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The Use of Collective Fields in the Acceleration of Particles

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Abstract

Collective electric and magnetic fields arising from charges in beams and plasmas can reach very high intensities without spark breakdown and thus can be advantageous in the acceleration of particles. Three examples of collective-acceleration mechanisms are discussed: the collapsing pinch, non-linear plasma waves, and the electron ring.

Introduction

The acceleration of particles by collective fields is an important new area of research because it contains the possibility of a new generation of relatively cheap accelerators. Also, it is interesting in its many new and challenging problems.

Let me begin by saying what is meant by collective fields and why they can be advantageous for the acceleration of particles. By collective fields we mean simply the electric and magnetic fields that are produced by collections of electric charges in a beam or in a plasma. Such fields are in contrast to those used in conventional accelerators, in which the fields are produced by charges and currents in solid walls. The main point of considering fields produced by

charges in a vacuum or in a plasma is that such arrangements can produce much higher fields without spark breakdown than those that can be produced conventionally, which usually are limited by field emission from the wall surfaces. Collective fields can be used either for accelerating or for guiding the beam in an accelerator, and both functions have been seriously considered. However, the emphasis at present is on their use as accelerating fields.

The History of Collective Acceleration

The history of collective acceleration goes back to 1952 when Alfvén and Wernholm[1] in Sweden proposed the acceleration of positive ions by the electric field near the moving focus of an intense electron beam. Although their experiments were unsuccessful because of a lack in beam intensity, it was a bold and imaginative idea. In 1956 several far-out ideas were proposed by three Russian workers: Budker[2] suggested that a stabilized relativistic electron ring could provide the guide field for a high-energy proton accelerator; Veksler[3] suggested the acceleration of clusters of ions and electrons through the use of collective fields; and Fainberg[4] suggested the use of plasma wave-guides and also the use of non-linear density waves in plasma as an accelerating mechanism.

At this time there was a flurry of excitement and enthusiasm, which slowly faded and was replaced by skepticism as various instabilities and other difficulties came to the surface. It is not surprising that these collective-field configurations should tend to be unstable because field strengths on the order of hundreds of MV per meter are involved. Conventional accelerators, by the way, are intensity limited by collective-field effects at field strengths that are several orders of magnitude smaller.

Now there is another upsurge in the field of collective acceleration, which has been stimulated by two factors. One is the recent development of high-current, relativistic electron accelerators, such as the Astron accelerator and the more recent kilo-ampere short-pulse accelerators. The second factor is the psychological breakthrough produced by the success with electron rings that was accomplished in Veksler's laboratory, now headed by V.P. Sarantsev. This success has attracted many workers to the field, and many new views and ideas have emerged to stimulate the field even further.

I mentioned collective field strengths in the range of hundreds of MV per meter, and you may ask "Why so high?" The answer is "The competition". For collective acceleration to be worthwhile, it must show some significant advantage over the competition of conventional accelerators. A rough but convenient figure of merit for comparing accelerator systems is the average energy gain per meter of structure. For conventional accelerators typical figures are:

proton or heavy-ion linac	1 - 1.5 MeV per meter
electron linac	7 - 10 MeV per meter
proton synchrotron $(\frac{E_{max}}{2\pi R})$	40 MeV per meter

From such a table you can see that for a collective-field device to be practical as a high-energy proton accelerator, it is very likely that field strengths of 100 MV per meter or higher would be required. However, for a heavy-ion accelerator smaller collective-field strengths might be adequate.

The Collapsing Pinch Mechanism

As my first example of a method of collective acceleration let me describe the mechanism discovered accidentally by Graybill and Uglum[5] of the Ion Physics Corporation about 3 years ago. They injected an intense pulse of 1.5 MeV electrons into a gas at low pressure and observed a very intense burst of ions having energies much higher than that of the incident electrons. These observations have been confirmed and extended by Rander Ecker, Yonas, and Drickey[6] at the Physics International Company. The system used is illustrated schematically in Figure 1. Their rather remarkable findings can be summarized as follows:

(a) Ion energy per charge = const. $\begin{cases} \text{5 MeV per Z (at I.P.)} \\ \text{2 MeV per Z (at P.I.)} \end{cases}$

(b) Narrow energy spread, $\lesssim 10\%$ (instrumental resolution)

(c) High ionization states predominate

(d) Large number of ions, estimated at 10^{13} - 10^{15} per pulse

(e) Narrow ion pulse widths, from 3 ns for H^+ ions to 10 or 20 ns for heavier ions.

