Deceleration of fast ion rarefied beam due to Cherenkov interaction with ion-acoustic waves

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The deceleration of a low-density beam of ions in plasma with developed ion-acoustic turbulence arising in strong electric field is described. The time and length of beam deceleration along and across the anisotropy axis of the wave number distribution of ion-acoustic waves are found. It is shown to what extent an increase in the strength of the electric field that generates turbulence is accompanied by a decrease in the time and length of braking. As the beam propagates along the anisotropy axis, its velocity decreases to approximately the velocity of ion sound, and the direction of propagation does not change. When the beam is decelerated with an initial velocity across the anisotropy axis, a velocity component appears along the anisotropy axis during deceleration, which results in the beam deflection from the initial direction. In this case, the modulus of the beam velocity at the end of deceleration is close to the ion sound velocity.

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I. INTRODUCTION

Ion beams are often used in studies of plasma properties in installations created as part of the controlled thermonuclear fusion (see, for example, [1–4]). In these studies it is important to know the patterns of ion beams penetration into a plasma. Such patterns are well studied under the conditions when the deceleration of ions occurs due to Coulomb interaction of beam ions with plasma particles [5–7]. The existence of an appropriate theory allows us to adequately describe the beam deceleration if the plasma state is close to thermodynamical equilibrium. In the installations with magnetic plasma confinement, states are often realized in which the effective temperatures of electrons and ions differ very much. Ion-acoustic waves can exist in nonisothermal plasma [8,9]. At the same time, under the effect of an electric field heating plasma, electrons can move relative to ions with a velocity greater than the velocity of ion sound. In such strong electric fields ion-acoustic turbulence (IAT) is developing. In these conditions the effective frequencies of particle collisions are determined not by ordinary collisions, but by their Cherenkov interaction with ion-acoustic waves. Therefore, in the plasma with developed IAT, we should expect the implementation of qualitatively new patterns of ion beam deceleration. This article is devoted to the study of the deceleration of a rarefied ion beam in a plasma with a developed IAT, which arises under the influence of an electric field $\mathbf{E}$.

Below the considered deceleration in the plasma of the ion beam propagating along and across the anisotropy axis of the IAT. It is shown how the beam velocity decreases over time or with distance increasing. In the case of beam propagation along the anisotropy axis of turbulence, ion deceleration is possible only along the vector $-e\mathbf{E}$, where e is the electron charge. Braking due to the Cherenkov interaction of the beam ions with ion-acoustic waves stops when the velocity of the beam ions decreases to the velocity of ion sound. Further deceleration, which occurs due to ordinary collisions of particles, is not considered. When the beam propagates across the anisotropy axis of IAT, simultaneously with a decrease in the transverse component of the velocity $u_\perp$, the longitudinal component of the velocity u_z changes along the vector $-e\mathbf{E}$. The features of the change in the u_z component depend on the magnitude of the field generating turbulence. In the weak field, the u_z component first increases, reaches a maximum, and then decreases. In this case, the beam deviates from the original direction by an angle greater than $\pi/4$. In the strong field, the u_z component first takes negative values, then changes its sign, reaches a maximum, and then decreases. As a result, the beam deflects by an angle less than $\pi/4$ from the initial direction. Explicit dependencies of the deceleration time and length on the plasma and beam parameters are established. It is shown to what extent an increase in the strength of the field generating turbulence is accompanied by a decrease in the deceleration time and length. Numerical calculations are performed in the case of deuterium ion beam penetration into hydrogen plasma. However, the results obtained can also be used to describe the deceleration of beams of another species of ions. To do this, it is enough to replace the ratio of charge q to mass m for deuterium with the ratio q_b/m_b for ions of b species. At the same time, the deceleration time and length will change in $(qm_b/e_bm)^2$ times, and the results of numerical calculations given in the text in the form of graphs and tables will remain unchanged.

II. GENERAL EQUATIONS

Consider a nonisothermal plasma, in which under the effect of a strong electric field $\mathbf{E} = (0, 0, E)$ a quasistationary

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distribution of ion-acoustic waves $N(\mathbf{k})$ is created, where $N(\mathbf{k})$ is wave number density in the wave number space $\mathbf{k}$. Let us study the effect of an ion beam with velocities greater than the velocities of ion-acoustic waves on such a plasma. The ion beam density is considered small compared to the plasma density. That permits neglect ion beam effect on the $N(\mathbf{k})$. To describe propagation of an ion beam in the plasma we use a kinetic equation for the ion distribution function of the beam $f = f(\mathbf{v}, \mathbf{r}, t)$:

$$\frac{\partial f}{\partial t} + \left(\mathbf{v}\frac{\partial f}{\partial \mathbf{r}}\right) + \frac{q}{m}\mathbf{E}\frac{\partial f}{\partial \mathbf{v}} = \frac{\partial}{\partial v_\alpha} D_{\alpha\beta}(\mathbf{v})\frac{\partial}{\partial v_\beta} f, \qquad (1)$$

where q and m are the charge and mass of beam ions. Small influence of relatively rare collisions of the beam ions with plasma particles is neglected. In (1) $D_{\alpha\beta}(\mathbf{v})$ is the quasilinear diffusion tensor describing interaction of beam ions with ion-acoustic waves:

$$D_{\alpha\beta}(\mathbf{v}) = \frac{q^2}{2\pi m^2}\int d\mathbf{k}\frac{k_\alpha k_\beta}{k^2}\frac{\omega_s^3}{\omega_{Li}^2}N(\mathbf{k})\delta(\omega_s - \mathbf{kv}). \qquad (2)$$

