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NEW ACCELERATION METHODS

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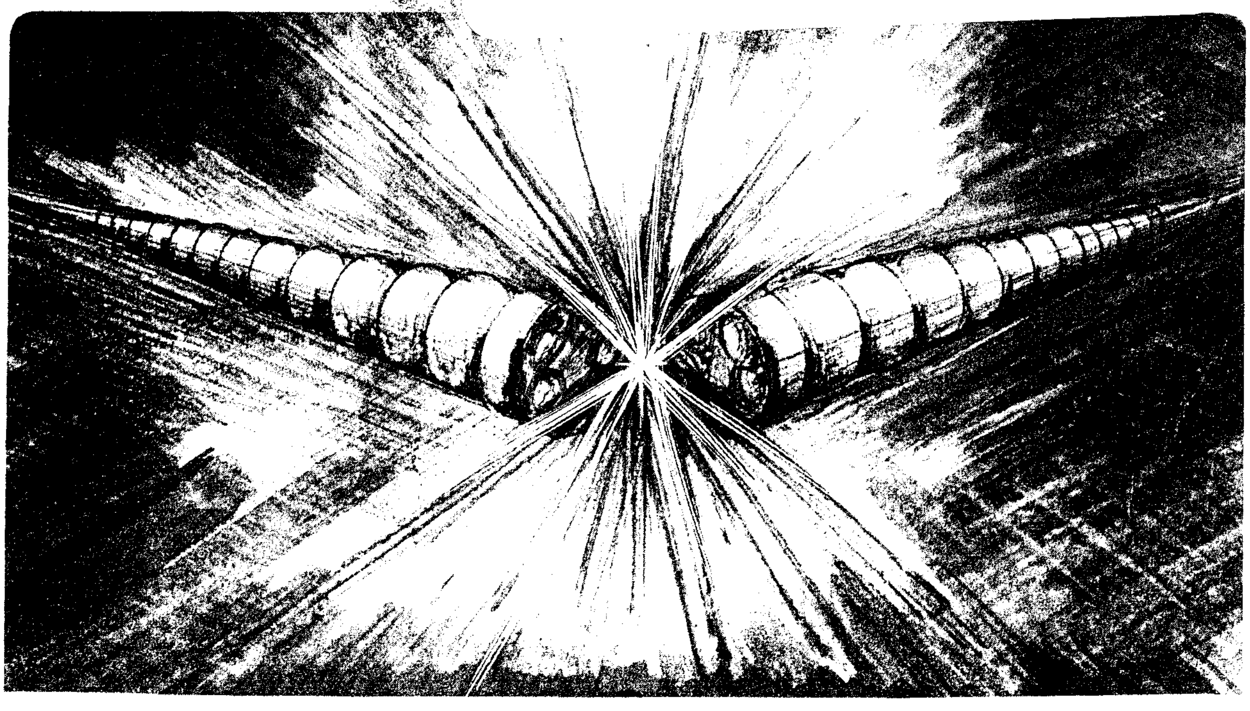

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NEW ACCELERATION METHODS

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I. INTRODUCTION

But a glance at the Livingston chart, Fig. 1, of accelerator particle energy as a function of time shows that the energy has steadily, exponentially, increased. Equally significant is the fact that this increase is the envelope of diverse technologies. If one is to stay on, or even near, the Livingston curve in future years then new acceleration techniques need to be developed.

What are the new acceleration methods? In these two lectures I would like to sketch some of these new ideas. I am well aware that they will probably not result in high energy accelerators within this or the next decade, but conversely, it is likely that these ideas will form the basis for the accelerators of the next century.

Anyway, the ideas are stimulating and suffice to show that accelerator physicists are not just "engineers," but genuine scientists deserving to be welcomed into the company of high energy physicists! I believe that outsiders will find this field surprisingly fertile and, certainly fun. To put it more personally, I very much enjoy working in this field and lecturing on it.

There are a number of review articles which should be consulted for references to the original literature.[1,2] In addition there are three books on the subject.[3,4,5] Given this material, I feel free to not completely reference the material in the remainder of this article; consultation of the review articles and books will be adequate as an introduction to the literature for references abound (hundreds are given).

At last, by way of introduction, I should like to quote from the end of Ref. 2 for I think the remarks made there are most germane. Remember that the talk was addressed to accelerator physicists:

"Finally, it is often said, I think by physicists who are not well-informed, that accelerator builders have used up their capital and now are bereft of ideas, and as a result, high energy physics will

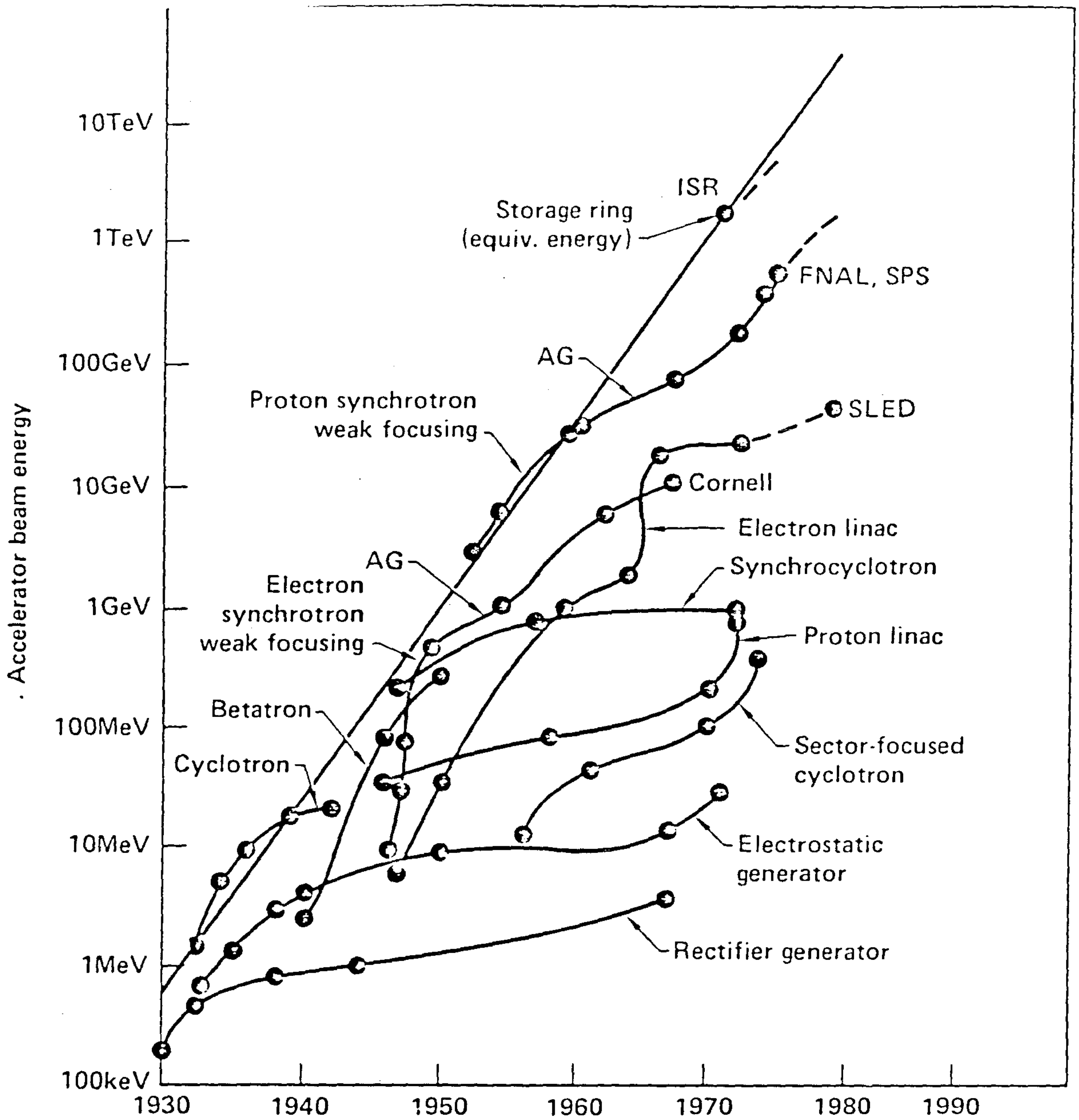


Fig. 1. The "Livingston chart" which shows energy of particle accelerators as a function of time.

eventually -- rather soon, in fact -- come to a halt. After all, one can't build too many machines greater than 27 km, and soon one will run out of space or money (almost surely money before space). This argument seems terribly wrong to me, and worse than that possibly destructive, for it will have a serious effect if it causes, as it well might, young people to elect to go into fields other than high energy physics. The proper response, I believe, is to point -- in considerable detail -- to some of the new concepts which show by example that we are far from being out of new ideas. Some of these concepts shall, in my view, be, or lead to, the "stocks in trade" of the next century, and thus they will allow high energy physics to be as exciting then as it is now. It is our job to make it all happen."

PART A: COLLECTIVE ACCELERATORS

II. OVERVIEW

Collective accelerators; i.e. accelerators which operate by accelerating the particles one really wants to accelerate by having them interact with other particles, have been considered for a very long time. The first thoughts were in the early 1950s and then the subject was given a considerable impetus by the work of Veksler, Budker and Fainberg in the mid 1950s. In the early 1960s both workers in the US and in the USSR discovered "naturally occurring" collective acceleration (described in Section III).

