Article

Received: 25.09.2023
Accepted: 05.12.2023

UDC 537.291

https://doi.org/10.31489/2024PH1/99-105

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Edge field of deflectorplates with expanding screens

Deflector plates consist of two parallel conductive plates that create a deflecting electric field. They can be used to control the flow of charged particles — electrons or ions. The effect of the edge field of deflector plates leads to a change in the velocity of charged particles in the longitudinal and transverse directions, consequently of which their real trajectories change, deviating from ideal ones, which violates the space-time resolution of corpuscular optical devices in which they are used. Apart from that, the electric field at the input to the plates of deflector can vary over time, which must also be taken into account when the deflector diverts the beam of charged particles. Thus, in many cases, the use of deflector plates with open ends is inappropriate, since uncontrolled scattering fields are formed. In this article, we can consider the field of deflector plates with expanded screens at the output, so that deflecting beams of charged particles can be used at the output of deflector plates. Using the methods of the theory of complex variable functions, analytical expressions for the edge field of deflector plates with grounded screens were obtained. Firstly, by grounding the screens and shielding the plates from the deflection field, we can localize the edge electric field and reduce the uncontrolled scattering fields, and secondly, such a field can be accurately calculated analytically.

Keywords: deflector plates, grounded screens, edge field, boundary problem of electrostatics, electron beam control.

Introduction

Deflector plates are two parallel plates that create a deflecting electric field. In their effect on charged particle beams, they are similar to the field of a plate capacitor and used for controlling electron beams in electron beam lithography [1–3], as well as in various electron beam instruments [4–6], and nowadays they have become a significant element in the ultrafast electron microscopy UEM [7–10], where they are used for deflections of the electron beam along the aperture when scanning the sample. All of these apps, a highly important role is played by the spatial and temporal resolution of the electron beam. It is not possible to achieve an increase in the resolution of the scanning beam without taking into account the effect of the edge field of deflection plates on the deflection of the beam of charged particles.

The impact of the edge field leads to a change in the electron velocity in both the transverse and longitudinal directions, hence of which their real trajectory deviates from the ideal one and this leads to a violation of the space-time resolution of KOS. Moreover, the electric field at the entrance to the deflector plates usually depends on time. Therefore, it is necessary to calculate the dynamic properties of the electron beam after its deflection by the deflector.

The influence of edge fields in electromagnetic sectors was first studied in the works [11–13], nevertheless, the results obtained in these works are difficult to apply to parallel deflector plates because unlike electromagnetic sectors the curvature of the electron trajectory in the deflector plates is not a constant value. Besides that, in deflector plates, as already noted, electric fields usually change over time, which also requires additional research.

Note that using the methods of the theory of functions of a complex variable, approximate mathematical formulas were obtained for the edge field of a plate and cylindrical capacitor with open ends [14, 15]. At that moment, it seemed to us that we were the first to consider the edge field of a plate and cylindrical capacitor in this approximation. But when we got acquainted with the work [16], we found in it a reference to the work of Maxwell [17], who obtained formulas for a plate capacitor at the end of the 19th century. So, we have priority only for the approximate description of the cylindrical capacitor field. By the way, in the review work on beautiful fields [16], 3D graphs of the edge fields of plate and cylindrical capacitors are also given. It should also be noted that in [14, 15] an original method of integrating the equations of motion is also proposed, in which the electric potential and the force function are used as independent variables, and new schemes of energy analyzers are calculated using this method [18]. An approximate account of the impact of the edge field on electron beams was made in [19, 20], but these studies cannot be considered exhaustive.

Experimental

Consider the case when expanding grounded screens are located at the outlet of the deflector plates. This case is shown in Figure 1, where the grounded screens form an angle $\alpha\pi$ with the reflex plates in the plane $z = x + iy$. In this figure, deflector plates with potential $\pm\frac{V}{2}$ are represented by thick lines, screens with potential V_0 are thin.