Here $\omega_s = kv_s/\sqrt{1 + k^2 r_{De}^2}$ is the frequency of ion-acoustic waves, $v_s = \omega_{Li} r_{De}$ is the velocity of ion sound, r_{De} is the Debye electron radius, and ω_{Li} is the plasma ions Langmuir frequency. We also assume that the velocity spread of the beam ions can be neglected, and their distribution function has the form

$$f(\mathbf{v}, \mathbf{r}, t) = n(\mathbf{r}, t)\delta(\mathbf{v} - \mathbf{u}(\mathbf{r}, t)), \qquad (3)$$

where $n = n(\mathbf{r}, t)$ is the density of the ion beam, and $\mathbf{u} = \mathbf{u}(\mathbf{r}, t)$ is their velocity. If the thermal velocity of the beam ions is much less (more than three times) than the velocity of the directed motion, then taking into account their thermal motion does not have a noticeable effect on further consideration. If the thermal velocity is greater than or comparable to u, then there is no point in talking about the beam. This last case is not considered further. Taking into account the explicit form of $f(\mathbf{v}, \mathbf{r}, t)$ (3) and integrating over velocities of Eq. (1), we obtain the continuity equation

$$\frac{\partial n}{\partial t} + \mathrm{div}(n\mathbf{u}) = 0. \qquad (4)$$

Further, multiplying Eq. (1) by v_α and integrating over velocities, taking into account the continuity equation (4) and the explicit form of the beam ion distribution (3), one gets

$$\frac{\partial}{\partial t}u_\alpha + \left(\mathbf{u}\frac{\partial}{\partial \mathbf{r}}\right)u_\alpha = \frac{q}{m}E_\alpha + \frac{\partial}{\partial u_\beta}D_{\alpha\beta}(\mathbf{u}). \qquad (5)$$

The density distribution of the number of ion-acoustic waves arising under the effect of the electric field $\mathbf{E}$ is axially symmetric $N(\mathbf{k}) = N(k, \cos\theta_k)$, where θ_k is the angle between wave vector $\mathbf{k}$ and vector $-e\mathbf{E}$, and $-e$ is the electron charge. Taking this into account and directing the z axis along the vector $-e\mathbf{E}$, we write the equation (5) for the components of the velocity vector $\mathbf{u} = (u_\perp, u_z)$ along and across the symmetry axis:

$$\frac{\partial}{\partial t}u_\gamma + \left(\mathbf{u}\frac{\partial}{\partial \mathbf{r}}\right)u_\gamma = \frac{q}{m}E_\gamma + \frac{\partial}{\partial u_\gamma}D(u_\perp, u_z), \qquad (6)$$

where $\gamma = \perp, z$, and diffusion coefficient has the form

$$D(u_\perp, u_z) = \frac{q^2}{\pi m^2}\int_{k_{\min}}^{k_{\max}} dkk\frac{\omega_s^3}{\omega_{Li}^2}\int_0^1 dxN(k, x)U(u_\perp, u_z, kr_{De}, x), \qquad (7)$$

$$U(u_\perp, u_z, kr_{De}, x) = \left[u_\perp^2(1 - x^2) - \left(\frac{v_s}{\sqrt{1 + k^2 r_{De}^2}} - xu_z\right)^2\right]^{-1/2}\eta\left[u_\perp^2(1 - x^2) - \left(\frac{v_s}{\sqrt{1 + k^2 r_{De}^2}} - xu_z\right)^2\right]. \qquad (8)$$

Here $\eta(y)$ is a Heaviside step function, and $x = \cos\theta_k$, $k_{\min}$ and $k_{\max}$ are the boundaries of the turbulence region in the space of wave numbers. When solving a system of equations for $u_\perp$ and u_z [see (6)], an explicit form of the function $N(k, x)$ will be needed. The consequences of the IAT theory used below are mainly presented in the review [10]. According to [10], the basis of the IAT theory is the kinetic equations for electrons and ions, which takes into account the Cherenkov interaction of particles with ion-acoustic waves, and the equation for $N(\mathbf{k})$. In this case, the equation for $N(\mathbf{k})$ takes into account the Cherenkov interaction of waves with particles and induced scattering of waves by ions. Approximate methods for constructing an analytical solution of a coupled system of equations for waves and particles are presented in [10]. Let us present the necessary results of the theory from [10]. Approximately, the function $N(k, x)$ can be represented as a product of two functions $N(k, x) = N(k)\Phi(x)$. In this case, the wave number modulo distribution has the form [10] [see formula (2.117)]