In the late 1960s, extending into the 1970s, considerable experimental work was done on the electron ring accelerator (see Section V). Work has been done on wave accelerators (see Section IV) throughout this period.

Yet now, in 1984, there is still no practical collective accelerator. Why? Because the controlled, repeatable, reliable, and inexpensive (This criterion has not yet been applied, but sooner or later it will be.) acceleration of ions by a collective device is very difficult indeed. We shall, in Part A of this article, indicate the basic physics which makes collective acceleration so difficult. Yet the promise is there, if we could only do it .... .

2.1 Motivation

In a conventional accelerator the particles which are being accelerated are tenuous and thus, to a good approximation.

$$\nabla \cdot \mathbf{E} = 0 \ ,$$

$$\nabla \times \mathbf{B} - \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} = 0 \ . \qquad (2.1)$$

In collective devices one has significant charge which one is handling and thus

$$\nabla \cdot \mathbf{E} = 4\pi\rho \ ,$$

$$\nabla \times \mathbf{B} - \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} = \frac{4\pi}{c}\mathbf{J} \ . \qquad (2.2)$$

As one can see this generalization allows an almost unlimited range of possibilities.

In conventional devices the external currents, which produce the E and B, are limited by the properties of materials. Consequently there are limits, for example on accelerating fields or bending radii, and these limits then produce the restrictions on performance of the devices. In collective accelerators, however, one can obtain very large $\underset{\sim}{E}$ and $\underset{\sim}{B}$ if one can contain, and control, the ρ and $\underset{\sim}{J}$. Thus there is the promise of improved performance as well as compactness and inexpensiveness.

How can one generate the collective $\underset{\sim}{E}$ and $\underset{\sim}{B}$? Either from stationary charges, which are not used in any device, or from streaming charges. One wants streaming charges so as to obtain a $\underset{\sim}{J}$ and, also, to reduce the forces of the streaming particles on each other. This reduction is the result of a cancellation between the electric forces and magnetic forces which is to order $1/\gamma^2$ when the particles are far from any boundary and moving in a straight line.

Typically, the charges and currents which "do the work" in collective accelerators are electrons generated by an intense relativistic electron beam (IREB). These devices are pulsed diodes with field emission cathodes and a foil anode or ring anode. Usually, these machines produce electrons of 10 kA to 100 kA, in the range of 1 MeV to 10 MeV, and with pulse lengths of 10 nsec to 100 nsec.

The electron density, since the beams have a radius from 1 cm to 10 cm are 10^{11} to 10^{13} cm^{-3}. A typical electric field is, then,

$$E\ (\mathrm{MV/m}) = \frac{6.0\ I\ (\mathrm{kA})}{r_b(\mathrm{cm})} \quad . \tag{2.3}$$

For I = 20 kA and a radius r_b = 1 cm this is a field of 120 MV/m which should be compared with the Stanford Linear Collider (SLC) which has a field of 17 MV/m, or with an ion linac (like LAMPF) which has a gradient of 1 MV/m.

2.2 Impact Acceleration

Consider a bunch of N_1 electrons of mass m moving at very high speeds ($\gamma >> 1$) which collide with a stationary light bunch of N_2 ions each having mass M. We must have

$$N_1\ m >> N_2\ M \quad . \tag{2.4}$$

Energy and momentum are, of course, conserved in this collision:

$$N_1\ m\gamma\beta = N_1\ m\gamma_1\ \beta_1 + N_2\ M\ \gamma_2\ \beta_2 \quad ,$$
$$N_1\ m\gamma + N_2\ M = N_1\ m\ \gamma_1 + N_2\ M\ \gamma_2 \quad . \tag{2.5}$$

See Fig. 2 for appropriate definitions. Solving these equations, one obtains the result that <u>each</u> ion receives an amount of energy

$$W = 2\gamma^2\ Mc^2 \quad , \tag{2.6}$$

which is a very large amount indeed.

Veksler believed this was the only way to attain really high energies. The Laser-Plasma Accelerator can be thought of from this point

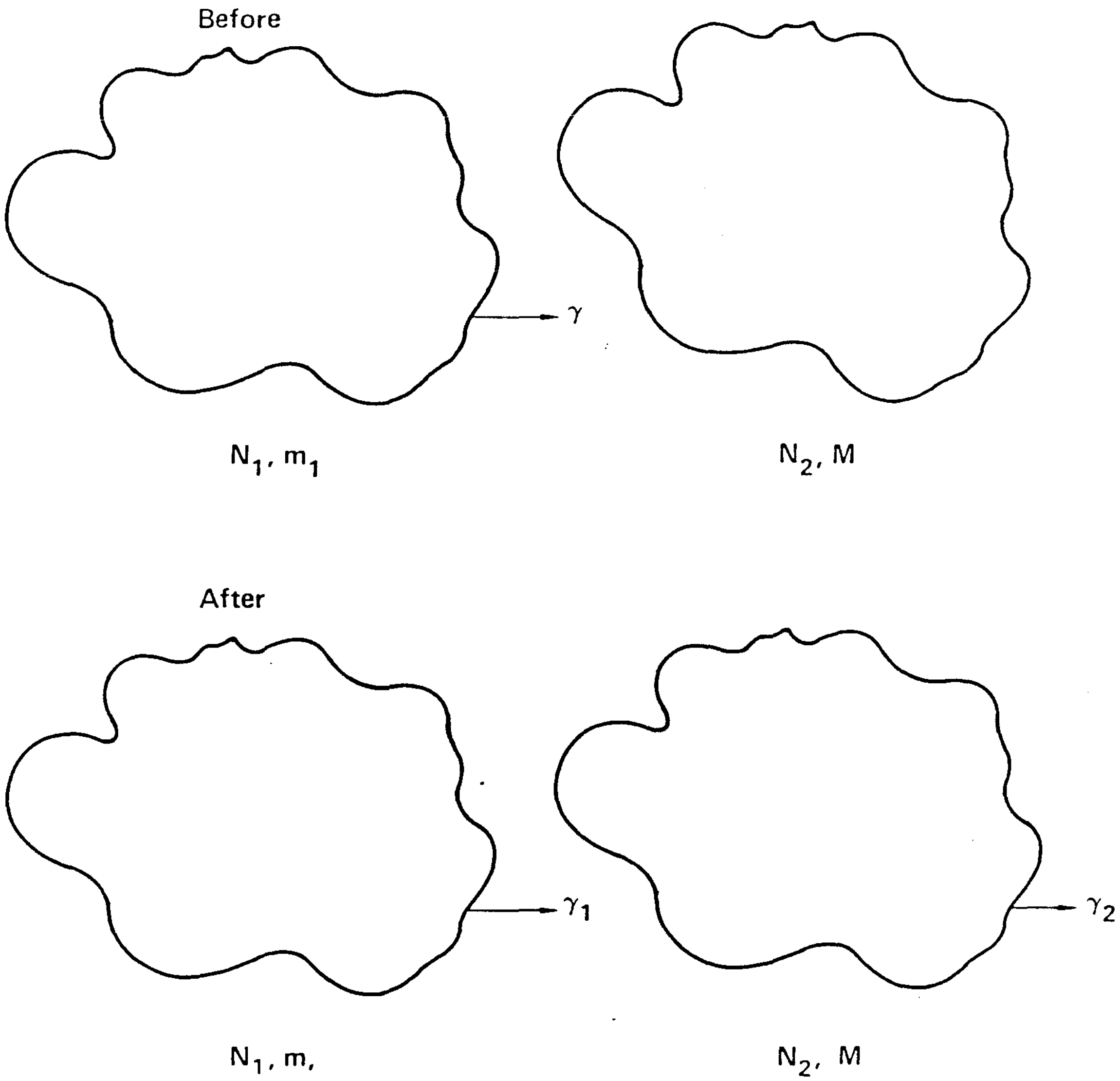


Fig. 2. An impact accelerator.

of view; the large bunch is a group of electrons making a ponderomotive well, which is the only way yet conceived for "holding a bunch together" during a collision. In fact, it was the inability to make integral bunches which prevented making any real progress along these lines.

2.3 Electron Beam Physics

We have noted that IREBs are central to most collective acceleration schemes and hence it is necessary to remark upon one or two key characteristics of such beams.

For an electrically neutral uniform beam, an electron at the beam edge has a cyclotron radius

$$r_{ce} = \frac{\beta_e \gamma_e mc^2}{eB_\theta(r_b)} \quad , \tag{2.7}$$

where $B_\theta(r_b)$ is the magnetic field produced by all of the other electrons in the beam; i.e.

$$B_\theta(r_b) = \frac{2I_e}{cr_b} \quad . \tag{2.8}$$

If $r_{ce} > r_b/2$ then the beam will not propagate, which occurs for

$$I > I_A \equiv \frac{\beta_e \gamma_e mc^3}{e} \quad . \tag{2.9}$$

This critical current, the Alfven-Lawson current, is in practical units

$$I_A = 17\,\gamma_e\ (\text{kA}) \quad . \tag{2.10}$$

Beams of $I > I_A$ can propagate by hollowing out or by having return currents within the beam so that the net current is less than I_A. In practice, most collective accelerators operate with $I < I_A$.

