MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Excitation of Alfvénic Modes via Electromagnetic Turbulence in Wendelstein 7-X

J. Riemann[1], S. V. Mendes[1], K. Rahbarnia[1], R. Kleiber[1], C. Slaby[1], A. Könies[1], M. Borchardt[1], A. Mishchenko[1], H. Thomsen[1], C. Büschel[1], A. v. Stechow[1], J.-P. Bähner[2], S. K. Hansen[2], E. Edlund[3] and the W7-X Team[1]

[1] IPP, Greifswald [2] MIT, Cambridge [3] SUNY, Cortland

EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Introduction

Experimental Results

Numerical Simulations

Summary

Supplementing Material

Introduction

The focus of this work is on the excitation of Alfvén eigenmodes observed in electron-cyclotron-heated plasmas in the Wendelstein 7-X stellarator.

Alfvénic modes:

- are a key consideration in the design of fusion devices
- can be excited by energetic particles (NBI, ICRH or fusion-born alphas)
  $\rightarrow$ resonant wave-particle interaction (well-understood)
  $\rightarrow$ "energetic-particle drive" paradigm
- act on larger scales and can lead to a redistribution of energetic particles
- may affect heating efficacy and can cause particle losses (1st wall damages)
- can mitigate turbulence through zonal-flow excitation
- have become subject to multi-scale studies

Introduction

Alfvénic modes persisting throughout entire discharges are observed in nearly all experimental programs conducted on Wendelstein 7-X.†

- applies also to discharges without energetic particles
- even if present, “energetic-particle drive” could be ruled out by simulations ††
- similar observations were also made at other fusion experiments
- an alternative driving mechanism (wave-wave) had to be identified
- interaction with turbulence suggested - not yet substantiated by numerical model

This work proposes coupling between electromagnetic ITG turbulence and Alfvénic modes as an explanation for their excitation in Wendelstein 7-X. Results from extensive gyrokinetic simulations support this hypothesis and are in the same frequency and mode number range as found experimentally.

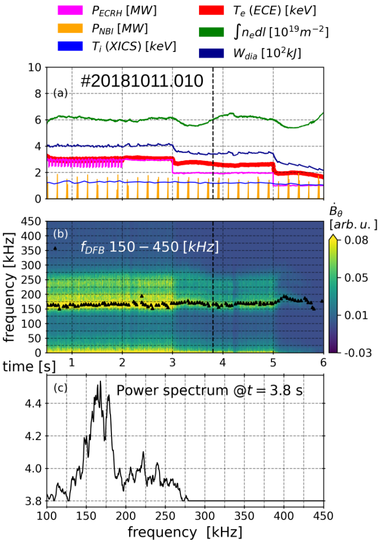
† S. V. Mendes et al., Nuclear Fusion **63** (2023), †† C. Slaby et al., Nuclear Fusion **60** (2020)

Experimental Results (I)

- 477 experimental W7-X programs analyzed [†]
- magnetic fluctuations measured by Mirnov coils
- broad spectrum of magnetic fluctuations $\dot{B}_\theta$
- frequencies scale with Alfvén frequency

experimental program #20181011.010 :

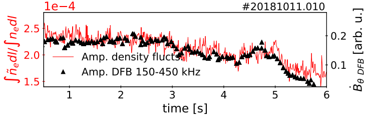
- dominant frequency band between 150-200 kHz
- subdominant frequency band for 220-250 kHz
- frequency peaks at $f \approx 170$ kHz and $f \approx 225$ kHz
- single modes identified with SSI method [††]
- most probable poloidal mode numbers:
  $m = 2$ (166 kHz), $m = -2$ (170 kHz), $m = 3$ (178 kHz)

