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RECENT ADVANCES IN COLLECTIVE ION ACCELERATORS*

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Abstract. The main developments in the field of collective effect accelerators during the past decade are briefly reviewed and major progress since the 1979 Particle Accelerator Conference is discussed. Important advances were made in vacuum drift tubes with localized ion source and wave accelerators. Recent results of the successful acceleration of heavy ions at the University of Maryland are described.

Historical Background and Overview

The interest in collective effect accelerators dates back to the ideas that Budker and Veksler presented at the 1956 High Energy Accelerator Conference at Geneva.[1] These ideas led to the development of the Electron Ring Accelerator (ERA) concept at Dubna that is still being pursued there today.

The Symposium on Electron Ring Accelerators[2] at the Lawrence Laboratory at Berkeley in 1968 laid the groundwork for the ERA project at Berkeley and marked the beginning of collective accelerator research in the United States in general. Shortly after this Symposium, ERA programs were also initiated at Garching (in 1969), at Karlsruhe (1970) and at the University of Maryland (1972).

The acceleration of positive ions to energies above 1 MeV by collective effects was observed for the first time in 1970 in experiments by Graybill and Uglum[3] in the United States and by Korop and Plyutto[4] in the Soviet Union. Graybill and Uglum injected a 1.6 MeV, 30 kA electron beam into a gas-filled drift tube and demonstrated the collective acceleration of ions from the filling gas to energies ranging from 5 MeV for protons to 20 MeV for nitrogen. Korop and Plyutto, on the other hand, accelerated carbon and aluminum ions to 10 - 15 MeV in a 300-kV vacuum discharge experiment. In the ERA projects, it soom became apparent that instabilities, particularly the negative-mass instability, would limit the electric field gradients to values considerably below 100 MV/m that was originally thought possible. The ERA thus was no longer attractive as a proton accelerator for high energy physics and the Berkeley project was terminated in 1976. In the wake of this decision, the other ERA projects in the U.S.A. and Germany were also discontinued. In Dubna, the main interest from the beginning has been in the collective acceleration of heavy ions where the ERA is attractive, even with more modest field gradients of 10 - 20 MV/m. At the 1978 Conference on Collective Methods of Acceleration[5], the Dubna group reported the successful acceleration of nitrogen and heavier ions at rates of 2 - 4 MeV/amu per meter[6]. During the last two years their main effort has apparently been devoted to the acceleration of xenon ions and to the use of electric fields (rather than magnetic expansion) for the acceleration of the ion-loaded ring.

In 1973, Drummond and Sloan[7] proposed the Auto Resonant Accelerator (ARA) in which a travelling electron cyclotron wave with increasing phase velocity is created in an intense relativistic electron beam. The wave serves as a moving potential well for the acceleration of positive ions, and its phase velocity is controlled by decreasing the magnetic guide field for the electron beam. For the past few years, the ARA project at Austin, Texas, has been the largest collective accelerator program in the United States.

Another form of a wave accelerator, the Converging Guide Accelerator (CGA), was proposed in 1976 by Sprangle, Drobot and Manheimer.[8] In the CGA concept, the phase velocity of a slow space charge wave in the electron beam is controlled by varying the cross section of the waveguide in which the beam propagates. This method is being studied experimentally at Cornell University. The successful generation of waves with the desired phase velocities was reported both for the CGA (in 1978)[9] as well as for the ARA (in 1981)[10]; the electric field gradients inferred from the experimental data were 5 - 6 MV/m in the CGA case and 10 MV/m in the ARA case. No ion acceleration has been demonstrated as yet in these wave accelerators.

