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OPTIMIZATION DESIGN FOR THE ELECTRON EMISSION SYSTEM USING IMPROVED POWELL METHOD

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Abstract

The electron emission system, which may mostly decide the main properties of the whole electron optical system, is a crucial element for an electron gun. The design of the electron emission system is more important compared with other electron lenses in the electron gun. In this paper, an optimization design method for the electron emission system is presented by using an Improved Powell Method with linear search for the one dimensional search. The optimal structure parameters with a criterion of minimum objective function value for this system are provided. The computed results may show that this direct search optimization method is feasible and useful for the optimal design of the electron emission system as well as other electron optical systems.

Key Words: Electron Optics, Electron Emission System Design, Direct Search Optimization Method, Improved Powell Method

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Introduction

Since the fine electron beam technique is applied widely in modern physics and advanced scientific technology, the optimization design of the electron (ion) optical system has gradually received more attention. Some optimization design methods for searching optimum axial field distribution and then reconstructing the electrode shapes from the optimized axial potential distribution (APD) have been reported [6,7,9,11]. The new progress for the optimum design of electron optical systems based on the optimized APD is that, a novel approach to electron/ion optical synthesis and optimization was presented by M. Szilaygi in recent years [8], in which, the optimum APD's were sought by dynamic programming or optimal control procedures in the form of continuous curves constructed of cubic splines; an effective algorithm was proposed for the reconstuction of the electrodes or polepieces. However, some of these designs have complicated electrode configurations, even some electrodes with complicated curve surface reconstructed from optimized APD are not easy to manufacture. Hence, there is more difficulty in finding reasonably shaped electrodes or polepieces to generate these axial field in these methods [5]. The Direct Search Methods: Simplex and Complex Method, the unconstrained and constrained method, have been proposed for the optimization design of electron (ion) optical systems by the authors in 1982,1984,1987[2-4]. Using these methods, the final optimal structure of an electron optical system can be directly obtained with a criterion of minimum objective function value (e.g. aberration coefficient), so that, these methods without using a reconstruction procedure are better suited than other optimum methods for the optimization design of electron (ion) optical systems. Another direct search method: Hooke-Jeeves's method was proposed as an optimum design method for an *a priori* given multielectrode lens which was used as a high-quality ion optical system by M. Szilagyi and J. Szep in 1988 [10]. It may show that the direct search methods have been gradually used for the optimization design of electron (ion) optical systems.

As we well know, an entire electron optical system (i.e. a complete electron gun) usually consists of two main elements (lenses), an electron emission system (cathode lens) and a main focusing system (focusing lens), in electron beam devices or narrow cathode-ray tubes. The electron emission system is a basic element of an electron gun. Its proper design is decisive as to the quality of an electron beam device or a cathode-ray tube. Because the physical mechanism of electron motion in the electron emission system is more complex, the relations between the characteristic parameters of electron optical properties and the structural parameters cannot be described as a simple function. Especially, the proper objective function and search arguments in the optimization method cannot be decided easily. It causes more difficulty for the optimization design of an electron emission system. For these reasons, the optimization design for the electron emission system which is a crucial element of an electron optical system has hitherto not been studied in details. It is well known that the "triode" structure is mostly selected as a basic structure of an electron emission system. However, the electron optical properties are affected greatly by the choice of the geometrical structure parameters of the electron emission system under the same electric conditions. How to determine the optimal geometrical structure parameters of a "triode" emission system is still an important subject that may decide the main property of a whole electron optical system. In this paper, a physical model is proposed to apply to the optimization design of a "triode" electron emission system as a practical example. The optimal structural parameters of this electron emission system with a criterion of minimum objective function value is presented by using the Improved Powell Method (IPM)– a direct search optimization method.

Optimization Principle and Method

Optimization Model

The Improved Powell Method, an unconstrained optimization method, was used for the optimization design of an emission system in the electron gun. The mathematical programming form of unconstrained optimization problem is

$$\min_{\mathbf{x}\in R^n} f(\mathbf{x}), \tag{1}$$

where $f(\mathbf{x})$ is the objective function defined in the n-dimensional space R^n. $\mathbf{x} = (x_1 \ldots x_n)$ is the search argument vector.

