COMPUTER SIMULATIONS OF INDUCTIVE OUTPUT TUBES

P. Schütt, A. Skocic, T. Weiland
Darmstadt University of Technology, Germany*

Abstract

An Inductive Output Tube (IOT) differs from a klystron in several aspects which require special treatment in computer simulations. The MAFIA TS2/TS3 codes have been extended accordingly: The port approximation allows the interaction of the bunch with a higher order mode. This is possible because the the port position is no longer fixed to the grid boundary. In order to enable the calculation of the gain of an IOT, it is essential to simulate the emission process at the gated emission gun. Therefore, several new features have been added: to save CPU-time, the time step for the particle path integration is allowed to be a multiple of the field calculation time step, if particles are very slow (speed much lower than c). The space charge limited cathode current may be calculated in a quasi- static mode for fixed potentials. This includes finite thermal initial velocity as well as the varying influence of the anode field on the cathode.

1 INTRODUCTION

In the medium power UHF regime, a new design of RF sources has been used successfully for more than 10 years: the Inductive Output Tube[1]. The basic components are: a gated-emission gun, a resonator (output cavity), and a collector for the spent beam. The gun consists of a cathode and a closely spaced grid. The grid support together with the cathode forms a resonant input cavity which can be used to generate RF voltage at the operating frequency between grid and cathode. A DC bias voltage on the grid shuts off the electrons between bunches and controls the bunch length. The bunched electrons are then accelerated in the anode potential. As they traverse the output resonator gap, they excite the resonator RF and lose energy. The spent beam then enters the collector where the remaining kinetic energy is converted to thermal energy in the collector walls.

Unlike IOTs, conventional klystrons lose some of their design efficiency when they are operated below saturation, because only the RF component of the beam is reduced and not the DC beam current. In contrast to this the cathode current of an IOT is controlled by the drive power.

The goal of our investigations is to analyse whether this IOT concept can be applied to the high power L-Band requirements of TESLA (“TeV Superconducting Linear Accelerator”, DESY)[2]. In order to keep the gun voltage low, we plan to investigate a device with a hollow beam where the output cavity is excited in a higher order mode (HOM), as was suggested by CPI[3, 4].

We plan to use the MAFIA[5, 6] package for the design. This package offers modules for the RF investigation of the resonant cavities as well as Particle-in-Cell (PIC) modules for the self-consistent calculation of the electron motion.

* work supported partly by DFG (Deutsche Forschungsgemeinschaft)

2 EXTENSIONS TO THE PORT APPROXIMATION

In the MAFIA module TS2 (PIC for rotationally symmetric structures), we use the Port Approximation[7] to calculate the steady state of the buncher cavities in a klystron. This method replaces the cavity by a socalled “port” and the mode parameters. At the port, the electric field of the mode is inscribed as a time dependent boundary condition. Amplitude and phase of this field are adjusted to fulfill the steady state condition

$$\begin{aligned} \underline{\hat{u}} &= \underline{Z}\,\underline{\hat{i}}_{ind} \\ \text{with} \quad \underline{Z}(f) &= \frac{R}{Q} \cdot \left(\frac{1}{Q_e} + j\left(\frac{f}{f_0} - \frac{f_0}{f}\right) \right)^{-1} \end{aligned}$$

Here, $\underline{\hat{u}}$ is the complex amplitude of the axis voltage at the mode frequency and $\underline{\hat{i}}_{ind}$ is determined from the power exchange between beam and resonator

$$P(t) = \int_{V_{Cav}} \vec{J}(r,z,t) \cdot \vec{E}_M(r,z)\, dV$$

Usually, the port is located in the cavity gap at the radius of the beam pipe and the calculation is reduced to the beam pipe volume.

For the HOM IOT that we want to design (see figure 1), this approach is not practical. If the whole collector volume is calculated, a port at the mesh boundary lies close to a minimum of the field pattern of the mode. Moreover, in this case, the effect of an amplitude change in the port does not reach the beam fast enough to enable a stable relaxation to steady state.

To improve this, the port approximation was extended to allow an arbitrary port position in the calculation volume. The simulation result shows clearly, that the correct mode is excited at this port. The output power can then easily be determined.

