NEW DIRECTIONS IN LINEAR ACCELERATORS*

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Summary

Current work on linear particle accelerators is placed in historical and physics contexts, and applications driving the state of the art are discussed. Future needs and the ways they may force development are outlined in terms of exciting R&D challenges presented to today's accelerator designers.

Context of (Linear) Accelerator Development

A classification of particle accelerators has been proposed by Lawson[1] to illustrate the physical principles used in various accelerator types. Figure 1 shows a division between machines where the accelerating field at a point varies harmonically and those in which it does not. These categories are then divided, depending on whether the particles move in free space or in a medium, which could be a plasma or an intense beam of a different kind of particles. The free-space category is subdivided, depending on whether the charges that produce the accelerating and focusing fields are all bound in metals or dielectrics or are free parts of a plasma or particle beam.

		CATEGORY 1		CATEGORY 2
		ACCELERATED PARTICLES IN FREE SPACE		ACCELERATED PARTICLES IN A MEDIUM
		CATEGORY 1.A NO FREE CHARGES IN SYSTEM	CATEGORY 1.B FREE CHARGES IN SYSTEM	
ACCELERATING FIELDS	HARMONIC	● Linacs ● Synchrotrons ● Inverse Free-Electron Laser	● Linac plus rf Drive System	● Inverse Cherenkov ● Beam-Wave ● Laser Beat-Wave
	NONHARMONIC	● Betatron ● Induction Linac ● Electrostatic Accelerator	● Ion-Drag Accelerator ● Wake-Field Accelerator	● Ionization Front ● Electron Ring

Fig. 1. Classification of accelerators used by Lawson.

Another way of describing this classification in a generic sense is that most applied accelerator systems today are in Category 1 and are based on classical electromagnetic (EM) physical principles. Category 2 basically involves plasma physics, which is now much less tractable and has not led to significant practical application in accelerator technology.

Progress on the energy frontier in Category 1 was driven by physics research needs and usually is charted from the 1930s in the form of the Livingston Chart, fig. 2, showing that particle accelerator energy has increased by a factor of about 25 every 10 years. The corresponding cost per MeV has decreased by a factor of about 16 per decade.[2] The physics principles on which all of these devices work were deduced long ago; the energy increases were possible because of cost reductions from thorough exploitation of parameters, engineering perfection, systems integration, and advanced manufacturing methods.[3]

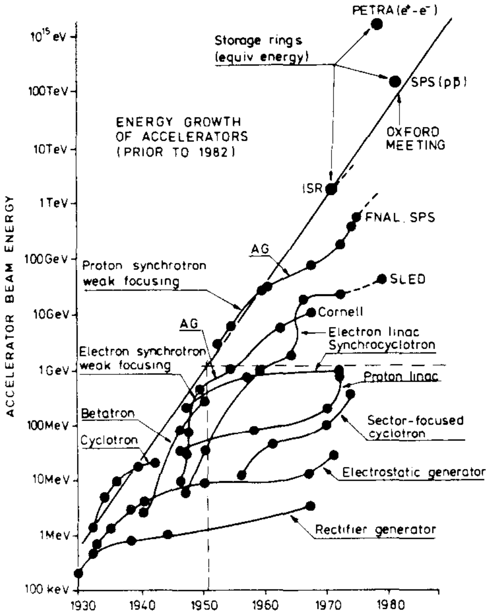

Fig. 2. The Livingston chart, showing the evolution of various types of accelerators with time.

At the same time, the need for more intense sources led to Category 1 systems of higher intensity, culminating for ion machines in the meson factories like LAMPF, which produces a proton beam of 1-mA average current at 800 MeV. These machines, and corresponding electron accelerators, must consider collective effects in the accelerated beam, but do not rely on them for acceleration. More and more modern applications are forcing this collective-effect boundary, requiring better understanding of plasma effects in the beam itself or as an efficient acceleration mechanism; therefore, an understanding of plasma physics is becoming a prerequisite for the young workers in this field.

