Spatial channeling of energy and momentum of energetic ions by destabilized Alfvén eigenmodes

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Outline

- **Introduction**

- **Spatial channeling of energy & momentum (eigenmode channeling)**

- **Effects of channeling**

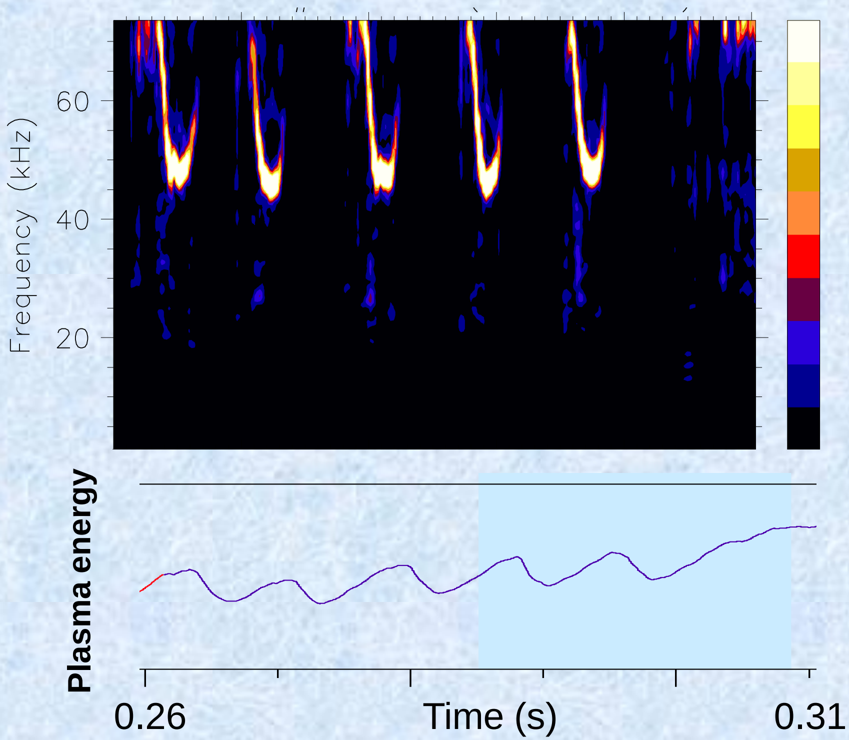
Role of energetic-ion-driven instabilities

Consequences of instabilities can be different

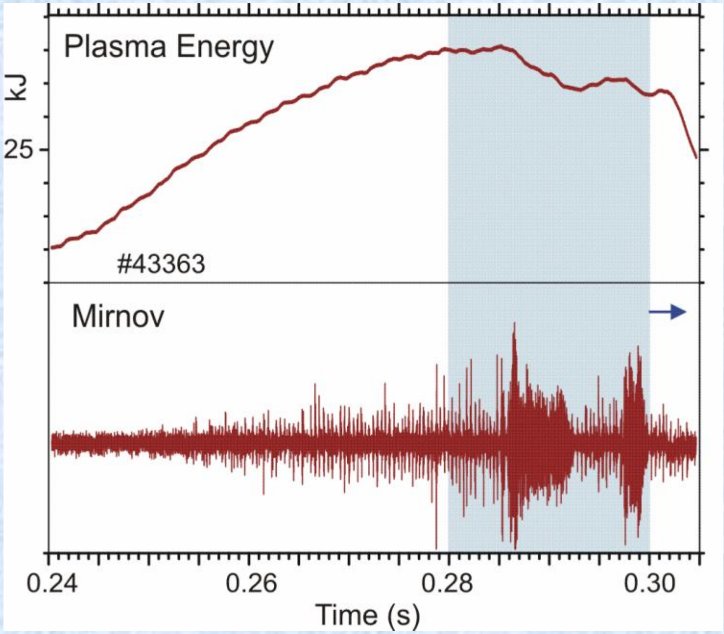
- ✓ **Weak influence on confinement of plasma and energetic ions**
  instability can be used for plasma diagnostics
- ✓ **Anomalous loss of energetic ions**
  well known effect
- ✓ **Deterioration of the plasma energy confinement**
  studied not sufficiently
- ✓ **Spatial channeling (eigenmode channeling) of energy and momentum of energetic ions**
  topic of this presentation

