

ION ACCELERATION WITH INTENSE LINEAR ELECTRON BEAMS

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Acceleration of ions using collective field techniques is currently receiving much attention in several laboratories throughout the world (Reference 1). The most extensive theoretical and experimental programs are those concerned with the electron ring accelerator. A small effort has also been carried out using intense relativistic electron beams in linear geometry and, to date, ions with an energy of about $5 \text{ MeV}/Z$, where Z is the charge state of the ion, have been reported for various ion species. The intriguing aspect of these experiments is that as little as one sixth of the electron beam pulse is used to bunch and accelerate the ions at which time the acceleration appears to be rather abruptly terminated. In this paper we address possible reasons for the cutoff of the acceleration process and suggest experiments to check these speculations.

SUMMARY OF EXPERIMENTAL DATA

For reference, a summary of the experimental data from the experimental groups of Graybill and Uglum at Ion Physics Corporation (IP) (Reference 2) and Rander at Physics International Company (PI) (References 3 and 4) is given below. We assume that the data refer to the same accelerating process although there are differences in the nature of the beam front propagation:

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. 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. The proton pressure range for IP is from about 50 to 300 μm .

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 than $1/\gamma^2 = 1 - \beta_e^2$, where γ is the electron energy, $E/m_e c^2$. 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 percent, the limit of the spectrometer resolution. This energy spread for PI covers two proton pulses.

5. The total number of accelerated ions per ion pulse is in the range of 10^{12} to 10^{15} particles. The ion pulse widths range from 3 nsec for protons and 5 nsec for deuterons, to about 10 nsec for helium and nitrogen.

6. Multiple ion pulses (two) have been reported by Rander et al. This feature can be accounted for by approximately twice as long a beam pulse width for the PI beam as compared to the IP beam. The pulse separation is inversely proportional to the filling gas pressure for H_2 . The pressure dependence of the pulse separation is shown in Figure 1 (Reference 5).

7. The first ion pulse may be moving with the beam front (Reference 4) or behind the beam front (Reference 2). The

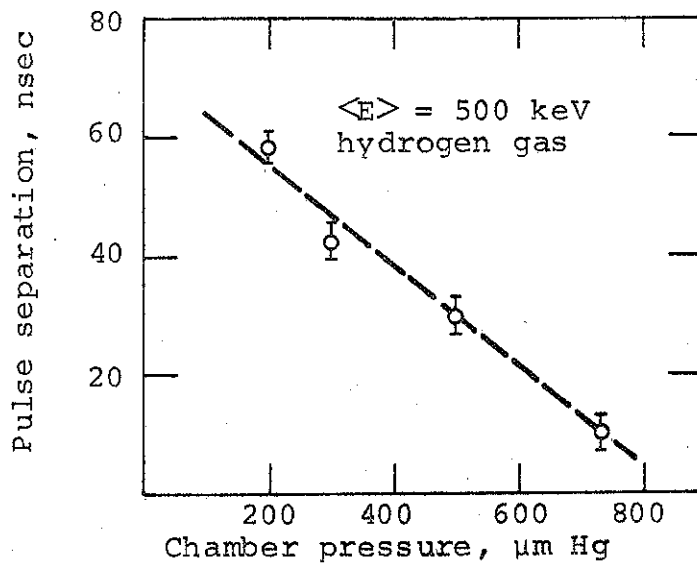
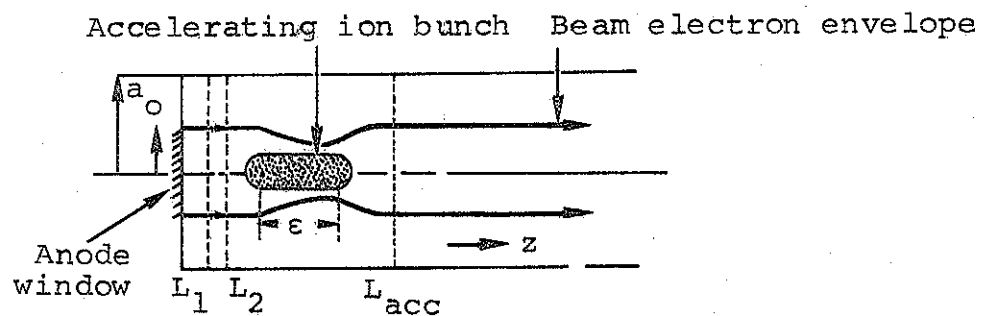


Figure 1 Proton pulse separation versus pressure.