$$N(k) = \sqrt{2\pi}\pi\frac{r_{De}^2}{r_{Di}^2}\frac{n_i m_i v_s}{k^4}\frac{\omega_{Li}}{\omega_{Le}}\left(\frac{\omega_s}{kv_s}\right)^3\left[\ln\frac{\omega_{Li}}{\omega_s} - \frac{1}{2}\left(\frac{\omega_s}{kv_s}\right)^2 - \frac{1}{4}\left(\frac{\omega_s}{kv_s}\right)^4\right], \qquad (9)$$

where m_i and n_i are the mass and the density of plasma ions, r_{Di} is the Debye plasma ions radius, and ω_{Le} is the electron Langmuir frequency. In the region $kr_{De} \ll 1$, formula (9) gives the Kadomtsev-Petviashvili spectrum, and at $kr_{De} \gg 1$ it reproduces the Galeev-Sagdeev scaling. In turn, the distribution over angles $x = \cos\theta_k$ depends on the magnitude of the field strength E. In a relatively weak field (see [11] or formula (2.210) from [10]. The slight difference between (10) and (2.210) is due to the derivation of (10) with greater accuracy)

$$\Phi(x) = \frac{4E}{3\pi E_N(1+\delta)x}\frac{d}{dx}\frac{x^4}{(1-x+\varepsilon)^{1-\alpha}},$$
$$E < E_N(1+\delta)^2, \tag{10}$$

where $\varepsilon = -K\ln K$, $\alpha = -\ln 2/\ln K$, and $K = 4E/3\pi E_N(1+\delta)^2\ln 2$ are small parameters, δ is the ratio of the damping rate of ion-acoustic waves on hot resonant ions to the damping rate on electrons (see [12]), and the field strength E_N is determined by the plasma parameters and has the form

$$E_N = \frac{m_e v_s \omega_{Li}}{6\pi e}\frac{r_{De}^2}{r_{Di}^2}, \tag{11}$$

where m_e is the electron mass. In a stronger field (see [10,13], or formula (2.128) from [10])

$$\Phi(x) = \frac{2}{\pi x^2}\sqrt{\frac{E}{E_N}}\frac{d}{dx}\int_0^x \frac{t^5 dt}{\sqrt{x^2-t^2}}Q(t), \qquad E > E_N(1+\delta)^2, \tag{12}$$

$$Q(t) = \left[0.26 - 0.19t^2 + 0.31t^4 + t^2\sqrt{1-t^2}(0.09-0.31t^2)\ln\frac{1+\sqrt{1-t^2}}{t}\right]^{-1}. \tag{13}$$

The functions (9), (10), and (12) completely determine the diffusion coefficient (7), which, taking into account the explicit form of $N(k)$ (9), can be represented as

$$D(u_\perp, u_z) = \nu_f v_s^3 \int_{z_{\min}}^{z_{\max}} \frac{dz}{(1+z^2)^3}\left[\ln\frac{\sqrt{1+z^2}}{z} - \frac{0.5}{1+z^2} - \frac{0.25}{(1+z^2)^2}\right]\int_0^1 dx\Phi(x)U(u_\perp, u_z, z, x), \tag{14}$$

where $z_{\min} = k_{\min}r_{De} \ll 1$ and $z_{\max} = k_{\max}r_{De} \gg 1$, and ν_f is the frequency characterizing deceleration of the ion beam:

$$\nu_f = \frac{\omega_{Li}}{\sqrt{8\pi}}\frac{r_{De}^2}{r_{Di}^2}\frac{\omega_{Li}}{\omega_{Le}}\left(\frac{qm_i}{e_i m}\right)^2. \tag{15}$$

The expression for the diffusion coefficient (14) and the system of equations (6) for the velocity components $u_\perp$ and u_z allow us to consider the features of ion beam deceleration depending on the level of turbulence and the orientation of the ion beam relative to turbulence symmetry axis.

The proposed consideration is valid in the case of low-density beam deceleration. We indicate a restriction on the beam density. When the beam velocity u is greater than v_s, the beam ions provide an additional contribution to the increment of ion-acoustic instability and could affect the IAT. For example, in the case of the ion beam with a small thermal velocity spread, when

$$f(\mathbf{v}) = \frac{n}{(2\pi)^{3/2}v_b^3}\exp\left[-\frac{(\mathbf{v}-\mathbf{u})^2}{2v_b^2}\right], \tag{16}$$

where $v_b = \sqrt{\kappa T_b/m}$, κ is the Boltzmann constant and T_b is the effective temperature of the beam, the contribution to the instability increment is equal to

$$\gamma_b = \sqrt{\frac{\pi}{8}}\frac{\omega_{Lb}^2}{\omega_{Li}^2}\left(\frac{\omega_s}{kv_b}\right)^3(\omega_s - \mathbf{ku})\exp\left[-\frac{(\omega_s-\mathbf{ku})^2}{2k^2v_b^2}\right], \tag{17}$$

where ω_{Lb} is the beam ions Langmuir frequency. This formula takes place without taking into account the effect of IAT on the increment. IAT is decreasing the increment only. At the same time, γ_b does not exceed

$$\gamma_m = \sqrt{\frac{\pi}{8}}\frac{\omega_{Lb}^2}{\omega_{Li}^2}\omega_s\left(\frac{\omega_s}{kv_b}\right)^2. \tag{18}$$

