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**Design and Performance Analysis of an Electrostatic Energy Analyzer  
Based on Multipole-Spherical Fields**

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A design of an electrostatic mirror energy analyzer for the analysis of charged particle beams based on a newly synthesized field is proposed. The electrostatic field of the analyzer is formed as a superposition of an axially symmetric multipole field and a spherical field. The structure of the electrostatic field formed by the superposition of axially symmetric octupole and spherical fields has been investigated. It is shown that varying the parameters determining the contribution of multipole components allows controlling the aberration properties of the electron-optical system. Conditions for compensating for second- and third-order aberrations have been obtained by selecting appropriate values for the weight coefficients of the hexapole and octupole components, which allows for a significant improvement in the focusing properties of the field. Numerical modeling of the electron-optical system and calculation of charged particle trajectories were carried out using the "FOCUS" simulation program. Two regimes of angular focusing were found. The first mode corresponds to second-order angular focusing at a particle input angle of 68°, while the second regime implements third-order focusing at an input angle of 90°. The instrumental functions of the device were constructed, and the relative energy resolutions and luminosities of the analyzer were evaluated. The proposed electron-optical schemes can be used in the development of high-resolution spectrometers for analyzing charged particle beams in space research, as well as spectrographs for the energy-angle analysis of solid surfaces.

*Keywords:* charged particle energy analyzer, multipole approach, electrostatic field, numerical modeling, trajectory analysis

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*Introduction*

Modern research in the fields of plasma physics, space technology, and accelerator technology is closely linked to the task of diagnosing charged particle beams. In outer space, charged particle beams are formed under the influence of complex electromagnetic processes and carry information about the state of plasma, solar activity, and the interaction of magnetospheres with the solar wind. To study them, high-precision instruments capable of measuring the energy characteristics of particles over a wide range of energies are required. One of the key tools used in such studies is an energy analyzer that operates by controlling particle trajectories in electrostatic and magnetic fields [1].

The development of energy analyzers is becoming particularly relevant in the context of expanding space missions and increasing requirements for measurement accuracy. Modern devices must provide high energy resolution, stable operation, and compact dimensions. In addition, the development of numerical modeling methods for electron-optical systems allows the creation of new types of analyzers with improved characteristics.

A number of recent studies have presented various types of energy analyzers, including spherical, cylindrical, and toroidal configurations used for space experiments [2–5]. For example, top-hat analyzers are widely used in space missions due to their wide viewing angle and high sensitivity, which makes them effective for recording particle distributions in three-dimensional space [6, 7]. In addition, specialized devices are being developed to measure the energy spectra of ions and electrons in rarefied plasma conditions, which require high accuracy and resistance to external influences. Thus, the development and study of electrostatic energy analyzers for determining the energy characteristics of charged particle beams is a relevant scientific problem that is important both for fundamental research in plasma physics and for practical applications in accelerator technology and charged particle beams diagnostics.

One perspective direction in the development of charged particle energy analyzers is the use of a multipole approach to synthesize new electrostatic fields. A significant contribution to the development of this approach has been made in [8, 9], where the use of multipole configurations to improve the focusing properties of analyzers is proposed. These studies show that the superposition of multipole fields with axially symmetric electrostatic fields, in particular cylindrical ones, allows the formation of effective focusing systems and increases the energy resolution of electron devices. This approach was further developed in works devoted to multipole-cylindrical field configurations.

In previous studies by the authors, considerable attention was paid to the analysis of electrostatic energy analyzers based on the use of multipole-cylindrical fields. In particular, multipole-cylindrical fields, which are a superposition of multipole and axially symmetric cylindrical fields, have proven effective in forming the focusing properties of the working field of an energy analyzer and controlling the trajectories of charged particles. A number of studies [10–12] have shown that the use of multipole-cylindrical fields can significantly improve the characteristics of energy analyzers by increasing the focusing accuracy and reducing aberrations.

This work proposes a new configuration of an electrostatic field based on the superposition of multipole and spherical fields. Unlike previously studied multipole-cylindrical systems, this configuration has enhanced capabilities for controlling aberrations in the electron-optical system. This allows for significant improvement in the focusing properties of the field and increased efficiency in the energy analysis of charged particle beams.

The aim of this work is to study the theoretical development of an electrostatic energy analyzer based on a field formed by the superposition of multipole and spherical fields, as well as to investigate the focusing properties of the system.

