BEAM FRONT ACCELERATORS

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ABSTRACT

An intense relativistic electron beam cannot propagate in a metal drift tube when the current exceeds the space charge limit. Very high charge density and electric field gradients (10^2 to 10^3 MV/m) develop at the beam front and the electrons are reflected. When a neutral gas or a plasma is present, collective acceleration of positive ions occur, and the resulting charge neutralization enables the beam to propagate. Experimental results, theoretical understanding, and schemes to achieve high ion energies by external control of the beam front velocity will be reviewed.

1. INTRODUCTION

When an intense relativistic electron beam (IREB) is injected into a metal drift tube, or encounters a discontinuity in its environment, such that the beam current exceeds the space charge limiting current, it stops propagating. A "virtual cathode" associated with very high charge density and electric field gradients (10^2 to 10^3 MV/m) develops at the beam front and the electrons are decelerated and reflected by the negative space-charge potential. When the drift tube is filled with a neutral gas at a suitable pressure (e.g. H_2 at $\sim$ 0.1 Torr) or when a plasma is present at the entrance of the drift tube, collective acceleration of positive ions from the gas or plasma occurs, and the resulting charge neutralization enables the beam to propagate. This effect was first discovered accidentally by Graybill and Uglum in 1968 during experiments with an intense electron beam in a gas-filled drift tube[1)]. The typical geometry of such an experiment is illustrated in Fig. 1a.

After the discovery of Graybill and Uglum, many experiments with gas-filled drift tubes were performed during the early seventies. It was found that the peak ion energy increased with pressure until an upper pressure limit is reached beyond which no ion acceleration occurs. For ions with positive charge Ze, the kinetic energy, E_i, can be expressed in terms of the electron kinetic energy, E_e, or the electron beam voltage, V_b, as

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$$E_i = \alpha Z E_e = \alpha Z e V_b \,, \qquad (1)$$

where α is the energy amplification factor. The experimental energy spectrum has an exponential shape with an effective value of $\alpha \cong 1$ for the bulk of the ions and with $\alpha \sim 3\text{-}10$ for a distinct high-energy tail. Though many theoretical models were proposed, the best explanation of the many experimental observations was given by Olson in his comprehensive theory.[2] Olson also proposed the Ionization Front Accelerator (IFA) as a scheme to control the beam front propagation velocity and thus achieve higher ion energies. We will discuss this scheme in Section 3 of this paper.

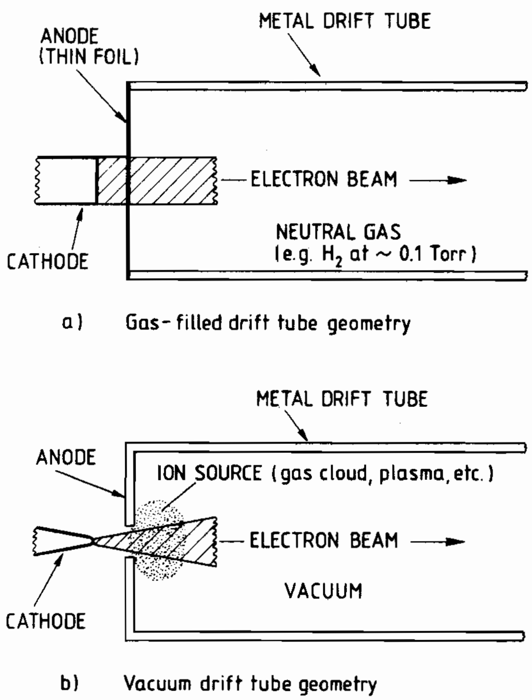

Figure 1

Typical experimental configurations for collective ion acceleration with intense relativistic electron beams (IREB): (a) IREB injection into drift tube filled with neutral gas, (b) IREB injection through localized gas cloud or plasma into a vacuum drift tube.

In 1974, J. Luce at Livermore pioneered a somewhat different collective ion acceleration method[3]. He used dielectric material in the anode of the IREB generator and injected the electron beam through a hole in the anode into a vacuum drift tube. With such a system, now known as a "Luce diode", and by using special ring-shaped electrodes (called "lenses" by Luce) in the vacuum drift tube, he reported ion energies that were significantly higher than those in the gas filled drift tubes. The highest value for the amplification factor reported by Luce was $\alpha \sim 45$ for protons. Subsequently, experiments with "Luce diodes" were performed at the University of Maryland and several other laboratories. The Maryland group, recognizing that the dielectric served as the source of positive ions, developed a new system which provided better reproducibility and external control of the experiments. In this new configuration, the dielectric is replaced by a standard metal anode and the electron beam is injected into the vacuum drift tube through a well localized ion source in the form of a gas cloud or a laser-produced plasma. This system is shown in Fig. 1b. In experiments with such a system, positive ions of various gas and metal species were accelerated to peak energies of about 5 MeV per nucleon[4). The total kinetic energy of about 900 MeV for Xenon ions is the highest energy achieved so far in collective acceleration experiments anywhere.

