Particle Accelerators in the Future.
Will Lasers and Plasmas be used?

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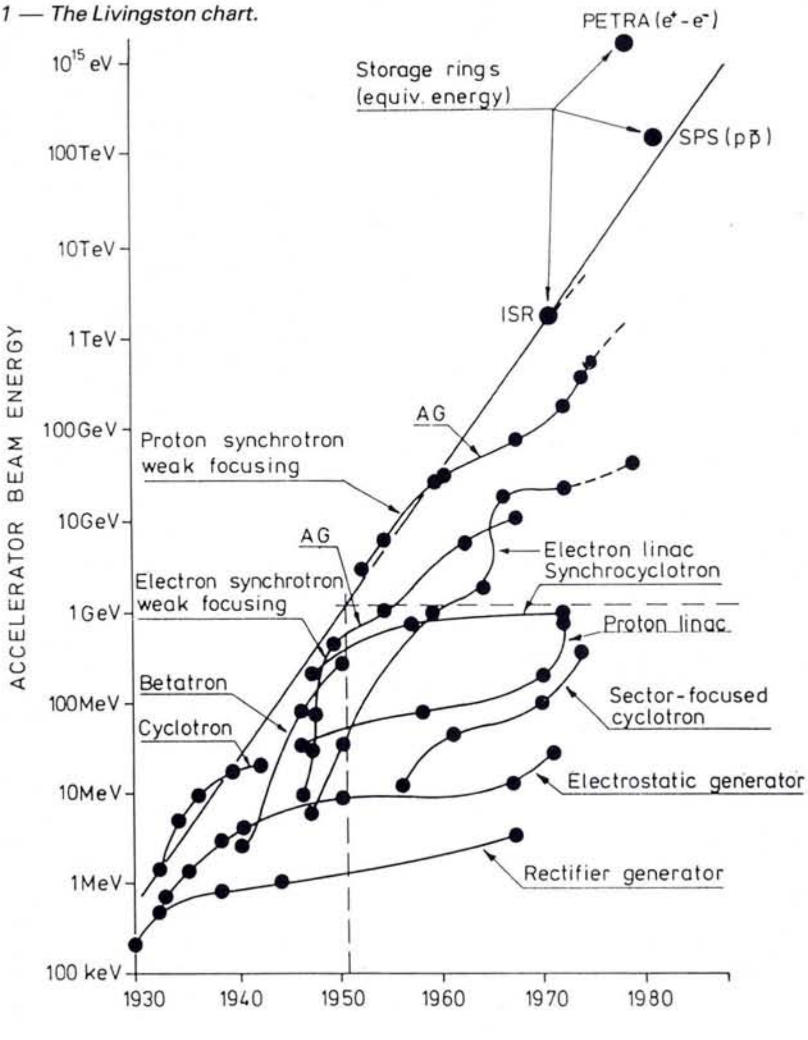
Collisions of accelerated particles have been extensively used in the XXth century to probe the laws of nature. Since the early days of Cockroft and Walton, the energy of the projectile has been increasing very quickly and, as shown by the recently updated Livingston chart (Fig. 1), a number of techniques have been used to accelerate charged objects. In all cases, the energy attained grows ever more slowly as time elapses. However, the envelope exhibits an exponential trend due mainly to the advent of new technologies. For the time being, storage rings in which electrons, protons (and their antiparticles) circulate are the best performers.

Now, many feel that the tunnels of LEP (Large Electron Positron collider) at CERN in Europe and, if constructed, the SSC (Superconducting Super Collider) in the USA will house the largest and... last circular colliders. Indeed, such machines suffer limitations. First, their size is enormous: tens of kilometers in circumference and the cost is proportional to the particle energy squared. Furthermore, in the case of electrons, synchrotron radiation prevents an energy increase on a circular trajectory beyond 100 GeV or so, *i.e.* the foreseen performance of LEP-2 True, there is no worry about synchrotron radiation in the case of protons. But these projectiles are composites and roughly, only 1/6th of the centre of mass energy is available for an elementary process involving quarks. The signal to noise ratio decreases accordingly. So far, the highest centre of mass energies are found in proton machines. The SSC project aims at 20 TeV protons encountering 20 TeV antiprotons. It stirs some controversy within the community of physicists (see *Physics Today*, February and May 1988).