#### *Materials and Methods*

The axially symmetric field  $U(\rho, \xi)$  satisfies Laplace's equation, whose differential operator is the sum of two operators separated by coordinates  $\rho$  and  $\xi$ :  $\Delta = T + \tau$  [8]. In the case of spherical coordinates, operators  $T$  and  $\tau$  are defined by the formulas:

$$\begin{aligned} T &= \frac{d}{d\rho} \left[ (1+\rho)^2 \frac{d}{d\rho} \right]; \\ \tau &= \frac{1}{\sin \theta} \frac{d}{d\theta} \left[ \sin \theta \frac{d}{d\theta} \right]. \end{aligned} \quad (1)$$

Let us introduce a set of functions  $f_n(\rho)$  and  $\varphi_n(s)$ , accepting the following rules for their generation:

$$Tf_n = -f_{n-1}, \quad (2)$$

$$\tau\varphi_n = \varphi_{n-1}, \quad (3)$$

where  $n = 1, 2, 3, \dots$

Solutions to equations  $Tf_0 = 0$ ,  $\tau\varphi_0 = 0$  were used as basic functions.

A function of two variables  $V_n(\rho, s)$ , constructed from elements of sets (2) and (3), is harmonic, i.e., it satisfies the condition  $\Delta V_n = 0$ :

$$V_n(\rho, s) = \varphi_n f_0 + \varphi_{n-1} f_1 + \varphi_{n-2} f_2 + \dots + \varphi_1 f_{n-1} + \varphi_0 f_n = \sum_{m=0}^n \varphi_{n-m} f_m. \quad (4)$$

The coordinate  $s = \theta$  is the azimuth angle in the spherical coordinate system, in the symmetry plane of the field  $\theta = \pi/2$ . The fundamental solution of Laplace's equation in this case is the function  $f_0 = \frac{1}{1+\rho} - 1$ , satisfying the condition  $f_0(0) = 0$  on the sphere  $\rho = 0$ . In accordance with rules (2)–(4) of the spherical quadrupole, hexapole, and octupole fields:

$$U_q(\rho, \theta) = \ln(\sin \theta) + 1 - \ln(1 + \rho) - \frac{1}{1 + \rho}, \quad (5)$$

$$U_h(\rho, \theta) = \left[ 2 - \ln(\sin \theta) \right] \left[ 1 - \frac{1}{1 + \rho} \right] - \ln(1 + \rho) \left[ 1 + \frac{1}{1 + \rho} \right]. \quad (6)$$

$$U_{oct}(\rho, \theta) = \frac{1}{2} \left[ \ln(\sin \theta) \right]^2 - \frac{1}{2} \left[ \ln \left( \tan \frac{\theta}{2} \right) \right]^2 + \left[ \ln(1 + \rho) + \frac{1}{1 + \rho} - 2 \right] \ln(\sin \theta) + \frac{1}{2} \left[ \ln(1 + \rho) \right]^2 - 2 \ln(1 + \rho) - \frac{1}{2(1 + \rho)^2} - \frac{1}{1 + \rho} + \frac{3}{2}. \quad (7)$$

### Results and Discussion

Figure 1 shows the family of equipotentials of the spherical octupole  $U_{oct}(\rho, \theta)$ . For convenience, Cartesian coordinates  $x = (1 + \rho)\sin\theta$ ,  $y = (1 + \rho)\cos\theta$  are used. The figure shows that the field is divided into four regions with potentials of opposite signs. Here, the field is calculated only in one half-plane.

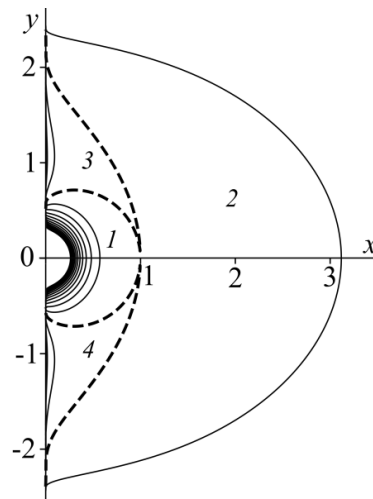


Figure 1. Family of equipotentials of the spherical octupole  $U_{oct}(x, y)$ :  
1, 2 and 3, 4 are regions of potentials of opposite signs

The dynamics of changes in the structure of the electrostatic field formed by the superposition of an axially symmetric octupole and spherical fields has been investigated. Particular attention is paid to the influence of the parameter  $\mu$ , which determines the relative contribution of the spherical component. The potential of the total field, which is a superposition of the spherical octupole (7) and the spherical field

$$U(x, y) = U_{oct}(x, y) + \mu \left[ \frac{1}{\sqrt{x^2 + y^2}} - 1 \right], \quad (8)$$

where  $\mu$  is the coefficient that determines the weight contribution of the spherical field.

The equipotential families of the octupole-spherical field (8), formed by the superposition of an axially symmetric octupole and a spherical field, have been calculated (Figs. 2 and 3).

