BALLISTIC FOCUSSING OF BEAMS BY ION DISCHARGING IN A CONICAL MAGNETIC FIELD

V. T. Astrelin and E. M. Syresin

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An effective method of producing high power ion flows is the oscillating electron system [1-4]. Such systems permit production of a beam with current density $j_i \approx$ 1-10 kA/cm^2 with ion energies E $\approx$ 1 MeV. Such beams can be used for plasma heating in long solenoidal systems, but are useful in controlled thermonuclear synthesis only with a significant increase in current density. Since ion beams obtained by this method are accelerated in a quite long magnetic field, the amount of compression achievable is limited by the attainable magnetic field. The severity of this limitation can be decreased by discharging the ions into neutral atoms with further ballistic focussing. Such a focussing method was first proposed in [5]. Its basic principle is the following: the ion beam enters from the acceleration region into a region with conical magnetic field, where the ions are neutralized on a gas target. The flow of neutrals thus obtained converges to a point, and unneutralized ions and the neutralizing electrons exit from the system along the diverging magnetic field. A diagram of the focussing system is shown in Fig. 1, where the dashed curves are trajectories of neutrals and the solid ones are magnetic field force lines, L is the focus distance, z = 0 is the magnetic field focus position, z_M is the position of the neutralizing target, Δz is the length of the target, ΔL is the length of the transition region.

The possibility of realizing this technique depends on the efficiency of neutralization. If we consider proton beams at energies E $\simeq$ 0.5-1 MeV the neutralization section is so small that the concept becomes completely inapplicable. On the other hand, for ions with atomic weight of 10-40 a.u. the situation becomes more favorable, since at E $\simeq$ 0.5-1 MeV neutralization of such ions in a gas of the same element is close to resonant and occurs with sections exceeding the stripping section [6, 7].

The maximum neutral flux density at the focus point is determined by the angular scattering of the ion flow. In order that the beam should not take on additional angular scattering in the region of transition from the homogeneous to the conical field, this transition should be quite smooth, i.e., its length ΔL should be 3-4 times greater than the ionic Larmor radius r_L, calculated from the total energy.

The goal of the present study is a clarification of the requirements for length of the transition region from homogeneous to conical magnetic field, study of the effect of initial angular scattering on beam compression, and choice of optimum parameters of the magnetic system for maximum increase in flux density.

1. Calculation of Ion Beam Ballistic Focussing. Assuming the beam radius R_0 to be small in comparison to the focal distance L, we will use the paraxial approximation to describe the magnetic field, in the framework of which the field components are calculated in the following manner:

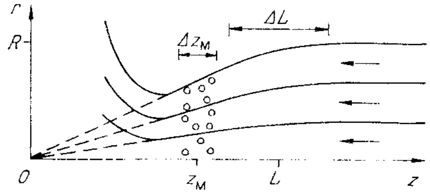

Fig. 1

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$$H_r = -rH'/2,\ H_z = H.$$

Here z, r are cylindrical coordinates; H is the field on the system axis. To specify the field on the axis we use the approximation $H = H_0(1 + \exp(-\nu^{2\alpha})/\nu^{2\alpha})^{1/\alpha}$, $\nu = z/L$. For $\nu >> 1$ the magnetic field is homogeneous; for $\nu << 1$, conical: $H = H_0/\nu^2$. The length of the region of transition ΔL from the homogeneous field to the conical is defined by the parameter α, $\Delta L \sim L/\alpha$.

We will find the change in transverse ion velocity related to the nonadiabatic nature of motion in the transition region. We choose a travelling coordinate system such that the Z-axis coincides with the tangent to the force line, the Y-axis is directed along the normal to the force line, and the X-axis is along the binormal. We write the equation of ion motion in the paraxial approximation:

$$\begin{aligned}
\dot v_y &= \omega v_x + \frac{1}{2H}\frac{\partial H}{\partial z} v_y v_\parallel - \frac{v_\parallel^2}{R},\\
\dot v_x &= -\omega v_y + \frac{1}{2H}\frac{\partial H}{\partial z} v_x v_\parallel,\\
\dot v_\parallel &= \frac{v_y v_\parallel}{R} - \left(v_x^2 + v_y^2\right)\frac{1}{2H}\frac{\partial H}{\partial z},
\end{aligned} \tag{1.1}$$

where $\omega = eH/mc$ is the Larmor frequency; v is the ion velocity along Z; $R = 4H^2[r(3H'^2 - 2H''H)]$ is the radius of curvature of the force line in the paraxial approximation; r is the radius of the force line at point z.