Current Applications that Compel Development

It is important to stress that a number of present programs are very challenging to accelerator designers and should be considered as new directions in their own right. It would probably surprise most of those attending this conference to know how little of the capability and established technology of modern linacs is understood or appreciated outside our own small linac community—even the larger accelerator community is generally unaware of the substantial advances, especially in high-intensity topics, made in the past decade. The small number of machines built during this decade is part of the problem. Another interesting fact is that much of this research and development work was sponsored by nontraditional sources interested in building linacs for a wide variety of applications. The operational status now being achieved by some of these endeavors is making a large impact on the general awareness that augurs well for the future.

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Nuclear and particle physics, and the increasingly blurred interface between these traditional fields, continue to stimulate linac development, as attested by many papers at this meeting. The most compelling questions involve understanding beam breakup (BBU) phenomena in the collider, microtron, and other high-intensity electron-linac projects, and the development of advanced klystron amplifiers and accelerator structures for both pulsed and cw application.

The primary accelerator-based project for the fusion program at present is FMIT, a facility for fusion materials development. The cw, very high intensity nature of this machine presented great challenges to accelerator designers in two major areas. To achieve reasonable system efficiency, space-charge forces in the accelerated beam have to be allowed, requiring a comprehensive understanding of the limits and parameter choices that maximize efficiency while minimizing residual beam losses so that machine maintenance problems will not be too severe,[4-6] a prime example of the encroachment of plasma physics on classical linacs design mentioned above. The other challenge is in the engineering requirements of such a high-power, cw system that must run with very high availability.

The heavy ion fusion (HIF) program also has been a primary motivation toward understanding space charge and instability limits in both rf and induction-linac machines,[6-8] and toward development of practical techniques for phase-space manipulation and control that will not spoil the brightness. In the rf approach, work is required on how to funnel several beams together at appropriate places along a linac tree and on how to inject, store, extract, and compress beams in storage rings and final transport systems. Beams in induction linacs (IL) also must be run near the space-charge limit for high efficiency and the IL must achieve precise accelerating waveforms.

Free-electron lasers (FELs)[9] present challenging demands on electron-linac performance; considerably more intense beams with better emittance, compared with existing machines, are required, and this intensity makes understanding and control of BBU phenomena essential for both acceleration and energy-recovery deceleration. Applications of such FELs to infrared or ultraviolet light sources, process chemistry, and other industrial uses are under study. In a different approach, FELs amplifier experiments using multikiloampere induction linacs are under investigation at the Lawrence Livermore National Laboratory (LLNL).[10]

There are, of course, many more topics for detailed development. We should not overlook the importance that nearer term, more evolutionary, work will have both in practical applications and in teaching us how to take larger steps.

Accelerator structures receive a great deal of attention and will continue to require imaginative and dedicated work. Present topics include the radio-frequency quadrupole (RFQ) and the very interesting RFQ-like structures being studied in the USSR that replace the drift-tube linac (DTL)[11]; high-beta ion structures such as the side-coupled, disk-and-washer (DAW), and others; and advanced standing-wave structures for electrons. In RFQ design, the primary challenge is resonant coupling of the drive to the cavity. This would reduce the tuning, or electrical, sensitivity of the structure to a level equivalent to the sensitivities of the on-axis fields on the acceleration beam dynamics. Resonant coupling would allow longer, more complicated RFQs to be used. The high-beta structure challenge is to find a good compromise among the practical requirements for good mode isolation, shunt impedance, accelerating gradient, coupling, and other factors. A primary difficulty is that no 3D cavity design codes of sufficient accuracy exist, so development now depends on expensive hardware modeling. The need for 3D codes also extends to beam dynamics, magnet design, and advanced rf power-generation design.

Future Needs and Development Directions

All of the above areas will continue to demand higher energy, intensity, brightness, and systems requirements in various combinations. But it appears that some fundamental as well as practical limits are being reached using the classical approaches of Category 1 (fig. 1). In high-energy physics (HEP) particularly, the energy/cost-per-MeV differential is large, in spite of the progress made, and the scale of machines has become so large that the superconducting super collider (SSC) may be the last such device feasible. All applications will stress higher intensities, including HEP where adequate luminosity is necessary to get reasonable event rates.

