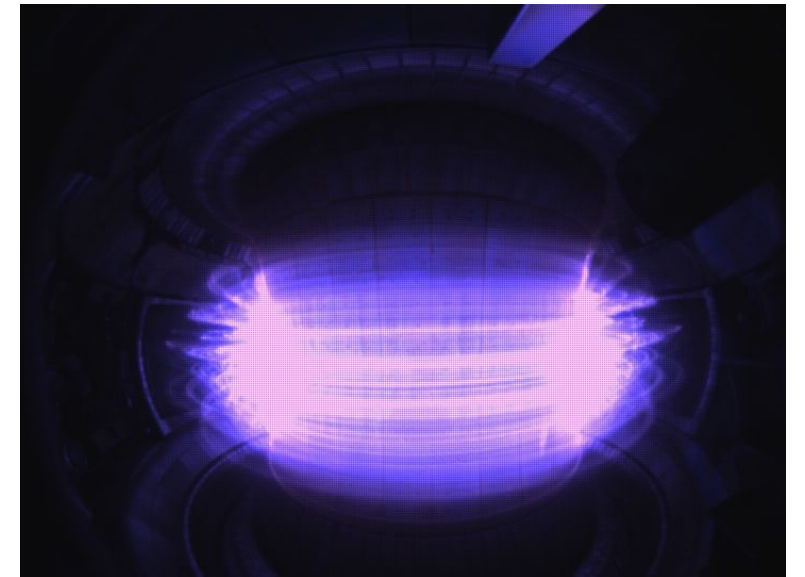
Damage to JET PFC (credit: iter.org)

# How to mitigate the runaways?

$$Damage = \frac{\textit{density} * \textit{energy}}{\textit{surface}}$$



ITER benign termination scheme  
→ Sending neutrals to diffuse RE on wide surfaces

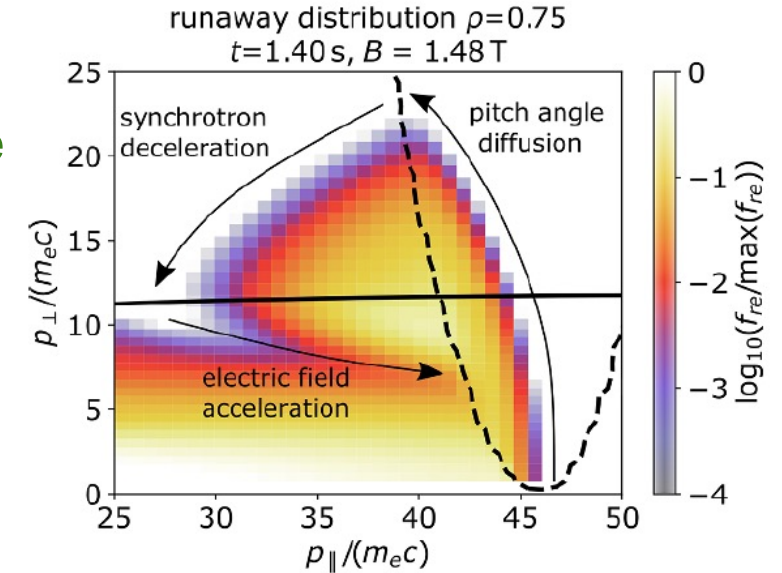


# How to mitigate the runaways?

Increase the radial transport of RE

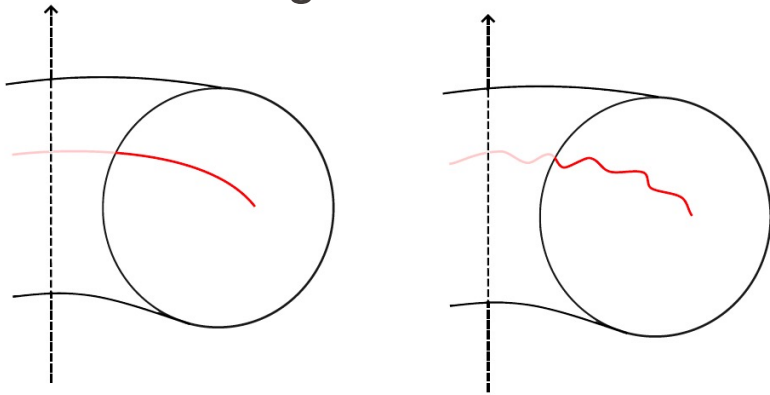
Increase their pitch-angle scattering so that they radiate their energy

$$Damage = \frac{density * energy}{surface}$$

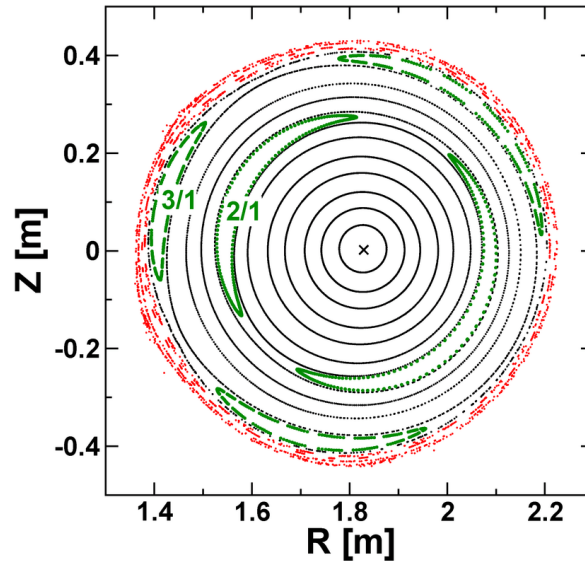


[T. Wijkamp 2024]

