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ICE in Toroidal Plasmas

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ICE in Toroidal Plasmas

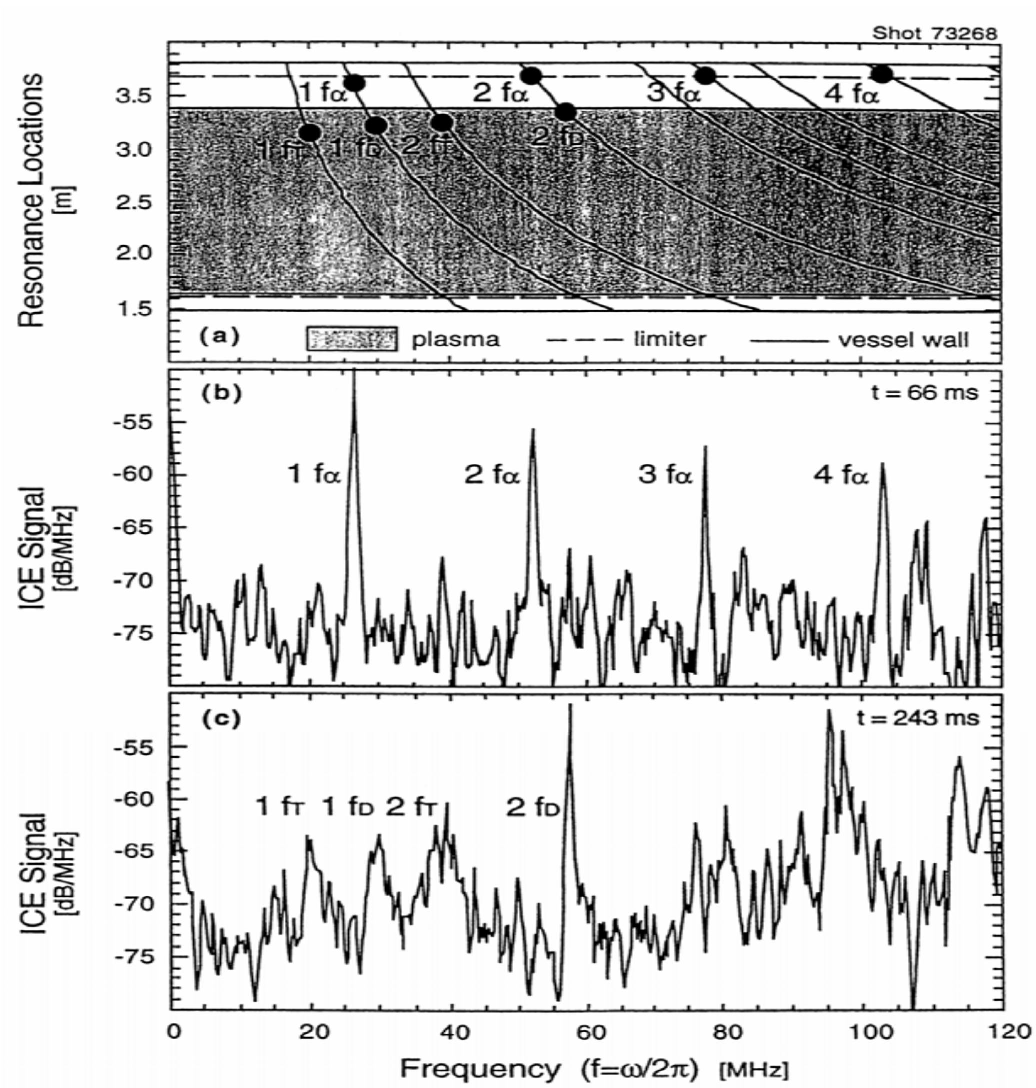
Interest of ICE to yield information of fast ions

Emission spectra characterised by narrow peaks corresponding to harmonics of the cyclotron resonance of fast ions at the edge.

