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A NOVEL DESIGN OF AN ENERGY ANALYZER FOR CHARGED PARTICLES BASED ON A NON-UNIFORM ELECTROSTATIC FIELD

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Abstract. *A new design for an energy analyzer based on an axial symmetric non-uniform field has been proposed. Using the superposition method of a cylindrical field and second-type axially dodecapole, the electron-optical scheme for the energy analyzer has been developed. Numerical modeling of the electron-optical scheme of the device was performed, and its analytical characteristics were obtained. It is shown that the proposed design combines high resolution and effective luminosity. The results confirm the feasibility of using the developed device for studying charged particle beams in outer space.*

Keywords: energy analyzer, non-uniform field, multipole, modeling, charged particle beams.

1. Introduction

Satellites and spacecraft often encounter systematic effects caused by increased charged particle beams. These adverse radiation effects include single event upsets, anomalous background, increased radiation exposure to astronauts, and premature aging of spacecraft components (computers, detectors, etc.). Current strategies to mitigate these risks include a variety of engineering solutions to address these problems. This also includes a deep understanding of the physical processes that occur during flight and the impact of the environment on the entire spacecraft. Therefore, measurements of the ionizing radiation environment in near-Earth orbit are critical to reducing risks to satellite systems and crewed space missions. Spectrometers began to be used as the main instrument for space research more than half a century ago. The main analytical element of a spectrometer is an analyzer. The operation of all analytical devices is based on the use of the characteristics of charged particle motion in fields created by corresponding electrode systems. One of the main problems and areas of development in energy and mass spectrometry is related to the improvement of electrode systems.

Cylindrical mirror type analyzers are widely used in the study of resonance phenomena in gases, in spectroscopy for chemical analysis, for obtaining spectra of secondary electrons, photoelectrons, and Auger electrons, as well as in space research. The cylindrical mirror analyzer has become a basic element of various electron spectrometers manufactured in countries near and far abroad by leading instrument-making companies [1,2]. Electrostatic analyzers of charged particles, tuned to specific potentials, are classified according to their geometry: cylindrical, spherical, toroidal, and others. They are used to analyze the energy, mass, and angular characteristics of charged particle beams in space plasma. There is a relationship between the geometry of the electrodes that create the electrostatic field and the electron-optical characteristics of the analyzers. These regularities must be taken into account when designing electrostatic analyzers for space experiments.

Modern developments demonstrate a wide range of solutions. In particular, [3] describes a low-energy particle electron instrument built on board the Arase spacecraft (Exploration of energization and Radiation in Geospace). The instrument is designed to measure the three-dimensional electron distribution function in the energy range from 19 eV to 19 keV. The instrument is based on a toroidal top-hat electrostatic energy analyzer. Results show that the instrument works well in space, and the measurement results are good for scientific purposes. In [4], an analyser for deep space and interplanetary missions was developed, capable of registering the flux, composition, and direction of highly penetrating particles in deep space. It is noted that the analyzer can fill a gap in the observation of galactic cosmic rays in the GeV region and provide accurate information on the spectrum, composition and timing of energetic particle emission from the Sun. The authors note its importance for space weather research and radiation safety. In [5], a brief review of three new instruments designed to measure ion composition in the magnetosphere is presented. The authors emphasize that monitoring of ion composition in geosynchronous orbit is not currently performed, and it is an important component for understanding the dynamic space environment in near-Earth space. The focus is on unique methods of measuring ion composition in detector sections located after the electrostatic analyzer. The work [6] presents the results of numerical calculations of a high-resolution analyzer based on a confined cylindrical field designed to study the fluxes of charged particles in outer space. The combination of high energy resolution with high transmittance, simplicity of construction and compactness make this device very promising for space technologies.

