Whistler wave destabilization by a runaway electron beam in COMPASS

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Introduction

Runaway electrons (RE) represent a serious issue for the integrity of the tokamak [1]. Several strategies currently exist for controlling and suppressing RE beams in tokamak plasmas, such as use of massive gas injection, pellet injection or use of resonant magnetic perturbations [2]. An alternative strategy to control the RE beam energy was proposed, which relies on the resonant interaction between high energy electrons and whistler waves [3]. Kinetic instabilities developing in a RE beam were discussed in [4] and more recently the destabilization of whistler waves in presence of a RE beam was studied in [5]. The non-local effect on whistler wave amplification and damping was assessed in [6] by using a ray-tracing code. RE-driven whistler waves in a tokamak plasma were first observed directly in [7], and a detailed study of radiofrequency (RF) emissions in presence of a RE beam was carried out in [8]. Here a simple model for the description of RF waves destabilization in presence of a RE beam in COMPASS is proposed, to support experimental results. Two different situations are considered: the one in which the waves are spontaneously generated inside the plasma and the one in which the waves are injected from the outside by an antenna.

Theoretical model

Wave propagation is calculated using ray-tracing method in toroidal geometry for a circular plasma. The whistler wave dispersion relation can be deduced from the more general dispersion relation $D = (\varepsilon_{11} - n_\parallel^2)(\varepsilon_{11} - n^2) + \varepsilon_{12}^2 = 0$, where ε_{11} and ε_{12} are the elements of the dielectric tensor, while n is the wavenumber $n = kc/\omega$, in the limit $\omega_{ci} \lesssim \omega \ll \omega_{ce}$. With these simplifications, the dispersion relation reduces to $\omega^2 = k^2 v_A^2 (1 + k_\parallel^2 c^2/\omega_{pi}^2)$. The linear growth rate γ of the wave is calculated using analytical formulas [5]. The main resonances here considered are the anomalous Doppler and Cherenkov. The RE distribution function adopted here is valid in the limit of near-critical electric field ($E/E_c \geq 1$), which is the case of our experimental conditions. The RE beam is assumed to be uniformly distributed inside $r/a = 0.5$, and rapidly drop outside (Fig.1). Other radial distributions were considered, leading to similar results.

The collisional damping of the wave Γ is calculated as shown in [6]. This calculation, in the whistler wave limit, leads to the simplified formula

$$\Gamma \approx \frac{\nu_e}{2}\left(1+\frac{\omega^2\omega_{pe}^2}{\omega_{ce}^2\omega_{pi}^2}\right)\frac{\omega_{pi}^2\omega_{ce}^2}{\omega_{pe}^4}(n^2+n_{\parallel}^2) \qquad (1)$$

where ν_e is the electron-ion collisional frequency. In the range of frequencies of interest, the collisional damping is significantly reduced. The condition for wave destabilization is that the growth rate is larger than the collisional damping, $\gamma - \Gamma > 0$.

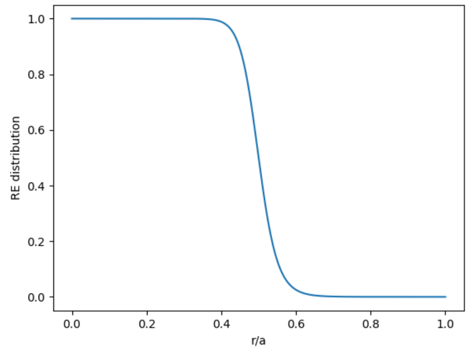

Figure 1: RE beam distribution

Emission inside the plasma

For the application to spontaneous generation inside the plasma, the waves are initialized in a chosen radial position inside the RE beam and the initial wavenumbers n_y, n_z are assigned. n_x is determined by the dispersion relation, the condition for wave propagation being $n_x^2 > 0$. The growth rate and damping of the wave are calculated along the wave path. Waves with different frequencies were simulated, in the range of a few 100 MHz. The regions of maximum amplification in the poloidal plane and in the space of wave vectors $k-\theta$, where θ is the angle with respect to the magnetic field, can be identified. An example of wave propagation and amplification for waves initialized at $r/a = 0.4$ for 100 MHz is displayed in Fig.2.