In contrast to the experiments with neutral gas, the results obtained in vacuum drift tubes are not yet fully understood. However, theoretical studies at the University of Maryland have identified several key features of the acceleration mechanism. In particular, a moving virtual cathode appears to be most consistent with the experimental data. The motion of the beam front and the virtual cathode can be influenced by the use of special electrodes (as was demonstrated by both Luce and the Maryland group). This led to the proposal of the helix-controlled Beam Front Accelerator (BFA) which is now being studied at the University of Maryland. The BFA concept will be discussed in Section 4.

Collective ion acceleration in the beam front motion schemes (IFA, BFA) is intimately connected with the propagation of electron beams near or above the space-charge limit. Therefore, in Section 2, we shall first present a brief review of the various phenomena that limit the propagation velocity of an IREB in neutral gas or vacuum. Before doing so it is worthwhile to point out some major differences between the beam front accelerators (IFA, BFA), on the one hand, and the Electron Ring Accelerator (ERA) and the Wave Accelerators, on the other hand. Both the ERA and the wave accelerators originated from theoretical ideas by Veksler, Budker and Feinberg in the fifties before intense relativistic electron beam generators were developed and experiments performed. By contrast, the beam front accelerator concepts evolved from theoretical analyses of experimental observations that occurred almost accidentally and that were neither expected nor predicted. It took many years of research and development to achieve collective ion acceleration in the ERA; wave accelerators have not been successful so far though the generation of slow waves with modest electric field gradients ($\sim$ 10 MV/m) has been demonstrated. However, the parameter dependence and scaling in these schemes is well understood since they are based on theoretical models. By contrast, collective ion acceleration in the beam front accelerator occurs naturally; the problem is to understand the observation and to control the natural processes and to develop scalable acceleration schemes. Another difference is the fact that beam front accelerators operate at higher currents (near and above the space charge limit), and that the field gradients in the beam front accelerators are at least one order of magnitude greater than in the ERA and wave accelerator cases.

2. LIMITING CURRENTS AND ELECTRIC FIELD GRADIENTS IN INTENSE RELATIVISTIC ELECTRON BEAMS

The electron beams used in these collective ion acceleration experiments are single pulses, typically between 10 and 100 ns long, with peak currents in the range from 10 to 100 kA, and peak energies between 0,5 to 5 MeV. All experiments so far have been done on a "single-shot" basis, i.e. one shot at a time which is repeated every few minutes. Repetition rate capability for these accelerators is being developed at Sandia Laboratories and at Livermore. A high-voltage pulse is applied to a diode (cathode-anode), and the electrons emitted from the cathode are accelerated and injected into a metal drift tube through either a thin foil or a hole in the anode. In the drift tube the electron beam can be focused by applying a uniform axial magnetic field or via charge neutralization if a neutral gas is present.

The electron beam generates very high electric and magnetic fields which have a strong effect on the motion of individual electrons. Moreover, the energy stored in these fields must be supplied from the kinetic energy of the beam. If a neutral gas is present, ionization takes place by collision with the beam electrons. The secondary electrons from these ionizing collisions are instantly ejected from the beam region to the walls and the remaining positive ions provide partial or full charge neutralization of the electron beam. Comoving or counterstreaming ions and electrons may also affect a partial or full current neutralization.

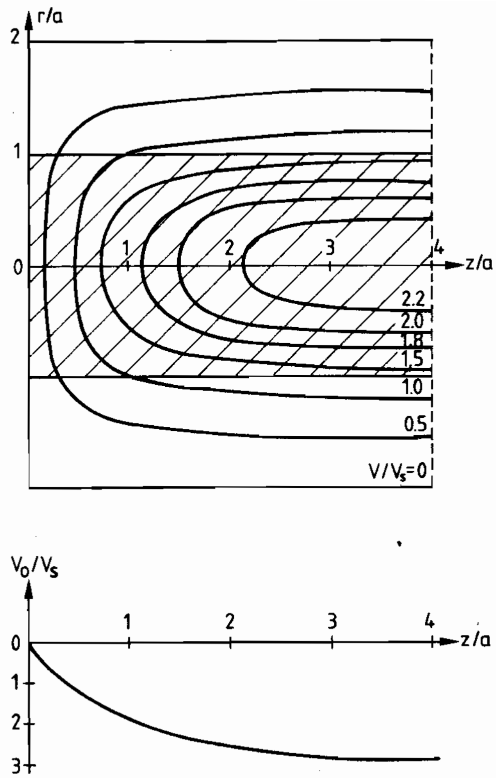

Figure 2

Potential distribution of electron beam with radius a entering a drift tube with radius b = 2a. Top: equipotential lines in units of V_s = 30 I/β. Bottom: potential variation along beam axis.