In electron optics, the crossover of electron trajectories in the emission system was usually taken as an object of a main focusing lens in the electron optical system. The size of the electron beam spot at the image plane of a main focusing lens is proportional to the crossover radius r_c formed by electron trajectories in the emission system. It is thus required to minimize r_c in the any particular case. Therefore, the electron properties of the whole electron gun depend on the design of the emission system. A typical "triode" emission system with plane cathode is shown in Fig. 1. It is well known that the crossover radius r_c is varied with the geometrical and electric parameters of an emission system. Especially, under the same electric parameters, the crossover radius r_c depends on the distance d_{km} from the cathode K to the modulation (i.e. grid) electrode M, the distance d_{ma} from the modulation electrode to the acceleration electrode A, and r_m and r_a ,the radii of aperture of the modulation and acceleration electrode, respectively. t_m and t_a are the thicknesses of modulation and acceleration electrode, respectively, in Fig. 1. In most cases, the r_m and r_a are fixed, so the d_{km} and d_{ma} are important factors for minimizing the r_c value.

In the present case, the crossover radius $r_c(\mathbf{x})$ was taken as an objective function. According to the memory size and speed of the computer we used, two geometrical parameters, the d_{km} and d_{ma}, were taken as the search parameters, i.e. the components of search argument vector $\mathbf{x}$ under other fixed parameters. Since the crossover is a minimum section of the electron beam envelope in the emission system, the crossover radius $r_c(\mathbf{x})$ cannot be written in a closed analytical function form. The value $r_c(\mathbf{x})$ can only be determined after completing the calculation of the electrical field and electron trajectories in the emission system space using a general numerical computation method. Thus, the optmization methods based on the derivative calculation of objective function $r_c(\mathbf{x})$, (e.g. Gradient method etc.), cannot be used for the optimization design of the electron emission system. However, the Direct Search Methods can be suited to it. In the Direct Search Methods, it is not necessary to know the functional relation between the objective fuction and search arguments and it needs to calculate only the objective functional value (e.g. r_c in the emission system). The Direct Search Method may be suitable for the optimization design of an electron emission system.

Improved Powell Method

Powell's Method is one of the direct search methods in the optimization method[1]. The Improved Powell Method (IPM) presented in this paper has some advantages: superlinear convergence rate, simple iteration and reasonable results, since all the information of the given or searched points are used for the next optimum search in the IPM. The "Success–Fair Try" method was applied for the linear search in the IPM. It is also an ideal method for a one dimensional linear search.

IPM iterative process. The IPM iterative process is summarized as follows:

(i). Set an initial point $\mathbf{x}^0$ in the n-dimensional space and given $\varepsilon, \eta > 0$;

(ii). For the 1^{st} iteration, k=1, set n indepedent unit vectors $\mathbf{d}_1^1, \mathbf{d}_2^1, \ldots, \mathbf{d}_n^1$ under the condition:

$$|det D_1| = \left|det(\mathbf{d}_1^1, \mathbf{d}_2^1, \cdots, \mathbf{d}_n^1)\right| \geq \varepsilon; \tag{2}$$

(iii). Let $\mathbf{t}_0^k = \mathbf{x}^{k-1}$, make a one–dimensional linear search of the objective function $f(\mathbf{x})$ along the direction $\mathbf{d}_1^k$ and get $\mathbf{t}_1^k$; then, from $\mathbf{t}_1^k$ make a one–dimensional linear search of objective function $f(\mathbf{x})$ along the direction $\mathbf{d}_2^k$ and get $\mathbf{t}_2^k$; $\cdots$; from $\mathbf{t}_{n-1}^k$ make a one–dimensional linear search of objective function $f(\mathbf{x})$ along the direction $\mathbf{d}_n^k$ and get $\mathbf{t}_n^k$, to satisfy

$$f(\mathbf{t}_j^k) = \min_{\lambda}(\mathbf{t}_{j-1}^k + \lambda \mathbf{d}_j^k),$$

$$for \quad 0 \leq j \leq n; \tag{3}$$

(iv). If $\|\mathbf{t}_n^k - \mathbf{t}_0^k\| \leq \eta$,then go to step (vi), else take

$$\mathbf{d}_{n+1}^k = \frac{\mathbf{t}_n^k - \mathbf{t}_0^k}{\|\mathbf{t}_n^k - \mathbf{t}_0^k\|}, \tag{4}$$

and from $\mathbf{t}_n^k$ make a one–dimensional linear search of $f(\mathbf{x})$ along the direction $\mathbf{d}_{n+1}^k$ to get $\mathbf{x}^k$;