The miniaturized device developed in [7] is an electrostatic analyzer with improved geometry. The use of a spiral shape allows to obtain an instrument that is 2.7 times smaller in volume than a conventional cylindrical electrostatic energy analyzer with a comparable input cross section, while improving the energy resolution by 10%. The size reduction is the first step towards miniaturization of such instruments for in situ measurements of space plasma properties. In [8], an instrument was proposed for space plasma physics research capable of measuring the total ion velocity distribution function as well as the velocity distribution function for individual particles with mass per charge (*m/q*). The device consists of a deflecting system, a toroidal energy per charge (*E/q*) analyzer, and a hemispherical condenser that serves either as a second stage *E/q* analyzer or as a controllable time-of-flight velocity filter. The deflector system maintains a full 360 degrees azimuth tilt angle and allows selection of ions for analysis in the toroidal section. Current research is focused on improving electrostatic analyzers, including methods for resolving space plasma components [9], developing a top-hat design with a time gate for measuring low-energy ions 10[], and analytical approaches to modeling new mass spectrometer designs [11].

In works [12,13], a new approach to solving Laplace's equation for the analytical representation of circular multipoles is proposed. This new class of axial symmetric Laplace fields is based on the superposition of a cylindrical field and components of new harmonic functions - circular multipoles. Although a wide range of potential fields has been developed within the multipole approach, research into the effect of these fields on charged particle beams remains of practical interest. To date, the most attention has been paid to analyzers based on hexapole-cylindrical, octupole-cylindrical, and decapole-cylindrical fields [14-16]. Further research should be aimed at identifying optimal combinations of multipole fields that reduce aberrations and increase the efficiency of the devices.

Given the growing demands of modern technologies for the study of charged particle beams, the further development of the theory of energy analyzer focusing is becoming a relevant problem. Of particular importance is the search for electron-optical systems based on new electrostatic fields or combinations of known mirror configurations. In particular, it is necessary to investigate the possibilities of correcting geometric aberrations in deflector energy analyzers by using axial symmetric multipoles. The aim of this work is to develop and study the design of a charged particle energy analyzer based on the superposition of a cylindrical field and a circular dodecapole in order to improve its electron-optical characteristics and energy resolution.

2 Structure of electrostatic multipoles with rotational symmetry

According to [12], the energy analyzer field can be constructed as a superposition of the base field and a set of circular multipoles coaxial with the base field. In the case of an electrostatic deflection field, this construction looks as follows:

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$$g(R,\xi) = \ln R + qU_q(R,\xi) + sU_S(R,\xi) + \omega U_{oct}(R,\xi) + dU_{dec}(R,\xi) + ..., \tag{1}$$

where $\ln R$ is basic cylindrical field, $U_q, U_S, U_{oct}, U_{dec}$ are circular multipoles (quadrupole, hexapole, octupole, decapole, etc., $q, s, \omega, d, ...$ are weight coefficients of multipoles, R, ξ are relative radial and axial coordinates.

The first-type axially dodecapole is described by the following harmonic function:

$$u_{dd}(\rho,\xi) = R^6 - 18R^4\xi^2 + 24R^2\xi^4 - \frac{16}{5}\xi^6, \tag{2}$$

The nodal point (2) is located on the symmetry axis ξ. Figure 1 shows the family of equipotential lines of the first-type axially dodecapole. The dotted lines in this and subsequent figures denote zero equipotential lines.

The second-type axially dodecapole is described by the following function:

$$\tilde{u}_{dd}(R,\xi) = R^6 \ln R - 18\left(\ln R + \frac{1}{3}\right)R^4\xi^2 + 24\left(\ln R + \frac{5}{6}\right)R^2\xi^4 - \frac{16}{5}\left(\ln R + \frac{11}{6}\right)\xi^6, \tag{3}$$

Fig. 2 shows the family of equipotentials of the second-type axially dodecapole. A characteristic feature of this function is the presence of a node point located on the symmetry axis (R=ξ=0). The construction of the family of equipotential lines were carried out using Python package. The zero potential lines converging at the nodes separate regions of opposite sign. As can be seen from Figure 2, unlike the the first-type axially dodecapole, the structure of the second-type function is much more complex. First, there is an additional region (shaded in the figure) isolated from the main zero potential line. Second, there is a saddle point *S* with coordinate R_s in the plane of symmetry. For function (3), this coordinate is R_s = 0.84648, and the potential at this point is -0.06131.

