PLASMA AS A UNIQUE MEDIUM FOR THE PERSPECTIVE HIGH-GRADIENT ACCELERATION OF CHARGED PARTICLES

I.N. ONISHCHENKO

National Scientific Center "Kharkiv Institute of Physics and Technology"
(1, Akademichna Str., Kharkiv 61108, Ukraine; e-mail: onish@kipt.kharkov.ua)

UDC 533.992

The recent results in the worldwide development of advanced methods of acceleration of charged particles, in which plasma plays the unique role as a high-gradient accelerating medium, are presented. The wakefield intensity of about 100 GeV/m excited in plasma by a ultrashort terawatt-petawatt laser pulse or a high-charge relativistic electron bunch has been experimentally achieved. A laser-driven wakefield accelerator of an energy of above 1 GeV at centimeter-lengths and a beam-driven wakefield accelerator doubling the energy of a 42-GeV electron bunch at a meter-length have been demonstrated. Such new facet of plasma as an accelerator structure illuminates prospects of building the colliders in the TeV-energy range with acceptable size and cost for high-energy physics and compact advanced tabletop accelerators based on T^3 lasers for the creation of bright sources of light and γ-ray radiation and applications in nano-material science, chemistry, biology, medicine, and industry.

1. Introduction

Never before have the questions we can ask about the Universe by means of accelerator-based experiments been more compelling. The exploration searching for the origin of matter and the Universe requires producing the highest energy state to investigate the Nature on the smallest scale which involves the fundamental particles and forces. In this research direction, particle accelerators have played the main role of tools as microscopes to study the smallest world of the Nature, of which the size can be seen into nearly one-trillionth micron with the present high-energy frontier colliders producing a center-of-mass energy of 100 GeV. Today we are launching forth into a new energy regime of the order of TeV, in which the profound fundamental questions on the origin of mass, the predominance of matter over antimatter, the existence of supersymmetry, and so on are expected to be answered. High-energy ion accelerators including proton and heavy-ion colliders can reveal the *in situ* synthesis of the nuclear matter by producing quark-gluon plasmas at the quark-hadron phase transition temperature of around 10^{12} K, which is thought as the high-energy density state in 10^{-5} s after the Big Bang of our Universe.

Yet the rate of progress in this field is lagging. It is a truism that the progress in particle physics is paced to a large extent by the progress in accelerators. Center-of-mass interaction energies were increasing steadily by almost a factor of 100 every 25 years. The fact that the pace has now slowed dramatically can be seen in the traditional Livingstone plot [1] that records the evolution of accelerator facilities and the consequent advance of the energy frontier. Construction of the Large Hadron Collider (LHC) is on the finishing stage, and the International Linear Collider (ILC) in the first approach as a 500-GeV linear e^+/e^- collider and later on as a TeV-machine is still in the planning stage. These two devices of tens kilometers in size need efforts of many countries and a big budget. We realize that 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 allow one to accelerate charged particles with electric fields up to 100 MV/m at most, which is the limit stably produced in cavities because of the electrical heating and breakdown of metallic surfaces. A remarkable scaling down of high-energy accelerators will be simply brought about by using much higher accelerating fields than the present limits. By replacing the metallic walls of conventional structures with "plasma-walls", many limitations are avoided and very high gradients can be achieved.

Plasma that plays the important role in thermonuclear researches and many high-tech applications recently has sparkled its new bright facet in high-energy physics. The use of plasma as an electrodynamic medium [2], in which traveling waves of the high amplitude ($E \sim \sqrt{n}$, n is the plasma density) can be excited, allows one to realize the acceleration of charged particles with the acceleration rate of up to hundreds of GeV/m. Restriction of the acceleration rate in the traditional accelerating schemes, caused by the surface electric breakdown, formation of plasma, and electrodynamic structure change, is absent in the considered scheme, since plasma itself is an electrodynamic structure of the accelerator. Additional advantage of the electrodynamic structure using plasma is the phase-radial stability of a beam of accelerated particles that results in the higher current of the beam.

In this context, various novel concepts of charged particle accelerators that utilize super-high fields of lasers and plasmas have been advocated for the past four decades. Tremendous progress in producing the accelerating electric field of the order of 100 GV/m for a pulsed laser driver and 50 GV/m for an electron bunch driver have made.

In the present work, the historical background (Section 1), beam driven plasma wakefield accelerators (Section 2), and laser driven plasma wakefield accelerators (Section 3) are overviewed. The presented results have been obtained in many laboratories of the world, including the Kharkiv Institute of Physics and Technology (Ukraine). In the last section, the perspectives are discussed and some conclusions are made.

2. Historical Background

Historically, the growing scientific interest in the novel acceleration concepts and advanced accelerator technologies has been started at the 2nd Geneva Conference in 1956. In the first suggestion of Ya. Fainberg [2], plasma was used as a medium, in which the high-gradient accelerating field can be achieved due to charge separation. A simple estimation of the maximum value of such a field excited in plasma of density n_p can be obtained using the Poisson equation

$$\mathrm{div} E = -4\pi e \delta n_p. \quad (1)$$

Supposing that plasma electrons and ions are fully separated $\delta n_p \sim n_p$ on the distance of a wavelength $\lambda_p \equiv 2\pi/k_p = 2\pi c/\omega_p$, where $\omega_p = \sqrt{4\pi e^2 n_p/m}$ is the plasma frequency, we find

$$E_{\max}[\mathrm{V/cm}] \approx \sqrt{n_p}[\mathrm{cm}^{-3}], \quad (2)$$

e.g., $E_{\max} \approx 100$ GV/m for $n_p = 10^{18}$ cm^{-3}.

Certainly, the maximum wakefield amplitude $E_{\max}$, corresponding to the wave breaking at the full separation of all negative and positive plasma particle charges achieved without high intensity driver. Only in 1979, J. Dawson *et al.* proposed to use an ultrashort high-power laser impulse as a driver for plasma wakefield excitation [3] and, later on in 1985, a short relativistic electron bunch of a large charge (or a sequence of bunches of the same total charge) [4]. In these two schemes, the ponderomotive force of a driving laser pulse or the space charge of a driving electron bunch displaces plasma electrons. Plasma ions exert a restoring force. Space charge oscillations are excited. Wake phase velocity is equal to the driver velocity (auto-phase matching). The length of a driver (laser pulse/electron bunch) should be less than the plasma wavelength. In this case, the shorter wavelength results in a higher wakefield intensity due to the condition $E_{\max} \sim n_p^{1/2}$.

The advances of high peak power lasers and intense charged-particle beams pushed forward many proof-of-principle experiments of novel laser and plasma accelerator concepts worldwide during the past decade.

At present, ultrashort ($\sim$ femtoseconds) and high power ($\sim$ terawatts) laser pulses of optical wavelengths generated by the so-called T^3-lasers (Terawatt Table-Top lasers) can provide a laser driver. These new optical high-power sources should substitute RF-sources of the Second World War times (magnetrons, klystrons, etc.). The history of the tabletop system development is the following [5]. 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 the 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 Gigawatts to Terawatts – a jump of 3 to 4 orders of magnitude. At present, there are several laboratories with tabletop laser systems of power in the Petawatt range – LLNL (USA), RAL (UK), and JAERI (Japan). By focusing the laser power on a 1-mm spot, the 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 the laser intensity for table-top-size systems at 10^{23} W/cm^2.

In [5], the technical feasibility to build a large scale CPA pumped by a megajoule system of the type of the NIF (National Ignition Facility) in the USA and the LMJ (Laser Megajoule) in France is explored. Power in the zettawatt range (10^{21} W) could be produced, yielding a focused intensity of 10^{28} W/cm^2.

