RESEARCH NEEDS OF THE NEW ACCELERATOR TECHNOLOGIES*

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Summary

A review is given of some of the new accelerator technologies with a special eye to the requirements which they generate for research and development. Some remarks are made concerning the organizational needs of accelerator research.

1. - INTRODUCTION

The subject which I want to discuss in this article is very extensive and thus I must drastically limit the scope of my remarks or this article will be very long indeed. I shall, firstly limit myself to the advances in high energy physics (HEP) thus leaving out, for example, the very interesting use of stochastic cooling for nuclear physics, the development of new special - purpose accelerators for medical, industrial, and military use, and the development of novel ion-sources for heavy ion research such as the electron cyclotron resonance source (ECR) or the electron beam ion source (EBIS).

There are presently under construction a large number of new facilities for HEP. These include TeV-1, TeV-2, Isabelle, Tristan, LEP, SLC, UNK, and the Chinese machine. Beyond this, in the design/proposal stage are electron-proton facilities at each of HERA, BNL, Tristan, LEP, and the Fermi Lab, and the electron-positron facility CESR II. I shall, secondly limit myself to facilities beyond those listed thus not going into, for example, the very interesting research on beam-beam effects or the development of a powerful source for TeV-1, or the making of micron-size beams by cooling rings and the research on beam-beam beamstrahlung and beam-beam destruction for the SLC.

As I see it, there are two very large machines in the future of HEP. The first is a big proton machine (say 10 TeV) which would also be a p-p collider (10 TeV x 10 TeV). Such a device would certainly require superconducting magnets and stochastic cooling and I intend to comment upon both of these technologies. The second large machine is an electron linear collider (say 300 GeV x 300 GeV) which, probably will consist of a high-gradient linac. I will remark on two possible ways to make high-gradient accelerators.

Beyond the facilities of this century, which probably are those already mentioned, one certainly should look to exotic methods of acceleration. It is not clear that any of these methods will result in a practical HEP accelerator, but the machines beyond the ones listed (and even them!) will be so-expensive as to necessitate that one research the new technologies in order to really try to make them work. I thus will briefy review (and this is my third -- and final -- limitation upon this article) some collective accelerators and some laser accelerators and devote most attention to those concepts which appear especially fruitful at this time. One should note, however, that I have put the impact of these new approaches -- if there is any impact at all -- into the next century. Thus there is considerable time for R&D and it would be premature at this time, in my judgement, to eliminate any of the novel concepts and diverse approaches.

Finally, I end with some remarks about the organizational structure which accelerator research seems to require.

2. - THE NEXT GENERATION MACHINES

Probably, the next generaion of large machines will be a proton fixed target machine wich is also a $\bar{p}$-p collider and an electron-positron linear collider. These machines will require superconducting magnets, stochastic cooling, a high-gradient linac, and many other developments. In this section I limit myself to the three items mentioned. In each case, the presentation is oriented towards R&D topics which are suggested by the current status of the technology. My approach is not meant to be -- and it certainly isn't -- exhaustive, but rather only to show how much must be done, and therefore, how rich the field is in suggesting R&D programs.

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2.1. - Hard-Superconducting Magnets

In the design of a large (say, 10 TeV) proton machine cost will be the determining factor. To give some appreciation to this remark, consider scaling the Tevatron (1 TeV) to 20 TeV: One finds that the machine costs over $3 x 10^9, and that more than half of this money goes to the magnets.

Thus there is a premium on reducing magnet costs. It isn't clear, at the present time, whether the cost minimum (for the whole machine) is obtained with (say) 2.5 Tessla super-ferro magnets[1] (in which the field shape is in large measure determined by the iron while the current is carried by superconductors), or, at the other extreme, with 10 Tessla magnets. Certainly the Europeans, having the LEP tunnel, will want to develop as high-field magnets as one can -- within some fiscal bound.

Leaving aside the interesting problems associated with developing expensive magnets in the 2.5 T to 5.0 T range, I would like to review, here, some of the R&D topics required for the development of 10 T magnets.

A very excellent discussion of 10 T magnets had been given by C. Taylor et al.[2] and much of my material, as well as Figs. 1-4, comes from that paper.

The first thing is that for even a small bore of $r \approx 3$ cm one needs a current density of $j \approx$ 400 A/cm^2. This large current density requires both new materials (i.e., Nb_3 Sn) and new low operating temperatures (i.e., 1.8°K) as can be seen in Fig. 1. The Nb_3 Sn material is very

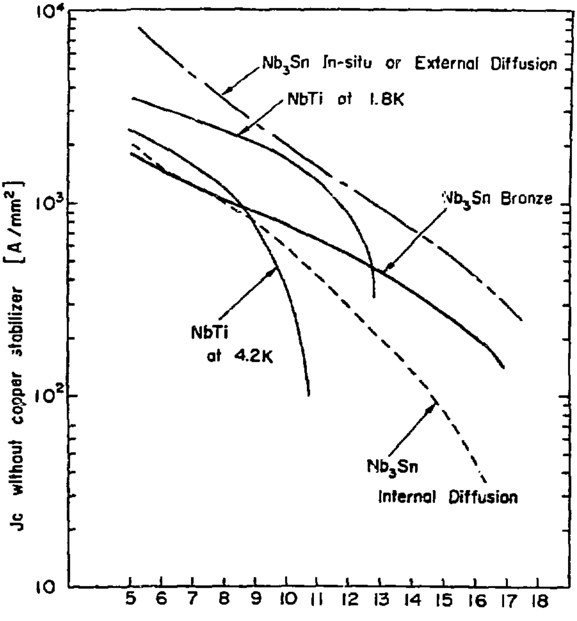

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Figure 1. Critical current density for a non-stabilized NbTi and Nb_3 Sn conductor.

brittle and, probably, has to be created *in situ* by a reaction process which takes 100 hours at 700°C. Thus insulations need to be able to withstand these conditions, which suggest one area of research.

Also, the forces developed in a 10 T magnet are very large. The location of the peak force varies with the design, as shown in Fig. 2. Thus mechanical deformation is a problem and experimental data on creep is needed. Also very little is known about strain-deterioration for transverse loading of Nb_3 sn cable.

