SUCCESSES IN DEVELOPMENT OF ADVANCED ACCELERATION METHODS (OVERVIEW)

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The most recent results on laser and plasma accelerators are presented and discussed, along with the future developments and their impact on table-top accelerators and related applications, as well as the impact of particle acceleration using plasmas in the quest for the energy frontier. Ultra intense laser and particle beams are pushing particle acceleration using plasmas to regimes unconceivable just a few years ago: 1 GeV monoenergetic electron beams from a laser-plasma accelerator, energy doubling of the 42 GeV SLAC beam, controlled injection of monoenergetic relativistic electron beams, and quasi-monoenergetic MeV ion beams are just some of the groundbreaking experimental results in 2006. In the next couple of years, more exciting developments in laser and plasma accelerators are to be expected. New PW-range laser systems and R&D programs in this field are spreading all over the world, and large-scale numerical simulations are providing information with unprecedented details.

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1. INTRODUCTION

Never before have the questions we can ask about the universe by means of accelerator-based experiments been more compelling. Yet the rate of progress in this field is lagging. It is a truism that progress in particle physics is paced in large measure by progress in accelerators. Center-of-mass interaction energies were increasing steadily by almost a factor of 100 every 25 years. That the pace has now slowed dramatically can be seen in Fig.1 [1], the traditional Livingstone plot 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 International Linear Collider (ILC) in the first approach as a 500-GeV linear e^+e^- collider (LC500) is still in the planning stage.

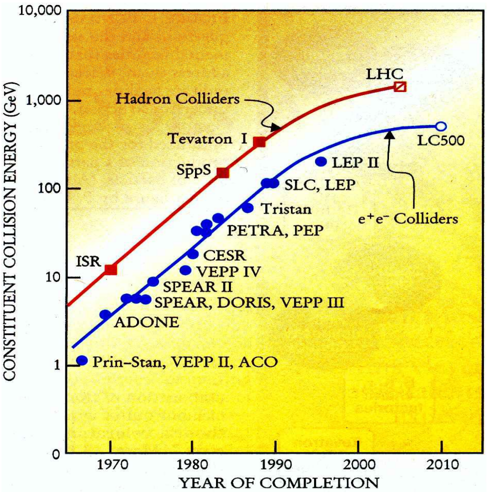


Fig.1. Effective constituent collision energy of hadron colliders (top curve) and electron-positron colliders (bottom curve), plotted against completion date

Present high-energy accelerators become too large and costly, and possibly they approach the end of the road. A remarkable scaling down of high-energy accelerators will be simply brought about by using much higher accelerating fields than the present limits not exceed 100 kV/cm for metallic accelerating structures. 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. 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 accelerating electric field of the order of 100 GeV/m for pulsed laser driver, and 50 Gev/m for electron bunch driver.

Since my previous overviews [2-4] of the new methods of charged particles acceleration based on wakefield excitation many appreciable successes have been achieved and reported at Laser and Plasma Accelerators Workshop 2007 (LPAW2007) [5]. In 2006 ultra intense laser and particle beams are pushing particle acceleration using plasmas to regimes unconceivable just a few years ago: 1 GeV monoenergetic electron beams from a laser-plasma accelerator, energy doubling of the 42 GeV SLAC beam, controlled injection of monoenergetic relativistic electron beams, and quasi-monoenergetic MeV ion beams. At LPAW2007 these prominent results were completed with new more exhaustive investigations, including: Experiments at SLAC on energy gains in excess of 42 GeV over a plasma length of 85 cm [6]; Laser wakefield experiments and simulations at the LOASIS laboratory of LBNL to produce and investigate electron bunches with low energy spread and divergence at energy of 1 GeV and acceleration gradients on the order of 100 GV/m, and to use these beams to generate intense THZ radiation [7]; results of three recent experiments – performed at Lawrence Berkeley National Laboratory, Rutherford Appleton Laboratory, and Max Planck Institute for Quantum Optics – in which using plasma channel formed in a gas-filled capillary discharge waveguide quasi-monoenergetic electron beams were generated with energies above 1 GeV [8]; model that 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 [9]; scheme to use an intense electron beam in a plasma to create a second witness beam and convert that beam into a precise positron beam load on an electron wake [10]; the first demonstration of undulator radiation in the visible range of the spectrum from 45…75 MeV electron beams from a wakefield accelerator and showing that, when driven by a 1 GeV accelerator, a sub-

10fs brilliant radiation source can be produced [11]; Cu, Al and Au targets were used for Target-Normal-Sheath-Acceleration of protons and heavy ions. Proton energies up to 30 MeV were measured [12].