The high-energy frontier is bounded by economic constraints rather than technical ones. To make progress, we are going to need more capital efficiency (GeV/M\$) and thermodynamic efficiency (GeV/MW and luminosity/MW).[12] As a near-term challenge, systems with ac-power to beam-power conversion efficiencies of at least 10% are considerably better than what we can do today. The high-intensity frontier, besides requiring the same capital and thermodynamic efficiencies, forces collective effects or plasma physics to be considered as well. To start with, the current per accelerating channel is raised into the space-charge-dominated regime to obtain good efficiency. If even more current is needed, then arrays of channels would be used. Some saving could be made by combining several channels into a common electromagnetic envelope with common vacuum, water, and other ancillary systems.

RF Power and Accelerator Structure Tradeoffs

The cost of an rf linac is roughly the rf power cost plus the cost of the accelerator structure. We can use this simple relationship to elaborate the relative influence of today's rf power and accelerator-structure subsystem efficiencies, and to indicate development directions that should be taken.[13,14]

The structure power cost varies inversely with length, whereas the structure cost varies directly with length. Therefore, there is a strong tradeoff between accelerating gradient(E_0) and length, and choice of the maximum achievable accelerating gradient is *not* a priori desirable.

It does seem reasonable, however, to expect that we would want to exploit the accelerator structure to some physical limit, even though the cost relation warns us to be careful. The applicable physical limit will depend on the application and could be, for example, removal of average waste power, voltage breakdown, surface damage due to high peak power, magnetic field limitations, space-charge limit on current, and so on. Typical rf linacs today might be designed at around 440 MHz for the RFQ/DTL, and around 1320 MHz (X3) for the high-beta stage. Peak surface fields (E) of about twice the Kilpatrick Limit[15](E_{KP}) would be practical: 40 mV/m at 440 MHz and 64 MV/m at 1320 MHz. The experience factor $K = E/E_{KP}$, by which E_{KP} may be multiplied for modern structures, appears to be as high as 2.5-3.0 for RFQs, and up to 2.0 for DTL and high-beta structures.

All the peak surface field, however, is not used for acceleration--geometry factors in practical structures reduce the effective gradient on-axis by some factor. This factor can be minimized but usually at some cost, for example, in shunt impedance Z or transit-time factor, which would directly offset the increased accelerating gradient E_0. For example, one structure with many desirable properties is called the DAW type (fig. 3). The addition of noses around the beam hole increases the transit-time factor, at some loss in shunt impedance, and increases the peak-surface-field to accelerating-field ratio (E/E_0) from 1.94 with no nose to 5.37 with full nose. The Vaguine

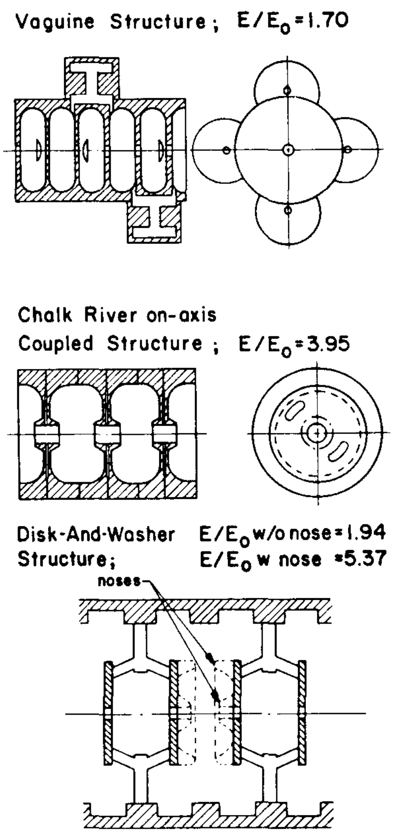

Fig. 3. Cross sections of four coupled-cavity linac (CCL) types: the DAW with and without nose, the Chalk River on-axis coupled structure,[16] and the Vaguine structure.[17] E/E_0 is the ratio of peak surface field to accelerating gradient.

