# WAKEFIELD ACCELERATION BASED ON HIGH POWER PULSED LASERS AND ELECTRON BEAMS (OVERVIEW)

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The physical principles are considered on intense wakefields excitation in plasma and dielectric by high-power short laser pulse or by a train of electron bunches for high-gradient acceleration of charged particles with purpose to elaborate the concept of future compact accelerators for high-energy physics and high technology applications, and also for creation of contemporary short pulsed radiation sources. The results of investigations on laser's acceleration in vacuum, electrons acceleration in plasma by high power laser pulse with obtaining beams of small angle and energy dispersion, concepts of plasma and dielectric wakefield accelerators are presented. The perspective research program of the schemes of laser/beam acceleration in plasma and dielectric is considered.

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## 1. INTRODUCTION

Since the previous overview [1] on the new methods of charged particles acceleration based on wakefield excitation many appreciable successes have been achieved.

First of all it concerns precision monoenergetic bunch of accelerated electrons with a small angle dispersion obtained at interaction of ultrashort Petawatt laser pulse with plasma [2-6]. These results promise to consider as realizable the creation of tabletop accelerators with accelerating field gradient of order 100 GeV/m, i.e. 3 order more comparatively to traditional ones. At present a new record energy in excess of 300 MeV has been set [6] for acceleration of electrons by laser-produced plasma.

Not less impressive result has been recently obtained in acceleration of electrons by plasma wakefield excited by short intense bunch in plasma column [7]. At accelerating field gradient 27 GeV/m electrons were accelerated up to energy 2.7 GeV, i.e. GeV threshold is overcome in advanced acceleration method concept.

Electron acceleration to GeV energy by a short high-power laser pulse in vacuum proposed in [8] seems very designing in spite of Lawson-Woodward theorem prohibition.

Along with these frontier achievements in laboratories abroad there are some new results in wakefield investigations carried out in NSC KIPT. In [9] beam focusing with wakefield excited in plasma by a train of electron bunches is presented. Dielectric wakefield acceleration is investigated for waveguide approach and for resonator concept [10].

## 2. HIGH POWER ELECTROMAGNETIC SOURCES FOR FUTURE ACCELERATORS

Recently obtained results on high gradient acceleration are obtained by using ultrashort ~ femtoseconds and high power ~terawatts laser pulse of optical wavelengths generated by so called $T^3$ -laser (Terawatt Table-Top laser). It allows to solve the problem of non-reasonable growth of dimension and costs of accelerators for TeV-PeV energies claimed by contemporary high energy physics (e.g. LEP at CERN has diameter 27 km comparable with circle road around Paris of averaged diameter 31 km). These optical high power sources should substitute RF-sources of the Second World War times (magnetrons, klystrons etc.) which provide in conventional accelerating structures accelerating rate only 10…30 MeV/m.

Compact advanced tabletop accelerating systems based on $T^3$ lasers can be used for creation of bright sources of light and γ-ray radiation and have a practical interest for industrial applications.

History of tabletop system development is the following [11]. After a rapid increase in the 1960s with the invention of lasers, followed by the demonstration of *Q* switching and mode locking, the power of lasers stagnated due to the inability to amplify ultrashort pulses without causing unwanted nonlinear effects in the optical components. This difficulty was removed with the introduction of the technique of chirped pulse amplification (CPA), which took the power of tabletop lasers from the Gigawatt to the Terawatt – a jump of 3 to 4 orders of magnitude. At present there are several laboratories with tabletop laser system of power in Petawatt range – LLNL (USA), RAL (UK), JAERI (Japan).

By focusing laser power on a 1 mm spot size present systems deliver focused intensities in the $10^{20}$ W/cm$^2$ range. In the near future, CPA systems will be able to produce intensities of the order of $10^{22}$ W/cm$^2$. As indicated in Fig.1, we will see a leveling off of laser intensity for tabletop-size systems at $10^{23}$ W/cm$^2$.

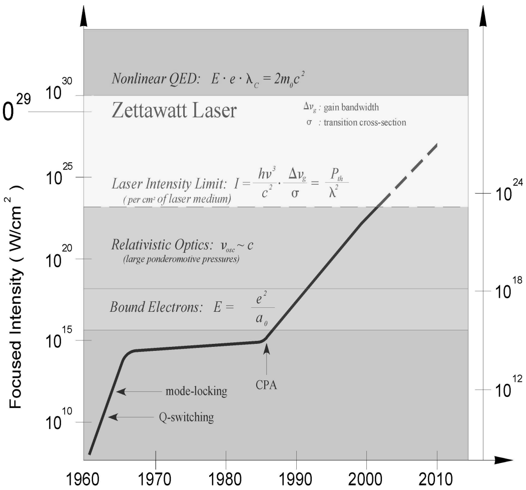


*Fig.1. Laser-focused intensity vs years for tabletop systems*

In [11] technical feasibility is explored to build a large scale CPA pumped by a Megajoule system of the type of the NIF (National Ignition Facility) in the U.S. and the LMJ (Laser Megajoule) in France. Power in the zettawatt range ($10^{21}$) could be produced, yielding a focused intensity of $10^{28}$ W/cm$^2$.

