Italian National Agency for New Technologies, Energy and Sustainable Economic Development

Prospettive in Astrofisica del Plasma

The anomalous Doppler effect in tokamaks and in pair plasmas

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Cyclotron resonances

$$\omega - k_{\parallel} v_{\parallel} = n\,\Omega_{ce} / \gamma$$

- *n* > 0 : electron goes *n* Landau levels *down*
  - n = 2, thermal electrons: ECE, a workhorse tokamak diagnostic for electron temperature (mm waves)
  - Large *n*, runaway electrons: REIS, an insightful diagnostic for in-flight RE (IR/VIS light)
- Cherenkov resonance *n* = 0
- *n* < 0 : elecron goes *n* Landau levels ***up***, **the anomalous Doppler resonance**
- Energy for Landau levels and photon from loss of parallel momentum $\hbar\, k_{\parallel}$

Anomalous Doppler resonance (n = -1)

$$\omega - k_{\parallel} v_{\parallel} = -\Omega_{ce} / \gamma$$

- Parallel momentum decreses and
- Perpendicular momentum increases:
- Pitch angle scattering
  - **Enhancement of synchrotron emission**
  - **Mitigation of RE energy**

- Resonant wavenumber $$k_{\parallel} = \frac{1}{v_{\parallel}} \left(\omega + \frac{\Omega_{ce}}{\gamma} \right)$$

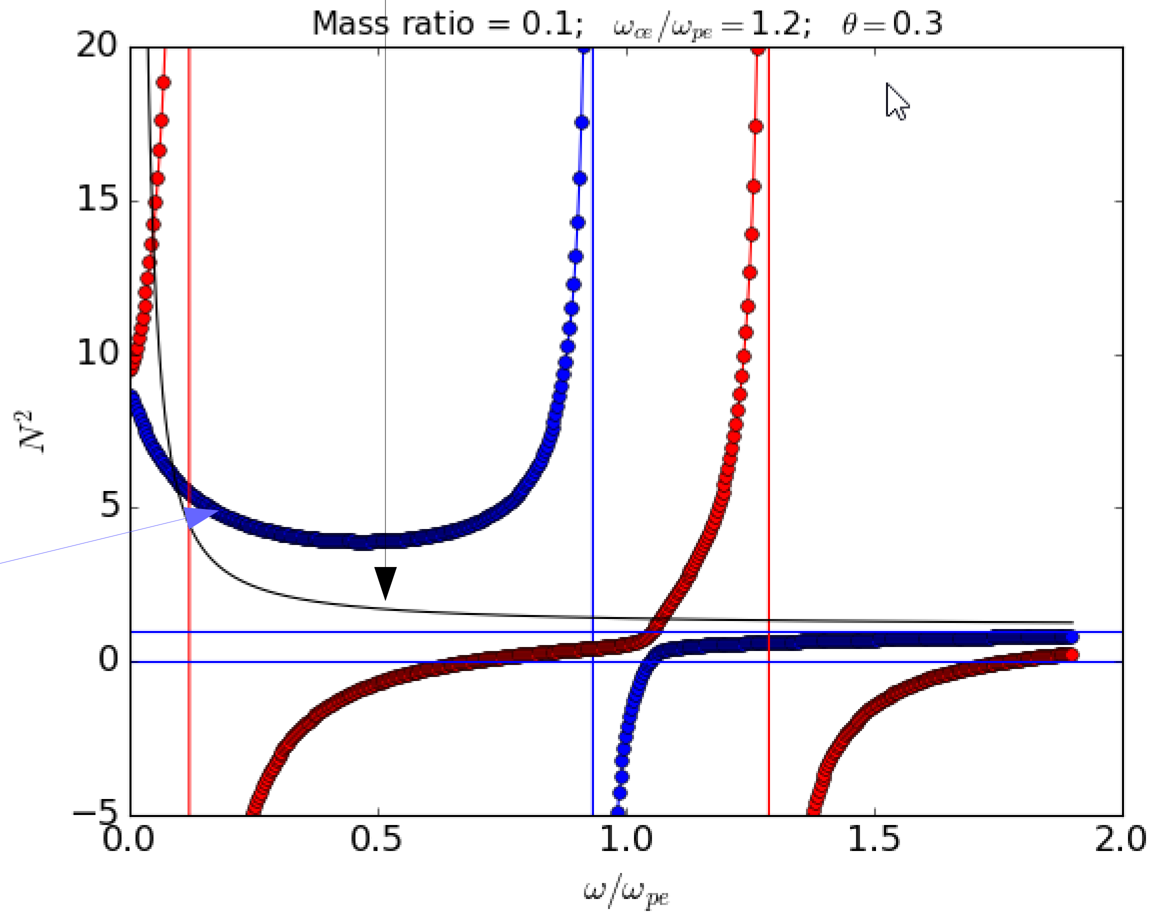
- Refractive index $$N = \frac{1}{\cos\theta \ \beta_{\parallel}} \left(1 + \frac{\Omega_{ce}}{\omega \ \gamma} \right) > 1$$

