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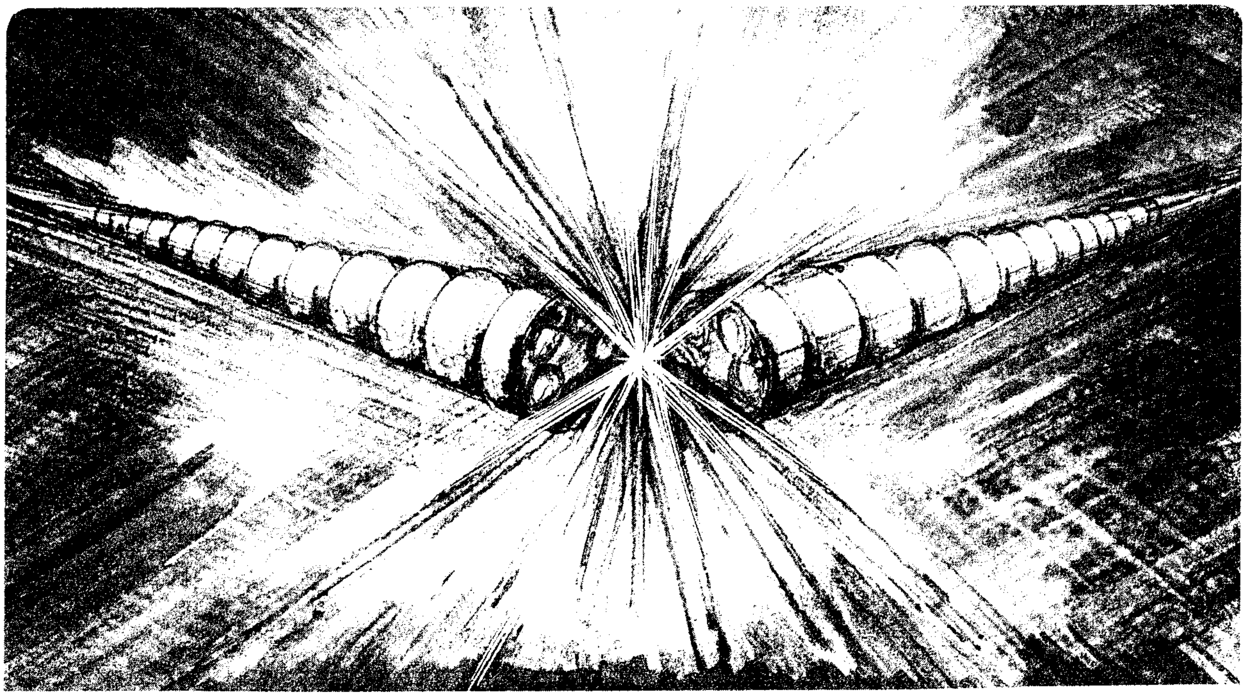

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The first thing our group did was compile the various acceleration schemes, of which we know, so that we could determine which were being covered by the other groups and which were truly "other schemes". The compilation proved useful to us and would, probably, prove useful to readers of this volume. It is presented in Table I.

Perhaps the most revealing thing that this Table discloses is the large number of particle driven schemes. This is in sharp contrast with the conference three years ago and, also, I might add, in sharp contrast with the name of this workshop. It was decided, however, to consider novel schemes; not just laser acceleration schemes.

Both lasers and particle beams are a source of high peak power, but particle beams can be an inexpensive (especially if they are of low energy and induction-accelerator-produced) source of high average power. Therefore it is most natural that the novel acceleration schemes invoke either lasers or particle beams; the necessary "trick" is to use this power; i.e. to convert the power to a proper accelerating field.

After examining the schemes listed in Table I; the group determined that they only needed to consider the various devices listed in Table II. Fortunately, invited talks (and hence invited papers for these Proceedings), contributed papers to these Proceedings, or published papers cover the schemes listed in Table II. Consequently, this summary can be brief. We shall, simply, take the schemes in the order of Table II.