We will assume the transverse particle velocities to be small. For this to be true it is necessary that their initial values be small, and that the previously mentioned condition $\Delta L \gtrsim (3\text{-}4)r_L$. For $v_\parallel \gg v_\perp = (v_x^2 + v_y^2)^{1/2}$ in the first approximation $v_\parallel = \mathrm{const}$, and in the variables $I = v_\perp/H^{1/2}$ and $\varphi = \arctan(v_x/v_y)$ system (1.1) has the form

$$\frac{dI e^{i\varphi}}{d\nu} = -i\frac{L\omega}{v_\parallel} I e^{i\varphi} - \frac{v_\parallel L}{RH^{1/2}}.$$

Solving this system, we obtain

$$I e^{i\varphi} = \frac{v_{\perp 0}}{H^{1/2}} e^{i\varphi_1} - \int_{\nu_0}^{\nu} \frac{v_\parallel L}{RH^{1/2}} e^{i\frac{L}{r_L}\int_{\nu}^{\nu'}\frac{H}{H_0}d\nu''} d\nu'. \tag{1.2}$$

Here $\varphi_1 = \varphi_0 - \frac{L}{r_L}\int_{\nu_0}^{\nu}\frac{H}{H_0}d\nu$ is the phase of Larmor rotation at the point with coordinates ν and r; ν_0, $v_{\perp 0}$, $\varphi_0 = \arctan(v_{x0}/v_{y0})$ are the initial values of longitudinal coordinate, transverse velocity, and particle phase. Integrating on the right side of Eq. (1.2), we find the components of the transverse velocity v_x and v_y as functions of ν and the radius r_0 [8]:

$$\begin{aligned}
v_x &= v_{\perp 0}\left(\frac{H}{H_0}\right)^{1/2}\sin\varphi_1 + v_\parallel\frac{r_0}{L}\delta\sin\varphi_2\left(\frac{H}{H_0}\right)^{1/2} + v_\parallel\frac{r_0}{L}\gamma\left(\frac{H}{H_0}\right)^{1/2},\\
v_y &= v_{\perp 0}\left(\frac{H}{H_0}\right)^{1/2}\cos\varphi_1 + v_\parallel\frac{r_0}{L}\delta\cos\varphi_2\left(\frac{H}{H_0}\right)^{1/2},
\end{aligned} \tag{1.3}$$

where $r_0 = r(H/H_0)^{1/2}$ is the initial radius of the ion trajectory, equal to r at the point ν; $\varphi_2 = (L/r_L)\,\mathrm{Re}\int_{\nu}^{\xi_0}(H/H_0)\,d\xi$; ξ_0 is the coordinate of the null of the function $H(\xi)$ in the complex plane;

$$\delta = \frac{\pi}{2}(1+2\alpha)\left(\frac{\alpha}{\alpha+1}\right)^2\frac{L}{r_L}\exp\left(-\frac{L}{r_L}\mathrm{Im}\int_{\nu}^{\xi_0}\left(\frac{H}{H_0}\right)d\xi\right);$$

$$\gamma = (1+4\alpha)\frac{r_L}{L}\nu^{4\alpha+2}.$$

The first terms in system (1.3) are related to the adiabatic invariant $v_{\perp}^2/H$, the second ones describe the effects of nonadiabatic motion arising upon passage of the particles through the transition region. The third term in the expression for v_x is of drift origin, and is caused by the presence of centrifugal force, related to curvature of the magnetic field force line.

Depending on the coordinates of the neutralization point, the neutrals formed have differing transverse velocities. As a consequence, beam focussing for an extended target is significantly degraded. System aberrations also can have a marked effect on flow compression. It is obvious that one of the conditions for optimum focussing is smallness of aberrations in the neutralization region. The measure of aberrations in the focussing system is the angle formed by the force line with the direction to the focus: $\chi = r/z - H_r/H_z$. Assuming that the neutralizing target is located in a magnetic field close to conical we have $\chi \simeq (r_0/L)\nu^{4\alpha}$.