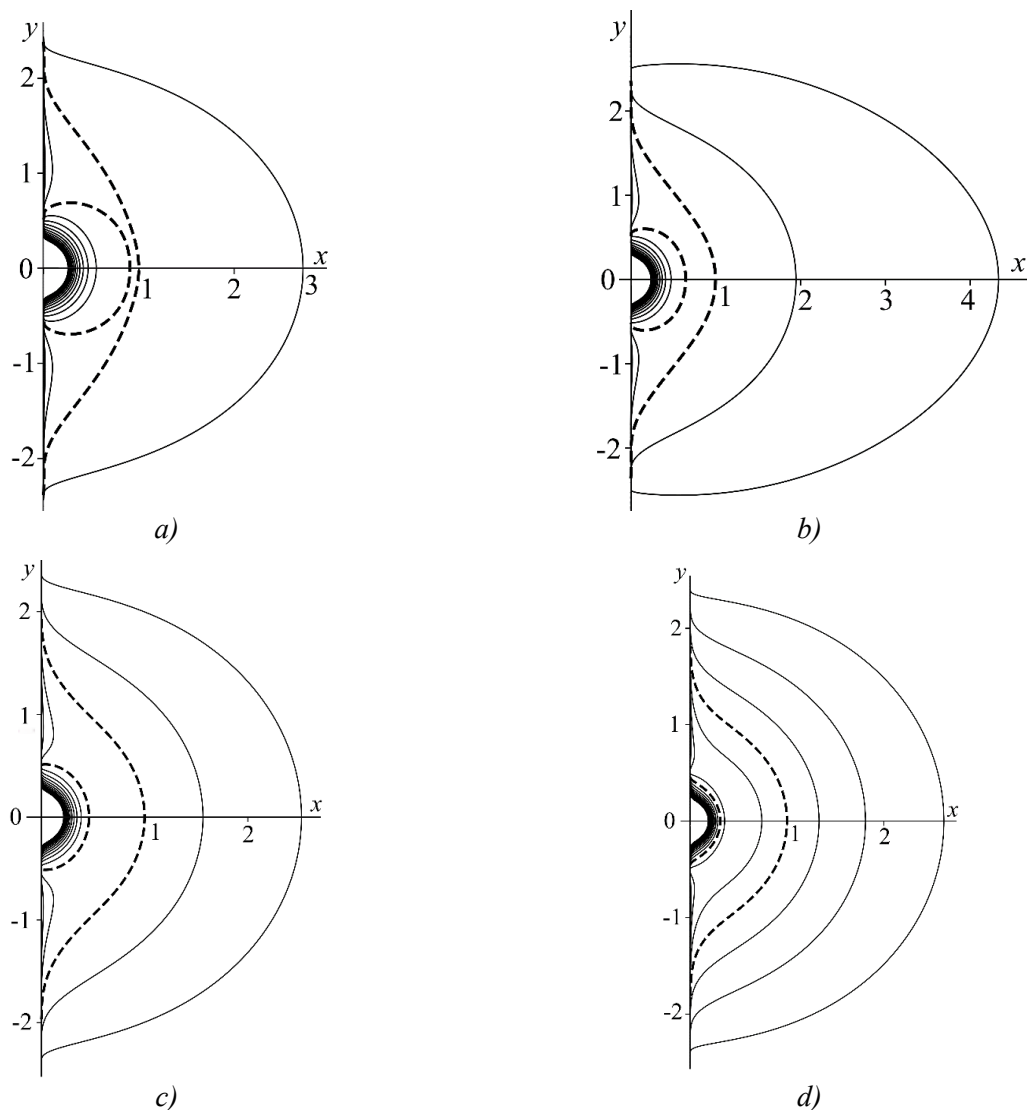


Figure 2. Equipotential octupole-spherical field:  
 $a - \mu = 0.1$ ;  $b - \mu = 0.5$ ;  $c - \mu = 1$ ;  $d - \mu = 1.75$

It has been shown that at low values of the parameter  $\mu$ , the field retains the characteristic features of octupole symmetry. The contribution of the spherical component is perturbative and does not lead to a significant restructuring of the field. It has been established that with an increase in  $\mu$ , the equipotential lines are deformed due to the strengthening of the radially symmetric contribution of the spherical field. In the range of intermediate values of the parameter, a noticeable change in the configuration of equipotential lines is observed, associated with the simultaneous influence of the octupole and spherical components. With a further increase in  $\mu$ , the spherical component begins to dominate, as a result of which the equipotential lines acquire a quasi-radial character, and the octupole structure is almost completely suppressed. Thus, the parameter  $\mu$  determines the nature of the spatial distribution of the potential and ensures the transition from a field with a pronounced angular dependence to a field with predominant radial symmetry.

Unlike the case of positive  $\mu$  values, where the spherical field enhances radial symmetry, negative values (Fig. 3) result in increased non-uniformity of the potential distribution and more complex deformation of the field structure.

