7. W. P. Wolf, "Cooling by adiabatic magnetization," Phys. Rev., 115, 1196 (1959).
8. V. V. Druzhinin, V. M. Mel'nikov, and V. V. Shkarubskii, "The magnetocaloric effect in strong magnetic fields," Fiz. Tverd. Tela, 21, 1750 (1979).
9. V. V. Znamenskii and N. G. Fakidov, "The magnetocaloric effect in pulsed magnetic fields," Fiz. Met. Metalloved., 13, 312 (1962); A. S. Nikitin, A. S. Andrienko, et al., "Magnetic phase transitions and the magnetocaloric effect in Tb—Y alloys," Zh. Eksp. Teor. Fiz., 73, 228 (1977).
10. C. Kittel, The Quantum Theory of Solids [Russian translation], Nauka, Moscow (1967).
11. V. V. Druzhinin and Yu. P. Irkhin, "The spin Hamiltonian for exchange interactions in rare-earth metals," Zh. Eksp. Teor. Fiz., 51, 1856 (1966).
12. A. A. Antipin, S. P. Zapasskii, and S. G. Lukter, "Electron spin resonance on impurity ions in glasses," in: Abstracts for the Seventh All-Union Symposium on Crystal Spectra [in Russian], Leningrad (1982).

SIMULATING THE RETARDATION OF AN UNCOMPENSATED ELECTRON BEAM IN A THIN ABSORBER

V. I. Boiko, E. A. Gorbachev, and V. V. Evstigneev

UDC 537.533.7:539.124.17

1. Introduction. Advances in accelerator engineering have extended the range of applications for high-current electron beams HCEB [1]. A feature of the interaction between HCEB and matter is that allowance must be made for the inherent magnetic fields in the beam and the change in the properties of the medium through which it passes. There are many experimental difficulties, while the algorithms are complicated and many different conditions are used with HCEB (vacuum gas, plasma, solids, and geometry associated with boundary conditions), while there are various interaction mechanisms with the matter and fields, so the problem has not been completely solved. Theoretical models are approximate and usually involve the assumption of one or two interaction mechanisms with matter and fields (problems in electron optics [2-5], Coulomb scattering, and the effects of electric fields [6] or magnetic ones [7, 8] for the beam, as well as magnetohydrodynamic description [9]), together with simplifying assumptions. We have previously considered the quasistationary treatment of relativistic HCEB absorption at currents, where we made allowance for Coulomb scattering and the effects of the electric and magnetic fields of the beam in two-dimensional geometry, particularly the relative contribution from these to HCEB retardation [10, 11].

Here we consider the passage of an uncompensated HCEB through a thin target, which is of practical interest in relation to extracting the beam through an anode foil or a foil in a drift chamber, as well as to the use of foils as constructional components in diagnostic equipment.

2. Model and Calculation Program. An iteration method was used in this quasistationary method, which enables one to split up the self-consistent treatment into a series of non-self-consistent ones [4, 5], together with the Monte Carlo method for calculating the beam particle paths with allowance for Coulomb scattering. We used two-dimensional geometry with azimuthal symmetry, which included the exit foil in the accelerator, the cylindrical drift tube, the absorber (in general, of arbitrary thickness and having a coaxial hole), and the collector (Fig. 1). This general geometry enables one to consider a large range of transport problems (absorption in thin targets and total-absorption absorbers, and also transport and collimation with allowance for the component of the electron flux scattered in matter).

The following conditions are required if a quasistationary treatment is to apply. Firstly, it is assumed that the magnetic-field diffusion depth into matter is comparable with the electron range or with the absorber thickness. This condition is obeyed for most high-current accelerators with characteristic pulse lengths of about 10^{-7} sec for foil thicknesses $\leqslant 10^{-4}$ m. Secondly, the fast-electron energy relaxation time in a condensed medium is $\sim 10^{-11}$-10^{-12} sec, and the retardation times in megavolt electric fields of $\leqslant 10^{-10}$ sec

Tomsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 20-25, November-December, 1984. Original article submitted August 30, 1983.

