






## HIGH-FREQUENCY ELECTROMAGNETIC WAVES DESTABILIZED BY RUNAWAY ELECTRONS IN A NEAR-CRITICAL ELECTRIC FIELD

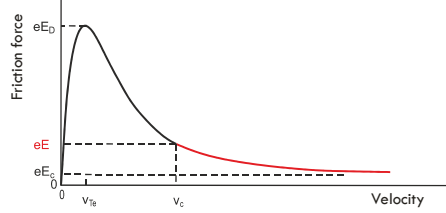
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## Runaway electrons

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□ For electric fields higher than the critical field: accelerating force exceeds the friction force → **runaway electrons**

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## Particle-wave interaction

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Dispersion relation of the plasma waves:

$$\left( \epsilon_{11} - \frac{k_{\parallel}^2 c^2}{\omega^2} \right) \cdot \left( \epsilon_{22} - \frac{k_{\perp}^2 c^2}{\omega^2} \right) + \epsilon_{12}^2 = 0$$

$k$ : wave number  
 $\omega$ : wave frequency  
 $c$ : speed of light

$\underline{\underline{\epsilon}} = \underline{\underline{1}} + \underline{\underline{\chi}}^e + \underline{\underline{\chi}}^i$   
Dielectric tensor

$$= \chi_{11}^e \left( \frac{k_{\parallel}^2 c^2}{\omega^2} - \epsilon_{22} \right) + \chi_{22}^e \left( \frac{k_{\perp}^2 c^2}{\omega^2} - \epsilon_{11} \right) - 2\chi_{12}^e \epsilon_{12}$$

→  $\delta\omega$  response
→ Growth rate  $\gamma_i = \text{Im}(\delta\omega)$

Perturbative analysis
Imaginary part

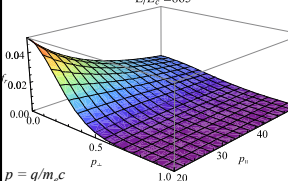
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## Distribution function

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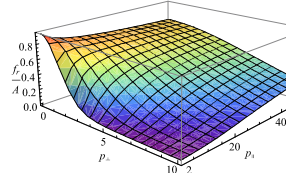
High electric field

$E/E_c = 865$



Near-critical field

$E/E_c = 1.3$



$p = q/m_e c$  normalized momentum

T. Fülöp, PoP 13(062506), 2006
P. Sandquist, PoP 13(072108), 2006

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## New approximations

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High electric field distribution function  
T. Fülöp, PoP 13(062506), 2006

↕

Ultrarelativistic resonance condition

↕

Magnetosonic-whistler wave

Near-critical field distribution function

↕

General resonance condition

↕

Electron-whistler wave

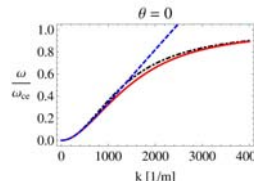
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## Whistler waves

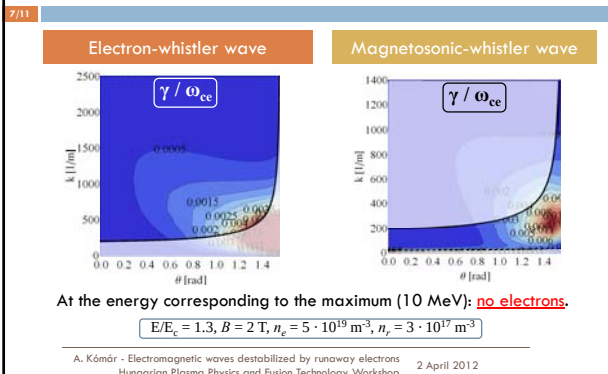
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- **Electron-whistler wave**  
A. Kómár, BSc thesis, BME TTK, 2011  
 $\omega_{ci} \ll \omega$      $\omega_{ce} \sqrt{m_e/m_i} \ll \omega$
- **Magnetosonic-whistler wave**  
T. Fülöp et al., PoP 13(062506), 2006  
 $\omega_{ci} \ll \omega \ll \omega_{ce}$
- **Whistler wave**  
S. Sazhin, Whistler-mode waves in a hot plasma, Cambridge Univ. Press, 1993

