TRANSPORT CAUSED BY TAE

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OUTLINE OF LECTURE 5B

• Qualitative estimates of fast ion transport induced by TAE

• Orbits comparable to \( a \): enhanced prompt losses due to TAE

• Orbits smaller than \( a \): onset of particle orbit stochasticity and transport due to the resonance overlapping

• Experimental measurements of confined and lost fast ions

• Trapped ion redistribution by TAE inside the \( q=1 \) radius (“tornado” modes)

• Multi-mode experiments on JET

• Summary
QUALITATIVE ESTIMATES – 1

- The *unperturbed* orbit of a particle is determined by three invariants:

\[
\mu \equiv \frac{Mv^2}{2}; \quad E \equiv \frac{Mv^2}{2}; \quad P_\phi \equiv -\frac{e}{c}\varphi(r) + RMv_\phi
\]

- In the presence of a *single TAE* mode with perturbed quantities $\propto \exp i(n\varphi - \omega t)$, the wave-particle interaction is invariant with respect to transformation

\[
t \rightarrow t + \tau; \quad \varphi \rightarrow \varphi + \frac{\omega}{n}\tau
\]

- In the presence of the TAE, neither $E$ nor $P_\phi$ is conserved for particle orbit, but their following combination is still invariant:

\[
E - \frac{\omega}{n}P_\phi = \text{const}
\]

- Change in the particle energy is related to change in particle radius produced by TAE

\[
\Delta E = \frac{\omega}{n} \Delta P_\phi \approx \frac{\omega e}{nc} \psi' \Delta r
\]

- The relative change in particle energy is much smaller than in particle radius:

\[
\frac{\Delta v}{v} = \frac{\omega}{\omega_a} \cdot \frac{\Delta r}{L_a}; \quad \text{where} \quad \omega_a \equiv \frac{nq\rho_a v}{2rL_a} \gg \omega
\]

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QUALITATIVE ESTIMATES – 2

• The interaction between TAE and fast particles causes *radial transport of the particles at nearly constant energy*

• This type of interaction is extremely unpleasant as it may deposit a population of fusion born alphas too close to the first wall

• Losses of fusion born alphas must be minimised down to few percent (<5% on ITER) for avoiding the first wall damage

• The radial redistribution also gives a non self-consistent alpha-heating profiles etc. and may affect the burn

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TWO MAIN TYPES OF THE TAE-INDUCED TRANSPORT

• Fast ion orbits comparable to the machine radius, $\rho_\alpha / a \approx 10^{-1} \div 1$. A single-mode ‘convective’ transport is observed in present-day machines (DIII-D, TFTR, JET, JT-60U). TAE-induced enhancement of prompt losses is important, losses $\propto \delta B^2_{TAE}$

• For ITER with parameter $\rho_\alpha / a \approx 10^{-2}$ the dominant channel of alpha-particle transport is predicted to differ from present-day machines.

• On ITER, higher-$n$ ($n > 10$) TAEs will be most unstable. The radial width of a poloidal harmonic will be more narrow, $\Delta_{mode} \propto r_{AE} / nq$, but the number of unstable modes may be significantly larger than in present-day tokamaks

• Resonance overlap will lead to a global stochastic diffusion of energetic ions over a broad region with unstable AEs, with transport $\propto \delta B^2_{TAE}$
MODELLING TAE-ORBIT INTERACTION (HAGIS CODE)

S.D. Pinches et al., Computer Physics Communications 111 (1998) 133

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HAMILTONIAN APPROACH FOR $\delta f$

Trajectory of each individual macro-particle follows the Hamiltonian approach [White & Chance, Phys. Fluids 27 (10) 1984] leading to equations of the type:

\[
\frac{\partial \psi_p}{\partial \Theta} = \frac{1}{D} \left[ I \frac{\partial \tilde{A}_\zeta}{\partial \Theta} - g \frac{\partial \tilde{A}_g}{\partial \Theta} \right], \quad \frac{\partial \psi_p}{\partial \zeta} = \frac{1}{D} \left[ I \frac{\partial \tilde{A}_\zeta}{\partial \zeta} - g \frac{\partial \tilde{A}_g}{\partial \zeta} \right], \quad \frac{\partial \psi_p}{\partial P_g} = \frac{g}{D}, \quad \frac{\partial \psi_p}{\partial P_\zeta} = -\frac{I}{D}
\]

For the shear Alfvén modes, the assumption $\tilde{A} = \tilde{a}(x,t) \cdot B_0$ is used;