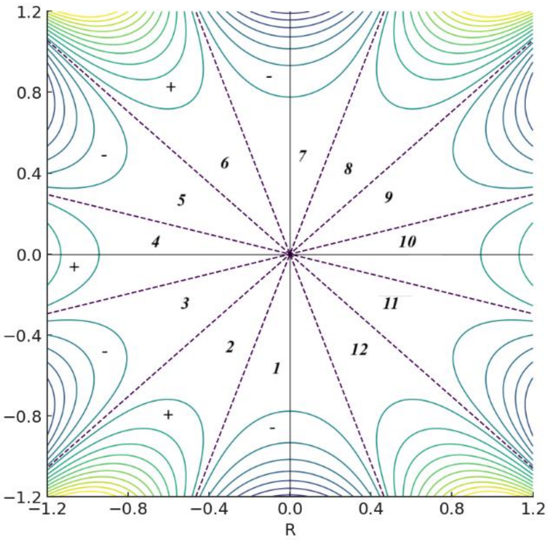

Fig.1. Family of equipotentials of the first-type axially dodecapole

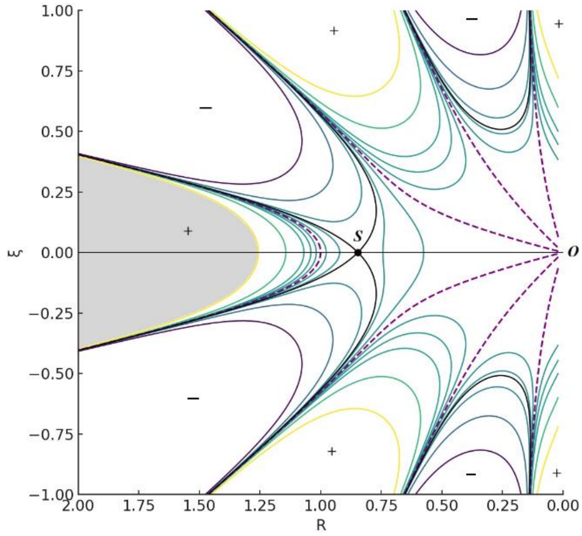

Fig.2. Family of equipotentials of the second-type axially dodecapole

The potential distribution under consideration is defined as a superposition of a logarithmic cylindrical field and the second-type axially dodecapole. It is described by the following expression:

$$U(\rho,\xi) = \omega\,\tilde{u}_{dd}(R,\xi) + \mu \ln R \tag{4}$$

where $\mu \ln R$ is potential of an axial symmetric cylindrical field, μ is coefficient specifying the weight contribution of the cylindrical field, $\tilde{u}_{dd}(\rho,\xi)$ is potential of the second type axially dodecapole, ω is weight contribution of the dodecapole.

Series of Figures 3 and 4 demonstrate families of equipotentials of the total field (4), formed by the superposition of the second type axially dodecapole and a logarithmic cylindrical field. In the series of Fig. 3, the families of equipotentials of the total field are presented for various positive values of the coefficient μ (μ>0) with a constant weighting factor ω=1. At small values of μ, the characteristic sectoral structure of the dodecapole with a pronounced "petal-like" shape of the equipotentials is preserved. The figures illustrate how, with increasing μ, the composite field gradually transforms from the dodecapole case (μ=0, Fig. 2) into a distribution approaching the cylindrical configuration.