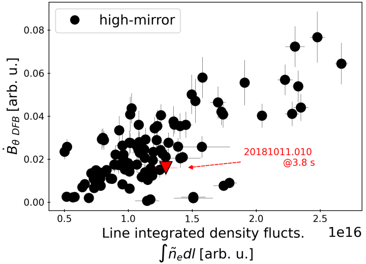


[†]Mendes et al., NF **63** (2023), [††]SSI = stochastic system identification

Experimental Results (II)

- predominant ITG turbulence observed in W7-X
- turbulent density fluctuations measured with PCI[†]
  diagnostic signal: $\int \tilde{n}_\mathrm{e}\mathrm{d}l / \int n_\mathrm{e}\mathrm{d}l$
- dominant frequency band (DFB) tracked in time
  using a special algorithm
- temporal evolution of turbulence (PCI signal) and magnetic fluctuations $\dot{B}_\theta$ (Mirnov signal) is found very similar over entire discharge
- Alfvénic fluctuation amplitudes and turbulence level are correlated





experimental findings suggest hypothesis:

Alfvénic broad-band fluctuations in W7-X are driven by ITG turbulence.

[†] Phase Contrast Imaging in W7-X: J.-P. Bähner et al., Journ. Plasma Phys. **87** (2021)

Numerical Simulation Setup

- numerical simulation model case was constructed to confirm this hypothesis
  → use global electromagnetic gyrokinetic particle-in-cell code EUTERPE †
- model case setup:
  - pressure profile closely matching experimental program #20181011.010
  - consistent 3D VMEC equilibrium for KJM configuration
  - computational domain: annulus with $0.32 \leq r/a \leq 1.0$
  - Fourier modes up to $k_\perp \rho_\mathrm{i} \approx 0.67$ considered
  - extensive numerical simulation ($\approx 10^6$ CPU hours)

- modifying assumptions:
  - $T_\mathrm{e} = T_\mathrm{i}$ for numerical simplicity and since predominant ITG activity expected
  - up-scaled (≈factor 6) temperature & down-scaled density **but** pressure maintained to keep resolution and computational cost low (shift of mode activity)
    $\Rightarrow$ frequencies scale as: $f_\mathrm{exp} = f_\mathrm{sim}\sqrt{T_\mathrm{exp}/T_\mathrm{sim}}$

† R. Kleiber et al. Computer Physics Communications **295** (2024)

Numerical Results - Time Traces

- most prominent modes shown
- early ITG (high-*m*) activity

  high poloidal mode numbers *m*
- Zonal Flow & Alfvénic modes

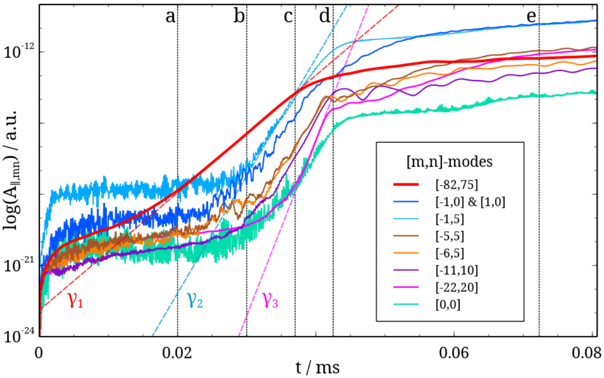
  when ITG has passed threshold
- growth rate cascade

  $$\gamma_1 : \gamma_2 : \gamma_3 = 1\gamma : 2\gamma : 3\gamma$$

  2γ observed earlier with zonal flows via energetic particles (“forced-driven” ZFs)[†]

  NEW: 3γ yet to be explained theoretically!
- results suggest causal chain:

evolution of radially integrated Fourier Amplitudes of $A_{||}$



Alfvénic modes driven by ITG instabilities through nonlinear interaction

---

[†] Todo et al., Nucl. Fusion **50** (2010); Z. Qiu et al., Nucl. Fusion **57** (2017)

