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COLLECTIVE ACCELERATORS

a study carried out for the

UNITED STATES DEPARTMENT OF ENERGY

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PREFACE

This is the report of a study group formed at the request of the United States Department of Energy to consider the state of the field of collective accelerators. The idea of a study was conceived in discussions among Ryszard Gajewski, Division of Advanced Energy Projects of the Office of Basic Energy Sciences, Terry F. Godlove, Laser Fusion Division of the Office of Inertial Fusion, and David F. Sutter, Advanced Technology Research Development Branch of the High Energy Physics Division of the Office of High Energy and Nuclear Physics, who believed that the time had come for a technical study of the field and of its possible applications.

A study group was formed with the following members:

Richard J. Briggs	Lawrence Livermore Laboratory
Timothy Coffey	Naval Research Laboratory
Francis T. Cole (chair)	Fermi National Accelerator Laboratory
Denis Keefe	Lawrence Berkeley Laboratory
Frederick E. Mills	Fermi National Accelerator Laboratory
Phil L. Morton	Stanford Linear Accelerator Center
Claudio Pellegrini	Brookhaven National Laboratory
Norman Rostoker	University of California, Irvine
Andrew M. Sessler	Lawrence Berkeley Laboratory

The objectives of the study were:

1. Review and summarize presently proposed concepts of particle accelerators utilizing collective interactions for acceleration or confinement.

2. Identify broadly defined applications relevant to DOE missions. Evaluate and assess the potential impact of these concepts on those applications.

3. Evaluate and assess the likelihood in each case that the concept will lead to a feasible device.

4. Estimate, if possible, the cost and time of developing each of the conceptual approaches deemed promising to the stage of a proof-of-principle prototype.

5. Evaluate and assess the level of current R & D efforts in collective-effects accelerators in other countries.

The study group invited the following people to serve as technical experts to advise the group:

John A Nation	Cornell University
Craig L. Olson	Sandia National Laboraties
Martin Reiser	University of Maryland
M. L. Sloan	Austin Research Associates
Phillip Sprangle	Naval Research Laboratory

In addition to the help of these experts, the study group benefited from the help of Capt. Brendan B. Godfrey, USAF Reserve, who prepared material for our report. Use has also been made of a recently published review by Denis Keefe. We are indebted to all these people for their considerable aid to our work.

The study group met December 9, 1980, in Chicago to organize the study. We met February 19-20, 1981, at Sandia Laboratories, March 9 at the Naval Research Laboratory, and March 10 at the University of Maryland. During these meetings, we heard presentations from workers in the field of collective accelerators. We met April 13-14 at Fermilab to work on our conclusions and this report.

Our conclusions are listed in the Executive Summary that follows this preface. The body of the report describes the concepts of the various kinds of collective accelerators, the status of various devices and of the electron-beam generators used in them, applications, the work in other countries, and our conclusions and discussion. An appendix to the report contains descriptions submitted by some (but not all) of the groups working in the field.

It is a pleasure to thank the laboratories who hosted our meetings and the people who helped us. We hope that our report will, in return for their efforts, be of value to the field of collective accelerators.

EXECUTIVE SUMMARY

Collective accelerators are particle accelerators that utilize the collective fields of charges and currents in the region of the beam being accelerated. In contrast, conventional accelerators, such as high-voltage systems, cyclotrons, linear accelerators, and synchrotrons, all utilize external fields produced by magnets, radiofrequency amplifiers and cavities, and high-voltage systems.

Experimental and theoretical work on collective accelerators has been carried on since the decade of the 1950's, with the hope that such devices could provide attractive, economical alternatives to conventional accelerators for the many applications for which particle accelerators are now used. A considerable number of groups are active in this work in the United States.

The Department of Energy is interested in the possibilities of collective accelerators for application to DOE missions. This is the report of a group organized to study the status of collective accelerators. The conclusions of the study are:

1. THE BASIC PHYSICS APPEARS TO BE SOUND FOR ALMOST ALL THE KNOWN COLLECTIVE-ACCELERATOR CONCEPTS. THE ONLY CONCEPT HAVING SEVERE DIFFICULTIES IN PRINCIPLE IS THE INVERSE-DRAG FAMILY OF DEVICES. ELECTRON RING ACCELERATORS CAN BE COMPETITIVE WITH SPACE CHARGE AND WAVE ACCELERATORS.

2. THERE ARE MANY DIRECT APPLICATIONS OF INTEREST TO THE DEPARTMENT OF ENERGY FOR WHICH COLLECTIVE ACCELERATORS MAY WELL BE APPROPRIATE AND MAY HAVE ADVANTAGES OVER CONVENTIONAL DEVICES.

3. IN ADDITION TO MOVING TOWARD DIRECT APPLICATION, WORK ON COLLECTIVE ACCELERATORS WILL HAVE IMPACT ON THE DEVELOPMENT AND ADVANCEMENT OF RELATED FIELDS OF PHYSICS.

4. NO COLLECTIVE-ACCELERATION CONCEPT IS READY FOR CONSTRUCTION OF A MAJOR PROTOTYPE. COLLECTIVE-FOCUSING DEVICES, ESPECIALLY PULSELAC, ARE CLOSEST TO THE PROTOTYPE STAGE. ALL OTHER DEVICES NEED AT LEAST 2 TO 3 YEARS OF FURTHER WORK TO ATTAIN PROOF OF PRINCIPLE.

5. THE FIELD OF COLLECTIVE ACCELERATORS HAS A STRONG NEED FOR CONTINUITY OF SUPPORT. A 5-YEAR PROGRAM AT A TOTAL COST OF $5 MILLION PER YEAR WOULD GREATLY ADVANCE OUR UNDERSTANDING OF COLLECTIVE ACCELERATORS, BOTH THE FUNDAMENTAL PHYSICS CONCEPTS AND THE VALIDITY OF PARTICULAR DEVICES. WORK AT UNIVERSITIES WILL CONTINUE TO BE AN IMPORTANT PART OF THE FIELD, BOTH FOR UNDERSTANDING OF FUNDAMENTAL PHYSICS AND FOR THE TRAINING OF STUDENTS.

6. THERE IS ACTIVE WORK ON COLLECTIVE ACCELERATORS IN OTHER COUNTRIES, ESPECIALLY IN THE SOVIET UNION. WORK IN THE UNITED STATES IS ON A PAR WITH OR AHEAD OF ANY WORK ABROAD OF WHICH WE ARE AWARE, EXCEPT THAT SOVIET WORK ON THE ELECTRON RING ACCELERATOR HAS ADVANCED TO THE ENGINEERING-PROTOTYPE STAGE.

7. THE FIELD OF COLLECTIVE ACCELERATORS COULD BE ADVANCED, NOT ONLY BY MORE CONTINUOUS SUPPORT, BUT ALSO BY INCREASED COMMUNICATION AND COORDINATION OF THE EFFORTS OF INDIVIDUAL GROUPS.

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A STUDY OF COLLECTIVE ACCELERATORS

1. INTRODUCTION

Conventional particle accelerators make use of externally produced electric and magnetic fields to accelerate particles and to focus or contain them. Such conventional accelerators have been developed in many different configurations for many different applications ranging from high-energy physics (HEP) at particle energies of hundreds of GeV to industrial applications at a few hundred keV. There are many thousands of particle accelerators now being operated for these applications. The design and construction of particle accelerators has reached a very advanced state in the last few decades and there is considerable understanding of the performance limitations of these devices. There are now a number of serious, well thought-out proposals to design and build conventional accelerators of very high energy for applications in HEP and of very high intensity for application to controlled-fusion work and many other areas.

In comparison, the field of collective accelerators is small, with approximately a dozen small groups actively working in the United States and a roughly equal number in all other countries. Collective accelerators are by no means as far along in design as conventional accelerators, but appear to hold out great promise for improved performance.

Collective accelerators make use of the electric and magnetic fields of charged particles in the region of the accelerated particles, for acceleration, for focusing, or for both. That is, there are additional charges and currents in this region and in general $\nabla \cdot \mathbf{E}$ and $\nabla \times \mathbf{B}$ are different from zero. In principle, very large accelerating and focusing fields are possible and the fundamental goal of collective accelerators is to make use of these large fields to build high-performance accelerators very economically.

2. CONCEPTS OF COLLECTIVE ACCELERATORS

Many different devices have been proposed for collective acceleration or focusing. In our review, we have divided these into five general classes as follows:

(i) Space-charge accelerators
(ii) Wave accelerators
(iii) Electron ring accelerators
(iv) Inverse-drag accelerators
(v) Collective-focusing accelerators

2.1. Space-Charge Accelerators

Intense relativistic electron beams (IREB) are used in space-charge accelerators to provide potential wells to pull ions along with the beam. There is an electrostatic limiting current I_L given approximately by[1]

$$I_L = I_0 \frac{(\gamma^{2/3} - 1)^{3/2}}{(1 + 2 \ln \frac{b}{a})(1 - f_e)} ,$$

where $I_0 = mc^3/e = 17$ kiloamperes , $\gamma = (1 - \beta^2)^{-1/2}$, is the total energy in units of the rest energy, $\beta = v/c$, a is the beam radius, b is the radius of the conducting pipe in which the beam moves, and f_e is the fraction of neutralization of the electron charge by positive ions.

There is also a magnetic limiting current $I_A = I_0 \beta\gamma$, the Alfven-Lawson current. For most cases of physical interest, the magnetic limit is much greater than the electrostatic limit.

An electron beam accelerated from a cathode to an anode will not propagate past the region of the anode if its current is greater than I_L. Space charge will therefore accumulate, creating a potential well for positive ions, a **virtual cathode.** This kind of potential well is the basis of space-charge collective accelerators.

This acceleration concept was discovered experimentally in 1968 by Graybill and Uglum[2] and has been developed extensively at many laboratories. A potential well that can reach a depth of more than 1 MV can be formed and ions can be attracted and accelerated. Proton energies of several times the electron beam energy have been observed. The ions can be created "naturally" by collisions of the electron beam with background gas, as in the Graybill and Uglum work, or ions can be introduced artificially, as a gas by a puff valve, or by collisions of the electron beam with an insulator anode, as in the Luce diode,[3] as a gas by a puff valve, or by a laser-produced plasma, as in the University of Maryland device.[4]

The ions partially neutralize the virtual cathode and bring the limiting current I_L up to the beam current. Then propagation takes place and the virtual cathode can move downstream of the anode, carrying ions with it and further accelerating them. In experiments with Luce diodes, 45 MeV protons have been observed.[5] Multi-stage Luce diode systems have been proposed by Adamski.[6]

It is of great interest in space-charge accelerators to control this motion of the potential well down the accelerator and several methods of doing this are under study. There are at least four devices in which a potential well is propagated at a programmed and increasing velocity by means of externally controlled elements.

In the Ionization Front Accelerator (IFA) of Olson,[7] in one operating regime, the electron beam is injected into a tube containing a low-pressure working gas, which has been chosen to be cesium vapor. The pressure is low enough that for the duration of the beam pulse, there is not enough ionization to allow the beam current to become less than the limiting current and so to propagate quickly. Arranged along the side of the tube is a series of light pipes through which carefully timed pulses of laser light can enter to ionize the cesium. Enough ions are produced upstream of the virtual cathode at the head of the beam to neutralize the beam space charge in that region and reduce the potential to zero. Downstream of the beam head, there is little beam present and the potential is also essentially zero there. Thus the potential well in the beam head provides an accelerating bucket that has a sharp gradient at the upstream side. By gradually advancing the region of ion creation by successive laser light pulses, the well can be guided forward at a predetermined rate to accelerate ions. Scaling studies indicate that, for example, protons of GeV energies could be produced in a compact IFA.

A slow-wave structure to control the motion of the potential well is being studied at the University of Maryland. This structure is initially charged to a high potential by the electron beam (or externally) and discharged to ground when the potential well arrives. The discharge pulse and thus the potential well travel with a velocity that is determined by the pitch angle of the slow-wave structure.[8]

Fisher[9] proposes to inject ions from a pulsed wall plasma to speed up the virtual cathode in a time-programmed manner. With the present equipment, he has achieved 10-MeV protons and feels it can be extended to 100 MeV.

Because it is unusual in having several features externally controllable, the Collective Particle Accelerator (CPA), now under test by Friedman, is an especially interesting concept.[10] In this, a hollow electron beam is injected below the limiting current, passed through a chopper to create a sequence of rings of charge which then enter a guide field made up of discrete

short solenoids. As the train of rings passes down the rippled guide-field, their radii throb alternately inward and outward. This produces an axial electric accelerating field that can be decomposed into two waves, a slow forward wave ($v < c$) and a backward wave that can be either slow or fast, depending on the choice of parameters. The phase velocity of the accelerating wave can be controlled by varying either the inter-ring spacing or the inter-magnet spacing and its amplitude can be varied by changing either the beam current or the magnetic-field strength. Note that the mechanism proceeds by the action of discrete rings of charge, each of which retains its identity, and thus is quite different from the wave accelerators discussed below. The electron rings also produce radial focusing of the ions.

2.2. Wave Accelerators

Another technique for the controlled collective acceleration of protons uses a negative-energy wave train grown on an electron beam propagating in a vacuum and confined by an axial magnetic field. The "plasma waveguide" proposed by Fainberg[11] was the first accelerator concept to use waves on an electron beam. There are two experiments in progress to study the potential for application of variable phase-velocity wave trains to collective acceleration. Both have recently succeeded in demonstrating the excitation and growth of the wanted waves and the suppression of other unwanted modes, but have not yet reached the point of injecting and accelerating ions. Although each of these experiments utilizes waves of very different character--one a cyclotron wave, the other a space-charge wave--both have the feature of exploiting a negative - energy mode. Thus, the greater the number of ions accelerated, the larger the amplitude of the accelerating field grows (until nonlinear saturation occurs). Large-amplitude wave excitation creates a longitudinal modulation of the space-charge potential and, hence, a sequence of accelerating buckets that propagate along the beam with the phase velocity of the wave. Acceleration of the ions is achieved by arranging for the phase velocity to increase from some initially low value at injection.

Auto Resonant Accelerator. This system utilizes a cyclotron wave (the so-called lower-hybrid Doppler-shifted cyclotron mode) which has the attractive feature that the phase velocity can be made very small; thus ions can be picked up from rest by simply injecting a puff of gas at the appropriate place.[12] The phase velocity of this wave is given by

$$v_{ph} = v_e/(1 + \frac{eB}{\gamma mc\omega_0}),$$

where the electron velocity v_e is close to the speed of light, $eB/\gamma mc = \Omega$ is the cyclotron frequency chosen for exciting the wave, and ω_0 is the impressed frequency. By choosing a high

field (high Ω) and relatively low frequency ω_0, the phase velocity can be made initially small ($\ll c$) for ion pickup. Thereafter the magnetic field can be diminished in a tapered way, the phase velocity increased and the ions accelerated.

A proof-of-principle experiment is underway at Austin, following extensive theoretical analysis. The procedure is to pass the beam (2.5 MV, 20 kA) through a double-helical resonant excitation section driven at $\omega_0/2\pi$ = 250 MHz to excite the wave. Next comes a dissipative helical growth section which loads the wave and thereby causes it to increase in amplitude. This has now been accomplished (and incipient non-axisymmetric modes suppressed) and potential wells of about 200 kV demonstrated, in modest magnetic fields ($\approx$2 kG).[13] Because the phase velocity is not small, the next step will be to pass the beam into a tapered solenoid (from 2 kG up to 20 kG) to slow down the wave to the point where ion pickup is possible. Finally the flared-field accelerating section will be added. It may be noted that high-phase velocities are more difficult to achieve in practice for this concept.

