OVERVIEW OF PLASMA BASED ACCELERATING SCHEMES

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Abstract

The group of accelerator concepts which exploit the ability of plasmas to support extremely high electric fields are reviewed here. The topic of Plasma Accelerators is introduced by a general discussion of the relativistic plasma waves which provide the accelerating structure for the two most studied plasma accelerator concepts; namely, the Beatwave and Wakefield Accelerators. Some recent results on beam loading, extraction efficiency, and emittance growth in these structures are also discussed. Current research highlights in the the several accelerator concepts will be presented as well as some other uses for plasma in the accelerator field such as plasma lenses and plasma wigglers.

Introduction

While the future of high energy physics is determined in the short term by the extrapolation of current technologies, in the long term it may be determined by what technologies can be advanced or invented to reduce the size, complexity, and cost of particle accelerators.[1] In particular, plasma accelerators hold some promise in that the plasma can support enormously large electric fields, orders of magnitude beyond state-of-the-art linear accelerators. A current sample of the broad, international research effort in this field is given in Ref. 2.

Plasma Accelerator Basics

The Plasma Beatwave and Plasma Wakefield accelerator concepts rely on the properties of relativistic electron plasma waves. In the following sections we will look at the properties of these waves as they relate to the acceleration of particles.

Relativistic Plasma Waves

Definition: Roughly speaking, a plasma wave is a disturbance in a plasma in which electrons are locally displaced (in a direction parallel to the propagation direction) from their unperturbed position. The electrons simply oscillate about the equilibrium point, being attracted to the positive space charge their displacement left behind, but overshooting their mark due to their own momentum. The oscillations lead to local compression (bunching) and rarefaction in the electron density (see Fig. 1(a)). When the electrons are disturbed with an appropriate phase relation, their oscillations comprise a traveling wave whose phase velocity can range from a few times the electron thermal velocity to infinity. In particular, plasma waves with a phase velocity v_p such that $\gamma_p = (1 - v_p^2/c^2)^{-1/2} >> 1$ are referred to as relativistic plasma waves. These are the waves which are useful for particle acceleration since a relativistic particle can stay in phase with this wave and thus gain significant energy from the wave.[3]

Plasma waves can be excited, for example, by sending charged particles through a plasma,[4] or by perturbing the plasma with modulated electromagnetic radiation.[5,6] The former case is wakefield excitation and the latter is beatwave excitation. These will be discussed in more detail later. There exist other means to excite plasma oscillations and we will mention some of them later as well.

Electric field structure: The bunching of the electrons mentioned above reduces the local electric potential leading to a potential variation as shown in Fig. 1(b) which implies the existence of a longitudinal electric field (E_l). The magnitude of this field can be derived from Gauss' Law;

$$\nabla \cdot E_l = 4\pi n_1 e \tag{1}$$

where n_1 is the perturbed electron density (the bunch density relative to the background density) which, for the sinusoidal wave approximation, can be at most equal to the background plasma electron density (n_o). Let's take $n_o = 10^{18}$ cm^{-3} and a wavenumber $k_p = c/\omega_p$ (where $\omega_p = 4\pi n_o e^2/m$ is the plasma frequency). Assuming that E_l varies as $\cos(k_p x - \omega_p t)$, Eq. 1 gives an electric field of 100 GeV/m. For different plasma densities, this maximum electric field scales as $n_0^{1/2}$. Figure 1(c) shows a typical plot of the longitudinal electric field vs. x which amounts to a slice down the x-axis (y = 0) of Fig. 1(b) (the derivative of that curve, actually). Figure 1(d) shows the radial field taken from the slice of Fig. 1(b) at $y = c/2\omega_p$. We see that there is a 90° phase difference between the longitudinal and the transverse fields of the plasma wave (this is obvious from inspection of the potential structure in Fig. 1(b)). The radial field will either focus (confine) or defocus the particle beam. Thus, there is 90° of phase available which is both accelerating and focusing. The accelerating phase is shown in more detail in Fig. 2.