Fig. 1 — The Livingston chart.



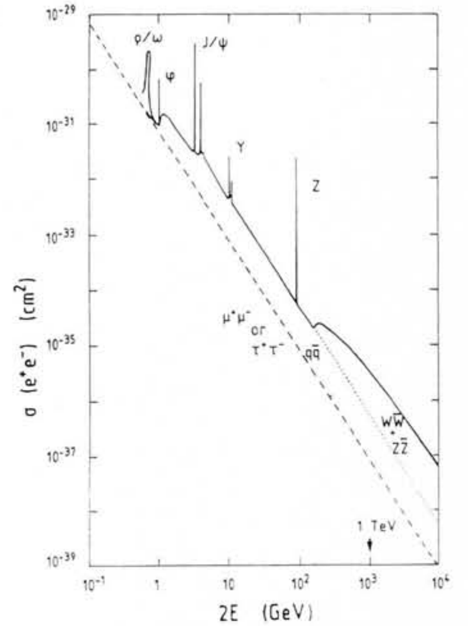


Fig. 2 — The e^+e^- cross-section as a function of the centre of mass energy (after U. Amaldi).

Accelerators of future generations are likely to be electron linear colliders. Such machines produce events whose cross-sections, given schematically in Fig. 2, show a general inverse square law dependence upon the centre of mass energy. In order to conserve a reasonable number of interesting reactions per unit time, the intensity of the beams, in practice divided into bunches, has to be increased. The relevant parameter for colliders is the luminosity

$$L = N^2hf/A$$

in which N is the number of elementary projectiles in a bunch, A is the cross-sectional area of the beam, h is an enhancement factor due to the pinching a bunch undergoes when encountering an equal density of charges with opposite sign; f is the repetition rate. The rate of events is the product of the luminosity and the reaction cross-section.

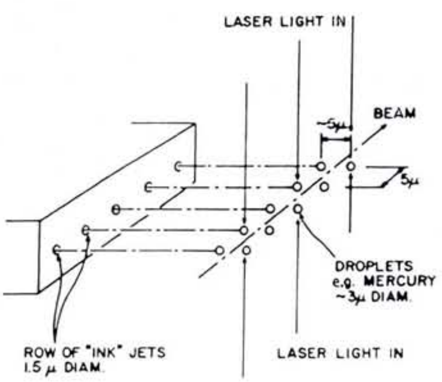


Fig. 3 — In a "droplet" accelerator the particle beam goes through a linac type open structure: a two dimensional array of tiny droplets of liquid metal into which laser light is coupled.

The challenge accelerator builders are facing, can then be stated as follows:

accelerate along straight paths:

electrons and positrons,

beyond 1 TeV

with a luminosity of 10^{34} cm^{-2}s^{-1},

over a length which compares with that of present machines.

A linear accelerator (linac) is usually made of a large number of resonant cavities fed by coherent electromagnetic radiation with proper phase velocity. The most effective technology so far, uses frequencies of about 3 GHz (wavelength 10 cm). The gradient does not exceed 20 MeV/m. It can be improved by a higher frequency. Consequently, designs for future conventional machines involve frequencies around 30 GHz. Three major limiting effects are identified: breakdown of the residual gas in the cavities, surface heating, superficial ionisation under the influence of high value electric fields (the so-called plasma limit). For all of these constraints, the maximum possible acceleration gradient increases with frequency, the trend being extended up to the optical range: hence the idea of using lasers. Another trick is to accelerate charged particles within a plasma: since matter is already ionized, the breakdown and plasma limits disappear.

Thus lasers and plasmas enter accelerator physics with three possibilities: lasers without plasmas, lasers interacting with plasmas, plasmas without lasers.

