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## COLLECTIVE-FIELD ACCELERATION OF HIGH-ENERGY IONS

J. S. Luce

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# COLLECTIVE-FIELD ACCELERATION OF HIGH-ENERGY IONS*



J. S. Luce
Lawrence Livermore Laboratory, University of California
Livermore, California 94550

## ABSTRACT

A collective-field accelerator has evolved from experimental and theoretical research at the Lawrence Livermore Laboratory that uses a high-vacuum diode with an adjustable graphite cathode as well as an insulated anode, and that operates with a relativistic electron beam with $\nu/\gamma$ of ~1. Alternate gradient lenses are used to focus collectively accelerated particles. The gradients are produced by alternate dielectric and grounded lenses. The dielectric lenses are self charged by the electron beam creating a potential difference in reference to the grounded lenses. These lenses focus both electrons and ions by convective processes. Deuterons have been accelerated in pulses of $\sim 10^{14}$ producing up to $10^{11}$ D-D neutrons per burst by impingement on suitable targets. Hydrogen, deuterium, carbon, fluorine and chlorine ions have been accelerated to produce both light- and heavy-ion reactions. Analysis of activation data shows that heavy ions with >6 MeV per nucleon and protons with ~15 MeV energy have been produced. Theoretical analysis indicates that the collective ion acceleration mechanisms arise from interactions with plasma-wave trains created by near-resonant, beam-cavity interactions and accelerated (in group velocity) through density and temperature gradients in the secondary plasma beyond the anode.

## INTRODUCTION

The first attempt to accelerate positive ions with the self-field generated by high energy electrons was made by Hannes Alfvén and Olle Wernholm in 1952.[1] The potential of this exciting new concept was recognized by many scientists and by 1956 several schemes had been proposed to accelerate ions by this method.[2-6] The promise of economical, compact accelerators that would accelerate particles with powerful self-generated fields created considerable optimism among early workers. This enthusiasm has gradually tempered because of technological difficulties and the need for more comprehensive theory. Funding has also been attenuated by the very successful (and expensive) development of the alternate-gradient strong-focusing principle that is now an essential feature of many particle accelerators throughout the world. It is interesting to note that not until recently has alternate-gradient focusing been considered in collective field accelerators. In 1974 the first preliminary experiments using self-charged lenses were initiated at the Lawrence Livermore Laboratory (LLL).

Many workers have made contributions in the field of collective particle acceleration.[7-47] Linear collective field acceleration of positive ions has up until now been more effective than other methods being investigated. This system is being studied at LLL and several other laboratories in the USA and the USSR. Discussions in this document are limited to linear systems.

The experimental geometry, conditions, and degree of success that have evolved from the LLL program are significantly different from other collective acceleration experiments known to us. Fortunately, both the geometry and the vacuum conditions that optimize the collective acceleration mechanism are particularly well suited for adoption as a production ion accelerator.

## THE LLL COLLECTIVE FIELD ACCELERATOR

Research with the LLL collective field accelerator using a Pulserad 422 E-beam machine that delivers 2500 J of energy at 2 MeV in 60 ns has been reported in the literature.[48,49] However, the device has undergone rapid evolutionary changes that are still in progress. Consequently the configuration and results reported herein have not as yet been published.

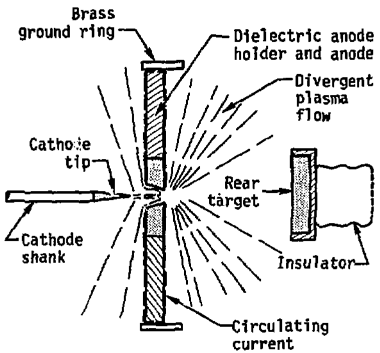


Fig. 1. Original LLL collective field acceleration geometry.

The first geometry used for collective field acceleration[4-8] is shown in Fig. 1. When the E-beam machine is triggered the relativistic electrons move more or less uniformly along the cathode surface. Low-energy positive ions produced on the surface of the cathode prevent space-charge blowup of the electron beam. The flow of current along the cathode produces a strong $B_\theta$ field, constraining the electrons to the small diameter cathode and ejecting a relatively uniform electron beam into the cathode-anode gap.