Non-thermal emission given by cyclotron instabilities.

Correlation with neutron yield over six orders of magnitude.

ICE from TFTR Super shot



In the early phase the cyclotron resonances are localised outside the plasma.

In the later phase inside plasma.

S. Cauffman *et al*,
Nucl Fusion **35**(1995)1597

Conditions for cyclotron emission for weak drive:

1. There has to exsist weakly damped eigenmodes.

2. The distribution function has to increase in energy along the characteristics of the quasi-linear operator defining the ion-cyclotron interactions.

Wave-Particle Interactions

$$\Delta W = eZv_{\perp}^{res}\,\mathrm{Re}\left\{\left(e^{-i\zeta}E_{+}\,\mathrm{J}_{n-1}(k_{\perp}\rho)+e^{i\zeta}E_{-}\,\mathrm{J}_{n+1}(k_{\perp}\rho)\right)\sqrt{\frac{i\pi}{\ddot{\vartheta}}}\exp i\vartheta_{0}\right\}$$

ΔW increase as $\ddot{\vartheta} \to 0$

As for tangential resonances at the outboard side of the orbits.

Whether an ion takes or delivers energy to the wave depends on the difference between the phase of the wave oscillation and the gyro phase of the ion, ϑ_0.

Decorrelated interactions describe a 1D-diffusion process along the characteristics defined by:

$$\Delta P_{\phi} = \frac{n_{\phi}}{\omega}\Delta W \qquad \Delta\Lambda = (\Lambda_{r} - \Lambda)\frac{\Delta W}{W}$$

Wave-Particle Interactions

On averaged ions give energy to the wave, if the distribution function increases along the characteristics with respect to energy

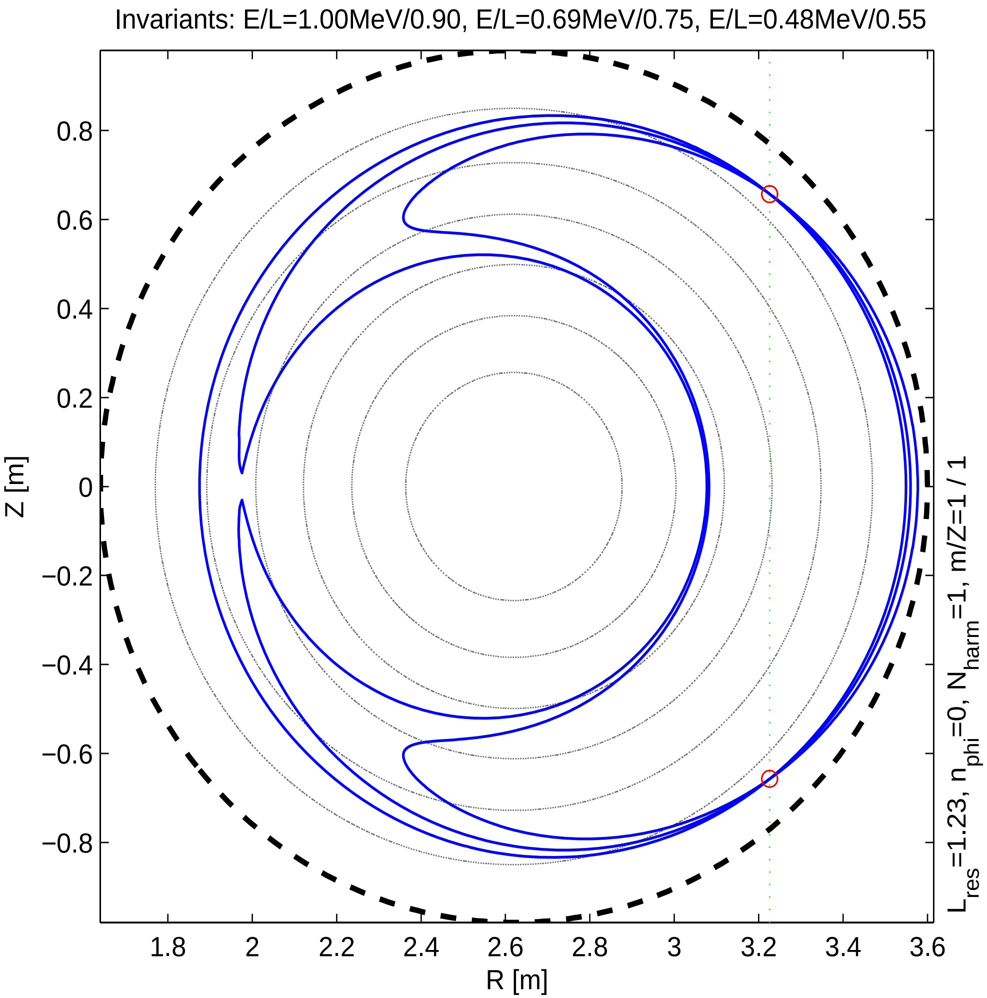
$$\left\{ \frac{\partial f}{\partial \upsilon_{\perp}} \left(1 - \frac{k_{//}\upsilon_{//}}{\omega} \right) + \frac{k_{//}\upsilon_{\perp}}{\omega} \frac{\partial f}{\partial \upsilon_{//}} \right\} > 0$$

