TWT Beam Transport Design Tools Based on FEM and the Particle Path Approach

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Abstract — This work reports some results from the 2D axisymmetric codes, XMGUN and XMAGUN, based on the Finite Element Method (FEM) and the particle path equation in the design of electron guns, Periodic Permanent Magnets (PPM) and collectors to be used on Traveling-Wave Tubes (TWTs). The XMGUN code was used to model the particle trajectories in an electron gun, a PPM structure and a collector. Using XMGUN a 30 *kV* electron gun, 4.9 *A* and 0.94 µPerv, working under the space charged condition, with grids and control grids and a single stage collector with secondary emission were designed. The radial and longitudinal magnetic fields, in the drift tube, due to a PPM structure, were obtained using the XMAGUN code. These fields are mapped into the first-order finite elements structure data, and XMGUN will be used to determine the particles path.

I. INTRODUCTION

TWT is widely used as high power microwave amplifier in radar, commercial communication and broadcasting systems. In order to reduce design time and development costs and improve a TWT performance, typically with highly complex geometry, simulation codes have been widely used. 2-D gun codes used to model electron guns and collectors are TRACK [1] and XMGUN [2] while 3-D gun codes are MICHELLE [3] and EOS [4].

The XMGUN code was developed to determine the non-relativistic macroparticle trajectories in axis-symmetric: electron gun, drift tube and collector. The macroparticle trajectories were established using the particle path non-linear second-order differential equation instead of the motion equation. The XMAGUN [5] code was used to determine the magnetic field in the drift region due to a PPM structure with or without pole piece. A 0.94 µPerv, 4.9 *A,* 30 *keV* electron gun and a single stage collector, with secondary emission, modeled with XMGUN are presented. The magnetic field due to a PPM structure with five permanent magnets, using the FEM approach with XMAGUN, is also presented.

This work is organized as follows. Section II presents the physical formulation of the path equation and the magnetic field due to a PPM structure, and the simulation results using XMGUN and XMAGUN. Finally, conclusions follow in Section III.

II. PHYSICAL FORMULATION AND SIMULATIONS

A. Particle Path Equation

The particle path equation, in the presence of electric and magnetic fields, under the condition $(v/c)^2 << 1$, is obtained using the energy conservation law and the Busch's theorem. The particle path equation is given by:

$$\frac{d^2 r}{dz^2} = \left[\frac{1 + \left(\frac{dr}{dz} \right)^2}{2Q} \right] \left(\frac{\partial Q}{\partial r} - \frac{\partial Q}{\partial z} \frac{dr}{dz} \right), \tag{1}$$

where Q is the generalized potential:

$$Q = \psi - \frac{\eta}{8\pi^2} \left(\frac{\Phi_M - \Phi_k}{r} \right)^2, \tag{2}$$

where ψ is the scalar potential, η is the electron charge mass ratio, Φ_M and Φ_k are magnetic fluxes evaluated at the surfaces bounded by the circles with radius r_M and r_k respectively. The subscripts M and k denote the present position and the launch position respectively. An in house 4th order Runge-Kutta integrator was used to solve the path equation.

XMGUN was benchmarked against the Pierce parallel diode and current density errors below 1% were found even with a coarse mesh [3].

B. Axial Magnetic Field

The PPM structure shown at Fig.(1) was studied by Santra et al. [8]. The axial magnetic field of an infinite PPM, $0 \le r < r_{f1}$, is [9]

$$B_z(z,r) = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4B_g \sin(n\pi g/L)}{I_0(2n\pi r_{f1}/L)n\pi} \times I_0(2n\pi r/L)\cos(2n\pi r/L) \tag{3}$$

where $B_g = H_d \cdot T/g$ is the magnetic field intensity in the gap separated by the g length, I_0 is the modified Bessel function of the first kind of zeroth order, L is the magnet length . H_d is the magnetizing field determined from the intercept between the load line and the magnetization curve of the magnets used. The load line $K=(T/A)P_t$ is established by calculating all the magnetic circuit permeances P_t [8], where A is the cross-sectional area of the magnet.

C. Simulations

1) *Electron Gun*

Using XMGUN, the electron gun with the geometry presented in Fig. 1 yields 4.9 *A*. This electron gun was modeled with grids and shadow-grid. 1 kV equipotentials and the radial position r_{95} where beam electric current it is 95% of the total electric current are also shown.

2) *PPM Magnetic Field*

Five permanent magnets with the parameters shown at Table I was modeled with XMAGUN. The magnetic field was evaluated at the center of the PPM structure. Although it is not an infinity structure, the magnetic peak at the center was benchmarked against the analytical solution (3) and the

ANSYS [10] simulation. Good agreement [7] was observed for different $r_{ext}=r_3-r_{m2}$, where r_{m2} was kept constant while r_3 varied. The flux lines are presented in Fig. (3).

3) *Single Stage Collector*

A single stage collector with secondary emission due to 16 macroparticles and 1.2 kV equipotentials are presented in Fig. 5. The initial macroparticles energy is, on average, 30 *keV*. The collector was biased with 3 kV.