1. INVERSE CHERENKOV ACCELERATOR

Employing a cylindrically symmetric configuration one finds

$$E_r \Big|_{\max} = \frac{0.582\ E_0}{\tan\theta} \quad ,$$

$$E_z\ (r=0) = E_0 \cos\psi \quad ,$$

where ψ is the phase angle. Gas breakdown limits the maximum value of E_r, which for picosecond pulse lengths in hydrogen gives maximum accelerating gradients (E_0) of up to a few GeVs/m.

A numerical example, using a large CO_2 laser ($\lambda = 10\,\mu m$) of $P = 7\times10^{13}$ W, an accelerating length of 50 meters, and a Cherenkov angle of 20 mrad (H_2 at 1.5 atmos), yields an accelerating gradient of 500 MeV/m and a net energy increase of 25 GeV. If this were

Table I Novel Accelerator Concepts

1. Plasma Accelerators (Beat-Wave, Surfatron)
    a. Laser excited (L)
    b. Particle beam excited (PB)
2. Inverse Cherenkov Accelerator (L)
3. Inverse Free Electron Lasers (L)
    a. Regular kind
    b. Gas loaded
    c. Two-wave
    d. Three-wave, etc.
4. Droplets, Gratings, Open Structures
    a. Laser excited (L)
    b. Transverse Electron Resonance Accelerator (PB)
5. Plasma Focus (L)
6. Two-Beam Accelerator (PB)
7. Wake-Field Accelerator (PB)
    a. Electron ring excited
    b. Electron beam excited
    c. Photon beam excited
    d. Intense electron beam (plus laser) excited
    e. Radial implosion of electrons
    f. Photo diode initiated pulse
8. Improved Power Sources (PB)
9. Periodic Plasma Waveguides
10. Collective Accelerators (PB)
    a. Ionization - Front Accelerator
    b. Moving Potential Well Accelerator
11. Laser Focusing Schemes (L)

employed as an "after burner" at the Stanford Linear Accelerator Center (SLAC) it would raise the beam energy from 50 GeV to 75 GeV while increasing the emittance (due to gas scattering) by 10^{-5} mrad. (The present SLC emittance is 3×10^{-5} mrad. The gas scattering effect, while not negligible, is acceptable.) More details can be found in Ref. 1.

Table II Devices Considered By The Other Schemes Group

1. Inverse Cherenkov Accelerator (Fontana)
2. Three-Wave Accelerator (Abedi)
3. Transverse Electron Resonance Accelerator (Csonka)
4. Plasma Focus (Hora)
5. Radial Implosion Accelerator (Channell)
6. Laser Focusing (Channell)

2. THE THREE-WAVE ACCELERATOR

It has been observed by Abedi that the Two-Wave Accelerator (where the static field wiggler is replaced with an electromagnetic wave and the other wave is the accelerating beam) can be improved by employing three waves.[2] Two of the waves play the role previously played by the wiggler; i.e. they produce a dynamical wiggler.

If we compare a Two-Wave Accelerator and a Three-Wave Accelerator we see that the two waves which produce the wiggle motion in the Three-Wave Accelerator can constructively interfere and, hence, produce twice the gradient. If we look at the energy efficiency; i.e. how much gradient one gets for a given amount of wave power, then one can show that the Three-Wave Accelerator is $\sqrt{2}$ times as efficient as a Two-Wave Accelerator.

3. TRANSVERSE ELECTRON RESONANCE ACCELERATOR

A near-field accelerator has the advantage, in comparison with a plasma accelerator, that the longitudinal, or accelerating, field can be of the order of the transverse field (E_T) in the laser beam (ω_0). Thus very high accelerating fields can be obtained rather than $(\omega_p/\omega_0)\ E_T$ as in a plasma accelerator (which could nevertheless be adequately large).