The most intense short relativistic electron bunch was obtained at the Stanford Linear Collider (SLC), which is the highest energy linear accelerator in the

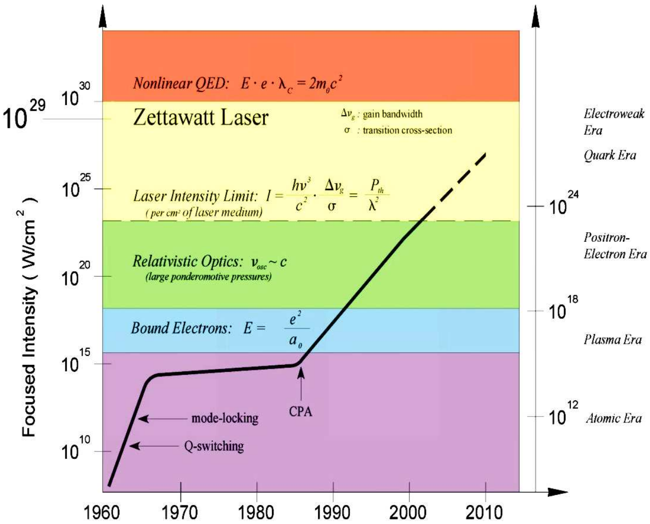

Fig. 1. Laser-focused intensity vs years for table-top systems

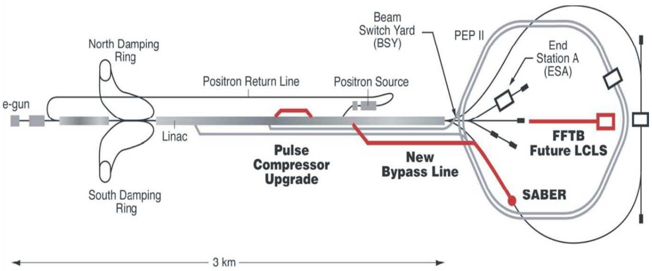

Fig. 2. SLC layout

world, being 2 miles in length and and 50 GeV in energy. Figure 2 shows the scheme of the SLAC (Stanford Linear Accelerator Center) installation including FFTB (Final Facility Test Beam), at which a single bunch of 1.8×10^{10} electrons from SLC 50-GeV Linac was compressed to a length of 12–40 μm by means of the ultra-short bunch facility – Pulse Compressor Upgrade (chicane) [6].

The advanced accelerator research and development result from the interdisciplinary collaboration of science and industries to produce a wide range of applications in nano-, material, bio-, and medical sciences, nuclear and particle physics, and astrophysics. As seen in the diagram of Fig. 3, this perspective field of science is based on the achievements of three relating sciences – Accelerator Science, Plasma Science, and Laser Science. Each of them is solving its own planned problem with large size and enormous budget – TeV collider ILC, thermonuclear reactor ITER, and MJ laser devices NIF and LMJ for inertial fusion, respectively. Owing to new ideas in the novel concepts of the advanced accelerators, the use of the obtained physical results and the created

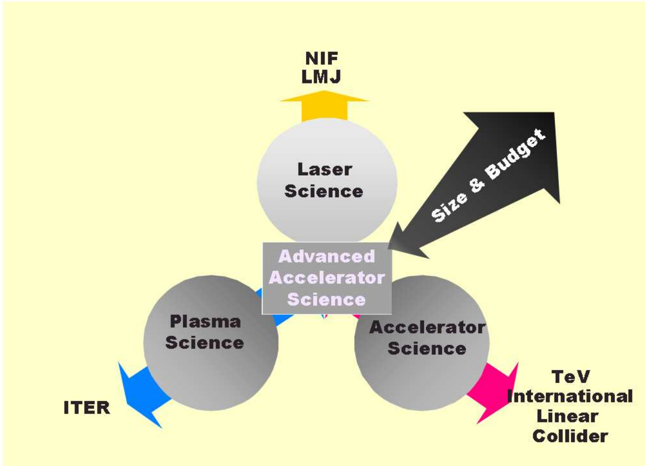

Fig. 3. Diagram of Advanced Accelerator Science disposition

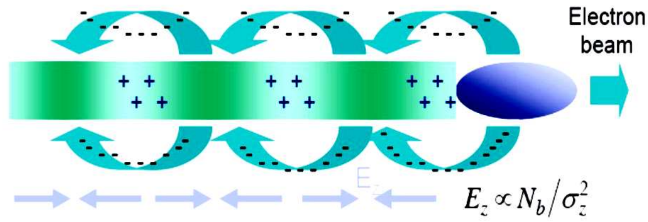

Fig. 4. Plasma Wakefield Accelerator concept

installation inside these three sciences allows one to develop Advanced Accelerator Science which provide high-energy physics with colliders of the future and high technology, biology, and medicine with compact accelerators of essentially smaller size and lower cost.

3. Beam-Driven Wakefield Acceleration

A physical mechanism of the Plasma Wake-Field Accelerator (PWFA) concept proposed in [4] is explained in Fig. 4. The space charge of a driving beam displaces plasma electrons. Plasma ions exert a restoring force. As a result, space charge oscillations (wakefield) are excited.

The wake phase velocity is equal to the bunch velocity (auto-phase matching). At that, for a symmetric bunch transformer ratio $E_{Z,\mathrm{accel}}/E_{Z,\mathrm{decel}} < 2$. The excited longitudinal electric field needed for particle acceleration is proportional to the bunch charge Q_b and the inverse-squared length of a bunch σ_z, i.e. $E_Z \sim Q_b/\sigma_z^2$. In the linear regime, the excited field $E_Z = (n_b/n_p)E_{\max}$, where n_b is the beam density. Simulation has shown that, in the nonlinear and nonstationary regimes, this amplitude is increased by several times.

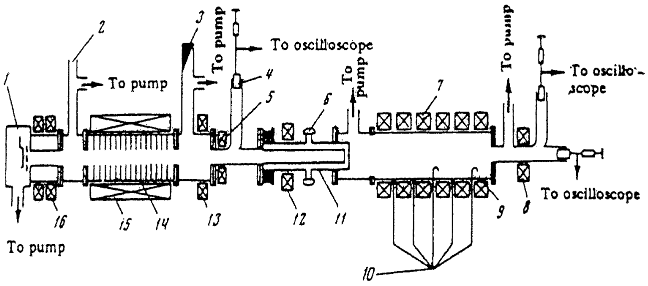

Fig. 5. Block diagram of the apparatus: *1* – electron gun, *2* – vacuum waveguide line, *3* – microwave load, *4* – Faraday cup, *5, 8, 12, 13, 16* – beam correction and focusing systems, *6* – electrodynamic valve, *7, 15* – solenoids, *9* – interaction chamber, *10* – microwave diagnostics elements, *11* – plasma gun, *14* – linac

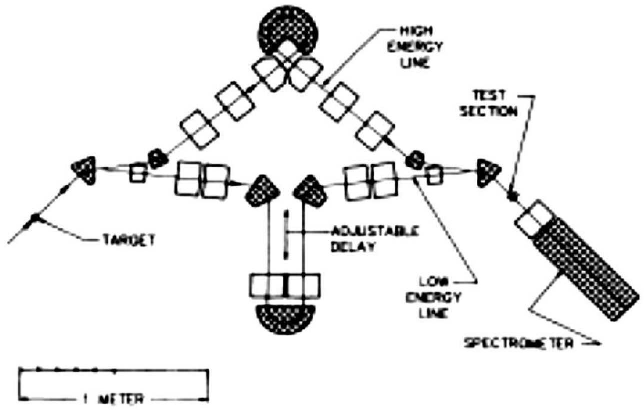

Fig. 6. Schematic of the ANL-AATF layout

Inspired by the ideas stated in [2, 4], the first proof-of-principle experiments have been performed in many laboratories, including KIPT (Ukraine), ANL (USA), KEK (Japan), Novosibirsk INI (Russia). The first experimental realization of the proposal advanced in [2] was performed in KIPT [7–9]. The theoretical consideration of the interaction of a single electron bunch and a train of bunches with linear plasma was carried out in [10]. A single bunch with moderate relativistic electrons is decelerated during the wakefield exciting, spread over energy and phase, trapped into the excited wave, and partially accelerated. The bunch spreading and, accordingly, the deterioration of wakefield excitation coherency, leads to a decrease of the field amplitude. For ultrarelativistic electrons, the wakefield saturates due to a plasma nonlinearity giving a much more (by 3–4 times) wakefield amplitude. It was shown that, for a train of bunches with the total charge equal to the large charge of a single bunch, the excited wakefield amplitude is the same because of the excitation coherency. At that, the bunch repetition frequency should coincides with the plasma frequency. The weak relativism of electrons and the plasma nonlinearity restrict the amount of bunches which are excited coherently. These results grounded experiments that were performed in KIPT. In Fig. 5, the experimental setup is shown.

