Particle-in-cell simulations on spontaneous thermal magnetic field fluctuations

F. J. R. Simões Jr., J. Pavan, R. Gaelzer, L. F. Ziebell, and P. H. Yoon

Citation: Physics of Plasmas (1994-present) **20**, 100702 (2013); doi: 10.1063/1.4825249
View online: http://dx.doi.org/10.1063/1.4825249
View Table of Contents: http://scitation.aip.org/content/aip/journal/pop/20/10?ver=pdfcov
Published by the AIP Publishing

PHYSICS OF PLASMAS **20**, 100702 (2013)

Particle-in-cell simulations on spontaneous thermal magnetic field fluctuations

F. J. R. Simões, Jr.,[1,a)] J. Pavan,[1] R. Gaelzer,[2] L. F. Ziebell,[2] and P. H. Yoon[3]
[1]*Instituto de Física e Matemática, UFPel, Pelotas, RS, Brazil*
[2]*Instituto de Física, UFRGS, Porto Alegre, RS, Brazil*
[3]*Institute for Physical Science and Technology, University of Maryland, College Park, Maryland 20742, USA*

(Received 12 September 2013; accepted 2 October 2013; published online 25 October 2013)

In this paper an electromagnetic particle code is used to investigate the spontaneous thermal emission. Specifically we perform particle-in-cell simulations employing a non-relativistic isotropic Maxwellian particle distribution to show that thermal fluctuations are related to the origin of spontaneous magnetic field fluctuation. These thermal fluctuations can become seed for further amplification mechanisms and thus be considered at the origin of the cosmological magnetic field, at microgauss levels. Our numerical results are in accordance with theoretical results presented in the literature. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4825249]

The plasma emission is the most fundamental problem in basic plasma physics and space plasmas. It is known that unmagnetized plasmas with perpendicular free energy can give origin to purely growing electromagnetic mode excited via classical Weibel instability.[1–3] In the last few years, some theoretical[4–7] and computational[8,9] efforts have been made to investigate this issue. According to this scenario, the Weibel instability is driven by the anisotropy of the particle velocity distribution of plasma. Due to this anisotropy, currents and waves are generated in the plasma.[10] The free energy related to the anisotropy is transferred to magnetic field energy.

Recently, a general theory for spontaneous electromagnetic fluctuations in an unmagnetized plasma was discussed by Schlickeiser and Yoon,[5] considering the non-relativistic limit. As an illustrative example, the authors consider the case of the non-relativistic isotropic Maxwellian distribution function, using the Klimontovich and Maxwell equations. However, no computational simulation has been performed to confirm that theory. The purpose of the present work is to perform particle-in-cell (PIC) simulations to verify the theoretical prediction of the general theory for generation of electromagnetic fluctuation from thermal emission in a non-relativistic regime.

As we shall show, the spontaneous thermal emission can originate both high-frequency spontaneously emitted electrostatic field fluctuations and spontaneous emission of magnetic field fluctuations in an equilibrium plasma. To perform the simulations we utilize the PIC simulation code KEMPO 1D (Kyoto ElectroMagnetic Pic cOde)[11] in a modified version.[12]

Our numerical simulations are realized in one-dimensional electromagnetic PIC code with periodic boundary conditions. It is important to notice that although our code is 1D in configuration space (x-axis), it is 3D in velocity space, electric and magnetic fields. Also, one can obtain diagnostics for spatial profiles of electric and magnetic fields $(E_{x,y,z}, x)$, $(B_{y,z}, x)$, 3D transverse fields $E_{y,z}$, B_{yz}, and particle velocity components $v_{y,z}$ along the x-axis. From that, we can obtain the wave dispersion relation ($\omega - k$ diagrams) for $E_{x,y,z}(\omega, k)$ and $B_{y,z}(\omega, k)$.[11,13]

For numerical simulation we explicitly assume the ambient magnetic field equal to zero, $B_0 = 0$, which implies the electron cyclotron frequency is given by $\Omega_{ce} = 0.0$. This assumption is important to assure that there is no magnetic field fluctuations in our numerical scheme at $t = 0.0$. All electrostatic and electromagnetic fluctuations are induced in the system from self-consistent solution of Maxwell and motion equations.

We utilize 2048 spatial grid points, with distances normalized by λ_{De}, where $\lambda_{De} = (\varepsilon_0 k_B T / n_0 e^2)^{1/2}$ is the Debye length, and grid spacing $\Delta x = 1.0\lambda_{De}$. We run the simulations for a total of 524 288 time steps, with $\Delta t = 0.02\omega_{pe}^{-1}$, which means that the system is allowed to evolve until $\omega_{pe} t = 10, 485.76$. This long time run is necessary because we are looking for low frequency emissions, and in numerical simulations this is performed by setting the minimal frequency in the numerical system as $\omega_{min} = 2\pi/(n_t \Delta t)$, where n_t is the total amount of time steps. In our numerical system all frequencies are normalized by the electron plasma frequency, and the velocities are normalized by the speed of light *in vacuo c*.

