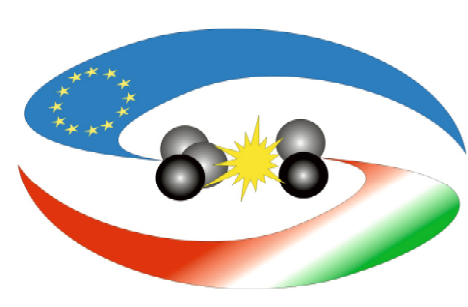
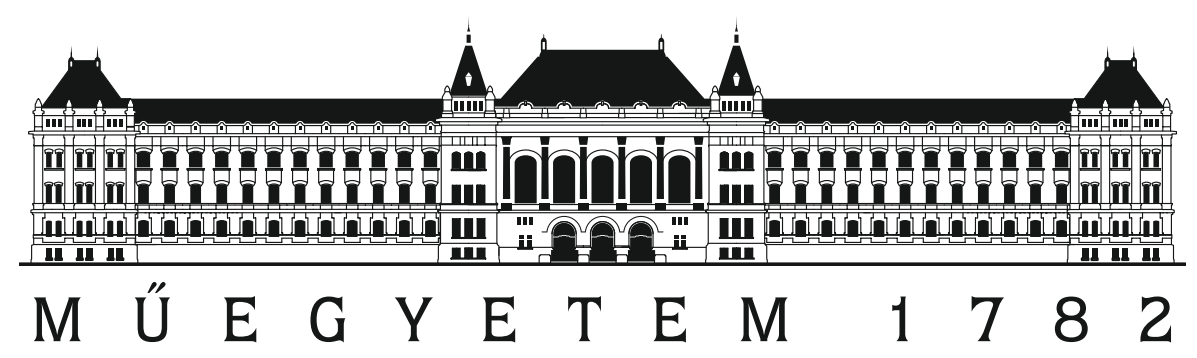




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High-frequency electromagnetic waves destabilized by runaway electrons in a near-critical electric field

A. Kómár¹, T. Fülöp², G. I. Pokol¹

1) Department of Nuclear Techniques, Budapest University of Technology and Economics, Association EURATOM, Budapest, Hungary

2) Department of Applied Physics, Chalmers University of Technology, EURATOM-VR Association, Göteborg, Sweden

E-mail contact: komar@reak.bme.hu

Introduction, motivation

Relativistic runaway electrons are produced in plasmas when the electric field is larger than a certain critical field (E_c). The **anisotropy of the runaway electron distribution can lead to destabilization of plasma waves** through wave-particle resonant interaction.

Recent work [1] has shown that **even in disruptions the electric field** in the core region of the plasma is only **slightly above the critical** electric field. This work considers whistler wave instability driven by an anisotropic electron distribution in near-critical field.

Dispersion of the waves

The dispersion relation of high frequency plasma waves with the electromagnetic and cold plasma approximation [2]:

$$\left(\epsilon_{11} - \frac{k_{\parallel}^2 c^2}{\omega^2}\right) \left(\epsilon_{22} - \frac{k^2 c^2}{\omega^2}\right) + \epsilon_{12}^2 = 0 \quad \epsilon = \mathbf{1} + \chi^i + \chi^e + \chi^r$$

