THE CHALLENGE OF ULTRA-HIGH ENERGIESuULTIMATE LIMITS, POSSIBLE DIRECTIONS OF TECHNOLOGY, AN APPROACH TO COLLECTIVE ACCELERATION

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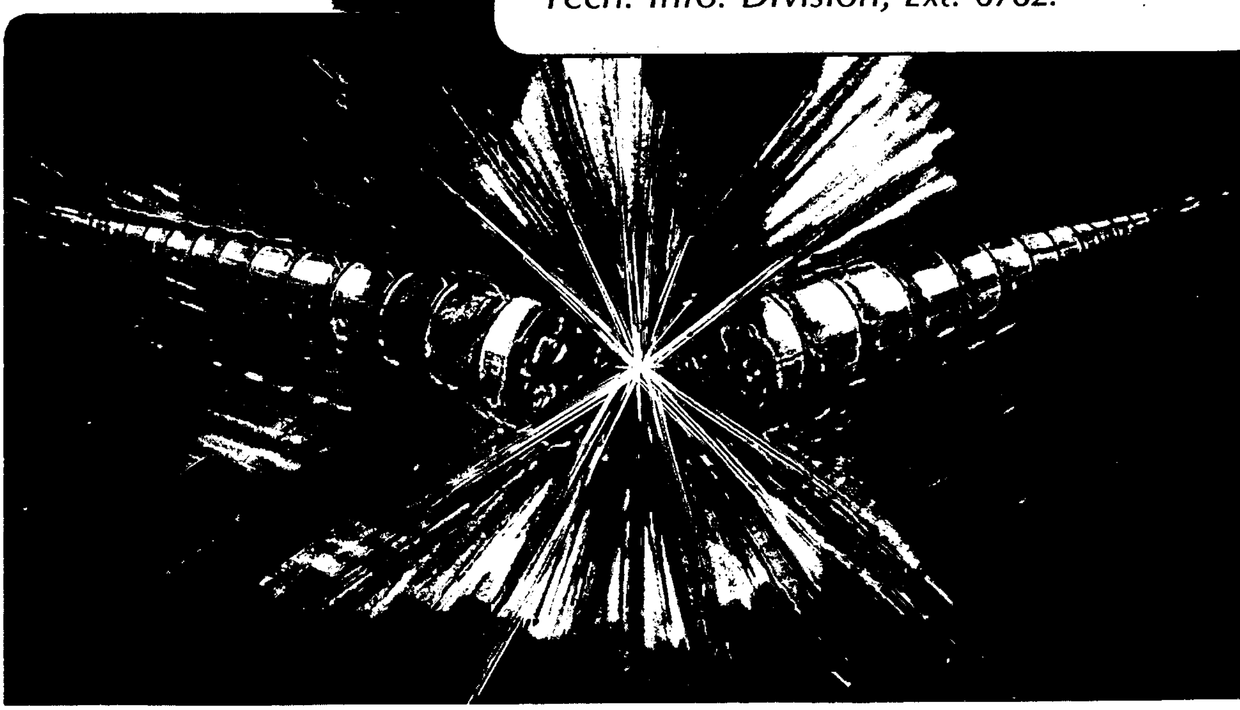

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ULTIMATE LIMITS, POSSIBLE DIRECTIONS OF TECHNOLOGY, AN APPROACH TO COLLECTIVE ACCELERATION*

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Presented during the Panel Discussion at the ECFA-RAL meeting
"The Challenge of Ultra-High Energies"
Oxford, September 27-30, 1982

Panel Members:

U. Amaldi (Chairman)
D. Keefe
J.D. Lawson
B. Richter
M. Tigner
G. Voss
W. Willis

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FOREWORD

At the request of Panel Chairman Amaldi, the oral version of this report was largely devoted to a recapitulation and critique of the various methods of collective acceleration, including plasma-laser methods, which had been presented at the meeting. Non-plasma methods that use microwaves or lasers were addressed by Richter[1]. Since the Proceedings of this Meeting contain the full reports of the works presented by many authors, it is inappropriate to repeat here that summary but not, of course, to include personal critical comments. This leaves me more room now to discuss some aspects of "the challenge of ultra-high energies" for which there was time only to make a bare mention in the oral version.

