MODEL OF ENERGETIC ION PRODUCTION BY INTENSE ELECTRON BEAMS

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Recent experiments with intense linear electron beams have produced ions with energies exceeding the beam kinetic energy. We present a localized beam-pinch model explaining the phenomena.

Interest in linear electron-beam, collective-field acceleration concepts has been renewed in the past year by the observations of Graybill and Uglum[1] and Rander et al.[2,3] These investigators have obtained protons and deuterons up to 5 MeV in energy using 250-keV to 1-MeV electron beams with currents in the 50-kA range over a 50-cm drift-chamber length. Minimum average accelerating fields of 10^5 V/cm have thus been experimentally verified. The experiments have naturally generated speculation about the nature of the accelerating mechanism and the scaling of ion energies with beam and drift-chamber parameters. Wachtel and Eastlund[4] have suggested the Veksler "inverse Cherenkov" effect, while Rostoker[5] and, independently, Uglum, McNeill, and Graybill[6] have proposed accelerated space-charge potential-well models. We propose a different mechanism, the localized pinch model,[7] whose predictions agree with presently established features of the experimental data.

In the experiments an electron beam is injected through a thin metallic entrance (anode) window into a right cylindrical conducting drift chamber with a small hole in the center at the downstream end. The beam and ions pass through the hole into a magnetic field where the beam and ions are separated; the ions are then diagnosed using time-of-flight, magnetic-spectroscopy, and nuclear-emulsion techniques. Various neutral gases at pressures from 10 to 300 μm are ionized by the beam. The salient features of the experimental data[1-3] are these:

(1) The peak ion energies are proportional to Z, the ion charge number, as would be the case if ions were accelerated by a stationary electrostatic field.[8] The particle energy per unit charge is proportional to I^2, where I is the beam current. The experimental uncertainties allow a current dependence from $I^{3/2}$ to $I^{5/2}$.

(2) The ion energy is nearly independent of filling gas pressure over a range of a factor of 6 in pressure.

(3) The ion pulses are formed and accelerated after the fractional electrical neutralization,

$$f_e \equiv (-)\frac{\text{ion charge density}}{\text{electron charge density}},$$

becomes greater that $1/\gamma^2 = 1-\beta_e^2$, where γ is the electron energy E/m_0c^2.[9] The condition for radial force neutralization and the onset of beam pinching is $f_e \sim 1/\gamma^2$.

(4) The proton energy spread (full width at half-maximum) is <20 %, the limit of the spectrometer resolution.

(5) The total number of accelerated ions per ion pulse is in the range of 10^{12} to 10^{14} particles.

(6) Multiple ion pulses have been reported by Rander et al.[2]

In the localized pinch model (LPM), a moving "slug" of ions always sees roughly the same accelerating field. By a slug of ions, we mean a localized enhancement in the ion density created near the anode window when the beam starts to pinch appreciably. It turns out that with the experimental beam parameters, the pinching can occur so rapidly that nonadiabatic beam-envelope collapse conditions are realized; i.e., the pinching occurs over distances of a few beam radii. It is the very presence of the high ion-density region which shorts out the radial electric (space-charge) field, allows pinching, and generates ion accelerating fields. We are thus considering a self-synchronized accelerating process. To understand how this works in more detail, consider the diagram in Fig. 1.

In our idealized model we assume a zero rise length of the ion-density inhomogeneity, a constant beam current, $\beta_{Li} \ll \beta_L$, where $\beta_L c$ is the average longitudinal velocity of the beam electrons, and that β_{Li} is approximately constant over times $\epsilon/\beta_{Li}c$. Moreover, we assume that the chamber end plates are "far away," that the background ion charge per unit length is constant, and that the beam and background ions are in equilibrium upstream from region 1 at a_0. The ion and electron charge densities are taken uniform in radius out to the envelopes.