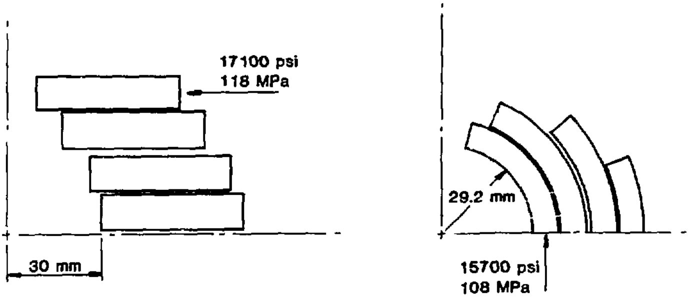

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Figure 2. Magnitude and position of the point of maximum stress in a 10 Tessla layer-type and a 10 Tessla block-type magnet.

The stored (magnetic) energy in a 10 T magnet is very large: If the bore is 3 cm then the stored energy is 0.3 MJ/meter. On the other hand one wants to use very little copper conductor (for stabilization) in order to keep the current density high. Just how little copper can be employed must be determined by the construction of models.

A consequence of minimum stabilizing copper is rapid heating after a quench. In order to reduce the quench, current quickly requires a low inductance magnet; i.e., a small number of turns in the magnet. The construction of small-bore coils of large-cable is difficult and demands further study and, probably, reaction of the Nb_3 Sn *in situ* .

Two possible realizations of magnets are shown in Figs. 3 and 4. Both of these have "cold iron," which is probably necessary just to hold the coil together. Work on these 10 T magnets is going on at a number of places including KEK and LBL. The work includes study of the above-mentioned problems, the training of magnets, and the deterioration of magnets (if any) with strain.

Clearly much resesrch and development is needed on superconducting magnets and much of this work seems most suitable for a "small" laboratory; i.e., not necessarily at Fermi Lab or CERN.

2.2. - Stochastic Cooling

The development of cooling of beams haw created a revolution in particle-handling. There are two methods which are practical at the present time.

The first practical method is electron beam cooling which was invented by G. Budker and demonstrated to work in Novosibirsk. Subsequently, experimental devices were constructed at CERN and Fermi Lab. The cooling requires, for a reasonably fast rate of cooling, that the proton beam be at not more than a few hundred MeV. Thus, because it takes too long to decelerate particles, there seems to be no application of this technique to HEP and I shall not discuss it, here, further. (The Indiana Cooling Project, however, does employ electron cooling in a nuclear physics application.)

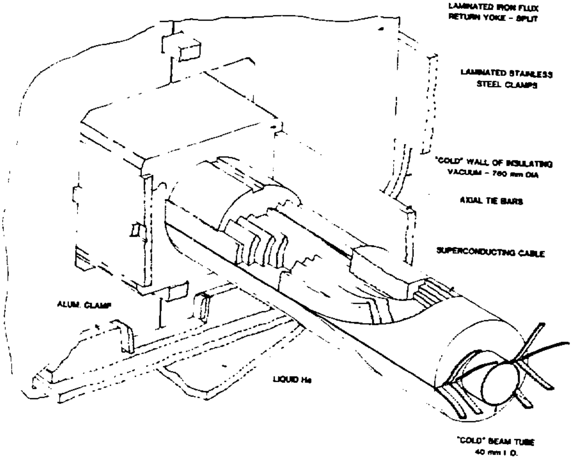

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Figure 3. Schematic diagram of a layer-type magnet.

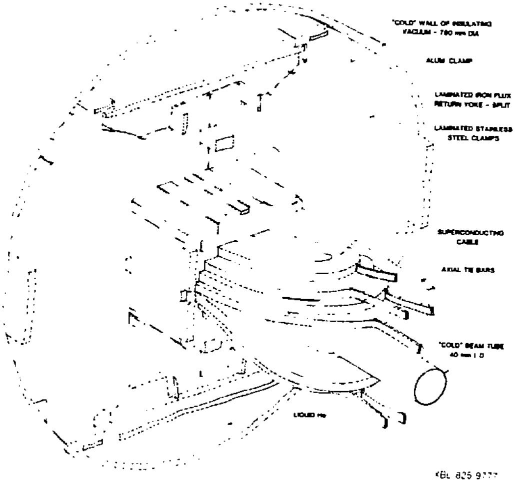

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Figure 4. Schematic diagram of a block-type magnet.

The second practical method of cooling is stochastic cooling which was invented by S. Van de Meer and demonstrated, first, on the ISR at CERN. Subsequently, much work has been done on it at CERN on ICE and at Fermi Lab on the 200 MeV ring. Stochastic cooling is the basis of the AA Ring at CERN and the TeV-1 Project at Fermi Lab.

Stochastic cooling is really, "stochastic heating on top of systematic cooling" to employ a characterization due to Glen Lambertson. I am grateful to him not only for this phase, but for much of the material in this section, as well as for Figs. 5-7.

In Fig. 5 one can see the degree to which stochastic cooling is relied upon in the p-p projects. The increase in density is about a factor of 10^4! Figure 6 shows an electronic block diagram of a stochastic cooling system. The bandwidth of the system is 600 MHz and the 800 nsec element introduces a time delay of that amount. The system puts out 1 watt. The notch filter is a cable of length equal to half of the circumference of the machine, while the compensator simply corrects for imperfections in the notch filter. Finally, Fig. 7 shows the mechanical realization of part of the system; namely, the pick-up electrode.

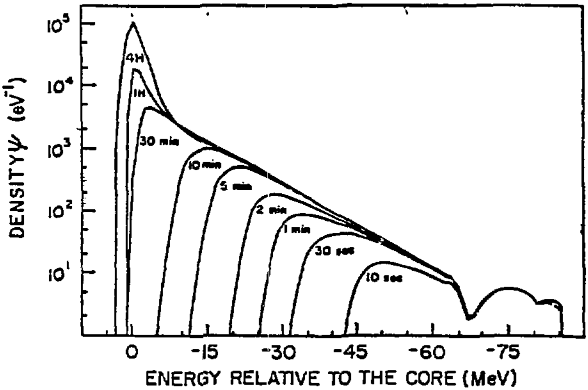

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Figure 5. Density of particles as a function of energy in the TeV-1 design.

What are the limitations to stochatic cooling? Firstly, the cooling rate decreases as the beam becomes more intense. Secondly, for bunches which are short in length one gets "poor mixing" and, again, the stochastic cooling rate decreases. Thirdly, noise in amplifiers is an important contribution to the cooling rate.

