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The Simulation of Effected Feedback on the Chaos, Instability Oscillations Electron in the Pierce Diode

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ABSTRACT

The effect of the delayed feedback on the complex modes of oscillations in an electron flow with an overcritical current generated in the Pierce diode is studied. The dependence of the system dynamics on the delay time (d) and the feedback factor (A) is considered. It is demonstrated that chaotic oscillations can be suppressed by appropriately choosing the feedback parameters. Also studied are the physical processes in the electron flow that accompany transitions between various oscillation modes.

KEY WORDS: Pierce diode, electron–plasma, virtual cathode, chaos, instability, electron beam, Maxwell equation.

INTRODUCTION

The Pierce diode is one of the classical models in high-frequency plasma electronics [1, 2].The classical Pierce diode is the simplest model of a collision less bounded plasma system [1]. It is an one–dimensional electrostatic model consisting of two electrodes with a short circuit, an emitter (x=0) and a collector (x=l) From the emitter a mono energetic beam of electrons is injected, and is absorbed completely at the collector. The electrons are neutralized by an immobile ion-background of the same density as the electron beam at x=0,The classical Pierce diode can be described by one fluid equation for electron density and electron velocity and the Poisson equation for the electric potential.

Being simple, this model exhibits a lot of features typical of the dynamics of an electron beam in various real electronic devices and is widely used for analyzing certain types of instabilities in electron–plasma systems [3]. The model represents two infinite plane parallel grids penetrated by a mono energetic infinitely wide electron beam. The charge density in the flow and its velocity at the entrance to the system are constant. The space between the grids is uniformly filled by neutralizing immobile ions, so that the neutralizing charge density equals the unperturbed charge density in the flow. The Pierce parameter is $a = \frac{L\omega_\rho}{v_o}$ $\omega_\rho = \sqrt{\frac{\eta\rho_o}{\varepsilon_o}}$ the plasma frequency of the electron flow; ρ_0 and $v0$ are the unperturbed density and velocity of the flow, respectively; *L* is the distance between the planes ; η is a specific electron charge; and $\varepsilon 0$ is the permittivity of vacuum) is a unique parameter determining the dynamics of the electron flow in such a system.

The Pierce instability develops in the system at $\alpha>\pi$.The instability forms a virtual cathode in the beam [2, 3].This phenomenon is used to generate ultrahigh-power microwave pulses in such microwave electronic devices as vircators [4]. Note that, in a narrow range of values of the Pierce parameter (around $\alpha \sim 3\pi$), the development of the instability is suppressed by the nonlinearity, and the diode appears to be completely transparent for the beam. In this case, one can describe the system within the framework of the hydrodynamic theory. Earlier, it was demonstrated [5] that, in this case, the system may exhibit chaotic oscillations.

Discussion of model

In this paper we consider a vircator with delay feedback and beam modulation (vircator {klystron with delay feedback). Fig. 1 shows a model of investigated device.

In our conjuration a small cavity is located between the beam source and the drift space.

An annular electron beam with overcritical current I is injected thought the cavity into drift space with the guide of an axial mageticeld. A VC formed in drift space, where it's oscillates in the time and space. The resonance frequency of cavity is equal VCO frequency. In consequence, an injected electron beam is modulated in the input cavity on the frequency approximately equal to VCO frequency. On the collector end the cylindrical drift space reduces into coaxial output of microwave radiation. It _lls by the conducting media to the modeling of output of microwave power. The electromagnetic signal from output waveguide operates on the injected beam after transmitting through delay line with value of delay time. This external delay feedback leads to velocity modulation

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of the beam. The numerical simulation is carried out by using a mathematical model that given by the Vlasov's equation for the electron beam plus Maxwell's equations.