(f) 2 separate ion pulses observed under certain conditions.

(g) Acceleration occurs over a distance of only a few centimeters near the entrance window. Therefore, the accelerating fields are estimated to be on the order of 40 to 50 MeV per meter!

The theoretical model that best fits these data is that of Putnam[7], in which he includes both a potential well due to the unneutralized charge at the head of the beam and a collapsing pinch where the beam has become neutralized from ionization. The dominant mechanism is the collapsing pinch which produces an electric field (decelerating for the electrons, but accelerating for positive ions) proportional to $I \frac{dL}{dt}$, where I is the beam current, and dL/dt is the rate of change of inductance due to the pinch. Such a field is consistent with the constant energy gain per ionic charge that was observed. Calculations of the hydrodynamic details also are consistent with this picture.

This same mechanism is very likely the source of energetic ions that have been observed in many places from unstable gaseous and spark discharges. For example, Korop and Plyutto[8] have observed ions of about 2 MeV per charge state from 300 kV spark discharges. Also, one is reminded of the energetic ions from unstable discharges that produced neutrons and much confusion in the early days of controlled thermonuclear research. In any case, we have good evidence here of very intense collective fields.

Acceleration by Non-linear Plasma Waves

My second example of collective acceleration uses intense longitudinal space-charge waves propagating through a plasma. In such waves there is charge separation, and Fainberg[4] has suggested using the resultant collective electric field for the acceleration of ions. At high intensities, the space-charge waves become non-linear, and the phase velocity can have values appropriate for acceleration. Electric field strengths of 2,000 megavolts per meter are possible, according to the Russian workers. Another important feature of such plasma waves is that they are less prone to catastrophic instabilities than the other collective field mechanisms that have been considered. This relative stability arises from the transient role that a group of particles

plays as the space-charge waves sweeps through. Irregularities in this case tend to decay away in space rather than to grow into catastrophic instabilities.

The best way of creating these intense space-charge plasma waves is thought to be by shooting kilo-amperes of electrons into a gas or plasma. (See Fig. 2.) If the incident electron beam is slightly modulated, the density waves can grow in amplitude as the electron beam goes through the plasma, an effect which has been experimentally observed with low intensity electron beams at the Kharkov laboratory. In this way the intense space-charge waves can hopefully be stimulated and controlled in a relatively easy manner. For stable wave motion to exist in the plasma, the plasma particles should not be picked up and carried with the space-charge wave. Thus, the ions to be accelerated must be specially injected and captured in the moving potential well of the wave.

This method of collective acceleration is in a very early stage of development, and it would be premature to judge its chances of success. Basic work on the properties of plasma waves has been going on in Fainberg's laboratory in Kharkov for a number of years, but, as far as I know, no acceleration of ions has been accomplished or even tried. However, in Russia this method of collective acceleration has stimulated a great deal of interest and activity. When I attended a Russian accelerator conference about a year ago, I found that two other laboratories were building kilo-ampere electron guns for the purpose of serious work in this field and a great deal of theoretical interest generally. As far as I have heard, no work on this process is going on outside of Russia.

Acceleration by Electron Rings

My third example of collective acceleration is the electron ring method, which is the most popular of all the methods at present. At least 8 laboratories in the world have programs in electron ring research.

