35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, P-5.090 (2008)

New model of a travelling-wave tube

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Introduction

The travelling-wave tube (TWT) is a device wherein an electron beam interacts with a longitudinal propagating wave. It was invented by Kompfner in 1943 as a microwave amplifier in which a hyperfrequency signal is amplified while an electron beam is slowed down [1]. This device is still used in radar, spatial telecommunications, and electronic counter-measures domains where robustness, large bandwidth and high output power are required.

Beside its industrial use, the TWT is used as a simple and efficient tool to study the one dimensional wave-particle interaction in plasma physics. In this utilization, the wave-guide plays the part of a plasma without its instabilities and noise. Non-linear instabilities and chaos control have been studied in such a device [2,3].

In both contexts, numerical simulation plays an essential part in directing experiments, and in industrial development. Indeed, it allows to understand a particular situation before its actual realization.

Travelling-wave tube modelization

Since the invention of TWT, several models have been developed and used [4-6]. A common feature of these models is their frequency approach, i.e. they assume that a finite number of frequencies are involved in the wave-particle interaction. A problem with this approach is that it assumes one knows *a priori* the frequencies that will be involved. But several phenomena like instabilities may happen at frequencies that are not simply connected with the input frequency, and consequently require a preliminary work to determine involved frequencies. A remedy to this problem is a time domain approach.

Slow-wave structure model

To achieve strong interaction between electric wave and electrons, both must propagate at roughly the same velocity. One uses a slow-wave structure (SWS) made of a cylindrical metallic tube which contains a metallic helix as sketched in Fig.1. As the electric wave travels along the helix, its axial velocity nears the electrons velocity.

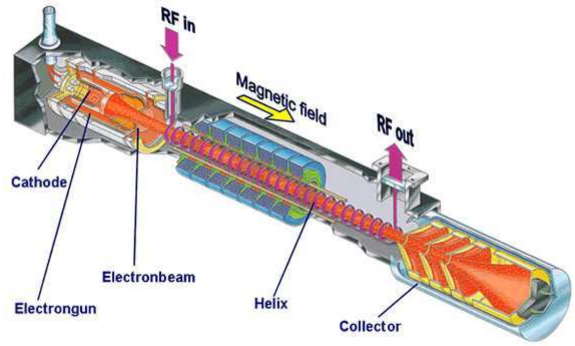

Figure 1: sketch of a travelling-wave tube

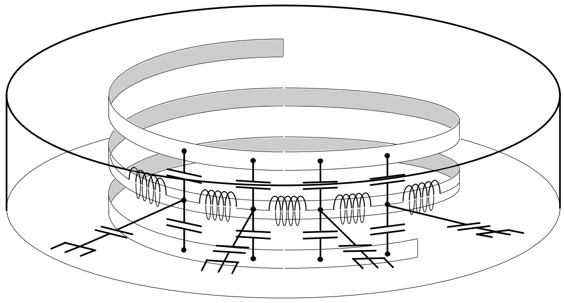

Figure 2: wave-guide discretization

We propose to modelise the SWS using an equivalent circuit approach in time domain. As seen in Fig.2 each point on the helix is coupled inductively with two neighbouring points on the helix, and capacitively with a point on the metalic sheath and two points that lie on the helix one turn foreward and one turn backward. The lowest degree of descretisation is to take two points per helix turn. It gives the equivalent circuit seen in Fig.3. The metallic sheath is taken as zero potential. The dispersion curve of this equivalent circuit is shown in Fig.4 together with the dispersion curve of an actual TWT. One notices that the equivalent circuit is able to propagate direct waves as well as backward waves, and to present a gap when one dissymmetrizes its parameters. One also see that both dispersion curves matches for low phase velocities.

Time evolution of the equivalent circuit is obtained by solving Kirhoff's equations of the cicuit. Hence one obtains a differential system of the form: $\dot{U} = M.U$, where U contains capacitance voltages and inductance currents of the equivalent circuit. The solution of this system is given by: $U(t) = e^{M.t}U(0)$.

