EXPERIMENTS ON RESONATOR CONCEPT OF PLASMA WAKEFIELD ACCELERATOR DRIVEN BY A TRAIN OF RELATIVISTIC ELECTRON BUNCHES

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The experimental installation was elaborated to increase plasma wakefield amplitude by means of using plasma resonator that allows all bunches of the train to participate in wakefield build-up contrary to waveguide case, in which due to group velocity effect only a part of the bunches participates. Experiments on plasma producing with resonant density, at which a coincidence of the plasma frequency and bunch repetition frequency is provided, are carried out. The first results of the measurements of beam energy loss on plasma wakefield excitation and energy gain by accelerated electrons are presented.

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1. INTRODUCTION

During the past decade some prominent experiments [1-9] have been done on high gradient acceleration of charged particles that gives the essential impact to develop new concepts of colliders for high energy physics and small size accelerators for high technology and application in material science, medicine, biology etc. The performed experiments are based on super-intense plasma wakefield excitation by a short laser pulse of high power (hundreds terrawatts) [2-5] or by a short electron bunch of the large charge (several nanocoulombs) [3-9]. The latest news of the world-wide activity in this field has proceeded from the Laser and Plasma Accelerators Workshop (9-13 July, 2007, Portugal) [10-14]. In the case of laser-driven plasma wakefield the energy gain of accelerated electrons achieved 1 GeV [11] at accelerating gradient above 100 GeV/m. For the electron bunch driver (42 GeV SLAC beam) energy gains in excess of 42 GeV over a plasma length of 85 cm was obtained [14], i.e. energy doubling was observed.

Traditionally for NSC KIPT experiments on plasma wakefield accelerator concept a long train of relativistic electron bunches, produced by electron linear resonant accelerator, instead of a single bunch of the charge equal to the total charge of the train both for the purpose of electrons acceleration [15] and bunch focusing [16,17]. The similar approach with a train of bunches is considered to investigate experimentally at BNL [18] and the concept of a multibunch plasma afterburner for linear colliders was simulated in [19].

However, as it has been shown in dielectric wakefield accelerator scheme [20], considered multibunch regime in waveguide case does not allow using all bunches of a train in build-up of the maximal wakefield intensity because of excited field removal with group velocity from the interaction region. By this reason for the parameters of the real experiment only a small part of a train gives the contribution to build-up the maximum of the wakefield amplitude. This problem can be overcome in the frame of so called resonator concept [21], in which excited wakefield is reflected from exit side of the resonator and return to the front side at the moment, when the next bunch is injected.

In the present work the elaborated experimental installation providing multibunch regime along with resonator concept for increase of the plasma wakefield amplitude is described. Results on plasma generation in metal resonator by using beam-plasma discharge [22] are presented. Preliminary experiments on wakefield excitation and electrons acceleration in this wakefield were carried out, and electron energy spectra are shown and discussed. Some conclusions related to further investigation is given.

2. EXPERIMENTAL SETUP

Experiments on the investigation of wakefield excitation in plasma resonator are carried out at the installation, which scheme is shown in Fig.1.

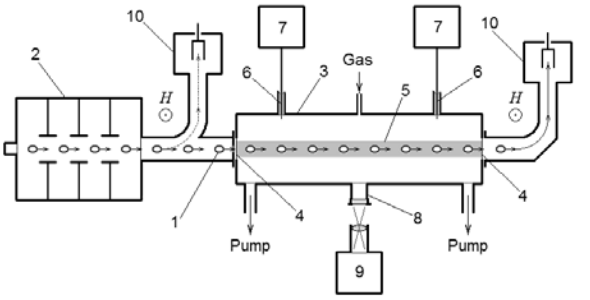

Fig.1. Scheme of the installation: 1 - electron bunches, 2 - electron linac, 3 - cylindrical resonator, 4 - Ti-foil, 5 - plasma, 6 - HF-probes, 7 - HF-oscillations registers, 8 - window, 9 - spectrograph,10 - magnetic analyzers

For wakefield excitation in plasma a train of bunches, which is produced by means of the linear resonant accelerator "Almaz-2", is used. Parameters of the beam: energy 2…4.5 MeV, pulsed current 1…0.5 A, pulse duration 2 μsec, modulation frequency of the beam (bunch repetition frequency) 2805 MHz. Each pulse consists of a periodic sequence of $6 \cdot 10^3$ electron bunches. Bunch duration is 60psec and time interval between bunches 300 psec. Each bunch has diameter at accelerator exit 1 cm, length 1.7 cm, charge 0.32…0.16 nC. At realization of experiments there is the possibility to change the width of the electron energy distribution function in range from 8% up to 50% by changing the modulation frequency over the range 0.15%.

