



Novel simulation method of space charge effects in electron optical systems including emission of electrons



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ABSTRACT

We present a comprehensive numerical method for iterative computation of electron optical systems influenced by space charge which can accurately describe all effects in an optical system, including areas near a cathode tip and all crossovers. We use two different algorithms of evaluating the space charge distribution in different parts of the system. The Monte-Carlo based particle-in-cell method is used in the vicinity of the cathode. The algorithm based on the calculation of the current density distribution from an aberration polynomial is used for the rest of the system. We introduce a re-meshing algorithm which adapts the finite element mesh used for the field calculation in each iteration to the actual space charge distribution to keep it sufficiently fine in all areas with non-zero space charge. The algorithm is finally tested on a design of an experimental electron-welding machine developed at the ISI of the CAS.

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1. Introduction

All electrons in the electron-optical system generally interact with each other. These repulsions affect electron trajectories and the presence of the electrons itself alters the electrostatic field in the system. In many cases it is not computationally feasible to simulate the interaction between each pair of electrons in the beam. The standard approximation uses the concept of space charge based on the collective effect of the beam. The space charge is a charge density distribution corresponding to the actual current density distribution in the system. The space charge distribution influences the electrostatic field in the system, leading to a change in the current density distribution. This process continues until an equilibrium is attained. In a simulation it can be modeled as a self-consistent iterative computation as in previous work made at the ISI of the CAS [1].

The influence of the space charge on individual electrons grows with the total current in the electron beam, and its local maxima are in the areas with high current density, such as crossovers. Another crucial area of the system is the vicinity of the cathode, where the velocity of the electrons is low and the corresponding current density high. The space charge can generate potential barrier around the cathode and limit the emission of electrons, and the total current in the system. The basic computations of this effect are based on the model of the infinite planar diode and leads to the well-known analytical Langmuir-Child law [2] determining

the current density limited by space charge. The electrostatic field can be computed analytically in this simple case too. More complicated geometries, such as spherical diode, were studied later by Kasper in paper [3] and Read and Bowring in paper [4] but no analytical solution for the general curved cathode exists.

For the evaluation of emission limited by space charge three standard approaches are used. First of them is a local application of Child's law on small spatial domains in the vicinity of the cathode surface. This method is commonly used for simulation of Pierce guns [5], but Kasper shows in [3] that it can be inaccurate in the case of thermionic guns with significant potential barrier.

The second approach is based on a local fit of the analytical model. The method was proposed by Weysser in [6] and Porter shows in [7] that it models spherical or cylindrical diodes very accurately. Some important limitations, such as the presumption of non-intersecting trajectories, are still present. A generalized method, applicable for weakly curved cathodes, was proposed by Kasper in [3] or Hawkes in [8], and it is used for example in [1].

The last one of the three methods for the evaluation of space charge limited emission is the Monte-Carlo-based particle-in-cell method originally described by Kang in [9] as counting method which can be easily used to simulate the whole optical system. This method is advantageous for systems with weak space charge effects according to the Kasper's study [3]. Its main disadvantage is a low computational speed. On the other hand it is most straightforward and applicable for any geometry, and its accuracy is easy to control by the number of traced particles. This method is used especially during last years, when the computation power of computers rapidly increases, for example by Iiyoshi [10].

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For the determination of space charge in an electron optical system sufficiently far from the cathode are commonly used the particle-in-cell method [1] and the charge tube method presented by Read in [11]. In the particle in-cell-method, the simulated system is divided into a large set of cells and the time the traced particles spend in each cell is determined. It is necessary to have sufficiently small cells around the crossovers for good results. The formation of a hollow beam in the second iteration caused by a non-realistically high current density in crossovers was described in [1]. Other inaccuracies are caused by cells located in the peripheral regions of a beam not encountering any particles, which generates zero space charge.

The problem with the accuracy in crossovers is improved by the charge tube method, which uses narrow tube cells around the traced trajectories. On the other hand, a huge number of trajectories has to be computed to eliminate the areas with no cells in the wide parts of the beam. Both methods have several empirical parameters, especially the charge-tube method is highly sensitive to the value of the tube diameter.

The other possible method for determination of space charge far from the cathode is proposed in our previous paper [12]. It is based on calculations of the current density from the aberration polynomial described by Oral and Lencová in [13] and its main advantage is strongly improved accuracy. Same authors show that the aberration polynomial calculations can be performed in any part of the system, where trajectory slopes are sufficiently small [14]. This method is not applicable to the whole electron optical system, because trajectories have typically large slopes in the area close to the cathode surface.

The purpose of this paper is to present a comprehensive simulation method applicable to any rotationally symmetric electron optical system modeling all space charge effects with good accuracy and computing time.