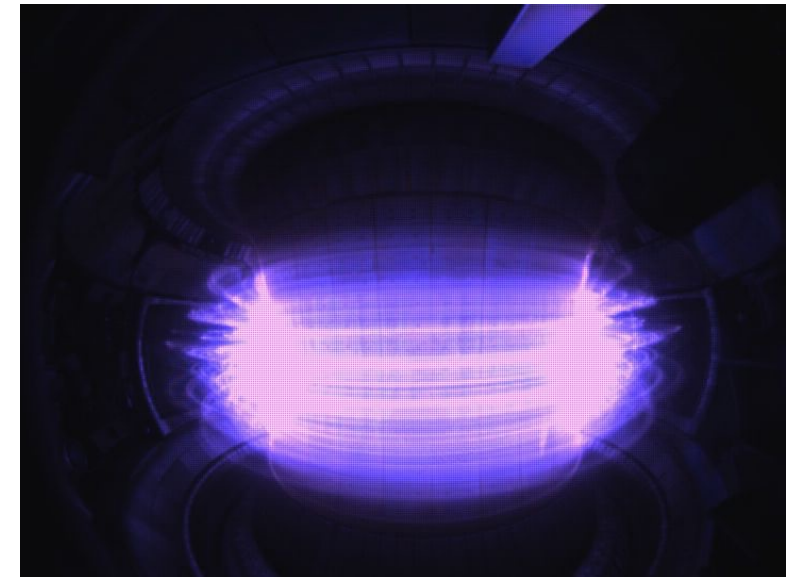
Magnetic flutter



Magnetic island



Olivier Panico



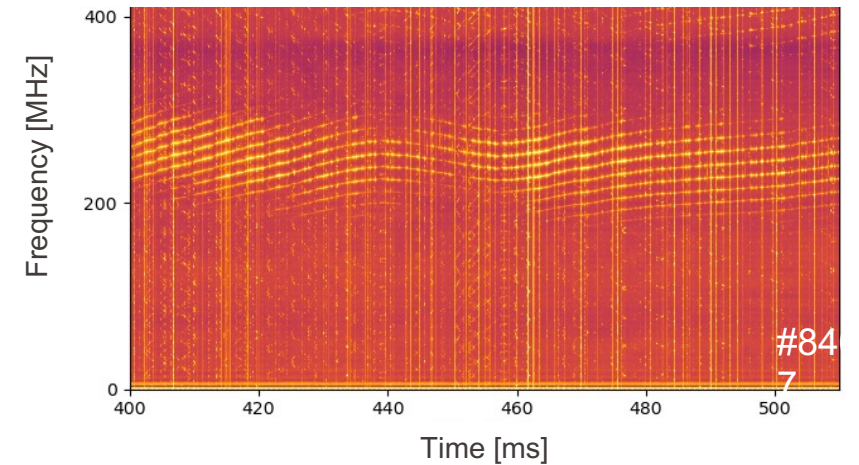
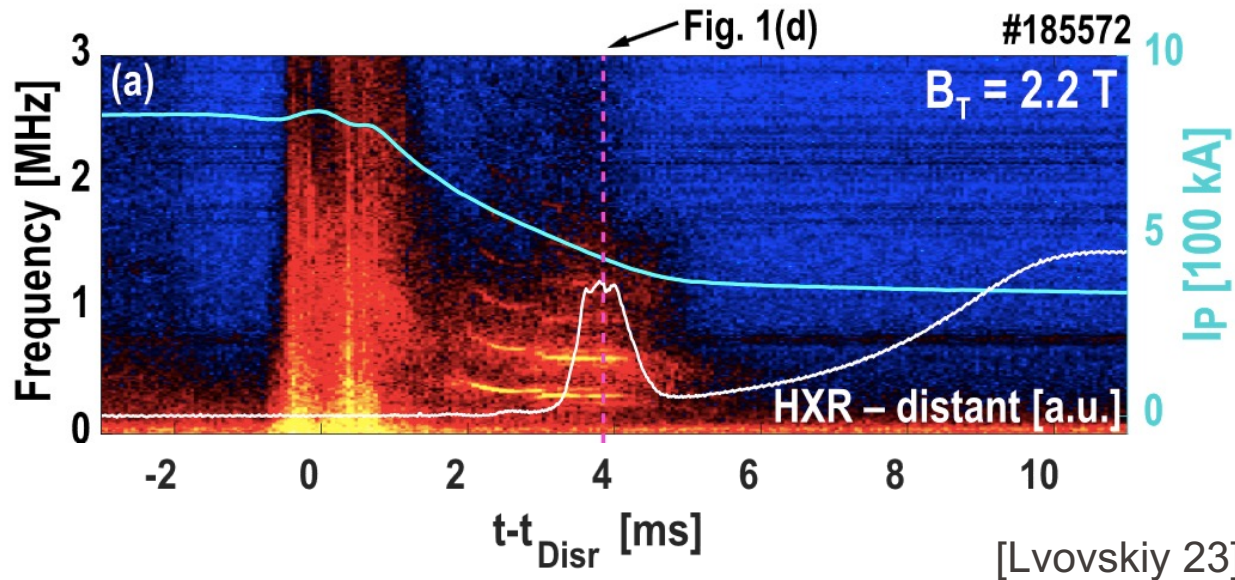
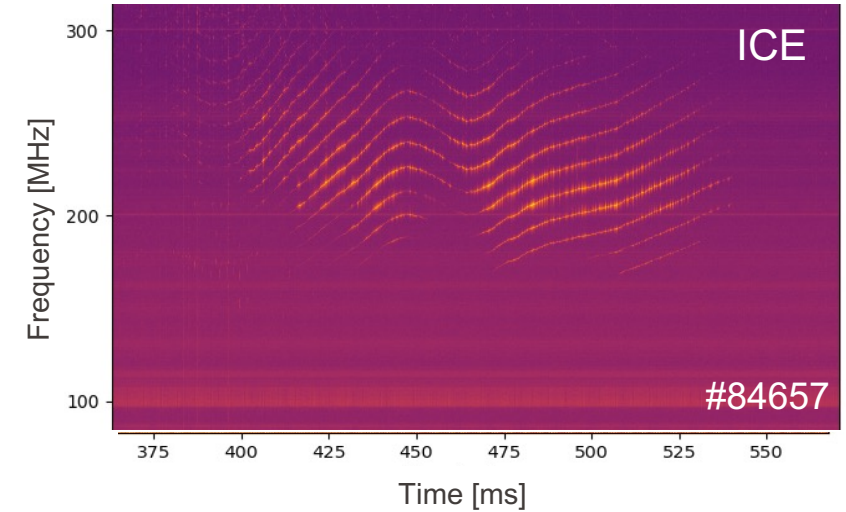
Courtesy of U. Sheikh

