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Whistler wave destabilization by a runaway electron beam in COMPASS

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Runaway electrons: how to mitigate them?

Different strategies have been designed for controlling and suppressing runaway electrons:
Massive Gas Injection (MGI), Shattered Pellet Injection (SPI), Resonant Magnetic Perturbations (RMPs)

These strategies, although very succesfull, present significant challenges

Electromagnetic (EM) waves are routinely used to achieve specific goals (heating, current drive, control/suppression of NTM) with great precision and efficiency

Finely targeted injection of radiofrequency (whistler) waves represent a potential tool

Background

"The kinetic theory of runaway electron beam instability in a tokamak", Parail & Pogutse (1978)

Whistler wave destabilization by a ultra-relativistic RE beam in a tokamak proposed in 2006*

Model extended to the near-critical regime (small parallel electric field) in 2013☥

External whistler wave injection proposed as tool for engineering RE phase space†

Mechanism recently proposed to explain precipitation of fast electrons in the high atmosphere$

Principle

Radiofrequency waves can be excited by runaway electrons and affect their energy by pitch-angle scattering

*T. Fulop, G. Pokol, P. Helander, M. Lisak., Physics of Plasmas 13, 062506 (2006)

☥A. Komar, G. Pokol, T. Fulop, Physics of Plasmas 20, 012117 (2013)

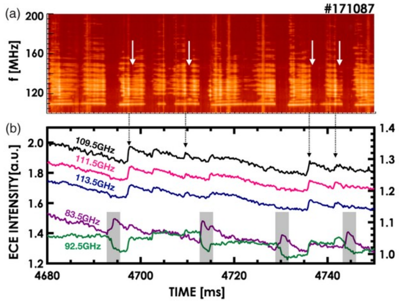
†Z. Guo et al., Physics of Plasmas 25, 032504 (2018)

$X.J. Zhang et al., Nature Communications 13 (2022)

Experimental observations

RE-driven whistler waves in a tokamak plasma first observed in 2018*

Whistler activity over multiple frequencies followed by periods of strong suppression



Drops in whistler activity preceeded by increase in ECE emission → pitch-angle

Study of radiofrequency emissions in presence of a RE beam in 2021☥

Experiments aimed at observing RE-generated radiofrequency waves in TCV and COMPASS

*D.A. Spong et al., Physical Review Letter 120, 155002 (2018)

☥P. Buratti et al., Plasma Physics and Controlled Fusion 63, 095007 (2021)

Linear stability and ray propagation

In presence of a RE beam, some EM waves can be driven unstable (anisotropic dispersion relation)

RE distribution function → calculated analytically in the near-critical limit ($E/E_c \gtrsim 1$)*

Contribution of RE beam to dispersion relation → small perturbation (linear approach)

Principal waves involved identified with electron-whistler waves and magnetosonic-whistler waves

Linear growth rate must be compared with electron-ion collisional damping ($\gamma - \gamma_d > 0$)

Main resonances considered: anomalous Doppler (m=-1), Cherenkov (m=0)

Normal Doppler (m=+1) not compatible with the whistler dispersion relation and the requirement $P_{res}>0$

*A. Komar, G. Pokol, T. Fülöp et al., Physics of Plasmas 20, 012117 (2013)

Linear stability and ray propagation

Ray tracing technique allows to follow the wave trajectory by solving a system of ODEs:

$$\frac{dr}{dt}=\frac{\partial D}{\partial k_r}/\frac{\partial D}{\partial \omega},\ \frac{dk_r}{dt}=-\frac{\partial D}{\partial r}/\frac{\partial D}{\partial \omega}$$

$$\frac{d\theta}{dt}=\frac{\partial D}{\partial k_\theta}/\frac{\partial D}{\partial \omega},\ \frac{dk_\theta}{dt}=-\frac{\partial D}{\partial \theta}/\frac{\partial D}{\partial \omega}$$