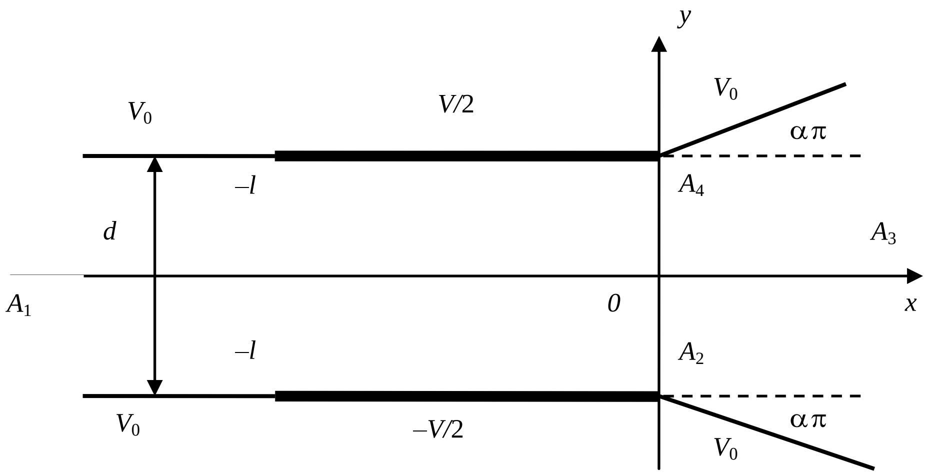
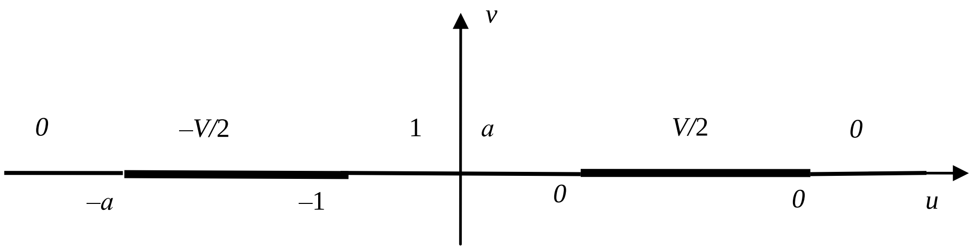


Figure 1. Schematic representation of deflector plates with divergent screens

The mapping of the quadrilateral $A_1 A_2 A_3 A_4$ with two vertices A_1 and A_3 at infinity, shown in Figure 1, to the upper half-plane $w = u + iv$ is carried out by the following conformal Schwarz-Christoffel transformation [21]:

$$z = C\int_{-1}^{w}\frac{(w^2-1)^{\alpha}\,dw}{w^{2\alpha}} + C_1 . \tag{1}$$

Here the following correspondence of the vertices of the quadrilateral to the points of the real axis of the *w*-plane is performed: $A_1 - -\infty$, $A_2 - -1$, $A_3 - 0$, $A_4 - +1$. The boundary value problem in the *w*-plane is shown in Figure 2.



(2)

Figure 2. Boundary value problem in the w -plane

Same as in works [22–24], we will consider that the potential of the screens $V_0 = 0$, and the distance between the conductive plates is equal d . For the distribution of the potential in the *w*-plane, we obtain the following expression:

$$\varphi(u,v) = \frac{V}{2\pi}\left(\operatorname{arctg}\frac{u+1}{v} - \operatorname{arctg}\frac{u+a}{v}\right) + \frac{V}{2\pi}\left(\operatorname{arctg}\frac{u-1}{v} - \operatorname{arctg}\frac{u-a}{v}\right). \tag{3}$$

The value $a>1$ depends on the type of transformation (1), that is, on the value of the angle α and on the length of the deflector plates l.