(v). Calculate

$$\begin{aligned} |A_m| &= \|\mathbf{t}_m^k - \mathbf{t}_{m-1}^k\| \\ &= \max_{1\leq j\leq n} \|\mathbf{t}_j^k - \mathbf{t}_{j-1}^k\|, \end{aligned} \tag{5}$$

and

$$|det D_{k+1}| = \frac{|A_m|}{\|\mathbf{d}_{n+1}^k\|}|det D_k|; \tag{6}$$

if $|det D_{k+1}| \geq \varepsilon$, then reset new n search directions: take $\mathbf{d}_{n+1}^k$ to replace $\mathbf{d}_m^k$ and fix other search directions, let k=k+1, return to step (ii) to start a new iterative calculation;

if $|det D_{k+1}| < \varepsilon$,then do not change any search direction and let k=k+1, return to step (ii) to start a new iterative calculation;

(vi). End the iterative calculation.

Linear Search Method–"Success–Fair Try" Method. The iterative process of the "Success–Fair Try" is shown in following:

(i). Set $\lambda > 0$, $\beta > 1$, $0 < \alpha < 1$, $\xi > 0$;
(ii). Set initial point $\mathbf{x}^0$ and search direction $\mathbf{d}$;
(iii). Let $\mathbf{x} = \mathbf{x}^0$ and $f_1 = f(\mathbf{x})$;
(iv). Calculate $f_2 = f(\mathbf{x} + \lambda\mathbf{d})$;
(v). If $f_2 < f_1$ then go to step (vi), else go to step (vii);
(vi). Let $\mathbf{x} = \mathbf{x} + \lambda\mathbf{d}$, $f_1 = f_2$ and $\lambda = \beta\lambda$, then go to step (iv);
(vii). If $|\lambda| < \xi$, then go to step (viii), else let $\lambda = -\alpha\lambda$ go to step (iv);
(viii). End the iterative calculation.

The selection of the values of η, ε and ξ depends on the calculating accuracy and the speed and memory size of a computer used.

Determination of The Objective Function Value

As pointed out above, the objective function value, crossover radius r_c, is a radius of the minimum section of electron beam envelope, which is formed by electron trajectories emitted from the cathode in the emission system. Usually, r_c can be determined by 10 electron trajectories emitted from 4 initial points with 3 angles at the effective emitted section of cathode (shown in Fig.2). The emitting radii of 4 initial points are 0,$r_k/3$, $2r_k/3$ and r_k, respectively. r_k is a radius of effective emitted section of cathode which depends on the geometrical and electric parameters of emission system: r_m, r_a, d_{km}, d_{ma} and V_m, V_a. The initial emitted angles are set as $+\theta$, 0 and $-\theta$. In our calculation, $\theta = \pi/4$. Therefore, in order to determine r_c, the electric field and electron trajectories should be calculated under the given boundary conditions, the given geometrical parameters: d_{km}, d_{ma}, r_m and r_a, and the electric parameters: electrode potentials V_m, V_a (cathode potential $V_k = 0V$, the potential of first anode of the main focusing system $V_{a1} = 10kV$).

The r_c value is computed automatically after calculating the electric field and the electron trajectories for the each optimum search process using the curve fitting technique and linear interpolation method.

Calculation of Electric Field and Electron Trajectories

The electric field and electron trajectories were calculated for each optimum search process in the IPM. The calculation method is summarized as follows:

Calculation of electric field. In the emission system, space charge effects cannot be neglected. The evaluation of the electric field is a boundary value problem of a rotationally symmetrical Poisson's equation. The finite difference method with successive overrelaxation was used for the numerical calculation of Poisson's equation. The iterative formulas of the Poisson's equation for calculating the potentials in the space of emission system are given by:

$$V_{i,j} = \left(\frac{1}{a^2} + \frac{1}{b^2}\right)^{-1} \times$$
$$\left\{\frac{V_{i+1,j}}{2a^2} + \frac{V_{i-1,j}}{2a^2} + (1 + \frac{b}{2r})\frac{V_{i,j+1}}{2b^2} + (1 - \frac{b}{2r})\frac{V_{i,j-1}}{2b^2} + \frac{\rho_{i,j}}{2\varepsilon}\right\},$$
$$for \quad r \neq 0, \tag{7}$$