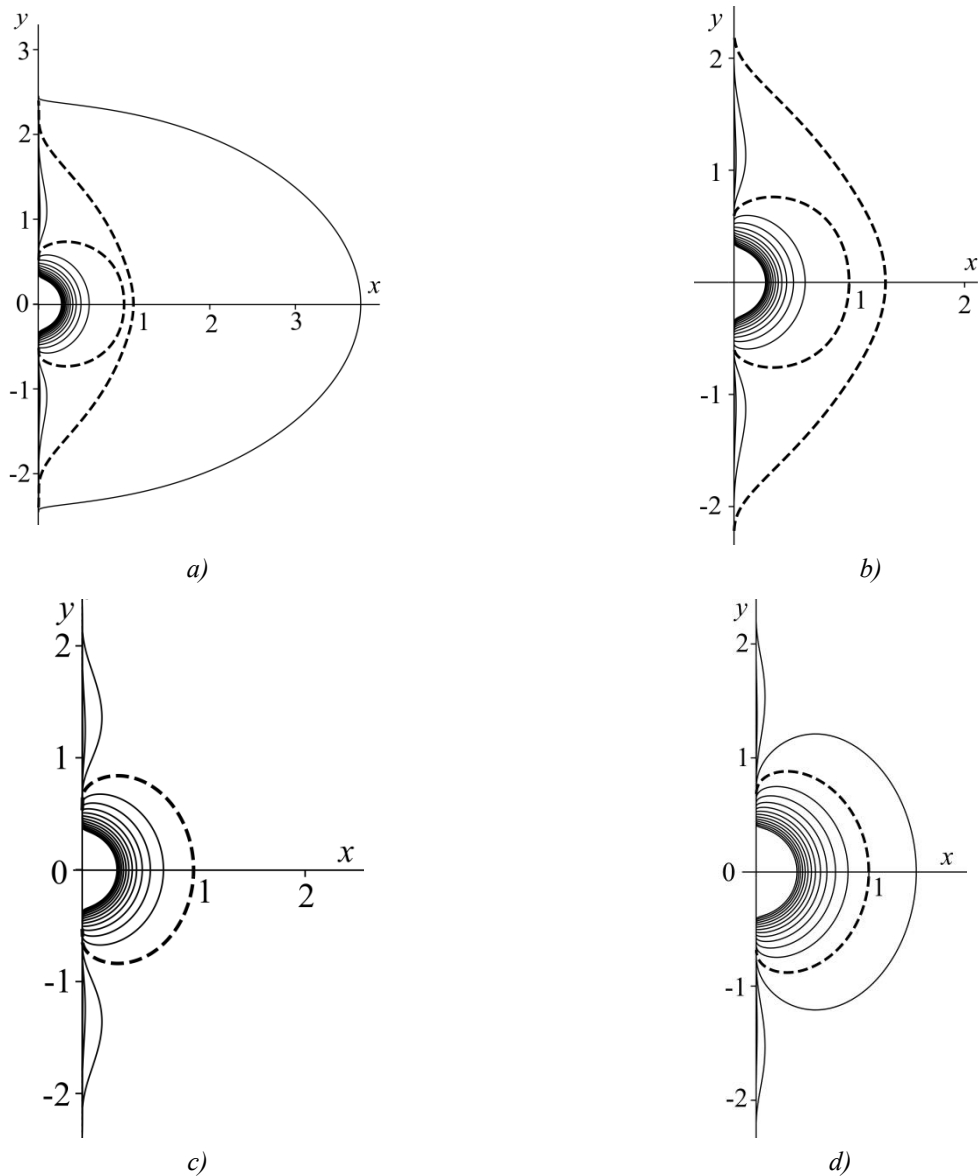


Figure 3. Equipotential octupole-spherical field:  $a - \mu = -0.1$ ;  $b - \mu = -0.5$ ;  $c - \mu = -1$ ;  $d - \mu = -2$

To construct an energy analyzer with specified characteristics, it is necessary to know the field distribution and determine the shape of the deflecting electrodes throughout the entire working volume of the device, which significantly exceeds the localization area of the analyzed beam. The field of the energy analyzer is considered as a superposition of multipoles and a spherical field:

$$\frac{U(\rho, \xi)}{U_0} = g(\rho, \xi) = U_0(\rho, \xi) + qU_q(\rho, \xi) + \beta U_h(\rho, \xi) + \omega U_{oct}(\rho, \xi) + dU_d(\rho, \xi) + \dots, \quad (9)$$

where  $U_0(\rho, \xi)$  is the base field, and  $U_q(\rho, \xi)$ ,  $U_h(\rho, \xi)$ , etc. are components of an axially symmetric multipole field;  $q$ ,  $\beta$ ,  $\omega$ ,  $d$  are the weighting coefficients of the multipole components.

Table 1 shows the values of the decomposition coefficients (9), representing the contribution of each multipole component.

