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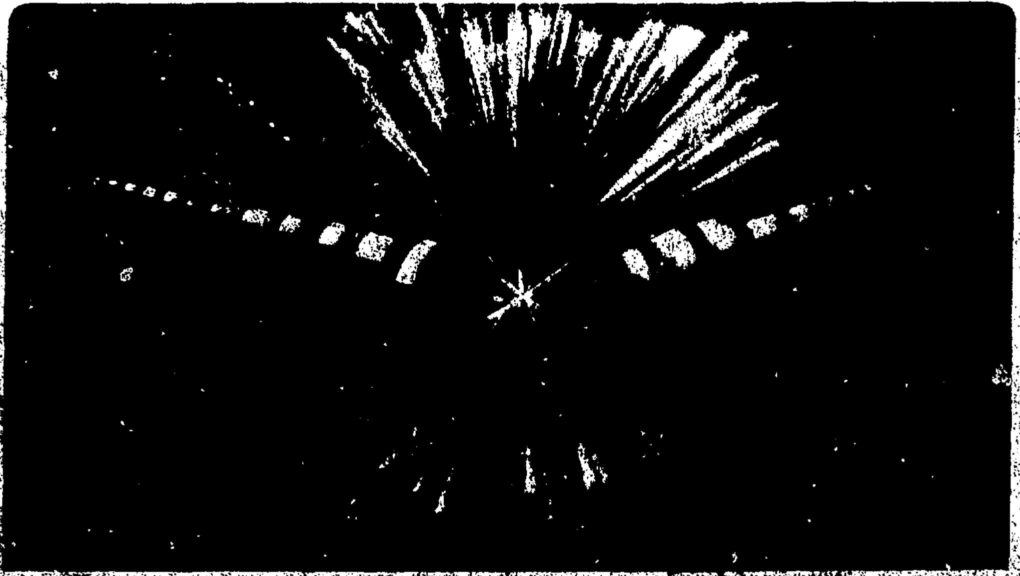

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FUTURE ACCELERATOR TECHNOLOGY*

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ABSTRACT

A general discussion is presented of the acceleration of particles. Upon this foundation is built a categorization scheme into which all accelerators can be placed. Special attention is devoted to accelerators which employ a wake-field mechanism and a restricting theorem is examined. It is shown how the theorem may be circumvented. Comments are made on various acceleration schemes.

INTRODUCTION

We know the high-energy accelerators of the present: TEV I, TEV II, SPC, CERN Collider, PEP, PETRA, CESR, etc. and we look forward to the accelerators of the near future: TRISTAN, SLC LEP, HERA, SSC, UNK, etc. What about the distant future? Can we continue to build ever-larger machines? The circumference of LEP is 27 km; the SSC is projected to have a circumference of 83 km.

An examination of the Livingston graph, Fig. 1, accelerator energy as a function of time, shows that the envelope of accelerator types is a straight line on the semi-log plot. Available energy is ever-increasing, but even more important is the fact that any one technology (a squiggly line on Fig. 1) saturates in its capability; it is only the envelope of lines which continues to rise.

The message is clear: we must develop new technologies, new squiggly lines, if we are to stay on, or anywhere near, the exponential rise in energy which we have experienced in the past. In this paper we survey various technologies which may, someday, contribute squiggly lines to the Livingston graph.

A general survey of new accelerator technologies has been given recently,[1] while much more detailed papers can be found in the proceedings of the two conferences, one held in 1982 and one held in 1985, devoted precisely to the very subject of novel acceleration techniques.[2,3]

CATEGORIZATION

All accelerators use the electromagnetic force. Depending upon the frequency employed one has acceleration by a DC

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potential drop, by rf waves, or by lasers. The last are particularly potent having fields at a focus of 10^4 - 10^6 MV/m(this is with "present - day" lasers). The last should be compared with the accelerating gradient of the Stanford Linear Collider (SLC) which is the largest gradient of any practical accelerator and is 17 MV/m.

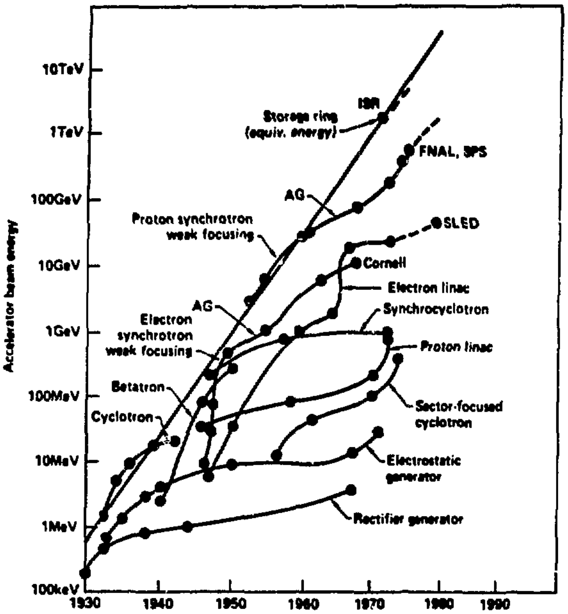

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Fig. 1 The Livingston graph of accelerator energy as a function of time. At the same time as energy has been increasing exponentially cost per unit energy has been decreasing exponentially.

