Self-consistent Study of Fast Particle Redistribution by Alfvén Eigenmodes During Ion Cyclotron Resonance Heating

T. Bergkvist, T. Hellsten and T. Johnson

Alfvén Laboratory, Royal Institute of Technology, Stockholm, Sweden, Association Euratom-VR

Outline

- ✔ Experimental observations
- ✔ Alfvén eigenmode dynamics
- ✔ Code development
- ✔ Simulation of AE dynamics
- ✔ Simulation on the effect with several AEs

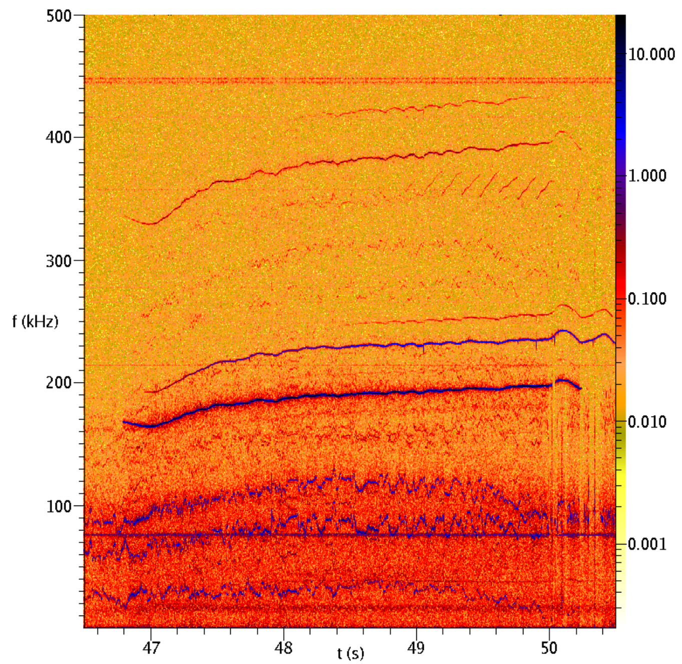
Details of the distribution function

Alfvén eigenmodes (AEs) excited during ICRH in JET.

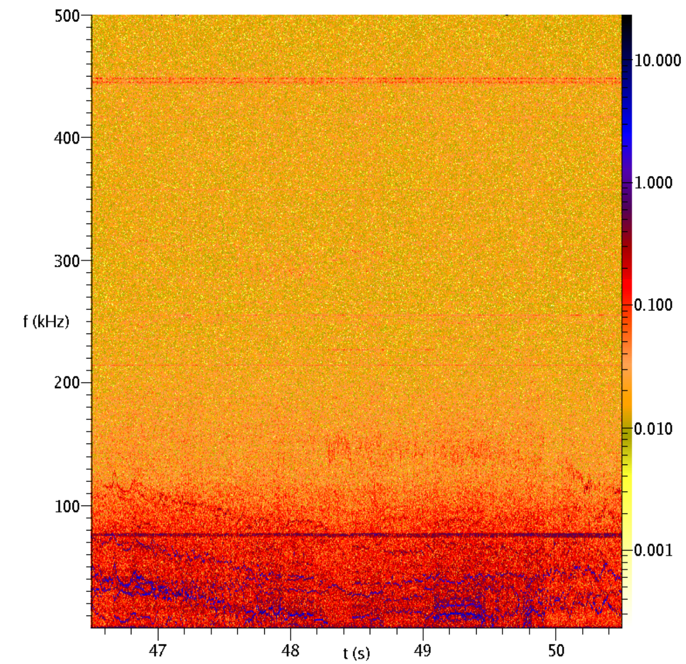
Phasing of antenna important.
    => details of distribution function important

*Mantsinen, M, J. et. al., PRL **89** (2002)*

+90^0



-90^0

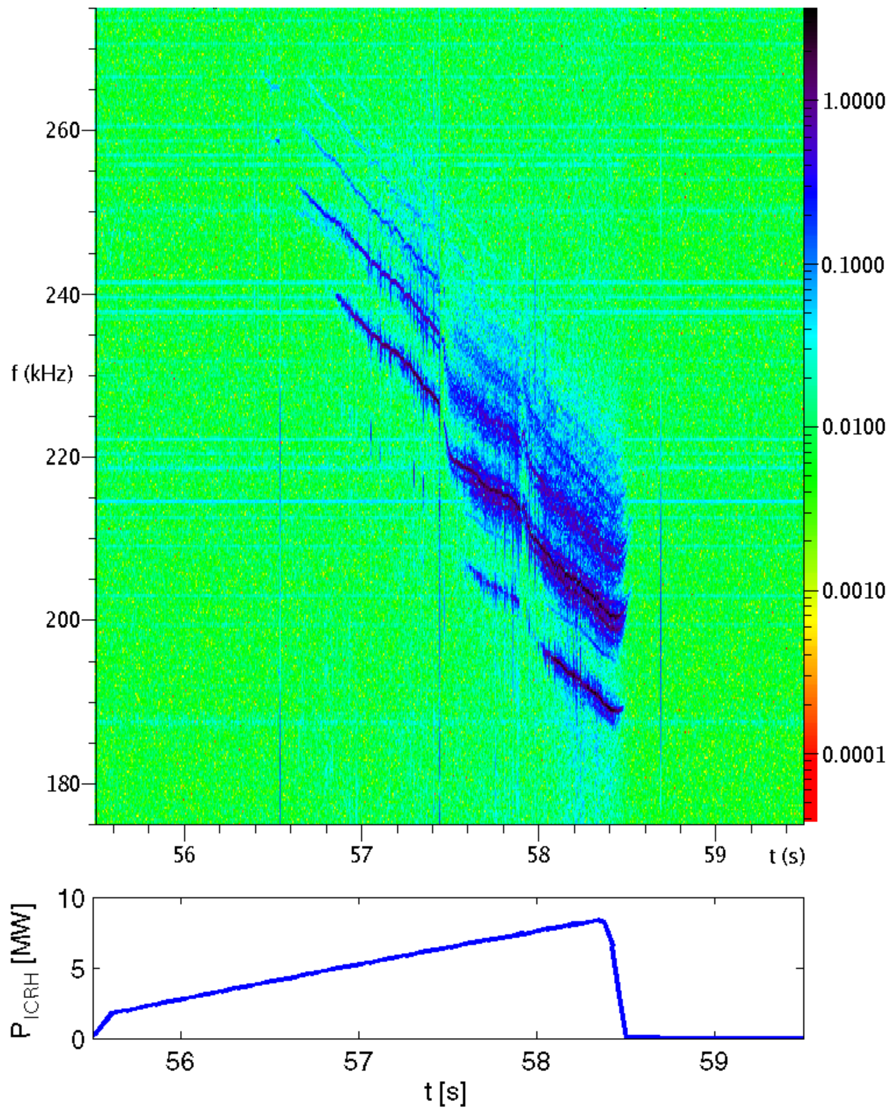


Fast damping of TAE

Fast termination of ICRH excited Eigenmodes when ICRH is switched off

Cannot be explained by resistive damping or slowing down.

*Wong, K.L., et. al, Phys. Plasmas **4** (1997) 393*
Testa, D., et. al, EPS conf. proc. (2005)

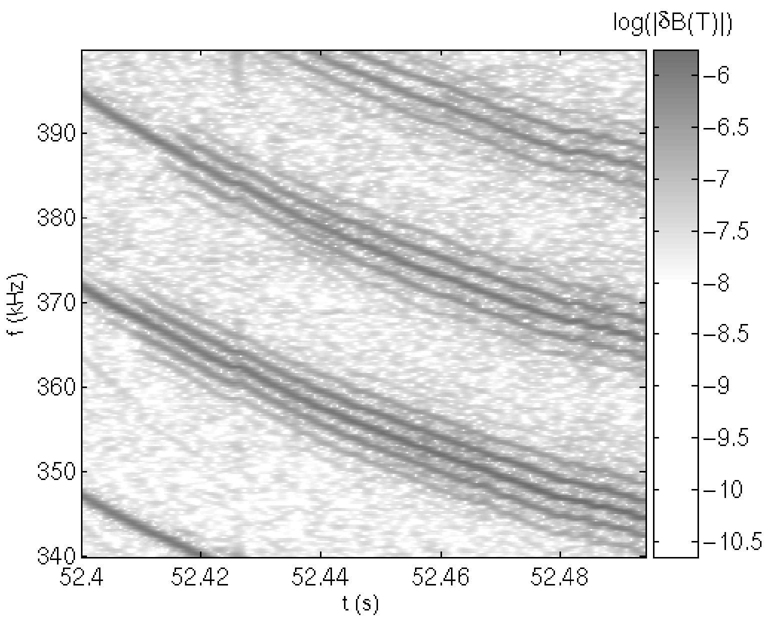


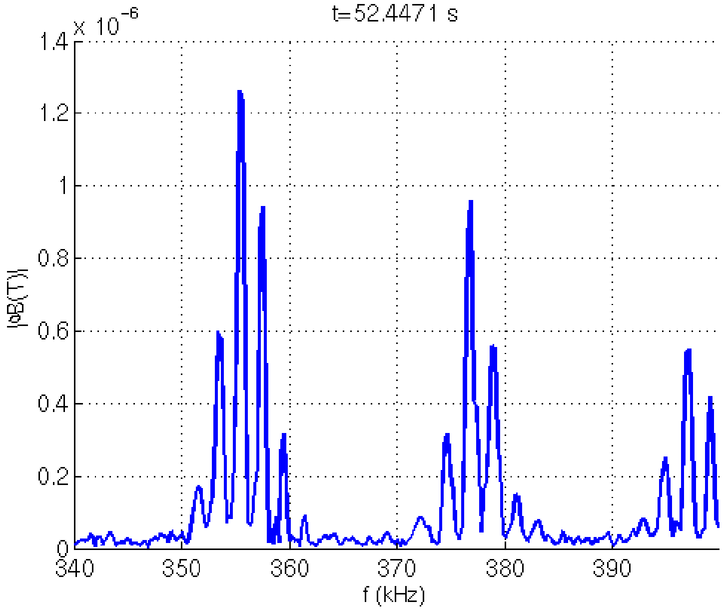
Splitting of mode frequency

Splitting of the mode frequency produces side bands.

Side bands are centred around the frequency of the mode with a shift of ~2 kHz.

Fasoli, A., et. al, Phys. Rev. Lett. ***81*** *(1998) 5564*





Outline

- ✔ Experimental observations
- ✔ Alfvén eigenmode dynamics
- ✔ Code development
- ✔ Simulation of AE dynamics
- ✔ Simulation on the effect with several AEs

Important effects

ICRH decorrelates the interactions and restores the distribution function.