- Note:
- a_0 = Beam envelope at injection
 - $L_1 \approx R/2.4$ = beginning of pinch active region
 - L_2 = Growth length of ion bunch
 - L_{acc} = Acceleration length
 - ϵ = Length of ion bunch

Figure 2 Ion acceleration model geometry.

different behavior of the beam front propagation with respect to the first ion pulse is most likely due to the higher v/γ of the PI beam, where $v/\gamma \equiv I \text{ (amps)}/17,000 \beta_L \gamma$ is a measure of the ratio of the average transverse to longitudinal energy of the beam electrons, and $\beta_L c$ is the average streaming or longitudinal velocity of the beam. The IP beams were typically $v/\gamma \sim 0.8$, whereas PI beams were $v/\gamma \gtrsim 2$.

THE LOCALIZED PINCH MODEL (LPM)

Several models have been advanced to explain the experimental results (References 6, 7, and 8); however, we shall consider the acceleration in the context of the LPM (Reference 9). This model, although speculative, does agree with presently established features of the experimental data. Referring to Figure 2, we trace the history of the acceleration process.

As the beam comes out of the anode window into the neutral gas, the front velocity, v_f , is "slow":

$$v_f \approx L/\tau_N \quad (1)$$

where L is approximately equal to the distance over which beam energy is degraded by the longitudinal electrostatic space-charge field, and τ_N is the electrical neutralization time due to collisional ionization of the background gas by beam electrons. Typically, L is about one centimeter and τ_N ranges from 36 to 216 nsec for IP hydrogen experiments, giving front velocities from 3×10^{-2} to 5×10^{-3} cm/nsec. The simple formula (Equation 1) merely states that the beam front moves the distance of the electrostatic well width over the charge neutralization time.

When the beam front passes $L_1 \approx R/2.4$, where R is the chamber radius, the radial electrostatic field is no longer shorted out by the end plate and the beam enters the "pinch-active" region. As f_e exceeds $1/\gamma^2$, the E_z field due to pinching causes ion bunching in appropriate pressure ranges, i.e., if

$$v \gtrsim 6 \left[\frac{[\gamma^2 \sqrt{\gamma-1}/\beta_L] a_o/\tau_N (m_i/Zm_p)}{\ln (a_o/a_1)} \right]^{2/3} \quad (2)$$

where a_o is in centimeters, τ_N is in nsec, m_i/m_p is the ratio of the ion to the proton mass, and a_1 is the beam radius for f_e approximately equal to 1. It should be emphasized that this formula is only a rough estimate for ion bunching. Moreover, if the beam is pinching in the diode, or, in other words, if a_o is decreasing with increasing current at the anode window, the criterion of Equation (2) could be circumvented.

The E_z field due to pinching around the ion bunch can be estimated for the case where the ion velocity is less than $\beta_L c$:

$$E_z \text{ (V/cm)} \approx 4.4 \times 10^5 (v/\gamma)^{1/2} \frac{v}{a_o \beta_L} \left(f_e^o + \frac{\Delta\lambda_i}{|\lambda_e|} \right)^{1/2} \quad (3)$$