Lasers

Lasers are also attractive because of the high (transverse) electric field which can be obtained by focussing a coherent light beam with an ordinary lens. The frequency independent correspondence between intensity I and electric field is

$$I = c\varepsilon_0 |E|^2.$$

In the early sixties, Q-switched lasers could be focussed to intensities of about 10^{12} W/cm^2, *i.e.* a field of 1.8 GV/m. Nowadays, it is possible to get intensities 10^6 times bigger, yielding a field of 1.8 TV/m. Now the problem is: how to use this capability for producing high electric fields?

To the best of the author's knowledge, the first proposal for the use of a laser in particle acceleration is to be credited to K. Shimoda (Tokyo) who, in 1962, described an inverse Cerenkov process in a dielectric medium. In this scheme, a transverse wave propagates inside a high pressure gas. The direction of propagation is at an angle θ with respect to the trajectory of a charged particle with velocity u $(\beta = u/c)$. The electric field has a component E_z along the latter. E_z can be used for acceleration provided the angle satisfies the Cerenkov matching condition

$$\eta\beta\cos\theta = 1$$

where η is the refractive index (>1) of the medium in which acceleration takes place. This can be achieved in various geometries which have been investigated by J. Fontana (UC Santa Barbara). Gradients of about 1 GV/m are expected with a CO_2 laser intensity of about 10^{15} W/cm^2, a value well below the breakdown threshold for picosecond pulses.

Other ways of using lasers mimic the usual behaviour of linacs. Since the wavelength is so small, cavities are replaced by either gratings or periodic structures consisting of rows of spherical conductors. In a proposal by R. Palmer (Brookhaven), droplets of mercury are injected by an "ink jet" device, synchronously with laser beams impinging transversally on the particle beam (Fig. 3). The light couples resonantly to the quadrupoles formed by pairs of droplets. This results in an accelerating field along the trajectory of the particles.

Another possibility stems from the properties of the Free Electron Laser (FEL), a device which involves the interaction between a laser wave, a spatially periodic transverse magnetic field structure (the wiggler) and a relativistic electron beam. In the reference frame in which the electrons are at rest, the wiggler is equivalent to an electromagnetic wave. Beating occurs between this pseudo electromagnetic mode and the laser wave. This induces, through the Lorentz force ($\mathbf{v} \times \mathbf{B}$ terms), a periodic longitudinal electric field which can be considered as an assembly of short wavelength cavities travelling with a phase velocity u_R which depends on the laser frequency and wavenumber and on the wiggler wavenumber. Two cases of interest can be shown in a "phase space" plot in which the abscissa is the coordinate in a reference frame moving with the velocity u_R and the ordinate is the Lorentz factor $\gamma(=(1-u^2/c^2)^{-1/2})$ measured in the laboratory frame (Fig. 4: trapped or passing electron trajectories can be seen). Assume that in a bunch, all electrons have the same initial energy, high enough to ensure that no particle is on a trapped trajectory. When a bunch is longer than a wavelength (Fig. 4a), after a while, some electrons are accelerated, others are decelerated. The energy balance is such that the particles as a whole lose energy which is gained by the field. This is the free electron laser regime in which laser light is amplified. On the contrary a bunch much shorter than a wavelength can be accelerated, provided its initial phase with respect to the travelling longitudinal wave is properly chosen (Fig. 4b): the Inverse Free Electron Laser (IFEL).

Order of magnitude calculations by C. Pellegrini (Brookhaven) show that acceleration rates of about 1 GeV/m can be