The decorrelation can lead to overlap of several modes in phase space.

The decorrelation is important:

✔ leads to an effective broadening of the resonant region in phase space
✔ increases energy transport
✔ affects the saturation level
✔ increases the overlap of several modes in phase space

Alfvén eigenmode dynamics

Resonant ions will undergo a superadiabatic oscillation in phase space of the invariants of the equation of motion for the drift orbit (W, P_ϕ, μ).

1-D Characteristic: $\Delta P_\phi = \frac{n}{\omega} \Delta E$

$\Delta \mu = 0$

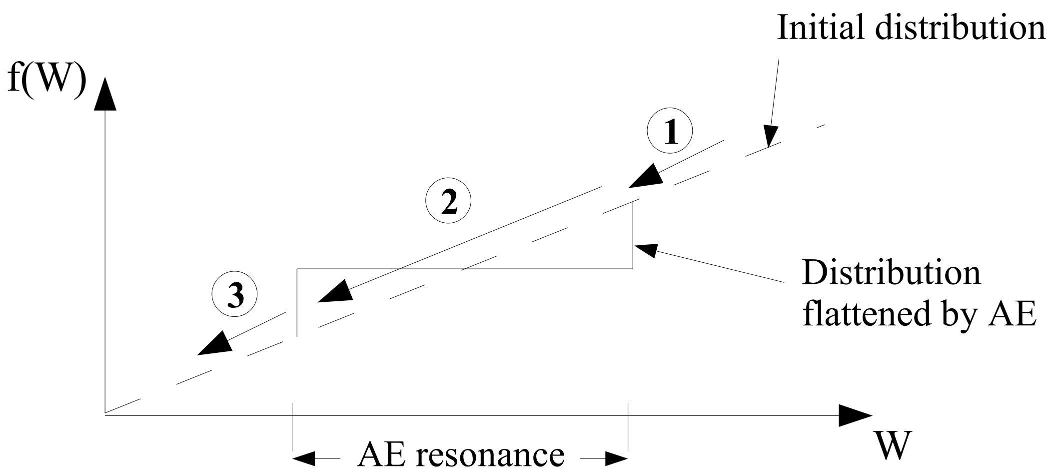
Collisions and interactions with other waves (ICRH) will decorrelate the AE interaction leading to a flattening of the distribution function along the characteristic.

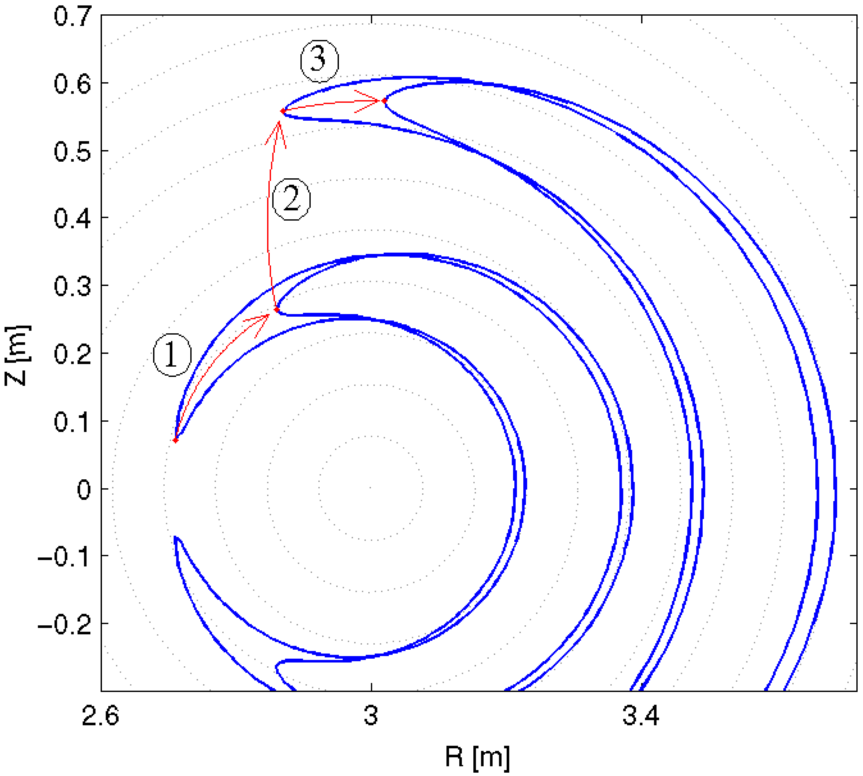
Distribution function increases with energy => energy transfer from ions to AE.

Alfvén eigenmode dynamics

- ✔ Without decorrelation of the AE interaction
  => superadiabatic oscillation of the orbit invariants.
- ✔ In the presence of decorrelations
  => Distribution function is flattened by a diffusive process.
- ✔ ICRH and collisions will partially restore the distribution function in the resonant region
  => Further transfer of energy from ions to an unstable AE.
- ✔ The decorrelation and local renewal rate of the distribution function increases with energy for ICRH, whereas they decrease with energy for Coulomb collisions.
- ✔ Coulomb collisions => superadiabatic oscillation of fast ions
  ICRH => diffusion of fast ions

Alfvén eigenmode dynamics





① High energy ion enters AE resonance through interaction with ICRH

② AE interaction flattens the distribution

③ Ion leaves the AE resonance through interaction with ICRH

Outline

- ✔ Experimental observations
- ✔ Alfvén eigenmode dynamics
- ✔ Code development
- ✔ Simulation of AE dynamics
- ✔ Simulation on the effect with several AEs

AE interaction

Unperturbed guiding centre orbits are described by the invariants

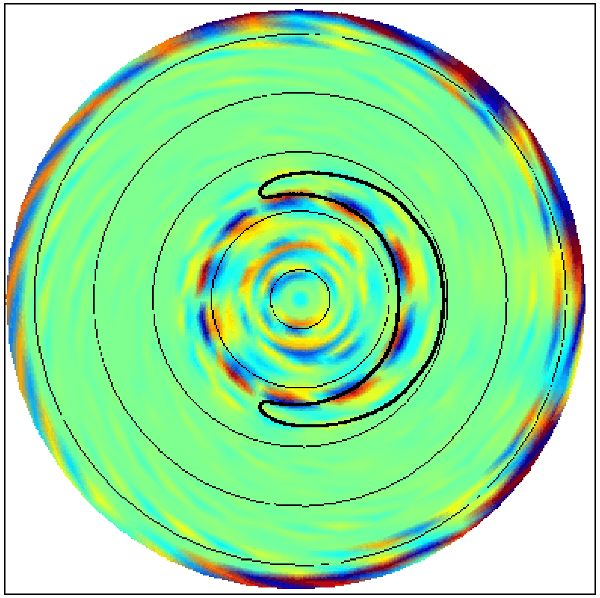
$$(E, \Lambda, P_\phi) \quad \Lambda = \frac{\mu B_0}{E}$$

Wave-particle interactions and Coulomb collisions displaces an unperturbed drift orbit in the phase space described by guiding centre orbit invariants.

$$\Delta E = \int_0^{t_N} q \boldsymbol{V_D} \cdot \boldsymbol{E_1} + \mu \frac{\partial B_{1\|}}{\partial t} = \sum_{k=1}^{N} q \Re (e^{i \vartheta k} \Delta E_0)$$

$$\Delta \mu = 0 \Rightarrow \Delta \Lambda = \frac{-\Lambda \Delta E}{E + \Delta E}$$

$$\Delta P_\phi = \frac{n_\phi}{\omega} \Delta E$$



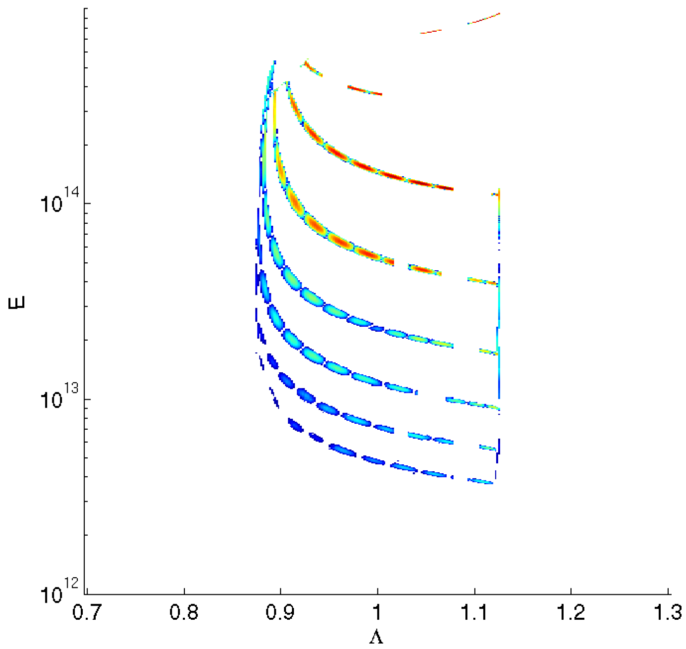
Resonance condition: $n \omega_\phi - m \omega_\theta - \omega \pm n_0 \frac{2\pi}{\tau_b} = 0$

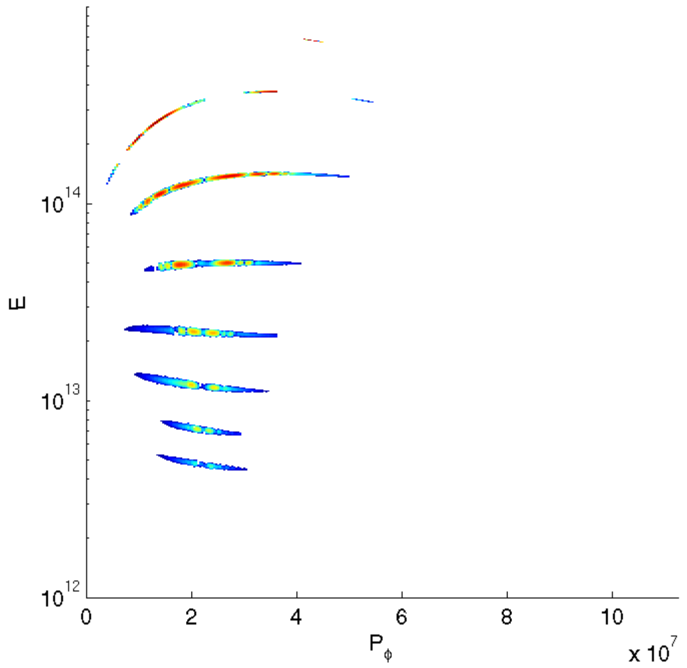
Resonance condition

Phase decorrelations result in stochastic changes of the phase difference between the ions and AE.

$$\left(n\,\omega_\phi - m\,\omega_\theta - \omega \pm n_0 \frac{2\pi}{\tau_b}\right)\tau_d \leqslant 2\pi$$

Outside the resonant region the phase between ion and AE varies rapidly and only gives small contributions.