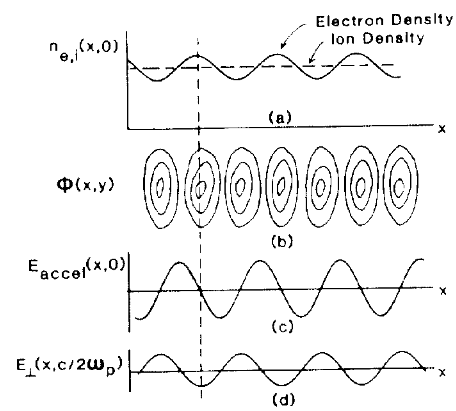

Figure 1: The (a) density, (b) potential (contours), (c) longitudinal electric field, and (d) transverse electric field vs position for an electron plasma wave.

Acceleration in Plasma Waves

General considerations: A charged particle placed in the longitudinal electric field of the electron plasma wave will be trapped by the wave if it has a certain minimum velocity which is a function of the wave phase velocity and amplitude. This corresponds to the orbit sketched in Fig. 2. Here we see the potential variation vs position and the orbit of a trapped particle. The particle is trapped if it is travelling forward in the wave frame

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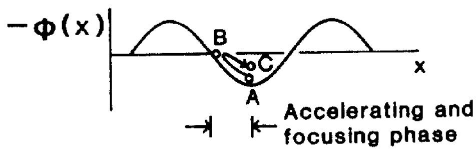

Figure 2: Negative of the electric potential vs longitudinal position showing the orbit of a trapped particle and the useful accelerating phase.

or if it is traveling backwards but is reflected in the forward direction before reaching the point labeled "B", beyond which it would be lost due to defocusing. Suppose we inject our particles at the point "B" with zero velocity relative to the wave. In that case, the maximum (phase-slip limited) energy gain is given by:

$$W_{max} = \varepsilon \gamma_p^2 mc^2 \qquad (2)$$

which occurs in a quarter wavelength in the wave frame but in a distance l_{accel} given by[7]

$$l_{accel} \approx \gamma_p^2 \, c/\omega_p \qquad (3)$$

where $\varepsilon = n_1/n_0$ is the normalized wave amplitude. We see in Eqs. (2) and (3) a tradeoff which must ultimately be made. Equation (2) says to get to higher energy we must increase γ_p but, from Eq. (3), our plasma system may become longer than is practical from other considerations. In the "Surfatron" scheme, the phase-slip limitation on the maximum energy is eliminated by using a transverse DC magnetic field to prevent the particles from slipping in phase while still allowing the particles to see the large electric field.[8]

Extraction of wave energy: In this section we will look at how the accelerating bunch extracts energy from the relativistic plasma wave described above. This is best understood by looking at the physical interpretion of the mathematical model used to calculate the beam loading.[9] A single charged particle traveling through a plasma leaves behind it a wake in the form of a plasma wave. The

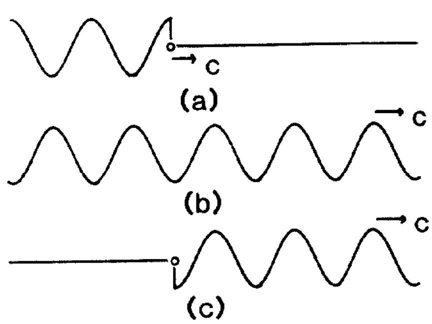

Figure 3: (a) Longitudinal wakefield of a single charge traveling through a plasma; (b) electric field of a general plasma wave; and (c) resultant field when wave (b) is fully loaded with particles from (a).

width of the wake is approximately c/ω_p. In this case, the particle looses energy as the length of the plasma wave increases (see Fig. 3(a)). Now consider the same particle traveling through a plasma with a preexisting plasma wave of the same shape but 180° out of phase as shown in Fig. 3(b). We intuitively use superposition principles to say that the resultant field is reduced now by an amount equal to the wake field of Fig. 3(a). This is indeed the case as shown by Katsouleas et al.[10] who demonstrated that beam loading efficiencies could reach nearly 100% by placing a large enough bunch of charges at just the right phase in the accelerating field. In this case, the electric field of the plasma wave is completely absorbed by the accelerating bunch as shown in Fig. 3(c). There are problems with this 100% beam loading, though. Since a bunch of electrons has a finite length, the first electron in the bunch of Fig. 3(c) will see the full accelerating field whereas the last electron will see virtually no field. Thus the energy spread will be 100%. A solution to this problem is to tailor the shape (that is, the axial number-density profile) of the accelerating bunch so that the wake field of each charge adds up in such a way that the net (accelerating plus wake) field is constant within the accelerating bunch.[9] This is shown in a simulation result in Fig. 4. The ideal shape is a triangle with the highest density at the leading edge. In this case, the main cause of energy spread is phase slippage of the beam, with the leading edge