Fig. 2 shows the electrostatic potential distribution of a cylindrical beam with radius a and uniform charge density injected into an evacuated metal drift tube with radius b. The equipotential lines are shown near the anode for the case b = 2a. Potentials are indicated in units of

$$V_s = \frac{I}{4\pi\varepsilon_o v} = \frac{30\ I}{\beta} \quad . \tag{2}$$

At a distance z >2b, the electric field has only a radial component (assuming a constant beam radius in this uniform beam model). The potential difference between beam axis (r = 0) and beam edge (r = a) is V_s, given in (2). The potential difference between beam axis (r = 0) and wall (r = b) is

$$V_o = V_s\ (1 + 2\ \ln b/a) \quad , \tag{3}$$

and the maximum radial electric field at the beam edge (r = a) is

$$E_{r,max} = \frac{2V_s}{a} = \frac{60\ I}{\beta a} \quad . \tag{4}$$

As an example, for $I = 3x10^4$ A, $\beta \cong 1$, $a = 6x10^{-3}$ m, $b = 2a$, one gets $V_s = 0.9$ MV, $E_{max} = 300$ MV/m, and $V_o = 2.15$ MV. Thus, if V_b denotes the accelerating diode voltage, the kinetic energy of the electrons, eV_b, must be greater than eV_o to overcome the negative potential barrier on the beam axis. In our example we must have $eV_b > 2.15$ MeV. Incidentally, from the calculated field pattern of Fig. 2, one infers that there is a high axial electric field at the anode plane z = 0, r = 0) given by

$$E_{z,max} \approx \frac{75\ I}{\beta a} . \qquad (5)$$

In our example this implies a gradient of 375 MV/m.

What happens when the potential on the beam axis approaches the accelerating diode voltage ? As $V_o \to V_b$, the beam is stopped by its own space charge, and the electrons are reflected back to the anode. The current where this limit occurs is known as the space-charge limiting current. It was first derived by Bogdankevich and Rhukadze in 1971 and may be expressed in the form[5)]

$$I_L = I_o \frac{(\gamma_b{}^{2/3} - 1)^{3/2}}{(1 + 2 \ln b/a)\ (1 - f_e)} , \qquad (6)$$

where $I_o = \frac{4\pi\varepsilon_o\ mc^3}{e} = 1.7x10^4$ A for electrons, and γ_b is the relativistic energy factor defined as

$$(\gamma_b - 1)\ mc^2 = eV_b . \qquad (7)$$

The factor f_e in the denominator represents fractional space charge neutralization by positive ions.

In addition to the radial electric field E_r, there is an azimuthal magnetic field B_Θ due to the beam current. The associated Lorentz force $v_z B_\theta$ on the beam electrons is radially inward, i.e. focusing and counteracting the repulsive electric force. A net strong focusing force results when the space charge field is neutralized ($f_e = 1$). As was first shown by Alfvén[6)] and later by Lawson[7)], this force stops and reflects the beam electrons (pinch effect) when the current exceeds the critical limit

$$I_A = I_o\,\beta\gamma = 1.7 \times 10^4\ (\gamma^2-1)^{1/2}\ \text{A}\ . \qquad (8)$$

Note that $I_A > I_L$.

The energy stored in the electric and magnetic self fields of an electron beam of length L is given by

$$W = \frac{I^2 L}{4\pi\varepsilon_o c^2}\left(\frac{1}{4} + \ln\frac{b}{a}\right)\left[\frac{(1-f_e)^2}{\beta_f^{\,2}} + (1-f_m)^2\right], \qquad (9)$$

where f_e represents the fractional charge neutralization and f_m the fractional current neutralization.

This field energy must be supplied from the kinetic energy of the beam electrons, i.e. the kinetic energy at the beam front equals the kinetic energy at injection minus the field energy. This energy conservation law may be expressed in the form of a power balance, namely

$$I(\gamma_f - 1)\,\frac{mc^2}{e} = I(\gamma_o - 1)\,\frac{mc^2}{e} - \frac{W}{L}\,\beta_f c\ . \qquad (10)$$

Of particular interest is the case of a charge-neutralized beam ($f_e = 1$) where an upper limit is reached when $v_f = 0$, i.e. all of the injected beam power is converted into magnetic field energy. The current in this power-balance limit is given from Eqs. (9) and (10) by

$$I_P = I_A\,\frac{4}{1 + 4\ln b/a}\,\frac{\gamma_b(\gamma_b - 1)}{\gamma_b^{\,2} - 1}\ . \qquad (11)$$

It differs from the magnetic limit I_A mainly by the geometry factor $4/(1 + 4\ln b/a)$ which represents the field between beam ($r = a$) and wall ($r = b$) that was neglected by Alfvén and Lawson. Solving (10) for β_f in the case $\gamma_f = 1$ ($v_f = 0$), one obtains an upper limit, the so-called power-balance limit, for the beam front velocity:

$$\beta_f = \frac{V_b}{I}\,\frac{1}{7.5\,(1 + 4\ln b/a)}\ . \qquad (12)$$

This limit plays an important role in the Olson theory of collective ion acceleration in neutral gas[2)], as will be discussed in the next section.

The above theory, in particular the space-charge limiting current, was based on the nonphysical "uniform" beam model which by implication assumes that an infinite axial magnetic field forces all electrons to travel along straight lines. A more accurate self-consistent theory of a magnetically focused electron beam was presented by the author in 1977[8)]. It yields the following relations for the beam current I, the relativistic energy factor γ_b, and the applied uniform magnetic field B_o:

$$I = \frac{I_o}{2} (\gamma_o^2 - 1)^{1/2} (\frac{\gamma_a^2}{\gamma_o^2} - 1) \quad , \tag{13}$$

$$\frac{\gamma_b}{\gamma_o} = \frac{\gamma_a}{\gamma_o} + (\frac{\gamma_a^2}{\gamma_o^2} - 1) \ln \frac{b}{a} \quad , \tag{14}$$

$$B_o = \frac{mc}{ea} (\frac{\gamma_a^2}{\gamma_o^2} - 1)^{1/2} [(\frac{\gamma_a}{\gamma_o} + 1) - (\frac{\gamma_a}{\gamma_o} - 1) \frac{a^2}{b^2}] \quad , \tag{15}$$

where γ_o, γ_a, γ_b refer to the electron energy at the beam axis (r = 0), beam edge (r = a) and wall (r = b).