A second space charge limit is much more severe than the above, and more central to the operation of collective accelerators. Consider a beam of current I_e and fractional neutralization f, sent into a tube of radius R. A potential develops, between the beam center and the tube, which is just

$$V = \left(\frac{I_e}{\beta_e c}\right) (1 - f)\ [1 + 2\ \ell n\ R/r_b] \quad . \tag{2.11}$$

If this is equal to the electron kinetic energy $(\gamma_e - 1)\,mc^2$ then the beam will not propagate. Equating, one finds

$$I_l = \frac{\beta_e(\gamma_e - 1)\left(\frac{mc^3}{e}\right)}{[1 + 2\ \ell n\ R/r_b]\ [1 - f]} \quad . \tag{2.12}$$

For f = 0 we get a limiting current which is less than I_A. For $I_e > I_l$ the beam will not propagate but neutralize itself (so that $f \rightarrow 1$ and I_l exceeds I_e) and then propagate on. The time scale for neutralization dominates the propagation speed which can be far less than one might expect; i.e. the speed of light.

There are many other space charge limits of IREBs, as well as many other interesting aspects of their physics, but we have enough for this review of collective accelerators.

III. SPACE CHARGE WELLS

If an IREB is simply injected into a gas, as shown in Fig. 3, then ions will be accelerated. Note that this is a collective phenomena; it certainly isn't single particle acceleration by the potential-drop of the IREB generator for that potential is going the wrong way.

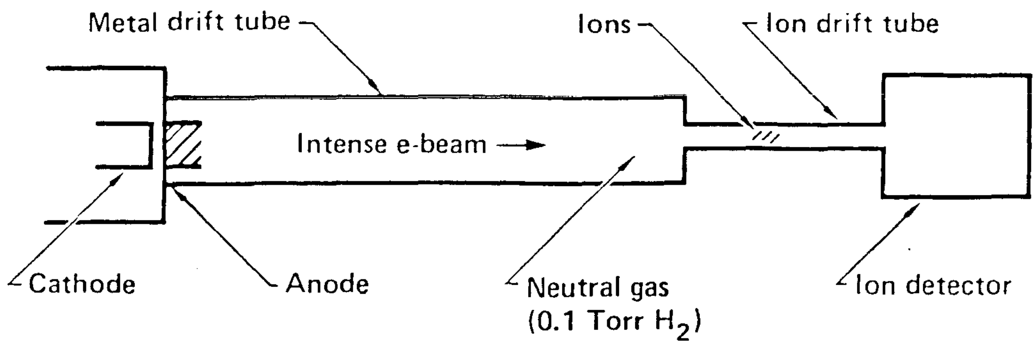


Fig. 3. Schematic drawing of a moving space charge well accelerator.

Alternatively, if an IREB is injected into a vacuum, but produced by means of a plastic ring anode (a copious source of ions), then accelerated ions will be observed.

Roughly, one obtains about 10^{13} protons, of up to 10 MeV, and with a pulse width of 10 nsec. The physical mechanism, in the case of a beam sent into a gas, is believed to be the following. The beam is arranged to be of greater current than the space charge limit I_1 and hence it propagates but a short distance and then stops (a "virtual anode"). After a bit the beam is neutralized and propagates a bit further. This process, since the beam velocity is low, can accelerate ions from rest. There is, clearly, a space charge well associated with the beam front and hence the idea of a space charge well accelerator.

Of course the situation is, in reality, very complicated with the IREB changing in time, 3D effects, photo-ionization, impact-ionization, etc. Much of this has been studied, in most detail by numerical simulations. One must explain, and roughly one can, a potential well of depth 2 or 3 times the beam kinetic energy, (One might think there would be exact equality, but remember that the situation is dynamic and electrons keep streaming into the well and hence make it deeper.) a well-extension of 1 - 2 times the pipe radius, and a well-velocity sufficiently low as to pick-up ions from rest.

Once one realizes that a space charge well can be formed by an IREB then one "only" needs to control its velocity and one has an accelerator. Much effort, needless to say, has gone into beam-front velocity control. One system proposed by Olson, that is conceptually simple, is shown in Fig. 4. Here laser pulses, properly timed, are used to create plasma into which the IREB propagates at a controlled speed. This device has actually been made to control beam front velocity, but no ions have yet been accelerated.

Alternatively, pulsed wall plasmas have been considered. Also, study has been made of slow-wave structures with which heavy ions have been accelerated in a more effective way than without such structures.

This approach has not yet resulted in a practical accelerator. It seems unlikely that one can obtain very high energy particles this way, but perhaps one can make an accelerator for one of the many hundreds of uses to which low-energy accelerators are put (such as food treatment, chemical polyrization, or medical uses).

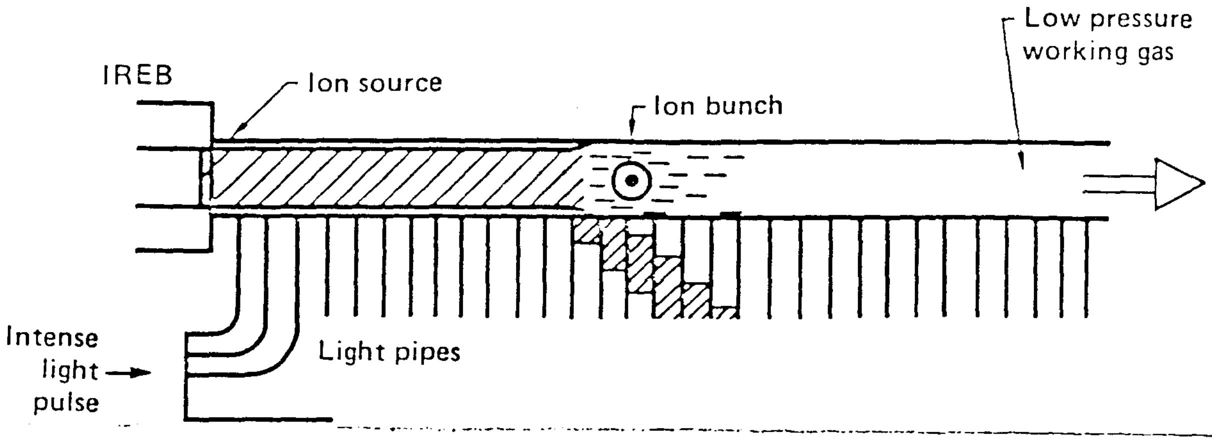


Fig. 4. The Ionization Front Accelerator.

IV. WAVE ACCELERATORS

Wave accelerators are based upon the idea that an IREB is a non-neutral plasma which can support waves. If these waves are unstable then they will grow, at the expense of the beam kinetic energy, and thus can produce a large electric field suitable for the acceleration of ions.

In order to be proper for the acceleration of ions the wave phase velocity must be controlled, variable, and reproducible. Furthermore it must be a "reasonably good" wave; i.e. it must be coherent over many wavelengths and for times greater than the acceleration time.

Firstly, we need to be able to stably propagate an IREB. This can be done in the presence of a longitudinal magnetic field, B, but not otherwise. Such flow is called Brillouin flow and requires that three conditions be met:

$$\omega_p^2 < \frac{\gamma_e \Omega}{r_b} \quad , \tag{4.1}$$

$$2\,\omega_p^2 < \gamma_e^2\, \Omega^2 \quad , \tag{4.2}$$

$$\omega_p^2\, r_b^2 < 4c^2 \quad , \tag{4.3}$$

where the plasma frequency, ω_p, is

$$\omega_p^2 = \frac{4\pi n e^2}{\gamma_e m} \quad , \tag{4.4}$$

and n is the laboratory beam density, and the cyclotron frequency, Ω, is

$$\Omega = \frac{eB}{\gamma_e mc} \quad . \tag{4.5}$$

Condition Eq. (4.1) is that the self electric field is smaller than the confining magnetic field. The Eq. (4.2) is just the relativistic form of the usual condition for Brillouin flow. And Eq. (4.3) is simply Eq. (2.10).

It is a relatively simple matter to find the longitudinally propagating waves on a cylindrical (and wide) electron beam. The dispersion relation is algebraic in the frequency of the wave and has 8 modes. A number of different programs have been based upon experimental work focused upon one mode or another.

There is only one mode which has a phase velocity which can be made very small, as was noted by Drummond and Sloan. This mode is called the Doppler-shifted cyclotron mode and has

$$\omega = k\, v_e - \Omega \quad , \tag{4.6}$$

or a phase velocity

$$v_{ph} = \frac{\omega}{k} = \left(\frac{\omega}{\omega + \Omega}\right) v_e \quad . \tag{4.7}$$

By varying B as a function of z one can vary v_{ph}. This has been done, as well as to grow the desired wave (and no other wave!), but the program was terminated before ions were accelerated.

Other workers, as I have noted, have focused upon other waves as well as upon waves which come about from ion-electron oscillations (as contrasted with pure electron modes). Suffice it to note that there is not yet, to date, a practical wave accelerator.

V. ELECTRON RING ACCELERATOR

An electron ring accelerator (ERA) is a device having a compact ring of electrons which has an associated electric field which can, then, be used to accelerate ions. A schematic of the device is shown in Fig. 5. At one time, this approach attracted many workers and a good number (6 or so) of groups. Now there is only the Dubna group still extant. This was the very first group, having been started by Veksler, who conceived the idea, about two decades ago.

