Title

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Publication Date

1990-06-01

LBL-29114 Abs.

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UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Presented at the European Accelerator Conference, Nice, France, June 12–16, 1990, and to be published in the Proceedings

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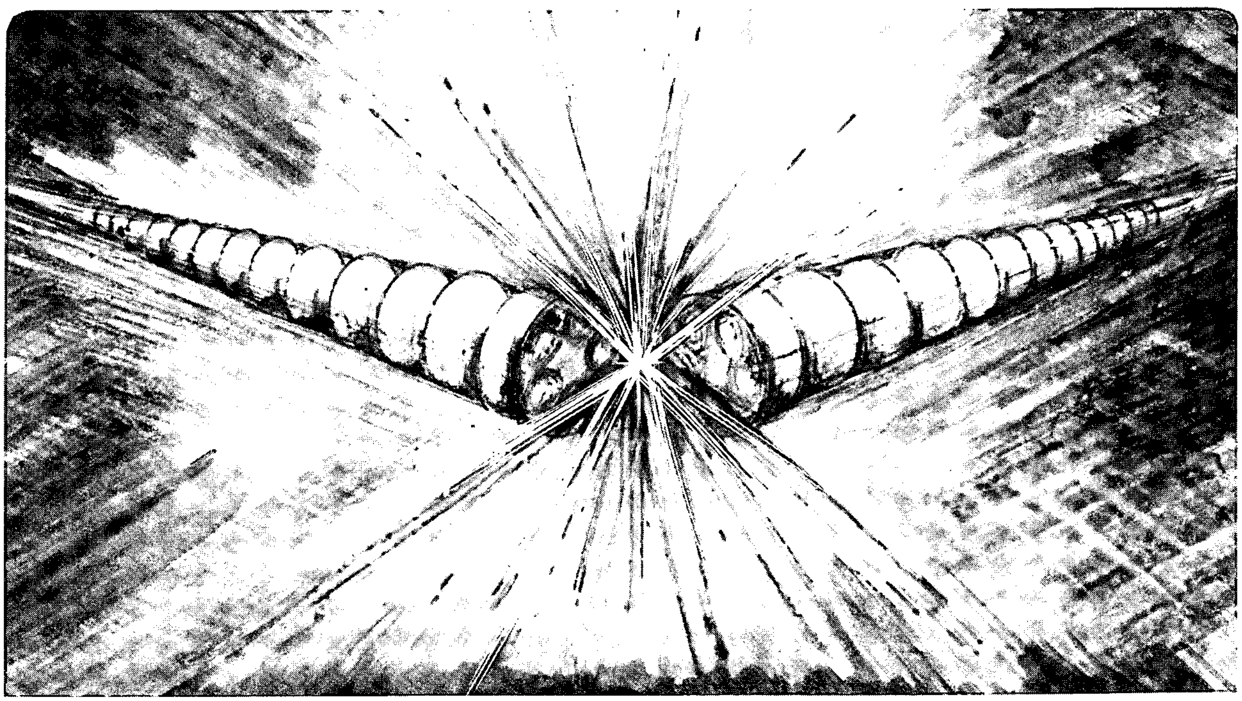
June 1990



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

NEW TECHNIQUES FOR PARTICLE ACCELERATORS*

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Abstract

A review is presented of the new techniques which have been proposed for use in particle accelerators. Attention is focused upon those areas where significant progress has been made in the last two years—in particular, upon two-beam accelerators, wake-field accelerators, and plasma focusers.

I. Introduction

Although novel methods for acceleration have been considered for a very long time, it was at Los Alamos in 1982, at the first Workshop on The Laser Acceleration of Particles[1], that efforts were made to systematically characterize the various concepts. Subsequent workshops in that series, at Malibu[2], at Madison[3], and at Lake Arrowhead[4] have detailed the very large progress made, during the decade, on advanced accelerator concepts. During the same period, a series of workshops was held in Europe: at Oxford[5], at Frascati[6], and at Orsay[7]. The interested reader will wish to study much in these seven volumes.

I want, in this review, to discuss the present state of novel concepts. I must do that with only a minimum of repetition, while making my presentation accessible to many. Not easy ! Rather than work within the general framework developed at Los Alamos I simply list, in Table 1, the concepts that still remain viable at this date. The Table has many references; not a complete list, but enough as to allow the reader to enter the original literature without too much difficulty. (As a result, detailed ideas will not be further referenced in this review.) Into the list in Table 1 has been built my personal prejudice, for I have ordered concepts, with the most interesting devices, the most likely ideas to come to fruition, in my opinion, listed first in each Category. (Naturally the concepts that I work on are high on the list, but any other ordering would be less than honest.)