Space-Charge Wave Accelerator. The second wave system being studied for acceleration employs a negative-energy slow space-charge wave grown on the beam during its propagation through a slow-wave excitation structure. The behavior of slow space-charge waves has been long studied in the case of vacuum tubes, but there are some differences for relativistic high-current beams. The expression for the phase-velocity.

$$v_{ph} = v_e \Big/ \left(1 + F\frac{\omega_p}{\omega_0}\right),$$

where ω_0 is the impressed frequency; ω_p is the beam plasma frequency (relativistic) and F is a plasma-frequency reduction factor that depends on the ratio of the beam diameter to pipe diameter.

It was pointed out by Sprangle et al. at NRL[14] that an accelerator could be built by injecting a beam of constant diameter into a pipe whose walls converged in tapered fashion towards the beam (Converging Guide Accelerator, or CGA). Under such a circumstance, $F\omega_p$ can be made to decrease with distance in a programmed way and, accordingly, the phase velocity v_{ph} increased gradually as needed. Sprangle et al. gave arguments showing that such an accelerator could give 0.5 A of protons at 300 MeV in a length of 15 m. This concept has been extensively developed by Nation's group at Cornell.

Upon analysis, however, it turns out that one cannot practically realize low values for v_{ph}, in contrast with the cyclotron wave case. As v_{ph} tends to zero, the beam current I approaches the limiting current I_L. For this reason, values of v_{ph} below 0.2 c appear to be more difficult. There is interesting recent

theoretical work[15] considering the nonlinear regime. In this work, Hughes and Ott predict a significant decrease in the phase velocity of the slow space-charge wave at large wave amplitudes.

2.3. Electron Ring Accelerators

The electron ring accelerator (ERA) was proposed by Veksler in 1956.[16] There is a circulating electron beam of toroidal geometry in a magnetic mirror and ions are trapped in it. Acceleration takes place by means of an electric field or changing magnetic field along the axis of the toroid, perpendicular to the plane of the electron ring. The objective of the ring geometry is to preserve the stability of the electron beam. A space-charge electric field (the "holding power") that would accelerate the ions of several hundred MeV per/meter was originally considered feasible, but the estimated maximum holding power has decreased as a result of extensive work.

ERA is the most extensively investigated collective accelerator. There have been projects at Dubna in the USSR, Lawrence Berkeley Laboratory, University of Maryland, and Garching in Germany. Only the Dubna group is still working on ERA. They have reported significant successes.

2.4. Inverse-Drag Accelerator

Veksler proposed in 1956[17] that an electron "medium" (a bunch) traveling at large velocity with respect to charged particles could give energy to the charges through coherent scattering and through inverse Cherenkov radiation.

No significant experimental work has ever been carried out on this **inverse-drag** acceleration mechanism. But Irani and Rostoker have shown[18] that the bunches do not hold together long enough for any useful acceleration to take place, at least in a linear geometry. It is therefore believed by almost all workers that inverse-drag accelerators have severe difficulties in principle.

2.5. Collective Focusing Accelerators

The first proposal for an accelerator using collective fields for focusing particles was that of Budker.[19] The radial electric field of an intense electron beam in a circular accelerator was to be used to bend an ion around the circle. As the ion beam gained energy, it would move radially outward toward the large electric fields at the edge of the electron beam. The Budker proposal was found to have difficulties of principle. For example, the betatron wave numbers of the ion beam increase as the beam moves radially outward and many resonances are crossed. Work on the Budker collective focusing has not been carried on.

There are several more recent concepts that are being actively studied. Among them are:

(i) PULSELAC

The basic acceleration scheme is a conventional one using pulsed drift tubes to accelerate a long slug of ions. Ions are accelerated into a drift tube and, when the head of the beam reaches the downstream end, the voltage is removed from the drift tube and the succeeding one switched on. Instead of using conventional focusing, Humphries et al.[20] have arranged to inject electrons into the drift tubes to provide charge neutralization and transverse focusing of the ion beam; a convenient arrangement is an array of field-emission points. The key feature of the scheme, however, is to prevent the electrons from crossing the accelerating gap between successive drift tubes, so that they do not constitute an inordinate current drain on the power supply. This is accomplished by magnetic insulation; a magnetic field is applied in such a direction that the electrons perform magnetron orbits (with an $\mathbf{E} \times \mathbf{B}$ drift) but can never cross the gap and so drain the voltage generator. Obviously, fresh electrons must be injected into successive drift tubes.

Creating such a situation requires the drift tube to consist of two concentric tubes with an annular ion-beam contained between them. Conductors wound around the outer radius at the tips of the outer tube, and around the inner radius of the inner tube can provide a magnetic field to meet the requirement of magnetic insulation. A useful feature of this arrangement is that the $\mathbf{E} \times \mathbf{B}$ drift can carry the electrons around the axis again and again; thus charge-accumulation, which can be troublesome in other geometries, is avoided.

A set of plasma guns arranged in an annulus supplies about 3,000 to 4,000 A of carbon ions for injection; a 5-gap pulsed drift-tube system now in operation produces at its exit an impressive 3,000 A of carbon ions at an energy of 600 keV, with good emittance. These results seem to indicate that the mobile electron species can adjust its distribution in a benign way to provide focusing that is both strong and approximately linear.

(ii) COLLECTIVE FOCUSING ION ACCELERATOR

This concept, proposed by Rostoker, is closely related to the Budker proposal. Several novel features are included, however, that make the idea seem attractive. The basic idea is to create a bumpy toroidal magnetic field, i.e., a string of mirrors that closes on itself, and to inject a dense cloud of electrons with predominantly transverse velocities (i.e., no toroidal component). The electrons form a deep potential well into which ions are injected; the ions are then accelerated by pulsing a transformer exactly as in a betatron.

The key to the operation is the local trapping of the electrons in the multiplicity of mirrors. When the induced electric field is created, few electrons are accelerated because the loss-cone is sparsely populated. This has been verified in a small experiment at Irvine. Suppression of the toroidal electron current is essential to avoid taking all the energy from the generator. The design draws heavily on results from an early collective device[21] (HIPAC) at Avco-Everett in which the technique for injection of electrons with high transverse energy was developed. In addition, work on HIPAC succeeded in mapping out the regions of potential instabilities (diocotron, magnetron, ion-resonance)
and, as a result of that work, the proposed design pays careful attention to avoiding these hazards.

A table-top experiment is underway to demonstrate proton acceleration to a few MeV. The electron guiding field will be about 1 cm in minor and 1 m in major diameter. So far, collective focusing fields of 150 kV/cm have been achieved.

3. INTENSE ELECTRON BEAM GENERATORS

The collective accelerator concepts discussed in the previous section rely on an intense electron beam as the source of the acceleration field and (usually) as the only source of energy for the ion beam. For this reason, the electron beam generator requirements can strongly influence the feasibility and cost-effectiveness of the applications discussed in the following sections. Most of the collective accelerator experiments currently underway utilize relatively inexpensive "single-shot" pulse diode machines, an important factor in making significant experimental studies possible at low budget levels. Many applications require significant average power levels, however, so one needs to consider at least in general terms the viability of high rep-rate pulsed-power developments for the various concepts and applications.

3.1 Electron Beam Diodes

Electron acceleration in a single high-voltage diode region, with a cold surface as the electron source, is the most common technique for generation of intense electron beams. A very useful review of this pulsed-power and diode technology is given in the review article of Nation.[22] The highest power extremes of this technology is represented by Table I (reprinted from Ref. 22).

Electron beam diodes can generate beams with currents in excess of the Alfven-Lawson current $17\beta\gamma$ kA; in the relativistic limit ($\gamma \gg 1$) this corresponds to a "beam impedance" $V/I \sim < 30$ ohms. Indeed, for efficient power coupling to the beam from the pulseline, impedance matching and practical constraints on pulseline characteristics restrict beam impedances to the general range 0.5-100 ohms (exceptions being the ultralow impedances achievable with parallel pulse lines on a single diode, such as the Proto II machine in Table I).

Some of the space-charge collective-accelerator concepts require beam currents in excess of the limiting current for vacuum transport, i.e., of the order of the Alfven current. Wave accelerators must have currents less than the limiting current, so higher-impedance machines are required in this case and also in the ERA.

There has been very little effort towards developing rep-rate and lifetime capability with diode machines, which typically have shot rates of a few per hour or less and usage rates corresponding to 10^2 - 10^5 shots per year. It is quite clear that the ultra-high peak-power machines shown in Table I will not extrapolate in a direct way to a system capable of significant time-average power output and component lifetime capabilities of 10^7 - 10^8 pulses. Extension of the diode beam technology in these directions will likely require subdivision of the pulsed-power

system into parallel or series-parallel units with much smaller energy storage per section. Limits on the electron beam current densities in diodes capable of long lifetime will also require further study; an ongoing high rep-rate program at Sandia National Laboratories has been making significant progress in all these areas.

3.2 Linear Induction Accelerators

Modest electron beam currents (1 to 10 kA) at relatively high voltages have been obtained using multi-stage acceleration in linear induction accelerators. Indeed, the Electron Ring Accelerator program in the early 70's at LBL developed such an accelerator as the electron beam generator for their experiments on this collective-accelerator concept. As discussed above, wave collective accelerators could also utilize this kind of electron beam generator, but most of the space-charge concepts require beam impedances much lower than can conveniently be supplied by such a machine.

An induction linac can be viewed as analogous to a very-high-voltage E-beam generator in which the successive stages are coupled inductively (by the beam) rather than conductively (through spark gaps). There are two important consequences of this difference. First, the final voltage never appears as a voltage on a conductor to ground; instead it is manifested in the beam kinetic energy per ion charge. Thus the largest voltage to ground in the system is set by the voltage per stage which is often chosen in the region of a few hundred KeV. Second, the stored energy in each stage is isolated from the rest and can be kept at a modest level; this greatly aids the ability to attain long lifetime and high repetition rate.

A list of linear induction accelerators that have been built in the U. S. is given in Table II; this technology has also been described by Leiss[23] in a 1977 review article. Note that (with the exception of RADLAC and the Autoaccelerator) these machines operate (or used to operate) at a steady rep-rate of a few pulses per second; collective-acceleration schemes that can utilize electron beams in this parameter regime can therefore be considered for high rep-rate applications with little extrapolation in the electron beam generator technology. The cost of high rep-rate induction machines (per joule of beam pulse, say) is significantly higher than diode machines, of course, so it is not clear that they are an optimum choice for near-term experiments.

In summary, the technology for average-power electron beam generators with relatively modest currents (< 10 kA) and joules per pulse is relatively well developed, but extensive technology advances will be required before low-impedance (< 30 ohms), very high current (~ 1 MA) electron-beam sources with high rep-rate capability become available. Such low-impedance sources do not exist at present for applications requiring high average power.

These considerations were weighed by the study group when making the judgments about potential applications of the various collective acceleration concepts discussed in Section 5. In addition, low impedance will require that additional technology be developed before high repetition rate operation is feasible.

Table I.
Output Characteristics of Some Multi-Terawatt Generators.

Machine Name	Voltage (MV)	Current (MA)	Pulse Duration (nsec)	Power (TW)
Aurora	12	1.6	100	18
Hermes-II	10	0.1	100	1
Proto-II	1.5	6.0	24-40	10
Gamble-II	1.6	1.6	70	2.5
Blackjack-5	3	3	100	10
Python	2.5	2.5	100	6
PBFA	2-4	8-15	40	30

Table II.
Characteristics of USA Electron Induction Accelerators.

	Kinetic Energy (MeV)	Beam Current (kA)	Pulse Length (nsec)	Average rep-rate (max) (Hz)	High rep-rate Burst No. pulses
Astron injector, LLNL (1968)	6	0.8	300	60	800 Hz/100
ERA injector, LBL (1971)	4	1	45	5	--
NBS Prototype (1971)	0.8	1	2,000	< 1	--
ETA, LLNL (1979)	4	10	30	2	900 Hz/5
Radlac, Sandia (1980)	9	25	15	(single shot)	--
Autoaccelerator, NRL (1981)	4	50	10	(single shot)	--

4. STATUS OF SPECIFIC DEVICES

4.1. Space-Charge Accelerators

Ionization Front Accelerator (IFA)

Olson has built a prototype (IFA-1) and used it for experiments. Substantial control of the beam-front speed has been demonstrated. There is some evidence for ion acceleration (H^+, D^+, He^{++}), but the results are not conclusive because of limited data due to switching jitter in the present experiment. The data suggest that controlled accelerating fields of 50 MV/m have been achieved. A second device (IFA-2) to overcome these limitations is now being built.

Other devices have been built by Fisher (University of California, Irvine) and Doggett (N. Carolina State University). Energies greater than 10 ZeV_0 have been achieved in both cases.

Luce Diodes

In experiments by Nation's group at Cornell, peak proton energies of up to 22 times eV_0 have been recorded with intensity $N \sim 10^{10}$/MeV. The total number accelerated per pulse is about 5×10^{14}. The acceleration of ions to high energy is apparently not associated with the beam head, but with a large-amplitude wave on the beam.

More recently in experiments at the University of Maryland, the plasma ion source is generated by a localized gas cloud injected from a puff valve or from solid material bombarded by a laser. Xenon ions of 900 MeV have been observed, for example. Also, fully stripped heavy ion beams have been obtained in a plasma focus geometry which simply involves reversing the polarity of an IREB diode. Initial experiments indicate a very low emittance ion beam. Adamski at Boeing is designing a multi-stage machine.

Earlier studies by the Maryland group demonstrated that the electron beam motion and thus the ion energy can be controlled with a slow-wave structure. So far, they have increased the ion energy by a factor of two with this method. Adamski at Boeing is studying a multi-stage Luce diode system to achieve higher energies.

Collective Particle Accelerator

For experimental convenience, the present tests at NRL use the backward wave to demonstrate ion acceleration. Experiments have proceeded to the point of generating a train of discrete rings and propagating them along the bumpy solenoidal guide field for a distance of several meters.

4.2. Wave Accelerators

Auto Resonant Accelerator (ARA)

In pulsed experiments, cyclotron waves have been generated with the expected phase velocity and wave length. The inferred amplitude of the longitudinal electric field is 10 MV per meter.

Converging Guide Accelerator (CGA)

Experiments by Nation at Cornell with a 250-kV electron beam have shown successful growth of a slow wave in an iris-loaded structure at frequency of 1.1 GHz. The growth was rapid; accelerating fields of 6 MV per meter were generated. Below $v = 0.2c$, operation is so close to the limiting current that the system was highly erratic. A linear induction accelerator is presently being built as an alternative to the present Luce diode injector.

A program to use a cyclotron as an injector has been considered at NRL, but has been deferred.

4.3. Electron Ring Accelerators

At the 1971 High Energy Accelerator Conference in Geneva, V. P. Sarantsev reported the acceleration of α-particles to 30 MeV. This result was apparently not reproducible. Enthusiasm for the ring accelerator was further damped by theoretical analysis of instabilities, which showed that the holding power was limited to about 50 MV/m. The accelerator would therefore not be of great interest for high-energy physics. The ERA program at Berkeley was terminated in 1976. 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 confirmed the basic principle by accelerating ions to a few hundred keV.