In order to obtain a large field gradient one must make very compact rings having a large electric current. (The current is necessary for if the electrons were at rest, then their self-electric field would blow them apart. However if they move then the magnetic, current-current, force almost cancels the electrostatic repulsion.) The electric field from a ring is (roughly):

$$E\ (\mathrm{MV/m}) = \frac{(4.58 \times 10^{-12}) N_e}{R\ (\mathrm{cm})\ a\ (\mathrm{cm})} \quad , \tag{5.1}$$

where N_e is the number of electrons in the ring and R and a are the two radii of the torus.

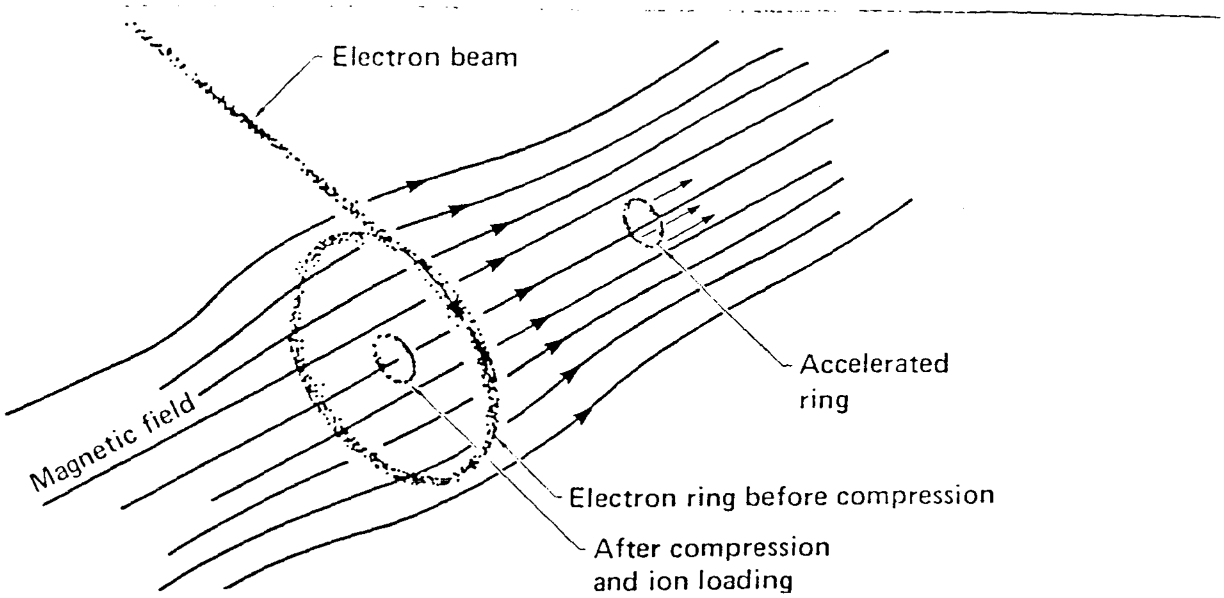


Fig. 5. The Electron Ring Accelerator in its simplest version. The acceleration of the ring, axially, is caused by a decreasing magnetic field.

Such a ring can most be conveniently made by injecting a larger ring and then "compressing" it by increasing the magnetic field enveloping the ring. For an axially symmetric field the azimuthal component of the canonical momentum, P_θ, is conserved and hence

$$R\ P_\theta - e\ R\ A_\theta = \text{const} \quad , \tag{5.2}$$

where the magnetic field is described by the vector potential A_θ.

For a uniform field of magnitude B

$$A_\theta = \frac{1}{2}\ BR \quad , \tag{5.3}$$

and since

$$P_\theta = eBR \quad , \tag{5.4}$$

we see that BR^2 is constant during compression. In the Berkeley ERA the major radius was compressed from 20 cm to 5 cm with ring current, correspondingly, increasing from 1/2 kA to 2 kA.

The minor ring dimensions are given by conservation of the adiabatic invariant

$$\frac{P_\theta Q a^2}{R} = \text{const} \quad , \tag{5.6}$$

where Q is the tune of the electrons. Although Q changes as compression is undergone (and decreases), a^2 damps a good bit.

Once one has a compact ring, with an associated large electric field, one "loads" the ring with ions. Not too many ($N_i < N_e$) so that there is still a large self electric field, but not so few $N_i > N_e/\gamma^2$ so that the ion-produced electric field will more than overcome the net electric repulsion. Thus the ring is self-focused both for its electron and for its ion component; a concept pointed out, in a slightly different context, by Budker.

Other means of focusing the ring are possible, such as image focusing, but we shall not discuss that here.

The ring is then accelerated axially and drags the ions along. Since the ions and electrons move at the same speed one picks up a factor of $M/m = 1837$ in the energy. This is not correct, however, for the electrons are rotating, and one only gains a factor of $M/m\gamma \approx 50$, which is still a sizeable factor. Alternatively, one can't accelerate the ring too quickly or the ions will be left behind. A measure of the rate of acceleration is just the peak field (Eq. (5.1)). Typically one can easily accelerate rings and great efforts must be made not to do it too quickly.

Rings can either be accelerated by electric fields (rf) or by an inverse compression process; i.e. by "magnetic expansion." It is not hard to show that, in the latter case, the ion energy W is given by

$$W = \frac{(1 - b^{1/2})\, Mc^2}{b^{1/2} + g} \quad , \tag{5.7}$$

where g is the ion mass loading

$$g = \frac{N_i M}{N_e m \gamma_c} \quad , \tag{5.8}$$

and γ_c is the electron (rotation) γ in the compressed state. The quantity b is the magnetic field falloff, which must not be too fast or the ions will be lost. For most rapid acceleration one should choose

$$b \equiv \frac{B_z}{B_c} = \frac{1}{\left[1 + \frac{3z}{2\lambda}\right]^{2/3}} \quad , \tag{5.9}$$

where λ is a characteristic falloff distance and can be expressed in terms of ring parameters:

$$\lambda \approx 2\pi \, \frac{RaMc^2}{e^2 N_e} \quad . \tag{5.10}$$

Amazingly enough, in view of the complexity of the concept, good quality rings have been made by three groups and ERAs have been made to accelerate ions (to a few MeV) in two laboratories.

The difficulties are many and the complexity of an ERA has prevented practical accelerators from being constructed. In addition, there is a severe space charge limit on making good quality rings; i.e. one cannot achieve really large acceleration gradients this way; in practice the limit is probably lower than 100 MV/m.

PART B: LASER ACCELERATORS

VI. GENERAL CONSIDERATIONS

At first sight it would appear that a laser would be ideal for accelerating particles. The fields at the focus of a powerful laser are 10^4 to 10^6 MV/m, which might be compared to that of the Stanford Linear Collider (SLC); namely a gradient of 17 MV/m. Considering, again, the large field of a laser one notes that it is in the wrong direction; namely it is transverse instead of longitudinal. Furthermore the field only extends over the focus and the depth of field is not very large and would be soon passed through by a high energy particle. And, in addition, a light wave travels, of course, at the speed of light and therefore is not in resonance with any material particle. One can see that acceleration by lasers is not easy; somehow one must contrive to get around the three difficulties mentioned. Surprisingly enough one can, in fact, accelerate with lasers. It is instructive to consider firstly, the effect of a plane wave on a charged particle. The motion which is given to the particle is shown in Fig. 6. One sees that there is no continuous acceleration; in fact after each period of the plane wave the particle is returned to rest. Suffice it also to note that for the most powerful lasers the acceleration in one quarter of a cycle is only to a few hundred MeV and therefore of no interest. (One should observe, however, that this mechanism is very effective when astronomical distances are involved; it is believed to be the primary source of cosmic rays, with the acceleration occurring in the field of a pulsar.)

The field pattern produced by <u>any</u> array of optical elements, provided one is not near a surface and not in a medium, is simply a superposition of plane waves. It is not very hard to generalize the

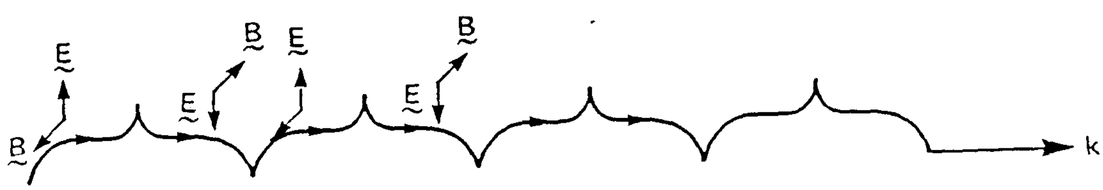


Fig. 6. Motion of an electron in a plane electromagnetic wave. The particle motion is determined by a combination of (reversing) transverse electric field which accelerates the particle and (reversing) transverse magnetic field which bends the particle. The net effect is that a particle is moved along in the direction of the wave, but is not accelerated.

considerations made for a single plane wave and conclude that for a relativistic particle, which moves very closely at a constant speed and in a straight line, there is not net acceleration! This fundamental theorem is most valuable for it allows one to discard schemes which won't work and focus one's thoughts in fruitful directions.

In order, then, to make a laser accelerator one must either be in a medium, or near a surface, or bend the particles. These various possibilities have all been pursued and lead to devices which will certainly work. (Most have already been demonstrated in the laboratory.) Whether or not practical accelerators can be made using these various approaches is something we do not know yet. Engineering considerations which, someday, will have to be made for any serious accelerator contender simply can't yet be made.

