Theory of cyclotron instability of hot electrons in ECRIS: origin, manifestation, and influence on plasma confinement

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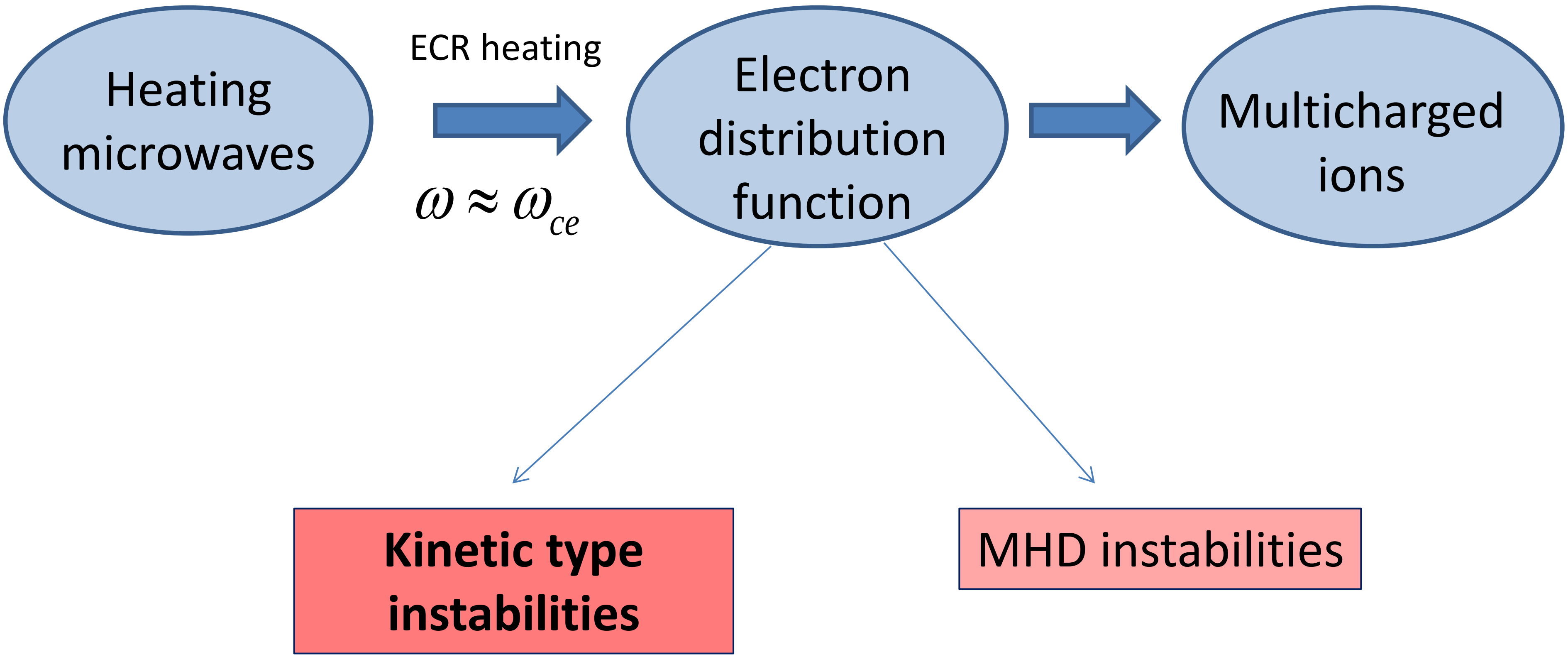
Outline

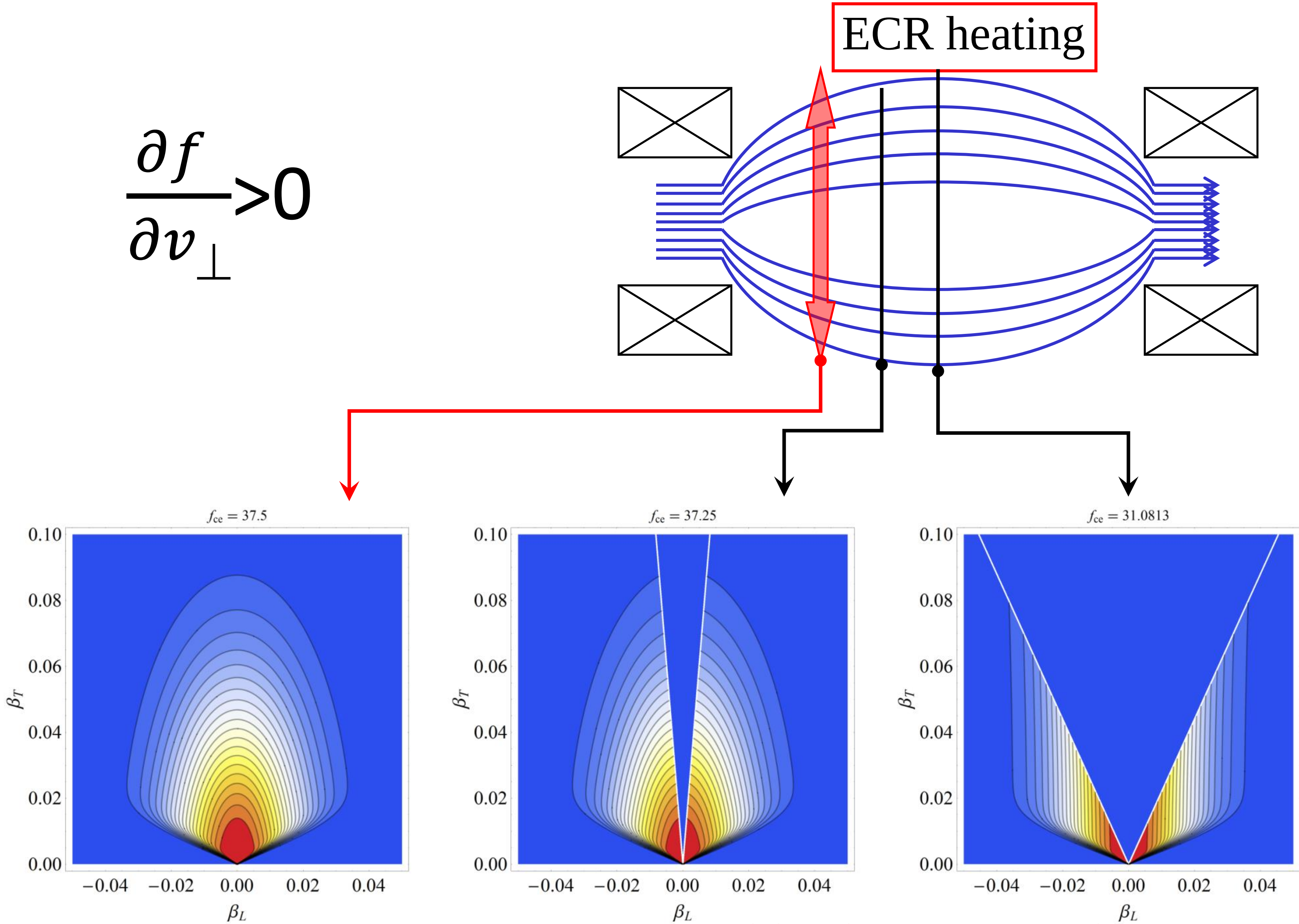
- ECR heating as a background for kinetic instabilities
- Cyclotron mechanism generation of electromagnetic waves in plasma
- Manifestation of cyclotron instability in ECRIS
- Cyclotron instability in CW and Afterglow regimes
- Current challenges and perspectives

