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DEVELOPMENT OF MIRROR ENERGY ANALYZER BASED ON ELECTROSTATIC QUADRUPOLE-CYLINDRICAL FIELD

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The article is devoted to the development of the mirror energy analyzer based on the electrostatic nonuniform quadrupole-cylindrical field. The motion of charged particles in the quadrupole-cylindrical field is investigated. Focusing properties of the electron-optical scheme of the energy analyzer are determined. The regime of the "ring-ring" type second-order angular focusing is found. The instrumental function of the device is obtained.

Keywords: energy analyzer, quadrupole-cylindrical field, focusing properties, angular focusing, instrumental function.

Introduction

For the investigation of nanostructured objects, one needs an arsenal of physical research methods that are distinguished by a rare combination of nanoscale spatial resolution and ability of elemental and phase analysis. To these methods, first of all, it is necessary to attribute electron spectroscopy. The implementation of methods of electron spectroscopy is based on the use of complex equipment, one of main elements of which is a dispersive energy analyzer of low- and medium-energy electrons.

The electrostatic energy analyzer of charged particles with a cylindrical field has found wide application in view of the high luminosity due to the presence of axial symmetry in the device, as well as the second-order focusing in the expansion beam angle [1]. The disadvantage of the known cylindrical mirror is that the high luminosityof this analyzer is realized only at a small resolution. It is impossible to reach both at the same time. For improve of electron-optical properties, it is necessary to modify the deflecting field by changing the outer electrode shape of the cylindrical mirror and forming the field with axial and radial potential gradients.

The construction method of axially symmetric electrostatic multipoles in coordinate systems, in which the Laplacian is the sum of second-order differential operators separated by coordinates, was first proposed in [2]. Axially symmetric multipoles in cylindrical and spherical coordinates are found. A multipole of different orders (quadrupole, hexapole, sextupole, decapole, etc.) has the symmetry plane perpendicular to the symmetry axis of rotation. On the basis of the superposition of the axially symmetric multipole and the cylindrical field, high luminosity energy analyzers of charged particle beams can be constructed. Energy analyzers based on electrostatic hexapole-cylindrical fields have been investigated quite well, and a large number of works are aimed at studying their electron-optical characteristics and functional capabilities [3-6].

The quasiconic analyzer, representing the new class of electron energy analyzers, was proposed in [7]. The analyzer has an axially symmetric field structure analogous to the cylindrical mirror analyzer, but differing from the latter by the nonuniformity of the field along the symmetry axis. This nonuniformity obeys the following formula:

$$U = \ln r - \left(\frac{r^2}{2} - z^2 \right) \qquad (1)$$

The structure of difference field (1) is close to the quadrupole-cylindrical field. The investigated mirror quadrupole-cylindrical field is constructed on the basis of the superposition of the cylindrical field $\mu \ln r$ and the axially symmetric cylindrical quadrupole:

$$U_q(r,z) = U_0\left(\mu + z\right)\ln r \qquad (2)$$

where μ is the coefficient that determines the weight contribution of the cylindrical field.

The quadrupole-cylindrical field (2) at value $\mu = 1$ coincides with the well-known Wannberg field [8]. The potential of the Wannberg field in the coordinate system *r, z* is described by the following expression

$$U = \frac{V}{\ln \frac{r_1}{r_o}}\left(1 + Az\right)\ln\frac{r}{r_o} \qquad (3)$$

where A is a small dimensionless parameter.

Wannberg numerically found that the analyzer with the proposed modified potential field (3) provides simultaneous focusing in the wide energy range and the focal surface can be approximated to the surface of the inner cylindrical electrode (at $r = r_0$) for energies within 7-16% of the central energy.

The purpose of work is the numerical calculation of the electron-optical parameters of the electrostatic energy analyzer of charged particles with the quadrupole-cylindrical field.

