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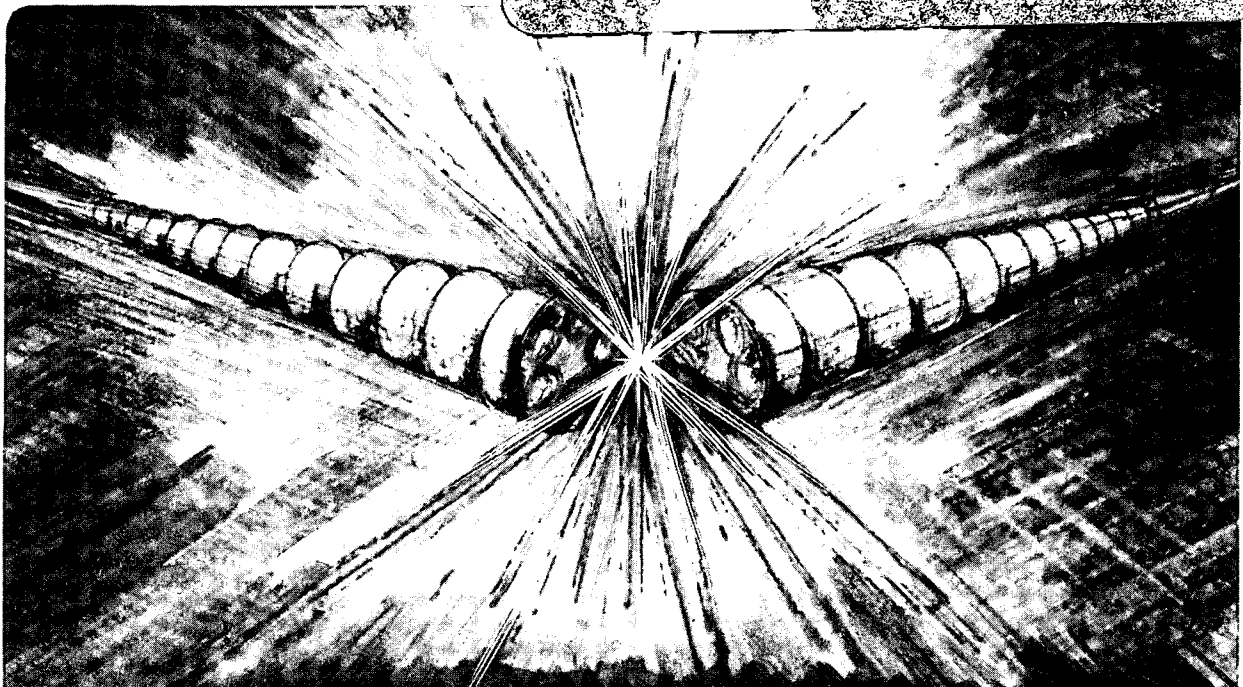
Presented at the High-Brightness Accelerators  
Conference, Pitlochry, Scotland, July 13-25, 1986

ADVANCED CONCEPTS FOR ACCELERATION

D. Keefe

July 1986

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ADVANCED CONCEPTS FOR ACCELERATION\*

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July 1986

\*This work was supported by the Office of Energy Research, Office of Basic Energy Sciences, U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.

## ADVANCED CONCEPTS FOR ACCELERATION\*

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### 1. INTRODUCTION

The study of advanced methods of acceleration has been largely concentrated on two quite different areas of applicability -- first, the acceleration of electrons and positrons to ultra-relativistic energies ( $> 1$  TeV) and second, the acceleration of protons and ions from rest or very low energies to a speed that is a significant fraction of the speed of light. Both applications share the common goal of seeking to achieve accelerating gradients far in excess of those obtainable with conventional accelerating structures, e.g.  $E \gg 10$  MV/m.

The energy frontier in high-energy physics has advanced exponentially with time simply because new inventions have been successively developed that have kept the accelerator costs within bounds. The largest accelerator under serious consideration to-day is the Superconducting Super-Collider (SSC) which will accelerate protons by the traditional synchrotron method to 20 TeV, and then act in the storage ring mode to collide two such beams together. It seems likely that the next step in energy beyond the SSC will employ the Linear Collider technology now being developed at SLAC, and will use electron-positron collisions in the multi-TeV range ("Equivalent" physics can be accomplished with electrons at about one-fifth the energy of protons). Electron linacs at such energies if based on today's technology would be prohibitive in cost, size and power consumption. If the message of the Livingstone Chart of exponential growth continues to hold, new accelerating concepts must be developed to enable us to advance in center of mass energy.

In contrast to electrons, which are relativistic ( $\gamma > 2$ ) when they leave a typical electron gun and can be accelerated with high gradient, ions gain velocity at a much lower rate. After the 500 m of linac in LAMPF, the protons have attained only a  $\gamma$  of 1.8. Hence much work has centered on collective methods of ion acceleration in which the charge density of an intense electron-beam (IREB) is modulated

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to produce very high fields within the beam that can then be used to accelerate ions embedded in the beam. These fields must be programmed to have a phase-velocity that varies in synchronism with the changing speed of the ions; the problems of creating slow-moving modulations and controlling their speed are indeed severe. The IREB sources are of two types, pulse-power single-gap diodes driven by a Marx generator and pulse-forming-line (PFL), or multigap induction linacs. The latter have the advantage of offering high repetition rate, high efficiency, and excellent beam quality.