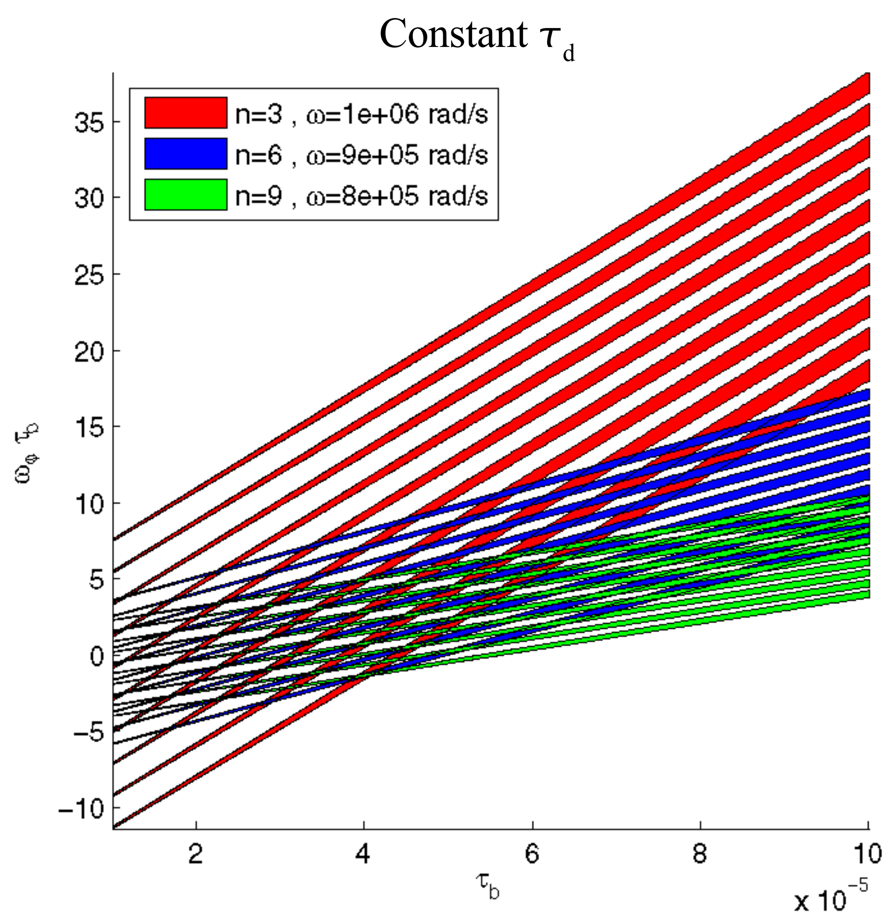


Resonance condition, several modes

✔Several modes with different toroidal mode numbers and frequencies can overlap in phase space
=> increased redistribution of resonant ions.

✔The width of resonant region is determined by collisions and ICRH.

Stronger ICRH
=> wider resonant regions
=> larger overlap
=> increased redistribution of resonant ions



Orbit averaged Monte Carlo code

For comparison and prediction of the AE dynamics it is important to

✔ Make self-consistent simulation of Alfvén wave excitation and ICRH

✔ Include the complex structure of the resonant regions in phase space

✔ Include the effects of decorrelation and partial restoration of the distribution function by ICRH and collisions

Because of finite orbit width effects, a Monte Carlo method is used to solve the orbit averaged distribution function.

The evolution of the distribution function including collisions, ICRH and AE interactions can be described by a stochastic diffusion equation.

Monte Carlo increments

The change in wave phase is given by the phase of the particle, but the particle phase is assumed to be random before the interactions

=> The expectation value for the change in wave phase is zero

=> Stochastic contribution to the change in mode amplitude

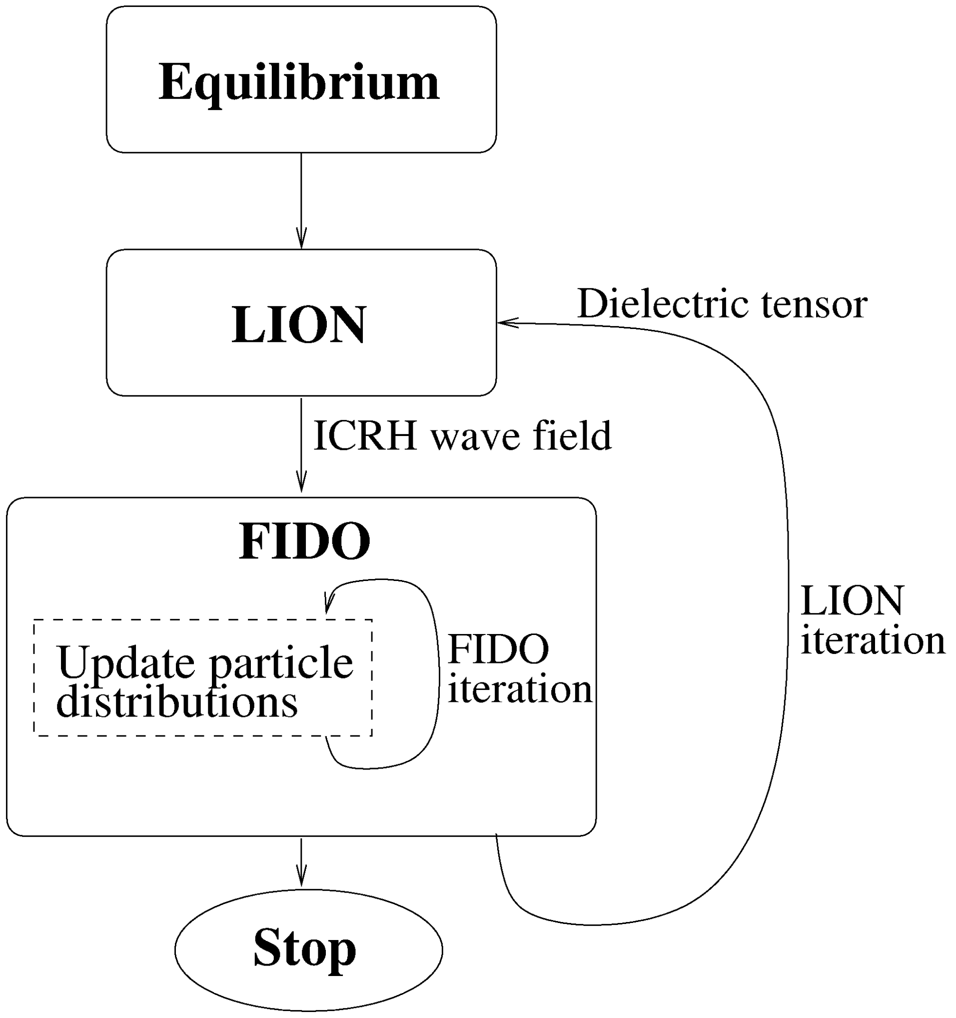
$$\begin{pmatrix} E^i_{N+1} \\ \Lambda^i_{N+1} \\ P^i_{\phi N+1} \end{pmatrix} = \begin{pmatrix} E^i_{N} \\ \Lambda^i_{N} \\ P^i_{\phi N} \end{pmatrix} + \overbrace{\begin{pmatrix} dE^C + \xi^C_1 \Delta E^C \\ d\Lambda^C + \xi^C_2 \Delta \Lambda^C \\ dP^C_\phi + \sum_{k=1}^{2} \xi^C_k \Delta P^C_{\phi k} \end{pmatrix}}^{Collisions} + \overbrace{\begin{pmatrix} dE^R + \xi^R_1 \Delta E^R \\ d\Lambda^R + \xi^R_1 \Delta \Lambda^R \\ dP^R_\phi + \xi^R_1 \Delta P^C_\phi \end{pmatrix}}^{ICRH} + \overbrace{\begin{pmatrix} dE^M + \xi^M_1 \Delta E^M \\ d\Lambda^M + \xi^M_1 \Delta \Lambda \\ dP^M_\phi + \xi^M_1 \Delta P^M_\phi \end{pmatrix}}^{MHD} + \ldots$$

$$A_{wave} = \sum dE^M + \xi^M_1 \Delta E^M$$

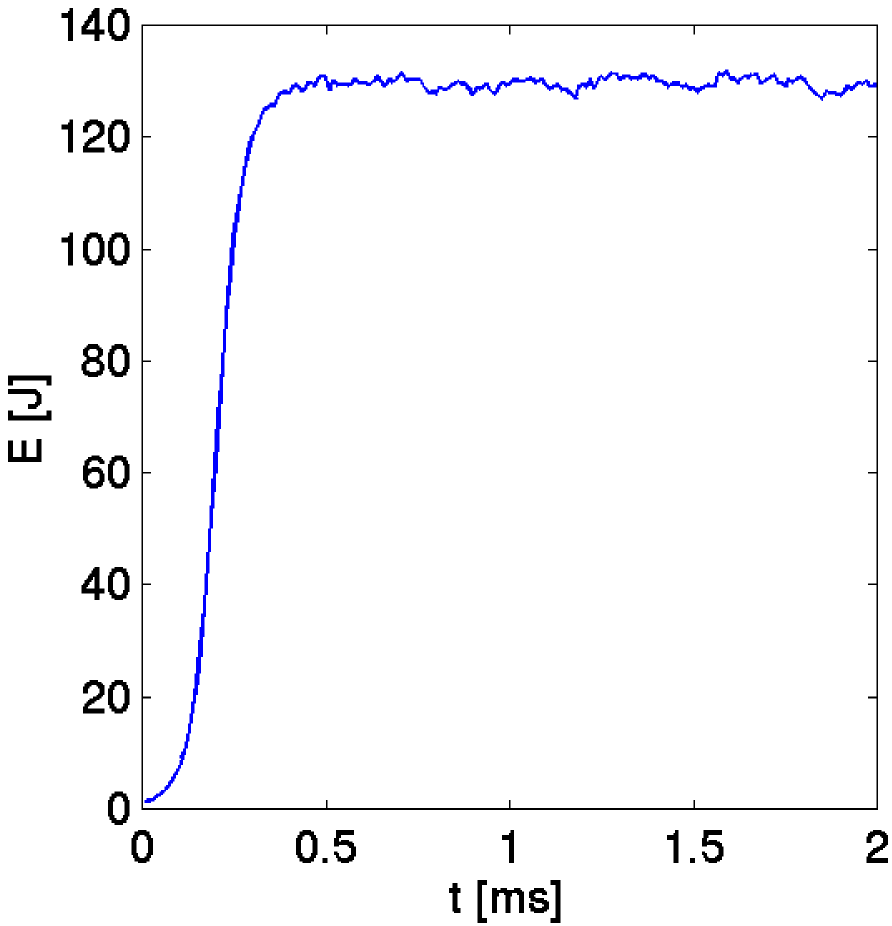
We use an analytic model of the AE structure!