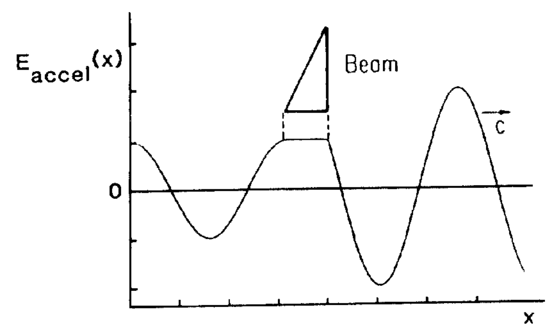

Figure 4: Beam loaded wave with the accelerated bunch shaped so that all particles experience the same accelerating field. Note that the field is constant within the bunch.

slipping out of the constant-field region and therefore seeing less acceleration than the trailing edge.

Beam emittance: One of the primary concerns in plasma accelerators is the possibility of unacceptable emittance growth due to the unusually large radial focusing fields. For narrow plasma waves (diam a such that $k_p a \approx 1$), the radial fields are on the same order as the axial fields as shown in Figs. 1(c) and (d). One could produce a very wide plasma wave ($k_p a \gg 1$) and accelerate particles on axis to reduce the influence of these fringing fields but, recalling that the wake of individual electrons is only $1/k_p$ wide, we see that this would reduce the efficiency since the wake of the accelerating bunch could not be arranged to overlap the accelerating field off axis. However, trade-offs can be made which lead to acceptable beam emittances.[11]

Excitation of Relativistic Plasma Waves

Beatwave excitation

General considerations: The most widely studied scheme for driving relativistic plasma waves is by beatwave excitation. We will not go into the mathematical details but will refer interested readers to the now extensive literature.[2,3,5,6,12–14] This idea was first applied to particle accelerators by Tajima and Dawson[5] in 1979 who considered an intense burst of photons plowing through a plasma, displacing plasma electrons from their equilibrium position by the ponderomotive force of the photon packet. They also suggested that the laser intensity needed could be reduced by using a long train of lower intensity photon packets spaced at the natural frequency of the plasma so that the plasma wave would be driven up resonantly instead of all at once. These regularly spaced photon packets are the result of beating two laser beams of different frequency (ω_1, k_1 and ω_2, k_2) together. If the lasers copropagate, then the phase velocity of the resulting "beatwave" is approximately equal to the group velocity of light in plasma ($v_g \approx \Delta\omega/\Delta k$) which is near the speed of light in vacuum; just what we want for a relativistic plasma wave. The resonance condition is that the difference frequency of the two laser beams be equal to the plasma frequency, or $\Delta\omega \approx \omega_p$.

Figure 5 shows the beating pattern of two laser beams along with the plasma wave they excite. We mentioned before that the beating pattern and therefore the phase of the plasma wave travels at approximately the group velocity of light in plasma which is given by $v_g = c(1 - \omega_p^2/\omega_1^2)^{1/2} = v_p$ which can be inverted to give $\gamma_p \approx \omega_1/\omega_p$. For an electron density of, say, 10^{17} cm^{-3} we will have $\gamma_p = 100$, W_{max} = 1 GeV, and L_{accel} = 15 cm for a wave amplitude ε = 0.25 and for lasers operation at around 1 µm.

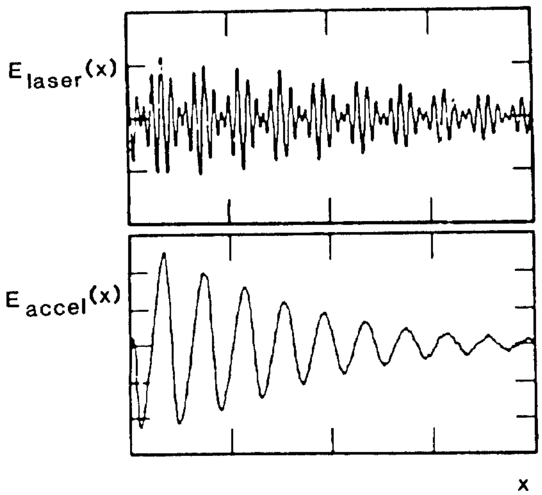

Figure 5: Total transverse electric field from the addition of two laser fields at slightly different frequencies ($\Delta\omega = 4\omega_0 = 5\omega_1$) (top figure); and, resulting electric field in a resonant plasma ($\omega_p = \Delta\omega$) excited by the ponderomotive force of the beating lasers (bottom figure).