Advanced concepts have been the subject of several recent conferences and workshops [Corbett et al. (1983), Bryant and Mulvey (1985), Channell (1982), Joshi & Katsouleas (1985)] in the hope that some might provide promising breakthroughs in technology, decades in the future. It has become customary to categorize advanced concepts in the following way:

Table 1: A Classification of Accelerator Schemes		
<u>Medium</u>	<u>Comment</u>	<u>Example Accelerators</u>
Vacuum (Near Field)	Tuned EM Wave	Advanced Linac Structures powered by microwave tube, free-electron laser, or optical laser
Vacuum (Near Field)	EM Pulse	Wakefield Transformer, Autoaccelerator, Switched power
Vacuum (Far Field)		Inverse Free Electron Laser (IFEL)
E (Electron)-beam		Auto-resonant (ARA) Ionization Front (IFA) Waves (e.g. space-charge) *Electron Ring (ERA)
Gas		Inverse Cerenkov (ICA)
Plasma		Laser Beat Wave (LBW) Plasma Wake Field (PWF)
<p>* ERA is fundamentally different from other E-beam devices in that the electrons providing the field remain in the frame of the ions rather than flowing through the region of charge modulation; the electron ring behaves more as a vehicle than a medium.</p>		

For relativistic electrons, the c.w. Near-Field devices offer the opportunity of moving continuously up in frequency from the conventional linac structures for which a highly sophisticated data-base of experience exists; calculations of expected beam quality and behavior,

and parameters such as projected efficiency, can be on more or less firm ground depending on how far one extrapolates downward in wavelength. For other entries in the Table, answers to such questions are much more speculative; laboratory demonstrations of the physics concepts do not, indeed, exist in many areas.

The accelerator examples listed in the Table offer, to varying degrees, the promise of controlled or staged acceleration in which the phase velocity of the field can be kept in synchronism (or nearly so) with the beam. (Acceleration by uncontrolled virtual cathode formation is not listed, for example).

Only selected examples will be reviewed in this paper; other reports at this meeting by Wilson, Cooper, Jameson and Neil will cover some of the topics in greater detail.

## 2. METHODS FOR RELATIVISTIC ELECTRONS/POSITRONS

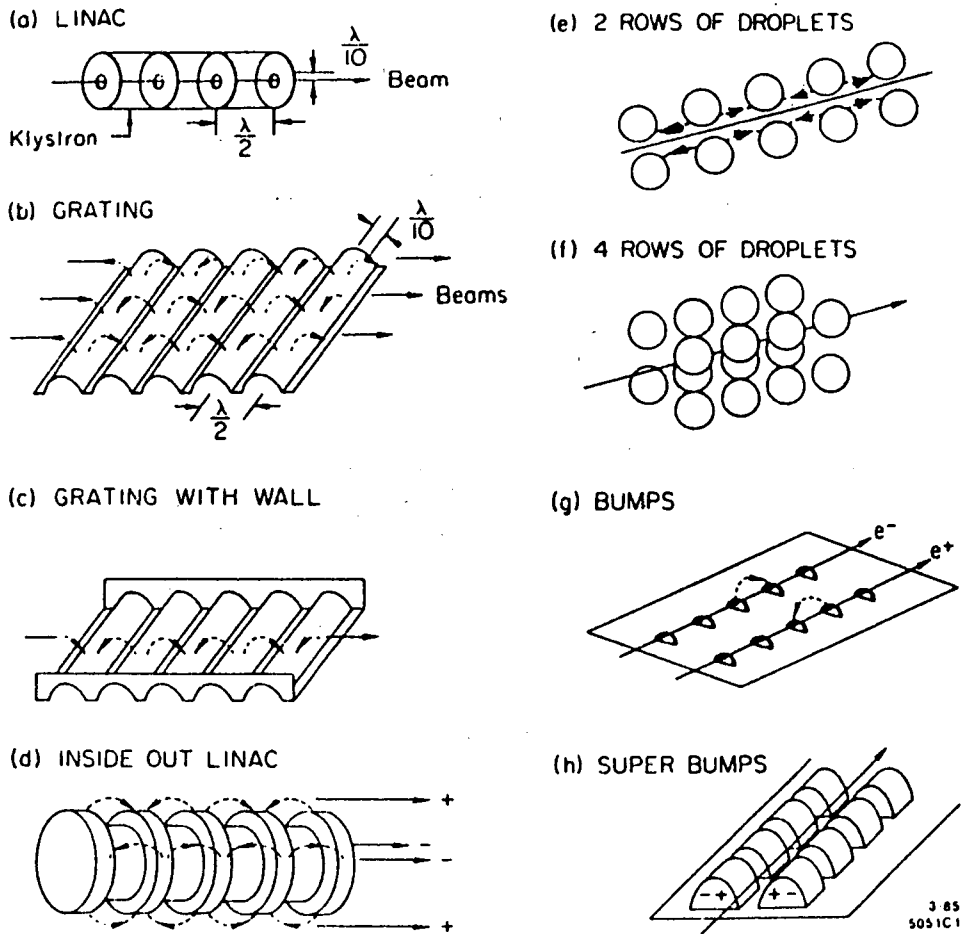
### 2.1. Approach

Obtaining high gradients in near-field vacuum structures is limited by the surface breakdown field. This limit is increased by using higher frequencies than today (SLAC operates at 3 GHz), hence the interest in pushing to shorter wavelength microwaves and, ultimately, lasers. Unconventional linac structures for very short wavelength excitation are discussed by Palmer (1985). See Fig. 1. We address below advanced concepts that seek to achieve fields beyond those attainable in microwave structures by use of two approaches:

- i) Develop the fields within a plasma either neutral or non-neutral; such fields can be local and need never appear near the structure walls (Sections 2.2.1-2.2.4).
- ii) Take advantage of the fact that the surface breakdown field in vacuum can be very large for extremely short pulses [ $V_b$  scaling roughly as  $(\tau)^{-1/4}$ ]. Very large fields on axis can be produced by radial line transformers (Section 2.3).