1. Modeling of the electron-optical scheme of the energy analyzer with the quadrupole-cylindrical field

The numerical program “Focus” [9] for modeling the systems of electronic optics was used as the main tool for numerical calculations. Results of the numerical calculation of the electron-optical scheme of the electrostatic energy analyzer of charged particles with the quadrupole-cylindrical field at A = -0.05 are presented below. The profile of the outer deflecting electrode is determined from the calculation of equipotential lines in the quadrupole-cylindrical field. Fig. 1 shows the equipotential portrait of the electrostatic quadrupole-cylindrical field at A = -0.05.

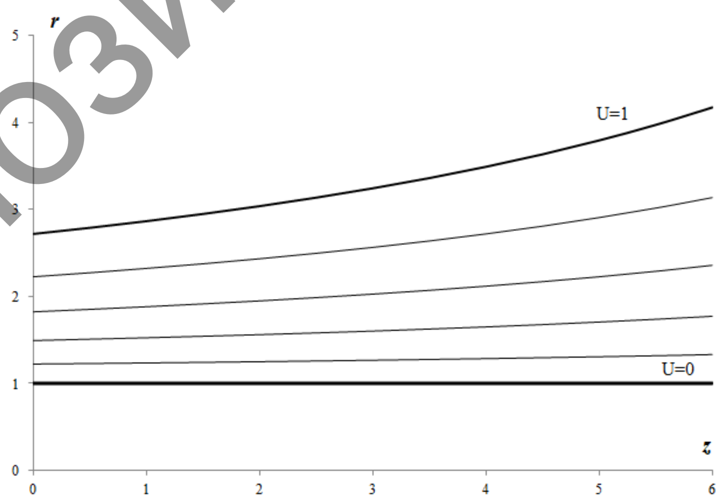

Fig.1. Equipotential portrait of the quadrupole-cylindrical field at A = -0.05

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Radial potentials (in z = 0 section) of the cylindrical and quadrupole-cylindrical fields are shown in Fig.2. As can be seen from the Fig. 2, the quadrupole-cylindrical field is more non-uniform than the cylindrical field.

Fig. 3 shows the axially symmetric construction of the energy analyzer with the quadrupole-cylindrical field at A = -0.05. The field is formed in the space between two axially symmetric coaxial electrodes. The inner cylindrical electrode (radius r_o) is grounded. The outer electrode under the potential Ucreates field nonuniformity and has a curvilinear profile $r = r_o \exp\left[\frac{\ln(r_1/r_o)}{(1+Az)}\right]$.

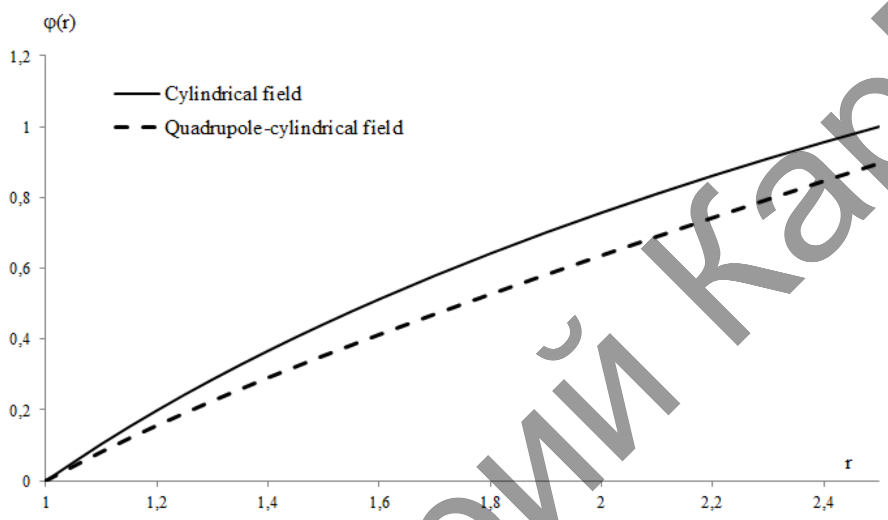

Fig 2. Radial potentials of a cylindrical and quadrupole-cylindrical fields (in the cross section z = 0)