The best results in collective ion acceleration so far have been achieved in drift-tube experiments. When an intense relativistic electron beam (IREB) with beam currents greater than the space charge limit is injected into a drift tube filled with a gas at low pressure, ion acceleration occurs naturally and has been routinely observed in many laboratories after the first experiments by Graybill and Uglum. If eV_o is the electron energy and Z the charge state of the ions, the peak ion energies are typically 2 - 3 times ZeV_o. Theoretically, it appears that the acceleration mechanism in gas-filled drift tubes is now reasonably well explained by a net space charge well which changes rapidly in time and space due to ionization processes. To achieve higher ion energies, Olson, in 1974, proposed the Ionization Front Accelerator (IFA)[11] where the ionization and acceleration processes are decoupled by use of a laser and light pipes. While some positive results with this scheme were achieved in a preliminary study (IFA1), a full-scale proof-of-principle experiment (IFA2) has not yet been carried out at this time.

The highest ion energies in collective acceleration experiments to date have been achieved in vacuum drift tubes where a source of ions is available to the electron beam at the entrance of the tube. This method was pioneered by Luce at Livermore who replaced the anode of the IREB diode with a dielectric material. The electron beam hits the dielectric and creates a plasma from which ions are accelerated into the vacuum drift tube. More recently, the University of Maryland group conducted experiments where the plasma is generated from a localized gas cloud[13] or from solid materials that are bombarded by a laser.[14] This method has produced the highest energies so far by collective effects in the laboratory (Xenon ions of about 900 MeV). It will be discussed in the next section.

Collective effects are of interest not only for the acceleration of ions but also for better focusing and containment of particle beams. Two examples in this category where acceleration is done by conventional external fields while focusing is provided by collective effects are the Collective Focusing Ion

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Accelerator (CFIA) at Irvine[15] and the PULSERAD project at Sandia Laboratories.[16]

Yet another application of collective effects is the auto accelerator[17], studied by Friedman at NRL, where the interaction between an electron beam and passive resonant structures leads to a transfer of energy from the majority of electrons to a smaller group of electrons. Friedman also studies a new collective ion accelerator concept.

During the past decade, three international symposiums on collective methods of acceleration were held, two at Dubna (1972 and 1976) and one in the USA (1978 at Laguna Beach). The proceedings of the last meeting have been published in a book[5], a summary of that meeting was presented at the last accelerator conference by Rostoker.[18] A detailed account of ideas, theories, and experimental activities prior to 1978, including a comprehensive bibliography, can be found in the book by Olson and Schumacher.[19]

A study group, chaired by Frank Cole of Fermilab, is presently evaluating the status and future of collective accelerators in the USA for the Department of Energy. Since the last particle accelerator conference in 1979, significant new results were achieved in the wave accelerators and the vacuum drift tube accelerators. In the next section, we will discuss these accelerators in a little more detail, with particular emphasis on the drift-tube work at the University of Maryland. Finally, in the last section of this paper, we will comment briefly on possible future directions and applications of collective accelerators.

Recent Progress in Wave and Vacuum Drift Tube Accelerators

The Space-Charge Current Limit in Drift Tubes

The vehicle used for collective ion acceleration in either the wave or the drift tube systems is an intense relativistic electron beam (IREB). Figure 1 shows a schematic picture of an IREB propagating in a drift tube. In the cylindrical beam depicted in the figure, the electron space charge produces a negative potential V (with respect to the drift tube wall) on the axis; its magnitude is proportional to the electron beam current I and is given by

$$V = \frac{I}{4\pi\epsilon_o v_z}(1+2\ \ln b/a)\ , \qquad (1)$$

where v_z is the mean axial electron velocity, a the radius of the beam and b the radius of the drift tube. When this potential approaches the cathode value V_o, the electrons lose all their kinetic energy and the beam stops propagating. The current at which this happens is known as the space-charge limiting current which is defined by the relation

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

where $(\gamma_o-1)m_oc^2 = eV_o$, $I_o = 4\pi\epsilon_o m_o c^3/e \simeq 17$ kA for electrons.

