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MINIATURE HIGHLY SENSITIVE ELECTRON SPECTROMETER FOR THE ANALYSIS OF CORPUSCULAR FLUXES

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The work is devoted to the theoretical development of miniature highly sensitive electron spectrometer for the analysis of the composition of corpuscular flows in a wide range of measured particle energies. The mirror type axially symmetric energy analyzer in the spectrometer is constructed on the basis of an electrostatic octupole-cylindrical field and has a long-focal-length distance. The focusing properties of the scheme have been calculated, and the luminosity and resolving power of the device have been evaluated. As part of a set of equipment for spacecrafts, the proposed device will allow to determine the composition of charged particles in unsteady flows in interplanetary space. Also when designing the device there is a possibility to combine several methods of analysis (for example, with mass-spectrometric methods), which will successfully complement each other, which will provide high information content of joint analysis. This tendency is observed in the creation of space research complexes, which, as a rule, include several independent methods of analysis.

Keywords: electron spectrometer, energy analysis, energy analyzer, electrostatic mirror, corpuscular-optical system.

Introduction

The main instruments used to study the processes in cosmic plasma are energy and mass analyzers of charged particle beams. Energy analyzers are based on the principle of separation of particle by their energy and recording their spectra. This makes it possible to obtain information on various particle parameters, including their velocity, energy, angular distribution, and composition. Energy analyzers are used in various space experiments. Energy analyzers are used to study the solar wind, magnetosphere, near-Earth space plasma and other areas of space physics. Many spacecraft, including satellites, probes and stations, are equipped with energy analyzers to make detailed measurements and collect data on charged particles in near-Earth space. The use of energy analyzers in space research is increasing the understanding of physical processes in the space environment.

Energy analyzers of the cylindrical mirror type have found wide application in the study of resonance phenomena in gases, in spectroscopy for chemical analysis, for obtaining spectra of secondary electrons, photoelectrons, auto electrons, Auger-electrons, as well as in space research, in the study of interaction of atomic particles with the surface of a solid body and plasma diagnosis. The cylindrical mirror analyzer has become a basic element of electron spectrometers of various purposes, produced in the near and far abroad by leading instrumentation companies [1,2].

Work [3] presented a description of a novel electrostatic optic that is designed to offer a 2π sr instantaneous field of view for characterizing space plasmas. The system comprises a series of concentric toroidal electrodes that create multiple independent channels for energy selection. The charged particles undergo deflection towards a shared planar imaging detector. The complete three-dimensional distribution function of charged particles is obtained through a single energy sweep. The resolution of the optics, both in terms of angle and energy, is determined by several factors. These factors include the number of toroidal electrodes, the radii of curvature of the electrodes, the spacing between them, and the angular aperture of the channels. The numerical simulations presented in this study demonstrated the performance of an initial implementation of the proposed concept, which is suitable for various space plasma physics applications. The preliminary version of this three-dimensional plasma analyzer has the capability to cover energy ranges from a few electron volts (eV) up to 30 kiloelectron volts (keV), typically with a channel-dependent energy resolution varying from 10% to 7%. The angular acceptance of the system is dependent on the incident particle's direction and ranges from 3° to 12°.

In work [4], a novel type of space plasma spectrometer, known as the wide field of view plasma spectrometer, was introduced. This spectrometer provides a field of view greater than 1.25π sr, while requiring fewer resources compared to traditional methods. The enabling component can be likened to a pinhole camera, where an electrostatic energy-angle filter is positioned at the image plane. The energy-per-charge of the particles is controlled by adjusting the bias voltage applied to the filter plate in relation to the pinhole aperture plate. For a given bias voltage, charged particles from different directions are focused by different angles to different locations. Particles with appropriate locations and angles can transit the filter plate and are measured using a microchannel plate detector with a position-sensitive anode. By employing a single high-voltage power supply, it becomes possible to achieve comprehensive coverage of both energy and angle, leading to significant resource savings. Additionally, this setup enables measurements to be conducted at rapid timescales.

In the study described in work [5], a novel approach was introduced for measuring plasmas with exceptionally high energy resolution. This was accomplished by combining a top-hat Electrostatic Analyzer (ESA) with an internally positioned Retarding Potential Analyzer (RPA). In situations where high resolutions are unnecessary, RPA can be grounded, allowing the instrument to function as a conventional, versatile plasma analyzer solely utilizing ESA.