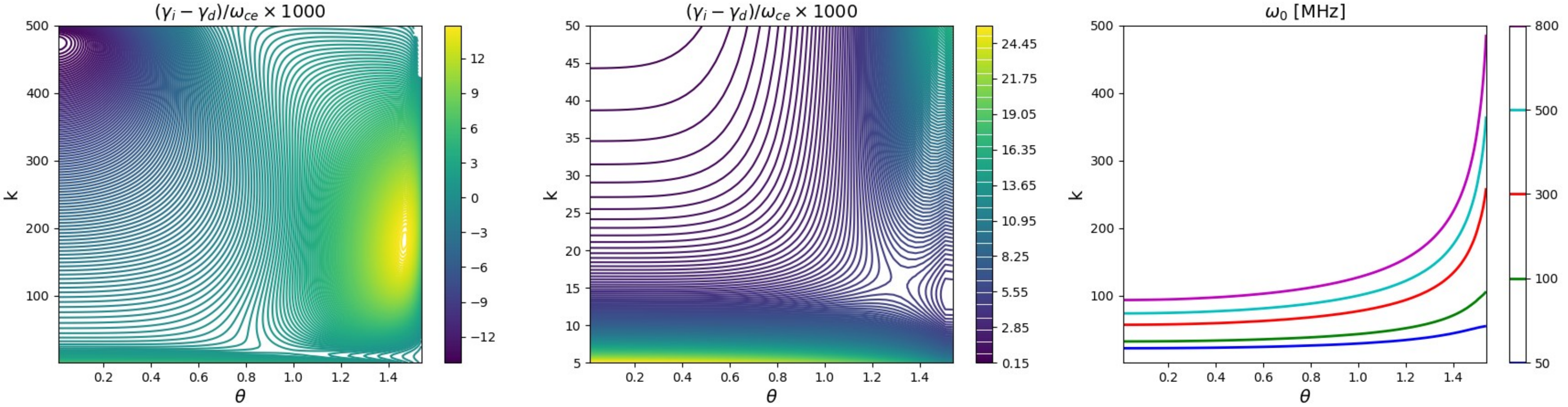
D dispersion relation of whistler waves; trajectories in the r-θ plane (poloidal cross-section)

The evolution of wave position and wave-vectors is followed inside the plasma*

*P.Aleynikov & B. Breizman, Nuclear fusion 55, 043014 (2015)

Instability triggering inside the RE beam

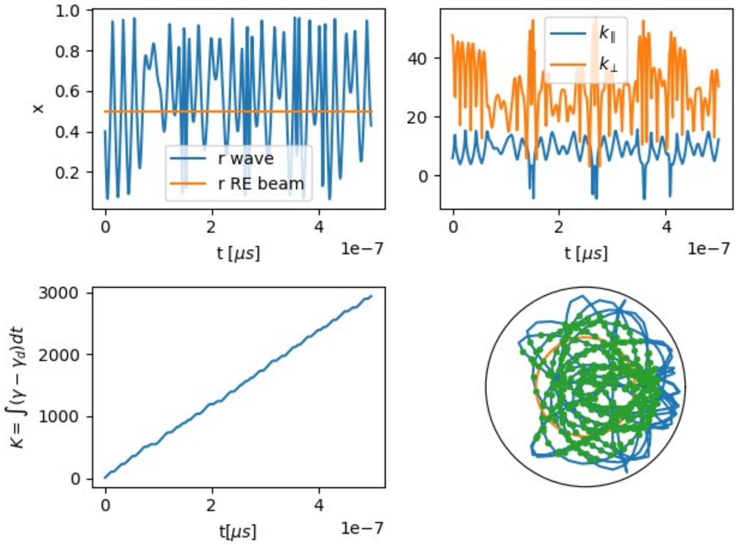
Anomalous Doppler (AD) and Cherenkov (C) resonances are considered:
AD has maximum for large k and large θ; C has maximum for small k and small θ