Some of the concepts are receiving very little work (such as I-5, I-7, I-8, I-9) while a few are receiving good effort, but have not yet yielded to this effort (such as I-6). Let me leave aside Category II, on the grounds that the work is not sufficiently "new", although we well-realize that often significant progress, really important progress, is made on things which aren't considered novel. In the first Category considerable work, and considerable progress over the last two years, has been achieved on I-1 to I-4; we shall go into these four concepts in some detail in Sections II and III. Category III consists of devices which aid in accelerator technology, but are not concepts for acceleration. (Back in 1982 we didn't even consider this Category.) Some of the most likely prospects for early realization are in this Category and we shall go into III-1 and III-2 in some detail in Section IV.

II. Two-Beam Accelerators

The Two-Beam Accelerator (TBA) was first proposed in 1982. Since that time a great deal of work has been done on the concept. Basically, an intense low-energy beam is employed to repeatedly produce microwaves which are then used to accelerate a beam to high energy. The concept is shown schematically in Figure 1.

Four versions have been developed: two employ a free electron laser (FEL) as the power converter (from electron beam power to microwaves) (TBA/FEL), and two employ a relativistic klystron (RK) as the power converter (TBA/RK). Two replenish the beam power with induction acceleration, and two with superconducting cavities.

The heart of the Two-Beam Accelerator is the power generation unit. These units could be used, individually, as power sources. Generally, the units seem too expensive (although that may not really be the case; the units, Relativistic Klystrons or Free-Electron Lasers, have the advantage that they are known to work). One can imagine putting a few units together, even mixing them up (the "after burner" concept); if one uses a large number of units then one arrives at a TBA.

Table I. New Techniques for Particle Accelerators

I. Accelerator Concepts

1. Two-Beam Accelerator (Relativistic Klystron)[8]
2. Two-Beam Accelerator (Free-Electron Laser)[9]
3. Plasma Wake-Field Accelerator[10]
4. Wake-Field Accelerator (Cu structures, dielectrics)[11]
5. Switched Power Accelerator[12]
6. Plasma Beat-Wave Accelerator[13]
7. Plasma Implosion Accelerator[14]
8. Inverse Free-Electron Laser[15]
9. Inverse Cherenkov Accelerator[16]

II. Power Sources

1. Klystrons[18]
2. Crossed Field Amplifiers[17]
3. Binary Pulse Compression[19]
4. CARMs[20]
5. Gyroklystrons[21]
6. Gyrocons[22]

III. Focusing, Compensation, Damping

1. Plasma Lens[23]
2. Adiabatic Compressor[24]
3. Plasma Compensation[25]
4. Plasma Damper[26]

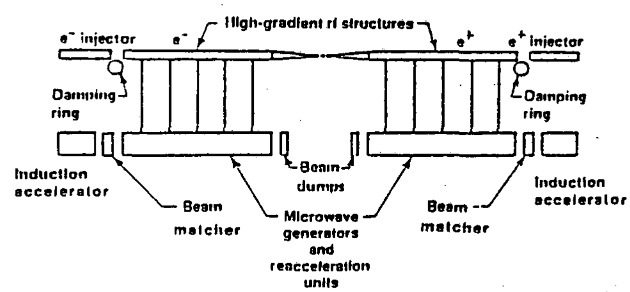

Fig. 1. Schematic of a Two-Beam Accelerator. The low energy drive beam provides power to the high energy beam. Reacceleration is provided by induction units or with superconducting RF cavities. Conversion of beam energy to microwaves is provided by either relativistic klystrons or free-electron lasers.

* Work performed by the Lawrence Berkeley Laboratory, for the US Department of Energy, Division of Nuclear and High Energy Physics, under Contract DE-AC03-76SF00098.

I would like to first, very briefly, review the status of the power generation units, and then turn to some TBA concepts.

1. Free-Electron Laser

The first experiment was done by the LLNL/LBL group in 1986. I remind you that, operating at 35 GHz, and using 850 A of 3.5 MeV electrons, they generated over 1 GW of peak power corresponding to an efficiency greater that 34%. Recently the KEK group has started an experimental program to generate 11.4 GHz radiation with an FEL.