Bunches of relativistic electrons (1) from the accelerator exit (2) are injected into the cylindrical resonator (3) of inner diameter 9 cm through the entrance end-wall closed by a Ti-foil (4) of thickness 35 μm. The length of the resonator is equal 53.5 cm that corresponds to 10 halfwavelengths of eigen mode of frequency equaled to bunch repetition frequency. Exit end-wall of the resonator, as well as entrance one, is hermetically closed by the same titanic foil, that allows to change pressure of working gas in the resonator over a wide range (from 10^{-2}Torr up to 760 Torr), at maintenance of high vacuum in accelerator sections. Electron bunches, propagating in working gas, ionize gas and create plasma (5) inside resonator. Several high-frequency probes (6) are installed, which signals are applied to registering systems (7).

The current of the beam electrons was measured by Faraday cylinder. The duration of plasma glow was determined with the help of FEU-29, whose maximum sensitivity is in the region of the visible spectrum.

For protection of FEU from X-radiation, arising at injection of the beam from an accelerator, it was placed outside of a zone of X-radiation, and light on FEU was transmitted by the optical waveguide of length 2 m.

Intensity of wakefield excited in plasma is determined by optical methods of diagnostics, in particular measuring spectral lines widening (i.e. using Stark effect). The temperature and density of plasma is measured by integral intensity and the ratio of amplitudes of spectral components of optical radiation. For these purposes the window (8) serves which is hermetically closed by quartz glass and is intended for an output of optical radiation from plasma. To maintain high Q-quality of the resonator and to prevent HF-radiation removal an optical window is closed by a metal grid. The analysis of optical radiation is carried out by means of spectrograph (9) of type ISP-51 and the double optical converter.

Losses of electron beam energy are estimated by change of its energy spectra before its injection into plasma resonator and after passage of the plasma resonator. Energy spectra are measured by means of the magnetic analyzers (10) located at the accelerator exit and at the resonator exit.

3. EXPERIMENTAL RESULTS

3.1. PLASMA GENERATION BY BEAM-PLASMA DISCHARGE

During electron bunches moving through the neutral gas plasma is producing by gas ionization due to collisions and beam-plasma discharge in plasma oscillation fields resulting of beam-plasma instability. The excitation of plasma wakefield and beam-plasma breakdown can be most effective, when the frequency of modulation of the beam ω_m is close or is multiple to a plasma frequency ω_p, i.e. $\omega_M \approx \omega_p = \left(4\pi n_p e^2 / m\right)^{1/2}$.

If plasma density increases above than this level, resonance is destroyed, intensity of wakefield, in which the discharge is developed, decreases and plasma density drops. It can result in relaxation oscillations of plasma density near its resonant value $n_p^* = \omega_M^2 m / 4\pi e^2$.

It is possible to receive an estimation of a necessary current density of the beam for creation of resonant conditions, at pressure close to atmospheric, using expression for plasma density, formed by REB at its transportation in a gas [23].

$$\frac{\partial n_e(z)}{\partial t} = \frac{I_b}{e A_p(z) E_{ei}} \left(\frac{dE}{dz}\right) - \alpha n_e n_i - k_{np} n_{e0}^2, \qquad (1)$$

here I_b is the beam current, $A_p(z)$ is the area of a plasma channel, formed by the beam, dE/dz is the ionization losses of the beam on a unit of length of a path, E_{ei} is the energy of ion-electron pair creation.

