NOVEL AND ADVANCED ACCELERATION TECHNIQUES

WAKEFIELD ACCELERATION. STATE AND PROSPECTS (OVERVIEW)

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The results of researches on the wakefield method of high-gradient acceleration of charged particles carried out within the framework of the projects "FACET" (SLAC), "BELLA" (LNBL), "AWAKE" (CERN) and in other laboratories, including NSC KIPT, are presented. The acceleration of charged particles in a plasma wakefield with acceleration rate up to 100 GeV/m excited by an intense electron bunch (PWFA) or by a powerful laser pulse (LWFA), and in a dielectric wakefield with acceleration rate up to 1 GeV/m excited by an intense electron bunch (DWFA) is considered.

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INTRODUCTION

Large Hadron Collider (LHC [1]) and designed and planned for construction lepton colliders (CLIC [2] and ILC [3]) producing the center-of-mass energy in TeV range are destined as the main tool to solve the fundamental problems of high energy physics. However, demanded further growth in the maximum energy of the future colliders has slowed down.

Present colliders based on conventional methods of particles acceleration became costly and time-consuming and close to the limit of what humanity can afford to build even with the joint efforts of many countries. This forces to explore new methods of accelerating particles to high energies.

Radical reduction of the length of linear high energy accelerators can be achieved using much higher accelerating fields than the utmost breakdown fields of 30…100 kV/m, which are used now in conventional methods. Therefore increasing the amplitude of accelerating fields becomes a decisive problem for reducing the size and cost of high energy accelerators. Such approach is the main one in motivation of the research of new promising methods of charged particles acceleration expanded all over the world.

1. CONCEPT OF WAKEFIELD ACCELERATION

The first understanding of the end of the path for conventional acceleration schemes was stated in [4 - 6], where the ideas of new acceleration methods were announced, including proposal Fainberg [6] to use plasma waveguides as accelerating structures.

Acceleration by collective fields of charge density waves excited in plasma radically differs from other conventional acceleration schemes by two essential advantages. Firstly, when using plasma as an accelerating structure, there is no danger of microwave breakdown, leading in the conventional accelerating structures of high energy colliders to the emergence of plasma and limitation of the maximal possible acceleration rate. Secondly, plasma can support accelerating high-frequency fields several orders higher than those achieved in conventional accelerating structures. Plasma of density n_p can support an electric field $E_{\max}=\sqrt{4\pi n_p mc^2}$, i.e. $E_{\max}(V/cm)\approx\sqrt{n_p}(cm^{-3})$, where m – mass of electron; e – charge of electron.

For the currently realized plasma densities, the magnitude of the maximum field E_{max} can reach the values of $10^7…10^9$ V/cm. In particular, for the plasma density $n_p=10^{18}$cm^{-3} E_{max}=100 GV/m, which is three orders of magnitude higher than the one planned in the constructed linear lepton collider CLIC [2]. Later, the idea of using space-charge waves in plasma was developed by J. Dawson and his colleagues [7, 8] as a wakefield acceleration scheme in which a high-gradient accelerating field is the wakefield excited in a plasma by a short powerful laser pulse or a short electron bunch with a large charge. The accelerating fields E_{acc}, excited in plasma, are determined by the intensity of the external exciting factor (driver), namely: $E_{acc}=\alpha E_{max}$, where $\alpha=n_b/n_p$, when the accelerating field is excited by an electron bunch and $\alpha=v_E^2/c^2$, when it is excited by a laser pulse. Here, n_b is the density of the bunch; v_E is the oscillatory velocity, which is gained by plasma electrons in the wakefield of the laser wave.

The progress in the development of lasers with a high peak power and the increase in the intensity of electron bunches of accelerators based on convential schemes made it possible to carry out many conceptual experiments based on the wakefield methods of high-gradient acceleration, including laser wakefield concept (LWFA-Laser WakeField Acceleration) and beam wakefield concept (PWFA-Plasma WakeField Acceleration).