 0021-8944/84/2506-0828$08.50

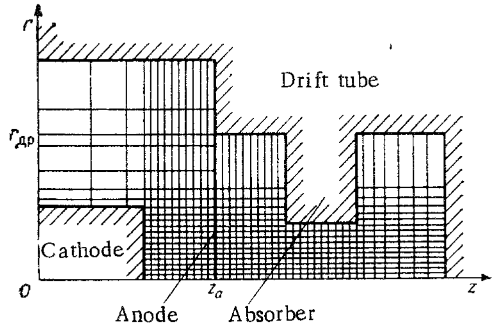

Fig. 1

are much less than the characteristic times for the changes in the parameters of the beam and the substance (about 10^{-9} sec). Thirdly, the wavelength corresponding to an electromagnetic-field frequency of about 10^9 sec^{-1} is much greater than the dimensions of the region considered of about 10^{-1} m. In that case, one can neglect effects related to the finite electromagnetic-field propagation speed.

The algorithm includes calculating the electron paths and calculating the fields from these paths. The particle paths in matter were calculated by the Monte Carlo method via a model for continuous energy loss, with the path split up into a finite number of segments, on which we allowed for a change in momentum due to multiple Coulomb scattering in accordance with a standard algorithm [12]. The angular distribution of the scattered particles was randomized from a Moliere distribution. Over the same segment, we also allowed for the additional change in momentum due to the inherent and external electric and magnetic fields, in accordance with the solutions to the relativistic electron-motion equation.

The electric field $E\{E_r, 0, E_z\}$ and the magnetic field $\mathbf{H}\{0, H_\varphi, H_z\}$ of the beam were calculated on a coordinate grid in a cylindrical coordinate system throughout the relevant region (Fig. 1) by reference to the charge and current densities, which were determined at the stage of calculating the particle paths as in the current-tube method [4, 5].

See [10] for a complete description of the algorithm and program. The mean time required to calculate the spatial, angular, and energy characteristics was about 1.5-2 h with an M-222 computer working with a coordinate grid of dimensions about 30 × 30 and 5-7 iterations. Figure 2 shows the block diagram for the program.

3. Simulating High-Current Electron Beam Retardation in a Thin Absorber. The interaction of an HCEB with a foil is such that it is necessary to consider the beam within and outside the absorber and to incorporate the boundary conditions for the fields, which are determined by the given geometry. The calculations were performed for aluminum foil anodes of thicknesses $5 \cdot 10^{-5}$ and 10^{-4} m in a cylindrical drift chamber of radius $1.5 \cdot 10^{-2}$ m and length $9.5 \cdot 10^{-2}$ m. The current in the uncompensated beam was up to 50 kA and the initial beam radius was $2 \cdot 10^{-3}$ m.

The conductivity of the resulting plasma is quite high at these current densities, so the effects of the electric field in the foil can be neglected [9]. Boundary conditions representing grounding of the foil and drift chamber were used for the electric field behind the foil.

We assumed that the foil receives a collimated electron beam with known parameters (current, energy of 1 MeV, radius, and initial direction). The operation of the diode was not calculated in this case, but in calculating the electron absorption in the foil we allowed for the effects of the steady electric field in the diode of 10^8 V/m on the particles backscattered from the foil.

The results showed that the main features of the absorption in a foil are determined by the production of a negative space-charge region behing the foil. The electrons passing through the foil encounter a potential barrier, whose height is comparable with the kinetic energy. The longitudinal projection of the retarding electric field behind the foil is $2.2 \cdot 10^9$ V/m at the axis of the beam for a current of 50 kA and a foil thickness of 10^{-4} m, but it falls rapidly to zero at a distance of about $6 \cdot 10^{-4}$ m along the OZ axis behind the foil, and it is then replaced by an accelerating field. For a current of 10 kA, the retarding field