Basic principles of ECR heating



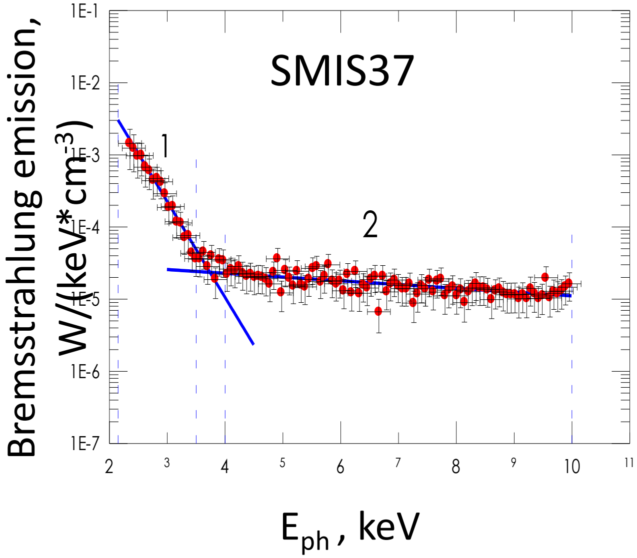
Anisotropic EDF as one of ECR discharge features

$$\frac{\partial f}{\partial v_\perp} > 0$$



Unstable electron distributions

Multicomponent plasma of pulsed ECR discharge



Different isotropization time!