Anomalous Doppler resonance

$$N = \frac{1}{\cos\theta \;\; \beta_{\parallel}}\left(1 + \frac{\Omega_{ce}}{\omega \;\; \gamma}\right) > 1$$

- Electron-ion cold plasma dispersion relation

Three crossing points, one on the whistler branch, is it important?

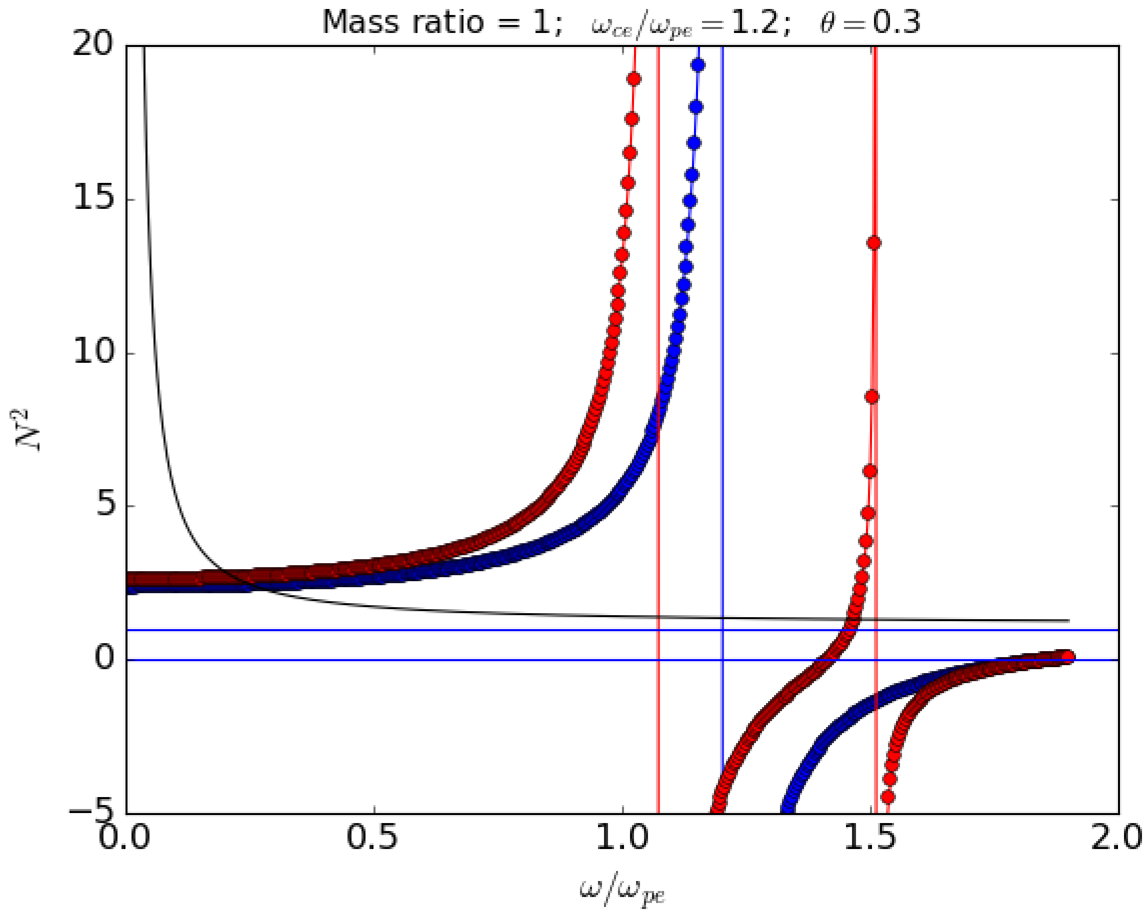


Anomalous Doppler resonance

$$N = \frac{1}{\cos\theta\ \beta_{\parallel}}\left(1 + \frac{\Omega_{ce}}{\omega\ \gamma}\right) > 1$$