The first term in a right member (1) yields number of electrons, produced by the beam. The second and third terms determine losses of plasma electrons, which are determined by a dissipative recombination with a constant α and three-dimensional trapping of plasma electrons by oxygen molecular with constant k_{np}. Here n_i is the ion density, which equals in our case to electron density n_e. and plasma density n_p. Using value dE/dz and E_{ei} from [24], α and k_{np} from [25], we obtain, that the minimum current density, at which the resonant plasma with density $n_p^* \approx 10^{11}$ cm^{-3} can be produced during the time less than pulsed beam duration, is equal $J_{\text{кр}} \approx 0.2$ A/cm^2.

The first experiments (without exit foil of the chamber) have shown, that at injection of REB in air of atmosphere pressure, the plasma with intensive glow in visible range of a spectrum is produced. The duration of plasma glow ($t \approx 5$ μs) considerably surpasses pulse duration of the beam current ($\tau = 2$ μs) (Fig.2,a,b).

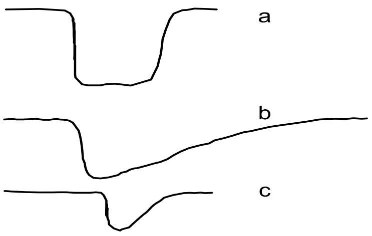

Fig.2. The oscillograms: a - current pulse of a beam; b - signal of plasma glow; c - signal of X-radiation

The beginning of the plasma glow is not synchronized with beam current pulse, namely the glow starts at 0.3 – 0.4 μs after the beginning of a current pulse). The maximum amplitude of the glow is on the second half of current pulse. At smaller pulse duration of the beam ($\tau < 0.5$ μs) the glow is not observed. The most intensive glow is observed in the region, located at distance $l = 5\ldots10$ cm from the exit foil of the accelerator.

Plasma density n_p, formed by the beam, in these experiments was determined on its conductivity σ by the special microwave probe [26]. At high pressure of neutral gas and frequency of the applied field $\omega = 10^4$–10^7 sec^{-1} this conductivity $\sigma = e\, n_p \mu_e$. The electron mobility μ_e at given density and temperature of neutral gas was determined under the tables [23]. The measurement accuracy of plasma density by such method is within the limits of 20%.

The results of measurement of plasma density have shown, that in the region of intensive glow ($0 < l < 10$ cm) the plasma is longitudinally uniform (Fig.3), and its density is $n_p \approx (5\times10^{11})$ cm^{-3}, so the plasma frequency is equaled to frequency of the beam modulation ($\omega_p \approx \omega_M$). At larger distances from the exit ($l > 10$ cm) plasma density decreases, that is explained by decreasing of the current density of the beam due to its angular divergence and dissipation of the beam electrons during its interaction with plasma in a resonance region.

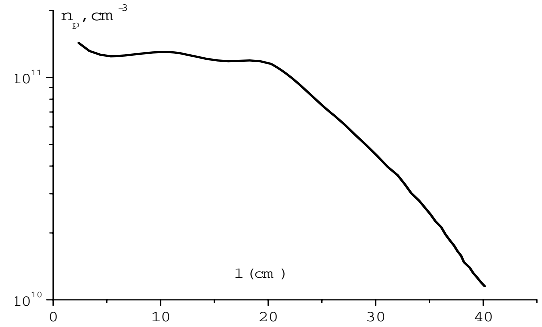

Fig.3. Distribution of plasma density along the axis of the beam propagation

The measurements by the x-ray sensor and chamber-obscurer have shown presence of region of soft X-radiation generation, which coincides with region of maximum plasma glow. The pulse of X-radiation is shorter than a current pulse of the beam and corresponds to the second half of this pulse (Fig.2,c).

It is necessary to mark, that REB interacts most effectively with plasma, formed at its transit through molecular gases with many electrons in atom (air, oxygen). Through the hydrogen and helium REB passes with much smaller energy losses of electrons and all other physical effects are expressed much more weakly.

3.2. ELECTRON BEAM ENERGY SPECTRUM – PLASMA WAKEFIELD EXCITATION AND ELECTRONS ACCELERATION

The energy distributions of the beam electrons, past through the plasma, formed in atmosphere by beam, apart 2, 6, 15 and 25 cm from an exit foil of an accelerator are shown in Fig.4. In this preliminary experiment the exit foil of the chamber was absent.