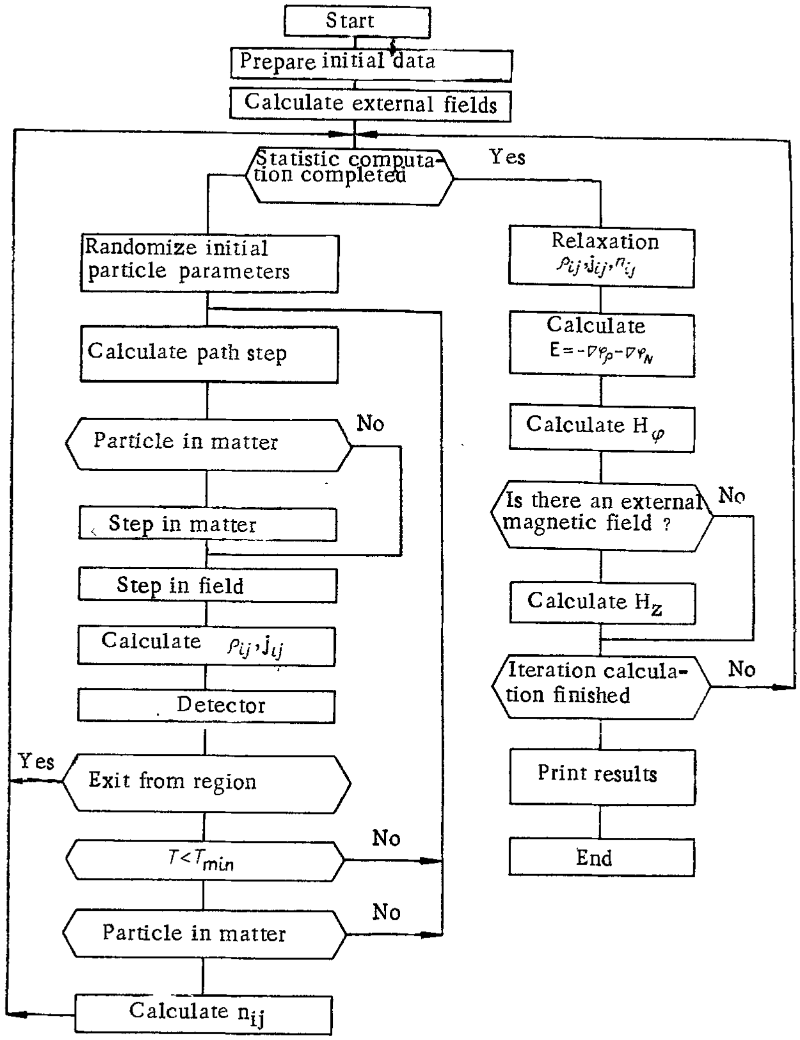

Fig. 2

is less than about $7\cdot10^8$ V/m, but the extent of it along the axis increases to $2.5\cdot10^{-3}$ m. The radial projections of the electric field did not exceed $4.7\cdot10^8$ and $1.9\cdot10^8$ V/m for currents of 50 and 10 kA correspondingly.

The retardation and scattering at the barrier cause the beam to become inhomogeneous, in conjunction with the effects of its own magnetic field, and the spectral and angular characteristics are deformed. The energy spectrum varies in accordance with the electric-field distribution. Directly behind the foil, the spectrum becomes continuous and contains a large number of slow particles. After passage through the potential barrier, the continuous spectrum is displaced to higher energies (Fig. 3).

