SURVEY OF ADVANCED ACCELERATION TECHNIQUES

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Abstract

In this paper I will survey some of the notable progress that has been made on advanced techniques for particle acceleration. Rather than trying to cover every technique superficially I will restrict myself to talking about three schemes that are showing promise: the inverse free electron laser (IFEL), the laser-wakefield acceleration (LWFA), and the beam-driven plasma-wakefield acceleration (PWFA). The progress made in all these schemes was recently presented at the AAC2004 Workshop at Stonybrook in June and in many instances the results presented by the authors are as yet unpublished.

INVERSE FREE ELECTRON LASER RESEARCH (IFEL)

In an IFEL, one uses a periodic magnet array (a.k.a., a wiggler or an undulator) to cause electron trajectory to oscillate as the electron beam traverses the array (Fig. 1). A laser beam is co-propagated with the electron beam. Now net energy exchange is possible from the laser beam to the electron if the resonance condition

$$\gamma^2 = \frac{\lambda_w}{2\lambda_L}\left(1+\frac{K^2}{2}\right) \qquad (1)$$

is satisfied. Here γ is the relativistic Lorentz factor, λ_w and λ_L are the wavelengths of the wiggler and the laser respectively, and $K = eB_o\lambda_w/2\pi mc$ is the wiggler strength parameter. Clearly, as the beam energy (γ) increases one has to either increase λ_w by tapering the wiggler or increase K or both.

The IFEL principle can be used to bunch the electron beam on the laser wavelength scale. Here the idea is to velocity modulate the electron beam by sending it through a short section of an undulator. The velocity modulated beam then bunches as it goes through a magnetic chicane.

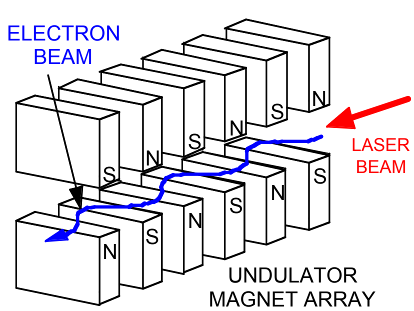

Figure 1: Schematic of the Inverse-Free Electron Laser.

Recent Experiments on the IFEL Scheme

There have been two notable recent experiments on the IFEL scheme. In the first experiment, knows as STELLA[1] for Staged Electron Laser Acceleration, a beam of nominally 45 MeV electrons from the Advanced Test Facility (ATF) at BNL was first sent through an IFEL pre-buncher magnet. This magnet was followed by a chicane compressor and then a second tapered undulator. A CO_2 laser was sent collinearly with the electron beam. The laser was focused at the center of the tapered wiggler to give a peak intensity of $\sim 2 \times 10^{12}$ W/cm^2. This meant that the laser intensity in the pre-buncher section was much lower. Nevertheless, it was sufficient to achieve a ±0.5% momentum modulation. The chicane delivered a bunched beam at the entrance of the tapered undulator. Since the same CO_2 laser beam is used to microbunch the beam and accelerate the pre-bunched beam, phasing between the two is preserved. A spectrometer which analyses the beam exiting the tapered undulator shows acceleration of the pre-bunched beam with an average gradient of 27 MeV/m. The capture efficiency of the pre-bunched beam under optimum condition was over 80% and the accelerated beam has $\lesssim$1% energy spread.[2]

This experiment is extremely significant because it showed many firsts: staged laser acceleration, acceleration of monoenergetic beam and extremely good capture efficiency.

The STELLA collaboration is now planning to do a much higher gradient two-staged laser acceleration experiment. In this method an IFEL prebuncher is used as before to micro-bunch the electron beam on the laser wavelength scale. However, this is followed by a plasma wave excited by the same intense laser in a plasma. Since gradients on the order 1 GeV/m are readily observed in plasmas, it is hoped that mono-energetic acceleration at high gradients can be demonstrated using this two-stage approach that combines IFEL and plasma wakefield technologies.[3]

In a second recent experiment at UCLA's Neptune laboratory, a more powerful, 300 GW, CO_2 laser was used in conjunction with a strongly tapered undulator. Consequently, the nominally 14 MeV electron beam was accelerated out to more than 30 MeV with a peak gradient of > 50 MeV/m.[4] These gradients are beginning to get interesting to be of use in practical devices.