2. Simulation algorithm

We divide the simulated electron optical system into two separate parts by some dividing plane perpendicular to the optical axis for our computations. Both of these parts are computed separately by different methods, but in principle, the same self-consistent iterative computational scheme adapted from [1] is utilized.

The process starts with the computation of all fields not influenced by the space charge. After that the process continues with evaluating emission characteristics in front of the dividing plane. The particle-in-cell method is used in this area. We have chosen this method because the power of modern computers is sufficient, so that the heavy computational demands of this method are no longer limiting.

A certain number of iterations is performed until the difference between electrostatic fields in two following iterations is less than a predefined tolerance or the self-consistent loop starts to stagnate. After that the initial conditions in dividing plane and total current in the system are evaluated and another self-consistent iteration loop is started.

In the second self-consistent loop, computing the part of the electron optical system behind the dividing plane, the method based on the evaluation of an aberration polynomial, described in detail in [12], is used. The stopping criterion is the difference between electrostatic fields in two following iterations again. The simplified computational scheme of whole algorithm is shown in Fig. 1.

2.1. Field computations

We use the Galerkin method described for example in Khurshed's monograph [15] with linear shape functions on a gen-

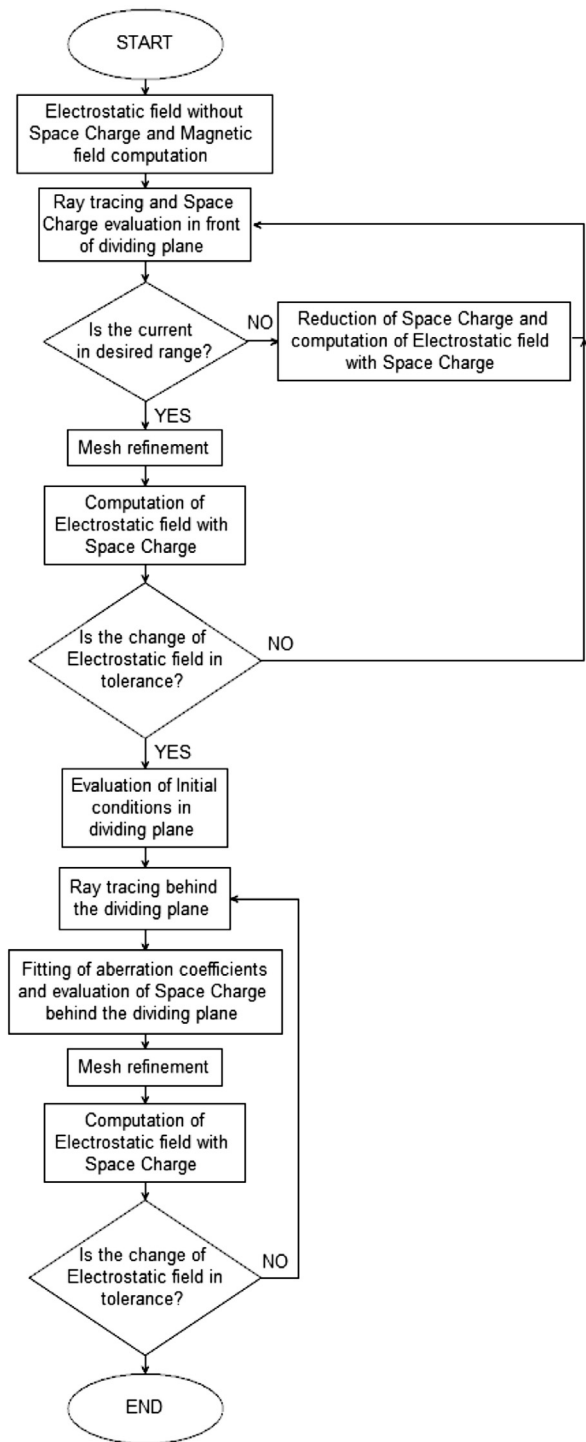


Fig. 1. The simplified computational scheme of the algorithm for computing a field affected by space charge in an entire particle optical system. The process consists of two separate self-consistent loops that operate on different parts of the system using different methods.

eral triangular mesh in cylindrical coordinates for solving the field equations. Modified coordinates $[r^2, z, \varphi]$ which provide a near-axis r^2 correction [15], are used for the final iteration of computation of saturated magnetic lenses.

The near-axis r^2 correction for electrostatic fields was not used for simplicity, but generally it can be added. Possible inaccuracies in field evaluation during tracing near the axis were mitigated by an extremely fine triangular mesh and by the interpolation method which tends to smooth out inaccuracies in the potential values in

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