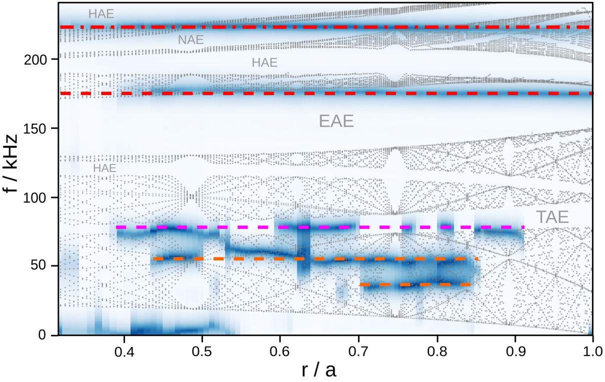
Numerical Results - Spectrogram (Rescaled)

- $f_{\text{exp}} = f_{\text{sim}} \sqrt{T_{\text{exp}} / T_{\text{sim}}}$
- frequencies & [m,n]-modes:

175 kHz	→ $[\pm 1,0]$	EAE
225 kHz	→ $[-1,5]$	NAE
77 kHz	→ $[-5,5]$, $[-6,5]$	TAE
35 kHz	→ $[-11,10]$	
50 kHz	→ $[-11,?]$	

- different mode numbers found
  - only one field period modelled
    $\Rightarrow$ only one toroidal mode family
    ($n = 0, \pm 5, \pm 10, \ldots$)
  - experimental uncertainties?

DMUSIC spectrogram including poloidal modes with $|m| = 1, 5, 6, 11$ & linear(!) continuous spectrum (CONTI)



Numerical results mainly align with experimental findings.

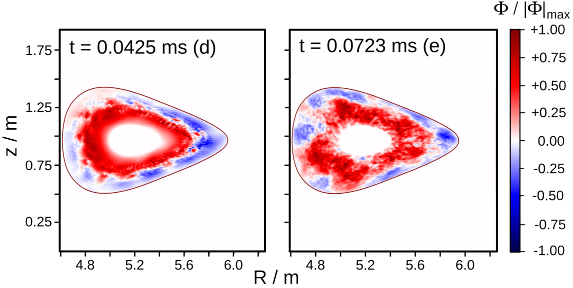
Numerical Results - Poloidal Mode Structures

- electrostatic potential Φ
- triangular cross section of W7-X

  close to Mirnov coil arrangement
- snapshots at different times

  time labels d & e
- charactristic structures
  - fine-scale remnants of ITG
  - $[-11, 10]$-mode structure

    $\rightarrow$ related to 10/11-resonance at $r/a = 0.75$
  - zonal flow
  - low-*m* structures



early (d) and late (e) nonlinear phase

Summary

- Excitation of long-wavelength Alfvénic modes was observed in W7-X.
- Energetic particles and a “forced-driven” mechanism could be ruled out.
- Excitation of Alfvénic modes via electromagnetic ITG turbulence was suggested.

- **Extensive nonlinear simulations were performed with EUTERPE.**
- **Remarkably good agreement with experimentally observed frequencies.**
- **Results allow new qualitative insight into complex excitation mechanism.**

- Findings may open new perspectives for understanding of nonlinear phenomena.
- EUTERPE is a valuable tool for further collaborations with the experiment.

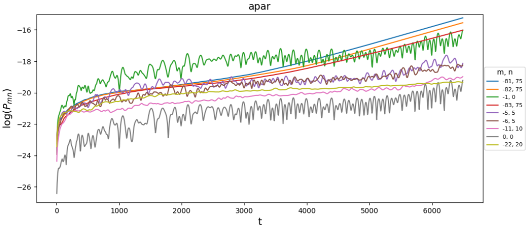
This work was carried out within the framework of the EUROfusion Consortium (Grant Agreement No 101052200 - EUROfusion).

All simulations were performed on MARCONI at CINECA HPC (Italy) using resources granted to projects TSVV13, TSVV10 and EUGY.