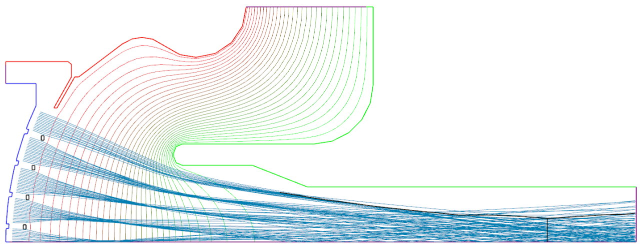

Fig.1. An axially symmetric electron gun with grids and shadow-grids simulation with XMGUN. 1.2 *kV* equipotentials and the r_{95}, the locus that comprises 95% of the total current, are also shown.

TABLE I
PPM GEOMETRY VALUES USED IN XMAGUN SIMULATIONS

Variable	Value	Variable	Value
r_{m1}(mm)	3.5	r_1(mm)	8.7-6.3
r_{m2}(mm)	7.5	tp(mm)	1.3
T(mm)	2.95	g(mm)	2.25
r_{f1}(mm)	1.6	$L/2$(mm)	4.25
r_{f2}(mm)	3.05		

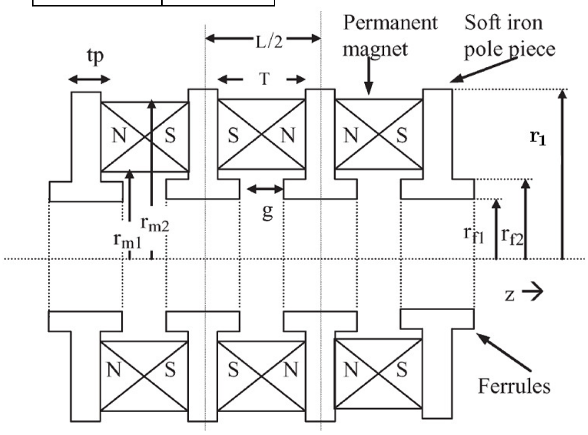

Fig. 2. PPM parameters used on the XMAGUN simulations: magnet inner radius $\mathbf{r_{m1}}$; magnet outer radius $\mathbf{r_{m2}}$; magnet thickness **T**; pole piece inner radius $\mathbf{r_{f1}}$; ferrule outer radius $\mathbf{r_{f2}}$; pole piece outer radius $\mathbf{r_1}$; pole piece thickness $\mathbf{t_p}$; gap length **g**; half magnet period **L/2**.

III. CONCLUSION

The FEM formulation was used to determine the scalar potential and magnetic potential. An in house 4th order Runge-Kutta integrator was use to solve the path equation for the macroparticles in an electron gun with grids and shadow-grids and in a single stage collector with secondary emission. In the center of a PPM structure, with five permanent magnets and pole pieces, the axial magnetic field was benchmarked against the analytical solution and the ANSYS, and as result, good agreement was observed. It is under development ray trace the macroparticles path in a four stage depressed collector, considering secondary emission, and in a PPM structure.

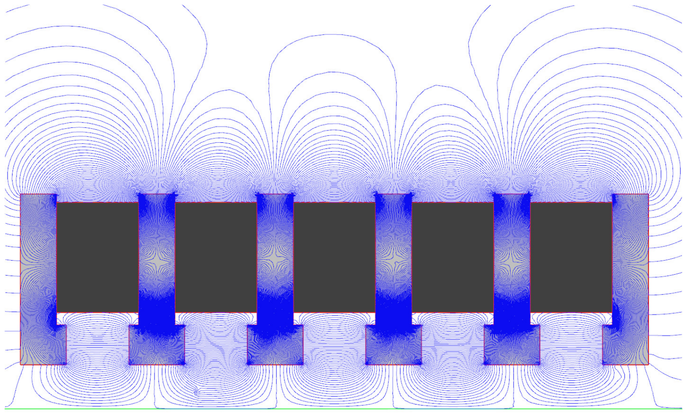

Fig. 3. Magnetic fields produced by a PPM structure with 5 pole pieces modeled with XMAGUN where the model has approximately 22k nodes and 43k elements.

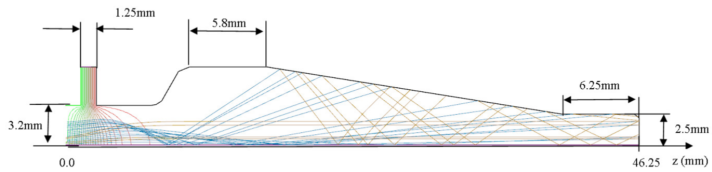

Fig. 4. Primary (blue) and secondary (cyan) electron trajectories on a collector modeled with XMAGUN with approximately 3.1k elements and 1.7k nodes. It's also shown 1.2 *kV* equipotentials.

IV. REFERENCES

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