A possible mechanism is interactions with high-energy barely detrapped co-passing ions at the plasma edge.

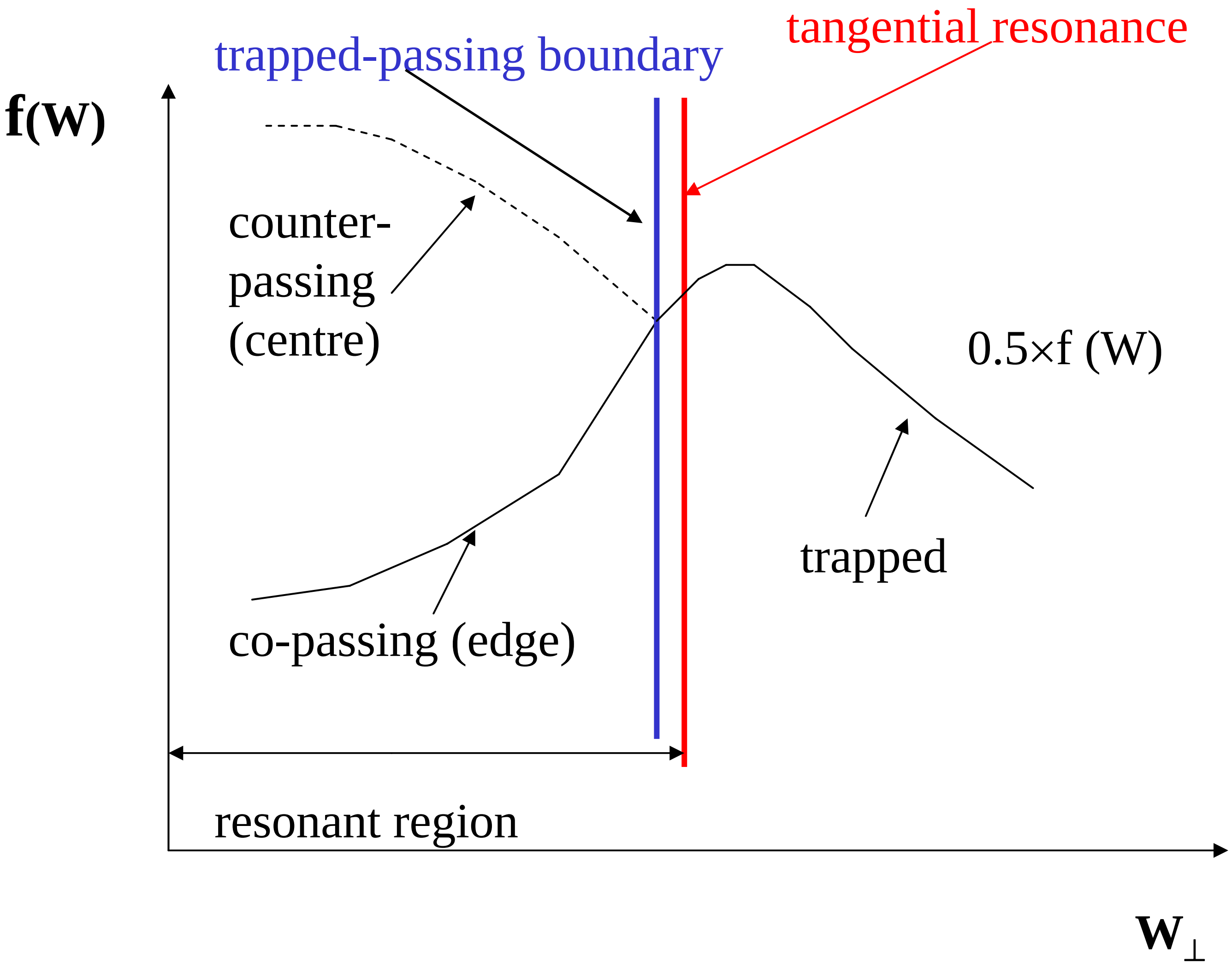
Detrapping and interactions with barely co-passing ions