The space-charge limit plays an important role in linear beam collective accelerators. When $I > I_L$, the beam stops near the anode, and the electrons are reflected back towards the diode or the drift tube wall. A deep negative potential well, αV_o (with $1 < \alpha < 3$), forms near the anode, as indicated in the dashed curve of Figure 1. The associated electric field gradients, E_z, can reach very high values in the range above 100 MV/m depending on the beam current density, J, according to the relation[20]

$$E_z = \left(\frac{4m_ocJ}{e\epsilon_o}\right)^{1/2}(\gamma_o^2-1)^{1/4} \qquad (3)$$

When a plasma is present near the anode plane, as in the drift tube accelerators, collective ion acceleration takes place and the electron beam, its space charge partially neutralized by the positive ions, can propagate in the drift tube even if $I > I_L$.

Wave Accelerators

The wave accelerators operate at beam currents below the space charge limit I_L. The key idea here is to excite a travelling wave in the beam-drift tube system that has a phase velocity v_p less than the speed of light. One such waveguide mode is the "slow cyclotron wave" that results from the interaction between the beam and a magnetic guide field; its phase velocity is given to good approximation by the relation

$$v_p = v_z(1+\omega_c/\omega)^{-1}\ . \qquad (4)$$

Here v_z is the mean axial electron velocity, $\omega_c = eB/\gamma m_o$ the electron cyclotron frequency, and ω the frequency of the wave. By decreasing the magnetic field, and thus ω_c, with distance one can increase v_p and thereby accelerate ions trapped in the wave buckets from low to high velocities. This is the principle of the ARA.[7] The mean beam radius increases with distance according to the adiabatic scaling law a^2B = const., the beam envelope is rippled with amplitude Δr and the potential on axis varies periodically, as depicted in Figure 2. The electric field gradient is roughly given by

$$E_z \propto I(B/\gamma)(\Delta r/a)\ . \qquad (5)$$

An obvious problem with the ARA concept is that E_z decreases very rapidly as B falls off along the waveguide. Thus multiple staging schemes would be required to achieve very high energies; however, increases in the wave frequency ω from one stage to the next could cause problems in matching the ion bunches into the decreasing wave buckets without significant losses. Recently, the ARA group reported the successful generation of slow cyclotron waves with the theoretically expected phase velocities and wavelength and with inferred amplitudes of $E_z \simeq 10$ MV/m were achieved.[10]

In the Converging Guide Accelerator (CGA), a longitudinal slow space charge wave is used rather than a cyclotron wave. By decreasing the guide tube radius b with distance, one decreases the potential well on the beam axis, according to Equation (1), which in turn increases the mean kinetic energy $(\gamma-1)m_oc^2$ and axial velocity v_z of the electrons. The phase velocity is roughly given by (with ω_p = electron plasma frequency)

$$v_p \simeq v_z(1+\omega_p/\gamma\omega)^{-1}. \qquad (6)$$

A problem with the CGA is the difficulty of achieving low phase velocities for the early part of the acceleration process. Thus preacceleration of the ions may be necessary. In the project at Cornell University, space charge waves with phase velocities $v_p \geq 0.25c$ and amplitudes of 5 - 6 MV/m were demonstrated[9] for the first time in 1978.

Vacuum Drift Tube Accelerator Results at the University of Maryland

Several experimental configurations are being studied at the University of Maryland Collective Ion Accelerator which is shown schematically in Figure 3. The IREB generator produces electron beam pulses with typically 35 kA peak current, 1.5 MeV peak energy, and 30 ns pulse width. Diagnostics used in the drift tube section include time of flight probes, nuclear reaction, and cellulose nitrate track analysis in combination with thin foils for energy selection. The four anode geometries being studied are shown in Figure 4 and will be described below.

Luce diode and slow-wave structure. Initial experiments at our laboratory (by Boyer, Kim, and Zorn) provided the first independent confirmation of Luce's pioneering results.[21] A typical Luce diode geometry used in our experiments is shown in Figure 4(a). The dielectric insert (polyethylene, for instance) is charged up by the front of the electron beam. Surface breakdown and electron bombardment then form the plasma from which the ions are accelerated by the rear part of the electron beam pulse. The results of our experiments with Luce diodes[21,22] can be summarized as follows: (a) Maximum proton energies of 8 - 10 MeV were routinely achieved. (b) The use of special electrodes or slow-wave structures produced a well-defined high-energy beam component of 16 $\pm$ 1 MeV. (c) The peak energy is roughly proportional to the electron beam power. (d) In some proton experiments evidence of a high-current regime ($I \geq 200$ A) with narrow pulse width (≥ 4 ns) was found. Such a regime has not been observed in experiments with the puffed gas cloud where currents are usually a factor 10 lower. We believe that the high-current regime occurs only in a high-density plasma and we will search for it in the studies with laser-produced ions from solids.