### 2.2. Plasma Accelerators

The last few years have seen a rapid expansion of interest in devising ways of controlling large-amplitude waves in plasmas to make them useful for the acceleration of electrons to high energies. Some twenty-five years ago, the invention of the laser caused much speculation on whether the very large coherent electric fields it can



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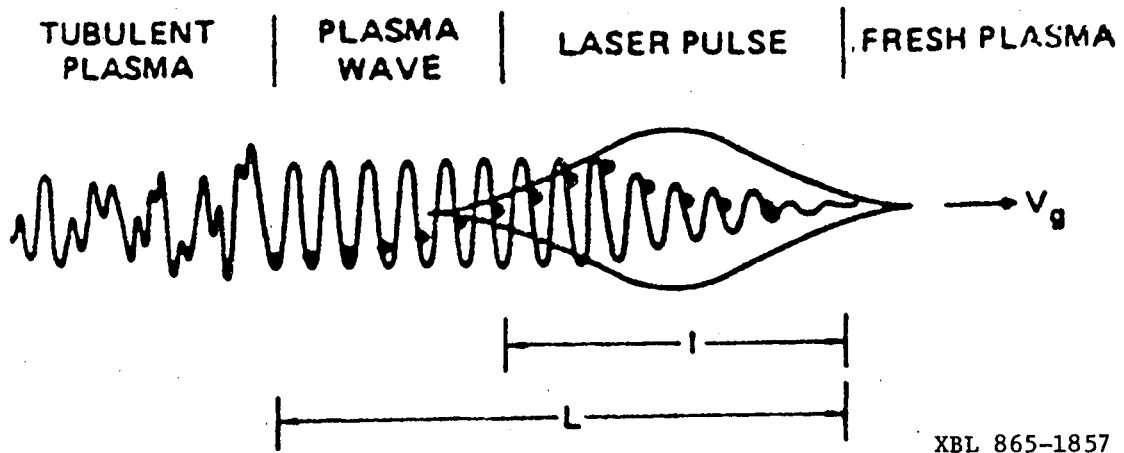
Fig. 1: Some unusual RF near-field structures discussed by Palmer (1985).

produce might be useful for acceleration. Unfortunately, the laser fields are transversely polarized and so could not be used for acceleration over long distances in vacuum. In a neutral plasma, however, the intense radiation from a laser can modulate the plasma to produce plasma waves (Langmuir waves) with longitudinal electric fields of enormous magnitude. These fields can accelerate particles - as witnessed in laser fusion experiments, where the effect is undesired - and, if the mechanism is controllable over significant distances, might offer for the future a compact way of producing very high energy electron beams. The interest in the use of plasma waves that followed the Tajima-Dawson (1979) proposal of the Beat-Wave Accelerator has led to several other suggestions for plasma accelerators, including the substitution of a particle beam for the laser to excite the waves. Several typical schemes are summarized briefly below.



### 2.2.1. Plasma Beat Wave Accelerator (PBWA)

Two coherent laser beams, with frequencies  $\omega_1$  and  $\omega_2$ , are injected into an underdense plasma with plasma frequency,  $\omega_p$ . If the difference frequency  $(\omega_1 - \omega_2)$  matches the plasma frequency,  $\omega_p$ , forward Raman scattering of the higher frequency beam ( $\omega_1$ ) gives rise to a photon of the lower frequency beam ( $\omega_2$ ) and a forward-going plasmon ( $\omega_p$ ). A very large electric field due to the temporary charge separation in the plasma can be built up resonantly and can propagate forward with a phase velocity  $v_p = c(1 - \omega_p/\omega)^2$  where  $\omega \approx \omega_1 \approx \omega_2 \gg \omega_p$ . (See Fig. 2.) The group



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Fig. 2: Build up of accelerating field which moves forward in beat-wave excitation method.

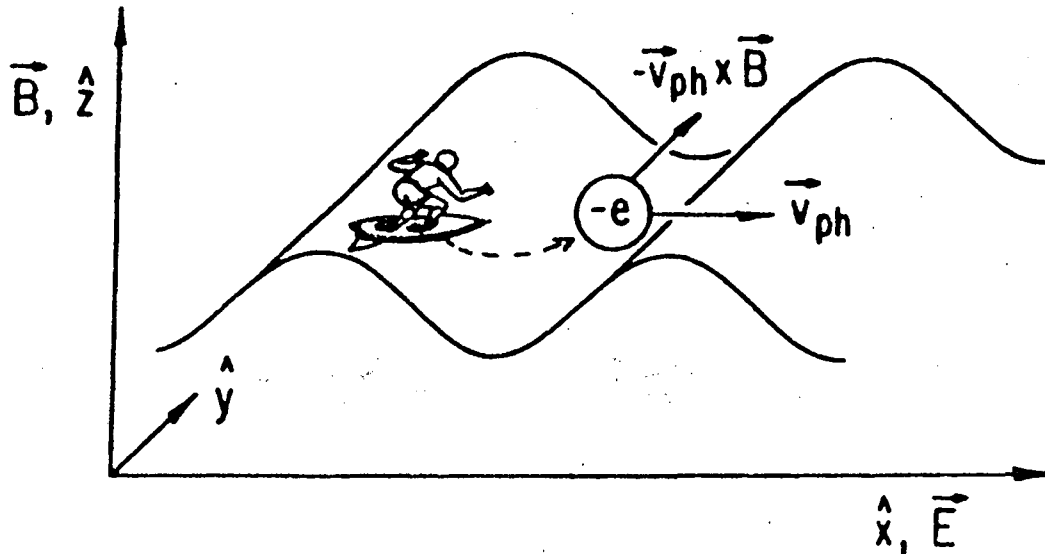
velocity of the light pulse is also equal to  $v_p$ ; thus the laser pulse and the wake of excited plasma waves move forward as a unit into the as-yet undisturbed plasma downstream.

For electrons moving in synchronism with the plasma wave the accelerating gradient (proportional to  $\omega_p$ ) can be very large, i.e.,

$$E(\text{volts per cm}) \approx [n_0 (\text{particles/cm}^3)]^{1/2}$$

or, for a plasma density of  $10^{18} \text{ cm}^{-3}$ , some 100 GeV/m. For the accelerated particle to remain synchronous, it should travel at a speed,  $v = v_p$ ;  $v_p$  is, however, less than  $c$ , and the accelerated particle will move forward out of synchronism at some limiting kinetic energy which is proportional to  $1/\omega_p^2$ , or  $1/n_0$ . Thus there is a competition between the desires for high gradient (large  $n_0$ ) and long accelerating distance (small  $n_0$ ).