THE CHALLENGE OF ULTRA-HIGH ENERGIES --

ULTIMATE LIMITS, POSSIBLE DIRECTIONS OF TECHNOLOGY, AN APPROACH TO COLLECTIVE ACCELERATION+

Denis Keefe

1. Introduction

The recent ICFA studies[2] and the U.S. study at Snowmass[3] lead to the conclusion that a plausible next generation of accelerators would have parameters in the range of 20 TeV for a p-$\bar{p}$ accelerator-collider, and 350 GeV for an e^+e^- linear collider. Such parameters do not rely for justification on any unique theoretical prediction such as a new mass-threshold. Instead, they represent a scaling of about one order of magnitude above machines now under construction (Tevatron, UNK, SLC, LEP) and, therefore, lead to "imaginable" accelerator designs. The purpose of the present meeting is to look ahead to still the "Next Step Beyond", to recognize where the limits may lie, and to identify the most promising research on accelerator physics which could provide us with tools to push back those limits.

Some implicit assumptions made below include:

a) The single pass Linear Collider experiment at SLAC will verify that e^+e^- linear colliders work as advertised,

b) Beyond ~ 200-300 GeV the unfavorable scaling of cost and size (~ $B^2\gamma^2$) of <u>circular</u> e^+e^- colliders will have driven them out of the competition with linear colliders.

c) The highest energy in the center-of-mass will provide the most exciting physics <u>and</u> is best obtained in a p-$\bar{p}$ (or p-p) accelerator-collider.*

Assumption (c) may be wrong. The extraordinary Centauro events observed occasionally in cosmic-ray experiments may suggest possible new physics for nucleus-nucleus (e.g., iron-air) collisions at an energy $\gtrsim$ 1 TeV/amu in the center of mass. If <u>total</u> C-M energy, for some reason, is more important

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*The attractive feature of being able to use just one ring for a p-$\bar{p}$ collider may not survive in the future. If a second (intersecting) ring is needed, the distinction between a p-$\bar{p}$ and a p-p collider disappears for the purpose of this discussion.

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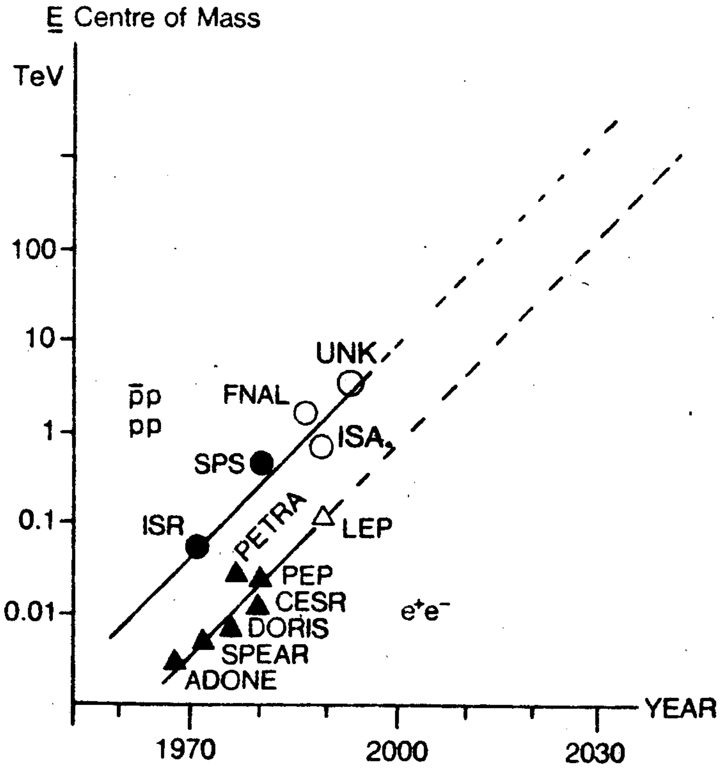

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Figure 1: The "Livingston Curves" show the exponential advance in center-of-mass energy with calendar time.

than γ_{cm}, then a p-$\bar{p}$ or p-p collider would be a poorer investment than a heavy-ion collider to study such physics. Worse, if new physics shows itself for high-energy multi-nucleon matter only, it might never appear at p-$\bar{p}$ or p-p or e^+e^- colliders, no matter how high the energy. A design for a future hadron collider ought to include the capability of its being converted - if ever needed - to a heavy ion collider.

