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CURRENT STATUS OF COLLECTIVE ACCELERATORS

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Abstract

The paper is based on the 3rd International Conference on Collective Methods of Acceleration held at Laguna Beach in May 1978.* Current status is considered for the Electron Ring Accelerator (ERA) Auto Resonant Accelerator (ARA), Ionization Front Accelerator (IFA), magnetically insulated ion diodes, Luce Diodes, and some more recent ideas, such as the Collective Focusing Ion Accelerator and Pulselac, where magnetic fields control the electron dynamics and electron space charge controls the ions.

In conventional particle accelerators, the electric and magnetic fields to accelerate and focus particles are produced externally. The condition that curl $\underset{\sim}{H}$ and div $\underset{\sim}{E}$ must be zero in the region of the particles to be accelerated sets rather strict limits on the shape and size of the fields $\underset{\sim}{E}$ and $\underset{\sim}{H}$. In conventional or "single particle" accelerators collective effects have been recognized even in early cyclotrons. The space charge of the charged particles defocuses the beam and sets a limit on the beam density or current. This limit is quite restrictive, particularly for heavy ions where magnetic focusing is very weak. Attempts to increase the limiting current by space charge neutralization as in the plasma betatron were not successful due to plasma instabilities. Collective effects have been known to accelerator physicists as something that causes trouble and should be avoided.

Collective acceleration means the use of the self-fields of assemblies of charges (almost always electrons) to focus and/or accelerate particles. Plasma physics is an essential ingredient and the jargon is more often that of plasma physics than accelerator physics. The earliest published attempt to make a collective accelerator was due to H. Alfven and O. Wernholm[1] who proposed to accelerate heavy particles by means of the combined charges of clusters of electrons produced by focusing an electron beam moving perpendicular to the acceleration direction. The electron beam was produced by a ribbon cathode and was focused by a "travelling" magnetic field. A modern form of this idea is the focusing instability that is discussed by K. V. Khodataev and V. N. Tsytovich.[2]

During the period 1950 - 1960 many ideas were investigated in the Soviet Union. The investigations were mainly theoretical and formed the basis for an experimental program that started in 1960 - 1961 at J.I.N.R. (Joint Institute for Nuclear Research at Dubna) and at the Physico-Technical Institute in Kharkov.

The electron ring accelerator was proposed by V. I. Veksler[3] and his collaborators in 1957. An electron ring is formed by injecting electrons from a linear induction accelerator into a magnetic mirror. The ring is then compressed by increasing the magnetic fields adiabatically. Ions are loaded in the ring by ionizing a small quantity of gas. The number of ions is always much smaller than the number of electrons in the rings so that the electric field from the space charge of the electrons is not significantly reduced. This electric field is required to contain the ions and is called the holding power. The ring including ions can then be accelerated by letting the ring drift into a decreasing magnetic field or by applying electric fields as in a conventional linear accelerator. The key problem is of course stability. Veksler's original paper dealt mainly with equilibrium of the ring, compression and acceleration. A holding power of several hundred Megavolts/meter was considered feasible.

At the 1971 High Energy Accelerator Conference in Geneva, Sarantsev reported the acceleration of α-particles to 30 MeV. However, this result was evidently not reproducible. Enthusiasm for the ring accelerator was further damped by the theoretical analysis of instabilities[4] which showed that the holding power was limited to about 50 Megavolts/meter. Therefore the accelerator would not be of great interest for high energy physics. The ERA program at Berkeley was terminated. However, three active groups continued to investigate the ERA - at Garching in West Germany, the University of Maryland in the United States, and Dubna in the USSR.

Since 1971 ERA research has concentrated on improving the quality of the rings at Dubna and Garching or on a different approach to forming the ring at Maryland. A small-scale ion acceleration experiment at Garching[5] confirmed the basic principle by accelerating ions to a few hundred keV.

In 1978 the Dubna group reported new results on ion acceleration.[6] They have accelerated about 5×10^{11} - N^{14} ions at a rate of 4 MeV/meter nucleon and heavier ions at a rate of 1.5 - 2 MeV/meter nucleon. The acceleration was over a length of 50 cm. At the end of the compression the magnetic field was 15 k-Gauss and the electron energy was 20 MeV. The electron ring contained about 10^{13} electrons within a final major radius of 3 cm and a minor radius of about 2 mm.

The Garching group[7] has developed a new machine called "Pustarex" which is close to a realistic accelerator configuration. $3 - 6 \times 10^{12}$ electrons have been captured and transported. The final dimensions of the ring are similar to the Dubna device.

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No ions have been accelerated yet. The Maryland[8] group tries to form and trap a ring by moving electrons through static magnetic fields. A relativistic electron beam is passed through a magnetic cusp causing the beam to rotate. Then about 1 - 4 x 10^{12} electrons are trapped in a magnetic mirror by resistive walls as proposed by Christofilos.[9] The electron cloud is an elongated ring - about 5 cm radius and 10 - 20 cm long with a very low holding power of .5 M-volts/meter.

The ERA has now emerged from the theory and promises phase, to where there is real experimental data. There is nothing to suggest that the theoretical limitations previously found are incorrect or too pessimistic.