No fundamental difficulties have been encountered with high impedance as a result of the small diameter cathode, although major alignment problems and destructive filaments were encountered until an all-graphite cathode structure was used. It is believed that the presence of low-energy positive ions on the cathode reduces impedance and greatly enhances electron flow. When the electrons leave the end of the cathode they enter a hard vacuum and are no longer space-charge neutralized. Consequently, the electron beam blows up to a larger diameter determined by the geometry and pressure in the cathode-anode gap. The electrons impinge on the inside surface of an anode containing the proper element to produce the ions desired for acceleration. When the electrons strike the insulated anode several events occur. The insulated anode behaves as a resonant cavity, which modulates the beam. An intense plasma is formed primarily behind the anode in the space between the anode and the rear target. This plasma provides the ions that are collectively accelerated toward the rear target. Initially part of the return current flows out of the cathode side of the insulated anode hole like the point of a cusp-shaped plume. The outer periphery of this cusped-current sheet impinges on grounded surfaces thus completing the circuit. The sheet contains both ions and electrons since activation is detected where the current sheet reaches ground potential. Ions also impinge on the cathode where $N^{13}$ is detected when deuterons derived from a deuterated polyethylene anode are produced. The ions accelerated in the cathode-anode region have relatively low energy compared to the collectively accelerated ions from the plasma formed between the insulated anode and the rear target. The ions that impinge on the rear target flow in the same direction as the primary electron beam so it can be safely stated that these ions are accelerated by collective fields produced by the primary electron beam. The ions flowing in the opposite direction with the return current are probably also accelerated by a collective process because of the electric fields in the return current sheet. Ions reaching the cathode, however, appear to be accelerated by an electrostatic field produced by the applied machine voltage. A sheath is clearly discernable between the cathode and the anode plasma as shown in the open shutter photographs in Fig. 2.

The intense plasma formed between the anode and the rear target produces a widely

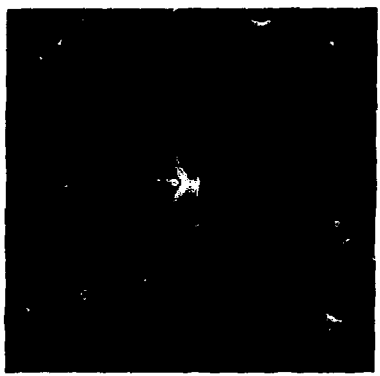

Fig. 2. Cathode sheath.

Fig. 3. Divergent flow of ions and electrons.

divergent flow of ions and electrons as shown in Fig. 3. This divergence is typical of linear collective field accelerators.[50] It was postulated that the convective nature of the plasma would make it possible to treat it as a cloud of energetic electrons. If this were true it would be logical to assume that the plasma could be focused by a suitable lens. This hypothesis has been shown to be correct and improved focusing as well as higher energy ions have been achieved with a self-charged lens. Figure 4 shows the focusing achieved with this lens and Fig. 5 shows the geometrical arrangement used.

The cathode is a graphite rod 2 mm in diameter, which is fed through a tapered graphite transition piece with compound tangent angles providing an average angle of about 28°. This parameter, as well as the length and average diameter of the transition piece, is determined by the diameter of the machine cathode shank into which the transition piece is fitted.

The anode is a 6-mm-thick piece of selected plastic containing the necessary element to produce the ion specie desired. This anode has a stepped structure, and is pressed into a plastic disc anode holder 11 cm in diameter by 6 mm in thickness, providing the insulation required for efficient operation. A second plastic plate is used with the anode to prevent it from being blown out by the beam. The anode has a hole 9.5 mm in diameter and the lens is located 6.25 cm behind the anode.

The improvements resulting from the use of a single lens led to experiments with multiple lenses. A four-stage lens system was developed using alternate gradient focusing. These gradients were achieved by using alternate dielectric and conducting lenses. The dielectric lenses were charged to a high potential by the electron beam whereas the conducting lenses were grounded. The last lens was found to be defocusing when used with a grounded rear target. This defocusing was caused by the lack of a gradient between the (grounded) last lens and the grounded rear target. Removing the fourth grounded lens left three lenses and a grounded rear target acting as a lens. This arrangement provided the best focus achieved to date and the highest energy ions. This lens system was designed by impinging the collectively accelerated beam on the lenses and using the resultant radiated areas to determine various geometrical parameters

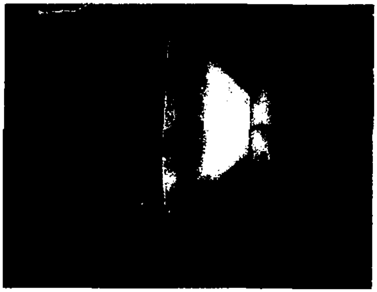

Fig. 4. Focusing lens. The apparent plasma on the right-hand side of this photo is a reflection of the actual focused plasma.