The discussion below includes some views on ultimate limits to achieving high energy and on which aspects of technology for ring- and for linear-accelerators may pay off in the future. For the first, the problem is the guide-field and for the second, the impediment is the abysmally low electrical efficiency of rf acceleration methods. A merging between the thinking that has gone into certain (but not all) collective methods and the more traditional accelerator concepts could have encouraging consequences.

2. Energy Frontiers - The New Limits:

Several practical factors conspire to become, at the same time, almost insuperable for the "Step Beyond":

(i) Capital Cost: Lawson[1] reminds us that while the cost per MeV has diminished with time, upward progress along the "Livingston curve", (Figure 1) has involved monotonically increased cost so that future machine costs will be measured in billions of U.S. dollars. Not unconnected is the question of:

(ii) Constituency: In the ultra high energy era, the number of particle physicists involved will probably diminish as the lower energy machines are turned off and the number of affordable interaction regions shrinks towards one. At the same time, the partial cross-sections for a given channel of interest may well follow the same diminishing trend. Measured in "dollars per event-physicist", the degree of difficulty in getting support for further new accelerator construction will unfortunately become greater as the energy goes up.

(iii) Electricity: To maintain a reasonable event rate from a collider the beam power must increase with energy, because lowering the accelerated beam current is not an option if luminosity is to be kept high. An average power consumption of a (few x 100 MW) is probably the upper limit set by both the size of the annual power bill and the ability or willingness of the utilities to supply such a large single-user load. A power level of 1 GW could require a dedicated on-site power station; the additional capital cost of 3 G$(US) would be intolerable.

(iv) Site: The energy gradients in MeV per meter of structure for linacs and rings differ today, and will continue to do so in the immediate future, by an order of magnitude or slightly more (See Table 1). This factor of 10-20 discrepancy is reflected in the vertical displacement between the two Livingston curves for protons and electrons. A point emphasized by many speakers, and also below,

Table 1

EXAMPLE ENERGY GRADIENTS, dT/dz (MeV/meter of structure)

Electrons		Protons	
Accelerator	dT/dz *	Accelerator	dT/dz
SLAC (original)	7 MeV/m	FNAL original	80 MeV/m
SLAC (SLED I)	11 MeV/m	FNAL (Tevatron B = 5 Tesla)	170 MeV/m
SLAC (SLED II, future)	18 MeV/m	? (B = 10 Tesla, future)	340 MeV/m

*These values are set by limitations in microwave power sources and are much less than the breakdown limit.

is the need to push up the gradient for single-pass linac systems to 100 MeV/m, or more, so that in the path to ultra-high CM energies, electrons can begin to enter into competition with protons. With present, or slightly-scaled, technology one can see that the end of the line for hadron accelerators will be independently set by a site size comparable with national or state boundaries. For example, a 1000 TeV $p\bar{p}$ ring with 10 Tesla magnets has a diameter of 1000 km - a nation-sized device that represents not too great a factor beyond the envisioned Next Step of 20 TeV. ("not too great", that is, if we contemplate the immensity of the "desert".)

In practice, sites for large circular tunnels are more difficult to find than sites for linear colliders. For the latter there are the many possibilities of using existing long linear rights-of-way such as railroads, highways, utility power-runs, etc. A circular tunnel can, however, offer an interesting way of housing colliding linacs if we allow the "linacs" to have a gentle curvature to conform to the tunnel lay-out. (Synchrotron radiation is negligible in a slightly-bent single-pass high gradient structure.) Two colliding linacs each stretched once around the circumference of the LEP tunnel could provide 2 x 1 TeV if operated with a gradient of 33 MV/m, which is well below the sparking limit of an S-band structure. The energy could be increased by recirculation.