Table 1

Parameter \ Installation	KIPT, Ukraine, 1971	ANL, USA, 1988	KEK, Japan, 1990
Energy (MeV)	2	21	250(500)
Bunch duration (ps)	57	7	10
Length (mm)	17	2.1	3
Diameter (mm)	10	2.8	2–3
Charge (nC)	0.32	4	5–10
Number of bunches	6×10^3	1	6
Plasma lenght (cm $^{-3}$)	10^{11}	$(4 \div 7)\times10^{10}$	4×10^{11}
Plasma lenght (cm)	100	33	20
Weke field (MV/m)	0.2	5.3	60

A train of 6×10^3 electron bunches (each had 0.32 nC in charge, 1.7 cm in length, and 1 cm in diameter) from a 2-MeV linac was injected into plasma of density 10^{11}cm^{-3}. The plasma frequency was equal to a bunch repetition frequency of 2805 MHz. A wakefield intensity of 0.2 MeV/m was excited. To that moment, it was interpreted as a result of the beam-plasma interaction [8]. Using a train of 20-MeV bunches in plasma of density 5×10^{15}cm^{-3}, the record electric field of 40 MeV/m was achieved [9, 10].

The refined proof-of-principle PWFA-experiment was fulfilled at the Argonne National Laboratory AATF [11]. The configurations of a driver and witness beams are shown in Fig. 6.

The variable time delay of a witness bunch eliminated from the driver bunch at the target was provided by means of the magnetic system like a trombone. It allows measuring the spatial distribution of a wakefield behind the pump bunch (driver) (see Fig. 7). The total driver charge was 2.1 nC, and the plasma parameters $L = 28$ cm and $n_p = 8.6\times10^{12}$cm^{-3}. In this experiment, the 1.6 MeV/m acceleration by an excited wakefield was demonstrated.

Parameters of the installations and results of the first proof-of-principle experiments are presented in Table 1.

In the frame of E-157/162/164/164X/167 University–National Lab Collaborations (SLAC; UCLA – University of California, Los Angeles; USC – University of Southern California) [6, 12–16], the outstanding experimental results were obtained on electrons acceleration with the plasma wakefield excited by an intense relativistic electron bunch, by firstly demonstratiing the breakthrough of a GeV barrier of

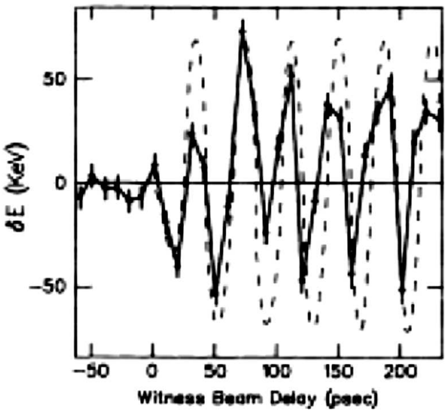

Fig. 7. Witness energy-centroid change δE vs the time delay behind a driver. Theoretical predictions are given by the dashed line

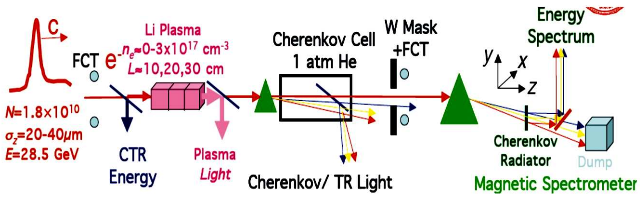

Fig. 8. Schematic of the PWFA experiment at SLAC and the diagnostics

energy gain in advanced accelerators. PWFA experiments were performed at the installation of SLAC (see Fig. 2) at FFTB-facility, and the further experiments will be transferred to the SABER-installation.

The basic idea for experiments at SLAC is to use a single SLC bunch both to excite the plasma wakefield (the head of a bunch) and to witness the resulting acceleration (the tail of a bunch). These experiments have aimed to extend the high-gradient plasma wakefield acceleration from the mm-scale to the m-scale. An accelerating gradient of up to 1 GeV/m was induced in a 1.4-m-long plasma module [13].

The schemes of PWFA experiments and the used diagnostics are presented in Fig. 8. A single bunch of 1.8×10^{10} electrons from a SLAC 50-GeV linac was compressed to a length of 12–40 μm by means of an ultra-short bunch facility (compressor chicane)) aimed to increase the plasma wakefield intensity, by taking the $1/\ \sigma_z^2$ bunch length scaling into account. The neutral lithium vapor (parameters of lithium vapor in a heat-pipe oven − $n_0 = (0.5 \div 3.5)\times 10^{17}$ cm^{-3}, $T = 700 \div 1050$ °C, L=13, 22, 31, 90 cm, $P_{\rm He} \approx 1 \div 40$ Torr) is fully ionized by the large radial electric field of the compressed

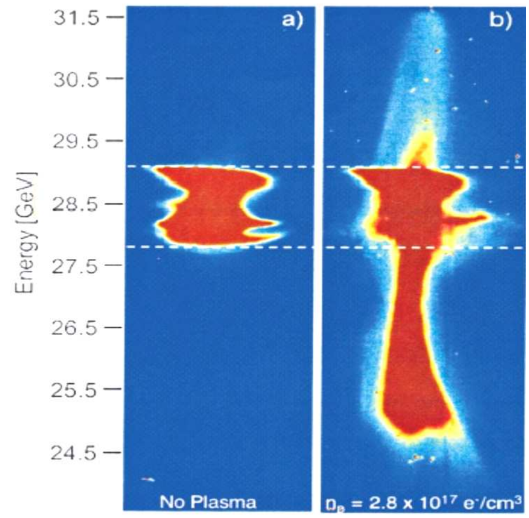

Fig. 9. Single bunch energy spectra downstream from the plasma for (a) the case of no plasma and (b) the 10-cm-long lithium plasma with a density of 2.8×10^{17} 1/cm^3

electron bunches, and the plasma density is then equal to the lithium vapor density.

For the diagnostics of trapped and accelerated particles, the transition radiation and Cherenkov light were used. A Cherenkov cell gives the spectrum of low-energy trapped particles, whereas a magnetic spectrometer gives the spectrum of high-energy trapped particles.

The PWFA scaling with bunch length and plasma length was shown. In Table 2, the theoretical $1/\sigma_z^2$ bunch length scaling is presented. It was confirmed in experiments, by demonstrating an increase of the accelerating electric field for shorter bunch lengths.

In the first PWFA experiment [13] at the 28.5 GeV SLAC FFTB electron beam with a 20-μm rms bunch length, the maximum energy gain of up to 4 GeV was obtained over a 10-cm-long lithium plasma with a density of 2.8×10^{17} 1/cm^3, though the energy spread was 100% (Fig. 9). About of 7% of the bunch particles were accelerated to energies higher than the maximum incoming energy.