What are the cures? Clearly, to alleviate the first limitation, one wants more frequencies included in the system. Since in practice one is limited to about an octave in band width, one is forced to raise the central frequency in order to increase the span of frequencies included by the system. Presently the systems are in the range of 1-4 GHz and one can imagine operation in the (say) 10-40 GHz range. In order to improve the "mixing" one can go to non-linear buckets; i.e., third and fifth harmonic cavities in the rf system. And, to alleviate the third limitation one wants to develop very low noise amplifiers. Presently, commercial amplifiers have a noise temperature of 200°k, but at LBL an amplifier has been built, which operates in the very-wrong range of 50-450 MHz, but has a noise temperature of only 50°k.

These proposed cures suggest many important R&D projects. There is, for example, the development of low-noise amplifiers at high frequencies. Thus a goal of a noise temperature of 50°k at 1-4 GHz seems possible. Beyond that (in central frequency) one can't even speculate comfortably.

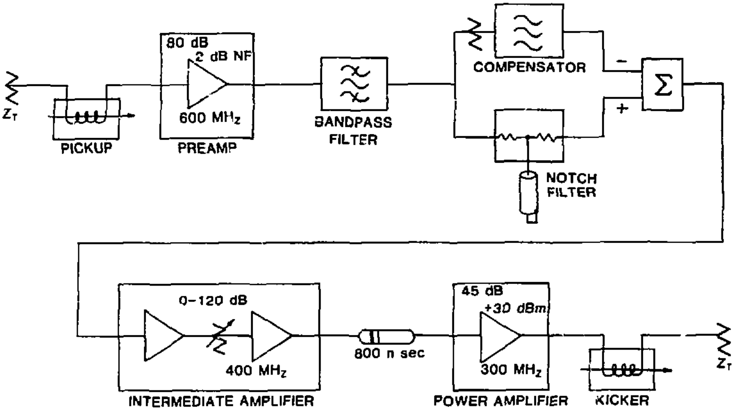

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Figure 6. The circuitry for the longitudinal damping system on the 200 MeV cooling experiment at Fermi Lab.

One should, also, study the effect of non-linearities, which help on the stochastic cooling rate, on other phenomena. In particular the non-linearities probably make the beam-beam limit more severe, and nobody knows how much and, hence, whether this is an important problem or not.

Finally, going to a high central frequency means that dispersion on the cabels, which are employed to take signals from the pick-up to the kicker, becomes more severe. In the range 1-4 GHz the use of cooled, or even superconducting, cabels is being explored. At the higher frequencies of 10-40 GHz perhaps the signals need to be sent by microwaves and/or lasers. The development of such a system, with its fast converters is non-trivial.

So much, then, for this discussion of stochastic cooling. Clearly a variety of problems have been identified, some quite suitable for the large laboratories/or presently involved in p-p projects and some quite suitable for small laboratories universities who are interested in making contributions to the improved cooling system of the future.

2.3. - Power Sources Near 1 cm Wavelength

The SLAC structure will be employed in the Stanford Linear Collider (SLC) which will have 50 GeV electrons collide with 50 GeV positrons. The gradient will be 17 MeV/m. In the future one thinks of (say) 300 GeV x 300 Gev and with the same gradient we would need two linacs each with a length of 18 km. This is not impossible to contemplate (LEP has a circumfrence of 27 km) but a higher gradient would certainly be attractive.

In addition, the beam power in a 300 GeV linac, in order to have a luminosity of 10^{32} cm^{-2} sec^{-1}, is about 2.5 MeV. Thus it is important to have an efficient structure so that a significant fraction of the power necessary to excite the structure goes into the beam.

Both of these problems can be alleviated by going to higher frequency than is used in the SLAC structure. A factor of ten -- to a 1 cm wavelength rather than the present 10 cm -- would reduce the stored energy by a factor of 10^2. The filling time would go down to (about) 100 nsec which will help to increase the break-down field. At S-band the Novosibirsk people have achieved a gradient of 100 MeV/m and since the limit should go at least as fast as $f^{1/2}$ (no one knows, presently, what the limit is.) One should be able to achieve, at a 1 cm wavelength, a gradient of 250 MeV/m.

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Figure 7. The pick-up electrode for the longitudinal cooling experiment at Fermi Lab.

The primary reason that linacs have not been built at 1 cm is that there is no good high-power source at this frequency (30 GHz). There are a number of possible power sources, but all of these need development. Some approaches have been reviewed by Perry Wilson^3 and include conventional kylstrons pushed to higher frequency and, perhaps, combined with storage cavaties as shown in Fig. 8 (from P. Wilson's paper). Another approach, which is already under development at SLAC, is a photocathode in which the photons (from a laser) are (easily) modulated and, hence, produce a modulated electron stream. This is shown in Fig. 9 which is also from P. Wilson's paper.

Another possibility is to employ cross-field devices such as the magnetron or the gyrotron. One can even consider relativiatic beams in a transverse gryotron or a more direct use of the negative-mass instability such as is being examined by the Maryland Group.

All of these approaches demand a significant amount of R&D; but the "pay-off" in terms of high-gradient linacs would be very large.

There are less conventional approaches to a high-gradient structure and I would like to comment upon these now. Of course the laser accelerators are addressed to just this end and will be discussed in Section 3. Of particular interest, in this regard, is the Inverse Free Electron Laser Accelerator.

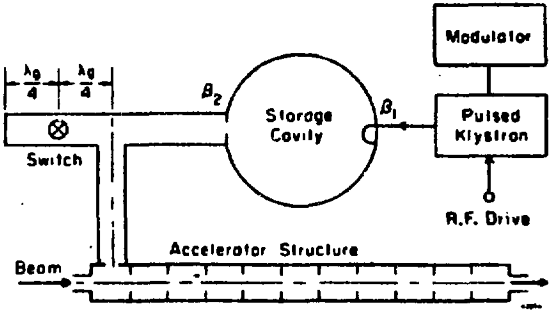

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Figure 8. Pulse compression by energy storage and switching.

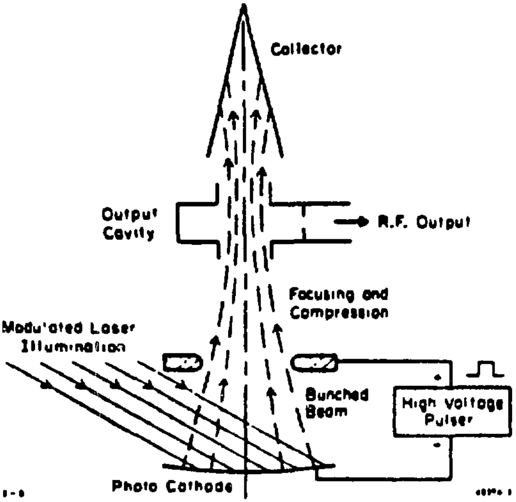

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Figure 9. Schematic of photocathode microwave device.

