

PROGRESS IN PLASMA WAKEFIELD ACCELERATION DRIVEN BY A SHORT INTENSE BUNCH OF RELATIVISTIC ELECTRONS

I.N. Onishchenko

*NSC "Kharkov Institute of Physics and Technology", Kharkov, Ukraine,
e-mail: onish@kipt.kharkov.ua*

The recent experimental results on frontier values of accelerating gradient and energy gain achieved by advanced acceleration methods based on intense plasma wakefields driven by a high-power short laser pulse or a large charge electron bunch are overviewed. Physical principles are considered for high-gradient acceleration of charged particles with purpose to elaborate the concept of future compact accelerators, which are called for high-energy physics and high technology applications, and also for creation of contemporary short pulsed radiation sources. The results of investigations on laser plasma wakefield accelerator (LWFA) generating precise monoenergetic beams with a small angle divergence and on plasma wakefield accelerator (PWFA) achieving breakdown through GeV barrier energy gain at SLAC by use wakefield excited by a short intense electron bunch in 1 m length plasma are presented. The possibility of PWFA application to doubling the energy of a future linear collider without doubling its length is considered.

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1. INTRODUCTION

In investigation nature on the smallest scale, which is composed of the fundamental particles and forces, high energy particle accelerators play a main role of tools as microscopes. The energies of most interest for high energy physics today have reached the multi-TeV level, on which profound fundamental questions are 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.

As particle accelerators increased their energy frontier at an exponential rate 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. Practical limitations on the size and the cost of linear colliders can only be overcome if the acceleration per unit length is significantly increased. By replacing the metallic walls of conventional structures with "plasma-walls" many limitations are avoided and very high gradients can be achieved. 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 and made tremendous progress in producing the record accelerating electric field and in achieving breakdown through GeV barrier energy gain.

A recent laser-driven plasma wakefield acceleration (LWFA) experiment has measured an accelerating gradient of 100 GeV/m [1-4]. Although plasma-based experiments have shown impressive advances in their accelerating gradients, they are quite short, extending over only a few mm [5]. For the electron bunch driven plasma wakefield acceleration (PWFA) [6,7] it has been recently demonstrated the excitation of accelerating gradients as large as 30 GV/m using the ultra-short, 28.5 GeV electron bunches now available at the Stanford Linear Accelerator Center

(SLAC). As a result, the electrons in the back of the bunch gained about 3 GeV over the 10 cm-long plasma with a density of $2.5 \times 10^{17} \text{ cm}^{-3}$. In recent experiments, 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. Moreover, systematic measurements show the scaling of the energy gain with plasma length and density. These are key steps toward the application of beam-driven plasma accelerators to doubling the energy of a future linear collider without doubling its length.

On the aspects of quantity and quality of accelerated particles and radiations, recent experiments succeeded in demonstrating the remarkable capability for producing bright high quality particle beams and radiations with a simple experimental apparatus on a table top, which the conventional accelerators have been unable to do. These aspects arouse great interest in applications of the advanced accelerator technology to many research fields such as material, chemical, biological, medical and industrial sciences, where a large costly high-energy accelerator can not be used.

This presentation shows the way from the first experiments in NSC KIPT, Argone Lab., and KEK on plasma wakefield acceleration driven by a single electron bunch or a sequence of bunches to the great recent results at SLAC in which 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. Systematic measurements show the scaling of the energy gain with plasma length and density. The experiments are being prepared with plasma length of about one meter. These are the key steps toward the application of beam-driven plasma accelerators to doubling the energy of a future linear collider without doubling its length.