In 1978, the Dubna group reported new results on ion acceleration. They have accelerated about 5×10^{11} - N^{14} ions at a rate of 4 MeV/nucleon, and heavier ions at a rate of 1.5-2 MeV/nucleon. The acceleration was over a length of 50 cm. At the end of the compression, the magnetic field was 15 kG 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.

Since 1978, the ERA programs at Garching and Maryland have been discontinued. The Dubna group has continued, devoting effort to acceleration of neon, argon, krypton, and xenon ions to 3.2 MeV/nucleon and to the use of electric fields rather than magnetic expansion for acceleration of the ion loaded ring. They reported recently[24] that they have accelerated rings with electric fields and that they are authorized to build a heavy-ion ERA to reach 20 MeV/nucleon as an injector to higher-energy heavy-ion accelerators.

4.4 Collective Focusing Accelerators

Pulselac. Injectors have been developed, for example 5-kA, 120-kV nitrogen beams with a 0.5 μsec pulse; carbon beams at 2 kA have been post-accelerated in a second independent gap at 200 keV. A radial magnetic field gap has been shown to confine electrons stably at a field stress of 0.5 MV/cm. Neutralization of beams in transport regions with a space-charge balance of better than 0.2 percent has been demonstrated. Most of the elements of a possible 5-TW/cm^2 inertial-fusion test system have been tested.

Collective Focusing Ion Accelerator (CFIA). A toroidal cyclic accelerator has been considered. There is a toroidal magnetic field provided by discrete coils so that the magnetic field is "bumpy;" i.e., it forms a set of mirror cells around the torus. Electrons are confined to single mirror cells forming a series of "Gabor-like" lenses around the torus. The space charge of electrons focuses ions up to a charge density of about 10 percent of the electron charge density. The acceleration involves a conventional induced toroidal electric field as in a betatron. The motion of electrons around the torus is prevented by the mirrors, but the ions respond significantly to the confining and accelerating electric fields and can thus be accelerated around the torus while there is no electron flow as in ion diodes. This scheme has no particular advantages over a conventional accelerator for bending an ion beam, but it has considerable advantage for focusing or increasing the space-charge limit. For the acceleration of a large number of ions, the CFIA could provide a reduction of major radius, compared with a conventional accelerator, by a factor of $M/5mZ \sim 10^3$.

The technology of electron injection and trapping has been developed. An electron line density of 4×10^{11} electrons/cm has been injected, trapped and contained for a few milliseconds. An induced toroidal field of 10 V/cm has been applied. It produced a toroidal electron current corresponding to less than 0.5 percent of the trapped electrons and is also below the noise threshold. The electron-focusing structure has been established and experiments on injection and acceleration of ions have just started.

5. POSSIBLE APPLICATIONS OF COLLECTIVE ACCELERATORS

We have reviewed the performance requirements for potential applications within the Department of Energy areas of responsibility. The performance capabilities of each collective-accelerator concept have then been judged against these requirements.

The results of this analysis are in Table III. In each of the fourteen applications of potential DOE interest, we have summarized the performance characteristics needed by an accelerator. These characteristics are based either on the performance of existing accelerators now in use or, where no accelerator is presently available for the application, on our estimate of the performance characteristics required. We also give in the table our assessment of the potential of each class of collective accelerators for each of the fourteen applications.

Historically, many collective accelerator concepts were created with the thought of accelerating particles to very high energies in a simple and elegant (and therefore inexpensive) manner. The intended application motivating this work was high-energy physics, where achieving very high energy particle beams has become limited by the economics of size and construction rather than the technology. The early promise of very high accelerating-voltage gradients in collective devices, gradients not apparently achievable in conventional radiofrequency structures, was the key technical factor. But the success of circular accelerators in reaching the particle beam energies and intensities needed for physics research have forestalled the use of linear devices, except in very high energy electron linacs. The present generation of proton synchrotrons can reach 1000 GeV energies in a structure 6000 meters long, and thus any linear device must be capable of an accelerating gradient of at least 160 MV/m sustained over kilometer distances in order to compete. We have therefore concluded that the acceleration of charged particles to very high energies is an unlikely application of collective accelerators.

There are, however, many other applications of great interest at lower energies--as can be seen in Table III. This includes the use of collective acceleration and collective focusing devices as the early, lower energy stages of the multistaged devices employed in facilities for high energy physics. The areas of most promising application are those which require relatively high intensity beams of ions with energy less than about 1 GeV and having low pulse-to-pulse repetition rate. Our assessment is that some of these applications are appropriate for collective devices now being developed and that funds invested in an effort to carry the relevant collective devices through the proof-of-principle stage would be well spent.

TABLE III. REQUIREMENTS FOR APPLICATIONS AND SUITABILITY OF COLLECTIVE ACCELERATOR CATEGORIES

	Application	Particle	Kinetic Energy	Peak Power or Intensity	Duty Factor or Average Power	Accelerating Gradient	Space Charge	Wave Accel.	Collective Focusing Accel.	ERA
1.	HEP Direct	p e	1000 GeV[1] 50 GeV[2]	10^{13}/pulse 10^{13}/pulse	NA NA	> 100 MeV/m > 100 MeV/m	Unlikely	Unlikely	Unlikely	Unlikely
2.	HEP Injector	H^- p	200 MeV 200 MeV	20 MW[3] 200 MW[3]	0.3% 0.03%	> 2 MeV/m 2 MeV/m	Potential	Potential	Potential	Unlikely
3.	Inertial Fusion	A = 10-30 U	0.1 GeV ~ 10 GeV	100 TW 100 TW	20 MW 20 MW	> 2 MeV/m 1-10 MeV/m	Promising	Unlikely	Promising	Unlikely
4.	Magnetic Fusion	A > 1	120 keV[4]	NA	~100%/ 10-100 MW	NA	Unlikely	Potential	Unlikely	Unlikely
5	Nucleon Physics Kaon Factory	p	3-10 GeV	NA	~100%/ 100 kW	50 MeV/m	Unlikely	Unlikely	Unlikely	Unlikely
6.	Nuclear Physics Heavy Ion	A >> 1	> 10 MeV/A	NA	NA 1W/A	NA	Promising[5]	Promising[6]	Promising	Promising
7.	Ion Sources	A >> 1	Z·100 keV	10^{11}/sec	100%	NA	Promising[5]	Unlikely	Potential	Potential[5]
8.	Pulsed Neutron Spallation (IPNS)	p,d	1 GeV	$3\cdot10^{13}$/pulse	< 10^{-6}/5 kW	> 2 MV/m	Promising	Promising	Potential	Unlikely
9.	Material Studies (FMIT)	d	30 MeV	100 mA	100%	> 2 MV/m	Unlikely (Potential)[7]	Promising (Potential)[7]	Unlikely (Potential)[7]	Unlikely
10.	Industrial Studies	A > 1	1 MeV/A	NA	10-100 kW/A	NA	Potential	Unlikely	Potential	Potential
11.	Medical Therapy	A = 1 A > 1	300 MeV/A	NA	NA	30 MeV/m	Promising	Promising	Promising	Promising
12.	Medical Isotope Production	A = 1 A > 1	10 MeV/A	10^{12}/sec	NA	> 2 MeV/m	Potential	Potential	Unlikely	Potential
13.	Fission Breeding	d,p	1 GeV	0.2-1A	300 MW	> 2 MeV/m[8]	Unlikely	Unlikely	Unlikely	Unlikely
14.	Fusion Breeding (Tritium)	d,p	?	?	100 MW	?[8]	Unlikely	Unlikely	Unlikely	Unlikely

NA = Not applicable or pertinent

[1]Energy of Fermilab Tevatron
[2]Energy of upgraded SLAC linear accelerator
[3]Parameters of existing injector linacs (FNAL, BNL)
[4]Parameters of TFTR injector
[5]Low duty-factor applications only
[6]As part of a hybrid system

6. COLLECTIVE-ACCELERATOR WORK IN OTHER COUNTRIES

Most foreign work on Collective Accelerators is in the Soviet Union. The largest effort is apparently at Dubna in Sarantsev's group. This work has been mainly on the ERA, although there have been recent rumors of new work on other collective accelerators. A few years ago the size of the group was estimated at 300.

The reported Russian work on linear collective accelerators involves contributions from several laboratories. Most of this work involves experiments that have duplicated results obtained previously in the U.S. A list of the known laboratories with active research efforts is appended. (It is difficult to know the size and scope of the efforts at some USSR laboratories, especially Tomsk and Kharkov.)

The only known research on Collective Acceleration in other countries is a small effort in the D.D.R.(East Germany), and work in two laboratories in Japan. The Japanese entry into the field is relatively new.

LABORATORY	RESEARCHERS	AREA
USSR:		
Joint Institute for Nuclear Research, Dubna	Sarantsev, Ivanov, plus ~300 (E,T)	ERA + other new acceleration methods
Lebedev Physical Institute, Moscow	Kolomensky plus ~6 (E,T)	IREB/gas, dielectric walls, etc.
	Lebedev (T)	beat wave accelerator
	Tsytovich (T)	FIA (focusing instability accel.)
	Rabinovich (T,E)	reviews on collective accelerators
	Agofonov (T)	space charge wave
Radio Technical Institute, Moscow	Khodataev (T)	FIA (focusing instability accel.)
Physical Technical Institute, Kharkov	Fainberg + many (E,T)	wave accelerator
	Tkach et al (E)	wave accelerator
Kharkov State University, Kharkov	Kucherov (T)	IFA
	Ivanov et al (E)	ARA
Institute for Nuclear Research, Tomsk	Didenko, Bistritsky,Usov + ~4 (E,T)	IREB/gas Luce diode
Institute of Nuclear Physics, Novosibirsk	Ryutov, Koidan et al (E,T)	reflex electron accelerator
	Velikov et al (T,E)	beat wave accelerator
Sukhumi Institute, Sukhumi	Plyutto, Korop, Mkheidze et al (E,T)	vacuum diodes plasma diodes
EAST GERMANY:		
Zentralinstitut fur Electronenphysik East Berlin, DDR	Hinze, Alexander et al (T)	1-D theory of IREB/gas
JAPAN:		
Kanazawa Univ., Kanazawa	Masuzaki, Koinori, Nakaniski, Kawasaki (E,T)	space-charge accelerator (localized gas)
Osaka Univ. Osaka	Tamura et al (E)	space-charge accelerator (metallic ions)

T = theory, E = experiment

7. CONCLUSIONS OF THE STUDY

After presentations, laboratory visits, study, and debate, the study group has reached certain general conclusions as to the state and future of collective accelerators. These are presented and discussed below.

1. THE BASIC PHYSICS APPEARS TO BE SOUND FOR ALMOST ALL THE KNOWN COLLECTIVE-ACCELERATOR CONCEPTS. THE ONLY CONCEPT HAVING SEVERE DIFFICULTIES IN PRINCIPLE IS THE INVERSE-DRAG FAMILY OF DEVICES. ELECTRON-RING ACCELERATORS CAN BE COMPETITIVE WITH SPACE CHARGE AND WAVE ACCELERATORS.

Although it may be difficult to achieve the desired field configurations experimentally, the space-charge accelerator, wave accelerator and electron-ring accelerator concepts appear from our study to be soundly based on well-understood physical laws. Collective-focusing devices may have difficulty in particular geometries, but the physics underlying them seems to be correct.

Grave doubts have been cast on the inverse-drag mechanism. Irani and Rostoker have shown that in linear geometry a bunch does not stay together long enough to accelerate particles. It is possible that this difficulty may not be fatal in some toroidal geometries.

A large amount of detailed experimental and theoretical work has been carried out on the ERA concept, much more than on other kinds of collective accelerators. The principle of ERA has been proven in these experiments and so ERA is in fact at a more advanced stage than other concepts. It has limitations, but they are well understood. ERA is useful for heavy ions and has an advantage in its high repetition rate. The vigorous USSR program at Dubna has achieved noteworthy results in these directions. Proposals to utilize ERA should be given serious consideration.

2. THERE ARE MANY DIRECT APPLICATIONS OF INTEREST TO THE DEPARTMENT OF ENERGY FOR WHICH COLLECTIVE ACCELERATORS MAY WELL BE APPROPRIATE AND MAY HAVE ADVANTAGES OVER CONVENTIONAL DEVICES.

There are many applications of collective accelerators, as injectors in high-energy physics, in lower-energy research, and in industrial, medical, or advanced technical applications. It is our conclusion that in view of these many potential applications, a substantial research effort in the field of collective accelerators is warranted.

Many of the concepts of collective acceleration began with the idea of application to high-energy physics. But, as Table III shows, acceleration of charged particles to very high energies is an unlikely application of collective accelerators.

3. IN ADDITION TO MOVING TOWARD DIRECT APPLICATION, WORK ON COLLECTIVE ACCELERATORS WILL HAVE IMPACT ON THE DEVELOPMENT AND ADVANCEMENT OF RELATED FIELDS OF PHYSICS.

The basic physics of collective accelerators is very close to that in plasmas and in high-intensity and beam-cooling effects in conventional accelerators. These fields will be advanced by the theoretical and experimental work done on collective acceleration. We all know many examples of cross-fertilization between disciplines and we believe that this is happening and will continue between collective accelerators and the fields mentioned above.

4. NO COLLECTIVE-ACCELERATION CONCEPT IS READY FOR CONSTRUCTION OF A MAJOR PROTOTYPE. COLLECTIVE-FOCUSING DEVICES, ESPECIALLY PULSELAC, ARE CLOSEST TO THE PROTOTYPE STAGE. ALL OTHER DEVICES NEED AT LEAST 2 TO 3 YEARS OF FURTHER WORK TO ATTAIN PROOF OF PRINCIPLE.

Further work is needed to bring most devices to proof of principle. At that time, it will be appropriate to consider proposals for further prototype stages, which will probably need to be on a much larger scale.

We have some concern that for various reasons (some discussed in 5 below), experimental work in some groups is deflected from what we regard as the true proof-of-principle, the acceleration of particles. In addition, because of experimental difficulties, some proof-of-principle experiments are not definitive and further work is required.

5. THE FIELD OF COLLECTIVE ACCELERATORS HAS A STRONG NEED FOR CONTINUITY OF SUPPORT. A 5-YEAR PROGRAM AT A TOTAL COST OF $5 MILLION PER YEAR WOULD GREATLY ADVANCE OUR UNDERSTANDING OF COLLECTIVE ACCELERATORS, BOTH THE FUNDAMENTAL PHYSICS CONCEPTS AND THE VALIDITY OF PARTICULAR DEVICES. WORK AT UNIVERSITIES WILL CONTINUE TO BE AN IMPORTANT PART OF THE FIELD, BOTH FOR UNDERSTANDING OF FUNDAMENTAL PHYSICS AND FOR THE TRAINING OF STUDENTS.

The difficulties of obtaining support for work on collective accelerators have been a strong impediment to progress in this field of research. Senior investigators have had to spend considerable parts of their time searching for support rather than leading the technical work of their groups. There has also been some (perhaps subliminal) pressure to concentrate on somewhat glamorous short-range goals as part of the effort to get support.

