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Author

Sessler, A M

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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

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A.M. Sessler

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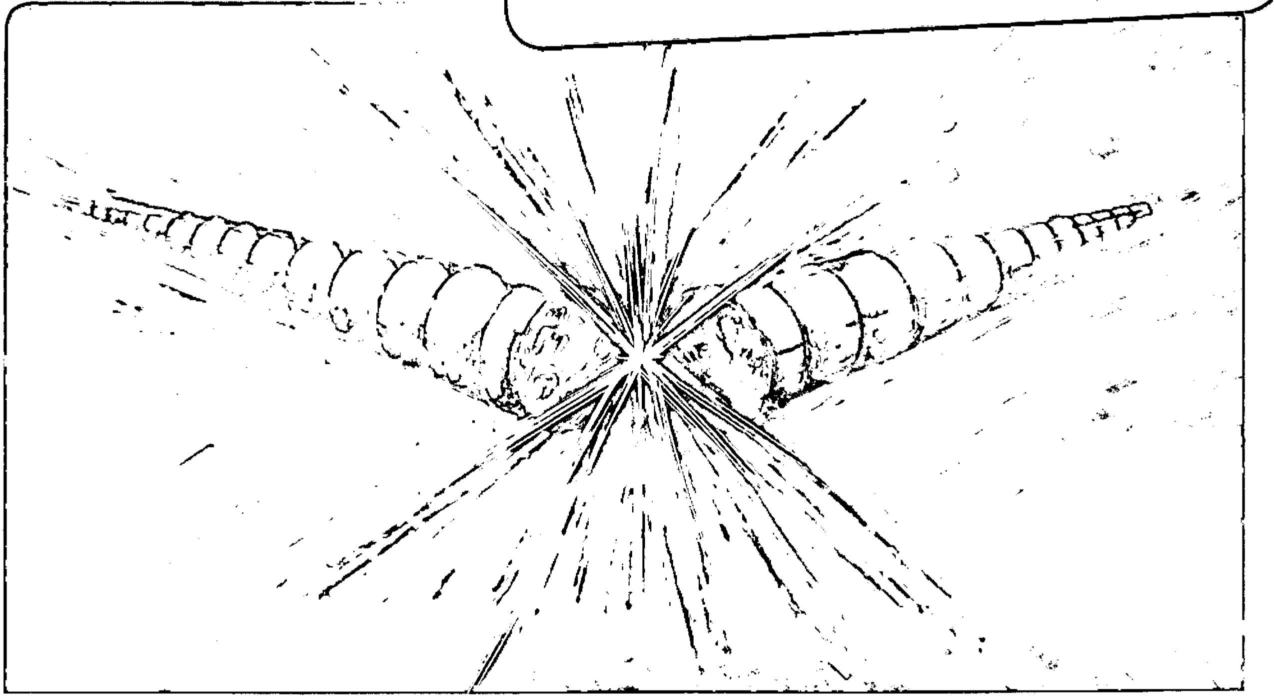

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LASER ACCELERATORS*

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

Summary

Laser accelerators may be conveniently characterized, by their mode of operation, into media, far-field, and near-field accelerators. The first category -- media accelerators -- include the Inverse Cherenkov Effect Accelerator, the Plasma Focus Accelerator, and the Beat Wave Accelerator (BWA). The second category -- far-field accelerators -- include the Two-Wave Device and the Inverse Free Electron Accelerator (IFEL). The third category -- near-field accelerators -- includes conventional linacs scaled to small dimensions, dielectric sheets, small holes in dielectric cylinders, and gratings. Attention is devoted to an example from each category; namely (1) the BWA, (2) the IFEL, and (3) the linac scaled to small dimensions (about 30 GHz) and powered by a free electron laser (FEL). Finally, special attention is given to grating accelerators.

Introduction

The use of the large electric fields of lasers for the acceleration of particles has fascinated physicists for many years. Last year, a first Workshop devoted to this topic was held and the Proceedings of this Workshop make interesting reading.[1] It was concluded, in the Brief Report on this Workshop, that "the potential of laser-driven accelerator devices justifies devotion of resources for their further study and experimental exploration."

