LBL-16483

CONF - 830822--23

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion
Research Division

LBL--16483

DE83 017747

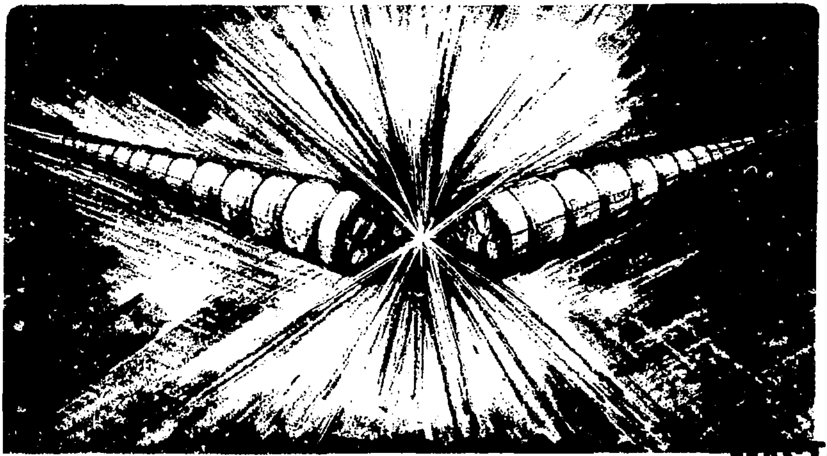
Presented at the 12th International Conference on High-Energy Accelerators, Fermi National Accelerator Laboratory, Batavia, IL, August 11-16, 1983

NEW CONCEPTS IN PARTICLE ACCELERATION

A.M. Sessler

August 1983

NOTICE
PORTIONS OF THIS REPORT ARE ILLEGIBLE.
It has been reproduced from the best available copy to permit the broadest possible availability.



MASTER

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

LBL-16483

NEW CONCEPTS IN PARTICLE ACCELERATION*

Andrew M. Sessler
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
August 8, 1983

I. Introduction

At the First International Conference on High Energy Accelerators, in 1956, there were a number of papers on the subject of novel -- or "far-out" -- schemes for the acceleration of particles.[1] Interest in novel schemes has persisted through the years, for all of us realize that the continued development of high energy particle accelerators demands the development, to practicality, of new technologies. In fact, it takes but a glance at the famous (updated) Livingston curve to see that the continued progress in time, especially in proton accelerators, is given by the envelope of curves corresponding to different technologies.[2]

Progress in the attainment of ever-higher energies, in the next decades, will depend upon the continued development of the newer technologies which are presently employed in accelerators. I think, for example, of superconductivity or stochastic cooling: Both of these technologies still have lots of room for improvements and these improvements will, surely, be made in the years to come.

Looking beyond the next decades, in fact into the next century, the view of course gets somewhat obscured. Yet all of us would agree that it is likely that new, good ideas will come along. In fact, such new concepts are essential if we are to remain on the Livingston curve, or anywhere near that curve.

It is my task to report to you on some of the fledgling ideas which might lead to practical accelerators in the next century. As I have already noted, and now want to emphasize, one's view of the next century is very clouded. Yet, we need to have a picture of where we are going, even if that picture is hazy, so that we may know upon what to work, and, much more practically, so as to ascertain what is meritorious of support.

As I look at the various proposed new concepts, most of them, quite naturally, seem hard to take seriously. Especially is this so when they are compared to the large complexes at CERN, Fermilab, or SLAC. But we know that from small table-top experiments can come very big and reliable devices. Size, alone, and even reliability are not valid criteria by which one can judge new concepts.

What criteria should one employ? Certainly "potentiality" is one. Concepts which have no potentiality for a very high energy accelerator can be eliminated as being of little interest. Similarly, because the cross sections for interesting reactions fall rapidly with increasing energy, concepts which are limited in the beam current which they can accelerate can also be eliminated.

A second criterion is "practicality." Concepts which require unreasonably tight mechanical tolerances, or clearly will result in unreasonably expensive devices, can be eliminated.

Some concepts, while not suitable for a high-energy accelerator, can be viewed as stepping stones along the way to a practical device. Thus, the concepts could lead to the familiarization of physicists with a technology which might be expected to some day be relevant to high-energy accelerators. I think, for example, of concepts which employ lasers.

What, then, do I see as new concepts which merit serious attention? Obviously, each person will see different ones worthy of pursuit, but perhaps you will allow me to focus upon those concepts which, in my judgement, are interesting.

Amongst the myriad of novel concepts, I would pick four which appear particularly attractive to me. They are the Wake-Field Accelerator[3], the Two-Beam Accelerator[4], the Inverse Free Electron Laser[5], and the Laser Plasma Wave Accelerator.[6] Let me hasten to add that I have probably not included the best concept, and, maybe, none of these concepts will lead to practical accelerators. But remember I have been asked to look very far into the next century. The view is murky, but this is what I see. With the clear understanding that my choices are not meant to be exhaustive, i.e., are not to be used to eliminate other concepts, let me speak positively about these four concepts.