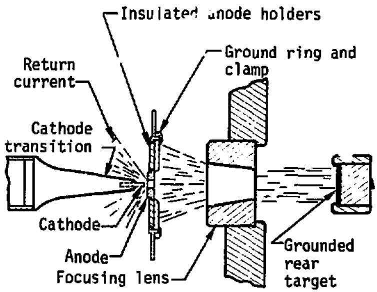


Fig. 5. New geometry with focusing lens.

Fig. 6. Multiple lenses.

such as length of the lenses, gap distances and hole sizes.

Figure 6 shows the present device in operation. It can be seen that plasma is created in each of the lenses. Thus a series of plasmas are present, isolated by vacuum and high potentials. The electron bunches produced by the oscillating anode pass through these plasmas and probably create additional plasma waves in each isolated plasma. There are strong indications that ions formed in these lens plasmas are also accelerated to the rear target. It is also of interest that the second and third lenses have no effect unless a plasma is formed in the lenses.

These lenses have a lens-to-lens gap of 2.54 cm and a lens length of 3.81 cm. The hole sizes beginning with the first lens are 6.35 cm, 6.98 cm and 7.62 cm respectively. A rear target holder is located 6.25 cm behind the exit of the focusing lens. It holds grounded metal targets when radioisotope production is desired, and teflon[51] or deuterated polyethylene ($CD_2$) targets for neutron production. The actual grounding of the rear target is a complicated procedure involving careful attention to impedance and breakdown. Figure 7 shows the focusing achieved with a grounded rear target when it is used as a fourth lens.

## EXPERIMENTAL RESULTS

Important figures of merit used to evaluate the performance of collective accelerators include the number of elementary particles that can be accelerated and the various isotopes that can be produced. At this time we have accelerated hydrogen, deuterium, carbon, fluorine and chlorine ions to produce such light- and heavy-ion reactions as

$^{65}Cu(p,n)^{65}Zn$, $^{63}Cu(p,n)^{63}Zn$, $^{63}Cu(p,2n)^{62}Zn$, $^{56}Fe(p,n)^{56}Co$, $^{58}Fe(p,n)^{58}Co$, $^{12}C(d,n)^{13}N$, $^{13}C(p,\gamma)^{13}N$, $^{27}Al(^{12}C,He,n)^{34}Cl$, $^{27}Al(^{19}F,D)^{44m}Sc$, $^{27}Al(^{19}F,D)^{44}Sc$, $^{27}Al(^{19}F,t)^{43}Sc$, $^{27}Al(^{37}Cl,n)^{63}Zn$, $^{27}Al(^{12}C,{}^{4}He,{}^{3}He)^{32}P$, and $^{65}Cu(^{12}C,2n)^{75}Br$, etc.

Unfortunately this list of radioisotopes is necessarily incomplete since the data from numerous runs have not been evaluated. In the coming months we also plan to irradiate several heavy elements such as Ta, Au, Pt, Ho, etc. with Hg ions.

Although incomplete, these data do indicate a high efficiency for ion acceleration that is confirmed by measurements of $10^{14}$ deuterons per shot with an average energy of >12 MeV. Thus about 190 J of energy is being delivered by these deuteron bursts. Heavier ions with ~6 MeV per nucleon have also been observed. The efficiency of conversion of electron beam energy (2500 J) to ion energy is therefore over 7% and the neutron production efficiency from deuterons incident upon deuterated polyethylene and teflon targets (~$10^{11}$ per shot) is approximately 100 times larger than in other ion acceleration systems.

While it is obvious that much research remains to be done, recent technological advancements suggest that the time has come when it is appropriate to begin considering applications of collective field accelerators.

Fig. 7. Irradiation of grounded copper target.

## APPLICATIONS OF COLLECTIVE FIELD ACCELERATIONS

### ACCELERATOR APPLICATIONS

The encouraging results discussed in the previous section naturally lead to speculation regarding the future role of collective acceleration in producing radioisotopes economically in widely distributed locations and the impact this would have on the related fields of nuclear physics, chemistry and medicine. While it is true that a repetitively pulsed electron-beam machine would be necessary for these and most other applications, it is appropriate to begin investigating these possibilities with present nonrepetitive electron-beam machines.