Collective acceleration from a localized gas cloud. In this configuration, shown in Figure 4(b), the anode is made of stainless steel and a gas cloud is injected by a puff valve into the electron beam path. The front end of the electron beam ionizes the gas and the resulting plasma then serves as an ion source. Experiments with various gas species (H, He, N, Ne, Ar, Kr, Xe) were performed, and the following results were obtained[13]: (a) The maximum energy in the ion beams is about 5 MeV/amu -- independent of the ion mass; the bulk of the ions have energies in the range of 1 - 2 MeV/amu. (b) The total charge contained in the ion bunches is approximately the same for all ion species ($\approx 10^{12}$e) except for H where it is a factor 2 higher. (c) The charge states of the ions have not been measured yet. (d) The highest energies were obtained from Xenon where approximately 10^7 ions/cm^2 have energies in the range of 600 to 900 MeV.[23]

Collective acceleration from a laser-produced plasma. In these experiments[14] which have just begun last summer, a target of solid material (C, Al, Fe, W, etc.) is mounted on the rear of the anode and bombarded with a 15-Joule ruby laser (15 ns pulse width) as shown in Figure 4(c) just prior to the firing of the electron pulse. Preliminary results indicate the following: (a) Maximum energies are in the range of 5 MeV/amu as in the gas experiments. (b) The energy distribution of the ions peaks closer to the maximum energy and the spread in energy is significantly smaller than in the case with gas clouds.

Pulsed-power plasma focus experiments. Recently, M. J. Rhee[24] of our group conducted experiments in which the polarity of the diode voltage is reversed i.e., the "anode" is negative with regard to the "cathode." The geometry, which is shown in Figure 4(d), differs from conventional plasma focus devices in that the power source is an IREB generator. In the preliminary experiments with various substances, Rhee obtained energetic ion beams with the following properties: most of the ions are fully stripped, the maximum energy is in the range of 1 MeV/amu, the intensity peaks at the high energy end, and the emittance is extremely small ($< 5\times10^{-6}$ m-rad). It appears that the ions are formed in a very dense, tiny plasma focus which acts almost like a point source. The ion acceleration mechanism in this case can be attributed to inductive electric fields associated with the voltage breakdown between the electrodes.

Our experimental program is backed up by a small in-house theoretical effort which, we hope, will lead to a better understanding of the acceleration process and the scaling laws.[25] R. Faehl of Los Alamos Scientific Laboratory is collaborating with us in developing numerical simulation techniques capable of modeling the experimental configuration. We are particularly interested in a theoretical explanation of the high-energy component of the ion beam.

Future Developments and Applications

The field of collective accelerators has narrowed down to a few schemes. The best collective ion acceleration results to date have been achieved in vacuum drift tubes with an anode plasma as an ion source. However, the inferred high-field gradients above 100 MV/m exist only over a short distance of the order of 10 cm. Acceleration to higher energies is possible with slow-wave structures[22] where an energy increase of a factor of 2 has been obtained in experiments so far. Staging of such accelerators, as proposed by Adamski[26], is another possibility to increase the energy. Otherwise, the vacuum drift tube system can be used as an inexpensive injector with unique beam properties not available from conventional sources. A well-known problem in high-power accelerators (spallation neutron source, heavy ion fusion, etc.), for instance, is the focusing limit[27] at low energies which necessitates the use of expensive accumulator rings or beam compression systems to achieve the required high current levels at full energy. A collective accelerator producing high beam currents at energies of 5 - 10 MeV/amu would alleviate this problem. On the other hand, for low-intensity heavy ion facilities, the collective accelerator could replace the expensive pre-stripper machines such as tandems, linacs or cyclotrons[28]: the energies of a few MeV/amu are high enough to achieve efficient stripping to very high charge states in a foil, and (after stripping) the ion beam could be injected directly into the main post-stripper facilities (cyclotron, synchrotron, linac). Considerable work remains to be done in the future to demonstrate these capabilities of the vacuum drift tube accelerator.