However, there are difficulties; namely (1) the field is in the wrong direction, (2) the field is only intense at a focus and a focus isn't very deep so that a particle quickly passes out of the strong field region, and (3) there isn't synchronism between a material particle and a luminous wave.

A particular accelerator scheme must overcome all three of these problems. Infact, as we know, for accelerators <u>do</u> exist, all three problems can be overcome. Before one goes more deeply into the various schemes it is useful to put the above observations on a more formal basis.

A theorem-form of the argument has been formulated by R. Palmer.[4]

<u>Assume</u>:

1. The interaction with light takes place in a vacuum.
2. The interaction takes place far from all dielectrics and conductors.
3. The accelerated particle is sufficiently relativistic that its motion is in a straight line and with constant ($\simeq$ c) velocity.

Then:

There is no acceleration.

We shall not give a proof of this theorem here, but--in a way--it is obvious. Thus all accelerators must violate one, or more, of the hypotheses of the theorem. This allows us to conveniently categorize all accelerators as we have done in Table 1.

Although the categorization of Table I is very useful, people have not devised various schemes with the theorem and categorization in mind. It is, therefore, useful to list all of the pratical high-energy accelerator schemes, of which I am aware, by type. (Of course these could be easily categorized and it is useful to do that.) The result is presented in Table II. One notes in this list that essentially all of the schemes employ the large peak power of lasers or of particle beams. This is quite natural for there is need for large peak power and there are very few other possible choices.

How do the schemes of Table II address the three problems, which we noted at the start of this section, with acceleration by an electromagnetic wave? In diverse ways, and it is a good test of ones understanding of each scheme to see how this is accomplished. For example, take the Surfatron. (See Refs. 2 and 3.) Here the transverse waves of two laser beams are employed, via the beat wave and the non-linear mechanism of a ponderamotive well, to resonantly excite a plasma wave. The plasma wave is longitudinal; i.e. the electric field is now longitudinal; that is, it is "pointing in the right direction." The plasma is expected to provide self-focusing of the light; i.e. to make a channel for the light so that the focus is very deep and not "outrun" by the particle. Finally, synchronization is maintained by having a (small) vertical magnetic field so that the particle gains transverse velocity, and mass, as it is accelerated, but its longitudinal velocity is unaltered and "synchronism is maintained" with the plasma wave.

As a second example consider the laser excitation of an open structure. In this configuration the incident laser light excites a surface wave which has a major component of field along its direction of motion. This is possible within a wavelength of surface, but not--of course--in free space where the solutions of Maxwell's equations must be transverse waves. The wave can be made to run along the surface; i.e. to maintain acceleration over long distance. Synchronisms is maintained for-- as we all know--slow wave structures can be built by (suitably loading a longitudinally smooth metal structure so that the phase velocity of the wave is less than c).

WAKE-FIELD ACCELERATORS

In a wake-field accelerator a large number of particles, N_1, of rather low energy, E_1, are used to accelerate a small number of particles, N_2, to a very high energy. Conservation of energy yields a simple relation between the energy gain of the second group of particles, ΔE_2, and the energy loss of the first group. For a passive structure clearly

$$N_2(\Delta E_2) \leq N_1 E_1,$$

since the first group of particles can't lose more energy than they have.

We thus obtain a restriction on the energy gain of a particle of the second group,

$$\Delta E_2 \leq \frac{N_1}{N_2} E_1 .$$

We can make N_1 very large and thus make the "transformer ratio," defined by

$$\Delta E_2 = R E_1,$$

very large.

The wake-field theorem[5] puts a restriction on the transformer ratio R:

<u>Assume</u>:

1. The bunches of particles can be approximated by delta functions.
2. The two bunches move on the same straight line through the device.
3. The device is arbitrary (It could be made of metal, or contain a plasma, etc.), but passive.

<u>Then</u>:

The transformer ratio is less than or equal to two; i.e.

$$R \leq 2.$$

We shall not prove this theorem here; I urge the reader to attempt to construct his own proof. (Hint: No new physics needs to be put in! One only employes conservation of energy, but recalls that it applies for all values of N_1 and N_2.)