These three equations relate the experimental parameters I, γ_b, B_o, a, b; given two of the five parameters one can calculate the other three quantities.

From the above equations we can derive the modified space-charge limiting current by setting $\partial I/\partial\gamma_o = 0$. In the case b = a, one finds for γ_o the relation

$$\gamma_o^2 = \frac{\gamma_a^2}{2} \cdot [(1 + 8\,\gamma_a^{-2})^{1/2} - 1] \ . \tag{16}$$

Substitution of (16) into (13) yields the space-charge limiting current. Finally, we note that the beam front velocity in this self-consistent model is defined as

$$\beta_f = \frac{(\gamma_o^2 - 1)^{1/2}}{\gamma_o} \quad . \tag{17}$$

Let us now briefly discuss what happens when the beam current exceeds the space-charge limiting current I_L. Only a simplified, one-dimensional theory yields analytical answers in this case. For $I > I_L$, one finds that a virtual cathode forms at a very small distance d_m from the anode (injection) plane. The charge density at the virtual cathode is many times greater than the injected beam density, and the potential at the minimum, V_m, may be less than the cathode potential V_b, as illustrated in Fig. 3. Both d_m and V_m oscillate with small amplitudes about mean values obtained from the theory.

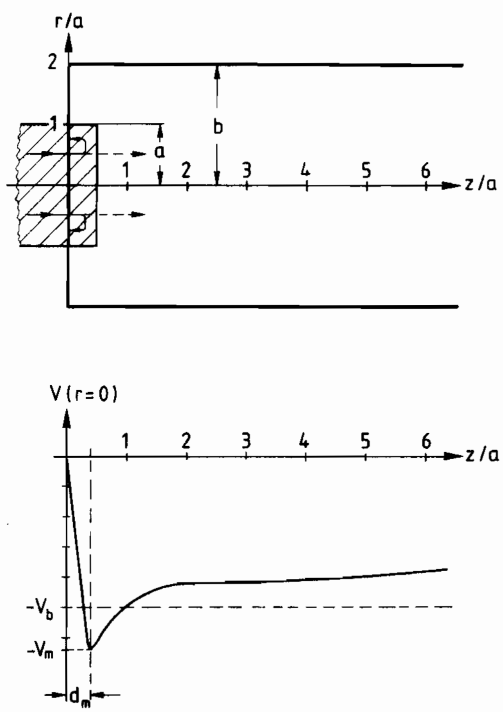

Figure 3

IREB injection into drift tube when current is above the space-charge limit ($I > I_L$). Top: Beam front stops at short distance d_m from anode, electrons are reflected. Bottom: Typical potential variation along beam axis; the potential minimum V_m at virtual cathode exceeds the beam voltage V_b.

Of particular importance with regard to collective ion acceleration is the electric field at z = 0 which may be expressed in the form

$$E\,[\mathrm{MV/m}] = \frac{2.04}{a_{[\mathrm{m}]}} \left(\frac{I}{I_o}\right)^{1/2} (\gamma_b^2 - 1)^{1/4} . \qquad (18)$$

As an example, for $I = 2I_o = 34$ kA, $\gamma_b = 3$, $a = 10^{-2}$ m, one finds $E = 485$ MV/m. On the other hand, for $I = 5I_o = 85$ kA, $\gamma_b = 5$ and $a = 10^{-2}$ m, one obtains $E = 1{,}010$ MV/m. These high electric field gradients and the potential well associated with the virtual cathode at the beam front play, according to our understanding, a crucial role in the observed collective ion acceleration processes, as will be discussed in the next two sections.

3. COLLECTIVE ION ACCELERATION IN NEUTRAL GAS, THE IFA CONCEPT

When an IREB is injected into a metal drift tube filled with neutral gas at a pressure p, ionization of the gas molecules by the electrons takes place. As positive ions are formed and accelerated in the electrostatic potential well of the beam, they too can contribute to ionization by collision with gas molecules. Following Olson's theory[2)], the most important parameter determining the physical effects is the time τ_N it takes to neutralize the space charge of the beam (i.e. the ion density equals the electron density). For hydrogen gas (H_2) Olson obtained the relation

$$\tau_N \sim 1.0 \ [p(\text{Torr})]^{-1} \ \text{nsec} \ , \tag{19}$$

i.e. τ_N is inversely proportional to the pressure p, as one expects. The beam physics and ion acceleration depend on the rise time t_R and total pulse length t_p of the electron beam and the pressure p of the neutral gas.

In the low pressure regime ($p < p_T$, $\tau_N > t_p$), a virtual cathode forms, the electrons are reflected and no beam propagation occurs. It is assumed, of course, that the beam current during the entire pulse length remains above the space-charge limit. Positive ions created in the potential well of the electron beam can be accelerated to kinetic energies of $E_i \lesssim eV_b$ (assuming a potential well depth of $V_o \cong V_b$).

