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Ionization-Recombination Process as a Means of Indicating the Degree of Focusing of a Beam of Charged Particles or Ionizing Radiation

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Abstract—A method for controlling the focusing of an ionizing-radiation beam, for example, a beam of charged particles, is proposed. Ionization is one of the most widely used radiation-detection methods. The effect of the recombination of charge carriers in the working substance of the detector, accompanying ionization, is usually considered as undesirable, which reduces the accuracy of measuring the radiation parameters. However, this effect can be useful and be the basis of a method for determining the maximum degree of focusing of a beam of particles or ionizing radiation. At a fixed value of the total beam current (ionizing-radiation flux), the maximum focusing is determined from the minimum value of the ionization current in a wide-aperture ionization chamber, which is used as a detector. The signal of the ionization chamber changes during focusing even at a fixed value of the beam current due to the dependence of the intensity of the recombination of charge carriers in the working substance of the chamber on their bulk density. The bulk density of carriers, in turn, is proportional to the distribution density of particles of the ionizing-radiation beam in the volume of the working medium of the ionization chamber.

Keywords: charged-particle beams, indication of the degree of focusing, ionization-recombination process

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INTRODUCTION

Intense charged-particle beams and X-rays are widely used in scientific research [1–4], medicine [5–8], and production technologies [9–13]. Maintaining a given beam-density distribution in the working area is an important task, the solution of which requires constant monitoring of the beam parameters. To do this, it is necessary to regularly measure their current values in order to then use them in the formation of control signals for beam-focusing actuators. The optimization of mapping schemes and control of the beam parameters in modern beam technologies is an urgent task. In this paper, we consider a simple-to-implement method for controlling the focusing of an ionizing-radiation beam, which requires the minimum number of measured parameters.

PROBLEM STATEMENT

We consider the problem of the focusing of a beam of ionizing radiation or charged particles in a given spatial region (working area). Let us also single out the area for indicating the beam parameters (the control zone). Let us set the task of ensuring the maximum degree of focusing in the control zone. Thus, the condition for the uniqueness of solving the focusing problem will be satisfied. If the optimal (for a specific technology in which the beam is used) degree of focusing required in the working area is not the maximum, then it is sufficient to shift the focusing control zone along the beam relative to the working area (Fig. 1b) and again control the maximum degree of focusing.

Ensuring the maximum degree of focusing of ionizing radiation (a beam of charged particles or photons) is equivalent to obtaining the maximum radiation-flux density in the control zone. Traditional methods of recording the distribution of the radiation-flux density (the current of a beam of charged particles) involve scanning it with a sensor with small transverse dimensions or using arrays of detectors or screens that convert it into a distribution of secondary radiation. The disadvantage of traditional methods is their complexity and sensitivity to transverse displacements of the beam during its focusing.

In this work, we propose a method for indicating the degree of beam focusing, which is practically insensitive to transverse displacements of the beam during focusing. For indication, the effect of ionization is used, which occurs in the working substance placed in the path of the beam in the control zone.

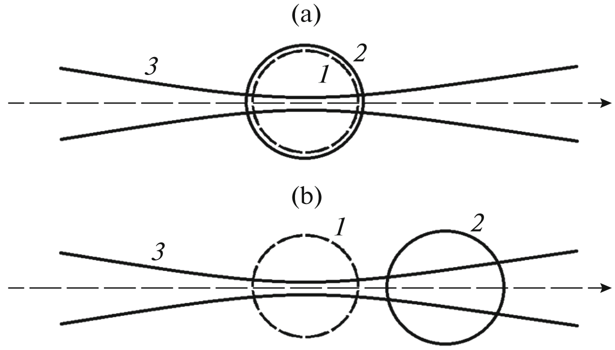

Fig. 1. Options for location of the control zone relative to the working zone: (a) the zones are combined; (b) the working area is shifted relative to the control area to the area of the defocused beam: (*1*) beam-parameter indication zone (control zone), (*2*) work zone, (*3*) a beam of accelerated charged particles or ionizing electromagnetic radiation.

Let us assume that the working substance is a gas in an ionization chamber. Let the working volume of a flat ionization chamber with transverse dimensions exceeding those of the beam and a given longitudinal (along the beam axis) size be the beam indication zone. The chamber is located perpendicular to the beam axis, the intensity of the beam of charged particles (or the flux of ionizing radiation) passing through the chamber (beam current) is fixed. The electric current in the ionization chamber is the only parameter recorded during the effect of focusing on the beam. The ionization current is determined by the parameters of the working medium of the ionization chamber, the size of its working volume, the voltage applied to the chamber electrodes, and the beam intensity [14–16].