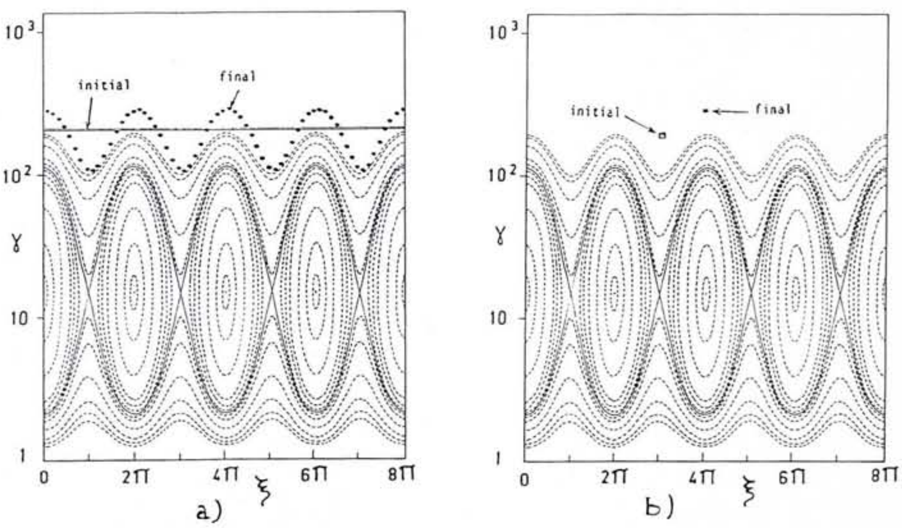


Fig. 4 — The "phase" portraits of electron bunches in a longitudinal periodic electric field. a) the Free Electron Laser regime, b) the Inverse Free Electron Laser.

obtained in the IFEL. However, an important shortcoming is the energy lost by wiggling electrons as spontaneous synchrotron radiation. Such losses scale as γ^4. It seems therefore reasonable to limit the applications of the IFEL principle to final energies below 1 TeV with average acceleration gradients of the order of 100 MeV/m.

Plasmas

Plasmas contain charges of opposite sign: electrons and ions and at equilibrium the medium is electrically neutral. The lighter component, *i.e.* the electron gas, is the most sensitive to any kind of external electromagnetic perturbation and in consequence, the electron density oscillates with respect to the value which ensures electrical neutrality. These oscillations propagate as longitudinal waves with frequency close to a value that is density dependent; the plasma frequency. Such plasma modes carry electric fields alternatively parallel and antiparallel to the direction of propagation. An electron with a velocity close to the phase velocity of such a wave is under the influence of a slowly varying electric field. It can be either accelerated or decelerated according to its position (relative phase) with respect to the density oscillation. The situation is very similar to that of a surfer riding high amplitude ocean waves (Fig. 5).

The use of plasmas appears to be the only way to reach acceleration gradients well over 1 GeV/m. Two methods have been proposed in order to generate plasma waves of large amplitude: i) resonant beating of two electromagnetic (laser) waves, ii) wakes.

The former has been demonstrated computationally by T. Tajima and J.M. Dawson (UCLA) exploiting an older idea. Imagine two laser waves with slightly different frequencies impinging on a plasma. If the frequency difference is equal to the plasma frequency, the electrons in the plasma oscillate longitudinally in resonance. An electron plasma wave is generated with initially a large linear growth rate. The phase velocity of the plasma wave is equal to the group velocity of the optical waves. In terms of frequencies and Lorentz factor, it turns out that

$$\gamma_R = \omega_0/\omega_p$$

where γ_R corresponds to the phase velocity of the plasma wave, ω_0 is the mean laser frequency and ω_p is the plasma frequency. Owing to various physical mechanisms, the plasma wave amplitude is expected to saturate at a level based on the detuning which results from a relativistic oscillation velocity in a large amplitude longitudinal electric field. Other effects which have been investigated by plasma physicists include modulational instability (coupling of a plasma mode to other plasma modes) and Raman cascades (coupling of EM modes to plasma modes).

Normally a major shortcoming of plasmas is their poor stability, whereas in beatwave acceleration, one expects to make use of an instability which has to be controlled through the saturation mechanisms, a very unusual situation in plasma physics.