2. PLASMA WAKEFIELD ACCELERATOR DRIVEN BY E-BUNCH (PWFA)

In proposal [13] plasma was used as a medium, in which due to charge separation high-gradient accelerating field E_{max} {MV/m}$\approx\sqrt{n_p}$ {cm^{-3}} (n_p is plasma density) can be achieved. Certainly, maximum wakefield amplitude E_{max}, corresponding to wave breaking at full separation of all negative and positive plasma particle charges on a distance of plasma wavelength, can not be achieved without high intensity driver.

In [14] the short (less than plasma wavelength) relativistic electron bunch with a large charge (or a sequence of bunches with the same total charge) was proposed to use as a driver for plasma wakefield excitation. In Fig.2 physical mechanism of the Plasma Wakefield Accelerator (PWFA) is explained. Space charge of driving beam displaces plasma electrons. Plasma ions exert restoring force. In result space charge oscillations (wakefield) are excited. Wake phase velocity is equal to bunch velocity (auto-phase matching). At that for symmetric bunch transformer ratio $E_{z,\ accel}/E_{z,\ decel} < 2$. Excited longitudinal electric field needed for particle acceleration is proportional to bunch charge Q_b and inverse-square-law of bunch length σ_z, i.e. $E \sim Q_b/\sigma_z^2$. In linear regime excited field $E=(n_b/n_p)E_{max}$, where n_b is beam density. In nonlinear and nonstationary regime this amplitude is increased to several times more value.

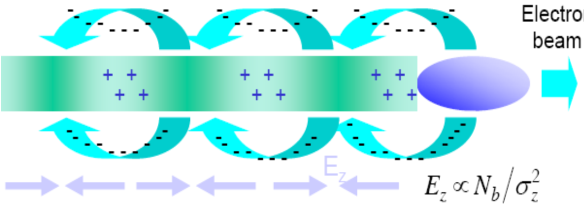


Fig.2. Plasma Wakefield Accelerator concept

The first experimental realization of proposal [13] was performed in KIPT [15-17]. In Fig.3 the experimental setup is shown.

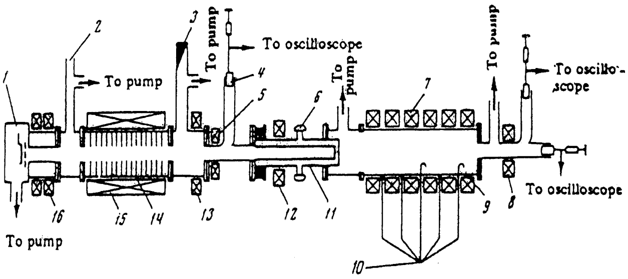


Fig.3. Block diagram of the apparatus:
1 - electron gun; 2 - vacuum waveguide line; 3 - microwave load; 4 - Faraday cylinder;5,8,12,13,16 - beam correction and focusing systems;6 - electrodynamic valve; 7,15 – solenoids; 9 - interaction chamber; 10 - microwave diagnostics elements;11 - plasma gun; 14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

A train of $6 \cdot 10^3$ electron bunches (each of 0,32 nC charge, 1.7 cm length, and 1 cm diameter) from 2 MeV linac was injected into plasma of density 10^{11} cm^{-3}. Plasma frequency was equal to bunch repetition frequency 2805 MHz. Wakefield intensity 0.2 MeV/m was excited. To that moment it was interpreted as a result of the beam-plasma interaction [15]. Using a train of 20 MeV bunches in plasma of density $5 \cdot 10^{15}$ cm^{-3} the record electric field 40 MeV/m was achieved [16, 17].

Refined proof-of-principle PWFA-experiment was fulfilled at Argonne National Laboratory AATF [18]. Driver and witness beams configuration is shown in Fig.4.

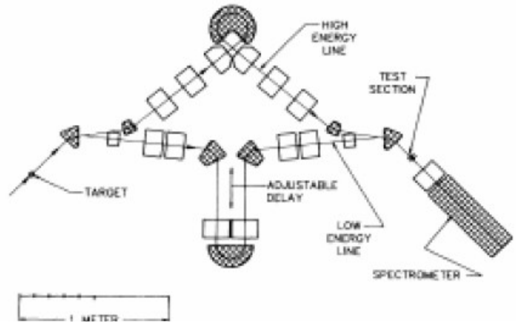


Fig.4. Schematic of ANL-AATF layout

The variable time delay of the witness bunch eliminated from the main bunch at the target was provided by means of magnetic system like a trombone. It allows measuring spatial distribution of the wakefield behind the pump bunch (driver) (see Fig.5). Total driver charge 2.1 nC, plasma parameters L=28cm and $n_p = 8.6 \cdot 10^{12}$ cm^{-3}. In this experiment 1.6 MeV/m acceleration by excited wakefield was demonstrated.