Decomposition coefficients (9) for multipole components

$\varepsilon_i$	Spherical field $1 - \frac{1}{1+\rho}$	Quadrupole $q \frac{\partial U_q}{\partial \rho} \Big _{\rho=0}$	Hexapole $\beta \frac{\partial U_h}{\partial \rho} \Big _{\rho=0}$	Octupole $\omega \frac{\partial U_{oct}}{\partial \rho} \Big _{\rho=0}$
$\varepsilon_1$	-2	-q	0	0
$\varepsilon_2$	3	2q	$-\beta/2$	0
$\varepsilon_3$	-4	-3q	$4\beta/3$	$\omega/6$
$\varepsilon_4$	5	4q	$-29\beta/12$	$-\omega/2$

The data in Table 1 shows that connecting a quadrupole component to the base field affects the parameters of the energy analyzer calculated in the first approximation, connecting a hexapole component affects the parameters starting from the second approximation, and connecting an octupole component affects the parameters starting from the third approximation.

Hexapole and octupole components are added to the basic electrostatic spherical field (quadrupole component is absent):

$$g(\rho, \xi) = 1 - \frac{1}{1+\rho} + \beta U_h + \omega U_{oct}. \quad (10)$$

Image smearing in focus is determined by angular aberrations. With an increase in the angular divergence of the charged particle beam, the greatest contribution to image smearing is made by cubic aberration, which limits the resolution and thus the sensitivity of the device.

The introduction of these multipole components affects the aberration coefficients of the second and higher orders, enabling their targeted control and optimization of the electron-optical characteristics of the system.

The coefficient of quadratic angular aberrations that smear the image of the source in the radial plane is determined by the following formula:

$$A_{II}(\varphi) = -\frac{K}{2\eta^2} [1 - \cos \sqrt{\eta}\varphi] + \frac{1 + \frac{K}{2\eta}}{3\eta} [\cos \sqrt{\eta}\varphi - \cos 2\sqrt{\eta}\varphi], \quad (11)$$

cube aberration coefficient is determined by the following formula:

$$A_{III}(\varphi) = \frac{\pi}{2\eta^2 \sqrt{\eta}} \left[ \frac{1}{3} \left( 4\eta + K + \frac{5K^2}{2\eta} \right) - \frac{3}{4} Q - \eta(1+\eta) - \frac{\eta}{2} \right], \quad (12)$$

where  $\eta = 3 + \varepsilon_1$ ,  $K = 6 + 4\varepsilon_1 + \varepsilon_2$ ,  $Q = 4 + 6\varepsilon_1 + 4\varepsilon_2 + \varepsilon_3$ .

According to Table 1, the decomposition coefficients (9) are:  $\varepsilon_1 = -2$ ,  $\varepsilon_2 = 3 - \frac{\beta}{2}$ ,  $\varepsilon_3 = -4 + \frac{4}{3}\beta + \frac{1}{6}\omega$ .

The weight components  $\beta$  and  $\omega$  are found based on the requirement that the quadratic and cubic aberrations be zero:  $A_{II} = A_{III} = 0$ . It is determined that  $\beta = 3$ ,  $\omega = 3$ . With these values, simultaneous compensation of second- and third-order aberrations is achieved, which improves the focusing properties of the energy analyzer.

In the case of  $\beta = 3$ ,  $\omega = 3$ , the equipotential equation for the following field is obtained:

$$g = \frac{1}{\sqrt{x^2 + y^2}} - 1 + \beta U_h + \omega U_{oct}. \quad (13)$$

Numerical modeling of the electron-optical scheme of an electrostatic mirror energy analyzer was performed, implementing a field configuration in the form of a superposition of multipoles and spherical components. The modeling was performed using the "FOCUS" software package [13], designed to calculate axially symmetric corpuscular-optical systems and analyze the trajectories of charged particles in electrostatic fields.

The geometry of the analyzer's electrode system was determined based on the equipotential surfaces of the field formed by the superposition of multipole and spherical components. An electrostatic field is formed between the electrodes, with a deflecting potential  $U = \text{const}$  applied to the outer electrode. The source of charged particles is located on the axis of the device.

Figure 4 shows the distribution of electrostatic potential in the electron-optical system of the energy analyzer. The field is calculated by numerically determining the potential values at the nodes of the discretized region. For a clear presentation of the results, a color scale is used, in which higher potential values correspond to warm shades, and lower values correspond to cold shades.