Here f_e^o is the fractional electrical neutralization represented by background ions ($f_e^o \gtrsim 1/\gamma^2$), $\Delta\lambda_i$ is the increase in ion charge/length of the bunch over background, and λ_e is the electron charge/length. If $v/\gamma \sim 1$, $a_o \sim 1$ cm, $\gamma \cong 3$, $\beta_L \approx 0.9$, $E_z \approx 7 \times 10^5$ V/cm for f_e^o and $\Delta\lambda/|\lambda_e| \approx 1/\gamma^2$. This field is strong enough to degrade the electron kinetic energy over a distance of the order of a beam radius, causing an E_z contribution from electron charge bunching, proportional to $\partial\lambda_e/\partial z$. The mechanism is self-synchronized - the presence of the enhanced ion charge of the bunch causes pinching, generates accelerating fields, and the electron bunching contributes to longitudinal

phase stability. It is perhaps interesting to note that once a sharply defined ion bunch is formed, i.e., the rise length of the ion density enhancement is of the order of a few beam radii, the accelerating field approaches a saturation value and becomes insensitive to the actual value of $\Delta\lambda_i$. Both contributions to the E_z field saturate at the same value:

$$E_z^{\text{sat}} \text{ (V/cm)} \cong \frac{60 I(\text{amps})}{a_0} \cong 3 \times 10^6 \text{ V/cm} \quad (4)$$

for our example. Experimental data implies accelerating fields within a factor of five or less of this value (Reference 4).

The number of accelerated ions grows up to a distance L_2 , i.e., until the moving bunch can no longer pick up background ions created by either preceding beam electrons or by the ions of the bunch themselves. The accelerating field is not high enough to accelerate ions from rest to the velocity of the bunch over distances of the order of the beam radius. The passing bunch now leaves an ion current, I_{ion} , in its wake and the magnitude of I_{ion} decreases as the bunch velocity increases. (The implications of this wake ion current are discussed below.) The bunch continues to accelerate up to a distance, L_{acc} , where experimental data suggests a rather abrupt termination of the accelerating process. The PI data suggest that L_{acc} is less than or equal to 7 centimeters (Reference 4), and the IP data suggest about 20 to 30 centimeters (Reference 7).

CUTOFF MECHANISMS FOR THE ACCELERATION PROCESS

Several possible reasons for the nature of the cutoff mechanism, and relatively simple experiments to check these speculations, are here discussed.

Perhaps the most obvious reason is that the accelerating fields lose synchronization with the ion bunch and accelerate "fresh" background ions. This would be the case if the potential well reached an acceleration value such that field becomes too low to trap the ions. This cutoff mechanism has been proposed by N. Rostoker (Reference 6). The process could terminate acceleration for the IP beam where the beam front precedes the ion bunch, or for the second ion pulse with PI data. In any case, the mechanism is not relevant to the first PI proton bunch since the beam front stays with the ions.

If a well does accelerate and leaves the coherently accelerated bunch behind, one would expect to observe at appropriate pressures a distribution of ions with energies in the tens of keV range generated by the well as it proceeds to the end of the drift chamber. The energy spectrum would, of course, depend on the acceleration history of the well.

Let us consider the IP proton data to illustrate this point. The observed proton energy was 4.8 ± 0.9 MeV, corresponding to an ion velocity/ $c \equiv \beta_i \approx 0.1$; the drift chamber length was 50 cm and L_{acc} was approximately equal to 25 cm. We need to know the kinetic energy given an ion created in a potential well of depth V as the well moves by it. For simplicity, we consider a well moving with constant velocity, βc , and obtain from relativistic kinematics an expression for the kinetic energy, K.E., imparted to ions as the well moves by:

$$K.E. = M_i c^2 \left\{ \gamma^2 (1-\alpha) - 1 - \beta \gamma [\gamma^2 (1-\alpha)^2 - 1]^{1/2} \right\} \quad (5)$$

where M_i is the ion rest mass, $\gamma = 1/\sqrt{1-\beta^2}$, $\alpha = ZeV/\gamma M_i c^2$, and V is the well depth. If $\alpha \ll 1$, Equation (5) reduces to $K.E. \approx [Z^2 (eV)^2 / M_i c^2]^{1/2} \beta^2$. Thus, for protons, and $\beta \geq 0.1$, $eV \approx 1$ MeV, the

background ion energy from the accelerating well is ≤ 53 keV. The time for such an ion to travel the remainder of the drift chamber (~ 25 cm) would be ≈ 78 nsec, during which time the beam would have certainly neutralized the potential barrier at the downstream end of the chamber at the $300 \mu\text{m}$ pressure value. Thus, independently of the acceleration history of the well, the ions would be observable. It would be important in any experiment to carefully check the background ion arrival time with respect to the high energy ion pulse. This would rule out background ion acceleration from beam inductive fields which might be important after space charge neutralization.