2. LASER-PLASMA WAKEFIELD ACCELERATION CONCEPT (LWFA)

In the first experiments on laser-plasma wakefield acceleration, the acceleration rate was obtained, which was much higher than that in conventional accelerators. However, the quality of the beam obtained in these experiments is unsatisfactory because of the large energy and angular spread. In 2004, experiments were carried out independently in different laboratories of the world-Japan [9], England [10], France [11], USA [12], in which accelerated monoenergetic beams with small angular divergence were obtained. The pulse of a powerful laser was injected into a supersonic gas jet to create plasma and excite in it a wakefield in which plasma electrons were accelerated. In [11], a high-quality electron beam was produced with a divergence of 10 mrad, a charge of 0.5±0.2 nC at energy 170±20 MeV. Consequently, the energy of the bunch was 100 mJ, i.e. the transformation ratio of the laser energy to the electron beam energy was 10%.

In all four experiments [9 - 12], high-quality electron bunches (normalized emittance of less than 1 mm mrad, duration of tens of femtoseconds, charge of the order of 1 nC) are formed and accelerated with a rate of the order of 100 GeV/m under conditions for which the length of acceleration is consistent with the length of the dephasing of the beam with the wakefield, and the intensity of the laser is such that the beam load is strong enough to prevent a new capture of plasma electrons.

The problem so far remains the necessity to increase substantially the acceleration length to obtain the energy of the particles required by high-energy physics. In [13] the achieved maximal particle energy for laser-plasma wakefield acceleration is 300 MeV. A further increase in the acceleration length was achieved when using a plasma waveguide formed at a capillary discharge of 1 cm long, considerably exceeding the Rayleigh length. The accelerated beam of 1 GeV was obtained [14].

The first experimental demonstration of capture (so-called self-injection) and acceleration of electrons to energy much higher than 1 GeV with a small energy and angular spread is presented in [15]. In this experiment, a more powerful PW laser was used and the plasma density was optimized. PW pulses are injected into plasma of much lower density than in previous experiments. It allows to overcome the physical barriers prevented the acceleration above 1 GeV: a) dephasing the excited wakefield and the accelerated electrons, and b) erosion of the laser pulse.

Linearly polarized pulses from a Texas PW laser with duration of 150 fs, a wavelength of 1.057 μm, and energy of 150 J were focused on an input aperture of 1.5 mm radius of a gas cell 7 cm long filled with helium at a pressure of 1…8 Torr. [16]. It was shown that the maximum energy of 2 GeV electron bunches with an explicit energy maximum at 2 GeV with energy spread of only a few percent (5%) and unprecedented sub-mrad angular spread is achieved in a narrow range of plasma densities of $(4…6)·10^{17}$ cm^{-3}. In this case the so-called bubble-mode (behind the laser pulse a bubble with spilled electrons is formed instead of the wake wave) and at the same time physical barriers for acceleration above 1 GeV are eliminated. Numerical simulation shows that with an improvement in the quality of focusing of the laser pulse, it is possible to accelerate the plasma electrons to almost 10 GeV even with the available at present pulse energy.

Further progress in increasing the maximum energy in the laser-plasma wakefield accelerator is expected to be realized in the project "BELLA" [17], performed in the laboratory of LBNL (USA). For this, the power of the laser used should be increased to 1 PW level, which will make it possible to create a 10 GeV laser-plasma wakefield accelerator as a block for future multimodal colliders based on laser drivers. Currently, in LBNL, when laser pulses with a peak power of up to 0.3 PW are injected in a pre-created plasma waveguide as a 9 cm length capillary discharge of plasma density $7·10^{17}$ $см^{-3}$, electron bunches with an energy of up to 4.2 GeV, 6% energy spread, charge of 6 pC and an angular divergence of 0.3 mrad are obtained [18].

The scheme of TeV collider, based on LWFA-modules, accordingly to the project "BELLA" in LBNL [19] is shown in Fig. 1.