LASER WAKEFIELD ACCELERATOR (LWFA)

Now I will describe recent breakthroughs in the laser-plasma accelerator field. In particular I will confine my remarks to the so-called LWFA scheme (see Fig. 2) where a short but intense pulse of photons, approximately half a plasma wavelength long excites a relativistic, $v_\phi \sim c$, wake behind the laser pulse[5]. Simple estimates using Gauss' law show that the longitudinal electric field associated with such wakes scales as $\sqrt{n_e}$. This scaling has been shown to be valid over a range of densities from 10^{16}cm^{-3}–10^{20}cm^{-3} and maximum gradients of up to 200 GeV/m have been obtained over a mm.[6] Thus typical energy gains have been in the range from tens to 200 MeV with monotonically decaying electron energy distribution up to some maximum energy. The electrons have been mostly self-trapped by a process known as wavebreaking.[7] The charge emitted from the plasma has been in the few nanocoulomb range and the angular divergence of the emitted electrons has been narrow (few degrees). Clearly, the next challenges facing the laser-plasma accelerator researchers are: a) increasing the energy gain up to the so-called dephasing limit by increasing the interaction length , b) demonstrating that a "monoenergetic" beam can be produced from such accelerators and that this beam is short compared to the wavelength of the accelerating structure and c) staging.

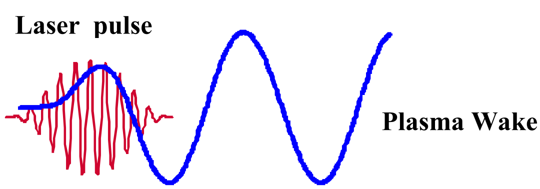

Figure 2: Schematic of the laser wakefield accelerator.

Recent Experiments on Increasing the Plasma Length

The length of the region over which a plasma wake can be excited is limited by the diffraction of the laser beam to roughly $L_{diff} = \pi\lambda_R = \pi^2 w_o^2/\lambda$. To overcome this limit the laser beam must be guided in a waveguide formed in the plasma. Fortunately a plasma with a parabolic transverse density profile with a minimum on its axis acts as a guiding structure for photons. (see Fig. 3)

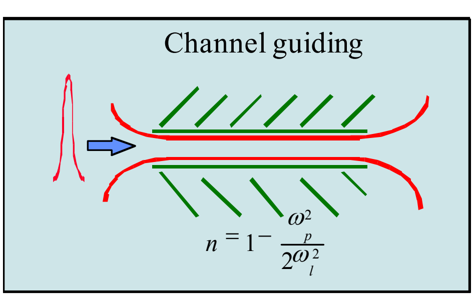

Figure 3: Schematic of a plasma channel for guiding a laser beam.

Researchers are pursuing different schemes for generating plasma channels for guiding high power laser beams. These basically fall into four categories: a) plasma heating followed by hydrodynamic expansion of the heated column[8], b) ablation of wall material in a capillary discharge[9], c) z-pinch discharges[10], and d) gas filled capillary discharges[11]. Of these hydrodynamically formed plasma channels have been shown to guide the highest intensity (~2×10^{18} W/cm^2) laser pulses. On the other hand hydrogen filled capillary discharges promise much longer length plasma waveguides approaching the dephasing length limit of $L_{dph} \sim (\lambda_p/2)/(1-v_g/c)$.

Recent Experiments "Monoenergeitc Beam" Generation

In a rf driven particle accelerator, the energy spread of the beam is small because, the bunch length is much smaller than the rf wavelength. In LWFA experiments the plasma wavelength is on the order 10 µm (30 fs) and the challenge of externally injecting a pre-bunched beam is made far more challenging than in the IFEL case by the extremely large radial fields ($E_r \sim E_z \sim$ 100 GeV/m). So the ultrashort bunches must somehow be generated in situ. Various methods for locally triggering the trapping of electrons from the plasma itself using a second laser pulse have been proposed but to-date none has been shown to produce the desired effect. However, recently, three groups LBNL (USA), L.O.A. (France) and RAL (U.K.)[12] have independently and serendipitously shown quasi-monoenergetic acceleration of ~ hundred pico-coulomb charge of electrons to ~ 100 MeV. In all three schemes an extremely short laser pulse blows out the plasma electrons mainly radially which snap back behind the laser pulse forming an accelerating bucket (both in real space and in phase space). Some of the electrons are self-trapped from the walls of this bucket and begin to be accelerated. The beam loading due to these self-trapped electrons in so severe that the trapping soon terminates. At the same time laser pulse evolves both in the frequency domain and in the time domain such that the group velocity of the modified pulse slows down. Now the dephasing length is reduced and some of the accelerating electrons overtake the accelerating portion of the longitudinal field and begin to slow down while electrons trapped later are still gaining energy. The fortuitous confluence of this extremely nonlinear laser and wake evolution leads to a relatively monoenergetic beam of electrons in phase space.[13]

Using more powerful 100 TW class lasers that are coming online it should be possible to obtain relatively monoenergetic bunches of electrons containing 0.5 nC of charge with energies around 500 MeV in the near future.