These intensities well beyond the current intensity accessible will open up a new physical regime. Direct applications of zetawatt lasers in fundamental physics envelope the following areas:

♦Direct electron acceleration. There are many instances that break the Lawson-Woodward theorem which prohibits any overall acceleration for fully oscillatory electromagnetic waves in vacuum in infinite space. For example, it may be possible in extreme relativistic regime that electrons are accelerated to very high energy, immediately reaching the speed of light and becoming in phase with the photon over a sufficiently long distance, so that by the time they become dephased, the electromagnetic wave may decay away for some reason, such as by radiative decay or pump depletion Thus it is possible to see electrons at energies of up to ~100 TeV at the laser intensity of $10^{26}$ W/cm$^2$ and even up to ~10 PeV at $10^{28}$ W/cm$^2$. The accelerating gradient is 200 TeV/cm and 2 PeV/cm, respectively. Note that such energies (100 TeV and 10 PeV) if collided, correspond to $10^{19}$ and $10^{23}$ eV for fixed target experiments. These energies rival or exceed those of the highest energy cosmic rays, which are observed up to $3\times10^{20}$ eV. Perhaps the present extreme parameters in the energy frontier may herald some new phenomena. One such example may be the test of Lorentz invariance [12] in extreme high energies.

♦Direct baryon acceleration. Early Petawatt Laser experiment [13] showed that protons have been accelerated much beyond a megaelectron volt. About 10% of laser energy (300 J) was converted into proton energy – 30 J (beyond 1 MeV). The main mechanism of laser proton acceleration in the this experiment is due to the space charge set up by energetic electrons that are driven forward away from the back surface of the target slab. In simulation [14] it was shown that at a laser intensity of I=$10^{23}$ W/cm$^2$, protons are accelerated beyond a gigaelectron volt. If this process of proton acceleration scales with the intensity, we may be able to see 100 GeV protons and 10 TeV at $I$=$10^{26}$ and $10^{28}$ W/cm$^2$, respectively. For the case $10^{28}$ W/cm$^2$ about $10^{11}$ protons should be accelerated beyond 10 GeV. However, it may also be possible that this process is now due directly to the photon pressure beyond the intensity regime of $I$=$10^{24}$ W/cm$^2$. The energy expected through this mechanism is about the same as that through the space charge mechanism.

♦Fast ignition fusion. The concept of fast ignition in laser-driven inertial fusion [15] concludes to separate the roles of lasers into two functions: one to compress the fuel with the least amount of entropy increase so that the fusion fuel is compressed to a highest density with the least amount of laser energy, and the other is to heat the fuel to the thermonuclear ignition temperature (~ 10 keV) when the main compression is achieved. Instead of required [15] laser beam of ~10 psec duration the intensity $10^{20}$ W/cm$^2$ to be absorbed at the critical density ~$10^{21}$…$10^{22}$ cm$^{-3}$, creating a beam of electrons in the several MeV range, authors of [11] suggest that an alternative method of fast ignition by a much shorter-pulse laser (10 fs, $10^{25}$ W/cm$^2$ ). Since the resonance frequency reduces inversely proportional to $\sqrt{n_e}$, the resonance density becomes on the order of $10^{25}$ cm$^{-3}$, a very close proximity of the fully compressed fuel. This way allows avoiding the difficult and long energy transport of the electron beam from the density region of < $10^{22}$ cm$^{-3}$ to $10^{26}$ cm$^{-3}$.

♦Gamma ray emission. Although the well-known Bremsstrahlung $x$ rays (and gamma rays) by electrons through the collision with nuclei are expected to remain important, the Larmor radiation is the most intense in the extreme relativistic regime among all radiation mechanisms through the interaction with matter (in this case free electrons). In addition, gamma rays of nuclear origin are also expected. When an intense laser is directed at a high-energy electron beam, the well-known energy enhancement of the laser photon happens by the factor $\gamma^2$ or up to the electron energy itself through Compton scattering.

♦Superhot matter. Intense laser pulse may be nearly totally absorbed by only several of atomic clasters [16]. Moreover the chaos of electron orbits sets in within a few femtoseconds, thus making the absorption of the laser ultrafast. Further, upon removal of electrons from the claster, ions of the cluster Coulomb explode, gaining a large fraction of electron energy. If we arrange matter in such a way as to absorb nearly all laser energy over the thickness of a few microns on a (1 μ)$^2$ spot, the average energy per particle is approximately $10^2$ and $10^4$GeV, at $I$=$10^{26}$ and $10^{28}$ W/cm$^2$, respectively. Such superhot matter is expected to generate copious positrons through the Breit-Wheeler process and perhaps other nonlinear quantum electrodynamic (QED) processes.

♦Nuclear reactions. A large number of nuclear excitations is expected, i.e. nuclear transmutations through generated gamma rays have been observed [17]. If a heavy metal is irradiated, the energy per nucleon exceeds 1 GeV. It allows expecting about $10^7$ nuclear events per laser shot, which may include such a process as quark-gluon plasma formation.

Either by direct baryon acceleration, or target/cluster irradiation we will access the nuclear regime of matter reminiscent of the early epoch of the big bang.