This experiment has verified the dramatic increase in the accelerating gradient predicted for short drive

T a b l e 2

$N = 1.8\times10^{14}$	"Long"	"Short"
σ_z (μm)	≈ 730	20–40
n_e (cm^{-3})	1.0×10^{14}	0.7×10^{17}
$E_{\rm acc}$ (GV/m)	≈ 0.1	>10
f (GHz)	90	2400
λ_p (μm)	3333	125

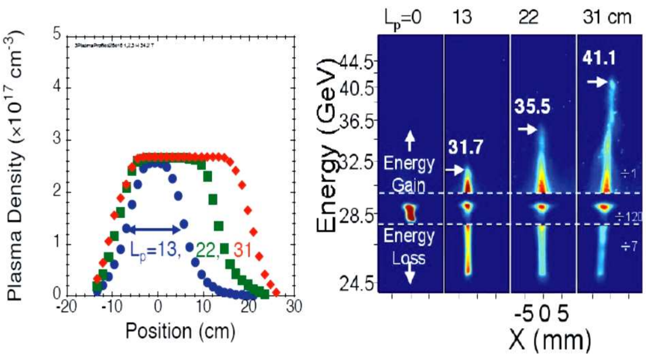

Fig. 10. Longitudinal distribution of the plasma density and bunch energy spectra for three values of the plasma length

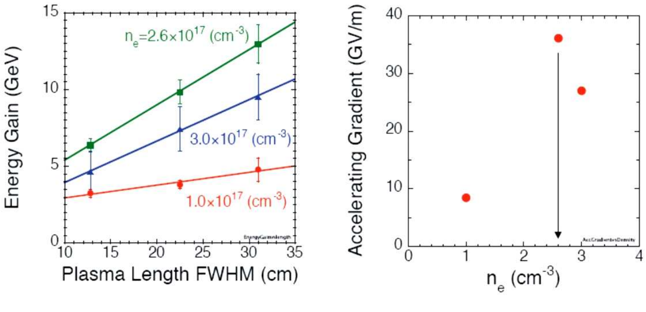

Fig. 11. Energy gain vs the plasma length and the accelerating gradient vs the plasma density for $N_b = 1.8 \times 10^{10}$, $E = 28.5$ GeV, $\sigma_z \approx 20$ μm

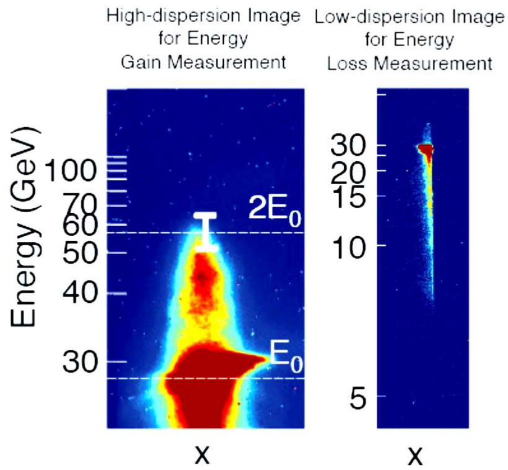

Fig. 12. Energy doubling experiment with a 28.5-GeV electron bunch and a 60-cm-long plasma

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 a much 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.

3.1. Demonstration of energy gain larger than 10 GeV in a plasma wakefield accelerator

In the experiments [14] submitted to EPAC-2006, Scottland, energy gains in excess of 10 GeV, by far the largest in any plasma accelerators, have been measured over a plasma length of 30 cm. PWFA scaling with plasma length was shown. Energy gain increases with plasma length L_p and reaches 13.6 GeV with L_p=31 cm (see Fig. 10), i.e. the same accelerating gradient $\approx$ 40 GV/m as for the case of 4 GeV with L_p=10 cm in the first experiment.

Energy gain grows linearly with plasma length at distances of 10–31 cm. Accelerating gradient of 36 GV/m over L_p=31 cm is achieved for the optimal plasma density n_p=2.6×10^{17}cm^{-3} (see Fig. 11).

3.2. Energy doubling experiments. Plasma "afterburner"

The demonstration of the scaling of the energy gain with plasma length allows applying the beam-driven plasma accelerator to doubling the energy of a future linear collider without doubling its length. The linear dependence of the energy gain on the plasma length is observed for a distance over 30 cm. The energy doubling experiment with a 28.5-GeV bunch ($\sigma_z \approx 20$ μm) was successfully performed using the plasma length $L_p \approx 60$ cm and the plasma density n_p=2.6×10^{17} cm^{-3} [14]. In Fig. 12, the results of gain and loss measurements illustrate the energy doubling by bunch energy spectra.

The higher the energy of an electron bunch, the longer should be the plasma length. The recent PWFA experiments [6, 12, 16] demonstrated that the energy of electrons from a 42-GeV SLAC beam can be doubled if the plasma length L_p is only 85 cm. This milestone is a result of the detailed previous experiments, in which the beam and plasma parameters were varied systematically to maximize the energy gain. In particular, these experiments with various plasma lengths and densities have shown that the acceleration process is stable and reproducible. The observed energy gain increases linearly with the plasma length. With a bunch of 25 μm in length, the plasma density that yields the largest acceleration is $n_p = 2.7\times10^{17}$ cm^{-3}. The average unloaded accelerating gradient is of the order of 40 GV/m.

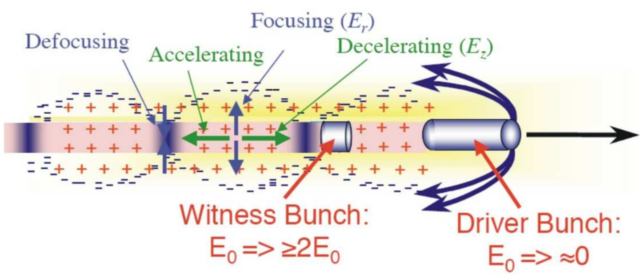

Fig. 13. Scheme of the 2-bunch PWFA

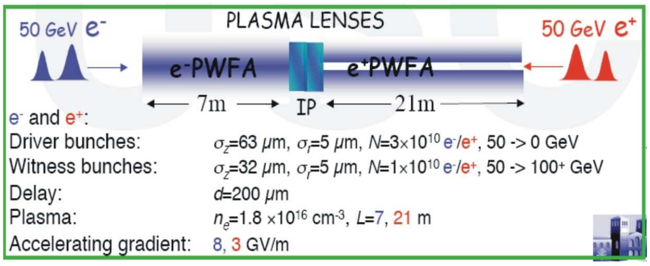

Fig. 14. Layout of a 100-GeV e^-e^+ Collider based on SLAC electron and positron 50-GeV bunches, and a Plasma Afterburner

There are some troubles with the further energy gain increase for a longer plasma length (L_p = 113 cm): the peak energy is lower than that for the 85-cm oven; the beam appears also less focused. The head erosion is supposed to be a reason for the energy gain limitation.

In the future experiments, the attention will be given to possibilities to overcome the head erosion, the evolution of the drive beam emittance, and the pre-ionizition of the plasma. The acceleration of positrons and the development of a two-bunch scheme are very important for future colliders.

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 the plasma density are adjusted accordingly, the measured accelerating gradient in a two-bunch scheme should continue to increase as the drive bunch length is shortened. In Fig. 13, the principle of a 2-bunch plasma accelerator is depicted. Typical 2-bunch PWFA parameters are as follows: $n_p \approx 10^{16}$ cm^{-3}, $f_p \approx 900$ GHz, $\lambda_p \approx 300$ μm; $G \approx 10 \div 20$ GeV/m; $N_W \approx 0.5 \times 10^{10}$ e$^-$, $N_D = 3N_W$; $\sigma_D \approx 60$ μm, $\sigma_W \approx 30$ μm, $\Delta t \approx 150$ μm.