$$V_{i,j} = \left(\frac{1}{a^2} + \frac{2}{b^2}\right)^{-1}\left(\frac{V_{i+1,j}}{2a^2} + \frac{V_{i-1,j}}{2a^2} + \frac{2V_{i,j+1}}{b^2} + \frac{\rho_{i,j}}{2\varepsilon}\right),$$
$$for \quad r = 0. \tag{8}$$

where a and b are the axial and radial steps of rectangular mesh, respectively;(Generally, $a = 0.1d_{km}$ and $b = 0.05$ to $0.08\ r_m$ in the region from cathode K to acceleration electrode A). r is the distance from the axis to the mesh nodal point. $\rho(r,z)$ is the distribution of the space charge density.

The residual error in the overrelaxation iteration is defined as follows:

$$V_w^{(k+1)} = w(V^{(k+1)} - V^{(k)}), \tag{9}$$

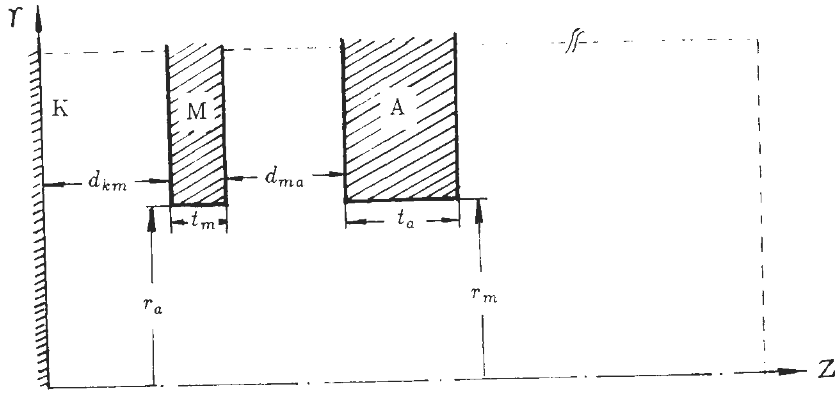

Fig. 1. "Triode" Emission System Structure

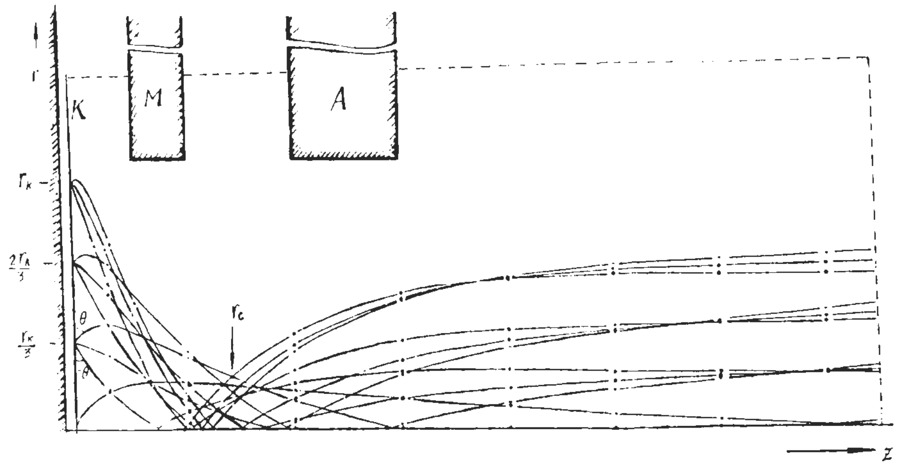

Fig. 2. Electron Trajectories in Emission System

where k is the iteration number and w is an overrelaxation factor. The value w, which depends on the number of mesh nodal points and the iteration calculation order, is a key to the rate of convergence. There is a method for selecting the optimum w value to improve the rate of convergence in our computation program[4].

Calculation of the electron trajectories. The electron trajectories as well as the distribution of the space charge density $\rho(r, z)$ depend on the potential distribution of the electric field. However, the potential distribution of the electric field is affected by the distribution of the space charge density. Therefore, the solution of the Poisson's equation should be a self–consistent solution of the potential distribution $V(r, z)$ that can be obtained by using the normal iterative calculation method.