In this review paper we shall sketch the concepts and experience which led to the above-quoted conclusion. Of course this paper is not a substitute for Ref. 1, but we hope it will serve as an introduction to Ref. 1.

There are many papers in the literature on the laser acceleration of particles, and two excellent review papers have been presented at this very series of conferences.[2,3] They provide the background with which the reader can readily tackle this paper; in fact, this review is simply an up-date of the review by Palmer. Attention is also called to the fine review of the Workshop which recently appeared in Physics Today.[4]

General Principles

Prior to the Workshop a few people, no doubt, had a clear understanding of what could, and could not be done with electric fields so as to accelerate particles. Most people, however, had quite a cloudy view of this subject and the literature, unfortunately, did little to help for one could find in it schemes which would work, schemes which would not work, theorems which proved certain configurations would not work, and very complicated proposals some of which worked and some of which didn't work. Perhaps the most important output of the Workshop is a community of physicists who understand what can and can not be accomplished.

As is often the case in physics, once a situation is understood it turns out to be very simple and one can't understand how it could ever have appeared to be complicated.

To accelerate particles by the oscillating field of an electromagnetic wave one must maintain the particles in synchronism with the wave. (Otherwise the acceleration will be cancelled out by deacceleration such as is experienced by a free electron subject to a passing pulse of light, which one can think of as many Fourier components each of which does nothing on the average.) In addition to synchronism one must have, of course, an electric field component along the direction of the particle motion.

There are only two ways to achieve these conditions: (1) either one slows the wave down (and lets the particle travel in a straight line), or (2) one bends the particle continuously and periodically (and lets the light wave travel in a straight line). (I suppose one can combine these two concepts, but that only complicates the subject and, so-far, all proposed devices employ only one method or the other.)

1. Slow Electromagnetic Wave. Conventional linacs work this way: One makes a slow wave structure in which the electromagnetic field "bounces around" in a periodic structure or, as it is usually described, the wave has a phase velocity less than in free space and hence can resonate with a particle.

This concept can be used at higher frequencies than have been employed to date and one interesting concept, which we shall discuss at greater length below, is "simply" (There are great technological difficulties.) the extension of slow-wave linacs to (say) 30 GHz.

It is not possible to construct a slow-wave device of the usual (cylindrical) type at very high frequencies such as that of a 10 μm CO_2 laser. However it is possible to make planar slow wave structures which can be periodic (gratings) or dielectric loaded (and not necessarily periodic). Of course, just as in ordinary linacs, one must be (roughly) within a wavelength of the walls of such a structure. Thus devices of this class are called Near Field Accelerators.

There is another way in which one can slow an electromagnetic wave down; namely to have it travel in a media. Devices of this type are called Media Accelerators. In this case the particle which is to be accelerated must also travel in the medium and hence is subject to scattering which limits the length of such a device. The Inverse Cherenkov Effect Accelerator is simply such an accelerator.

(One can try to be clever and make a hole in the medium so the particle is not subject to scattering. Clearly, the hole cannot have a radius much larger than a wavelength, and thus one is simply considering, again, a Near Field Accelerator; i.e., a small hole in a cylindrical dielectric slow wave device.)

The media, which slows the electromagnetic wave, could be more responsive to the wave than simply becoming polarized, as is typically the case when

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there is an ordinary index of refraction. Thus if the media is a plasma, and for very intense light pulses ionization will happen to <u>any</u> media, there opens up the very interesting possibility of a collective field laser accelerator. The Beat Wave Accelerator, which will be discussed later, is exactly this.[5]

2. Periodic Particle Bending. Alternatively to slowing the electromagnetic wave down, one can wiggle the particle so that the motion is, partially, along the transverse electric field of the accelerating light wave. Of course, synchronism with the electromagnetic wave is necessary and this is simply accomplished by wiggling the particle periodically and having the particle pass through one period of the structure while one period of the electromagnetic wave passes the particle. Devices of this type do not have to have the particle close to a material boundary and, hence, are called Far Field Accelerators.