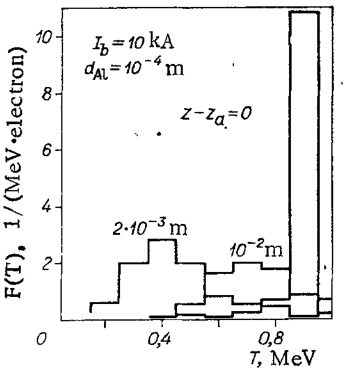

Fig. 3

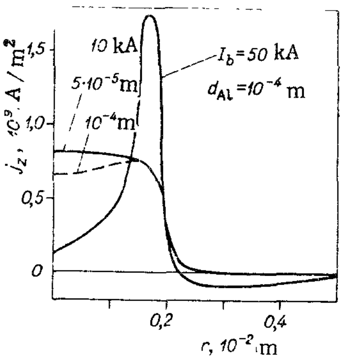

Fig. 4

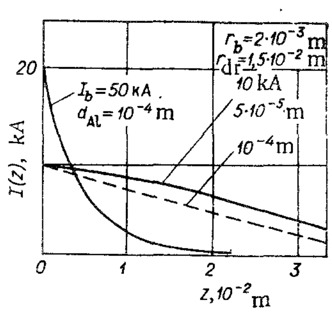

Fig. 5

The scattering at the potential barrier causes some of the electrons to return to the foil, and there is a current from particles moving in the reverse direction, while the spatial distribution of the current density becomes inhomogeneous (Fig. 4). As the beam current increases, there is an appreciable tendency to produce a tubular beam, which agrees with analytical consideration of self-consistent stationary states for HCEB in a cylindrical waveguide [13].

Figure 5 shows the current in the beam extracted through the foil as a function of the longitudinal coordinate. With an initial current of 50 kA, the current behind the foil decreases rapidly, and at a distance of about $2\cdot10^{-3}$ m it becomes small, i.e., the extraction and transport of an uncompensated HCEB are inefficient. For an initial current of 10 kA, there are mainly scattering at the barrier and smooth current reduction due to electron loss at the walls of the drift chamber.

The electron reflection from the barrier on the one hand and in the field of the diode on the other side of the foil causes the electrons in the uncompensated beam to pass repeatedly through the foil, and then there is elevated energy deposition in the foil by comparison with the weak-current case. For example, the electrons in a beam with an initial current of 50 kA on average pass 2.4 times through an aluminum foil of thickness 10^{-4} m, and the energy lost in the foil increases from 4% for a low-current beam to 15% of the initial energy, i.e., by about a factor 3.8. Table 1 gives the energy deposited in aluminum foils of thickness d, the mean number of electron intersections p, and the mean axial angles of the electrons behind the foil in ranges in angle ϑ of $0 - \pi/2$ and $0 - \pi$ (the beam incident on the foil is collimated), in each case as a function of beam current.

The energy deposition from the uncompensated beam exceeds that arising solely from the inherent beam field (charge neutralization), which is defined by the standard formula (charge neutralization), which is defined by the standard formula $\alpha = 3I_b/2I_A$, where I_b is the beam current and $I_A = 17\beta\gamma$(kA) is the Alfven current. The absorption mechanism for the uncompensated beam in a thin absorber corresponds to the following energy deposition:

$$\Delta T = Sd\left[1 + a(p-1)\left|\int\limits_{\pi/2}^{\pi} \frac{F(\vartheta)}{\cos\vartheta}\,d\vartheta\right|\right], \tag{3.1}$$

where S(T) are the specific ionization energy losses and $F(\vartheta)$ is the angular distribution of the particles in the foil. Formula (3.1) is derived from a detailed analysis of the absorption mechanism and generalization from the result. The foil absorbs the energy deposited by the forward beam and the energy of particles reflected from the barrier behind the foil

TABLE 1

d, 10^{-6} m	I_b, kA	$\langle\vartheta\rangle$ $0-\frac{\pi}{2}$, deg	$\langle\vartheta\rangle$ $0-\pi$, deg	p	ΔT, rel. units
50	0	12	12	1,0	1,0
100	0	19	19	1,0	1,0
50	10	13	15	1,0	1,2
100	10	24	32	1,2	1,6
100	50	28	75	2,4	3,8

or from the diode field ahead of the foil and returning to it. The first term is the standard expression for the energy loss in the foil, which involves the assumption of constant specific ionization losses in the foil, which is so in this case. The second term incorporates the repeated passage through the foil of electrons scattered $p - 1$ times and the angular distribution $F(\vartheta)$ of these. The Larmor radius of an electron in the inherent beam field is much greater than the foil thickness in the current range quoted, so the energy lost by the scattered particles in the foil is proportional to the path length, i.e., $d/\cos\vartheta$. The calculations show that the electron energy distribution at high energy deposition factors is close to isotropic, namely proportional to $\cos^2\vartheta$, in the forward and reverse directions, so for definiteness the limits of integration can be taken from $\pi/2$ to π. This formula agrees with computer calculations to within about 15%. Its applicability is restricted by the effects of the expanding plasma and the beam neutralization. The coefficient $a \approx 0.6$ incorporates the uncertainty in specifying p and $F(\vartheta)$ within the foil.

