Observation and interpretation of tornado modes coupled to near-axis Alfvén cascade eigenmodes in JET sawtoothing plasmas

R. Calado, F. Nabais, S. Sharapov, J.P. Bizarro

GTM meeting

28/05/2021
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Motivation

Two types of modes seemingly coupled:

- Upward frequency sweeping modes in the range 100-200 kHz
- Modes within the frequency range 225-250 kHz with some frequency modulation

1st type resembles Alfvén Cascades (ACs)

2nd type was previously identified as tornado modes*

Applicability to MHD spectroscopy of post-sawtooth dynamics?

Tornado Modes Preceding Sawtooth Crashes

First reported by the JT-60U Team

Called “Tornado” because of non-Alfvénic frequency sweeping (not ~$B/\rho^{1/2}$)

Identified as TAE inside the $q=1$ radius, with the “twist” frequency caused by the proximity to magnetic axis

1 M. Saigusa et al., PPCF 40 (1998) 1647
The “Alfvén Cascade” Modes in Reversed Shear Discharges

First observed in JT-60U negative shear plasmas

Observed then in JET, DIII-D, ASDEX-Upgrade, C-MOD, MAST, NSTX, TCV...

Interpreted as Eigenmodes residing at maximum points of Alfvén continuum caused by the zero magnetic shear

ACs are usually associated with non-monotonic q(r)-profiles. However, the possibility of AC existence in plasmas with monotonic but very flat q-profiles was predicted in [B.Breizman et al., Phys. of Plasmas 10 (2003) 3549]

1. Y.Kusama et al., PPCF 38 (1998) 1215
Outline

Experimental conditions and observations

Identification of the modes
Numerical calculation of mode structure and frequency

Energetic ion population drive
Resonances and orbits contributing to mode drive along its evolution

Conclusion
Experimental conditions

Auxiliary plasma heating was on-axis ICRH of hydrogen minority ($n_H/n_e=2.5\%$) with flat power waveform

Diagnostic NBI blips necessary for MSE measurements crucial for reconstruction of q-profile close to the axis

Density approximately constant; temperature evolution indicates sawtooth oscillation

JET machine parameters: 2.7 T magnetic field, 2 MA plasma current

Observation of near-axis coupled AC type and tornado modes

Tornado modes are TAEs and so they are associated with specific $q_{n,m}=(m-1/2)/n$

We are between sawteeth so $q_0$ is close to unity but gradually decreasing in time, and the modes have $m=n$

As the $q$-profile decreases $q_0$ crosses $q_{n}=(n-1/2)/n$ and the corresponding tornado mode is then allowed to exist, which explains why they appear one by one from high to low toroidal mode numbers.

ACs and tornado modes are observed in interferometry diagnostics but not in magnetics which are peripheral.

Modes very close to magnetic axis
Outline

Experimental conditions and observations

Identification of the modes
  Numerical calculation of mode structure and frequency

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Conclusion
Retrace back from late stage tornado

Starting point in final stage of tornado modes ➤ Retrace back plasma evolution ➤ Establish connection between ACs and tornado modes
Rescaling $q_0$ to mimic post-sawtooth plasma evolution

Before sawtooth crash $q_0<1$, crash raises $q_0$, then it gradually decreases.

We have EFIT equilibrium reconstruction with MSE measurements refined with HELENA for $t=19.9s$.

Equilibrium reconstructed q-profile is rescaled to reproduce plasma evolution after sawtooth crash.

For each step (i.e. for each $q_0$) MHD code MISHKA is used to scan for the existence of modes close to the axis.
Near-axis cascades in very flat q-profile

q-profile is very flat near the axis but nonetheless monotonic

ACs are usually connected to shear reversal; however, they can be allowed in the right conditions if q-profile is sufficiently flat*

Tornado modes: TAEs inside $q=1$**

AC modes: near-axis, flat q cascades


$\text{AC} \rightarrow \text{tornado transition occurs at } q_0 = \frac{(n-1/2)}{n}$

All modes have the same evolution

1\textsuperscript{st} stage: grand cascade with higher $n$ modes sweeping faster in frequency*

