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New ideas on acceleration to Planckian energies

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A plasma can sustain electric fields that are many thousands of times stronger than those of the most powerful present-day conventional particle accelerators. Plasma-based accelerators thus offer exciting new possibilities and point towards superhigh energies in the future – a promising first step towards Planckian energies.

THE primary motivation for building particle accelerators of ever-increasing energy has come from high energy physics. Starting from the thirties when cyclotron accelerators generating energies of a million electron volts (MeV) provided the necessary tools to study nuclear reactions in the laboratory, the modern day synchrotrons and linear accelerators of up to trillion electron volts (TeV) are helping us probe the fundamental forces of nature and understand the conditions of the early universe. They provide the only controlled and direct means of testing theoretical models, such as the standard model, and explore questions and problems beyond the realm of these models. Unfortunately, the conventional accelerator technology is approaching practical limits and cannot take us to the energy range of interest to high energy physics in the near and long-term future. What are these energies? In the near term, the interest lies in the 10 TeV–100 TeV range where deviations from the standard model can be tested. And in the long term if quantum gravity, the ultimate frontier of high energy physics has to be explored, then one must attain Planckian energies which are of the order of 10^{19} GeV. Conventional accelerators certainly cannot take us there. Infact, the operating principle on which the present-day accelerators are based is about half a century old and one has more or less reached the limits of technology here. Basically these accelerators use strong magnetic fields to guide particles which are propelled by strong electric fields created in vacuum by RF sources. The guide field cannot be raised substantially since they will exceed the structural forces of the magnetic materials used and the electric field strengths are likewise limited by material breakdown limits. The maximum electric field one can obtain is about 1 MV/cm, i.e. 100 MV/m. Thus, to accelerate particles to 10 TeV, one needs to construct an accelerator that is about 100 km in length. The enormous capital costs and the engineering complexities involved in building such devices considerably diminish their future viability. The cancellation of the Superconducting Supercollider (SSC) is a telling example of the kind of fate that can befall such devices. It also underscores the need to come up with new ideas and look for alternative schemes.

Fortunately, plasma particle acceleration, a new technology that has made rapid advances in the past few years, offers a promising alternative. A plasma is a state of matter which is at a temperature where all the atoms are completely ionized. Such a state has overall charge neutrality but local imbalances in charges can give rise to large longitudinal electric fields. These fields, which cause the plasma electrons to oscillate back and forth around the massive ions – the so-called plasma oscillations – can be effectively used for particle acceleration.

Unlike in a conventional accelerator, these are not dc fields – infact a plasma strongly opposes the existence of dc fields – but one is talking here of oscillating fields due to travelling waves. Thus, to accelerate particles one has to have them moving nearly at the speed of the wave so that in the moving frame the fields appear to be almost dc. Since a plasma is already an ionized medium, it is not subject to any further electron dissociation (electrical breakdown) and hence the accelerating electric fields can, in principle, be thousands of times stronger than what conventional accelerators can provide. Typically, the maximum electric field is proportional to the amplitude of the charge imbalance (fluctuation) and to the square root of the plasma density. Plasma densities in the range of 10^{16} cm^{-3} to 10^{21} cm^{-3} are not difficult to produce in the laboratory and the maximum electric fields that they can sustain can therefore be of the order of 100 MV/cm to 30 BV/cm. These are about a factor of 10^3 superior to conventional RF systems. With such fields a plasma accelerator, of only a few 100 metres length, can produce the acceleration energies of the 87 km SSC!

How does one create these fields in the plasma to accelerate particles? I will discuss here the basic principles of two promising methods – the Beat Wave Accelerator and the Wake Field Accelerator. I will summarize their theoretical and experimental achievements to date and briefly discuss their prospects as practical accelerator devices of the future.

