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Abstract

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ON THE USE OF AN ELECTROSTATIC FIELD OF THE DIFFERENCE TYPE IN THE SPECTROSCOPY OF BEAMS OF CHARGED PARTICLES

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The most important task in the spectroscopy of beams of charged particles is to find ion-optical systems that ensure the creation of high-luminosity spectral instruments with great resolving power. Ion-optical systems for this purpose must have large dispersion combined with perfect focusing.

The field of a cylindrical capacitor, widely used at the present time, makes it possible to achieve good focusing of a weakly divergent beam of charged particles, but it has comparatively small dispersion. Increasing the dispersion in such fields can be accomplished by increasing the radius of the equilibrium trajectory; however, this is practically disadvantageous. Therefore, in order to increase the dispersion without changing the radius of the equilibrium trajectory, fields that decrease with radius more rapidly than the field of a cylindrical capacitor have begun to be used. In particular, the use of the field of a spherical capacitor ([1–4]) in electrostatic analyzers and mass spectrographs leads to a twofold increase in dispersion at an unchanged radius of the equilibrium trajectory, which makes it possible to increase the resolving power and luminosity of instruments without increasing their dimensions. The application of a spherical capacitor in electrostatic analyzers and in a mass spectrograph with double focusing ([5]) proved highly effective. In recent years, calculations have appeared of the ion-optical properties of other types of inhomogeneous electrostatic fields ([6], [7]) for the purpose of increasing dispersion and improving focusing; however, in practice these fields have not been used.

A field of the difference type possesses interesting properties ([8]). One of the special cases of a difference field is determined by radial and axial components of the form

$$E_r = \frac{E_1}{r} - E_2 r, \tag{1}$$

$$E_z = 2E_2 z, \tag{2}$$

Fig. 1

Figure 1: Fig. 1

where E_1 and E_2 are certain constants connected with the inhomogeneity coefficient η and the radius of the equilibrium trajectory in the following way:

$$\eta = 2 - \frac{2\frac{E_2}{E_1}r_0^2}{1-\frac{E_2}{E_1}r_0^2}, \qquad \eta = 3 + \frac{\partial E}{\partial r}\cdot\frac{r}{E}\Big|_{r=r_0}. \tag{3}$$

The difference field is focusing in the radial and axial directions; moreover, Berber' s rule ([9]) is applicable to it in a generalized form: the source S, the vertex of the effective sector angle $\Phi\sqrt{\eta}$, and the image P lie on one straight line (Fig. 1).

The displacement of the image b from the equilibrium trajectory at the first-order focusing point is expressed by the formula:

$$b = \delta\frac{r_0}{\eta}\left(1+\frac{q}{p}\right) - \Delta r_0\left(\frac{q}{p}\right), \tag{4}$$

where δ is a quantity characterizing the spread in particle energy, and Δr_0 is the width of the entrance slit.

Fig. 1. L_1—distance from the source to the front edge of the field, L_2—distance from the image to the rear edge of the field, Φ—sector angle

The energy dispersion

$$D = \frac{db}{d\delta} = \frac{r_0}{\eta}\left[1+\frac{q}{p}\right] \tag{5}$$

depends substantially on η. As $\eta \to 0$, $D \to \infty$.

A more exact expression for the displacement is obtained by taking into account the second-order aberration terms (10) in the following form:

$$b = r_0\left[\frac{\delta}{\eta}\left(1+\frac{q}{p}\right) - \frac{\Delta r_0}{r_0}\left(\frac{q}{p}\right) + \delta^2\alpha_1 + \psi_r^2\alpha_2 + \right.$$
$$\left. + \left(\frac{\Delta r_0}{r_0}\right)^2\alpha_3 + \delta\psi_r\alpha_4 + \delta\frac{\Delta r_0}{r_0}\alpha_5 + \psi_r\frac{\Delta r_0}{r_0}\alpha_6\right], \tag{6}$$

where ψ_r is the angle of divergence of the particle from the equilibrium trajectory at entry into the field; $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5$, and α_6 are aberration coefficients, which are complicated functions of q and p.