When the ion envelope radius is constant $\approx a_0$ in region 1, the beam envelope equation can be written as

$$\frac{\partial^2 a_e}{\partial u_i^2}=\frac{1}{\beta_L^2c^2}\left\{\left(\frac{-e}{m_0\gamma}\right)[E_r-\beta_L B_\theta]_{r=a_e}+\frac{C_e}{a_e^3}\right\}\approx-\frac{2}{\gamma\beta_L^2}\left[\left(f_e^{\,0}+\frac{\Delta\lambda_i}{|\lambda_e|}\right)\frac{a_e}{a_0^2}-\frac{1}{\gamma_L^2a_e}\right]+\frac{C_e}{\beta_L^2c^2a_e^3},\quad 0\le u_i<\epsilon, \tag{1}$$

where $\nu\equiv I/\beta_L I_0$ with $I_0=17$ kA, $f_e^{\,0}=\lambda_{i0}/|\lambda_e|$, $\gamma_L=(1-\beta_L^2)^{-1/2}$, and C_e is a constant proportional to the electron beam emittance.[10] The field E_z along the beam axis ($r=0$) resulting from envelope motion is

$$E_z\approx\frac{2\lambda_e}{a_e}\frac{\partial a_e}{\partial u_i},\quad u_i>0. \tag{2}$$

This field is always in the direction of electron flow during the beam envelope contraction, in contrast to the case of an external-field-driven pinch collapse with Ohmic current. Equation (1) can be reduced to quadrature, but for our purposes we merely estimate a turning length for the beam envelope u_{it}, giving

$$E_z(\mathrm{V/cm})\approx 4.4\times10^5(\nu/\gamma)^{1/2}\frac{\nu}{a_0\beta_L}\left(f_e^{\,0}+\frac{\Delta\lambda_i}{|\lambda_e|}\right)^{1/2},\quad 0<u_i<u_{it}. \tag{3}$$

Equation (3) underestimates the collapse velocity since we have assumed a constant ion-envelope radius. The maximum collapse velocity would obtain if $a_i\simeq a_e$ in region 1.[11]

Typical experimental parameters of $\nu/\gamma\approx1$, $a_0\simeq1$ cm, $\gamma\simeq3$, and $\beta_L\simeq0.91$ give $E_z\approx7\times10^5$ V/cm if $f_e^{\,0}\simeq1/\gamma^2$ and $\Delta\lambda_i/|\lambda_e|\approx1/\gamma^2$.[12] In this case, the electrons would lose all of their kinetic energy over a distance of the order of the beam radius. Our assumption that $\partial\beta_L/\partial u_i\approx0$, $0<u_i<u_{it}$, is violated. This example leads us to the concept of a "strong-inductance dominated" pinch collapse. Generally speaking, if $\nu/\gamma\ll1$, the pinch is slow and $u_{it}\gg a_0$, whereas, if $\nu/\gamma\sim1$, the pinch is strong-inductance dominated; i.e., the magnetically driven beam collapse is so fast that the "IdL/dt" longitudinal electric field[13] degrades the electron kinetic energy over distances of the order of the beam radius. Then λ_e increases with u_i and the current drops as electrons are lost radially, thus retarding further pinching.[14] This condition is a "saturation" condition in that further increases in $\Delta\lambda_i$ do not appreciably increase E_z. The maximum E_z field value for a given current is $E_z^{\,\mathrm{sat}}$ (V/cm) $\approx 60I/a_0$ with I in amperes, obtained by taking $\partial a_e/\partial t\approx c=$ velocity of light. In the example, $E_z^{\,\mathrm{sat}}\simeq3\times10^6$ V/cm.

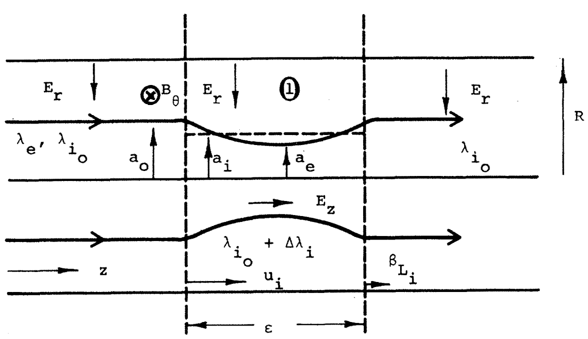

FIG. 1. The ion acceleration model. β_{Li} = longitudinal β of ion slug $=v_{z_{\mathrm{ion}}}/c$; ϵ = length of moving ion slug of region 1; λ_e = electron beam charge per unit length; λ_{i0} = background ion charge per unit length; $\Delta\lambda_i$ = increment in ion charge per unit length in region 1; a_0 = ion and electron radius upstream from region 1; a_e = beam-envelope radius in region 1; a_i = ion-envelope radius in region 1; B_θ = beam magnetic field; E_r = radial electric field; E_z = longitudinal (z-directed) electric field; R = radius of outer conducting pipe; $u_i=z-\beta_{Li}ct$ = distance from upstream head of ion slug in the stationary frame of the ions.