Another approach is that of the Wake-Field Accelerator, wich has been proposed by G. Voss and T. Weiland.[4] In this scheme the wake-field from a low-energy beam is employed to drive a beam of particles to very high energy. Voss and Weiland have made calculations which show that a graident of 100 MeV/m can be obtained in this way. Figures 10 and 11, from the report by Voss and Weiland, shows two possible geometries for such an accelerator.

Recently, and so-far this work is unpublished, Voss and Weiland have been thinking about use of an electron ring of (about) 3 cm major radius and 5 x 10^{12} particles to drive, in a cylindrical geometry in which the driven beam is at the center of the ring, 10^{11} particles at a gradient of (about) 200 MeV/m.

This concept suggests many topics for R&D: One needs to optimize structures, build one or two meters of structure after proper consideration is given to stability and focussing questions, and then actually employ two beams in the structure. Clearly a great deal of R&D is needed before this concept evolves into a practical accelerator, but the approach is quite exciting since the potentiality (which has only been slightly touched upon here) is very great.

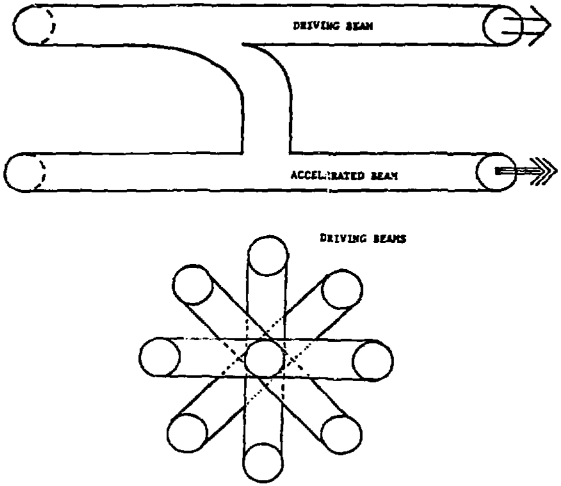

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Figure 10. A simple two-beam wakefield transformer and a possible arrangement for a multiple beam star transformer based on the two-beam principle.

Still another approach is provided by the use of a Free Electron Laser (FEL) as a power source for a conventional linac operating at (say) 30 MHz. This has been proposed, and explored to some extent, in Ref. 5.

The basic idea is to use a low-energy, relatively intense beam (3 MeV, 1 kA) of 100 nsec duration in a "steady-state" FEL to generate 250 Mw/m; i.e., 25 J/m of rf energy at 30 GHZ. The "steady state" FEL is a device in which energy is given to the beam by induction units at just the same rate as energy is lost from the beam by going through a wiggler. In the present applicaton the induction units give 1/4 MeV/m to the low-energy beam which, in turn, supplies enough energy to accelerate 10^{11} particles to 375 GeV. The colliding beam is about 1 mm long and 100μ across (as in the SLC). A repetition rate of 1 kHz would then yield a luminosity of 4 x 10^{32} cm^{-2} sec^{-1}.

The power requirements are given by (1) the efficiency of the accelerating structure, which is about 20% (in order to keep transverse wave field effects tolerable), (2) the coupling efficiency of the FEL to the accelerating structure which is guessed to be 80%, and (3) the efficiency of the induction accelerator which should be about 50%. Since, in this example, the beam power is 12 Mw, one requires 150 Mw from the mains.

Note that this accelerator, like that of Voss and Weiland is a "two-beam accelerator." I think that "two-beam" devices, and of course the collective accelerators are all of this type, deserve further study. They may well represent the direction which future accelerators will take.

Finally, one should note that the FEL as a power source suggests research on accelerating structures, coupling efficiency, break-down fields, and -- of course -- on a "steady-state" high-power FEL (which does not exist at the present time, but according to paper-studies will work as described).

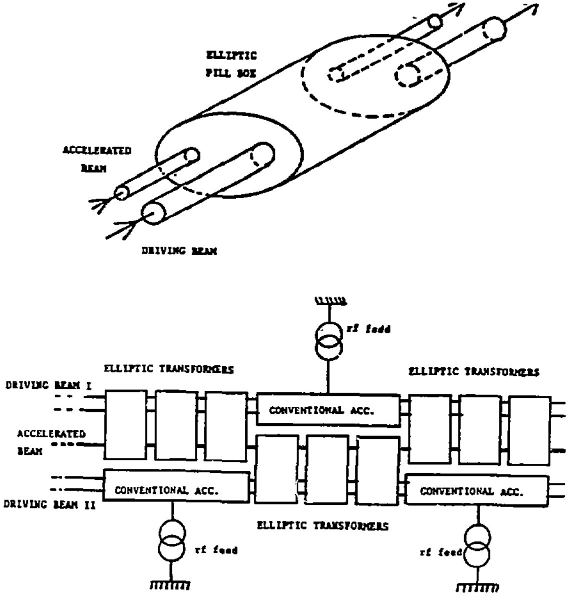

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Figure 11. A two-beam elliptic pillbox acting as a wakefield transformer with a small pipe for the accelerated beam and a big one for the driving beam and a possible layout of a three beam linac with conventional sections for reaccleeration of the driving beams.

3. - BEYOND THE NEXT GENERATION

If we look beyond the next generation of accelerators there are a large number of schemes which have the potential of producing reliable accelerators with advantageous features. None of these schemes is presently at such a state -- all require a large amount of research. Since the orientation of this article is on the research needs of the new technologies it actually suffices to simply list most of the interesting ideas; the requirement for R&D, and even the nature of the R&D is really quite obvious.

There are collective accelerators and laser accelerators which we need to consider. The collective accelerators have been recently reviewed[6] and they have been described in a recent review article.[7] A rather comprehensive description of the various schemes, and the physics behind the schemes, may be found in the book by Olson and Schumacher.[8] Because of the general availability of this book, detailed references will not be given in Sections 3.1-3.4. The laser accelerators have been studied in a Workshop which took place in 1982.[9] Most of the material upon which this section is based can be found in Refs. 6. 7, and 9; and, in particular, Figs. 12-19 are taken from the review article of Ref. 7, while Figs. 20-23 are taken from Refs. 9.