♦Nonlinear QED. Threshold of pair production derives from the simple argument that it is the field necessary for a virtual electron to gain an energy $2m_0c^2$ during its lifetime $\delta t$, imposed by the Heisenberg uncertainty principle $\delta t = h/m_0c^2$, the energy gain length, and $c\delta t$ is the Compton length $\lambda_c$. Hence, the breakdown field $ES$, the Schwinger field, is $E_S = m_0c^2/e\lambda_c$ where $\lambda_c$ =0.386 pm, $E_S$ =2.3·10$^{16}$ V/cm (i.e. $I_S$ =10$^{30}$ W/cm$^2$). At this field, fluctuations in vacuum are polarized by laser to yield copious pairs of real electrons and positrons. At the intensity 10$^{28}$ W/cm$^2$, the electric field is only an order of magnitude less than the Schwinger field. Even below the Schwinger field, the exponential tail of these fluctuations begins to cause copious pair productions.

♦"Horizon physics". The acceleration due to the electric field of the laser at this intensity is huge: $a_e$ ~10$^{30}$ and 10$^{31}$ cm/s$^2$, at $I$ = 10$^{26}$ and 10$^{28}$ W/cm$^2$, respectively. According to Einstein's equivalence principle, a particle that is accelerated feels gravity in the opposite direction of the acceleration. An observer at rest sees the horizon at infinity if there is no gravitation. On the other hand, an observer near a black hole sees the horizon at a finite distance where the gravitation diverges. Equivalently, an observer who is being accelerated (feeling immense equivalent gravity) now also sees the horizon at a finite distance. Any particle ("observer"- a wave function) that has a finite extent has one side of its wave function leaking out of the horizon. The Unruh radiation is emitted when this happens [18]. The Unruh temperature is about 10$^4$ and 10$^5$ eV, for $I$=10$^{26}$ and 10$^{28}$ W/cm$^2$, respectively.

Considered laser systems could bring many frontiers of contemporary physics, i.e., particle physics, nuclear physics, gravitational physics, nonlinear field theory, ultrahighpressure physics, relativistic plasma and atomic physics, astrophysics, and cosmology together.

## 3. SUCCESSES IN NEW TRENDS OF PARTICLES ACCELERATION [19]

Today we are launching forth into a new energy regime of the order of TeV in which profound fundamental questions is expected to be answered on the origin of mass, the predominance of matter over antimatter and the existence of supersymmetry and so on. High energy ion accelerators including proton and heavy-ion colliders can reveal in-situ synthesis of the nuclear matter by producing quark-gluon plasmas at the quark-hadron phase transition temperature around one-trillion Ks, which is thought as the high energy density state at 10$^{-5}$ seconds after the Big Bang of our universe.

High energy electron accelerators have been utilized as synchrotron light sources generating short wavelength radiations in a wide range of sciences, such as material, chemical, biological, medical and industrial sciences. Brilliant collimated X-ray radiations delivered from the third generation synchrotron light source composed of several GeV electron storage rings reveal to us the structure and functions of DNA and proteins in biological cells. Intermediate energy ion accelerators around 1 GeV beam energy are active in therapy of cancers as a successful medical application.

As particle accelerators increased their energy frontier at an exponential rate as shown in the known Livingston chart and enlarged their applied fields in the past century, we realize present high- energy accelerators become too large and costly, and possibly they approach the end of the road. High energy accelerators today are based on high power RF technologies that accelerate charged particles with electric fields up to 100 MV/m at most, which is the limit stably produced in metallic, electromagnetic cavities because of electrical surface heating and breakdown. As illustrated with the future linear collider beyond the TeV energy range, the overall accelerator complex will range from tens to hundreds of kilometers long and amount to enormous expenditure to build.

High-energy frontier particle colliders today need a huge size and cost to be built with conventional RF accelerator technologies. This has been a primary motivation in advanced accelerator research for more than two decades. Therefore the advanced accelerator physics and development are oriented to researches on high gradient particle acceleration driven by high energy density laser or particle beams as well as generation of high-intensity, high-quality radiation and particle beams. The outcome of the advanced accelerator research will revolutionize applications of particle accelerators in a wide range of sciences, not only the future high-energy physics but also material, bio-, and medical science.

In the past decade the worldwide experiments of laser-plasma particle acceleration have boosted their frontier of particle beam energy and intensity. A trend in experimental results indicates a rapid increase of electron energies accelerated by laser-driven plasmabased concepts, whose rate is three to four orders of magnitude over the past ten years in coincidence with increase of the laser ponderomotive energy (Fig.2). A recent laser electron acceleration experiment carried out by using 160 J, 650 fs (~250 TW) pulses at RAL demonstrated the highest energy laser acceleration at the maximum energy of 350 MeV, though with 100% energy spread, whose energy spectra can be characterized by a power law rather than a Maxwellian distribution. The highest energy electrons are observed for a focused laser intensity of 3×10$^{20}$ W/cm$^2$.

In the plasma wakefied acceleration driven by the intense electron beam, Joshi et al. carried out PWFA experiments at the 30 GeV SLAC FFTB electron beam with 20 mm rms bunch length, where the maximum energy gain of up to 4 GeV was obtained over a 10 cm long lithium plasma, though the energy spread was 100%. This result is the first demonstration of the breakthrough of a GeV barrier in plasma accelerators.