1) Ambient plasma
T_e ~ 300 eV
N_e ~ 10^{13}-10^{14} cm^{-3}

Dispersion wave properties

2) Hot electrons
T_h ~ 10 keV
N_h ~ 10^{10} – 10^{11} cm^{-3}

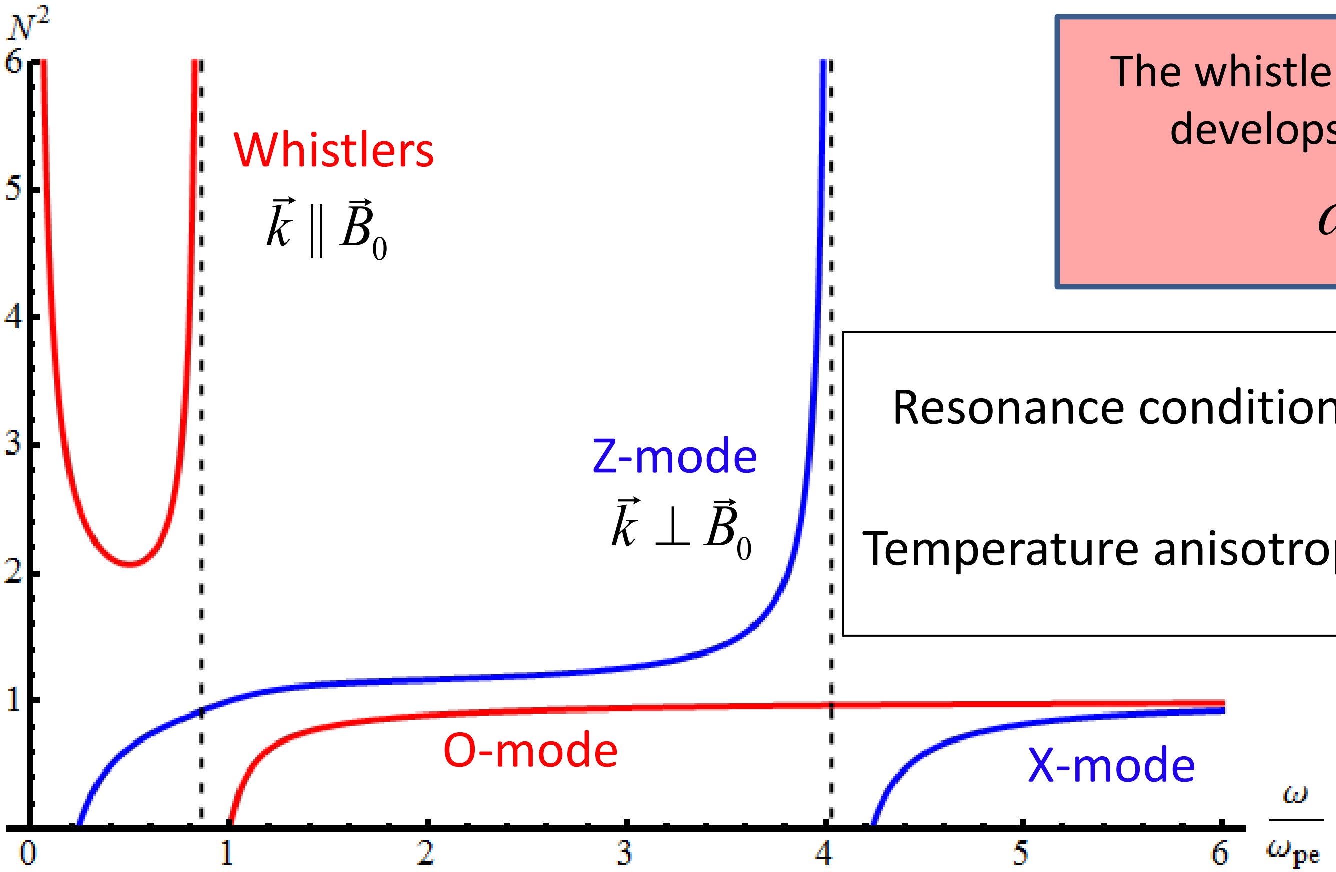
$$T_{hot\perp} >> T_{hot\parallel}$$

Anisotropy of EEDF determines generation and amplification of the waves

3) Relativistic electrons
E_h ~ 300-400 keV
N_{rel} ~ 10^8 – 10^9 cm^{-3}

Play a key role on the initial stage of discharge

Unstable modes which can interact with energetic electrons



The whistler cyclotron instability develops in dense plasma:

$$\omega < \omega_{ce} \leq \omega_{pe}$$

Resonance condition: $\omega - k_{\parallel} \upsilon_{\parallel} = \omega_{ce}$

Temperature anisotropy: $T_{hot\perp} >> T_{hot\parallel}$

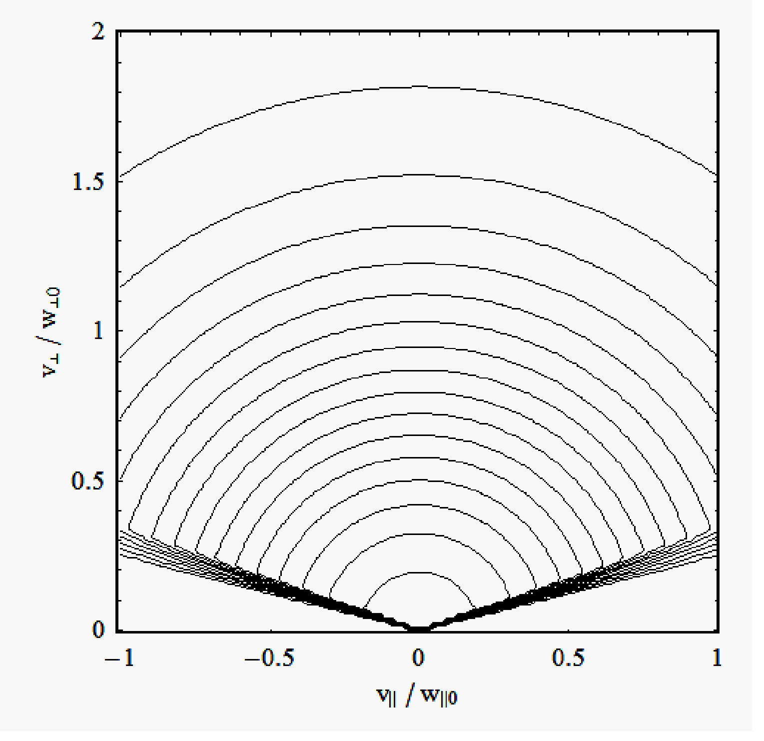
In rarefied plasma the cyclotron instability develops on the Z-mode (slow extraordinary wave) or X-mode (fast extraordinary wave) with quasi-perpendicular propagation to the magnetic field

X-mode: $\omega_{pe} < \omega_{ce} < \omega$

Z-mode: $\omega_{pe} < \omega < \omega_{ce}$

Growth rate for anisotropic Maxwellian EDF with loss cone

$$f(v_\perp, v_{||}) = \frac{N_h}{\pi^{3/2}\mu w_\perp^2 w_{||}} \exp\left[-\frac{v_\perp^2}{w_\perp^2} - \frac{v_{||}^2}{w_{||}^2}\right]\Theta(\alpha)$$