2. MOTIVATION FOR PLASMA ASSISTANCE

Historically the growing scientific interest in the novel acceleration concepts and advanced accelerator technologies have been started at the 2nd Geneva Conference in 1956 in three reports presented by V.Veksler [8], G.Budker [9], and Ya.Fainberg [10]. There the intense fields of space charge (so called "collective fields") were proposed for particle acceleration to high energy at reasonable

length. Simple estimation of the maximum value of such field excited in plasma of density n_p can be obtained using Poisson equation

$$\text{div}E = -4\pi e\delta n_e$$

and supposing that plasma electrons and ions are fully separated $\delta n_e \sim n_p$ on a distance of wavelength $\lambda_p \approx 2\pi/k_p = 2\pi c/\omega_p$

$$E_{max} [V/cm] \approx \sqrt{n_p} [cm^{-3}]$$

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

Later J.Dawson et. al. proposed to use for excitation intense plasma field (so called “wakefield”) short high-power laser pulse [11] (LWFA) or short intense electron bunch [12] (PWFA). In these two schemes ponderomotive force of driving laser pulse or space charge of driving electron bunch displaces plasma electrons. Plasma ions exert restoring force. Space charge oscillations are excited. Wake phase velocity is equal to driver velocity (auto-phase matching). The length of driver (laser pulse/ electron bunch) should be less than plasma wavelength, at that wavelength shorter results higher wakefield intensity due to condition $E_{max} \sim n_p^{1/2}$. According to Wilson theorem the transformer ratio $k = E_{z, accel}/E_{z, decel} < 2$ for symmetric bunch.

3. PROGRESS IN NEW TRENDS OF PARTICLES ACCELERATION

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. A recent laser electron acceleration experiment carried out by using 160 J, 650 fs ($\sim 250 \text{ TW}$) 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 $3 \times 10^{20} \text{ W/cm}^2$.

In the plasma wakefield acceleration driven by the intense electron beam, Joshi et al. carried out PWFA experiments at the 30 GeV SLAC FFTB electron beam with 12μ 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.

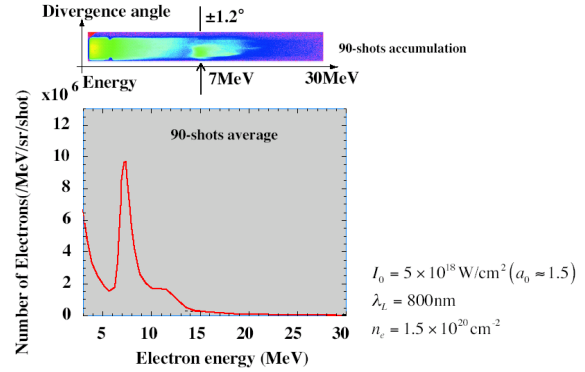
3.1 LASER WAKEFIELD ACCELERATION (LWFA)

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 π mm mrad and about 10 femtosecods pulse length with a charge of the order of 1 nC, making them attractive as po-

tential 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) [1]. Ti:sapphire laser: wavelength-800 nm, power-2 TW, pulse width-50 fs, focus diameter-5 μ , focus intensity- $1.5 \times 10^{18} \text{ Wcm}^{-2}$. Target: supersonic gas (N₂, He) jet. Plasma density (0.4... $4.4) \times 10^{20} \text{ cm}^{-3}$, N₂; (0.4-1.3) $\times 10^{20} \text{ cm}^{-3}$, He.

Results on electron beam production with energy 7MeV and divergence angle are shown in Fig. 1.



Normalized emittance $\epsilon_n = \gamma\sigma\delta\theta \approx 0.7\pi \text{ mm mrad}$

Fig. 1. Spectrum of accelerated electrons in [1]

◆ C.D.Murphy et al. (ILC/RAL, UK) [2]. The experiment used the high-power Ti:sapphire laser system at the Rutherford Appleton Laboratory (Astra). The laser pulses ($\lambda=800 \text{ nm}$, $\tau=40 \text{ fs}$ 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 $2.5 \times 10^{18} \text{ Wcm}^{-2}$. 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 $n_e=3 \times 10^{18} \text{ cm}^{-3} - 5 \times 10^{19} \text{ cm}^{-3}$. 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. 2.