2. Relativistic Klystron

A great deal of work has been done on the Relativistic Klystron (RK), with perhaps the most interesting results those of the LLNL/SLAC/LBL group. They have been able, operating at 11.4 GHz, and using a 550 A, 1.3 MeV electron beam sent through a multi-cavity klystron, to extract 290 MW of peak power in a pulse of about 50 ns, corresponding to an efficiency of 40%. The CERN group is building a facility for studying the generation of microwaves at 28 GHz.

3. Concepts

In the RK version of the TBA the microwaves may be easily transferred from the drive structure to the high gradient structure (HGS). The FEL is a very effective source of microwaves, but the extraction is non-trivial. On the other hand an RK can only be made to work up to some critical frequency (which seems to be close to the experimental studies at 11.4 GHz). Operation at higher frequencies has distinct advantages of economy in capital cost and operating cost, but seems to require an FEL.

The most straightforward method of extracting microwaves is with a "septum coupler". However, this approach, in a very restricted experimental study, was observed to be limited by breakdown at low microwave intensity. Theoretical studies of microwave extraction have resulted in a number of possible configurations, no one of which is ideal.

An interesting method for removing microwaves, in a RK, has been proposed by H. Henke. This method employs a drive cavity and a high gradient structure in close resonance, so that beats between the two structures result in transfer of energy from the driver structure to the HGS. In the coupled cavity version of the TBA/FEL, the method proposed by Henke (for an RK) is used in the FEL version. In addition, the coupled cavity TBA can be operated in a mode where the energy of particles is close to constant, which is quite advantageous as has been emphasized by R. Pantell.

In order to employ beats between the drive structure and the HGS there must be cavities that "hold" the microwave field for a significant fraction of the beat cycle. In the usual FEL the microwave field is travelling with roughly the same velocity as the particles, but it is possible to have a phase velocity that allows for slippage of one wave while traversing one period of the wiggler (the well-known FEL resonance condition) and yet have a group velocity that is zero, i.e. allows the electromagnetic pulse to remain stationary in space. In short, one can operate an FEL in the "strong slippage" regime, and that is just what is employed in the coupled cavity scheme.

Putting all these ideas together, we arrive at the configuration shown in Figure 2. Experiments are being done at Northstar, and are being considered by UCLA, MIT, and LLNL.

III. Wake-Field Accelerator

Wake-field accelerators employ a large charge (the "drive beam") or a photon pulse (the "drive pulse") to create fields in a structure, which fields are then employed to accelerate a small charge to high energies. Typically, the small charge is just a few RF cycles behind the drive beam, and the structure is either made of conventional materials or is a plasma. Equivalently, one can think that the drive particles leave behind a wake which accelerates the following group of particles. In short, an intense beam of low energy drives a few charges to high energy.

Clearly, conservation of energy requires that the accelerated charge must be smaller than the drive charge. The wake-field theorem, also based only upon conservation of energy, has much stronger implications. It says that if a point charge is sent through a passive structure on the same trajectory as the drive charge, also assumed to be a point charge, then the accelerated particles can gain, at most, twice the energy of the drive particles. This tends to defeat the whole concept. All wake-field schemes attempt to circumvent the theorem either by shaping the drive beam or by employing different trajectories for the drive and accelerated beams. (In addition "staging" is employed.) A measure of the degree of circumvention of the theorem is the "transformer ratio", which typically is designed for structures made of conventional materials to be 10, or so, rather than 2.

Another general theorem is the Panofsky-Wentzel theorem which relates the radial variation of the longitudinal wake (the accelerating force) to the longitudinal variation of the transverse wake (the focusing, or defocusing, force). This theorem must be carefully observed when making a structure which will provide acceleration and (only modest) focusing.

1. Copper Structures and Dielectric Structures

A wake-field transformer, of copper, and with the drive beam a circular beam and the accelerated beam on axis, as shown in Figure 3, has been developed by the DESY group. A drive beam of 6 bunches, each of 5 nC, and separated by 2 ns, resonantly excited the structure and accelerated particles. The inferred gradient was 1.2 MeV/m over 16 cm. The DESY group has plans to build a large transformer driven by 90 bunches and with a transformer ratio of 35.

The Argonne group has explored the use of a dielectric tube, which has the distinct advantage of simplicity and compactness. In Figure 4 is shown the tube used in an experiment, the measured wake, and the theoretical wake. A drive beam of 2 nC, and length 25 ps, was driven through a tube of length 50 cm with radius 1.3 cm. The dielectric, having a constant of 6, had an inner radius of 0.6 cm. The measured gradient was 0.3-0.5 MeV/m, which is in excellent agreement with the theory.