This method of collective acceleration was invented by Veksler[9] and co-workers in Dubna, U.S.S.R., and first reported in 1967. It is an ingenious and sophisticated system, whose main component is an intense ring of relativistic electrons circulating in axial magnetic field. The electric field in this ring is the collective field with which we want to accelerate ions. But, before considering the acceleration process, let us consider the interesting properties of the ring itself. (See Fig. 3.) It is only a slight exaggeration to say that such a ring of rotating electrons is almost stable by itself. By this I wish to emphasize that the repulsive coulombic field ϵ_c felt by a moving electron is mostly compensated by an attractive Lorentz force equal to $-\beta^2\epsilon_c$, which tends to produce the magnetic pinching effect. As a result the net repulsive force on the moving electron is reduced to $\epsilon_c(1-\beta^2) = \epsilon_c/\gamma^2$, where β and γ are the usual relativistic symbols for velocity and total energy. That is, because of the electron motion in the ring the net force felt by the electrons is equivalent to that of a much smaller number of static electrons -- smaller by the factor $1/\gamma^2$. For this factor to be appreciable, we see that the electrons must be quite relativistic. We can see also that the net repulsive force can be completely compensated and made attractive by the addition of a relatively small number of positive ions. That is, if the ratio of

ions to electrons is greater than $1/\gamma^2$, both the electrons and the ions feel attractive forces, and so the system tends to be stable, even though there is a great excess of negative charge. Such a ring of electrons lightly loaded with ions is the famous relativistic stabilized electron ring devised by Budker.[2]

Features of Ring Acceleration

Let us now consider how this electron ring can be used to accelerate ions. The maximum electric field felt by the ions in a uniform ring can be expressed in terms of the electron current (I) and the minor ring radius (a):

$$\epsilon_{max} \text{ [volts/m]} = 60 \text{ I/a [amp/m]}$$

A ring of 1,000 amperes with a 1 mm minor radius, for example, has a maximum field strength of 60 MV per meter, which indicates the range of parameters of practical interest. If the ring is somehow accelerated, the ions will be similarly accelerated, as long as the accelerating force on the ion $M_+\ddot{z}$ is less than the maximum electric force binding the ion to the ring. If the rate of acceleration exceeds this limit, the ions will, of course, spill out of the ring and be left behind.

One interesting feature of accelerating ions by means of an electron ring is that since all the particles are being accelerated at the same rate, their rates of energy gain and hence their effective accelerating fields are proportional to their masses. For example, a proton accelerated by an electron ring having a γ of 20 gains energy 100 times faster than each electron. Thus, an external field strength of, say, 1 MV per meter is sufficient for accelerating a lightly loaded electron ring that is itself accelerating protons at the rate of

100 MeV per meter.

Acceleration of the rings can be accomplished either by electric or by magnetic fields. In the electric case the rings are accelerated by axial electric fields, like those in a pulsed linear induction accelerator. An axial magnetic field must also be provided to maintain and guide the ring. Radio-frequency electric accelerating fields can also be used, but they tend to be more expensive and more difficult to synchronize with the ring than the pulsed electric fields. Electric acceleration will presumably be used for acceleration to very high energies, as it can be carried on as far as you want, as long as the ring is stable and does not radiate too much energy. I will speak about stability problems later. The radiation problem represents an interesting limitation to this method of acceleration. The electrons in the ring in effect radiate coherently when they encounter a discontinuity such as an accelerating gap. Since this coherent energy loss is proportional to the square of the number of electrons while the energy gain from the gap is only linear, there exists a number of electrons beyond which the ring will lose more energy than it gains from the accelerating gap. This is a real limitation and must be taken into account in the design of the accelerating column.

Magnetic acceleration of an electron ring will take place if the ring is simply placed in a constant axial magnetic field whose strength slowly decreases in the direction of acceleration. This acceleration is like the expulsion of a particle from a magnetic mirror. Or to say it in another way, the magnetic moment of the electron ring interacts with the axial gradient of the magnetic field to produce the acceleration. The required gradient of the field is rather small. For example, a gradient of only 13 gauss per cm is adequate for accelerating a 5 cm

radius electron ring that is accelerating protons at a rate of 100 MeV per meter. Thus magnetic acceleration is amazingly simple. But, unfortunately it can be carried only so far. Its basic limitation is that the static magnetic field can not add energy to the ring system. It can serve only to transform the electron rotational energy into longitudinal motion, in which the ions partake. Another limitation is that the maximum rate of acceleration must drop as the ring proceeds down a magnetic acceleration column because the electric field of the ring decreases as the ring expands. This expansion is caused both by loss of rotational energy and by the drop in the axial magnetic field. Thus there is a point where magnetic acceleration is no longer worthwhile. This point is typically taken to be where the ring radius has doubled, which occurs where magnetic field has dropped by a factor of 4.