The e$^-$ and e$^+$ beam capabilities of SLAC SABER will provide the unique opportunity for the development of a 1-TeV Linear Collider Plasma Afterburner [17]. The main parameters of the afterburner with asymmetry of electron and positron lines are presented in Fig. 14. The

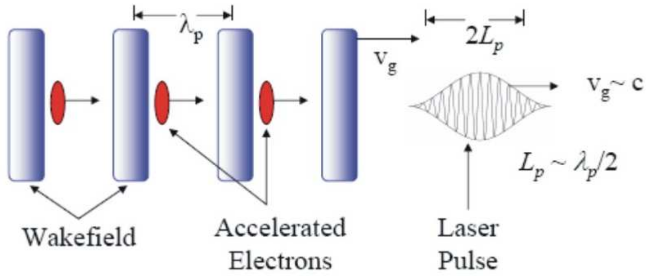

Fig. 15. Laser Wakefield Accelerator concept

peculiarity of the positron side was taken into account [18].

4. Laser-Driven Wakefield Acceleration (LWFA)

Another way to produce a high-intensity plasma wakefield for the acceleration of particles [3] includes the use of a short high-power laser pulse. In this case, the ponderomotive force of a laser pulse expels plasma electrons and excites the wakefield amplitude $E = (v_E^2/c^2)E_{\max}$, where v_E is the oscillatory velocity in the laser electric field.

A laser pulse creates a large-amplitude plasma wave, whose phase velocity is approximately the laser pulse group velocity v_g. Laser pulse length L_p is shorter than the plasma wavelength $\lambda_p = 2\pi c/\omega_p$. The principle of the acceleration of electrons by a laser-driven plasma wakefield is illustrated in Fig. 15. The plasma channel can provide the optical guiding to extend the acceleration length.

Sensational experimental results in the LWFA scenario have been independently obtained in Japan [19], UK [20], France [21], and the USA [22] on the plasma electron trapping and acceleration producing monoenergetic electron beams with a small-angle diversity. These beams are of high quality having a small normalized emittance below 1 πmm mrad and the pulse length of about 10 fs with a charge of the order of 1 nC, which makes them attractive as potential radiation sources for ultrafast time-resolved studies in biology and materials science, as well as an injector for future FELs and linear colliders. The acceleration gradient of above 100 GeV/m and the 300-MeV energy gain on the diffraction length [23] allow one to consider such installations as "table-top" accelerators.

◇ K. Koyama *et al.* (AIST, Japan) [19]. A Ti:sapphire laser: wavelength – 800 nm, power – 2 TW, pulse width – 50 fs, focus diameter – 5 μm, and focus

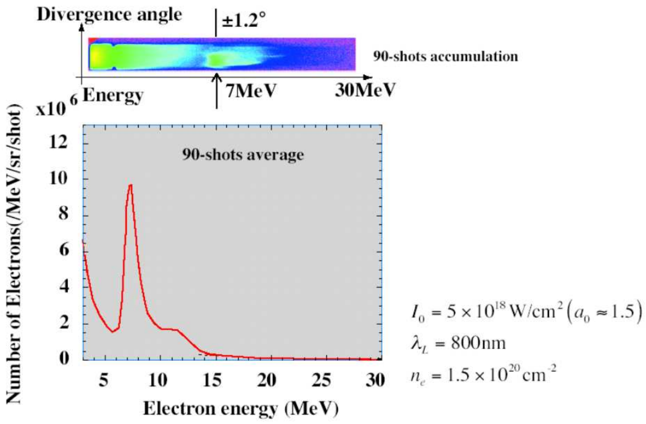

Fig. 16. Spectrum of accelerated electrons in [19]

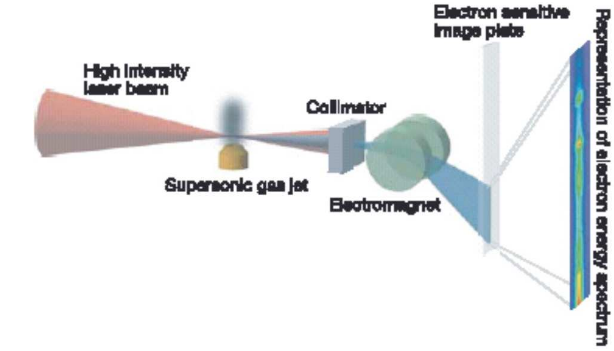

Fig. 17. Scheme of the experimental setup in [20]

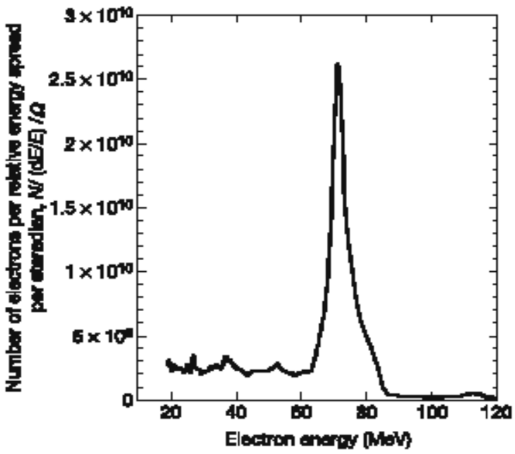

Fig. 18. Measured electron spectrum at a density of 2×10^{19} cm^{-3} in [20]. Laser parameters: E = 500 mJ, τ = 40 fs, $I \approx 2.5\times10^{18}$ Wcm^{-2}

intensity – 1.5×10^{18} Wcm^{-2}. Target: supersonic gas (N_2, He) jet. Plasma density $(0.4\div4.4)\times10^{20}$ cm^{-3}, N_2; $(0.4\div1.3)\times10^{20}$ cm^{-3}, He. The results on electron beam production with an energy of 7 MeV and the divergence angle are shown in Fig. 16.

◇ C.D. Murphy *et al.* (ILC/RAL, UK) [20]. The experiment used a high-power Ti:sapphire laser system at the Rutherford Appleton Laboratory (Astra). The laser pulses (λ=800 nm, τ=40 fs with an energy of approximately 0.5 J on the 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 2.5×10^{18} Wcm^{-2}. The electron density n_p as a function of the 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 the backing pressure within the range n_p=$3\times10^{18}\div5\times10^{19}$ cm^{-3}. Electron spectra are measured using an on-axis magnetic spectrometer. Other diagnostics used the included transverse imaging of the interaction and radiochromic film stacks to measure the divergence and the total number of accelerated electrons. The schematic of the installation is shown in Fig. 17.

The measured energy spectrum of accelerated electrons at a density of 2×10^{19} cm^{-3} with the laser parameters E=500 mJ, τ=40 fs, and $I\approx2.5\times10^{18}$ Wcm^{-2} is shown in Fig. 18.

◇ V.Malka *et al.* (Ecole Polytechnique, France) [21]. Here it was demonstrated that the quality of electron beams can be dramatically enhanced within a length of 3 mm. This new regime was reached by using the ultrashort 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 1J of the laser energy at a central wavelength of 820 nm. It was focused onto the edge of a 3-mm-long supersonic helium gas jet using an f/18 off-axis parabola. The diffraction-limited focal spot had the diameter r_0 = 21 μm at FWHM, producing a vacuum-focused laser intensity of $I = 3.2\times10^{18}$ Wcm^{-2}. For these high laser intensities, the helium gas was fully ionized by the foot of a laser pulse and the ionization did not play a role in the interaction. Higher plasma density was $n_p = 2\times10^{19}$ cm^{-3} (see the experimental configuration in Fig. 19).