We have concluded that collective accelerators are a worthwhile field of research, as discussed in our earlier conclusions. The work on individual devices should therefore be supported to completion of proof-of-principle experiments. We judge that a

5-year program at a total cost of $5 million per year (compared with the present level of $2-3 million per year) will carry the work on present devices to this point.

6. THERE IS ACTIVE WORK ON COLLECTIVE ACCELERATORS IN OTHER COUNTRIES, ESPECIALLY IN THE SOVIET UNION. WORK IN THE UNITED STATES IS ON A PAR WITH OR AHEAD OF ANY WORK ABROAD OF WHICH WE ARE AWARE, EXCEPT THAT THE SOVIET WORK ON THE ELECTRON RING ACCELERATOR HAS ADVANCED TO THE ENGINEERING-PROTOTYPE STAGE.

Many of the contemporary concepts in collective accelerators were originated by Soviet scientists (Budker, Fainberg, Veksler). Work is continuing on the ERA concept at Dubna and on wave accelerators at several laboratories. (Soviet scientists have participated well in international conferences and we know a considerable amount about the work at some USSR laboratories.)

There are relatively small efforts in other countries, East Germany and Japan.

7. THE FIELD OF COLLECTIVE ACCELERATORS COULD BE ADVANCED, NOT ONLY BY MORE CONTINUOUS SUPPORT, BUT ALSO BY INCREASED COMMUNICATION AND COORDINATION OF THE EFFORTS OF INDIVIDUAL GROUPS.

We have found as a result of our review that there are significant disparities in the amount and sophistication of diagnostic apparatus. Individual groups are aware of the work of other groups, but not of the development of their experimental methods and the up-to-date status of theoretical work. Some relatively informal meetings of workers in the field and the possibility of exchanging equipment would help the progress of all the work in the field. More work is needed on beam-diagnostic equipment development. More effort also needs to be made to maintain communication between workers in this field and workers in conventional accelerator technology.

We are by no means suggesting any tight control or formal communication methods. We believe that the individuality of the efforts in this field is of great importance.

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APPENDICES

IONIZATION FRONT ACCELERATOR (SANDIA)

The Ionization Front Accelerator (IFA) is a high-gradient, high-power, collective ion accelerator in which ions are trapped and accelerated in a strong potential well at the head of an intense relativistic electron beam (IREB).[1] The IFA was invented by Olson in 1973,[2] and proof-of-principle experiments were performed in 1977-1979.[3-5] In these experiments (IFA-1), accurately-controlled potential well motion was demonstrated, and ion data sets indicated that controlled accelerating fields of 50 MV/m had been achieved over 10 cm. A test bed accelerator (IFA-2) is now being planned that should produce controlled accelerating fields of 100 MV/m over 1 meter.[6] The IFA offers the real prospect of a compact, inexpensive, ion accelerator that should find wide applications in, e.g., nuclear physics, heavy ion physics, neutron generation, meson generation, material sciences, radiography, and inertial fusion.

In the IFA concept, as shown in Fig. 1, the potential well at the IREB head is made to move with the desired phase velocity by actively controlling the ionization of a suitable background working gas. Laser photoionization is employed, and a laser sweep is effected by using transit time delays in a programmed light pipe array. A moving ionization front is created, and the potential well at the IREB head follows this moving ionization front synchronously. Ions are trapped and accelerated in the moving potential well up to high energies. The IFA is a direct extension of the collective acceleration process that occurs when an IREB is injected into neutral gas.[1-7] The IFA provides a direct means for controlling the observed large accelerating fields (~100 MV/m) over large distances.

The IFA has many unique features. (1) The IFA utilizes the **largest accelerating field** possible from a uniform IREB, and the IFA should be able to maintain this accelerating field over the full acceleration length. Ultimately, the IFA should be able to produce accelerating fields of 100 MV/m to 1 GV/m. (2) The IFA has **no delicate IREB requirements.** Fluctuations in IREB current or voltage may alter the potential well characteristics slightly, but will not affect the well location which is determined entirely by the swept laser. (3) The IFA exhibits a **power amplification effect**, in which the instantaneous ion beam power should greatly exceed the driving electron beam power. For example, an instantaneous proton beam power of 10 TW at 1 GeV should be obtained with an electron beam power of 0.1 TW at 3 MeV. (4) The **phase velocity control accuracy** required for the IFA is readily achievable, even for GeV proton energies. Picosecond-type accuracies are attainable since, e.g., a 1 mm length of light pipe gives a 5.6 psec delay. (5) The IFA is a **scalable** accelerator. For the IFA-1 case of acceleration of protons from rest to 5 MeV in a distance of 10 cm, only 6.5 nsec of a small IREB (0.6 MeV, 20 kA) was used. This should scale to produce up to 1 GeV protons with 40 nsec of a moderate-sized IREB (3 MeV, 30 kA).

IFA design parameters for three development cases are given in Table 1. Case 1 represents the IFA proof-of-principle experiments (IFA-1) which have already been performed. Case 2 represents the IFA test bed accelerator (IFA-2), which is now being initiated. Case 3 represents a 1 GeV proton demonstration accelerator. Note that the characteristic IFA ion pulse has a very high power with a short pulse length. By going to larger IREB's, the IFA current and pulse length can be substantially increased. For example, for scaling of the IFA for heavy ion fusion, an IFA system was conceived that could produce 50 beams, each of 0.8 kA of 12 GeV U^{+60} ions for 1 nsec with an energy spread of < 0.25% and an unnormalized emittance of < 12 π cm mrad.[8] In addition, IFA pulses can be stacked end-to-end to extend the pulse length. In this manner, an IFA system has been conceived that would produce 100 kA of 1 GeV protons in 4 nsec pulses. Theoretical conversion efficiencies of IREB energy into IFA ion energy are ~32% for 300 MeV protons, ~16% for 25 GeV uranium ions, and ~10% for 1 GeV protons.[1] These efficiencies may be significantly increased by increasing the ion loading or by recouping some of the lost IREB energy.

For the IFA proof-of-principle experiments (IFA-1), cesium (Cs) was the working gas, and 2-step photoionization was used with a dye laser for Cs excitation and a frequency-doubled ruby laser for photoionization of Cs from the excited state.[2] Over 1000 shots were fired on the IFA-1 IREB machine, which include over 400 complete IFA system shots. The IFA proof-of-principle experiments were performed in three phases. **Phase 1 experiments**, in which the effective IREB-induced ionization cross section for Cs was measured, were successfully completed in 1977.[3] These results demonstrated that a neutral Cs density of $10^{15}cm^{-3}$ could be used without interfering with the IFA operation. Since typical IREB densities for use with the IFA are roughly $10^{12}cm^{-3}$, this means that the Cs has to be ionized only about 0.1% for the IFA to work as planned. **Phase 2 experiments** were successfully completed in 1978.[4] Accurately-controlled motion of the front of an IREB was observed with three different programmed sweep rates, using time-dependent beam front diagnostics. These results demonstrated that the IFA-controlled motion of the potential well at the head of an IREB had been achieved. **Phase 3 experiments** concerned IFA ion acceleration and involved extensive studies of ion sources and ion diagnostics unique to the IFA.[5] Three different ion data sets were obtained that imply that controlled accelerating fields of 50 MV/m have been achieved (over an acceleration length of 10 cm). These results are apparently the first demonstration of a **scalable** linear collective ion accelerator, and they provide a real basis for further development with the IFA-2 system.

For the test bed accelerator (IFA-2), studies were performed on alternate working gases and a new working gas, NN dimethyl aniline (DMA), was discovered by Woodworth.[9] This gas operates at room temperature and requires only one laser (XeCl). This new working gas represents a major breakthrough for the IFA in regard

to simplicity and ease of operation. IREB drift experiments have just been completed to measure the effective IREB-induced ionization cross section of DMA.[6] These experiments were designed to demonstrate the feasibility of DMA for the IFA (just as similar experiments earlier had demonstrated the feasibility of Cs). The new result is that DMA has an effective ionization cross section that is only slightly larger than that of Cs. This means that it should be possible to use DMA in the IFA at a pressure at which the neutral DMA density is much higher than the IREB density, and yet at a pressure where IREB-induced ionization may be neglected.

Currently, new laboratory space has been acquired for the IFA in the Laser Research and Development Department. The IFA-1 system was just moved to this laboratory, where it is planned that the IFA-2 experiments will be performed. We are presently considering ways of modifying a Physics International IREB machine (that is in the IFA laboratory) so that it will have the parameters needed for IFA-2, as listed in Table 1. In addition, the IFA-2 machine must have a low-jitter triggered gas switch, and a small current rise-time. Recent results at Sandia indicate that it should be possible to laser trigger such switches with sub-nonosecond jitter. A single laser could therefore be used both to switch the spark gaps and sweep the ionization front. Adjacent to the new IFA laboratory is the laboratory where the initial DMA photoionization experiments were performed. Further microwave transmission experiments are planned to accurately measure the photoionization cross section. These results will permit us to finalize the laser power requirements for IFA-2.

The IFA research group will now involve the part-time efforts of C. Olson, J. Woodworth, C. Frost, R. Klein, and J. Poukey. The IFA-2 experiments are to be performed in the Laser Projects Division (supervised by R. Gerber), which is in the Laser Research and Development Department (managed by J. Geerardo). The IFA theoretical work is to be performed in the Plasma Theory Division (supervised by J. Freeman), which is in the Particle Beam Fusion Research Department (managed by G. Kuswa). All of this work will be performed in the Pulsed Energy Programs Directorate under G. Yonas.

Our program plan for long range IFA development is as follows. The IFA proof-of-principle experiments were performed in FY77-79 at a funding level of ~$100K/year (~$50K/year from DOE, Nuclear Sciences and ~$50K/year from the Air Force Office of Scientific Research-AFOSR). For the current year (FY81), we are to receive $55K from AFOSR, $50K from the Air Force Weapons Laboratory, and matching funds ($105K) from Sandia. Funding for FY82 is uncertain. Progress on the IFA is clearly funding limited, and a level of $300K-$500K per year is needed for 2-3 years to perform the IFA-2 experiments. Upon successful completion of the IFA-2 experiments, the next logical step would be to construct a 1 GeV proton IFA demonstration experiment. Research, development, and construction of this device would cost about $5M over 2-3 years. Following successful completion of

this demonstration accelerator, we would be in a position to design and construct user-oriented IFA's for specific applications. A wide range of applications exist, and the size and cost of the IFA's needed would vary accordingly.

Potential unclassified DOE applications of the IFA are numerous. Because it is compact and inexpensive, it could be widely used for research in nuclear physics and heavy ion physics. With appropriate targets, the IFA could be the basis for an intense neutron source or a meson facility. Because of its high power, the IFA should find new applications in material sciences. For inertial fusion, the IFA could form the basis for a heavy ion fusion (HIF) reactor. Also, the IFA could be used for HIF deposition experiments, or as a diagnostic accelerator. As spin-offs, the IFA could be used as an accelerator for cancer therapy or medical radiography.

Interest in linear collective acceleration existed at many U. S. laboratories in the 1970's (Ion Physics Corporation, Physics International, Sandia Laboratories, Air Force Weapons Laboratory, Austin Research Associates, Naval Research Laboratory, University of Maryland, Cornell University, University of California at Irvine, North Carolina State University, Lawrence Livermore Laboratory, Boeing, Harry Diamond Laboratory, etc.),[1] but research was severely restricted due to a lack of adequate funding. Related experimental work has been performed in the Soviet Union at the Levedev Institute in Moscow, and at the Institute of Nuclear Physics at Tomsk.[1] Related theoretical work has been performed at the Akademie der Wissenschaften der DDR in East Berlin, at the Lebedev Institute in Moscow, at the Radiotechnical Institute in Moscow, at Kharkov State University, and at the Institute of Nuclear Physics at Tomsk.[1]

To date, IFA research has produced substantial results at very low cost. Because of the unique potential offered by collective accelerators such as the IFA, it appears valuable to vigorously pursue research on such collective accelerators.

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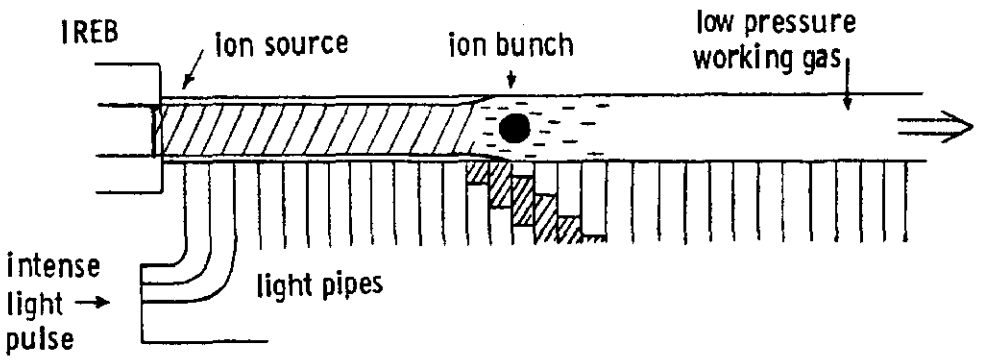

FIGURE 1. IONIZATION FRONT ACCELERATOR (IFA).

TABLE 1. IFA PARAMETERS

	IREB	acceleration region	protons
IFA-1	0.6 MeV 20 kA 0.5 cm radius 10 nsec 0.01 TW 0.1 kJ	50 MV/m 1.2 cm diameter 10 cm length 6.5 nsec of IREB used to accelerate protons	5 MeV 0.8 kA 0.25 cm radius 0.17 nsec 0.004 TW 0.7 J
IFA-2	1.2 MeV 30 kA 1 cm radius 30 nsec 0.04 TW 1 kJ	100 MV/m 2.2 cm diameter 1 m length 16 nsec of IREB used to accelerate protons	100 MeV 5 kA 0.5 cm radius 0.08 nsec 0.5 TW 40 J
1 GeV example	3 MeV 30 kA 1 cm radius 40 nsec 0.09 TW 3.6 kJ	100 MV/m 2.2 cm diameter 10 m length 40 nsec of IREB used to accelerate protons	1 GeV 10 kA 0.5 cm radius 0.04 nsec 10 TW 400 J

PULSELAC PROGRAM (SANDIA)

1. Physical Principles

The main concern of the Pulselac Program is the collective transport of high intensity ion beams utilizing neutralization of the beam space charge by externally supplied electrons. Actual acceleration is conventional and can be performed using inductive linac technology. The neutralization processes are similar to those that have allowed development of light ion diodes.[1] The main difference between Pulselac and ion diode work is that we have sought a detailed theoretical understanding of neutralized transport as opposed to the empirical diode approach, and we are addressing the problem of multi-stage acceleration in high repetition rate systems.

In regions with no applied electric field, neutralization can occur naturally. Because of their low mass, electrons can be rapidly pulsed into the ion beam volume until there is a balance of space charge. Systems tend towards the neutralized state which approaches thermodynamic equilibrium. Neutralization can be easily obtained, and the beams are generally stable. This contrasts to schemes for collective ion acceleration, where electrons must be maintained in highly non-equilibrium distributions to support strong electric fields. Our work in the field of neutralized transport has been devoted to proving that in real systems effective neutralization can be provided by externally produced electrons and determining the time variation of the process for application to pulsed beams.[2-5]

In order to accelerate intense ion beams, neutralization in the presence of applied electric fields must be considered. In this case, beams cannot be effectively neutralized unless there is some method to control the motion of electrons, preventing them from being pulled out of transport regions across the acceleration gap. Although grids and foils are in principle a possibility, we feel that they are impractical and have concentrated on the use of transverse magnetic fields in the acceleration gaps.[4,6,7] These fields prevent electron flow, but allow the ions to pass unimpeded. A gap has been described[6] that used radial magnetic fields; this is probably the only possible geometry that allows multi-stage ion acceleration and stable electron confinement. An important aspect of the presence of electrons near the gap is that they can also modify applied fields. In this case, magnetic field lines define equipotential surfaces that act as virtual foils, allowing electrostatic transverse focusing.