For the electron plasma species we consider the thermal velocity $v_e = 0.025$, with no drift velocity $v_d = 0.0$, and 2048 super-particles per grid cell. Also, we consider Maxwellian ion and electron species with equal temperature, $T_e = T_i = T$, and realistic ion-to-electron mass ratio, $m_i/m_e = 1836$. It is important to notice that we consider both ions and electrons with gyrotropic distribution functions.

Figure 1 shows the $\omega - k$ diagram obtained from the x (longitudinal) component of the electric field by Fourier transforming in space along the x axis and in time. For reference, we also plot both the theoretical Langmuir (Bohm-Gross) dispersion relation $\omega^2 = \omega_{pe}^2(1 + 3k^2\lambda_{De}^2)$ (dotted curve) and the numerical solution (continuous curve) of the dispersion equation

$$2k^2\lambda_{De}^2 - Z'\left(\frac{\omega/\omega_{pe}}{\sqrt{2}k\lambda_{De}}\right) = 0,$$

[a)]Electronic mail: fernando.simoes@ufpel.edu.br

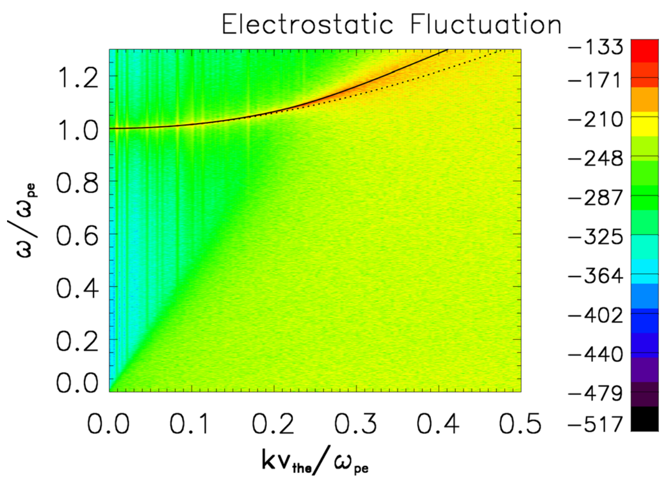

FIG. 1. ω-k diagram obtained from the time and space evolution of the x (longitudinal) component of the electric field, E_x. The theoretical Langmuir dispersion relation and numerical solution of the dispersion equation are represented by a dotted and full line, respectively.

where $Z(\zeta)$ is the well-known Fried & Conte function.

By comparison with Fig. 1 from Schlickeiser and Yoon,[5] one can see that the present results are in agreement with the theoretical prediction of the general theory for spontaneous electromagnetic fluctuation in the non-relativistic limit. To avoid that at any time during the simulation some particle attains speed comparable to the light speed, the velocities are checked at every simulation time step, in order to guarantee preservation of the non-relativistic regime.

Shown in Fig. 2 is the simulated dispersion diagram, ω-k, generated from the magnetic field fluctuation. It is possible to see that for a given normalized wave number kv_e/ω_{pe} the spontaneously emitted magnetic field fluctuation maximizes at zero frequency, $\omega/\omega_{pe} = 0$, which is merely the collective Weibel mode. A result like this was also obtained by Yoon and can be seen in Fig. 3 of Ref. 6. This result is important because it shows that the spontaneous magnetic field perturbation can be amplified as the Weibel instability. Also, our PIC-simulation results confirm the general theory proposed by Schlickeiser and Yoon[5] for non-relativist limit.

We emphasize that in our simulation we do not impose a temperature gradient, in contrast with previous simulation work.[9] The results obtained in the present paper were obtained assuming isotropic Maxwellian distributions and have shown the occurrence of spontaneously emitted weakly amplified magnetic field fluctuations. However, it has to be pointed out that kappa distribution functions produce good quality fittings for solar wind measurements.[14–17] Therefore it may be interesting to perform PIC simulations for conditions similar to those presented here, but assuming kappa distribution functions, for comparison with the simulations made using Maxwellian distributions, and for comparison with recent theoretical analysis.[18] We are presently working along this line and intend to report our findings in a forthcoming paper.