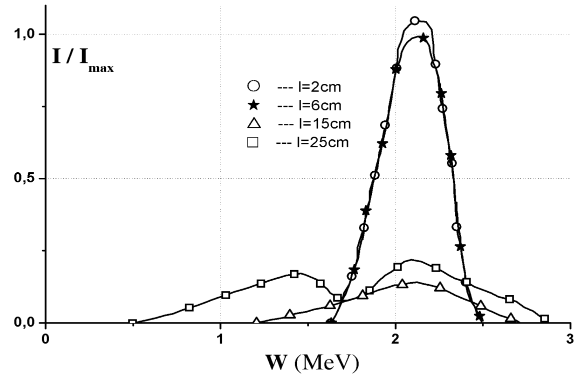

Fig.4. Energy distributions of beam electrons at different distances from an exit foil

It is visible, that if near to the foil the energy distribution is close to a distribution in vacuum, after transit of the resonant region a considerable change of the electron energy distribution demonstrating the energy loss up to 25 % of the electron bunch energy.

Judging by the high-energy tail in energy distribution, some part of electrons gains additional energy, so they have energy larger their initial energy before injection. Estimated acceleration gradient is about 3 MeV/m. On larger distances from an exit foil ($l > 25$ cm) the change of the energy distribution in comparison with vacuum are less noticeable, as the electrons, which lose its energy at collective interaction with plasma, are acquiring considerable angular dissipation and do not fall in an analyzer.

At increase the beam electron energy distribution width up to 50% the energy loss of electrons equals 100-120 keV that coincides with the value of ionization and radiation energy losses of a relativistic electron at its propagation in air of atmospheric pressure over a distance 25 cm, for the case of collective interaction absence.

At decreasing of the beam current $I_b \leq 200$ mA, it was revealed, that all effects, connected with collective interaction of the beam, disappear. This current value is critical and is well agreed with minimum current, which is necessary for creation of resonant plasma density, determined by expression (1).

4. DISCUSSION AND CONCLUSIONS

The results of the preliminary experiment have shown, that at transporting of a train of $6 \cdot 10^3$ electron bunches of charge 0.32 nC and energy 2 MeV each with a narrow width of an electron energy distribution $\Delta W/W \leq 10\%$ at bunch repetition frequency 2805 MHz, in neutral gas of atmosphere pressure the localized equilibrium and resonant plasma of density $n_p^* \approx 10^{11}$ cm^{-3} is produced, with which electron bunches effectively interact, exciting plasma wakefield.

The essential electron bunch energy losses, measured in the experiment, observation of X-ray and microwave radiation from the interaction region, and also the dependence of these effects on the width of an electron energy distribution, evidences the effective excitation of wakefield in plasma by a sequence of relativistic electron bunches. Remarkable amount of electrons are occurred in accelerating phase and gains energy of about 0.5 MeV over a distance 15 cm.

The next step of theoretical and experimental investigations come to the improvement of plasma resonator design, namely a Ti-foil will be installed at the exit end of longitudinally homogenous plasma to reflect excited plasma wakefield. In theory the radial inhomogeneity of plasma should be taken into account.

The second step is caused by a small degree of gas ionization at atmosphere pressure. Large amount of neutral particles does not prevent both excited wakefield and relativistic electron bunches propagation. However in such conditions dissipative beam-plasma instability is developing, at which the beam losses are spent mainly on plasma electrons heating at a comparatively low level of excited plasma field [27]. To overcome this problem gas pressure will be lowered up to 10^{-2} Torr. It allows obtaining wholly ionized plasma with resonant density.

Besides an auxiliary quasi-continuous electron beam of low energy is provided for plasma production of resonant density by means of collisional ionization and then by beam-plasma discharge.

At last the methods of witness bunches formation in the multibunch approach should be elaborated.

In the scheme of the installation, presented in this work, corresponding units for solving problems mentioned are indicated. Some additional diagnostics are supposed to apply.