We have just argued, that in order to have continuous acceleration one must either (1) slow the wave down (i.e. be in a medium or near a surface) or (2) bend the particle in a periodic manner. The various approaches, categorized in this way, are presented in Table 1. Notice that conventional linacs are simply devices where one is close to a surface, which is easy when one is using 10 cm radiation (as in the SLC), but not so easy when one is talking about 10 micron light (CO_2 lasers). In the remaining sections of this article I will go into some of the approaches categorized in Table 1.

Table 1. Electromagnetic Force Acceleration Alternatives

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)

    b) Use a single-sided (i.e. a grating) 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)

    c) Use dielectric slabs

    d) Put wave in a passive media (Inverse Cherenkov Effect Accelerator)

    e) Put wave in an active media (Plasma-Laser Accelerator)

2. Bend particles continuously and periodically (and let laser wave go in straight line)

    a) Wiggle particle and arrange that it goes through 1 period of wiggler just as 1 period of the electromagnetic wave goes by. (Inverse Free Electron Laser)

    b) Wiggler particle with an electromagnetic wave rather than a static wiggler field. (Two-Wave Accelerator)

    c) Use cyclotron motion of particle to do the bending. (Cyclotron Resonance Accelerator)

VII. THE INVERSE FREE ELECTRON LASER ACCELERATOR

Of the various devices, listed in Table 1, which bend the particles and hence operate far from any material surfaces, the simplest one (and the only one we will discuss in this article) is the Inverse Free Electron Laser (IFEL).

Firstly, we need to discuss Free Electron Lasers. These are central not only to the IFEL, but also to the Two-Beam Accelerator (see Sec. V).

Free Electron Lasers (FEL) are devices for conversion of electron beam energy to coherent electromagnetic energy. Invented by John Madey, they are presently of great interest with theoretical work and experimental work taking place throughout the world. The Inverse FEL simply operates by running the effect backwards. At first thought this makes no sense, but then one realizes that FELs can make radiation in parts of the spectrum where there are no coherent sources (such as the infra-red or the VUV), while the Inverse FEL could employ powerful available sources (such as the CO_2 laser) at appropriate wavelengths.

How does an FEL work? Simply by sending an electron through an alternating magnetic field so that the electron will undergo periodic transverse motion, i.e. "wiggle." Now a resonance condition is satisfied; namely that an electromagnetic wave, travelling in the forward direction and faster than the particle, passes over the particle by one period as the particle undergoes one period of wiggle motion. There is another way to describe the very same thing and it goes this way (see Fig. 7): An energetic electron, characterized by its relativistic γ, will "see the wiggler foreshortened by a Lorentz contraction and hence oscillate at a higher frequency than one would expect (i.e. compute non-relativisticly) by just a factor of γ. In the frame in which the electron is at rest on the average the electron is simply oscillating. Thus it will radiate. Back in the laboratory this radiation will be Doppler shifted. In the forward direction, the radiation is up-shifted in frequency by a factor $(1 + \beta)\gamma$, and thus the radiation is, in total, up-shifted by the factor $2\gamma^2$. It is this capability of frequency up-shifting and tunability (via energy variation) which makes FELs of such interest.

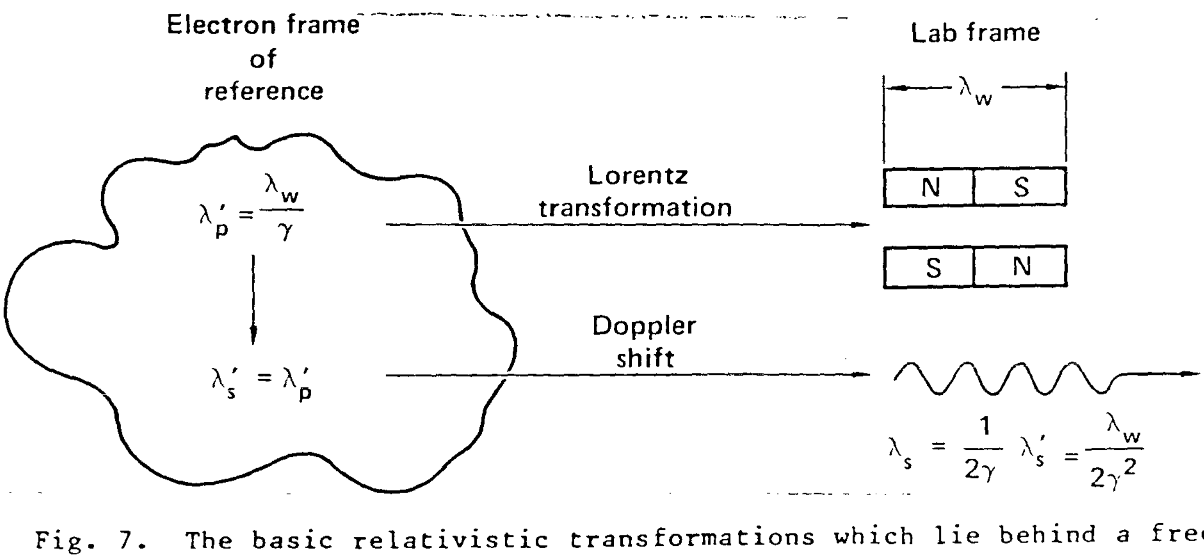


Fig. 7. The basic relativistic transformations which lie behind a free electron laser.

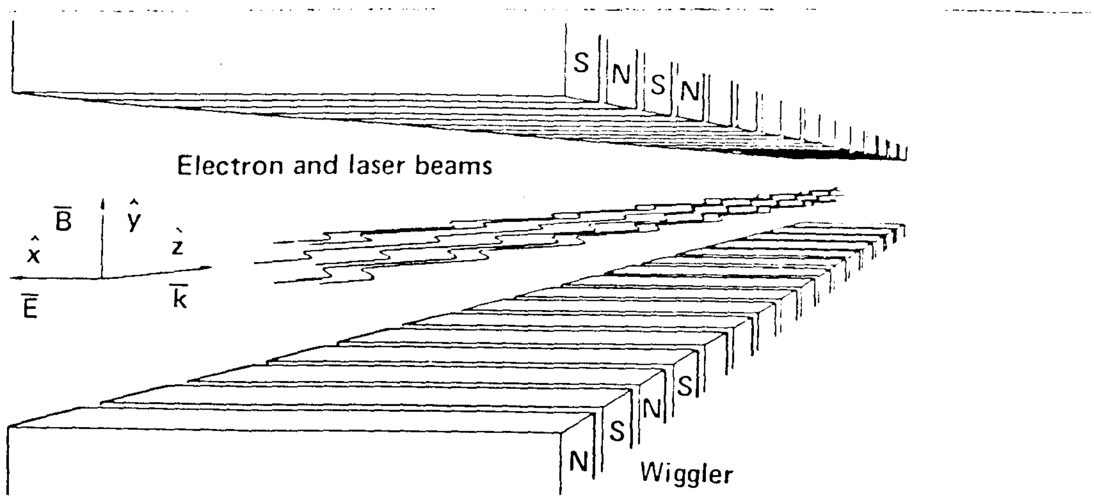


Fig. 8. The Inverse Free Electron Laser Accelerator.

Clearly, an Inverse FEL, such a device is shown in Fig. 8, will produce incoherent radiation, for the particles are going through a "wiggler," the very devices one employs in synchrotron radiation facilities in order to produce copious quantities of radiation. In fact incoherent radiation of energy must be balanced against coherent gain of energy in an IFEL and this balance drives the design. However, it appears possible, nevertheless, to attain very high energies; namely, 300 GeV with an average gradient of 100 MeV/m, with parameters as shown in Table 2.

A "practical" concern, actually a vital concern, is whether or not one needs many laser amplifiers or whether the intense laser light can be transported for kilometers and "used" over and over again. Theoretical work on this subject is being done at Brookhaven.

VIII. THE PLASMA LASER ACCELERATOR

Although an electromagnetic wave doesn't accelerate particles, it does move them along as is shown in Fig. 6. This effect can be used to good purpose. Suppose one shines a packet of light on to a medium having lots of free electrons; i.e. a plasma. The electrons will be moved and it is not very hard to appreciate that the density under the packet will be higher than normal. (The ions, which must be present in the plasma to maintain electrical neutrality, will hardly respond to the electromagnetic wave.)

How can this effect be accentuated? One very good way, proposed by Tajima and Dawson, is to illuminate the plasma with <u>two</u> laser beams of angular frequencies ω_1 and ω_2 whose difference is just the plasma frequency ω_p. In this way the beat frequency resonates with the plasma and most effectively bunches the plasma. This bunching results in an electrostatic longitudinal field which can, then accelerate particles.

Table 2. Possible parameters of 300 GeV x 300 GeV Inverse Free Electron Collider.