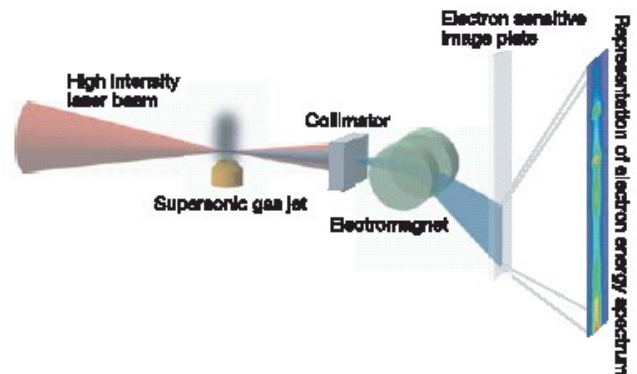


Fig. 2. Scheme of experimental setup in [2]

Measured energy spectrum of accelerated electrons is shown in Fig. 3.

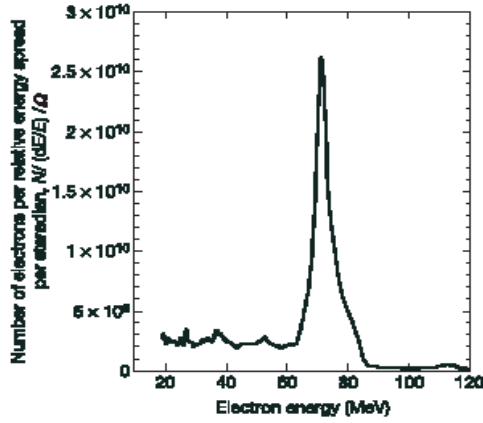


Fig.3. Measured electron spectrum at a density of $2 \times 10^{19} \text{ cm}^{-3}$ in [2]. Laser parameters: $E=500 \text{ mJ}$, $\tau=40 \text{ fs}$, $I \approx 2.5 \times 10^{18} \text{ Wcm}^{-2}$

◆ V.Malka et al. (Ecole Polytechnique, France) [3]. 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 $0.5 \pm 0.2 \text{ nC}$ of charge at $170 \pm 20 \text{ MeV}$. From the above, it can be 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 $33 \pm 2 \text{ fs}$ 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 $r_0=21 \mu\text{m}$ at FWHM, producing a vacuum-focused laser intensity of $I=3.2 \times 10^{18} \text{ Wcm}^{-2}$. 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. High-plasma density was $n_e=2 \times 10^{19} \text{ cm}^{-3}$.

◆ W.P.Leemans et al. (LBNL, USA) [4]. 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 $80 \pm 1.8 \text{ MeV}$). Bunches with energy up to 150 MeV have been observed on separate shots. Applied technique involves the use of a pre-formed 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 $4.5 \times 10^{19} \text{ cm}^{-3}$. 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 $8.5 \mu\text{m}$ FWHM spot by an $f/4$ off-axis parabola giving an intensity of $1.1 \times 10^{19} \text{ Wcm}^{-2}$. Propagation of the laser was monitored with a side interferometer (using a 2ω probe laser) and 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 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 realizing a 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 [5].

◆ K.Krushelnick et al. (Imperial College London, UK) [5]. The experiment was performed using the Vulcan Petawatt Nd:glass laser system, which produced pulses of 160 J in a duration of $\tau=650 \text{ fs}$ (FWHM). The laser was focused to a $6 \mu\text{m}$ 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 $3 \times 10^{20} \text{ Wcm}^{-2}$ in vacuum.

The spectrum recorded at $n_p=7.7 \times 10^{18} \text{ cm}^{-3}$ 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.

There are two explanations of the processes of trapping and accelerating of plasma electrons resulting in production of precise monoenergetic electron beams with a small divergence and a short duration - transverse wave breaking injection [13] and bubble acceleration [14].