Obviously, if $\gamma_m \ll \nu_f$, then before the beam affects the IAT, its velocity will decrease to v_s and there will be no affect. Taking $\omega_s \approx kv_s \approx \omega_{Li}$ for evaluation, we rewrite the inequality $\gamma_m \ll \nu_f$ as

$$\frac{n}{n_i} \ll \frac{1}{\pi}\frac{\omega_{Li}}{\omega_{Le}}\frac{T_b}{T_i}\frac{m_i^2}{m^2}. \tag{19}$$

This inequality imposes a restriction on the beam density at which the theory is definitely applicable. Since the thermal motion of ions was not taken into account when considering beam deceleration, this inequality makes sense provided that $\kappa T_b \ll mu^2$.

III. ION BEAM DECELERATION

Consider the propagation of deuterium ion beam in hydrogen plasma. Assume that the densities of electrons n_e and ions n_i are equal to 10^{13} cm^{-3}, and their temperatures differ by six times: $T_e = 300$ eV, $T_i = 50$ eV. Under these conditions we have the velocity of sound $v_s = 1.7 \cdot 10^7$ cm/s, parameter $\delta = 6$ [12], characteristic collision frequency $\nu_f = 2.9 \cdot 10^7$ s^{-1}, and field strength $E_N = 13$ V/cm. The frequency ν_f determines effective deceleration time τ_{eff}, which depends on the electric field strength: $\tau_{\text{eff}} = \nu_f^{-1}(E_N/E)\max\{1+\delta, \sqrt{E/E_N}\}$. In this case, deceleration distance can be estimated as $\sim v_s\tau_{\text{eff}}$.

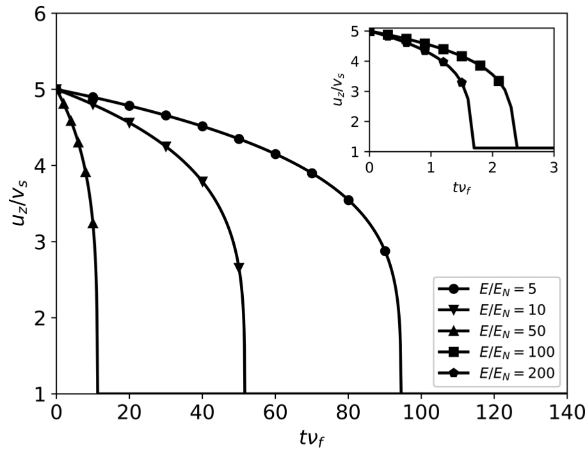

FIG. 1. Change in beam velocity u_z in time at $u_z(0) = 5v_s$.

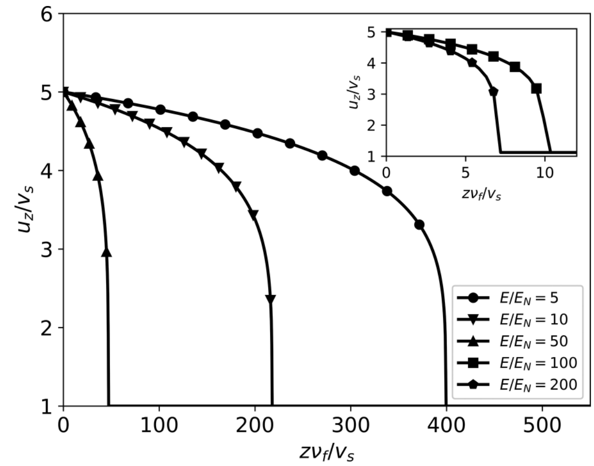

FIG. 2. Change in beam velocity u_z in space at $u_z(0) = 5v_s$.

For $\gamma = z$, one of the equations (6) contains electric field, which generates turbulence. This field also affects the ion beam velocity. However, this influence is relatively small. In particular, for $u \sim v_s$, $E/E_N \sim (1+\delta)^2$ and $(qm_i/e_i m) \sim 1$, the corresponding term in Eq. (6) can be neglected because $(1+\delta) \ll \omega_{Le}/\omega_{Li}$ [12]. In the numerical solution of Eq. (6), the term qE_γ/m is omitted. The relatively weak influence of the electric field on the motion of the beam ions is due to the fact that the effect of the effective friction force arising due to the Cherenkov interaction of ions with ion-acoustic waves is almost an order of magnitude stronger in the conditions under consideration.