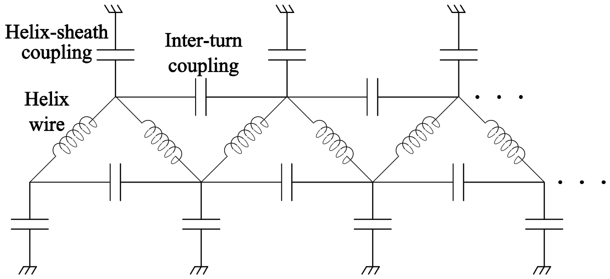

Figure 3: discretization with two points per helix turn

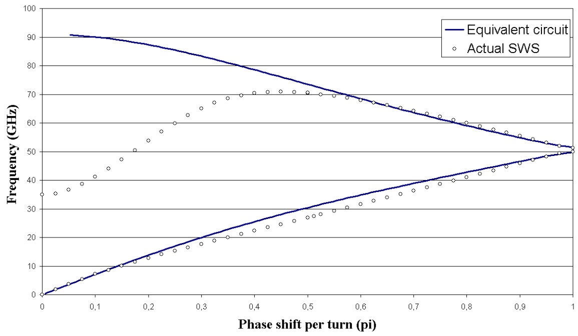

Figure 4: dispersion curves

Electron beam dynamics

We assume a one-dimensional beam. The phase space is assumed to be a set of discrete points (x_i, v_j), and the beam is described by a distribution function $f(x_i, v_j)$. Time evolution of the electron beam is given by one-dimensional Vlasov equation: $\frac{df}{dt} + v\frac{\partial f}{\partial x} + \frac{q}{m}(E_{SWS} + E_{SC})\frac{\partial f}{\partial v} = 0$, where q is the electron charge, m is the electron mass, $E_{SWS}(x_i)$ is the electrical field due to the SWS and $E_{SC}(x_i)$ is the space-charge field. The solution of Vlasov equation is made with the “Piecewise Parabolic Method” [7] that is based on time splitting of Vlasov equation into two advective equations [8], and on solving successively both equations. This method is fast and conserves positivity and monotonicity of $f(x_i, v_j)$ [9].

Interaction between the beam and the slow-wave structure

$E_{SWS}(x_i)$ is calculated at each time step as a function of the voltages of the equivalent circuit. $E_{SC}(x_i)$ is obtained by solving Poisson’s equation. We use an analytical solution for a one-dimensional discretized beam in a metallic cylinder.

While the electron beam is submitted to electric fields, it induces current in the SWS. This current is induced in the inter-turn capacitances, which are the only parts of the equivalent circuit that are acting on the beam. Shockly-Ramo’s theorem is used to calculate at each time step the variation of the voltage of inter-turn capacitances [10].

Time evolution of the travelling-wave tube

As seen above, the behaviour of a TWT involves several phenomena, and time evolution of each phenomenon is described by an equation. Hence, the whole time evolution is obtained by successive resolution of these equations. This approach is called time splitting.

Some qualitative results

We present here two qualitative simulations. In both simulations the electrons are emitted at the left-hand side of the SWS. In the first case, we inject a continuous beam along with a harmonic signal, and observe in Fig.5 the bunching of the beam. In the second simulation, as seen in Fig.6, we inject a modulated beam and no signal. We then observe the growth and saturation of a signal. Computation time is about 3 minutes on a standard office computer (2GHz, 1Go of RAM).

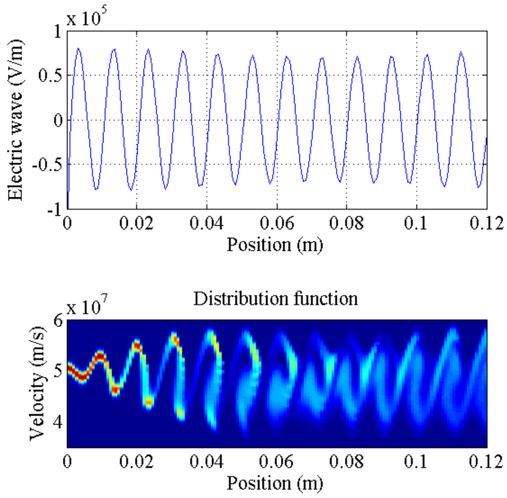

Figure 5 : Signal acting on beam

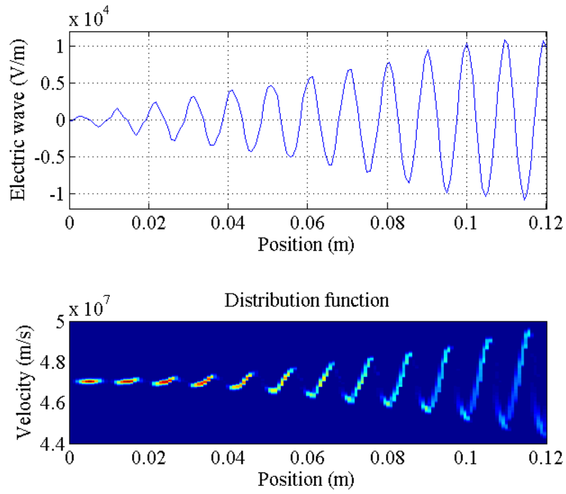

Figure 6 : Beam acting on electric field

Conclusion and perspectives

We suggested a new manner to simulate a travelling-wave tube. Even though this new approach must be improved, it demonstrates that current standard computational resources allow to treat the TWT simulation problem directly in time-domain. The continuation of this work aims to aquire the most reliable time-domain model for the slow-wave structure.

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