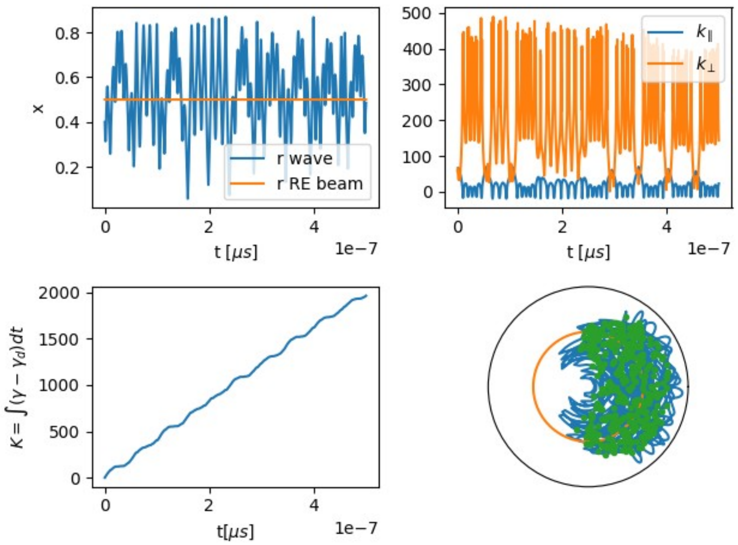


Wave destabilization

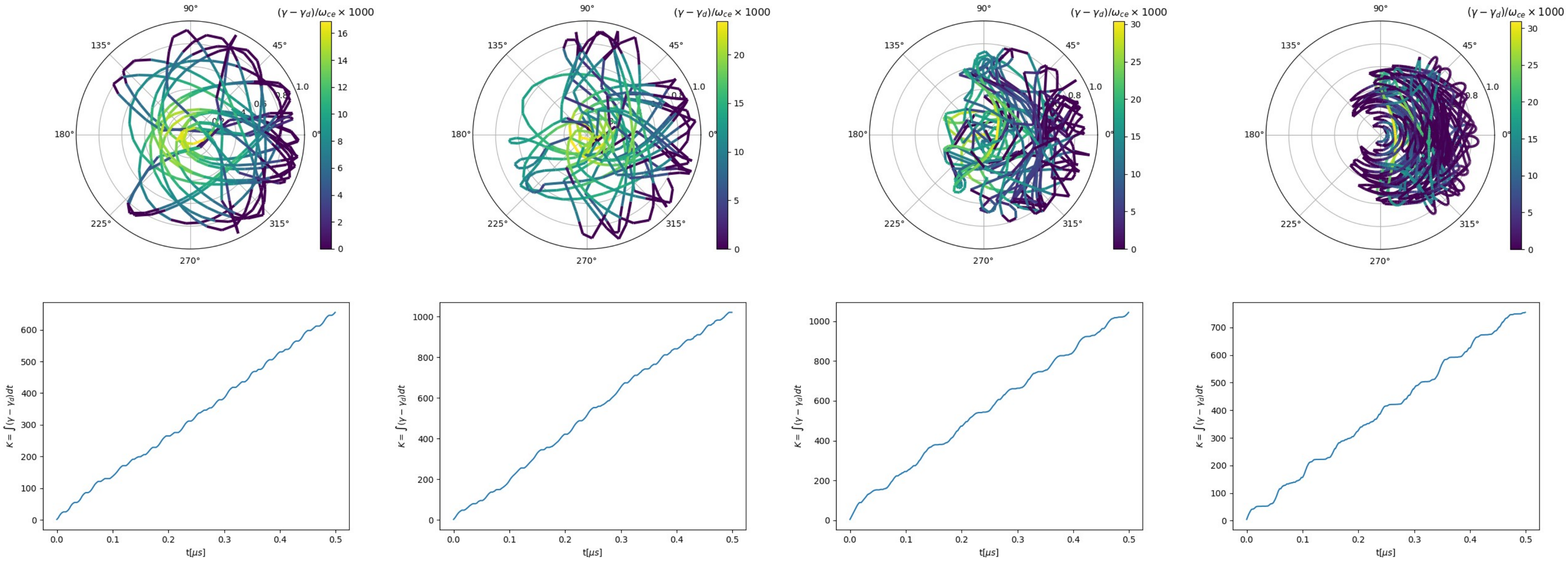
Guess on the RE distribution: uniformly distributed inside r/a=0.5, rapidly decreasing outside

Wave emitted at r/a=0.4, θ=0, frequency 50 MHz (left) and 500 MHz (right)