Our idealized model assumed that the rise length of the ion density inhomogeneity, l_i, was zero, but, of course, any laboratory ion pulse would have a finite rise length. Nonadiabaticity requires $l_i\lesssim a_0$ when $\nu/\gamma\sim1$. We now develop a sufficient criterion for formation of a nonadiabatic collapse. Near the anode window the longitudinal electrostatic field retards the beam front at injection into the neutral gas until collisional ionization generates approximate charge neutrality over a time scale τ_N.[15] When the beam front has passed the beginning of the "pinch-active" region at $z\approx R/2.4$, where the electrostatic field is now primarily radial, the beam starts to pinch as f_e exceeds $1/\gamma^2$. A nonadiabatic condition is generated if the pinching is fast enough so that

$$\partial j_{\mathrm{ion}}/\partial_z>\partial\rho_{\mathrm{ion}}/\partial t, \tag{4}$$

where j_{ion} is the z component of the ion current due to the E_z pinching field, and $\partial\rho_{\mathrm{ion}}/\partial t$ is due to collisional ionization. Then pinching near the beginning of the pinch-active region is retarded, but immediately downstream it is enhanced because the ion background growth rate is increased; in other words, this process steepens the gradient of $\Delta\lambda_i$. If we estimate $\partial j_{\rm ion}/\partial z$ using E_z from the beam radial contraction at constant current $[E_z \propto (I/a_e)(da_e/dt)]$ over the time interval from $f_e = f_e^0$ to $f_e \approx 1$, Eq. (4) gives

$$\nu \gtrsim 6\left[\frac{[\gamma^2(\gamma-1)^{1/2}/\beta_L](a_0/\tau_N)(m_i/Zm_p)}{\ln(a_0/a_1)}\right]^{-2/3} \tag{5}$$

for a_0 in centimeters and τ_N in nanoseconds, where m_i/m_p is the ratio of the ion to proton mass, and a_1 is the beam radius for $f_e \simeq 1$. If the contraction is adiabatic, $\ln(a_0/a_1) \approx \frac{1}{2}\ln[1 + C_i m_i/ZC_e\gamma m_0]$, with C_i the background ion emittance. Equation (5) gives $\tau_N \gtrsim 42$ nsec for ion bunching in hydrogen using the maximum $\nu \approx 2.8$ of Graybill and Uglum, $a_0 = 1$ cm, $\beta_L \simeq \beta_e$, and $\ln(a_0/a_1) \approx 1$, a reasonable agreement with their upper pressure cutoff where $\tau_N \simeq 36$ nsec.[16]

Growth of $\Delta\lambda_i$ will continue until $\beta_{Li} \gg \beta_{Li0}$, where β_{Li0} refers to the velocity attained by background ions accelerated by E_z over a time $\epsilon/\beta_{Li}c$, or until the ion supply upstream is depleted, whichever occurs first. In our discussion, we have tacitly assumed that the background ions had zero net acceleration as the pulse passed. This is only true when slightly upstream from region 1, the contribution to E_z from the variation of the ion charge per unit length (oppositely directed to the beam collapse field) is strong enough to completely decelerate the background ions. While the ion pulse is growing near the anode, a net ion current, $I_{\rm ion}$, flows behind the pulse proper requiring an ion supply to maintain the current. When the supply is depleted an electrostatic well is re-established near the anode, which degrades the electron kinetic energy and terminates further acceleration of the pulse. As collisional ionization continues near the anode, the whole process starts over again, i.e., multiple pulses are formed. If several charge species are present near the anode, the ions with highest Z/m_i ratio (protons) would be bunched and accelerated first.

The above arguments imply that the acceleration time $t_{\rm acc}$ is determined by the ion supply and effective pinching volume; i.e.,

$$\int_t^{t_{\rm acc}+t_1} I_{\rm ion}\,dt \sim \text{const}$$

for given beam and drift-chamber parameters. The time t_1 is the time at which a nonadiabatic collapse is achieved. The condition in turn implies that the acceleration length, $L_{\rm acc}$, is independent of Z/m_i and that $t_{\rm acc} \propto (m_i/Z)^{1/2}$. Using $E_z \approx 7\times10^5$ V/cm from our example, the experimental ion energies of Ref. 1 correspond to $L_{\rm acc} \approx 7$ cm. The beam-front velocity measurements of Rander et al.[3,17] also indicate that the acceleration occurs over a region of the order of a few centimeters length near the anode window.