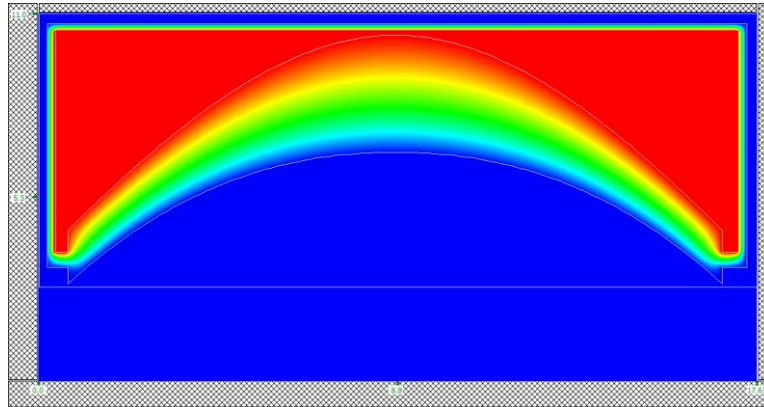
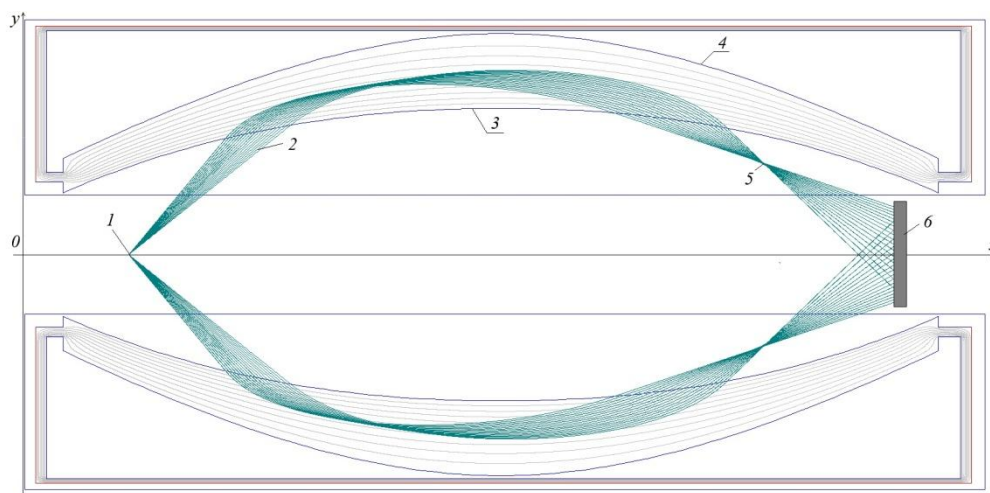


Figure 4. Distribution of the electrostatic field in the electron-optical scheme of an energy analyzer based on an octupole-spherical field

In the first of the operating regimes found, the angle of incidence of the central trajectory is  $68^\circ$ , and the spread of the angle of incidence of the particles relative to the trajectory of the central particle is  $\pm 4^\circ$ . In this regime, the electron-optical scheme implements second-order “axis-ring” type angular focusing: according to the scheme, a beam of charged particles with energy  $E/V = 0.5$  enters the analysis field from a point electron-optical source *1*. As a result of reflection from the field, charged particles are focused into a ring image *5* and enter the detector *6* (Fig. 5). By changing the deflection potential of the upper electrode, we obtain the energy spectrum of particles in the analyzed beam.



*1* — point source; *2* — particle trajectories; *3* — inner electrode;  
*4* — outer deflection electrode; *5* — ring image; *6* — detector

Figure 5. Trajectories of charged particles in an energy analyzer (regime 1, central entrance angle  $68^\circ$ )

The instrumental function of the device  $N(E)$ , characterizing the dependence of the number of registered particles on the relative energy, is shown in Figure 6. The relative energy resolution of the analyzer in this regime is  $\Delta E/E = 2\%$  at a luminosity of  $\Omega/2\pi = 13\%$ .

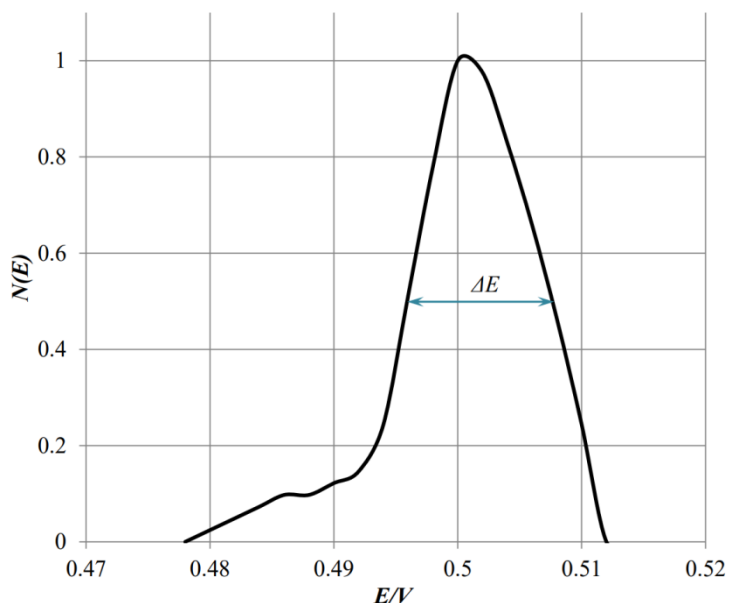
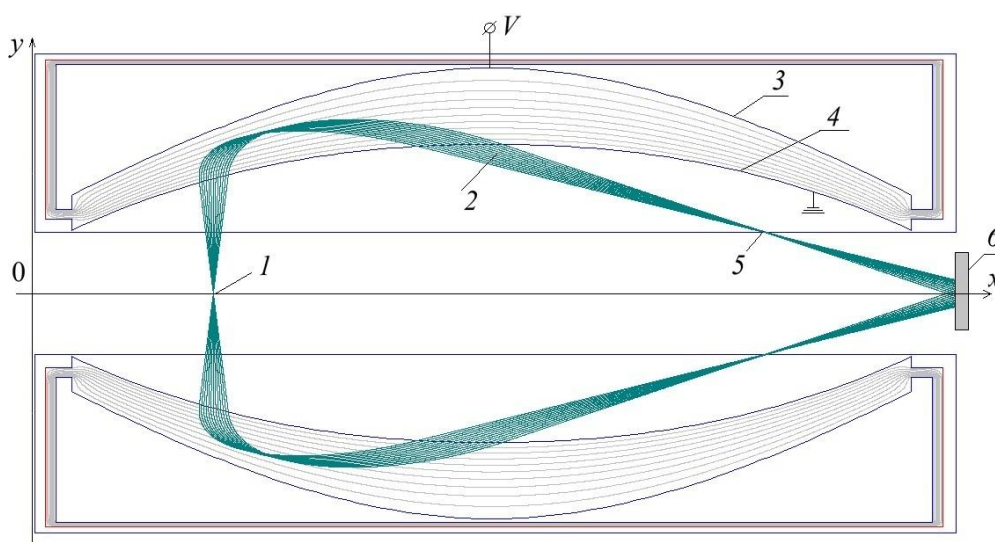