(v) Accelerator Physics: In contemplating the societal problems that can limit kinetic energy, we tend to forget that there are also several issues concerning beam physics and stability (See for example, references 2 and 3.). New features of concern for future $p\bar{p}$ colliders include the huge stored energy in the beams (which can be the equivalent of a ton or more of TNT), and a significant amount of energy loss by synchrotron radiation.

3. A Search for Solutions:

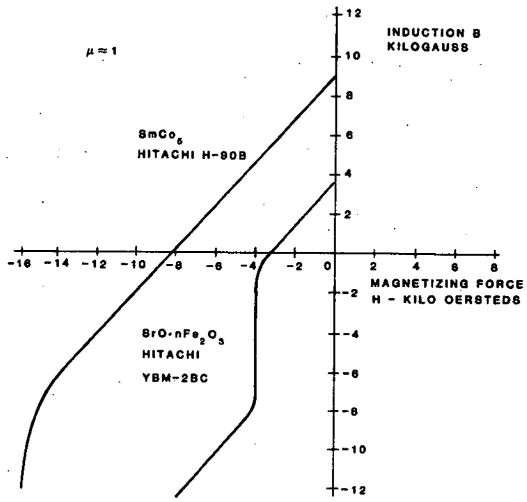
The above remarks are intended, not as an exercise in gloom, but as a reminder of the directions in which solutions need to be developed. What we can not guess today are the new inventions, technology revolutions and material developments that are sure to turn up in the coming decades and cannot but be to our advantage. (Imagine, for example, how the discovery of an inexpensive room-temperature superconductor would change the picture.) Nonetheless, there are many obvious ideas to be explored to alleviate the somewhat different problems of $p\bar{p}$ colliders and linear colliders.

$p\bar{p}$ Collider-Ring: If one considers an accelerator-collider system that takes, say, five minutes to accelerate, and five days to circulate the full energy beam, it is clear that the time-averaged power to the beam is negligible. There are therefore no great gains to be had by striving for higher gradient and greater efficiency in the rf system. Likewise a beam-energy recovery system is pointless. The guide-field magnets represent the dominant electric power load. For superconducting magnets the energy is mainly consumed by the refrigeration system.

Recently, there has been some debate about the most suitable magnetic field to choose for the superconducting guide-field magnets.[3] Where the site issue is controlling, e.g. if one wishes to use an existing tunnel, the highest practicable field (~ 10 T) is preferred. If the site issue is not controlling, however, Wilson has pointed out advantages in using iron-dominated superconducting magnets at 2 T ("superferric" design).[3, 4] If analysis shows that there is merit in the superferric approach, namely that a guide field of 2 T is acceptable, then it seems to me that serious attention should be given to an all-mechanical design based upon the newly available unit-permeability permanent magnet materials and using iron to shape the fields.

The mechanical manipulation of magnets - either permanent magnets such as Alnico or gradient electromagnets - to supply a pulsed guide field during acceleration has been the subject of speculation by several people in the past. There are two major reasons for raising the subject again, however. First, the field-superposition property of the $\mu \simeq 1$ permanent magnets gives a new degree of freedom. Second, the long acceleration time and the very long flat-top time peculiar to an accelerator-storage-ring device are especially well-matched, in the one case to a slow mechanical system and in the other, to a zero-power permanent magnet system.

Several materials are known that have $\mu \simeq 1$ in the second B v. H quadrant (Fig. 2) and if blocks of material are arranged in a chosen configuration the resultant field distribution is a direct superpositon of the independent fields, i.e. each block behaves like an air-core current-sheet loop.[5] One of the best-known materials is the rare-earth Samarium-Cobalt, which has the highest peak BH-product, and has found application for undulators and for linac quadrupole lenses. Unfortunately, it is expensive and for large-scale application to a storage ring one would choose other materials, such as barium or strontium ferrite which have a peak BH product one-quarter that of $SmCo_5$ but are only one-hundredth the unit cost. Enough material must be used to drive sufficient flux into the iron pole-tips to provide 2 T in the median plane; even so, the cost per meter of bending magnet turns out to be less than that for a superferric magnet and ancillary refrigeration.