Plasma beat wave accelerator

The basic idea of plasma-based accelerators relies on the generation of electrostatic plasma waves travelling close to the velocity of light. Such plasma waves can then readily accelerate electrons to the required energies. In the plasma beat wave scheme, such waves are excited by mixing two collinearly propagating laser beams with frequencies ω_1, ω_2 and wave vectors $\mathbf{k}_1$, $\mathbf{k}_2$ such that their frequency difference matches the plasma frequency, i.e. $\omega_1 - \omega_2 = \Delta\omega \sim \omega_p$. The electrons respond resonantly to the beat frequency and give rise to large plasma oscillations. The wavenumber of the plasma wave is given by $k_p = \Delta k = \mathbf{k}_1 - \mathbf{k}_2$ and its phase velocity $v_{ph} = \omega_p/k_p$ is then equal to the group velocity of light in plasma $v_g \approx \Delta\omega / \Delta k \approx c(1 - \omega_p^2 / \omega_1^2)^{1/2}$ if $\omega_1, \omega_2 \gg \omega_p$. If a charged particle is injected into this wave at approximately the same velocity as the wave then it will stay in phase with the field, absorb energy from it and steadily accelerate. The process is analogous to a surfer gaining energy from an ocean wave as he rides the wave and slides down its slope. The idea of the beat wave scheme was first put forward by T. Tajima and J. M. Dawson[1] in a classic paper in 1979.

The strength of the longitudinal electric field E can be estimated approximately from Gauss's law, $\nabla \cdot E \approx ik_pE = n_1$ where n_1 is the oscillating density perturbation. This gives the result

$$E = |\phi k_p| \approx 0.96\varepsilon\sqrt{n_0}\ \mathrm{V/cm},$$

where ϕ is the wave potential, $\varepsilon = n_1/n_0$ is the plasma wave amplitude and n_0 is the plasma density expressed in cm^{-3}. An electron falling through this potential will gain an energy ΔW given by

$$\Delta W \approx 2\varepsilon\gamma_{ph}^2 mc^2,$$

where γ_{ph} is the relativistic Lorentz factor $\gamma_{ph} = (1 - v_{ph}^2 / c^2)^{-1/2} \approx \omega_1 / \omega_p$. Substituting for γ_{ph} we see that

$$\Delta W \approx 2\varepsilon mc^2\omega_1^2 / \omega_p^2.$$

Thus for a chosen frequency ω_1 the accelerating gradient E is maximized for large ω_p but the corresponding maximum energy gain ΔW is reduced due to the inverse dependence on ω_p. As the electron gains energy from the wave, it slips forward in phase and this dephasing limits the maximum energy gain. The length over which this dephasing occurs is given by

$$L \approx \frac{\Delta W}{eE} = 2\gamma_{ph}^3 / k_0.$$

The energy limit due to dephasing can be overcome somewhat if the electrons move at an angle to the direction of the wave propagation – again much like a surfer riding a wave at an angle to get a longer ride and move faster. The electrons can be made to move at an angle by applying a magnetic field perpendicular to the plasma wave's direction. Other factors that can limit the interaction length are diffraction of the laser beams, pump depletion of the laser beams and turbulence effects. At high laser intensities the plasma dielectric properties favour a self-focusing of the laser light, thus compensating for the diffraction effects. Likewise, the radial electric fields of the plasma waves help keep the accelerated electrons in focus. The accelerated electrons also give rise to a strong current which produces strong confining magnetic fields and aid the unimpeded progress of the electrons along the axis. Laser-induced turbulence, which impedes the formation of plasma waves, can be minimized by shortening the laser pulse length. The idea is to operate on time scales over which the ions remain virtually stationary so that ion sound waves cannot be excited. With the advent of nanosecond (and now picosecond) laser pulses, it is possible to avoid plasma turbulence over extended lengths. Many of these phenomena have been extensively investigated and tested in computer simulations.