The Hechtel's Series Method was used for the calculation of the electron trajectories. The initial velocity of the electrons emitted from the thermionic cathode was considered in the calculation of electron trajectories. It is equivalent to about $0.1V$ in the case of oxide-coated thermionic cathode.

Computed Results

In the IPM optimum search process, the search argument vector x has two components: $d_{km} = B$ and $d_{ma} = F$, and the other parameters: r_m,r_a,V_m and V_a are fixed. In our calculation, $r_m = r_a = 0.24\ mm$, $t_m = 0.10mm$, $t_a = 0.20mm$, $V_m = -40V$ and $V_a = 400V$. Thus, this optimization problem for the design of the emission system became a 2-dimensional extreme value problem. We set $\varepsilon = 0.08, \eta = 0.005, \xi = 0.0005, \alpha = 0.4, \beta = 1.5$ and initially $\lambda = 0.01$ in the IPM. In order to avoid the localizations of searching optimum results, the two initial points and directions shown following were taken as the initial conditions for the optimum search :

A. initial point: $\mathbf{x}^0 = (B, F) = (0.10, 0.22)$; initial search directions: $\mathbf{d}_1^1 = (0.707, 0.707)$ and $\mathbf{d}_2^1 = (-0.707, 0.707)$.

The optimum search path is shown in Fig. 3. 46 points listed in Table 1 were searched along the optimum search path in the whole optimum iterative process. In

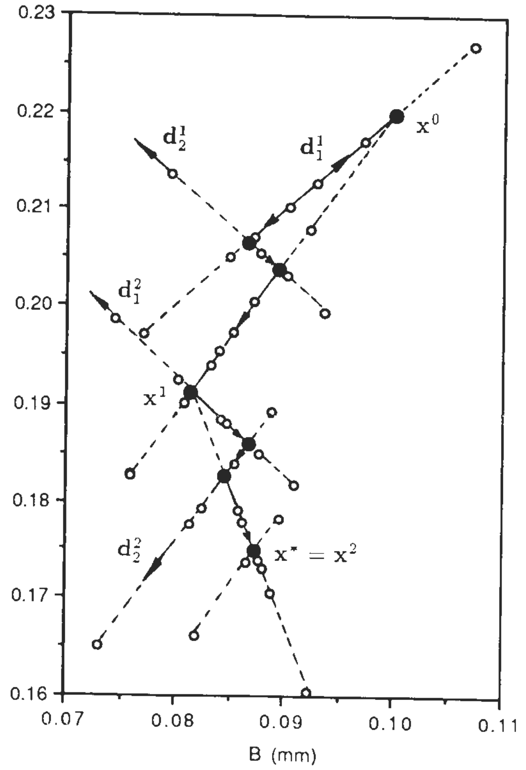

Fig. 3 Optimum Search Path
Initial point (B,F)=(0.10, 0.22)
Initial direction d_1^1 =(0.707, 0.707), d_2^1 =(-0.707,0.707)

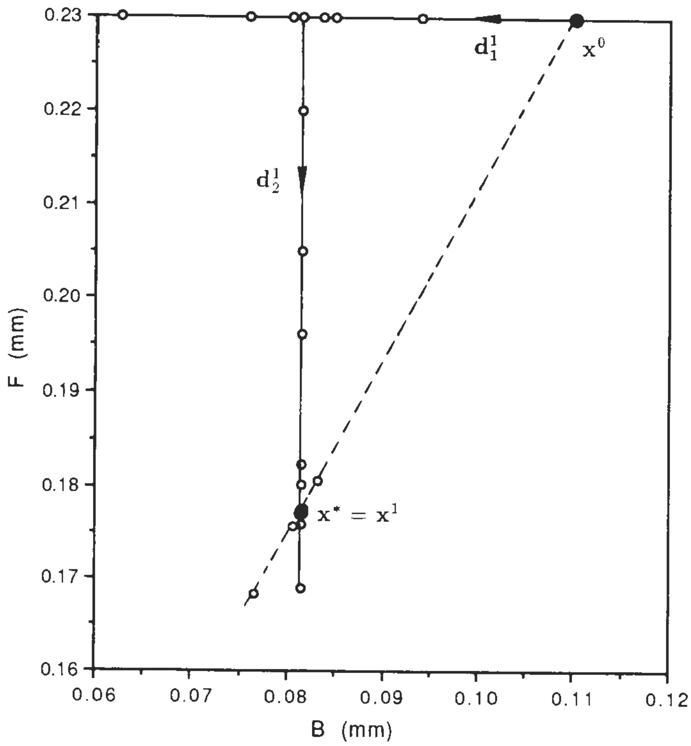

Fig. 4 Second Optimum Search Path
Initial Point (B,F) = (0.11, 0.23)
Initial Direction d_1^1 = (-1, 0), d_2^1 = (0, -1)