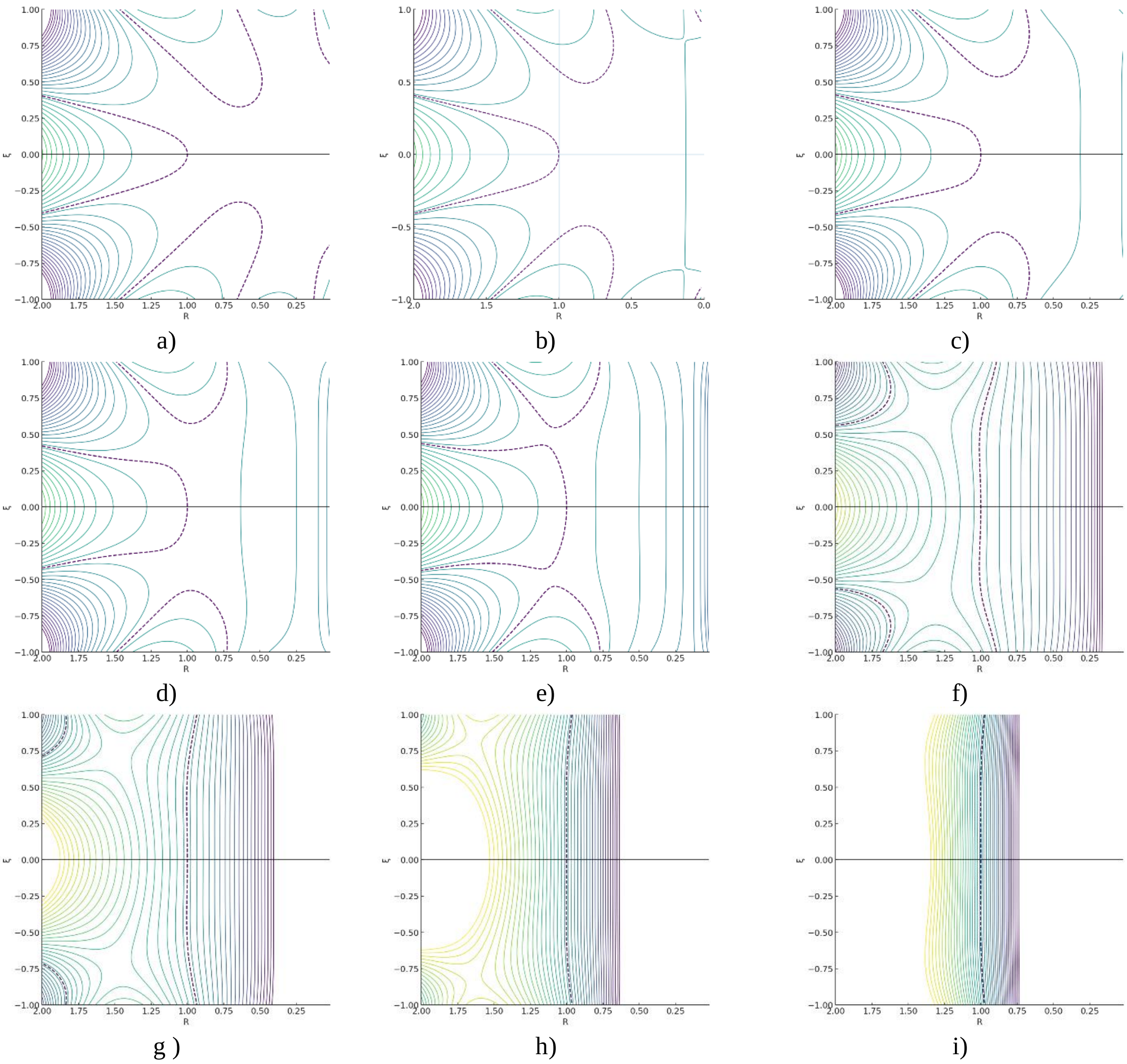

Fig. 3. Family of equipotentials of the total field $U(\rho,\xi)=\omega u_{dd}(R,\xi)+\mu\ln R$ for various values of the coefficient μ (μ>0), a constant weighting factor ω=1: a) μ=0.1; b) μ=1; c) μ=2, d) μ=5, e) μ= 10; f) μ= 50; g) μ= 100; h) μ= 200; i) μ= 300.

In the series of Figures 4, the families of equipotentials of the total field are presented for various negative values of the coefficient μ (μ<0) with a constant weighting factor of the dodecapole field ω=1. For negative values of μ, the transformation of the composite field occurs in a "mirror-like" manner relative to the case of positive μ. At small absolute values of μ, the characteristic dodecapole structure with a clearly defined "petal-like" form of the equipotentials is preserved. As |μ| increases, the cylindrical component becomes fully dominant, and the configuration of the equipotentials of the composite field approaches that of a cylindrical distribution.