Laser wavelength	1 μm
Laser power	50 Tw
Synchronous phase, sin ϕ_0	.866
Laser electric field	0.22 TV/M
Waist radius	0.7 mm
Electron energy, input	250 MeV
Undulator initial period	3.8 cm
Undulator field	1.0 T
Initial helix radius	0.04 mm
Accelerator length	3 km
Electron energy, final	294 GeV
Average acceleration gradient	98 MeV/m
Final helix radius	0.5 m
Final undulator period	4.3 m
Crossing point β	1.0 cm
Disruption parameter	10
Number of particles per bunch	4.2×10^{10}
Repetition rate	1.6 kHz
Luminosity	10^{32} $cm^{-2} s^{-1}$
Laser energy per pulse	10 kJ
Average power (η = 10%)	320 Mw

Note that the overall effect is to turn the transverse field of the laser into a longitudinal field. This is often described as having taken place through the "ponderomotive force," but we have nothing more than the simple Lorentz forces on electrons.

If the plasma is underdense then the two laser waves will propagate. The condition is simply that

$$\omega_1, \omega_2 >> \omega_p \equiv \left(\frac{4\pi n e^2}{m}\right)^{1/2} , \tag{8.1}$$

where n is the plasma density. The laser waves satisfy, in a plasma, the dispersion relation

$$\omega^2 = \omega_p{}^2 + c^2 k^2 , \tag{8.2}$$

where ω is the frequency (ω_1 or ω_2) of the laser wave and k is the wave number of this wave in the plasma.

For a plasma wave (k, ω) the dispersion relation is:

$$\omega^2 = \omega_p^2 + 3 k^2 \left(\frac{KT}{m}\right) , \tag{8.3}$$

where KT is the plasma temperature (in energy units).

It is not difficult to show that the beat wave will have a phase velocity v_g, and a group velocity, v_p:

$$v_p \approx v_g \approx c\left(1 - \frac{\omega_p^2}{\omega_0^2}\right)^{1/2} , \tag{8.4}$$

provided $\omega_0 - \omega_1 = \omega_p$ and KT is not too large. This is shown in Fig. 9.

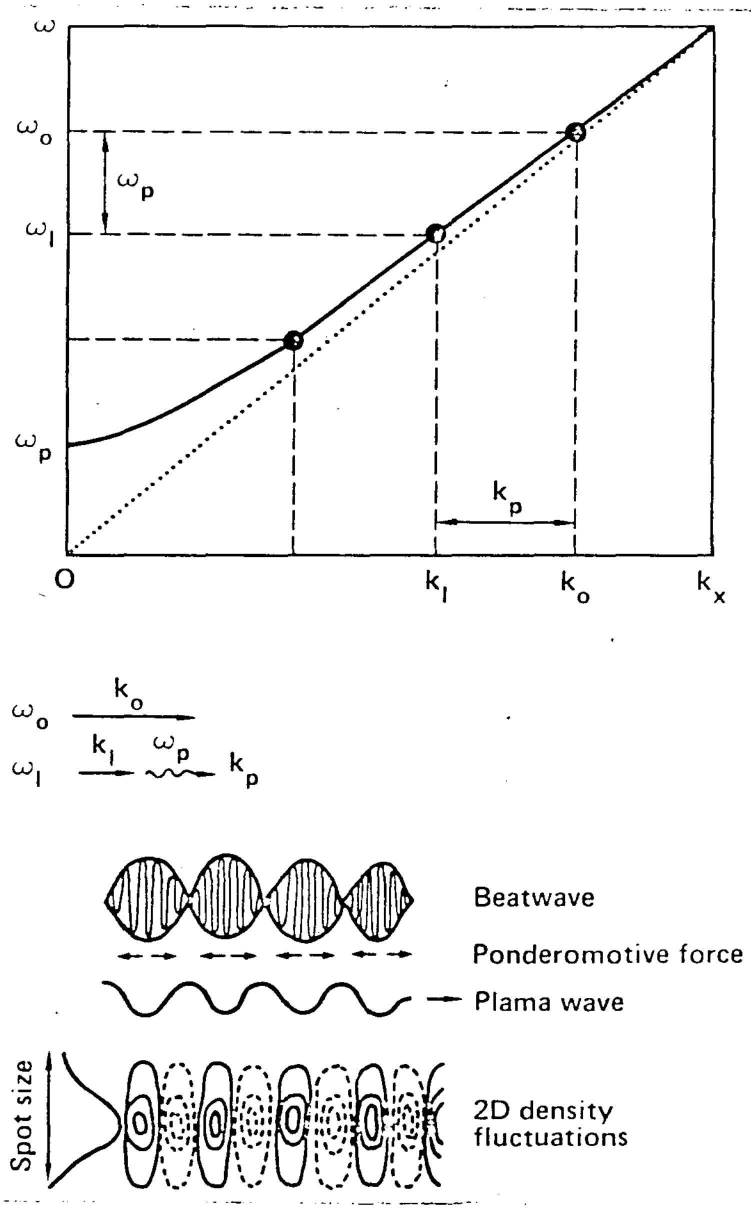


Fig. 9. a) Diagram showing the dispersion relation for electromagnetic waves (laser light) of frequency ω_0 and ω_1. b) Resonant excitation of a plasma density wave showing its two-dimensional structure. Contour solid lines (dotted lines) show increasing (decreasing) density.

Because there is synchronism between the beat wave and the plasma wave, the density modulations of the plasma, which is precisely what a plasma wave is, will resonantly grow. Just how large this wave will become and to what extent harmonics will develop is a non-linear problem which can only adequately be attacked by numerical methods. If the bunching is complete (100%) then the resulting longitudinal gradient is

$$eE_L = \frac{m\omega_p c}{e} = (4\pi\ n\ r_0^3)^{1/2}\ (\frac{mc^2}{r_0}) \quad , \tag{8.5}$$

where $r_0 = e^2/mc^2$ is the classical electron radius and $(m\ c^2/r_0) = 1.8 \times 10^{14}$ MeV/m. For a plasma density of 10^{17} cm^{-3}, which can be obtained in a θ-pinch, one obtains $eE_L = 2 \times 10^4$ MeV/m which is a very large gradient indeed.

The very large accelerating gradient which seems potentially possible in the beat-wave accelerator explains why this concept has attracted so much attention. The gradient is large because the densities attainable in plasmas are large and because the bunching takes place over very small distances. One might compare this to other collective acceleration methods (Part A) where the typical accelerating media is an intense relativistic electron beam. In such beams the densities are, at most 10^{14} cm^{-3} and the "bunching distance" is the size of a beam; i.e. centimeters.

In order to determine the degree to which the plasma will bunch, one must resort to numerical simulations for the phenomena is clearly highly non-linear and beyond analytic evaluation. Extensive simulations have been done in a one-dimensional approximation and a small amount of work has been done with a two-dimensional model. The computations show that the bunching is very close to 100%.

Although the electric field can be very high in the laser plasma accelerator, a particle will soon get out of phase with the plasma wave and not be accelerated further. An analysis was given in the very first paper on the subject. Because the wave frame, moving with velocity v_p given by Eq. (8.4), it is natural to define

$$\gamma = \omega_p/\omega_0 \quad . \tag{8.6}$$

Then one can show that an electron can "pick up" a maximum energy increment

$$\Delta E = 2\gamma^2\ mc^2 \quad . \tag{8.7}$$

Note, firstly, that this involves γ^2, not γ. Note, secondly, that this formula is just like Eq. (2.6); i.e. the moving ponderomotive well "impacts" coherently with an electron.

Will the plasma behave as expected? There is some reason to be optimistic for the laser beams can be expected to organize the plasma and control the plasma. Furthermore, the beat-wave density formation is a rapid process and the acceleration can be over before the plasma undergoes many instabilities. Theoretical calculations are suggestive, but a definitive answer must, of course, come from experiment. To date, little experimental work has been done and few, if any, results have been obtained.

The device described so far has the defect that as particles are accelerated they will, slowly of course because they are very relativistic, get out of synchronism with the plasma wave. Thus staging is required, and consequently one must tackle the problems associated with transporting and periodically focusing laser beams.

It has been observed by Katsouleas and Dawson that the imposition of a transverse magnetic field will allow the particles to always remain "in-step" with the plasma wave. A diagram showing this is reproduced as Fig. 10. The magnetic field must not be too large (no problem in practice) or the particle will no longer be "trapped" by the plasma density wave, nor can it be too small so as to have a good acceleration rate. The rate of energy gain is, in the direction of the wave.

$$\frac{dw}{dx} = 0.1\,\frac{\text{GeV}}{\text{cm}} \left[\frac{B(\text{kG})}{\frac{n(\text{cm}^{-3})}{10^{16}}\ \frac{\lambda}{\mu\text{m}}}\right] \frac{n^{1/2}(\text{cm}^{-3})}{10^{16}}\ , \tag{8.8}$$

where the magnetic field is B, and λ is the wavelength of the laser light. The factor in square brackets in Eq. (8.8) is the fraction of the peak bunching field and probably cannot be made to exceed 0.1 in practice.

In this accelerator, the "Surfatron," particles move transverse to the wave for it is in this direction that they accelerate. However, the transverse distance, Δy, doesn't have to be very big and is given by

$$\frac{\Delta y}{\Delta x} = \left(\frac{1}{30}\right)\left(\frac{\lambda}{\mu\text{m}}\right)\left(\frac{n(\text{cm}^{-3})}{10^{18}}\right)^{1/2}\ . \tag{8.9}$$

where Δx is the longitudinal length of the accelerator.