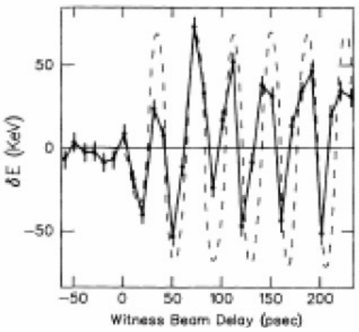


Fig.5. Witness energy-centroid change δE vs time delay behind driver. Theoretical predictions are given by the dashed line

In the frame of E-157/162/164/164X/167 University–National Lab Collaborations (SLAC – Stanford Linear accelerator Center, UCLA – University of California, Los Angeles, USC – University of Southern California) [6,19-22] outstanding experimental results were obtained on electrons acceleration with plasma wakefield excited by intense relativistic electron bunch, firstly demonstratiing the breakthrough of a GeV barrier of energy gain in advanced accelerators. In Fig.6 scheme of SLC installation is shown including FFTB (Final Facility Test Beam) where PWFA experiments were performed and now transferred to SABER.

The basic idea for experiments at SLAC 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). These experiments have 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 [19].

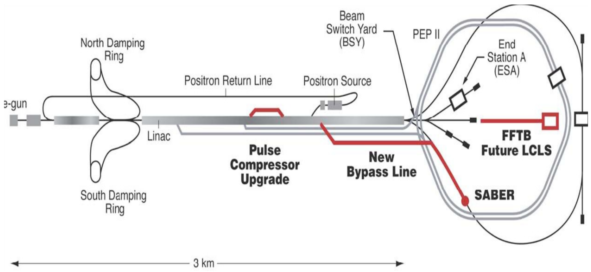


Fig.6. SLAC layout

The scheme of PWFA experiments and used diagnostics are presented in Fig.7. A single bunch of 1.8×10^{10} electrons from SLAC 50 GeV linac was compressed to the length of 12…40 mμ by means of ultra-short bunch facility (compressor chicane)) aimed increase the intensity of plasma wakefield taking into account the $1/\sigma_z^2$ bunch length scaling. The neutral lithium vapor (parameters of vapor in a heat-pipe oven – $n_0=(0.5…3.5)\times10^{17}$ cm^{-3}, T=700…1050°C, L=13,22,31,90 cm, $P_{He}\approx1…40$ Torr) 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.

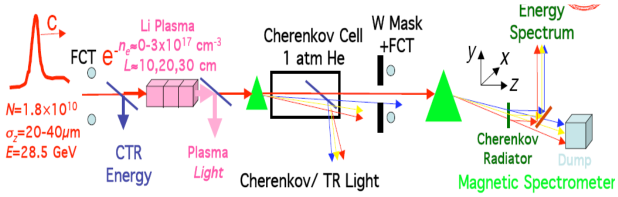


Fig.7. Schematic of PWFA experiment at SLAC and diagnostics

For diagnostics of trapped and accelerated particles transition radiation (TR) and Cherenkov light was used. Cherenkov cell gives low energy trapped particles spectrum. Magnetic spectrometer gives high energy trapped particles spectrum.

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

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

In the first PWFA experiment [19] at the 28.5 GeV SLAC FFTB electron beam with 20mμ rms bunch length the maximum energy gain of up to 4 GeV was obtained over a 10 cm long 2.8×10^{17} atoms/cm^3 lithium plasma, though the energy spread was 100% (Fig.8). About of 7% of the bunch particles accelerated to energies higher than the maximum incoming energy.

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.