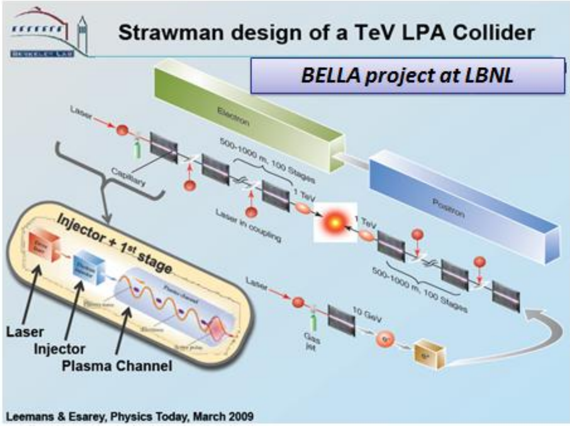

Fig. 1

3. BEAM-PLASMA WAKEFIELD ACCELERATION CONCEPT (PWFA)

The first experiments on the wakefield acceleration of electrons by plasma waves excited by relativistic electron bunches (PWFA) were in fact carried out in KIPT [20, 21] when studying the instability of a relativistic electron beam in plasma. The sequence of short (less than excited wakefield wave length) bunches of relativistic electrons, produced on a linear resonant electron accelerator (energy 2, 14, and 20 MeV, number of bunches up to $6·10^3$, bunch repetition frequency 2.705 GHz, charge of each bunch 0.32 nC, its length and diameter are 1.7 cm and 1cm, respectively) was injected into the plasma of the resonant density (the plasma frequency is coincided with the frequency of bunch repetition), produced with coaxial plasma gun. The maximum increase in the energy of the electrons of bunches occurred in the accelerating phases of the excited wakefields was 4 MeV at a plasma column length of 10 cm. This indicated the excitation of a wakefield with an amplitude of 40 MV/m Only after the appearance of theoretical papers [7, 8], the above results were interpreted as the acceleration of electrons in the fields excited in plasma by a sequence of bunches (PFWA) [22, 23].

In KEK (Japan), for wakefields excitation in plasma jf density $9·10^{11}$ cm^{-3} a sequence of 6 bunches with an energy of 250 and 500 MeV and a total charge of 5…10 nC was used [24]. The maximum energy loss of the bunch was 12 MeV at a length of 20 cm, which corresponds to electric field strength of 60 MV/m.

In ANL (USA), for the first time, an experiment was performed with a single bunch-driver of a large charge which excites the wakefield in plasma and a bunch-witness of a smaller charge whose energy is changed with a variation in the delay of its injection into the plasma, that allows to judge the characteristics of the excited wakefield [25]. The electron bunch-driver (energy 21 MeV, charge 4 nC, length and diameter 2.1 mm and 1.4 mm, respectively) was injected into plasma of density $(0.4…7.0)·10^{13}$ cm^{-3} and length of 3.3 cm. Before the injection point the bunch-witness, which was diverted by a magnetic field along a trajectory, the length of which was varied by means of moving magnets, and then, with an adjustable delay, was directed behind the bunch-driver. The delay between these bunches could vary from 0.2 to 1.0 ns. The measured energy of accelerated witness in dependence of the delay, indicated its acceleration in the wakefield of excited plasma oscillations with an amplitude of 5.3 MV/m.

Thus, it can be concluded [26, 27] that the first experiments on multi-bunch excitation of wakefields in plasma (multi-bunch PWFA) for high-gradient electron acceleration were performed in KIPT, 1972 and KEK, 1990, and on single bunch excitation of the wakefields in plasma (single-bunch PWFA) in ANL, 1988.

Subsequent experiments to excite the wakefield in a meter-long plasma were carried out on a 3 km collider of the Stanford Linear Accelerator Center (SLAC) using a single electronic bunch with small dimensions and a large charge. The high intensity and low emittance the electron bunch with an energy of 42 GeV passed through a column of lithium vapor; before the head of the bunch a completely ionized plasma was created due to vapor ionization by coulomb field, in which the bunch excited strong plasma wakefield.

In the experiments at the SLAC (E-157/E-162 [28]), the goal was to obtain a high-gradient accelerating wakefield when injected into a 1.4-m long plasma and a density of 10^{14} cm^{-3} of an electron bunch with an energy of 30 GeV and a density more than plasma density. In the first experiment [29], a single 28.5 GeV bunch of 1.8×10^{10} electrons of the SLAC-accelerator was compressed to a length of 12 μm (40 fs.). The density of plasma 10 cm in length was equal to the density of lithium vapor 2.8×10^{17} atoms / cm^3. About 7% of the electrons of the tail of the bunch accelerated to energies above the initial, on average 2.8 GeV more. The maximum acceleration of the electrons of the trailing edge of the bunch was 4 GeV at a plasma length of 10 cm, i.e. it occurred with an accelerating gradient of 40 GV/m. This result was, firstly, the first demonstration of the 1 GeV barrier overcoming for the accelerators based on advanced acceleration methods. Secondly, the obtained acceleration rate was 40 GeV/m, more than three orders of magnitude higher than the rate 30 MeV/m planned for the ILC.