In the 1956 CERN symposium, I. B. Fainberg[10] wrote a paper on plasma waveguides and suggested the possibility of making moving potential wells in a plasma or electron beam by means of a wave propagating in it. The wave can be created and grow in amplitude in a natural way through collective instabilities. The method is an improvement of a conventional linear accelerator where the travelling wave is a wave of the plasma so that the accelerating and focusing fields can be much larger than they would be for an externally produced travelling wave. One form of this idea is the Auto Resonant Accelerator (ARA)[11] that makes use of the negative energy electron cyclotron wave where phase velocity is

$$u_p = \frac{\omega}{\omega + \omega_c} V_B \qquad (1)$$

ω is the wave frequency, V_B is the electron beam velocity, and $\omega_c = eB/\gamma mc$ is the electron cyclotron frequency. The phase velocity u_p can be controlled with the static magnetic field B. The ARA is the largest collective accelerator program in the United States. Most of the work is done by Austin Research Associates in Texas. Some theoretical work is done at Los Alamos. Seven papers on this subject were presented at the Laguna Beach Conference and are published in the proceedings.[6] The objective of the program is a proof of principle experiment involving a 3 M-volt, 30 k-amp, 200 nanosec E-beam. The wave frequency is 250 M-Hertz and the magnetic field B is to vary from 25 k-Gauss to 2 k-Gauss over a distance of 4 meters. The objective is to accelerate a 30 ampere proton beam to 30 MeV. A great deal of theoretical work has been done on this idea. A pulse line has been constructed with a very precise wave form (less than 10% droop and high frequency ripple less than .5%), and some electron beam/pulse line experiments have been done.

Another form of wave accelerator is the Converging Guide Accelerator[12] (CGA) that makes use of the fact that the phase velocity of a slow space charge wave can be controlled by varying the cross section of the drift tube in which a relativistic electron beam propagates. An experimental program at Cornell University[13] has achieved slow waves with large electric field amplitudes. Phase velocity control has been documented for phase velocities from .3c to .76c. The next step will be ion injection and acceleration. The injector will provide 20 MeV ions from a Luce diode.

Some important theoretical considerations about linear wave accelerators have been discussed by K. V. Khodataev and V. N. Tsytovich.[2,14] For example, in order that the ARA (or any other wave accelerator) be a significant improvement on a conventional linear accelerator in ion current, holding power, etc., the cyclotron wave must be strongly non-linear. In that case the phase velocity is not controlled by the magnetic field as for a linear wave. In order to design a "respectable" collective accelerator the authors claim that one must understand the strongly non-linear stage. In their paper they carry out a study of the instability that they call the cyclotron-focusing instability which is appropriate to the ARA. They conclude that ion energies in excess of 1 - 200 MeV could not be attained in a single stage device. Higher energies (500 - 1000 MeV) would require a multiple stage scheme which is questionable because the acceleration rate decreases as the ion velocity increases. Self-accelerating non-linear modes in the form of solitons are considered as an alternative to the non-linear cyclotron-focusing mode.

The acceleration of ions by means of an electron beam launched into a gas filled drift tube started with an experiment in contrast to the other methods that started with theory. Graybill and Uglum[15] injected a 1.6 MeV electron beam into a gas filled drift tube and accelerated protons and deuterons to 5 MeV, Helium ions to 9 MeV, and Nitrogen ions to 20 MeV. Korop and Plyutto[16] accelerated carbon and aluminum ions to 10 - 15 MeV in a 300 k-volt vacuum discharge experiment.

Since 1970 experiments have been done in many laboratories similar to the above experiments. In the earlier experiments the energy for protons was usually a factor of 2 - 3 times the electron energy which could be explained by a deep potential well formed by the electron beam.[17] In more recent experiments the proton energy is as much as a factor of 10 greater than the electron energy, which has been explained by an ionization controlled potential well.[18] There is a general consensus that if the energy of protons could be increased further, say by another factor of 10, this type of accelerator would be quite useful because of its simplicity and high yield of ions - usually 10^{13} or more ions per pulse.

To make further progress, C. Olson has proposed to decouple the ionization from the acceleration process by designing an experiment with a laser and light pipes, so that the ionization is produced and controlled by external means. This is a very difficult experiment and has taken about 3 years to get the first positive results that were reported at the Laguna Beach Conference.[14] They include evidence for laser controlled E-beam propagation in a background gas of Cesium and some preliminary evidence for ion acceleration on nitro-cellulose film.

Considerable progress has also been achieved with experiments where an E-beam is injected into a vacuum drift tube with dielectric walls. Ions for neutralization of the E-beam are produced at the wall by surface flashover. Ions distributed in energy up to about ten times the electron energy have been observed. A considerable amount of data have been obtained with a relatively modest effort at Spire Corporation, Naval Research Laboratory,[20] North Carolina State University, and the Lebedev Institute.