The surfatron concept is a proposal to circumvent this difficulty by application of a magnetic field at right angles to the direction of propagation of the beat wave. The accelerated particles thereby acquire a small transverse component of velocity with respect to the direction of light propagation and can thus keep in step with the wave even when their speed exceeds  $v_p$ . (See Fig. 3.) This technique can be shown



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Fig. 3: A magnetic field gives sideways motion to keep the particles in phase with the wave.

to have the desirable property of phase-stability. The laser beams in a surfatron must, of course, have significant lateral extent to accommodate the sideways motion of the accelerated particles. An alternative scheme proposed by Katsouleas et al. (1983) called "optical mixing" results in significantly less width; here the two laser beams are tilted at a slight angle to each other and the plasma wavefronts move at an angle to the direction of the accelerated beam.

While extensive work with computer simulation has taken place, much more needs to be done to sort out the complicated physics of wave-wave and wave-particle interactions when a high-power laser interacts with a plasma. Instabilities can occur and ultimately, very short laser pulses (10-50 psec) must be employed to avoid such unwanted waves. Initial experiments on exciting plasma waves have taken place at UCLA, RAL, and LANL. The most successful of these, by Joshi et al. (1985) at UCLA, using two laser beams at  $\lambda = 10.6 \mu\text{m}$  and  $9.6 \mu\text{m}$ , has demonstrated the generation of the fast plasma beat-wave in a plasma of the right

density ( $10^{17} \text{cm}^{-3}$ ) for resonance. The scale length of the wave region was about 1 mm and a field of some 500 MV/m has been inferred.

The beat wave accelerator is unique among advanced concepts in the magnitude of the accelerating fields it could perhaps achieve. A vast amount of theory and simulation is still needed to sort out the extraordinarily complex physics of the interaction of intense laser beams with plasma. In addition, a succession of scaled experiments, beginning with a demonstration of modest acceleration, will be needed over many years to establish whether a viable accelerator system is possible and, if so, what its limitations are. Developments in high-power laser technology will also be needed.

### 2.2.2. Plasma Wake Field Accelerator (PWFA)

Excitation of intense Langmuir waves in a plasma can alternatively be achieved by use of small, intense bunches of relativistic electrons rather than by laser light. There is already a substantial technology base for the production of such bunches by electron linacs; by contrast, technology advances are needed for lasers (e.g., pulse length  $\sim 10$  picoseconds, higher wall-plug efficiency) before an attractive laser-plasma accelerator system might be proposed.

In the plasma wake-field accelerator (PWFA) proposed by P. Chen et al. (1984), the driving stream of electron bunches, with dimensions less than a plasma wavelength, excite plasma waves by virtue of a two-stream instability -- as opposed to the ponderomotive force in the laser case. The plasma waves growing in the wake of each driving bunch to large amplitude (and eventually becoming turbulent) can produce a very high gradient and so accelerate a second driven bunch travelling in phase with the wave. The attainable gradients, and the phase-slip problem are the same as for the PBWA.

The energetics governing the acceleration of the driven bunches at the expense of the acceleration of the driving bunches (assumed to be much higher in intensity) was quickly perceived for the PWFA as related to the classic beam-loading problem in conventional accelerators, namely, the maximum kinetic energy gain per driven particle will not exceed twice the kinetic energy of a driving particle. Thus, a driving beam of 1 GeV electrons could add nearly 2 GeV to the high-energy particles, meaning that acceleration to the TeV range would require many stages. (In principle, if the charge profile within the already tiny drive bunch could be tapered, the "transformer ratio" could be increased above two; this seems, however, difficult to achieve in practice.)

Use of an electron beam rather than laser light to excite accelerating plasma waves seems to offer some practical advantages. As mentioned, the technology is largely in hand, and the wall-plug efficiency could be significantly greater. Unless laser self-focussing is found to be realizable in a controlled and reproducible way, the laser beam divergence sets a limit to the length of the acceleration region (Rayleigh length) obtainable with a laser. Wave excitation by an electron beam can be maintained over a longer distance, first because of the very small emittance and, second, because the electrons can be confined by magnetic quadrupoles (i.e., non-material lenses) exterior to the plasma.

An interesting proof-of-principle experiment with a 22 MeV short-pulse linac (now 30 psec; being modified for 5 psec operation) is in the planning stage at ANL, by Rosenzweig et al. (1985).

### 2.2.3. Plasma "Grating" Accelerator

Simulation studies of the surfatron indicate that particle energy gain is limited by wave dynamics rather than by particle dynamics. While most of the laser energy is transferred to plasma wave energy, the plasma wave group velocity is very small, and the energy that can be transferred to the driven beam diminishes with distance. Important consequences of this pump energy depletion are reflected in limitations on the acceleration distance and in the overall electrical efficiency.

In an effort to circumvent pump depletion, Katsouleas et al. (1985) have explored the possibility of injecting laser light from the side, along the length of the accelerating region. In this case, therefore, one can choose the laser beam (one frequency only) to be polarized parallel to the direction of acceleration. Creating a periodic density modulation in the same direction along the plasma then leads to a beat-wave between the laser light-wave and the zero-frequency density wave, which is analogous to the two-laser beat-wave in the PBWA. Thus a propagating accelerating plasma wave can be set up with analogous properties but in a different -- and presumably more favorable -- geometry. Work on this approach has consisted, so far, of some simulation studies.

