Ion acceleration by displacing the crossover of a strong current electron beam using a "gas" lens

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Several schemes were proposed in the last few years to accelerate ions by scanning strong-current electron beam (SEB).[1–3] In addition to the schemes in which the ions are accelerated in a direction perpendicular to the SEB propagation, ions can also be accelerated by moving a potential well along the beam.[2] The main problem in this case is how to move this well, for this calls for external fields comparable with the SEB fields and varying at a high rate, so as to ensure the required rate of increase of the ion energy.

We propose and consider in this paper an effective method, based on the use of a gas lens, of producing and moving an SEB crossover constituting a potential well. It is known that when an SEB is injected in a neutral gas the latter becomes ionized. The secondary electrons are then ejected from the beam practically instantaneously within a time on the order of nanoseconds under the influence of the SEB space charge forces. The remaining positively-charged ions neutralize in part the charge of the beam, and after a definite ion density $n_i = n_e/\gamma_e^2$ is reached, where γ_e is the relativistic factor of the electrons, the beam starts to descend. Accordingly, the convergence angle of the beam changes after passing through the gas lens . This shifts the crossover into the acceleration region of the ions, whose energy is determined then both by the depth of the potential well and by the rate of its displacement (Fig. 1). By adjusting the pressure in the lens and also the lens geometry it is possible to attain the required synchronism between the motion of the potential well and the motion of the ions. Thus the beam "itself" produces the fields needed to produce and move the crossover.

We neglect the action of the longitudinal component E_z of the self-field of the beam of uniform cross section on the dynamics of the electrons, and we assume also that the electron velocity v_z is constant along the SEB propagation direction, while the transverse motion is nonrelativistic. In the self-similar approximation,[4] the dynamics of an SEB in an ionized medium is described by the following equations:

the equation of continuity

$$\frac{\partial p}{\partial t'} + 2up + \frac{\partial p}{\partial x} = 0, \tag{1a}$$

the force equation

$$\frac{\partial u}{\partial t'} + u^2 + \frac{\partial u}{\partial x} = p - q, \tag{1b}$$

the ion production equation

$$\frac{\partial q}{\partial t'} = p, \tag{1c}$$

where the dimensionless variables t', x, p, u, and q are used

$$t = \frac{\tau}{\gamma_e^2} t', \quad z = \frac{\tau v_z}{\gamma_e^2} x, \quad n_e = \frac{2\gamma_e^7 m_e}{\tau^2 4\pi e^2} p, \quad v_r = \frac{\gamma_e^2}{\tau} ur, \quad n_i = \frac{2\gamma_e^5 m_e}{\tau^2 4\pi e^2} \tag{2}$$

and τ is the average ionization time.

We consider the slow variation (compared with the time of flight of the electrons through the lens) of the parameters and SEB; necessitated by the requirement that the crossover not move too rapidly, to keep the

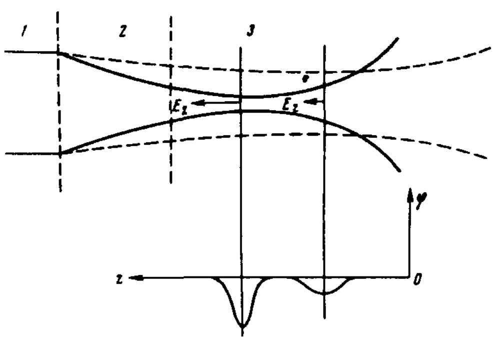

FIG. 1. Ion acceleration with a lens: 1—electron beam, 2—gas lens, 3—acceleration region.

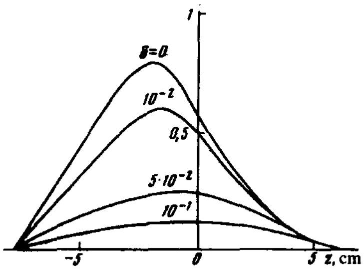

FIG. 2. Dependence of the rate of crossover acceleration on the initial ion parameters ($\delta = v_{i0}/c$).

ions from falling out of the potential well. This leads to the following limitation on the parameters of the beam and of the gas lens: $\tau/\gamma_e^2 \gg z_0/v_z$, where z is the longitudinal dimension of the lens. The time scale of the crossover displacement is then quite rigidly restricted. On the one hand, it is limited by the instant of time τ/γ_e at which compression of the beam and motion of the crossover begins. On the other hand it is limited by the gas breakdown time τ, when the backward current impedes the contraction of the beam.

The motion of the crossover and the acceleration of the ion take place outside the gas lens (in vacuum). Solution of the system (1) makes it possible to find the parameters of the beam (the angular divergence α_0 and the radius r_0) with time on the boundary with the acceleration region. Using the obtained values of $\alpha_0(t)$ and $r_0(t)$ and the relations for the envelope of the beam in vacuum,[5] we can calculate the values of the longitudinal accelerating fields in the crossover at various instants of time

$$E_z(\eta_\bullet) = \frac{60I}{r_0\sqrt{A}} e^{\eta_H^2} \int_{\eta_H}^{\eta_k} d\eta\, e^{-\eta^2} \left\{ \frac{F(\eta) - F(\eta_\bullet)}{\sqrt{[F(\eta) - F(\eta_\bullet)]^2}} - \frac{F(\eta) - F(\eta_0)}{\sqrt{[F(\eta) - F(\eta_0)]^2 + Ae^{2\eta^2}}} \right\}, \tag{3}$$

where

$$F(\eta) = \int_0^\eta e^{t^2} dt, \quad A = 6\cdot 10^{-5} I/\gamma_e^3, \quad \eta^2 = a^2/4A.$$

Calculations show that in spite of the decrease of the beam radius r_0, the angular convergence α_0 increases simultaneously. This leads to a time variation of the potential-well dimensions (depth and radius), i.e., the longitudinal accelerating fields in the crossover are given by

$$E_z = \epsilon(t)[z - z_c(t)] \tag{4}$$

$z_c(t)$ is the coordinate of the crossover. Starting with the instant of time when the crossover begins to move towards the gas lens, the coefficient $\epsilon(t)$ increases montonically and is well approximated by a function of the type dk^f, where d and k are constants determined by the parameters of the beam and of the gas lens, and $f = \gamma_e^2(t/\tau)$. The crossover moves towards the gas lens with acceleration, and the region of uniform-acceleration motion is determined by the parameters of the beam and of the gas lens. By varying the properties of the gas lens along its axis, say by introducing a pressure gradient, it is possible to vary the dimensions of this region.

To estimate the maximum energies of the accelerated ions and to choose the crossover-motion regime, it is necessary to consider the motion of an ion in a field of the type (4). Analyzing the ion motion and assuming that the ion drops out of synchronism with the moving potential well if its trajectory crosses its rear boundary, we can obtain the region of permissible initial ion positions and velocities. Figure 2 shows the dependence of the possible acceleration of the crossover on the initial positions and velocities of the accelerated ions. For example, for electron beams with currents ~100 kA and $\gamma_e \sim 5$ the energy of the accelerated ions is of the order of several dozen MeV. This energy corresponds to a characteristic ionization time $\tau = 5$ nsec. Such times can be obtained by filling the lens with Xe at a pressure 0.1 Torr or with N_2 at 0.25 Torr. The earlier calculations were made for protons. It should be noted that the proposed method is preferable for the acceleration of heavy ions, since it requires lower gas pressures in the lens, owing to the smaller velocity of the crossover, and decreases its breakdown probability. The described method can be used to accelerate ions in wide range of e/m to energies on the order of dozens of MeV/nucleon. The method is simple to realize and to adjust, and does not require complicated experimental equipment.

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