The first two concepts, the Wake-Field Accelerator and the Two-Beam Accelerator, are both two-beam accelerators, in that they employ a relativistic beam as an integral part of the accelerator and as an intermediary to the beam which one is accelerating to very high energy. I think that the next large jump in accelerator capability will be to employ external fields to manipulate a first beam which then accelerates a second beam of particles. That is why I chose to focus your attention on these devices. Collective accelerators, of course, fall into this class of devices. None of them has yet led to a practical high energy machine, and, in my opinion, it seems doubtful that those proposed so far will lead to such a device. In contrast, the two devices that I wish to discuss appear likely to lead to practical devices. They both are, as you will see, easier to achieve than any of the collective accelerators proposed so far, in that the two beams are kept quite separate from each other. Maybe this separation is a first step towards more complicated, but more advantageous schemes.

The Inverse Free Electron Laser Accelerator I single out because it combines complicated and sophisticated particle handling (in the wiggler) with laser acceleration. Perhaps other laser accelerators will prove to be more advantageous than this one, but development of the Inverse Free

---

* This work was supported by the U.S. Department of Energy under contract No. DE-AC03-76SF0009

Electron Laser will teach us a great deal about laser beam manipulation and, even, about building lasers especially for particle accelerators. I think that laser accelerators demand our attention and this accelerator, perhaps more than others, would seem to be a good device upon which to put one's effort.

Finally, I call your attention to the Laser Plasma Wave Accelerator because it has tremendous potentiality. It is also the "most difficult" of the various concepts which I want to discuss. "Accelerator physics is hard enough, we don't need to add to our problems those of plasmas (which are notoriously unstable)", is a statement often made by accelerator physicists. Yet, it is just plasmas which can give the very large fields which accelerator physicists seek. Collective accelerators are usually plasma accelerators and we have not yet been able to make them work in a practical device. The Laser Plasma Wave Accelerator is also a collective accelerator, but it employs a laser to "organize" the plasma motion. Thus, perhaps, it will prove easier to realize than some of the other collective schemes. In any case, I wanted to focus your thoughts upon this device for it involves the interesting physics of highly non-linear plasma motion and laser interaction with plasma which are basic to this concept and would appear to be an essential ingredient of any concept which produces really large acceleration gradients.

II. The Wake-Field Accelerator

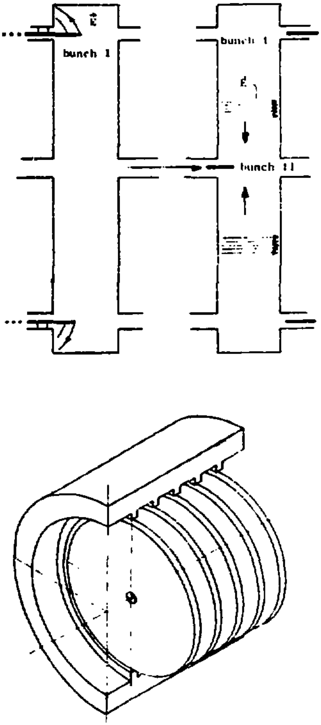
The Wake-Field Accelerator was invented by Gus Voss and Tom Weiland, no doubt as an outgrowth of their study of the deleterious effects of wakes in electron storage rings.[3] Their recent work is described in a contribution to this conference and they are currently planning to perform an experiment.[7]

Of the four concepts which I want to discuss, this is, by far, the simplest. Of course "simplicity" is not a criticism of the concept; in fact, perhaps it is just the opposite for the Wake-Field Accelerator looks as if it can be made to work, and, furthermore, it appears capable of achieving gradients of (say) 500 MeV/m. This is considerably greater than the (proposed) gradient in present-generation machines; namely, the SLC with its 17 MeV/m, and is probably adequately great for the next generation of machines or even for the generation beyond that.

When a bunch of charged particles passes through a structure of varying shape then it will excite a wake electromagnetic field whose shape is not necessarily that of the charge bunch. This phenomena is well-known and well-understood; it has been calculated (usually for cylindrical structures) and measured experimentally, and the two approaches agree.

Particles inside or behind the bunch feel a longitudinal electric field whose integral over time, for fixed position relative to the bunch, is called the wake potential. Particles near the front of the bunch are deaccelerated, but those behind the bunch, generally, are accelerated. Unfortunately, this wake potential is usually not large enough to make a practical accelerator.

However, one can make -- really in a variety of ways -- a wake potential transformer; i.e., a device in which a low energy high current beam creates a very high gradient at some other position. Such a possible configuration is shown in Fig. 1 and the result one would obtain with such a structure, as determined by calculation, is shown in Fig. 2. The parameters which one might have in such an accelerator are given in Table 1, and a possible collider, employing a Wake-Field Accelerator, is shown in Fig. 3.

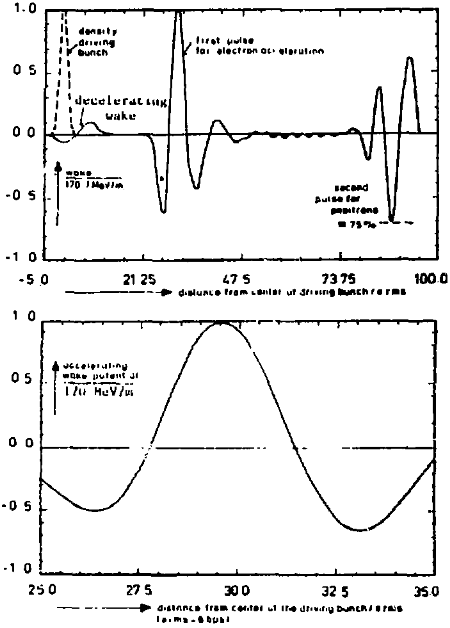


XBL 838-10919

Fig. 1. a) A Wake-Field Accelerator consisting of a cylindrically symmetric pill box with a central hole for the high energy beam and an outer ring for the low energy beam; b) a conceptual view of a possible realization of the Wake-Field Accelerator. Each subsection is one of the pill boxes shown in Fig. (1a). (From Ref. 3).