Consider two configurations of beam propagation in the plasma. First, assume that the initial velocity of the ion beam is directed along the vector $-e\mathbf{E}$ and is equal to $5v_s$ or $3v_s$. Note that if the initial velocity is directed against the vector $-e\mathbf{E}$, then there is no deceleration due to the Cherenkov interaction with ion-acoustic waves, since there are no ion-acoustic waves having a component of the wave vector directed against the vector $-e\mathbf{E}$. Due to axial symmetry of the distribution of ion-acoustic waves in the case under consideration, the transverse velocity component does not arise. The numerical solution of the approximate equation (6) is shown in Fig. 1 and Fig. 2. Figure 1 shows dependencies of u_z/v_s on $\nu_f t$ obtained for several values of E/E_N. The curves in Fig. 1 illustrate the decrease in time of the beam velocity at the selected point in space and are obtained in disregard of the term $\mathbf{u}(\partial/\partial\mathbf{r})u_z$ in Eq. (6) for the velocity u_z. In another case, the curves in Fig. 2 show how the beam velocity changes in space provided that the deceleration process has been established and the time derivative $\partial u_z/\partial t$ can be neglected. In addition, in Table I numerical values of t_f time and z_f distance of deceleration are given. The deceleration stops when u_z is close to v_s. The absence of significant deceleration at u_z lower v_s is associated with an abnormally rapid decrease in the density of the number of ion-acoustic waves with phase velocity lower v_s. According to Fig. 1, Fig. 2, and Table I, the stronger the electric field, i.e., the higher the turbulent level, the shorter the time and distance of the ion beam deceleration. It can be seen from Fig. 1, Fig. 2, and Table I that as the beam velocity approaches the velocity of sound, the braking process accelerates sharply. Therefore, the time and length of the beam deceleration at an initial velocity of $3v_s$ is more than an order of magnitude less than at an initial velocity of $5v_s$. When the beam is decelerated along the vector $-e\mathbf{E}$, the ions move along a straight line. Moreover, according to the continuity equation $nu_z = const$, that is, the beam density increases as it decelerates $n \propto 1/u_z$. The second case corresponds to the situation when the initial velocity of the ion beam is directed across the axis of anisotropy of turbulence and is equal to $5v_s$ or $3v_s$. In this case, simultaneously with the decrease of the transverse component of the velocity $u_\perp$, there is a change in the longitudinal component u_z, which was absent in the initial state. The change in u_z is due to the fact that, simultaneously with a decrease in the transverse component of the velocity, the beam deflects along the anisotropy axis of turbulence. Patterns of the deviation depend on the type of the function $\Phi(x)$—distribution of ion-acoustic waves over wave vector angles. In a relatively weak electric field, when $E < E_N(1+\delta)^2$ and distribution (10) takes place, an increase in the velocity u_z in the direction of the vector $-e\mathbf{E}$ is replaced by a subsequent decrease. In this case, the final value of u_{zf} is greater than $u_{\perp f}$ (see Table II). In a stronger electric field when $E > E_N(1+\delta)^2$ and the distribution has the form (12), the behavior of u_z is different. First, the velocity u_z increases against the direction of the vector $-e\mathbf{E}$, i.e., it takes negative values (see Fig. 4 and Fig. 6). Then u_z reaches minimum and begins to increase, as in a weaker field. As a result, the final value of u_{zf} is less than $u_{\perp f}$ (see Table II). This behavior is most clearly manifested when the beam is decelerated with

TABLE I. Times and lengths of beam deceleration along the electric field.

	$u_z(0) = 5v_s$		$u_z(0) = 3v_s$	
E/E_N	t_f (10^{-6} s)	z_f (cm)	t_f (10^{-7} s)	z_f (cm)
5	3.26	234	1.91	8.36
10	1.78	128	1.09	4.76
50	0.39	27.7	0.28	1.22
100	0.08	6.07	0.05	0.22
200	0.06	4.21	0.04	0.15

TABLE II. Times and lengths of beam deceleration across the electric field, as well as velocities upon termination braking across the electric field.

	$u_\perp(0) = 5v_s$					$u_\perp(0) = 3v_s$				
E/E_N	t_f (10^{-7} s)	z_f (cm)	r_f (cm)	$u_{\perp f}/v_s$	u_{zf}/v_s	t_f (10^{-7} s)	z_f (cm)	r_f (cm)	$u_{\perp f}/v_s$	u_{zf}/v_s
5	6.58	7.57	42.9	0.431	0.902	1.59	1.81	6.45	0.431	0.902
10	5.26	5.45	34.2	0.490	0.872	1.25	1.26	5.06	0.491	0.871
50	0.977	0.028	6.29	0.811	0.585	0.202	0.047	0.797	0.811	0.585
100	0.691	0.020	4.45	0.811	0.585	0.143	0.035	0.565	0.811	0.585
200	0.489	0.013	3.15	0.812	0.584	0.101	0.023	0.401	0.811	0.585

