The thermo-Alfvénic instability — from toy model to torus

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Plasma losses

- **Turbulent transport** is expected to be the dominant mechanism of heat and particle losses in tokamaks, as well as neoclassically optimised stellarators.
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![Figure 1: STEP equilibria from Kennedy et al. (2023)](image)
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- Radial gradient of the plasma pressure is a **source of free-energy** for unstable perturbations, typically on scales comparable to the particle gyroradii

\[
k_{\parallel}L \sim 1, \quad k_{\perp}\rho_{s} \sim 1 \quad \Rightarrow \quad \frac{k_{\parallel}}{k_{\perp}} \sim \frac{\rho_{s}}{L} \ll 1 \quad \Rightarrow \quad \text{gyrokinetics}
\]
Plasma losses

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- Radial gradient of the plasma pressure is a **source of free-energy** for unstable perturbations, typically on scales comparable to the particle gyroradii.

- Understanding the microinstability properties of tokamak plasmas, and the resultant turbulence, is key to successful reactor design.
Electromagnetic fluctuations

Electromagnetic fluctuations will be larger in reactor-relevant tokamak scenarios due to a higher values of the **plasma beta**:

\[
\beta_s = \frac{\text{thermal pressure}}{\text{magnetic pressure}} = \frac{8\pi n_0 s T_0 s}{B_0^2}.
\]
Electromagnetic fluctuations

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$$\beta_s = \frac{\text{thermal pressure}}{\text{magnetic pressure}} = \frac{8\pi n_{0s} T_{0s}}{B_0^2}.$$ 

This is particularly true for spherical-tokamak (ST) designs, e.g., MAST, STEP, NSTX-U, and ST40.

Figure 2: From Costley (2019)
ST confinement scaling

Figure 3: From Valovič et al. (2011) (left), Kaye et al. (2013) (right)
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- Experimental MAST and NSTX data demonstrated a favourable scaling of confinement time with normalised collisionality:

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Shown to be consistent with the stabilisation of core micro-tearing modes, and a subsequent reduction in electron turbulent transport, at lower \( \nu_* \).
Unfinished business...

- Problem solved?
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- Problem solved? No!
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- **Uncertainty** about the fundamental physics responsible for commonly observed electromagnetic modes, e.g., the

  | micro-tearing mode (MTM) | or | kinetic ballooning mode (KBM) |
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- Nonlinear simulations of local gyrokinetic turbulence sometimes **fail to saturate** at an experimentally-permissible level in the electromagnetic regime; see, e.g., Pueschel *et al.* (2013); Giacomin *et al.* (2023).
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▶ **Key question:**

Can we distil the **essential physical ingredients** behind electromagnetic destabilisation by constructing simplified models?
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Local constant-curvature approximation
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Local constant-curvature approximation

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- Tokamak instabilities are distinguished from other plasma instabilities by the particular \textit{configuration of equilibrium gradients}
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Tokamak instabilities are distinguished from other plasma instabilities by the particular configuration of equilibrium gradients.

Consider a local “toy” model with radial equilibrium gradients that are constant along the field line:

\[
L_T^{-1} = - \frac{1}{T_0e} \frac{dT_0e}{dx}, \quad L_B^{-1} = - \frac{1}{B_0} \frac{dB_0}{dx}.
\]
Low-beta electron dynamics

- All that follows is derived in an asymptotic limit of gyrokinetics.

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| Fields:     | $\phi, A_\parallel, \delta B_\parallel, \delta n_e, u_\parallel e, \delta T_e, \ldots$ |
| Frequencies:  | $\omega \sim k_\parallel v_{the} \sim \omega_* e \sim \omega_{de} \sim k_\parallel v_A$ |
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- Low-beta limit orders out parallel (compressive) magnetic-field perturbations. Not always a good approximation; e.g., in STEP (see Kennedy et al., 2024)
- Considering timescales comparable to the electron streaming rate; appropriate for electron-scale instabilities.
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<td>$\rho_i^{-1} \lesssim k_\perp \sim d_e^{-1} \ll \rho_e^{-1}, \quad k_\parallel L_T \sim \sqrt{\beta_e}$</td>
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- Considering timescales comparable to the electron streaming rate; appropriate for electron-scale instabilities.