$$-i\omega\rho' + v_0 \frac{\partial n'}{\partial z} + \rho_0 \frac{\partial v_z'}{\partial z} = 0$$

$$-i\omega v_z' + v_0 \frac{\partial v_z'}{\partial z} = -\frac{e}{m}\frac{\partial \psi}{\partial z}$$

$$-\frac{\partial^2 \psi}{\partial z^2} = 4\pi e \rho'$$

$$\psi(0) = \psi(L) = v_z'(0) = \rho'(0) = 0$$

The external feedback is introduced by modulating the potential difference between the input and output grids of the diode by a signal taken from a certain cross section $x = x_{FB}$ of the interaction space. Let this signal be represented by the oscillations of the space charge density $\rho(x_{FB}, t)$ in the intergrid space. The introduction of such a feedback is equivalent to connecting a feedback circuit (waveguide) with a delay line to the interaction space. The feedback circuit is excited by oscillations in the electron flow. The signal from the delay line enters the interaction space.

$$\varphi(1,t) = f_{FB}(t) = a(\rho(x_{FB}, t-d) - \rho_0).$$

Here, A is the feedback factor determining the fraction of the oscillation power tapped into the feedback circuit and d is the feedback delay. In this case, we need to determine the signal in the feedback circuit at the time interval $t \in [-d, 0)$. Assuming that the processes in the system start developing at the time moment $t = 0$ and that the charge density is unperturbed ($\rho(x, t) = \rho_0$) at $t < 0$), we represent the initial distribution of the function f_{FB} as

$$f_{FB}\,|_{t\in[-d,0)} = 0$$

The results of the studies show that the position of the feedback point x_{FB} in the interaction space scarcely affects the dynamics of the system. Therefore, we fix this quantity so that x_{FB} =0.2. Thus, the dynamics of the system with the feedback is determined by the Pierce parameter α and the feedback parameters: delay time d and factor A. We numerically solve continuity equation (1) and equation of motion (2) by an explicit two-layer (in time) scheme with counter flow differences. Poisson equation (3) was integrated in each time step by the error vector propagation method [5]. The steps of the numerical scheme in space Δx and time Δt were 0.005 and 0.003, respectively.

Oscillation behavior

Fig. 2 shows power spectra, reconstructed phase portraits and time series of electric oscillations from output waveguide for two dynamical regimes in considered scheme, obtained with the electron beam current of 6.3 kA and the initial electron energy of 560 kev for different values of delay time τ .

For value of delay time $\tau \sim 0.1T_0$ or $\tau \sim T_0$ where $T_0 = 1/f_0$ is the oscillation period on resonance frequency f_0 of input cavity, we recognize weakly non-regular VCO with single base frequency (Fig. 2a; $\tau = T_0$). This frequency is approximately equal to value of f_0. In second case (Fig. 2b), when the value of delay time is approximately equal to T0/2, VCO dynamics is diverged from the previous case. As seen from Fig. 2b, frequency spectrum contains two independent frequencies with approximately equal spectrum power. Phase portrait is homogeneous and system demonstrates strong non-regular oscillations.

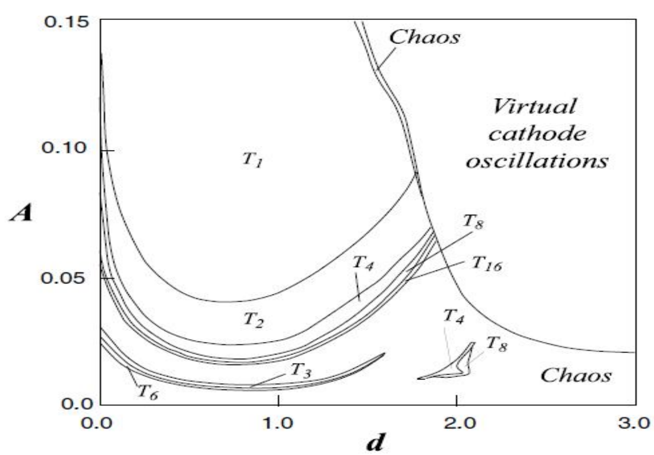


FIG.1. Oscillation regimes reproduced on parameter plane (A, d) ($\alpha = 2{:}86\pi$, $x_{df} = 0.2$)