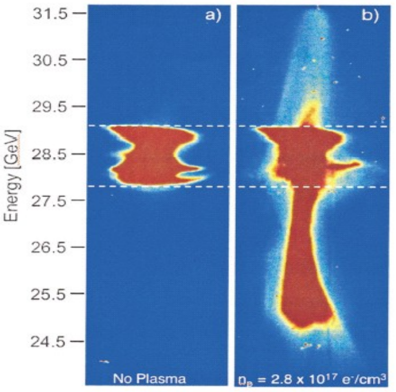


Fig.8. Single bunch energy spectra downstream from the plasma for (a) the case of no plasma and (b) a 10 cm long 2.8×10^{17} e/cm^3 lithium plasma

2.1. DEMONSTRATION OF ENERGY GAIN LARGER THAN 10GEV IN A PLASMA WAKEFIELD ACCELERATOR

In the experiments [20], submitted to EPAC-2006, Scotland, 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 (Lp) and reaches 13.6 GeV with Lp=31 cm (see Fig.9), i.e. the same accelerating gradient ≈40 GV/m as for 4 GeV with Lp=10 cm in the first experiment.

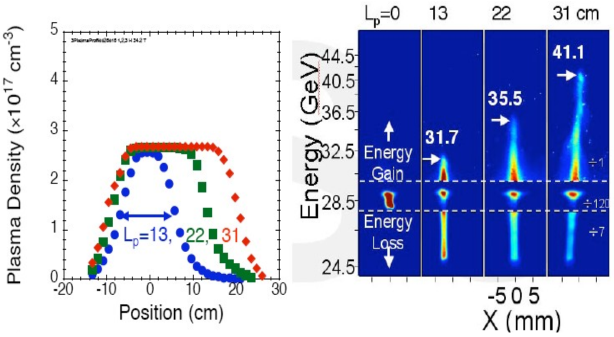


Fig.9. Longitudinal distribution of plasma density and bunch energy spectra for three values of plasma length

Energy gain grows linearly with plasma length at distance 10…31 cm. Accelerating gradient of 36 GV/m over Lp=31 cm is achieved for plasma density $n_p=2.6\times10^{17}$cm^{-3} (see Fig.10).

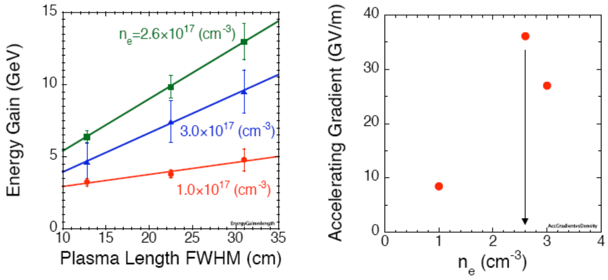


Fig.10. Energy gain vs plasma length and accelerating gradient vs plasma density for $N_b=1.8\times10^{10}$, $E=28.5$ GeV, $\sigma_z\approx20\ \mu m$

2.2. ENERGY DOUBLING EXPERIMENTS. PLASMA "AFTERBURNER"

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.

Linear dependence of energy gain upon plasma length is observed for a distance over 30 cm. Energy doubling experiment with 28.5 GeV $\sigma_z\approx20\ \mu m$ bunch was successfully performed using plasma length Lp≈60 cm and plasma density $n_p=2.6\times10^{17}$ cm^{-3} [20]. In Fig.11 gain and loss measurements judging by bunch energy spectra that illustrates energy doubling.

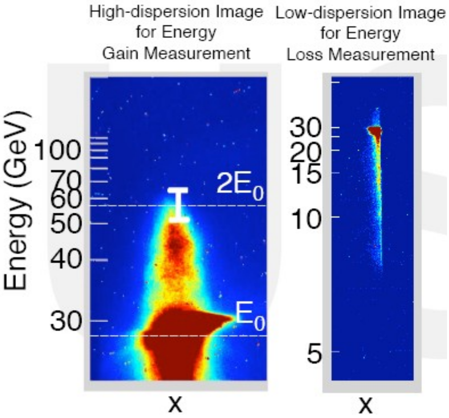


Fig.11. Energy doubling experiment with 28.5 GeV electron bunch and 60 cm long plasma

For higher energy of electron bunch plasma length should be longer. Recent PWFA experiments [6, 22, 23] demonstrated the energy of electrons from the 42 GeV SLAC beam can be doubled over a plasma length of only Lp=85 cm. This milestone is the result of 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 plasma length. With a bunch 25 μm-long, 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.

There are some troubles with further energy gain increase for longer plasma length (Lp=113 cm): peak energy is lower than for the 85 cm oven; beam appears also less focused. Head erosion is supposed the reason for energy gain limitation.

In the future experiments attention will be paid on possibilities to overcome head erosion, evolution of the drive beam emittance, pre-ionize the plasma. Positrons acceleration and development 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 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.12 the principle of 2-bunch plasma accelerator is depicted.