Figure 20,*a* shows the picture of an electron beam when no magnetic field is applied. The electron beam is very well collimated, with a 10-mrad divergence; to our knowledge, this is the smallest divergence ever measured for a beam emerging from a plasma accelerator. Figure 20,*b* shows the deviation of a beam when a magnetic field is applied. The image shows a narrow peak around

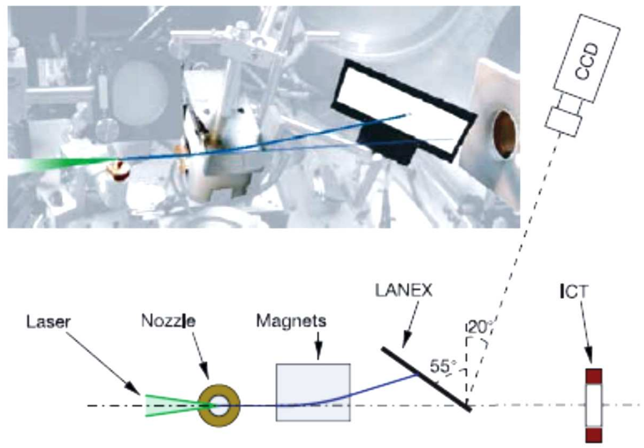

Fig. 19. Experimental set-up. Top, picture of the experiment; bottom, diagram. An ultrashort ultraintense laser pulse is focused onto a 3-mm supersonic gas jet and produces a highly collimated 170-MeV electron beam. LANEX is a phosphor screen; CCD – charge-coupled device camera; ICT – integrating current transformer

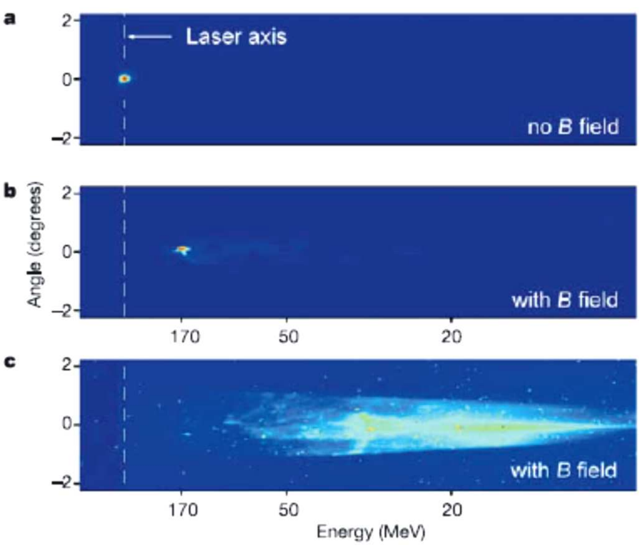

Fig. 20. Raw images obtained on the LANEX screen. The vertical axis represents the beam angular divergence. When a magnetic field is applied, the horizontal axis represents the electron energy. The white vertical dashed line is drawn at the intersection of the laser axis with the LANEX screen

170 MeV, by indicating the efficient monoenergetic acceleration. For comparison, Fig. 20,*c* shows an image obtained at a higher electron density in the plasma ($n_p = 2 \times 10^{19}$ cm^{-3}). Here, electrons are randomly accelerated to all energies, and the number of high-energy electrons is low. In addition, the beam divergence is much larger than that in Fig. 20,*b*.

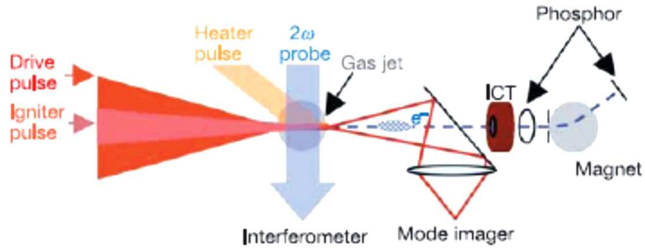

Fig. 21. Technique with the use of a preformed plasma density channel

Finally, the charge contained in this beam can be inferred using an integrating current transformer: the whole beam contains (2 ± 0.5) nC, and the charge at (170 ± 20) MeV is (0.5 ± 0.2) nC. From the above, we can deduce that the electron beam energy was 100 mJ. Thus, the energy conversion from a laser to the electron beam was 10%.

◇ W.P.Leemans *et al.* (LBNL, USA) [22]. In the works mentioned above, however, the acceleration distances (the diffraction/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 the 100% electron energy spread, which limits potential applications. Here, we have 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 (86±1.8) MeV). Bunches with energy up to 150 MeV have been observed on separate shots. The 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 (see Fig. 21).

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. 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 the axis expanded outward, driving a shock wave. This shock resulted in a density depletion on the axis and a nearly parabolic transverse density profile which was tuned by adjusting the timing and energies of the beams.

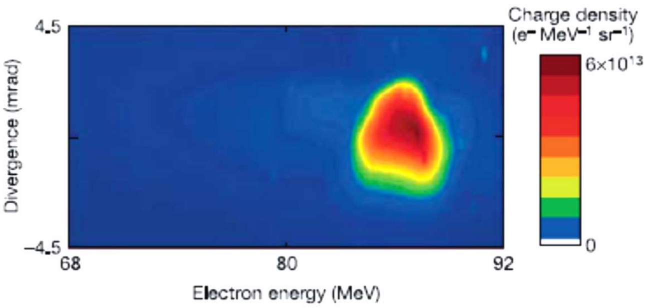

Fig. 22. Single-shot electron beam spectrum and the divergence of a channel-guided accelerator showing a narrow distribution at (86 ± 1.8) MeV and a 3-mrad divergence FWHM

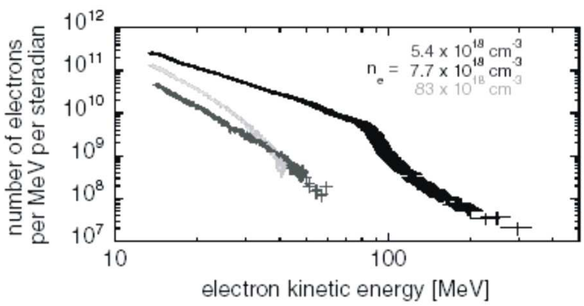

Fig. 23. Three examples of electron energy spectra observed at various background electron densities for the laser intensity $\sim 3 \times 10^{20}$ Wcm $^{-2}$

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 $1.1{\times}10^{19}$ Wcm^{-2}. Propagation of the laser pulse was monitored with a side interferometer (using a 2ω probe laser) and a mode imager CCD. The electron beam accelerated by the plasma wave was analyzed using an integrating current transformer, 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 the mode over many diffraction lengths.

As shown in Fig. 22, the channel-guided accelerator produced high-charge electron beams with small energy spread at high energies, a unique feature that has not been observed in the previous laser plasma acceleration experiments.

Hence, femtosecond bunches have been produced containing $2{\times}10^9$ electrons with geometric and normalized r.m.s. emittances ε_x below 0.05–0.01 πmm mrad and below 1–2 πmm mrad r.m.s., respectively. The peak current is of the order of 10 kA with emittance comparable with the best state-of-art RF facilities.

A high-quality electron bunch is formed when the acceleration length is matched by the plasma density changing to the dephasing length, and when the laser strength is such that the beam loading is sufficiently strong to turn off the 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 to realize a high gradient of the accelerating field of order of 100 GeV/m. The problem is to enlarge the length of the accelerating process and hence the final energy of accelerating particles. The maximal record energy at the laser-plasma acceleration is above 300 MeV [5].