- Electron-positron plasma

Three crossing points, no whistler branch



Anomalous Doppler instability

- Some electrons emit photons and increase their pitch angle
- Some electrons absorb photons and decrease pitch angle
- Positive drive if the distribution function is stretched ahead (a natural condition for runaway electrons in a tokamak)

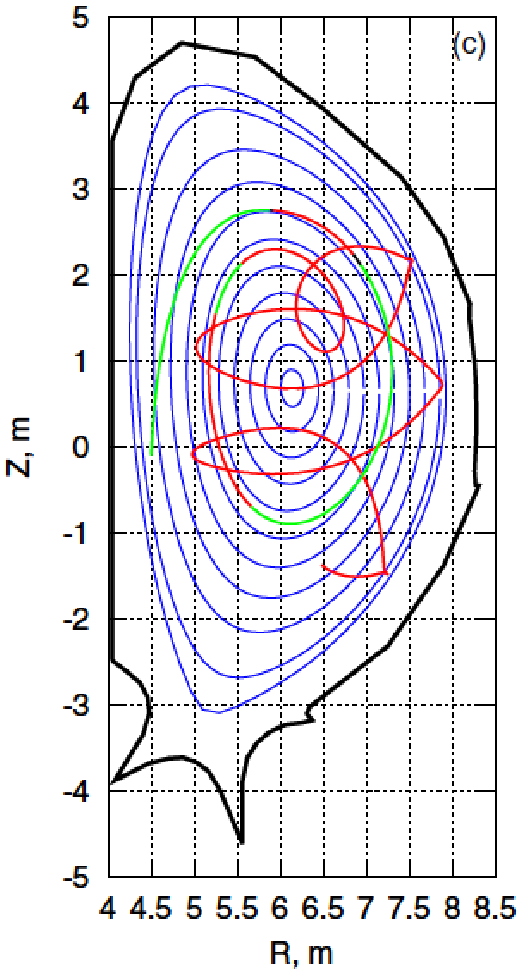
- Damping by collisions and by Cherenkov resonance with electrons at lower energy

- All the above is well established

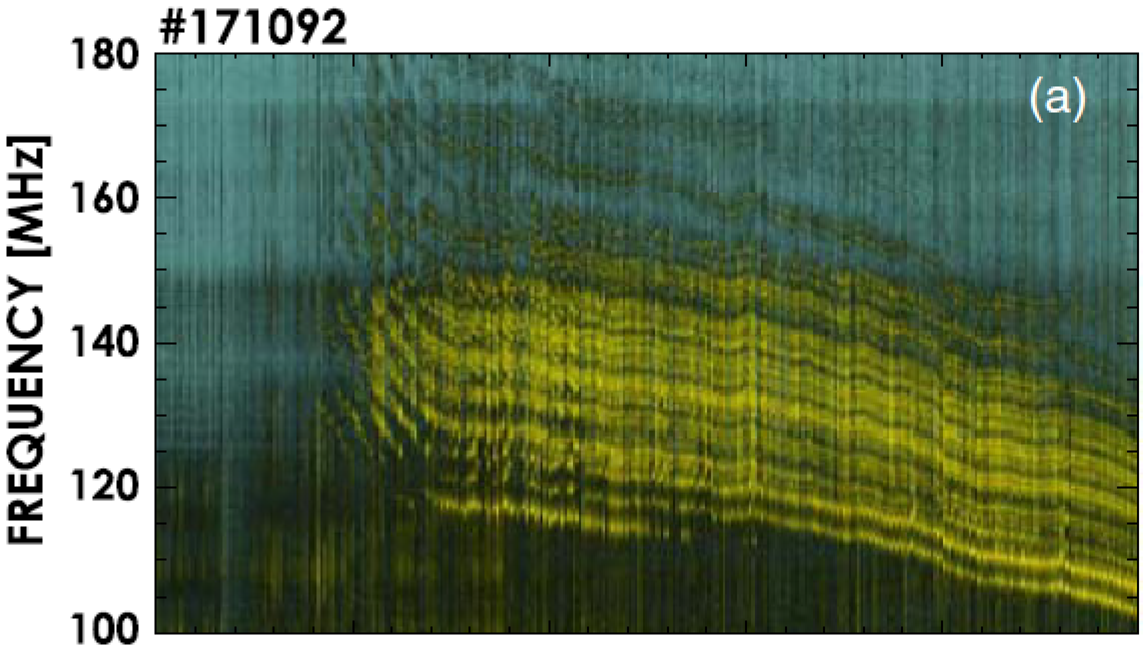
- More recent considerations:
  - propagation of emitted waves in a finite plasma
  - Non linear behaviour

- A fundamental question: impulsive relaxations (as often observed also in FTU) or saturated turbulence?