### 2.3. Pulsed E-beam, Pulsed Laser Accelerator

Following the very successful demonstration that an intense relativistic electron beam (IREB) of 10 kA, 3-50 MeV, can be guided in a straight line over a long length (50 m) by a laser beam, Briggs (1985)

proposed that such a beam might be helpful in creating the rapid acceleration of a small bunch of very high energy electrons following several centimeters behind the tail of the drive beam. While transient low density plasmas are involved, extended plasma wave phenomena, which can often lead to uncontrolled and undesired effects, are not invoked. Two lasers are used (one long pulse, one short pulse) to control the sequence of events, but these are used basically to cause ionization in gas and are of modest intensity. High-gradient acceleration of the driven beam is envisaged to take place as a result of four steps (see Fig. 4):

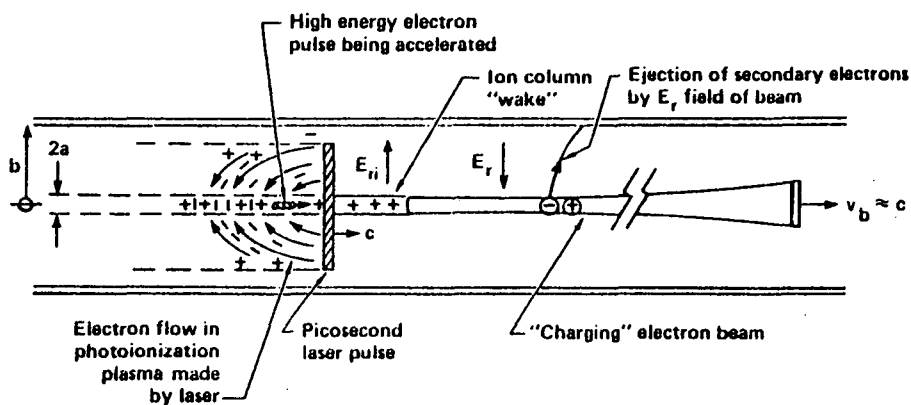


Fig. 4: Schematic of the Electron Beam/Laser accelerator

- i) A uv laser photo-ionizes a narrow column of gas along the axis of the drive-beam accelerator. The gas (benzene) density needed is in the range of  $10^{13}$  -  $10^{14} \text{ cm}^{-3}$  -- orders of magnitude less than the plasma densities referred to in earlier sections.
- ii) The electron beam is injected on axis. As it propagates, it rapidly expels the cold electrons created during Step (i) leaving an ion column about a millimeter across on axis, and furthermore, creates additional ionization thus enhancing the density of positive ions on axis. (Note that Step (i), in fact, is not absolutely necessary as the ion-beam will propagate stably down the tube by virtue of creation of the pulses, the ion column remains on axis for some nanoseconds before dispersing. Steps (i) and (ii) have

been demonstrated at the Advanced Technology Accelerator at LLNL, with a 10 kA 50 nsec long beam.

- iii) Next, a one picosecond laser pulse (a few Joules) is injected in coincidence with the high-energy beam bunch to be accelerated. In time it should follow the driving beam tail by about one nanosecond, creating a broad plasma column whose head follows closely behind the drive pulse tail. Transversely, the light pulse should be larger than either the driving or driven beam.
- iv) Finally, cold electrons created off axis by the picosecond laser pulse rush radially inward towards the residual positive ion column on axis. Briggs has shown that this inward flow of electrons can create a large electric field on axis that could accelerate the high-energy bunch with a field of perhaps 250 MV/m or more. Also, transverse focussing of the driven high-energy beam is taken care of automatically by the presence of the on-axis positive-ion column.

Special attention has to be paid to generating and maintaining a sharp edge on the tail of the drive beam; this requirement, together with the dispersion of the laser light and the energy depletion of the charging beam, will result in the need for multiple stages to reach the TeV region. The length per stage, however, could be substantially greater than in the PBWA and PWFA. It is especially noteworthy that this concept is not a wakefield accelerator, the function of the leading beam simply being to create enhanced ionization on axis and to eject the cold electrons (in the process, of course, acting as an energy source). Thus, the system is not subject to the transformer ratio limit of two referred to in 2.2.2 for the PWFA; instead, the ratio of kinetic energy gain (driven) to kinetic energy loss (drive) can be of order 10,000.

The applicability of the scheme to the acceleration of positrons has not been considered in any detail. Both an accelerating and a focussing field suitable for positrons will occur some distance behind the optimum location for electrons, corresponding to about a half a plasma oscillation period. Simulation studies are needed to determine the quality and reproducibility of this field.

Because of the multi-stage nature of the process envisioned, a sequence of experiments will probably be needed to establish whether the concept works or not, and to determine how reliable and reproducible it

could be. An encouraging technological aspect is that an induction linac driven by magnetic modulators based on new ferromagnetic materials has recently been operated at LLNL at a repetition rate of 10 kHz; extension of this pulsing technique well into the megahertz range seems to be straightforward.

#### 2.4. Inverse Cerenkov Accelerator

A relativistic particle ( $\beta \approx 1$ ) travelling through a refractive medium produces Cerenkov radiation continuously along its path at a cone angle  $\theta$ , where

$$\cos \theta = 1/\beta n,$$

and  $n$  is the refractive index of the medium. In the limit of large  $\gamma$  and small angles, this can be rewritten:

$$2(n-1) = \theta^2 + \frac{1}{\gamma^2}$$

so that  $\theta \approx \text{constant}$  if  $\theta \gg 1/\gamma$ . In the inverse process, coherent laser light is brought in with a corresponding conical geometry and a particle on axis sees a continuous accelerating field  $E \sin \theta \cos \psi$ , where  $E$  and  $\psi$  are the laser field and phase. Such an interaction over a distance of a few centimeters has been experimentally observed by Fontana and Pantell (1983) at Stanford. An interesting feature of this mechanism is that the slipping out of phase of the particle with the accelerating field frequently noted earlier need not occur. If  $\psi$  lies between  $\pi/2$  and  $\pi$ , particles are both focussed to the axis and accelerated; furthermore, the motion is phase-stable.

To use this mechanism to accelerate electrons (or positrons) to high energy requires an index of refraction corresponding to about 1 atmosphere of hydrogen gas. To minimize multiple scattering, one would like to choose as low a gas pressure as possible; this, however, would decrease the accelerating component of the electric field by decreasing  $\theta$ . Conical illumination over significant distances can be accomplished by containing the laser light within a reflecting cylinder.