- - - - -

Clearly, one can employ other transformer geometry than the cylindrical geometry discussed here, and the interested reader is referred to the papers by Voss and Weiland. Almost surely, the best geometry is not that which has been presented in this first example. In addition, one can readily imagine using, for the low-energy beam, electron rings as they have already been achieved. If this



XBL 838-10920

Fig. 2. a) Results of a numerical calculation for the geometry of Fig. 1. The outer radius is 6.0 cm and the central hole has a radius of 0.2 cm. The pill boxes are separated by a plenum of 0.05 cm and are 0.4 cm wide. The beam parameters are given in Table 1; b) A magnified view of the accelerating pulse of Fig. 3a. (From Ref. 3).

-----

is done, one can see one's way to gradients of 500 MeV/m or greater.

Now, of course, one must go much more deeply into the subject. For example, one must study beam dynamics. Is the low energy beam stable transversely (even when immersed in a strong solenoidal magnetic field)? What about longitudinally? Note that in this example the low-energy bunch is taken to be a Gaussian with a width of only 6.6 psec. What will be the effect of the self-wake upon the low-energy bunch? What about the effect of the wake of the high-energy bunch upon the low-energy bunch?

The analagous studies must be made of the high-energy beam. Here the situation is more complicated for the high-energy beam is driven by the low-energy beam. Thus, for example, one must be concerned by the transverse wake effect of a (slightly) displaced low-energy beam.

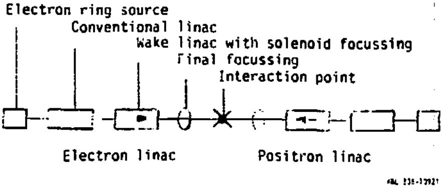


Fig. 3. Layout of a 50 GeV x 50 GeV collider Wake-Field Accelerator (from Ref. 3).

Table 1. Possible parameters of 50 GeV x 50 GeV Wake-Field Accelerator collider.

Nominal particle energy	50 GeV
Total length of the electron linac	550 m
Total length of the positron linac	650 m
Gradient of the conventional linac	25 MeV/m
Gradient in the wake field transformer	170 MeV/m
Average power consumption	8+8 MW
Peak power	3900 MW
Number of high energy particles per bunch	10^{11}
Number of particles in the driving bunch	$6x10^{12}$
Efficiency of the wake transformer	16
Repetition frequency	100 Hz
r.m.s. bunch length of both beams	0.2 cm
Wake-Field transformation gain	10.2
DRIVING BEAM:	
Number of particles	$6x10^{12}$
Energy at the entrance of the wake trasnf.	5.5 GeV
Energy at the end of the wake transf.	0.5 GeV
Maximum phase slip between driving beam and accelerated beam	0.5 ps
Maximum particle energy loss (self fields)	1.8 MeV/m
Peak transverse momentum kick per unit length due to elf fields	6.9 keV/mc
Solenoid field strength	7 T
Maximum particle deviation for a constant beam misalignment of $\delta = 100\ \mu m$	1 mm
HIGH ENERGY BEAM:	
Number of particles	10^{11}
Maximum particle energy loss (self fields)	15.2 MeV/m
Peak transverse momentum kick per unit length due to self fields	18.9 keV/m

Suffice it to say, in this review article, that Voss and Weiland have been studying these questions and are still optimistic about achieving a practical Wake-Field Accelerator.

III. The Two-Beam Accelerator

The Two-Beam Accelerator was invented by Andrew Sessler.[4] The idea has not been taken up by anyone else nor has he worked on it beyond that which he described in the original paper, one and a half years ago, which may say something about the significance of the concept or the funding situation, or both.

The reader will please indulge me; clearly I am prejudiced, in devoting a section to this concept, but I feel it is a new concept worthy of calling to your attention.

The Two-Beam Accelerator has a high-gradient structure which is a conventional linac, perhaps disk loaded, operating at a higher frequency than present linacs by (about) an order of magnitude. At this high frequency, near 30 GHz, one should easily be able to obtain gradients of many hundreds of MeV/m. It is also true that the energy stored in the structure, for given gradient, goes down as the inverse power squared of the frequency and hence becomes within the realm of possibility in a very high-energy collider such as 300 GeV x 300 GeV.

In this frequency range there are no adequate high-peak-power sources except, possibly, a free electron laser (FEL). The Two-Beam Accelerator employs a FEL which is powered by an intense low-energy beam. A schematic of such a configuration is shown in Fig. 4.

An FEL as a high-peak-power source has yet to be demonstrated although experimental work at the Naval Research Laboratory and at the Lawrence Livermore Laboratory suggest that such an FEL can be constructed. Of course, it is a long way from these single-pass FEL's to a steady-state FEL, but I believe it is correct to think that a high-efficiency, single-pass FEL is at the heart of the idea and that a Two-Beam Accelerator can be made to work, but perhaps not economically, if an FEL can be made to work as predicted.

Possible parameters for a Two-Beam Accelerator are given in Table II and a block diagram of a 375 GeV x 375 GeV collider is shown in Fig. 5.