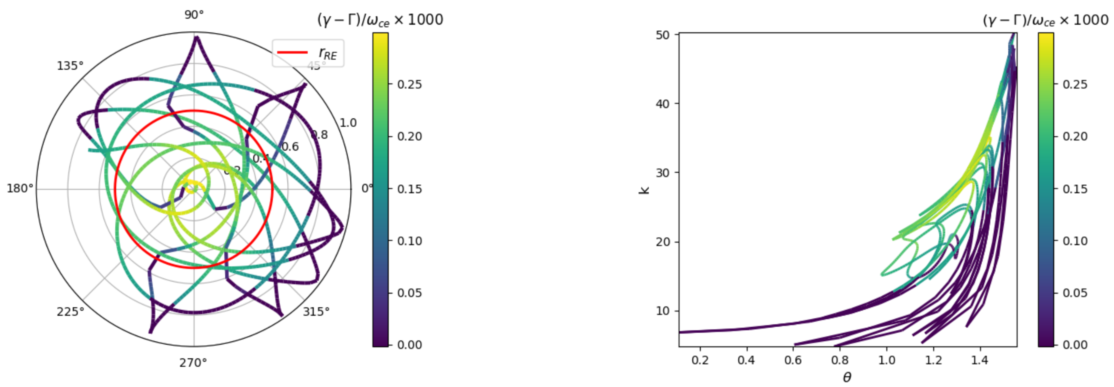

Figure 2: Trajectories in the poloidal plane (left) and in the $k-\theta$ plane (right) for 100 MHz

The non-local character of wave amplification and damping (convective effects [6]) can be evaluated by calculating the time integral of $\gamma - \Gamma$ along the wave trajectory, $K = \int(\gamma-\Gamma)dt$.

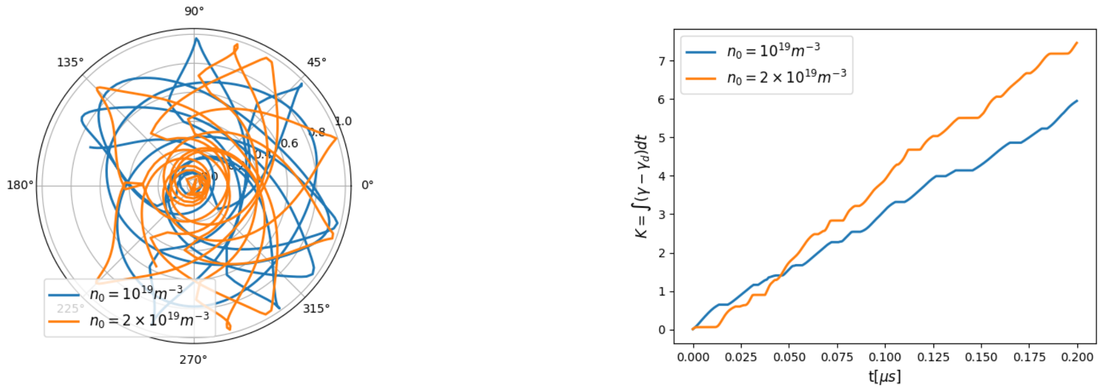

Figure 3: Trajectories in the poloidal plane (left) and wave amplification (right)

An example of wave trajectories and corresponding wave amplification for two choices of the central density and for 100 MHz is displayed in Fig3. In the considered experimental conditions (low central density, $n_e = 1 - 2 \times 10^{19} m^{-3}$), collisional damping is small, so the wave is always amplified. The wave amplifications K is positive for all the considered frequencies, meaning that a broad spectrum of perturbations can be driven unstable under these plasma conditions.

External injection by an antenna

For experiments in COMPASS, two in-vessel square-loop antennas were used to receive and transmit RF waves, with a frequency in the order of a few hundreds MHz. The antenna spectrum was computed analytically according to "Antenna theory and design", Wiley (2012). Different initial values of n_y, n_z were chosen. Wave accessibility condition ($n_x^2 > 0$) limits the range of n_y, n_z that can propagate ($n_z, n_y \lesssim 2 - 5$ for injection from $r/a = 0.99$).