In this scheme, the usable laser intensity is limited by ionization breakdown in the gas. More damaging, however, for high-energy applications is multiple scattering in the hydrogen gas which produces an intolerable increase in beam emittance for acceleration to energies in excess of a few tens of GeV.

## 2.5. Inverse Free-Electron Laser

This concept falls within the far-field vacuum category in that no medium is used and the laser accelerating field is many wavelengths away from neighboring surfaces. Neil will later discuss the free-electron laser in which a fast-electron beam is wiggled in a spatially reciprocating magnetic field and emits synchrotron radiation in the forward direction with a wavelength  $\lambda \approx L/2\gamma^2$  where  $L$  is the magnetic-field periodicity. The electrons lose energy while the photon field is amplified by coherent lasing action.

In the inverse device, the electrons are injected into a wiggler field and irradiated in the direction of motion with an intense laser beam, which can give energy to the electrons in a resonant way, by the inverse process. Since the laser light is of fixed wavelength,  $\lambda$ , a transverse magnetic field is added to maintain the condition  $\lambda = L/2\gamma^2$  as acceleration proceeds and  $\gamma$  increases.

Pellegrini (1982) has presented a design for an IFEL for 300 GeV electrons. The synchrotron radiation loss (which increases as  $B^2\gamma^2$  -- just as in a storage ring) becomes intolerable at higher energies.

## 2.6. Switched Radial-Line Accelerators

The field that can be sustained without breakdown by an accelerating gap in vacuum depends upon the pulse duration for pulses shorter than, say, one microsecond. For nanosecond and subnanosecond durations the field can be many times the static breakdown field. This concept relies on supplying a very short voltage pulse to the periphery of a pair of parallel discs which have a small hole on-axis through which the accelerated beam passes. As the pulse travels inwards to the axis of the radial transmission line it becomes amplified exactly in the fashion Wilson has described earlier for the Wake-field Accelerator (WFA). Indeed the disc structures when stacked together very much resemble the WFA structure except for details at the periphery, where the drive electron beam is replaced by a sequence of suitably phased, independent switches.

This method was proposed in 1968 for the acceleration of electron-rings (containing ions; see Section 3) from low energies to high energies. Hartwig (1968) has reported results for a copper disc structure fed at 16 points on the periphery (to simulate an approach to ideal symmetry) and indeed he observed the expected voltage



amplification (about x2.5) for pulses in the 1-3 ns range. The transformer ratio was not large for this application because the hole in the plates had to be several centimeters in diameter to allow for passage of the electron rings.

Interest in the method was renewed when Willis (1985) pointed out the possible advantages for ultra-high energy electron linacs. Here the pulse-length could be vastly shorter ( $\sim 10$  psec) and the hole size much smaller ( $\sim 1$  mm) leading to a much higher breakdown limit and a larger transformer ratio. He estimated that accelerating gradients of 1 GV/m might be achieved. The need for switching times of order 1 psec has stimulated studies of laser-switched gallium-arsenide switches. The amount of laser energy needed to accomplish the switching at a kilohertz rate may be very large, however.