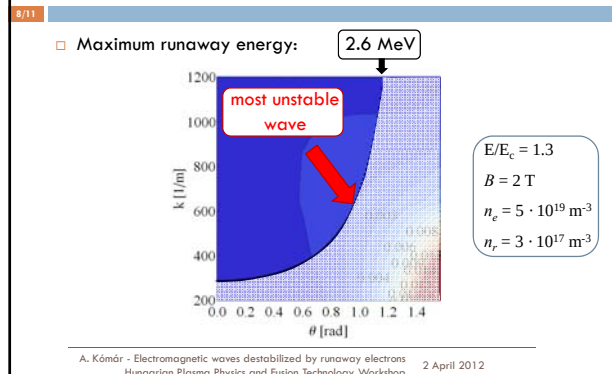


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## Growth rate in near-critical field



## Most unstable wave



## Damping rates of the wave, stability

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- Damping rates:
    - Collisional damping: of electron-ion collisions
    - Convective damping: the runaway beam has a finite radius,  $L_r$
  - Stability:
 

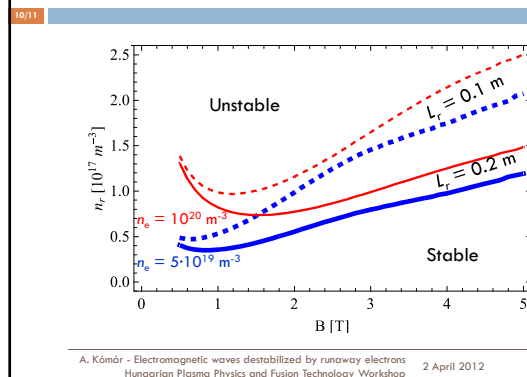
Finding **(Growth rate – Damping rates) = 0**  
(for the most unstable wave)

↓

Critical runaway density

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## Stability limit in near-critical field



## Conclusions

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- Runaway electron – wave interaction in near-critical electric field
  - Extending the previous approximations
    - General resonance condition
    - New whistler approximations
  - Linear stability
    - The **most unstable wave** is an electron-whistler wave, dependent on the maximum runaway energy
    - **Stability threshold**: higher for higher magnetic field

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## General resonance condition

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- Runaway susceptibilities: calculated based on the distribution function,  $\iiint d^3p$
- **Implicit** resonance:

$$p_{\text{par}} + \frac{n\omega_{ce} - \omega_0 \cdot \gamma(p_{\text{par}}, p_{\text{perp}})}{k_{\parallel}c} = 0$$

Ultrarelativistic  $\gamma \approx |p_{\text{par}}|$       General case  $\gamma = \sqrt{1 + p_{\text{perp}}^2 + p_{\text{par}}^2}$

$$p_{\text{res}} = \frac{-n\omega_{ce}}{k_{\parallel}c - \omega_0}$$

$$p_{\text{res}} = \frac{-k_{\parallel}c(n\omega_{ce} + \omega_0) \pm \sqrt{(k_{\parallel}^2 c^2 - \omega_0^2)(1 + p_{\text{perp}}^2) + (n^2 \omega_{ce}^2)}}{k_{\parallel}^2 c^2 - \omega_0^2}$$

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## Why the whistler wave?

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- Resonance condition is physical if:  $p_{res} > 0$

- In ultrarelativistic approximation:

$$p_{res} = \frac{-n\omega_{ce}}{k_{\parallel}c - \omega_0} \Rightarrow \boxed{k_{\parallel}c - \omega_0 > 0 \text{ and } n < 0} \text{ or } \boxed{k_{\parallel}c - \omega_0 < 0 \text{ and } n > 0}$$

- In the general case:

$$\Rightarrow \boxed{k_{\parallel}c - \omega_0(k, \theta) > 0} \text{ and } n \leq 0$$

**Whistler wave**

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