3.1 - Collective ACcelerators: The Electron Ring Accelerator

The Electron Ring Accelerator (ERA) -- originally conceived by Veksler -- is one of the oldest collective accelerator concepts. The basic idea is shown in Fig. 12. First an intense electron ring of compact size (major radius a few cm and minor radius a few mm) is produced by injecting an electron beam into a "compressor" and then shrinking the electron ring and simultaneously increasing the electron's energy by means of betatron action. The ring is then "loaded" with ions and accelerated by either magnetic expansion or by electric fields. An alternative way to form a suitable ring for accelerating ions is shown in Fig. 13, but this scheme has never been tried-out experimentally. In Fig. 14 still another method of forming rings is depicted.

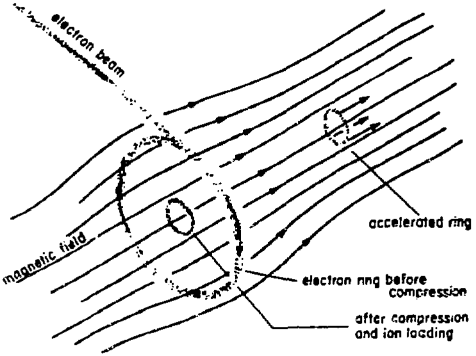

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Figure 12. The Electron Ring Accelerator (ERA).

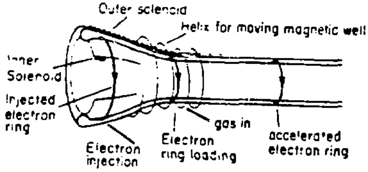

Figure 13. The ERA static-field compressor.

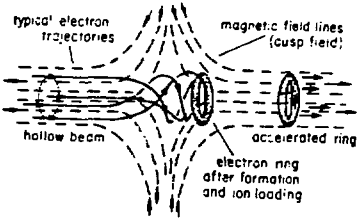

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Figure 14. The Maryland ERA scheme using a cusp magnetic field.

Extensive theoretical and experimental work has been done on the ERA. Experimental programs existed at Dubna, Berkeley, Garching, Karlsruhe, and Maryland. The Dubna group has reported accelerating nitrogen and heavier ions, by magnetic expansion at 2-4 MEV/amu-meter, to a few MeV. The Garching group also achieved, as early as 1974, ion acceleration by this method, and in 1981 the Dubna group accelerated electrically loaded electron rings.

However the small gradients which have so-far been achieved (if the gradient is made larger -- and this is very easy to do -- then because the rings are not "powerful enough," ions are lost from the ring and hence not accelerated) and the general complexity of the ERA has been sufficiently discouraging to most workers that at the present time only the Dubna group remains active in ERA research.

It is believed that the ERA is likely to have a "pay-off" in nuclear physics rather than in high-energy physics. Although this may be the case, it seems premature to conclude that the ERA is not of interest to HEP. That much more R&D needs to be done on this approach is obvious; details of the present approach, and hence details of what developments are needed, can be found in Refs. 7 and 8 and the original sources cited therein.

3.2. - Collective Accelerators: Waves and Beams

The concept of a wave accelerator is to produce a wave on a relativistic electron beam in such a way that particles are accelerated by the wave. Thus the phase velocity of the wave must be controllable and vaiable. If, in addition, the accelerating wave is an unstable mode of oscillation of the electron beam then the wave will grow at the expense of the electron kinetic energy.

The wave of interest must grow -- and remain coherent -- over distances which are long compared to the wavelength of the disturbance. Also, the accelerating wave must grow while other waves -- (which are not desired) remain small. Thus mode-coupling must be very small even in the non-linear regime which, surely, characterizes the desired wave. In addition, the accelerating wave must grow even while its phase velocity is increasing and significant energy is being removed from the desired wave by the ions which are being accelerated.

Despite these severe requirements on wave accelerators there has been experimental study of wave accelerators at Austin, Ithaca, and the Naval Research Laboratroy (NRL). The program at Austin went on for many years (about 10), but has recently been terminated. Also, I believe, there is no future work on wave accelerators being done at the NRL.

Theoretical analysis proceeds by considering all of the modes of a non-neutral cylindrical plasma inside of a conducting pipe. It is not difficult to determine that, as Sloan and Drummond first noted, there is only one wave -- namely, the Doppler-shifted lower cyclotron wave -- which has a phase velocity which is both very small and controllable.

The Autoresonant Accelerator (ARA) is based upon the use of exactly this mode. Figure 15 shows a schematic of this device. By using helical conductor surroundings they were able to grow the desired wave -- and no other wave -- to large amplitude (more than 10 Mv/m) and, furthermore, to produce the wave with as low a phase velocity as 0.060c and, also, (under some other conditions) with a phase velocity more than three times this value. Thus all of the conditions for the acceleration of ions appear to be in hand; the program was -- most unfortunately -- terminated before these various elements could be put together, as would be needed, to actually achieve ion acceleration.

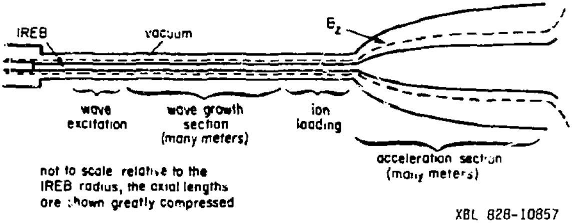

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Figure 15. The Autoresonant Accelerator (ARA).

The Converging Guide Accelerator (CGA) is shown in Fig. 16. It was first proposed by Sprangle, Drobot and Manheimer and is being experimentally pursued at Cornell (Ithaca). They have achieved a field strength of 6 MV/m, but the wave phase velocity can not be made (as one would expect) less than 0.2 c, so that a relatively high injection energy is required. It is not yet clear to what extent the wave phase velocity can be controlled by the converging walls.

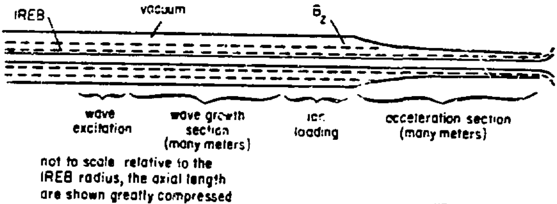

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Figure 16. The Convering Guide Accelerator (CGA).