# High-frequency waves generated by fast electrons

- ☞ We observe high frequency waves during RE experiments on many tokamaks:
  - DIII-D: [Spong 2018, Heidbrink 2018, Lvovskiy 2019]
  - FTU: [Bin RSI 2022, PRL 2022]

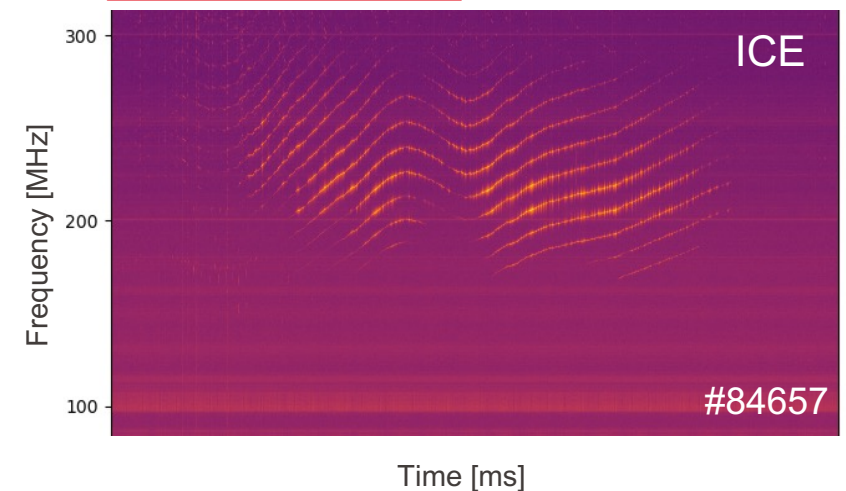
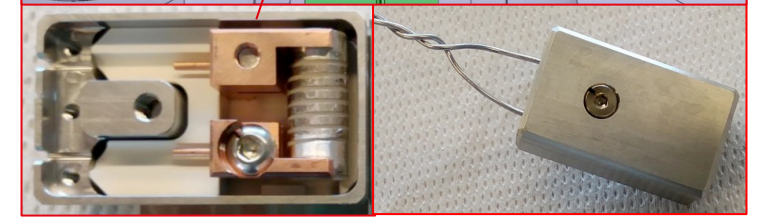
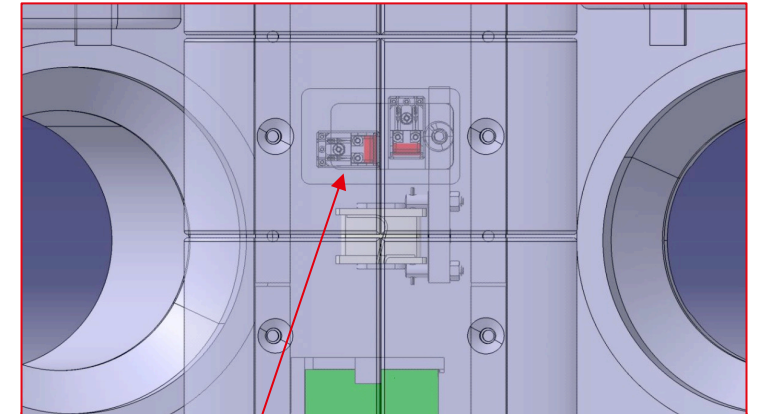
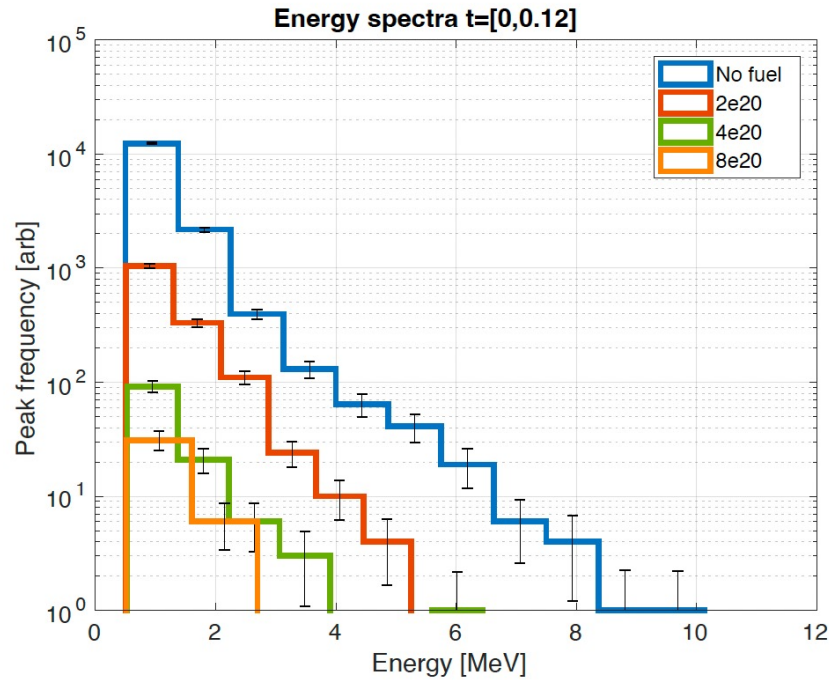
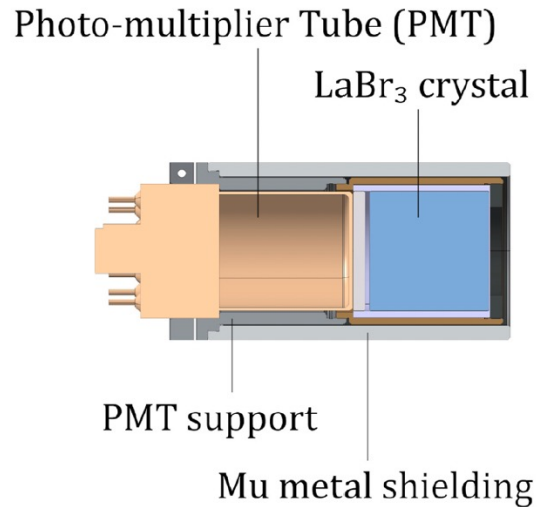
Both in the Alfvénic & the lower hybrid range ( $\Omega_{ci} \ll \omega \ll \Omega_{ce}$ )

