Alfvén Cascades and Internal Transport Barriers on JET

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S.E.Sharapov et al., 8\(^{th}\) IAEA TM on Energetic Particles, 6-8 October 2003, San-Diego.
Internal Transport Barrier (ITB) Triggering Events

In JET shear-reversed discharges, ITB most often starts from $q_{\text{min}}$ radius when $q_{\text{min}}(t)$ passes an integer value$^1$

At later times, the ITB radius evolves independently of $q_{\text{min}}$ position

ITB starts from ITB triggering event, observed as a sudden increase in $dT_e/dt$ (at constant heating power) when $q_{\text{min}}(t)$ passes an integer value

$T_e$ measured with ECE. An increase in the slope is observed at $t=5.1$ s

$^1$E.Joffrin et al., Proceed of the 19$^{th}$ IAEA Conference, EX/P1-13, Lyon (2002)
ITB Triggering event in reversed magnetic shear

Te [keV] (Experimental determination) Pulse 55750

Alfven Cascade

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ITB criterion for pulse 55750

\[ \rho_{ITB} = 0.01 \]

(see Tresset et al., Nuclear Fusion 42, 520 (2002))

\[ \rho_{ITB} \propto -C \cdot T_e^{-1/2} dT_e / dR \]

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Aim:

- Develop diagnostics allowing to monitor $q_{\text{min}}(t)$ (not the whole profile $q(r)$!) in order to identify exact timing of the ITB triggering events

Technique: MHD spectroscopy, i.e.:

- Monitor Alfvén Cascades associated with $q_{\text{min}}$ – these modes are easily excited by ICRH-accelerated ions in JET
Alfvén Cascades

• Radius of \( q_{\text{min}} \) is an extremum point for shear Alfvén waves \( \omega^2 = \omega^2_A(r) \equiv k^2_A(r) \ V^2_A(r) \):

\[
\left. \frac{d \omega_A(r)}{dr} \right|_{r=r_{\text{min}}} = 0, \quad V_A(r,t) \approx \text{const}
\]

so that an extremum of radial refraction index \( N_r = c k_r / \omega \) can form a high-Q “waveguide” for shear Alfvén waves localised at \( q_{\text{min}} \).

• These high-Q Alfvén waves form a discrete spectrum, due to the periodicity and boundary conditions, and are called Alfvén Cascades (ACs)\(^2,3\)

• AC of mode numbers \( n, m \) has frequency close to the extremum value of shear Alfvén spectrum,

\[
\omega^2_{AC} \approx \omega^2_A(r_{\text{min}}) \equiv k^2_m(r_{\text{min}}) \ V^2_A(r_{\text{min}}), \quad k^2_m(r_{\text{min}}) = |n - (m / q_{\text{min}})^2| / R_0^2
\]

and is localized\(^3\) at the position of \( q_{\text{min}} \)

Time evolution of $q_{\min}(t)$, $k_{\|\min}(t)$ and eigenfrequency of AC

- During the current ramp-up phase, $q_{\min}(t)$ decreases, and $k_{\|\min}(t)$ changes in time accordingly:

$$\frac{dk_{\|\min}(r_{\min}, t)}{dt} = \frac{m}{R_0} \frac{d}{dt} q_{\min}^{-1}(t)$$

- Since the frequency of an AC is close to the frequency of shear Alfvén wave at $q_{\min}$, $\omega_{AC}^2 \approx k_{\|\min}^2 (r_{\min}) V_A^2 (r_{\min})$, the AC frequency tracks the $q_{\min}(t)$ evolution:

$$\frac{d\omega_{AC}(t)}{dt} \approx \frac{d}{dt} k_{\|\min}(r_{\min}, t)V_A = m \frac{V_A}{R_0} \frac{d}{dt} q_{\min}^{-1}(t)$$

- ICRH-accelerated energetic ions easily excite Alfvén Cascades in JET. By observing Alfvén Cascades, we can monitor $q_{\min}(t)$ and identify the times favourable for the ITB triggering events.