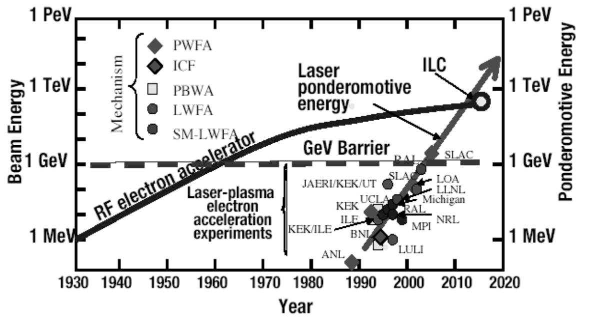


*Fig.2. Evolution of the electron beam energy frontier of the RF electron accelerators (solid curve) and the maximum electron energy plots achieved by the worldwide laser and plasma accelerator experiments. The arrow shows evolution of the focused laser intensities represented by the ponderomotive energy, which is the particle kinetic energy given by the laser field*

### 3.1. LASER WAKEFIELD ACCELERATION (LWFA)

The most prominent experimental results today [2-5] is the monoenergetic electron beam acceleration in LWFA, which were presented by Koyama (Japan), Murphy (UK), Malka (France) and Leemans (USA) independently. Moreover, their beams have properties of high quality having a small normalized emittance below 1 πmm mrad and about 10 femtosecods pulse length with a charge of the order of 1 nC, making them attractive as potential radiation sources for ultrafast time-resolved studies in biology and material science as well as an injector for future FELs and linear colliders.

♦K. Koyama et al. (AIST, Japan). Ti:sapphire laser parameters are: wavelength 800 nm, power 2 TW, pulse width 50 fs, focus diameter 5 μ, focus intensity $1.5\times 10^{18}$ Wcm$^{-2}$. Target: supersonic gas jet-gas; N2, He. Plasma density $(0.4…4.4)\times10^{20}$ cm$^{-3}$; N2; $(0.4…1.3)\times 10^{20}$ cm$^{-3}$; He.

Results on electron beam production with energy 7 MeV and divergence angle are shown in Fig.3.

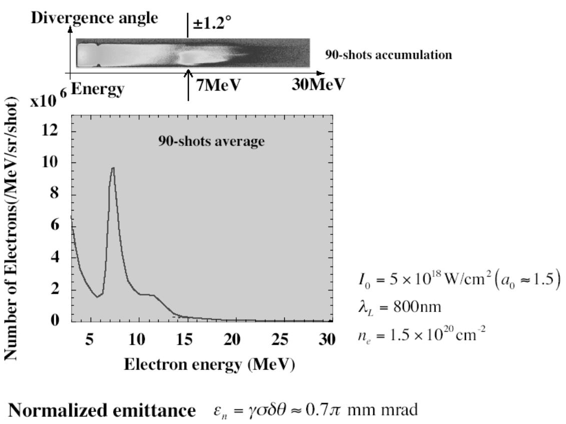


*Fig.3. Spectrum of accelerated electrons in [2]*

♦C.D.Murphy et al. (ILC/RAL, UK). The experiment used the high-power Ti:sapphire laser system at the Rutherford Appleton Laboratory (Astra). The laser pulses (λ=800 nm, τ=40 fs with energy approximately 0.5 J on target) were focused with an f/16.7 off-axis parabolic mirror onto the edge of a 2-mm-long supersonic jet of helium gas to produce peak intensities up to $2.5\times 10^{18}$Wcm$^{-2}$. The electron density ($n_e$) as a function of backing pressure on the gas jet was determined by measuring the frequency shift ($\Delta\omega=\omega_{pe}$) of satellites generated by forward Raman scattering in the transmitted laser spectrum. The plasma density was observed to vary linearly with backing pressure within the range $n_e=3\times 10^{18}…5\times10^{19}$ cm$^{-3}$. Electron spectra are measured using an on-axis magnetic spectrometer. Other diagnostics used included transverse imaging of the interaction, and radiochromic film stacks to measure the divergence and total number of accelerated electrons. The schematic of installation is shown in Fig.4.

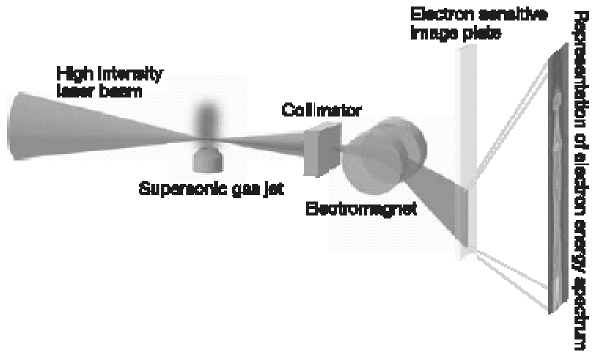


*Fig.4. Experimental set-up*

With careful control of the plasma density and at a higher laser power only one very narrow single peak in the spectrum (i.e. monoenergetic electron beam was observed (Fig.5)).