As in the IFEL case, the electron wave can be regarded as cavities travelling with the phase velocity. Now, the group velocity is zero: energy does not propagate. The plasma wave is restricted to the interaction region wherein, if properly phased, short bunches of electrons can be accelerated until they reach the point where the field vanishes. Then they enter a region in which they undergo a decelerating force. Acceleration thus takes place over a limited length and the energy gain (W_A) is associated with an acceleration length (L_A). These two quantities obey scaling laws:

$$W_A \sim (1/n_0\lambda_0^2)(I\lambda_0^2),$$
$$L_A = 2(\omega_0/\omega_p)^2 c/\omega_p \sim 1/n_0^{3/2}$$

for the acceleration energy (limited by relativistic detuning) and length respectively. I (the laser intensity) is for both beams at the average wavelength λ_0; n_0 is the electron density of the background plasma.

The maximum amplitude a plasma wave may acquire corresponds to an oscillating density equal to the background density. This wavebreaking condition implies a given value for the product $I\lambda_0^2$. Some significant figures for this case are given in Table 1. The laser wavelengths are those for which high power has been demonstrated, *i.e.* CO_2 (10 μm), Nd (1 μm), and KrF (0.25 μm).

Owing to the scaling laws, two cells in this Table are equivalent. Now, in the upper right corner, it is indicated that electrons can be accelerated up to 16 TeV in a single pass. This requires the interaction, over several kilometers, of a very high intensity radiation from an eximer (KrF) laser, with a low density plasma. It looks unrealistic. On the contrary, reaching 10 MeV over a fraction of a millimeter by the interaction of a CO_2 or a Nd laser with a dense plasma can be done in any plasma laboratory equipped with a high power laser. All the physics investigated in the latter conditions is of interest for an accelerator project with different parameters. Those corresponding to the middle of Table 1 appear as reasonable compromises for accelerator stages in the future.

Experimental tests of beatwave acceleration have been under way for several years in the kind of set-up schematically represented in Fig. 6. Large amplitude plasma waves were detected at UCLA by C. Joshi and coworkers, in situations corresponding to the lower left corner of Table 1: a CO_2 laser emitting two frequencies is aimed at plasmas formed in a θ-pinch or a low pressure arc. The estimated electric field in the plasma wave is found to be in the range 0.3 to 1 GV/m. Fields of the same order of magnitude have just been obtained in France at the Ecole Polytechnique: the experiment uses the same coupling between electromagnetic and plasma waves although the initial conditions are different from those at UCLA (forward Raman scattering of a single laser frequency instead of two beating frequencies).

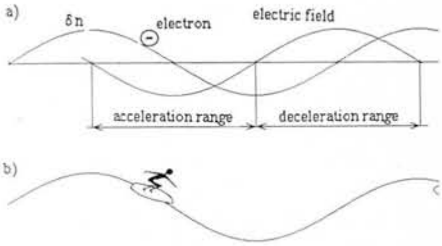


Fig. 5 — a) Electric field and density perturbation in a plasma wave, b) the surfer analogy.

Table 1 — Maximum energy and acceleration length in beatwave accelerators

n_0(cm^{-3})	λ_0(μm) I (W/cm^2)	10 1.3×10^{15}	1 1.3×10^{17}	0.25 2×10^{18}	Gradient
10^{15}		10 GeV 4 m	1 TeV 400 m	16 TeV 6.4 km	**2.5** GeV/m
10^{16}		1 GeV 13 cm	100 GeV 13 m	1.6 TeV 210 m	**6** GeV/m
10^{17}		100 MeV 4 mm	10 GeV 40 cm	160 GeV 6.4 m	**25** GeV/m
10^{18}		10 MeV 0.13 mm	1 GeV 1.3 cm	16 GeV 21 cm	**60** GeV/m
10^{19}			100 MeV 0.4 mm	1.6 GeV 6.4 mm	**250** GeV/m

Wakefields

Lasers are by no means essential for driving longitudinal waves in a plasma. Another effective way is the following: in a plasma or in the free electron gas of a metal, the free electrons are disturbed by a passing short bunch of charged relativistic particles which are thus followed by a longitudinal wave. There is no growth rate and the amplitude, which can be very large, of this wakefield, depends on the length, shape and density distribution of the driving bunch. In cavities also, a bunch of relativistic particles induces a wake. The effect has been investigated at DESY by T. Weiland and coworkers, using a hollow beam as a driver.