Like the Wake-Field accelerator, the Two-Beam Accelerator is a power transforming device in which the low-energy beam is an intermediary. Presently, linacs employ klystrons which have electron beams; the Two-Beam Accelerator takes the klystrons to higher energy (a direction in which they have been steadily moving) and combines them so that only one electron beam is employed throughout the accelerator. Thus the power flow is from the power lines to an induction linac, to a low-energy beam, to radiation (via a wiggler), to the high-gradient structure, and then finally to the high-energy particles for which the whole device is constructed.

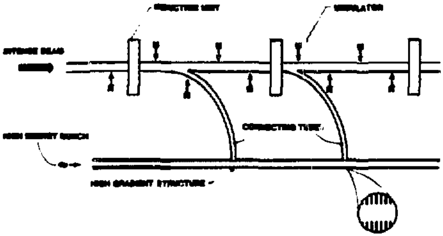
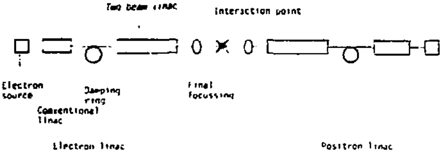


Fig. 4. A conceptual design of a Two-Beam Accelerator showing, symbolically, a steady state FEL with its high current beam and the high-gradient structure which accelerates particles to very high energies.

Table 2. Possible parameters of 375 GeV x 375 GeV Two-Beam Accelerator collider.

Nominal particle energy	375 GeV
Total length of the electron linac	2.0 km
Gradient of the conventional linac	25 MeV/m
Gradient in the Two-Beam Accelerator	250 MeV/m
Average power consumption	150 Mw+150 Mw
Overall efficiency	8%
Repetition rate	1 kHz
Energy of driving beam	3 MeV
Driving beam length	25 nsec
Driving beam current	1 kA
Number of high-energy particles	10^{11}
Length of high-energy bunch	1 mm
Focal length in high-gradient structure	10 m
Crossing point β	1.04 cm
Disruption parameter	0.9
Bremstrahlung parameter	0.05
Luminosity	$4x10^{32} cm^{-2} sec^{-1}$



XBL 838-10922

Fig. 5. Layout of a 375 GeV x 375 GeV collider Two-Beam Accelerator. With a gradient of 250 ~~MeV/m~~ the total length is about 5 km.

- - - - -

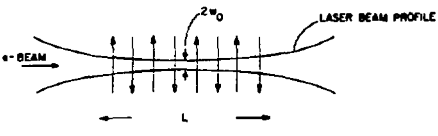
There are many questions which need to be answered such as how does one fabricate such a small high-gradient structure and how does one prevent it from breaking down? Or, how does one construct a steady-state FEL and with what efficiency can one transmit microwave power from the FEL to the high-gradient structure? These are also beam-dynamic questions such as how does one keep the transverse wake field, which will distort a bunch along its length and hence reduce the luminosity when micron-size bunches collide, to a manageable level. Suffice it to say that at least on a preliminary look the Two-Beam Accelerator appears to be attractive and not to have any "fatal flaws."

IV. The Inverse Free Electron Laser Accelerator

The Inverse Free Electron Laser Accelerator could be simply a Free Electron laser (FEL) run backwards.[5] This device can be quite powerful, as was first emphasized by Philip Sprangle and then carried further by Claudio Pellegrini.[8]

Alternatively, and perhaps even more simply, a longitudinal magnetic field is all that is needed, as was pointed out, a very long time ago, by Andrew Kolomenski and Andre Lebedev.[9,10]

In the FEL case one can rather directly design a single-pass accelerator employing, for this purpose,



XBL 833-8516

Fig. 6. A schematic representation of a single stage Inverse Free Electron Laser Accelerator. From Ref. 5, p. 151).

- - - - -

the equations governing an FEL. (See the treatment by P. Morton in these Proceedings.) In doing this one must be sure, for example, that the electron beam is always smaller than the laser beam. The latter has, for a Gaussian beam, its propagation characterized by a Rayleigh range, R; i.e.,

$$r(z) = \left(\frac{\lambda R}{\pi}\right)^{1/2} \left[1 + \left(\frac{z}{R}\right)^2\right]^{1/2} \tag{4.1}$$

where $r(z)$ is the laser beam radius at longitudinal position z, and λ is the wavelength of the light. Thus a small spot size at the focus ($z=0$) will inevitably lead to a wide beam at other positions. But a small beam size is necessary to obtain the very large laser electric fields needed for effective acceleration.

Nevertheless, it is possible to combine these facts and still obtain significant acceleration as is shown in Table III and Fig. 6. The choice exhibited in this table is a result of matching the wiggler *resonance condition with the particle* energy in two different ways. The resonance condition is:

$$\lambda = \frac{\lambda_0}{2\gamma^2}\left[1 + \left(\frac{e\, B_0 \lambda_0}{2\pi\, m_0 c^2}\right)^2\right], \tag{4.2}$$

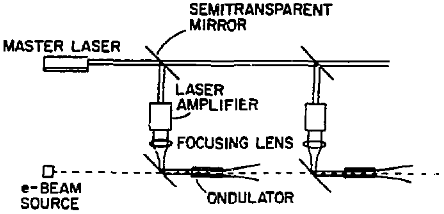
where λ_0 is the wavelength of the wiggler, B_0 is the wiggler peak field, and λ is the laser wavelength as above.