Results and Discussion

The integral in (1) for rational α is expressed in elementary functions and reduces to the integral of the binomial differential. So, for $\alpha=0$ we come to the case considered in [22–24], and for $\alpha=1$ we get, as in the case of deflector plates without screens:

$$z=\frac{d}{2\pi}\left(e^{w}+w+1\right)+\frac{l}{2}; \quad (4)$$

at $\alpha=1/2$:

$$z=-\frac{d}{\pi}\left[\ln\left(w+\sqrt{w^{2}-1}\right)-\frac{\sqrt{w^{2}-1}}{w}\right]+i\frac{d}{2}; \quad (5)$$

at $\alpha=1/4$:

$$z=\frac{2d}{\pi}\left[\sqrt[4]{w^{2}-1}+\frac{1}{4}\ln\left(\frac{\sqrt[4]{w^{2}-1}-1}{\sqrt[4]{w^{2}-1}+1}\right)-\frac{1}{2}\operatorname{arctg}\sqrt[4]{w^{2}-1}\right]. \quad (6)$$

Differentiating both parts (1) we find partial derivatives:

$$\frac{dz}{dw}=\frac{\partial x}{\partial u}+i\frac{\partial y}{\partial u}=\frac{\partial y}{\partial v}-i\frac{\partial x}{\partial v}=C\frac{(w^{2}-1)^{\alpha}}{w^{1+2\alpha}}. \quad (7)$$

Now we find the inverse partial derivatives $\frac{\partial u}{\partial x}$ and $\frac{\partial u}{\partial y}$, as well as $\frac{\partial v}{\partial x}$ and $\frac{\partial v}{\partial y}$:

$$\frac{\partial u}{\partial x}=\frac{\frac{\partial y}{\partial v}}{\frac{\partial x}{\partial u}\frac{\partial y}{\partial v}-\frac{\partial x}{\partial v}\frac{\partial y}{\partial u}},\quad \frac{\partial u}{\partial y}=\frac{\frac{\partial x}{\partial v}}{\frac{\partial y}{\partial u}\frac{\partial x}{\partial v}-\frac{\partial x}{\partial u}\frac{\partial y}{\partial v}}, \quad (8)$$

$$\frac{\partial v}{\partial x}=\frac{\frac{\partial y}{\partial u}}{\frac{\partial y}{\partial u}\frac{\partial x}{\partial v}-\frac{\partial x}{\partial u}\frac{\partial y}{\partial v}},\quad \frac{\partial v}{\partial y}=\frac{\frac{\partial x}{\partial u}}{\frac{\partial x}{\partial u}\frac{\partial y}{\partial v}-\frac{\partial y}{\partial u}\frac{\partial x}{\partial v}}. \quad (9)$$

To find the field of deflector plates with divergent screens, we write down the following expressions for the derivatives of the potential:

$$\frac{\partial\varphi}{\partial x}=\frac{\partial\varphi}{\partial u}\frac{\partial u}{\partial x}+\frac{\partial\varphi}{\partial v}\frac{\partial v}{\partial x},\quad \frac{\partial\varphi}{\partial y}=\frac{\partial\varphi}{\partial u}\frac{\partial u}{\partial y}+\frac{\partial\varphi}{\partial v}\frac{\partial v}{\partial y}. \quad (10)$$

To create a picture of the electric field lines the differential equation can be numerically integrated:

$$\frac{dx}{dy}=\frac{\frac{\partial\varphi}{\partial x}}{\frac{\partial\varphi}{\partial y}}. \quad (11)$$

Thus, we have built a mathematical model for calculating potentials, as well as for calculating potential derivatives. It can be used to study the dynamics of charged particle beams in deflector plates with expanding screens.

Conclusion

The work considers the edge field of deflector plates with expanding screens. The complexity of the problem is due to the fact that it is impossible to explicitly determine the electrostatic potential as a function of the geometric coordinates of the corpuscular optical system. Therefore, various mathematical techniques are used to overcome this difficulty. Analytical expressions for the potential, taking into account the type of the edge field, are obtained using methods of the theory of functions of a complex variable. The potential distribution in the upper half-plane is also considered. This made it possible to investigate the nature of the edge field of deflector plates with expanding screens. It is shown that the use of grounded shields leads to the localization of the marginal electric field near the edge of the deflector plates. As a result, the use of grounded screens localizes the edge electric field near the edge of the deflector plates, in an area characteristic dimensions of which are of the order of the distance between the plates *d*. Localization of the edge field also reduces the influence of uncontrolled scattering fields, which increases the accuracy of numerical calculations and their correspondence to the real physical situation.