Fig. 3, the $\mathbf{d}_1^2$ and $\mathbf{d}_2^2$ are two second search direction vectors, the $\mathbf{x}^* = \mathbf{x}^2 = (B, F) = (0.0873, 0.1749)$ with a minimum objective function value $r_c = 0.0618$ is an optimum point (No. 42 point in Table 1). So the $B = d_{km} = 0.0873$ and $F = d_{ma} = 0.1749$ are the optimum structural parameters under given conditions.

B. initial point: $\mathbf{x}^0 = (B, F) = (0.11, 0.23)$; initial search directions: $\mathbf{d}_1^1 = (-1, 0)$ and $\mathbf{d}_2^1 = (0, -1)$.

The optimum search path is shown in Fig. 4. 24 points listed in Table 2 were searched along the optimum search path. The optimum point $\mathbf{x}^* = \mathbf{x}^1 = (B, F) = (0.0814, 0.1771)$ was obtained through only one time iterative process in the present case (No. 15 point in Table 2). The objective function value r_c is 0.0623 at this optimum point.

Discussion and Conclusions

From the computed results, we can obtain the following conclusions: A. Two optimum points are searched for starting from two different initial points and directions. There is an optimum area around these optimum points in the B and F 2-dimensional search plane. B. Since the locations of two optimum points on the 2-dimensional search plane are more close, it may be sure that the optimum search localizations will be avoided if more than 2 different points and directions are selected for the initial points and search direction in the IPM optimum search process. C. If the $B = 0.0873$ and $F = 0.175$ are selected as the structural parameters d_{km} and d_{ma} of an electron emission system under the same other conditions,the electron beam spot will be decreased about 20% that is verified by measurement of MTF (Modulation Transfer Function) of a model emission system with the optimum d_{km} and d_{ma} in comparison to other parameter values of d_{km} and d_{ma}. D. The optimization model and the decision of the objective function and search argument vector described above are reasonable and the IPM is feasible and useful for the optimization design of the electron emission system as well as other electron optical systems. The "Success–Fair Try" method is also an efficient method for the one dimensional optimum search. E. Generally, the arguments $(x_1 ... x_n)$ of the objective function are the set of all electron optical system parameters that are allowed to vary, and their domain R is bounded by some constraints. If the constraints of the search parameters which depend on the desired technical requirements are put in the IPM, the IPM can be used for a constrained n-dimensional optimization method (in most case, $n > 2$). F. Recently, field emission electron

Table 1. Searched points along 1st Optimum Search Path
Fixed parameters: $r_m=r_a=0.24$, $t_m=0.1$, $t_a=0.2$ (mm),
$V_k=0$, $V_m=-40$, $V_a=400$, $V_{al}=10k$ (V)
Initial point: (B,F)=(0.10, 0.22) Initial directions: $d^1{}_1=(0.707,0.707)$, $d^1{}_2=(-0.707,0.707)$