One of the most impressive features of linear collective field accelerators is their inherently low capital cost. Equally or even more impressive is their surprisingly low operating cost. It can be predicted with considerable confidence that the LLL device will in a reasonable time be able to produce radioisotopes automatically. Automatic operation has already become a reality with certain electron-beam machines used in the so called "flash x-ray" mode. The basic simplicity of these devices assures the success of complete automation including permanent records of machine performance and radiation levels from the target. Human intervention would be needed only in the case of malfunctions or maintenance of equipment. The low cost of these accelerators (probably about half a million dollars for a large machine) would put them within the reach of many scientific organizations that are now unable to participate in advanced accelerator research.

It is probable that if a modest but determined research effort were funded, collective field accelerators could be developed that would open up new fields of research not feasible with present machines. Because of the universality of the collective field principle such machines could theoretically accelerate the ions of all the elements. Since all the elements would also be available as targets, the entire spectrum of possible reactions would, in principle, become available for exploration — limited only by the ultimate energy of the ions and the time required for such an enormous task. When the advances that have been made at LLL in focusing collective beams are considered, the achievement of high-density clashing beams also becomes a real possibility. Since these beams contain both ions and electrons they are space-charged neutralized and their particle density would grossly exceed the density attainable with present space-charge-limited devices. The utilization of laser beams to create highly focused preionized paths for plasma waves is an exciting possibility for further improvements in beam focus. In view of the many surprises that have resulted from high-energy light-ion reactions it appears inevitable that many new discoveries await experimenters using the intense heavy-ion bursts that would be available with a successful high-energy collective accelerator. At a minimum, new radioisotopes and transuranic elements could be anticipated.

Other unique characteristics of collective accelerators that may lead to new research include the use of hybrid beams containing electrons and ionic mixtures. Polarized beams and targets may result from the presence of shock waves produced in the diode region. Metallurgical changes could be expected in irradiated samples exposed to these shock waves and intense bursts of high energy ions and electrons. While these fast pulses have many useful applications, their radiation will swamp out most detection equipment developed for CW operation. This would of necessity eliminate many of the classical experiments now conducted with conventional accelerators. Collective accelerators can be viewed as a different kind of accelerator with characteristics that open up new facets of research not necessarily competitive with present machines.

### INJECTOR APPLICATIONS

Collective field accelerators have potential advantages as injectors for frequency modulated accelerators. Even in its present primitive state the LLL device has achieved >6 MeV per nucleon, approaching the performance of tandem Van de Graaffs and Linacs.

Both tandems and Linacs can provide steady-state operation while the collective accelerator is strictly a pulsed device. When these devices are used as injectors, however, steady-state operation is a doubtful advantage since the machines used for final acceleration are usually frequency modulated and require only periodic injection.

Actually Van de Graaffs and Linacs should not be considered injectors since the injectors they require themselves probably cost at least as much to build and operate as would a linear collective field accelerator. Certainly collective accelerators would outperform the injectors now used for Van de Graaffs and Linacs by a wide margin.

A little-understood phenomenon makes it possible to separate high-energy ions from the primary electron beam in the LLL device. It has been found, for a given set of conditions, that the electron beam "blows up" and disperses at a precise distance from the anode. This dispersion occurs in a completely reproducible manner provided operational conditions are not varied. The dispersion of the electron beam does not affect ion acceleration, since the ions are carried by plasma waves. The dispersion of the primary electron beam is useful, however, since it reduces the flow of high energy electrons from the injector. The ions that enter the main accelerator would be accelerated as at present.

The ion injector application of a collective field accelerator fails to exploit the full potential of the method. A much more interesting possibility is to use several stages of collective acceleration. Empirical data indicate that well-insulated targets that charge to a high negative potential reduce the energy of the accelerated ions whereas grounded targets increase their energy. This result indicates that the highest energy ions are achieved when the potentials are arranged to produce the maximum accelerating fields for electrons.

This has led to the idea of using an E-beam machine for initial collective field acceleration and a reversed charged (+ potential) Van de Graaff for the second stage. Ideally this second-stage device would be involved in the acceleration process only, thus greatly reducing power requirements. For the purpose of this experiment it may be possible to use a standard Van de Graaff with a target in the + terminal or a Van de Graaff-type pulsed E-beam machine that is reversed charged to produce a + terminal. The advantage of the latter machine is its large current capacity.