The wave accelerators (ARA and CGA) are at advanced stages of the proof-of-principle experiments and results on ion acceleration can be expected in the very near future. The great challenge for the wave accelerators is to produce higher field gradients than conventional linacs with reasonable power efficiency (i.e., a high shunt impedance $Z_{sh} = E_z^2/P$) to keep the rf losses low.

Ultimately, the application of collective accelerators depends on the development of repetition rate capability for the IREB generators. Large efforts in this direction are under way at Livermore and Sandia. Until this problem is solved, the tasks for the drift tube accelerators is to demonstrate the suitability of the accelerated ion beams for specific applications and for other schemes to show the feasibility in the proof-of-principle experiments that are under way or planned.

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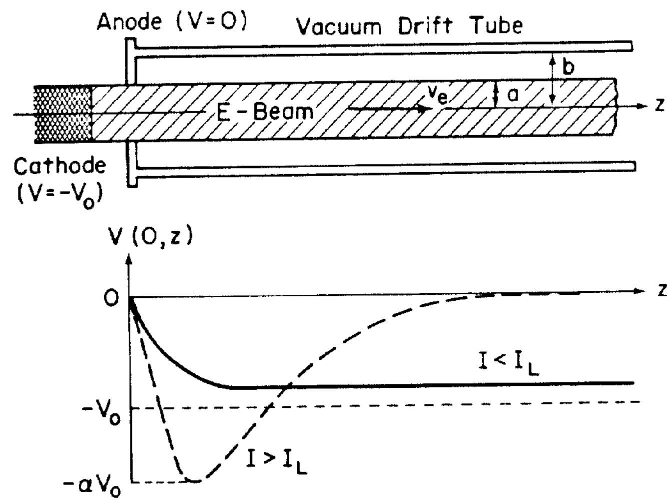

Figure 1. Electron beam propagating through a vacuum drift tube and potential on beam axis; the dashed curve indicates the potential when the beam current exceeds the space charge limit ($I > I_L$) and electrons are reflected back (virtual cathode formation).

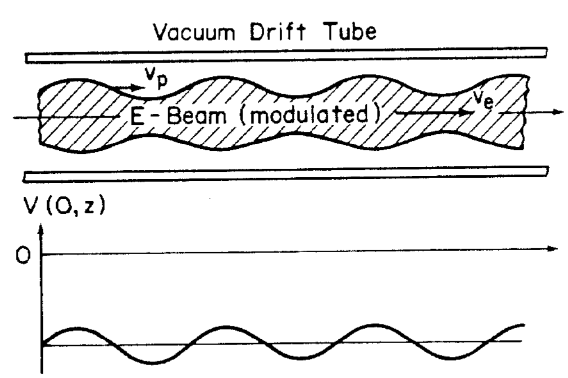

Figure 2. Radial modulation of electron beam profile and associated potential variation in the presence of a slow cyclotron wave.