The magnetic accelerating process serves to provide a multiplying factor for the ion total energy. This factor is 2 for lightly loaded rings in a column terminated where the ring radius doubles. That is, protons can be magnetically accelerated from rest to 1 GeV kinetic energy (total energy goes from 1 to 2 GeV), or equally well they can be magnetically accelerated from 50 GeV to 100 GeV. The first 50 GeV would, of course, be obtained by electric acceleration of the ring.

<u>Ring Formation</u>

The electron ring is formed by coiling and trapping in a weak-focusing magnetic field the beam from a moderate-energy electron gun. The ring is conveniently formed at a relatively large radius and then it is compressed as much as possible by increasing the magnetic field. Compression of the ring is desirable because it serves to increase the electric field greatly and also to reduce the cross-section of the accelerating column. Because of this function these ring-forming devices are called compressors . A drawing of a compressor system used at the Lawrence Berkeley Laboratory is shown in Figure 2. Its principal components are a ceramic vacuum chamber and 3 sets of coils which are pulsed sequentially to compress the ring from 18 to 3.5 cm. The right hand side of the innermost coil has been lengthened to form a short magnetic accelerating column. The ring can be loaded with ions simply by admitting a short puff of the desired gas and letting it be ionized by the electrons in the ring. The electron density can be so high that with heavy ions very high ionization states can be reached in a millisecond, which is an attractive feature for heavy-ion applications.[10]

Ring Stability

The principal difficulties in the formation and use of electron rings are a rich variety of beam instabilities. During compression the principal instabilities in the work at Berkeley have been the coherent transverse and longitudinal instabilities. During the past year we have been limited by the longitudinal, or negative-mass, instability to electron intensities of a few times 10^{12} electrons per ring, whereas we should like about 10^{13}. This instability is driven by the azimuthal electric field created by non-uniformities in the ring density. Such fields tend to cause clumping around the ring and excessive spreading in energy and in radial width. We are fighting this instability by smearing out non-uniformities with energy spread in the incident beam and also by reducing the azimuthal fields by means of nearby conducting surfaces.

Another effect that threatens to limit electron ring acceleration is the ion-electron instability. Theoretically disastrous resonances

can occur between the azimuthal motion of the electrons and the transverse motion of the ions, and at present it is a controversial subject as to whether these can be avoided or mitigated at the high field strengths wanted for a high-energy proton accelerator.

Status of Electron Ring Acceleration

The electron-ring group in Berkeley has achieved stable compressed rings of good quality having currents up to 700 amperes. The maximum electric field of such ring is about 12 MV per meter, which is high enough to be interesting, but not yet high enough for practical application. As mentioned earlier, we have encountered a series of coherent beam instabilities, which we have been exploring and learning to control.

The Russian workers at Dubna have not only already achieved very intense and stable rings but also have demonstrated the acceleration of ions.[10] Sarantsev and co-workers have reported field strengths of 60 MV per meter in rings having 7.5×10^{12} electrons and no disastrous instabilities. Furthermore, they reported in January 1971 the acceleration of alpha particles to an energy of 29 MeV by magnetic acceleration over a distance of 40 cm, which requires an electric field strength in the electron ring of at least 40 MV per meter.

The German workers at Garching and at Karlsruhe also have made electron rings for some time, but they have been limited by low-intensity injectors. Just now they are approaching intensity levels where you might expect coherent instabilities to occur, so that their evidence is not yet available. The other four laboratories doing electron-ring research also have no experience as yet in this subject.

We cannot yet offer a good explanation why it is that the Dubna compressor system is less prone to the negative mass instability than ours in Berkeley. However, we are happy to see their results because they indicate that electron-ring accelerators are indeed feasible and that practical machines are not far off.