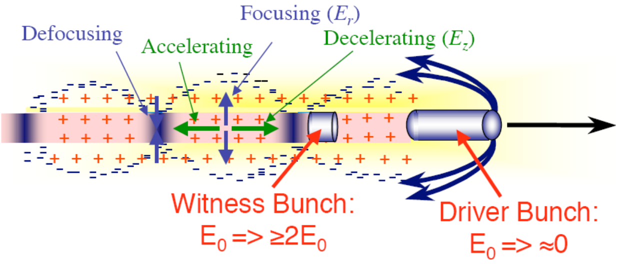
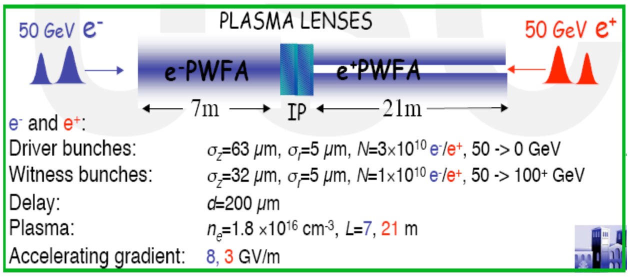


Fig.12. Scheme of 2-bunch PWFA

Typical 2-bunch PWFA parameters are followings: $n_p\approx10^{16}$ cm^{-3}, fp ≈ 900 GHz, λp ≈ 300 μm; G ≈10…20 GeV/m; $N_W\approx0.5\times10^{10}$ e$^-$, $N_D=3\ N_W$; $\sigma_D\approx60$ μm, $\sigma_W\approx30$ μm, Δt ≈ 150 μm.

The e$^-$and e$^+$ capabilities of SLAC SABER will provide unique opportunity for development of 1 TeV Linear Collider Plasma Afterburner [24]. The main parameters of the afterburner with asymmetry of electron and positron lines are presented in Fig.13. The peculiarity of positron side was taken into account [10].



e$^-$ and e$^+$:
Driver bunches: $\sigma_z=63\ \mu m$, $\sigma_r=5\ \mu m$, $N=3\times10^{10}$ e$^-$/e$^+$, 50 -> 0 GeV
Witness bunches: $\sigma_z=32\ \mu m$, $\sigma_r=5\ \mu m$, $N=1\times10^{10}$ e$^-$/e$^+$, 50 -> 100$^+$ GeV
Delay: $d=200\ \mu m$
Plasma: $n_e=1.8\times10^{16}$ cm^{-3}, L=7, 21 m
Accelerating gradient: 8, 3 GV/m

Fig.13. Layout of 100 GeV, e$^-$/e$^+$ Collider based on SLAC electron and positron 50 GeV bunches and Plasma Afterburner

3. LASER WAKEFIELD ACCELERATION (LWFA)

Another way to produce high intensity plasma wakefield for particles acceleration [25] concludes to using short laser impulse of high power (LWFA). In this case ponderomotive force of laser impulse expels plasma electrons and excites wakefield amplitude $E=(v_E^2/c^2)E_{max}$, where v_E is oscillatory velocity in the laser electric field.

Laser pulse creates 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 $\lambda_p = 2\pi c/\omega_p$. Principle of electrons acceleration by laser driven plasma wakefield is illustrated in Fig.14. Plasma channel can provide optical guiding to extend acceleration length.

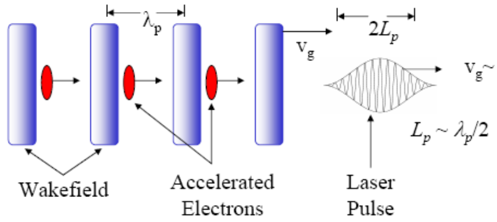


Fig.14. Laser Wakefield Accelerator concept

Sensational experimental results in LWFA scenario have been independently obtained in Japan [27], UK [28], France [29], and USA [30] on 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 π·mm 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. Acceleration gradient above 100 GeV/m and energy gain on a distance of diffraction length 300 MeV [31] allow considering such installations as “table-top” accelerators.

Interpretation of physical mechanism of trapping into acceleration plasma electrons (self-injection) is evidently demonstrated in Fig.15 [26].