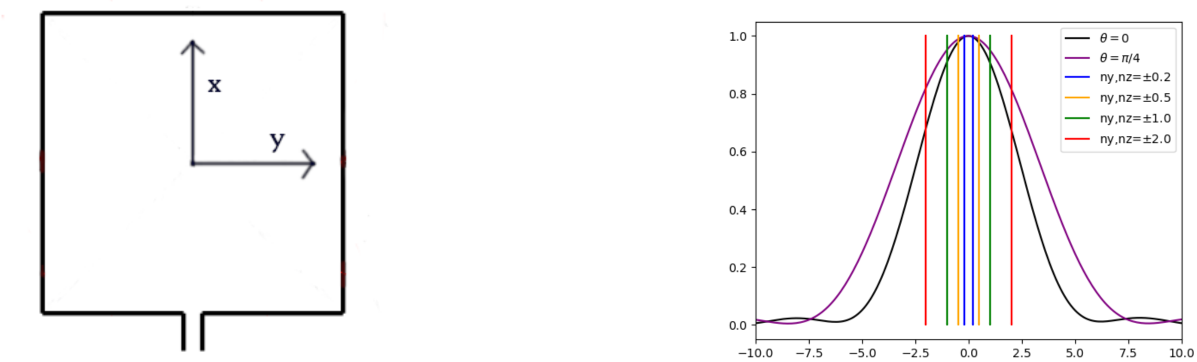

Figure 4: Schematic picture of the antenna (left) and poloidal spectrum for two different inclinations with respect to the horizontal plane (right)

An example of wave propagation and amplification for waves injected from $r/a = 0.99$, with the choice $n_y = n_z = 2$ for the initial wave numbers, is displayed in Fig.5.

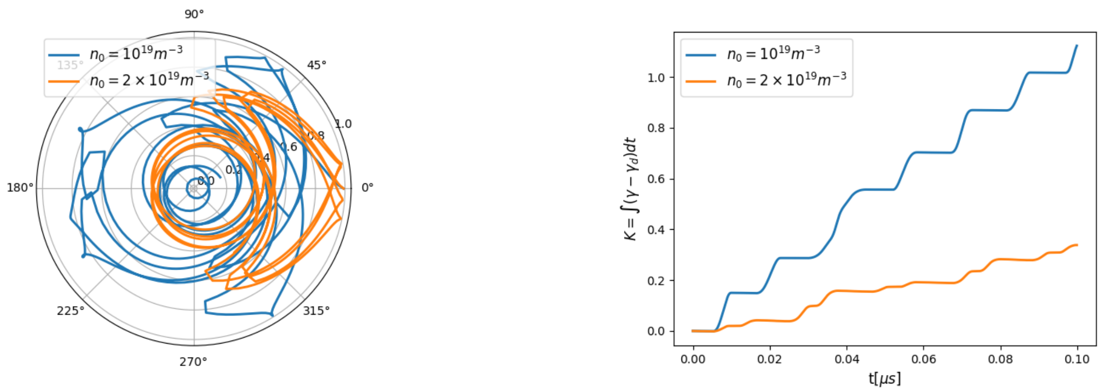

Figure 5: Trajectories in the poloidal plane (left) and wave amplification (right) for $n_y = n_z = 2$

Wave amplification subtracts energy from the RE beam. Early injection of whistler waves in the discharge might help cutting off the high-energy tail of the RE dstribution.

Conclusions

A simple model for the description of whistler wave destabilization and propagation in presence of a RE beam was developed. The model was applied to the spontaneous generation of whistler waves inside the plasma and to the external injection by an antenna. The regions of maximum wave amplification in the physical space and the space of wave vectors can be identified. The spectrum of the antenna was calculated and the accessibility condition for the wave was assessed. By introducing some inclination for the antenna, the poloidal spectrum becomes broader, while moving the antenna further into the plasma improves the wave accessibility. A model for evolution of the RE distribution and of the wave energy must be implemented.

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