There has been controversy, over the last year, about transverse wakes in a dielectric structure, but all parties now agree in that there is a wake whose value is about the same as in a copper accelerating structure. Nevertheless, dielectric structures may be of interest. They must be resonantly excited (because the heating is excessive in regular, resonant, excitation) and hence must be employed as wake-field structures. A major concern is electric breakdown, and that remains to be studied experimentally, but it seems unlikely that a gradient in excess of a few hundred MeV/m can be attained (but that value is nevertheless of interest). A second major concern is that of transverse stability of the accelerated beam, which must be very good if micron size beams are to be brought into collision. The Argonne group has plans to build a large dielectric wake-field transformer having a transformer ratio of 1.5 and attaining 1 GeV.

2. Plasmas

Wake-fields in plasmas have been observed at Argonne where with a plasma of 30 cm length and density of 10^{13} cm^{-3}, and a beam of 5×10^{11} cm^{-3}, they measured a gradient of 5 MeV/m.

Subsequent work at KEK was done in a plasma of 2-9 x 10^{11} cm^{-3}, and length of 75 cm. Using a 5 bunch comb of 1 nC pulses separated by 10 cm, they measured an acceleration, at the last bunch, of 7 MeV/m.

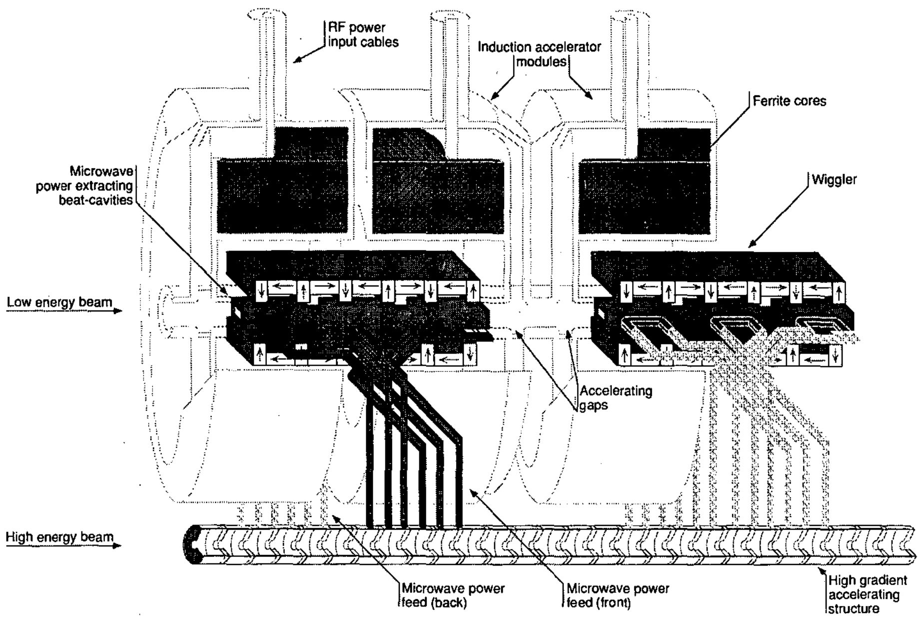

Fig. 2. Schematic of a Coupled Cavity version of the Two-Beam Accelerator with re-acceleration by induction units and microwave generation is by means of a free-electron laser. The coupling to the high gradient structure is by means of waveguides.

In order to obtain a high transformer ratio, one can contemplate drive bunches which are shaped so that the bunch intensity ramps up and then drops to zero quickly (in less than the ω_p^{-1} time). Thus plasmas give the hope of achieving very large gradients (of the order of 10 GeV/m) and transformer ratios of tens. An experiment to achieve 100 MeV, in 7 cm (gradient of 1 GeV/m) and a transformer ratio of 7, is being considered by UCLA.