◇ K.Krushelnick *et al.* (Imperial College London, UK) [23]. The experiment was performed using the Vulcan Petawatt Nd:glass laser system which produced pulses of 160 J with the duration τ=650 fs (FWHM). The laser was focused to a 6-μm-diameter spot at the edge of a supersonic helium gas jet of 2 mm in diameter using an f =3 off-axis parabolic mirror. This produces peak intensities in excess of $3{\times}10^{20}$ Wcm^{-2} in vacuum.

Figure 23 shows three electron energy spectra observed at different electron densities which are representative of the trend observed over the range $n_p = 5 \times 10^{18} \div 1.4 \times 10^{20}$ cm^{-3}.

The spectra have large energy spreads typical of laser-plasma interactions, although not all the spectra in this experiment 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_p=$7.7{\times}10^{18}$ 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.

An interpretation of the physical mechanism of trapping the plasma electrons into acceleration (self-injection) is evidently demonstrated in Fig. 24 [24].

In a plasma excited by a laser pulse, the wake potential rises until it steepens and breaks. Electrons from the plasma are caught in the 'whitewater' and surf the wave (Fig. 24,*a*). The load of electrons deforms the wake, by stopping the further trapping of electrons from the plasma (Fig. 24,*b*). As the electrons surf to the bottom of the potential, all they arrive, by bearing a similar amount of energy (Fig. 24,*c*).

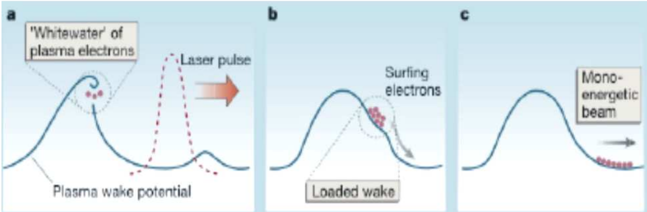

Fig. 24. Physical mechanism of self-injection and monoenergetic beam acceleration in LWFA

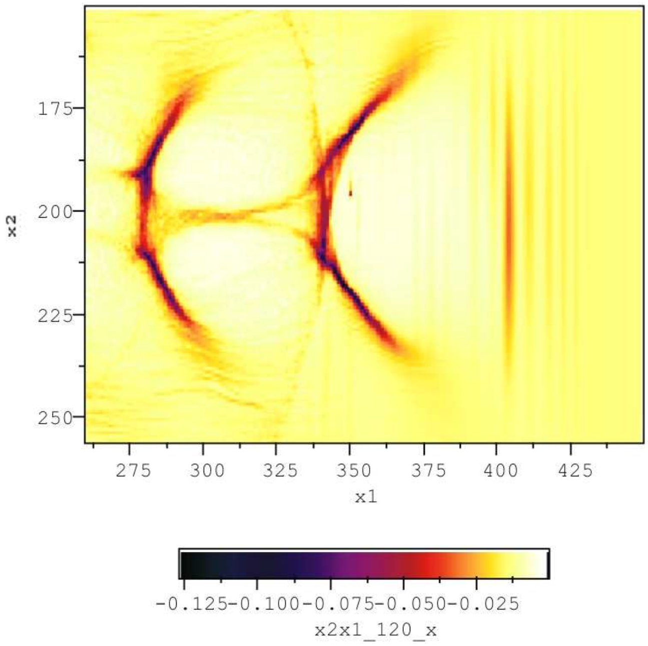

Fig. 25. Transverse wave braking injection [25]

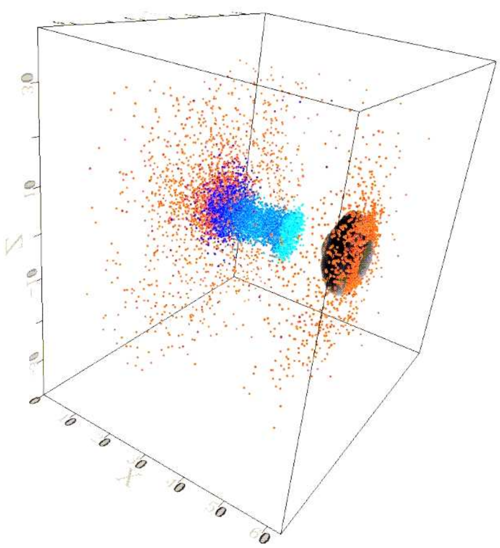

Fig. 26. Bubble acceleration [26]

There are two other physically similar explanations of the processes of trapping and accelerating of plasma electrons resulting in the production of precise monoenergetic electron beams with a small divergence and a short duration, namely, the transverse wave breaking injection (Fig. 25) [25] and the bubble acceleration (Fig. 26) [26].

The latest results on LWFA were reported at the workshop LWFA-2007 [26]. During the last few years, laser-driven plasma accelerators have been shown to generate quasi-monoenergetic electron beams with energies up to several hundred MeV. Extending the output energy of laser-driven plasma accelerators to the GeV range requires the operation at plasma densities by an order of magnitude lower, i.e. 10^{18} cm^{-3}, and increasing the distance over which the acceleration is maintained from a few millimeters to a few tens of millimeters. One approach for achieving this is to guide the driving laser pulse in the plasma channel formed in a gas-filled capillary discharge waveguide. The beam energy was increased from 100 MeV to 1 GeV [28] by using a few-cm-long guiding channel at lower densities driven by a 40-TW laser, which demonstrated the anticipated scaling to higher beam energies. Bunches with the 30-pC charge and the 2.5-% energy spread were observed at 1.0 GeV. Three recent experiments [29] performed at LBNL, RAL, and Max Planck Institute for Quantum Optics demonstrated obtaining quasi-monoenergetic electron beams with energies as high as 1 GeV. In addition, the simultaneous measurements of the electron energy and the energy and the spectrum of the transmitted pump laser radiation were performed, which helps to clarify the mechanisms responsible for electron injection and acceleration.

In [30], the first results of experiments on the self-injection and acceleration of monoenergetic electron beams with multi-100 MeV energy in the highly relativistic regime referred to as the "bubble" regime were reported. Based on these results, a model is presented for the self-injection and acceleration of plasma electrons pre-accelerated in the relativistic laser field, which is capable of describing the production of high-quality beams. The model leads to a scaling law that predicts the laser-plasma conditions required for a design of GeV-to-TeV range laser wakefield accelerators in the ultra-relativistic regime which is produced by petawatt lasers. In this regime, it was prospected for applications to a compact X-ray FEL and high-energy frontier accelerators.

Recent advances in developing a compact radiation source driven by a laser-plasma wakefield accelerator was reported in [28, 31]. It was first demonstrated that 45–75 MeV electron beams from a wakefield accelerator produce radiation in the visible range of the spectrum, and a sub-10-fs brilliant radiation source can be produced when driven by a 1-GeV accelerator. Furthermore, it was presented the evidence that the electron beams produced in a wakefield accelerator have characteristics, which are very competitive with those on conventional accelerators, and show promise for a future driver of free-electron lasers. Other methods of producing hard X-ray pulses using betatron radiation from an accelerating beam in a plasma channel were also discussed.

5. Conclusions

The advanced accelerator physics and its development are oriented to researches on high-gradient particle acceleration driven by a high-energy density laser or particle beams as well as the generation of high-intensity high-quality radiation and particle beams. The outcome of the advanced accelerator research will revolutionize the applications of particle accelerators in a wide range of sciences, not only the future high-energy physics but also materials, bio-, and medical sciences.

In the past decade, the worldwide experiments on laser-plasma particle acceleration have boosted their frontier of particle beam energy and intensity. A trend in experimental results indicates a rapid increase of the energy of electrons accelerated by laser-driven plasma-based installations, whose rate is increased by three to four orders of magnitude for the past decade in coincidence with increase in the laser ponderomotive energy (Fig. 1). The recent laser-driven electron acceleration experiments carried out in several laboratories by using terawatt laser pulses demonstrated obtaining quasi-monoenergetic electron beams with energies up to 1 GeV. According to the scaling law, petawatt lasers can provide a design of TeV-range laser wakefield accelerators.