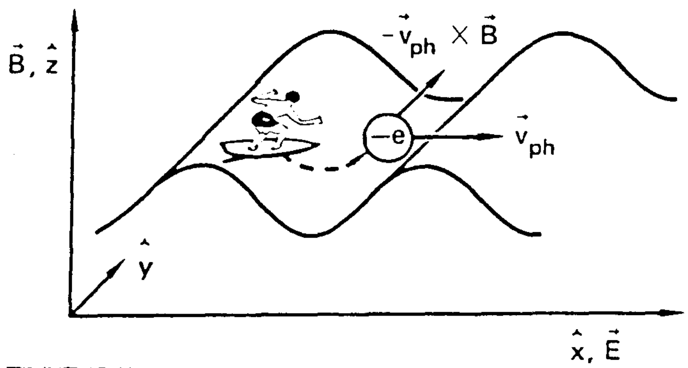


Fig. 10. A diagram of the Surfatron Accelerator Principle in which a transverse magnetic field keeps particles in phase with the plasma density wave even as the particles are accelerated.

In summary the plasma laser accelerators have great potential and there is room for invention so that there are already a number of variations which have been conceived. The fundamental question (in physics) is whether one can control a plasma and laser beams and make them act as one desires. Later, one must address the "engineering" questions of making short pulse, intense lasers, etc.

PART C: MULTI-BEAM ACCELERATORS

IX. THE TWO-BEAM ACCELERATOR

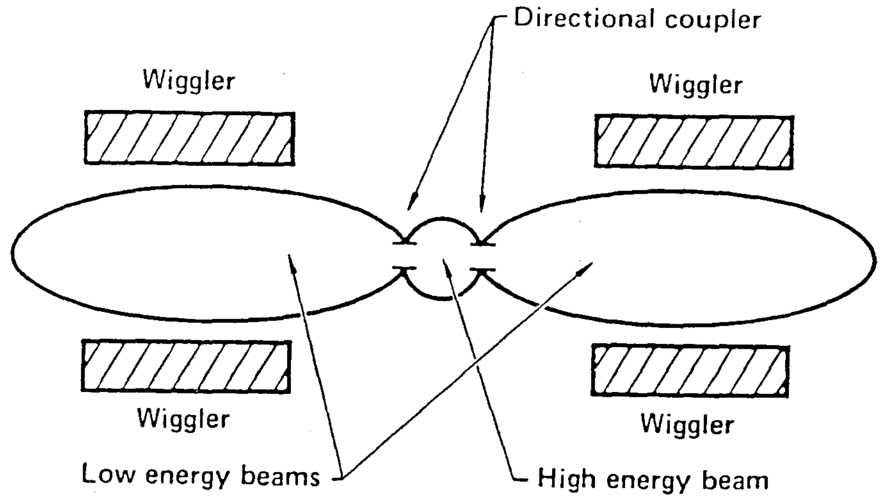
In this, and the next section, I want to discuss multi-beam accelerators; the Two-Beam Accelerator and the Wake-Field Accelerator. Each of these concepts involves two beams in an essential manner. They both employ a relativistic beam as an integral part of the accelerator and as an intermediary to the beam which one is accelerating to very high energy. I think that the next large jump in accelerator capability will be to employ external fields to manipulate a first beam which then accelerates a second beam of particles. Collective accelerators, of course, fall into this class of devices. None of them has yet led to a practical high energy machine, and, in my opinion, it seems doubtful that those proposed so far will lead to such a device. In contrast, these two concepts appear likely to lead to practical devices. They both are, as you will see, easier to achieve than any of the collective accelerators proposed so far, in that the two beams are kept quite separate from each other.

The Two-Beam Accelerator is based on the observation that in order to get to ultra-high energy in a conventional linac and still keep the power requirements of such an accelerator within bounds, one must go to higher frequency accelerating fields than are presently employed. The reason for this is that the stored energy, which is proportional to the transverse area of the linac, goes down as the square of the frequency for the transverse size is simply proportional to the radio-frequency wavelength. The reason one doesn't go to (say) ten times the frequency of SLAC is simply that there are no power sources in this range.

At 30 GHz, ten times the frequency of SLAC, possible power sources are multi-beam klystrons, photo-cathode klystrons, gyrotrons, etc., but none of these is sufficiently developed to be employed at present. One possibility is a Free Electron Laser which theoretically would appear to be able to be used for this purpose and on which good progress has been made experimentally.

If one uses a Free Electron Laser as a power source, then it is possible to consider one extended source, rather than many lumped sources as in the present linacs, and thus one arrives at the Two-Beam Accelerator. A low-energy beam is sent through a wiggler so that it produces, by means of the FEL process, copious amounts of microwave radiation. This radiation is then funneled into a rather conventional, but quite small, linac in which the high-energy beam is accelerated. The energy of the low-energy beam must be constantly replenished, and this is done by conventional induction units, which are quite efficient (60%). An artist's conception of how such a device might look is shown in Fig. 11.

At the very core of the concept is the FEL. The generation of microwave radiation by FELs is being studied and although, microwaves in the tens of megawatt range have already been achieved, there are many questions which need to be answered such as what is the effect of other (unwanted) wave guide modes. (The separation in phase velocity of unwanted modes is why the wave guide is shown as elliptical in Fig. 11.)



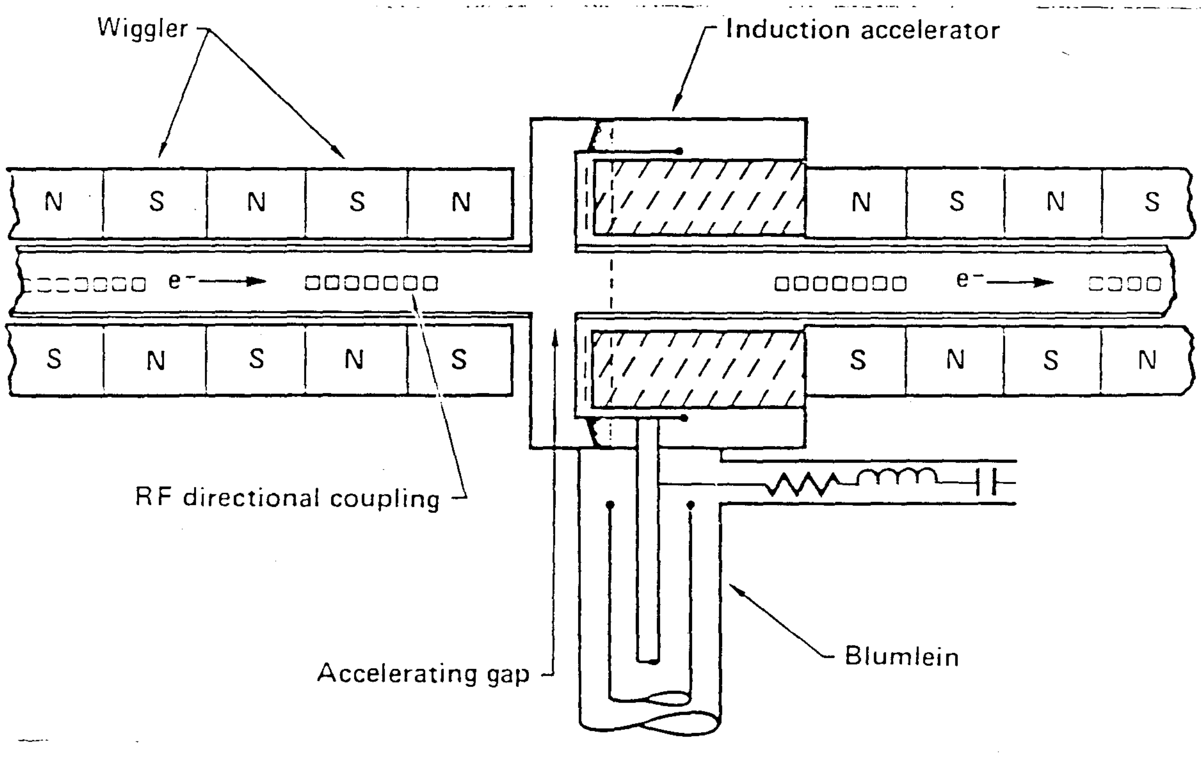


Fig. 11. Diagrammatic representation of a Two-Beam Accelerator. The low-energy beams are made to undergo wiggle motion and hence radiate by free electron laser action. This radiation is then used to accelerate the desired, high-energy, beam in a conventional linac. Fig. (11a) is a transverse cross section and Fig. (11b) is a longitudinal cross section of the device.

Table 3. Possible parameters of 375 GeV x 375 GeV Two-Beam Accelerator collider.

Nominal particle energy	375 GeV
Total length of the electron linac	2.0 km
Gradient of the conventional linac	25 MeV/m
Gradient in the Two-Beam Accelerator	250 MeV/m
Average power consumption	150 MW+150 MW
Overall efficiency	8%
Repetition rate	1 kHz
Energy of driving beam	3 MeV
Driving beam length	25 nsec
Driving beam current	1 kA
Number of high-energy particles	10^{11}
Length of high-energy bunch	1 mm
Focal length in high-gradient structure	10 m
Crossing point β	1.04 cm
Disruption parameter	0.9
Beamstrahlung parameter	0.05
Luminosity	$4 \times 10^{32} cm^{-2} sec^{-1}$

In the Two-Beam concept the FEL is operated in "steady state." This is novel and nothing is known, experimentally, about this mode of operation. In particular, it is necessary to not have loss of particles for kilometers. Theoretical work, which has been based on the KAM theorem and the Chirikov criterion, yields conditions which can be satisfied.