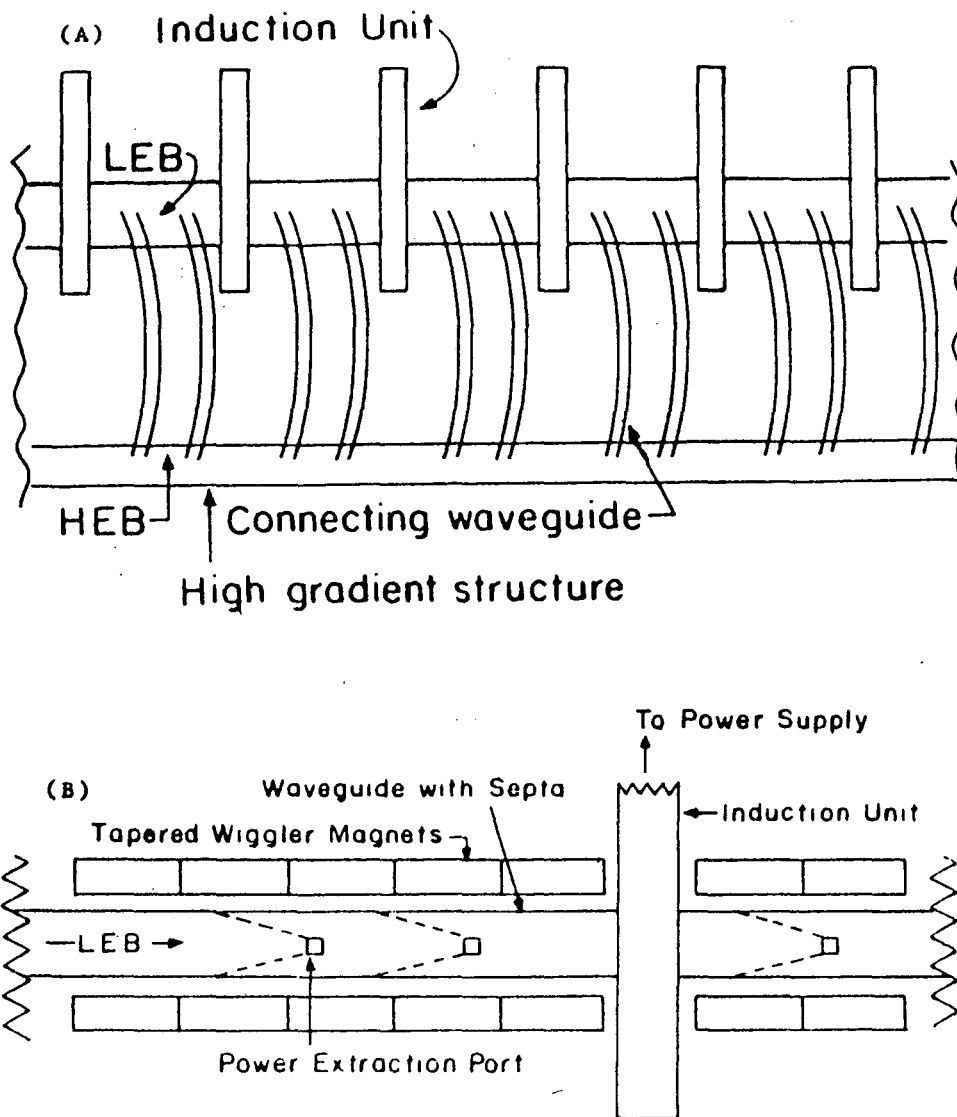
### 2.7. Two-Beam Accelerator

Hopkins et al. (1984) have proposed using the immense power ( $\sim 1000$  MW) available in the 30 GHz range from free electron lasers to power an ultra-short-wave linac structure ( $\lambda \approx 1$  cm). The concept is shown in Fig. 5. The low energy beam -- a few MeV -- has thousands of amperes and as it loses energy to the microwave radiation in the wigglers it is periodically rejuvenated by further induction acceleration modules. Gradients of 200 MeV/m and more have been observed in test structures. The Livermore FEL work will be discussed later by Neil.

### 3.0. Advanced Concepts for Ion Acceleration

In the past twenty years, several avenues have been explored in an attempt to harness the collective fields of intense electron beams to accelerate ions from low to high energies. Some of these methods could also be used, in principle, to accelerate high energy electrons or positrons. To date, only three methods have been successful in accelerating ions in a moderately orderly way, and then only to modest energies of the order of tens of MeV/amu.

Early observations of collective ion acceleration were with disorderly processes in which an intense electron beam formed a virtual cathode which halted the propagation of the beam by the large space charge potential at its head. When ions were formed -- either from a background low-pressure gas or surface flashover of an insulator (Luce diode) -- the virtual cathode became neutralized and the beam front propagated forward. In the process of dynamic relaxation of the virtual



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Fig. 5: The two-beam accelerator concept showing (a) the power generating (LEB) and high gradient structures (HEB) side-by-side and (b) the low energy beam in the wiggler structure.

cathode, ions were accelerated with a broad energy spectrum centered about two to three times the electron kinetic energy. While these results were interesting, this so-called "natural" acceleration process is basically uncontrollable and incapable of significant extension.

A degree of control proposed by Olson (1974) was to use a laser beam to produce a spatially narrow region of ionization of the background gas just in front of the virtual cathode; by programming the motion forward of the laser beam, the virtual cathode (and the large accelerating field at its head) could be dragged along in synchronism

with the accelerating ions. (See Fig. 6.) This method has recently been shown to work (Olson 1985); a modest number of protons and deuterons were accelerated to an energy of 10 MeV over a distance of 0.3 m.

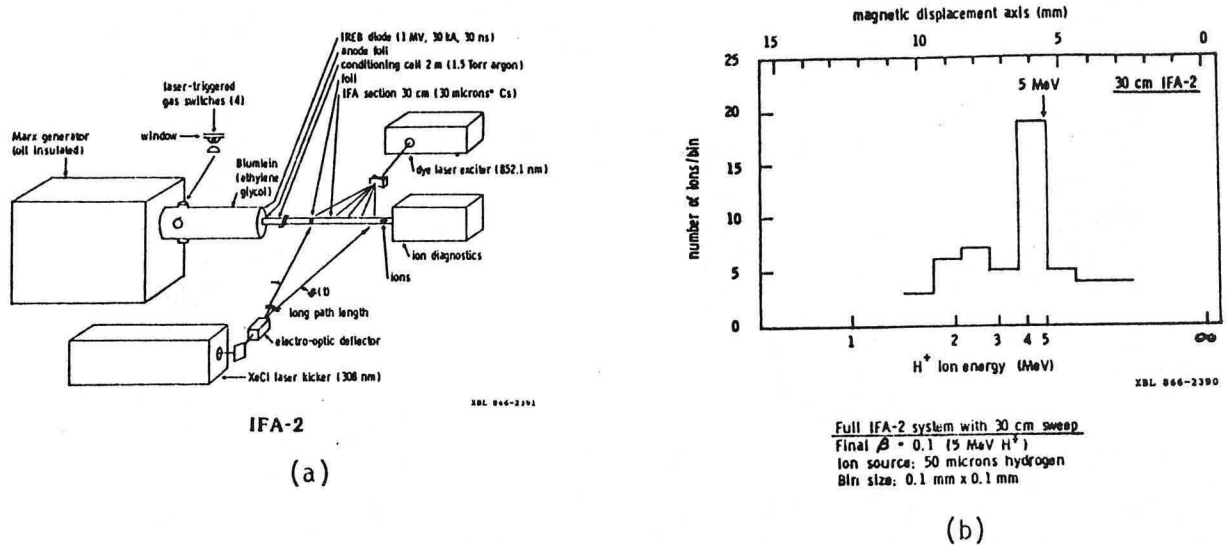
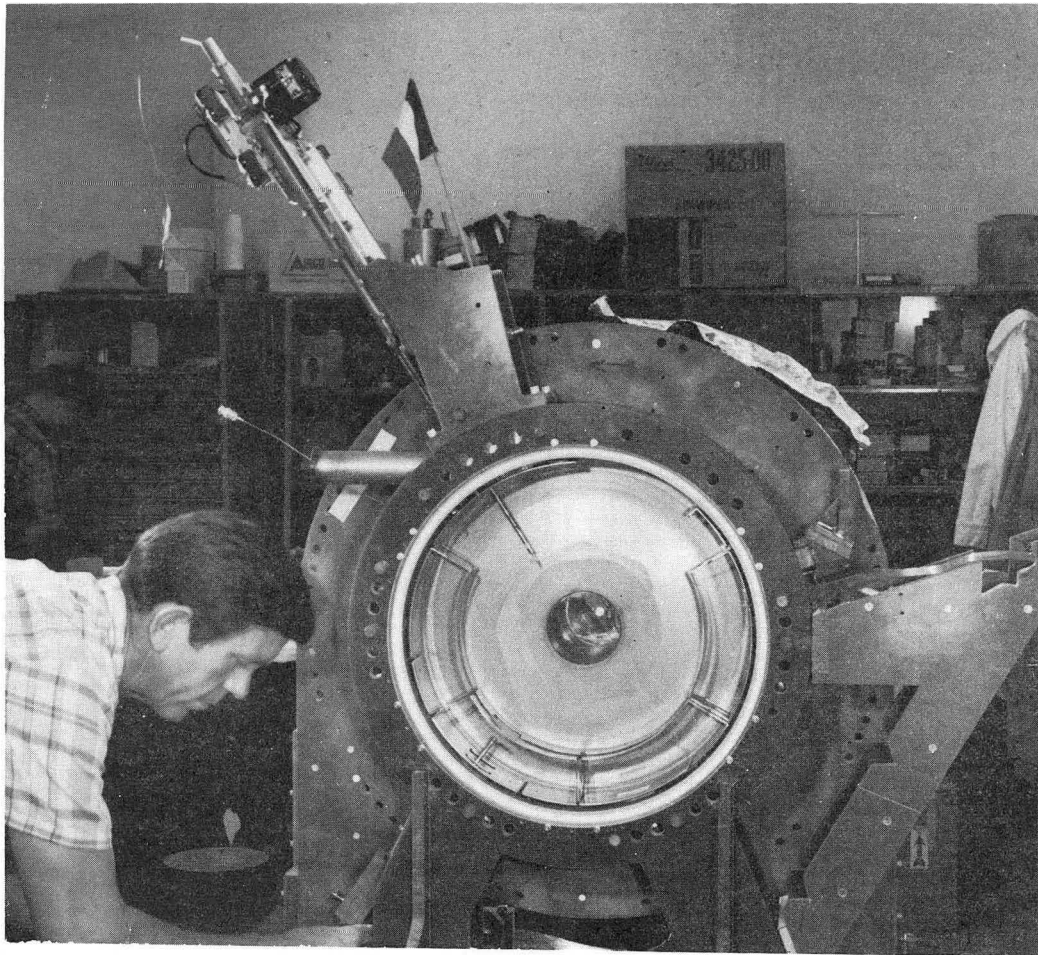