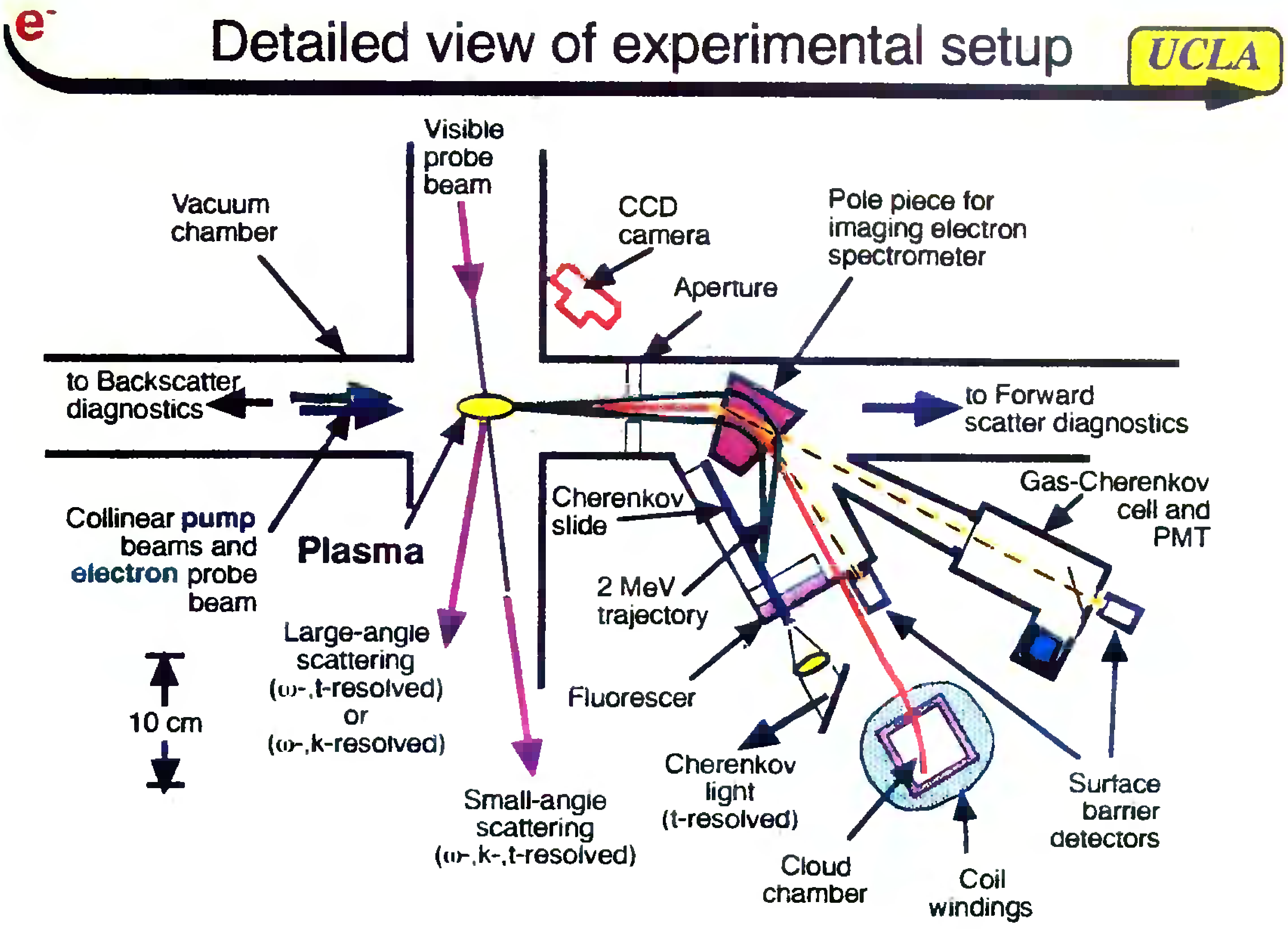

Figure 1. Schematic of the UCLA Plasma Beat Wave Accelerator experiment (courtesy C. J. Joshi).

There have also been a large number of experiments on the beat wave scheme starting almost from the time of its first proposal in 1979. One of the leading contributors is the Indian physicist C. J. Joshi, who began his early experiments in Canada and then achieved some spectacular results in a series of experiments at UCLA[2]. The initial experiments established the generation of large-amplitude plasma waves. Subsequently acceleration of externally injected electrons to progressively higher and higher energies has also been observed. In the UCLA setup, typically, a two-frequency beam from a 200-GW CO_2 laser (with wavelengths of 10.5 and 10.2 μm) is focused into the plasma as shown schematically in Figure 1. A 2-MeV electron beam generated in a linac is passed through this plasma region. The temporal and spatial properties of the plasma oscillations generated by the beating laser waves are studied by optical scattering techniques. The electric fields are directly probed by measuring the energy gain or loss of the electrons. A maximum energy gain of 28 MeV corresponding to an acceleration rate of 2.8 GeV m^{-1} has been observed[3]. The density perturbation of the plasma wave is about 23% and the ambient density is around 9×10^{15} cm^{-3}.