3.2 BEAM PLASMA WAKEFIELD ACCELERATION (PWFA)

Inspired by the ideas stated in [8-12] the first proof-of-principle experiments have been performed in many laboratories (see Table), including KIPT (Ukraine), ANL (USA), KEK (Japan), Novosibirsk INI (Russia).

Parameters and results of the first proof-of-principle experiments

	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	$6 \cdot 10^3$	1	6
Plasma density, cm^{-3}	10^{11}	$4 \cdot 7 \cdot 10^{10}$	$4 \cdot 10^{11}$
Plasma length, cm	100	33	20
Wake field, MV/m	0.2	5.3	60

Experiments at SLAC on advanced acceleration methods aim at demonstrating high gradient acceleration in a 1 m long plasma cell. Plasma modules of this length would be well suited for building a future linear collider. The intended use of the existing SLAC linac for the proposed experiment limits the achievable gradient to about 1 GeV/m. Though not as high as achieved by other plasma-based experiments, this gradient is much larger than in any metallic structure. The basic idea for these experiments is to use a single SLC bunch to both excite the plasma wakefield (head of the bunch) and to witness the resulting acceleration (tail of the bunch).

The E-157 experiment at SLAC has aimed to extend 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. The experiment measures deceleration, acceleration and transverse focusing of the high power SLAC linac electron beam.

The E-162 experiment at SLAC was a continuation of the E-157 experiment. It aimed to extend high-gradient plasma wakefield acceleration from the mm-scale to the m-scale and to expand measurements on positron beam.

E157/E162 experiments have successfully observed many of the predicted phenomena: multiple betatron oscillations of the beam as the plasma density is increased; propagation of a matched beam through the plasma; sloshing of the tilted beam and the electron hosing instability in an ion column; dynamic focusing of the beam; X-ray emission due to betatron motion in the ion column; focusing of a positron beam; acceleration and deceleration of the drive beam.

The E-164 experiment at SLAC on high gradient plasma-wakefield acceleration using ultrashort electron bunch with number of electrons N_b (shortening of electron bunch length from $\sigma_z = 0.6$ mm (E157/E162) to 100 μ (E164) by means of ultra-short bunch facility (USBF)) aimed increase the intensity of plasma wakefield 36 times taking into account the $1/\sigma_z^2$ bunch length scaling of the accelerating gradient accordingly to the dependence

$$E_{\text{linear}} = 240 \text{ MV/m} \cdot [N_b/4 \times 10^{10}] \cdot [0.6/\sigma_z(\text{mm})]^2$$

The physical scheme of PWFA is presented in Figure 4. In a plasma wake field accelerator, the space charge of a particle bunch displaces the electrons of a preformed quiescent

plasma to produce a large plasma wake field that can accelerate a subsequent bunch at a very high rate.

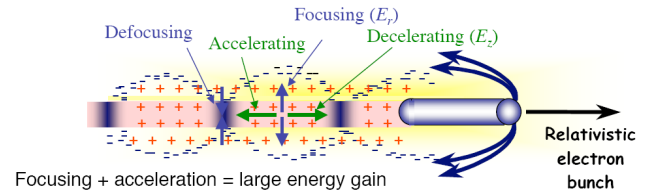


Fig. 4. Physical mechanism of the PWFA

Simulation of nonlinear wakefield excitation shows essential enhancement of the peak accelerating gradient (Fig. 5).

$$E_{\text{peak}} \approx 3-4 E_{\text{linear}}$$

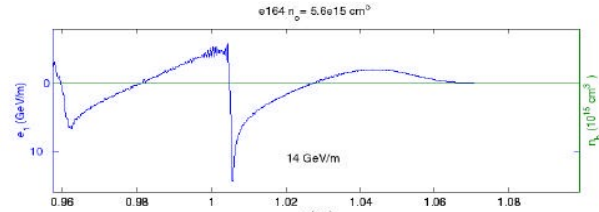


Fig. 5. 2D simulation results from OSIRIS code of a 100 μ bunch containing 2×10^{10} electrons propagating through a $5.6 \times 10^{15} \text{ cm}^{-3}$ plasma. The peak accelerating gradient is 14 GeV/m

In Fig. 6 the results of simulation of energy loss of the bunch head and energy gain of the bunch tail is presented for the parameters of E-164 experiment with 100 μ length bunch. It is seen maximum energy gain 4.4 GeV over 30cm long plasma.