A joint team (J. Norem, J. Simpson *et al.* from Argonne National Laboratory, J. Rosenzweig *et al.* from the University of Wisconsin) has built an experiment at Argonne and wakefields have recently (1988) been detected in cavities as well as in plasmas. An electron linac produces 22 MeV bunches, one of which is followed by a smaller 15 MeV probe bunch whose delay with respect to the first is accurately adjusted. Both are sent through a test section which can be fitted either with cavities or with a hollow electrode device producing a low density plasma. An electron spectrometer records the changes in the energy of the driven bunch (Fig. 7). Experimental conditions are such that the energy variations are small although the existence of the wake is clearly demonstrated.

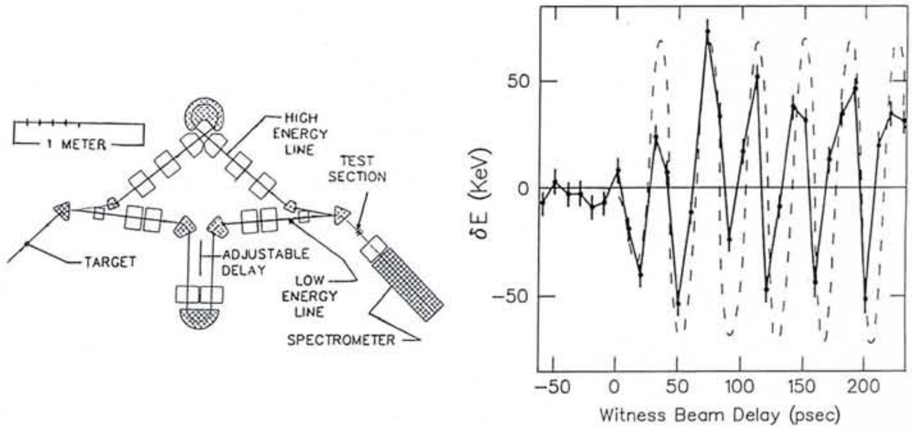


Fig. 7 — The Argonne-Wisconsin experiment on wakefields: a) scheme of the set-up, b) wakefield in a plasma.

The wakefield effect has consequences on plasma acceleration in general. Any particle bunch travelling within a plasma induces a wake, even when the bunch is being accelerated by a plasma wave. In these circumstances the wake either totally or partially wipes out the initial wave behind the bunch thus satisfying energy conservation requirements. This puts an upper limit on the number of particles in a bunch that can be accelerated in a plasma wave: roughly, the resulting electron density should not exceed the amplitude of the plasma oscillations.

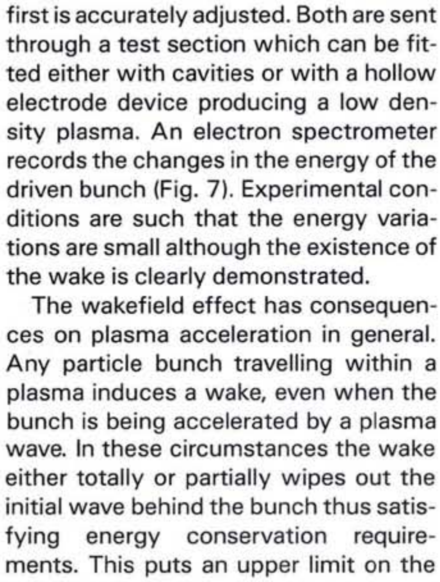


Fig. 6 — Scheme of a beatwave experiment. The presence of a high amplitude electron plasma wave can be evidenced by the spectrum of the auxiliary ruby laser radiation passing through the plasma (Thomson scattering).