Growth and damping rates for whistlers and X-mode

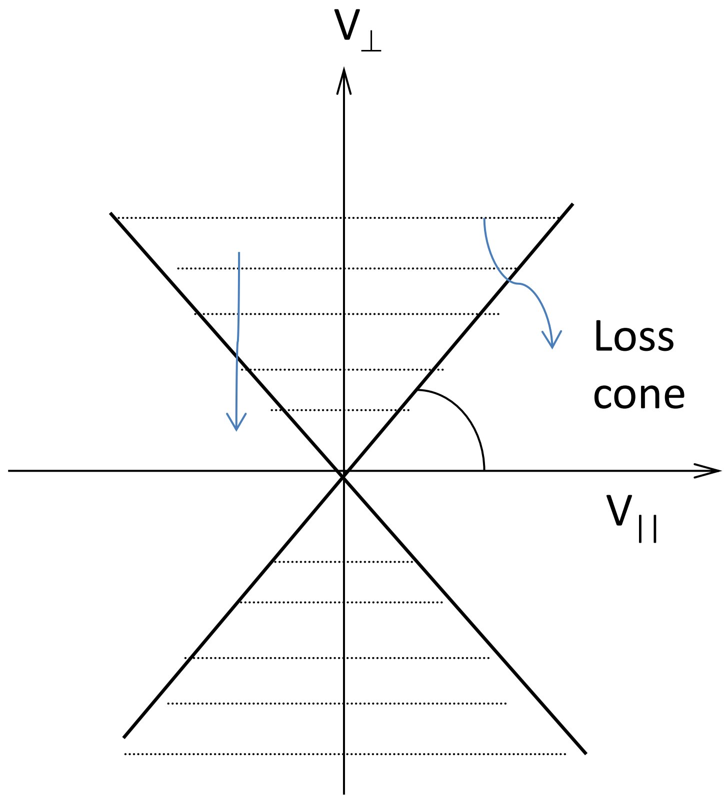
$$\gamma_{\mathrm{w}} \propto \omega_{\mathrm{ce}} \frac{N_{\mathrm{e,hot}}}{N_{\mathrm{e,cold}}} \left(\frac{\langle E_{\perp} \rangle}{\langle E_{\parallel} \rangle} - 1 \right) \mathrm{e}^{-\xi \frac{B^2}{\langle E_{\parallel} \rangle N_{\mathrm{e,cold}}}}$$

$$\gamma_{\mathrm{X}} \propto \omega_{\mathrm{ce}} \frac{N_{\mathrm{e,hot}}}{N_{\mathrm{e,cold}}} \left(\frac{\langle E_{\parallel} \rangle^2}{\langle E_{\perp} \rangle m_{\mathrm{e}} c^2} \right),$$

$$\delta_{\mathrm{w}} \approx \frac{\omega}{\omega_{\mathrm{ce}}} \nu_{\mathrm{e}} + \frac{v_{\mathrm{g}} |\ln R|}{L}$$

$$\delta_{\mathrm{X}} \approx \nu_{\mathrm{e}} + \frac{v_{\mathrm{g}} |\ln R|}{L},$$

Manifestation of cyclotron instability



- Generation of electromagnetic emission (10-100 ns, up to several kW)
- Fluxes of hot electron from the trap
- Generation of X-ray bursts

Basic «maser» equations for non-linear stage of cyclotron instability

N – «inversion» or density of hot particles

$$dN/dt \approx -\kappa N E + J(t)$$
$$dE/dt \approx \langle \gamma - \delta \rangle E$$

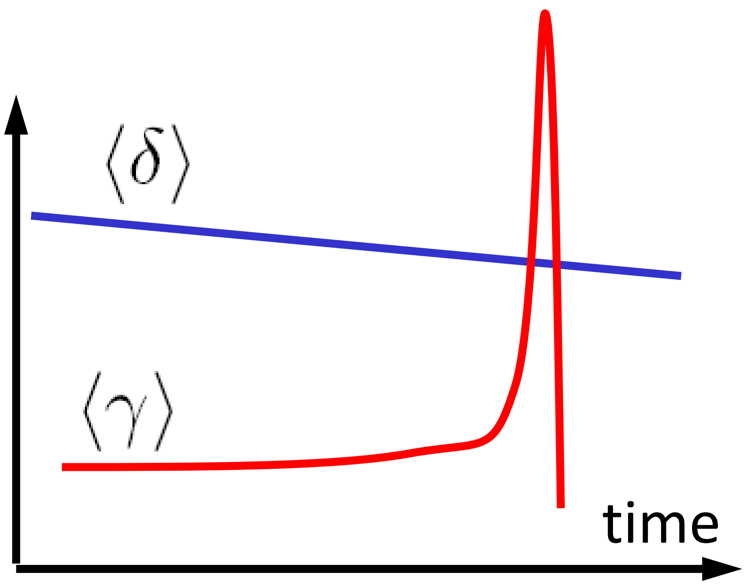
J – source of hot particles

E – electromagnetic energy of emission

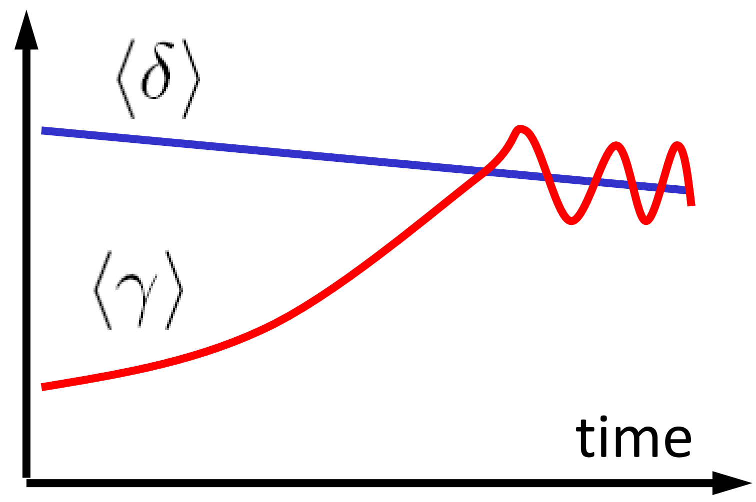
Growth rate: $\gamma = 2\, \mathrm{Im}\, \omega \sim N$