In order to make a high-energy accelerator one needs many stages of acceleration. This could be accomplished as indicated in Fig. 7, but the cost of so many laser amplifiers would be very high. Alternatively, it should be possible to refocus the laser light periodically so that it can be "used" over and over again. Assuming this can be done, a subject we return to below, one can, as Pellegrini has, derive parameters for a high-energy collider. Possible parameters are set out in Table 4 and it *can be seen that an Inverse Free Electron Laser* makes a very interesting machine.

The periodic focusing (period from 4 cm to 4 m) beams of 5 x 10^{13} watts for distance of 3 km is the major problem which faces this concept. A number *of possible approaches were considered in the* Workshop on Laser Acceleration of Particles.[5] Pellegrini has considered an over-moded metalic wave guide.[8] Experimental work is needed so as to ascertain just how difficult is the transport of laser beams.

Table 3. Possible parameters of a single-stage *Inverse Free Electron Accelerator. The two columns* refer to the case in which the wavelength of the wiggler is constant or the peak magnetic field of the wiggler is constant.

	λ_0 = 10 cm	B_0 = 1 T
LASER PARAMETERS		
Power	2×10^{13}W	2×10^{13}W
Pulse duration	1 ns	1 ns
Spot size	0.25 cm	0.25 cm
Wavelength	1 μm	1 μm
Electric field	2.8×10^{10}v/m	2.8×10^{10}v/m
Interaction length	39 m	39 m
UNDULATOR PARAMETERS		
Period	10 cm	3.8 ▸ 23 cm
Magnetic field	0.3 ▸ 3.8 T	1 T
Synchronous phase	π/3	π/3
ELECTRON BEAM PARAMETERS		
Energy	250 Mev> 4.2 GeV	250 MeV ▸ 3.8 GeV
Current	<5 KA	<5 KA
Beam radius	0.2	0.2 cm
Average accelerating field	101 MeV/m	90 MeV/m
Oscillation amplitude	0.007 cm	10^{-2}cm
Energy spread	10^{-4}	10^{-4}
Synchrotron radiation loss at γ_f	300 keV/m	20 KeV/m



XBL 833-8517

Fig. 7. Multi-staging of an Inverse Free Electron Laser Accelerator in which many laser amplifiers are employed (from Ref. 5, p. 152).

- - - - -

Besides the transport and repeated focussing of laser beams, this concept requires high-repetition rate lasers (1600 Hz vs one or two shots a day), efficient lasers (say 20% vs several percent), and good beam quality at a high power level (coherence length of kilometers vs meters). It should be noted, however, that high-powered lasers have been developed for laser inertial fusion and not for laser accelerators. So one can expect some progress, but whether enough progress is unclear.

Table 4. Possible parameters of 300 GeV x 300 GeV Inverse Free Electron Collider.

Laser wavelength	1 μm
Laser power	50 Tw
Synchronous phase, sin ϕ_0	.866
Laser electric field	0.22 TV/M
Waist radius	0.7 mm
Electron energy, input	250 MeV
Undulator initial period	3.8 cm
Undulator field	1.0 T
Initial helix radius	0.04 mm
Accelerator length	3 km
Electron energy, final	294 GeV
Average acceleration gradient	98 MeV/m
Final helix radius	0.5 m
Final undulator period	4.3 m
Crossing point β	1.0 cm
Disruption parameter	10
Number of particles per bunch	4.2×10^{10}
Repetition rate	1.6 kHz
Luminosity	10^{32} cm^{-2}s^{-1}
Laser energy per pulse	10 kJ
Average power (η=10%)	320 Mw

One interesting possibility is to generate the laser light by means of an FEL. For this purpose, one could employ an intense low energy beam and thus one is, again, envisioning a two-beam accelerator. (Note, however, that the efficient generation of high-power 1 μm radiation appears to be more difficult than the generation of 1 cm radiation.) The use of a permanent magnet wiggler and an induction linac should allow achievement of an efficiency greater than 20%.

V. The Laser Plasma Wave Accelerator

The idea of using a laser to generate a density wave in a plasma which could then be employed (because of its longitudinal field) to accelerate particles was due to Toshi Tajima and John Dawson.[11,12] Subsequently, they proposed using two laser beams to make a beat wave and hence to increase the conversion efficiency from laser energy to plasma wave energy.[6] A further refinement -- a very important improvement by Katsouleas and Dawson -- is to add a transverse field so as to maintain synchronism between the accelerated particles and the laser beams.[6]

This concept has been studied experimentally, by Joshi, Tajima, Dawson, Baldis, and Ebrahim.[13,14] In fact, at least three groups are pursuing experimental studies; namely the California group (UCLA), the New Mexico group (LANL), and the Canadian group (NRC).[15]

Because the phenomena is highly non-linear, it proves impossible to study the plasma motion, in adequate detail, purely analytically. Thus one must resort to numerical simulations. This has been done by the UCLA group, as well as Sullivan and Godfrey.[6,16]

Finally, by way of describing the literature, the reader may find the "accelerator physics" approach of Ruth and Chao very useful, and the recent review by Lawson of value.[17,18]

In this concept, two laser beams, of frequency ω_0 and ω_1, are fired into a plasma and produce a beat wave. If the plasma is underdense; i.e.,

$$\omega_0, \omega_1 >> \omega_p = (\frac{4\pi ne^2}{m})^{1/2} \qquad (5.1)$$

where n is the plasma density, then the laser waves (k_0, ω_0), will propagate (i.e., not damp) in the plasma with the dispersion relation

$$\omega_0^2 = \omega_p^2 + c^2 k_0^2 \qquad (5.2)$$

where k_0 is the wave vector of the laser light.