In the high pressure regime ($p > p_T$, $\tau_N < t_p$), the beam becomes fully neutralized in time τ_N which is less than the pulse duration t_p. The beam, therefore, is able to propagate with a beam front velocity $\beta_f = L_W/\tau_N c$, where L_W is the width of the well region. Positive ions trapped in the moving potential well on the beam front are accelerated to a maximum velocity of $v_i \cong v_f \cong L_W/\tau_N$, which in view of (19) increases with gas pressure p. When the gas pressure gets high enough such that the electron beam gets neutralized during its rise time t_R before the current I reaches the limiting value I_L, no virtual cathode forms, the beam never stops and no ion acceleration should occur. The condition for this to happen is $\tau_N \lesssim \tau_R = (I_L/I)t_R$. Olson calls it the "runaway regime". Fig. 4 illustrates the beam front and ion velocity variation with pressure for the three regimes. At pressures $p > p_R$, where no ion acceleration takes place, the electron beam front velocity is limited by the power-balance relation (12). In most experiments this velocity was significantly greater than the maximum ion velocity observed, in agreement with Olson's theory.

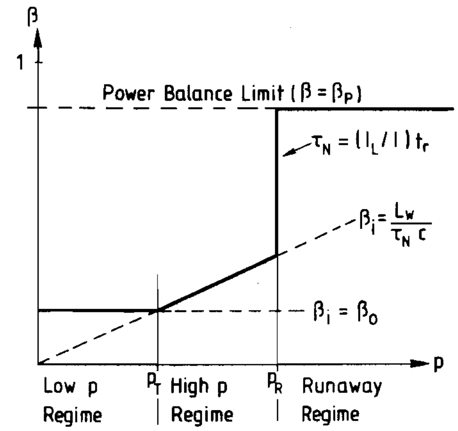

Figure 4

Electron beam front and ion velocity variation with neutral gas according to Olson's theory.

It is clear from the above model that further increase of the ion energies can be achieved only by avoiding the runaway effect, i.e. by external control of the beam front velocity. Olson proposed to accomplish such control in the Ionization Front Accelerator (IFA) concept schematically shown in Fig. 5. The drift tube is filled with a "working gas" at a pressure low enough that ionization by beam electrons is insignificant. Instead, the intense light pulse from a laser source is used to ionize the gas. Light pipes of increasing length allow one to control the arrival time along the drift tube and thus the propagation velocity of the beam front. Positive ions trapped in the unneutralized space charge well at the head of the beam are accelerated as the well propagates with increasing velocity that is determined by the arrival sequence of the laser pulses. The upper limit for the beam front and ion velocity is given by the power balance relation (12). Olson estimated that a 100 ns IREB pulse should be more than sufficient to achieve 1 GeV protons.

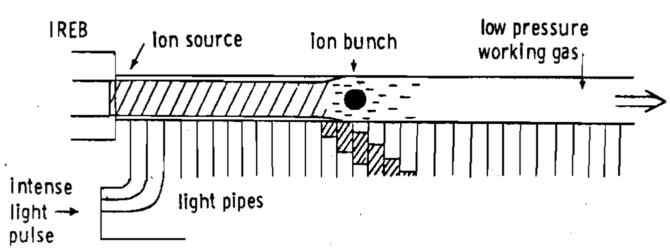

Figure 5

The Ionization Front Accelerator (IFA) scheme. The IREB is charge-neutralized by laser-light ionization of a low-pressure working gas. The unneutralized beam front forms a potential well for positive ions. Beam front velocity and thus ion acceleration is controlled by arrival of light pulses via light pipes of increasing length. (Courtesy of C.L. Olson).

It is important to point out that the IFA scheme can also operate below the space charge limit I_L. In this case the electron beam propagates even without the laser. However, the laser ionization produces a sharp transition within the beam pulse behind which the beam is fully neutralized and in front of which the space charge is unneutralized. Again one obtains an ionization beam front which travels at an increasing velocity (less than the actual beam front) as determined by the sweep of the laser pulses.

After completion of a "proof-of-principle" experiment (IFA-1) with encouraging results (proton energies of about 5 MeV), Olson has recently started the "test bed accelerator" project (IFA-2). This project aims at proton energies of 100 MeV. It features an improved electron beam generator with better reproducibility and low jitter, and a new working gas (NN dimethyl aniline - DMA) that operates at room temperature and requires only one laser (XeCl) for the ionization process[9)]. Results with this new system are expected within the next year.