TYPICAL MAGNETIZATION CURVES FOR
RARE EARTH COBALT AND STRONTIUM FERRITE

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Figure 2.

While the cost of electricity for a permanent-magnet ring running for days in the collider mode is virtually nil (in practice some trimming and correcting electromagnetic elements would be needed), energy must be supplied occasionally for a period of minutes, to depress the field to the injection value and allow it to ramp back up during acceleration. This could be done electrically at the expense of adding bucking coils and a power supply, but a recent development due to Halbach[6] suggests a more elegant purely mechanical method. Figure 3 shows a samarium-cobalt quadrupole design that can be tuned from B ≈ 0 to B ≈ 1.2 T at the pole tip by a mechanical rotation by 90° of the outer iron cylinder, on which are mounted some of the $Sm\text{-}Co_5$ blocks. In the one case, the outer blocks drive flux in the iron to cancel the contribution from the pole-to-pole blocks and, in the other, to aid it. The design is readily extendible to dipoles (180° rotation needed). The energy required for the mechanical rotations during injection and acceleration could be stored either electrically or mechanically.

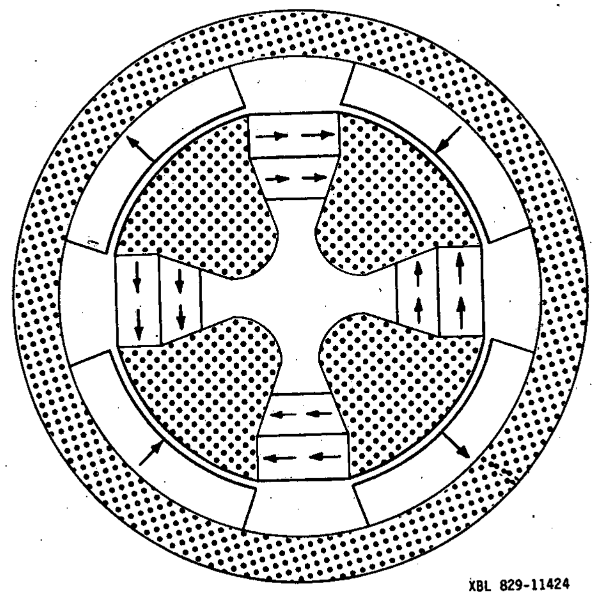

Figure 3: A quadrupole design using $SmCo_5$ (open areas with magnetization arrows) and iron (shaded) with a pole-tip field tunable from 0 to 1.2 T by rotating outer ring. (Ref.6) The concept is applicable to dipole or other multipole magnets.

e^+e^- Linear Colliders: The issues here are almost the opposite of those for $p\bar{p}$ rings - the guide field presents no difficulties and the two main concerns are the electrical efficiency from the power line to the beam, η, and the accelerating gradient, E.

Tigner[1] has given an excellent analysis of the situation and it remains for me only to concur with most of his remarks. His proposed goal is $\eta \approx 10\%$, $E \gtrsim 100$ MV/m. Part of the difficulties stem from the fact that electron linacs today operate at very low efficiency, a few percent, where certain scaling laws are unfavorable. For example, increasing the gradient in a given structure by increasing the voltage, V, leads to structure losses that rise as V^2 and hence an efficiency that drops as 1/V; matters would not be at all as bad if one were already operating with a high microwave-to-beam efficiency, say, 50% or more. Nonetheless, in many regards the search for high gradient and the search for high-efficiency tend to be in opposition to each other. The situation can get better, however, as the microwave frequency is increased (but not indefinitely, as some of Tigner's examples show).

As Table I shows, linacs lag behind rings by a large factor in energy gradient. The desire for higher gradient is mainly driven by the need to reduce Capital Cost and not so much at this time by the limitations of Site. The push for high efficiency is crucial to avoid the Electricity limit.