Cyclotron interactions taking energy from the ions reduce the perpendicular energy and Λ.

There are few co-passing high-energy ions at the plasma edge and many marginal trapped, the distribution function will therefore be decreasing with energy, and hence be unstable.



Variation of the distribution function along a wave-particle characteristic



Interactions where $f(w_\perp)>0$ can cause instabilities.

Tangential resonances prevent interactions where $f(w_\perp)<0$.

Absorbed power

$$P = \mathrm{Re}\left\{ \frac{-i\omega}{8\pi} \iint \underline{E}^{*}\, \underline{\underline{\chi}}^{A}\, \underline{E}\; r dr d\theta \right\}$$

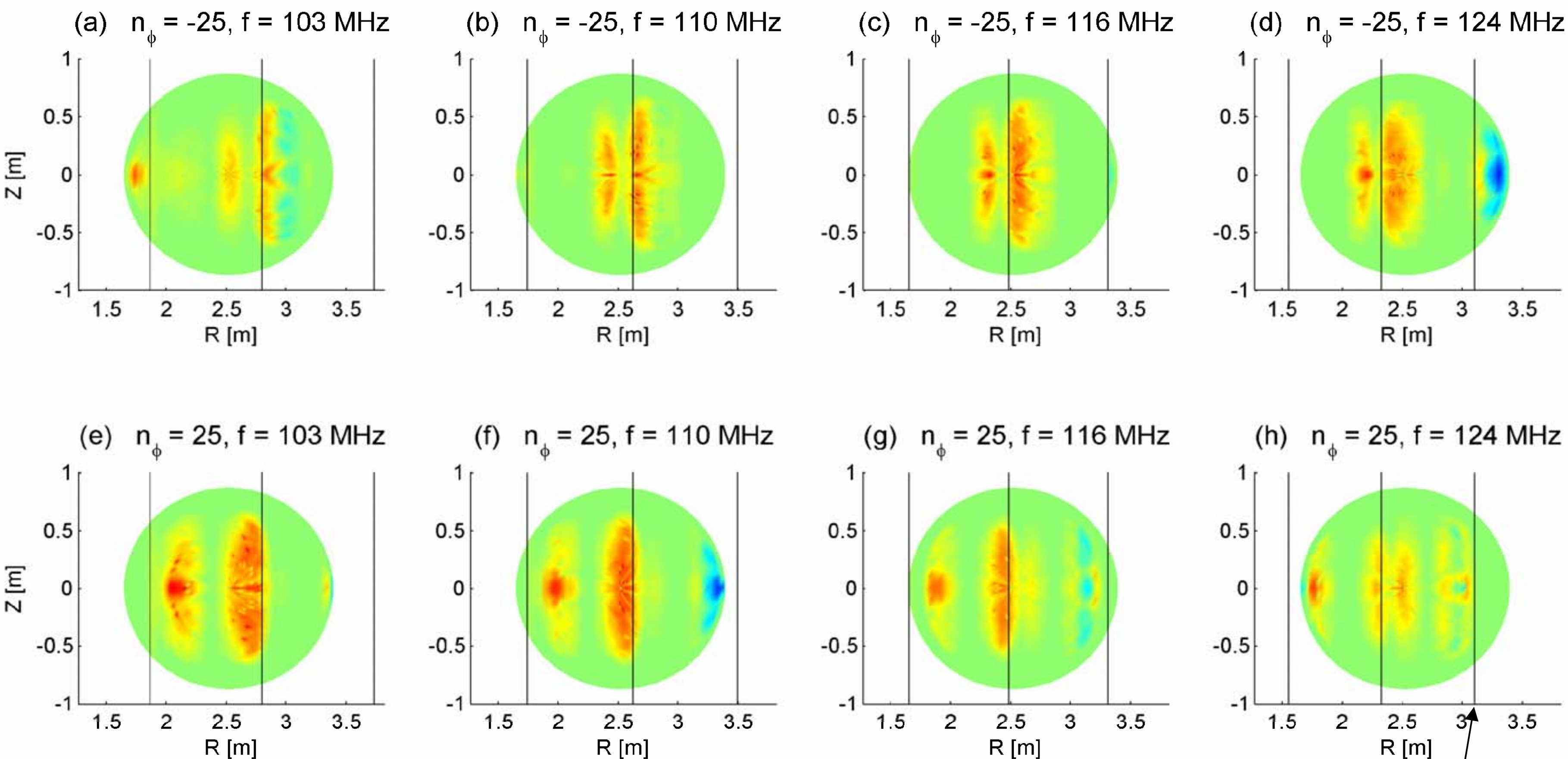
where
$$\underline{\underline{\chi}}^{A} = \frac{\omega_p^2}{\omega\omega_c} \int_0^{\infty} 2\pi\upsilon_{\perp} d\upsilon_{\perp} \int d\upsilon_{//} \frac{\omega_c}{\omega - \underline{k}\cdot\underline{\upsilon} - n\omega_c} \underline{\underline{S}}_n$$