The main idea of the proposed method is to use the dependence of the ionization current in the chamber on the density of the beam of charged particles (or ionizing electromagnetic radiation). At a fixed beam intensity, this dependence is due to the recombination of nonequilibrium charge carriers that appear in the working medium of the ionization chamber upon interaction with the beam. The probability of the recombination of charge carriers is proportional to the product of the volume densities of positive and negative charge carriers generated by the beam.

As a result of recombination, some of the carriers drop out of the charge-transfer process before they reach the boundary of the working volume of the ionization chamber. This leads to a change in the distribution of the flux density of ionizing particles and the total ionization current. The minimum ionization current will be observed at the maximum degree of focusing of the beam of ionizing particles. Thus, by minimizing the ionization current during the effect of focusing on a beam of ionizing particles, it is possible to achieve the maximum degree of its focusing in the controlled zone.

SIMULATION OF THE PROCESS OF INDICATING THE DEGREE OF FOCUS

To illustrate the possibility of using the ionization-recombination process to indicate the degree of focusing of a beam of fast charged particles (or an ionizing-radiation beam), let us consider the dependence of the current in the ionization chamber on the spatial distribution of the beam.

On average, each beam particle generates a certain amount of charge carriers in the volume of the ionization chamber, which is determined by the geometry and properties of the working substance. The density of the transverse distribution of the beam in the control zone $J(x, y)$ is varied using a focusing actuator (for example, a quadrupole magnetic lens). The number of electric charge carriers generated in the volume of the chamber as a result of ionization is proportional to the beam intensity, so the corresponding ionization current in the chamber (in the absence of carrier losses) can be written as

$$I_{0IC} = q_e\eta\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} J(x,y)\,dxdy, \quad (1)$$

where η is the carrier-injection coefficient, and q_e is the electron-charge modulus.

We assume that the beam (current) intensity $I = q_e\eta\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} J(x,y)\,dxdy$ remains fixed for any change in the beam-density distribution. If there were no charge-carrier recombination, then the magnitude of the electric current flowing through the ionization chamber would also be fixed and independent of the intensity distribution of the beam incident on the ionization chamber.

As a result of recombination of a part of the charge carriers in the working substance of the chamber, the ionization current decreases. Since the probability of recombination (for single ionization) is proportional to the square of the carrier-distribution density ($n = n^- = n^+$) in the volume of the working medium of the chamber [15], it is possible to write the equation for the density of the ionization current of the chamber in the steady state:

$$J_{IC} = q_e\eta J(x,y) - \kappa J_{IC}^2, \quad (2)$$

where κ is the recombination coefficient. Solving this quadratic equation for J_{IC}, we obtain an expression for the ionization-current density:

$$J_{IC}(x,y) = \frac{1}{2\kappa}\left(\sqrt{4\kappa\eta q_e J(x,y)+1}-1\right). \quad (3)$$

Integrating (3) over coordinates in the recording plane (transverse to the beam), we obtain an expression for the ionization current:

$$I_{IC}(\kappa,\eta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{1}{2\kappa}\left(\sqrt{4\kappa\eta q_e J(x,y)+1}-1\right)dxdy. \quad (4)$$

As an example, we consider the beam-density distribution in the form of a symmetric two-dimensional Gaussian distribution centered on the beam axis:

$$J(x, y, \sigma) = \frac{I}{\pi\sigma^2} \exp\left(-\frac{x^2 + y^2}{\sigma^2}\right), \quad (5)$$

where I is the intensity of the ionizing beam (current of the beam of charged particles), σ is the parameter of the transverse distribution of the beam. The total beam intensity

$$I(\sigma) = \frac{I}{\pi\sigma^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \exp\left(-\frac{x^2 + y^2}{\sigma^2} dxdy\right) = I \quad (6)$$

has a fixed value during focusing (does not depend on σ). To describe the focusing process, we will use the dependence $\sigma = \sigma(U)$, where U is the parameter for controlling the focusing actuators. We consider a one-parameter distribution of the radiation-flux density, so we will use one parameter U of focus control. Let us simulate the dependence of the parameter σ of the beam-density distribution on the parameter U by a function that has a minimum at a certain parameter value $U_{\min}$:

$$\sigma(U) = (U - U_{\min})^2 + \sigma_{\min}. \quad (7)$$

Using the parameter $\sigma_{\min}$, we set the parameter value corresponding to the maximum degree of beam focusing; $U_{\min}$ is the value of the control parameter U corresponding to maximum beam focusing. The model dependence $\sigma(U)$ is shown in Fig. 2.