Another very important aspect of the Two-Beam concept is the coupling mechanism of the low-energy wave guide to the high-energy wave guide. Also there are questions of focusing and beam stability.

Many of these questions have only been looked at briefly, but so far it looks good. Possible parameters for a full-scale machine are given in Table 3. An experimental program has been initiated at Berkeley/ Livermore.

X. THE WAKE-FIELD ACCELERATOR

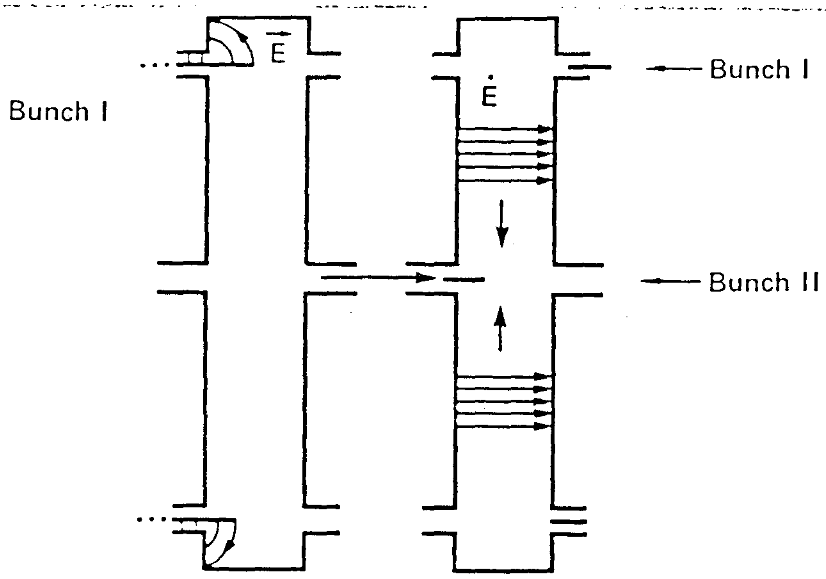
Of all the new acceleration methods discussed in this article, the Wake-Field Accelerator (i.e. this very last section) is, by far, the simplest.

Of course "simplicity" is not a criticism of the concept; in fact, perhaps it is just the opposite, for the Wake-Field Accelerator looks as if it can be made to work, and, furthermore, it appears capable of achieving gradients of (say) 500 MeV/m.

When a bunch of charged particles passes through a structure of varying shape then it will excite a wake-electromagnetic-field whose shape is not necessarily that of the charge bunch. This phenomena is well-known and well-understood; it has been calculated (usually for cylindrical structures) and measured experimentally, and the two approaches agree.

Particles inside or behind the bunch feel a longitudinal electric field whose integral over time, for fixed position relative to the bunch, is called the wake potential. Particles near the front of the bunch are decelerated, but those behind the bunch, generally, are accelerated. Unfortunately, this wake potential is usually not large enough to make a practical accelerator.

However, one can make -- really in a variety of ways as was first noted by Weiland & Voss, -- a wake potential transformer; i.e. a device in which a low energy high current beam creates a very high gradient at some other position. Such a possible configuration is shown in Fig. 12. The parameters which one might have in such an accelerator are given in Table 4.



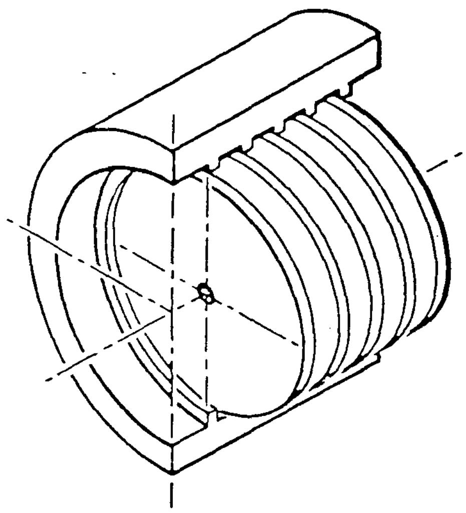


Fig. 12. A cylindrical realization of the Wake-Field Accelerator. The low-energy beam is in the form of a ring. It produces a wake which is transformed by the cylindrical geometry into large accelerating field at the high-energy beam which is on axis.

Table 4. Possible parameters of 50 GeV x 50 GeV Wake-Field Accelerator collider.

Nominal particle energy	50 GeV
Total length of the electron linac	550 m
Total length of the positron linac	650 m
Gradient of the conventional linac	25 MeV/m
Gradient in the Wake-Field transformer	170 MeV/m
Average power consumption	8+8 MW
Peak power	3900 MW
Number of high energy particles per bunch	10^{11}
Number of particles in the driving bunch	$6x10^{12}$
Efficiency of the wake transformer	16
Repetition frequency	100 Hz
r.m.s. bunch length of both beams	0.2 cm
Wake-Field transformation gain	10.2
DRIVING BEAM:	
Number of particles	$6x10^{12}$
Energy at the entrance of the wake transf.	5.5 GeV
Energy at the end of the wake transf.	0.5 GeV
Maximum phase slip between driving beam and accelerated beam	0.5 ps
Maximum particle energy loss (self fields)	1.8 MeV/m
Peak transverse momentum kick per unit length due to self fields	6.9 keV/mc
Solenoid field strength	7 T
Maximum particle deviation for a constant beam misalignment of δ = 100 μm	1 mm
HIGH ENERGY BEAM:	
Number of particles	10^{11}
Maximum particle energy loss (self fields)	15.2 MeV/m
Peak transverse momentum kick per unit length due to self fields	18.9 keV/m

Clearly, one can employ other transformer geometry than the cylindrical geometry discussed here. Almost surely, the best geometry is not that which has been presented in this first example. In addition, one can readily imagine using, for the low-energy beam, electron rings as they have already been achieved. If this is done, one can see one's way to gradients of 500 MeV/m or greater.

Clearly, if one is serious about the Wake-Field Accelerator then one must go into it in much more detail. Beam dynamic questions come to mind such as whether the low energy beam is stable (both longitudinally and transversely). Notice that it is subject not only to its own wake, but also that of the high energy beam. The same questions need to be asked of the high energy beam.

Many of these subjects have been looked into, only superficially so far, and appear to only put minor constraints on the device. As a result, an experimental program has been undertaken at DESY to study the Wake-Field Accelerator.

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PROBLEMS

1. Consider the equilibrium flow of a cylindrical beam of current, I, and radius, r_b, in a longitudinal field of magnitude B. Show that the motion, Brillouin Flow, is described by

$$\ddot{x} = \frac{\omega_p^2}{2} x + \Omega \dot{y} \quad ,$$

$$\ddot{y} = \frac{\omega_p^2}{2} y - \Omega \dot{x}$$

where ω_p is the plasma frequency:

$$\omega_p^2 = \frac{4\pi n e^2}{m} \quad ,$$

and Ω is the cyclotron frequency

$$\Omega = \frac{eB}{mc} \quad .$$

2. Show that the criterion for Brillouin flow is

$$2\omega_p^2 < \Omega^2 \quad .$$

Generalize this to a beam which is fractionally neutralized to degree, f, and obtain

$$2\omega_p^2 \; (1 - f) < \Omega^2 \quad .$$

3. Derive the relativistic Child's Law, as was done by Jory and Trivelpiece, thus obtaining an accurate estimate of beam stopping. Show that for a beam of current density, J, the relation between distance, x, and the potential $U(x) = eV(x)mc^2$ is:

$$x = \left(\frac{mc^3}{8\pi Je}\right)^{1/2} \int_0^{U(x)} \frac{dy}{(y^2 + 2y)^{1/4}}$$

4. Show that the relativistic Child's Law reduces, non-relativisticly, to

$$x \approx V^{3/4} \,/\, J^{1/2}$$

$$\text{or} \quad J \approx V^{3/2} \,/\, x^2$$

in accord with the usual expression. Show that in the ultra-relativistic case

$$J \approx V \,/\, x^2 \quad .$$

5. Derive the formula for ideal acceleration of a loaded electron ring; namely Eqs. (5.7) - (5.10). In particular, show that the field falloff parameter λ is given by

$$\lambda \simeq 2\pi \frac{Ra\ Mc^2}{e^2 N_e} \quad .$$

6. When light of wavelength, λ, is focused to a spot of radius, r, then the "depth of field" is given by the Rayleigh length, $\mathscr{L}$, where

$$\mathscr{L} = r^2 / \lambda \quad ;$$

i.e. this is the distance over which the focus extends. Derive this formula.

7. Use the concept of Rayleigh length to derive the formula for the maximum energy gain, ΔW, which an electron gets by passing through the focus of an intense laser of power, P. Show that

$$\Delta W = e \left(\frac{8\pi P}{c}\right)^{1/2} \quad .$$

8. The free electron laser resonance condition is

$$\lambda = \frac{\lambda_w}{2\gamma^2} (1 + K^2/2) \quad ,$$

where λ is the wavelength of the radiation, λ_w is the wavelength of the wiggler, λ is the relativistic factor of the electron beam, and

$$K = \left(\frac{eB_w}{mc^2}\right) \left(\frac{\lambda_w}{2\pi}\right) \quad ,$$

and B_w is the peak value of the sinusoidal wiggler field. Derive this condition.