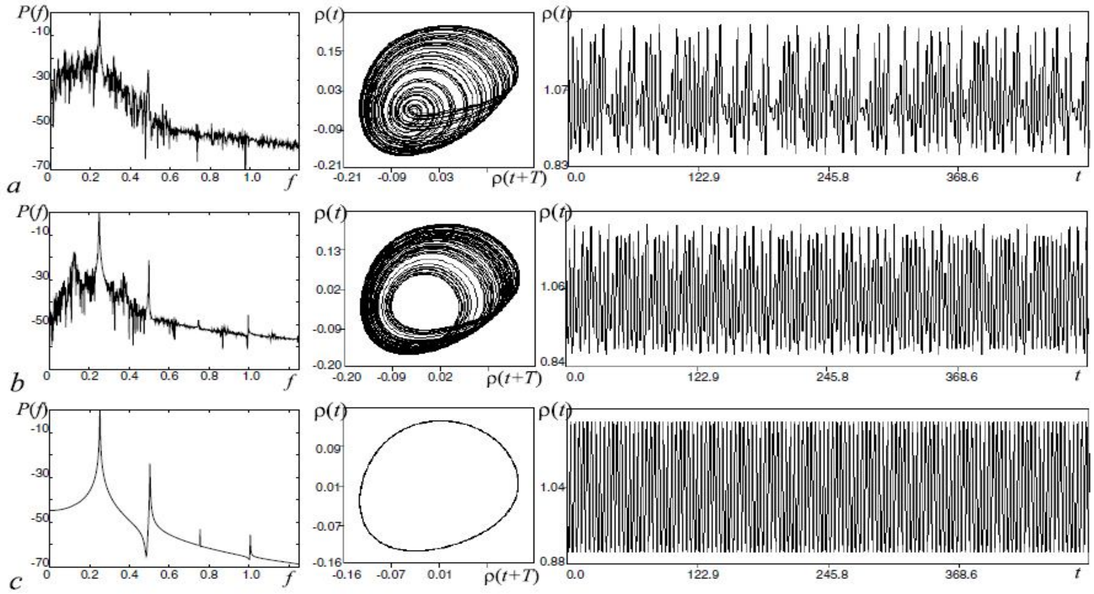


Fig.2. Power spectra, phase portraits, and time realizations of the oscillations of the space charge density of electron flow $\rho(t)$ in the cross section $x = 0.2$ for various oscillation modes: (a) in the absence of feedback, (b) A =0.008 and $d = 0.9$, and (c) $A = 0.05$ and $d = 0.9$.

The results of the increase in factor A depend on the time delay in the feedback circuit. If $d > \tau/2$, the increase in A results in the complication of the oscillations in the electron flow. The chaotic dynamics remains qualitatively unchanged. However, the power spectrum, the phase portrait, and the time realization become more complicated, and the amplitude of oscillations

Increases the further increase in the feedback factor at $d > \tau/2$ yields a dynamic which is completely determined by the development of instability in the electron flow.

Recall that the dynamics of the processes in the diode space is determined by two main mechanisms: the Pierce instability and the limitation of this instability by the nonlinearity. The feedback with $d > 1.8$–2.0 and $A > 0.02$ destroys the mechanism of the nonlinear limitation and provides unlimited growth of instability. The amplitude of oscillations rapidly increases with time. After a certain moment, the flow contains electrons backscattered to the injection plane. There appears a virtual cathode oscillating in time and space. This cathode reflects a portion of the electron flow back to plane $x = 0$. The hydrodynamic model of the electron beam correctly describes the processes in the diode space only in the absence of the overtaking and reflection of the particles. In the presence of reflections, Esq. (1) and (2) become invalid and must be replaced by; for example, the kinetic Vlasov equations (see, for example, [6]. In this work, we do not analyze the features of the modes involving the initiation of the virtual cathode. Therefore, we restrict ourselves to mapping the values of parameters providing the formation of the virtual cathode. In the diode space with the feedback, the appearance of the reflected particles and the formation of the virtualcathode take place at the critical value of the feedback factor AVC, which depends on the delay time. It can be seen from the maps of the modes that AVC decreases with increasing d. The boundary of the area of the virtual cathode oscillations is well described by the empirical formula AVC(d) = 0.03(d Ð τ/4)4 + 0.18.