- In a straight (unsheared) magnetic field, the flux-freezing scale $d_e = \rho_e/\sqrt{\beta_e}$ demarcates the transition between the electrostatic and electromagnetic regimes.
Electrostatic regime
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At $k_{\perp}d_e \gg 1$, electrons are allowed to stream freely across unperturbed field lines. Instabilities extract free energy from the ETG via the usual $E \times B$ feedback mechanism.
Electrostatic regime

- At $k_\perp d_e \gg 1$, electrons are allowed to stream freely across unperturbed field lines. Instabilities extract free energy from the ETG via the usual $E \times B$ feedback mechanism.
- For $k_\parallel \rightarrow 0$, we recover the familiar curvature-mediated ETG (2D interchange mode, Horton et al. 1988):

$$\omega = \pm i \left(2\omega_d\omega_e\tau\right)^{1/2}.$$
Curvature-mediated ETG

\[
\frac{d}{dt} \frac{\delta n_e}{n_{0e}} = - \frac{\rho_e v_{the}}{L_B} \frac{\partial}{\partial y} \frac{\delta T_e}{T_{0e}} \tag{Continuity}
\]

\[
\frac{d}{dt} \frac{\delta T_e}{T_{0e}} = - \frac{\rho_e v_{the}}{2L_T} \frac{\partial \varphi}{\partial y} \tag{Temp. advection by \( E \times B \)}
\]
Curvature-mediated ETG

\[
\frac{d}{dt} \delta n_e = -\frac{\rho_e v_{\text{th}}}{L_B} \frac{\partial}{\partial y} \frac{\delta T_e}{T_{0e}}', \\
\frac{d}{dt} T_{0e} = -\frac{\rho_e v_{\text{th}}}{2L_T} \frac{\partial \varphi}{\partial y}'.
\]

A temperature perturbation with \( k_y \neq 0 \) has alternating hot and cold regions along \( \hat{y} \).
Curvature-mediated ETG

\[
\begin{align*}
\frac{d}{dt} \delta n_e & = -\frac{\rho_e v_{th e}}{L_B} \frac{\partial}{\partial y} \delta T_e, \\
\frac{d}{dt} T_{0e} & = -\frac{\rho_e v_{th e}}{2L_T} \frac{\partial \varphi}{\partial y},
\end{align*}
\]

- Velocity dependence of magnetic drifts \( v_{de} \) creates an electron density perturbation (hot particles drift faster than cold ones).
- This electron density perturbation has only \( k_y \neq 0 \).
Curvature-mediated ETG

\[ \frac{d}{dt} \frac{\delta n_e}{n_0e} = -\frac{\rho_e v_{\text{th}}}{L_B} \frac{\partial}{\partial y} \frac{\delta T_e}{T_0e}, \quad \frac{d}{dt} \frac{\delta T_e}{T_0e} = -\frac{\rho_e v_{\text{th}}}{2L_T} \frac{\partial \varphi}{\partial y}, \]

- The electron density perturbation creates, via a quasineutral Boltzmann-ion response, alternating electric fields \( E \).
- Gives rise to an \( E \times B \) drift that reinforces the initial perturbation.
Electromagnetic regime
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- At $k_{\perp} d_e \ll 1$, $\delta B_{\perp}$ is created as electrons drag field lines around.
Electromagnetic regime

- At $k \perp d_e \ll 1$, $\delta \mathbf{B}_\perp$ is created as electrons drag field lines around.
- Modifies parallel gradients, e.g.,

\[
\frac{1}{T_{0e}} \nabla || (T_{0e} + \delta T_e) = \nabla || \frac{\delta T_e}{T_{0e}} + \frac{\delta B_x}{B_0} \frac{1}{T_{0e}} \frac{dT_{0e}}{dx} = \nabla || \frac{\delta T_e}{T_{0e}} - \frac{\rho_e}{L_T} \frac{\partial A}{\partial y}
\]

⇒ introduces another mechanism by which the perturbations can go unstable.
Electromagnetic regime

- At $k_{\perp}d_e \ll 1$, $\delta B_{\perp}$ is created as electrons drag field lines around.
- Modifies parallel gradients, e.g.,

$$\frac{1}{T_{0e}} \nabla_\parallel (T_{0e} + \delta T_e) = \nabla_\parallel \frac{\delta T_e}{T_{0e}} + \frac{\delta B_x}{B_0} \frac{1}{T_{0e}} \frac{dT_{0e}}{dx} = \nabla_\parallel \frac{\delta T_e}{T_{0e}} - \frac{\rho_e}{L_T} \frac{\partial A}{\partial y}$$

⇒ introduces another mechanism by which the perturbations can go unstable.
Curvature-mediated **thermo-Alfvénic instability** (cTAI):

\[ \omega = \pm i \left[ 2\omega_{de}\omega_e(1 + \tau) \right]^{1/2}. \]