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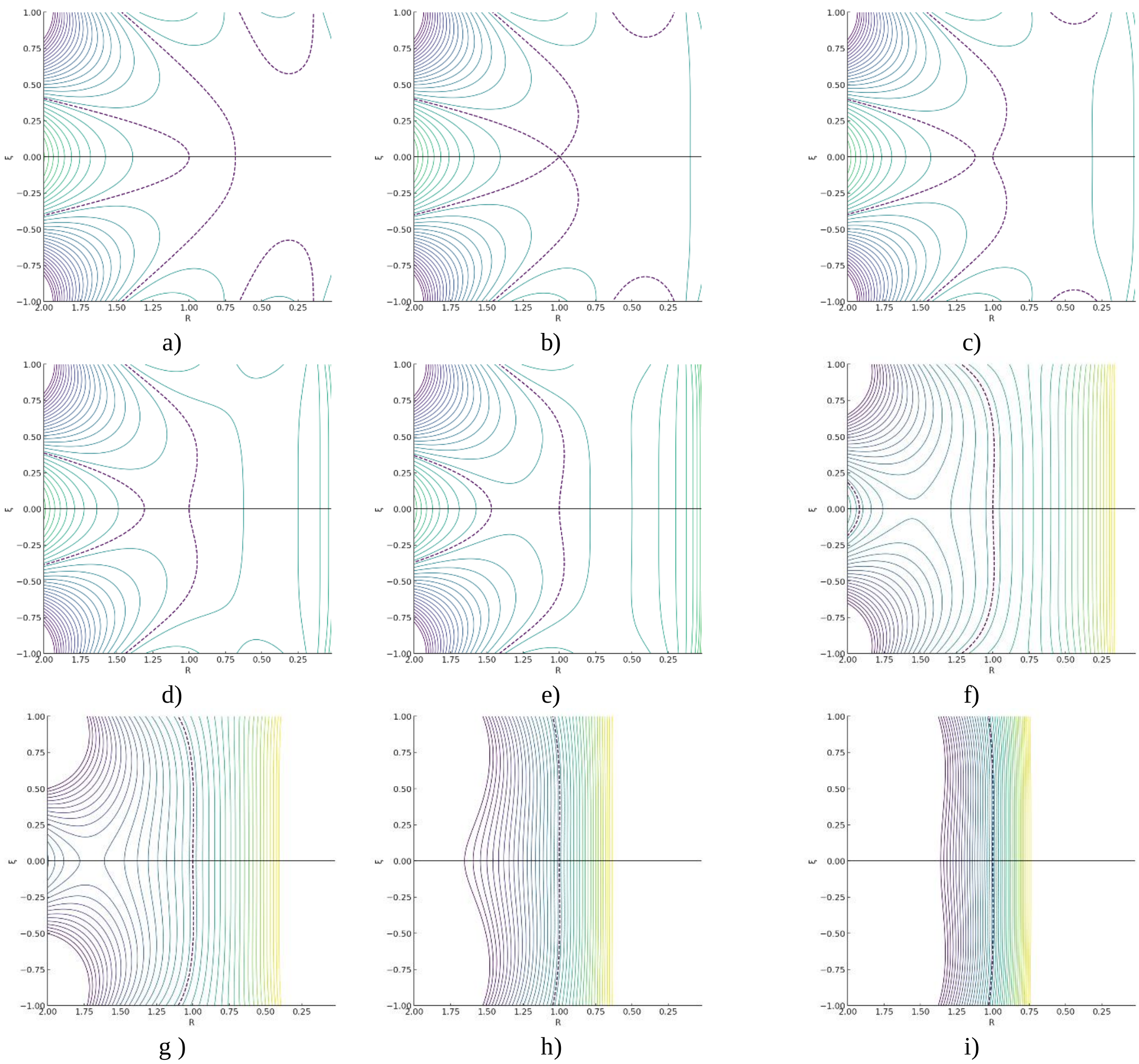


Fig. 4. Family of equipotentials of the composite field $U(\rho,\xi) = \omega u_{dd}(R,\xi) + \mu \ln R$ for various values of the coefficient μ (μ<0), a constant weighting factor ω=1:
a) μ=-0.1; b) μ=-1; c) μ=-2, d) μ=-5, e) μ=- 10; f) μ= -50; g) μ=- 100; h) μ=- 200; i) μ= -300.