Figure 6. Instrumental function in 2nd order angular focusing regime (regime 1, central entrance angle  $68^\circ$ )

The second operating regime of the analyzer implements third-order angular “axis-ring” type focusing at a particle input angle of  $90^\circ$  (Fig. 7). In this regime, the analyzer operates as follows: a beam of charged particles emerging from a point source  $1$  with a  $180^\circ$  angle of divergence in a plane perpendicular to the symmetry axis and with a  $90^\circ \pm 3^\circ$  angular divergence in the axial plane enters the analyzer field. As a result of reflection from the field, a ring image  $5$  is formed. The equality of the angle of inclination of the axial trajectory  $90^\circ$  at the analyzer input ensures the achromatic mode of the device.



$1$  — point source;  $2$  — particle trajectories;  $3$  — outer deflecting electrode;  $4$  — inner electrode;  $5$  — ring image;  $6$  — detector

Figure 7. Trajectories of charged particles in an energy analyzer (regime 2, input angle  $90^\circ$ )

The instrumental function of the analyzer in this regime is shown in Figure 8. In this focusing regime, the analyzer achieves a relative energy resolution of  $E/\Delta E = 1.8$  at a luminosity of  $\Omega/2\pi = 10\%$ .

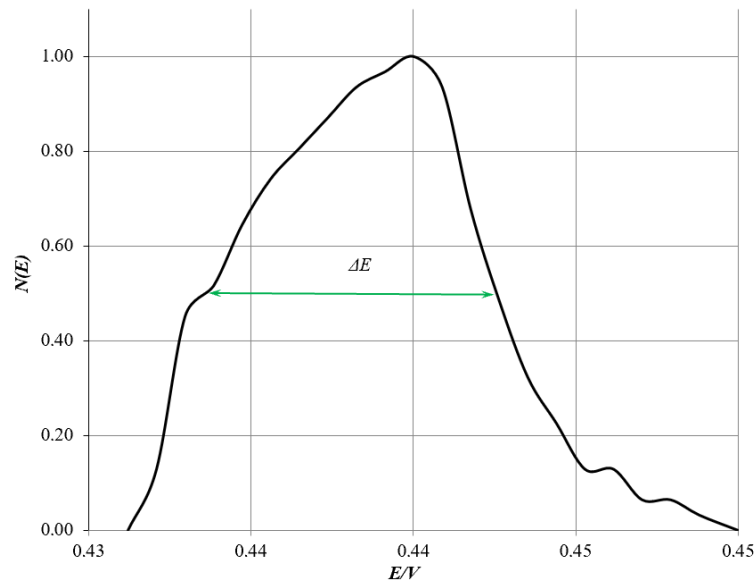


Figure 8. Instrumental function in 3rd order angular focus regime (regime 2, input angle  $90^\circ$ )

This electron-optical scheme is suitable for constructing a spectrograph simultaneously by energy and by the polar angle of particle emission, which is of considerable interest for studying the surface of solids using electron spectroscopy methods.

Thus, profiling the analyzer electrodes in accordance with function (13) is a sufficient condition for compensating for the quadratic and cubic aberrations. This ensures high-order focusing without the introduction of additional corrective elements.

### Conclusion

The structure of the electrostatic field obtained by superposition an axially symmetric octupole and a spherical field has been investigated.