*Can those modes be leveraged to expel or limit the maximum energy of runaway electrons?*



# EPFL Diagnostics for both the runaways and the waves

- Hard X-ray spectra from collisions between fast particles
- Coils / antenna for electromagnetic fluctuations



# Simulations of RE driven waves

☞ Coupling of 2 codes

LUKE: 3-D relativistic guiding-center Fokker-Planck code

- Kinetic equation for electrons
- Electric fields, collisions, avalanche generation, radiation losses, **wave-particle interactions**

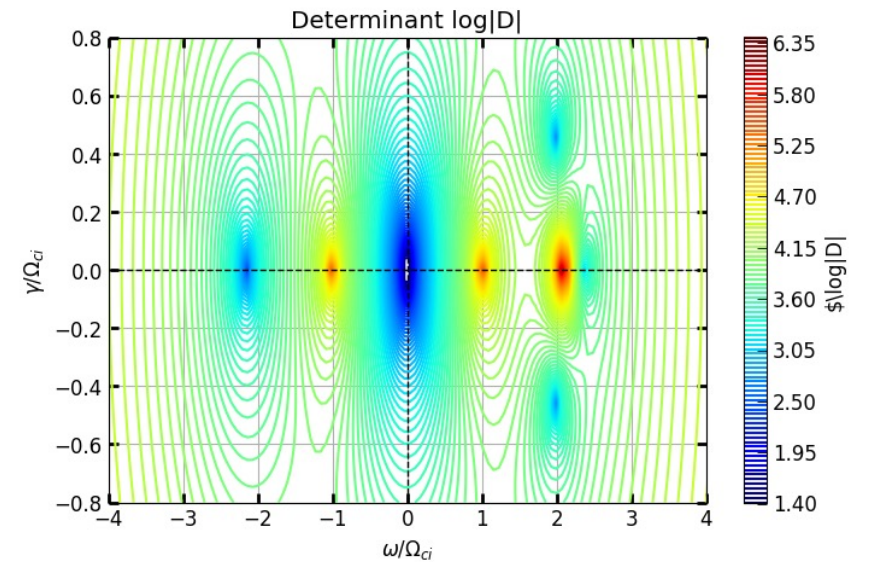
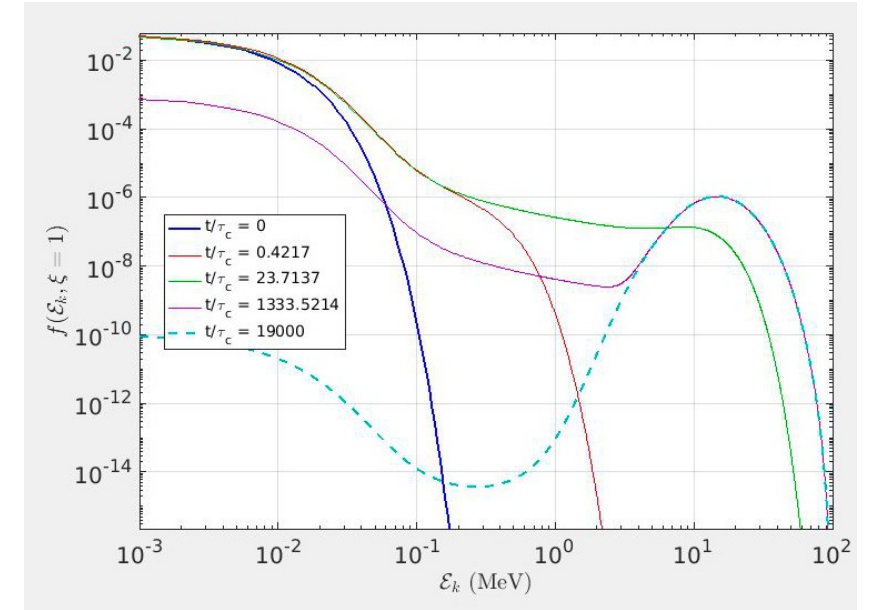
Provide electron distribution function as a function of

$$p_{\perp}, p_{\parallel}$$

Arbitrary Linear Plasma Solver (ALPS)

- Solves relativistic dispersion relation for hot plasmas
- Arbitrary distributions
- Typical parameters for tokamaks:

$$\frac{v_{alfven}}{c} \sim 10^{-4} - 10^{-2} \quad ; \quad \beta \sim 10^{-5} - 10^{-2}$$



## ☞ Coupling of 2 codes

LUKE: 3-D relativistic guiding-center Fokker-Planck code

- Kinetic equation for electrons
- Electric fields, collisions, avalanche generation, radiation losses, **wave-particle interactions**