SELFO Code

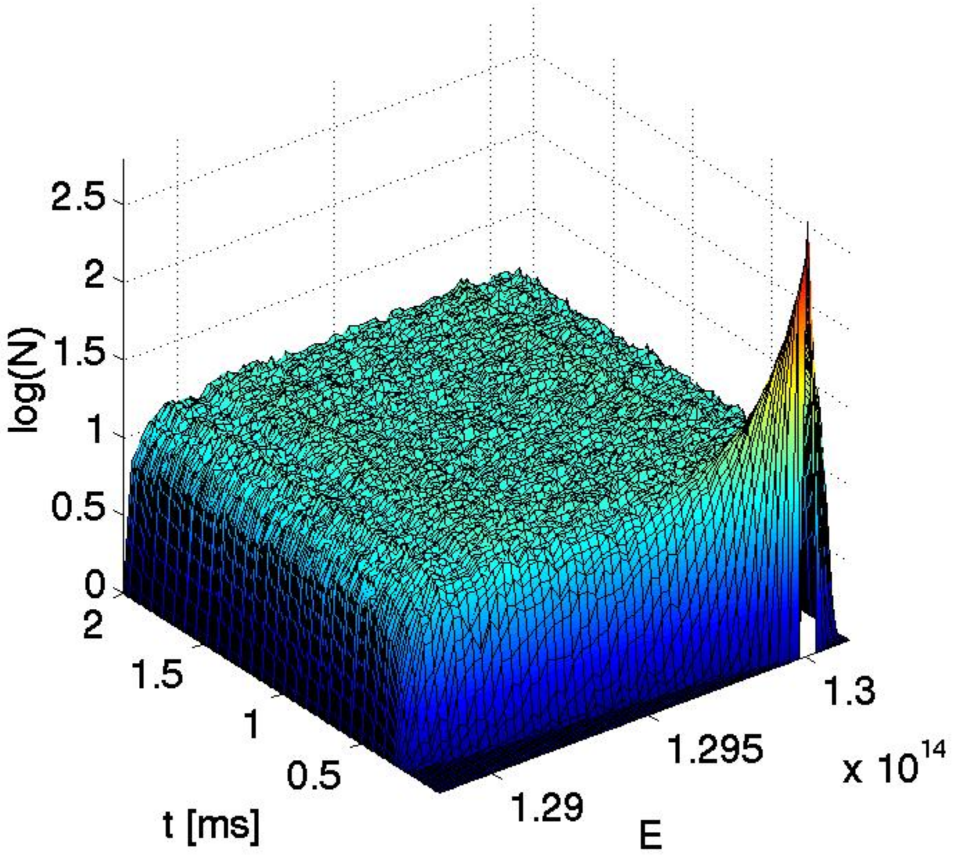
- ✔ Code for self-consistent calculations of the ICRH power deposition and distribution function
- ✔ The number of FIDO time steps during a LION iteration varies during the simulation.



Test of code



140
120
100
80
60
40
20
0
E [J]
0
0.5
1
1.5
2
t [ms]



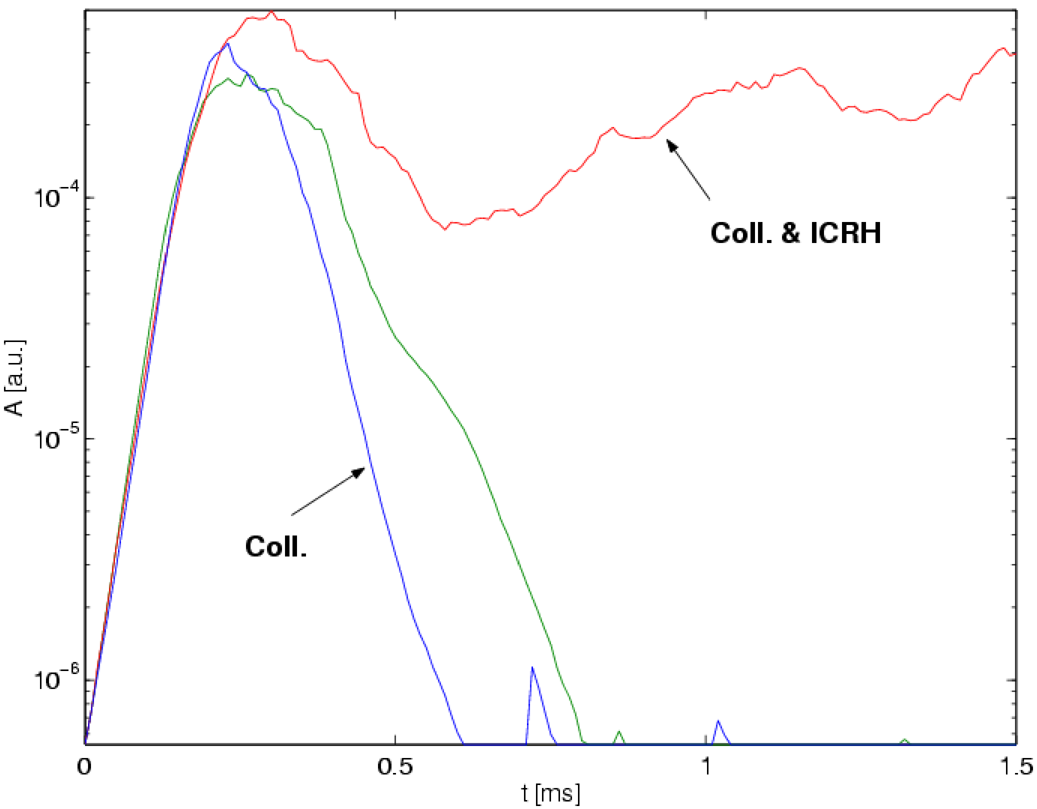
log(N)
2.5
2
1.5
1
0.5
0
2
1.5
1
0.5
t [ms]
1.29
1.295
1.3
x 10^14
E

Outline

- ✔Experimental observations
- ✔Alfvén eigenmode dynamics
- ✔Code development
- ✔Simulation of AE dynamics
- ✔Simulation on the effect with several AEs

Excitation of a TAE

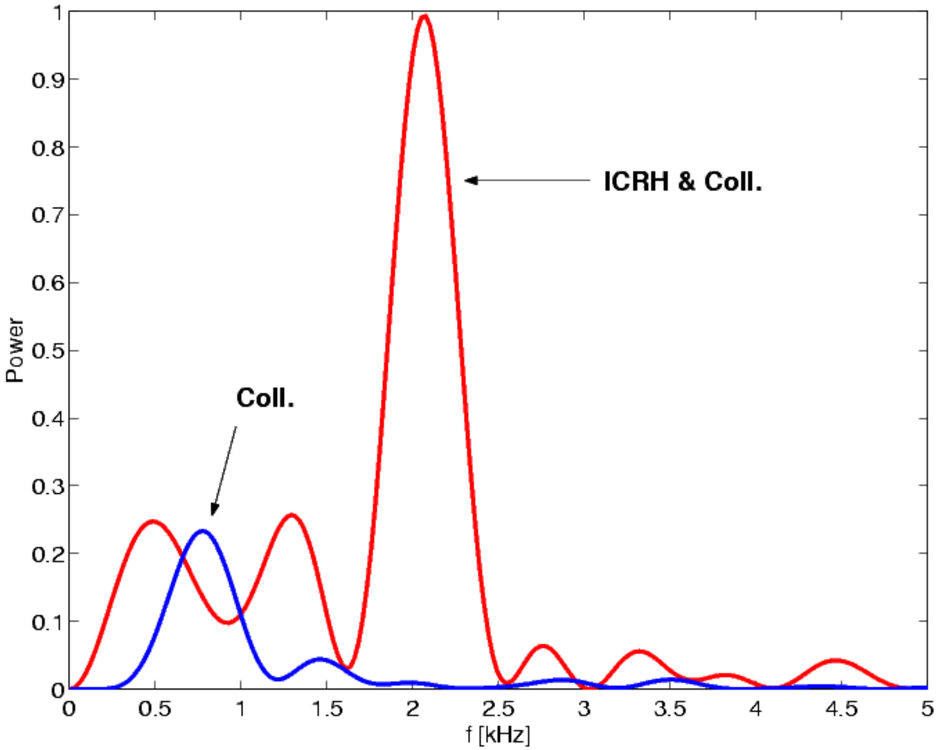
- ✔ Study the effect of the renewal of the distribution function by ICRH and collisions.
- ✔ In absence of collisions and ICRH the unstable mode grows up and decays.
- ✔ Collisions and/or ICRH partially restore the distribution function.