A wide-field-of-view electrostatic analyzer has been designed specifically for the L5 mission, offering all-sky coverage [6]. The prototype model of this analyzer has been calibrated using a ground-based facility. The results exhibit a satisfactory agreement with the numerical model calculations, showcasing the analyzer's capability for space plasma measurements on board 3-axis stabilized spacecraft, such as the L5 mission.

The design of the analyzer proposed in work [7] is capable of measuring plasma characteristics in a solid angle of 2 π sr in one act of data registration. The all-sky spectrometer of hot cosmic plasma comprises two stages: the first stage involves an original conical lens design, which transforms an extremely broad inflow of particles into a narrow cone-shaped beam; the second stage employs a hexapole-cylindrical configuration functioning as an energy analyzer for the narrow cone-shaped flow. The work outlines the calculations and simulations conducted to assess the proposed analyzer, utilizing original numerical and approximate analytical methods for designing electron and ion optical systems. The main device parameters are computed and presented.

This paper [8] proposes a long focal-length axially symmetric hyperbolic energy analyzer. The work has represented results of calculation of analytic parameters of energy analyzer with an axis-ring type of focusing. The design features of energy analyzer are described and the results of its experimental examination are given.

The study of work [9] involves the computation of the equipotentials of cylindrical octupoles with both symmetric and antisymmetric planes. Additionally, the calculation and analysis of equipotential portraits are performed for electrostatic axially-symmetric octupole-cylindrical fields. The analysis considers various weight contributions from the cylindrical field and circular octupole components.

The electron-optical scheme of the axially-symmetric electrostatic energy analyzer based on octupole-cylindrical mirror is proposed in work [10]. "Ring-ring" type third-order angular focusing scheme of the energy analyzer is found. This proposed analyzer demonstrates both compactness and high corpuscular-optical parameters. The instrumental function of the device has been built.

The concept proposed in this article involves utilizing axial symmetric multipole-cylindrical fields in the design of the energy analyzer. A key requirement for this energy analyzer is to have long-focal-length distance, enabling the use of multiple analysis methods and accommodating additional devices, such as mass analyzers. By employing several analysis methods, it becomes possible to overcome the limitations associated with individual methods and obtain a more comprehensive understanding of the investigated corpuscular fluxes.

The paper proposes the results of numerical modeling electron-optical scheme of the octupole-cylindrical energy analyzer. Miniature highly sensitive electron spectrometer of charged particles can be built on the basis of the proposed scheme of the energy analyzer.

The modeling of scheme of energy analyzer was performed using the CAE "Focus" numerical simulation software for electron optics systems [11,12].

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1 Modeling of the octupole- cylindrical energy analyzer scheme

The potential of the electrostatic octupole-cylindrical field is described in the coordinate system *r,z* by the following expression:

$$U(r,z) = \mu \ln r + \omega U_{oct}(r,z)\,, \tag{1}$$

where

$$U_{oct}(r,z) = \frac{1}{4!}z^4 + \frac{1}{2}z^2\left\{\frac{1}{4}\left(1-r^2\right)+\frac{1}{2}\ln r\right\} + \frac{1}{64}r^4 + \frac{1}{16}r^2 - \frac{1}{8}\ln r\left[\frac{1}{2}+r^2\right] - \frac{5}{64}, \tag{2}$$

is circular octupole, μ is the coefficient specifying the weight contribution of the cylindrical field *lnr*, ω is the weight component of the circular octupole.

Based on the simulation results, the "axis-ring" type second-order angular focusing regime in the electron-optical scheme of the energy analyzer in the case of a point distant source on the symmetry axis is found. At the same time, the coefficient specifying the weight contribution of the cylindrical field *lnr* $\mu = 2$, the weight component of the circular octupole $\omega = 1$. Fig.1 shows a scheme of second-order angular focusing of "axis-ring" type of the energy analyzer at $\mu = 2$, $\omega = 1$ in the case of a point distant source of charged particles on the symmetry axis.