Beatwave issues: Some of the issues currently being addressed are in relation to the efficiency of coupling the laser energy to the wave energy. Katsouleas worked out the distance in which the laser pulse would be exhausted by pump depletion based on the rate at which the pump pulse left energy behind in the form of (basically zero group-velocity) plasma waves.[7] Actually, it is more complicated than that since the (initially simple) two-frequency electromagnetic spectrum evolves into a complex, "breathing" spectrum of multipli-resonant sidebands as the pulse propagates down the system. This spectrum must extend downward in frequency quite deeply in order to efficiently couple photon energy into plasmon energy, according to Manley-Rowe relations.[15] This complex issue is one of the current research topics.[16,17]

A potentially severe limitation to the length of a beatwave accelerator stage comes from the discrepancy between a typical laser beam's depth of focus and the acceleration length given in Eq. 2, which was 15 cm in our example above. Several groups are studying the propagation of extremely intense light beams in plasmas, looking for parameters which will allow the light beam to remain focussed for many standard focal depths due to "relativistic self-focusing".[18-20]

Recently, Darrow et al.[21] discovered a competing effect related to the presence of large amplitude ion acoustic waves (which are also excited by the laser pulse). Collective Thomson scattering was used to study the wave spectrum in a resonant plasma under two-frequency illumination. It was found that there was a large spectrum of electron plasma waves which may be driven up at the expense of the accelerating wave. Analytical, numerical and computational (particle simulations) studies showed that this effect can, under some conditions, limit the amplitude of the relativistic plasma wave below the usual saturation level due to relativistic detuning, and may have been playing a role in a previous experiment.[22]

Recent experiments have shown that long, uniform plasmas can be generated by laser beams (the same beams which will drive the beatwave) by multi-photon ionization in the visible (at Rutherford Appleton Laboratory in England)[23] or tunneling ionization in the infrared (at INRS in Canada)[24]. These results are encouraging for the plasma wakefield concept as well, as will be discussed later. In both experiments, the required laser intensity to produce the plasma was around 10^{13} - 10^{14} W/cm^2. This illustrates the extremes one must go through to do experiments at high densities (n_0 = 17^{17} cm^{-3}). A group in Italy has proposed to scale the beatwave experiments down to the more accessible range of 10^{11} - 10^{13} cm^{-3} and use high power millimeter waves to drive the wave.[25] Such an experiment would have the potential of making detailed measurements of electromagnetic sideband generation and large amplitude wave effects.

An experiment nearing the operational phase at UCLA is to measure the accelerating properties of the plasma wave by injecting bursts of test particles into the wave from a 1.5 MeV electron linac. As shown schematically in Fig. 6, a beam of electrons is injected through a hole in the laser focusing mirror and focused together with the laser beam into a "theta-pinch" plasma source. The

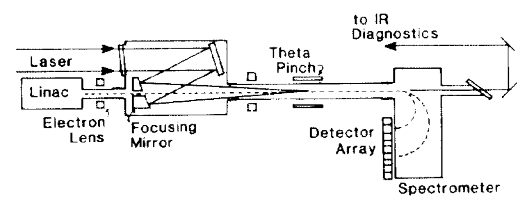

Figure 6: Schematic of the experimental setup at UCLA for beatwave acceleration of injected electrons.

accelerated electrons will be dispersed in energy by a 180° magnetic spectrometer coupled to an array of silicon and germanium surface barrier detectors. With the CO_2 laser operating on the 9.6 µm and 10.3 µm lines, with an anticipated energy per line of 10 J in a 300 psec pulse, the expected energy gain of the injected electrons is to about 15 MeV, or an order of magnitude gain in energy over 15 mm or so.