The Driving Role of ITG Activity

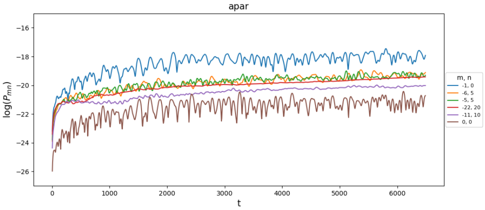
The role of ITG activity was tested.

1. ITG modes included in Fourier filter
   → low-*m* modes follow ITG growth



ITG activity inculded

2. ITG modes excluded from Fourier filter
   → now growth of low-*m* modes



ITG activity suppressed

Phase Space Diagnostics

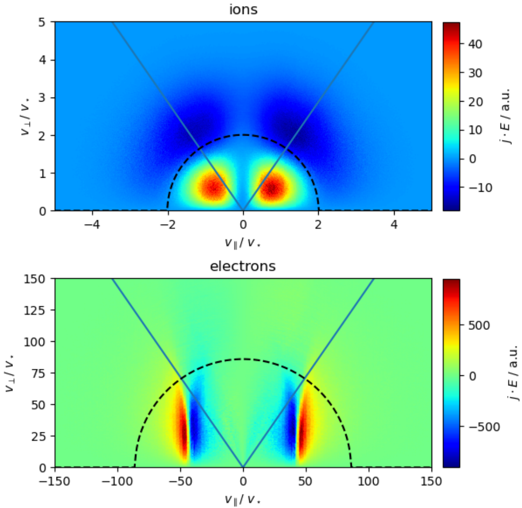
- integrated energy transfer ($\mathbf{j} \cdot \mathbf{E}$) between particles and E-field

  $j \cdot \mathbf{E} > 0$: field $\longrightarrow$ particle

  $j \cdot \mathbf{E} < 0$: field $\longleftarrow$ particle
- ions

  characteristic footprint of toroidal ITG
- electrons

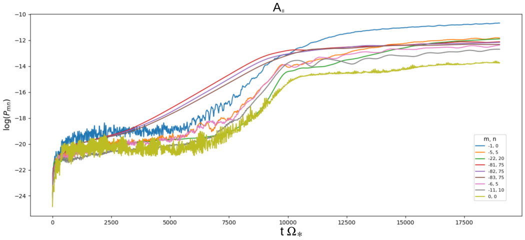
  Landau-like resonance
- no trapping effects

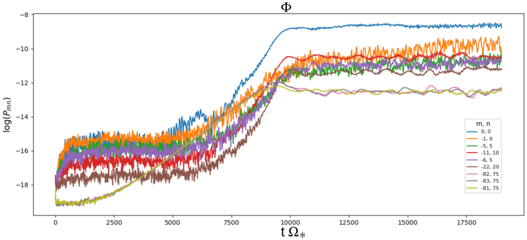


Time Traces: Electrostatic vs. Vector Potential

evolution of radially integrated Fourier Amplitudes

- $A_{||}$: very clear signals
- Φ : fast fluctuations
- electrostatic vs. magnetic nature of different modes visible
- different saturation behaviour





Some Parameters

simulation:

- $T_* = 3.75$ keV $(T_0 = 10$ keV$)$
- $n_* = 6.12 \cdot 10^{18}$ m^{-3} $(n_0 = 6.98 \cdot 10^{18}m^{-3})$
- $B_* = 2.46$ T
- $v_* = 5.99 \cdot 10^4$ m/s
- $\Omega_* = 2.35 \cdot 10^8$ s^{-1}
- $\rho_{\mathrm{i}*} = 2.55 \cdot 10^{-3}$ m
- $\beta = 8.6 \cdot 10^{-4}$

experiment:

- $T_0 \approx 1.5$ keV
- $n_0 \approx 5 \cdot 10^{19}$ m^{-3}

radial reference position: $s_* = 0.5$ $(r_*/a = 0.71)$