For a plasma wave (k, ω) the dispersion relation is:

$$\omega^2 = \omega_p^2 + 3 k^2 (\frac{KT}{m}) \qquad (5.3)$$

where KT is the plasma temperature (in energy units).

It is not difficult to show that the beat wave will have a phase velocity v_π, and a group velocity, v_ϕ:

$$v_\phi \approx v_g \approx c(1 - \frac{\omega_p^2}{\omega_0^2})^{1/2} \qquad (5.4)$$

provided $\omega_0 - \omega_1 = \omega_p$ and KT is not too large. This is shown in Fig. 8.

Because there is synchronism between the beat wave and the plasma wave, the density modulations of the plasma, which is precisely what a plasma wave is, will resonantly grow. Just how large this wave will become and to what extent harmonics will develop is a non-linear problem which can only adequately be attacked by numerical methods. If the bunching is complete (100%) then the resulting longitudinal gradient is

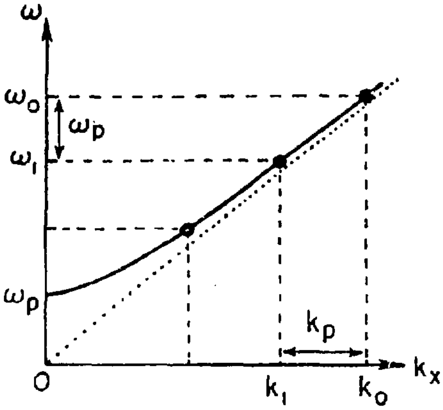
$$eE_L = \frac{m\omega_p c}{e} = (2\pi\ n\ r_0^3)^{1/2} (\frac{mc^2}{r_0}), \qquad (5.5)$$

where $r_0 = e^2/mc^2$ is the classical electron radius and $(m\ c^2/r_0) = 1.8 \times 10^{14}$ MeV/m.

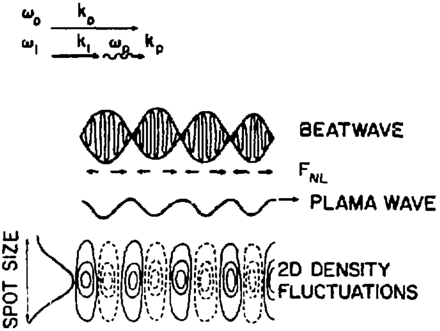
Particle simulation studies, so far limited to one dimensional studies, have been extensively made of this resonant process. Figure 9 shows one result of Sullivan and Godfrey. The plasma can develop harmonics and (unwanted) plasma electrons can be accelerated to considerable energy. These two undesirable effects are shown in Fig. 10 which was obtained by Mori, Joshi and Dawson.

Experimentally, particles of 1.4 MeV have been observed.[13] Higher energy particles, 10 MeV electrons, have also been observed by the Canadian group.[15] These observations have been taken as a confirmation of the theoretical picture sketched above.

The beat-wave-plasma effect appears to be useful for making a particle accelerator. Probably one would want to inject particles which are to be accelerated and arrange things so that plasma electrons are not "captured" by the moving buckets of the density wave. Also, probably, one cannot produce the 100% bunching of Eq. (5.5), but (say)



XBL 838-10917



XBL 838-10918

Figure 8. a) Diagram showing the dispersion relation for electromagnetic waves (laser light) of frequency ω_0 and ω_1. (From Ref. 8 p. 174); b) Resonant excitation of a plasma density wave showing its two dimensional structure. Contour solid lines *(dotted lines)* show *increasing (decreasing)* density. (From Ref. 5 p. 30).

- - - -

only 10% bunching. "Practical" considerations like this have been well-treated by Ruth and Chao.[17] Based on their model the Rutherford Appleton Group has developed a "reference design" whose parameters are given in Table 5.[18] Theoretical and experimental advances which would allow one to construct such a machine would indeed be welcome, for, after all, obtaining 25 GeV particles in a 5 meter device would be a most significant accomplishment!

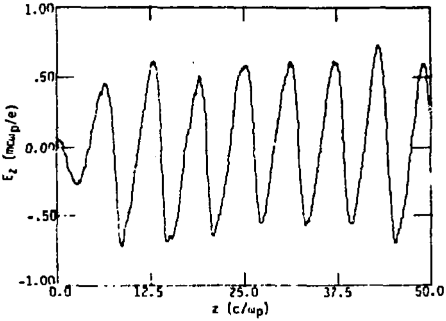
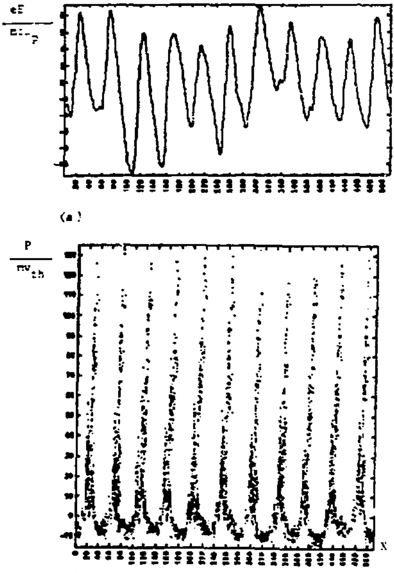


Fig. 9. Longitudinal electric field as a function of distance at time $\tau = 120\ \omega_p^{-1}$ in a beat wave accelerator. Laser electric field strengths are 6.0 $mc\omega_p$, $\omega_0 = 10.6\ \omega_p$, $\omega_1 = 9.6\ \omega_p$, and KT = 10 keV is the plasma temperature. (From Ref. 5 p. 63).