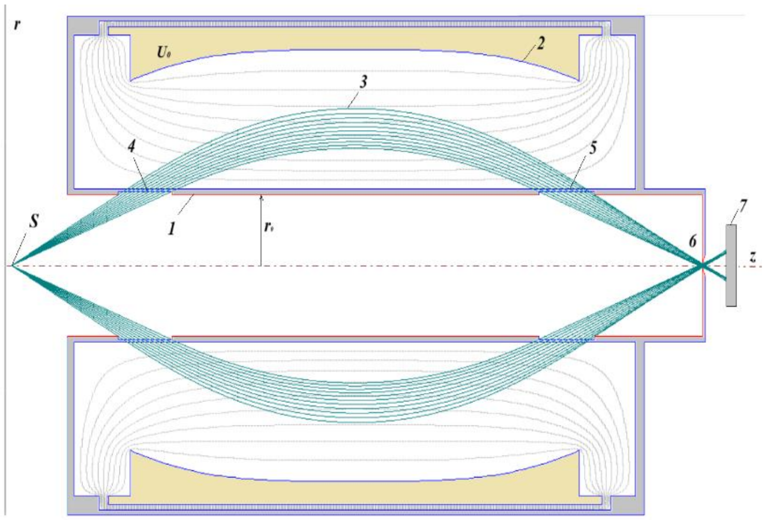
Thus, at small values of the coefficient μ, which determines the contribution of the cylindrical field, the total field retains the equipotential structure characteristic of the dodecapole. At larger values of μ, the multipole component is almost completely suppressed, and the structure of the field becomes purely cylindrical. Therefore, the analysis of the families of equipotentials of the total field demonstrates that varying the parameter μ makes it possible to effectively control the spatial structure of the field.

3. Modeling of the energy analyzer scheme based on an non-uniform electrostatic field

The electrostatic multipole-cylindrical field is formed in the space between two axially symmetric coaxial electrodes. The inner electrode has a cylindrical shape with radius r_0 and is kept at zero potential, while a deflecting potential U_0 is applied to the outer curvilinear electrode, whose profile follows one of the equipotential lines of the total field. In this study, the primary interest is focused on determining the shape of the outer deflecting electrode. As a result of analyzing the calculated equipotentials, a configuration was selected that can be implemented in the form of an outer deflection electrode.

The results of numerical modeling of the particle energy analyzer, which was designed using the selected shape of the outer deflection electrode, are presented below. The electron-optical scheme modelled using the numerical program “Focus”, which is designed for modelling corpuscular optics systems [17].

Figure 5 shows the electron-optical scheme of an energy analyzer based on the superposition of a cylindrical field and the second type axially dodecapole. The image is shown in the radial *r* and axial *z* planes. The scheme is symmetrical about the central *z*-axis. The profile of the outer deflecting electrode (2) coincides with the equipotential of the total field at the selected parameters μ = -50, ω= 1.



1 – inner cylinder, 2 – outer deflecting electrode, 3 – charged particles, 4 – entrance window, 5 – exit window, 6 – exit diaphragm, 7 – collector, *S* – source of charged particles

Fig. 5. Electron-optical scheme of the dodecapole - cylindrical mirror energy analyzer

From source S, located at a distance Δ=2.5 from the analyzer, charged particle beams (3) are emitted, which enter the field through the entrance window (4) on the inner cylinder (1). Under the action of the electrostatic field, the charged particle beams are deflected towards the axis. Particles that pass through the exit window (5) in the inner cylindrical electrode (1) and the limiting exit diaphragm (6) reach the collector (7), where they are registered. In the “axis-axis” angular focusing regime, the ratio of the analyzer's tuning energy E_0 to the potential *V* is $E_0/V = 1.175$ eV/V. It follows that by changing the potential *V* of the outer deflection electrode, the energy spectrum E_0 of charged particles can be scanned sequentially. Table 1 shows the corpuscular-optical parameters of the particle energy analyzer.