$$\underline{\underline{S}}_n = \upsilon_{\perp} \begin{pmatrix} \left(\dfrac{n\omega_c J_n}{k_{\perp}\upsilon_{\perp}}\right)^2 & \dfrac{in\omega_c J_n J'_n}{k_{\perp}\upsilon_{\perp}} \\ -\dfrac{in\omega_c J_n J'_n}{k_{\perp}\upsilon_{\perp}} & \left(J'_n\right)^2 \end{pmatrix} \left\{ \frac{\partial f}{\partial \upsilon_{\perp}} \left(1 - \frac{k_{//}\upsilon_{//}}{\omega}\right) + \frac{k_{//}\upsilon_{\perp}}{\omega} \frac{\partial f}{\partial \upsilon_{//}} \right\}$$

Integrating with respect to θ gives

$$P \approx \frac{\omega}{4} \int r dr \int_{-\infty}^{\infty} d\upsilon_{//} \frac{\omega_p^2}{\omega\omega_c} \int_0^{\infty} 2\pi\upsilon_{\perp} d\upsilon_{\perp} \frac{\omega_c \upsilon_{//}}{\left|\ddot{\vartheta}\right| qR} \underline{E}^{*} \underline{\underline{S}}_n \underline{E} \Big|_{\theta 0}$$