an initial velocity of $5v_s$. At the initial velocity of $3v_s$, the initial decrease of u_z to negative values is weaker. For this reason, the final length of deceleration along the anisotropy axis is greater than at an initial velocity of $5v_s$ (see Table II). In all cases, the braking process stops when the beam velocity modulus is almost the same as the velocity of sound. At the same time, the magnitude of both velocity components is less than v_s. In the weak field, the component u_{zf} is slightly larger than $u_{\perp f}$. That is, at the end of braking, the beam propagation direction is inclined to the anisotropy axis at an angle less than $\pi/4$. On the contrary, in a strong field, u_{zf} is less than $u_{\perp f}$, and the beam inclination angle to the anisotropy axis is greater than $\pi/4$ (see Table II). Since the deceleration of the beam across the symmetry axis of the IAT is considered under the assumption that there is no inhomogeneity along the symmetry axis, then from the continuity equation it follows $nu_\perp =$ const. In this case, the beam density increases along its curved trajectory according to the law $n \propto 1/u_\perp$.

The described patterns of beam velocity changing are shown in Fig. 3–Fig. 6, where the numerical solution to Eq. (6) is shown. Figure 3 and Fig. 4 illustrate the change of the velocity components $u_\perp$ and u_z in time, and Fig. 5 and Fig. 6 in space. Comparison of curves for $u_\perp$ and u_z allows us to see how much the beam velocity will deviate from the initial direction during deceleration. Table II shows the characteristic values of t_f times and $r_{\perp f}, z_f$ deceleration distances depending on the generating turbulence field strength. In addition, Table II shows the values of $u_{\perp f}$ and u_{zf} when braking stops.

Comparing Fig. 1 and Fig. 2 with Fig. 3 and Fig. 5, as well as data from Tables I and II, it can be seen that when the beam propagates across the anisotropy axis, the beam deceleration lengths and times are less than when the beam propagates along the vector $-e\mathbf{E}$. More effective deceleration in this case arises due to the fact that in accordance with the Cherenkov interaction condition $\omega_s = \mathbf{ku}$, ions with a velocity greater than v_s interact with waves having a small component of the wave vector $\mathbf{k}$ in the direction of the vector $\mathbf{u}$. At the same time, according to formulas (10) and (12), ion-acoustic waves are mainly concentrated in the directions close to the direction of the vector $-e\mathbf{E}$. As with the longitudinal propagation of the beam, the deceleration time and length decrease with an increase in the generating turbulence field strength. This statement is clearly illustrated in Fig. 3–Fig. 6 and the data in Table II. Calculations of deceleration are performed for a deuterium ion beam. However, they are also suitable in the case of deceleration of a rarefied ion beam with a different charge e_b and mass m_b. To obtain relevant results, it is enough to change the effective frequency ν_f (15) in $(e_b m/q m_b)^2$ times. At the same time in $(q m_b/e_b m)^2$ times the deceleration time and length will change.

IV. CONCLUSION

The results of calculations of the time and length of deceleration of the monoenergetic ion beam in plasma with developed IAT generated by a strong electric field are presented above. IAT makes it possible to decelerate beam ions

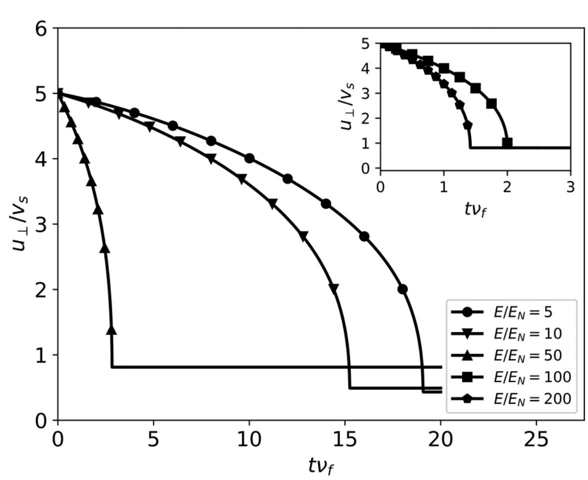

FIG. 3. Change in beam velocity $u_\perp$ in time in the case of $u_\perp(0) = 5v_s$.

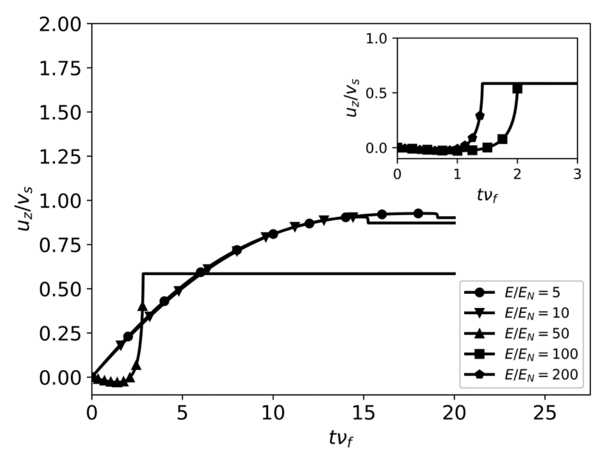

FIG. 4. Change in beam velocity u_z in time in the case of $u_\perp(0) = 5v_s$.