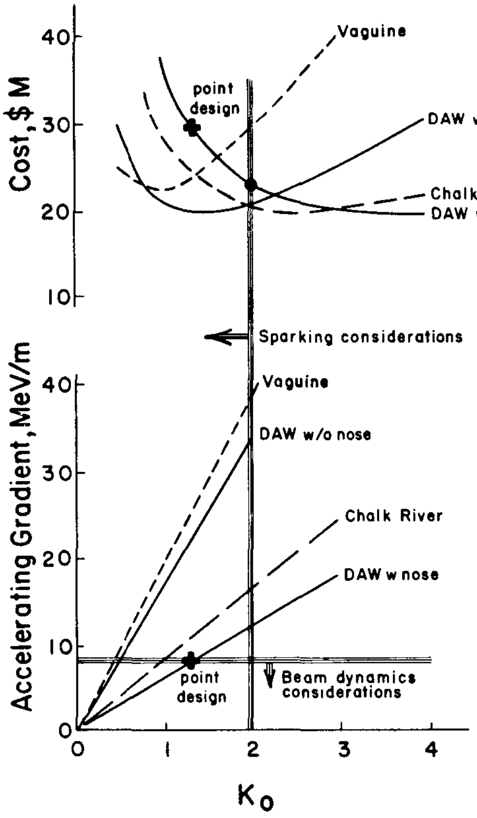

Fig. 4. Cost estimate for the SSC injector linac as a function of K, the ratio of peak-surface-field E in the CCL accelerating structure to Kilpatrick Limit E_{KP} = 32 MV/m at 1320 MHz, and the CCL accelerating gradient E_0 as function of K. Curves for the four CCL geometries of fig. 3 are plotted.

structure has a somewhat better efficiency in using peak surface field as accelerating field, with the Chalk River structure intermediate.

The fabrication cost/unit length of all these structures is roughly the same, \$50-100 K/m. The tradeoffs among shunt impedance ($\sim$50-100 MΩ/m), transit time (0.8-0.92), and other detailed factors also are not dramatic. Therefore, the gradient-versus-length cost tradeoff must dominate the choice of optimum gradient. Figure 4 illustrates this result, showing the cost curves for a linac that was designed as an injector for the proposed SSC, and relating E, E_{KP}, and E_0 for the four structures. The cost minima are all at about \$20 M and require an accelerating gradient of $\sim$20 MeV/m. The available E_0 (30-40 MeV/m) at K = 2 of the more efficient structures cannot be used economically, but the 20 MV/m E_0 giving the cost minimum is available below the sparking limit. The less efficient structures cannot reach the cost minimum without sparking, although this is not too serious because the cost minima are broad.

A great deal of rf accelerating structure development has occurred at frequencies $\leq$3 GHz, and it is unlikely that major increases in shunt impedance will occur. The cost per peak rf watt at low duty factor is relatively independent of frequency in this frequency range, and is expensive. The best way to use a higher E_0 and make the length shorter would be to reduce the unit rf power costs. We will return to this.

Note that something else is going on in fig. 4. If 40-MV/m accelerating gradient is available for the CCL, but we can only use half that for economic reasons, why did we limit the SSC injector point design by more than another factor of 2, to 8 MV/m? The CCL and DTL accelerating gradients were assumed fixed throughout; this is the common practice. Computer simulation showed transverse emittance growths through the DTL and CCL of 1.47 and 1.76. Much of this growth is because the beam from the preceding stage has not been properly conditioned for minimum emittance growth in the next stage. We know[4,5] that the transverse and longitudinal phase-space energy contents must be kept roughly equal (termed equipartitioned) at all stages of an accelerator, or transients will occur in the particle distribution that force emittance transfer between planes until equipartitioning occurs. In typical linacs, the longitudinal phase-space energy is larger than the transverse, and the transverse emittance grows, especially when an abrupt change in parameters excites new transients. The very high accelerating gradients suggested by the cost optimization would exacerbate the emittance growth considerably if we injected directly into the CCL at those gradients. The longitudinal emittance also would deteriorate from the effect of rf waveform nonlinearities. To realize the desired transverse emittance and energy spread for the point design, we limited the CCL accelerating gradient to 8 MV/m. Even then, the equipartitioning condition is badly violated and considerable emittance growth occurs in the transverse plane. The cost impact of operating at this nonoptimum gradient is significant.