Anti-Hermitian susceptibilty tensor element χ_{xy}



$\omega = 4\omega_{CHe}$

Edge localised magnetosonic eigenmode

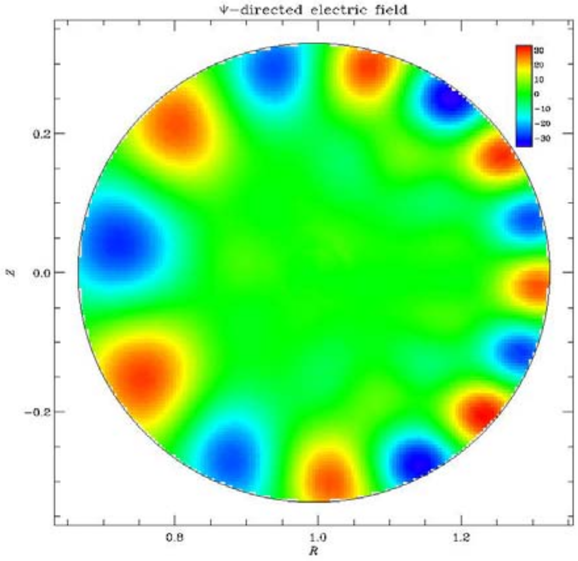
LION code

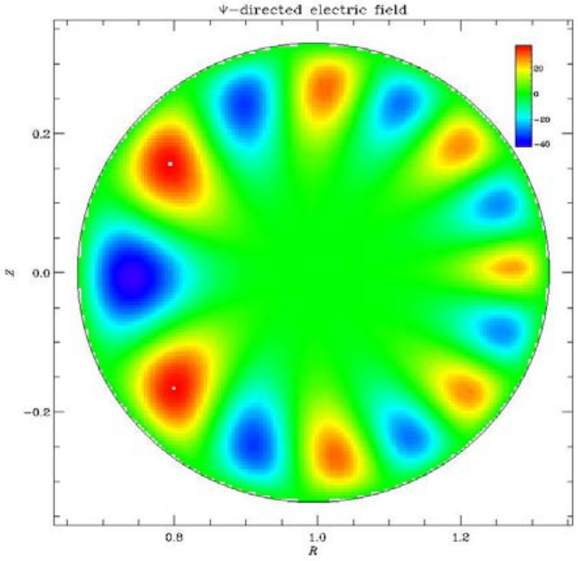
$$\nabla\times\nabla\times\underline{E}-\frac{\omega^2}{c^2}\underline{\underline{\varepsilon}}\cdot\underline{E}=i\mu_0\omega\underline{J}_{ant}$$

model

$$E=\frac{E_0(r,\theta)}{(1+\varepsilon\cos\theta)^{2/3}}\exp i(m_0(\theta+e_0\sin\theta)-\omega t)$$

$E_0 = C_1\mathrm{Ai}(x) + C_2\mathrm{Bi}(x)$ in the plasma
$E_0 = C_3\exp(-bx)+ C_4 \exp(+bx)$ in the vacuum.





Note: eigenmodes propagate poloidaly around the magnetic axis!
T. Hellsten et al Physics of Plasmas **10** (2003) 4371.

$$\Delta r/r_0 = 1.86m_\theta^{-2/3}-2.41m_\theta^{-4/3} + \ldots$$

Conclusions

A consistent picture of ICE in toroidal plasmas has been obtained: including excitation of edge localised magnetosonic eigenmodes with a realistic alpha particle distribution function.

Edge localised magnetosonic modes can be excited even for steady state distribution functions by interacting with barely de-trapped co-passing ions and marginally trapped ions.

Conclusions

The most likely mechanism is interactions with counter-current propagating waves reducing interactions with the stable part of the distribution function.

Enhancement of the unstable interactions by tangential resonaces is important.

Interactions with counter-current propagating modes, with the resonance just inside the plasma, require stronger localisation of the mode to avoid stable interactions.