Substituting (5) into (4), we obtain an expression for the electric current through the chamber:

$$I_{IC}(\kappa, \sigma, q_e, \eta) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{1}{2\kappa} \left(\sqrt{4\kappa\eta q_e J(x, y) + 1} - 1\right) dxdy. \quad (8)$$

The focusing process is modeled by the dependence of the ionization current on the control parameter U, expressed in (8) through the parameter $\sigma(U)$. This dependence is shown in Fig. 3 for different values of the parameter $\sigma_{\min}$. The minima on the curves of the ionization current in the chamber correspond to the maximum density of charge carriers generated by the beam in the control zone and, consequently, to the maximum focusing of the ionizing beam. The depth of the minimum depends on the parameter $\sigma_{\min}$, which models the minimum value of the distribution parameter σ for a particular focusing system.

Thus, for the simplest example of a one-parameter distribution of the density of an ionizing-radiation beam, the essence of the proposed method for indicating the degree of its focusing is demonstrated. In the case of two or more focusing control parameters, the minimum ionization current is sought by successive scanning of all control parameters. The process can be automated using one of the known methods for minimizing a two-dimensional function [17, 18].

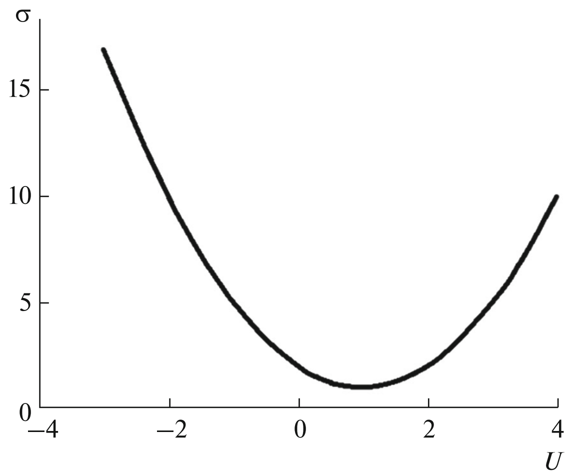

Fig. 2. Model dependence (7) of the parameter σ of the distribution of the beam density on the parameter U of focus control: $U_{\min} = 1$, $\sigma_{\min} = 1$.

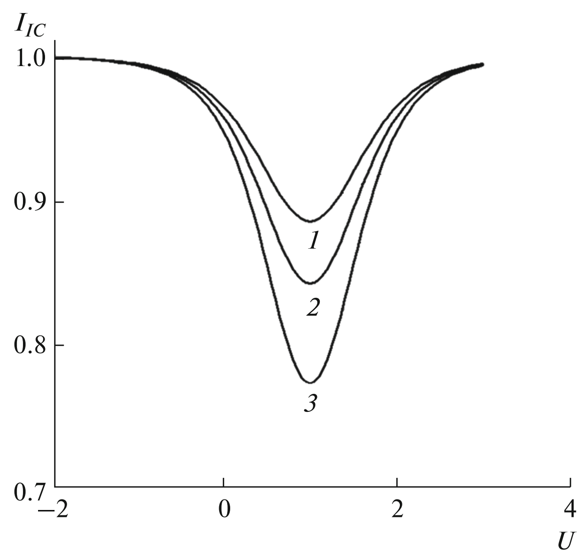

Fig. 3. Dependence (8) of the electric current through the ionization chamber on the focus-control parameter U. The calculation results were carried out at fixed values of the parameters ($I = 1$, $\kappa = 1$, $\eta = 1$, $U_{\min} = 1$) for different values of σ: (*1*) 0.6; (*2*) 0.8; (*3*) 1.

EXPERIMENTAL

The proposed method was tested in an experiment on the focusing of an electron beam with an energy of 150 MeV at the LUE-300 accelerator of the Kharkiv Institute of Physics and Technology. The electron beam was focused using a short-focus quadrupole magnetic lens. A parallel beam with transverse dimensions on the order of 5 mm was focused at the accelerator output just behind the output foil of the accelerator. The degree of focusing was controlled using a flat ionization air chamber, one of the electrodes of which was the output foil of the accelerator, and the second was a thin insulated metal plate, to which an electric voltage of about 100 V was applied. The thickness of the air layer in the chamber was 1 mm. At maximum beam focusing (at the minimum ionization current), which could be provided by the quadrupole lens, the transverse dimensions of the electron beam at the output of the accelerator were about 50 μm. At an average beam current of approximately 5 μA, an accelerator operating-pulse duration of about 2 μs, and a duty cycle of 5×10^3, the beam pulse-current density reached a value on the order of 10 A mm^{-2}, which 10^4 times exceeded the density before focusing. During the experiment, it was found that the focusing of a beam of relativistic electrons using an ionization chamber can be successfully carried out at such high beam current densities (small sizes of the focused beam) that other methods no longer work (for example, using a screen coated with a phosphor). The presented method for controlling the focusing of beams of ionizing particles or radiation is registered as an invention [19].