Of course this subject has been studied much more deeply than can even be suggested by this review. Nevertheless, many problems remain to be studied while the potentiality of these devices is really unknown at the present time.

3.3. - Collective Accelerators: Moving Potential Wells

The very first observations of collective acceleration, by Graybill and Uglum and by Plyutto, were--most probably -- observations of ions accelerated by moving potential wells. Figure 17 shows a device in which "naturally occuring" acceleration can be observed. Typically electron streams of 30 kA and a few MeV electrons, produce (about) 20 MeV nitrogen ions.

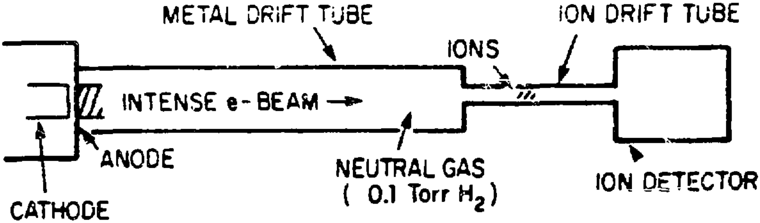

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Figure 17. A device for observing "naturally occuring" collective ion acceleration.

In order to convert this process, which presumably results from the potential well at the beam head, into an accelerator which is capable of reaching high energies, one needs to control the beam front velocity. One scheme for doing this is the Ionization Front Accelerator (IFA) of Olson, which is depicted in Fig. 18. Olson has been able, in this way, to control, and steadily increase, the beam front velocity. The evidence, to date, is not conclusive concerning ion acceleration, but it would appear that definitive acceleration should be achieved rather soon.

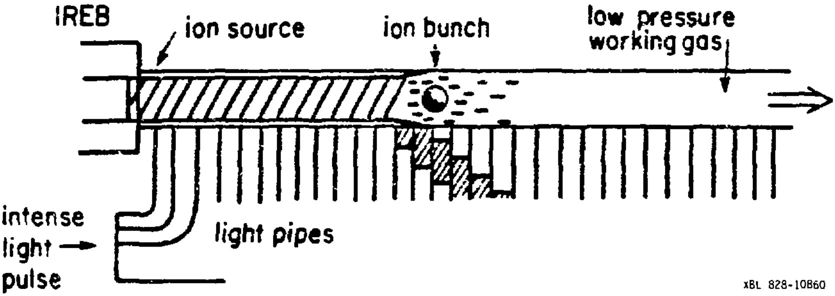

Figure 18. The Ionization Front Accelerator (IFA).

A second scheme, which is being pursued by Rei.er at Maryland, employs an external slow wave structure (a helix) to control beam front velocity. In this way he has achieved (about) a factor of two increase in ion energy over that which occurs without a slow wave structure.

It is not known what limits to ion energy exist for this approach, or that of the IFA. Thus both schemes appear to have the promise of contributing to HEP.

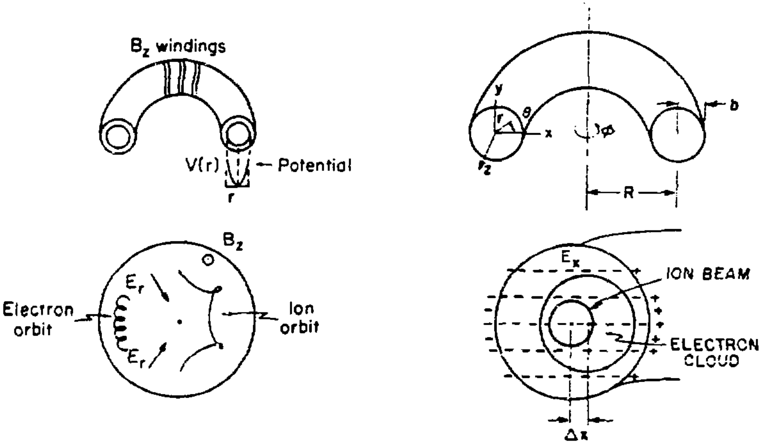

Figure 19. Particle dynamics in a Collective Focusing Accelerator (CFA); (a) Particle orbits; and (b) equilibrium positions of ions and electrons.

3.4. - Collective Accelerators: Collective Focusing Accelerator

Collective effects can be employed not only to accelerate particles, but also for the focusing of praticles (as in the Gabor lens) and for the gross bending of particles. In the later case, which has been proposed by Irani and Rostoker, a cloud of electrons (n 10^{13} cm^{-3}) can hold -- in a 3 m device -- uranium of 100 GeV (and 60 times ionized). The device is shown in Fig. 19, which has been taken from their paper. Of course there are many questions which such a scheme raises and many of them are being addressed by the Irving group.

Also, under this section, mention should be made of the very interesting work by Hymphries on the Pulselac. This is a space-charge compensation scheme which has shown experimentally to work to a considerable degree. The research opens up a considerable number of applications while raising a large number of R&D topics.

3.5. - Laser Accelerators: Media Accelerators

Laser accelerators hold out the promise of reaching high energies with a technology which is new to accelerator physicists. Of course the problem is that an electromagnetic wave is a teansverse wave, i.e., "the field is pointing in the wrong direction" and hence does not accelerate an electron. Figure 20, which is from Ref. 10, depicts this problem graphically. Since there is no acceleration from a plane wave there is no acceleration from a wave packet.

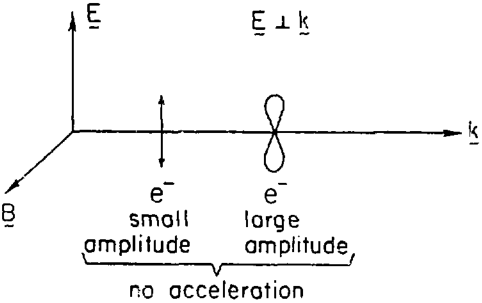

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Figure 20. Particle motion in a propagating plane electromagnetic wave. The wavenumber k is perpendicular to electric field E and magnetic field B. No net acceleration along the k-direction is achieved.

There are, of course, a number of ways in which electromagnetic radiation can be employed to accelerate particles. Some of these are implied by the discussion of Fig. 21. (Also taken from Ref. 10).

In a medium the velocity of light is slowed and the phenomenon of the radiation of a charged particle moving faster than the velocity of light in the medium is the Cherenkov effect. The reverse, can be used to accelerate particles. In fact, in this way one can -- in principle and with lasers that now exist -- accelerate electrons to tens of GeV. A next experiment is outlined in Fig. 22. The needs for R&D are obvious, and need not be amplified here.