REFERENCES

1. C. Joshi. Plasma accelerators // *V mire nauki.* 2006, №5, p.17-23.
2. K. Koyama E. Miura, S. Kato, et al. Generation of

quasi-monoenergetic high-energy electron beam by plasma wave // *AIP Conf. Proc*. 737, 528, 2004.
3. S.P.D. Mangles, C.D. Murphy, Z. Najmudin, et al. Monoenergetic beams of relativistic electrons from intense laser–plasma interactions // *Nature.* 2004, v.431, 30 Sept. p.535-538.
4. C.G.R. Geddes, Cs. Toth, J. Van Tilborg, & W.P. Leemans, et al. High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding // *Nature.* 2004, v.431, p.538-541.
5. J.Faure, Y.Glinec, A.Pukhov,... & V.Malka, et al. A laser–plasma accelerator producing monoenergetic electron beams // *Nature.* 2004, v.431, p.541-544.
6. M.J. Hogan, C.D. Barnes, C.E. Clayton,…& C. Joshi, et al. Multi-GeV Energy Gain in a Plasma-Wakefield Accelerator // *Phys. Rev. Lett.* 2005, v.95, 054802-1-4.
7. P. Muggli, S. Deng, T. Katsouleas, et al. Demonstration of Energy Gain Larger than 10GeV in a Plasma Wakefield Accelerator // *10-th European Particle Accelerator Conference (EPAC-2006)* Edinburgh, Scotland, 26-30 June 2006 Abstract ID:2433-WEOAPA01.
8. R. Ischebeck. Energy Doubling of 42 GeV Electrons // *12th Advanced Accelerator Concepts Workshop; AIP Conf. Proc*. Melville New York.-2006, v. 877, p.3-7.
9. P. Muggli. Beam Plasma Physics Experiment at the FFTB // *SABER-Workshop* 03/16/06, http://www-conf.slac.stanford.edu/saber/proc/PAPERS/A03.PDF.
10. C.G.R Geddes, O. Albert, E. Esarey, S. A. Gaillard, et al. Wakefield acceleration of GeV beams, density ramp controlled injection, radiation diagnostics & full scale simulations at LOASIS // *Laser and Plasma Accelerators Workshop* (*LPAW2007*). 9-13 July, 2007. Azores, Portugal. Book of Abstracts, p.5
11. S.M. Hooker, E. Brunetti, E. Esarey, J. Gallagher, et al. Plasma Accelerators Driven in Capillary DischargeWaveguides // *Ibid*., p.19.
12. K. Nakajima, Scaling on laser-plasma accelerators with self-injection of electron beams toward extreme high-energy // *Ibid*., p.35.
13. T. Katsouleas, E. Oz, X. Wang, P. Muggli, et al. Solving the positron side of a plasma afterburner for a linear collider // *Ibid*., p.40.
14. P. Muggli, SLAC/UCLA/USC-E-167-collaboration. Energy doubling of 42 GeV electrons in a 85 cm-long plasma wakefield accelerator // *Ibid*., p.17.
15. A.K. Berezin, V.A. Kiselev, I.N. Onishchenko, Ya.B. Fainberg, et al. Plasma wakefield excitation by a pulse, containing a regulated amount of short bunches // *Fiz. Plazmy.* 1994, v.20, №7-8, p.663-670; *Plasma Phys. Rep*. 1994, v.20, p.596; *Plasma Phys. Rep.* 1994, v.20, p.606.
16. I. Onishchenko, Ya. Fainberg, N. Ayzatsky, et al. Focusing of Relativistic Electron Bunches at the Wakefield Excitation in Plasma // *Bulletin of the APS.* 1997, v.42, N.3, p.1340. *Proc PAC'97.* V.II. p.651-653.
17. V.A. Kiselev, A.F. Linnik, I.N. Onishchenko, V.V. Uskov. Measurements of wakefields in plasma by a probing electron beam // *Problems of Atomic Science and Technology*. *Series «Plasma Physics» (13).* 2007, №1, p.110-112.
18. P.Muggli, T. Kallos, T. Katsouleas, et al. Multi-bunch Plasma Wakefield Accelerator Experiments at the BNL ATF// *Abstract S1.00034*. 2008 APS April Meeting and HEDP/HEDLA Meeting, April 11-15, 2008; St. Louis, Missouri.
19. R. Maeda, T. Katsouleas, P. Muggli, et al. Possibility of a multibunch plasma afterburner for linear colliders //*Phys. Rev. ST-Accelerators and Beams*. 2004, v.**7**, p.111301.
20. I.N. Onishchenko, D.Yu. Sidorenko, G.V. Sotnikov //*Phys. Rev*. E. 2002, 65, p.066501-1-11.
21. V.A. Kiselev, A.F. Linnik, T.C. Marshall, et al. Research on wake field excitation in a cylindrical dielectric waveguide and resonator by a sequence of relativistic electron bunches // *VI Int. Workshop "Strong Microwaves in Plasmas".* N. Novgorod, Russia, July 25-August 1, 2005.
22. P.M. Lebedev, I.N. Onishchenko, V.I. Schevchenko, et al. Theory of beam-plasma discharge //*Fiz. Plasmy*. 1976, v.2, №2, p.407-413.
23. L. Olsen // *Phys. Rev*. 1974, v.9, №12, p.2631-2635.
24. Makh-Daniel. *Processes of collisions in the ionized gas.* M.: "Mir", 1977.
25. V.P. Grigor'ev, A.I. Korjaki, A.G. Potashev. Numerical simulation of plasma channel forming and the electron beam dynamic // *Fiz. Plasmy*. 1984, v.10, №4, p.783-787 (in Russian).
26. A.S. Fisher, R.H. Ronteel, J. Feinstein, T.L. Delonty // *J. Appl. Phys*. 1988, v.64, №2, p.572-578.
27. A.A. Ivanov, V.V. Parail, T.K. Soboleva. Nonlinear theory of interaction between a monoenergy beam and dense plasma // *JETP*. 1972, v.63, №5(11), p.1678-1688.