Plasma wake field accelerator

One of the major technical complexities of the Beat wave Accelerator Scheme is the resonant matching condition, which requires that the frequency difference of the two laser beams be equal to the plasma frequency. This puts severe constraints on the required uniformity of the plasma. Nonuniformities because of ambient electron density gradients or because of random density fluctuations cannot be tolerated. An alternative scheme, called the Laser Wake Field Scheme is a more rugged and simple method in which plasma waves are created by a sudden impulse with a short and intense laser pulse. The laser pulse rise time is of the order of a plasma period. Just as a speeding boat pushes the water aside at the prow and leaves a wake behind it, the laser pulse pushes aside the plasma electrons which rush back at the exit of the pulse and give rise to plasma oscillations. This plasma wake travels at the group velocity of the laser pulse. Electrons placed in the wake field can then be accelerated in the same fashion as discussed in the previous section. Wake fields can also be generated in a plasma by using a short bunch of energetic electrons instead of a laser pulse – it is then called the electron beam wakefield accelerator. For optimum gain it is necessary to tailor the driving beam profile so that it has a slow rise (over many plasma periods) followed by a rapid falloff.

The wakefield concept has also been extensively studied in computer simulations and detailed theoretical analyses. Two of the key questions in this scheme relate to the nature of the nonlinearly coupled electromagnetic and plasma wave excitations in a cold plasma with relativistically intense laser fields and the typical group velocity of such structures in the plasma. In this context, some exact one-dimensional nonlinear solutions for modulated light pulses coupled to plasma waves have been recently analysed[4]. The solutions are in the form of soliton pulses which may be viewed as a light wave trapped in a plasma wave that it generates itself. The front of the pulse generates the plasma wave, which is then reabsorbed by the tail of the pulse. Such pulses are not only of interest for particle acceleration but can be used for photon acceleration as well. Numerical results also give a fairly accurate estimate of the group velocity of these pulses and elucidate the nonlinear relationship between the group velocity, amplitude and frequency of the wave. Some of the other limitations discussed for the beat wave accelerator e.g. diffraction effects, pump depletion, etc. also apply to the wake field accelerator. Ideas such as relativistic guiding and plasma density channels have been proposed for overcoming diffraction effects. A novel idea that has been recently proposed[5] envisages the use of an active medium that can not only continuously replenish the loss of the laser energy to the wakefield (thereby eliminating pump depletion) but also accelerate the group velocity of the pulse to a desired value (thereby maintaining phase resonance with the trapped electrons).

Early experiments on the wake field accelerator (using electron beams as drivers) were done by David B. Cline *et al.*[6]. Direct observations of the laser wakefield accelerator have recently been reported by Roger Falcone and his colleagues[7]. Experiments at the Institute of Laser Engineering[8] at Osaka report generating laser wakefields with gradients of 30 GV/m over a distance of 0.6 mm.

Future prospects

Plasma-based accelerators are an active area of research today and a great deal of theoretical and experimental work is in progress. Several variants of the above two basic schemes, such as the inverse free electron laser, the inverse Cerenkov accelerator, laser driven grating Linac, etc., also exist and are receiving increasing attention. The beat wave scheme is probably the one that has been the most actively pursued. Major experiments are being carried out at UCLA in the USA, the Imperial College, London and the Rutherford Appleton Laboratory, Didcot in the UK and at the Ecole Poltechnique, Palaiseau in France. In a recent collaborative experiment between these centres, gradients of 100 GV/m were observed (maximum measured energy gain of 44 MeV in 350 μm). This is by far the highest collective-wave field ever produced in the laboratory.

In view of all this recent experimental progress, the prospects of accelerating a significant number of electrons to one GeV energy in the near future appear very promising. The technologies associated with the laser, plasma and the electron beam injector are available and the key issues related to plasma production, plasma wave excitation, control of instabilities and optimization of the acceleration process appear to be sufficiently well understood. On the basis of this progress, there has recently been a proposal[9] to construct a 1 GeV plasma beat wave accelerator by the UCLA group. Table 1 lists the principal parameters of this proposed accelerator. The main goal of this experimental accelerator would be to demonstrate the acceleration of a substantial number of electrons (of the order of 10^8) to about 1 GeV energy with a reasonable energy spread without the need to employ laser beam guiding.

Table 1.