XBL 838-10925

Fig. 10. a) Longitudinal electric field as a function of distance in a beat wave accelerator; b) Plasma electron momentum (in units of the thermal momentum) as a function of distance. (From C. Joshi).

Table 5. *Reference design parameters for a plasma beat wave accelerator having an energy gain of 25 GeV in one stage.*

Laser angular frequency	$1.78 \times 10^{15}\ s^{-1}$
Plasma frequency	$7.2 \times 10^{12}\ s^{-1}$
Plasma density	$1.6 \times 10^{16}\ cm^{-3}$
Accelerating gradient	5 GeV/m
Laser pulse duration	100 psec
Laser energy	8.5 kJ
Length of accelerator	5 meters
Final particle energy	25 GeV

I have not mentioned all of the reasons why a beat wave accelerator may not work. Naturally, since the world seems to be populated with a considerable number of skeptics, many such reasons have been developed. Perhaps it suffices here to say that potentially deleterious effects are being studied both theoretically and experimentally. The interested reader should consult the literature for extensive information on this subject.

As interesting as the beat wave version of a laser plasma wave accelerator is, it suffers from the defect that as particles are accelerated they will, slowly of course because they are very relativistic, get out of synchronism with the plasma wave. Thus staging is required, and consequently one must tackle the problems associated with transporting and periodically focusing laser beams.

It has been observed by Katsouleas and Dawson that the imposition of a transverse magnetic field will allow the particles to always remain "in-step" with the plasma wave.[6] A diagram showing this is reproduced as Fig. 11. The magnetic field must not be too large (no problem in practice) or the particle will no longer be "trapped" by the plasma density wave, nor can it be too small so as to have a good acceleration rate. The rate of energy gain is, in the direction of the wave,

$$\frac{dw}{dx} = \left(0.1\ \frac{GeV}{cm}\right)\left[\frac{B(kG)}{\left(\frac{n}{10^{16}}\right)\left(\frac{\lambda}{1\ \mu m}\right)}\right] {\frac{n}{10^{16}}}^{1/2} , \qquad (5.6)$$

where the magnetic field, B, is measured in kG and λ is the wavelength of the laser light. The factor in square brackets in Eq. (5.6) is the fraction of the peak bunching field and probably cannot be made to exceed 0.1 in practice.

In this accelerator, the "Surfatron," particles move transverse to the wave for it is in this direction that they accelerate. However, the transverse distance, Δy, doesn't have to be very big and is given by

$$\frac{\Delta y}{\Delta x} = \left(\frac{1}{30}\right)\left(\frac{\lambda}{1\ \mu m}\right)\left(\frac{n}{10^{18}}\right)^{1/2} , \qquad (5.7)$$

where Δx is the longitudinal length of the accelerator. It has been suggested by Joshi that one can use one wide laser beam and one narrow laser beam, for, after all, the beam pulse is narrow and simply moving at an angle with respect to the density wave.[5] In this way, one can greatly reduce the problems of (1) making a large volume plasma and (2) obtaining the requisite laser beam energy. The proposed geometry is shown in Fig. 12.

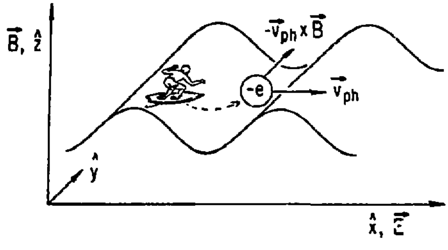


Fig. 11. A diagram of the Surfatron Accelerator Principle in which a transverse magnetic field keeps particles in phase with the plasma density wave even as the particles are accelerated. (From Ref. 6).

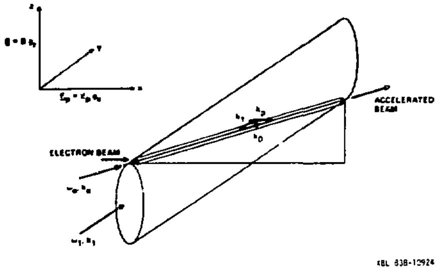


Fig. 12. The geometry of a Surfatron with optical mixing at a small angle. In the wave frame the electrons move parallel to the plasma density wave factor. (From C. Joshi).

\- - - - -

The required laser power density is given by

$$P = \frac{10^{18}}{\left(\frac{\lambda}{1\ \mu m}\right)^2}\ \frac{W}{cm^2} . \qquad (5.8)$$

With these theoretical tools it is easy to come up with a "reference design" for a Surfatron. This has been done, and suffice it to say that with a 100 kG magnetic field, which is high, but attainable, and with a laser of 100 kJ and a pulse width of 10 nsec (which is not available at present, but perhaps can be attained with suitable research and development), one can produce 100 GeV particles in a device of 3.2 meters length. Clearly, this concept has potentiality!

VI. Conclusion

In this review I have covered four new concepts in particle acceleration. Of course, as is appropriate for a review, I have not gone into each approach equally deeply nor have I, in any of the cases, gone into the subject to the depth that one can find in the original papers, some of which are even included in this Conference.