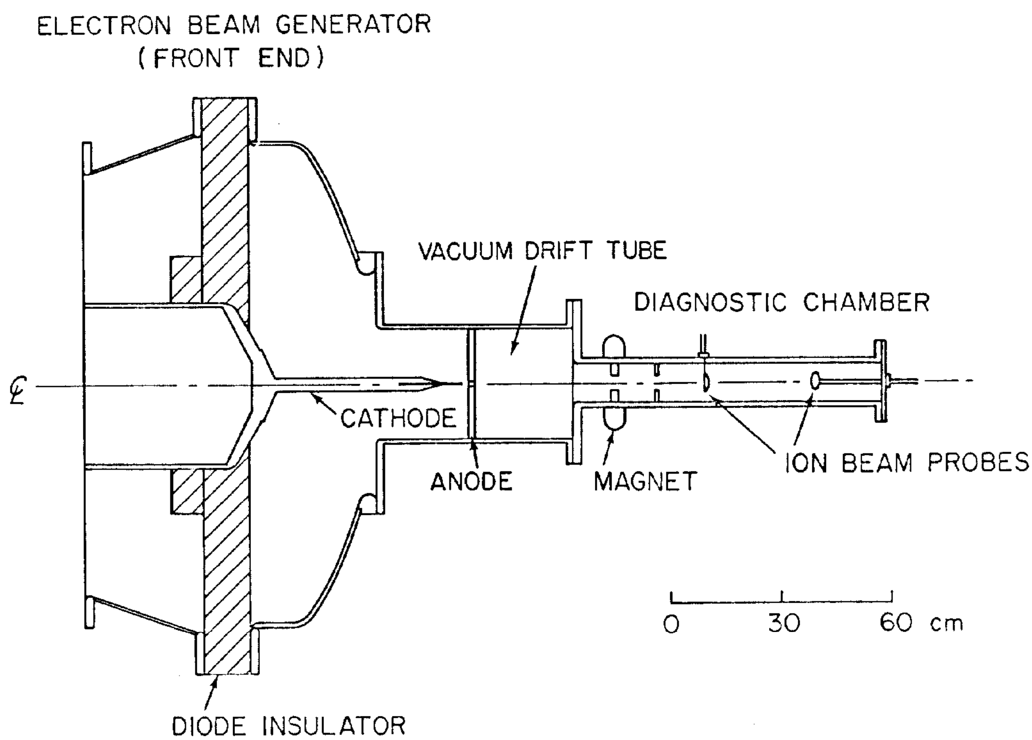

Figure 3. Schematic of University of Maryland collective ion accelerator (diode, vacuum drift tube and diagnostic chamber).

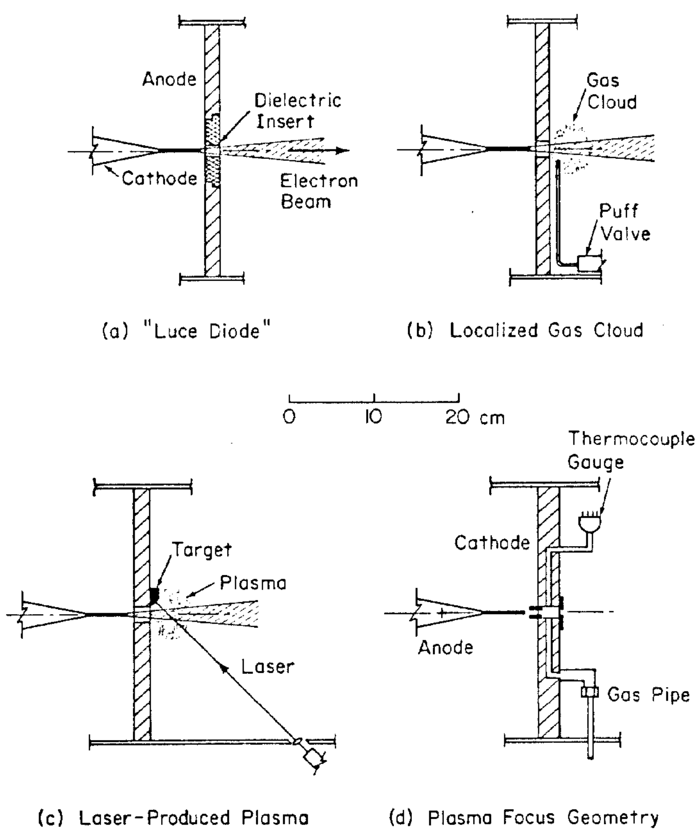

Figure 4. Different anode geometries in the collective ion acceleration experiments at the University of Maryland.