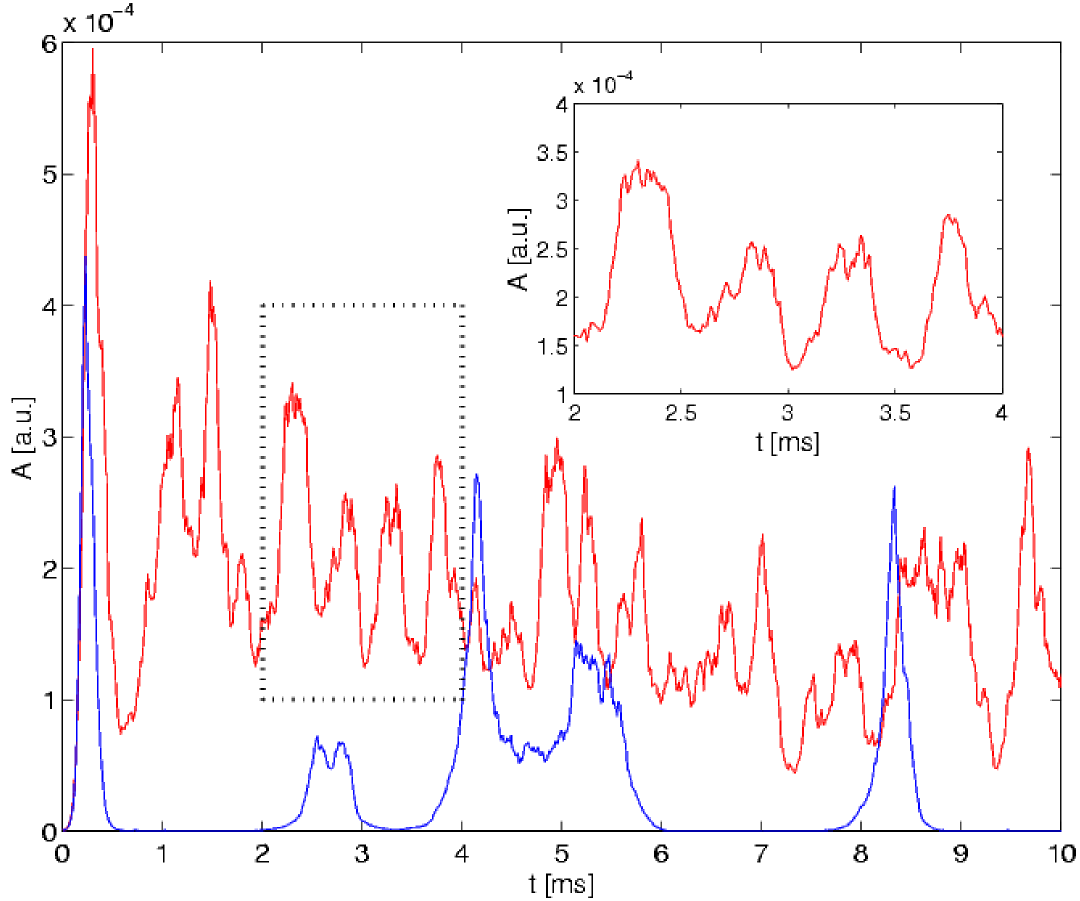


Fluctuation of mode amplitude

The characteristic oscillation period is related to the effective collision frequency.
Fasoli, A., et. al, Phys. Rev. Lett. ***81*** *(1998) 5564*

Collisions: τ~1.5 ms
Collisions & ICRH: τ~0.5 ms





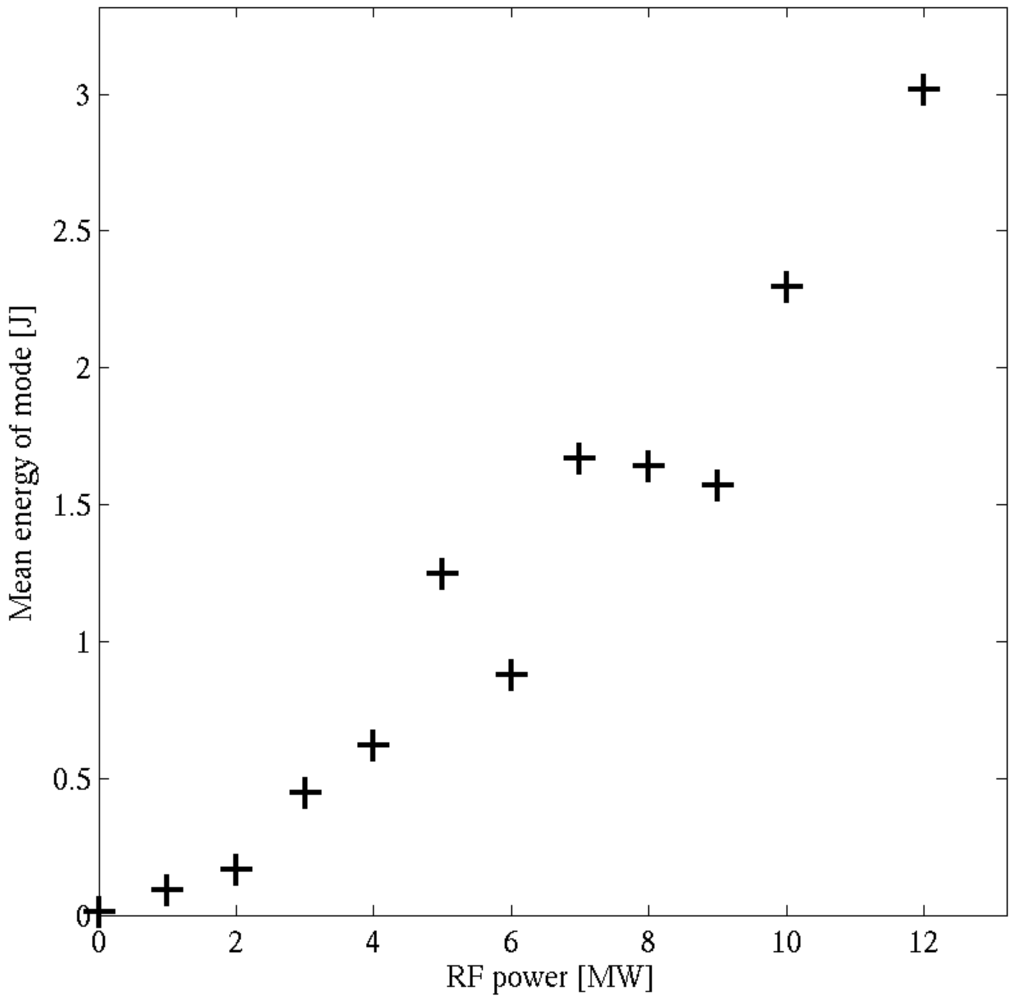
Redistribution of fast ions

$$\Delta E_{AE} = \iint \Delta E_r \boldsymbol{\Gamma}_{AE} \cdot \boldsymbol{ds}\, dt \propto \int A^2 dt$$

$$\Delta r = \Delta P_\phi \frac{1}{eZ} \left(\frac{\partial \Psi}{\partial r} \right)^{-1}$$

Time-averaged redistribution of resonant ions is related to the time-averaged mode energy.

Redistribution increases with RF power.



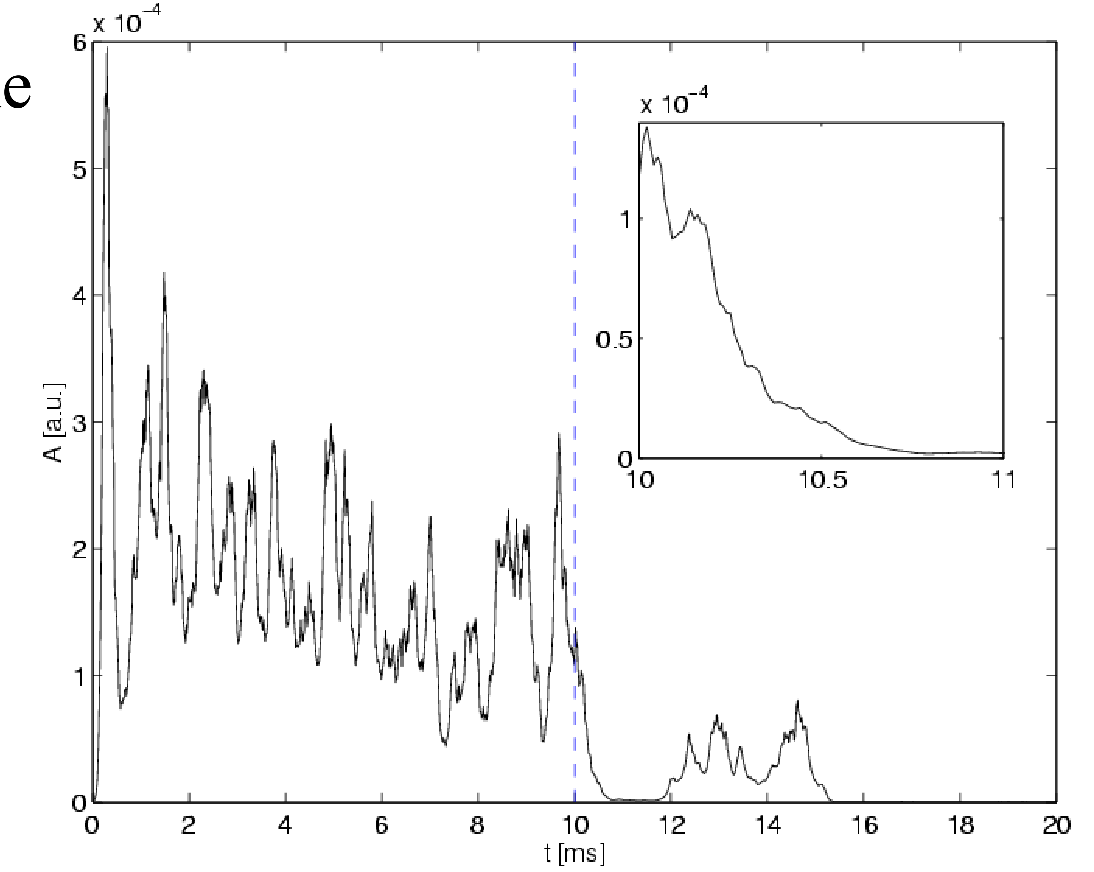
Fast termination of the mode

The intrinsic damping by the stable part of the distribution function of the resonant ions rapidly damps the AE when ICRH is switched off.