Table 1. Corpuscular-optical parameters of the dodecapole - cylindrical energy analyzer

Parameters	Values
Focusing type «axis- axis»	
Focusing order	2
Focusing angle	39°
X focusing coordinate	33.4737
Y focusing coordinate	-0.816079
Reflection parameter, *P*	0.99
Energy dispersion, *D*	6.9

Fig. 6 shows the instrumental function of a mirror energy analyzer, which, as noted above, provides second-order angular “axis-axis” focusing. The exit diaphragm with a radius of R_d=0.027r_0 was placed at the focal point, where r_0 is the radius of the inner cylindrical electrode. The optimal angle range was 39°±5°. The luminosity of the energy analyzer was 11% of 2π, and the relative energy resolution was R=ΔE/E=0.7%.

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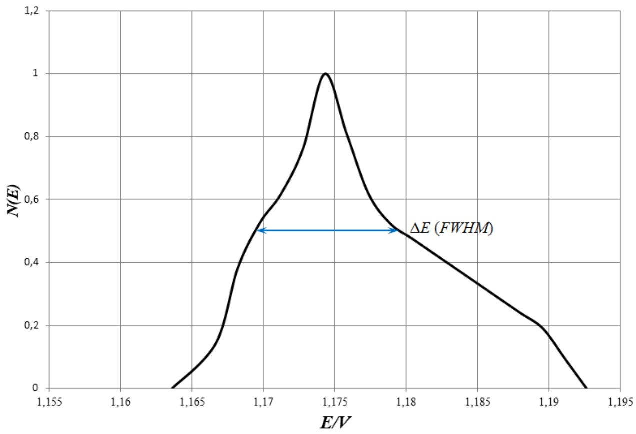

Fig. 6. The instrumental function of a mirror energy analyzer

In comparison with the decapole–cylindrical energy analyzer operating in the “axis–ring” focusing regime [16] (R = 0.74% at a luminosity of 8.2% of 2π), the proposed mirror analyzer (“axis–axis” focusing) provides a comparable energy resolution of R = 0.7% while achieving a higher luminosity of 11% of 2π.

4. Conclusion

The structure of axial symmetric multipole fields, in particular, the axially dodecapole and its superposition with a logarithmic cylindrical field, has been investigated. The equipotential series of the investigated field showed that changing the parameter μ, which determines the contribution of the cylindrical field, allows controlling the spatial structure of total field. The selection of the optimal configuration of equipotentials opens up the possibility of practical implementation of the outer deflecting electrode of the analyzer. Numerical modeling showed that the proposed design provides the second-order “axis-axis” type angular focusing. The corpuscular-optical characteristics of the device indicate the high efficiency of the proposed scheme: the relative energy resolution of about R≈0.7% makes it possible to use the device for high-precision energy analysis, and the luminosity of about 11% of 2π, is a significant indicator for compact mirror systems.

Thus, the use of a superposition of a cylindrical field and a second type axially dodecapole allows the creation of an energy analyzer with strong focusing capability, high energy resolution, and sufficient luminosity. The results obtained confirm the promise of the developed design for studying charged particle beams in outer space.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRediT author statement

Kambarova Zh.T.: Writing - Review & Editing; Investigation, **Saulebekov A.O.:** Conceptualization, Writing - Original Draft, Methodology; **Kassymov, S.S.–** Methodology, Editing. The final manuscript was read and approved by all authors.

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References

1 Zashkvara V.V., Ashimbaeva B.U. (1998) Cylindrical mirror analyzer with adjustable angular focusing. *Journal of Electron Spectroscopy and Rel. Phen.*, 94, 89 – 96.