dielectric tensor

Electron-whistler wave

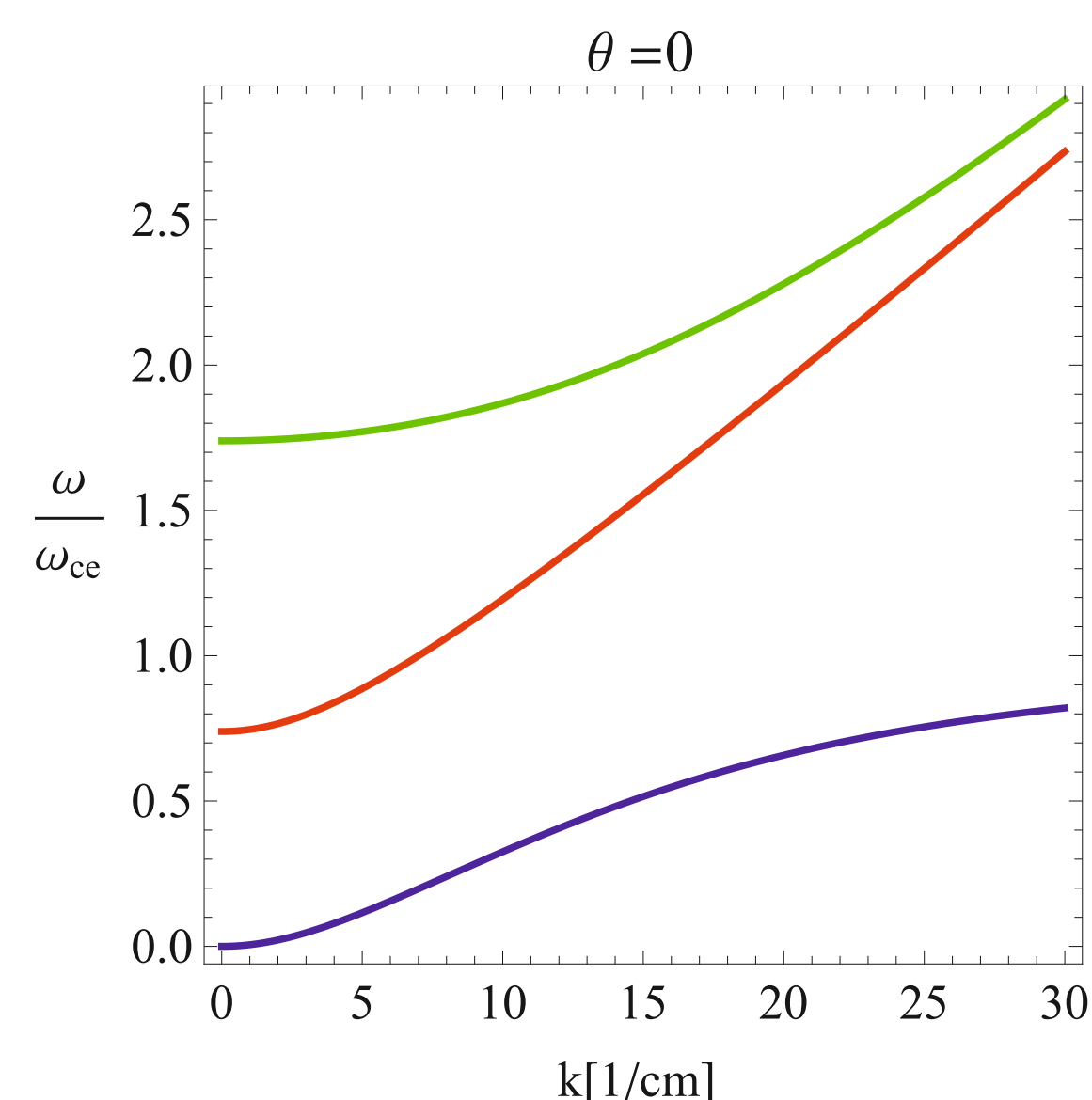
Valid for $\frac{\omega_{ce}}{\sqrt{m_i/m_e}} \ll \omega \sim \omega_{ce}$