To accomplish this one needs to have microstructures of the order of a wavelength (λ) in size and to be within λ of them with the accelerated particles. Such small dimensions and high laser power (needed for the large gradient) bring up the questions of the size of beams and the integrity of the microstructures in this environment. Closing our eyes to these practical questions, for we are firstly interested in matters of principle, we see that an accelerator can be envisioned which has small microstructures of solid density spaced longitudinally so that there is an accelerating wave propagating along them.

Such a device has been proposed by P. Csonka,[3] with the added features that he proposes the microstructures be excited by a particle beam and that the excitation be resonant. In this case one can "build up" very large fields, much larger fields than in the laser itself. One needs a resonance between the plasma frequency (ω_p) and the frequency of the exciting microbunches (ω_0).

Csonka has proposed generating the microbunches by a free electron laser (FEL) or a transverse optical klystron (TOK). The advantage of particle beam excitation, besides that of decreased capital cost and increased efficiency of producing the requisite power, is that a focusing (quadrupole) mode can be excited rather than a dipole mode (as would be generated by a laser).

A numerical example[3] with microbunches, of length 10 μm, radius 10 μm, and containing 10^9 electrons, would excite microstructures to 10 GeV/m even if there is no resonant excitation. With resonant excitation the gradient becomes correspondingly larger.

Of course, many questions need to be addressed such as: 1) How small can one make microbunches? 2) How close to the microstructures can one send them? 3) At what value do various non-linear effects saturate the resonant excitation? The concept does appear, however, to merit further study.

4. PLASMA FOCUS

It is well-known that when a powerful laser is shown onto a slab of material the laser light is self-focused down to a waist which is very small. It has been observed, at Los Alamos National Laboratory (LANL), that electrons are produced with energies greater than 50 keV and that ions are produced with energies greater than 100 MeV and that the energy of these ions is proportional to their atomic number.

Theoretical explanation of these facts have been given by Hora and co-workers.[4] In fact, even as early as at the first Workshop, Hora emphasized that plasma foci of laser light could be employed t accelerate particles and that this effect was most interesting for the acceleration of ions.

The theoretical explanation proceeds from a two-fluid hydrodynamic code in which charge neutrality is <u>not</u> assumed. (Clearly, it is necessary to remove this usual assumption if one is interested in studying accelerating electric fields.) The analysis predicts two interesting, and important, features. Firstly there are density depressions, named cavitons, which are extensive in length (100 optical wavelengths) and; secondly there is significant charge separation, called a double layer, which is actually inverted in sign from what one might expect. The combination leads to high fields over large distances; i.e. to significant acceleration.

On the basis of this theory, which agrees with the present experiments, Hora has predicted that a powerful CO_2 laser (2×10^{14}W) with a short rise-time (150 psec) will accelerate an ion with Z=50 to 30 GeV (an energy of 600 MeV/nucleon). In this case the caviton is 100 laser wavelengths, i.e. 0.1 cm in length, and the longitudinal accelerating field is 3×10^7 MeV/m. Furthermore, it appears possible to stage this acceleration many times.

Experiments using the Antares laser, whose pulse length is longer than 150 psec, can be expected in the near future. They will be most important for the Plasma Focus Accelerator.

5. RADIAL IMPLOSION ACCELERATOR

It was observed, by Channell, that a gradient of 3 GeV/m is "equivalent" to a magnetic field of 100 kG; and that such a field can be made available for acceleration if a magnetic field of this magnitude is changed with a velocity approaching that of light.[5] Of course, moving a magnetic field is the basis for all accelerators (except the DC machines), so this concept is readily accepted by accelerator physicists.

The proposal is to use an axial current to make an azimuthal magnetic field which then is imploded by means of an intense radial current. The result is an axial electric field, the accelerating field. Rough estimates,[5] obtained from a snow-plow model, show that a radial current, of electrons of 10 MeV, of 160 kA/cm^2 is needed. This is about the magnitude of current densities obtained in the light ion inertial fusion program at Sandia and so appears attainable with present technology.