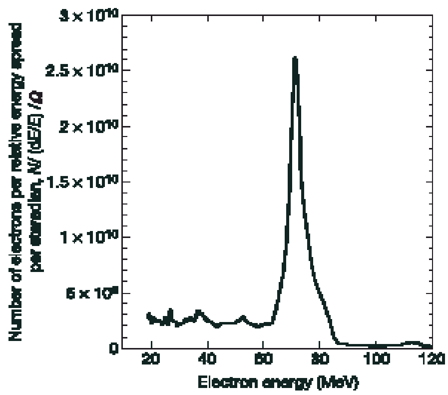


*Fig.5. Measured electron spectrum at a density of $2\times 10^{19}$ cm$^{-3}$. Laser parameters: E=500 mJ, τ=40 fs, $I \approx 2.5\times10^{18}$Wcm$^{-2}$*

♦V.Malka et al. (Ecole Polytechnique, France). Here it was demonstrated that the quality of the electron beams can be dramatically enhanced. Within a length of 3 mm, the laser drives a plasma bubble that traps and accelerates plasma electrons. It leads to the generation of high-quality electron beams with 10 mrad divergence and 0.5 ±0.2 nC of charge at 170±20 MeV. From the above, it can deduced that the electron beam energy was 100 mJ. Thus, the energy conversion from the laser to the electron beam was 10%. Contrary to all previous results obtained from laser–plasma accelerators, the electron energy distribution is quasi-monoenergetic. The number of high-energy electrons (170 MeV) is increased by at least three orders of magnitude with respect to previous work.

This new regime was reached by using the ultrashort and ultraintense laser pulse generated in a titanium-doped sapphire, chirped pulse amplification laser system. The laser pulse had a 33±2 fs duration (FWHM), and contained 1 J of laser energy at central wavelength 820 nm. It was focused onto the edge of a 3-mm-long supersonic helium gas jet using a f/18 off-axis parabola. The diffraction-limited focal spot had a diameter of $r_0$=21 μm at FWHM, producing a vacuum-focused laser intensity of I=3.2×10$^{18}$Wcm$^{-2}$. For these high laser intensities, the helium gas was fully ionized by the foot of the laser pulse and ionization did not play a role in the interaction. Higher plasma density was $n_e$ =2×10$^{19}$ cm$^{-3}$.

♦W.P.Leemans et al. (LBNL, USA). In the works mentioned above, however, acceleration distances (the diffraction or Rayleigh length) have been severely limited by the lack of a controllable method for extending the propagation distance of the focused laser pulse. The ensuing short acceleration distance results in low-energy beams with 100 per cent electron energy spread, which limits potential applications. Here it was demonstrated a laser accelerator that produces electron beams with an energy spread of a few per cent, low emittance and increased energy (2× 10$^9$ electrons at 80±1.8 MeV). Bunches with energy up to 150 MeV have been observed on separate shots. Applied technique involves the use of a preformed plasma density channel to guide a relativistically intense laser, resulting in a longer propagation distance.

In the channel-guided laser wakefield accelerator, the plasma channel was formed in a supersonic hydrogen gas jet by two pulses fired 500 ps before the drive pulse. The supersonic gas jet was 2.4 mm long at an atomic density of 4.5×10$^{19}$ cm$^{-3}$. A cylindrical filament of plasma was ionized by an intense (60 fs, 15 mJ) igniter pulse, collinear with the pulse that drives the plasma wave and focused at f/15 near the downstream edge of the gas jet. The plasma was subsequently heated to tens of eV by inverse bremsstrahlung, using a long (250 ps, 150 mJ) pulse incident from the side for efficient heating. The resulting hot plasma filament on axis expanded outward, driving a shock wave. This shock resulted in a density depletion on axis and a nearly parabolic transverse density profile which was tuned by adjusting the timing and energies of the beams.

The plasma wave was driven by a 500 mJ pulse of 55 fs FWHM, focused at the upstream edge of the channel to an 8.5 μm FWHM spot by an f/4 off axis parabola giving an intensity of 1.1×10$^{19}$Wcm$^{-2}$. Propagation of the laser was monitored with a side interferometer (using a 2 ω probe laser) and mode imager CCD. The electron beam accelerated by the plasma wave was analyzed using an integrating current transformer (ICT), a phosphor screen, and a magnetic spectrometer. The laser mode at the channel exit is a well defined spot of 24 mm FWHM containing 10% of the input energy. This indicates the effectiveness of the channel in maintaining the drive beam intensity and mode over many diffraction lengths.

A high-quality electron bunch is formed when the acceleration length is matched by plasma density changing to the dephasing length, and when the laser strength is such that beam loading is sufficiently strong to turn off injection after the initial bunch of electrons is loaded.

The results open the way for compact and tunable high-brightness sources of electrons and radiation.

These four experiments have shown the possibility of realization high gradient of accelerating field of order 100 GeV/m. The problem is to enlarge the length of accelerating process and hence the final energy of accelerating particles. The maximal record energy at laser-plasma acceleration is above 300 MeV [6].

♦ K.Krushelnick et al. (Imperial College London, UK). The experiment was performed using the Vulcan Petawatt Nd:glass laser system, which produced pulses of 160 J in a duration of τ=650 fs (FWHM). The laser was focused to a 6 μ diameter spot at the edge of a supersonic 2 mm diameter helium gas jet using an *f*=3 off-axis parabolic mirror. This produces peak intensities in excess of 3×10$^{20}$ Wcm$^{-2}$ in vacuum.