In the plasma wakefied acceleration driven by an intense electron beam, Joshi *et al.* carried out PWFA experiments using a 50-GeV SLAC FFTB electron beam with 20-μm rms bunch length, where the maximum energy gain of up to 42 GeV was obtained over a 85-cm-long lithium plasma, though the energy spread was 100%.

In Fig. 27, the evolution of the energy increase of conventional and advanced accelerators with time is

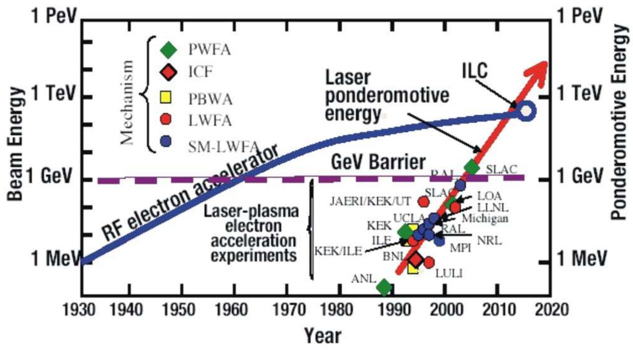

Fig. 27. Evolution of the electron beam energy frontier of RF electron accelerators (solid curve) and the maximum electron energy plots achieved by the worldwide laser and plasma accelerator experiments. The arrow shows the evolution of focused laser intensities represented by the ponderomotive energy which is the particle kinetic energy given by a laser field

shown [32]. It is seen that, to the date of the collider ILC commissioning, the advanced plasma accelerator will achieve the 1-TeV energy.

1. M. Tigner, Physics Today January, 36 (2001).

2. Ya.B. Fainberg, Geneva: CERN **1**, 84 (1956).

3. T. Tajima and J.M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).

4. P. Chen, J.M. Dawson, R. Huff, and T. Katsouleas, Phys. Rev. Lett. **54**, 692 (1985).

5. T. Tajimaa and G. Mourou, Phys. Rev. ST-Accelerators and Beams **5**, 031301-1-5 (2002).

6. R. Ischebeck, in *12th Advanced Accelerator Concepts Workshop:* AIP Conf. Proc., Melville New York **877**, 3 (2006).

7. A.K. Berezin, L.I. Bolotin, A.M. Egorov, V.A. Kiselev, and Ya.B. Fainberg, JETP Lett. **13**, 498 (1971).

8. V.A. Kiselev, A.K. Berezin, I.A. Grishaev *et al.*, JTP Lett. **4**, 732 (1978).

9. A.K. Berezin, V.A. Kiselev, I.N. Onishchenko, and Ya.B. Fainberg, Preprint KIPT Acad. of Sci. UkrSSR, Kharkov, N 89-3 (1989).

10. Ya.B. Fainberg, V.A. Balakirev, I.N. Onishchenko *et al.*, Plasma Phys. Rep. **20**, 674 (1994).

11. J.B. Rosenzweig *et al.*, Phys. Rev. Lett. **61**, 98 (1988).

12. P. Muggli, in *LPAW2007, July 9–13, 2007. Azores, Portugal: Book of Abstracts* (2007).

13. M.J. Hogan, C.D. Barnes, C.E. Clayton,. . . & C. Joshi *et al.*, Phys. Rev. Lett. **95**, 054802-1-4 (2005).

14. P. Muggli, S. Deng, T. Katsouleas *et al.*, in *10-th European Particle Accelerator Conference (EPAC-2006) Edinburgh, Scotland, June 26-30, 2006:* Abstract ID:2433-WEOAPA01.

15. P. Muggli, in *SABER-Workshop 03/16/06* (2006); http://www-conf.slac.stanford.edu/saber/proc/PAPERS/A03.PDF.

16. I. Blumenfeld *et al.*, Nature **445**, 744 (2007).

17. C. Joshi, V Mire Nauki **5**, 17 (2006).

18. T. Katsouleas, E. Oz, X. Wang, P. Muggli *et al.*, in *LPAW2007, July 9–13, 2007. Azores, Portugal: Book of Abstracts* 40 (2007).

19. K. Koyama, E. Miura, S. Kato *et al.*, AIP Conf. Proc. **737**, 528 (2004).

20. S.P.D. Mangles, C.D. Murphy, Z. Najmudin *et al.*, Nature **431**, 535 (2004).

21. J. Faure, Y. Glinec, A. Pukhov, ... & V. Malka *et al.*, Nature **431**, 541 (2004).

22. C.G.R. Geddes, Cs. Toth, J. van Tilborg, . . . & W.P. Leemans *et al.*, Nature **431**, 538 (2004).

23. S.P.D. Mangles, B.R. Walton, M. Tzoufras, . . . & K. Krushelnick *et al.*, Phys. Rev. Lett. **94**, 245001 (2005).

24. N. Kirby, D. Auerbuach, M. Berry *et al.*, in *12th Advanced Accelerator Concepts Workshop:* AIP Conf. Proc., Melville New York **877,** 41 (2006).

25. S.V. Bulanov, F. Pegoraro, A.M. Pukhov *et al.*, Phys. Rev. Lett. **78**, 4205 (1997).

26. A. Pukhov and J. Meyer-ter-Vehn, Appl. Phys. B **74**, 355 (2002).

27. *Laser and Plasma Accelerators Workshop LPAW2007. July 9–13, 2007. Azores, Portugal: Book of Abstracts.*

28. C.G.R. Geddes, O. Albert, E. Esarey, S.A. Gaillard *et al.*, in *LPAW2007, July 9–13, 2007. Azores, Portugal: Book of Abstracts* 5 (2007).

29. S.M. Hooker, E. Brunetti, E. Esarey, J. Gallagher *et al.*, in *LPAW2007, July 9–13, 2007. Azores, Portugal: Book of Abstracts* 19 (2007).

30. K. Nakajima, in *LPAW2007, July 9–13, 2007. Azores, Portugal: Book of Abstracts* 35 (2007).

31. D.A. Jaroszynski, J.G. Gallacher, R.P. Shanks *et al.*, in *LPAW2007, July 9–13, 2007. Azores, Portugal: Book of Abstracts* 7 (2007).

32. K. Nakajima, in *9th Plenary Meeting of the Asian Committee for Future Accelerators, November 2, 2004*, 1 (2004).

ПЛАЗМА ЯК УНІКАЛЬНЕ СЕРЕДОВИЩЕ ДЛЯ ПЕРСПЕКТИВНОГО ВИСОКОГРАДІЄНТНОГО ПРИСКОРЕННЯ ЗАРЯДЖЕНИХ ЧАСТИНОК

І.М. Онищенко

Р е з ю м е

Представлені останні результати розвитку в усьому світі нових методів прискорення заряджених частинок, в яких плазма відіграє унікальну роль високоградієнтної прискорюючої структури. Експериментально досягнута інтенсивність кільватерних полів порядку 100 ГеВ/м, що збуджуються в плазмі надкоротким тераватним–петаватним лазерним імпульсом або релятивістським електронним згустком з великим зарядом. Продемонстровані кільватерний прискорювач з лазерним збудженням на енергію понад 1 ГеВ і кільватерний прискорювач з пучковим збудженням, що подвоює енергію 42 ГеВ електронного згустку на метровій довжині. Така нова грань плазми як прискорюючої структури висвітила перспективу спорудження колайдерів на ТеВ-діапазон енергії з прийнятними розмірами та вартістю для фізики високих енергій і нових компактних настільних прискорювачів, що базуються на T^3-лазерах, для створення яскравих джерел світла і γ-випромінювання та застосувань в наноматеріалознавстві, хімії, біології, медицині та промисловості.