Of course the concept, which is quite new, needs further theoretical study. Questions which need to be studied include: 1) How stable is the implosion? 2) How is the magnetic field initiated? 3) What is the wall damage? Perhaps the first question is the most important, for the proposal seems to be subject to 2-D Rayleigh-Taylor instabilities (heavy electrons on top of light magnetic field). The second question also needs to be addressed; perhaps an electron beam (axially directed) is used to set-up the azimuthal magnetic field.

The scheme, if it can be made into a practical accelerator, seems to offer a number of advantages. Perhaps paramount, is the fact that the use of induction accelerated electrons as the main power source suggests a high efficiency for the device. Also, because the scheme is non-resonant it should be good for accelerating low velocity particles and it should be rather easy to stage accelerating sections.

6. LASER FOCUSING

The necessity for high luminosity in linear colliders was emphasized at this workshop. To achieve this requires large beam power, and consequently very efficient accelerators (so as to keep the demand for average power, and hence the operating costs, within bound), or it requires very small beams at the crossing point. To achieve the latter requires a tight focus; i.e. a powerful lens with small aberrations (both chromatic and spherical). It also requires adequate control of the beam position.

It was pointed out, by Channell,[6] that a laser beam can be employed to give very strong focusing. In a vacuum, as is well-known, the electric and magnetic forces of the light beam, upon a particle, just cancel. In a gas this cancellation no longer occurs but now the changed velocity of the light wave implies that after some distance the light and the particles will be out of phase. Thus, the device must be of finite, and appropriate, length.

Of course, some particles will have a phase relative to the laser light such that they are defocused, while others will have a phase such that they are focused. Channell proposes having two lenses, separated by 180° (plus a large number of 360° phase changes), so as to produce net AG focusing. (Measuring, and correcting, relative phase is quite within present capability.)

Channell has produced a numerical example, employing a laser of only 10^{10}W, a gas pressure of 10 atmos, a waist size of 0.2 mm, and a length of 0.6 cm. The focal length, for a 50 GeV particle, is 30 m and corresponds to an equivalent gradient of 90 kG/cm (for a magnet of the same longitudinal extent).

A different configuration, namely a cylindrical configuration such as he has developed for the Inverse Cherenkov Accelerator, has been proposed by Fontana. The focal length of a lens of length L, for a particle with relativistic factor γ, subject to laser light of wavelength λ and power P is given by

$$f \simeq (2.5 \times 10^3) \frac{\gamma\lambda^{3/2}}{\theta^3 L^{1/2} P^{1/2}} ,$$

where θ is the Cherenkov angle and all quantities are in MKS units. If, for example, we have hydrogen at 10 atmos (θ=52 mrad), $\lambda = 10^{-5}$m (CO_2 laser), $\gamma = 10^5$ (50 GeV), L=1 cm, and P=10^{10}W then f=5.3 meters.

The advantages of these laser focusing schemes is the high field gradient which can be achieved, with even a modestly sized laser, and the fast accurate control of the focusing. The speed with which the focusing can be turned on or off should prove most useful to linear collider designers and linear collider users. If the field breakdown of the gas can be increased, or even exceeded, without degrading the lens, then really high focusing gradients can be achieved.

7. CONCLUSIONS

The working group came to the following conclusions:

a. None of the schemes is revolutionary; i.e. changes drastically what we think or what we are doing.

b. Experimental work will be done which will be relevant to the Plasma Focus Accelerator, but no work is being done on any of the other ideas.

c. More theoretical work is needed on the Radial Implosion Accelerator and Laser Focusing concept before experimental work is initiated.

d. The Inverse Cherenkov Accelerator is ready for further experimental study and such study would teach one about high-power laser optics and gas media behavior under high fields. (When does it break down, and is breakdown in the form of a ring of fire bad for acceleration along the axis?)

e. The development of focusing schemes looks like an area in which more effort will pay off. These are not laser, or even novel, accelerators, but could be important for attaining a high-luminosity, high-energy collider.

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