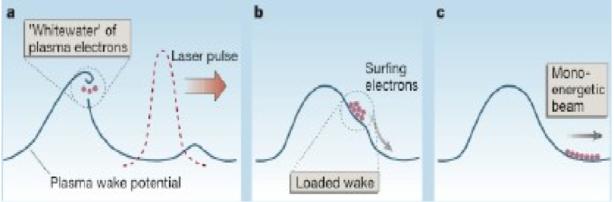


Fig.15. Physical mechanism of self-injection and monoenergetic beam acceleration in LWFA

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.15,a). The load of the electrons deform the wake, stopping further trapping of electrons from the plasma (Fig.15,b). As the electrons surf to the bottom of the potential, they each arrive bearing a similar amount energy (Fig.15,c).

There are two other physically similar 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 [18] and bubble acceleration [19].

The latest results on LWFA were reported at the workshop LWFA-2007 [5]. 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 operation at plasma densities an order of magnitude lower, i.e. 10^{18} cm^{-3}, and increasing the distance over which acceleration is maintained from a few millimetres to a few tens of millimetres. One approach for achieving this is to guide the driving laser pulse in the plasma channel formed in a gas-filled capillary discharge waveguide. Beam energy was increased from 100 MeV to 1 GeV [7] by using a few-cm long guiding channel at lower density, driven by a 40 TW laser, demonstrating the anticipated scaling to higher beam energies. Bunches with 30 pC charge and 2.5% energy spread were observed at 1.0 GeV. Three recent experiments [8] performed at LBNL, RAL, and Max Planck Institute for Quantum Optics demonstrated obtaining quasi-monoenergetic electron beams with energies as high as 1 GeV. Besides simultaneous measurements of the electron energy and the energy and spectrum of the transmitted pump laser radiation were performed, which help illuminate the mechanisms responsible for electron injection and acceleration.

It was shown [9] the first results on self-injection and acceleration experiment of monoenergetic electron beams with multi-100 MeV energy in the highly relativistic regime, referred to as the ”bubble” regime. 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 [7, 11]. The first demonstration of undulator radiation from 45…75 MeV electron beams from a wakefield accelerator produce radiation in the visible range of the spectrum and show that, when driven by a 1 GeV accelerator, a sub-10fs brilliant radiation source can be produced. Furthermore, it was presented evidence that the electron beams produced in a wakefield accelerator have characteristics which are very competitive with conventional accelerators, and show promise a future driver of a 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.

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УСПЕХИ В РАЗВИТИИ НОВЫХ МЕТОДОВ УСКОРЕНИЯ (ОБЗОР)

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Представлены и проанализированы новые результаты по лазерно-плазменным и пучково-плазменным ускорителям. Рассмотрены перспективы их дальнейшего развития, направленные на создание малогабаритных («настольных») ускорителей и их применение, а также на ускорение частиц с использованием плазмы до сверхвысоких энергий. Ультраинтенсивные лазеры и пучки частиц ускоряют частицы в плазме в режимах, немыслимых всего несколько лет назад: 1 ГэВ моноэнергетические электронные пучки в лазерно-плазменных ускорителях, удвоение энергии 42 ГэВ пучка SLAC, квази-моноэнергетические мегаэлектронвольтные ионные пучки – только некоторые из значительных экспериментальных результатов прошлого года. В следующие несколько лет ожидается еще более интенсивное развитие лазерно-плазменных и пучково-плазменных ускорителей. Новые лазерные системы петаваттного диапазона и исследовательские программы в этой области расширяются на весь мир, а крупномасштабное численное моделирование поставляет информацию с беспрецедентными деталями.

ЗДОБУТКИ В РОЗВИТКУ НОВИХ МЕТОДІВ ПРИСКОРЕННЯ (ОГЛЯД)

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Представлено та проаналізовано нові результати по лазерно-плазмових та пучково-плазмових прискорювачах. Розглянуто перспективи їх подальшого розвитку, спрямовані на створення малогабаритних («настільних») прискорювачів та їх використання, а також на високоградієнтне прискорення частинок до надвисоких енергій. Ультраінтенсивні лазери і пучки частинок прискорюють частинки в плазмі в режимах, немислимих всього декілька років тому: 1 ГеВ моноенергетичні електронні пучки в лазерно-плазмових прискорювачах, подвоєння енергії 42 ГеВ пучка SLAC, квазі-моноенергетичні мегаелектронвольтні іонні пучки – тільки деякі із значних експериментальних результатів минулого року. В наступні декілька років очікується ще більш інтенсивний розвиток лазерно-плазмових та пучково-плазмових прискорювачів. Нові лазерні системи петаватного діапазону й дослідницькі програми в цій області розширюються на весь світ, а крупномасштабне чисельне моделювання поставляє інформацію з безпрецедентними деталями.