These Van de Graaff possibilities are suggested as inexpensive methods for investigating the principle of multistaged collective accelerators. Basically this class of ideas is much more appealing than using a collective field accelerator as an injector for a conventional machine, but both applications should be considered.

## CTR APPLICATIONS OF COLLECTIVE FIELD ACCELERATION

During the past few years various methods have been proposed for compressing D-T pellets to achieve thermonuclear hurn. These systems involve the use of photons, electrons, ions, collectively accelerated ions and electrons as well as high energy neutrals.[52-66] In this section the compression of D-T pellets by collective acceleration is briefly considered. This concept differs from previous suggestions that only considered collectively accelerated ions and electrons.[60] Here we also present qualitative justification for investigating the compression of D-T pellets with high velocity colloids that are collectively accelerated by the LLL method. Two unreported "quick and dirty" experiments conducted at LLL apparently show that colloid acceleration has occurred in the system. Because of lack of priority no diagnostic measurements were made. However, carbon and copper powders injected into the anode hole were found plated on the rear door of the vacuum chamber. This is not necessarily surprising since high velocity colloids have been accelerated with other plasma devices. The simple facts are basically encouraging: the LLL device accelerates sharp bursts of heavy ions to relatively high energies achieving about >6 MeV per nucleon. It may be feasible to extrapolate from accelerating heavy ions to small colloids. It has been observed that performance of the LLL device depends upon a large density gradient between the pulsed plasmas in the anode and lens apertures as well as the vacuum volume surrounding these plasmas. This observation is consistent with the theory of wave group trapping and acceleration, which corresponds in its fundamental process to a large number of phenomena that are commonplace in physics and in the everyday world. It arises basically from the fact that a nonuniform diffusion process will give rise to a <u>net</u> flow from regions of large diffusion rates into regions of lower diffusion rates, appearing formally as the effective pressure (first term) in the expansion of the diffusion equation for a nonuniform process:

$$\frac{\partial}{\partial \underline{x}} \cdot \left( \underline{\partial}\,(x)\, \frac{\partial}{\partial \underline{x}}\, f(\underline{x},t) \right) = \left[ \frac{\partial}{\partial \underline{x}} \cdot \underline{\partial}(\underline{x}) \right]$$

$$\cdot \frac{\partial}{\partial \underset{\sim}{x}} f(\underset{\sim}{x},t) + \underset{\sim}{\partial}(\underset{\sim}{x}) : \frac{\partial}{\partial \underset{\sim}{x}} \frac{\partial}{\partial \underset{\sim}{x}} f(x) \ .$$

As such, it is responsible for such diverse phenomena as concentration of suspensions in liquids by ultrasonic vibrations, the Kundt's tube phenomenon, strong focusing in accelerators, runaway electrons in strong electric fields, and the piling up of trash in a freeway divider strip — the important point being that like thermodynamics it is an extremely robust phenomenon.

Short pulses (a few ns duration) of collectively accelerated particles have been observed with the LLL device. These short pulses are both unique and necessary if collective field acceleration is to be used in compressing thermonuclear pellets. It would be logical to study these possibilities theoretically considering both the ions of the elements and appropriate colloids; bearing in mind that momentum transfer as well as ablation can now be considered in pellet compression.

## INJECTION AND TRAPPING OF COLLECTIVE BEAMS

There is some preliminary work under way to study trapping of collectively accelerated ions in gas-filled drift tubes. While these experiments are interesting it would appear fundamental that it is necessary to use only ions and electrons in a vacuum volume because of the untenable electron exchange losses that occur in gases. Experiments conducted in several laboratories show that nonadiabatic effects allow injection and trapping of high-energy beams in appropriate magnetic "bottles." The successful injection and containment of collective beams would lead to important studies of ionic[67] slowing-down nuclear chain reactions[68] heretofore impossible to achieve.

Among the various injection technologies only the LLL system provides both high energy ions and electrons for injection into suitable high vacuum traps. A major loss mechanism in fusion devices is that caused by collisions between high energy ions and slow electrons. Since slow electrons would not be present during the time scale of these experiments it would be possible for the first time to study very hot plasmas in which ion-ion collisions dominate.

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