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ЭКСПЕРИМЕНТЫ ПО РЕЗОНАТОРНОЙ КОНЦЕПЦИИ ПЛАЗМЕННОГО КИЛЬВАТЕРНОГО УСКОРИТЕЛЯ, ИСПОЛЬЗУЮЩЕГО ПОСЛЕДОВАТЕЛЬНОСТЬ РЕЛЯТИВИСТСКИХ ЭЛЕКТРОННЫХ СГУСТКОВ

В.А. Киселев, А.Ф. Линник, В.И. Мирный, И.Н. Онищенко, В.В. Усков

Разработана экспериментальная установка для увеличения амплитуды кильватерного поля при использовании плазменного резонатора, который позволяет всем сгусткам последовательности участвовать в увеличении амплитуды кильватерного поля, в отличие от волноводного случая, для которого из-за эффекта групповой скорости в этом участвует только часть сгустков. Выполнены эксперименты по получению плазмы с плотностью, обеспечивающей совпадение плазменной частоты и частоты следования сгустков. Представлены первые результаты измерений потерь энергии пучка на возбуждение кильватерных полей в плазме и приобретаемой энергии ускоряемыми электронами.

ЕКСПЕРИМЕНТИ З РЕЗОНАТОРНОЇ КОНЦЕПЦІЇ ПЛАЗМОВОГО КІЛЬВАТЕРНОГО ПРИСКОРЮВАЧА, ЩО ВИКОРИСТОВУЄ ПОСЛІДОВНІСТЬ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОННИХ ЗГУСТКІВ

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Розроблена експериментальна установка для збільшення амплітуди кільватерного поля при використанні плазмового резонатора, який дозволяє усім згусткам послідовності приймати участь у збільшенні амплітуди кільватерного поля, у відмінність від хвилеводного випадку, для якого через ефект групової швидкості у цьому приймає участь тільки частина згустків. Виконані експерименти по отриманню плазми з густиною, яка забезпечує співпадання плазмової частоти и частоти проходження згустків. Представлені перші результати вимірювань втрат енергії пучка на збудження кільватерних полів у плазмі та здобутої енергії прискореними електронами.