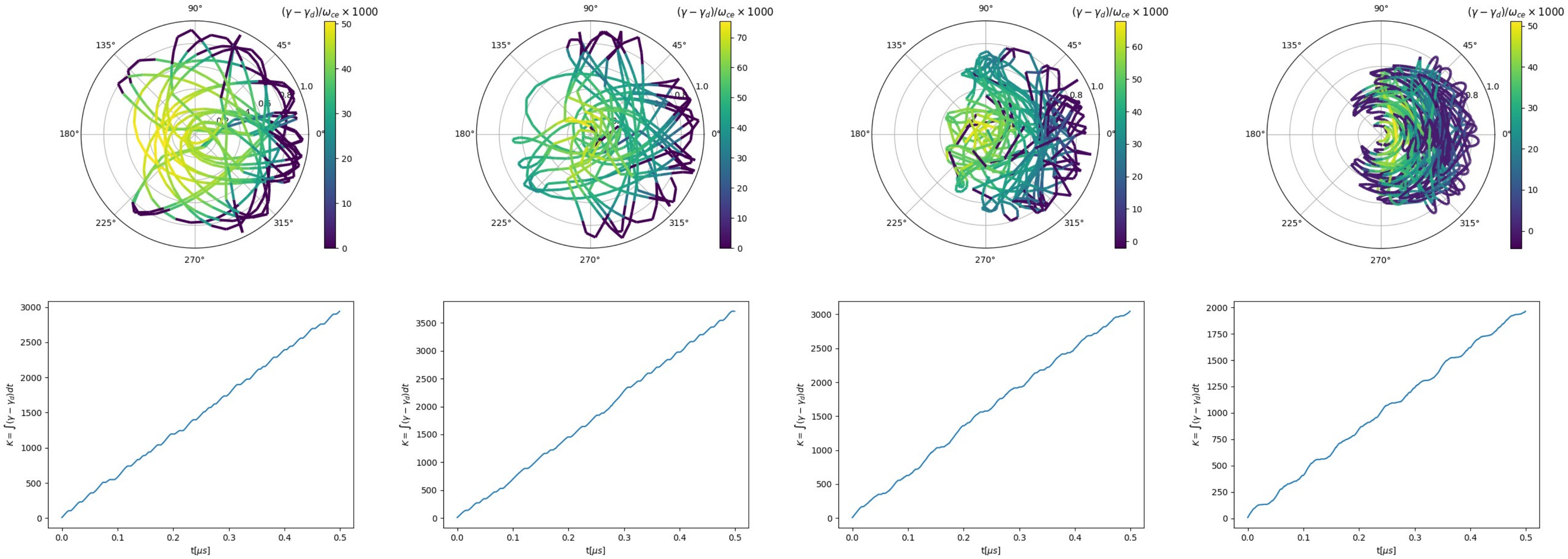




Only AD resonance; from left to right: 50MHz, 100MHz, 300MHz, 500MHz

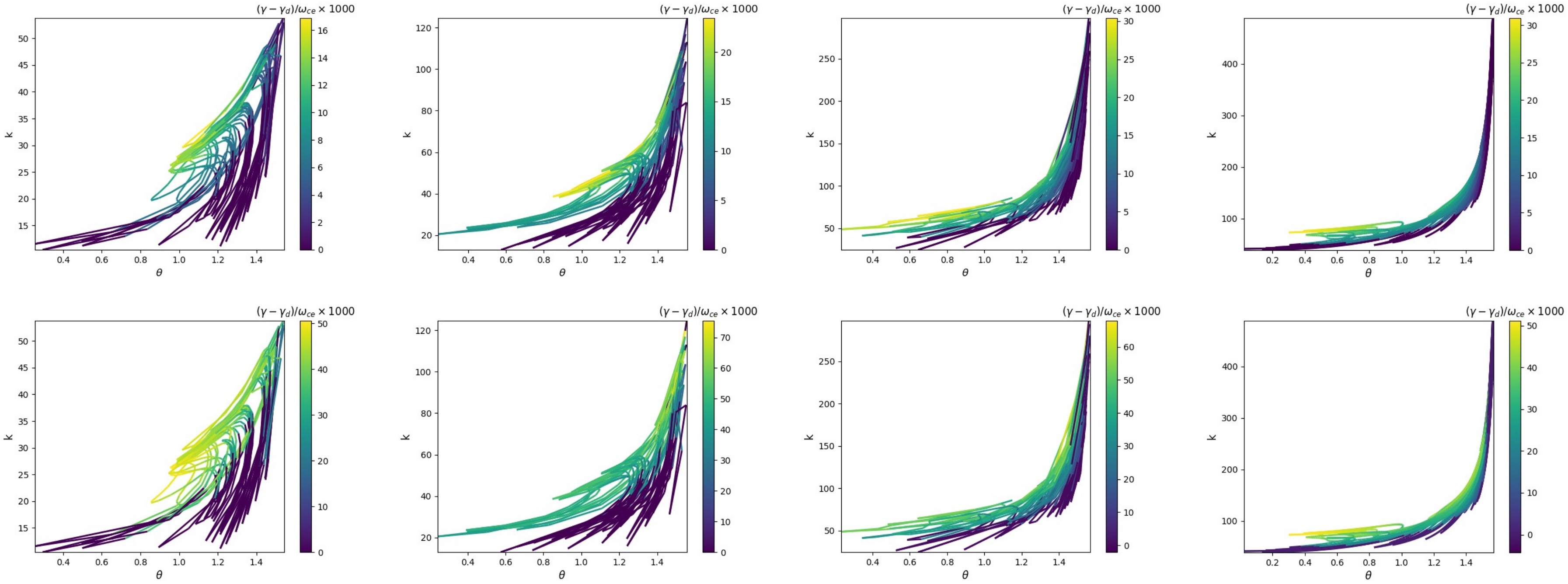


AD and C resonances; from left to right: 50MHz, 100MHz, 300MHz, 500MHz



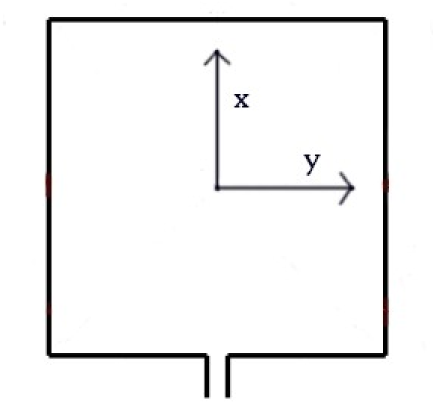
Only AD resonance (above), AD and C resonances (below)

From left to right: 50MHz, 100MHz, 300MHz, 500MHz



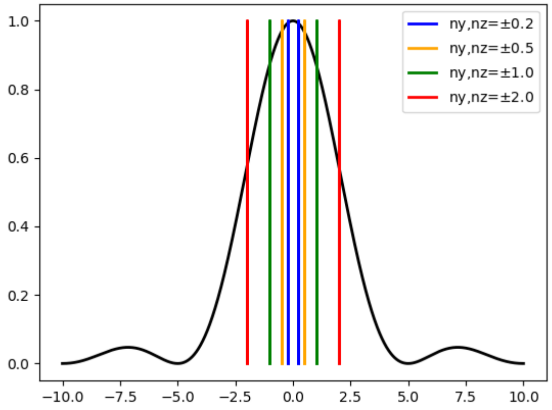
Injection by an antenna

Mitigation of RE beam energy by use of EM waves → engineering RE momentum space (Z. Guo et al., PoP 2018): “it amounts to cutting off the high-energy part of the runaway vortex (a cyclic path in momentum space) without impacting the runaway current”