CONCLUSIONS

The paper presents a method for indicating the maximum focusing of a beam of charged particles or ionizing electromagnetic radiation using the ionization-recombination effect of the interaction of radiation with matter. The maximum beam focusing at a fixed value of the pulse current (ionizing-radiation intensity) corresponds to the minimum current value in a wide-aperture ionization chamber installed at the beam in the control zone. The method is practically insensitive to lateral displacements of the beam in the working area during its focusing and can be effectively used in various technologies associated with the use of intense beams of ionizing radiation. The extreme simplicity of the presented method should be noted. The method was tested on the beam of the linear electron accelerator LUE-300 MeV, where it made it possible to control the maximum focusing of the beam when working with a short-focus quadrupole magnetic lens.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. Accelerators and Beams Tools of Discovery and Innovation (Division of Physics of Beams, Am. Phys. Soc., 2013). http://www.aps.org/units/dpb/upload/accel_beams_2013.pdf.
2. I. Y. Vladimirov, B. S. Ishkhanov, L. Y. Ovchinnikova, et al., Moscow Univ. Phys. Bull. (Engl. Transl.) **71**, 245 (2016). https://doi.org/10.3103/S0027134916030139
3. V. I. Pavlenko, R. N. Yastrebinskii, O. D. Edamenko, and D. G. Tarasov, Vopr. At. Nauki Tekh., Ser.: Fiz. Radiats. Povrezhdenii Radiats. Materialoved., No. 1, 129 (2010).
4. M. F. Vorogushin, V. A. Glukhikh, G. Sh. Manukyan, D. A. Karpov, M. P. Svin'in, V. I. Engel'ko, and B. P. Yatsenko, Vopr. At. Nauki Tekh., Ser.: Fiz. Radiats. Povrezhdenii Radiats. Materialoved., No. 3, 101 (2002).
5. M. Vretenar, Accelerators for Medicine. Academic Training Lecture Regular Programme (CERN, June 2018). https://indico.cern.ch/event/722936/
6. A. V. Grizlov, V. N. Iliin, S. V. Lamonov, et al., in *Proc. XI Int. Conf. on Charged Particle Accelerators Applied in Medicine and Industry* (St. Petersburg, 2005), p. 132.
7. A. S. Alimov, E. A. Alimov, A. N. Kamanin, et al., in *Proc. RuPAC 2008* (Zvenigorod, 2008), p. 267. http://www.researchgate.net/publication/238769202_Beam_parameters_measurement_of_technological_10_MEV_linac. Accessed October 11, 2021.
8. A. P. Chernyaev, M. A. Kolyvanova, and P. Yu. Borshchegovskaya, Moscow Univ. Phys. Bull. (Engl. Transl.) **70**, 457 (2015). https://doi.org/10.3103/S0027134915060090
9. V. I. Boiko, A. N. Valyae, and A. D. Pogrebnyak, Phys.—Usp. **42**, 1139 (1999). https://doi.org/10.1070/PU1999v042n11ABEH000471
10. R. A. Salimov, Phys.—Usp. **43**, 189 (2000). https://doi.org/10.1070/1070pu2000v043n02ABEH000671
11. A. G. Gurin, E. A. Kornilov, and R. S. Lozhkin, Elektrotekh. Elektromekh., No. 4, 47 (2013).
12. M. R. Cleland, in *Industrial Applications of Electron Accelerators* (CERN Accelerator School, Zeegse, 2005), p. 383.
13. S. Machi, in *Proc. Int. Topical Meeting on Nuclear Research Applications and Utilization of Accelerators* (Vienne, 2009), SM/EB-04.
14. D. H. Wilkinson, *Ionization Chambers and Counters* (Cambridge Univ. Press, New York, 1950).
15. Y. I. Bychkow, Y. D. Korolevn, and A. P. Khuzeev, Sov. Tech. Phys. **19**, 140 (1974).
16. A. V. Eletskii and B. M. Smirnov, Sov. Phys. Usp. **25**, 13 (1982). https://doi.org/10.1070/PU1982v025n01ABEH004494
17. R. Hooke and T. A. Jeeves, J. Assoc. Comput. Mach. **8**, 212 (1961).
18. J. A. Nelder and R. Mead, Comput. J. **7**, 308 (1965).
19. S. V. Blazhevich and V. A. Stratienko, USSR Patent No. 1667519, 1991.