Such a wiggling device, when operated in the reverse direction, and when the particle wiggling is accomplished by a static magnetic field, is known as a Free Electron Laser; when operated in the forward direction it becomes an Inverse Free Electron Laser Aceelerator.

The wiggling of the particle does not have to be done by a static magnetic field, but could be done by an electromagnetic wave. If a microwave field is employed for this purpose then the device is known as a Two-Wave Accelerator.[7]

The Beat-Wave Accelerator (BWA)

The Beat-Wave Accelerator (BWA) is a media accelerator in which the media is a plasma.[5,8] Two different lasers, at frequency ω_1 and ω_2 are arranged to fire in the same direction into a plasma. When the frequencies are such that $\omega_1-\omega_2$ is the plasma frequency ω_p then a resonance takes place and the plasma bunches at the beat frequency. This bunching produces a longitudinal electric field which, then, can be employed to accelerate particles.

One can think of the process of plasma-laser interaction as non-linear forward Raman scattering. This process can lead to a very large longitudinal electric field which is oscillatory and moves with a velocity close to, but less, than the velocity of light. To develop an acceptable accelerating field one needs to drive the plasma hard (so as to be in the non-linear regime) and have a very hot plasma (so as to Landau damp the backscattered Raman Wave). Although one can make some progress on this problem analytically, one-dimensional particle simulations have provided the most insight into the subject. In Fig. 1, obtained by Sullivan and Godfrey, can be seen how a large accelerating field is developed in the BWA.

First experiments have been performed by Joshi, et al., and support the theory, at least to the extent of demonstrating the acceleration of particles and the strong dependence on plasma temperature.

Of course, many questions need to be answered before a BWA is made into a practical device; some of these questions are listed in Ref. 1. Nevertheless, it is interesting to consider what a full-scale machine would be like. Figure 2 shows such a conceptual design.

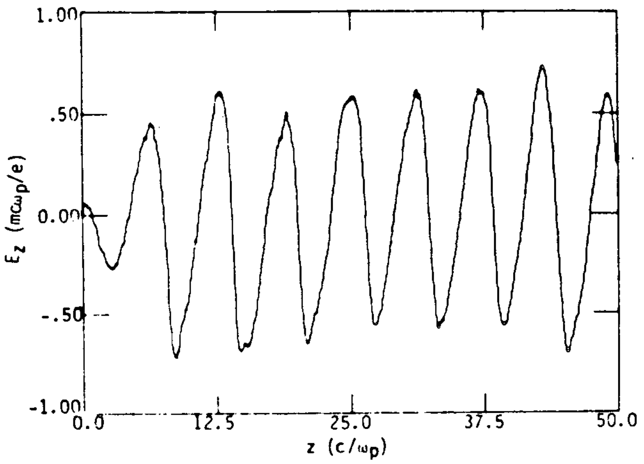

Fig. 1. Longitudinal electric field as a function of distance $\tau = 120\ \omega_p^{-1}$. Simulation parameters are $\omega_1 = 10.6\ \omega_p$, $\omega_2 = 9.6\ \omega_p$, the initial laser field strength is $5.0\ mc\omega_p$ and $T_e = 10$ keV is the plasma temperature. (From Ref. 1, p. 63).

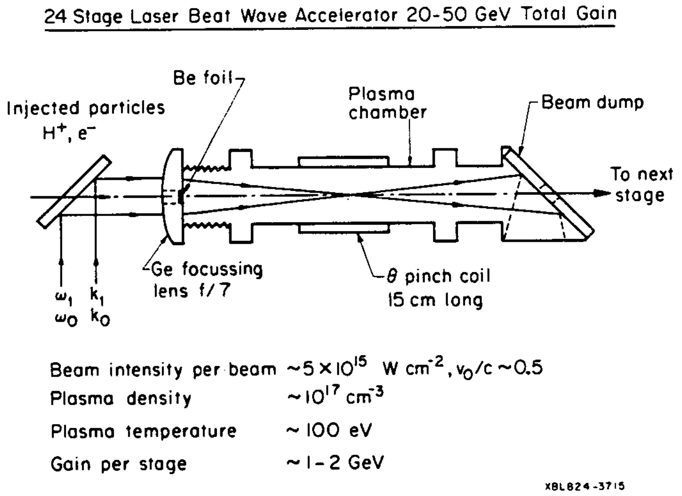

Fig. 2. A full-scale Beat Wave Accelerator for producing electrons of 20-50 GeV, with 24 stages and each stage giving 1-2 GeV to the electrons. (From Ref. 1, p. 25).