In subsequent experiments [30] with an increased plasma length of up to 30 cm, an energy gain of more than 10 GeV was measured.

The practically linear increase in the energy gain on the length of the plasma measured at SLAC [29, 30] was confirmed by a subsequent experiment with an increase in the plasma length to 85 cm [31]. This experiment allows obtaining a very important result consisting in doubling the energy of the tail part of the bunch-driver by excited plasma wakefields. An electron bunch with parameters: energy 42 GeV with a spread of 1.5 GeV, the number of electrons in the bunch $1.83\cdot10^{10}$ (charge 2.93 nC), bunch length is 15 μ was focused on chamber entrance of 10-μm diameter (so the average electron density in the bunch is $1.03\cdot10^{19}$ см$^{-3}$) and injected into a column of 85 cm-long lithium vapor with a density of neutral particles of $2.73\cdot10^{17}$ cm^{-3}. It was experimentally shown that an energy gain of more than 42 GeV was achieved in a plasma wakefield accelerator (PWFA) of 85-cm length, excited by a 42 GeV bunch-driver of a SLAC collider. The energy gain of a small fraction of the electrons of the injected bunch at a less than a meter length is the same as on the 3-km length of the SLAC collider using the conventional acceleration method. This is an important step demonstrating the perspective developing compact plasma wakefield accelerators for high-energy physics.

When the length of the column with lithium vapor was increased from 85 to 113 cm, the measured maximum energy was 71±11 GeV with less than 3% of the bunch electrons, which gained additional energy of more than 30 GeV. The reason for this saturation of the energy gain is the erosion of the head of the bunch: the front of the bunch expands because it is not subjected to the focusing force of the ion column. This expansion reduces the density of the bunch shifting the ionization front back along the bunch. Ultimately, the electric field of the bunch falls below the threshold for the formation of plasma, stopping the acceleration process before the energy of the bunch-driver is depleted.

Such restriction on the plasma length, which inevitably leads to the necessity of sectioning, is proposed to overcome, using relativistic proton bunches (PDPWFA-proton-driven plasma wakefield acceleration) instead of relativistic electron bunches. Due to greater mass of proton bunches are less susceptible to emittance erosion in strong excited fields [32, 33].

As for the excitation strong wakefield fields in plasma it is necessary to create plasma with a high density (at n_b/n_p is retained), so the wavelength of the plasma wakefield $\lambda_p=2\pi c/\omega_p$ is much smaller than the length a of the proton bunches of present proton accelerators ($(\lambda_p<<a$). Proton microbunches ($a \le \lambda_p$) are supposed to be formed by splitting a long bunch into several short ones, using self-modulation during beam-plasma instability [34].

At CERN, the AWAKE (Advanced Wakefield Experiment) project is being carried out, aimed at demonstrating the PDPWFA experimentally using a sequence of proton bunches with TeV-band energy as a driver [35]. Simulation showed [32] that a proton bunch of the type LHC (1 TeV, 10^{11} protons in the bunch) with a bunch length of 100 μm can accelerate the incoming 10 GeV electron beam to an energy of more than 500 GeV in a 500 m plasma with an average accelerating gradient of ≥ GeV/m. Recent studies [34] have shown that such gradients can be achieved with a long modulated proton bunch. It makes possible the experimental study of PDPWFA with existing proton bunches at CERN [35].

For the AWAKE experiment at CERN, a proton beam of an LHC type with an energy of 400 GeV but a higher intensity ($3\cdot10^{11}$ protons in the bunch) is extracted from the CERN SPS accelerator and is directed to the plasma cell to excite the plasma wakefield. The proton bunch will be focused to the size $\sigma_{x,y}$=200 μ near the entrance to a plasma cell of 10 m long with a density adjustable in the range $10^{14}\ldots10^{15}$ cm^{-3}. When a proton bunch with a length σ_z= 12 cm (0.4 ns) enters a plasma cell, it undergoes to self-modulation instability. It produces a sequence of ultrashort proton bunches, which can resonantly excite the intense wakefields [34].