2. Potential Parameters

Since we are considering conventional acceleration, average gradients of 1-2 MV/m are reasonable. The main difference from

conventional experience is that much higher currents of ions can be transported, in the range from a few to 100 kA at 10-100 A/cm^2. From the point of view of the inductive linac, core utilization would be much more effective. The current accelerated through a core is limited only by the capacity of the external generator, so if the transported current is increased a factor of 1000, the energy delivered to the beam per core will rise accordingly.

Pulselac gaps can be designed to operate in the range 0.1 to 1 MV. We have studied injectors and gaps in the pulselength range from 0.05 to 1 μs. With our present understanding of pulselength limitations, extension to 10 μs should be possible. We have investigated beam quality limitations both theoretically[4,8] and experimentally.[9] For instance, in Ref. 4 we considered the effects of non-linear electrostatic focusing in the acceleration gaps on the beam divergence. Although there is no difinitive answer, it appears possible that a focus to an inertial fusion target 0.5 cm in diameter over a 5 m path length can be attained.

A wide variety of ion species can be transported. Since space charge is largely alleviated, multiply ionized species can be used to obtain energy gains exceeding 10 MeV/m.

There are no sharply defined upper limits on transportable current density and total current. An example of a near-term possibility, a 5 TW/cm^2 inertial fusion test system, will be described in the presentation.

3. State of Development

We have performed experiments on ion generation for the last three years and are presently engaged in the construction of a demonstration inductive linac. The following are major results from the experiments.[9-13]

a) The radial-magnetic-field gap has been shown to confine electrons stably at high field stress (0.5 MV/cm).

b) Injectors have been run with controlled directed plasma sources, allowing choice of ion species, high repetition rate operation, and control of injector impedance by the plasma flux.

c) Injector current density more than an order of magnitude above conventional space charge limits has been demonstrated. This is the result of electron trapping in the applied magnetic fields.

d) Virtual electron cloud behavior, in good agreement with theory, has been demonstrated in both the injector and post-acceleration gaps.

e) Automatic neutralization of beams in transport regions with a space charge balance better than 0.2 percent has been demonstrated.

f) Nitrogen beams with total current of 5 kA have been produced in an injector of 120 kV over a 0.5 μs pulse. The system can be fired repetitively without maintenance. The reproducibility of voltage and current was better than 10 percent. A five stage injector has been used to produce 3 kA carbon beams with a divergence of 0.7 degrees.

g) Carbon beams at 2 kA have been post-accelerated in a second independent gap at 200 kV.

h) A gas injection plasma gun has been developed which can supply fluxes of nitrogen exceeding 50 A/cm^2 in a 2 μs pulse.

i) Large area pulsed electron sources have been developed which can supply over 10 A/cm^2 of electrons in a 2 μs pulse with very small energy investment.

These parameters are representative of the systems that could be constructed at the present level of support, rather than fundamental limitations on transport.

4. Applications

The major application that has been considered for Pulselac is as an inertial fusion driver.[6,7,14-17] The approach could solve a number of problems inherent in light ion and heavy ion fusion. In comparison to light ion diodes, we have pointed out that the feasibility of achieving breakeven parameters rises rapidly with increasing ion mass and energy.[18] With a multi-stage system, lower beam divergence can be obtained, beam self-magnetic fields are reduced to small perturbations, ion source requirements are within present capability, and energy transfer to the beam is expanded in space and time. With regard to the latter, gas switches with high repetition rate capability can be used.

Compared to conventional heavy ion fusion systems, a high current linac would be smaller and considerably less expensive. If the transport limits are relaxed, a wide parameter range of ion species and energy becomes available to achieve a better match to the target. A fusion system could be built up in a progressive, modular manner. With regard to the induction linac approach, a method of high current transport could eliminate core costs as a significant problem.

5. Program Plans

At present, we are constructing and testing Pulselac C, a demonstration induction linac. We have the ion injector in operation, and in the next year should have at least two post-acceleration cavities running. Experiments are planned on the physics of beam neutralization and focusing the beams using toroidal sector lenses. Funding is modest, coming almost entirely from the heavy ion fusion program. Interest from the Light and Heavy Ion Fusion Programs in developing beyond the present point to a near term fusion demonstration experiment is not great. Significant progress in the Pulselac approach will probably occur only if light ion diodes encounter technological obstacles.

6. Relationship To Other Work

The physics underlying Pulselac is closely related to light ion diodes. Because of the reproducibility and relatively high repetition rate of our apparatus, we are able to perform basic experiments on neutralized beams. The technology is closely related to induction linac work, particularly the LBL inertial fusion program. At present, there are three unique aspects to our work compared to light ion diode studies: 1) we are the only group investigating multi-stage acceleration of high intensity ion beams, 2) because of the effort we have put into gas sources, we have the capability of generating a wide variety of species, and 3) we are making an effort to combine neutralized beam physics with practical technology to make controllable beams.

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COLLECTIVE FOCUSING ION ACCELERATOR (IRVINE)

1. Underlying Physical Principles

The focusing principle was first enunciated by Gabor[1] who showed that the focal length of a lens for ion beams could be reduced by about 10^3 if the magnetic field confines electrons which focus the ion beam, compared to using the magnetic field directly. In the first case the focal length is $f_1 = (1/L)(V^2/\omega_i^2)$; in the second case $f_2 = (4/L)(V^2/\Omega_i^2)$ where L is the lens thickness, V is the ion velocity, $\Omega_i = ZeB/Mc$ is the cyclotron frequency, and $\omega_i^2 = 2\pi n_b Ze^2/M$. Assuming the lens can be filled with electrons up to a density $n_b = (1/20\pi)\ B^2/mc^2$, the threshold of the magnetron instability,[2] $f_1/f_2 = 5Zm/2M = 1.4 \times 10^{-3}$ for protons. Using this principle it should be possible to build compact ion accelerators. In spite of the fact that Gabor's paper was written 34 years ago there are no accelerators based on this principle and remarkably little research has been done.

We consider an embodiment of this principle in the form of a toroidal cyclic accelerator.[3] The toroidal magnetic field is produced by a discrete set of coils so that magnetic field forms a set of weak mirrors around the torus. Electrons are confined in this magnetic field. They do not move around the torus, but are confined to a single mirror cell, thus forming a series of Gabor lenses. The space charge of electrons confines or focuses ions up to a charge density of about 10% of the electron charge density. The acceleration is conventional; we consider an inductively produced toroidal electric field as in a Betatron. The motion of the electrons is adiabatic so that acceleration around the torus is prevented by the magnetic mirrors; the motion of ions is non adiabatic - it depends only on electric fields so that the toroidal electric field of 10-100 volts/cm should accelerate ions without accelerating electrons. This principle has been established in magnetically insulated ion diodes.[4]

2. Accelerator Parameters

In a cyclic ion accelerator the centripetal force is provided by the electrostatic field of electrons $ZeE = Mv^2/R$ which can be compared to $ZevB/c = Mv^2/R'$ in a conventional ion accelerator. Limiting the toroidal magnetic field to 50 kG leads to $E_{max} \cong 10^7$ volts/cm. The equivalent magnetic field in a conventional accelerator with $R' = R$ is $B = E/300\ \beta \cong 50$ kG assuming $\beta = V/c = 0.7$ for 100 GeV uranium ions. It is thus clear that the CFIA does not have any advantage for bending the beam, unless $\beta < 0.7$.

In a conventional accelerator the ion density is limited by space charge to $n_i' \lesssim B^2/4\pi Mc^2$. Assuming the same magnetic field B, and ion charge density equal to 10% of the electron charge density the limiting ion density n_i in a CFIA is $n_i \lesssim (0.1/Z)(B^2/8\pi mc^2)$. Therefore $n_i/n_i' = M/5mZ$ which is almost the same

factor that occurred in considering the Gabor lens. This means that to contain a given number of ions $N_i = (\pi a^2)(2\pi R)n_i$ the major radius of the beam R', must be larger in a conventional accelerator by the factor $R'/R = M/5mZ = 2860$ assuming for example that the ion is uranium with $Z = 30$. Parameters for a 100-GeV uranium accelerator[3] and a 2.6-GeV proton accelerator[5] have previously been published. In both cases accelerators that produce of the order of 10 kiloamperes of ions involve a major radius of less than 5 meters.

In a cyclic accelerator, confinement of the beam involves bending and focusing. The CFIA offers no advantage for bending except for low energy ions. There is an enormous advantage for focusing. The principle is similar to the Gabor lens. The magnetic field is translated into an electric field. The field is not amplified, i.e., $E < B$. However the electric field is much more appropriate than the magnetic field for focusing.

3. Current State of Development

During the past three years we have developed a small toroidal experiment with a major radius of 55 cm and a minor radius of 6 cm. Thermionic electron injectors that function in simple mirror geometry were previously developed, but several years of research were required to learn how to redesign the injectors to function in toroidal geometry. Because the gap spacing is critical it must be adjustable under vacuum. Each mirror cell requires a separate injector because trapped electrons are localized to a single mirror cell. Thus the torus had evolved to a system involving 16 mirror cells with separate injectors. We now trap an electron line density of 4×10^{11} electrons/cm which is only a factor of 1.5 less than the space charge limit. The electrons are contained for a few millisec or as long as the magnetic field lasts. Oscillations are observed characteristic of the diocotron mode, but there are no observable losses of electrons until the toroidal magnetic field decays by about 50%. An induced toroidal electric field of 10 volts/cm produced a toroidal current that is below the noise threshold - less than 0.5% of the trapped electrons. We have established the basic principles involved in electron trapping and confinement. Presently we are doing experiments on injecting and trapping of ions which will be accelerated with an air-core coil driven by a 40 kilojoule capacitor bank. We should be able to accelerate deuterium ions to about 10 amperes and 1 MeV with the present equipment.

4. Potential Applications

The first application we have considered is to Inertial Confinement Fusion with heavy ions. Indeed much of our work was inspired by the ERDA Summer Study[6] in 1976. The conceptual design[3] of a uranium accelerator indicates a reduction in size compared to conventional accelerators of the order of 10^3.

The second application involves using a few GeV protons to produce spallation neutrons for breeding fissile from fertile material. This has been discussed at a LASL summer study[7] in 1973. The conceptual design of a proton accelerator[5] was carried out with this in mind.

The application which could first be realized is to provide a source for conventional accelerators. Since the CFIA is also an efficient ionizer, an ion source of great flexibility can be developed.

5. Program Plan for Long Range Development

We expect that by the end of the present contract period (April 1, 1981) we will have accelerated deuterium ions to about 10 amperes and 1 MeV. This will complete the proof of principles that was started three years ago. The total budget during this period was about $600,000. We have proposed a new three year program for $793,000 and $243,000 for the first year. The objective is to improve the state of the art from the present modest parameters. During the first year the present experiment can be upgraded to produce about 300 amperes of 20-MeV protons. This involves increasing the electron density by operating the injectors at higher voltage, and an increase in the capacitor bank energy for the toroidal electric field from 40 to 200 kJ. We plan to carry out our research on ion injection, trapping, acceleration and extraction during the entire three year program. At the end of the first year we plan to design a new accelerator of larger major radius (a few meters) to produce a few kiloamperes of a few hundred MeV protons. The construction costs for this accelerator are not included in the budget request. Before the end of the next three year program we should be prepared to build modest energy high current sources for conventional accelerators. By the end of the program we should be able to build the high performance accelerators required for Inertial Confinement Fusion, or electro-breeding on a single pulse basis.

6. Similar Work; Other Countries

As far as we are aware there is no other work of this kind going on elsewhere in the USA or in other countries at this time.

7. Acknowledgements

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PLASMA-CONTROLLED COLLECTIVE ACCELERATOR (IRVINE)

Two schemes of collective ion accelerators have been studied at U. C. Irvine in the recent years. Both are of the moving potential well kind. In the first method a relativistic electron beam is injected into a drift tube. A strong magnetic field is imposed along the drift tube. The gas pressure and its density profile along the drift tube are controlled. Once a beam is launched into such a system where the gas pressure is not too high, the electric field associated with the head of the beam stops the electrons and turns them backward. The result of this phenomenon is the formation of a potential well (for positive ions) which slows down or even completely stops. The background gas, after a while, begins to break down and ions can fall into the well and neutralize it. Once this process takes place the beam can again pick up some velocity and move into a region where no ionization occurs and the whole process continues. The well which stops the beam can trap ions. The main problem in getting a successful accelerator is in controlling the well movement and speed. Using this scheme at UCI we were able to accelerate helium ions to energy of 14 MeV using an E-beam with the following properties: 800 keV, 80 kA, duration FWHM.

During the experimental work we have discovered that the control over the break-down wave at the front of the electron beam is very difficult and it is limited. The beam either stalls and does not move and very little acceleration takes place, or takes off and moves too fast and the ions are left behind with very low velocity. The region in between is the interesting one, but usually the potential well maintains itself only for short times and distances and that is the reason for the modest ion energy we have measured. Although it exceeds the diode voltage by a factor of 15, it is well below the theoretical limit. In order to overcome the difficulties which are caused by using the beam itself to control the production of the ions and the required neutralization, we proceeded with a modified scheme for a collective accelerator. In the second scheme, instead of having a neutral gas in the drift tube, we use one or more plasma guns to produce plasma that streams along the beam channel, but external to it. This can be easily achieved because of the strong magnetic field imposed on the system that can confine the plasma along the field lines. Once a beam is launched ions can cross the magnetic field lines into the beam channel, partially neutralize it, and allow the beam to propagate. Plasma electrons in the plasma channel can take care of the charge neutralization which must take place in such a process. The plasma density in space and time is controlled in the following way: The drift tube is filled with gas (hydrogen or helium) at a pressure of 10^{-4} Torr. (At this pressure very little ionization can be induced by the E-beam.) A ring-shaped low energy electron source 1-10 keV, 10-500 A is placed in the drift tube. (Fig. 1) The low-energy electrons are allowed to go through the background gas for some time before the E-beam launching (1-15 μsec). Due to the magnetic field, these electrons form a tubular beam which

ionizes the gas. The longer the beam is on, the higher the density of the plasma formed. By placing more than one electron source, a multiple cell configuration can be made. An electron source with the above properties was developed. The source consists of a ring made out of graphite string. The diameter of the string fibers is 7 μm and they field emit at very low electric field. Different cell configurations and various graphite brush sizes were used, and we don't know yet which configuration is optimal. We found that a two-cell configuration approximately doubled the ion energy of both hydrogen and helium. With single-cell configuration ~ 10^{10} protons with more than 4 MeV and ~ 10^9 helium with more than 6 MeV were accelerated. With two cells we have ~ 10^9 protons with more than 8 MeV and ~ 10^9 helium with more than 12 MeV.