I want to convey to you my enthusiasm for the promise of the novel approaches, which I have attempted to communicate to you by covering just four approaches, but these four in some detail. Remember that there are many more approaches, a good number of which have received even more analysis than the four I have discussed here, and any one of which might someday be brought to the point of producing a practical accelerator. One simply can't tell at this point which, if any, will "work". But equally, one can't eliminate most of these approaches, which is just why these various approaches make excellent subjects for research and development.

Finally, it is often said, I think by physicists who are not well-informed, that accelerator builders have used up their capital and now are bereft of ideas, and, as a result, high energy physics will eventually -- rather soon, in fact -- come to a halt. After all, one can't build too many machines greater than 27 km, and soon one will run out of space or money (almost surely money before space). This argument seems terribly wrong to me, and worse than that possibly destructive, for it will have a serious effect if it causes, as it well might, young people to elect to go into fields other than high energy physics. The proper response, I believe, is to point -- in considerable detail -- to some of the new concepts which show by example that we are far from being out of new ideas. Some of these concepts shall, in my view, be, or lead to, the "stocks in trade" of the next century, and thus they will allow high energy physics to be as exciting then as it is now. It is our job to make it all happen.

References

1. Veksler, V. I., "Coherent Principle of Acceleration of Charged Particles," CERN Symposium on High Energy Accelerators and Pion Physics, Geneva, 1956, p. 80, Budker, G. J. "Relativistic Stabilized Electron Beam," ibid, p. 68.

2. See, for example, Teng, L. C., "Perspectives of Future Accelerators and Colliders," 11th International Conference on High-Energy Accelerators, Burkhauser, Basel, 1980, p. 910.

3. Voss, G. A. and Weiland, T., "The Wake Field Acceleration Mechanism," DESY 82-074, Nov. 1982, (unpublished); Voss, G. A. and Weiland, T., "Acceleration by Wake Fields," Seminar on New Trends in Particle Acceleration Techniques, Capri, June 1-3, 1982, Laboratori Nazionali di Frascati dell INFN Report (1982), p. 162.

4. Sessler, A. M., "The Free Electron Laser as a Power Source for a High-Gradient Accelerating Structure," Laser Acceleration of Particles, Channell, P. J. (Editor), American Institute of Physics Conference Proceedings No. 91, New York, 1982, p. 154.

5. Pellegrini, C. "Report of the Working Group on Far Field Accelerators, ibid, p. 138.

6. Tajima, T. and Dawson, J. M., "Laser Acceleration by Plasma Waves," ibid, p. 69; Katsouleas, T. and Dawson, J. M., "A Plasma Wave Accelerator-Surfatron I", IEEE Trans. Nucl. Sci. Aug 1983 (to be published) and Phys. Rev. Lett. 51, 392 (1983).

7. Voss, G. A., private communication.

8. Pellegrini, C., "A High Energy $e^+ - e^-$ Collider Using an Inverse Free Electron Laser Accelerator," Proc. of the ECPA-RAL Meeting, Oxford, September 1982, p. 249, Sprangle, P. and Tang, C-M, IEEE Trans. Nucl. Sci. NS-28, No. 3, 3346 (1981).

9. Sprangle, P., Vlahos, L., Tang, C-M, "A Cyclotron Resonance Laser Accelerator, IEEE Trans. Nucl Sci. Aug 1983 (to be published).

10. Kolmenskii, A. A. and Lebedev, A. N., Sov. Phys. JETP 23, 733 (1966); Krasovitski, V. B. and Kurilko, V. I., Sov. Phys. Techn. Phys. 11, 1953 (1967).

11. Tajima, T. and Dawson, J. M. Phys. Rev. Lett. 43, 267 (1977).

12. Tajima, T., "Laser Acceleration by Plasma Waves for Ultra-High Energies," Proc. of the ECPA-RAL Meeting, Oxford, September 1982, p. 169.

13. Joshi, C. Tajima, T., Dawson, J. M., Baldis, H. A., Ebrahim, M. A., Phys. Rev. Lett. 47, 1285 (1981).

14. Joshi, C. "The Plasma Beatwave Accelerator Experiments," Proc. of the ECPA-RAL Meeting, Oxford, September 1982, p. 195.

15. Ebrahim, N. A. private communication; Joshi, C., private communication; Singer, S. private communication.

16. Sullivan, D. J. and Godfrey, B. B. "Simulation of the Plasma Beatwave Accelerator," Proc. of the ECPA-RAL Meeting, Oxford, September 1982, p. 209; Sullivan, D. J. and Godfrey, B. B., "The Plasma Beatwave Accelerator-II Simulations," Laser Acceleration of Particles, Channell, P. J. (Editor), American Institute of Physics Conference Proceedings No. 91, New York, 1982, p. 43; Mori, W. Joshi, C., and Dawson, J. M., "A Plasma Wave Accelerator-Surfatron II," IEEE Trans. Nucl. Sci., Aug. 1983, (to be published).

17. Ruth, R. D., and Chao, A., "Plasma Laser Accelerator: Longitudinal Dynamics, The Plasma/Laser Interaction, and a Qualitative Design, Laser Acceleration of Particles, Channell, P. J. (Editor), American Institute of Physics Conference Proceedings No. 91, New York, 1982, p. 94.

18. Lawson, J. D., "Beat-Wave Laser Accelerators: First Report of the R.A.L. Study Group", Rutherford Appleton Laboratory Report RL 83-057 (1983).