Commun. Comput. Phys.
doi: 10.4208/cicp.OA-2016-0091

Vol. **21**, No. 4, pp. 947-980
April 2017

Recovering the Damping Rates of Cyclotron Damped Plasma Waves from Simulation Data

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Received 21 June 2016; Accepted (in revised version) 19 September 2016

Abstract. Plasma waves with frequencies close to the particular gyrofrequencies of the charged particles in the plasma lose energy due to cyclotron damping. We briefly discuss the gyro-resonance of low frequency plasma waves and ions particularly with regard to particle-in-cell (PiC) simulations. A setup is outlined which uses artificially excited waves in the damped regime of the wave mode's dispersion relation to track the damping of the wave's electromagnetic fields. Extracting the damping rate directly from the field data in real or Fourier space is an intricate and non-trivial task. We therefore present a simple method of obtaining the damping rate Γ from the simulation data. This method is described in detail, focusing on a step-by-step explanation of the course of actions. In a first application to a test simulation we find that the damping rates obtained from this simulation generally are in good agreement with theoretical predictions. We then compare the results of one-, two- and three-dimensional simulation setups and simulations with different physical parameter sets.

AMS subject classifications: 65M75, 65T99, 82C10, 85A30

Key words: Simulation, space physics, plasma, cyclotron resonance, wave damping.

1 Introduction

Turbulence in a magnetized plasma, for example in the solar wind, develops a cascading spectrum of low frequency waves with ever shorter wave lengths. The spectrum is limited by processes of wave damping, such as Landau damping or the cyclotron resonance for waves propagating perpendicular or parallel to the magnetic field (or by a mixture of both for oblique waves). Since computer simulations of various plasma phenomena and

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especially of plasma turbulence are more and more common, it is also interesting to take a closer look at the representation of damping mechanisms in the simulation.

In this article we pick the cyclotron resonance of ions and low frequency waves, i.e. waves with a frequency ω below the cyclotron frequency Ω of the resonating particles. This process can be easily modeled using waves propagating parallel to a background magnetic field and a thermal spectrum of protons. We choose the particle-in-cell (PiC) approach, because it is a self-consistent method which treats kinetic effects in the plasma. Thus, it is expected that a PiC simulation captures cyclotron damping correctly. Of course, PiC is not the only numerical approach which includes cyclotron damping and other types of code might be used as well to study wave damping.

Determining damping (or growth) rates of plasma waves is not a trivial task. Properties, such as the wave length or wave number, can easily be obtained from looking at a real space representation of the field data or its Fourier transform in space. Another Fourier transform in time yields frequency information and the dispersion relation of the whole wave mode. It is even possible to recover the polarization of single waves or whole wave modes by adequately combining different components of the electromagnetic fields. However, obtaining the damping rate directly from real or Fourier space electromagnetic field data is challenging.

One approach, though, is to resolve the dispersion relation of the wave mode in question to such an extend that a broadening in frequency can be observed. For a single wave with frequency ω_0 it may be assumed that the wave's intensity, represented by its energy density W, follows a Lorentz profile over frequency ω:

$$W(\omega)=\frac{W_0\Gamma^2}{(\omega-\omega_0)^2+\Gamma^2} \tag{1.1}$$

which is centered around the wave's frequency ω_0 and has a width at half maximum of 2Γ, where Γ is the damping rate. Thus, fitting the Lorentz profile from Eq. (1.1) to the data yields the damping rate of the wave. This is a tedious process and the precision of the results strongly depends on a high resolution of the frequencies in the dispersion relation, which is often only achieved by the use of a massive amount of computational resources.

A simple and fast possibility of studying wave damping (or any other interaction of waves and particles) is to analyze the composition of the total energy in the simulation. By comparing the development of the total field energy and the kinetic energy of the particles – quantities which are often computed during the simulation and saved for diagnostic purposes – it becomes obvious when and to which extent energy is transferred between waves and particles. However, no information about the wave's properties, such as frequency and wave number, are contained in such a study and several similar processes cannot be distinguished. It might even not be possible to tell which wave mode participates in the process, especially in fully kinetic simulations which might contain several possible candidates.