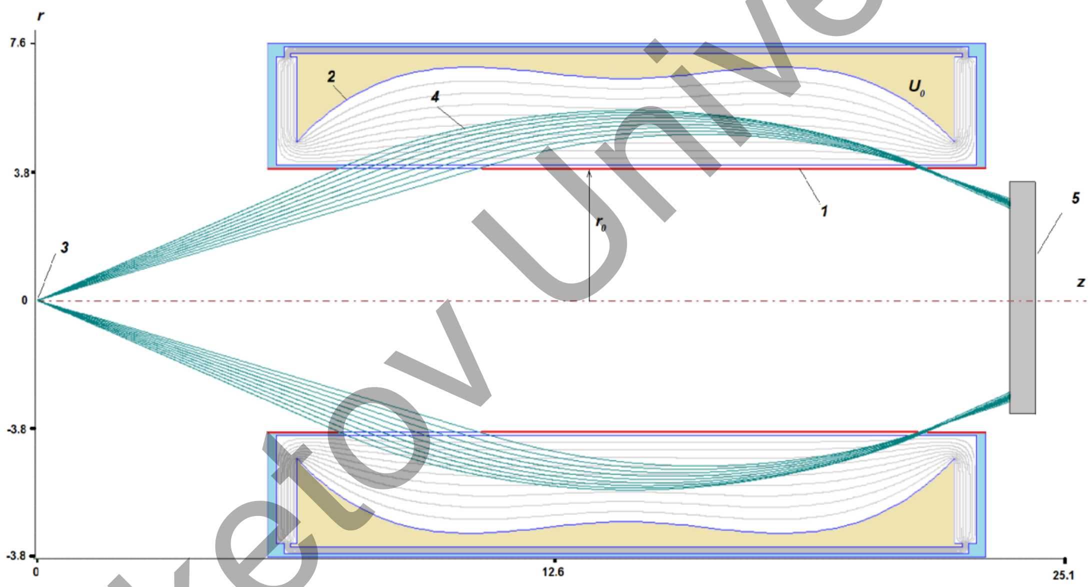


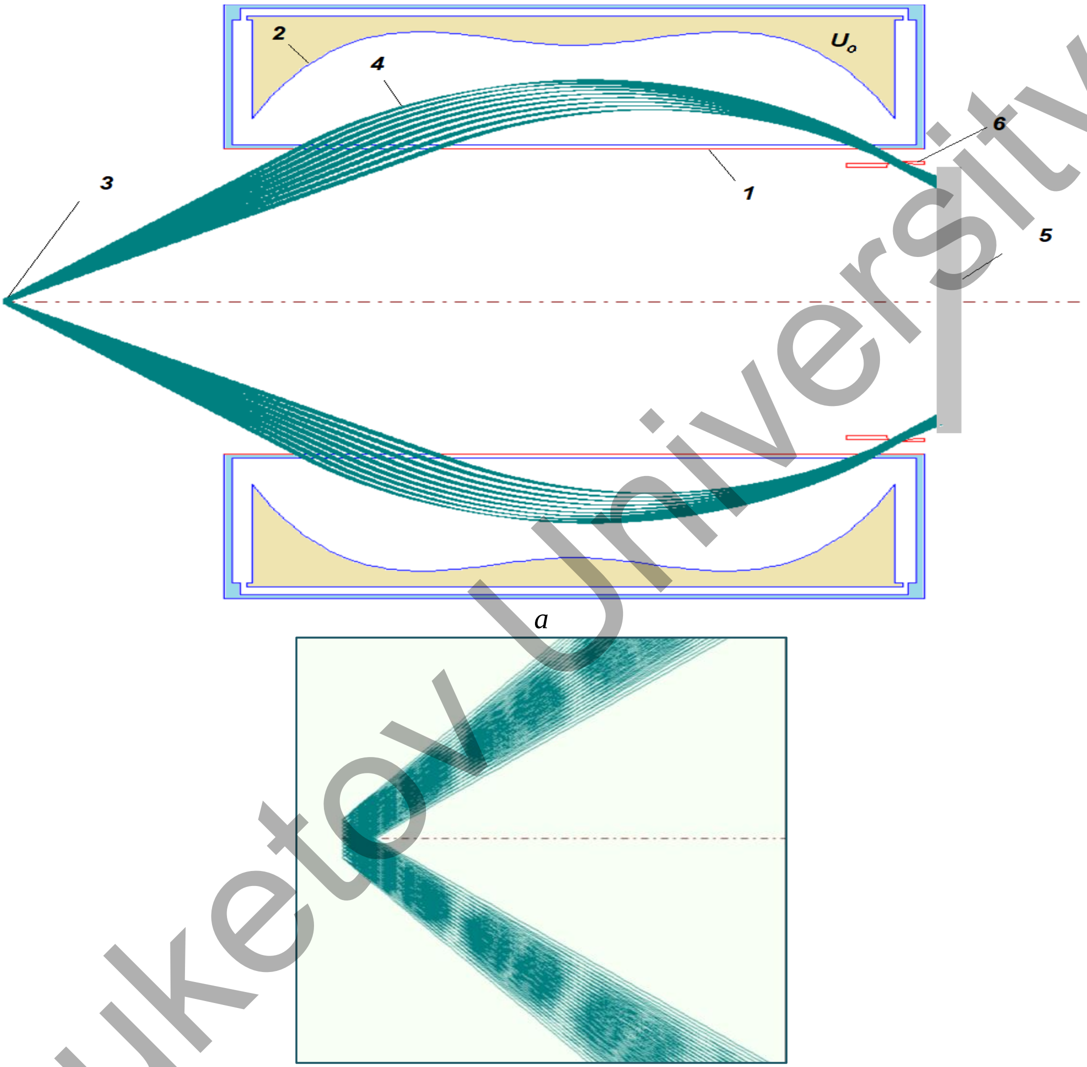
Fig.1. Regime of "axis-ring" type angular focusing in the electron-optical scheme of the energy analyzer based on the octupole-cylindrical field in the case of a point distant source on the symmetry axis: 1 - inner grounded cylindrical electrode, 2 - outer deflecting electrode, 3 – point source, 4 - charged particle beam, 5 - a position-sensitive detector