3 THE GATED EMISSION CATHODE

The electron beam in an IOT is produced in a gated emission gun. In order to calculate the gain of the IOT, it is

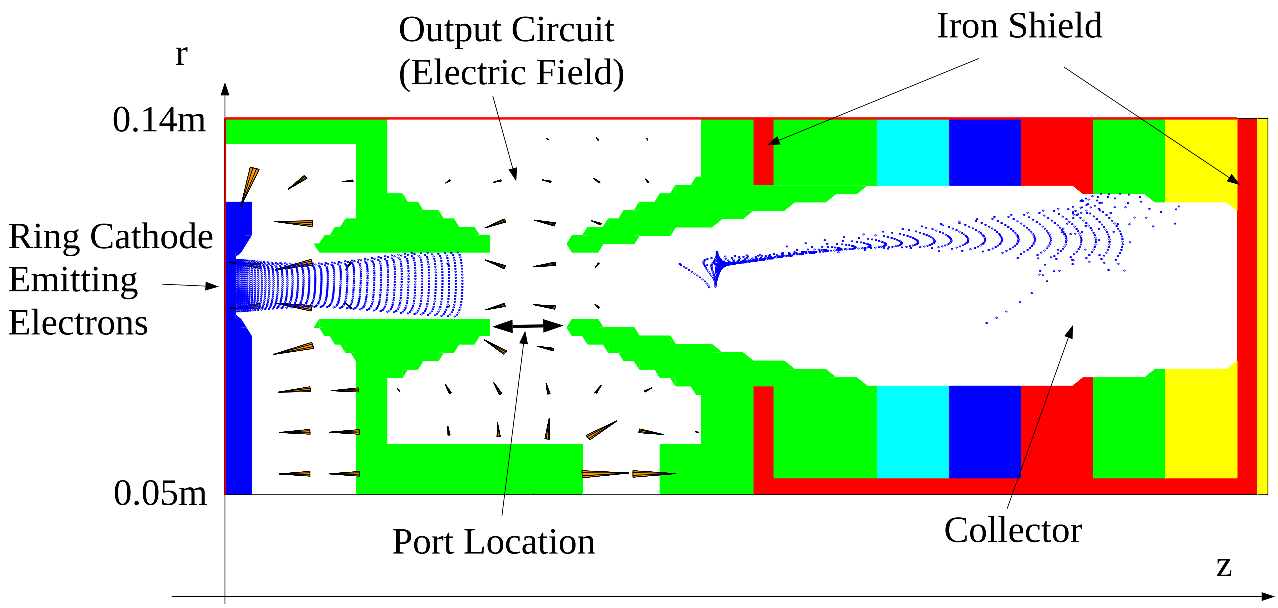

Figure 1: Typical simulation output. Electrons move from left to right. They are emitted from ring cathode. Passing the output cavity, electron bunches excite an RF field in a higher order mode. This is calculated using the port approximation for the indicated port.

essential to calculate this current for a given input power. This requires the correct treatment of the interaction of the beam with the input RF field, i.e. beam loading and space charge limited emission.

3.1 *Slow Particles*

While the saturation current for a given voltage can in most cases be calculated in a quasi-static mode (see 3.2), the voltage itself depends on the time history of the current and therefore is more naturally calculated in time domain. Unfortunately, particles in the region between cathode and grid are usually very slow ($E_{kin} \leq 100\mathrm{V}, \beta \leq 0.002$). This makes the time domain calculation very costly, because in PIC calculations the maximum time step is limited by the CFL criterion for FTDT calculations.

The solution to this problem is to decouple the calculation of the particle pathes from the calculation of the fields. If particles move so slowly that it takes ($n_C =$) several 100 timesteps to cross a mesh cell of the field calculation, then the current produced by those particles (which is the source of the electromagnetic fields) does not have to be updated in every timestep. It is sufficient to update it every m_{pt}'th step ($2 \leq m_{pt} \leq n_C/3$). This means, that the time step for the particle path integration is $m_{pt} * \Delta t$ and the CPU-time needed for the calculation is reduced nearly by the same factor.

3.2 *Electron Gun Space Charge Limited*

Not only for RF sources but also for many other applications, the computer simulation of electron guns is important. In many of those devices, a thermionic cathode emits the electrons. Very often, the cathode works under space charge limited conditions. This means, the current ist determined by the space charge density in front of the cathode. The analytical solution of the space charge distribution and the current is available only for simple geometries like parallel planes or concentric spheres (1d models). The most common models are Child's law and the Langmuir-Fry model.

Space Charge Limited Emission The critical aspect of a model describing current flow in a diode is the emission process of the electrons from the hot cathode. The number of emitted electrons is limited and the initial velocities are spread over a wide range. For space charge limited emission the charge distribution builds a potential minimum in front of the cathode. This causes an electric field which reflects the low energy electrons back to the cathode.

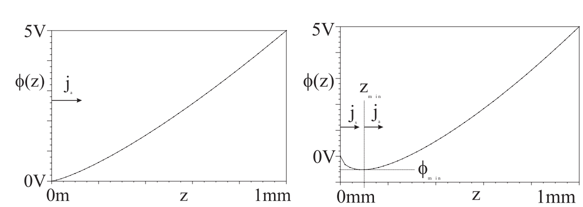

Figure 2: Potential distribution in front of the cathode according to Child's law (left) and the Langmuir-Fry model (right).