Fig.6 shows three electron energy spectra observed at different electron densities, which are representative of the trend observed over the range $n_e$=(5×10$^{18}$…1.4× 10$^{20}$) cm$^{-3}$. The spectra have large energy spreads typical of laser-plasma interactions, although in this experiment not all the spectra are well described by a quasi-Maxwellian distribution. The spectra with the most energetic electrons were more accurately described by a power law distribution. The spectrum recorded at $n_e$ =7,7×10$^{18}$ cm$^{-3}$ shows the highest observed electron energies. The signal descends into the background at 300 MeV. The beam divergence measurements show that close to the optimum density the beam divergence was approximately 50 mrad for electrons above 1.5 MeV.

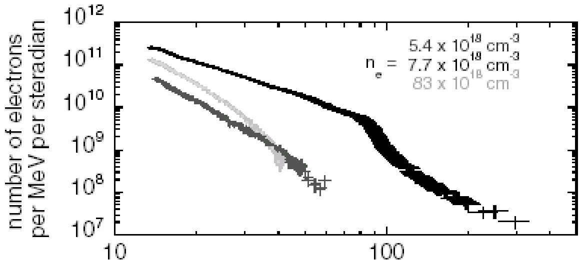


*Fig.6. Three example electron energy spectra observed at various background electron densities for laser intensity ~3 ×10$^{20}$ Wcm$^{-2}$*

### 3.2. BEAM PLASMA WAKEFIELD ACCELERATION (PWFA)

The latest new result at SLAC [7] on electrons acceleration in plasma wakefield excited by intense relativistic electron bunch is the first demonstration of the breakthrough of a GeV barrier in advanced accelerators promising to leave behind conventional coliders, e.g. ILC, before 2020 year (Fig.2).

The experiment described in [7] uses an ultrarelativistic electron bunch to simultaneously create a plasma in lithium vapor and drive a large amplitude plasma wave. When the electron bunch enters the lithium vapor, the electric field of the leading portion of the bunch ionizes the valence electron of each lithium atom in its vicinity leaving fully ionized neutral plasma for the remainder of the bunch. The plasma electrons are then expelled from the beam volume and return one-half plasma period later. The returning plasma electrons form density concentrations on axis behind the bunch leading to a large accelerating field for the particles in the back of the bunch.

A single 28.5 GeV bunch of $1.8\times10^{10}$ electrons from the Stanford Linear Accelerator Center (SLAC) linac was compressed to the length of 12 $\mu$ (rms). There are no techniques available to time resolve the spectrum of 12 $\mu$ (40 fs) bunches; consequently, the energy changes from the plasma are measured by comparing the time integrated energy spectrum of the bunch with and without the plasma (Fig.7). The neutral lithium vapor is fully ionized by the large radial electric field of the compressed electron bunches and the plasma density is then equal to the lithium vapor density (10 cm long $2.8\times10^{17}$ atoms/cm$^3$).

The no plasma case shows the ~1 GeV energy spread typical of the incoming compressed pulses. At right, the core of the electron bunch has lost energy driving the plasma wake while particles in the back of the bunch have been accelerated to 2.7 GeV over the maximum incoming energy. About of 7% of the bunch particles accelerated to energies higher than the maximum incoming energy.

Future two-bunch plasma accelerators will use one bunch to drive the wake and accelerate a second bunch with narrow energy spread. Provided the intrabunch spacing and plasma density are adjusted accordingly, the measured accelerating gradient in a twobunch scheme should continue to increase as the drive bunch length is shortened.

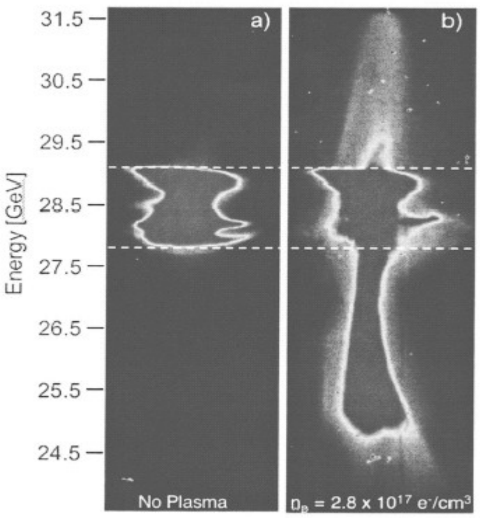


*Fig.7. Single bunch energy spectra downstream from the plasma for (a) the case of no plasma and (b) a 10 cm long 2:8×10*$^{17}$ *e/cm*$^3$ *lithium plasma*

This experiment has verified the dramatic increase in accelerating gradient predicted for short drive bunches and has reached several significant milestones for beam-driven plasma-wakefield accelerators: the first to operate in the self-ionized regime, the first to gain more than 1 GeV energy, and the largest accelerating gradient measured to date by 2 orders of magnitude. It is a crucial step in the progression of plasmas from laboratory experiments to future high-energy accelerators and colliders.