S.E.Sharapov et al., 8th IAEA TM on Energetic Particles, 6-8 October 2003, San-Diego.
Positive and Negative Shear Plasmas

**Top:** Power and current waveforms for positive shear plasma #49384

**Bottom:** Power and current waveforms for negative shear plasma #49382

$q(r)$-profiles for positive shear plasma #49384 and for negative shear plasma #49382

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Measured Spectrum of Alfvén Waves Excited by ICRH-accelerated Ions

TAE modes observed in pulse #49384 with monotonic q(r)-profile

Alfvén Cascades observed in reversed-shear pulse #49382
Properties of Alfvén Cascades

1) Each cascade may consist of many modes with different $n$’s from $n=1$ to $n=6$

2) The modes with higher mode numbers exhibit a more rapid frequency sweeping, $df/dt \propto n$.

3) The higher $n$ modes re-occur more often than the lower $n$ modes

4) Internal ECE measurements show that Alfvén Cascades are localised at $q_{\text{min}}$

Magnetic perturbations in JET with non-monotonic $q(r)$. ACs of $n=1$ to $n=6$ are observed below TAE frequency.

S.E.Sharapov et al., 8$^{th}$ IAEA TM on Energetic Particles, 6-8 October 2003, San-Diego.
Time Evolution of Alfvén Continuum Tip at $q_{\text{min}}$

$$\omega_{\text{Alfven}}(r_{\text{min}}, t) = k_{\parallel m}(r_{\text{min}}, t) V_A(r_{\text{min}}, t), \quad k_{\parallel m}(r_{\text{min}}, t) = \frac{1}{R} \left| n - \frac{m}{q(r_{\text{min}}, t)} \right|,$$

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Comments on theory of Alfvén Cascades

$$\omega_{AC} = |k_{\parallel\min}(r_{\min}, t)| v_A(r_{\min}, t) + \delta \omega \left( d\langle n_{\text{hot}} \rangle / dr, \ d^2 q / dr^2, ... \right)$$

The mode exists if

$$Q = Q_{\text{hot}} + Q_{\text{tor}} > 1/4,$$

Energetic ion contribution

$$Q_{\text{hot}} = -\frac{4 \pi e N q_0^3 \omega}{c B r_{\min} q_{\min}^* (m-nq_{\min})} \left. \frac{\partial \langle n_h \rangle}{\partial r} \right|_{r=r_{\min}}$$

Toroidicity effect

$$Q_{\text{tor}} = \frac{\omega^2}{2} \frac{R_0^2}{V_A^2 (1-nq_{\min}/m)} \frac{q_{\min}^3}{r_0^2 q_n^*} \frac{\epsilon_0 (\epsilon_0 + 2\Delta')}{1/4 - (m-nq_{\min})^2}$$

$$Q_{\text{hot}}$$ dominates for ACs driven by ICRH-accelerated ions in JET (n_h/n_e ~ 10^{-3}÷10^{-2}):

$$\frac{Q_{\text{hot}}}{Q_{\text{tor}}} \approx \frac{\omega_{Bh} n_h}{\omega n_e L_h m e^2 q_{\min}} \frac{r}{\left( 1 - (m-nq_{\min})^2 \right)} \approx (10÷100) \frac{1}{q_{\min}^2} \frac{1/4 - (m-nq_{\min})^2}{q_{\min}^2}$$

However, $$Q_{\text{tor}}$$ was dominant in ACs driven by low-density alpha-particles in TFTR

Comments on theory of Alfvén Cascades

“Sinusoidal” Alfvén Cascades (very rare!) remain yet unexplained (more in B.Breizman’s talk)

S.E.Sharapov et al., 8th IAEA TM on Energetic Particles, 6-8 October 2003, San-Diego.
CSCAS: the evolution of $n=1$, $n=2$, and $n=3$ continuum tips during $q_{\text{min}}(t)$ evolution

Alfvén Cascades observed in JET reversed-shear pulse #49382

$$\omega_{AC}(t) = \left| \frac{m}{q_{\text{min}}(t)} - n \right| \left( \frac{V_A(t)}{R_0} + \Delta \omega \right)$$
MHD spectroscopy from clustering of different $n$’s in time