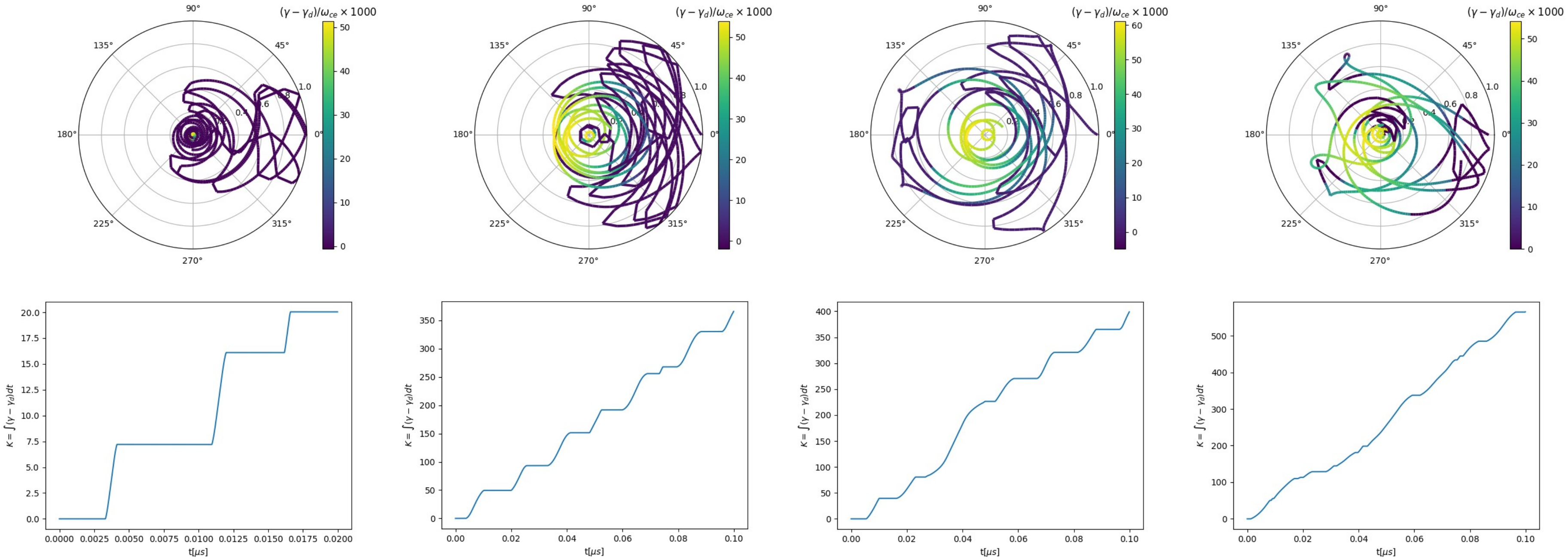


Spectrum of antenna calculated analytically*; only contribution from straight, horizontal front segment; thickness is neglected

*”Antenna theory and design”, W.L. Stutzman & G.A. Thiele, Wiley 2012

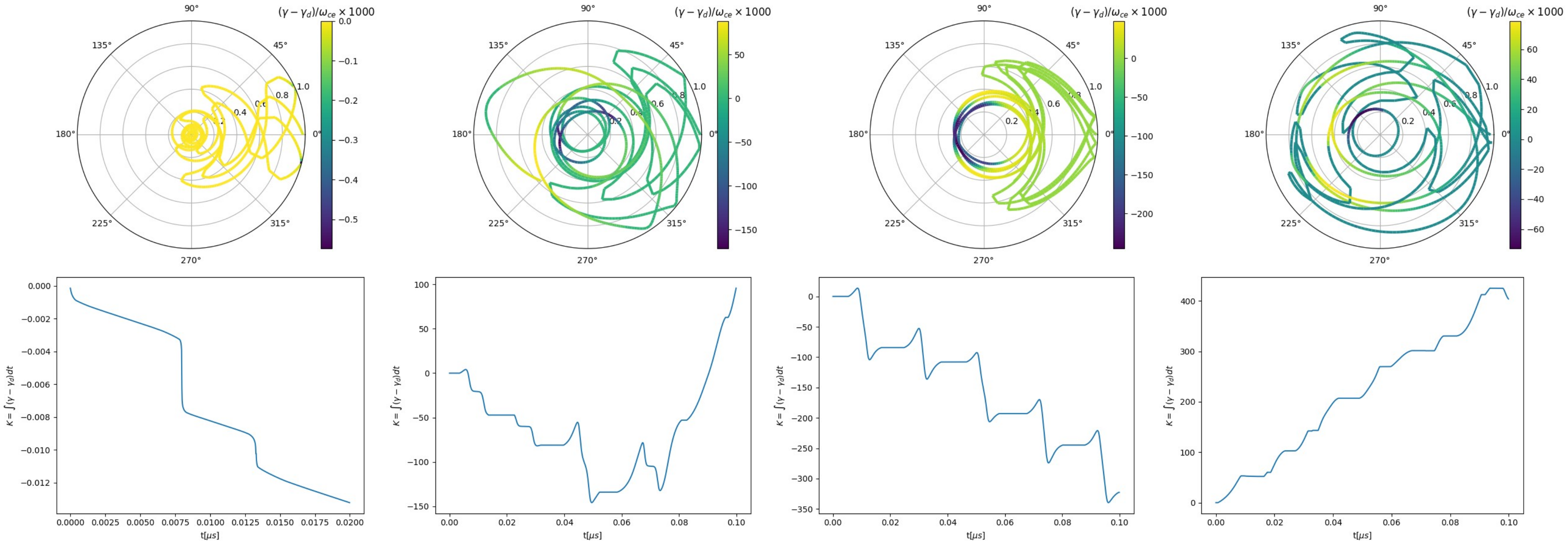


AD and C resonances, from left to right wavenumbers ny-nz take values 0.2, 0.5, 1, 2; n_0=1e13 cm^{-3}