No.	B	F	r	No.	B	F	r
1	0.1000	0.2200	0.0670	24	0.0743	0.1985	0.0707
2	0.1071	0.2271	0.0729	25	0.0842	0.1886	0.0634
3	0.0972	0.2172	0.0664	26	0.0802	0.1925	0.0608
4	0.0929	0.2129	0.0647	27	0.0867	0.1860	0.0625
5	0.0866	0.2066	0.0640	28	0.0906	0.1818	0.0635
6	0.0770	0.1970	0.0641	29	0.0847	0.1880	0.0627
7	0.0904	0.2104	0.0643	30	0.0877	0.1850	0.0626
8	0.0850	0.2050	0.0643	31	0.0813	0.1776	0.0624
9	0.0872	0.2070	0.0645	32	0.0730	0.1651	0.0656
10	0.0795	0.2136	0.0645	33	0.0845	0.1827	0.0621
11	0.0894	0.2037	0.0637	34	0.0889	0.1894	0.0630
12	0.0936	0.1995	0.0639	35	0.0824	0.1793	0.0626
13	0.0877	0.2054	0.0640	36	0.0854	0.1839	0.0629
14	0.0901	0.2031	0.0638	37	0.0880	0.1730	0.0620
15	0.0840	0.1954	0.0636	38	0.0922	0.1604	0.0604
16	0.0758	0.1828	0.0676	39	0.0859	0.1790	0.0625
17	0.0872	0.2004	0.0634	40	0.0889	0.1705	0.0630
18	0.0921	0.2080	0.0647	41	0.0877	0.1738	0.0619
19	0.0852	0.1974	0.0633	42	0.0873	0.1749	0.0618
20	0.0813	0.1913	0.0628	43	0.0862	0.1778	0.0623
21	0.0758	0.1826	0.0677	44	0.0818	0.1660	0.0653
22	0.0834	0.1940	0.0634	45	0.0895	0.1783	0.0631
23	0.0807	0.1901	0.0633	46	0.0865	0.1736	0.0627

Table 2. Searched points along 2nd Optimum Search Path
Fixed parameters: $r_m=r_a=0.24$, $t_m=0.1$, $t_a=0.2$ (mm),
$V_k=0$, $V_m=-40$, $V_a=400$, $V_{al}=10k$ (V)
Initial point: (B,F)=(0.11, 0.23) Initial directions: $d^1{}_1=(-1,0)$, $d^1{}_2=(0,-1)$

No.	B	F	r	No.	B	F	r
1	0.1100	0.2300	0.0755	13	0.0814	0.1487	0.0673
2	0.1000	0.2300	0.0692	14	0.0814	0.1960	0.0633
3	0.0850	0.2300	0.0651	15	0.0814	0.1771	0.0624
4	0.0625	0.2300	0.0713	16	0.0814	0.1690	0.0672
5	0.0940	0.2300	0.0666	17	0.0814	0.1803	0.0629
6	0.0814	0.2300	0.0646	18	0.0814	0.1758	0.0625
7	0.0760	0.2300	0.0648	19	0.0814	0.1776	0.0625
8	0.0836	0.2300	0.0649	20	0.0766	0.1683	0.0669
9	0.0805	0.2300	0.0648	21	0.0833	0.1806	0.0628
10	0.0814	0.2200	0.0645	22	0.0806	0.1757	0.0634
11	0.0814	0.2050	0.0639	23	0.0817	0.1777	0.0626
12	0.0814	0.1825	0.0630	24	0.0813	0.1769	0.0625

guns have been extensively studied. If some appropriate parameters of the configurations of electrode and/or polepeices are taken as search arguments and constraints, and some optical property parameters are selected as an objective function according to the actual technical requirements, the IPM can be used for the design of the field emission guns (e.g. the best field emission electron guns, in which the field emitting tip is immersed in a strong magnetic field).

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Discussion with Reviewers

J. Chmelik: When you optimize the crossover size the potentials on electrodes are fixed. Why don't you optimize the emission system also with respect to the electrode potentials?

Authors: The geometrical dimensions of the electron emission system (i.e. cathode lens in present case) were fixed after the elements of an electron gun had been assembled. However, the electrode potentials can be adjusted during the electron gun operation. So, the geometrical parameters are usually taken as first one to optimize. If the computer memory size and speed are big and high enough for optimizing multiparameter, you can optimize the emission system also with respect to the electrode potentials.

J. Chmelik: I don't understand equation (6) and the condition for replacing vector $\mathbf{d}_m^k$. Can you explain it more in detail?

Authors: It is a iterating step to establish the new search direction using $\mathbf{d}_{n+1}^k$ to replace $\mathbf{d}_m^k$ for the next search in the IPM optimum search process.

In order to avoid the degeneration of the set of the search direction vectors, $|\det D_{n+1}|$, the value of a determinant of the new search direction vectors set, should be a maximum value. Equation (6) can be derived from the operations of determinant when $\mathbf{d}_m^k$ is substituted by $\mathbf{d}_{n+1}^k$.

J. Chmelik: Why do you think the crossover size r_c is the best function for optimization? Instead of this, I would prefer to optimize for instance some effective emittance.