Magnetosonic-whistler wave

Valid for $\omega_{ci} \ll \omega \ll \omega_{ce}$

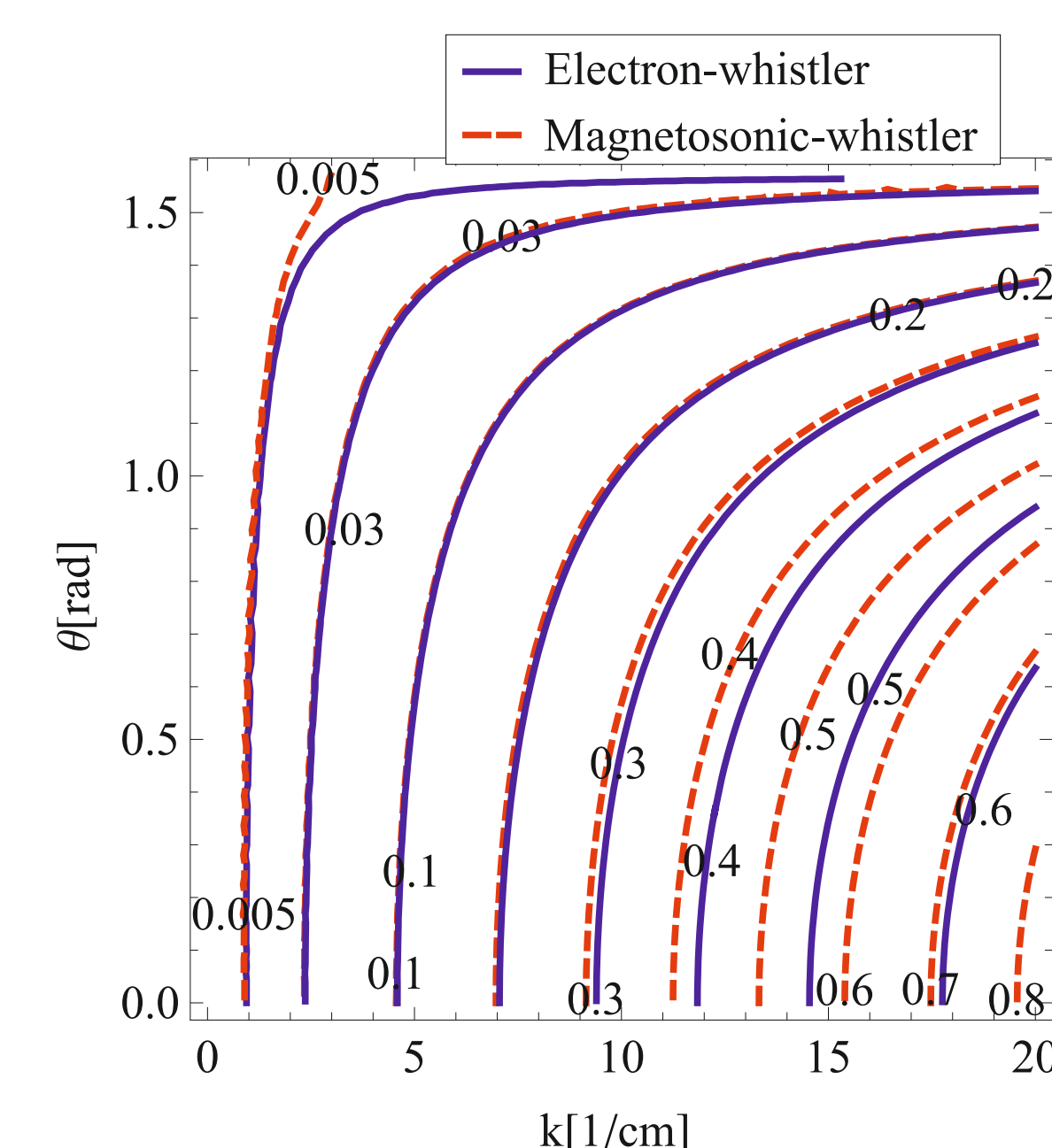
Three branches: the **electron-whistler** wave is the lowest frequency branch

Generalized version of the wave from Refs. [5-7]



The electron-whistler is in agreement with the whistler wave of S. Sazhin [3] for $B < 3$ T.

Comparison



Runaway contribution

Runaway electron population: taken into account with their susceptibility [2]
First order perturbative analysis