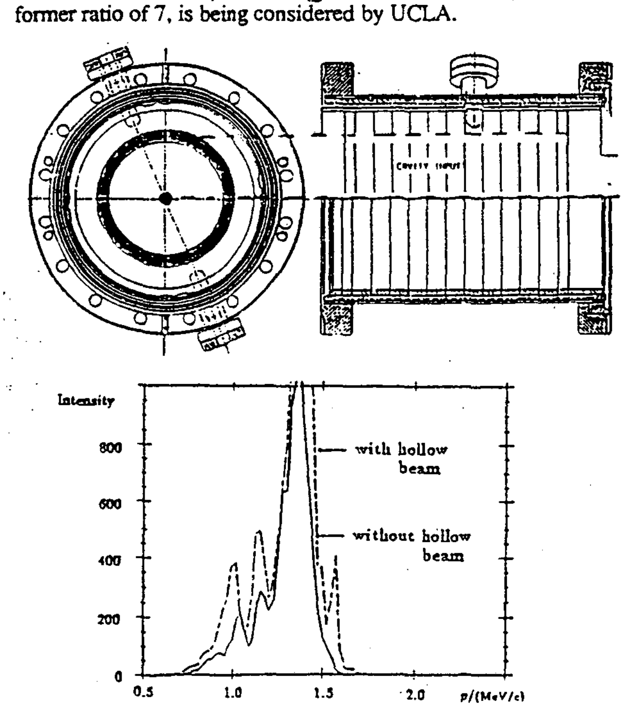

Fig. 3. The wake-field accelerator developed by the DESY group. A drive beam of 6 bunches, each of 5 nC, and separated by 2 ns, resonantly excited the structure and accelerated particles. The inferred gradient was 1.2 MeV/m over 16 cm. (Bialowons, et al 1987)

IV. Plasma Focusing

Plasma lenses, and the adiabatic focuser, both focus relativistic beams because the plasma shields out the beam's electric field. Since the electric and magnetic forces cancel, to order γ^2 in a freely propagating beam, shielding of the electric force leaves the magnetic force to focus the beam. This force can be very large; in a collider (where the beam is intense and focused to a very small radius) the resulting force is many orders of magnitude greater than can be achieved with conventional focusing elements.

At low density a plasma shields the electric forces, and not the magnetic. At high density it can shield both, which is the basis for the proposal of a plasma compensator that can reduce beamstrahlung. This idea will not be discussed here. (Item III-3)

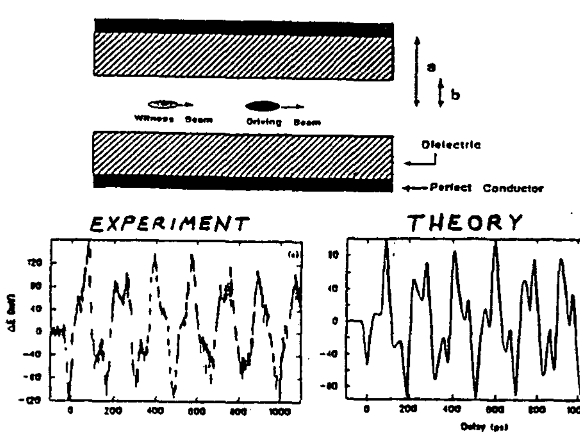

Fig. 4 . The dielectric wake-field experiment of the Argonne group. A drive beam of 2 nC, and length 25 ps, was driven through a tube of length 50 cm and a=1.3 cm, b=0.6 cm, and dielectric constant 6. The measured gradient was 0.3-0.5 MeV/m. (Gai, et al 1988)

The plasma density can either be higher than the beam density (overdense case) or lower than the beam density (underdense case). In the first case, since the beam is a perturbation, the plasma dynamics (which is the hard part of the problem) is easy. Furthermore, beams of both signs of charge experience almost the same behavior, for plasma electrons either move a bit in (so as to compensate the beam charge when the beam is positive) or they move a bit out (again to compensate the beam charge when the beam is negative). The plasma ions hardly move, since they are massive.

In the underdense case, and for a negatively charged beam, the plasma electrons get blown out of the beam, and even beyond that, so as to make a channel of ions. The motion of the plasma is clearly non-linear, and it is hard to analyze. A representation of the phenomena is shown in Figure 5. Because, in the laboratory frame, the focusing is simply due to the plasma ions, this is often called ion focusing. It has been shown, in many experiments, to be effective. Perhaps the most dramatic demonstration of ion focusing has been at Livermore, where a beam of electrons, of 10 kA, has been transported for more than 50 m.

In the underdense case the behavior of the beam very much depends upon the sign of charges in the beam. At first sight, the lens would seem not to be effective for positively charged beams, but numerical simulations show that plasma electrons are pulled in to the beam, make a very non-linear lens, but still provide some focusing.