The important questions of pulse growth times, stability, and lifetime require a more quantitative analysis; a linear stability investigation of ion-density inhomogeneities in partially neutralized beams is in progress. Intuitively, we argue that radial stability at least requires that the outward magnetic force on the ions be not greater than the radially inward electric field force, or

$$\beta_{Li} < [1 - (f_e^0 + \Delta\lambda_i/|\lambda_e|)]\beta_L.$$

If $\nu/\gamma \approx 1$, $\gamma \approx 3$, and $\Delta\lambda_i/|\lambda_e| = f_e^0 \approx 1/\gamma^2$, the ions are radially stable for $\beta_{Li} \lesssim 1$. We further note that in the strong-inductance pinch condition $E_z(r=0)/E_z(r=a_0) \approx 1 + (2\ln R/a_0)^{-1}$, which implies a small radial variation in E_z when $R/a_0 \gg 1$. The longitudinal synchronization or coherent acceleration length is limited by the loss of ions around $u_i = 0$ due to the finite rise length of E_z with u_i, which can be much less than a_0 in the strong-inductance pinch condition where E_z (electrostatic) contributions from $\partial\lambda_e/\partial u_i$ are important.

In summary, the LPM predicts energetic ion acceleration to occur after $f_e \simeq 1/\gamma^2$ if the bunching criterion of Eq. (5) is satisfied. For given beam parameters, Eq. (5) implies an upper limit on the pressure (shortest τ_N) and a lower pressure cutoff follows from the requirement that the time for attainment of $f_e \sim 1/\gamma^2$ must occur before the beam current starts to drop appreciably. The ion energy is $\approx ZE_z L_{\rm acc}$, where E_z is given by Eq. (3) for $eE_z a_0 \leqslant$ beam kinetic energy, and $L_{\rm acc}$ is argued to be the same for all ion species. Since $E_z \propto \nu^{3/2}/\beta_L$ for fixed γ, the predicted current dependence falls within the range observed by Graybill and Uglum.

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[8]Gas stripping complicates this interpretation of the data for nitrogen and argon ions.

[9]This feature is based on the collisional ionization rates used in Ref. 1.

[10]Emittance is a measure of the transverse beam energy. Its precise definition and the form of Eq. (1) are given by I. Kapchinskij and V. Vladimirskij, in *Proceedings of the International Conference on High Energy Accelerators and Instrumentation, Geneva, 1959*, edited by L. Kowarski (CERN Scientific Information Service, Geneva, Switzerland, 1959), p. 274.

[11]The quadrature of Eq. (1) and estimates of u_{it} and the beam-collapse minimum radius are discussed in detail in S. Putnam, Physics International Company Report No. PIFR-105, 1970 (unpublished). See also J. Lawson, J. Electron. Contr. 5, 146 (1958), for estimates of an approximate value for the radial collapse rate in the case $C_e = 0$, and $a_i = a_e$ during the collapse.

[12]We have estimated β_L using an approximate steady-state relation,

$$\beta_L{}^2 \approx [\beta_e{}^2 + (\nu/\gamma)(1-f_e)] / (1 + (\nu/\gamma).$$

[13]L is the effective beam-chamber inductance per unit length.

[14]Current-probe data of Ref. 3 suggest a correlation between the time for attainment of $f_e \sim 1/\gamma^2$ and a dip in the net drift-chamber current.

[15]See Ref. 5 for discussion of this point.

[16]Estimating τ_N near the anode is difficult because of possible electron avalanche effects and the spread in primary electron velocity.

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INTERACTION CROSS SECTION OF THE Q^- ENHANCEMENT

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We have observed coherent production of $K^-\pi^+\pi^-$ systems by K^- beams on nuclei and have measured the coherent production rate in the $Q(1300)$ region. Using the corresponding hydrogen and deuterium production rates we have calculated σ_{Q^-}, the Q^--nucleon total cross section. We find $\sigma_{Q^-} = 20.8_{-9.0}^{+7.2}$ mb at 10 GeV/c and $\sigma_{Q^-} = 20.8_{-8.4}^{+6.0}$ mb at 12.7 GeV/c.

Enhancements in the $(K\pi\pi)^\pm$ mass region near 1.3 GeV (Q region) have been reported by several groups observing interactions of high-energy $K^\pm$ beams on protons,[1] deuterons,[2] and heavier nuclei.[3] We report here an estimate of σ_Q, the Q^--nucleon total cross section. Our method consists in measuring the rate for coherent production of Q^- on nuclei. Then using a model which relates these results to Q^- production on protons and deuterons in terms of Q^--nucleon scattering, we