If a high beam efficiency, such as 30 percent or more, can be achieved then an efficient beam-energy recovery system will become important. Fortunately, the geometrical arrangement of linear colliders seems ideal for such a system.

4. Comments on Collective Methods of Acceleration

In judging how well collective acceleration may be expected to contribute in the ultra-relativistic domain, it is important to bear in mind that past work on collective methods has almost exclusively been concentrated on the problem of accelerating ions at low velocities. This in itself is a very difficult problem; some schemes work quite well at picking up the ions at near-zero velocity and accelerating them to $v \simeq 0.1$ c but run into difficulties beyond that, while others are better suited to acceleration at higher velocities but are ineffective near $v \simeq 0$. In my view, any such accelerator system to bring ions up from $v \simeq 0$ towards $v \simeq c$ must be a multi-staged device, with the early and late stages perhaps employing different principles of collective acceleration. The electron-ring accelerator stands unique in this regard: first, in having been conceived of from the beginning as a multi-stage device and, second, in having been demonstrated to work, in this mode, in the laboratory.[7] (Note however, that success with electron-ring acceleration has not come easily; it has taken 20 years and a large amount of research at several laboratories to obtain the results now reported from Dubna.)

The application of collective acceleration to ultra-relativistic energies ($\gamma >> 1$) needs, therefore, a change in attitude. Advances in the technology of high-energy accelerators have now set an ante which is very high ($\gamma \sim 1000$ for protons, $\gamma \sim 100{,}000$ for electrons) for any new player to face. Nonetheless, there are several features inherent in collective systems that could have exciting applications in the future. First is the possibility of using the strong electric field of an intense electron cloud to provide focussing and bending for positive ions (protons), a system first suggested by Budker[8] and now under study by Rostoker.[9] The discussion in Section 3 shows that for hadron colliders the enemy is the guide field, which in strength is approaching an ultimate limit of 10 T, or so; collective focussing has the potential for exceeding this considerably. (That such a scheme is inapplicable to anti-protons should be considered a detail at this point). Second, experiments have already demonstrated very high collective fields (~ 100-200 MV/m) albeit at low "phase-velocity" and over only short distances. Third, certain collective methods exploit a "negative-energy" feature in coupling to the accelerated beam; in this case the larger the beam loading the higher are the gradient and the efficiency.

In short, it seems that hadron colliders could benefit only from the collective focussing/guiding schemes, whereas e^+e^- linear colliders stand to gain from higher accelerating gradients and better efficiencies. There is little to say at this time about the first application (focussing/guiding) and we must await experimental results. We can, however, discuss certain features of a collectively driven linac for high γ. It is clear that the collective devices must be made modular, say, each a few meters in length, and stacked in series with suitable phasing, to form the high-energy linac. In a stacked sequence of collective accelerating modules such as this, one has the choice of extracting the spent driving electron beam at the end of each module and recovering its energy, or of reprocessing the beam and inserting it into a succeeding module. Operating parameters for the drive beams would be presumably in the few MeV, multi-kiloampere range.

With electric acceleration in mind and looking back at the catalog of collective schemes discussed by Sessler and by Nation,[1] I conclude the following:

(i) Localized space charge or controlled moving electrostatic wells have no application for large γ.

(ii) Slow waves on beams (cyclotron or space-charge) - and electron-rings - could be useful in principle, since v_{ph} can come close to c, but probably are impracticable. Since one has $v_{ph} < v_e < v_b < c$, where the subscripts denote the phase velocity, drive-beam velocity, and accelerated beam velocity respectively, the accelerated particles will tend to slip out of phase with the wave. This need not be a problem if the module length is chosen correctly and successive modules suitably phased. Much more serious, and probably fatal, is that the accelerating electric field of the wave varies as $(\gamma_e - \gamma_{ph_2})$ and hence tends to zero at high phase velocity. (As usual, γ is $(1-\beta^2)^{-1/2}$).