$$\text{Growth rate: } \gamma_i = \Im(\delta\omega) \sim \Im(\chi^r)$$

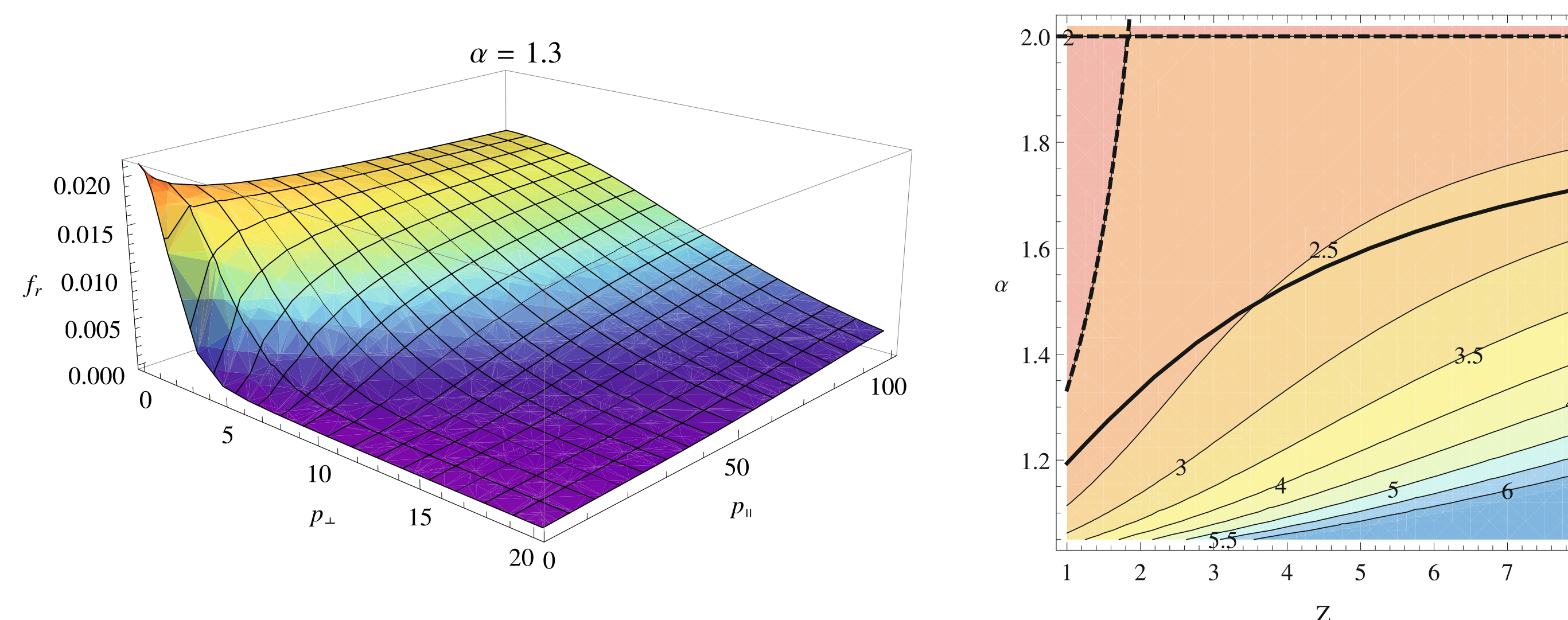
$$\Im\chi^r(\mathbf{k}, \omega) \sim \int_0^\infty dp_{\perp} \int_{-\infty}^\infty dp_{\parallel} \sum L(n) \left(\frac{\partial f_r}{\partial p_{\perp}} \frac{n\omega_{ce}}{\gamma} + \frac{\partial f_r}{\partial p_{\parallel}} \frac{k_{\parallel} c p_{\perp}}{\gamma} \right) \cdot \delta(\omega\gamma - k_{\parallel} c p_{\parallel} - n\omega_{ce})$$

Distribution function

The runaway distribution for near-critical electric field is [4]:

$$f_r(p_{\parallel}, p_{\perp}) = \frac{A}{p_{\parallel}^{(C_s-2)/(\alpha-1)}} \exp\left(-\frac{(\alpha+1)p_{\perp}^2}{2(1+Z)p_{\parallel}}\right) {}_1F_1\left(1 - \frac{C_s}{\alpha+1}, 1; \frac{(\alpha+1)p_{\perp}^2}{2(1+Z)p_{\parallel}}\right)$$

where $\alpha = E/E_c$, Z is the effective ion charge and $C_s = \alpha - \frac{(1+Z)}{4}(\alpha-2)\sqrt{\frac{\alpha}{\alpha-1}}$



To have a positive distribution: $C_s < \alpha + 1$.
The condition $f_r \rightarrow 0$ as $p_{\parallel} \rightarrow \infty$ requires that $C_s > 2$.

This gives a narrow region in the α - Z space where the distribution function is valid.