Further progress demand, and will obtain, theoretical and experimental work. The BWA is the most speculative of the laser accelerators (i.e., it may not be possible to construct a very high energy accelerator with this approach), but holds out great promise as it combines the best features of laser acceleration and collective acceleration.

The Inverse Free Electron Laser Accelerator (IFEL)

This device, which is a far-field accelerator, consequently has important advantages over representatives of the other classes of accelerators. Firstly, the particles and the laser beam do not go through a medium and thus problems of scattering and break-down of the media are avoided. Secondly, the accelerated beam is not constrained to be near a material boundary and thus problems of transverse emittance limitations and, much more importantly, beam loading limitations are greatly alleviated.

Thirdly, the acceleration region is removed from the boundaries and, hence, electric breakdown of the walls and heating (or even destruction) of the walls is avoided.

A picture of one element of this device is shown in Fig. 3, which is taken from the article by Pellegrini in Ref. 1.[9] A summary of Workshop activity on the IFEL can be found in this very article.

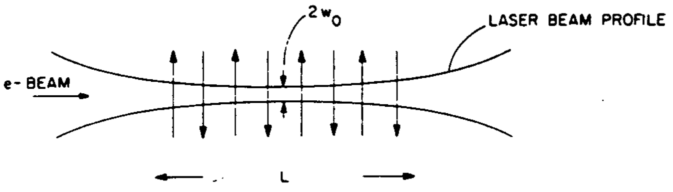

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Fig. 3. Schematic representation of an IFEL acceleration region. A laser beam and an electron beam traverse an undulator magnetic field of length L. The laser beam profile is assumed gaussian with a waist radius w_0. (From Ref. 1, p. 151).

Although significant acceleration can be achieved in one acceleration region, a high-energy acceleration requires many acceleration regions. This might be accomplished either by refocussing the laser beam (a technology which has not yet been developed, but may be amenable to attack) or by using multiple laser beams (which could become quite expensive). The second option, which surely can be accomplished, is shown in Fig. 4.

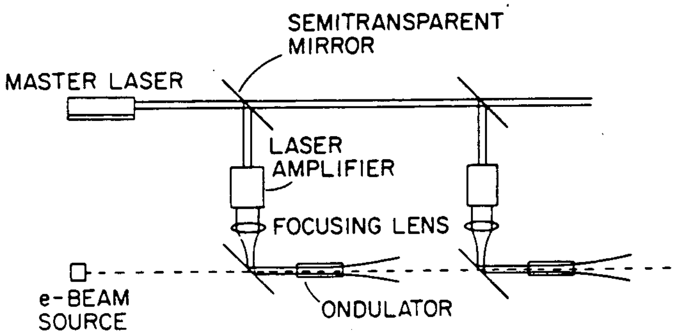

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Fig. 4. Conceptual design of an IFEL accelerator using multiple laser beams and acceleration regions. (From Ref. 1, p. 152).

In an IFEL one must preserve the resonance condition, which involves the electron energy, between the wiggler period and the laser frequency as the electron is accelerated. This can be accomplished either (1) by keeping the period of the wiggler constant and having the wiggler magnetic field increase down the accelerator or (2) by keeping the magnetic field of the wiggler at a constant amplitude and having the wiggler period become longer down the accelerator. (Of course, one could mix-up these two extremes.)

The second option has the advantage that the electron synchrotron radiation loss only increases as γ^2 (vs γ^4 in the first option). Up to a few GeV, which is the case in one accelerating region, either option can be employed.

Typical parameters, based on a laser of 2 x 10^{14} W and a pulse length of 1 ns are given in Ref. 1. One can accelerate currents of up to 5 kA to energies of 4.0 GeV in an accelerator of 40 m.