Research into how to maintain equipartitioning through a linac is an important area for further work. We do know what the matching and equipartitioning conditions are for the rms beam parameters and have some knowledge of parameter space to avoid if minimum emittance growth is desired. One clear requirement is that the beam must be handled gently, with gradual deformations to a new state. We might be able to use the optimum 20-MeV/m gradient for a substantial fraction of the CCL by injecting at a low gradient and gradually shaping the acceleration parameters to bring the gradient up to 20 MeV/m.

Our conclusion to this point is that cost for this example would be higher than optimum because the need to bound emittance growth forces us to choose a below-optimum accelerating gradient. The maximum accelerating gradient achievable is about twice the optimum; thus, the possibility for a shorter machine cannot be exploited economically. It is probable that R&D on linac design that maintains equipartitioning would yield more cost-effective designs and even better performance, but utilization of the achievable structure gradient of 40 MeV/m would require work on reducing the cost per rf watt.

This latter point is crucial. Much has been said about searching for accelerator structures with hundreds of MeV/m gradients, to make shorter machines, but if rf power costs are not brought down correspondingly, the high gradients would not be economical.

There are some other important design constraints that can only be alluded to here. Wake-field effects limit the maximum allowable beam-power[18] to stored-rf-power ratio to only about 10%. Boyd[19] has shown how a stagger-tuning concept might significantly enhance the achievable charge transfer through a linac operating in a stored-energy mode. Gluckstern, Cooper, and Channell[20] recently have extended the wake-field analysis to include the effects of coupling between accelerating cells and external focusing and to elucidate the transient and steady-state conditions. An amalgamation of these considerations is now needed.

On frequency scaling, fig. 5 diagrams the possible limits to accelerating gradient for a structure with peak-surface-field to accelerating-gradient ratio of 2. The Kilpatrick-Limit line, which scales as $f^{1/2}$, was added to the electron-induced breakdown and surface-heating limits derived by Tigner and Prosnitz.[18] A frequency around 30 GHz may be at about the point of diminishing returns, and gradients of a few hundred MeV/m may be possible, assuming beam-dynamics and other practical considerations would allow their use.

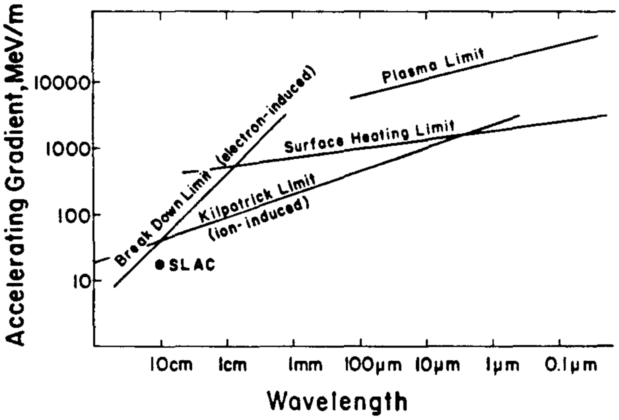

Fig. 5. Approximate limits on accelerating gradient, for structures with assumed ratio of peak surface field to accelerating gradient equal to 2, vs wavelength. Kilpatrick-Limit line also assumes peak surface field of twice Kilpatrick Limit.

As noted, cheaper rf at around 30 GHz would have to follow. Prosnitz[21] outlines high-power, high-frequency rf generator development work now in progress; there are disadvantages in that many of these devices are oscillators, rather than amplifiers in which amplitude and frequency or phase can be controlled, and many require high magnetic fields that add to the cost. Reliability also is not adequate yet. At high gradient, the amount of power required per meter is high, although at high frequency, the amount of energy needed per meter is dramatically reduced because $E^2 \propto \omega^2 U$. Tube-type sources can produce relevant unit-power/m at 10 GHz, but not yet at 30 GHz, where paralleling would be needed. Given these uncertainties, I have not tried to estimate the $/rf-watt cost for these drivers, but imagine that it would still be roughly equal to the present price. In this case, high accelerating gradient would not be economical. We proceed to discussion of ideas having the potential to resolve some of the cost dilemma.