γ_d/ω=0.6%

Experiments at JET *0.1-10 %*
Fasoli, A., et. al, Plasma Phys. Control. Fusion, ***39*** *(1997) B287*

Experiments at TFTR *~1 ms*
Wong, K., Plasma Phys. Control. Fusion, ***41*** *(1999) R1*

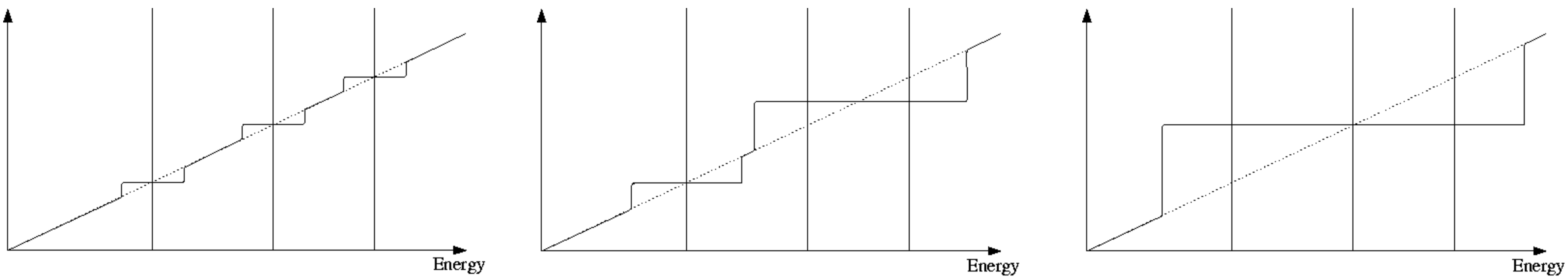


Outline

- ✔ Experimental observations
- ✔ Alfvén eigenmode dynamics
- ✔ Code development
- ✔ Simulation of AE dynamics
- ✔ Simulation on the effect with several AEs

Overlap of several modes

Modes overlapping in phase space may enhance transport of high energetic resonant ions



ICRH power increases

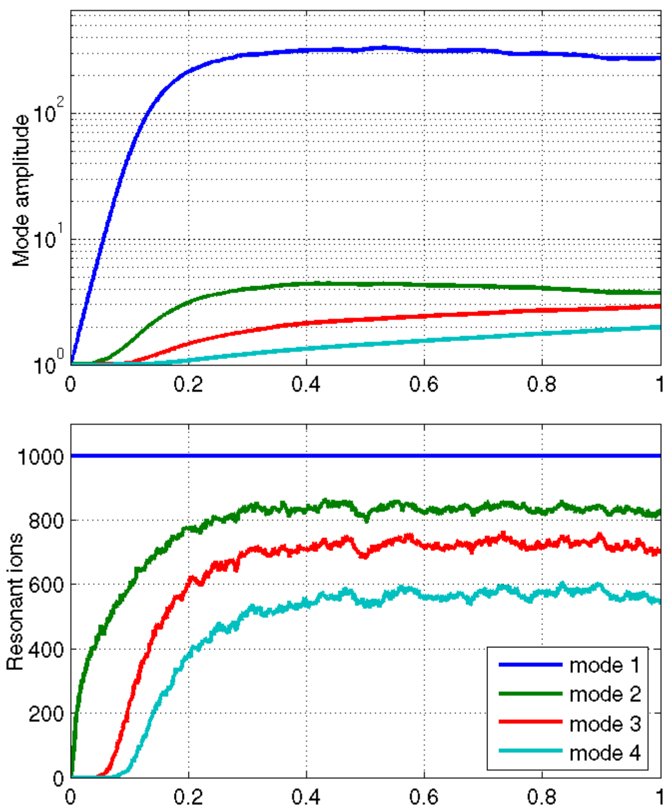
=> decorrelation time decreases

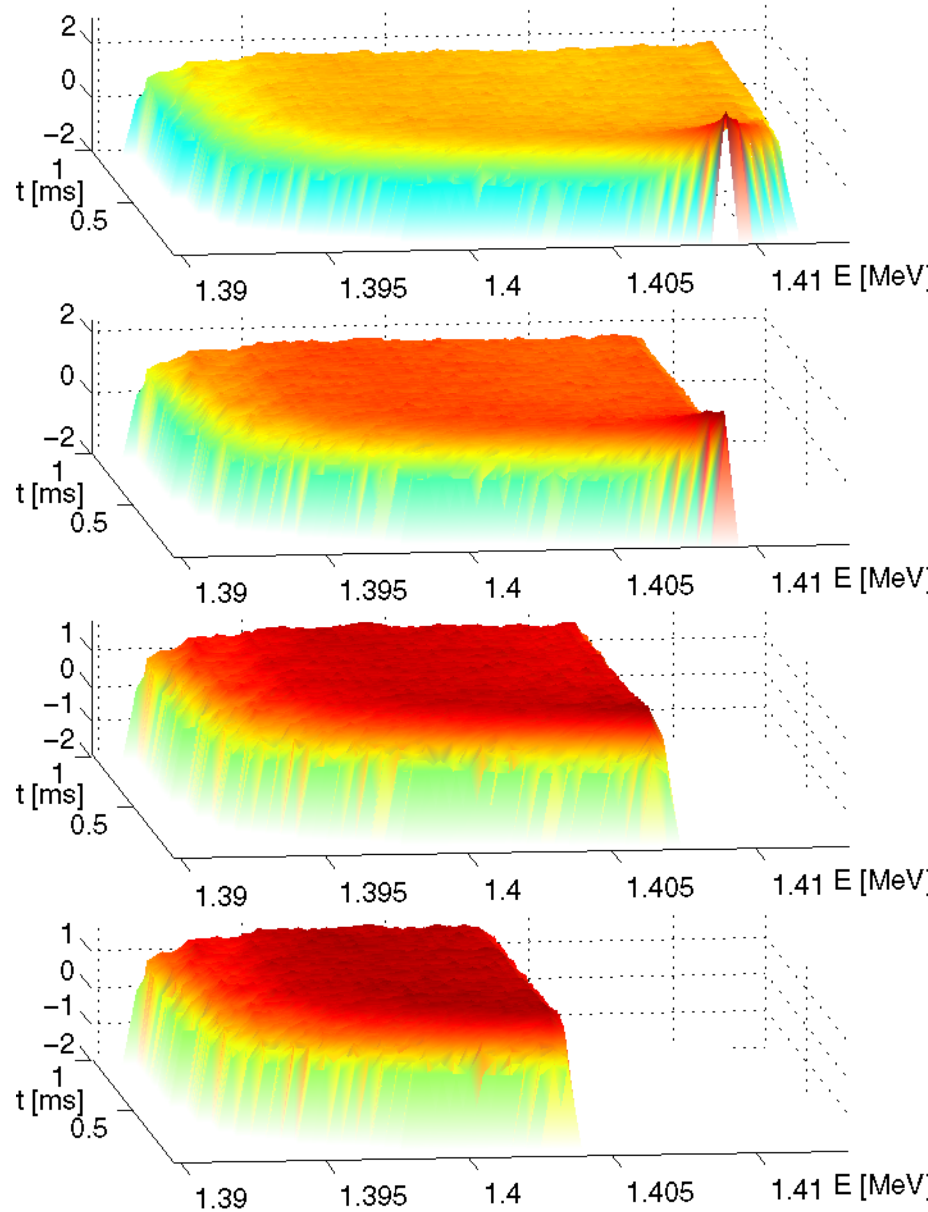
=> resonant region increases

=> overlap increases

4 modes aligned along the same characteristic

Initial unstable δ-function.
Same mode number n, and small shift in ω => ~ same characteristic



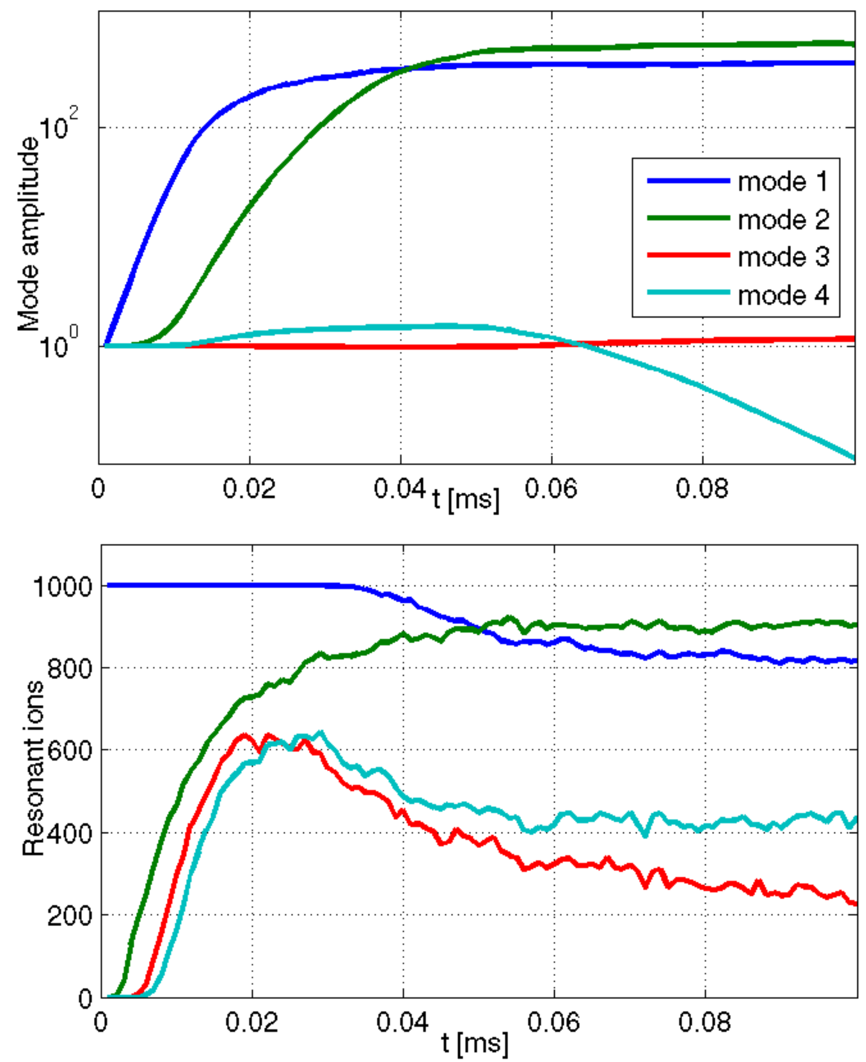


4 modes with different mode numbers

Initial unstable δ-function.

Different mode numbers n, and different ω.