Knowledge of the trajectory of an individual particle after neutralization permits calculation of the flow compression in the magnetic field focal plane. We select a group of ions moving in a homogeneous magnetic field in a ring of radius r_0 and thickness dr_0. After neutralization these particles arrive in the focus plane in a ring of radius $r_{\perp}$, thickness $dr_{\perp}$, with

$$r_{\perp}^2 = L^2\nu^2\left(\frac{v_x^2}{v_{\parallel}^2} + \frac{v_y^2}{v_{\parallel}^2} + \chi^2 + \frac{2v_y}{v_{\parallel}}\chi\right). \tag{1.4}$$

Substituting in Eq. (1.4) the expressions for v_x, v_y, and χ, we find

$$r_{\perp}^2 = L^2\theta^2 + \beta^2 r_0^2 + 2\beta r_0 L\theta\cos\varphi_3, \tag{1.5}$$

where $\theta = v_{\perp 0}/v_{\parallel}$; $\beta^2 = \delta^2 + \gamma^2 + \varepsilon^2 + 2\delta(\varepsilon^2 + \gamma^2)^{1/2}\sin\varphi_4$; $\varepsilon = \nu^{4\alpha+1}$; $\varphi_3 = \varphi_0 - \frac{L}{r_L}\int\limits_{\nu_0}^{\nu}\frac{H}{H_0}d\nu - \arctan\frac{\gamma + \delta\sin\varphi_1}{\varepsilon + \delta\cos\varphi_1}$; $\varphi_4 = \varphi_2 - \arctan(\gamma/\varepsilon)$.

The parameters δ, γ and ε have obvious geometric meaning: they are equal to the ratio of the particle trajectory radius in the focus plane $r_{\perp}$ to the initial radius with consideration of nonadiabatic motion, drift velocity, and aberrations. The initial angular scattering θ appearing in Eq. (1.5) may depend on a number of factors determined by the method by which the ion beam is generated. For the gas-dynamic generation method such factors could be the radial electric field E_r in the acceleration region, as well as fluctuations in the electric field generated by the nonequilibrium nature of the distribution function for the cloud of oscillating electrons [5]. As experiment shows, the characteristic angular scattering of ions with an energy $E \gtrsim 1$ MeV in a magnetic field $H_0 \gtrsim 10$ kG comprises $\sim$0.05 rad [9]. It should be noted that the angular scattering related to E_r can be suppressed by a strong magnetic field.

Depending on the initial phase φ_0 the neutral particles which were discharged at the point with coordinates r_0 and z enter the focal plane in a ring of radius $L\theta + \beta r_0 > r_{\perp} > |L\theta - \beta r_0|$ Since all phases are equiprobable, the neutral flux density at the focus is determined by the expression $2\pi dj r_{\perp} dr_{\perp} = A d\varphi_0$. Differentiating Eq. (1.5) with respect to φ_0 and determining the constant A from conservation of the neutral flux, we obtain

$$dj(r_{\perp}, z) = j_i\frac{H}{H_0}n_0\sigma_{10}dz\exp\left[-n_0(\sigma_{10} + \sigma_{01})(z_2 - z)\right]dF. \tag{1.6}$$

Here j_i is the density of the ion flux in the acceleration region; σ_{10} is the section for ion neutralization on a neutral; σ_{01} is the neutral stripping section; n_0 is the gas density in the target; z_2 is the coordinate of the target boundary;

$$dF = \frac{r_0 dr_0}{\left[\left(R_2^2 - r_{\perp}^2\right)\left(r_{\perp}^2 - R_1^2\right)\right]^{1/2}};\quad R_2 = L\theta + \beta r_0;\quad R_1 = |L\theta - \beta r_0|. \tag{1.7}$$

Integrating Eq. (1.7) over r_0, we have

$$F(r_{\perp}, z) = \frac{2}{\pi\beta^2}\{[(k + 1)F_1(\psi, (1 - k^2)^{1/2}) - (1 - k)F_1(\psi, k)] +$$
$$+ 2[(1 - k)\Pi(\psi_1, k, k) - k\Pi(\psi, (1 - k), (1 - k^2)^{1/2}]\},$$