2\textsuperscript{nd} stage: tornado mode

For mode with toroidal mode number $n$ the transition point occurs at $q_0 = q_n = \frac{(n-1/2)}{n}$

MHD spectroscopy of $q$-profile evolution after sawtooth crash:
$q_6 = 0.917; q_5 = 0.9; q_4 = 0.875; q_3 = 0.833$

Highly localised AC, tornado modes larger radial extent

n=4:

AC

Tornado

(a) $q_0 = 0.94$, $\omega / \omega_A = 0.254$

(b) $q_0 = 0.88$, $\omega / \omega_A = 0.541$

(c) $q_0 = 0.874$, $\omega / \omega_A = 0.566$

(d) $q_0 = 0.87$, $\omega / \omega_A = 0.562$
Multiple radial wavenumber modes exist in same “potential well”

\[ (a) \ \frac{\omega}{\omega_A} = 0.5172 \]

\[ (b) \ \frac{\omega}{\omega_A} = 0.5170 \]

\[ (c) \ \frac{\omega}{\omega_A} = 0.5165 \]

\[ (d) \ \frac{\omega}{\omega_A} = 0.5163 \]

Outline

- Experimental conditions and observations
- Identification of the modes
  - Numerical calculation of mode structure and frequency
- Energetic ion population drive
  - Resonances and orbits contributing to mode drive along its evolution
- Conclusion
Assess energetic hydrogen minority drive of n=4 mode

Ion orbits are characterised by the constants of motion \((E, P_\phi, \Lambda)\), \(P_\phi = Ze\Psi + v_//RB_\phi/B_0\), \(\Lambda = \mu B_0/E\)

Energetic ion population*:
- single \(\Lambda = 0.96\)
- Maxwellian distribution with temperature peaked on-axis of 527 keV
- radial density profile \(\rho = \rho_0(1 - \Psi_{\text{norm}})^2\)

Drive of n=4 mode is calculated with CASTOR-k at three steps of mode evolution

Low frequency cascade interacts with single, very narrow resonance

\[ \frac{\omega}{\omega_A} = 0.254 \rightarrow f \approx 92\text{kHz} \]

Single relevant interaction in a very narrow resonance

Corresponding orbit is non-standard and close to the axis
High frequency cascade interacts with two very narrow resonances

\[ \omega / \omega_A = 0.541 \rightarrow f \approx 195\text{kHz} \]

Two relevant interactions in very narrow resonances

Corresponding orbits are non-standard and close to the axis
Tornado mode interacts with two broader resonances

\[ \frac{\omega}{\omega_A} = 0.562 \rightarrow f \approx 203 \text{kHz} \]

Two relevant interactions in broader resonances

Corresponding orbits are non-standard and close to the axis
Energetic minority drives the mode

<table>
<thead>
<tr>
<th>Mode Type</th>
<th>$q_0$</th>
<th>$\omega/\omega_A$</th>
<th>$\gamma/\omega$ (%)</th>
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</thead>
<tbody>
<tr>
<td>Low frequency AC</td>
<td>0.94</td>
<td>0.254</td>
<td>0.196</td>
</tr>
<tr>
<td>High frequency AC</td>
<td>0.88</td>
<td>0.541</td>
<td>0.0168</td>
</tr>
<tr>
<td>Tornado</td>
<td>0.87</td>
<td>0.562</td>
<td>3.07</td>
</tr>
</tbody>
</table>

Intermediate drive in low frequency AC phase
Drive is weaker in high frequency AC phase
Drive is stronger during tornado phase

Mode experiences drive throughout its evolution

Lower drive in high frequency AC may explain why a gap is observed between ACs and tornado modes
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Conclusions

We have numerically reproduced mode evolution from the base of grand cascade to TAE frequency range followed by transition to tornado mode.

Fast upward sweeping modes were identified as highly localised near-axis AC made possible due to the very flat q-profile.

AC $\rightarrow$ tornado mode transition occurs when $q_0=q_n=(n-1/2)/n$, which we propose to be used as an MHD spectroscopy technique to track q-profile evolution post-sawtooth crash. Only magnetics data is sufficient.

Throughout plasma evolution the mode is excited by energetic minority species, though high frequency AC phase experiences weaker drive which may explain gap between ACs and tornado modes observed in diagnostics.