↓ Provide electron distribution  
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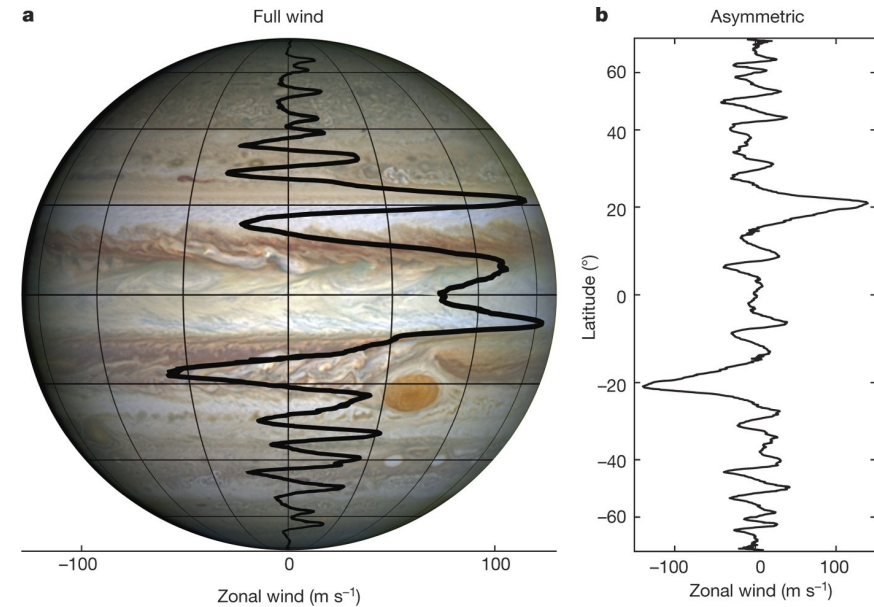
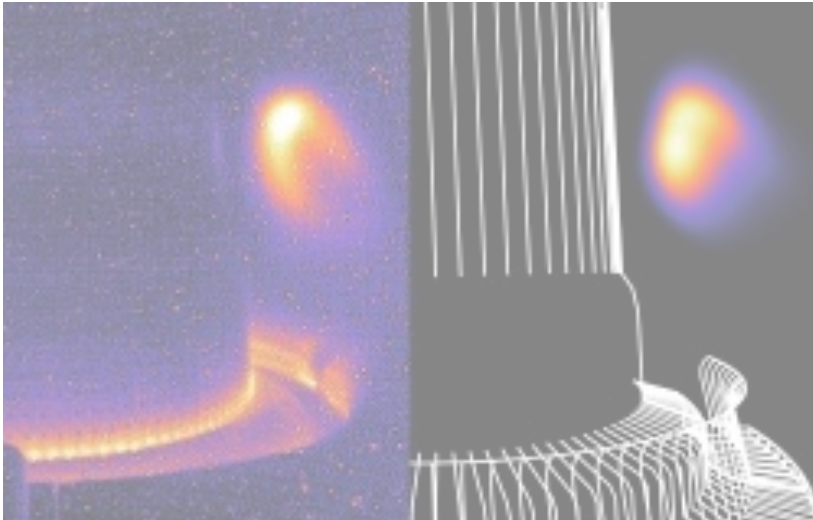
Arbitrary Linear Plasma Solver (ALPS)

- Solves relativistic dispersion relation for hot plasmas
- Arbitrary distributions (Chebyshev decomposition)

← Provide waves parameters:  
frequency, polarisation

# Possible synergies

- **Kinetic physics:** Interaction between waves and relativistic electrons in tokamaks
- **Turbulence:** Turbulence self-organization into zonal flows and associated transport



# Self-organization of turbulence into zonal flows

☞ Turbulence governs turbulent transport in the core

- **Turbulent flux** of heat / particles
- Local profile relaxation can produce **avalanches** → ballistic events of transport

[Diamond 95; Garbet 98; Sarazin 98; Politzer 00]

☞ **Zonal flows (ZFs)**

[Hasegawa 79; Diamond 05]

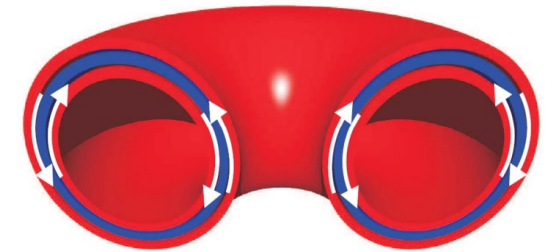
- Excited nonlinearly by turbulence: **Reynolds stress**  $\Pi_{tot}$

Electric:  $\Pi_E = \langle \tilde{v}_{Er} \tilde{v}_{E\theta} \rangle$  [Diamond 91]

Diamagnetic:  $\Pi_\star = \langle \tilde{v}_{\star r} \tilde{v}_{E\theta} \rangle$  [Smolyakov 00; Sarazin 21]

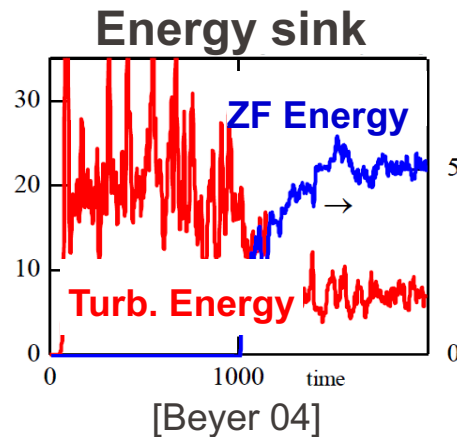
- Linearly stable: damped by **collisional friction**  $\mu$

