A Microscopic First-principle Model for Electron Cyclotron Emission Re-absorption and Evidence of Loss of Confinement above a Critical Density in Magnetized Plasmas

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The existence of electron ordered gyrational Larmor motion is at the basis of magnetic plasma confinement. It is well known that accelerated electrons will emit cyclotron radiation as described by basic electrodynamics. A non-relativistic electron population, at density n_e, temperature T_e in magnetic field with an intensity B, would emit a radiated power $P_e=e^4/(3\pi\varepsilon_0 m_e^3 c^3)B^2 n_e T_e$, which under fusion reactor condition would be very large (>1MW/m^3) [1]. However, this is not the power radiated from the plasma as this is found to be optically thick, particularly at the fundamental harmonic, $\omega_c=eB/m_e$.

To our knowledge, no definite microscopic explanation for radiation re-absorption in magnetized plasma has been given in the literature.

Here we propose a first-principle model, in which the plasma is conceived as a system of point electrons obeying Newton equations, in a constant magnetic field within a neutralizing background. The model is an extended and modified version of a classical many-body model of matter-radiation interaction already proposed in [2].

The force terms in Newton equation include both the retarded electromagnetic interactions among all particles and the radiation reaction force. For the electric field the well-known expression for an oscillating dipole is considered. The magnetic field due to electron motion is neglected, as well as the electron motion along the magnetic field, being the particle gyrocenters considered stationary and equally-spaced along a magnetic field line. Two significant results are obtained from this simple model:

- 1) re-absorption of the cyclotron radiation emitted by a single gyrating electron by the whole system of electrons indeed occurs (a basic justification of the optical plasma thickness to the fundament harmonic is thus proposed);
- 2) ordered electron gyrational motions exist only if particle density is below a threshold value. This critical density turns out to scale as B^2.

The first result is related to an identity proposed on the basis of strong physical consideration by Wheeler and Feynman in their Review of Modern Physics paper in 1945 on the foundations of electrodynamics [3]. This identity in a weak form is here proven for a magnetized plasma.

The second result comes from the analysis of the stability properties of the system, investigated by means of the computation of normal modes and determining the values of plasma parameters for which some frequencies become complex. An instability is found to occur for particle density above a critical value. This instability involves normal modes associated with wavelengths of the order of the mean electron distance. In a continuum description of the plasma this phenomenon is completely lost, i.e. it is a characteristic feature of the discrete structure of matter. Through this extremely simplified first principles model of a magnetized plasma, in which only electron dynamics perpendicular to the magnetic field is considered, the existence is proven of a critical density limit. Beyond this density threshold, the whole system becomes unstable, the Wheeler and Feynman identity is no more satisfied, ordered motions and magnetization are lost.

For typical magnetic field values used in the laboratory, the density limit predicted by the model is well in the range of the experimental densities. The instability described by the simple model could thus play a significant role in determining the confinement properties of magnetized plasmas.

References

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