Particle simulations of the non-linear electron oscillations in the classical Pierce diode

M. Kocan[1], S. Kuhn, D. Tskhakaya[2]
Plasma and Energy Physics Group, Institute for Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria, E-mail: martin.kocan@uibk.ac.at
[1]Permanent address: Department of Plasma Physics, Comenius University, Mlynska Dolina F-2, Bratislava, SK-84248, Slovakia
[2]Permanent address: Institute of Physics, Georgian Academy of Sciences, 380077, Tbilisi, Georgia

The classical Pierce diode [1] is a one-dimensional electrostatic bounded plasma system consisting of two parallel electrodes (an emitter at $x=0$ and a collector at $x=d$) with an external short circuit. A mono-energetic beam of electrons with density n_0 and velocity u_0 is injected from the emitter and absorbed at the collector. The region between the electrodes is filled with a neutralizing background of immobile ions with density n_0. Both the equilibrium and stability properties in the Pierce diode are controlled by the dimensionless system length, or *Pierce parameter*, $\alpha = \omega_{pe} d / u_0$, where $\omega_{pe} = \sqrt{n_0 e^2 / (\varepsilon_0 m_e)}$ is the electron plasma frequency at the emitter. For specific values of α, the uniform equilibrium exhibits period-doubling bifurcations, from which emerge non-linear oscillatory flows. In this work, we used particle-in-cell (PIC) simulations performed with the BIT1 code [2] (developed at Innsbruck University on the basis of the XPDP1 code from U. C. Berkeley [3]) to investigate the evolution of slightly perturbed uniform equilibria into the related non-linear attractor states for a broad range of α values. First to demonstrate the suitability of our code, the period-doubling route to chaos is re-investigated in detail in the narrow α band just below the value of $\alpha \cong 2.897\pi$. In both the linear and non-linear regimes, excellent agreement (better than 1.5%) is found with the results obtained previously by Godfrey [4] from the numerical integration of a full fluid model, and by Hörhager and Kuhn [5] from the three-harmonic fluid analysis. Having thus established that our method is perfectly adequate for these investigations, we will systematically present analogous results (linear instability oscillation frequencies and growth rates, transient non-linear phenomena, and time-asymptotic attractor states) for α domains in which these phenomena have not been considered in detail before. In particular, we will also study states which, due to their intrinsic complexity, are not accessible to fluid analysis and hence require a fully kinetic description such as ours. These investigations may provide a guideline for investigating similar oscillations in other bounded plasma systems.

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