Zonal flows

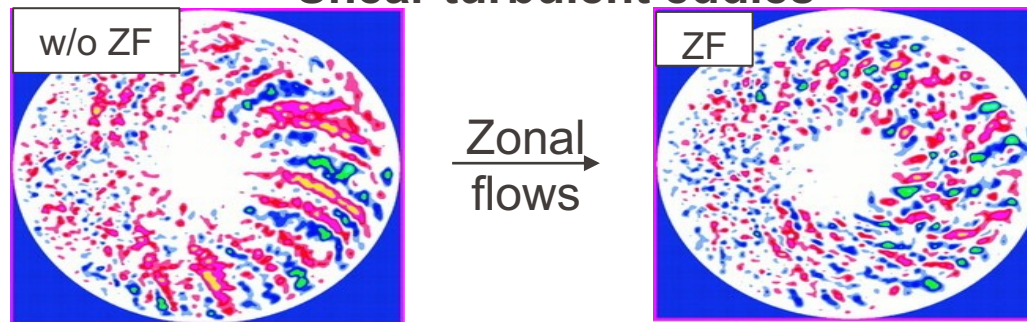


$$V_{ZF} = -\langle E_r \rangle / B$$

☞ ZFs quench turbulence



**Shear turbulent eddies**

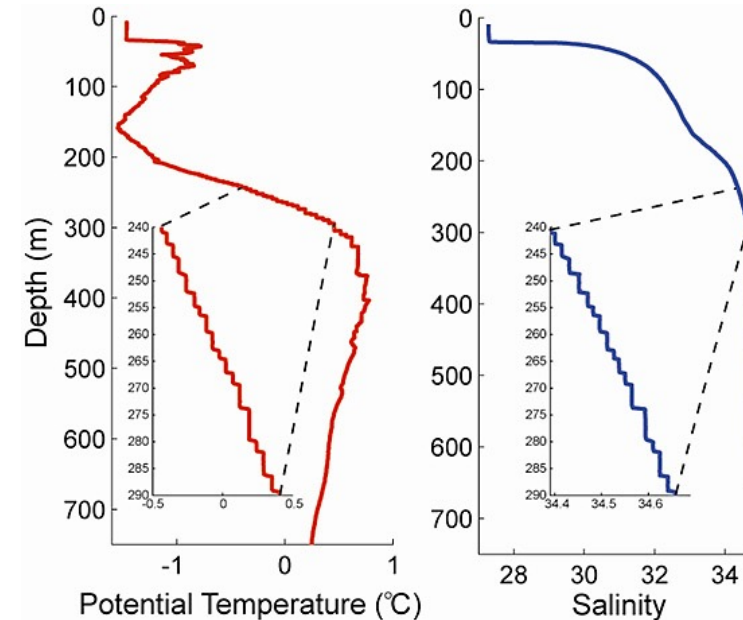
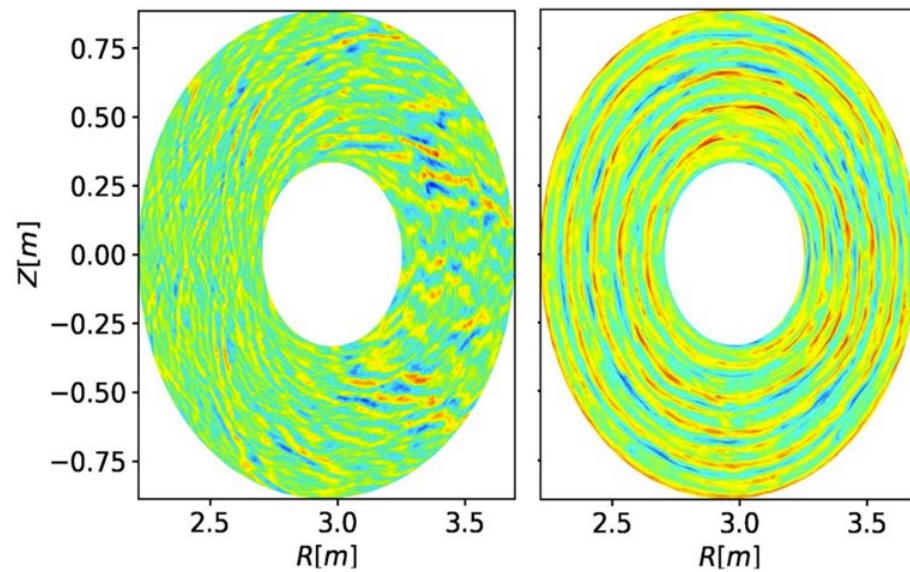


*Elec. Potential fluctuations  $\tilde{\phi}$*  [Lin 98]

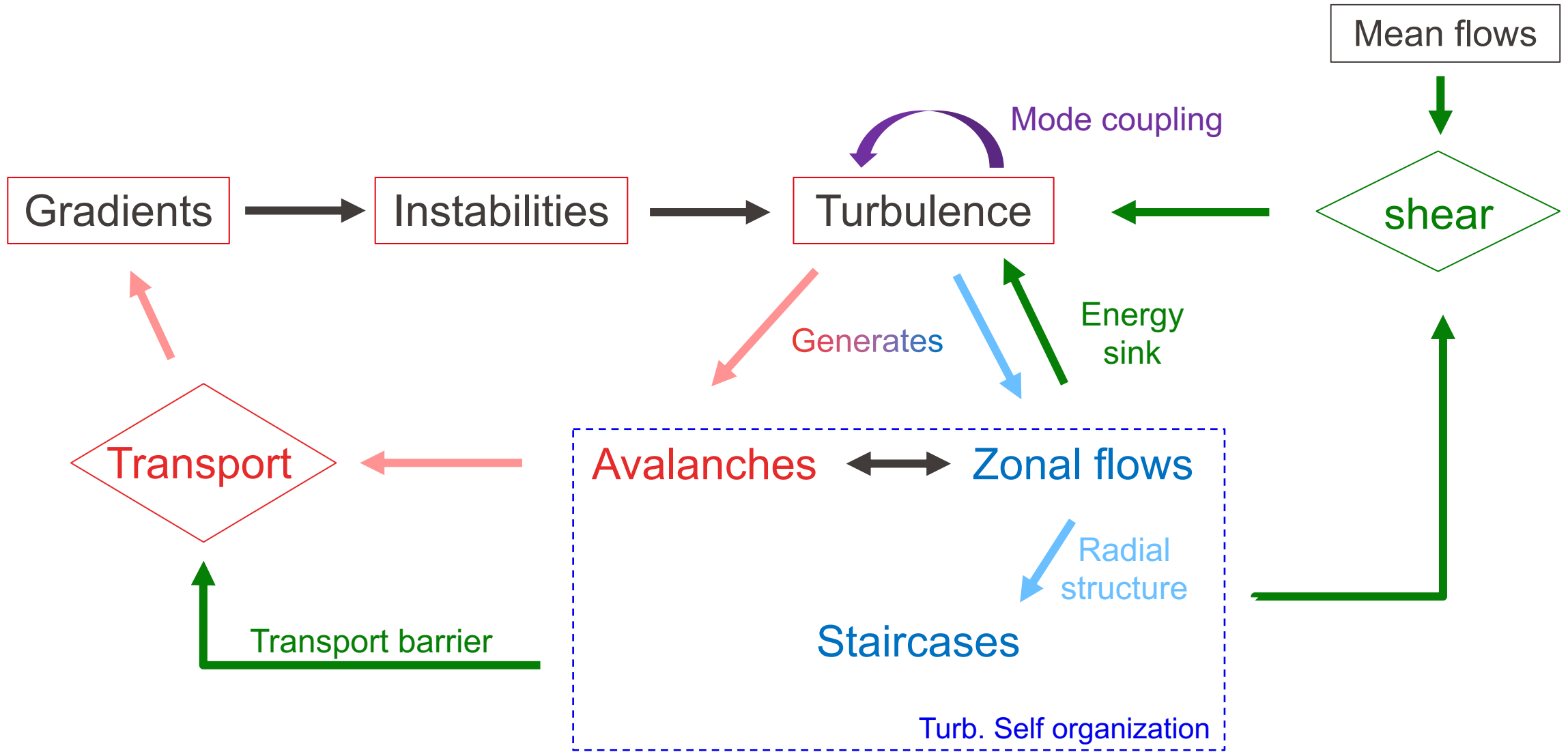
# Zonal flows can lead to staircase pressure profiles