The basic physics of an IFEL has been demonstrated in the work being done at LANL, MSNW, and TRW on the FEL. Thus the way would seem to be clear for a major experimental study of the IFEL. Only in this way, can one really learn what limitations there are in an IFEL. Of course, multiple acceleration stations is essential for a high-energy accelerator and this probably requires the capability of transport and refocusing of laser beams. The need for such capability is common to a number of laser accelerators and should be pursued.

The Two-Beam Accelerator (TBA)

One of the results of the Near-Field Working Group at the Workshop was the realization that many advantages could be achieved if a linac were operated at (say) ten times the frequency of SLAC; i.e., at a free-space wavelength of (about)1 cm.[10] In particular, it was thought possible to obtain a gradient of 400 MeV/m at this frequency. (Recall that for the SLC, SLAC will operate at a gradient of 17 MeV/m.)

In this frequency range there are no adequate high-peak-power sources, except, possibly, a free electron laser (FEL). The Two-Beam Accelerator (TBA) employs an FEL to produce radiation which then powers a conventional structure. One of the beams is intense (~ 1 kA), low energy (~ 3 MeV), and long (~ 30 m). The other beam -- the particles we are really interested in -- consists of a few particles (~ 10^{11}) in a short bunch (~ 1 mm) which are taken to very high energies (~ 375 GeV) in (about) 1.5 km. Operation at a repitition rate of 1 kHz -- which would be quite feasible for the FEL -- yields a luminosity of 4 x 10^{32} cm^{-2} sec^{-1}. A conceptual sketch of a TBA is shown in Fig. 5.

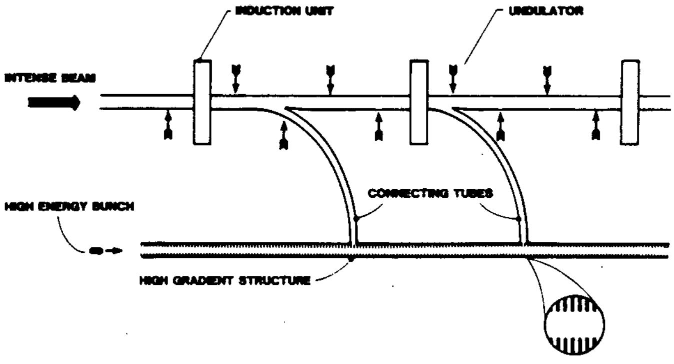

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Fig. 5. Conceptual design of a TBA showing the steady state FEL with its high current beam and the high-gradient structure which accelerates particles to very high energy.

The TBA is really a power transforming device; i.e., it takes power from the power lines to an induction accelerator, to a low energy beam, then to radiation (via a wiggler) which powers a high-gradient accelerating structure, and, finally, to the few high-energy particles one is interested in. Thus there are a number of components of a TBA which need to be studied (especially before optimizing the whole system).

Some components are, in light of the work of the last decades, rather straight-forward. We would, for example, put the induction accelerator in this class. Other parts of the TBA, however, require further development, such as, for example, the FEL and, most particularly, a "steady state FEL"; i.e., one that neither gains nor loses energy of its powering beam for many kilometers.

Some parts of the TBA need considerable study, such as the "pipes" which take the microwave power from the FEL to the accelerating column; i.e., this coupling needs to be investigated and optimized. Another part of the TBA which needs work is the high-gradient accelerating column which is very small and, yet, is required not to break down electrically.

All in all, however it was felt by many at the Workshop that learning how to build and operate an accelerator at 1 cm would be a good step from current experience at 10 cm towards a CO_2 laser at 10 μm. It may be possible to obtain this experience without the TBA; i.e., with some more conventional power source, but if it could be made to work the TBA has a certain neatness and compactness which is most attractive.

Grating Accelerators

The popular conception of a "real" laser accelerator is a grating accelerator. (See Fig. 6) This "popular conception" may be distorted for, as we have seen, there are a number of other laser accelerators such as the BWA, IFEL, and TBA which certainly work and may have attractive features. But grating accelerators certainly, also, work and they hold out the promise of obtaining very high energies (albeit for only a few particles) with very small energy expenditure.