Damping rate: $\delta = \nu_{eff} \sim \nu_{ei} + \nu_{ea}$

Generation starts: $\langle \gamma \rangle > \langle \delta \rangle$

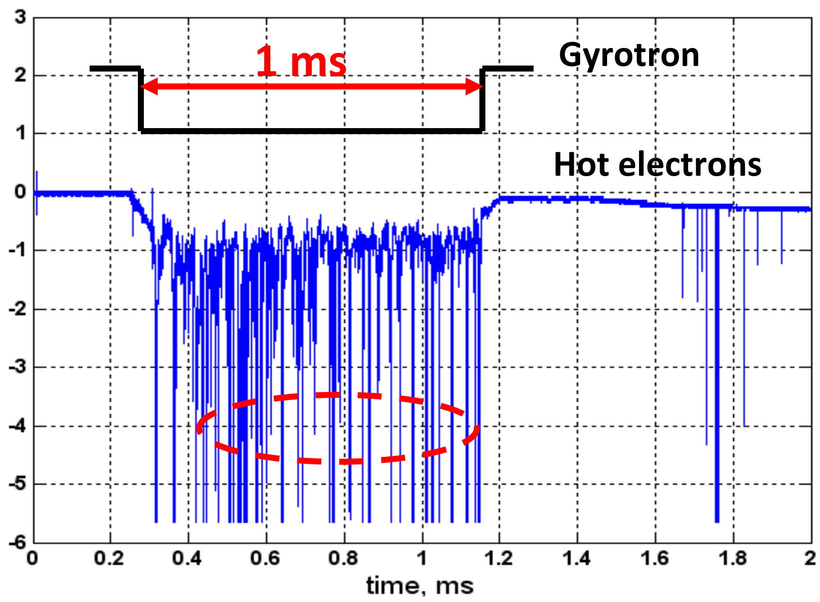


Regime of «giant» pulses

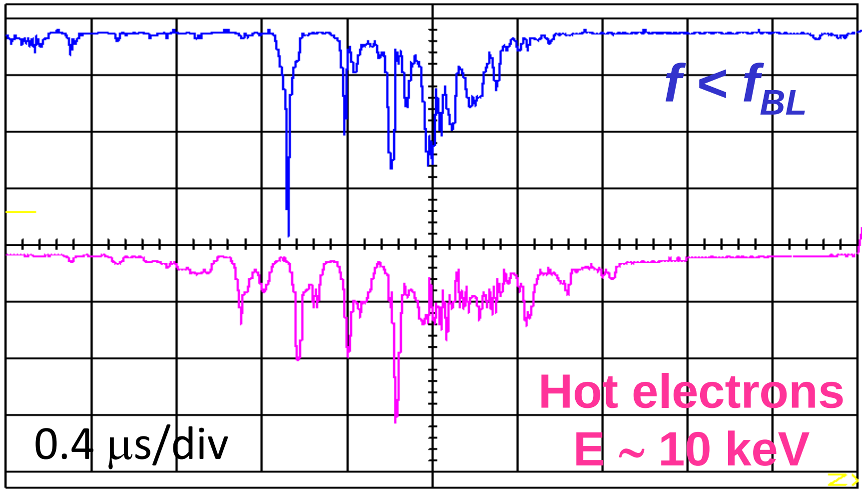


«Quasi-periodic» regime

Whistler cyclotron instability (SMIS 37)