Summary

The field of collective acceleration is rich in the possible methods that can be employed. I have been able to describe only three of them - the collapsing pinch, non-linear plasma waves, and the electron ring, which were chosen because they illustrate a good many of the concepts involved. Although the field is still quite young, I believe that it has already proved itself worthwhile and shows promise of an interesting future.

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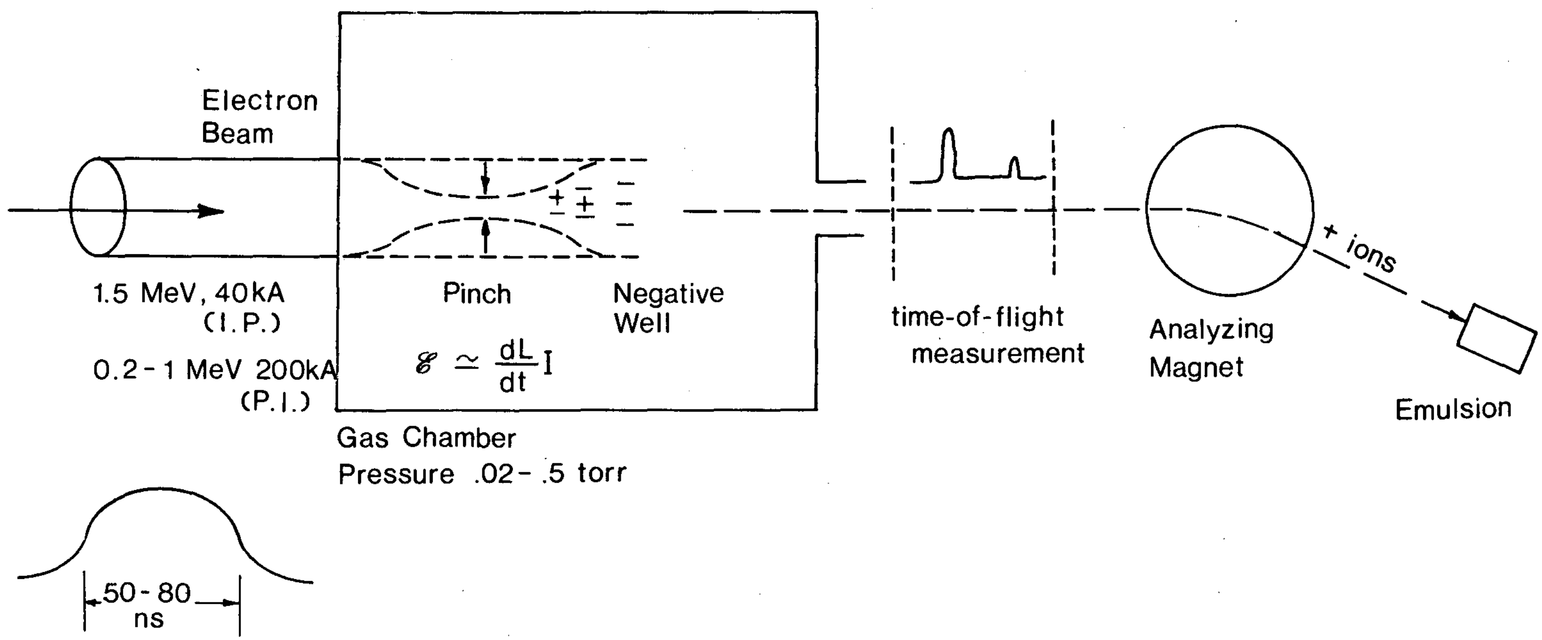
Figure Captions

Fig. 1 - System used in the observation of positive ions produced and accelerated by a short intense burst of relativistic electrons entering a gas chamber.

Fig. 2 - Schematic representation of ion acceleration by non-linear plasma waves produced by an intense, relativistic electron beam.

Fig. 3 - Some properties of the electric and magnetic fields in an electron ring.