The effective length and period of the modulated long bunch are determined by the length of the plasma wave (for AWAKE, usually λ_p=1 mm). A high-power laser pulse (2 TW) propagating coaxially with a proton bunch is used to ionize gas in a plasma cell, and also generates a seed of self-modulation of the proton bunch. An electron bunch with $1.25 \cdot 10^9$ electrons injected at an energy of 10…20 MeV serves as a witness for the acceleration in the plasma wakefield of proton bunches.

Further research on new acceleration methods at SLAC is planned to be carried out within the framework of the FACET program [36] on another beam channel of a SLAC collider with 23 GeV electron/positron bunches. Charge of each bunch is 3 nC (10 kA), diameter 10 μ, duration 50 fs. Experiments are aimed at improving the quality of the accelerated bunch (increasing the number of electrons in the bunch, reducing the energy and angular spread of electrons), for which the initial bunch of magnetic systems and / or masks is divided into a pair of bunch-driver (for excitation wakefield) and bunch-witness (for acceleration in wakefield).

In [37] it was reported an experiment on the SLAC in the framework of the FACET program that was directed on highly effective acceleration of a separate bunch-witness, which contains a sufficient charge to extract a significant amount of energy from a highgradient nonlinear plasma wakefield accelerator. In particular, an acceleration of 74 pC of bunch-witness in an accelerating gradient of 4.4 GV/m was obtained. The electrons of the this bunch gain an additional energy of 1.6 GeV with an energy spread of just 0.7% and an energy transfer efficiency from the wakefield to the bunch exceeds 30%. Such acceleration of a separate bunch, containing a substantial charge and having a small energy spread, with a high accelerating gradient and high energy transfer efficiency is an important milestone in the study of plasma wakefield acceleration for the development of the technology and design of compact and accessible accelerators. A perspective goal is the development of a PWFA as a block for future multi-section colliders for high-energy physics.

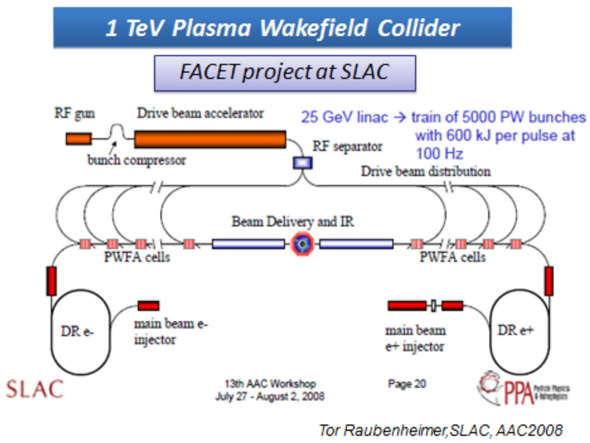

Fig. 2

The program "FACET" also includes studies of the accelerator scheme using the wakefield excited by SLAC collider bunches in dielectric structures, as well as the generation of high-power THz radiation.

Fig. 2 shows the scheme of 1 TeV collider, based on PWFA-modules, in the project "FACET" at SLAC [36].

4. BEAM-DIELECTRIC WAKEFIELD ACCELERATION CONCEPT (DWFA)

An accelerating structure loaded with a dielectric, in which the wakefield is excited by an intense electron bunch or a sequence of bunches, is another alternative candidate for the development of the future high-gradient accelerators, which can overcome the acceleration rate threshold for conventional accelerators of 100 MV/m. As it is shown in theoretical studies [38] and recent experiments [39], the maximum accelerating field in dielectric structures, limited by electrical breakdown due to tunneling and collision ionization, can exceed 1 GV/m, i.e. an order of magnitude greater than that of conventional metal accelerating structures. Demonstration of the breakdown threshold of 13.8 GV/m in the specific geometry of the dielectric wakefield accelerator (DWFA) in the THz range [39] is an encouraging result for the development of future DWFA with an accelerating gradient of the order of GV/m. Dielectric structures have a number of advantages due to the simplicity of the geometry, the ease of avoiding of harmful asymmetric modes, and realization such distribution of the transverse field, which impedes breakdown on the outer metal wall of the structure. Dielectric structures are more acceptable due to the advanced technology of manufacturing micro-products, dielectric uniformity, simpler microwave matching, etc.