4. COLLECTIVE ION ACCELERATION IN VACUUM, THE BFA CONCEPT

The physical mechanisms involved in collective ion acceleration when an IREB is injected through a gas or a plasma (see Fig. 1b) into a vacuum drift tube are not as fully understood yet as in the neutral gas case. However, the experimental data at the University of Maryland are consistent with a moving virtual cathode. Positive ions produced by collisions in the gas cloud or by laser bombardment of a solid target material are accelerated by the strong electric field of the virtual cathode that forms on the vacuum side of the gas cloud or plasma. The positive ions neutralize the electron space charge and, as a result, the electron beam front with the virtual cathode moves further down-stream. This "self-synchronized" propagation of electrons and co-moving ions depends on the ion density in the gas cloud or plasma, the rise time and pulse length of the electron beam, the drift tube geometry, the ratio of beam current to the space-charge limiting current, the beam voltage, and other factors. Many more systematic experiments will be required to explore the parametric dependence and to optimize the ion acceleration process. The major results of our studies at the University of Maryland so far can be summarized as follows:

a) The maximum proton energy increases roughly with the square root of the electron beam power, i.e. $E_i \propto (IV_b)^{1/2}$. This is in reasonable agreement with the formula (18) for the maximum electric field of the virtual cathode.

b) Positive ions of various gas species (from H to Xe) were accelerated to the same peak velocity of v = 0.1 c (corresponding to a kinetic energy of 5 MeV/n) independent of the ion mass. This result supports the concept of a moving potential well. We have so far, however, no satisfactory explanation why the peak velocity was 0.1 c in our experiments. Further systematic investigations showing how this velocity depends on experimental parameters have to be carried out in the future.

c) The total charge of the accelerated ion bunches is roughly constant (independent of ion species). This result indicates that the electron beam propagates as soon as a certain amount of fractional charge neutralization, f_e, is reached. It also shows indirectly that the number of accelerated ions is inversely proportional to the mean charge state of the ion distribution.

A special advantage of the evacuated drift tube compared with the neutral gas case is the fact that one can place electrodes into the beam path and try to control the beam front velocity. Preliminary experiments with one or two ring-shaped electrodes[10)] and subsequently with helical structures were very successful. Such "slow-wave" structures affect the beam front motion and allow a group of accelerated ions to remain in step with the potential well at the head of the electron beam. So far, we have demonstrated that a group of ions at the high-energy tail can be separated from the low-energy distribution and accelerated to higher energies[10)]. A factor 2 increase of the ion energy was achieved so far.

The early success with one or two ring-shaped electrodes led to the development of the helix-controlled beam front accelerator[11)] which is schematically illustrated in Fig. 6. After passage through the gas cloud or plasma and initial ion acceleration, the electron beam enters a slow-wave helical structure. The inner radius b of this structure is chosen small enough that the space-charge limiting current is greater than the beam current when the helix is at ground potential. However, if the helix is charged to a sufficiently high negative potential, the limiting current

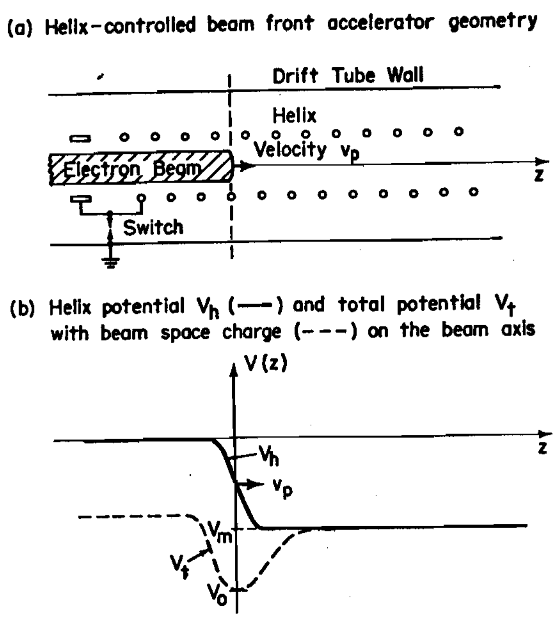

Figure 6

The Beam Front Accelerator (BFA) scheme: A slow-wave structure (e.g. helix) inside the vacuum drift tube is charged to negative potential V_h which is grounded with a switch when the IREB arrives. The grounding wave traveling along the structure with phase velocity v_p controls the beam front velocity and thus the acceleration of positive ions in the potential well at the beam front. (a) Schematic of experimental configuration. (b) Electrostatic potential variation along beam axis at time corresponding to beam front location shown in (a); positive ions trapped in potential well at beam front are accelerated as $v_p(t)$ increases with distance z.

decreases below the beam current and beam propagation stops. The energy factor γ_b in Eq. (6) must be replaced by $\gamma_b - \gamma_h$, where $(\gamma_h - 1)\, mc^2 = eV_h$ represents the decrease of the electron kinetic energy due to the negative helix potential V_h. The helix can be discharged by triggering a switch at the upstream end. The discharge voltage pulse, which grounds the helix, travels downstream with a phase velocity v_p that depends on the pitch angle angle Ψ of the helical structure and is given by

$$v_p \cong c \sin \Psi \qquad (19)$$

for high frequencies. By increasing the pitch angle one can increase the beam front velocity and thereby the energy of the ions that are trapped in the potential well of the virtual cathode.

In our experiments so far, the helix was charged up by the initial part of the electron beam pulse. The gap in the switch was adjusted such that voltage breakdown occurs when a threshold value is exceeded. Helix charging by an external geenerator and external triggering of the switch have to be studied in the future. It may in fact not be necessary since the image charges and currents in a slow-wave structure travel with velocity v_p which may be sufficient to slow down the beam front[12].