☞ **Staircases:** radially localized sheared flows & corrugated pressure gradient

- Set of **microbarriers** → expected beneficial for confinement
- Well-established in **simulations** but difficult to observe experimentally in tokamaks

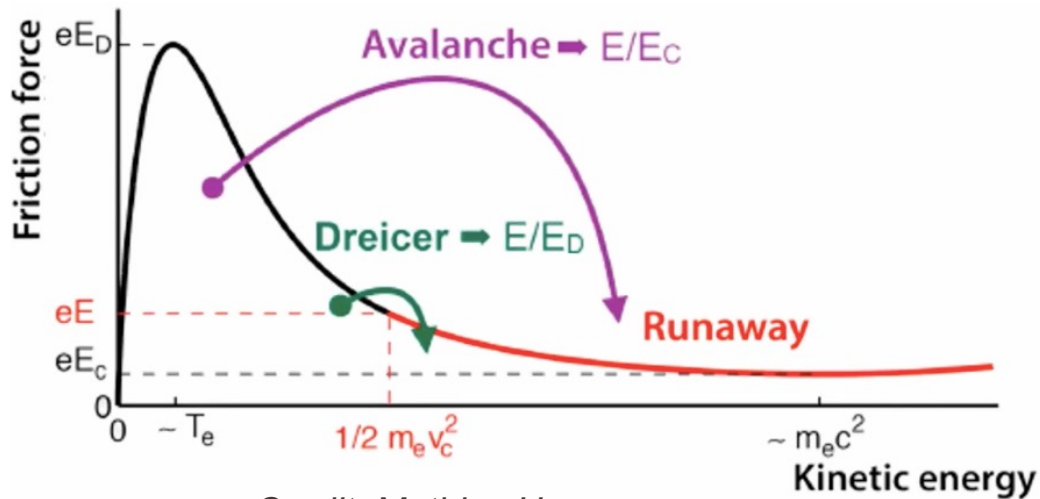
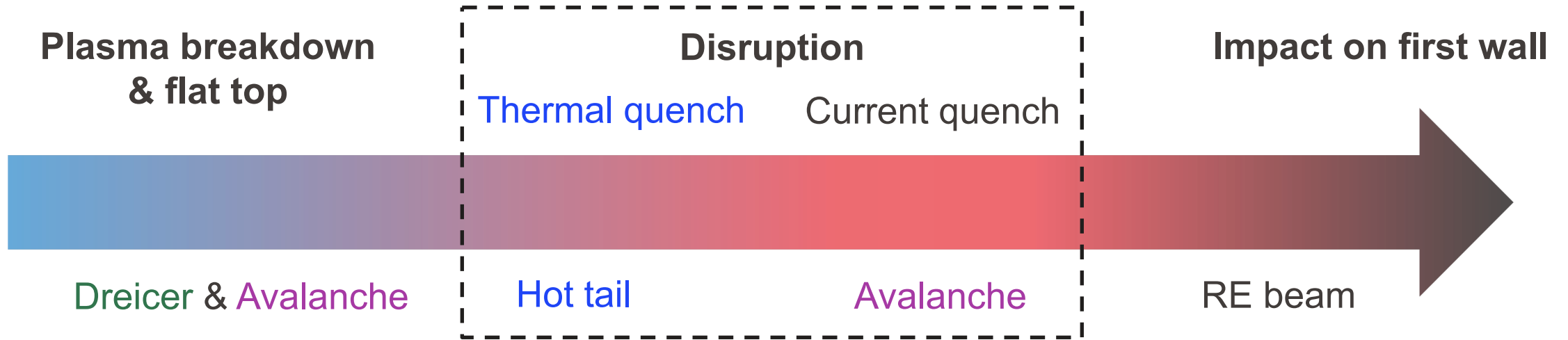