Decrease of plasma energy in W7-AS during Alfvén instabilities

W7-AS discharge #34723



W7-AS discharge #43363



A. Weller *et al,* Phys. Plasmas **8** (2001) 931
Ya.Kolesnichenko, Yu. Yakovenko, V. Lutsenko, R. White, A. Weller, Nucl. Fusion **50** (2010) 0840011

Anomalous electron heat conductivity

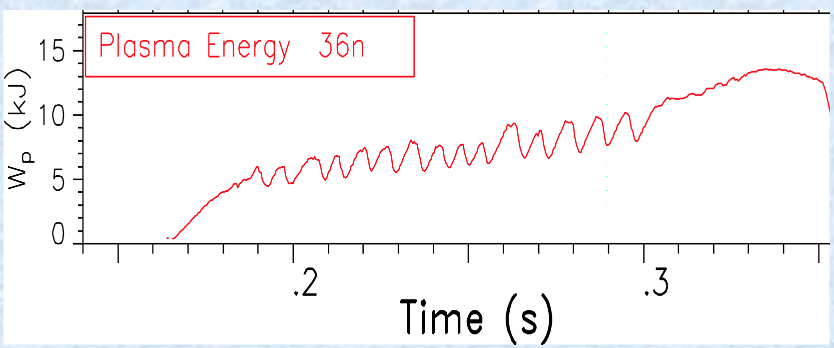
Physics: Wave enlarges the particle radial excursions Δ due to finite electric conductivity of the plasma and finite $\tilde{E}_\parallel$ whereas the Coulomb collisions provide a random walk. Depending on electron collision frequency and wave amplitude, various regimes are possible.

$$\xi_r = \frac{ick_\vartheta}{k_\parallel\left(\omega - k_\parallel V_\parallel\right)}\frac{\tilde{E}_\parallel}{B} - \frac{i\tilde{B}_r}{k_\parallel B} \equiv \xi_V + \xi_{fluid} \quad \Rightarrow \quad \Delta = ck_\vartheta \hat{E}_\parallel / (V_{Te} k_\parallel^2 B)$$

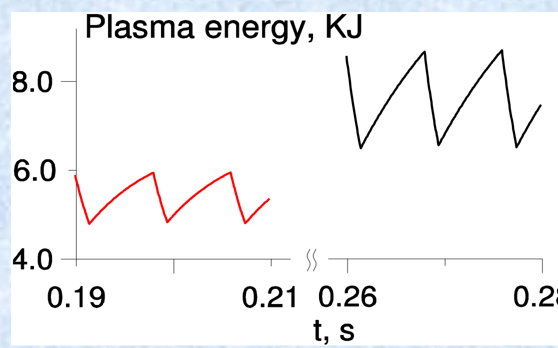
W7-AS: During the crash, plasma is in the anomalous collisional regime, $k_\parallel V_{Te} < v_e^{col}$.

[*T(0)=290 eV, n ~10*^{20} *m*$^{-3}$, $k_\parallel$ *~10*$^{-3}$ *cm*$^{-1}$].