In order to make an interesting wake-field accelerator one has to devise a scheme in which R is much larger than two. Thus the assumptions of the theorem need to be violated and all wake-field accelerators can be categorized by which of the assumptions they violate.

The electron-ring device, the wake-field transformer, has the second group moving along the axis of the electron ring thus violating the second assumption. The expected transformer ratio, here a consequence of the radial implosion of the electromagnetic wave, is between 10 and 20.

Bunch "shaping"; i.e. giving the bunch finite extent, and properly shaping it, is the basis of two recently proposed devices. The first is the resonant excitation of plasma waves by means of bunches of electrons[6] while the second scheme uses the first group to "charge up" a plasma and then creates a radial current implosion by a triggering laser.[7] (This scheme violates not only the first, but also the third, assumption.) In both schemes the expected transformer ratio is very large indeed.

COMMENTS

Little purpose would be served by my describing, here, some-- or even all-- of the acceleration schemes listed in Table II. Most of them have been described superficially in various review articles and comprehensively in the cited references. Rather I will make some comments, perhaps more of an editorial nature, on a number of the proposed approaches. The reader should understand that this section contains "opinions", as contrasted with "hard fact" and that, furthermore, these are the opinions of only one person and not even that of a committee of people!

Work on future accelerators can be divided into three broad sections. The first consists of improved power sources, the second of developments which might impact the next collider (The one after the SLC.), and the third of really far-out developments. Let us take them in turn.

The SLC will begin to provide experience with colliders next year. The run-in time is planned to be a number of years because there are many novel aspects to this device. Hopefully, it will work as predicted and, if so, there will be very large "user pressure" to as quickly as possible build another collider.

What form would such a collider take? It would, naturally, be built very similar to the SLC, but perhaps, to improve efficiency, cut power costs, and increase the accelerating gradient (so as to cut the length) it would operate at a higher frequency than SLC (10 cm wavelength rf). Maybe it would operate at a wavelength of 3 cm or 5 cm.

The development of power sources for such a collider is a major effort of a good number of laboratories. There is work both in the US and Japan, on the lasertron. There is work being done on gyrotrons in the US and (presumably) in the Soviet Union. There is some effort being put on Free Electron Lasers in the US and in Japan. And there is work on pulse multiplying, and on the use of intermediate superconducting linacs, in the US and in CERN.

The major effort is being put into the lasertron and it is hoped that the development effort will "pay off"; ie that the next collider will be built with them.

Turning, now, to schemes that might impact the next collider we find three. The first is the Switched Linac (SL) which is being pursued most vigorously at CERN and to some degree in the US. This scheme depends upon the development of laser switches and has associated with it many questions of jitter, lifetime, alignment, etc. Nevertheless it is a most interesting idea, directly matched to the requirements of a collider, and novel in its approach.

The second is a Wake-Field Transformer (WFT), perhaps with electron rings as the driver. This is being studied at DESY and, to a small degree, in Japan. The primary problem seems to be to provide a proper driving beam, although there are, also, questions of alignment, etc.

The third is the Two-Beam Accelerator (TBA). Work on this is being done in the US. That a free electron laser (FEL) is a prodigious source of power has already been demonstrated, as has the ability of a high-gradient slow wave structure to hold an accelerating gradient at least 10 times that of the SLC. Major problems, such as phase control of the rf and "steady-state" operation of the FEL, remain to be addressed experimentally.

We note that all three of these schemes aim for an accelerating gradient in the range of a few hundred MeV/m. All of them are devices in which one is "close to a conductor"; i.e. within a wavelength of the surface. All three have an effective wavelength in the 1 cm - 2 cm range. The SL and WFT are devices which use shock excitation of the accelerating structure while the TBA uses resonant filling. All three devices are specially designed to the needs of a collider. (Note that in a collider the bunch is only, about, 1 mm long which is quite different than the pulse train in most rf linacs. In SLAC it is 500 m long.) Finally, all three schemes hold out the hope for more efficient operation than the conventional linac. Needless to say, each these three devices would be quite a departure from the usual accelerator structure and, therefore, bring new problems to the accelerator physicist. We can't predict what problems will arise, but they will surely cost in time, money, and reliability. Very soon, in a few years, all three of these approaches, provided they still look attractive, will be ready for scale-up to the next level of experiments.

Turning, now, to really far-out developments the field is -- by definition -- wide open. However there are only two approaches which, so far, have received significant attention; namely, droplets, grating, and open structures or Near Field Accelerators (NFA) and Plasma - Laser Accelerators (PLA).

In both of these approaches one is seeking very high acceleration gradients; about a few GeV/m; namely another order - of - magnitude above the near term devices WFA, SL and TBA.