Fig. 2

Figure 2: Fig. 2

Figure 3

Figure 3: Figure 3

In the particular case, when the condition

$$\frac{\partial b}{\partial \Delta r_0} = 0 \tag{7}$$

is satisfied for some value $\delta \neq 0$, a number of aberration terms can be eliminated and the focusing thereby improved. In this case the width of the image will not depend on the width of the entrance slit, but will be determined by the angle of divergence of the particles at each point of the entrance slit. This property of difference fields can be used for concentrating broad beams of charged particles having the same energy.

Fig. 2. Diagram of the analyzer

For an experimental study of the properties of the difference field, we constructed an analyzer in which the beam of charged particles is turned through an angle $\Phi = 27^\circ$. The field expressed by equalities (1) and (2) was produced by means of two capacitor plates having the shape of equipotential surfaces determined from these equalities.

The analyzer (Fig. 2) has an equilibrium radius $r_0 = 200$ mm, a field nonuniformity coefficient $\eta = \frac{1}{6}$; the distances L_1 and L_2 can be varied in accordance with Berber' s generalized rule. The beam of charged particles consisted of electrons obtained with the aid of the electron gun of an 8LO29 cathode-ray tube, which was supplied by a stabilized voltage.

To the article by M. N. Korsunskii and V. A. Bazakutsa, p. 1029

Fig. 3. Photograph of the images of the entrance slits:
$a - \delta = 1.5 \cdot 10^{-3}$; $b - \delta = 3 \cdot 10^{-3}$
$c - \delta = 4.5 \cdot 10^{-3}$; $d - \delta = 6 \cdot 10^{-3}$

To the article by V. L. Dansker, p. 1171

Fig. 1. Effect of sympathectomy on the diameter of arterioles (a), venules (b), and arteriovenous anastomoses of the rabbit ear; I —before the sympathectomy

Figure 1

Figure 4: Figure 1

operation, II –on the 3rd day after removal of the superior cervical sympathetic ganglia. 32×

Experimental data have been obtained with this instrument that agree well with the calculated values. Thus, for example, at $L_1 = 120$ mm and $L_2 = 700$ mm the energy dispersion is 33 mm per 1% change in energy (calculated value 31.6 mm). If the source and the image are at the same distance from the boundaries of the field, $L_1 = L_2 = 330$ mm, the dispersion is 25.3 mm per 1% change in energy (calculated value 24 mm). The difference between the experimental and calculated values of the dispersion is explained by the fact that the real field has an η somewhat different from the theoretical value.

Thus, the energy dispersion of an electrostatic analyzer with a difference field exceeds the dispersion of an analogous analyzer with a cylindrical field by a factor of 12. In order to obtain the same dispersion with a cylindrical analyzer, its equilibrium radius would have to be increased to 2.4 m.

The experimental verification carried out of condition (7) confirmed the possibility of improving the focusing and concentration into a narrow line of a broad beam of charged particles of the same energy. Figure 3 shows photographs of the image of three slits 0.5 mm wide, located at a distance of 1 mm from one another, with the middle slit lying on the equilibrium trajectory. The distance of the entrance slit from the edge of the field is $L_1 = 140$ mm, and the distance of the image from the other edge of the field is $L_2 = 640$ mm. The photographs were taken for different values of δ. From Fig. 3 it is seen that at $\delta = 1.5 \cdot 10^{-3}$ all three images merge into one thin and sharp line. From these pictures it is also seen that the aberration distortions, even for rays not traveling along the equilibrium trajectory, do not exceed 0.25 mm.

Consequently, a difference field makes it possible to realize a compact, high-luminosity electrostatic analyzer with great resolving power and high dispersion. By realizing fields with as small an η as possible (at which focusing still occurs), the dispersion can be significantly increased. It should be noted that there is a possibility of realizing difference fields in which the inhomogeneity coefficient η can be varied at the experimenter' s discretion. This possibility consists, for example, in creating the required distribution of potentials near the equilibrium trajectory by means of electrodes in the form of circular plates, with a definite distribution of potentials on them.

The use of electrostatic fields of the difference type in combination with an inhomogeneous magnetic field of the difference type opens up the possibility of creating a compact, high-luminosity mass spectrograph with double focusing and high resolving power.

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Note: Figure translations are in progress. See original paper for figures.