Resonance condition

When evaluating the runaway susceptibility:

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

ω_0 : dispersion of the wave
 γ : relativistic factor
 ω_{ce} : electron cyclotron frequency
 c : speed of light

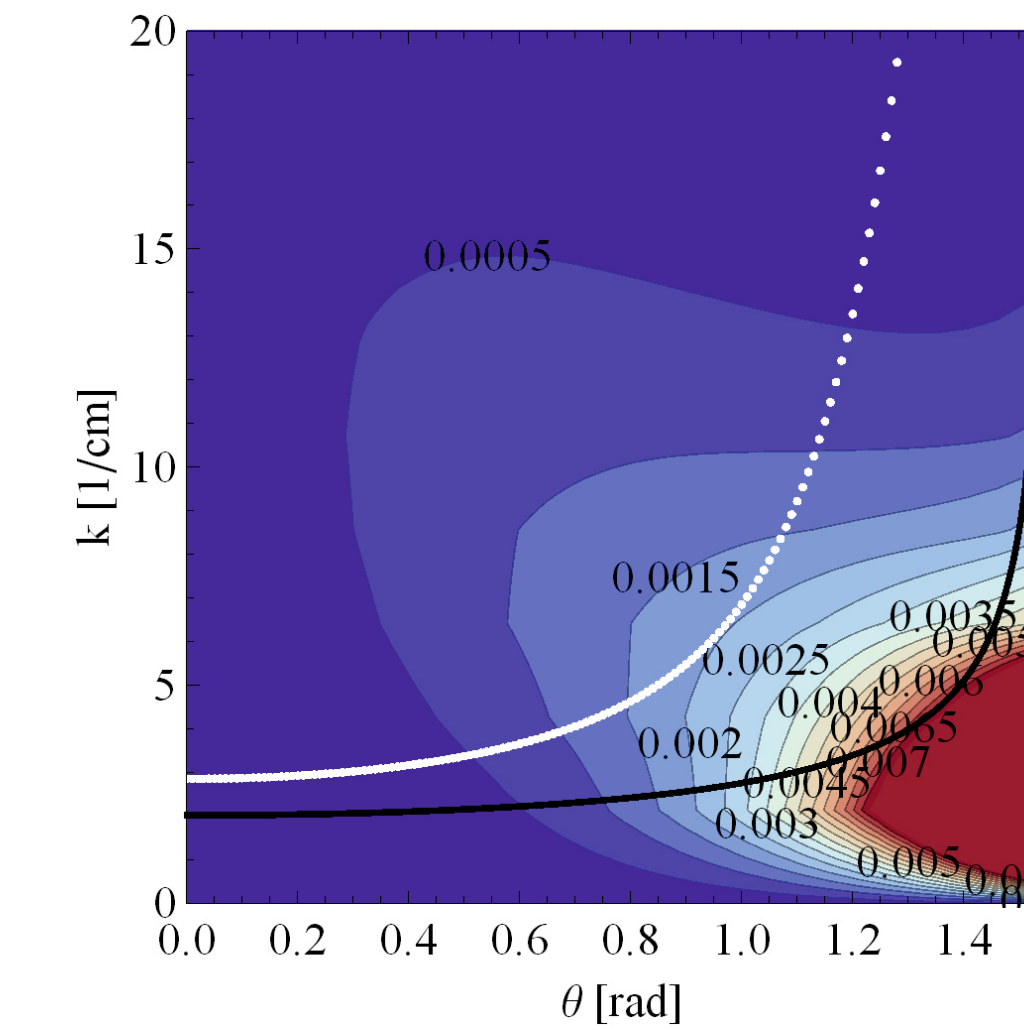
This is an **implicit condition** for the resonant momentum.

Previously [5-7] the ultrarelativistic limit was used, now a general formula is derived.