There is another way in which the media can allow for the acceleration of particles; namely, the media can be an active media. Thus if we consider a plasma media, then the plasma which, subsequently, by its collective electrostatic field can accelerate particles. This scheme was suggested by Dawson and Tajima and is explained in Ref. 10.

Essentially, the idea is to employ two laser beams, whose difference is the plasma frequency, to produce the plasma bunching. A general scheme of the device is shown in Fig. 23. Because the plasma can be quite dense and because the bunching is over distances comparable with the laser wavelength, the electrostatic accelerating field is very large. Thus the promise of this accelerator is great.

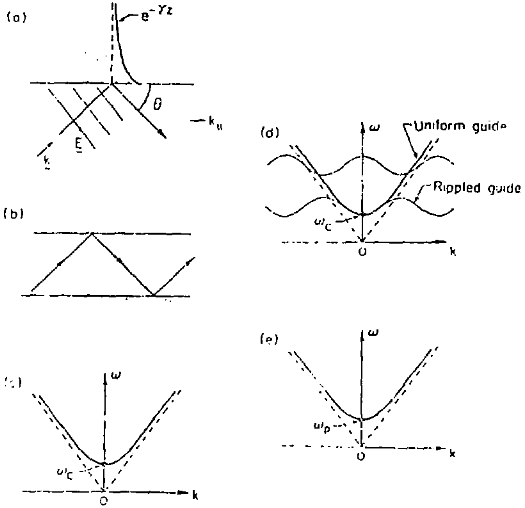

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Figure 21. Virtual photons and photons in a plasma. (a) A plane electromagnetic wave reflects on the metallic surface. There is a field component parallel to $k_{\parallel}$, E sin θ. In the metal the EM field exponentially decays. (b) If we put two metallic plates together, we get a waveguide. Again a field component parallel to k exists. (c) The dispersion relation of the EM wave in the waveguide. $k_{\parallel}$ is the parallel wavenumber. (d) The dispersion relation of the EM waves in the uniform and ripple waveguides. (e) The dispersion relation of the EM wave in a plasma.

Of course, there are many questions which the proposal raises and some of them have, already, been studied employing one-dimensional particle simulations. However, there are many 2-D questions which have not-yet been addressed.

Finally, one should note that a first experiment has confirmed the concept and resulted in 1.5 MeV electrons from a laser irradiated foil.

3.6. - Laser Accelerators: Near-Field Accelerators

Provided the particles are near a surface one can accelerate the particles, for an electromagnetic wave moving along the surface will have a longitudinally directed field. Of course the particles must be very near the surface; in fact within a wavelength, λ, of the surface for the surface-wave falls-off exponentially with characteristic-distance λ.

Various near-field accelerators have (1) dielectric sheets separated by a wavelength, (2) a dielectric rod having a cylindrical hole of radius λ down which the particles are accelerated, and (3) gratings over which the accelerated particles move. The last, is just the Smith-Purcell Effect run backwards and, of course, the particles must be within a wavelength of the grating surface. In fact, all the slow-wave linac structures (disk-loaded guides, jungle gym, etc.) are simply structures which have transverse dmiensions of the order or λ.

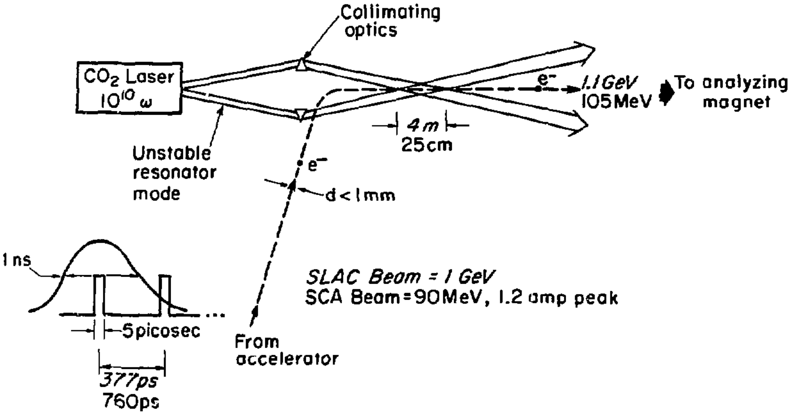


Figure 22. Layout of an Inverse Cherenkov Accelerator experiment.

The interest, then, is in reducing the dimensions of accelerating structures from the present values (λ = 10 cm in SLAC) to those associated with high-powered lasers (λ = 10 μm for a CO_2 laser). Thus one needs to develop one-sided accelerating structures. They may, for example, develop plasma electrons when irradiated with a high power laser and hence be shorted-out and no longer accelerating structures. This and many other questions, have been addressed in a very preliminary way, but much work remains to be done. Suffice it to say that no successful near-field accelerator has yet been build, but the motivation to develop this technology is now becoming greater.

3.7 - Laser Accelerators: Far-Field Accelerators

Far-field laser accelerators must employ something -- in all cases consider so-far a magnetic field -- to bend the particles so that they can resonate with the electromagnetic wave: i.e., pick up energy in contrast with the free particle of Fig. 20. A discussion of an Inverse Free Electron Laser has been presented elsewhere in this Seminar. Thus it is not necessary either to present the physical principles of this device or its promise. Suffice it to say that a good deal of R&D is suggested by this scheme.

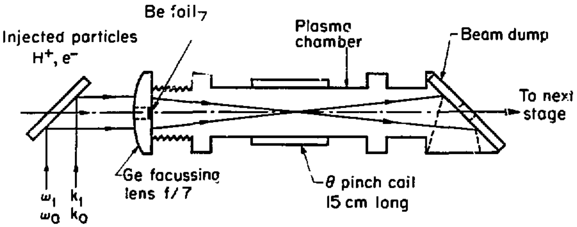
4. - ORGANIZATION OF ACCELERATOR R&D

In reviewing the new accelerator technologes and the contribution of various organizations to the accelerator art, I find myself reasoning along the following lines.