5. ELECTRON BEAM PROPAGATION AND COLLECTIVE ION ACCELERATION, THE "PISTON-PLASMOID" MODEL

From the previous discussion it is clear that electron beam propagation and collective ion acceleration are intimately connected. In a metal drift tube, an intense electron beam can propagate only when the beam current I is less than the space charge limit I_L. If not, propagation requires the presence of a charge-neutralizing positive ion background so that $I < I_L$.

When the drift tube radius is very large or when the electron beam is injected into free space (ideal vacuum), the space charge limiting current is practically zero ($I_L = 0$). Electron beam propagation in this case is possible only when co-moving positive ions are present. (An analogous situation exists in ion propulsion where co-moving electron beams are generated to neutralize the positive ion beam that emerges from the rocket engine.) When an intense electron beam is injected into free space from a solid conducting surface, the virtual cathode due to the negative space charge becomes a "mirror" which reflects all electrons back to the surface. If the solid conductor is replaced by a plasma with mobile charged particles, positive ions are extracted from the plasma surface and accelerated by the electric field associated with the electron space charge mirror. Provided that the plasma and ion density is sufficiently high, the layer of accelerated ions fully neutralizes the electron beam and the reflecting space charge mirror moves further downstream. The electron mirror in front of the electron and co-moving ion beam can be compared with the action of a "piston"[13]. This action which forces positive ions to follow the electrons is,in a sense,self-synchronizing and should continue, in principle, until the electron pulse terminates, or the supply of ions is cut off, or the co-moving ions have reached the same velocity as the injected electrons, whichever comes first. In the last case, the mirror disappears, no further electron reflections occur, electrons and co-moving ions form a charge and current-neutralized "plasmoid". Since the electric and magnetic fields associated with such a "plasmoid" are practically zero, no kinetic energy of the electron beam is converted into field energy. This "piston-plasmoid" model thus provides a mechanism by which ions are accelerated to the velocity of the injected electrons. The process is illustrated in Fig. 7 which shows schematically the various phases of the advancing electron and ion charge density

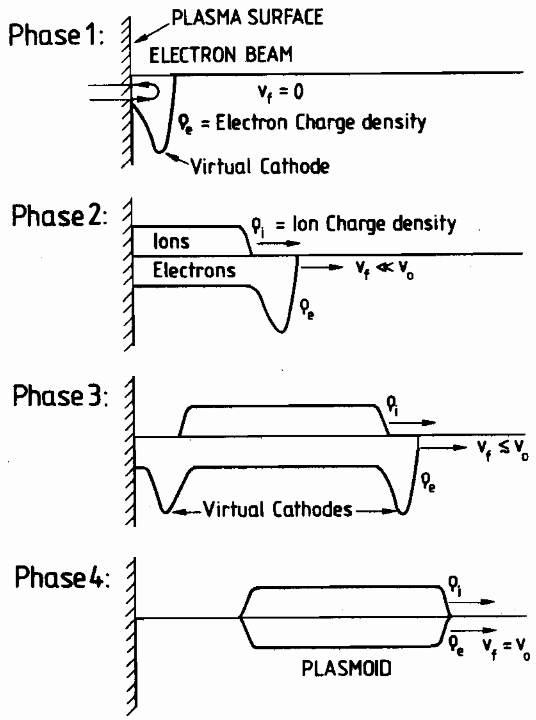

Figure 7

Suggested phases of plasmoid formation when an intense electron beam is injected into free space through a high-density plasma. Phase 1: Electron charge density ρ_e with virtual cathode (mirror) at time of injection. Phase 2: Positive ions of charge density ρ_i are extracted from plasma; beam front with virtual cathode moves with velocity $v_f \ll v_o$ (= electron velocity at injection). Phase 3: As v_f approaches v_o, a second virtual cathode (mirror) forms upstream separating the electron-ion bunch. Phase 4: The charge- and current-neutralized plasmoid ($\rho_i = \rho_e$, $v_i = v_o$) propagating with velocity $v_f = v_o$.

distributions. Just before the plasmoid state is reached, a second virtual cathode or electron mirror forms upstream from the beam front. This mirror prevents the reflected electrons from leaving the plasmoid and thereby separates the plasmoid from the rest of the beam.

In this model, the virtual cathode or mirror at the front of the advancing electron beam provides a mechanism to transfer energy to the positive ions. Indeed, each reflected electron gives up momentum in the amount

$$\Delta p = 2p_e = 2mc\beta_e\gamma_e \ , \qquad (20)$$

which is transferred to the positive ions extracted from the plasma. Let $J_e = en_ev_e$ denote the electron flux, v_i and M the velocity and mass of the ions, n_i the ion density, and L the length of the ion bunch. The momentum transfer (per second and square meter) from the reflecting electron stream to the ion bunch is then[13)]

$$\frac{dp}{dt} = \frac{d(Ln_i M v_i)}{dt} = 2\, n_e \gamma_e m (v_e - v_i)^2 \; . \tag{21}$$

For Ln_i = const, one obtains in the non-relativistic approximation the result

$$v_i = v_e \left\{ 1 - \left[1 + \frac{2n_e\gamma_e m}{MLn_i}\; v_e\; (t - t_o)\right]^{-1} \right\} \; . \tag{22}$$

which indicates that $v_i = v_e$ for $t \to \infty$.