### 3.3. VACUUM LASER ACCELERATION (VLA)

By using the definition in [8] the phase velocity was derived for focused Gaussian laser beam in vacuum and low phase velocity region with longitudinal electric field was found. Basing on this result the Capture and Acceleration Scenario (CAS) was proposed for experimental realization. For this powerful laser system I>$2\times10^{17}$ W/cm$^2$ (at $\lambda$=10µ), i.e. $a_0=eE_0/mc\omega$>4, electron injector (5…15 MeV) and electron spectrometer are needed. Cas accelerator should produce 100 MeV at $a_0$=10 and 2 GeV at $a_0$=100.

This result is controversial [20], because Gaussian beam is approximate representation of the field. Really this approximation contains elementary plane slow waves, which fulfill Cherenkov resonance. However Gaussian expression corresponds to parabolic approximation of exact wave equation, i.e. instead of $k_z=((\omega/c)^2 - k_x^2 - k_y^2)^{1/2}$ it was used
$k_{zpar}= \omega/c - c/2\omega\,(k_x^2 - k_y^2)$.

Nevertheless many attempts have been undertaken to get round the prohibition of Lawson-Woodward theorem, including theory and experiments [21].

### 3.4. BEAM FOCUSING BY PLASMA WAKEFIELD

Theoretical and experimental investigations of focusing processes during wakefield excitation in plasma by a regular sequence of relativistic electron bunches were performed [9]. In plasma along with space charge compensation and pinching of beam in self magnetic field electrons experience strong focusing by radial electric component of excited wakefield. Topography of wakefield and extent of focusing were calculated theoretically. Experimental researches were carried out using linac "LIK" and coaxial plasma gun. A sequence of bunches ((1.5…3.0)×10$^3$ bunches of electron energy 14 MeV). Was injected into plasma of length 0.5 m and electron density within the range 10$^{11}$…10$^{13}$ cm$^{-3}$.Each bunch of length 10mm and diameter 1.4 mm contains $2\times10^9$ electrons. Focusing effect was observed for middle part of beam macropulse 0.5…1.0 µs that gives 2 times current on the near axis small Faraday cup.

### 3.5. DIELECTRIC WAKEFIELD ACCELERATION

The main advantage of dielectric wakefield acceleration is multimode operation that allows to increase accelerating field due to its build up at many transversal modes interference resulting in picked field of enlarged amplitude. In NSC KIPT three issues arisen at intense wakefield excitation in dielectric structure were investigated theoretically and in experiment [10,22-25]. The wakefield in a dielectric waveguide/resonator excited by electron bunches can be enhanced by using a regular sequence of relativistic electron bunches (multi-bunch operation) [26], interference of many transverse modes to enlarge peak amplitude (multi-mode operation) [27], and resonant accumulation of wakefield in a resonator resulting from many bunches (resonator concept) [28].

The electron energy spectra of electron bunches for waveguide and resonator cases were measured, from which it was concluded that for an electron energy of 4.5 MeV and current 0.5 A, and dielectric length of 65 cm, the energy loss during the interaction was 12% for resonator and 3% for waveguide. Calorimeter measurements were found to be in agreement with results from the HF-probes and allow to determine the overall excited wakefield energy corresponds to bunches energy losses.

In cooperation with NSC KIPT Marshall and Hirshfield (Columbia and Yale Univ.,USA) are now consider the possibility of experimental realization rectangular stimulated dielectric wakefield accelerator [29]. It is possible that narrow, femtosecond duration, sheet-like bunches can be created and injected into an optical-scale dielectric-slab accelerator structure, which will allow generation therein of a very strong longitudinal accelerating electric field (~1 GV/m). This dielectric wake field accelerator structure is a vacuum device that will pass a train of 30 sheet bunches having energy ~500 MeV, approximately 10 μ×150 μ in transverse dimensions. The bunches are to be approximately 3.5 fsec in duration (~1 μm), each containing ~1 pC [30].

Femtosecond bunches obtained from a 500 MeV rf linac followed by a LACARA chopper were used to excite the dielectric structure with drive bunches and provide the energy for accelerating test bunches. The LACARA system requires a TW-level $CO_2$ laser, but uses it only for chopping the bunch train, not for acceleration. A schematic of this concept is shown in Fig.8. A solenoidal magnetic field of 1.7 T is used to set up a gyro-resonant interaction between the particles and the laser wave. The laser fields cause the bunch of electrons to spiral around the longitudinal axis, so that the electrons fall onto an annular pattern at the beamstop. The electrons intercepts the top half of the beamstop in one laser period. Thus a small hole in the beamstop will transmit a pulse of charge having duration of a few fsec, repeated every laser period (35.3 fsec) (Fig.9).

It was estimated the quantity of charge in this pulse to be approximately 1 pC, derived from a 1nC macrobunch; approximately thirty microbunches are generated from each macrobunch. A microbunch transmitted through the hole in the beamstop is distorted into a rectangular cross section shape ~35 cm downstream by a quadrupole. This rectangular cross section profile is maintained for several cm of axial travel and determines the location of the dielectric wake field structure. The longitudinal spreading of the fsec bunch due to space charge or finite emittance is not expected to broaden the bunch for a distance of at least 1m from the beamstop.