Measured



Calculated



$$\frac{dW_p}{dt} = -\frac{W_p}{\tau_E(t)} + P_{abs},$$

$$\tau_{E1} = 13\,\text{ms}$$

$$\tau_{E2} = 3\,\text{ms}$$

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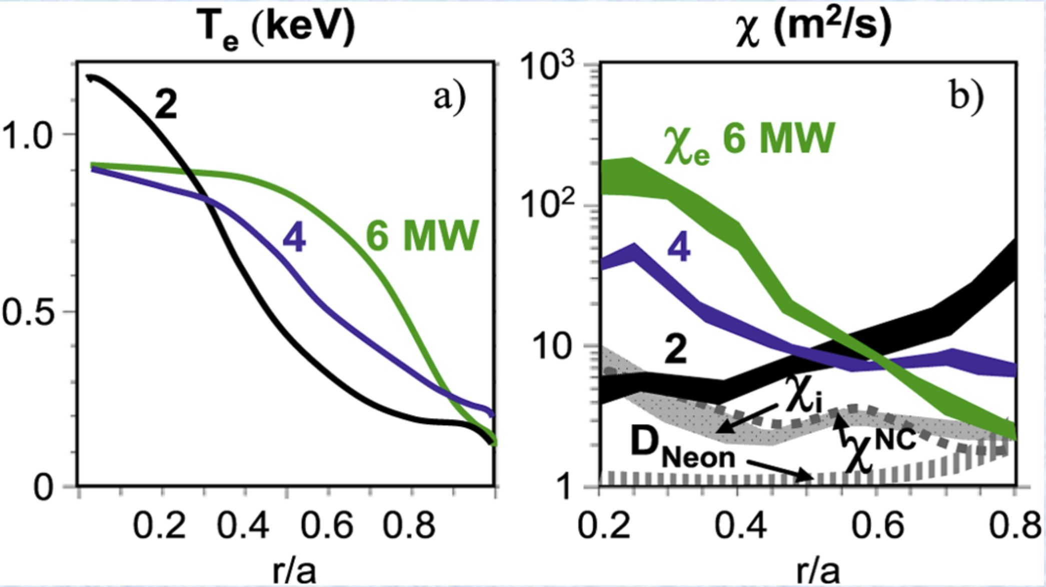
Deterioration of efficiency of plasma heating in NSTX during Alfvén instabilities

D. Stutman *et al*., Phys. Rev. Lett. **102**, 115002 (2009): **The increase of the injected power by a factor of 3 did not increase the central temperature.**



*At 6 MW, TRANSP calculated χ_e is strongly enlarged in the core region, **exceeding Bohm value**, and reduced at the periphery.*

N. Gorelenkov *et al*., Nucl. Fusion **50** (2010) 084012: **Multiple GAE modes lead to stochastic electron motion, which results in strong enhancement of electron heat conductivity.**

Plasma heating and heat flux caused by the waves

$$\frac{\partial F}{\partial t} = \frac{1}{\tau_b} \sum_{m,n} \left(\frac{\partial}{\partial \varepsilon} - \frac{n}{\omega} \frac{\partial}{\partial P_\varphi} \right) \tau_b \mathrm{D} \left(\frac{\partial}{\partial \varepsilon} - \frac{n}{\omega} \frac{\partial}{\partial P_\varphi} \right) F + C^{COL}$$

$$\mathrm{D} = \pi e^2 \sum_s |J|^2 \, \delta\left(\omega - m\langle \dot{\vartheta} \rangle + n \langle \dot{\varphi} \rangle - s\omega_b \right)$$

$$\frac{3}{2} n_e \frac{\partial T_e}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} r q_e = Q_e^w + Q^{col}$$

$$Q_e^w = -\sum_{m,n} \int \overline{d^3 V} \varepsilon \mathrm{D} \left(\frac{\partial}{\partial \varepsilon} + \frac{k_\vartheta}{M \omega \omega_B} \frac{\partial}{\partial r} \right) F$$

$$q_e = -\sum_{m,n} \frac{k_\vartheta}{M \omega_B \omega} \int \overline{d^3 V} \, \varepsilon \mathrm{D} \left(\frac{\partial}{\partial \varepsilon} + \frac{k_\vartheta}{M \omega \omega_B} \frac{\partial}{\partial r} \right) F - \frac{3}{2} \Gamma_e T_e$$

Q>> div **q** for $\omega > \omega_*$. **Heating by waves exceeds cooling!**

Therefore, anomalous transport can hardly explain Stutman's experiment.