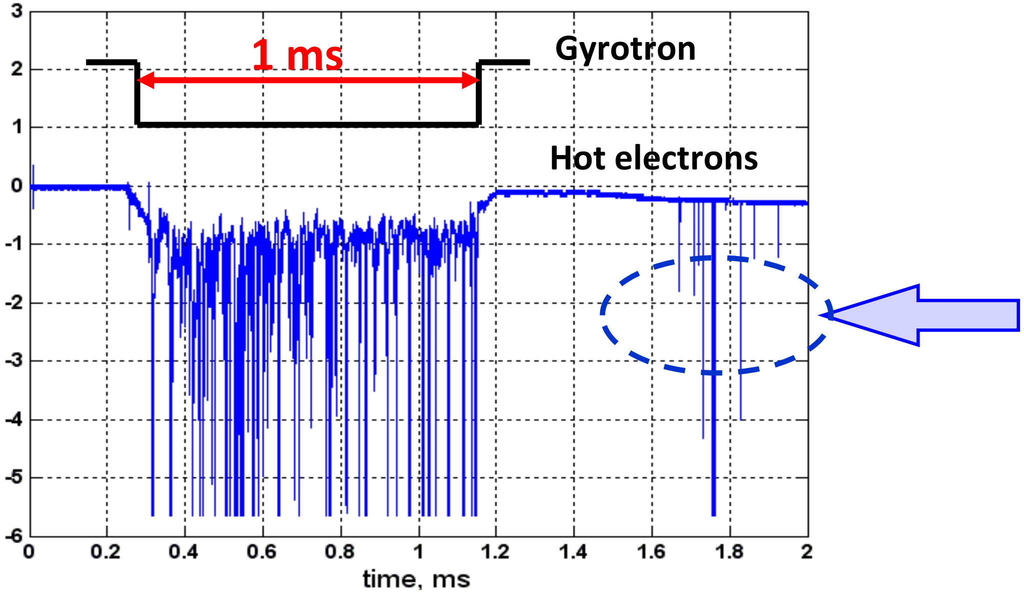


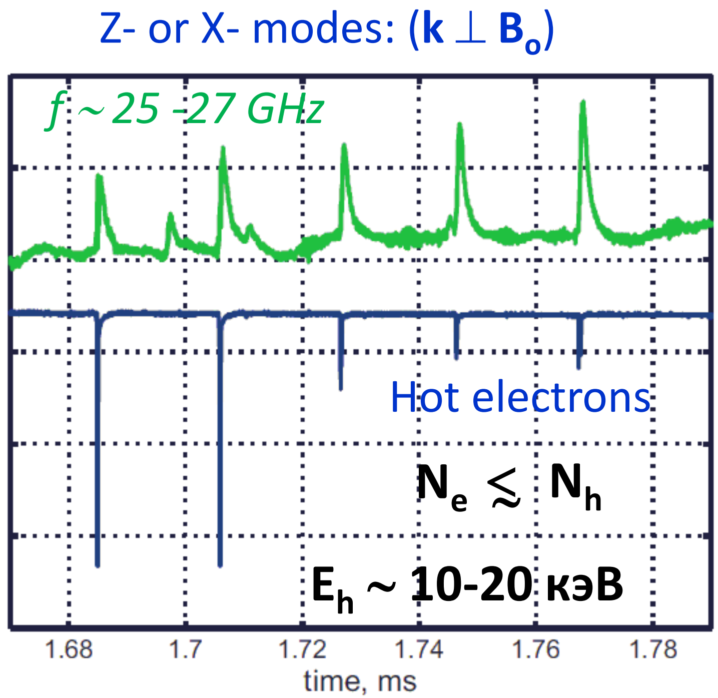
Whistler waves: (**k**||**B$_o$**)



Reported at ECRIS 02

Cyclotron instability in afterglow plasma (SMIS 37)





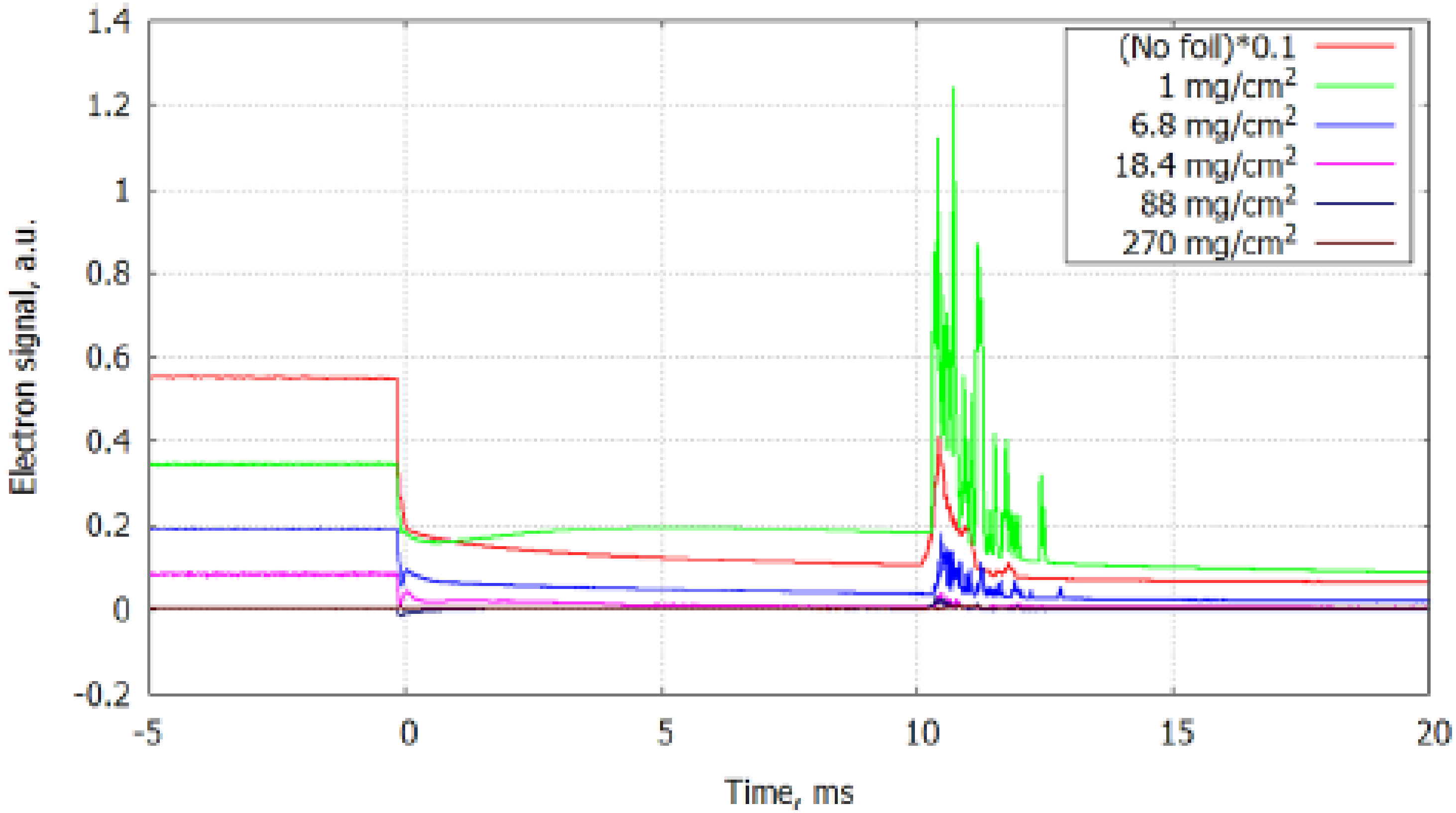
Cyclotron instability of extraordinary modes in decaying plasma