Wakefield Excitation

General considerations: Figure 3(a) shows the wake of a single charge passing through a plasma. If we replace the single charge with N_b charges, the wakefield behind the bunch is basically N_b times larger. We can now consider this wakefield as the relativistic plasma wave we'll be using for acceleration and so all the prior discussion on beam loading, etc. still applies. This does not make a good accelerator though. Within the bunch is generally a strongly varying retarding wakefield E_- which can be as much as half the maximum accelerating field E_+ behind the bunch. The "transformer ratio" R, or beam voltage out to beam voltage in, can be shown to be equal to E_+/E_- which at $R \approx 2$ is too small. In the above case, the N_b charges are all located in a axial distance shorter than a plasma wave wavelength λ_p. However, if we distribute the charges over a length much longer than λ_p and ramp the bunch density up slowly then the plasma will have time to respond to the imposed space charge and will move so as to neutralize the it. This greatly reduces the electric field in the bunch, leading to much higher transformer ratios.[26] In fact, it is found that $R \approx 2\pi N$ where N is the length of the driving bunch measured in plasma wavelengths. A particle simulation run is shown in Fig. 7. If the trailing

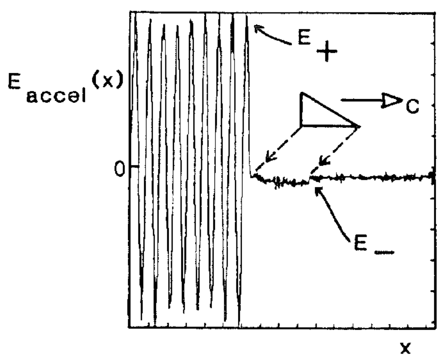

Figure 7: Results from a computer particle simulation of wakefield excitation showing the high transformer ratio achievable with a shaped driving bunch. Note the low and nearly constant deaccelerating field within the driver.

edge of the ramped driving beam is chopped off in a distance less than c/ω_p then, since the plasma was moving to shield out the space charge of the driving beam, the plasma just behind the beam will find itself depleted of electrons by the peak electron density n_b of the bunch. In other words, a plasma wave of amplitude $\varepsilon = n_1/n_0 = n_b/n_0$ will be excited. The field E_+ is then just given by Eq. 1.

If we take a driving beam of $\gamma_b = 10^4$ in a plasma of 10^{15} cm^{-3} and ask for a transformer ratio of 1000 then the driving beam has a length of about 16 cm and a fall time of 0.5 psec. The number of electrons in a bunch determines the accelerating field and thus the distance L_{accel} in which we will achieve the assumed transformer ratio. If $N_b = 1.7 \times 10^{11}$, then $n_b/n_0 = 0.1$ and $L_{accel} = 170$ m. The corresponding peak beam current is 100 A. If we relax R to 100 and N_b to 1.7×10^{10}, then $L_{accel} = 17$ m.

Wakefield issues: Plasma wakefield theory has developed very rapidly due to the strong similarity to wakefields in conventional linear accelerators. However, there are many aspects which are strictly plasma related, such as beam-plasma instabilities. The longitudinal two-stream instability was studied recently. This is important in the high current driving beam and could lead to longitudinal modulations which could break up the beam. It was concluded, however, that this could be density-gradient stabilized if the density ramp on the driver is steep enough.[27] This puts a limit on the length of the driver (for a given total charge) and hence a limit on the transformer ratio R given by

$$R < 0.03\, \gamma_b/(n_b/n_0)^{1/3}$$

which evaluates to $R < 10^3$ for $\gamma_b \approx 10^4$ and $n_b/n_0 \approx 0.1$.

Two transverse instabilities--self focusing (important for narrow beams) and Weibel or filamentation (important for wide beams)--have also been studied. It was found that imposing a strong axial magnetic field or adding a moderate transverse temperature to the beam could stabilize these instabilities.[28]

Two dimensional effects have been studied using a particle simulation and these show that the driving beam gains transverse momentum due to self-focusing but eventually stabilizes, producing a wakefield that is still formed by a longitudinal displacement of the background electrons as in 1-D.[28]

One of the limitations to the length of an accelerating stage is the inevitable phase slip between the driving and trailing bunches. A way to eliminate this phase slip was suggested which is to launch the driving beam into a rising density gradient. In this case, since ω_p is increasing, λ_p must reduce in order to keep v_p constant at c. This allows the accelerating structure to "catch up" with the accelerating particles.[27] One way to produce such a tailored plasma profile is with multi-photon ionization of a flowing neutral gas which makes the Rutherford results presented earlier all the more interesting.