Condition for Alfvén cascade to appear:

$$ m - n q_{\text{min}}(t) = 0,$$

$n$ and $m$ are integers

$\downarrow$

$n=1$ ACs occur when $q_{\text{min}}=1,2,3…$;

$n=2$ ACs occur when $q_{\text{min}}=1, 4/3, 5/3, 2, 7/3, 8/3, 3…$;

$n=3$ ACs occur when $q_{\text{min}}=1, 4/3, 5/3, 2, 7/3, 8/3, 3…$;

Alfvén Cascade, in which all $n$’s are present $\Rightarrow$ Grand Cascade. It occurs when $q_{\text{min}}(t)$ passes an integer value.
Alfvén Grand-Cascade as a Diagnostic Tool for ITB Triggering Event

$T_e$ measured with ECE. An increase in slope is observed at $t=5.1$ s

Alfvén grand-Cascade observed at $t=5.15$ s
Alfvén Grand-Cascade is visible even in high-noise plasmas

Magnetic spectrogram showing low-amplitude grand-cascade at $t \sim 6.5$ s in discharge #55557, $B_T=2.45$ and $I_P=2.2$ MA.

Electron temperature measured with ECE diagnostics in #55557. ITB triggering event is observed at $t \sim 6.4$ s
Correlation of Alfvén cascades with ITB formation

(Pulse 51579)
Correlation Alfvén cascade - ITB triggering event.

1- When Alfvén cascade and triggering event are both observed, they occur at the same same within 0.2s.

2- This indicates that the triggering event is related to \( q_{\text{min}} \) reaching a rational surface.

3- This correlation is observed for a large variety of plasma conditions:
   
   \[ 1.5 < I_p < 2.8 \, \text{MA} \]
   \[ 2.45 < B_T < 3.4 \, \text{T} \]
   \[ 3 < P_{\text{TOT}} < 17 \, \text{MW} \]
Alfvén grand Cascades versus the ITB triggering events

- Correlation between Alfvén grand-Cascades and the ITB triggering events was established in JET discharges with different types of the pre-heating, i.e. with
  - LHCD,
  - ICRH+LHCD,
  - ICRH only,
  - NBI only,
  - with pellets
Developing ITBs via detecting Alfvén grand-Cascades

- For each scenario, run a probe discharge with 2-3 MW of ICRH only. Detect all the Alfvén grand-Cascades associated with integer \( q_{\text{min}} \) (usually \( q_{\text{min}} = 3, 2 \) are used)

- Identify the relevant times favourable for ITBs, i.e. \( t(q_{\text{min}} = 3) \) and \( t(q_{\text{min}} = 2) \)

- In order to obtain ITB in subsequent discharges, repeat the probe discharge with main heating applied \(~200\) msec before the grand-Cascade time in the probe pulse
ACs show “density of rationals” in layer surrounding $q_{\text{min}}$:

Alfvén Cascades detected with O-mode reflectometry in interferometry mode
Back in history (1997): Alfvén Grand Cascade and ITB

Evolution of $T_e$, neutron yield, NBI and ICRH power in discharge #40410 $B_T=3.4$ T, $I_P = 3$ MA. Unidentified mode is detected at $t=7.1$ sec when the neutron yield takes off suddenly.

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Summary

- Alfvén Cascades = modes associated with $q_{\text{min}}$ excited by fast ions.
- Used successfully for monitoring the $q_{\text{min}}(t)$ evolution
- The **temporal correlation** between Alfvén grand-Cascades, ITB triggering events and integer values of $q_{\text{min}}$ has been established for a wide range of plasma conditions and pre-heating scenarios on JET
- A **technique for obtaining ITBs** in shear reversed plasmas by applying the main heating shortly before the AC time has been established on JET
- A **new way of detecting Alfvén Cascades with interferometry** has been found. These measurements give a high-accuracy monitoring of $q_{\text{min}}(t)$ and may lead to a systematic diagnosis of the transport properties of the layer surrounding $q_{\text{min}}$