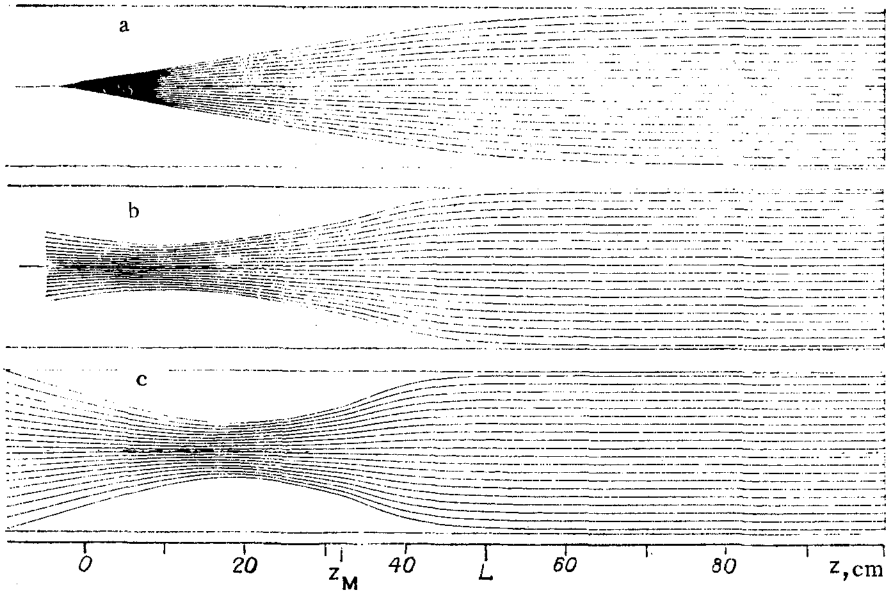

Fig. 2

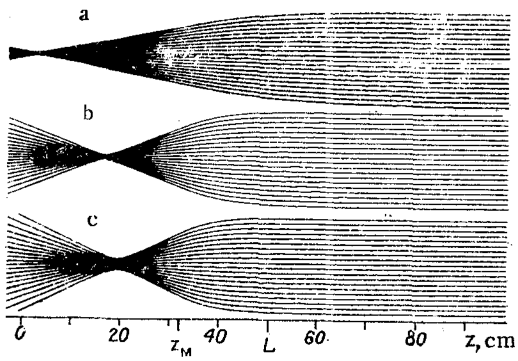

Fig. 3

where

$$k = r_\perp / L\theta, \ \psi = \arcsin(k_1) \quad \text{at} \quad L\theta > r_\perp > |L\theta - \beta R_0|;$$
$$k = L\theta / r_\perp, \ \psi = \arcsin\left(k_1^{-1}\right) \quad \text{at} \quad |L\theta + \beta R_0| > r_\perp > L\theta;$$
$$k_1 = \frac{r_\perp}{L\theta} \frac{L\theta - |r_\perp - \beta R_0|}{\beta R_0 + r_\perp - L\theta}; \ \psi_1 = \arcsin\left((1+k)^{-1/2}\right);$$

where F_1 and Π are normal Legendre elliptic integrals of the first and third sort.

In the absence of initial angular scattering of the beam ions $F(r_\perp, z) = \beta^{-2}$. Integrating Eq. (1.6) over r_0 and z, we find the neutral flux density in the focal plane of the magnetic system.

To verify the accuracy of the theoretical calculations a numerical calculation of ion trajectories in an inhomogeneous magnetic field was performed. The application program package "POISSON-2" was used [10]. The equation of motion of particles in the inhomogeneous magnetic field was solved by a third order Runge-Kutta method. The solution of the equation of motion can be used to determine particle coordinates in the magnetic field focal plane, knowledge of which permits finding the beam compression in the absence of initial angular scattering. Moreover numerical calculations make it possible to evaluate beam compression for all magnetic system parameters, where particle motion is not adiabatic.

2. Numerical Calculation Results. System analysis and optimization were performed for physically attainable beam parameters and magnetic fields. With consideration of this, values used for the acceleration region were H_0 = 70 kG, L = 50 cm, R_0 = 10 cm. All numerical calculations were performed for singly charged neon ions. These were chosen because at E ≈ 0.2-1 MeV the resonant neutralization section exceeds the stripping section and is quite high in