The results obtained in this work can also be used to describe the edge field of magnets with magnetic screens.

Acknowledgments

The work was carried out within the framework of a project with grant funding from the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (IRN AP09258546).

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Кеңейтілген экрандары бар дефлекторлық пластиналардың шеткі өрісі

Дефлекторлық пластиналар — бұл екі параллель өткізгіш пластиналар, олардың көмегімен ауытқитын электр өрісі жасалады. Олар қозғалған бөлшектердің, яғни электрондардың немесе иондардың ағындарын басқару үшін қолданылады. Дефлекторлық пластиналардың шеткі өрісінің әсері зарядталған бөлшектердің жылдамдығының көлденең де, бойлық та өзгеруіне әкеледі, нәтижесінде олардың нақты траекториялары идеалдан ауытқып өзгереді, бұл олар қолданылатын корпускулалық-оптикалық құрылғылардың кеңістіктік-уақыттық ажыратымдылығын бұзады. Сонымен қатар, дефлектор пластиналарының кіреберісіндегі электр өрісі уақыт өте келе өзгеруі мүмкін, сондықтан дефлектормен зарядталған бөлшектер шоғының ауытқыған кезінде ескерілуі қажет. Осылайша, көптеген жағдайларда ашық ұштары бар дефлекторлық пластиналарды қолдану мақсатты емес, өйткені бұл ретте бақыланбайтын шашырау өрістері пайда болады. Мақалада дефлекторлық пластиналардың кеңейтілген экранға шығу кезіндегі өрісі, яғни дефлекторлық пластиналардан шыққан зарядталған бөлшектердің шоғын қолдануға болатындығы қарастырылған. Кешенді айнымалы функциялар теориясының әдістерін қолдана отырып, жерге тұйықталған экрандары бар дефлекторлық пластиналардың шеткі өрісі үшін аналитикалық өрнектер алынды. Біріншіден, экрандарды жерге тұйықтау және плиталардың ауытқу өрісін қорғау арқылы біз шеткі электр өрісін локализациялаймыз және бақыланбайтын шашырау өрістерін басамыз, екіншіден, мұндай өрісті аналитикалық түрде дәл есептеуге болады.

Кілт сөздер: дефлекторлық пластиналар, жерге тұйықталған экрандар, шеткі өріс, электрстатиканың шекаралық есептері, электронды шоқпен басқару.

И.Ф. Спивак-Лавров, С.У. Шарипов, А.Б. Сейтен, А.А. Трубицын

Краевое поле дефлекторных пластин с расширяющимися экранами

Дефлекторные пластины представляют собой две параллельные проводящие пластины, с помощью которых создается отклоняющееся электрическое поле. Используются они для управления потоками заряженных частиц — электронов или ионов. Влияние краевого поля дефлекторных пластин приводит к изменению скорости заряженных частиц как в поперечном, так и в продольном направлении, в результате чего изменяются их реальные траектории, отклоняясь от идеальных, что нарушает пространственно-временное разрешение корпускулярно-оптических устройств, в которых они используются. Кроме того, электрическое поле на входе в пластины дефлектора может изменяться во времени, поэтому этот факт необходимо учитывать при отклонении пучка заряженных частиц дефлектором. Таким образом, во многих ситуациях применение дефлекторных пластин с открытыми торцами оказывается нецелесообразным, так как возникают неконтролируемые поля рассеяния. В настоящей работе мы рассмотрели поле дефлекторных пластин с расширяющимися на выходе экранами, для того чтобы на выходе из дефлекторных пластин можно было использовать расходящийся пучок заряженных частиц. С помощью методов теории функций комплексной переменной получены аналитические выражения для краевого поля дефлекторных пластин с заземленными экранами. Во-первых, заземляя экраны и экранируя отклоняющее поле пластин, мы локализуем краевое электрическое поле и подавляем неконтролируемые поля рассеяния, а во-вторых, такое поле может быть точно рассчитано аналитически.

Ключевые слова: дефлекторные пластины, заземленные экраны, краевое поле, граничная задача электростатики, управление электронным пучком.

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