External injection

AD and C resonances, from left to right wavenumbers ny-nz take values 0.2, 0.5, 1, 2; n_0=2e13 cm^{-3}



Wave destabilization

- Waves experience multiple reflections inside plasma volume → “convective” behavior
- Different frequences (~a few 100 MHz) can be destabilized and propagate in the plasma
- Both anomalous Doppler and Cherenkov resonances contribute to wave destabilization
- Maxima of wave destabilization can be determined in physical space and phase space

External injection

- Antenna produces spectrum with small y-z wavenumbers (main component is nx)
  - Larger ny-nz components produce larger wave destabilization but…
  - A cut-off at the plasma edge prevents large ny-nz from propagating
- Different plasma densities affect wave propagation and wave amplification

Conclusions

- Generation of waves inside the RE beam and external injection by an antenna was addressed
- Regions of maximum wave amplification were identified in real space and in phase space
- Some considerations on the efficiency of the antenna design can be made

What to do next

- Improve modelling of spectrum of the antenna with CST code, with port geometry
- Include quasi-linear evolution of RE distribution function for self-consistency
- Include radial transport of REs due to MHD perturbations

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Formulas

$$\omega_0 = k v_A \sqrt{1 + \frac{k_\parallel^2 c^2}{\omega_{pi}^2}}$$

$$\gamma \approx \frac{\omega_{pr}^2 \omega_{ci}^2}{\omega_0 \omega_{pi}^2} \left[\left(1 + \frac{k^2 v_A^2}{\omega_{ci}^2}\right) A_{11} + \left(1 + \frac{k_\parallel^2 v_A^2}{\omega_{ci}^2}\right) A_{22} + 2 \frac{\omega_0}{\omega_{ci}} A_{12} \right]$$

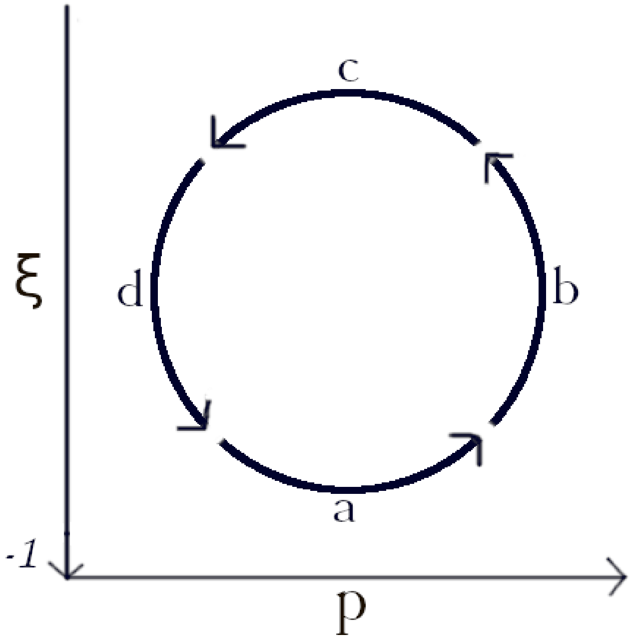
$$A_{11} = \frac{\omega_{ce}^2}{k_\perp^2 c^2} \int dp_\perp \, m^2 J_m^2(z) \, K(k_\parallel, p_\perp)$$

$$A_{12} = \frac{\omega_{ce}}{k_\perp c} \int dp_\perp \, m J_m'(z) J_m(z) \, K(k_\parallel, p_\perp)$$

$$A_{22} = \int dp_\perp \left(J_m'(z)\right)^2 K(k_\parallel, p_\perp)$$

$$z = \frac{k_\perp c p_\perp}{\omega_{ce}}, K(k_\parallel, p_\perp) = \frac{\left[m \omega_{ce} \frac{\partial f}{\partial p_\perp} + k_\parallel c p_\perp \frac{\partial f}{\partial p_\parallel} \right]_{p_{res}}}{\sqrt{\left(k_\parallel^2 c^2 - \omega_0^2\right)\left(1 + p_\perp^2\right) + m^2 \omega_{ce}^2}}$$

Runaway vortex



a) acceleration by the electric field at ξ close to -1 (field aligned)
b) pitch-angle scattering away from ξ=-1 at high energy
c) deceleration toward low energy due to radiative and coulomb damping
d) return toward ξ=-1 by the electric field at low energies

Strategy consists in cutting off the high-energy end of the runaway vortex