Waves propagation and detection



Nucl. Fusion **55** (2015) 043014
Stability analysis of runaway-driven waves in a tokamak
Pavel Aleynikov[1] and Boris Breizman[2]

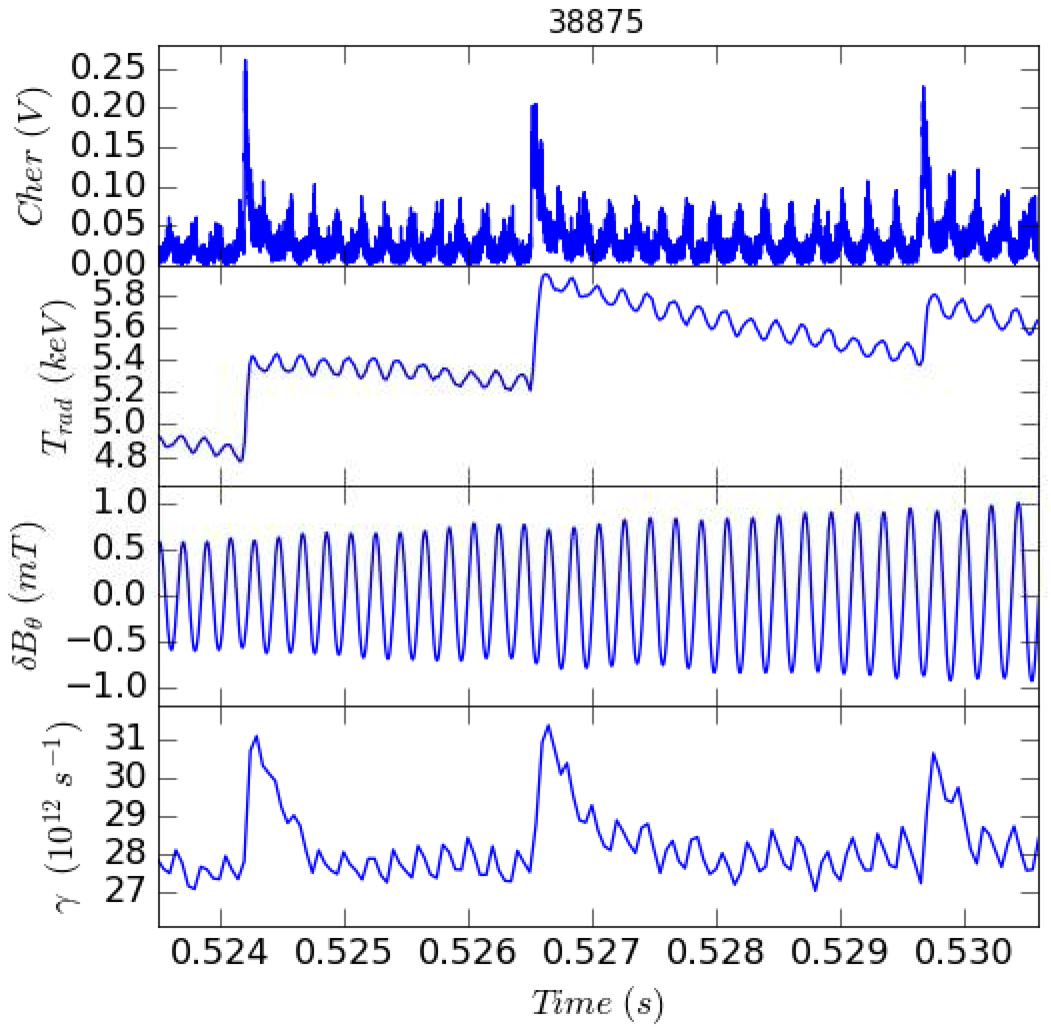


PRL 120, 15002 (2018)
First Direct Observation of Runaway-Electron-Driven Whistler Waves in Tokamaks
D. A. Spong et al

Perspectives

- Linear instability with realistic RE distributions (strong competition)
- Non linear calculations (strong competition)
- **Explain impulsive vs turbulent behaviour**
- **Export to pair plasma environments (and include ion minorities) to study rapid pitch angle scattering after long acceleration, related to gamma-ray flares**

Impulsive ADI in FTU



- **Suddenly enhanced RE losses from Cherenkov probe**
- **Suddenly enhanced synchrotron radiation**

The impulsive form is often observed