We do have detection problems. The signal-to-noise ratio in some cases is very poor and great efforts were made to improve it. The following table summarizes the results to date.

Plasma Configuration	Observed Energy Range	Method of Observation
5 - 6 cm ID plasma tube, full length of drift tube	2 - 3 MeV	Range-Energy
6 - 6 cm ID plasma, ≈ 30 cm long, 10 - 12 cm ID plasma, remainder of distance	4 - 8 MeV Protons 6 - 12 MeV α particles	Magnetic Spectrometer Range-Energy
10 - 12 cm plasma followed by 5 - 6 cm plasma	2 - 3 MeV	Range-Energy
10 - 12 cm plasma, full length of drift tube	0.5 - 2 MeV	Magnetic Spectrometer Range-Energy
5 - 6 cm plasma, 30 cm long, vacuum following	5 - 6 MeV	Magnetic Spectrometer

In recent years different schemes were tried and were found promising. The first is the dielectric guide collective accelerator, and the second is the controlled beam front motion collective accelerator. In some respect these two experiments resemble our scheme. In the dielectric guide collective accelerator ions are produced outside the beam channel, and are sucked into it and control the potential well associated with the beam. In the

second experiment external control (laser light) is used to control the production of the ions needed for the control of the potential well movement.

There is no magnetic field in these two experiments (a magnetic field interferes with the production of a plasma in a dielectric guide accelerator, and interferes with the neutralization of the beam in the controlled beam front accelerator). We think a magnetic field is necessary when high electron and deep well current is desired.

The program is supported by O.N.R. at a level of $50,000 a year. We think that at this level of support it would take at least three more years of studying to evaluate how promising is this method of collective acceleration.

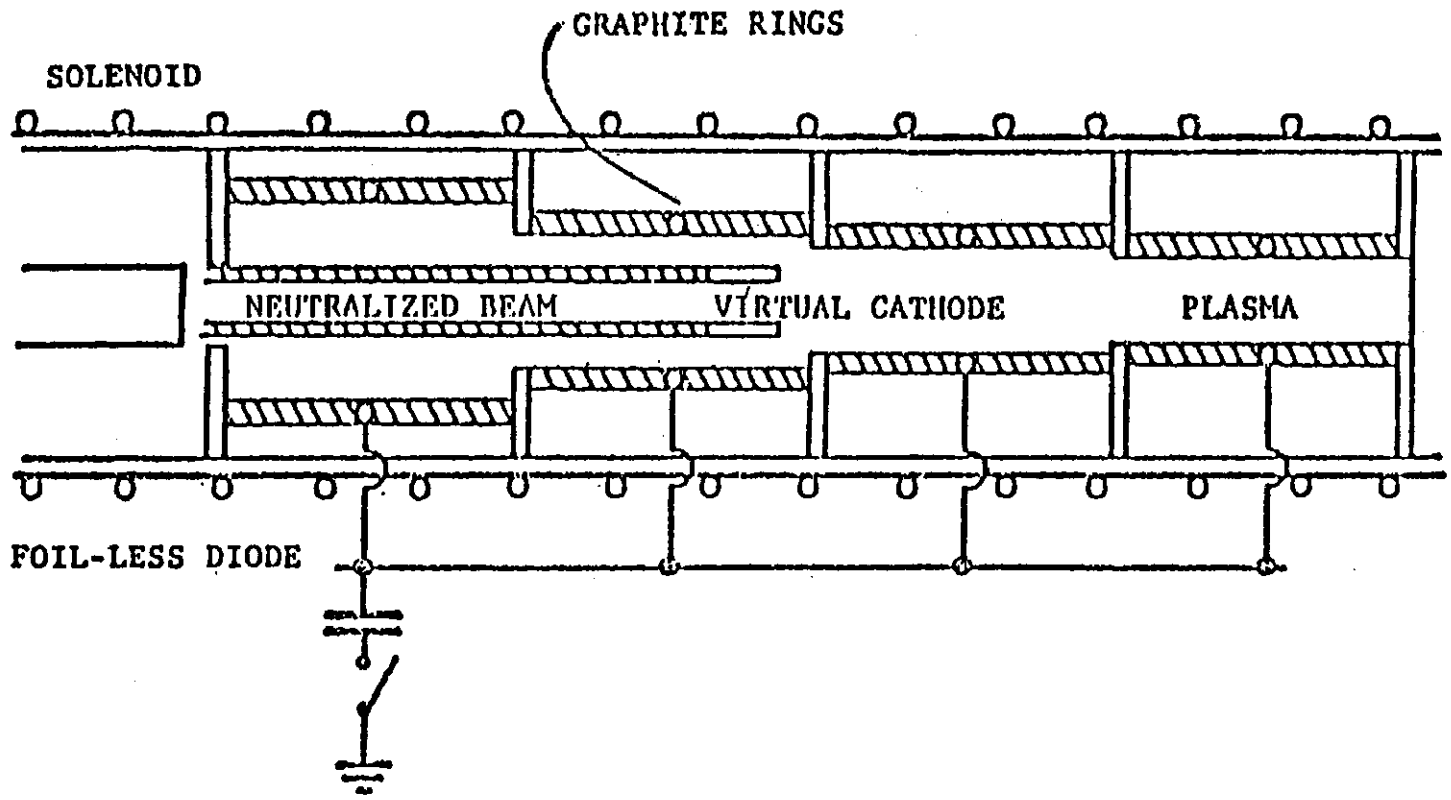

Figure 1. Plasma-Controlled Collective Ion Accelerator.

SUMMARY OF WORK ON THREE COLLECTIVE EFFECT ACCELERATORS-
(MISSION RESEARCH CORP)

I. LOCALIZED PLASMA SOURCE COLLECTIVE ACCELERATORS

1. **Physical Principles.** In a number of collective acceleration experiments, an electron beam creates a localized ion source near the anode, resulting in collective acceleration of some of the plasma ions. The first experiments were performed by Luce[1] who used a dielectric anode;[1,2] however, metal foils[3] and gas puffs[4] may in general also be used. Most of the early experiments were performed with short pulse machines (<50 nsec), making it difficult to establish the ion origin time and, hence, the acceleration mechanism. Recent studies have demonstrated that ions are produced throughout the electron beam pulse, with high energy ions (up to 22 times the electron energy) produced after the first 30 nanoseconds of a 100 nanosecond pulse. Because high energy ion acceleration occurs in a region where beam parameters are spatially and temporally uniform, the acceleration must be a wave-type process. The resulting ion energy spectrum is a truncated exponential $f(e) = f_0 \exp(-E/E_0)$ for $E < E_{max}$, with E_0 in agreement with generalized momentum limits for collective accelerators.[5] The predominant limitation to the peak achievable ion energy appears to be poor high energy ion confinement, due to the large beam self-magnetic field.

The wave mode responsible for acceleration appears to be a streaming mode at a frequency between the electron and ion plasma frequencies. Further work is required to discover which mode is responsible, and whether acceleration is stochastic or coherent. In addition, results indicate that higher energies may be associated with longer pulses. At present, Mission Research Corporation's CCUBE computer simulations are in agreement with the experiment for the first 30 nanoseconds.

2. **Parameters.** At present a modest electron beam generator[2] (0.6 MeV, 50 kA, 100 nsec) produces $3\text{-}8\times10^{14}$ protons of average energy 1.1 MeV, and a peak proton energy of ~15 MeV. The ion production efficiency is ~2-4% with a production (using a LiF target) of $>10^9$ neutrons/pulse. Much higher neutron yields would result from the use of deuterons rather than protons. Luce's experiments[1] using a 2-MeV machine produced $>10^{12}$ neutrons, and proton energies exceeding 40 MeV. In general, efficiency scales with power and $\ln R/a$ (R = drift tube radius, a = beam radius).

3. **Current Work.** Numerical work designed to elucidate the acceleration mechanism is in progress. The experimental work discussed above was performed by Cornell University. Future work (as yet unfunded) would address long pulse effects, control of the energy spectrum, rep-rate considerations, and possible applications of the presently existing technology.

4. **Applications.** Several industrial applications appear to be well suited to the small machine parameters presented above. The similarity between collective accelerator neutron output spectrum and a fission neutron spectrum, combined with the compact size of a long pulse electron beam machine, makes its use as an in-situ reactor shielding test facility practical. It is anticipated that a transformer-type, 1-50 Hz machine producing $>10^{11}$ n/pulse could be built for less than $100K. The source fluence is then $\sim 10^{17}$ n/sec for a 1 μsec pulse. Such a machine could be applied to neutron-induced γ analysis of coal process plant flow rates and compositions.[6] Applications of direct proton irradiation to erosive wear measurements[7] and reactor fuel tube analysis[8] are also possible. A ^{3}He accelerator could be used for fast, time resolved, charged particle activation analysis. In particular, creation of tracer isotopes could be used to map fast flows in jet and rocket engines due to the short pulse length.

5. **Program Plan.** If funding were available, a machine could be designed to address long pulse, rep-rate, and confinement issues, and promising areas of application could be defined.

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II. CONVERGING GUIDE ACCELERATOR

1. **Physical Principles.** The Converging Guide Accelerator concept[1] is recognized as one of the most promising collective ion acceleration mechanisms. It employs electron beam space-charge waves, which can be excited by a variety of slow-wave amplifiers. Wave velocity is controlled by spatial variation of the drift tube radius. Ion acceleration is accomplished by first trapping ions in the electrostatic wells of slowly moving waves and then allowing waves plus ions to accelerate gradually as they propagate along the electron beam in a drift tube of decreasing radius. In principle, ions can be accelerated in this way to velocities approaching that of the electron beam, which translates to ion energies some three orders of magnitude greater than that of the electrons.

Linear theory has shown, however, that the wave phase velocity drops to zero only as the guide tube radius reaches the maximum size permissible for beam propagation and then only for long wavelength, low frequency waves in a strong axial magnetic field.[2,3] Even in an infinite magnetic field there is a non-zero phase velocity limit for $\omega > 0$. The decrease in phase velocity at the space-charge limit is very abrupt. Work by Hughes and Ott[4] on large amplitude space-charge waves in an axially infinite, cylindrical geometry indicates that this result may be greatly modified by nonlinear effects. However, these low velocity waves have yet to be observed experimentally.

The status of Converging Guide Accelerator research is as follows. Wave growth has been demonstrated experimentally as fairly straightforward,[5] but satisfactory control of wave phase velocity has yet to be achieved.[6] Variation of wave amplitude as phase velocity and guide tube radius change has not been explored. No ions have been trapped or accelerated. Beam stability questions have been raised but not resolved. From a theoretical viewpoint, small amplitude wave velocity variation seems reasonably well understood. Work is only beginning on velocity variation of nonlinear space-charge waves and on amplitude variation of waves of any magnitude. No investigations of the reaction of the electron beam to high ion currents, including parasitic instabilities, wave loading, or equilibrium distortion, have been performed. Likewise, nonideal effects, such as beam temperature or voltage and current fluctuations, have been ignored.

2. **Potential Parameters.** Speculation on ion energy and current presupposes a knowledge of nonlinear effects on wave saturation, which does not currently exist. Theoretically, ion velocity will approach electron velocity as the guide converges. This implies GeV ions for even modest energy electron beams. Ion current is the largest unknown. Ion loading may cause the negative energy wave to grow. Optimistically, one might suppose that the number of ions loaded into the wave is limited only by the saturated wave field. This implies that high currents would be possible from high power electron beams. However, the effects of ions on beam equilibrium and stability, as well as how they affect wave phase velocity, are unknown and cannot be overlooked. Beam emittance ($p_\perp/p_\parallel$) will depend on the final ion energy and the wave potential. The process of ion loading will also play a role. The colder the ions are when trapped, the better the beam quality. Pulse duration will be comparable to the electron beam pulse. The efficiency and, therefore, size-scaling depends critically on the wave field saturation by trapped electrons. Efficiencies of 0.5-50% have been speculated.[1]

3. **Current Work.** We are presently involved in studying two aspects of Converging Guide Accelerator theory utilizing the linear cold beam fluid code, GRADR.[7] The first is the variation of space-charge wave phase velocity as a function of guide tube radius for a set wave frequency. The results show that wave

phase velocity does approach the beam velocity for practical frequencies (0.1-10 GHz) as the guide tube radius decreases to the beam radius.

The second area deals with the amplitude of the wave as it traverses the guide tube. The change in wave field amplitude can be obtained from conservation of wave energy flux. An appropriate expression for this property has been placed in GRADR. A WKB analysis has yielded wave amplitude, potential, phase velocity, ion energy and tube radius as a function of axial length. The primary conclusion is that, although the final ion energy is independent of wave frequency, higher wave frequencies produce larger accelerating fields.

4. **Applications.** Because of the extremely high energy and relatively high current which may be available in conjunction with good beam quality at relativistic ion energies, the most reasonable application would be as a heavy ion accelerator for inertial confinement fusion. The accelerator would be compact due to the high acceleration gradient and capable of accepting an arbitrary atomic weight ion.

5. **Program Plan.** If funding were available, future work would involve two-dimensional relativistic and electromagnetic simulation of space-charge wave growth, propagation, and amplitude variation in both infinite and finite magnetic fields. It would also simulate trapping of test ions, as well as a determination of the maximum ion currents which can be accelerated.

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III. LASER ACCELERATION OF PLASMA ELECTRONS

1. **Physical Principles.** The concept of laser electron acceleration advanced by Tajima and Dawson[1] has been studied in detail by Mission Research Corporation. The mechanism depends upon the interaction between an intense electromagnetic wave packet and the electrons of an underdense plasma. The nonlinear pondero-

motive force associated with the light wave's propagation in the plasma displaces the electrons. This leads to a charge separation and coincident restoring force producing a train of plasma oscillations. The phase velocity of the wake plasma wave is equal to the group velocity of the EM wave, which is derived from the dispersion relation $\omega^2 = k^2c^2 + \omega_p{}^2$ to be

$$\omega_p/k_p = v_p = v_g = (1 - \omega_p{}^2/\omega^2)^{1/2}c, \tag{1}$$

where ω_p is the electron plasma frequency, k_p the plasma wave number, v_p the plasma wave phase velocity, v_g the EM wave group velocity, ω the EM wave frequency, and c the speed of light. Because of the mobility of electrons, and the fact that large changes in energy for relativistic electrons translate into small velocity changes, the electrons are synchronous with the wave front for long periods.

In the wave frame the electrostatic field associated with the plasma can be viewed as a particle mirror with the maximum electron acceleration taking place when the electron experiences a momentum change of $2\gamma\beta mc$. Transforming back to the laboratory frame yields a maximum electron energy of $\gamma^{max}mc^2$ where $\gamma^{max} = 2\omega^2/\omega_p{}^2$.