As the foil thickness increases, so does the mean particle angle, which leads to more effective reflection from the barrier and to increase in the mean number of foil intersections, and thus to an increase in the energy loss in the foil. The reverse tendency occurs for a neutralized beam because of the different absorption mechanism, which is related to the electron magnetization: As the foil thickness increases, the rise in the contribution from Coulomb scattering hinders the magnetization, and the absorption effectiveness in the target falls [7].

The calculations agree qualitatively with the prediction from a theoretical study [14], which dealt with the formation of a fast-electron cloud on injecting a high-power relativistic electron beam into a vacuum or plasma. In particular, it was pointed out that a potential barrier could occur together with oscillations of the electrons around the anode foil and diode current gating, which was based on solving the kinetic equation, where elastic scattering at the nuclei and retardation at the atomic electrons were incorporated into the collision integral.

LITERATURE CITED

1. A. N. Didenko, V. P. Grigor'ev, and Yu. P. Usov, High-Power Electron Beams and their Applications [in Russian], Atomizdat, Moscow (1977).
2. J. Lawson, The Physics of Charged-Particle Beams, edited by A. A. Kolomenskii [Russian translation], Mir, Moscow (1980).
3. S. I. Molokovskii and A. D. Sushkov, High-Intensity Electron and Ion Beams [in Russian], Énergiya, Leningrad (1972).
4. N. P. Kanareva, V. Ya. Rivkind, and B. A. Samokish, "Calculating electron-optical systems of projector type," Opt.-Mekh. Prom., No. 10 (1969).
5. V. T. Astrelin and V. M. Sveshnikov, "Calculating the motion of a relativistic charged-particle beam in electromagnetic fields," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1979).
6. A. N. Didenko, S. A. Chistyakov, and A. P. Yalovets, "The interaction of a high-current relativistic electron beam with matter," At. Energ., 47, No. 5 (1979).
7. M. M. Widner, E. J. T. Burns, et al., "Electron deposition in thin targets," in: Proc. 2nd Int. Top. Conf. on High Power Electron and Ion Beam Res. and Technol., Vol. 1, Ithaca, N. Y. (1977).
8. E. Nardi, E. Peleg, and Z. Zinamon, "Self-magnetic field effects on energy deposition by intense relativistic electron beam," Plasma Physics, 20, No. 6 (1978).
9. V. V. Gorev, A. V. Koldoba, Yu. A. Poveshchenko, et al., Heating and Hydrodynamic Expansion of Matter on the Absorption of a High-Current Relativistic Electron Beam [in Russian], Preprint No. 132, Institut Prikl. Matematika, Moscow (1980).
10. V. I. Boiko, E. A. Gorbachev, and V. V. Evstigneev, "The distribution of relativistic electrons from a high-current beam in a solid-state target," Fiz. Plazmy, 9, No. 2 (1983).
11. V. I. Boiko, E. A. Gorbachev, et al., "The energy distributions of electrons from a high-current beam in matter: spatial and angular electron distributions for a high-current beam in matter," Izv. Vyssh. Uchebn. Zaved. USSR, Fizika, 5, No. 6 (1981).
12. V. F. Baranov, Electron-Radiation Dosimetry [in Russian], Atomizdat, Moscow (1974).
13. V. S. Voronin, Yu. T. Zozulya, and A. N. Lebedev, "Self-consistent stationary states for relativistic electrons in a drift space," Zh. Tekh. Fiz., 42, No. 3 (1972).
14. D. D. Ryutov and G. V. Stupakov, "Formation of a fast-electron cloud on injecting a high-power relativistic electron beam into vacuum," Fiz. Plazmy, 2, No. 4 (1976).