The first approach is to assume zero initial velocity and an unlimited number of electrons available on the cathode surface. Under these conditions, the space charge reduces the electric field on the cathode surface to zero. The current is proportional to $U^{3/2}$. This relation is known as Child's law[8] (see figure 2). A more realistic assumption is to describe the initial velocities by a Maxwell distribution. This model was studied by Langmuir-Fry[9, 10]. It includes the possible formation of a potential minimum.

Computer Simulation For the simulation of a gun it is necessary to combine the selfconsistent numerical solution of the electron flow and the analytical current calculation with an adequate emission model. The emission area is divided into a finite number of planes for the local fit to the analytical model. Each plane is associated with a macroparticle representing the emission. The macroparticles are tracked through the gun. Then the Poisson equation is solved. With the new field on the cathode surface, a new current is calculated. This procedure is repeated until convergence is achieved.

Simulation of a Diode For the simulation of a simple diode like a Pierce gun (see figure 3) both models may be applicable. In general, the comparison between the two models shows, that the current predicted by Child's law is always lower than the one given by the Langmuir-Fry model. The difference between the results of the two models is smaller for higher anode potential or, equivalently, for higher current density on the cathode. Hence Child's law

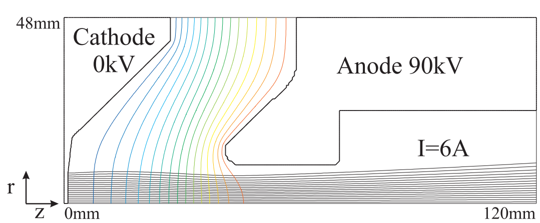

Figure 3: Pierce gun calculated with Child's law. Equipotential lines and particle trajectories are shown.

has its domain for high-voltage, high-current applications, while the Langmuir-Fry model is most usefull for low voltage applications. The limit for the Langmuir-Fry model follows from the achieveable resolution of the grid representaion: It can only be used, when the potential minimum is resolved both in space and in voltage.

Simulation of a Triode A gated emission gun, as it is used for example in the IOT, must be simulated with the Langmuir-Fry model. Figure 4 clearly shows the potential minimum in front of the cathode.

4 SUMMARY

Several new features have been added to the MAFIA TS2/TS3 modules in order to enable the simulation of IOT's. They are useful also for other applications, like electron guns.

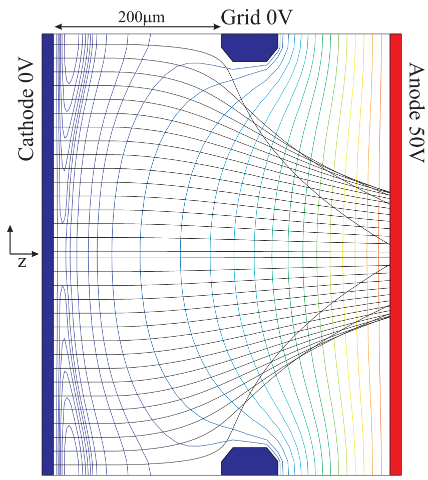

Figure 4: Gated emission gun calculated with the Langmuir-Fry model.

5 REFERENCES

[1] D.H. Preist, M.B. Shrader, *The Klystrode^{TM} — An unusual transmitting tube with potential for UHF-TV* Proc. IEEE 70 (1982)

[2] P. Schütt, T. Weiland, A. Gamp, Lu-Fuhai, *Feasibility Study of a HOM IOT for TESLA*, contrib. PAC 97, Vancouver, Canada, May 1997

[3] H. Bohlen, F. Friedlander, E. Lien *HOM-Klystrons, a possible "low-voltage" solution for high-power pulse applications* contrib. RF 96, Shonan Village, Japan, April 1996

[4] E.Lien, H.Bohlen, US Patent Application Serial No. 08/413,034

[5] T. Weiland, *On the Numerical Solution of Maxwell's Equations and Applications in the Field of Accelerator Physics*, Particle Accelerators, 1984, Vol. 15, S. 245-292

[6] The MAFIA collaboration, *User's Guide MAFIA Version 4.00*, CST GmbH, Lauteschlägerstr. 8, D-64289 Darmstadt, Germany

[7] S. Yu, *Particle-in-Cell Simulation of High Power Klystrons*, September 1984, SLAC/AP-34

[8] C. Child, *Discharge from hot CaO*, Phys. Rev. 32, 1911, p.492

[9] I. Langmuir, *The Effect of Space Charge and Initial Velocities on the Potential Distribution and Thermionic Current Between Parallel Electrodes*, Phys. Rev. 21, 1923, p.419

[10] T.C. Fry, *The Thermionic Current between Parallel Plane Electrodes; Velocities of Emission Distributed according to Maxwell's Law.*, Phys. Rev. 17, 1921, p.441