First, we must determine a relationship for the minimum wave E-field intensity, E^0_{min}, from trapping arguments and the nonlinear ponderomotive force equations. In the wave frame trapping requires that the potential be large enough to stop the electrons moving in the negative direction. Therefore, $e\phi^{wave} > \gamma mc^2$. Transforming back to the laboratory frame yields that $e\phi^{lab} = mc^2$. Using the relation that $E^{lab} = k_p\phi^{lab}$ and $v_p = v_g$ one obtains

$$E^{lab}_{min} = \frac{mc\omega_p}{e}\frac{c}{v_g} > \frac{mc\omega_p}{e}. \tag{2}$$

If one neglects ion motion due to the high frequency nature of the phenomena, the restoring force on the electrons is due solely to space charge. Thus, the nonlinear ponderomotive force per cm^2 can be equated to the energy density gradient of the resulting plasma wave, or

$$\frac{\nabla|E^{lab}|^2}{8\pi} = \frac{\omega_p{}^2}{\omega^2}\frac{\nabla E^{0\,2}}{16\pi}, \tag{3}$$

where E^0 is the EM wave electric field. Solving for E^0 and substituting E^{lab}_{min} from Eq. (2) yields

$$E^0_{min} = \sqrt{2}\,\frac{mc\omega}{e}\frac{c}{v_g} > \sqrt{2}\,\frac{mc\omega}{e}. \tag{4}$$

This is valid provided the laser pulse is shorter than the plasma period, $2\pi\omega p^{-1}$. If one takes the limit that the smallest focal area of any EM source is $\pi(\lambda/2)^2$, one obtains the minimum power requirement to be $(\pi/2)^2\ mc^2/e \cdot mc^3/e$ or approximately 21.5 gigawatts.

2. **Potential Parameters.** As stated above, particle energy scales as $(\omega/\omega p)^2$. In fact, if the laser wave amplitude exceeds the minimum required, relativistic effects reduce the ωp of the plasma leading to greater acceleration. The electron currents observed in one-dimensional electromagnetic simulations would be equivalent to tens of megamperes of current for a $10^{16}\ cm^{-3}$ plasma. Efficiencies of laser to particle energy are as high as 60% for a short, instantaneous rise laser pulse. Of course, long pulses would be less efficient. The accelerator would be compact. Since E^{lab} is proportional to ωp, field strengths of 1 GeV/cm would be obtained in a $10^{18}\ cm^{-3}$ plasma.

There are serious drawbacks to this scheme. The electron energy spectrum is exponential, resulting in poor beam quality. The duration of the main pulse is at most a plasma period (for a $10^{16}\ cm^{-3}$ plasma the plasma period is one pico-second). Most critical is the need for a large wave gradient. This implies a very short pulse ($\tau < 2\pi/\omega p$) with the minimum intensity, or a longer fast rise pulse with a higher intensity which meets the requirements of Eq. (3).

3. **Current Work.** We have just completed an analytical and computational study which developed the trapping arguments and minimum laser intensity needed for acceleration,[2] as described above. This research also showed that the mechanism is insensitive to plasma gradient and temperature. Also, the laser pulse length is not critical provided the gradient of intensity is sufficient.

4. **Applications.** The main use is in the area of high energy physics research. Laser electron acceleration would provide an extremely compact source of GeV electrons. A method to select only the highest energy electrons would have to be devised. In addition, research may yield a means of creating a monoenergetic pulse.

Another application would be to have the electron pulse impact a high Z target. The X-ray bremsstrahlung spectrum would be extremely broad and could be adjusted by varying $\omega/\omega p$ to model a nuclear burst. Thus, simulation on re-entry vehicles and other devices could be performed. The X-ray conversion technique may also prove useful to inertial confinement fusion.

5. **Program Plan.** There is no firm funding source to continue this research. We would like to model the injection of the pulse from one arm of the CO_2 laser at LASL (HELIOS) into a $10^{16}\ cm^{-3}$ plasma. Other studies would include attempts to improve the beam quality of the electron pulse.

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NOVEL ION ACCELERATION TECHNIQUES (CORNELL)

We summarize work at Cornell University in three areas of ion acceleration:

(i) Acceleration in Vacuum: The Luce Diode
(ii) Space Charge Wave Acceleration
(iii) Linear Induction Accelerators

The Luce Diode: Acceleration in Vacuum

Physical principles

An electron beam is injected into an evacuated drift tube. At the anode of the accelerator a localized ion source provides the protons for space charge neutralization of the electron beam. The protons are also accelerated, parallel to the E-beam. The proton energy spectrum is essentially exponential, although events have been recorded with a "bump on the tail" distribution. Peak proton energies, with $N \sim 10^{10}$/MeV, of up to 22 times the beam energy have been recorded. The total number of accelerated protons is of order 5×10^{14} per pulse. The proton acceleration is not associated with any identifiable phase front, e.g., the beam head. There is evidence, however, that the acceleration is associated with a large amplitude wave on the beam. Tentatively we associate the acceleration with a space charge wave driven by the electron-ion two stream instability. Although a large amplitude ~ 1 MV/cm wave is seen on the beam, late in the pulse at about the correct frequency, there are still a number of uncertainties regarding the nature of the acceleration. Work is needed to resolve the details of the acceleration mechanism and to determine if the acceleration is inherently stochastic or whether a coherent wave train can be established for the acceleration.

Beam Parameters

The work at Cornell has used a 500-700 kV, 45-60 kA, 100 nsec electron beam. Over 2×10^{14} protons are accelerated, to energies greater than the electron-beam energy, and transported in a 1 cm diameter beam through a distance of about 1 m. About 75% of the accelerated protons are lost to the tube walls, mostly after about 30 cm, due to the space-charge E-field force dominating over the $v \times B$ confining force. Experiments by Luce showed a comparable performance at an electron-beam energy of 2 MeV, i.e., 40-MeV protons were obtained. In addition to the performance quoted, we note that a relatively good repeatability of the system has been achieved by provision of an externally supplied electrostatic beam neutralization along the length of the drift tube.

Current State of Development

Consistent performance at the levels indicated is now routine. Short term work is aimed at improving the proton beam confinement, narrowing the bandwidth of the rf, and providing independently controlled proton sources for acceleration and for beam neutralization.

Applications

Using our existing facility we generate ~ 10^9 neutrons/pulse from a Lithium target. With a deuteron beam this number increases to ~ 10^{10} per pulse. Luce obtained, with a 2 MV system, 10^{12} neutrons per pulse. It would seem that the system could find use as a neutron source. Possible applications of such neutron sources have been indicated by Adler. Other applications will depend on the resolution of the coherent or stochastic nature of the acceleration.

Long Term Plan

Long term development of this system is worthwhile if a coherent acceleration can be established. Further work is needed to determine this feature of the acceleration.

Other Work

A number of laboratories in this country and in the USSR have carried out similar work. These include: AFWL, Boeing, Institute for Nuclear Physics-Novosibirsk, LLL, Lebedev Institute, N. Carolina State University, NRL, and Spire Corp. Simulation is being carried out at LASL.

Space Charge Wave Accelerators

Physical Principles

Ions are accelerated in a slow space-charge wave whose phase velocity is controlled by changing the effective plasma frequency of the wave. In principle the ions can be accelerated to velocities approaching that of the electrons.

Beam Parameters

Beam parameters are limited at low energy as well as at high energy. This arises because the wave-phase velocity can only approach zero (in linear theory) as the wave frequency and wave number go to zero, and as the beam current reaches its space charge limiting value. In the absence of nonlinear, or other

effects, this limits the useful phase velocity to ~ 0.2 c. The wave-electric field decreases as the phase velocity increases for a fixed amplitude wave. Hence, it will probably be necessary to stage the accelerator. The space-charge wave accelerator has a convenient configuration to permit this staging.

Nonlinear theory shows that the wave-phase velocity may be substantially lower than that predicted by linear theory. This is an important result as it provides the basis for a more useful configuration than that based on the linear theory.

Current State of Development

Experimental studies have shown that the required wave may be readily grown to large amplitudes. Studies have been centered on determining the low-phase velocity limit of the wave. High frequency response, time resolved measurements show a propensity on the part of the beam to exhibit instability at low-phase velocity conditions. The time evolution and control of the beam wave characteristics are currently the main topics of investigation.

Concurrently, we have developed a multi-beam capability for a wave acceleration experiment. This consists of a primary beam which is used to generate high-energy protons for injection into the wave and a second beam system which can produce a 2 kA, 300 kV, 400 nsec for beam wave growth and acceleration. The system permits time synchronizd operation of these generators and is designed to permit proton injection into the wave section.

Applications

The principle applications of the space-charge wave accelerator will be in the area of high current, high-energy beams with low atomic number ions. A promising application might be electro-nuclear breeding.

Long Term Plans

These depend critically on the results obtained for low-phase velocity operation. If this works out satisfactorily we are in a position to load ions into the wave to study ion acceleration capabilities in the test particle regime, i.e., essentially no loading of the wave. At present we have not yet convincingly demonstrated satisfactory operation with an overlap of proton velocity and wave-phase velocity.

Other Work

Simulation work is being carried out by Mission Research Corp. Other simulation and analytic studies have been carried out at NRL and at the Lebedev Institute in Moscow.

Linear Induction Accelerators

Although the linear induction accelerator is not a collective effects device, it does present novel features which may be of interest.

Physical Principles

A time-varying magnetic field is used to accelerate a beam of protons. Average accelerating fields of order 1 MV/m can be maintained. Proton-beam transport between successive stages of the accelerator requires beam neutralization to prevent radial loss.

Beam Parameters

Work at Cornell is on a proton beam of 1.1 MeV, 1 kA, 50 nsec duration. Protons are produced from a flashover anode, transported through an electrostatically driven gap, and then post-accelerated a further 700 keV by induction fields. We plan to upgrade the facility to ~ 2 MeV in the fall.

Current State of Development

This system was brought on line recently. Current activities have been centered on magnetic insulation of the induction gap and verification of the system performance.

Applications

Three obvious applications for ion beam systems are

(i) Simulation of beam transport for heavy ion fusion devices;

(ii) Generation of deuteron beams ~ 30-40 MeV for neutron production to simulate first-wall loading in a fusion device;

(iii) Acceleration of intermediate atomic number ions for fusion applications.

At present there is virtually no experience in post-acceleration or in ion-beam transport of moderate current beams.

Long Term Plan

To develop and study beam transport and post-acceleration techniques for proton beams using inductive accelerating fields. This work will include development of emittance measurement techniques for these beams and a study of emittance growth throughout the accelerator.

Other Work

The only other program known in this area is the Pulselac Program at Sandia.

NRL PROGRAM ON COLLECTIVE PARTICLE ACCELERATION

(A) Introduction

At NRL we have investigated two mechanisms for collective acceleration of charged particles. The first is an autoacceleration process[1-5] for electron acceleration and the second process is the CPA[6-7] (Collective Particle Accelerator) which can accelerate any kind of charged particles. Both mechanisms are the result of interaction between a pulsed-high-power electron beam with a secondary beam of charged particles. This interaction leads to energy transfer from the high power electron beam to the secondary beam. The maximum energy transfer (assuming 100% efficiency) cannot be larger than 0.5×10^6 Joules.

(B) Autoacceleration mechanisms

(a) Autoacceleration mechanisms[1-5] are the result of the mutual interaction between an electron beam and passive structures that are inserted in a conventional drift tube. The interaction leads to the redistribution of energy within the beam such that the majority of the electrons in the beam transfer their energy to only small portion of the beam (secondary beam). Two modes of autoacceleration processes have been tested at NRL.

(b) The first mode[1-2] was tested in 1973-1974. In this mode of operation a beam of relativistic electrons (current I, particle energy eV and duration T) was propagating in an axial magnetic field through an evacuated drift tube in which a coaxial cavity was inserted. The length ℓ of the cavity was chosen such that $\ell/c = T/4$. Under these conditions, when the beam reaches the cavity a voltage V_1 appears at the gap. The voltage has a bipolar form and $V_1 = IZ$ where Z is the characteristic impedance of the cavity. Electrons will lose energy eIZ per electron during the first half of the beam duration ($0 < t < T/2$) and gain the same amount of energy during the second half of the beam duration ($T/2 < t < T$).

We demonstrated that this process works and the energy of a 10 kA electron beam was increased from 0.5 MeV to 1.0 MeV.

(c) A new 5 MV, 100 kA, electron beam generator is presently under testing. Using the above technique a 10 MeV, 100 kA electron beam can be generated. By removing the slowed down electrons the process may be repeated and a beam of particle energy ~20 MeV may be generated.

(d) The efficiency of this process is 100% if no electrons are lost during the acceleration process. By using spatial magnetic field configuration, gap design, etc., one can keep good beam quality during the acceleration phase.

(e) The second mode of autoacceleration process[3-5] was tested in 1975-1979. In this mode of operation, a long duration electron beam with current that rises linearly for a time T to a maximum I_0 is propagating through N coaxial cavities. The return current "loads" each cavity with magnetic energy. The energy stored in each cavity is removed from the beam via a decelerating voltage. This voltage appears across the gap and is equal to L^{dI}/dt where L is the cavity inductance. At time T the current drops to a value I_0 in a time that is short in comparison to any time associated with a cavity. Under this condition a voltage $V = Z(I_0 - I_0)$ will appear across each gap. The total energy that the electrons will get is NVe. The acceleration process will last a time equal to 0.5 period of a cavity.

The autoacceleration mechanism has been confirmed experimentally with one and two cavity systems. X-ray and Faraday Cup measurements indicate that the bulk of the beam electrons are being accelerated to the full predicted energy. The beam energy has been increased by a factor of 14 from 200 KeV to 2.4 - 3.0 MeV in a two cavity system.

(f) The maximum electric field that can be generated by this process depends on the duration of the acceleration. If a beam with a fall time of 1 nsec can be achieved, maximum electric field of 100 MV/m will be generated.

(C) The CPA (Collective Particle Accelerator)[6-7]

(a) Let us visualize that at a certain frame of reference one has stationary rings (discs) of electrons spaced in a prearranged order. These rings (discs) contract and expand radially. Ions are attracted by a radially collapsed ring (disc) of electrons and are accelerated. As the ions enter into the ring (disc) the ring (disc) expands radially and the ions move freely toward a second ring (disc) which (at that time) is in a collapsed state. The ions are attracted to the second ring, etc. One can see that the force acting on the accelerated ions is impulsive in nature. Electrons can also be accelerated by the repulsive force of these rings.

The production of radially oscillating rings can be achieved by propagating a bunched annular IREB through a rippled magnetic field. When viewing this system at the rest frame of the IREB one can see oscillating rings of electrons (approximately).

When one writes the equation of motion of the rings (discs) and evaluates the nature of the electric field configuration which the rings generate (while propagating in the rippled magnetic field) one finds that this system comprises of large amplitude forward and backward "electric waves." These waves (which are not beam waves) have phase velocities which depend on the modulated beam wavelength, λ and on the rippled magnetic field wavelength, L. Charged particles with velocities matching the phase velocity of the wave will be accelerated. The average electric field associated with the wave is

$$E_{zo} \approx \frac{I/c}{4\varepsilon_0} \frac{r_1}{r_0 L}$$

where I is the current of the IREB r_0 is the equilibrium radius of the IREB and r_1 is the amplitude of the oscillation.

(b) At the Naval Research Laboratory an experiment was built to test the above idea. In the first stage of the experiment that was finished recently, an IREB was generated by applying a negative 1 MV voltage pulse to a foiless diode. The diode emitted an annular electron beam with 30 kA current for a 130 nsec duration. The beam was guided through an evacuated drift tube for a 5-6 meter length and was focused by a semi dc magnetic field of 10 kG. The IREB was modulated using an automodulating technique. $\lambda/4$ coaxial cavities were shock excited by the front of the IREB. The mutual interaction between the cavities and the IREB caused the generation of equally spaced rings of electrons.

The rings of electrons were allowed to propagate through a rippled magnetic field.

