Available online at www.sciencedirect.com

ScienceDirect

St. Petersburg Polytechnical University Journal: Physics and Mathematics 2 (2016) 103–110

www.elsevier.com/locate/spjpm

Synthesis of electrostatic fields for transportation of charged particle beams

Vladimir V. Pavlov*, Nadezhda K. Krasnova

Peter the Great St. Petersburg Polytechnic University, 29 Politekhnicheskaya St., St. Petersburg 195251, Russian Federation

Available online 27 May 2016

Abstract

In this paper, an approach to creating corpuscular-optical devices for transportation and transformation of charged particle beams has been elucidated. These devices are able to optimize and create the most convenient configuration of ionic or electron paths. The approach relies upon the inverse dynamics problem formulated on the basis of the Hamilton-Jacobi equation. The motion in the symmetry plane of a three-dimensional (3D) field was considered. The problem was solved by analytical methods. An algorithm for constructing electric fields providing the particle motion on the desired trajectories was described. A key to this algorithm lies with a concept of conformal transformation from the theory of complex-valued function. This procedure was illustrated by examples. Quadratic potential was chosen as a basis. Three functions of conformal transformation were considered, providing the rotation of the focused charged particle beam at a fixed angle, the transformation of divergent flow to parallel one. The calculated two-dimensional potentials were extended into 3D-space by power series expansion on transverse coordinate. Device embodiments were suggested on the basis of the calculated field structures.

Keywords: Inverse dynamics problem; Charged particle optics; Conformal transformation; Ideal focusing.

Introduction

Electron spectroscopy and mass spectrometry currently are by far the main tools for analyzing substances and materials. They are of great importance not only in fundamental research, but also in industry and applied science where they have extensive uses. Regardless of the type of study and object examined, it is a flux of charged particles that is subjected to analysis. For effective performance the analyzed beams should be formed according to the geometry and configuration of energy and mass analyzers [1–3]. Additionally, since it is the charged particles that carry all the information about the studied object, losses of electrons or ions should be minimized at all stages prior to their analysis, which poses the problem of creating a corpuscular-optical matching element, capable of providing the maximal yield of charged particles in the vicinity of the source and transmitting them to the analyzer input with minimal losses.

This task is partially solved by using electrostatic and magnetic lens [4], but this approach involves constructing a rectilinear path, which in turn increases the overall size of the system. Using mirrors or various

* Corresponding author.
E-mail addresses: vova-gt@yandex.ru (V.V. Pavlov), n.k.krasnova@mail.ru (N.K. Krasnova).

http://dx.doi.org/10.1016/j.spjpm.2016.05.009

(Peer review under responsibility of St. Petersburg Polytechnic University).

deflecting systems is not entirely satisfactory, since it is not always possible to provide the desired particle flux configuration.

This study demonstrates an approach to synthesizing devices that serve as both turning units and lenses focusing and transporting beams. Successful search for such systems has been carried out based on the scientific ideology of inverse dynamics problems, with the analytical theory for this ideology developed by professor Golikov (St. Petersburg Polytechnic University). This ideology has found its practical implementation in the design of devices with record-breaking performance and unique features [5].

Problem statement

Making a spectrometer involves constructing an ion-optical or an electron-optical path in a specific way. This requires all device elements (a source, an analyzer, and others) to perform to the best of their capacities, with mating components playing an important role. The problem of synthesizing such devices is the subject for our study.

In its most general form, the problem is formulated as the need to deliver the beam of analyzed particles from point A to point B. Additional requirements may also be imposed on organizing the particle packet in the analyzer input, for example, a packet with a fixed angular spread.

The proposed strategy for synthesizing such devices is in finding new electric fields that provide the required flux transformation, so that the entire flux radiating from a single point could also be focused into another point. The position of both points is given by the arrangement of spectrometer elements (the source and the analyzer). Let the required field have a plane of symmetry and let the perfect electron beam focusing be achieved in this plane.

Our synthesis strategy involves choosing an initial field whose potential is given analytically and in which perfect focusing is achieved at least in the plane of symmetry. Next, using the analytical methods of transformation (methods of the theory of complex-valued function, for the most part), we strive to obtain new potential structures where the beam focusing would remain perfect. Our study is based on the technique associated with using the conformal transformation of coordinates, so let us discuss this issue in more detail.

Conformal transformation of coordinates

The scientific ideology of the concept of conformal coordinate transformation in the Hamilton–Jacobi equation and its application to the synthesis of electrostatic fields combining perfect focusing in the plane of symmetry and energy dispersive properties have been described in Ref. [6]. Golikov was the first to propose this conversion algorithm for potential structures and to later put into practice the synthesis of corpuscular-optical systems [5]. Let us establish the main points of this method and provide the necessary commentary to the terms and equations used.

Mechanics historically developed in two main directions. One branch, which is customarily called classical mechanics, comes directly from Newton's laws of motion. The problem is in determining the behavior of a charged particle if the acting forces are known at any specific time, and it possesses an unambiguous solution. According to the second approach, commonly referred to as analytical mechanics [7], the study of equilibrium and motion is based on two main quantities: the kinetic energy and the force function; the latter is often replaced by potential energy. These two fundamental scalars contain the total dynamics of the most complex material systems, provided, however, that these scalars are assumed as a basis of some principle, rather than just an equation.

Let a particle occupy definite positions at some instants of time t_1 and t_2, characterized by two sets of coordinate values P_1 and P_2. Then the particle moves between these points in such a way that the time integral of the difference between the kinetic and potential energies should be of the least possible value. The integrand is called the Lagrange function of the system, and the integral is called the action. The principle of least action states the following:

The actual motion occurring in nature is that for which the action takes the least value.

The mathematical problem of minimizing a certain integral is associated with a particular mathematical branch called the calculus of variations. Vector and variation mechanics are two different mathematical descriptions of the same group of natural phenomena. Newton's theory is based on two main vectors, the momentum and the force, while variation theory is based on two scalar values, i.e., the kinetic energy and the force function. Aside from mathematical feasibility, the question is whether these two theories are equivalent. In case of free particles whose motion is unlimited by specified constraints, these two description ways lead to similar results. For systems with constraints, however, the analytical approach appears to be more effective and simple. The specified constraints are taken into account in a natural manner, as only the motion of the system along the