1. Plasma Lenses

In the overdense case, the focusing from a plasma lens depends upon the beam current. Thus there are strong spherical aberrations as well as a longitudinal variation of the focusing. Both effects limit the degree of focusing possible; i.e., the beam spot size which is achievable. All in all, and especially remembering that the background will be greater in this case, an overdense plasma seems less attractive than an underdense plasma.

In the underdense case, the focusing force does not depend upon the beam density (provided, only, that the plasma channel radius is larger than the beam radius), and hence the lens has fewer aberrations. (The beam pulse must be short enough so as to avoid ion motion.) A numerical example, for the SLAC linear collider, SLC, has a lens of only 0.6 cm with a focal length of 1.0 cm. It can focus a beam of electrons, of initial radius 6 μm, down to 0.5 μm and a beam of positrons, of initial radius 6 μm, down to 1.2 μm. It produces a luminosity in excess of the design luminosity. Background is, of course, an element of the lens, but perhaps it is not excessive; i.e., detectors can be designed to operate despite the background.

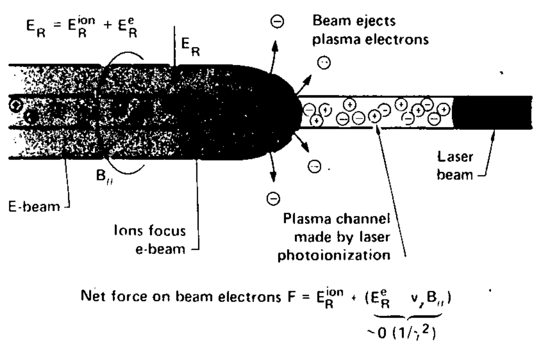

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Fig. 5. A drawing showing the behavior of a pre-ionized plasma channel down which a beam of electrons is sent. The drawing represents an underdense situation. The plasma electrons move out of the beam, forming a plasma channel inside of which the plasma ions focus the beam. The plasma focusing can be very strong.

2. Adiabatic Focuser

The adiabatic focuser is a variation of an underdense plasma lens in which the focusing is ever-increasing along the beam trajectory. This has the consequence that the beam is focused down to an ever-smaller size. In fact, the focuser is remarkably insensitive to particle energy; a consequence of the fact that the focusing is continuous. Thus it is possible to focus beams down to very small sizes; in fact sizes that are unobtainable with discrete lenses. The fact that there is a limit for discrete lenses, and evaluation of this limit, is due to Oide.

If the beam is large then, while oscillating in the adiabatic focuser, it radiates its energy away before it is compressed to a small size. If it is small enough, then it can be compressed beyond the Oide limit. The critical size is given in terms of a critical normalized emittance, which only involves fundamental constants, and is $(3^{3/2}\ 15^3\ \lambda_c)/(2^3\ 4^2\ 22\ \alpha^3)$, where λ_c is the Compton wavelength and α is the fine structure constant. Numerically the critical emittance is 6.17×10^{-6} m, which is a very attainable value. Numerical examples of adiabatic focusers have been produced, but no experiments have yet been done.

V. Conclusion

The Two-Beam Accelerator (TBA) is rather close to having "pay off". Two forms of the central elements (conversion of beam energy to microwaves) have been established, and experimental study of re-acceleration will be done in the near future. Considerable effort, both theoretical and experimental, is being put into the TBA by a number of different groups, and we can look forward to further progress.

Wake-field accelerators have been built and the central concept shown to be correct. Conventional material structures would seem to have limited applicability, although there is interest in pursuing this work in a number of places. Plasmas have considerable potentiality, but clearly the time scale is long. Further work would appear to be merited, and may be done at a number of places.

Plasma focusing devices have been studied theoretically, and shown to have considerable promise. The effect has been experimentally observed, but only as a side effect in wake-field studies. One would hope that a significant experimental program will soon be mounted so as to study the many features theoretically described, but I know of none planned. I do know of talk at LBL, UCLA, ANL, and KEK.

Finally, there are many new techniques for particle accelerators and, even a decade after formalization of the field, many old concepts still remain viable, while new concepts appear at a steady rate. It is important to note that some concepts have the suggestion of early promise, while others—requiring very much longer development—have the potentiality of significantly advancing our capabilities. We can look forward to ever-more progress as a good number of investigators (even more would be welcome) work on, and a good amount of support (of course, not enough) goes into, these activities.

I am pleased to acknowledge the work of my many colleagues upon which this review is based.

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