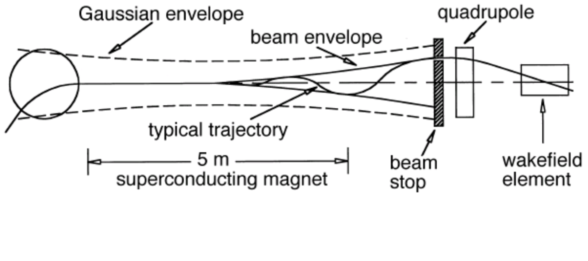


*Fig.8. Schematic of a LACARA-type accelerator used as a chopper for bunches obtained from a 500 MeV rf linac. The magnetic field is 1.7 T, and it uses a 5 TW circularly polarized $CO_2$ laser*

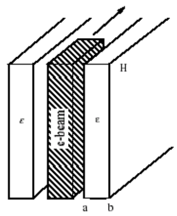


*Fig.9. Schematic of slab bunch within a planar optical dielectric wakefield structure*

A high acceleration field (~1 GeV/m) can be built up in this dielectric structure by superimposing the wake field radiation of several bunches; such a large field in a dielectric structure is thought to be possible [31] because the dielectric is exposed to an intense field for only ~ 0.3 nsec. It is interesting to comment that similar acceleration gradients are expected in a practical plasma acceleration scheme that could achieve GeV energy, yet the method we describe will enjoy the higher efficiency typical of the rf linac as compared with a laser power source.

## 4. FRONTIER RESEARCH ON ADVANCED ACCELERATOR PHYSICS IN ASIA

At present in Asia there is a growing tendency to create the frontier research field and projects studying advanced accelerator physics and technology (the largest number of involved laboratories comparatively to USA and Europe). In this context in 2004 at the satellite meeting of APAC2004, Korea seven countries – Japan, Korea, China, Taiwan, India, Israel, and Ukraine (now Russia is included too) – established the Asian Advanced Accelerator Community (AAAC) [19]. Advanced Accelerator research and development aim at understanding the physics and developing the technologies for producing high-energy and high-quality particle and radiation beams which are required for a wide range of sciences from basic sciences to applied sciences, including nuclear and particle physics, astrophysics, material and biological science, and medical and industrial applications as well. The goal of AAAC is to promote research and development of advanced accelerator physics and technology in Asia and to organize multinational collaboration network through which we develop the advanced accelerator researches that test new acceleration concepts and/or evolve prototype accelerators on the basis of advanced concepts and technologies according to the involving subjects and their developing status. AAAC will provide an active environment for exchanging information and creative ideas, and for efficiently sharing resources and laboratory infrastructure essential for the proposed experiments through the collaboration network so that the researches will make rapid progress. Under cooperation with the worldwide community of the advanced accelerator research, AAAC will contemplate aiding Asian researchers in creating new acceleration and radiation technologies for a wide range of sciences.

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## КИЛЬВАТЕРНЫЕ МЕТОДЫ УСКОРЕНИЯ, ОСНОВАННЫЕ НА МОЩНЫХ ИМПУЛЬСНЫХ ЛАЗЕРАХ И ЭЛЕКТРОННЫХ ПУЧКАХ (ОБЗОР)

***И.Н. Онищенко***

Излагаются физические принципы возбуждения интенсивных кильватерных полей в плазме и других средах мощным коротким лазерным импульсом или последовательностью релятивистских электронных сгустков для высоко-градиентного ускорения заряженных частиц с целью разработки концепции будущих компактных ускорителей для физики высоких энергий и ряда высокотехнологичных приложений, а также для создания современных коротко-импульсных источников излучения. Представлены результаты исследований по лазерному ускорению частиц в вакууме, ускорению электронов в плазме мощным лазерным импульсом и получению пучков с малым угловым и энергетическим разбросом, ускорению электронов плазменными и диэлектрическими кильватерными полями, возбуждаемыми релятивистскими электронными сгустками. Излагается перспективная программа исследований схем лазерного и пучкового ускорения в плазме и диэлектрике.

## КІЛЬВАТЕРНІ МЕТОДИ ПРИСКОРЕННЯ, ОСНОВАНІ НА ПОТУЖНИХ ІМПУЛЬСНИХ ЛАЗЕРАХ І ЕЛЕКТРОННИХ ПУЧКАХ (ОГЛЯД)

***І.М. Онищенко***

Викладені фізичні принципи збудження інтенсивних кільватерних полів у плазмі та інших середовищах потужним коротким лазерним імпульсом або послідовністю релятивістських електронних згустків для високо-градієнтного прискорення заряджених частинок з метою розробки концепції майбутніх компактних прискорювачів для фізики високих енергій і ряду високотехнологічних застосувань, а також для створення сучасних коротко-імпульсних джерел випромінювання. Представлені результати досліджень по лазерному прискоренню часток у вакуумі, прискоренню електронів у плазмі потужним лазерним імпульсом і отриманню пучків з малим кутовим і енергетичним розкидом, прискоренню електронів плазмовими та діелектричними кільватерними полями, збуджуваними релятивістськими електронними згустками. Наводиться перспективна програма досліджень схем лазерного та пучкового прискорення у плазмі і діелектрику.