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Eigenmode channeling of energy and momentum: basic idea

During Energetic-Ion-driven Instabilities the energetic ions emit the waves which are absorbed by the plasma.

Energetic Ion energy & momentum ⇒ **Waves** ⇒ **Bulk plasma**

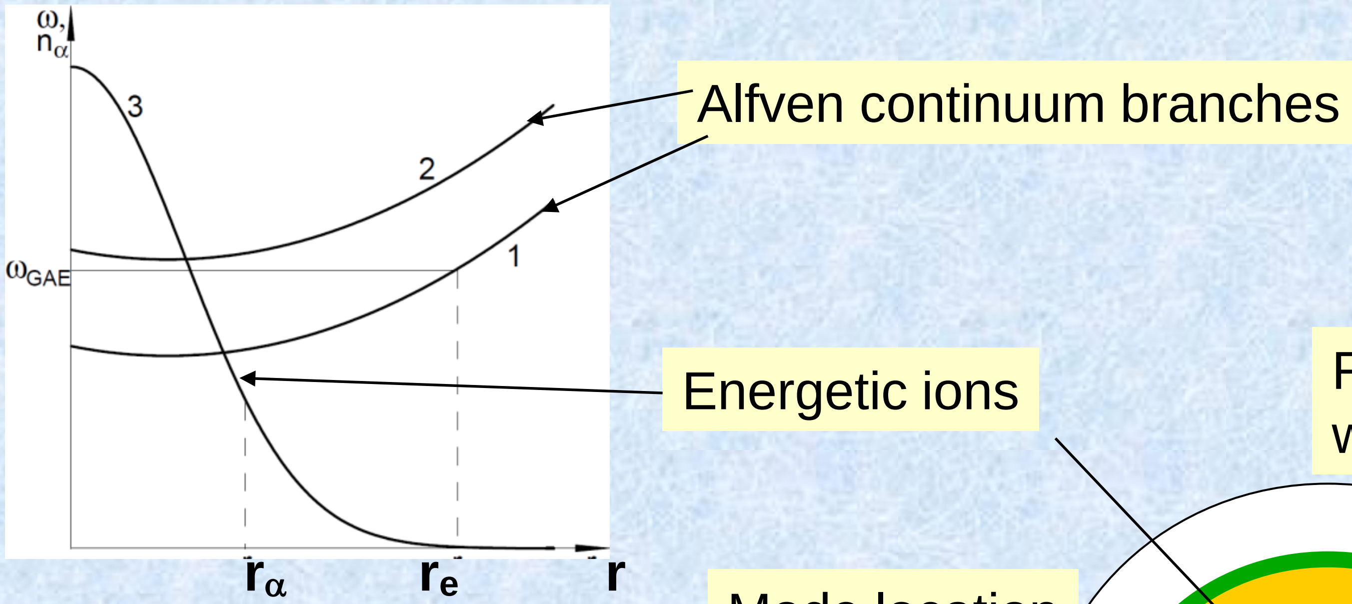
Typically, the region of emission (Region 1) does not coincide with the region of absorption (Region 2).