Nonlinear code: for the eigenmode structure provided by CASTOR or MISHKA, the mode amplitude and phase are evolving through (schematically):

\[
\frac{dA}{dt} = A_0 + \sum_{\text{particles}} (...) - \gamma_{\text{damp}} A, \quad \frac{d\phi}{dt} = \phi_0 + \sum_{\text{particles}} (...),
\]

for unchanged mode structure

$\delta f$ low-noise technique is used for deviation from $f_0$ computed by launching $>10^5$ macro-particles
MODE EVOLUTION FROM HAGIS

\[ \gamma_d/\omega = 2\%, \quad \beta\langle f \rangle = 3 \times 10^{-4} \]
FAST ION REDISTRIBUTION
DRIFT ORBIT STOCHASTICITY (HAGIS MODELLING FOR JET)

The analytically derived stochasticity threshold (Berk et al Phys. Fluids B5, 1506, 1993) is close to that obtained numerically:

\[ \frac{\delta B_r}{B_0} > r_{TAE} \cdot \left(64 m R_0 q S\right)^{-1} \approx 1.5 \times 10^{-3} / m \]

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NOTE

- TAE is ideal MHD mode and does NOT cause stochasticity of magnetic field

- The stochasticity affecting the fast ions arises in the DRIFT surfaces of the fast ions, NOT in the magnetic flux surfaces
STOCHASTIC TRANSPORT OF ALPHAS ON JET (HAGIS-95)
EXPERIMENTAL MEASUREMENTS OF LOST FAST IONS ON JET

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EXPERIMENTAL MEASUREMENTS OF CONFINED FAST IONS

- Intense gamma-ray emission comes from JET plasmas
- These gamma-rays come from nuclear reactions between fast ions with $E > E_{\text{crit}}$ and main plasma impurities C and Be
- The gamma ray spectrum is discrete, each nuclear reaction gives gamma-ray of certain energy
GAMMA-CAMERA ON JET

Schematic of the JET gamma camera used for the spatial gamma-ray emissivity measurements.
TYPICAL GAMMA-RAY IMAGE OF FAST IONS

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Gamma-ray spectra measured by the NaI(Tl) detector

$^{12}\text{C} (\text{D,}\gamma)^{13}\text{C}$
$E_\gamma = 3.1 \text{ MeV}$

$^{9}\text{Be} (^{4}\text{He},\gamma)^{12}\text{C}$
$E_\gamma = 4.44 \text{ MeV}$
SIMULTANEOUS MEASUREMENTS OF $^4$He AND D FAST IONS

Energy windows for ALL Gamma Camera channels

I  > 2.0 MeV (total)
II  2.5 - 3.5 MeV (D+C)
III  spare
IV  4.0 - 5.0 MeV ($^4$He+Be)
GAMMA-RAY IMAGES OF $^4\text{He}$ (E>1.7 MeV) and D (E>0.5 MeV)

Tomographic reconstructions of 4.44-MeV $\gamma$-ray emission from the reaction $^9\text{Be}(^4\text{He},n)^{12}\text{C}$ (left) and 3.09-MeV $\gamma$-ray emission from the reaction $^{12}\text{C}(D,p)^{13}\text{C}$ (right) deduced from simultaneously measured profiles.

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“TORNADO” MODES AND ENERGETIC ION TRANSPORT ON JET

- Tornado mode = TAE inside the q=1 radius. Usually precedes monster sawtooth crash. (Kramer, Sharapov et al, PRL 2004)

- Tornado modes are considered to be possible reason for expelling fast ions from the q=1 region and causing monster sawtooth crash due to the loss of fast ion stabilisation


\[ \gamma\text{-rays from reactions } ^{12}\text{C}(p, p'\gamma)^{12}\text{C} \]

\[ T_e \text{ at different radii show sawteeth at } t=11.4, \]
\[ t=13 \text{ s occurring after decreases of } \gamma\text{-intensity} \]

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Observed Gamma-ray Decrease Happens when TAEs within $q<1$ (tornado modes) and TAEs outside $q=1$ coexist.