To conclude, we have performed PIC simulations to show that even an isotropic Maxwellian plasma in a non-relativistic limit can produce spontaneous electromagnetic fluctuations. The results were obtained considering a situation different from that considered in previous analysis found in the literature, which have imposed temperature gradients as a source of free energy to generate the instabilities. Our results are in accordance with the general theory proposed by Schlickeiser and Yoon,[5] where Maxwellian velocity distribution functions for the plasma particles provide the thermal fluctuations of weakly amplified modes, as shown in Fig. 1 for the high-frequency electrostatic fluctuations and in Fig. 2 for the amplified magnetic field fluctuations. Also, our results suggest a new scenario for the generation of fast transverse electromagnetic fluctuations, where spontaneous electromagnetic emission can be generated by isotropic plasma distribution functions. These thermal fluctuations can became seed for further amplification mechanisms, like dynamos and/or kinetic Weibel-like plasma instabilities, and thus be considered at the origin of the cosmological magnetic field, at microgauss levels.

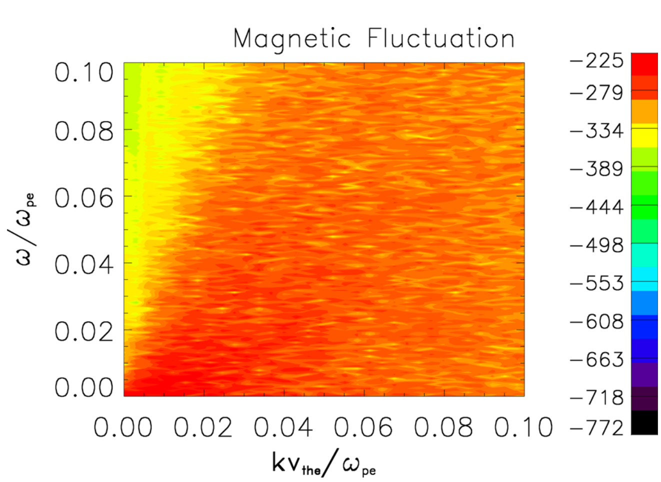

FIG. 2. ω-k diagram of the spontaneously emitted weakly amplified magnetic field fluctuation in a thermal electron distribution.

This work was partially supported by the Brazilian agencies CNPq and FAPERGS. P.H.Y. acknowledges NSF grant (Nos. AGS1138720 and AGS1242331) to the University of Maryland.

[1] E. S. Weibel, Phys. Rev. Lett. **2**, 83–84 (1959).
[2] B. D. Fried, Phys. Fluids **2**, 337 (1959).
[3] F. Califano, T. Cecchi, and C. Chiuderi, Phys. Plasmas **9**, 451 (2002).
[4] A. Bret, M. E. Dieckmann, and C. Deutsch, Phys. Plasmas **13**, 082109 (2006).
[5] R. Schlickeiser and P. H. Yoon, Phys. Plasmas **19**, 022105 (2012).
[6] P. H. Yoon, Phys. Plasmas **14**, 064504 (2007).
[7] P. H. Yoon, Phys. Fluids B: Plasma Phys. **1**, 1336 (1989).
[8] R. L. Morse and C. W. Nielson, Phys. Fluids **14**, 830 (1971).
[9] Y. Fujita, T. N. Kato, and N. Okabe, Phys. Plasmas **13**, 122901 (2006).
[10] M. V. Medvedev and A. Loeb, Astrophys. J. **526**, 697 (1999).
[11] Y. Omura and H. Matsumoto, *Computer Space Plasma Physics: Simulation Techniques and Software* (Terra Scientific Publishing Company, 1993).
[12] F. J. R. Simões, Jr., M. V. Alves, and R. Gaelzer, J. Geophys. Res. **115**, A06105, doi:10.1029/2009JA014841 (2010).

[13]H. Matsumoto and T. Sato, *Computer Simulations of Space Plasmas* (Terra Scientific Publishing Company, 1985).
[14]I. Zouganelis, J. Geophys. Res. **113**, A08111, doi:10.1029/2007JA012979 (2008).
[15]Y. F. Chateau and N. Meyer-Vernet, J. Geophys. Res. **96**, A02565, 10.1029/90JA02565 (1991).
[16]G. L. Chat, K. Issautier, N. Meyer-Vernet, I. Zouganelis, M. Maksimovic, and M. Moncuquet, Phys. Plasmas **16**, 102903 (2009).
[17]G. L. Chat, K. Issautier, N. Meyer-Vernet, and S. Hoang, Sol. Phys. **271**, 141–148 (2011).
[18]M. Lazar, P. H. Yoon, and R. Schlickeiser, Phys. Plasmas **19**, 122108 (2012).