A second possible acceleration cutoff would obtain if the beam electrons precede the ion pulse by a sufficient distance to give $f_e \approx 1$ in front of the ion bunch. Secondary electrons then "short out" or damp beam envelope oscillations. This possibility is again relevant to the IP ion pulse and the second pulse for PI. It seems unlikely that this mechanism is operative, however, inasmuch as it would imply ion energies inversely proportional to chamber pressure and would rule out multiple pulses.

A cutoff process relevant to the first PI ion pulse, where the beam front and ions travel together, would occur if the ion velocity eventually reaches values such that f_e of the background drops below $1/\gamma^2$. In other words, the collisional ionization rate due to the beam electrons and accelerated ions is no longer sufficient to maintain the $f_e^0 \approx 1/\gamma^2$ as the beam front penetrates the neutral gas. One can easily show that for ion energies greater than 1 MeV, the accelerated ions themselves can maintain $f_e^0 \geq 1/\gamma^2$ for typical experimental ion pulse lengths of 10 cm and $\beta_i \approx 0.1$. In any case, such a cutoff mechanism would be pressure sensitive and would give a higher energy for the second

ion pulse than for the first. Moreover, this cutoff could be overcome by a pressure gradient in the drift tube.

Finally, we come to a mechanism which appears to be a likely possibility in the present experimental configuration--depletion of the ion supply near the anode window. The ion supply may be depleted upstream from the pulse since the accelerating fields generate a wake ion current during pulse growth and acceleration. The electrostatic potential well is reestablished near the anode as the ions are removed by the ion current, and the electron kinetic energy is degraded downstream, thereby terminating acceleration. Such a mechanism would explain multiple pulse formation; the bunching and accelerating process repeats as the ion charge density again grows near the anode from collisional ionization. Also, this mechanism would explain the inverse dependence of pulse separation upon pressure, since $\tau_N \propto (\text{pressure})^{-1}$. An experimental check of this suggestion could be made by measuring the electron kinetic energy as a function of time. The number of beam electrons with energies of the order of the injected energy should drop significantly when the acceleration is terminated. It is important that these measurements be performed in the chamber interior to the electron-accelerating space charge fields near the downstream chamber endplate.

If the ion supply depletion hypothesis is experimentally verified, the obvious question remains as to how to extend L_{acc} ; i.e., how can the ion supply be enhanced? A method of effectively doing this would be to inject an accelerated ion bunch into a second accelerating stage. The wake ion current is then inversely proportional to $\beta_i^0 c$, the injected ion velocity, and the acceleration time in the second stage would be $\propto \beta_i^0 c$.

We conclude by briefly mentioning recent developments of interest in beam generation and transport for other ion acceleration methods using linear electron beam geometries. Some proposed methods are ion drag acceleration using high density electron bunches, impact acceleration of plasmoids, travelling magnetic mirror, and the Veksler coherent "inverse Cerenkov" technique, to name a few. The reader is referred to References 1 and 10 for a discussion of some of these techniques. Electron accelerators now exist or are in various stages of serious design study to yield beam energies in the megajoule range. The "Aurora" machine, for example, is a 15- to 20-MeV, 4-module accelerator with an ~ 400 kA/module and a pulse width of ~ 180 nsec. In general, machine technology is at the point where beams can be generated ranging in energy from ~ 100 keV to 20 MeV, and with currents from tens of kiloamperes to several megamperes. A further development in low-inductance gas switching technology has demonstrated capability of switching currents up to the megampere level with sub-nanosecond jitter (Reference 11). Thus, beams and accelerating gaps can be switched, modulated, and synchronized to meet requirements for acceleration lengths greater than single generator pulse widths.

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