The octupole-cylindrical field is formed in the space between the cylindrical inner electrode (1), which is under the ground potential, and the outer electrode with a curvilinear profile (2), on which the deflecting potential *Uo* is applied.

According to Fig. 1, particles (4) from a point source (3) enter to the analyzing field area of the analyzer through the entrance slit, then reflected from the outer deflecting electrode (2), they pass through the exit slit and are focused into ring image near the surface of the inner cylindrical electrode (1). Then they are registered by the a position-sensitive detector (5).

This scheme provides a long-focal-length distance. Distance from the point distant source to the energy analyzer, i.e. the optimal position of the point distant source relative to the left edge of the entrance aperture Z(source) = - 1.45 r_0. The potential of the outer deflecting electrode is equal to 1. The ratio of kinetic energy of the charged particle to the outer electrode potential is E/V=3.4 *E*[eV]/*U*[V]= 3.4. The range of initial entrance angles of particles into the analyzer is 24°±4°. The linear energy dispersion of device is 5.65. All dimensions are expressed in conventional units.

From the calculations it was found that the scheme is capable of collecting particles from sources of small size. Calculations carried out for the case of an extended source showed that even in this case it is possible to obtain regime with a third order focusing. The extended source is in the form of a disk with a diameter d=0.026 r_0. In the calculations, the extended source is divided into 10 equal parts, each of which will be a point source. The Figure 2 a,b show the scheme "axis-ring" type angular focusing in the energy analyzer in the case of an extended source (a) and magnified view of an extended source (b).



a

b

Fig.2. a - "Axis-ring" type angular focusing in the energy analyzer in the case of an extended source: 1 - inner grounded cylindrical electrode, 2 - outer deflecting electrode, 3, b - extended source source, 4 - charged particle beam, 5 - a position-sensitive detector, 6 – exit diaphragm

2 Calculation and analysis of the parameters of the system

Energy response of the energy analyzer was calculated for the cases of point and extended sources. Particles with different polar and azimuthal angles were summed.

To calculate the energy response for the case of point distant source, the exit aperture was placed near the surface of the inner cylindrical electrode. The range of initial particle entrance angles is 20°-28°, the range of initial energies (more precisely, *E/V*) is 3.366-3.434 (or ΔE=3.4±1%). Exit diaphragm width is 0.0077 r_0 (where r_0 is radius of inner cylindrical electrode).