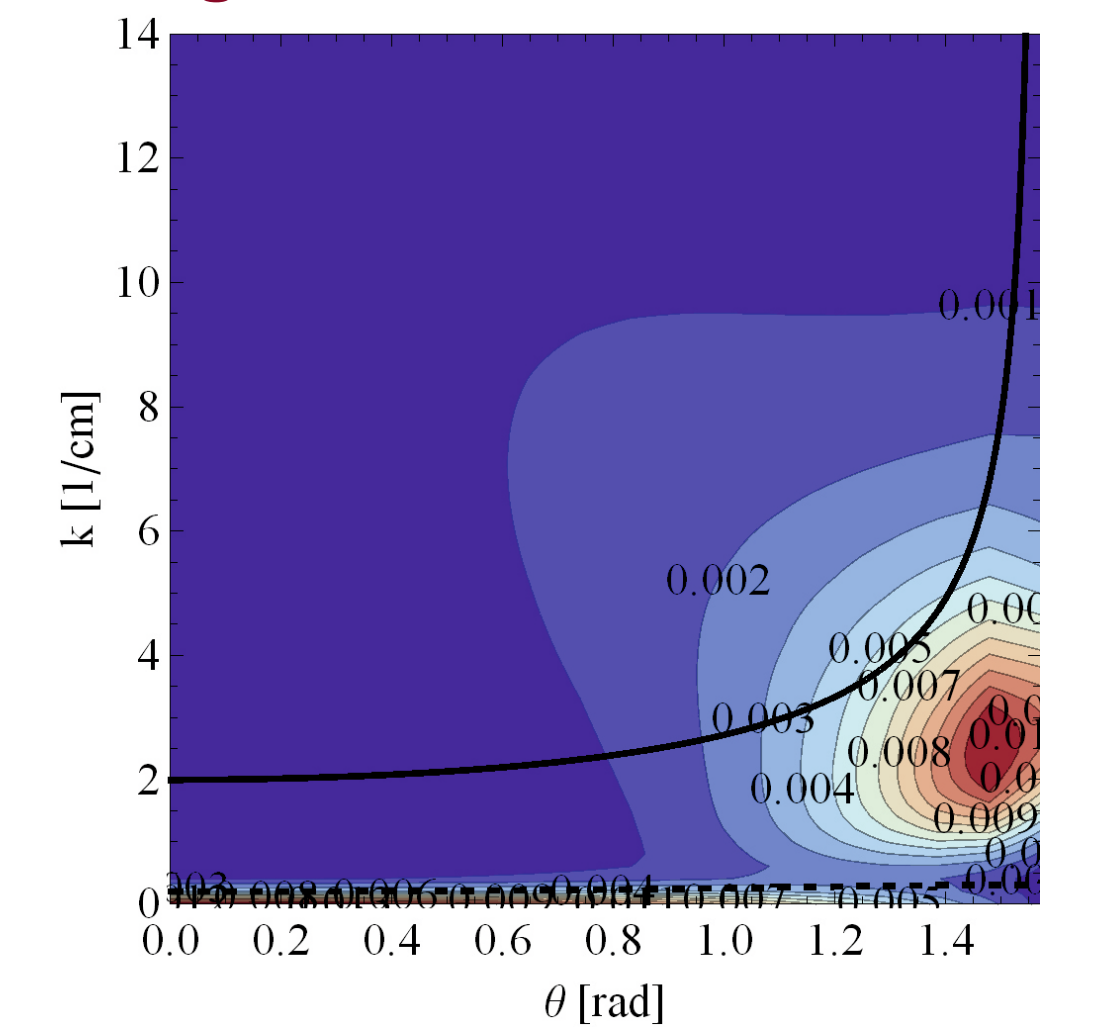
Degree of resonance: $n = 1$ Doppler,
 $n = -1$ **anomalous Doppler**,
 $n = 0$ **Cherenkov resonance**.