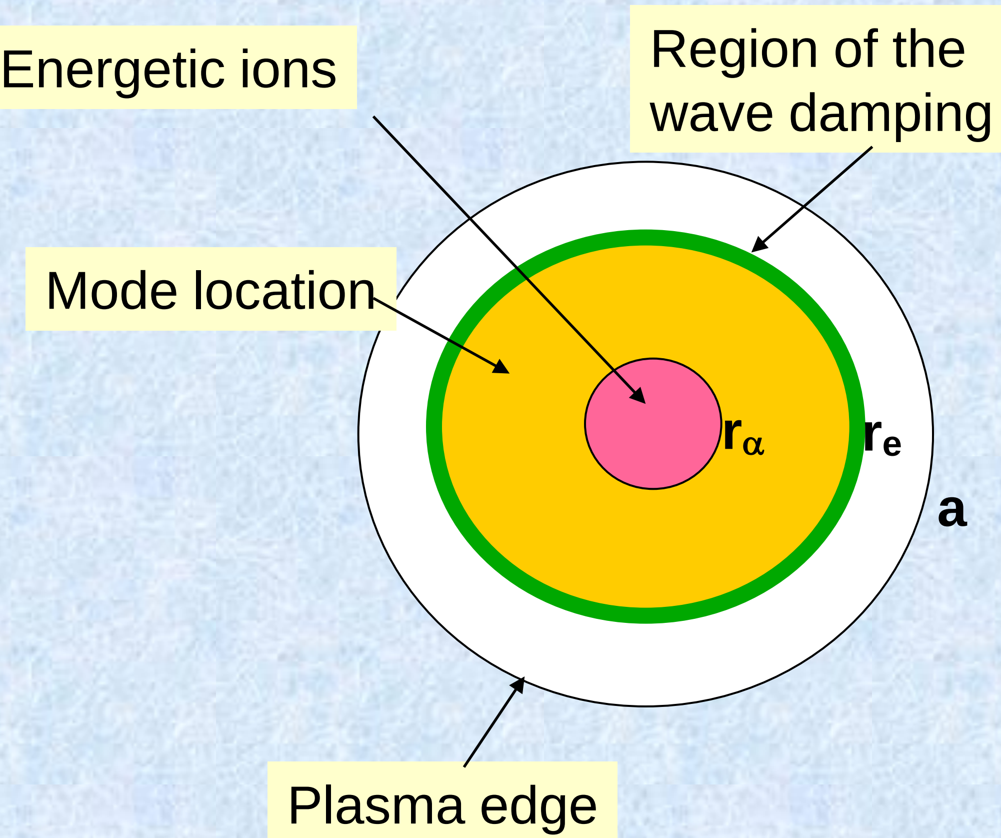
Region 1
Emission of the waves

Region 2
Absorption of the waves

This implies that the energy and momentum of energetic ions is channeled from Region 1 to Region 2.

Channeling by GAE modes





GAE mode receives the energy and momentum of the beam ions inside the region $r < r_\alpha$, but gives the energy and momentum to electrons at $r \sim r_e$.

Effects of channeling

Energy channeling leads to plasma heating by the energetic ions beyond the region of localization of the energetic ions

Momentum channeling leads to plasma rotation and frequency chirping

Energy channeling

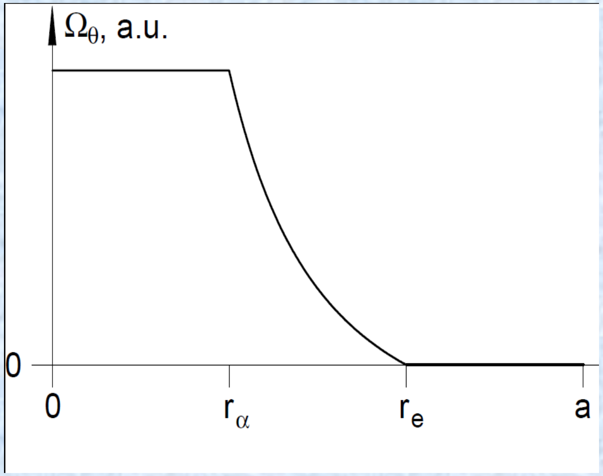
The energy channeling caused by GAEs leads to **the cooling of the plasma core** and **the increase of T_e at the periphery** when

(i) $r_\alpha < r_e$

(ii) $2\gamma_\alpha W \sim P_{inj}$

(iii) Fast ions in wide energy range are resonant:
$\Delta E^{res} = (E_1, E_2)$, with $E_1 \ll E_2 \sim E_0$, E_0 is the birth energy.