This rather simple analytical model needs to be refined and studied by numerical simulation. However, the main question is whether such plasmoids can be formed in laboratory experiments. There are a few observations which seem to indicate that short ion pulses with a current comparable to that of the electron beam have been generated. But further studies are needed to obtain conclusive data to test the validity of the piston-plasmoid model. The fast ion tail ejected together with electrons from the plasma formed by bombardment of small pellets or other solid targets with a high-power laser beam also suggest that such a plasmoid effect takes place. It may well be that this mechanism plays a role in cosmic ray acceleration. As is known from laser fusion and other studies, a large amount of the available energy generates streams of relativistic electrons. An energy-releasing event on the surface of a star could produce intense jets of high-energy electrons. These electrons cannot escape into the vacuum of free space. They are reflected by their own space charge which in turn provides a mechanism to accelerate ions from the plasma on the surface of the star.

To summarize, the key feature of the plasmoid model is that many reflecting electrons transfer momentum and thus kinetic energy to a small group of ions until the ions have been accelerated to the same velocity as the injected electrons. The question remains to be answered whether laboratory conditions can be achieved in which such self-synchronized ion acceleration and plasmoid formation takes place or whether we must rely on external control as in the IFA or BFA concepts discussed in the previous sections.

6. CONCLUDING REMARKS

It is interesting to compare the flow of energy in a conventional high-energy accelerator with that in a collective accelerator. In the conventional system, the electric energy from the power source is first converted into kinetic energy of the electron beams in the micro-wave tubes (Klystrons, etc.). This kinetic energy of electrons is then converted into the radio-frequency waves that finally accelerate the charged particles. Depending on the power requirements many such r.f. generators or amplifiers are placed at suitable intervals along the particle accelerator.

The collective acceleration with intense relativistic electron beams discussed here by-passes the r.f. generation and converts electron kinetic energy directly into positive ion energy. Whether this can be done in a controlled fashion and used to achieve ultra-high energies remains an open question and a great challenge for accelerator physics. Single-staged IFA or BFA devices, as described in this paper, will undoubtedly be limited to energies considerably below the TeV range required from an ultra-high energy accelerator. As with conventional r.f. power amplifiers, staging of collective accelerators would be necessary. The amount of kinetic energy that can be transferred to ions in each stage depends on the power IV_b and pulse length t_p of the electron beam. The upper limit for the achievable ion energy is given by the relativistic energy factor γ_e of the last electron beam generator. This applies both for beam front accelerators as well as for wave accelerators. If we take the design energy of 50 MeV of the ATA project at Livermore as a realistic, near-term goal, than $\gamma_e = \gamma_i = 100$, corresponding to a proton energy of about 100 GeV. To go beyond this limit, one has to explore "fast" waves - either shocks or harmonic waves - that travel along the electron beam pulse from the rear to the front with a speed greater than the electron velocity. At present the main objective of the existing collective accelerator projects is to demonstrate the feasibility of "slow-wave" schemes designed to accelerate ions from rest to energies in the range between 10 and 1000 MeV. The problems of staging and "fast-wave" schemes (which require the injection of relativistic ions) can be explored after these experiments have been successful.

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DISCUSSION

Amaldi. How can we stage such accelerators?

Reiser. In ordinary linacs there are staged klystrons every few metres. In the same way one could have electron beam generators at intervals. Our aim is to understand what happens in one stage before we can consider this problem in detail. The ultimate limit to energy is when the ion energy equals the electron beam energy.

Zotter. When an electron beam in a drift tube is below the space-charge limit the potential depression is largest on the axis, and above this limit you would expect the electrons on the axis to be reflected first. Why do you get the whole beam reflected at once?

Reiser. We find from numerical simulation that the beam comes to an abrupt stop and all the electrons are reflected, though those on the axis are reflected a little earlier. The critical distance over which this virtual cathode is formed is very short.

Schopper. You said that one of the aims of this type of acceleration is to bypass the r.f. system. Klystrons, however, are already rather efficient. Does this mean that you cannot gain in efficiency more than a factor of two?

Reiser. R.f. power is also lost in the structure of the linac. I think that you could gain in efficiency, but I do not know by what factor.

Nation. A general comment relevant to all collective accelerators. To a purist, it is not collective acceleration that we have been discussing. Tsytovich claims that any true collective accelerator the ions should arrange themselves so as to be in phase with whatever mechanism is responsible for the acceleration. We are only speaking of a half-way stage where we are trying to impose our will upon beams. In a fully collective system the system should be self-phased. The system adjusts itself so that the particles remain in the correct phase.

Participant. Would the device also work with relativistic electrons?

Reiser. Yes we have about 2.5 MeV. The ETA accelerator at Livermore will produce beams of 50 MeV.

Same Participant. Will you lose energy by radiation?

Reiser. Our present energies are too low for this to be important.

Lawson. What energies and accelerating fields have been achieved in your small scale experiments?

Reiser. About 500-600 MV/metre in the Maryland experiment over distances of 5 or 6 cms. We have not controlled the gas pressure, but just let in a puff. We are far away from what I would consider to be an optimum.

Schumacher. Could you make a comment on transverse focusing and the emittance of the accelerated ions?

Reiser. One result with a witness plate about a metre from the electrons shows an ion beam less than 1 cm in diameter. The ions focus the electrons and vice versa as in an electron ring.