Let us consider the system at the feedback delay time $d < \tau/2$. In this case, the increase in the feedback factor A leads to less complicated oscillations in the electron flow. It is possible to suppress the chaotic oscillations within a rather wide range of feedback parameters. The system exhibits periodic oscillations with various periods. This is clearly seen from the bifurcation diagram built using the local maxima of the time realization of the space charge density in the cross section with the coordinate $x = 0.2$ and delay $d = 0.9$

(Fig. 3) The analysis of the plane of parameters (Fig. 1) and the bifurcation diagram (Fig. 3) makes it possible to trace the transitions from one mode to another upon varying the feedback parameters. In the case of small values of feedback factor A, the oscillations in the diode remain chaotic but become less complicated. The bifurcation diagram in Fig. 3 shows that the attractor size monotonically decreases with increasing A. The windows of periodicity emerge in the chaos, and the transition to periodic oscillations via the reverse cascade of doubling periods takes place at $A > 0.3$. Figure 2b shows the characteristics of the corresponding chaotic oscillations. It can be seen that the attractor represents a narrow ribbon in the phase space. Such a type of limit set is typical of the chaotic mode emerging owing to the transition to chaos via the cascade of doubling periods. The noise pedestal in the power spectrum diminishes, which makes it easy to observe the harmonics and sub harmonics of the fundamental frequency f_0 . The further increase in feedback factor A results in the suppression of the chaotic oscillations and formation of the periodic oscillations with the cycle of period 1 (see Fig. 2c; $d = 0.9$ and $A = 0.05$). The transition involves a reverse cascade of doubling periods. The areas of the cycles with the periods *T*16, *T*8, *T*4, *T*2, and *T*1 are shown in the plane of the control parameters. Note that the maximum amplitude of oscillations of the space charge density $\rho(x, t)$ monotonically decreases to the unperturbed value $\rho 0$ of the density with increasing feedback factor *A* (Fig. 3).

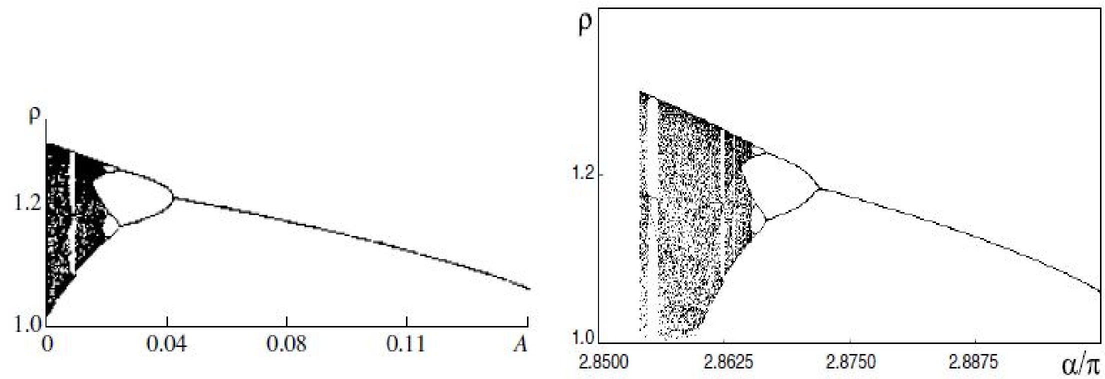


FIG. 3. Bifurcation diagram of the oscillations of the space charge density of electron flow $\rho(t)$ in the cross section x =0.2 at α = 2.86π and d = 0.9.