Momentum channeling and plasma rotation



Sketch of the plasma rotation during energetic-ion-induced instabilities for $r_\alpha < r_e$

This rotation leads to <u>transient frequency chirping</u> due to changing Doppler shift. When $r_\alpha < r_e$, the frequency chirping down takes place after the beginning of the instability.

A model for the NSTX experiments

Assume:

- No GAEs or weak GAEs at 2 MW; strong GAEs at 6 MW
- Electron transport at 6 MW is as weak as at 2 MW
- Plasma is heated by NBI through Coulomb collision at 2 MW, but mainly through the waves at 6 MW

$$T(r) = T(a) + 2\int_r^a \frac{dr'}{r'\kappa} \int_0^{r'} dr'' r'' \left(Q^b + Q^w\right)$$

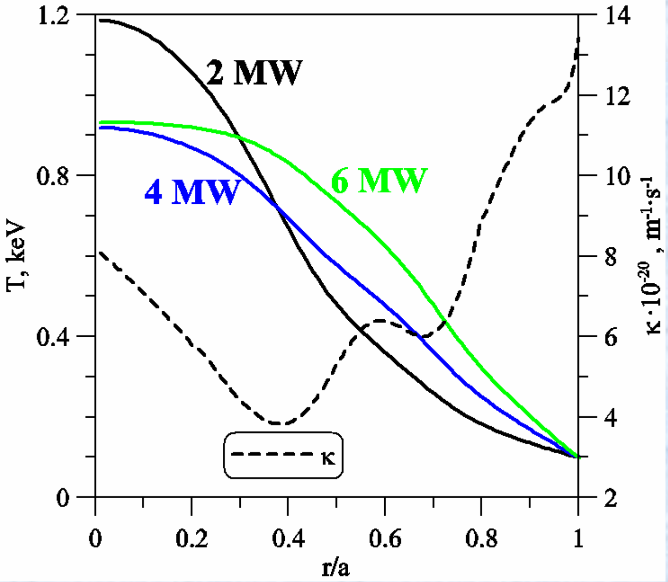
$$\kappa = n_e(\chi_e + \chi_i)$$

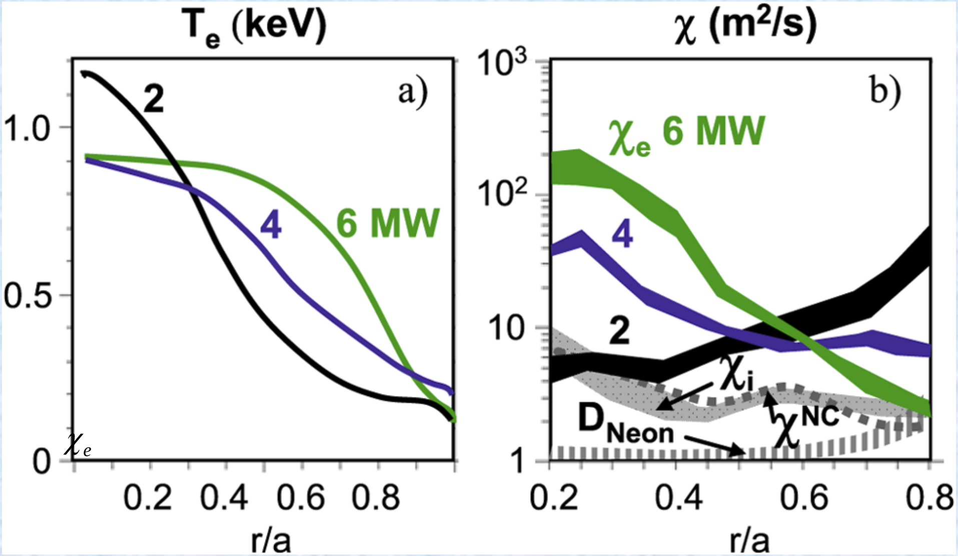
$$\int d^3 r Q^w = \nu P_{inj}^{total} \qquad \int d^3 r Q^b = (1-\nu) P_{inj}^{total},$$

$$Q^b \propto \exp\left(-\frac{12 r^2}{a^2}\right), \qquad Q^w \propto \exp\left(-\frac{\alpha_w (r-r_e)^2}{a^2}\right)$$

Here ν, r_e, and a_w are adjustable parameters.