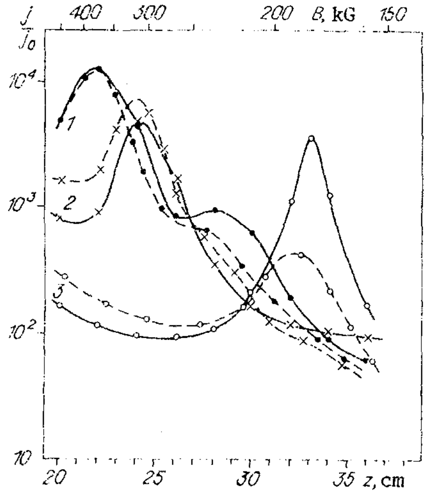

Fig. 4

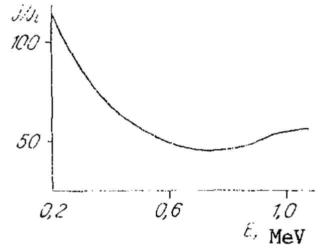

Fig. 5

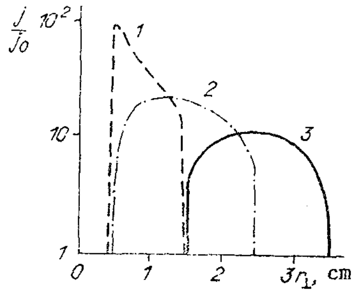

Fig. 6

absolute value [6, 7]. The dependence of beam compression on the parameter α, which characterizes the length of the transition from the homogeneous field to the conical one, is illustrated in Figs. 2, 3, which show trajectories of particles with E = 0.5 and 1 MeV respectively for α = 1, 2, 3 (a-c). Neutralization efficiency is 100%, and the coordinate of the thin dense target z_M = 32 cm. As calculations show and as is evident from Figs. 2, 3, at α = 2, 3, because of the strong dependence of beam compression on the coordinate of neutralization, effective focussing is possible only for beams which are close to monoenergetic. A field with α = 1 is optimal for focussing beams with a broad energy spectrum. As follows from Eq. (1.7), the greatest compression for ion beams with low angular scattering, neutralized on a thin dense target is achieved at $\delta^2 = \gamma^2 + \varepsilon^2$ and $\varphi_3 = \pi$, i.e., when the nonadiabatic effect is compensated by aberrations and drift velocity. As is evident from Fig. 4, depending on the target position z_M maxima are found in the compression coefficient j/j_0 corresponding to optimum focussing regions; j_0 is the density of the neutralizing ion flux, with solid lines being the result of numerical calculation and dashed, theoretical calculation. Curves 1-3 were obtained for E = 0.2, 0.5, and 1 MeV for α = 1.

The dependence of beam compression on particle energy for the case of neutralization of neon ions on a gaseous target of finite density $n_0 = 5 \cdot 10^{14}$ cm^{-3} and thickness (30 cm < z_M < 38 cm) is shown in Fig. 5.

The presence of initial angular scattering of the ions leads to the apppearance of a quite strong dependence of focused beam density on radius $r_\perp$. The beam becomes tubular, its radius varying over the range $L\theta + \beta R_0 > r_\perp > \min(L\theta, |L\theta - \beta R_0|)$. For low initial angular values beam compression is determined essentially by nonadiabatic motion, drift, and aberrations, while at $L\theta > \beta R_0$ it is determined by the initial angular scattering. The dependence of compression on initial angular scattering is shown in Fig. 6 for E = 500 keV, z_M = 32 cm (θ = 0.01, 0.03, 0.05, lines 1-3). Discharging of the ions occurs on a thin dense target. For optimum focussing parameters the critical angle value $\theta \sim \beta R_0/L$ comprises 1-2°.

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COPPER DIMERS IN THE VAPOR FLOW IN ELECTRON-BEAM VAPORIZATION

A. K. Rebrov, S. Ya. Khmel',
and R. G. Sharafutdinov

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Electron-beam heating is widely used in the industry. In particular, electron-beam vaporization is used for depositing coatings and thin films in a vacuum [1]. This heating method has been used lately for producing ultrafine powders, which are formed when the vapor is mixed with a gas [2]. The characteristics of the coatings and powders are determined to a considerable extent by the physical processes occurring in the vapor flow. The formation of gaseous-phase fluxes in electron-beam vaporization has not been investigated to a sufficient extent.

The contactless methods are the preferred ones among the known diagnostics methods. One of them is the electron-beam method, which is widely used in experimental investigations of rarefied gas dynamics [3, 4].

In our experiments, the electron beam was used both as a means of vaporization and as a probe. We have investigated the luminescence spectra of copper vapor, excited by an electron beam, with the aim of devising diagnostics methods for both the vapor and the condensed phases. The presence of the copper dimer in vapor flow was the subject of a special investigation.

The Cu_2 spectrum was first detected in the luminescence of copper vapor under thermal excitation in a King furnace [5]. Two systems of molecular bands corresponding to the $B^1\Sigma_u^+ - X^1\Sigma_g^+$, and $A^1\Pi_u - X^1\Sigma_g^+$ electron transitions were identified. Subsequently, they were registered during both radiation and absorption in a King furnace [6], in a supersonic vapor jet [7], in gaseous-phase production of clusters [8], and in pulsed laser vaporization of copper into a pulsed He jet or a steady-state jet of cold He [9-11]. Besides these band systems, the C–X system [9, 10] and many others [12] have been recorded.

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