It has been established that in the proposed electrostatic energy analyzer, based on the superposition of a spherical field and multipoles, the selection of coefficients  $\beta$  and  $\omega$ , which determine the weight contributions of the axially symmetric hexapole and octupole, allows controlling second- and third-order aberrations and compensating for angular quadratic and cubic aberrations.

Modeling of electron-optical scheme performed by the “Focus” program confirmed the feasibility of an electron-optical scheme of energy analyzer based on the superposition of axially symmetric multipoles and a spherical field. The proposed electron-optical system implements two independent operating regime: second-order focusing at a central entrance angle of  $68^\circ$  and third-order focusing at an input angle of  $90^\circ$ . The results obtained demonstrate the promise of using the superposition of multipole components and spherical field as a tool for targeted control of the aberration properties of electrostatic mirror analyzers.

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## **Мультипольді-сфералық өрістерге негізделген электрстатикалық энергия талдағыштарды жобалау және оның сипаттамаларын талдау**

Зарядталған бөлшектер шоқтарын талдауға арналған жаңа синтезделген өріс негізінде электрстатикалық айна типті энергия талдағыштың сұлбасы ұсынылды. Энергия талдағыштың электрстатикалық өрісі осьтік симметриялы мультипольдік мен сфералық өрістердің суперпозициясы ретінде қарастырылады. Осьтік симметриялы октуполь және сфералық өрістердің суперпозициясы арқылы қалыптасатын электрстатикалық өрістің құрылымы зерттелді. Мультипольдік құраушылардың үлесін анықтайтын параметрлерді өзгерту электрондық-оптикалық жүйенің абберациялық қасиеттерін басқаруға мүмкіндік беретіні көрсетілді. Гексаполь және октуполь құраушыларының салмақтық коэффициенттерінің сәйкес мәндерін таңдау арқылы екінші және үшінші ретті абберацияларды компенсациялау шарттары алынды, бұл өрістің тоғыстаушы қасиеттерін едәуір жақсартуға мүмкіндік береді. «Focus» сандық бағдарламасының көмегімен электронды-оптикалық жүйеге сандық моделдеу жүргізіліп, зарядталған бөлшектердің қозғалыс траекториялары есептелген. Бұрыштық тоғыстаудың екі режимі анықталды. Бірінші режим бөлшектердің енгізу бұрышы  $68^\circ$  болған кезде екінші ретті бұрыштық тоғыстауға сәйкес келеді, ал екінші режим енгізу бұрышы  $90^\circ$  болғанда үшінші ретті тоғыстауды жүзеге асырады. Құрылғының аппараттық функциялары құрылып, талдағыштың және сұлбаның салыстырмалы энергетикалық ажырату қабілеті мен жарық күші бағаланды. Ұсынылған электрондық-оптикалық сұлбалар ғарыштық зерттеулерде зарядталған бөлшектер ағындарын талдауға арналған жоғары ажыратымдылықты спектрометрлерді және қатты денелер бетінің энергия-бұрыштық талдауына арналған спектрографтарды әзірлеуде қолданылуы мүмкін.

*Кілт сөздер:* зарядталған бөлшектердің энергия талдағыштары, мультипольдік тәсіл, электрстатикалық өріс, модельдеу, траекториялық талдау

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## Проектирование и анализ характеристик электростатического энергоанализатора на основе мультипольно-сферических полей

Предложена схема электростатического зеркального энергоанализатора для анализа пучков заряженных частиц на основе нового синтезированного поля. Электростатическое поле энергоанализатора представляет собой суперпозицию осесимметричного мультиполя и сферического поля. Исследована структура электростатического поля, формируемого суперпозицией осесимметричного октупольного и сферического полей. Показано, что изменение параметров, определяющих вклад мультипольных компонентов, позволяет управлять абберационными свойствами электронно-оптической системы. Получены условия компенсации аббераций второго и третьего порядков за счёт выбора соответствующих значений весовых коэффициентов гексапольной и октупольной составляющих, что позволяет существенно улучшить фокусирующие свойства поля. С помощью программы «Focus» проведено численное моделирование электронно-оптической системы и расчет траекторий движения заряженных частиц. Найдены два режима угловых фокусировок. Первый режим соответствует угловой фокусировке второго порядка при угле ввода частиц  $68^\circ$ , второй режим реализует фокусировку третьего порядка при угле ввода  $90^\circ$ . Построены аппаратные функции прибора, оценены относительные энергетические разрешения и светосилы анализатора. Предложенные электронно-оптические схемы могут быть использованы при разработке высокоразрешающих спектрометров, предназначенных для анализа потоков заряженных частиц в космических исследованиях, и спектрографов для энергоуглового анализа поверхности твердых тел.

*Ключевые слова:* энергоанализатор заряженных частиц, мультипольный подход, электростатическое поле, моделирование, траекторный анализ

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