In previous experiments with E-beams and gas filled drift tubes it was found that a magnetic field of only a few hundred Gauss parallel to the beam greatly reduced the number of ions accelerated. The magnetic field makes the beam electron orbits essentially one-dimensional and significantly affects the ionization process. There are now three different experiments where collective acceleration is observed in the presence of a strong magnetic field.[21] At University of California, Irvine experiments are done with gas gradients and a strong magnetic field. Detailed measurements have been made of beam propagation as well as ion acceleration. It has been established that the beam electrons reflex; i.e., they form a virtual cathode from which they reflect, return to the diode and reflect again. Similar observations have been made in a reflex-tetrode at the Naval Research Laboratory. At the University of Maryland a variable pitch helix configuration has been used in addition to a constant applied magnetic field to increase the energy of protons from a Luce Diode. These experiments produce results for ions comparable to the earlier experiments with no magnetic field. However, the ions have in general a broad energy spectrum whereas they were rather monoenergetic in many previous[15] experiments with no magnetic field. A new theory involving reflexing electrons has been advanced by D. Ryutov.[22] According to this theory, the equation of motion for ions

$$nM \frac{d\tilde{v}}{dt} = -en\,\nabla\Phi \quad ,$$

is equivalent to the corresponding gas dynamic equation

$$\rho \frac{d\tilde{v}}{dt} = -\,\nabla P \quad ,$$

if we can specify $\Phi = \Phi(n)$ and $P = P(n)$. Φ is the electrostatic potential. n is the electron or ion density since quasi-neutrality is assumed. Physically the electrons reflexing between the diode and the virtual cathode accelerate ions due to the expansion of the electron gas. Ryutov solves a model where $\Phi = \Phi_o (n/n_o)^2$ which is equivalent to $P = P_o(\rho/\rho_o)^3$ and obtains an energy multiplication for ions $W_{max}/e\Phi = 2$ for non-relativistic electrons and 5 for relativistic electrons.

The most successful collective accelerator so far is the Luce diode which has produced 45 MeV protons. In this diode the anode is insulated. There is an exit hole in the anode for the electron beam. The electron beam creates a plasma in this exit hole from which ions are accelerated into a vacuum drift tube. Evidently in this configuration control over the motion of the electron beam and ion acceleration can be exerted by floating electrodes downstream from the anode plasma,[23] or by a slow wave structure.[21] In spite of the widespread interest generated in this device by experimental successes, it has been most resistant to theoretical modeling. This is now receiving more attention[24] as well as efforts to design multiple stage accelerators.[25]

Magnetically insulated ion diodes have been developed mainly at Cornell University.[26] In this type of diode the ion energy is simply given by the diode voltage and the magnetic field prevents electrons from being accelerated across the gap. S. Humphreys et al., have proposed a high current linear ion accelerator based on multi-stage magnetically insulated diode gaps. A 5-stage multi-kiloampere device called PULSELAC is being tested at Sandia Laboratories.[27]

The Collective Focusing Ion Accelerator (CFIA) introduced by the U.C. Irvine Group involves an electron beam confined by a magnetic field in toroidal geometry. The very large electric fields interior to the electron beam are used to confine or focus an ion beam. Acceleration is accomplished inductively by conventional methods. An essential feature is that the toroidal magnetic field is "bumpy." The mirror force on electrons prevents them from being accelerated around the torus. The magnetic fields have little effect on the ions whose motion is non-adiabatic and is determined by the electrostatic field of the electrons whose density is always much greater than the ion density. Focusing ions with electron space charge was first proposed by Gabor.[28] A cyclic accelerator with conventional acceleration and strong focusing by the fields of an electron beam was described by Budker.[29] More recently a related device called HIPAC[30] was studied at AVCO. Theoretical studies have been carried out on the C.F.I.A. and a proof of principle experiment has been constructed at U.C. Irvine.

Assuming that an intense electron beam can be confined in a torus, and also an intense positron beam, F. Winterberg has investigated the radiative collapse of an electron positron plasma. He suggests that the collapse will be limited only by quantum effects and $\gamma m c r_{min} \sim \hbar$. In this case if the current is 17 k-amperes, $\gamma = 100$, then $r_{min} \cong 10^{-13}$cm and the final collapse density would be $\rho_{max} \cong 10^{10}$gm/cm^3.

Looking back over the development of Collective Accelerators since about 1956, it is clear that although there has been a great deal of progress, the subject is much more complex than originally anticipated. As in the case of Controlled Thermonuclear Research, the initial attempts all failed, and for similar reasons. In both cases the initial failures led to many new proposals and ideas. According to C. Olson, there are 37 proposed Collective Accelerator Systems. The impression of this subject to a conventional accelerator physicist has been expressed by F. Cole--"You have to kiss an awful lot of frogs before you find prince charming." In the case of thermonuclear research, the initial failures led to a massive effort to understand and control instabilities, and a study of the non-linear behavior for instabilities that cannot be eliminated. This effort still continues on a large scale because the end result is important enough to justify such an effort and there are few other options. The situation in Collective Accelerators has many similarities including the underlying physics. Although it is a complex and difficult subject compared to conventional accelerators, it is not as difficult as thermonuclear research. The stability requirements are considerably less, and progress in terms of practical results has come much more easily.

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