(iii) Electron-beam Beat-wave Devices, in which two slow waves can be beaten together to generate a fast wave (ie. $v_{ph} \gtrless c$), clearly are applicable and worthy of much more study than they have received. The systems explored by Friedman and Velikhov have been described by Nation [1]; both employ an intensity-modulated electron beam which undergoes further (spatial) modulation by a zero-frequency wave, a periodic solenoid array in one case, a rippled wave-guide in the other. The result is a slow ($v_{ph} < c$) forward wave and a fast ($v_{ph} \gtrless c$) backward wave and the latter is clearly the one of interest for the high-γ domain.

(iv) Laser Beat-wave systems such as that described by Tajima, Soshi, and Sullivan[1] rely on beating two laser waves (ω_1 and ω_2, chosen such that $\omega_1 - \omega_2 = \omega_p$) in an underdense plasma (ω_1, $\omega_2 > \omega_c$). Although each wave has a phase velocity greater than c in underdense plasma, the beat action can produce a plasma wave that propagates at a phase velocity slightly less than c. Computer simulation of the non-linear optical mixing indicates a very high degree of charge modulation in the wave and consequently enormous accelerating gradients, perhaps in the range 1-100 GV/m.

Although there are many serious issues that remain to be addressed for the practical exploitation of this phenomenon (e.g. coherence length, phasing, staging), research that could lead to such high accelerating gradients seems well worthwhile pursuing.

Finally, it should be emphasised that both collective methods and far-field ("real-photon") methods share an advantage in principle over conventional methods in that the electric field at the location of the accelerated beam can be very high, while the field at the walls of the system remains within manageable limits. Ultimate collective accelerating gradients need not then be bounded by the breakdown gradient limits of material surfaces.

5. Power Sources and the Approach Toward Collective Acceleration

Previous sections have emphasised the need to strive for higher efficiency and higher gradient in a linac. Some day a collective method, in which the driving and driven beam are superimposed, may provide the answer to these two needs and, in addition, allow a gradient higher than that set by the breakdown strength. There is much room for improvement with present systems, however, before one actually needs the last feature offered by collective methods. SLAC for instance, when upgraded to 50 GeV for the SLC, will have a gradient of 17 MeV/m, still a factor of five or so below the electrical breakdown limit. Break down limits as high as 100 MeV/m have been reported at Novosibirsk. If one traces the direction of people's thought on improving linacs, it is towards geometrical and topological arrangements that approach closer and closer to the appearance of a collective device.

Figure 4 shows a simple sketch of a section of the S-band linac (λ = 10 cm) at SLAC. rf power for a 12 m length of the structure is derived from a single driving electron beam in a klystron less than two meters long, and fed through long waveguides that penetrate the shielding. The resonant structure acts as a voltage step-up transformer and 120 MeV can be delivered to the accelerated beam in the 12 m section.

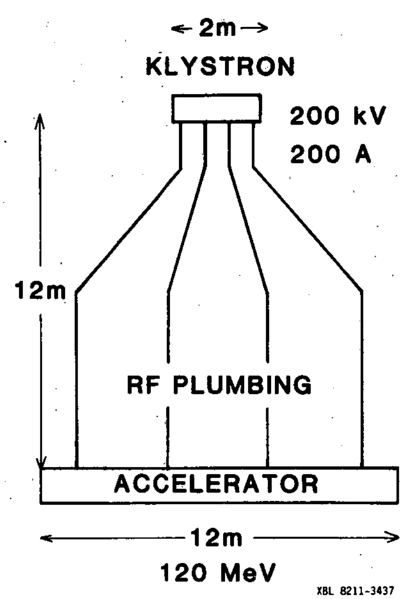

Figure 4: The schematic shows the disparity in length between the driving electron beam (klystron) and the accelerated beam in a section of the SLAC.