Authors: There are different objective function to be selected for the different actual technical requirements. In electron optics, the size of the electron beam spot at the image plane of a main focusing lens is proportional to the crossover size r_c. r_c is important characteristic parameter for the purpose which is to generate the smaller spot at image plane in the narrow electron beam devices and cathode-ray tubes. Please refer to the section: "Optimization Principle and Method" in the text of this paper.

J. Chmelik: Which laws of electron emission at the cathode are evaluated?

Authors: The Richardson-Dushman and Child-Langmuir laws are evaluated for the oxide-coated thermionic cathode. It is assumed that a Maxwellian distribution is satisfied for the velocity distribution of electrons emitted from cathode.

J. Chmelik: How do you calculate the space charge density in the beam? How is it determined from the ray tracings and allocated in the mesh points?

Authors: We use the "Charged Clouds-in Cells Method" to calculate the space charge density from the ray tracings and allocate it to the mesh points. Other methods such as "Centralized Current Method" can be used for it also.

J. Chmelik: How do you solve the problem of the extremely steep gradient of the space charge density in front of the cathode and the possible formation of a negative potential minimum?

Authors: In our numerical calculation method, the self-consistent solution of the Poisson's equation of electric field was obtained by using normal iterative method with successive overrelaxation. So the problem of the extremely steep gradient of the space charge density in front of cathode is not a serious problem and it was solved of itself.

T. Mulvey: Can you give any advice at this stage about the general design features of an optimized field emission gun?

Authors: The direct search optimization method presented in this paper is a common method. It can be used for the optimization design of any kind of electron emission system generally. In this paper, we take a triode (cathode lens) as an example to describe optimization method: how to decide an objective function and select the search arguments in electron optics. In principle, the optimization design method for a field emission gun is the same as that of the cathode lens, only the objective function and search arguments, which are defined and selected by desired technical requirements, may be different.

T. Mulvey: In order to make any search procedure effective it must be possible to vary all the relevant design parameters involved. Another crucial point is the choice of the design criterion. This must be simple yet realistic. There must also be a realistic assessment of the computing time required, which may be considerable, to reach a given accuracy. It would appear therefore that one must have adequate computer resources at one's disposal before it becomes worthwhile to embark on a computer search. ... There is no discussion of the minimum computing power that would be needed in a practical case, and how engineering constraints would be incorporated.

Authors: Yes, all of that indicated by T. Mulvey as above are right. Our optimum search procedure was run on the Honeywell DPS-8 computer about 15 minutes to reach the accuracy given in this paper. It can also be run on the IBM80386, even PC/AT. The computing time may be a little large but still considerable.

T. Mulvey: The diameters of a modulator and an anode are not varied during the optimizing, neither are the voltages on the electrodes. This means that only the spacing between cathode and modulator and that between modulator and anode are varied. ... There seems therefore vary little left for the computer to do.

Authors: If one have sufficient computer resources and computer speed is high enough, the relevant design parameters as more as possible must be involved to taken as the search arguments. Although only the d_{km} and d_{ma} are varied during optimizing in the present example according to the memory size and speed of computer we used which is indicated in this paper, other geometrical parameters (diameters of electrodes) are previously chosen based on the technical requirements and CAD results.

The voltages on the electrodes can be varied and optimum voltages can be obtained during the testing of an electron optical system, but the geometrical parameters cannot be changed once the elements of an electron optical system had been assembled. Please refer to the first answer.

T. Mulvey: The criterion to be satisfied is that the radius of the electron crossover should be a minimum. In a practical case this is not necessarily a critical parameter; much will depend on what lenses follow the gun. In addition the crossover radius is not a well defined quantity since the current density distribution depends strongly on the potential of the modulator.

Authors: Yes, what lens follow the gun (cathode lens), i.e. what kind of a main focusing lens, is an important problem for decreasing the size of electron beam spot at image plane of a main focusing. As an example of application of IPM, it is described in this paper that how to determine the optimum geometric parameters of a cathode lens under the same conditions (the same lens follow the gun). It is obvious that decreasing the r_c as far as possible is always important way for decreasing the size of electron beam spot. It has been explained in the text of this paper and answered as above. Of course, the current density distribution depends strongly on the potential of the modulator. In our optimization, the space charge effect and current density distribution were considered in the calculation and definition of the crossover radius.