Angle between the characteristics
=> 2D diffusion process
=> Very complicated behaviour of AE dynamics



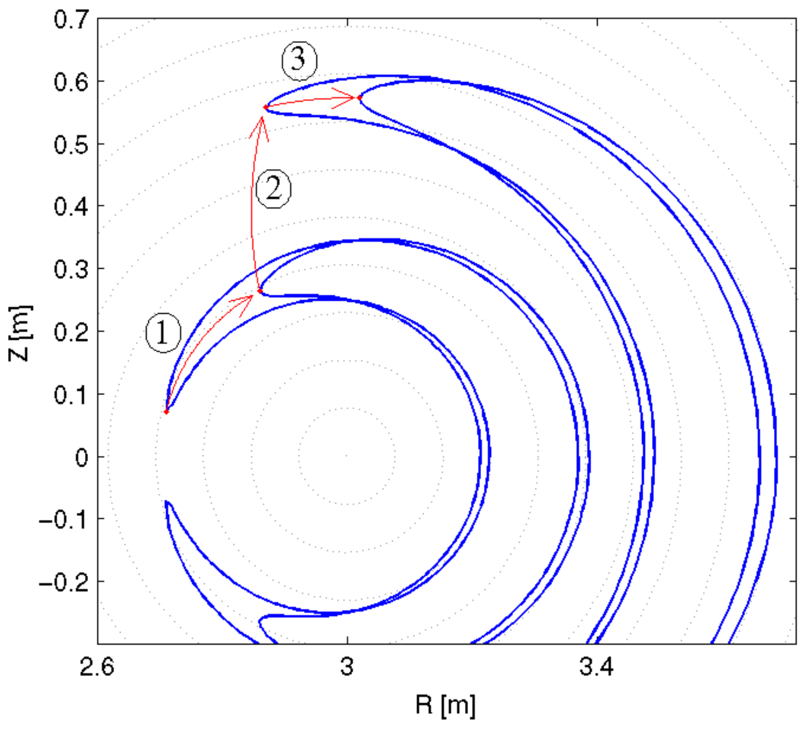
Redistribution of fast ions

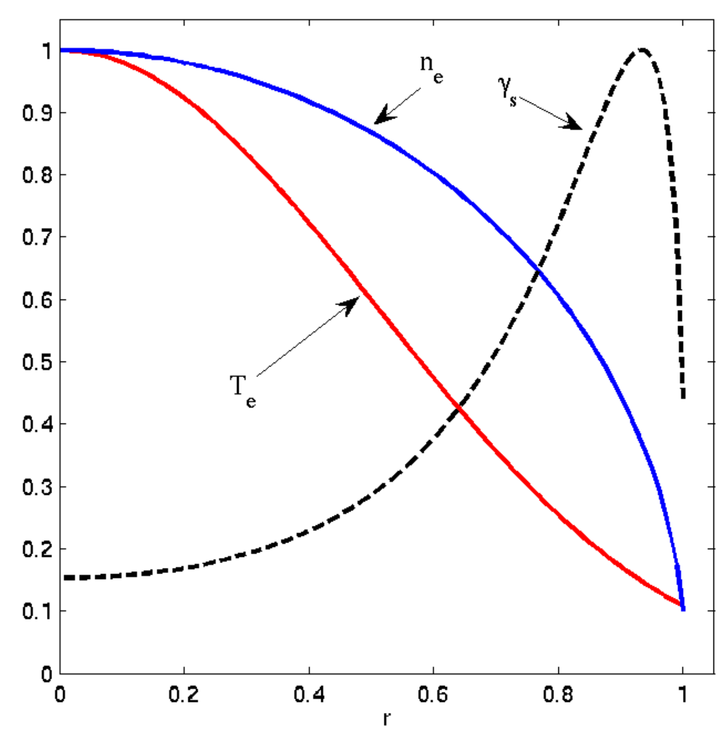
P_ϕ increases

=> turning points of trapped particles are displaced $\Delta r = \Delta P_\phi \frac{1}{eZ}\left(\frac{\partial \Psi}{\partial r}\right)^{-1}$

=> where the electron temperature is lower.

=> increased collision frequency between electrons and fast ions, $\gamma_s \propto n T_e^{-3/2}$

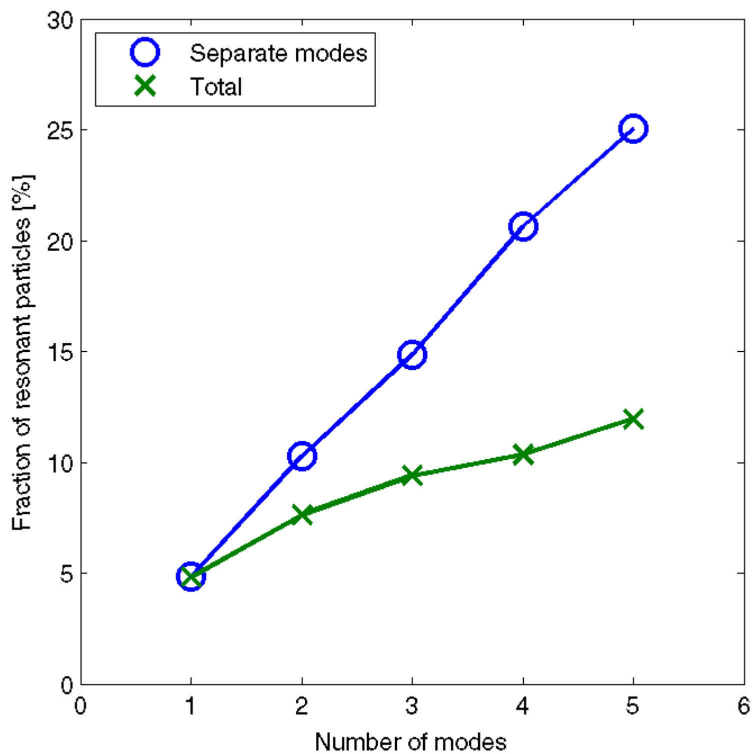




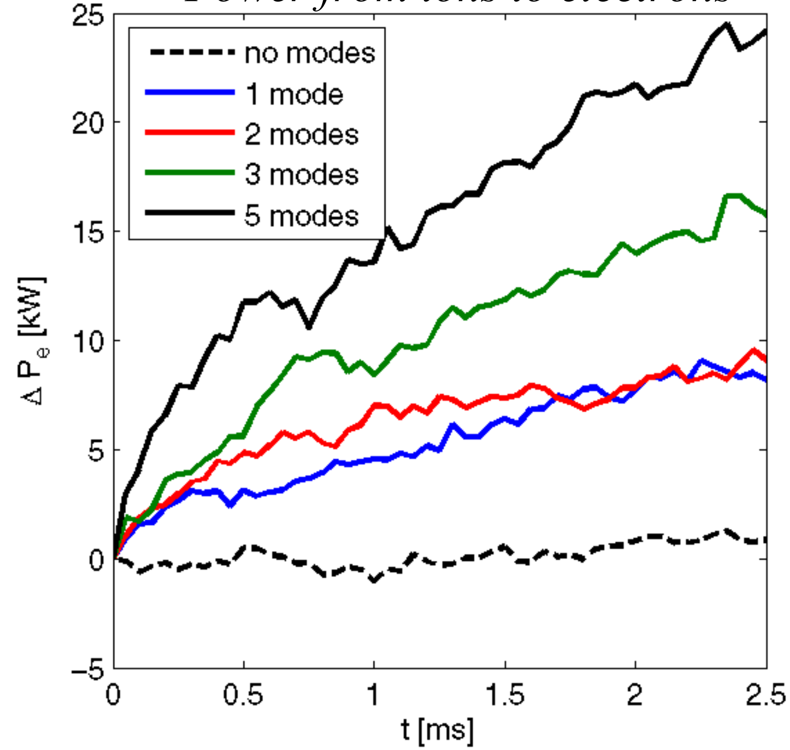
Redistribution of fast ions

✔Simulate unstable TAEs driven by external coils.

✔Adding more modes increases the radial redistribution of resonant particles.



Power from ions to electrons



Redistribution of fast ions

At the turning point $v_{\|}=0$

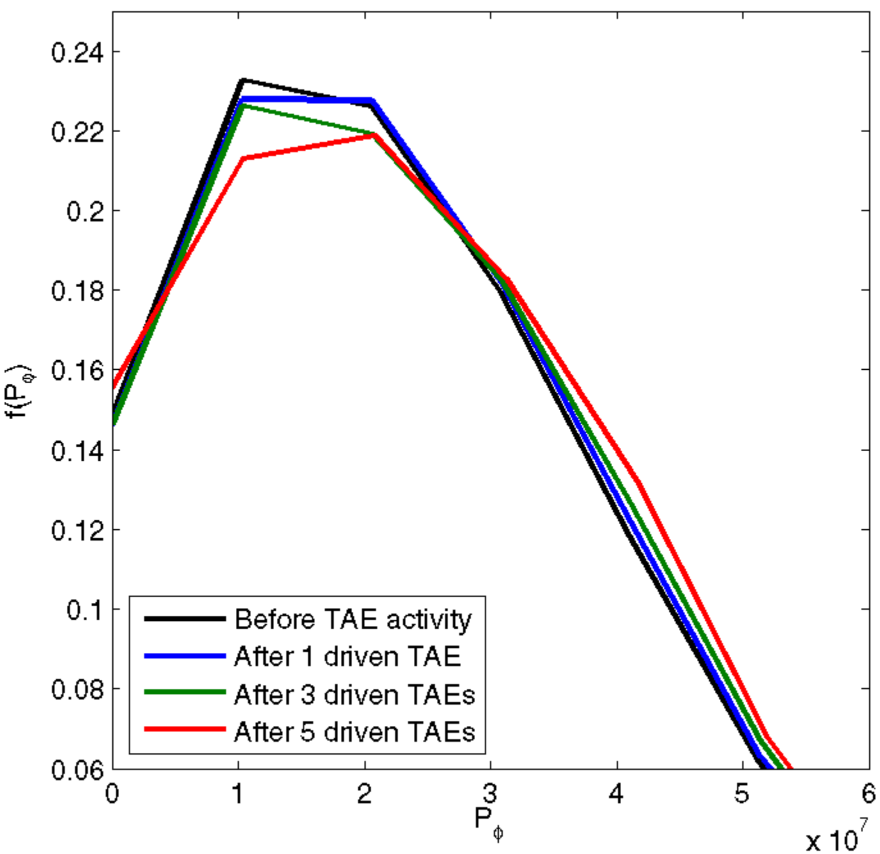
$$\Rightarrow \Delta P_\phi = \frac{eZ}{m} \Delta \Psi$$

In this scenario a change in P_ϕ of 10^7 corresponds to a radial shift of 5 cm at the location of the AEs.

A small effect on the total distribution function.

A large effect on a small part of the distribution function.