Most unstable wave

Electron-whistler wave



Magnetosonic-whistler wave



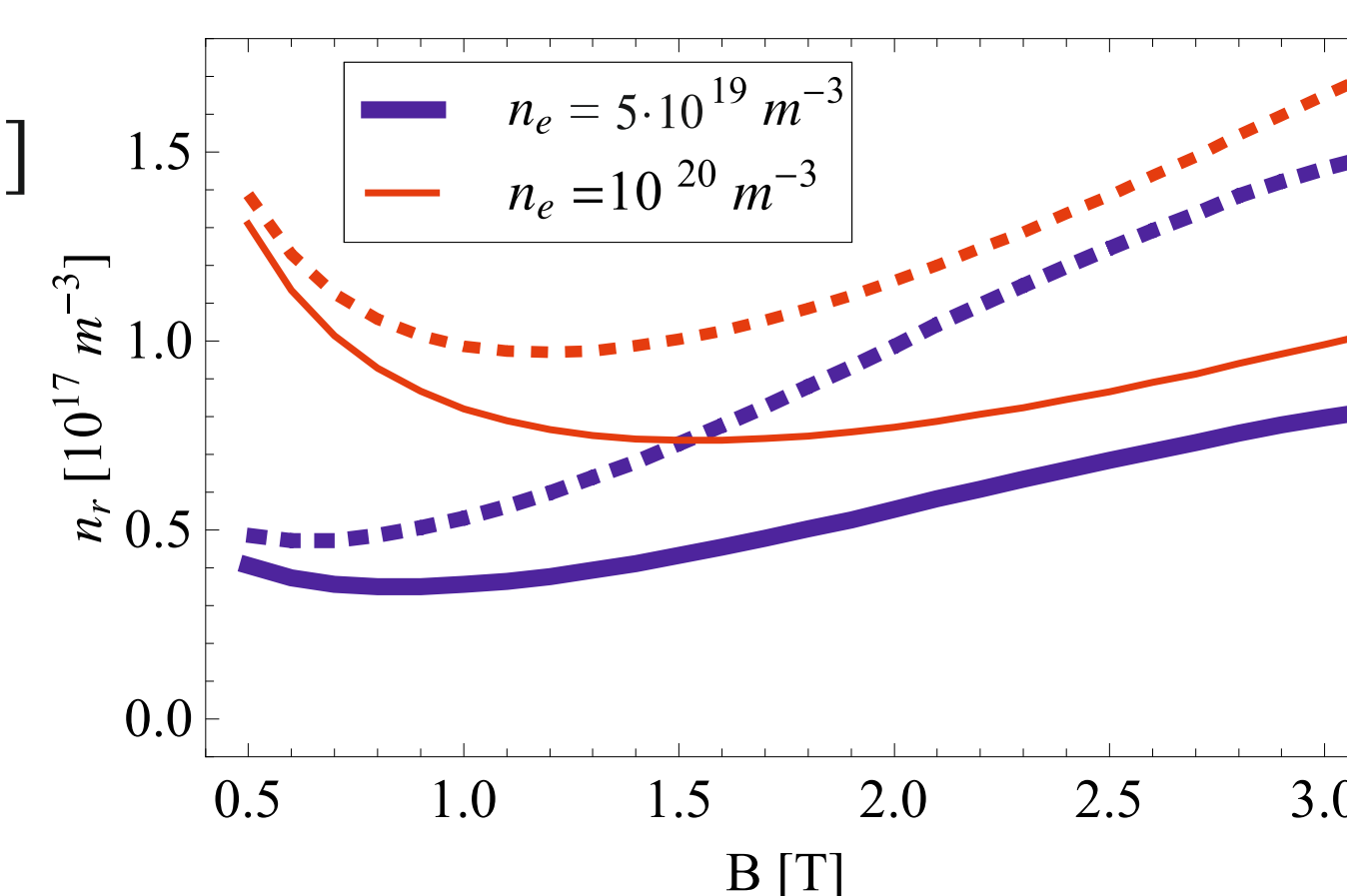
Maximum: in the magnetosonic-whistler region corresponds to **10 MeV runaway energy**

Most unstable wave: electron-whistler destabilized by the maximum energy runaways (white dots denote the energy of 2.6 MeV)

Stability: growth rate compared to the collisional and convective damping [6,8]

Temperature: 20 eV
(above 200 eV collisional damping can be neglected)

Runaway beam radius: 0.1 m (dashed)
0.2 m (solid)



Conclusions

By studying the runaway electron - whistler wave interaction in a near-critical electric field, we came to the conclusion that the results (growth rate, stability diagram) are **qualitatively similar to the high electric field case study** [5-7].

In order to investigate this case, **many aspects needed to be generalized** (wave dispersions, resonance condition), and this opened the way to the numerical study of this interaction.

References

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