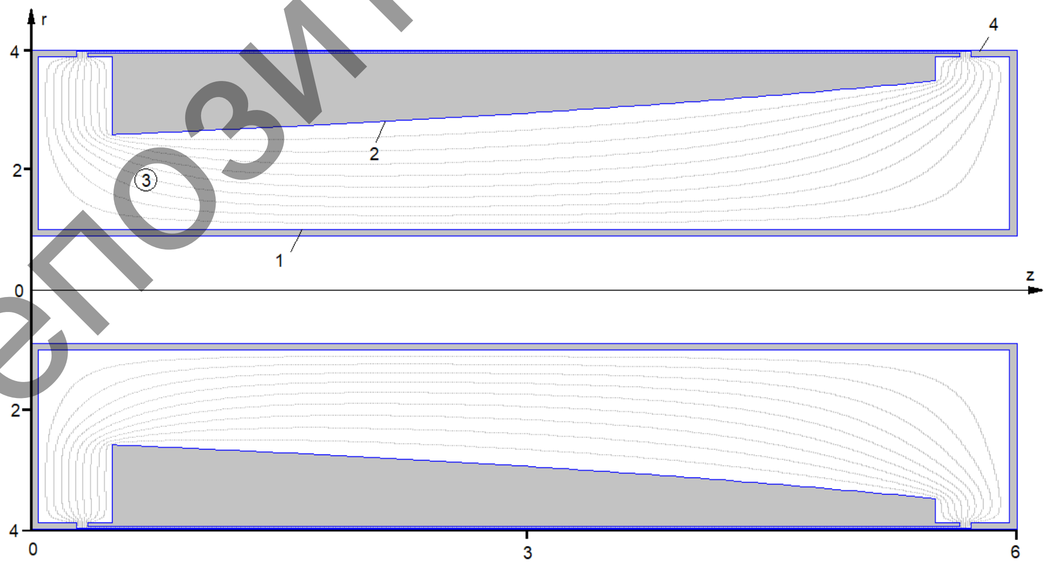

Fig. 3. The meridional cross section of the energy analyzer construction with the quadrupole-cylindrical field at A = -0.05: 1 – theinner grounded cylindrical electrode, 2 – the outer deflecting electrode, having a curvilinear profile, 3- field nonuniformity, 4 - magnetic screen

2. Results and discussion

As can be seen from Fig. 3 in the case A = -0.05, the outer deflecting electrode has the increasing exponential profile. At a small quantity of A = -0.05, the profile of the outer deflecting electrode is well approximated by a cone whose generatric line has a small angle of inclination with respect to the symmetry axis of the mirror equal to ~ 5.4 deg.

Fig. 4 shows the distribution of the electrostatic quadrupole-cylindrical field. Here, calculations of potentials values at the grid nodes of the partitioning region and painting the output field by color are carried out. Each point corresponds to the potential value: the larger the potential, the “warmer” the color.