P_ϕ distribution of trapped particles above 100 keV



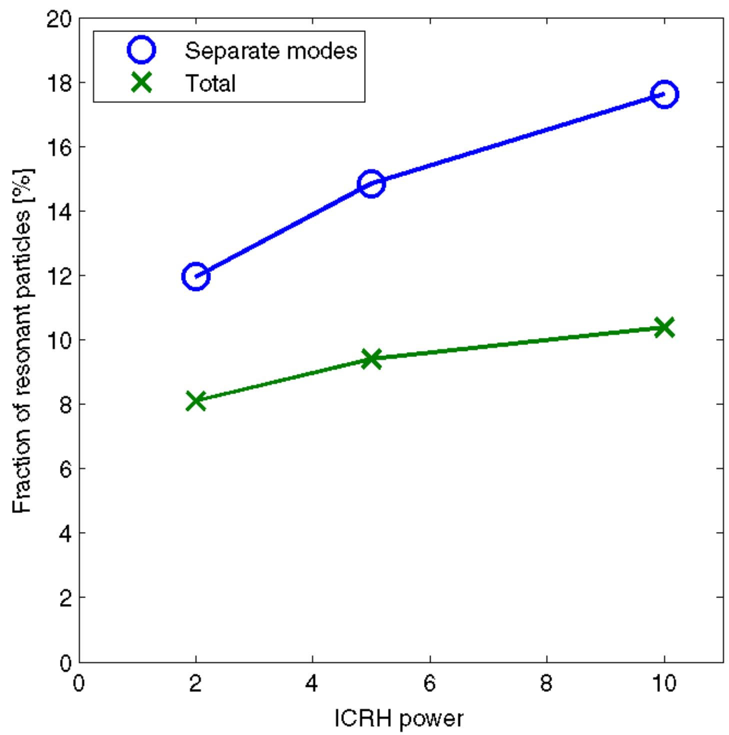
Redistribution of fast ions

Increased ICRH power

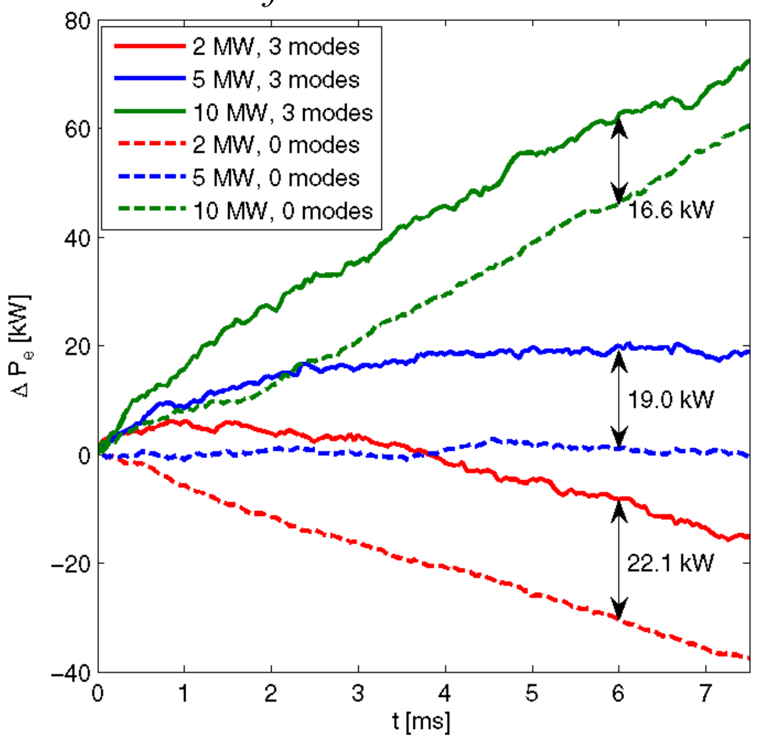
=> increased overlap in phase space

The distribution function is restored faster with higher ICRH power.

The redistribution by AEs and ICRH restoration reaches a steady state.



Power from ions to electrons



Conclusions

✔A code has been developed to treat excitation of MHD-modes, ICRH and collisions in a self-consistent way.

✔Decorrelation and restoration of the distribution function by collisions and ICRH have a strong effect on the excitation, saturation level and fluctuation of the mode amplitude.

✔In absence of restoration of the distribution function by collisions or ICRH an unstable AE grows up and damps by the intrinsic damping even in the absence of background damping.

✔Non-linear splitting of the mode amplitude. Strong restoration of the distribution function and decorrelation (ICRH) gives rapid oscillation. Weak restoration and decorrelation (collisions) gives a slow oscillation.

✔The fast decay of the mode amplitude as the ICRH is turned off. Simulations are consistent with experimental observations in both JET and TFTR.

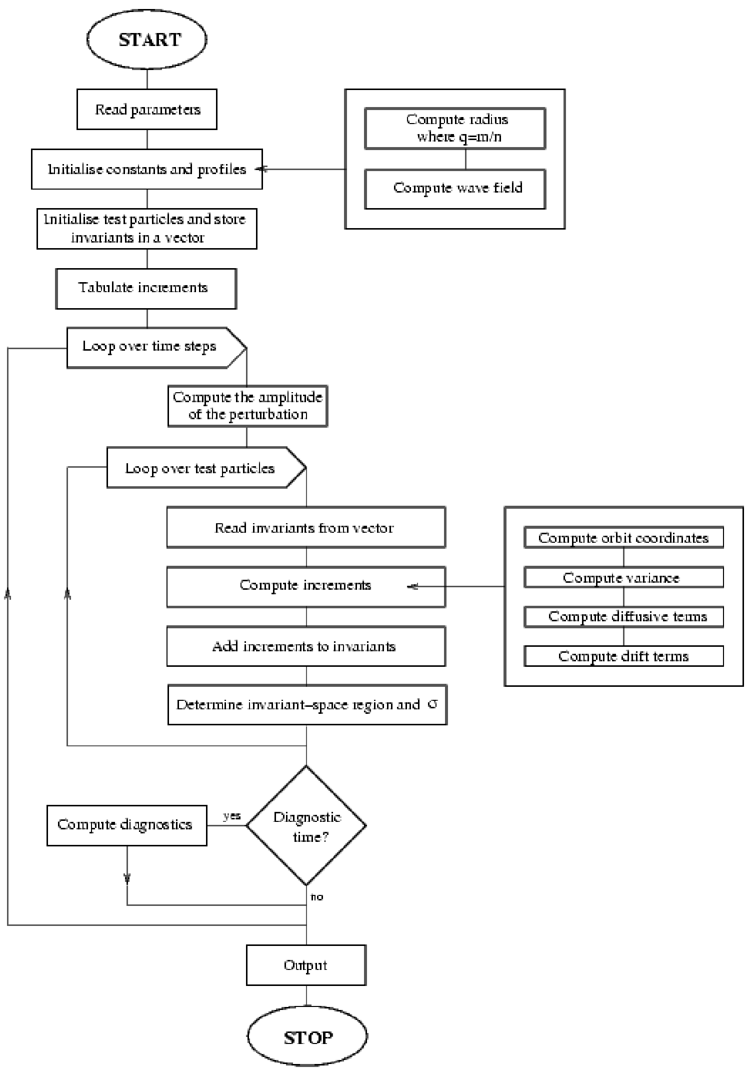
Conclusions

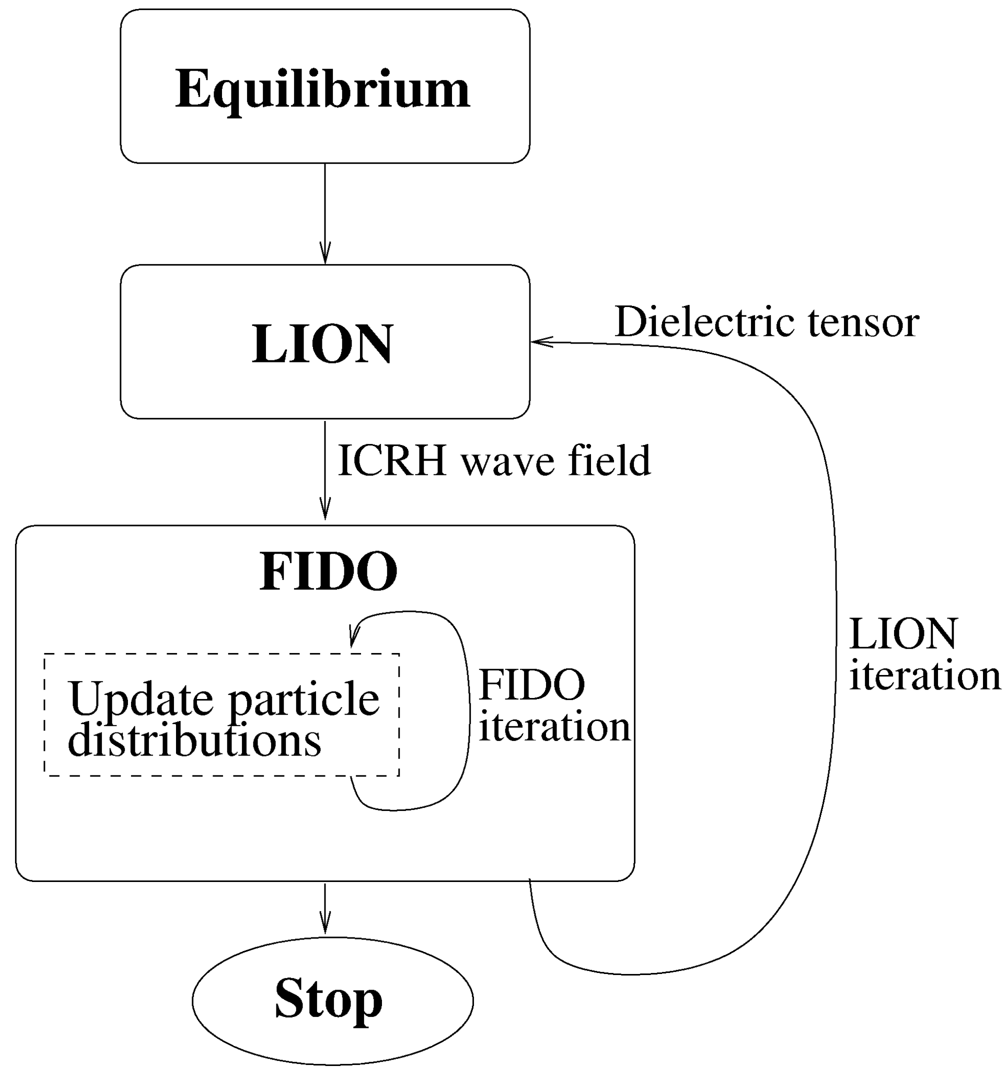
✔No significant effect on the ions cyclotron heating from one mode.

✔Several modes increases redistribution.

✔Increased ICRH power contributes both to increased overlap and faster restoration of distribution function.

SELFO Code


START
Read parameters
Initialise constants and profiles
Compute radius where q=m/n
Compute wave field
Initialise test particles and store invariants in a vector
Tabulate increments
Loop over time steps
Compute the amplitude of the perturbation
Loop over test particles
Read invariants from vector
Compute increments
Add increments to invariants
Determine invariant–space region and σ
Compute orbit coordinates
Compute variance
Compute diffusive terms
Compute drift terms
Compute diagnostics
yes
Diagnostic time?
no
Output
STOP


Equilibrium
LION
Dielectric tensor
ICRH wave field
FIDO
Update particle distributions
FIDO iteration
LION iteration
Stop