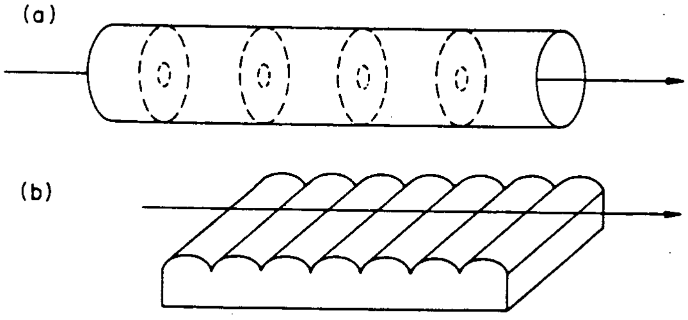

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Fig. 6. In Fig. 6a is shown a conventional linac (slow wave disk loaded structure) which could be scaled down to centimeter wavelengths, but not much further. In Fig. 6b is shown a grating linac which can certainly be scaled to micron wavelengths and can, like the conventional linac, accelerate particles. (From Ref. 1, p. 187).

Much effort, at the Workshop was devoted to grating accelerators.[11] Scaling laws with wavelength were derived and a comparison between conventional linacs and gratings was developed. In particular, it was seen that a grating accelerator will need very little RF energy.

Transverse stability of beams was studied and shown to be present in an alternating gradient version which appears to be achievable. Also, attention was given to the tolerances on gratings and shown not to impose unusually stringent requirements on the construction of grating accelerators.

Considerable attention was devoted to the limits on accelerating graidents. (Such things as surface destruction by heating, "shorting-out" of the grating by the plasma created by a very intense laser pulse, and electric breakdown.) It was shown that at (about) 1 cm wavelength operation one can expect gradients of 400 MeV/m, but that beyond that the growth is small (perhaps "only" reaching 800 MeV/m at 10 μm at the surface heating limit).

Beam loading was examined and shown to impose a serious limit on grating accelerators. (Essentially this is because the beam is, necesarily, so close to the conducting surface.) In particular, at 10 μm, one can probably only have 10^5 electrons in a bunch.

Clearly, much more work is demanded -- and needed--on grating accelerators, but grating accelerators hold out the promise of accelerating particles to very high energies.

Conclusion

The field of laser driven accelerators has been put upon a firm foundation and is "worthy of serious attention by the accelerator community".[12]

A number of schemes, which have both solid theoretical basis and experimental proof of the concept, need considerable more theoretical and experimental work before one can determine whether -- or not -- they have advantages over conventional accelerators. In this report we have gone into three schemes and mentioned a few others. It is much too early, however, to choose between schemes. It is also important to be open for new schemes, which may be better than any put forward to date.

On the other hand, also, the field needs to be advanced by research and development on areas which are device independent.[12] These include theoretical studies; material breakdown and damage studies; development of high-quality radiation sources; focusing, transporting, and manipulating high-power laser beams; and nonlinear effects in media. A start on some of these subjects has been made in the many contributed papers which can be found in Ref. 1.

Acknowledgments

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8. See Ref. 1 the articles by A. Sessler p. 10, C. Joshi, p. 28, D. J. Sullivan and B. B. Godfrey p. 43, T. Tajima and J. M. Dawson p. 69, and R. D. Ruth and A. W. Chao p. 94.

9. See Ref. 1, the article by C. Pellegrini p. 138.

10. See Ref. 1, the articles by R, Palmer p. 179, and A. Sessler p. 154.

11. See Ref. 1, the articles by R. Palmer p. 179, Kwang-Je Kim and N. Kroll p. 190, P. Wilson p. 199, T. Weiland, p. 203, N. Kroll p. 211, P. Csonka p. 216, N. Kroll p. 237, P. Channell p. 244, and P. Csonka p. 248, 266.

12. See Ref. 1, the article by P. Channell *et al.* p. 1.

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720