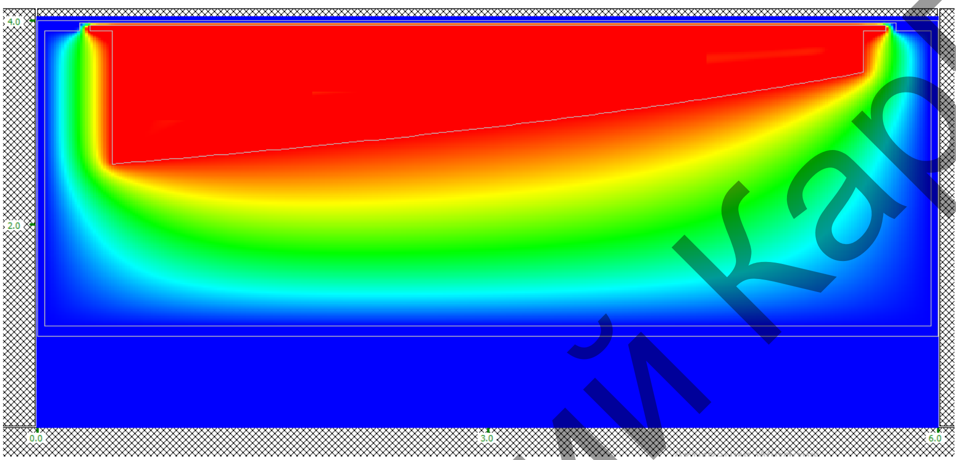

Fig.4. Distribution of the quadrupole-cylindrical field in the energy analyzer

Fig. 5 shows the electron-optical scheme of the energy analyzer with the quadrupole-cylindrical field, which provides the regime of “ring-ring”angular focusing. Range of entrance angles is $\Delta\alpha = 40^0 \pm 5^0$. The relative energy of the particles is E/U=1. The position of the source is x = 0.5; y = 0.25.

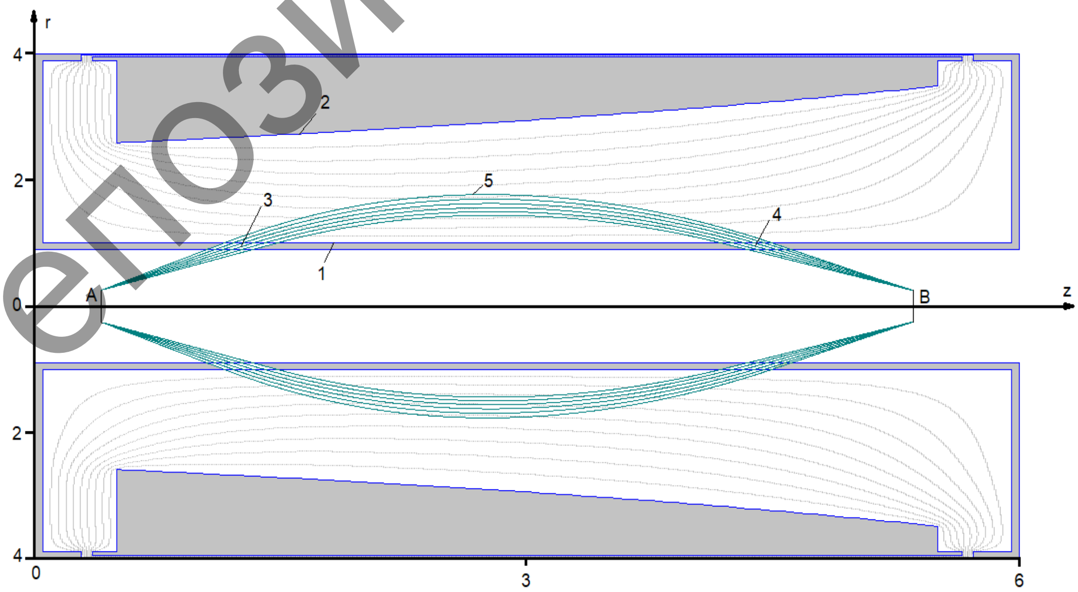

Fig.5. The electron-optical scheme of energy analyzer with the quadrupole-cylindrical field:
1 –the inner grounded cylindrical electrode, 2 –the outer deflecting electrode having curvilinear profile,
3 – ring entrance window, 4 –ring exit window;
A - thin ring source, B - ring image, 5-charged particles beams

Values of distance between the source and its image from the surface of the inner cylindrical electrode, which is considered positive inward from the radius r_o, equal to $\Delta_1 = \Delta_2 = 0.25$. All dimensions are expressed in conventional units. In the energy analysis regime, the charged particle beams comes from the thin ring source *A* and enters into the electric field through the entrance window on the inner cylindrical electrode. The electric field is created by a negative potential on the outer electrode with a curved profile. Further beam passes through the exit ring slit and is focused into the ring image *B*.