For future resonant rf devices the lines of reasoning or speculation have followed several steps (illustrated here by just a few examples)

Step 1: Use shorter wavelengths; the discussion of scaling by Tigner[1] shows the advantages. As the skin depth becomes smaller, waveguide losses become serious and the rf plumbing must be minimized. Sessler[10] has suggested using millimeter waves from a multistage free electron laser (FEL) - the driving electron beam being rejuvenated in a sequence of induction cavities. While details of the rf coupling are not mentioned, it is clear that the concept calls for the FEL and the millimeter rf accelerating structure to be run side-by-side in very close proximity.

Step 2: Incorporate the driving beam(s), the accelerator structure, and the accelerated beam in the same vacuum envelope. This arrangement simultaneously minimizes the rf transmission difficulty and eliminates nasty insulator problems. The proton klystron described by Skrinsky falls into this category. Another example grew from the suggestion by Maschke[11] that klystrons with higher power might be made not by going to higher voltage but, better, by using many beams of small cross-section and higher total current. When Faltens and I examined this idea a few years ago we concluded that the best way to use such a device was not as a power source for a separate accelerating structure, but to arrange the many small drive beams in an annular array around the structure and to accelerate the high energy beam on axis.

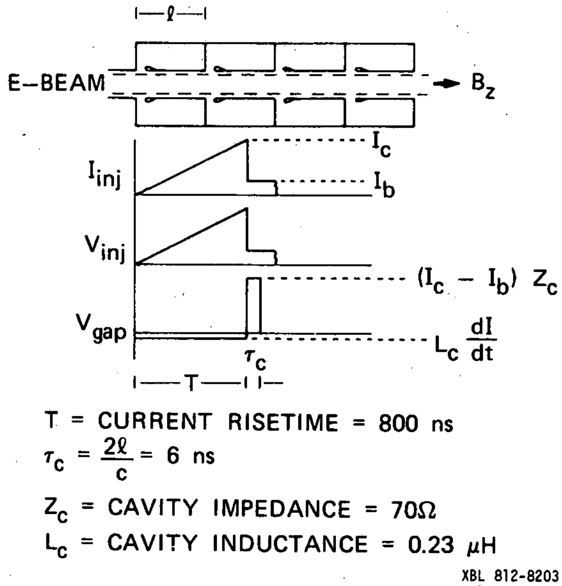

Figure 5: Schematic of four-cavity autoaccelerator with current and voltage profiles. (Ref. 13)

Step 3: Incorporate the driving beams(s), and the accelerated beam in the same envelope but without any structure intervening between them. The beat-wave accelerator schemes worked on by Friedman and by Velikhov (See Nation [1]) fall exactly in this category. The structures providing the zero-frequency wave lie entirely outside both beam components.

In his summary table, Lawson[1] noted the paucity of harmonic field acceleration schemes that utilized free charges in the accelerating system. Devices mentioned under Step 2 above probably fall under that heading and those under Step 3 certainly do.

Step 4, in which the driving and accelerated beams overlap in location, is not yet to hand.

An analogous progress in thought can be identified for non-resonant, i.e. pulsed, systems. The wake-field accelerator, described by Voss and

Weiland[1], incorporates an annular driving beam, a radial line, and the accelerated beam in the same envelope. The inward increase in impedance of the parallel plate radial lines provides voltage amplification of the 30 psec pulse on axis. (A related experiment wth much longer pulses - 1 nsec - and with discrete voltage pulses arranged on a circle has demonstrated the axial voltage amplification feature [12]).

Finally, one should note an unusual concept, the Autoaccelerator,[13] in which the driving and accelerated electron beams overlap in location but not in time (See Fig. 5). The energy in a large number of electrons in the first part of the beam is used, via the electromagnetic energy transferred to a coaxial cavity, to accelerate a smaller number towards the rear of the beam. The linear current rise (Fig. 5) charges the cavity, meanwhile producing a small decelerating voltage at the gap. When the current rise is halted and the current suddenly and drastically reduced, a very high voltage appears on the gap for a time equal to the double transit time of the cavity, and accelerates the tail of the pulse. A sequence of cavities, such as shown, would be self-synchronous and eliminate the need for high-voltage insulators. Friedman has demonstrated success with a single cavity but has had trouble operating a sequence of cavities.

Acknowledgments

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