$$\omega_{pe} \ll \omega_{ce}$$

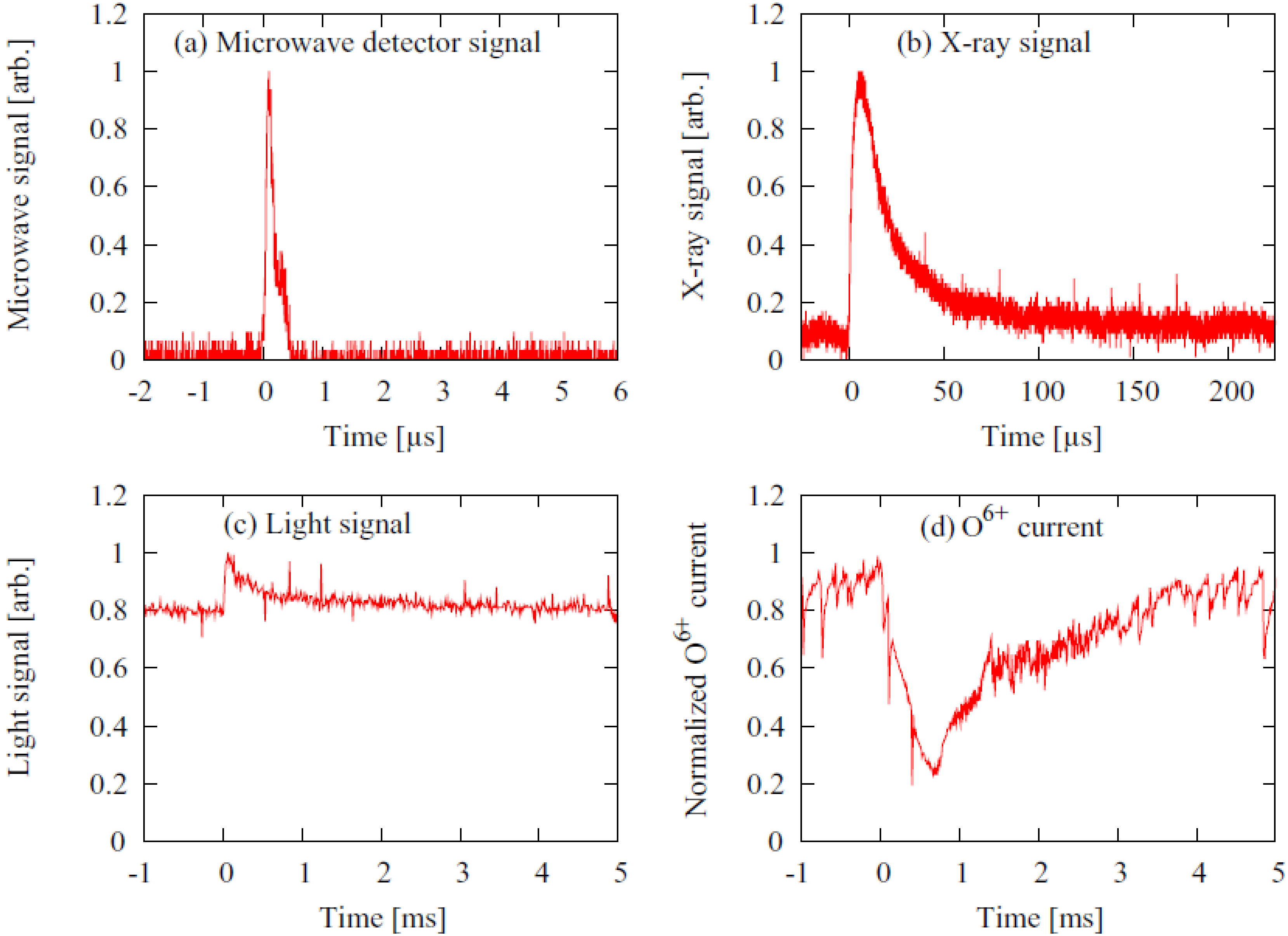
X-mode (ϑ~90°): $\omega_{pe} < \omega_{ce} < \omega$ Z-mode (k ⊥ B$_o$): $\omega_{pe} < \omega < \omega_{ce}$

Periodic precipitations of hot electrons without source of active particles!

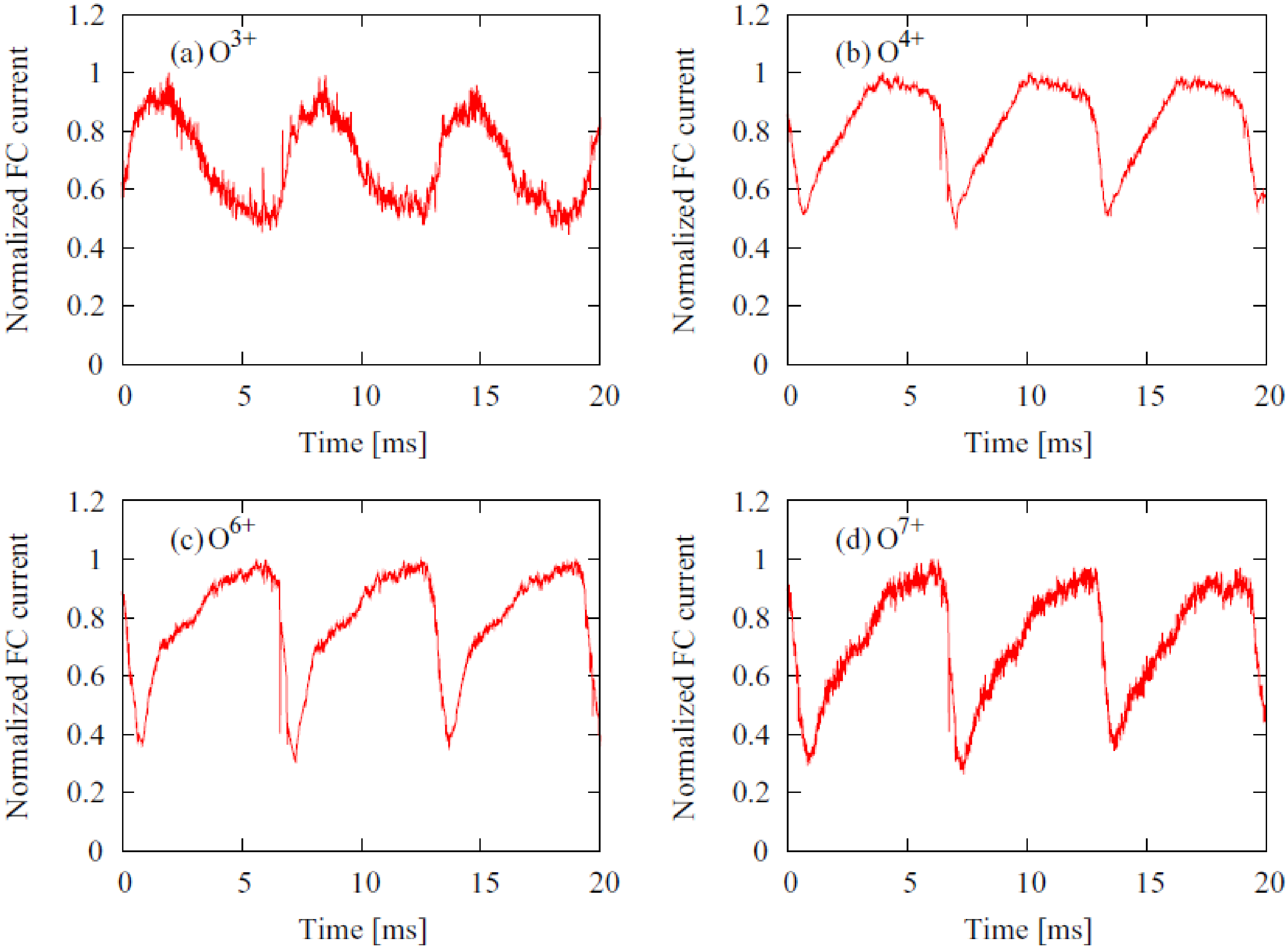
Afterglow-mode (JYFL 14 GHz)