Thus, the trajectory analysis of the scheme showed that the design of the energy analyzer based on the quadrupole-cylindrical field has "ring-ring" type second-order angular focusing in the near the central entrance angle of charged particles 39.5^0. The table presents calculation results of focusing properties of the energy analyzer on the basis of the quadrupole-cylindrical field at A = -0.05.

Table - Focusing properties of the energy analyzer on the basis of the quadrupole-cylindrical field at A = -0.05

Focusing type	«ring-ring»
Focusing order	2
Center focusing angle	39.5^0
X coordinate of focusing	5.422
Y coordinate of focusing	0.25
The total length of the electron-optical scheme, $l = L/r_0$	6
Reflection parameter, *P*	1

From results of the trajectory analysis of the system it is also determined that in the energy analyzer with the quadrupole-cylindrical field the condition for focusing line straightening is not realized and its conversion into the spectrograph mode is impossible. This result disproves conclusions aboutconditions for a certain approximation of the focal line to the surface of the inner cylindrical electrode, established numerically by Wannberg in [8]. For evaluation the quality of energy analyze the instrumental function was constructed based on results of the trajectory analysis. Fig.6 shows the instrumentalfunction of the developed device.

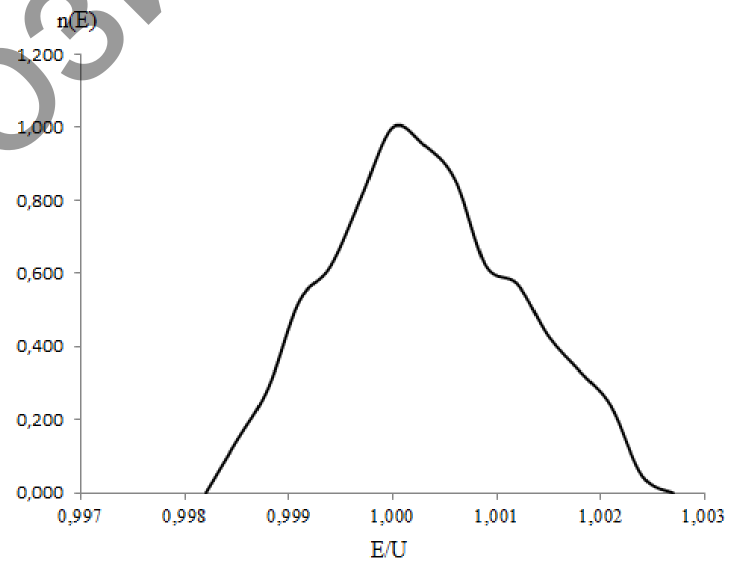

Fig. 6. The instrumental function of the energy analyzer of charged particles with the quadrupole-cylindrical field

From the analysis of the instrumental function of energy analyzer it follows that at luminosity $\Omega/2\pi=\left(\cos 45^0-\cos 35\ \right)\cdot 100\%=11\%$ the relative energy resolution $R=\Delta E/E_0\cdot 100\%=0.2\%$ is provided, where ΔE is the total width of the instrumental function at half-height from its maximum, E_0 is the setting energy of the energy analyzer corresponding to the maximum of the function. Resulting calculated parameters correspond to the optimal case.

Conclusions

The scheme of the energy analyzer based on the electrostatic mirror quadrupole-cylindrical field with the parameter A = -0.05 is investigated. The trajectory analysis of the system is carried out. Focusing properties of the proposed energy analyzer are determined. The second-order angular focusing regime of the “ring-ring” type is found by numerical modeling. The instrumental function of the energy analyzer is calculated. The energy analyzer based on theelectrostatic quadrupole-cylindrical field has a high energy resolution and a high luminosity.

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