One of the technological problems with wakefield production is the requirement that the fall time of the driving beam be much less than one plasma wave period. This could be reduced 2000 times by using ion plasma waves as was suggested by a group at LANL. However, this pushes the

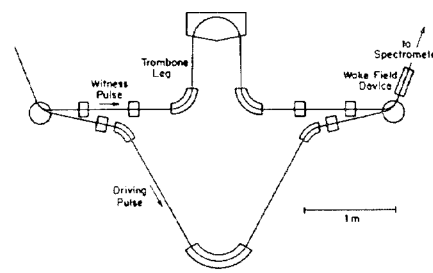

Figure 8: Schematic of the experimental setup at Argonne for wakefield acceleration. A small fraction of the 22 MeV driver is degraded in energy and directed through a trombone delay leg to provide a variable delay with respect to the driver.

technology in other area, such as beam current, in order to get back to the same accelerating field.[29]

There is one planned experiment which is nearly underway in wakefield acceleration.[30] In a Wisconsin-Argonne collaboration, the experiment (shown schematically in Fig. 8) is to send a 22 MeV driving beam and a 15 MeV trailing beam into a 15 cm long, 10^{13} cm^{-3} density plasma. Expected energy gains start at about 10 MeV over about 10 cm. But because the driving beam density is nearly equal to the plasma density, many nonlinear phenomena are expected, leading possibly to much larger accelerating gradients than one might expect from linear theory.[31] One expects pinching of the driving beam to further enhance these nonlinear effects.[32]

Other plasma accelerators

Another accelerator concept closely related to the standard plasma wakefield concept is that proposed by Briggs.[33] Referring to Fig. 9, a charging electron beam collisionally ionizes a neutral gas and expels the electrons to the wall where they are collected. When the charging beam passes, there is left behind an unneutralized column of ions. A trailing photoionizing laser pulse produces a cylindrically symmetric source of electrons which rush inward to produce a large axial electric field. The advantage of this scheme is that there is no independent plasma source to worry about and the free energy is derived from an relatively inexpensive, high current (induction linac) electron accelerator.

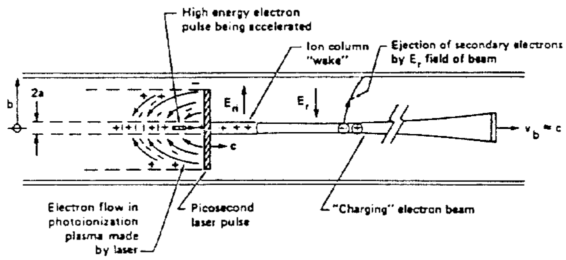

Figure 9: Schematic of the acceleration scheme proposed by Briggs.

Another accelerator uses the virtual cathode at the head of a stalled, high current relativistic electron beam to accelerate ions.[34] A photoionizing laser beam is used to neutralize the negative space charge at the head of the beam and thus allow the beam to propagate further into the neutral background gas. Positive ions trapped in the potential well of the virtual cathode are dragged along with the electron beam as it propagates, controlled by the low power laser beam. Experiments have already demonstrated successful acceleration.[34]

A plasma accelerator based on a plasma waveguide has also been proposed. Here, it is suggested that a filament of very intense laser light which is self-trapped in a dense plasma might automatically have the structure necessary for the acceleration of electrons. This is because a self-trapped filament of light can have an oscillatory radius which begins to look like a slow wave structure and hence a TM mode may be excited.[35]

Other Plasma Uses in HEP

One of the properties the plasma wave discussed earlier was that the radial fields can be as large as the accelerating fields. These large radial forces may be used to exert large focusing forces on a charged beam.[36] Calculations show that for a density of 10^{17} cm^{-3}, the equivalent magnetic focusing gradient is about 300 MG/cm.

Another use for plasmas in the accelerator community is to use the strong electric fields of plasma waves to wiggle electrons much like the permanent magnets of a free electron laser wiggle electrons but with an electric force rather than the Lorentz force. The extremely high wiggler strength ($a_w \sim 1$) with the small wiggler wavelength (100's of microns) puts plasma wigglers in a unique regime for FEL or synchrotron sources.[37]

Conclusions

The field of plasma accelerators has evolved from the conceptual stage with only the beatwave as a candidate to a broad field dealing with issues relevant to future TeV colliders. Experiments are now underway at various places around the world which should shed more light on the future of plasma accelerators.

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