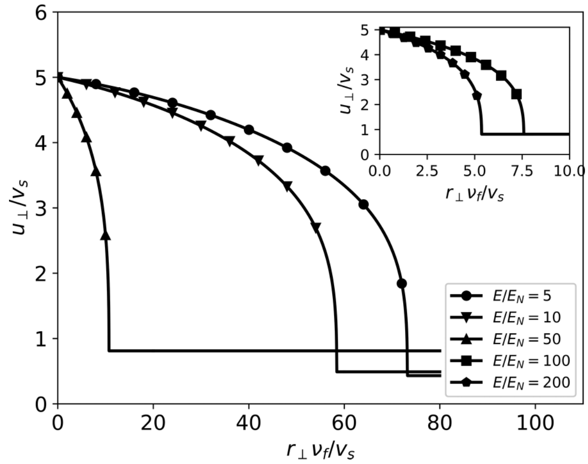

FIG. 5. Change in beam velocity $u_\perp$ in space in the case of $u_\perp(0) = 5v_s$.

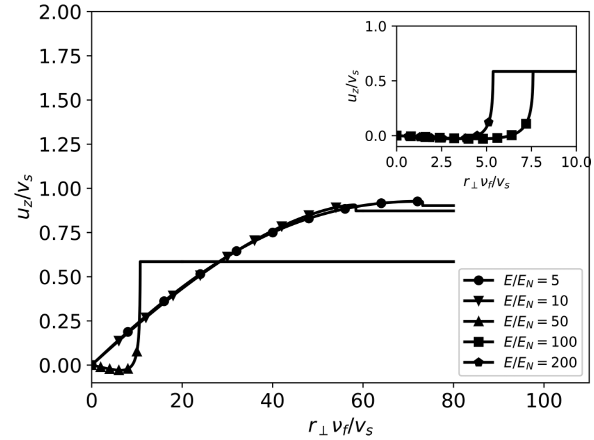

FIG. 6. Change in beam velocity u_z in space in the case of $u_\perp(0) = 5v_s$.

to a velocity close to the sound velocity. In the calculations, plasma parameters close to those found in experiments were selected [3,14–19]. The calculations are based on analytical expressions for the distribution of ion-acoustic waves over frequencies (9) and directions of the wave vector (10), (12). At the same time, the use of approximate formulas (10), (12) may lead to a noticeable error at the boundary of their applicability at $E \sim E_N(1+\delta)^2$. On the contrary, with E smaller or larger $E_N(1+\delta)^2$, the errors are relatively small. In addition, plasma heating installations have a magnetic field, which is usually directed along the electric field **E**. Such a field does not affect the deceleration of ion beams along the anisotropy axis of turbulence. At the same time, when the beam is decelerated across **E**, that is, across **B**, the effect of magnetic field on the beam ions can be significant if $\Omega t_f > 1$, where $\Omega = qB/mc$ is the cyclotron frequency, and c is the speed of light. For example, in the magnetic field with a strength of 10^3 G, the cyclotron frequency of deuterium ions is $\Omega = 5 \cdot 10^6\ \text{s}^{-1}$. This means that the above-described patterns of beam deceleration across the magnetic field will mostly remain at $E/E_N > 50$, and for lower magnetic field at lower E/E_N. In the strong magnetic field, when $\Omega t_f > 1$, the theory of ion deceleration across the magnetic field should be supplemented by taking into account changes in their trajectory in the magnetic field. Another limitation of the theory is due to the assumption of a low density of beam ions. At the same time, situations are possible when the beam ion density is comparable to the plasma density (see, for example, [20] and [21]). Under such conditions, it is necessary to take into account the effect of beam ions on the turbulence itself. Despite these shortcomings of the theory, it can be useful for the interpretation and planning of experiments, since there are no analogs yet.