Fig. 6: Ionization Front Accelerator

A unique method proposed by Veksler (1968) -- the electron ring accelerator (ERA) -- uses acceleration of a ring of relativistic electrons seeded with a small number of positive ions. The detailed principles of the method are discussed by Keefe (1970). Multigap acceleration of rings holding xenon ions has been achieved by Sarantsev et al. (1986) through a sequence of induction acceleration units at Dubna. Experiments on formation of suitable rings (major radius  $\approx 30$  mm, minor radius  $\approx 2$  mm, number of electrons  $\geq 10^{13}$ ) have been also carried out at LBL, Garching and Maryland but these efforts were not continued long enough to achieve controlled acceleration of ions. Figure 7 is a picture of the ring-forming apparatus at LBL. A 4-MeV electron beam of hundreds of amperes from an induction linac injector is injected on an orbit near the outside radius. Pulsed coils apply a magnetic field transversely to the ring and cause simultaneous acceleration (to 20 MeV) and compression of the ring (to  $R = 30$  mm). If ions are added in an amount of about 1% of the electrons they provide enough focussing to cancel the residual electrostatic self-defocusing and render the ring stable. When accelerated in an axial field the ring electrons respond with a transverse mass  $m_e \gamma \approx 40 m_e$  i.e. about 50 times lighter than a proton. Thus the ions trapped in the ring



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Fig. 7: The ring-forming chamber at LBL (1970). The rapidly pulsed inflection field can be seen at the outer radius. The injected beam enters from the top left.

experience an accelerating gradient very much larger than the externally applied field.

Excitation of waves on intense electron beams (i.e., dense non-neutral plasmas) has been explored in an effort to develop an orderly method of ion acceleration with a tailored velocity increase with distance [see Keefe (1981)]. The charge density modulations in the wave act as accelerating buckets. Efforts to grow cyclotron waves (E-beam in axial magnetic field) were never successful, but growth of a slow space-charge wave (E-beam in a disc-loaded wave guide) has been achieved at Cornell by Nation (1985). Reproducibility of the space-charge wave at low phase-velocity, however, is poor.

The most promising approach to wave acceleration on electron beams would seem to involve combining two waves, one of which is usually a zero-frequency wave provided, for example, by a rippled magnetic

solenoid field along the axis. Adjustments can be made easily to the periodicity of the magnetic field or to the ripple amplitude to allow one a number of external degrees of control. In experiments at NRL, Friedman (1979) has used a sequence of electron rings (formed by longitudinal chopping of a hollow beam) to inject a high-speed space charge wave of a somewhat unusual character. Space-charge waves of the conventional kind grown in a disc-loaded structure have been used by Nation at Cornell and have delivered some modest energy gain to low energy protons.

While such two-wave schemes are still in an infant stage of development, it is to be noted that, besides slow waves (of interest initially for slow ion acceleration), these systems can support fast waves with  $v_{\text{phase}} = c$  and hence, in the future, offer (in principle at least) the possibility of accelerating relativistic electrons or positrons in a collider.

In summary, most of the research on these other concepts has been with the aim of accelerating ions to intermediate energies and some, such as ERA, are of interest exclusively for ions. The physical mechanisms involved are very complicated and take years of study to understand. With the exception of the ERA, where acceleration (of ions) has been successfully extended to a multigap structure, the research has been most valuable in weeding out the less promising candidates and in identifying others (and there is no shortage of them) that seem worthy of pursuit. Major questions of interest such as available flux and beam quality (emittance, energy spread) remain to be addressed.

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This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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