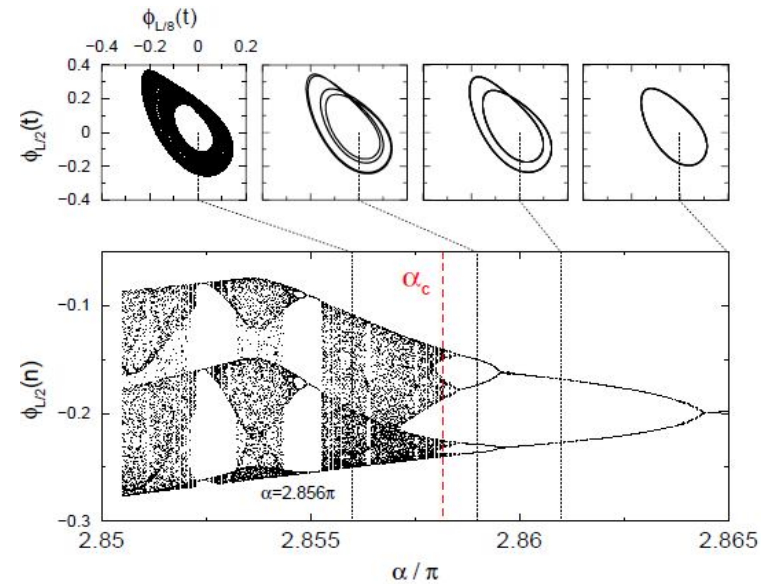
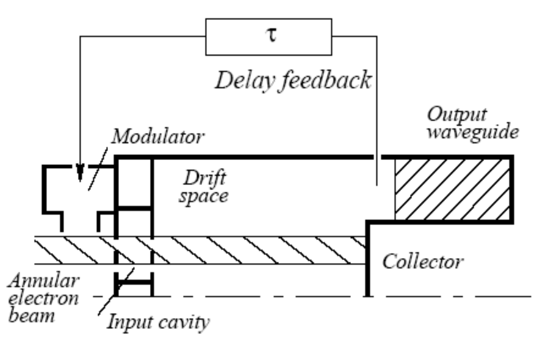


FIG. 4. The period-doubling route to chaos in the Pierce diode. The top row shows the phase space attractors of periodicity p=1, p=2,p=4 and the chaotic attractor (from right to left).

The bottom diagram is the bifurcation diagram obtained from the Poincar´e section of the respective attractors (dotted line)



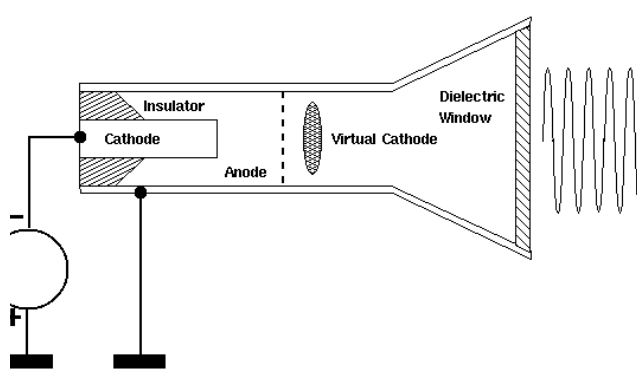


Fig. 5. model external feedback device Simple let VOC

CONCLUSION

We presented an analysis of the effect of delayed feedback on the chaotic oscillations in an electron flow with an overcritical current within the framework of a Pierce diode. The results of the numerical simulation of the Pierce diode demonstrate the suppression of the chaotic dynamics and buildup of the periodic oscillations of various types at certain feedback parameters. The chaotic dynamics is changed to the regular one when the feedback delay time is shorter than a half of the characteristic time of oscillations. This process involves a period-doubling cascade typical of the systems with a small number of degrees of freedom. The physical mechanism of suppression of chaotic oscillations is related to the variation in propagation conditions of the electron waves owing to the action of the feedback signal upon the beam. In practice, the suppression of chaos in the system under study can be used to eliminate undesired parasitic and noise like oscillations in the case when electron or ion flows exhibit a Pierce instability (this can happen in electron guns, devices of nuclear fusion, etc.) [7,8].

Characterization of the dynamics of an electron beam in the diode space with feedback takes place when the system approaches unstable uniform equilibrium, and the instability of oscillations in the electron flow increases. If the feedback delay time is about the characteristic time scale of oscillations, the complexity of oscillations grows owing to the increase in the amplitude of the oscillations and the consequent increase in the nonlinearity [9].

However, the growth of the power of the signal derived into the feedback circuit destroys the mechanism of nonlinear limitation of the developing instability. In this case, the development of instability gives rise to a virtual cathode, which means that the system contains electrons reflected from a potential barrier.

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