Staging

Recently, the NRL (USA) group[14] has attempted to do a two-stage plasma acceleration experiment. Here field ionization of a nitrogen gas with an intense laser produces forward going, mildly relativistic electrons that were subsequently further accelerated by a wakefield produced in a helium plasma. Only when electrons from nitrogen field-ionization were injected with the appropriate delay was there an enhanced emission of electrons with energies greater than 20 MeV indicating a causal relationship. Further results from this group are awaited with interest.

BEAM-DRIVEN PLASMA WAKEFIELD ACCELERATION

Plasma Wakefield Acceleration (PWFA) is one of the most vigorously pursued advanced acceleration scheme at this time. In this scheme the high-gradient wakefield is driven by an intense, high-energy charged particle beam as it passes through the plasma. In the case of an electron beam the space-charge of the bunch blows out the plasma electrons which rush back in and overshoot setting up a plasma oscillation (See Fig. 4). A second, appropriately phased accelerating beam, containing fewer particles than the drive beam, can now be accelerated by the wake. Both electron and positron beams can be used to drive plasma wakes. In the case of a positron beam the plasma electrons are "pulled in" instead of being expelled as in the case of an electron beam driver. The PWFA scheme is very attractive because of its potential to double the beam energy of a high energy accelerator beam in a single stage of acceleration that is only tens of meters long using existing state-of-the-art driver beams.

Recently there have been breakthrough developments

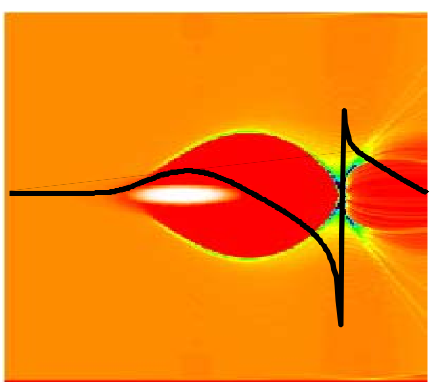

Figure 4: Schematic of the PWFA scheme.

on this scheme by the E164X collaboration[15] of scientists from UCLA, USC and SLAC using the 28.5 GeV electron beam from the Stanford Linear Accelerator. In earlier experiments this collaboration demonstrated acceleration of both electrons and positrons using typically 4 ps long bunches that contained a peak current of about 1 kA. When such e^+/e^- bunches were propagated through a 1.4 m long, ~ 5×10^{14}cm^{-3} density lithium plasma gradients on the order 50 MeV/m for e^+ and 200 MeV/m for e– were observed. The gradient scales as inverse square of the bunch length for a fixed number of particles. This scaling has been confirmed in computer simulations and useful gradients on the order 50 GeV/m

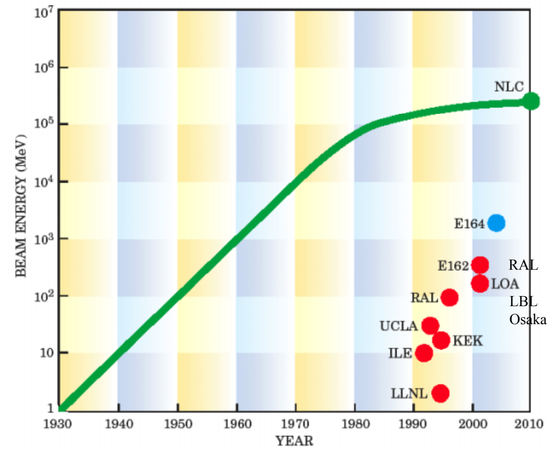

Figure 5: Maximum electron energies achieved in plasma acceleration experiments in different laboratories around the world.

have been observed using 35 μm long bunches with a peak current of ~10kA. Fortunately the Sub-Picosecond Pulse Source (SPPS) at SLAC has been able to deliver bunches as short as 20 μm. The self-fields of such short, intense bunches is large enough to field-ionize Lithium to produce long homogeneous plasmas with densities in the 10^{17}cm^{-3} range. Using such short beams the E164X experiment has conclusively demonstrated acceleration of electrons by up to 4 GeV in just 10 cm long plasma. Furthermore, the energy gain is limited by the energy acceptance of the Final Focus Test Beam (FFTB) beamline. If this were not the case energy gains of 10 GeV and perhaps even greater may be possible by simply extending the plasma length.

CONCLUSIONS

As one can see the Advanced Acceleration field is thriving with creativity and ingenuity. The beam-driven PWFA scheme is showing energy gain that are of interest to the HEP community and laser-plasma accelerator development is getting closer to delivering a GeV class accelerator on a "desktop."

I thank all the coworkers in the field of Advanced Acceleration technique whose work is mentioned in this paper. This work is supported by a DOE grant DE-FG03-92ER40727 at UCLA.

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