4.1. - Contribution of the Large Laboratories

The "large laboratories" have contributed, through the years, many important new accelerator ideas. We often tend to overlook this contribution, thinking of the big laboratories as places where established technologies are simply executed with precision; i.e., that the big laboratories have lots of good "engineers" and are "users" of ideas which are developed by many "physicists" who are located, usually, in the universities. One should remember, then, that stochastic cooling was discovered and developed at CERN and is being further developed by LBl and Fermi Lab. Superconductivity, for magnets, was made real by the Rutherford Lab ("Rutherford cable"), Fermi Lab magnets (in the words of A. Tollestrup "an exportable technology"), and by R. Palmer, et al. at Brookhaven. And, the whole concept of a linear collider, with micron-size beams made to collide, has been developed by SLAC.

24 Stage Laser Beat Wave Accelerator 20-50 GeV Total Gain



Beam intensity per beam	$\sim 5\times10^{15}$ W cm^{-2}, $v_0/c \sim 0.5$
Plasma density	$\sim 10^{17}$ cm^{-3}
Plasma temperature	~ 100 eV
Gain per stage	~ 1-2 GeV

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Figure 23. A full-scale Beam Wave Accelerator for producing electrons of 20-50 GeV, with 24 stages and each stage giving 1-2 GeV to the electrons.

It is often said that the big laboratories are "using up the reserve in accelerator technology." It is not so clear to me that this is a true statement.

4.2. - Contribution of the Small Laboratories

The "small laboratories" and the universities have contributed, through the years, many accelerator ideas. One needs not go back, for example, to the invention of the cyclotron by Lawrence, but can easily find more recent examples. One thinks of the development of superconducting rf cavities by Stanford University and by Cornell. Or one remembers the concept of electron cooling, conceived by Gersh Budker, developed by the Nuclear Physics Laboratory in Novosibirsk and to be used in the Indiana cooling project. This same laboratory has made important contributions to charge-exchange injection and, more recently, to the "lithium-lens" which will be used by Fermi Lab to help collect anti-protons.

At my own laboratory, and I will leave aside phase focussing because maybe our lab was "big" in 1947 although clearly it isn't now (although it is about the same size) there have been contributions to induction and rf linacs (Alvarez structures and the ERA injector), thin superconducting coils for detectors, and the TPC and bubble chamber detectors.

At MURA -- certainly always very small -- there were a myriad of contributions such as rf stacking (which made proton storage rings possible) and spiral focussing (which allowed the present - generation of cyclotrons: the 88", SIN, Triumph, Indiana, Michigan State, etc...).

And e^+-e^-) colliding beams were developed by Bruno Touchek et al. at Frascati and Orsay (ADA, Adone) and by Burt Richter et al. (first e^--e^-) at Stanford. Later this technology was "picked-up" by SLAC in Spear and PEP, and by DESY in Doris and Petra, and by Cornell in Cesr, and now by CERN in LEP. Here is an example of a good idea being taken up and "pushed" or "used" by the large laboratories.

4.3. - R&D Structure

So; clearly there have been contributions to the accelerator "art" made by both small universities and by large laboratories. What should be the pattern in the future? It has not been bad in the past, but will the past continue? I think not, unless we "do something" about the present trend. My reasons for saying this is that the "large labs" are becoming "larger," the quality of people in accelerator physics seems to be going down (Am I only growing old? Do our ancestors always look better than our offspring? Maybe they really were!), and it seems less "respectable" now to be an accelerator physicist than it was to be one in the past.

Clearly, there is need for R&D at the large laboratories. Equally clearly, such research will go on (despite anything we might say) for the very future of the large laboratories depends upon such R&D.

Equally clearly, we need to have accelerator R&D at the universities and small laboratories. These places have -- in the past -- contributed many innovative ideas. We can expect that they will do so in the future. Furthermore, they are the source of new people for the field via students. Such ideas are necessary if we are to stay on -- or even near -- the Livingston curve. (See Fig. 24) "Far-out ideas" are pushed far-out in time at the large laboratories for the very necessity of getting on with the current project -- and using all resources (the best people, money, space, computer time, etc.) to that end -- just means pushing "far-out" things off.

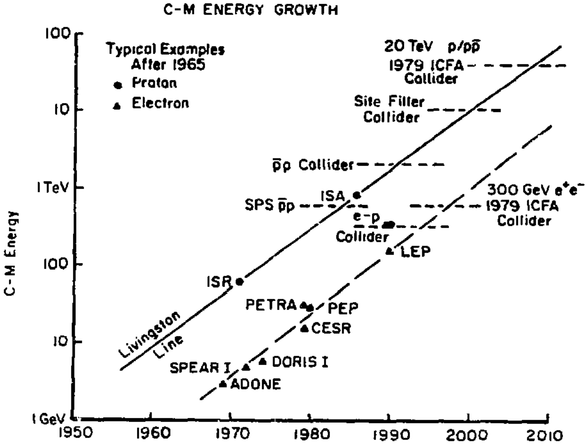

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Figure 24. Projection of the Livingston Chart Beyond 1980 for both Proton and Electron Colliders.

So there is space left for the small laboratories (i.e., those not building a big machine such as Frascati or Saclay or Rutherford) and the larger universities. We need money for this activity and nations need to be willing to give support to work which will not culminate in a big machine in that nation or a Nobel Prize, but -- nevertheless -- is very good work and very valuable work.

4.4. - Coordination of R&D

Probably there is the need for some coordination. Firstly, some of the research needs to be coordinated with the large laboratories. Secondly, some needs coordination on a national scale. (I could envision that laser acceleration work is centered at Frascati -- where they have a 10^{10} watt laser and a test electron beam as a start -- but done in large measure (maybe 50%) at universities.) Thirdly, some accelerator R&D should not be coordinated at all. Good ideas come from individuals. Of course, a central laboratory could hold conferences and serve as an information center. (I could envision a Seminar -- say in the summer of 1983 -- where one goes into much more detail than was possible to go into at this Seminar on (say) plasma accelerators (for 1 day) and EBIS (say) for 1 day, etc...)

4.5. - Conclusions

In summary then I see no lack of accelerator R&D topics: Worthwhile subjects of study which may not pay-off, but then again they might -- we just don't know, which is why they are good R&D topics.

I hope that the universities and small laboratories will make an active effort to again -- as they did in the past -- contribute to this field. Unless they do, experimental high energy physics will grind to a halt in the next century, and I for one hope that does not happen, for I am convinced that we need machines of ever higher energy and ever higher capability in order to check-up on the theorists. The theorists are almost certainly wrong, or not complete in their understanding of nature (they have always been in error in the past) and since I believe that physics is an experimental science I want to keep HEP that way which is why I want to see accelerator research ever-young and vital.

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