Evolution of Integrated Structures

Tigner[12] shows an evolution of a near-field linac circuit (fig. 6) that guides us from today's separate linac structure and microwave tubes to coupled source and accelerator structures along the lines of the energy-recovery FEL system and, finally, to a fully integrated structure in which the transformer action between a low-voltage/high-current driving beam is integrally coupled to a high-voltage/low-current accelerated beam. Such schemes belong in Category 1.B of fig. 1, with free charges in the EM source or the driving beam. The point is that there appears to be a possibly fruitful middle ground to explore, with collective-effect beams interacting indirectly through a vacuum medium, before attempting to tame the very formidable physics of Category 2.

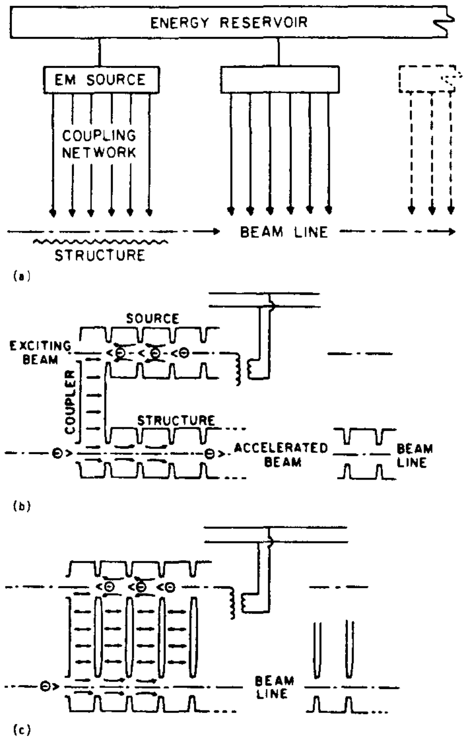

Fig. 6. Structure evolution from Tigner.

Tigner also shows the general aspects of system efficiency, beam power divided by prime power, as the product of power conversions through the system. In fig. 6.a, there is energy-reservoir efficiency to dc for the EM sources, and subsequent efficiencies for the sources, coupling network, the structure itself, and structure to beam. EM source, structure, and beam efficiencies are not very high, and overall efficiencies per bunch for HEP applications are now less than a per cent. The progression from fig. 6.a to 6.c is seen to be an attempt to more tightly couple the system and eliminate some of the serial inefficiencies. A wide variety of such integrated schemes have been proposed already and some development work is starting. A few will be outlined here.

Prosnitz[21] goes on to exploit fig. 5 by proposing a two-beam linac that would accelerate 5 x 10^{10} particles per bunch to 300 GeV at 1-kHz repetition rate in a 35-GHz, $\pi/3$-mode, Jungle-gym-type structure with Z = 210 MΩ/m, Q = 2.6 x 10^3, operating at 200-MeV/m accelerating gradient. The rf power requirement is 235 MW/m, but only 12 J/m with 50-ns pulses.

The driver would use a low-voltage (1.8-MeV) but high-current (500-A) electron beam and would convert its energy to 35 GHz rf, using distributed wigglers in a single-pass FEL source/amplifier. FEL wiggler and induction-linac sections would be alternated so that the electron beam energy lost in a wiggler section (decelerating gradient 1.6 MeV/m) would be made up in the next induction-linac section. With 1.8-MeV/m equilibrium beam voltage and 350-A bunched current, it is estimated that 570 MW/m of rf could be produced. The conversion efficiency is estimated to be very high, ≥70%, which is better than klystrons, especially high-peak-power klystrons, at 3 GHz and below. The rf is used to drive the high-voltage, low-current accelerated beam, so that the entire system is like a transformer.

A costing analysis[14] shows that the construction methods for the FEL/induction-linac driver might make the rf cost as low as 5 x 10^{-4} \$/rf watt, for which the optimum accelerating gradient would equal the design value of 200 MeV/m. So this approach, if the very formidable technical problems could be solved, could at least be run at the economic optimum. Not the least of the technical problems is to find a way to couple power out of the FEL generator over to the accelerator, or to combine them without a separate coupler.

At least two more of these integrated schemes will be discussed in detail at this conference—both use to advantage the wake fields discussed above as problems. Y. Chin of Tokyo shows how a tightly bunched drive beam passing through one focal point of an elliptically shaped cavity can generate a wake field that will propagate to the other focus point where it might be used to accelerate another beam. An experiment on this idea is also in progress at the high-peak-intensity electron-linac facility at the University of Osaka in Japan. G. Voss and T. Weiland of DESY also discuss their wake-field accelerator.