Focussing

The above ideas for particle acceleration cannot be restricted to one dimensional situations. Plasma waves as created either by lasers or in wakes are not plane waves. Interacting laser beams at the focus of a converging optical system have a finite lateral extension. This is also true for any real driving bunch. Consequently the plasma wave has a transverse structure. In cases of cylindrical symmetry, the electric field exhibits a complicated pattern. Since the field is irrotational, the longitudinal variations of the radial component are in quadrature with respect to the longitudinal. The existence of the radial component implies focussing properties and these are of immediate interest for particle accelerators.

Computations indicate that the focussing is quite strong and indeed the effect has been observed for short bunches with proper phasing, provided their radial extension is much smaller than the characteristic radius of the plasma wave transverse structure. Focussing is of course energy dependent. Situations can be found in which a bunch is accelerated and, at the same time, tightly focussed over an acceleration length. Wakefields are specially attractive in this connection. The effects of radial forces were seen in the recent Argonne-Wisconsin experiment. Furthermore, computer simulations by P. Chen, T. Katsouleas and coworkers at SLAC and UCLA, show that a thin precursor, a quarter wavelength ahead of a long bunch, can provide a purely radial focussing force within the latter. In this case, there is no acceleration at all.

Charged particle focussing in a plasma can be obtained in simpler cases. *In vacuo*, a bunch is stable provided the outgoing force due to the self consistent electric field, opposes the magnetic force associated with the equivalent electric current. When the bunch enters a plasma with a much higher electron density, a rapid neutralisation occurs. The magnetic force is no longer compensated and squeezes the bunch.

In all the above schemes, plasma focussing is very effective. Focal lengths are typically two orders of magnitude smaller than those resulting from conventional magnetic focussing.

Another possibility is the indirect use of a plasma. In a high intensity discharge known as the Z pinch, a plasma column serves as the conductor for a longitudinal current. This produces an azimuthal magnetic field. An equilibrium is reached when the plasma pressure is equal and opposite to the magnetic pressure. This state is essentially transient. However it can last long enough so that a magnetic field with a well defined geometry deflects the particles. Tests of such plasma lenses have been made at CERN in a device (ACOL) designed to collect antiprotons produced by proton bombardment of a cylindrical target made of iridium.

Perspectives

During the last ten years many studies have been made of particle acceleration using lasers and/or plasmas mostly of a theoretical and computational nature. A few experiments have produced significant but not conclusive results. The subject is still in a very preliminary stage. Further research has to be done in plasma physics in order to

- perform detailed investigations on laser interaction and wakefield creation,
- check by experiments the scaling laws,
- reach the high plasma wave amplitudes of interest for a future collider,
- demonstrate strong electron acceleration by longitudinal plasma waves,

- evaluate new ideas: one is the "surfatron" in which a transverse magnetic field is used to phase lock the particle to the wave, thus allowing an indefinite increase in energy; another is the plasma assisted Inverse Free Electron Laser.

These tasks have to be completed by detailed studies about bunched beams, how they are accelerated and focussed. Such investigations require a joint effort by plasma and accelerator physicists. To stimulate such a programme, workshops *e.g.* "Advanced Accelerator Concepts" (formerly Laser Acceleration of Particles) and meetings *e.g.* CAPRI (for Cooperative Accelerator Plasma Research Initiative) have been organized and are to be regularly held in the future.

It is also necessary to develop laser sources suited to this new application. They should deliver short wavelength (< 1 μm) picosecond pulses, with high power (> 100 GW) and repetition rate (1 kHz), and with an efficiency greater than 10%. None of the lasers listed in Table 1 meets all requirements: the wavelength of the CO_2 laser is too long; the Nd glass laser, when operated at high power, has a very low efficiency and cannot stand the repetition rate; it looks difficult to extract in short pulses, the energy stored in KrF mixtures. The necessary improvements in laser technology may benefit from progress originating from industrial needs: high power and efficiency associated with high repetition rates.

In conclusion, it should be emphasized that although lasers and plasmas do in principle provide solutions beyond the capabilities of familiar RF techniques, electron acceleration is a long term objective. On the contrary, the focussing properties of plasmas might, in the coming years, find applications in accelerator physics.

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