Two key differences to cETG: (i) it relies on \( k_{\parallel} \neq 0 \), and (ii) it does not require the \( E \times B \) feedback mechanism to be unstable.
Curvature-mediated TAI

\[
\frac{d}{dt} \delta n_e = -\frac{\rho_e v_{the}}{L_B} \frac{\partial}{\partial y} \delta T_e ,
\]
Continuity

\[
\frac{dA}{dt} + \frac{v_{the}}{2} \frac{\partial \varphi}{\partial z} = \frac{v_{the}}{2} \nabla \parallel \frac{\delta n_e}{n_{0e}} ,
\]
Parallel pressure balance

\[
\nabla \parallel \frac{\delta T_e}{T_{0e}} = \frac{\rho_e}{L_T} \frac{\partial A}{\partial y} ,
\]
Isothermality
Curvature-mediated TAI

\[
\frac{d}{dt} \frac{\delta n_e}{n_{0e}} = -\frac{\rho_e v_{\text{th}}}{L_B} \frac{\partial}{\partial y} \frac{\delta T_e}{T_{0e}}, \quad \frac{dA}{dt} + \frac{v_{\text{th}}}{2} \frac{\partial \varphi}{\partial z} = \frac{v_{\text{th}}}{2} \nabla || \frac{\delta n_e}{n_{0e}} , \quad \nabla || \frac{\delta T_e}{T_{0e}} = \frac{\rho_e}{L_T} \frac{\partial A}{\partial y},
\]

- A perturbation \( \delta B_x = B_0 \rho_e \partial_y A \) sets up a variation of total temp. along the perturbed field line as it makes excursions into hot and cold regions.
- Rapid thermal conduction along field lines creates a temperature perturbation that compensates for this.
Curvature-mediated TAI

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- Velocity dependence of magnetic drifts \( \mathbf{v}_{de} \) creates an electron density perturbation (hot particles drift faster than cold ones).
- This electron density perturbation has both \( k_y \neq 0 \) and \( k_\parallel \neq 0 \).
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\]

- The parallel density gradient must be balanced by the parallel electric field.
- Inductive part leads to an increase in $\delta B_x$, deforming the field line further into the hot and cold regions $\Rightarrow$ feedback.
Electron-scale instabilities: ETG and TAI

Both the sTAI and cTAI exist in the collisionless ($ν^* → 0$) and collisional ($ν^* ≫ 1$) limits, with the relevant parallel timescale being parallel streaming and thermal conduction, respectively.

The general physical mechanism is the competition between the diamagnetic drifts and temperature equilibration along perturbed magnetic field lines $\Rightarrow$ accessing the magnetic flutter drive.
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- Both the sTAI and cTAI exist in the collisionless ($\nu_* \to 0$) and collisional ($\nu_* \gg 1$) limits, with the relevant parallel timescale being parallel streaming and thermal conduction, respectively (see Adkins et al., 2022).

- The general physical mechanism behind the thermo-Alfvénic instability is the competition between the diamagnetic drifts and temperature equilibration along perturbed magnetic field lines $\Rightarrow$ magnetic flutter drive.
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Benchmarking against known results

Can we recover the TAI in gyrokinetics? Following results are from a collaboration with D. Kennedy (CCFE) and M. Giacomin (Padova)
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Benchmarking against known results

- Performed simulations of sTAI in GS2 and GENE. Adiabatic ions, $\beta_e = 0.09$, $L_{\text{ref}}/L_T = 105$, $k_{||}^{\text{min}} = 0.03\sqrt{\beta_e/L_T}$.
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- What about curvature? Both GS2 and GENE are able to recover cTAI in $\hat{s} - \alpha$ geometry with $q_0 = 1$, $r/R = 10^{-8}$. 
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- What about curvature? Both GS2 and GENE are able to recover cTAI in $\hat{s} - \alpha$ geometry with $q_0 = 1$, $r/R = 10^{-8}$.
- Eigenfunctions: sTAI has odd (tearing) parity, while cTAI has even parity.
Inching towards the torus

- Increase **complexity** further to better approximate a realistic tokamak: magnetic shear + Shafranov shift.

\[ \hat{s} = \frac{r \, dq}{q \, dr}, \quad \alpha = -R_0 q^2 \frac{8\pi}{B_0^2} \frac{dp}{dr} \]
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- It appears that the TAI instability mechanism appears to survive (some of) the transition to toroidicity.
Comparison with KBM and MTM

- Use “fingerprinting” to identify and class instabilities (see, e.g., Kotschenreuther et al., 2019)

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A minimal model of electromagnetic saturation?

sTAI Fluid Simulation

$|\delta \phi_{k_y}|^2(t)$

$|\delta A_{k_y}|^2(t)$
A minimal model of electromagnetic saturation?
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1. Introduction

2. The Thermo-Alfvénic instability

3. Returning to toroidal geometry

4. Summary
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Thank you for listening.

Questions?