Laser wavelengths	1.05 μm and 1.06 μm
Plasma density	10^{17} cm^{-3}
Plasma source	Multiphoton ionization
Laser pulselength	4 ps
Laser power	14 TW
Laser spot size (2σ)	200 μm
Rayleigh length (Z_0)	3.1 cm
Plasma homogeneity	±7%
Peak plasma wave amplitude	0.5
Peak gradient	160 MV/cm
Final energy	1 GeV

If this experiment is funded and if the pace of present progress continues, it is not unreasonable to expect the construction of 500 GeV machines based on plasma concepts within the next decade. What about Planckian energies? The plasma accelerators that we have just discussed and which rely on electrodynamics certainly cannot get us there. The maximum laboratory-produced plasma densities we can expect are of the order of 10^{27} cm^{-3} which could yield electric fields of the order of 10^6 GV/m. So to achieve an energy gain in the Planckian regime (i.e. 10^{19} GV) we would need an accelerator of 10^{13} m length! We, therefore, need to make a few more quantum leaps and dream up some more crazy ideas. What about tapping Quark Gluon Plasma (QGP) fields? Typically, if one considers the energy density in a hadron to be of the order of 2 GeV–fermi^{-3}, then the colour fields which can be of the same order of energy density can be estimated to be about ~3 × 10^{14} GV/m. Of course, such fields would only accelerate confined particles (quarks) but if one argues that the colour fields would also be strongly coupled to electrodynamic fields, then one is talking of very large electric fields indeed which could be used for electron acceleration. The energy gain would be severely limited though by length constraints (extent of the QGP). One can well speculate, therefore, about an entirely new technology – a QCD-based technology[10]. Such a development is not unconceivable and may happen sooner than we imagine. Meanwhile, plasma accelerators have certainly shown us a path to overcome the limitations of the present accelerator technology and move towards multi-TeV energies. This should serve as an encouragement to dream of higher goals.

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High Energy Physics in the 21st century – A summary

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NOT too long ago there was a startling suggestion by Stephen Hawking asking whether the end of Theoretical Physics was in sight. This was soon after the euphoria that accompanied the emergence of the string theory as a possible Theory of Everything and a feeling that there was now a satisfactory explanation for at least all of basic issues. After about ten years, we now perceive that unless new ideas for particle acceleration emerge, experimental high energy physics may be at an end. And that indeed can have a deleterious effect on theoretical High Energy Physics as well.

Particle Physics is, indeed, on important cross-roads at the moment. As described by D. P. Roy, we now have a standard model, with almost all experimental data in the energy range up to about TeV (10^{12} eV) accounted for, by means of about 20 parameters in a quantum field theory with adequate local symmetry. There are many hints as to what lies beyond the standard model and it is only to be expected that the situation will become clear once the experiments, currently being pursued, provide the necessary data.

As a check list, it is worth drawing up a collection of an immediate set of problems for the early 21st century as was done by Gross, Witten and Kane as a part of their assessment of outstanding questions.

(i) What determines the gauge symmetry at ordinary (?) energies (1 TeV) to be $SU(3)_c \otimes SU(2) \otimes U(1)$; $SU(3)$ signifying quantum chromodynamics and $SU(2) \times U(1)$, the unified electroweak theory of Salam and Weinberg?

(ii) How will gravity enter this picture? Through superstrings?

(iii) What is the nature of unification of the familiar forces? Is there a grand unified gauge symmetry group relevant at higher energies? Is such a unification a forerunner to incorporating gravity?

(iv) What constrains the quantum numbers of quarks and leptons? Why are the left-handed and right-handed fermions different? Is there a fundamental reason for us to have 'chiral' fermions?

(v) Why do we have different families or generations of fermions? How many? (The old version of the same question was asked by Rabi: Who ordered muon?)

(vi) What is the physics of Yukawa coupling? (What determines the masses and mixing angles of the quarks and leptons?)

(vii) Most abundant constituents of all matter are (u, d) quarks and electrons. Why are they so light in comparison with $W^{\pm}$, Z, top quark, Higgs (?) which appear to be in the 100 GeV range, presumably the natural scale of the theory.

(viii) Why is the vacuum energy (cosmological constant Λ) vanishing? How can we ensure this when the supersymmetry (boson ↔ fermion symmetry) is broken, as it indeed must.

We can be sure that as we provide answers to these issues, new queries will arise.

We observe that the main theoretical tools, that we now use, to answer the many puzzles, appear to be tak-