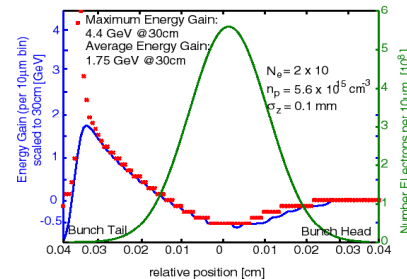


Fig. 6. Energy loss and gain of bunch electrons from head to tail of the 100 μ length bunch

The latest new result at SLAC [6,7] 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 colliders, including planned ILC, before 2020 year.

The experiment described in [6-7] uses an ultrarelativistic electron bunch to create plasma in lithium vapor and to 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 1.8×10^{10} electrons from the Stanford Linear Accelerator Center linac was compressed to the length of 12μ (rms). There are no techniques available to time resolve the spectrum of 12μ (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 $2.8 \times 10^{17} \text{ atoms/cm}^3$).

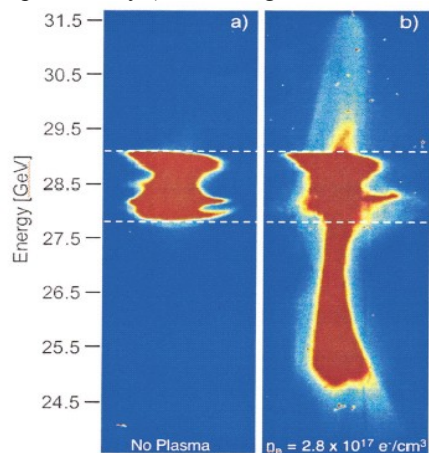


Fig. 7. Single bunch energy spectra downstream from the plasma for (a) the case of no plasma and (b) a 10 cm long $2.8 \times 10^{17} \text{ e/cm}^3$ lithium plasma

In the recent experiments [7], submitted to EPAC-2006, 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 . Demonstration the scaling of the energy gain with plasma length allows applying beam-driven plasma accelerator to doubling the energy of future linear collider without doubling its length.

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 two-bunch scheme should continue to increase as the drive bunch length is shortened.

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 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.

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ПРОГРЕСС В УСКОРЕНИИ ПЛАЗМЕННЫМИ КИЛЬВАТЕРНЫМИ ПОЛЯМИ, ВОЗБУЖДАЕМЫМИ КОРОТКИМ ИНТЕНСИВНЫМ СГУСТКОМ РЕЛЯТИВИСТСКИХ ЭЛЕКТРОНОВ

И.Н. Онищенко

Представлены последние экспериментальные результаты по получению высоких ускоряющих градиентов и достигнутых максимальных энергий в новых методах ускорения, основанных на интенсивных кильватерных полях, возбуждаемых в плазме мощным коротким лазерным импульсом или электронным сгустком с большим зарядом.

ПРОГРЕС В ПРИСКОРЕННІ ПЛАЗМОВИМИ КІЛЬВАТЕРНИМИ ПОЛЯМИ, ЗБУДЖЕНИМИ КОРОТКИМ ІНТЕНСИВНИМ СГУСТКОМ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОНІВ

І.М. Онищенко

Представлені останні експериментальні результати по отриманню високих прискорюючих градієнтів і досягнутих максимальних енергій в нових методах прискорення, заснованих на інтенсивних кильватерних полях, збуджених у плазмі потужним коротким лазерним імпульсом або електронним згустком з великим зарядом.