In the second stage of the experiment (in progress) charged particles will be injected from the end of the system.

We hope to achieve an electric field of the order of 5 MV/m and accelerate electrons, protons, and heavy ions.

(c) Although acceleration of particles has not been demonstrated, it is important to investigate the potentiality of this progress. The maximum accelerated field is

$$E \approx \frac{I/c}{4\varepsilon_0} \frac{r_1}{r_0 L} \approx 20 \text{ MV/m}; \; I \approx 2\times10^5 \text{ A}; \; L \approx 0.3 \text{ m}$$

When ions are accelerated L will have to increase in order that the wave will be synchronized with the ions. This will reduce the maximum electric field unless (r_1/r_0) can be increased.

The focusing field associated with the radial electric field can be as large as 300 MV/m.

The number of particles/unit length that can be accelerated is $\approx 0.1[(I/c)/e]$. Thus particle current exceeding kA's can be accelerated. These particles can be electrons, protons, or even heavy ions.

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COLLECTIVE ION ACCELERATOR RESEARCH AT THE UNIVERSITY OF MARYLAND

1. INTRODUCTION

The present research program at the University of Maryland involves the collective acceleration of ions by an intense relativistic electron beam (IREB) in a vacuum drift tube. The source of the ions is a well-defined, localized plasma near the anode of the IREB generator which is produced either by the electron beam itself or by external means (laser). This method has produced the highest energies achieved so far by collective effects in the laboratory (Xe ions of about 900 MeV). From the experiments it is inferred that ion acceleration takes place in a short distance of a few centimeters, with effective electric field gradients in the range above 100 MV/m. Theoretical studies have led to a qualitative understanding of many aspects of the acceleration mechanism; however, a quantitative self-consistent theory or numerical simulation explaining the high-energy component in the ion distribution is still lacking.

The IREB generator used in our experiments produces electron beam pulses with typically 30-40 kA peak current, 1-2 MeV peak energy and a pulse width of about 30 ns. Several different experimental configurations are being investigated:

(a) The "Luce diode" geometry where the ions (usually protons or light ions) come from a dielectric insert in the anode. In some of these experiments we demonstrated that the ion energy can be increased (by a factor 2 so far) with the use of slow-wave structures in the vacuum drift tube.

(b) Acceleration of various gaseous ion species (hydrogen to Xenon) from a localized gas cloud injected into the beam path by a puff valve.

(c) Acceleration of ions from laser-produced plasmas of solid materials. This work has just begun.

(d) Generation of fully stripped heavy ion beams (with energies near 1 MeV/amu and excellent emittance) in a plasma focus obtained by reversing the voltage polarity of the IREB diode. This work too has just begun.

Figure 1 shows the front end of our IREB generator with the vacuum drift tube and diagnostic chamber. Figure 2 illustrates typical anode geometries for the four types of experiments. These experiments and the results obtained so far will be briefly described in the next section.

Our collective accelerator program involves the participation of four faculty members (Drs. Destler, Reiser, Rhee, and Striffler) and three graduate students. It is funded by grants from the National Science Foundation (140 K$, expiring in December 1981) and the Air Force Office of Scientific Research (currently 55 K$, to be renewed March 1, 1981, at a level of 100 K$). A 15-Joule ruby laser was acquired with a grant from DOE (30 K$). Continuation of the program beyond 1981 will depend on the availability of funds to substitute for the NSF grant. The goals of our program will be discussed in the last section which also addresses the general questions asked by the Study Group.

2. DESCRIPTION OF RESEARCH PROGRAM

1. **Luce diode and slow-wave structure.** Our interest in collective acceleration in a vacuum drift tube was triggered by John Luce's pioneering work at Livermore six years ago. Luce reported that he obtained considerably higher ion energies with his dielectric anode and special electrodes in a vacuum drift chamber than the energies observed in gas-filled drift tubes (which correspond to typically 2-3 times the diode voltage). Initial experiments at our laboratory (by Boyer, Kim, and Zorn) provided the first independent confirmation of Luce's results.[1] The early theoretical studies, in particular by Kim, attributed the ion acceleration to the formation of a virtual cathode downstream from the plasma and coherent electron-ion motion. They laid the groundwork for subsequent theoretical investigations (the "piston" model[2] and the present work by Striffler) and provided valuable guidance for the more recent experiments conducted by Destler. A typical Luce diode geometry used in our experiments is shown in Figure 2(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 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 ± 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 ($I \gtrsim 200$ A) with narrow pulse width ($\gtrsim 4$ 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.

2. **Collective acceleration from a localized gas cloud.** In this configuration, shown in Figure 2(b), the anode is made of stainless steel and a gas cloud is injected by a puff valve into the region of the electron beam path right behind the anode. The front end of the electron beam (which is fired early in time before the gas cloud has expanded into the vacuum chamber) ionizes the gas and the resulting plasma then serves as an ion source. It should be noted that in all of these experiments, the electron beam current is above the limiting value and does not propagate into the drift tube unless positive ions are present. The advantage of the puff-valve (as well as the laser) is that it provides an external control not possible with the Luce diode. We performed experiments with various gas species (H, He, N, Ne, Ar, Kr, Xe) using time-of-flight probes (indicated in Figure 1), nuclear diagnostics (for the light ions) and cellulose film track analysis. The major results using a 1.5 MeV electron beam are the following[3]:

(a) The maximum energy in the ion beams is about 5 MeV/amu -- independent of the ion mass. The exact energy spectrum has not been measured yet. But it appears that there are intensity peaks in the distribution, one of them in the range of about 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 is not known at this time. We plan to make measurements in the future when an apppropriate analyzing system is available.

(d) The highest energies were obtained with Xenon where approximately 10^7 ions/cm^2 have energies in the range of 600 to 900 MeV.

3. **Collective acceleration from a laser-produced plasma.** In these experiments 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 2(c) just prior to the firing of the electron pulse. The electron beam passes through the plasma and accelerates positive ions. Preliminary results indicate the following:

(a) Maximum energies are in the range of 5 MeV/amu, independent of mass, as in the gas experiments.

(b) In contrast to the gas results, the energy distribution of the ions appears to peak closer to the maximum energy and the spread in energy appears to be significantly smaller than in case 2. We attribute this to the availability of ions in the laser-produced plasma when the electron beam arrives. Preionization by the laser thus provides an additional external control of the acceleration process.

4. **Pulsed-power plasma focus experiments.** Recently, M. J. Rhee[4] 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 2(d), is similar to that of plasma focus devices except that in this case the power source is the IREB generator. A plasma can be generated with gas from a puff valve -- either in the configuration of Figure 2(b) or that of Figure 2(d) -- and/or from materials mounted on the tip of the positive electrode as shown in Figure 2(d). 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 is not due to a net space-charge effect, but can be attributed to inductive electric fields associated with the voltage breakdown between the electrodes.

3. FUTURE PLANS AND POSSIBLE APPLICATIONS.

Our past and present efforts can be characterized as exploratory, aimed at identifying and understanding the various physical mechanisms responsible for the ion acceleration. Since ion acceleration occurs naturally, there is no proof-of-principle necessary. The short-term objectives are to study the physics, scaling laws, and constraints of these acceleration methods and to measure the phase-space and charge state distribution of the

ion beam for various experimental configurations (we will move our facility into a new laboratory this summer where space for an analyzing magnet and improved ion diagnostics will be available). A second IREB generator has been built in collaboration with the Harry Diamond Laboratory which produces longer pulses (~ 100 ns) and higher currents (~ 100 kA) as the present machine and will allow us to study how the ion beam properties scale with the pulse length and electron beam power. We have also built a 1-2 Tesla solenoid to provide confinement for both the electron beam and the ions which should improve the emittance and shot-to-shot reproducibility. Our experimental program is backed by a small in-house theoretical effort which, we hope will lead to a better understanding of the acceleration process and the scaling laws. Dr. R. Faehl of Los Alamos Scientific Laboratory is collaborating with us in developing numerical simulation techniques capable of modeling the experimental configuration. Computer studies by Faehl as well as by Striffler and Grossman of our group have shown many features of the ion acceleration process, but so far they have not produced the high-energy component of the ion beam that is observed experimentally.

We estimate that the present exploratory research phase of our program could be completed in approximately three years provided that an annual funding level of 200-250 K$ can be maintained. Our long-term goal beyond that is to determine the suitability of the ion beams for specific applications. This phase would include optimization of ion beam parameters, beam selection and transport, and additional acceleration (through one or two high-voltage gaps, for instance).

Ultimately, the application of collective accelerators depends on the development of repetition rate capability. Large efforts in this direction are under way at various laboratories (particularly Livermore and at Sandia). We intend to follow these developments closely and to evaluate their implications for a collective accelerator like ours.

Assuming that the repetition-rate problem can be solved, we see many possible applications for our collective accelerator, for example in spallation neutron sources, heavy-ion accelerators for nuclear physics or biomedical application, heavy-ion fusion, ion implantation, directed energy systems, etc. In most of these applications, our accelerator could serve as an inexpensive injector/preaccelerator with unique beam properties not available in conventional systems. A well-known problem in high-power accelerators (spallation neutron source, heavy-ion fusion, etc.), for instance, is the focusing limit 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: 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).

As pointed out earlier, the ion energies measured in our experiments are the highest achieved by collective effects in the laboratory so far. These energies are attributed to the action of very high voltage gradients (> 100 MV/m) over a short distance of the order of 10 cm. One of the most interesting questions concerning collective accelerators, in general, is whether perhaps more modest gradients (say between 10 and 100 MV/m) can be achieved in a controllable fashion over long distances. Several schemes, such as the Ionization Front Accelerator (IFA), the Auto-Resonant Accelerator (ARA), and the Converging Guide Accelerator (CGA), have been proposed to do that. The wave-type accelerators among them (ARA, CGA) require relatively high injection energies (in the range of 10 to 40 MeV for protons, for example). Should these accelerators prove to be feasible, a collective accelerator such as ours could serve as an injector. John Nation at Cornell, for instance, who studies the CGA, is also conducting research with Luce diodes. Adamski at Boeing had also been involved in Luce diode research. Some work with collective acceleration by linear electron beams in vacuum are also being pursued in the USSR and Japan.

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THE AUTO-RESONANT ACCELERATOR (AUSTIN RESEARCH ASSOCIATES)

The Auto-Resonant Accelerator (ARA) is a traveling-wave accelerator which makes use of a large amplitude traveling wave on a relativistic electron beam. The electron beam is immersed in a longitudinal magnetic field B, and the traveling wave is the lower branch of the upper hybrid cyclotron mode. This mode has the property that its phase velocity varies approximately as 1/B and thus the phase velocity of the wave can be easily varied by varying the externally-applied magnetic field. At the beginning of the accelerator section, the phase velocity is small, e.g., the velocity of a 50-keV proton. As the wave moves down the accelerator, the externally-applied magnetic field is decreased and the phase velocity of the wave increases asymptotically to the electron beam velocity as the magnetic field tends to zero. The potential well associated with this traveling wave is an absolute potential well for ions, which thus allows them to be accelerated in a natural way from low initial energies to high final energies with no need for external focusing of any kind. This accelerator can be configured either as a steady-state CW accelerator or as a short-pulse accelerator. In most of what follows, we will be discussing the steady-state accelerator. The principal attributes of this accelerator are the following:

1. **Large accelerating gradient.** Typical electric wave field strengths are of the order of the radial electric field of the electron beam. For example, a CW accelerator with a 1 kA beam of 3 mm radius gives an accelerating gradient of approximately 10 MV per meter. For short-pulse accelerators, much larger accelerating gradients can be obtained.

2. **Large ion currents.** In order to provide an absolute well for the accelerated ions, the ion density must be small compared to the electron density. This is most restrictive at injection. For an injection energy of 50 kV and an electron beam current of 1 kA, this requirement is $I_{ion} \ll 7$ A. Thus, ion beams in the ampere range appear quite feasible.

3. **No rf power requirement.** Since the wave in question is a negative energy wave, it can be grown to the appropriate amplitudes on the beam by a passive amplifier. Moreoever, because of the negative energy character of the wave, the acceleration of ions will cause the wave amplitude to increase. Instead of rf power supplies, dc power supplies must be provided which typically cost in the range of 5¢ per watt (in multi-megawatt sizes).

Potential Applications

We have considered several potential applications in some depth to assess the economic impact of this accelerator technology on industrial processes. Two of these are discussed briefly below:

Accelerator Breeding. The general concept of breeding fissile material by the use of high energy (GeV) ions and a multiplying target blanket system has been known for years. This idea has recently been reevaluated by Los Alamos, Brookhaven, Oak Ridge, and Livermore using (a) conventional accelerator technology, and (b) advanced reactor technology for the target-blanket. The accelerator was assumed to produce 300 mA of 1-GeV protons with an efficiency of 50%. The cost of the accelerator, although it varied among the different projections, was in the range of $600 million.

If Auto-Resonant Accelerators were an already-established technology, it would be reasonable to project, on the cost basis discussed aabove, that an Auto-Resonant Accelerator with the same output parameters but with 80% efficiency could be built for approximately $25 million.

The impact of this cost difference, of course, significantly alters the conclusions with respect to the economic attractiveness of accelerator breeding as an alternative to the fast breeder reactor. This has been reported on in an earlier report to the DOE. More recent considerations involving less sophisticated target-blanket configurations suggested by Prof. Schulten of Jülich lead to the conclusion that an Auto-Resonant Accelerator, combined with relatively inexpensive neutronics, could produce fissile material at a cost significantly less than the current cost.

Tokamak Heating. A second study has been undertaken to assess the ability and the practicality of heating tokamak fusion devices by the use of high-energy helium ions. In particular, 8-MeV singly-charged helium ions injected tangentially at the outside of a tokamak have been shown to produce plasma heating throughout the entire tokamak cross section. The deep penetration of the high-energy ion orbits is a result of the energy-dependent curvature and grad-B drifts.

An accelerator to produce 1-ampere current of singly-charged helium ions has been designed and a research program proposal to develop this accelerator and test its heating effectiveness is in preparation.

The heating requirement for large tokamaks has been assessed to be in the range of 100 MW. Conventional technology using neutral-beam injectors is projected to cost between one and two dollars per watt, leading to a total cost of between $100 million and $200 million for this type of tokamak heating.

Because of its low total cost, i.e., about 10 cents per watt, an Auto-Resonant Accelerator for this purpose would presumably cost approximately $10 million and because of the uniformity of the heating produced by high-energy helium, may well do a much more effective job of heating.

Current Status

At the current time, Austin Research Associates is completing a four-year Proof of Principle Program for a short-pulse Auto-Resonant Accelerator. Because of potential military applications, the technology used for this experiment is of the high voltage pulse power type. Although this does not easily lend itself to basic experiments, we have succeeded in establishing the major predictions associated with this accelerator, in that we have produced waves with accelerating potentials in excess of 10 MeV per meter and have controlled their phase velocities as predicted by theory.

Proposed Program Plan

If we could design a program plan for the long-range development of the steady-state Auto-Resonant Accelerator, it would successively develop (a) a single-stage Auto-Resonant Accelerator in the 10-MeV range, (b) a two-stage Auto-Resonant Acceleratror in the 50 to 100 MeV range, and (c) an energy recovery system to provide a high overall efficiency. We believe it is reasonable to achieve these goals in a three to five-year period at a level of effort of $1.5 million to $2 million per year.