The studies of wakefield excitation in the dielectric accelerating structure by a single electron bunch was started in ANL (USA) [40]. In the works of the NSC KIPT (Ukraine) [41] and the USA [42] the concept of a multi-bunch dielectric wakefield accelerator was developed, based on the excitation of wakefields by a sequence of bunches in a dielectric structure with a vacuum channel for the transit of bunches.

The concept of a multi-bank plasma-dielectric wake accelerator in which the vacuum channel is filled with plasma, that leads to the excitation of an additional plasma wakefield, is of promising interest. The presence of this field makes it possible to increase the excitation efficiency of the longitudinal wakefield and to provide, by focusing, the transverse stability of the exciting and accelerated bunches.

The first publications on this subject [43] prompted the deployment in the NSC of KIPT of broad theoretical and experimental studies [44] of the concept of the plasma-dielectric wakefield acceleration, in which the electromagnetic properties of plasma-dielectric accelerating structures are elucidated. The longitudinal and transverse structure of the excited electromagnetic field is investigated. The transverse force acting on the electrons of the bunch-driver is always focusing, and the transverse force acting on the particles of the accelerated bunch-witness is focusing only when the injection phase is appropriately selected.

In the multi-bunch excitation mode, the amplitude of the longitudinal wakefield can be increased by summing the fields of the radial modes of the dielectric waves only at the optimum plasma density, determined by the condition $\omega_p a \approx 2$ (ω_p is the plasma frequency, and a is the transit channel radius). Besides it is necessary, by varying the parameters of the vacuum dielectric structure, to preemptively select the frequency of the field to be excited in such a way that, when the plasma is filled, it ырщгдв coincide with the frequency of bunch repetition [45].

In ANL developed the project [46] of a dielectric wakefield collider of only 5 km length for the Higgs factory, almost an order of magnitude shorter than the planned International Linear Collider ILC [3]. Its scheme is shown in Fig. 3.

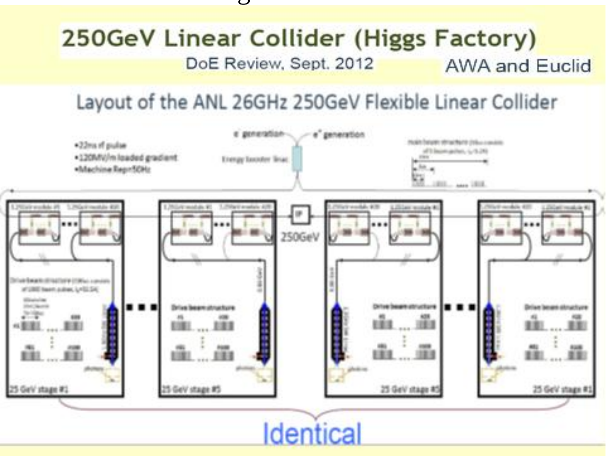

Fig. 3

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КИЛЬВАТЕРНОЕ УСКОРЕНИЕ. СОСТОЯНИЕ И ПЕРСПЕКТИВЫ (ОБЗОР)

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Представлены результаты исследований кильватерного метода высоко-градиентного ускорения заряженных частиц, выполненных в рамках проектов «FACET» (SLAC), «BELLA» (LNBL), «AWAKE» (CERN) и в других лабораториях, включая ННЦ ХФТИ. Рассмотрено ускорение заряженных частиц в плазменном кильватерном поле до 100 ГэВ/м, возбуждаемом интенсивным электронным сгустком (PWFA) или мощным лазерным импульсом (LWFA); и в диэлектрическом кильватерном поле до 1 ГэВ/м, возбуждаемом интенсивным электронным сгустком (DWFA).

КІЛЬВАТЕРНЕ ПРИСКОРЕННЯ. СТАН І ПЕРСПЕКТИВИ (ОГЛЯД)

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Представлено результати досліджень кільватерного методу високо-градієнтного прискорення заряджених частинок, які виконані в рамках проектів «FACET» (SLAC), «BELLA» (LNBL), «AWAKE» (CERN) і в інших лабораторіях, включаючи ННЦ ХФТІ. Розглянуто прискорення заряджених частинок у плазмовому кільватерному полі до 100 ГеВ/м, збуджуваному інтенсивним електронним згустком (PWFA) або потужним лазерним імпульсом (LWFA); та в діелектричному кільватерному полі до 1 ГеВ/м, збуджуваному інтенсивним електронним згустком (DWFA).