XBL 723-472

Figure 1

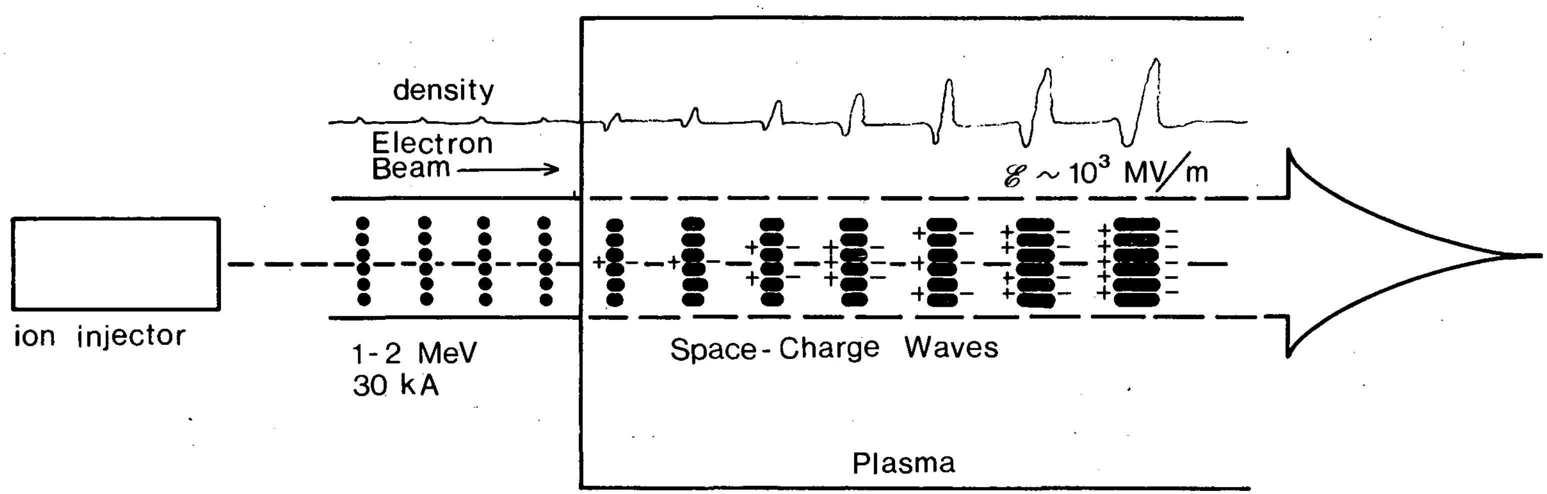


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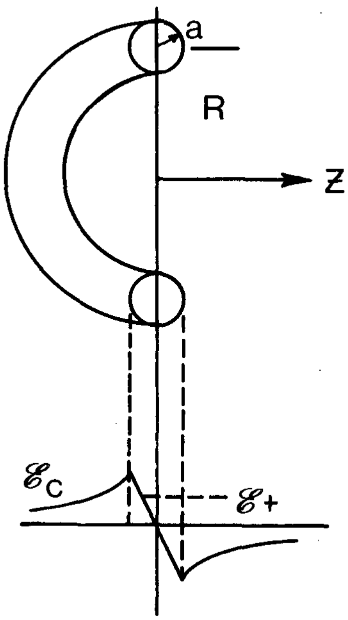
Figure 2



Electrons feel

repulsive Coulomb field $\mathscr{E}_c$

& attractive Lorentz field $-\beta^2 \mathscr{E}_c$

Net field $(1-\beta^2)\,\mathscr{E}_c = \mathscr{E}_c/\gamma^2$

Stabilized by $N_+/N_e \geq 1/\gamma^2$

Max $\mathscr{E}_c\,[\mathrm{v/m}] = 60\,I/a\,[\mathrm{amp/m}]$

When accelerating

$$q_+ \mathscr{E}_+ = M_+ \ddot{z}$$

$$\frac{\Delta E_+}{\Delta E_e} = \frac{q_+ \mathscr{E}_+}{e\mathscr{E}_{ext}} = \frac{M_+}{\gamma_\perp m_e} \simeq \frac{2000}{\gamma_\perp}$$

for protons

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Figure 3

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