[1] A. Fujisawa, A. Ouroua, J. W. Heard, T. P. Crowley, P. M. Schoch, K. A. Connor, R. L. Hickok, and A. J. Wootton, Ballooning characteristics in density fluctuations observed with the 2 mev heavy ion beam probe on the text-u tokamak, Nucl. Fusion **36**, 375 (1996).
[2] G. Zhuang, Y. Pan, X. W. Hu, Z. J. Wang, Y. H. Ding, M. Zhang, L. Gao, X. Q. Zhang, Z. J. Yang, K. X. Yu, K. W. Gentle, H. Huang, The reconstruction and research progress of the text-u tokamak in china, Nucl. Fusion **51**, 094020 (2011).
[3] M. Valovič, L. Garzotti, C. Gurl, R. Akers, J. Harrison, C. Michael, G. Naylor, and R. Scannell, H-mode access by pellet fuelling in the mast tokamak, Nucl. Fusion **52**, 114022 (2012).
[4] M. E. Austin, A. Marinoni, M. L. Walker, M. W. Brookman, J. S. deGrassie, A. W. Hyatt, G. R. McKee, C. C. Petty, T. L. Rhodes, S. P. Smith, C. Sung, K. E. Thome, and A. D. Turnbull, Achievement of reactor-relevant performance in negative triangularity shape in the diii-d tokamak, Phys. Rev. Lett. **122**, 115001 (2019).
[5] J. Jacoby, D. H. H. Hoffmann, W. Laux, R. W. Miiller, H. Wahl, K. Weyrich, E. Boggasch, B. Heimrich, C. Stockl, H. Wetzler, and S. Miyamoto, Stopping of heavy ions in a hydropen plasma, Phys. Rev. Lett. **74**, 1550 (1995).
[6] M. Roth, C. Stockl, W. Suss, O. Iwase, D. O. Gericke, R. Bock, D. H. H. Hoffmann, M. Geissel, and W. Seelig, Energy loss of heavy ions in laser-produced plasmas, Europhys. Lett. **50**, 28 (2000).
[7] A. Frank, A. Blažević, V. Bagnoud, M. M. Basko, M. Börner, W. Cayzac, D. Kraus, T. Heßling, D. H. H. Hoffmann, A. Ortner, A. Otten, A. Pelka, D. Pepler, D. Schumacher, A. Tauschwitz, and M. Roth, Energy loss and charge transfer of argon in a laser-generated carbon plasma, Phys. Rev. Lett. **110**, 115001 (2013).
[8] V. Y. Bychenkov, J. Myatt, W. Rozmus, and V. T. Tikhonchuk, Ion acoustic waves in plasmas with collisional electrons, Phys. Rev. E **50**, 5134 (1994).
[9] V. Y. Bychenkov, J. Myatt, W. Rozmus, and V. T. Tikhonchuk, Kinetic theory of ion acoustic waves in a plasma with collisional electrons, Phys. Rev. E **52**, 6759 (1995).
[10] V. Y. Bychenkov, V. P. Silin, and S. A. Uryupin, Ion-acoustic turbulence and anomalous transport, Phys. Rep. **164**, 119 (1988).
[11] V. P. Silin and S. A. Uryupin, Ion acoustic turbulence and heating of resonant ions, Sov. J. Plasma Phys. **12**, 596 (1986).

[12] V. P. Silin and S. A. Uryupin, Formation of hot resonant ions in a plasma with fully developed ion acoustic turbulence, Sov. J. Plasma Phys. **13**, 100 (1987).

[13] V. Y. Bychenkov, O. M. Gradov, and V. P. Silin, Ion acoustic turbulence and transport in a plasma in a strong electric field, Sov. J. Plasma Phys. **10**, 1 (1984).

[14] V. A. Kornev, L. G. Askinazi, M. I. Vildjunas, N. A. Zhubr, S. V. Krikunov, S. V. Lebedev, D. V. Razumenko, V. V. Rozhdestvensky, and A. S. Tukachinsky, Confinement of energetic ions in a tokamakplasma at magnetic field in the range of 0.7–1.0 T, Tech. Phys. Lett. **39**, 290 (2013).

[15] V. V. Bulanin, L. G. Askinazi, A. A. Belokurov, V. A. Kornev, S. V. Lebedev, A. V. Petrov, A. S. Tukachinsky, M. I. Vildjunas, F. Wagner, and A. Y. Yashin, GAM observation in the TUMAN-3M tokamak, Plasma Phys. Control. Fusion **58**, 045006 (2016).

[16] L. G. Askinazi, A. A. Belokurov, D. B. Gin, V. A. Kornev, S. V. Lebedev, A. E. Shevelev, A. S. Tukachinsky, and N. A. Zhubr, Ion cyclotron emission in NBI-heated plasmas in the TUMAN-3M tokamak, Nucl. Fusion **58**, 082003 (2018).

[17] T. P. Kiviniemi, P. Niskala, L. G. Askinazi, A. A. Belokurov, L. Chôné, A. D. Gurchenko, E. Z. Gusakov, T. Korpilo, S. V. Lebedev, S. Leerink, R. Rochford and A. S. Tukachinsky, Gyrokinetic simulation of transport reduction by pellet injection in TUMAN-3M tokamak, Plasma Phys. Control. Fusion **60**, 085010 (2018).

[18] N. N. Bakharev, Tokamak research in ioffe institute, Nucl. Fusion **59**, 112022 (2019).

[19] V. A. Kornev, G. I. Abdullina, L. G. Askinazi, A. A. Belokurov, S. V. Lebedev, D. V. Razumenko, A. S. Tukachinsky, and N. A. Zhubr, Optimization of atomic beam power loss in the beamline of the TUMAN-3M tokamak, Tech. Phys. Lett. **47**, 279 (2021).

[20] M. D. Gabovich, A. A. Goncharov, V. Va. Poritskii, and I. M. Protsenko, Excitation of ion Langmuir oscillations by a fast ion beam, Sov. Phys. JETP **37**, 655 (1973).

[21] M. D. Gabovich, L. S. Simonenko, I. A. Soloshenko, and N. V. Shkorina, Excitation of ion oscillations in plasma by a fast beam of negative ions, Sov. Phys. JETP **40**, 851 (1974).