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To calculate the energy response for the case of extended source (size of source d=0.026 r_0), the exit aperture was placed near the surface of the inner cylindrical electrode. The range of initial particle entrance angles is 20°-28°, the range of initial energies (more precisely, *E/V*) is 3.23-3.57 (or ΔE=3.4±5%). Exit diaphragm width is 0.084 r_0.

Figure 3 shows the energy response of the energy analyzer for the configurations of point and extended sources. Relative energy resolution of the system is defined as the ratio ΔE/E, where ΔE represents the full width at half maximum (FWHM) of the energy distribution curves, and E corresponds to the mean energy of the detected particles.

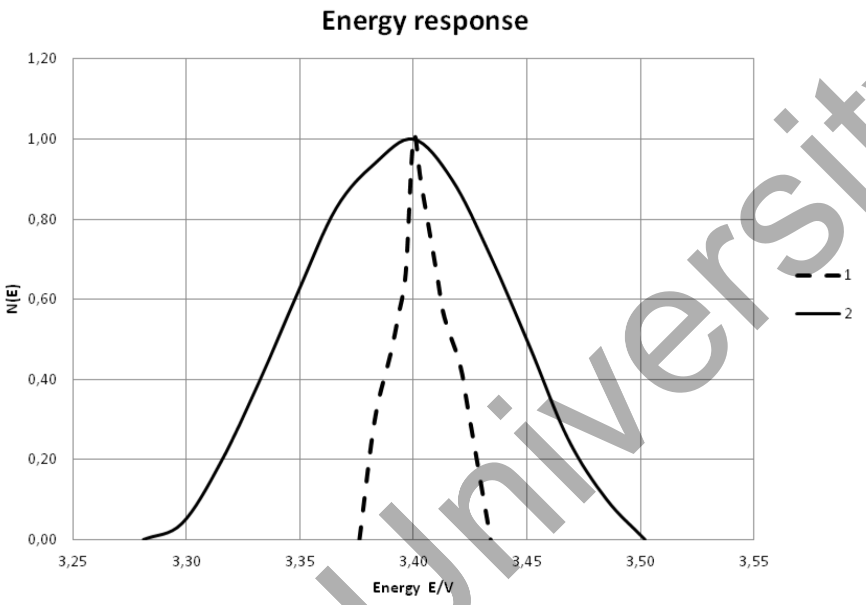

Fig.3. Energy response of the energy analyzer:
1 - for scheme with point source, 2 – for scheme with extended source.

The relatively high energy resolution is higher for the case of point distant source, reaching 0,59 % for "axis-ring" type angular focusing regime. The relatively energy resolution for case of extended source has a lower energy acceptance with 3.29% for "axis-ring" type angular focusing regime.

Table 1 presents the results of numerical calculation of the focusing properties of the octupole-cylindrical energy analyzer for the "axis-ring" angular focusing regime.

Table 1. Focusing properties of the octupole-cylindrical energy analyzer

Parameter	Point source	Extended source
Focusing order	2	3
Central angle of focusing	24°	24°
X_{foc} , coordinate of the focus point	22.78	21
Y_{foc} , coordinate of the focus point	3.3	4
Reflection parameter, *P*	1.0	0.8
Long-focal-length distance	1.45 r_0	1.45 r_0
ΔE/E (FWHM), %	0.59	3.29
Luminosity, Ω/2π , %	5.67	5.67
Linear energy dispersion, D	5.65	5.65
The total length of the electron-optical scheme, $l = L/r_0$	5.87	5.87

The luminosity of the corpuscular-optical device is equivalent to the geometric solid angle Ω of the particle collection. Luminosity of the energy analyzer for "axis-ring" type angular focusing regime is $\Omega/2\pi$=5.67 %.

The analyzer proposed in this work has the best resolution compared to the classical cylindrical mirror energy analyzer, and has the long-focal-length distance and small device dimensions.

Conclusion

A scheme of the energy analyzer with a large focal-length distance, which can be applied for spatial combination with the instruments to provide alternative research methods, was found. On the basis of the proposed numerical model of the energy analyzer can be designed miniature electron spectrometer for the energy analysis of corpuscular fluxes. The developed scheme of the energy analyzer satisfies all basic requirements, such as small dimensions of the analyzer (compactness), high focusing properties. The relatively high energy resolution of the analyzer allows a detailed analysis of the particle distribution function.

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