Calculated temperature and measured temperature in the NSTX experiments



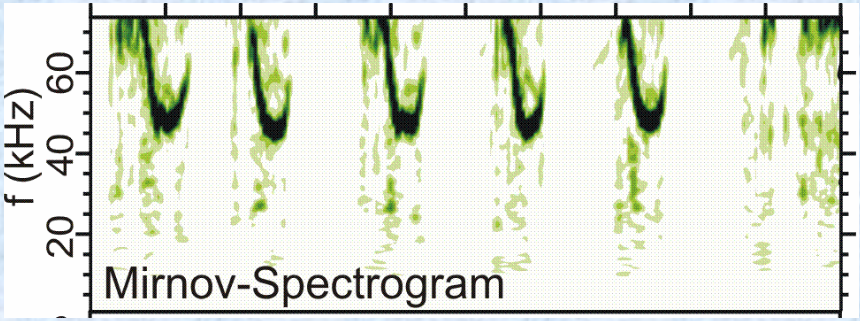


Temperature calculated in our model with r_e/a=0.6 and α_w =10; ν=0 for 2 MW; ν=0.82 for 4 MW; ν=0.98 for 6 MW; $\kappa = (\chi_i + \chi_e)\, n_e$; $\chi_e = \chi_e$ (2 MW) and $\chi_i = \chi^{NEO}$, $n_e(r)$ of *Stutman, EPS conf-2007*.

D. Stutman *et al*., PRL (2009): **Measured temperature and thermal conductivity coefficients.** *At 6 MW, χ_e is strongly enlarged in the core region and reduced at the periphery.*

Ya. Kolesnichenko, Yu. Yakovenko, V. Lutsenko, Phys. Rev. Lett. **104** (2010) 075001

Frequency chirping in Wendelstein 7-AS



time

Shot #34723

Estimate from our theory: $$\frac{u_{i\vartheta}}{V_{Ti}} = 2m\frac{\gamma_\alpha}{\omega}\frac{W}{n_i T_i}\frac{V_{Ti}\Delta t}{r}$$

For Alfven waves $$\frac{W}{n_e T_e} = \frac{2}{\beta_e}\left(\frac{\tilde{B}_\perp^2}{B^2}\right)$$

$$\beta_e = 7.25\%, \quad \tilde{B}_\perp / B = 10^{-3} \Rightarrow \frac{W}{n_e T_e} = 2.7\times 10^{-5}$$

We take $\gamma/\omega=10^{-2}$ (*Kolesnichenko et al.,* NF-2006) and that the chirping time =the pre-crash duration= 0.7 ms.

$$\frac{u_{i\vartheta}}{V_i} \sim 10^{-2} \quad \text{and} \quad \Delta\omega = \frac{\mathrm{m u_{i\vartheta}}}{r} \sim -23kHz$$

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Summary

- Destabilized eigenmodes can channel the energy and momentum of energetic ions to the region where the destabilized waves are damped.

- The energy channeling seems the main mechanism responsible for the deterioration of the efficiency of plasma heating during multiple GAE modes in NSTX experiments with high NBI power.

- The momentum channeling leads to plasma rotation and transient frequency chirping. It can explain strong frequency chirping in the W7-AS shot #34723.

- The plasma heating by the waves with $\omega >> \omega_*$ exceeds the plasma cooling through the thermal conduction and convection caused by the waves.