Pulse No: 60195, Probe H302: mode amplitude $\log(|\delta B(T)|)$

TAEs & tornadoes during **first** shaded time interval

TAEs & tornadoes during **second** shaded time interval
JET (2006): experiment with a more complete set of diagnostics

ICRH (hydrogen minority) and NBI power waveforms and $T_e$ measured with multi-channel ECE diagnostics in typical tornado mode discharge on JET (pulse #67673)
New high-quality detection of core-localised modes with far infra-red interferometry (JET discharge #67673)

Tornado modes detected with vertical channel passing through the magnetic axis of the JET interferometer

Geometry of JET interferometer with vertical lines-of-sight

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Four sets of tornado modes precede four monster crashes in #67673:

- $t = 11.25 - 11.75$ sec
- $t = 13.0 - 13.53$ sec
- $t = 15.1 - 15.68$ sec
- $t = 16.9 - 17.4$ sec

$n$ decreases one-by-one:

- $n = 8 \rightarrow 7 \rightarrow 6$
- $n = 9 \rightarrow 8 \rightarrow 7 \rightarrow 6 \rightarrow 5 \rightarrow 4$
- $n = 8 \rightarrow 7 \rightarrow 6 \rightarrow 5 \rightarrow 4 \rightarrow 3$

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Gamma-ray emission from deuterons (E>500 keV) colliding with carbon, $^{12}\text{C}(d,p\gamma)^{13}\text{C}$ decreases before crashes
Losses of energetic ions measured with scintillator outside plasma are different before and during sawtooth crashes

Ions with gyro-radii 6-10 cm are lost before sawtooth crash

Ions with gyro-radii 4-6 cm are lost during sawtooth crash
Loss measurements indicate increase during tornado activity
MODELLING TORNADO MODES

\[ V_r (\text{a.u.}) = \left( \frac{\psi_p}{\psi_{p_{\text{edge}}}} \right)^{1/2} \]

\[ s = \left( \psi_p / \psi_{p_{\text{edge}}} \right)^{1/2} \]

- Ideal MHD code used for computing these modes in JET with monotonic q-profile
- Redistribution of protons from the q=1 radius by tornadoes considered main cause of the decrease in gamma-ray intensity

**Orbits of 5 MeV protons**

- TAEs with \( n=3, 4 \) within the \( q=1 \) radius (tornado),
- and \( n=5,6 \) TAEs outside the \( q=1 \) radius

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TAE DRIVEN BY ICRH-ACCELERATED FAST IONS

- For trapped ions, the resonance $V_{\parallel} = V_A$ does not work, and drive comes via

$$\Omega = \omega - n \cdot \omega_\phi - p \cdot \omega_\theta$$
FAST ION ORBITS – ICRH

- ICRH auxiliary heating
- Distribution function described by
  \[ \Lambda = \mu B_0/E = 1 \]
  - Trapped orbits with turning points at ICRH resonance layer
- Orbit properties investigated using HAGIS code
• Determine natural particle frequencies, $\omega_\phi$ and $\omega_\theta$
THE RESONANCES

\[ \Omega_{np} = n \omega_\phi - p \omega_\theta - \omega = 0 \]

Regions of phase space where ICRH-accelerated ions resonate with \( n=3 \) tornado

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**EVOLUTION OF THE RESONANCES WITH MODE FREQUENCY**

Movement of resonant lines due to ALL tornado modes by sweeping frequency in 3% steps over 15%.

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ATTEMPT TO OBSERVE STOCHASTIC TRANSPORT DUE TO MULTIPLE MODES
EXPERIMENTS ON MULTI-MODE TRANSPORT ON JET: $^3\text{He}$ WITH $E>500$ keV MEASURED
Profile of Fast He$^3$ (Top) Measured Simultaneously with AEs (Bottom)

Notches of ICRH power (5 MW → 1MW) show modes most sensitive to $^3$He ions
NO GLOBAL STOCHASTICITY FOR SUCH AMPLITUDES

- Tens of AEs were excited, but no degradation of fast $^3$He observed in these $I=2.3$ MA discharges with orbit width of $^3$He ions $\Delta f/a << 1$. 
SUMMARY

- Interaction between fast ion and a wave in the form $\propto \exp \left(i \left(n \varphi - \omega t \right) \right)$ has invariant $E - \frac{\omega}{n} P_\varphi = \text{const}$

- TAE causes a radial transport of resonant fast ions at nearly constant energy

- Two main transport mechanisms can be identified depending on the ratio $\rho_a / a$:
  - convective single mode transport for large $\rho_a / a$
  - global multi-mode stochastic transport for small $\rho_a / a$

- Most present-day machines are in the regime of large $\rho_a / a$. Example: tornado modes on JET

- ITER will be in the regime of small $\rho_a / a$. Modelling of global stochasticity on, e.g. JET shows that amplitudes $\delta B_r / B_0 > 10^{-3}$ are required for that. Direct JET experiments on multi-mode transport could not achieve such numbers yet