Cyclotron instability. CW mode.



Influence of cyclotron instability on ion beam currents



Influence of cyclotron instability on ECRIS performance

Fluxes of precipitated hot electrons causes:

1. Huge X-ray pulses
2. Change plasma potential and plasma confinement
3. Results in highly charged ion beams oscillations

Microwave plasma emission due to instability can reach the power of several kW!

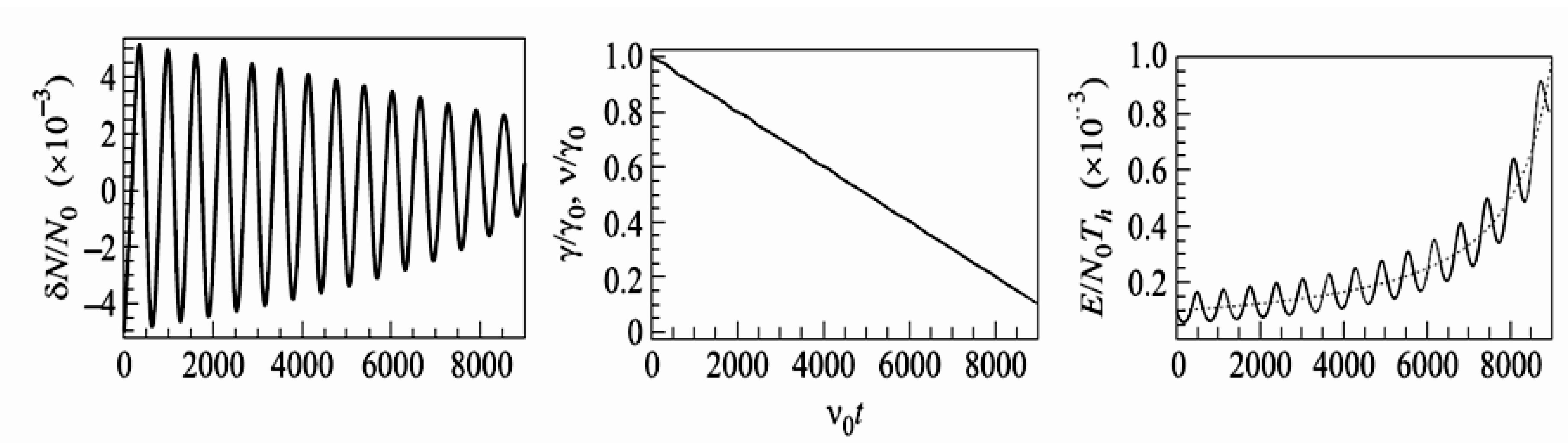
Perspectives and challenges

➢ <u>How can we limit the instability?</u>

- Plasma parameters for multi-charged ions and cyclotron instability are overlapped.

- Controlling the population of hot electrons

- Different regimes of quasi-stationary generation



Perspectives and challenges

- Plasma microwave emission as diagnostics of plasma parameters: plasma density and hot electron energy

- Additional heating by excited waves

- Simultaneous measurements of electron fluxes and waves intensity can give fundamental knowledge about wave-particle interactions , EDF formation due to ECR heating

- Laboratory modeling of similar phenomena in space plasmas

Summary

- ✓ Plasma in ECR ion sources is kinetically unstable due to the nature of ECR heating, when anisotropic velocity distribution of electrons is formed.
- ✓ Cyclotron instability results in generation of pulses of electromagnetic emission synchronously with hot electron precipitations from the trap.
- ✓ The power of generated microwave emission can exceed the primary heating power and fluxes of expelled electrons can change plasma potential.
- ✓ Precipitated electrons rapidly spoil plasma confinement resulting in decreasing of currents of highly charged ions. Also fluxes of hot electron to the chamber walls causes high power X-ray pulses.