2 Shugayeva T.Zh., Spivak-Lavrov I.F., Amantaeva A.Sh. (2025) Gridless Cylindrical Mirror Energy Analyzer for Electron Spectroscopy. *J. Phys.: Conf. Ser.*, 2984, 012030, https://doi.org/10.1088/1742-6596/2984/1/012030

3 Kazama Y., Wang B.J., Wang S.Y., et al. (2017) Low-energy particle experiments-electron analyzer (LEPe) onboard the Arase spacecraft. *Earth Planets Space*, 69, 165. https://doi.org/10.1186/s40623-017-0748-6

4 Ambrosi G., et al. (2019) The Penetrating particle ANalyzer (PAN) instrument for measurements of low energy cosmic rays. *IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)*, 1-8. https://doi.org/10.1109/NSS/MIC42101.2019.9059946

5 MacDonald E.A., Funsten H.O., Dors E.E., Thomsen M.F., et al. (2009) New Magnetospheric Ion Composition Measurement Techniques. *AIP Conf. Proc.*, 16, 1144 (1): 168–172. https://doi.org/10.1063/1.3169283

6 Ilyin A.M., Ilyina I.A. (2014) High-resolving electrostatic charged particles energy analyzer with fine tuning for space investigations. *Journal of Instrumentation*, 9, P08005. https://doi.org/10.1088/1748-0221/9/08/P08005

7 Amerl P.V., Yau A.W. (2005) Towards the miniaturization of a space-borne electrostatic energy analyzer: the miniature enhanced geometry electrostatic analyzer (MEGEA). I*nternational Conference on MEMS, NANO and Smart Systems*, 139-142. https://doi.org/10.1109/ICMENS.2005.128

8 Keller J.W., Chornay D.J., Hunsaker F.H., et al. (1999) Gated time-of-flight plasma composition analyzer for space physics research. *Rev. Sci. Instrum*., 70 (7), 3167–3172. https://doi.org/10.1063/1.1149881

9 Nicolaou G., Haythornthwaite R.P., Coates A.J. **(2022)** Resolving Space Plasma Species with Electrostatic Analyzers. *Front. Astron. Space Sci.*, ***9***, 861433. https://doi.org/10.3389/fspas.2022.861433

10 Gershman D.J., Avanov L.A., Collinson G., Tucker C.J., Barrie A., Chornay D.J., Paschalidis N.P., Rowland D., Moore T.E. **(**2023**)** A Gated Time-of-Flight Top-Hat Electrostatic Analyzer for Low Energy Ion Measurements. *Rev. Sci. Instrum***.**, **94**, 083304. https://doi.org/10.1063/5.0139022

11 Spivak-Lavrov I.F. (2016) Analytical methods for the calculation and simulation of new schemes of static and time-of-flight mass spectrometers. *Adv. Imaging Electron Phys.*, 193, 45–128. https://doi.org/10.1016/bs.aiep.2015.10.001

12 Zashkvara V.V., Tyndyk N.N. (1992) Axially symmetric multipole in magnetic analyzers. *Nuclear Instruments & Methods in Physics Research. Section A*, A321, 439-446.

13 Zashkvara V.V., Ashimbaeva B.U., Chokin K.Sh. (2002) Calculation of trajectories in a multipole cylindrical field. *Journal of Electron Spectroscopy and Rel.Phen.*, 122, 195-202.

14 Kambarova Zh.T., Saulebekov A.O., Trubitsyn A.A. (2022) The All-sky Spectrometer of Hot Cosmic Plasma. *The Astronomical Journal*, 164 (2), 47 (1-10). https://doi.org/10.3847/1538-3881/ac7561

15 Kambarova Zh.T., Saulebekov A.O., Kopbalina K.B., Tussupbekova A.K., Saulebekova D.A. (2021) About the possibility of creating an efficient energy analyzer of charged particle beams based on axially-symmetric octupole-cylindrical field. *Eurasian Physical Technical Journal*, 18(2), 96–102. https://doi.org/10.31489/2021No2/96-102

16 Kambarova Zh.T., Trubitsyn A.A., Saulebekov A.O. (2018) Axially symmetric energy analyzer based on the electrostatic decapole-cylindrical field. *Technical Physics*, 63, 11, 1667–1671. https://doi.org/10.1134/S1063784218110142

17 Sautbekova, Z.S., Trubitsyn, A.A. (2022) FOCUS CPM Software for trajectory analysis of real axially symmetric electrostatic mirrors: Methods and Algorithms. *Eurasian Physical Technical Journal*, 19(3), 91–96. https://doi.org/10.31489/2022No3/91-96

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