The NFA is being pursued in the US. It is still in the conceptual stage in that no experiments have yet been done at short wavelengths (like 10 μm). Some experimental work on open structures has been done in the microwave range. No one doubts that the electromagnetic properties of structures can be predicted. But the device depends on the inexpensive and reproducible construction of structures (such as making and properly firing droplets) as well as upon the properties of materials under intense radiation. Presumably the obtaining of a large luminosity in a collider will require very different parameters than one usually contemplates. (For example, much reduced charge per bunch to reduce image charge wake-field effects, but many bunches per unit time.)

The use of plasmas in high energy physics has been pioneered by the UCLA Group, who are still in the vanguard of effort on the Plasma-Laser Accelerator. This work has attracted the attention of a number of group and there is now effort in the US, Canada, Britain, and France. Quite a lot of progress has been made theoretically and a gradient of (about) 1 GeV/m has been demonstrated experimentally. Of course the acceleration length was only a few millimeters, but further work is in progress. Questions of phasing, transverse focusing, pump depletion, etc. must still be studied while the best geometrical configuration is also under study.

In addition, and very importantly, the efficiency of such as accelerator must be studied. (Lasers are notoriously expensive, if one is seeking high average power. They are also rather inefficient.) This accelerator requires the generation of an electromagnetic wave, transfer of the photon energy to plasma motion and, then, transfer of this energy to the high energy particles. But, the PLA is the most promising approach for obtaining real high gradients. (Perhaps, today, the economic minimum of a collider does not require very high gradients, but someday I suspect that we will want very high gradients.)

For the long-term; i.e. beyond the next collider and out into the next century we shall need some novel acceleration concepts. We can't start then; we better start now.

All of the work on new accelerator techniques is "table top" stuff. It is a long way from here to there, i.e., to what we need for high energy physics. One must build 3 meter models (currently the goal is 0.3 m scale models), then 30 meter devices and, then 300 meter machines before one could -- seriously -- consider making a 3 km accelerator.

But even a 30 m scale experiment is non-trivial in its cost. Capitol construction, operation for a few years, theoretical studies, and a research staff would -- very roughly, of course -- cost 10 M$.

A device at the 300 m scale would give high energy particles, (say) 100 GeV, given that one is aiming for a 1 TeV collider at full scale. This energy would be at interest to nuclear physicists, but not to high energy physicists. The machine, since its purpose is for high energy physics, is primarily being built to learn about accelerator physics. And the cost would be non-trivial (say) 10 times 10 M$ or 100 M$.

Do we -- the HEP community - world wide -- have this kind of money for accelerator R&D? I don't know, but I do know that without this kind of effort no really novel (I am excluding evolutionary changes to present power sources and linacs.) idea will even be brought to the point where it will contribute a

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TABLE I

Accelerator Categorization

1. Slow wave down (and let particle go in straight line)
    - a) Up frequencies from the 3 GHz at SLAC to (say) 30 GHz and use a slow wave structure. (Two-Beam Accelerator) (Violates 2)
    - b) Use a single-sided cavity (i.e., a grating) or droplets as a slow wave structure. (Now one can go to 10 μm of a CO_2 laser or 1 μm of a Nd glass laser) (Violates 2)
    - c) Use dielectric slabs (Violates 2)
    - d) Put wave in a passive media (Inverse Cherenkov Effect Accelerator) (Violates 1)
    - e) Put wave in an active media (Laser Plasma Accelerator) (Violates 1)
2. Bend particles continuously and periodically (and let laser wave go in straight line)
    - a) Wiggle particle and arrange that it goes through one period of wiggler just as one period of the electromagnetic wave goes by. (Inverse Free Electron Laser) (Violates 3)
    - b) Wiggler particle with an electromagnetic wave rather than a static wiggler field. (Two-Wave Accelerator) (Violates 3)
    - c) Use cylotron motion of particle to do the bending. (Cyclotron Resonance Accelerator) (Violates 3)

TABLE II

Accelerator Concepts

1. Plasma Accelerators (Beat-Wave, Surfatron)
    a) Laser excited
    b) Particle beam excited

2. Inverse Cerenkov Accelerator

3. Inverse Free Electron Laser
    a) Regular kind
    b) Gas loaded
    c) Two-wave, Three-wave, ...

4. Droplets, Gratings, Open Structures
    a) Laser excited
    b) Particle-beam excited

5. Plasma Focus

6. Two-Beam Accelerator

7. Wake-Field Accelerators
    a) Electron-Ring Excited
    b) Electron-Beam Excited
    c) Proton Excited
    d) Intense Electron Beam and Laser

8. Switched Linac

9. Collective Radial Implosion

10. Improved Power Sources
    a) Multi-Beam klystrons
    b) Lasertron
    c) Gyrotron
    d) Power multiplying devices

11. Ionization Front Accelerator