Also observed in Oceans: Salinity & temperature staircases

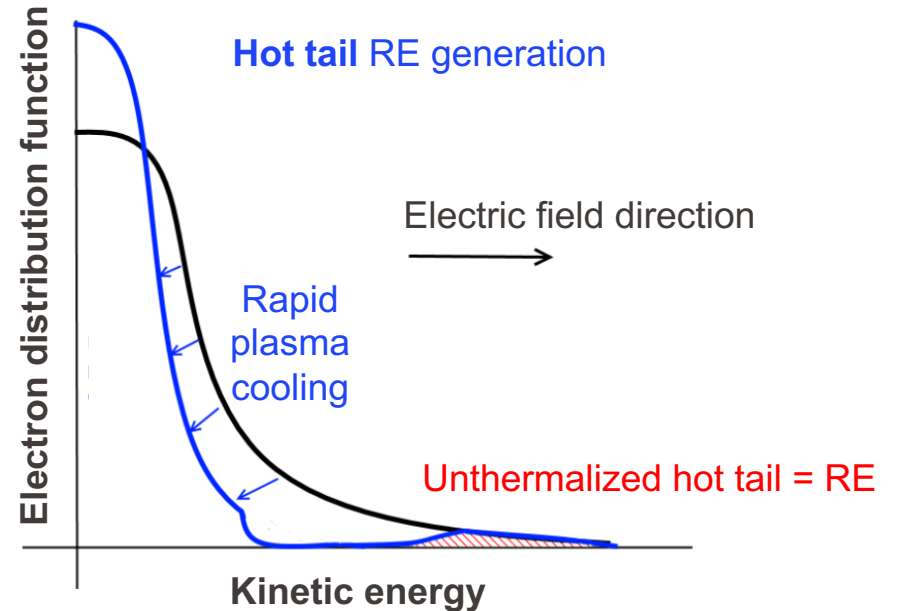


- **Kinetic physics:** Interaction between waves and relativistic electrons in tokamaks
  - Plasma conditions leading to RE driven waves?
  - Possibility for mode conversion, parametric instability?
  - Possibility of firehose / mirror instability?
  - Quasilinear / nonlinear interaction?
  - Possibility of externally launching the waves?
- **Turbulence:** Turbulence self-organization into zonal flows and associated transport
  - Observed in other fields?
  - For what turbulence parameters?

olivier.panico@epfl.ch



Credit: Mathias Hoppe



Credit: Ondrej Ficker

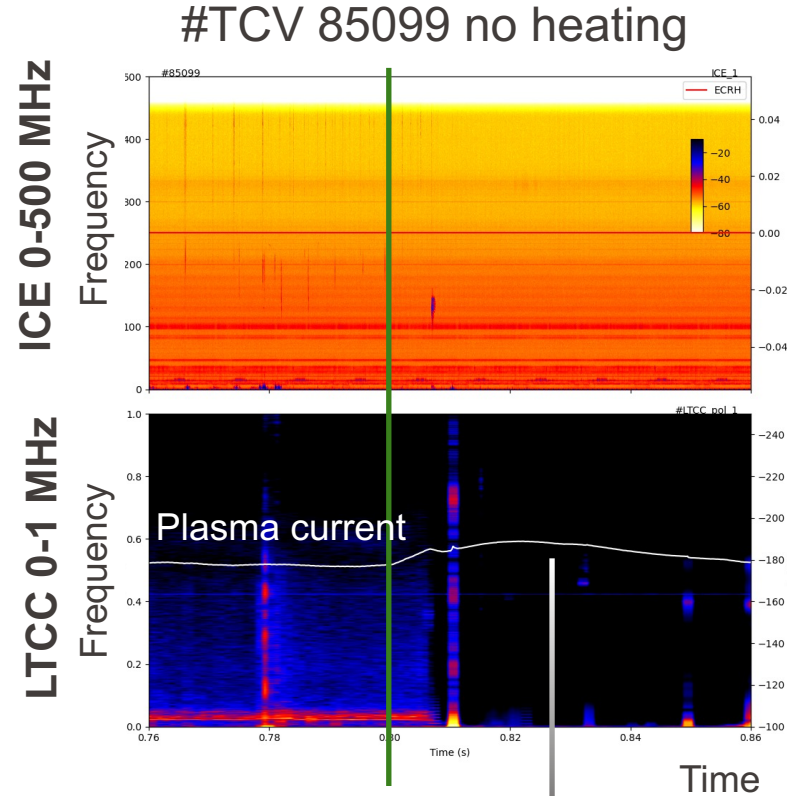
## Step 2: nonlinear modelling

### TCV recent experiments

- Disruption induced by massive gas injection (MGI)
- NBH applied around MGI
- Kinetic & Alfvénic** instabilities correlated with RE losses [Lier 2023]

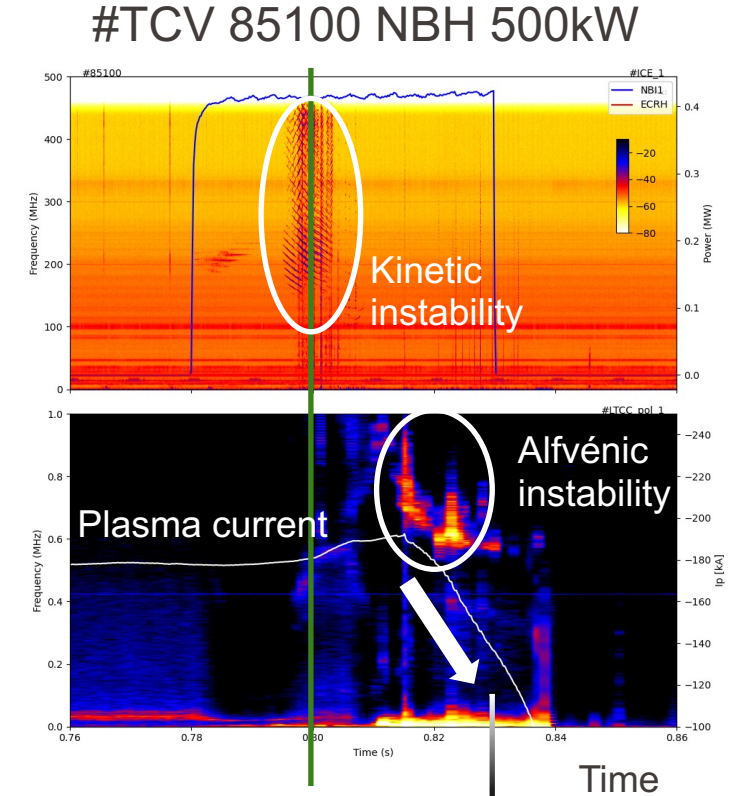
### Our goal

- Develop self-consistent modelling of RE dynamics and plasma instabilities
- Study of increased RE transport in the presence of instabilities



MGI induced disruption

RE carry steady post-disruption current



MGI induced disruption

Increased RE losses during instability & current decay