The transformer action implicit in fig. 6 provides a key for imagining other schemes. A. Maschke once discussed a "low-impedance" driver approach in which a cylindrical cavity would be densely covered by many loop-coupled, low-voltage triode drivers, providing fields for an accelerated beam on-axis. A "medium-impedance" approach might couple klystrons, with electron beams in the hundred-kV range, directly to the accelerator cavity. Other schemes use induction-linac-generated beams driving the coupling cells of an off-axis coupled-linac structure, with the drive beam refreshed every so often by another induction-linac section. A "high-impedance" scheme might use a driver linac followed by a storage ring to generate a high-voltage driver beam of the proper time structure to feed into an accelerator structure.

Short Update on Laser Beat-Wave Accelerator

An experiment was conducted[22] on the Los Alamos Helios laser without modification to two-line operation to search for production of ultrahigh energy electrons by interaction of an intense (10^{16} W/cm^2) 10-μm beam with a preformed plasma. Simulations had indicated that forward Raman scattering of a single-frequency laser beam could produce acceleration to several MeV. Figure 7 shows the setup. One Helios beam, defocused to 500 μm on a target, is used to create the preformed plasma, which expands for 4 ns. The second beam then excited the plasma with 600 J in 1 ns, with 10^{14} to 10^{16} W/cm^2 by changing focusing. The interaction region was probed to assure the plasma was underdense, and to look for sub-MeV and many-MeV electrons.

The conclusion from the visible-light diagnostics (streak imaging and shadowgraphy) suggests that the plasma beyond 1 mm from the target surface was indeed underdense. [Light will not propagate through a plasma above the critical density (Nc)—where the plasma and laser frequencies are equal.] The plasma shape and density profile were well determined. The peak plasma density at 1.5- to 2.0-mm separation lay between Nc and Nc/4, with no backscatter interaction observed at much larger separations (lower densities).

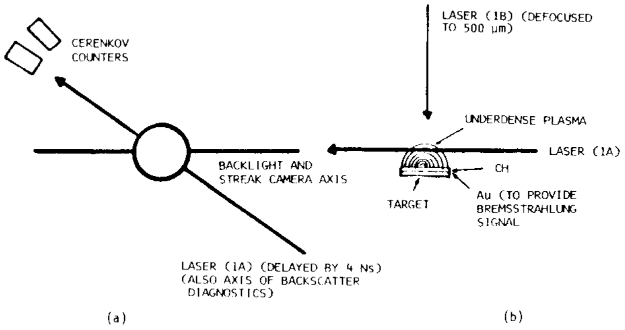

Fig. 7. Side view (a) and top view (b) of setup for laser beat-wave accelerator experiment.

Spectrometer measurements put bounds of ≤10% on the absorption of laser light into sub-MeV electrons at 1-mm separation; this was encouraging. Sensitivity prevented observation of a predicted temperature rise in the low-density plasma.

There was a gap in the detection capability from 1-15 MeV; Cerenkov counters for energies above 15 MeV were used to look for high-energy electron production, but no signals were observed. In future work, this instrumentation gap and better sensitivity must be addressed.

The Helios laser rise time is about 300 ps. This may be too slow—analysis shows channel rarefaction and dephasing effects on a 30- to 60-ps time scale. Also, the use of one laser frequency is not as good as two in terms of maximum electron energy or coherence; however, two frequencies cause even faster channel rarefaction. Further experiments have been proposed on Antares, using two frequencies and rise-time enhancement.

Multidisciplinary Emphasis

Finally, the multidisciplinary nature of accelerator technology is emphasized. The physics and engineering disciplines must interact very closely to produce equipment that can provide effective particle acceleration within the multitude of practical constraints and with efficient, reliable operation. Reference 23 indicates some of these activities from an engineering orientation. Plasma physics will be required, as will materials science.

The way looks exciting. As pointed out by Tigner, a dedicated commitment—personal as well as institutional—will have to be made and sustained to advance along that way.

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