Collective acceleration of laser plasma in a nonstationary and nonuniform magnetic field

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Abstract. This paper presents the new experimental results concerning acceleration of deuterium ions extracted from laser plasma in the rapid-growing nonuniform magnetic field in order to initiate the nuclear reactions D(d, n)\textsuperscript{3}He and T(d, n)\textsuperscript{4}He. For obtaining of laser plasma a Nd: YAG laser (\(\lambda = 1.06 \mu\text{m}\)) that generates in Q-switched mode the radiation pulses with the energy \(W \leq 0.85 \text{ J}\) and duration of \(\tau \approx 10 \text{ ns}\) was used. Rapid-growing magnetic field was created with the discharge of Arkadyev-Marx pulsed-voltage generator to conical coil with the inductance of 0.65 \(\mu\text{H}\). At characteristic discharge time of 30 ns, the rate of magnetic field growth achieved \(2 \cdot 10^7 \text{ T/s}\). Ion velocity was determined with the time-of-flight technique. During the experiment on deuterium plasma an ion flux velocity of \(\sim 3 \cdot 10^8 \text{ cm/s}\) was obtained, which corresponds to the deuteron energy of \(\sim 100 \text{ keV}\). Herewith, for target power density of \(\sim 5 \cdot 10^{11} \text{ W/cm}^2\) obtaining of up to \(10^{15}\) of accelerated deuterons and up to \(10^8\) of neutrons per a pulse is expected.

1. Introduction
Currently, for generation of fast neutrons, as well as at implementation of a number of implantation and ecologic technologies, the devices based on deuterium ions electrostatic accelerators are often used. The drawbacks of these devices consist in restrictions for density of accelerated ions flux, which are related to impact of spatial charge, low efficiency at ions acceleration and to presence of associated X-ray emission induced with electrons of ion-electron, auto-electron or explosive emission. These drawbacks are to the great extent eliminated with implementation of effective acceleration of quasinutral plasma.

Another aspect proving work relevance is in active experimental research of magnetic-inertial thermonuclear synthesis that requires the description of physical processes occurring in high-temperature dense plasma within the strong magnetic field.

There exist known methods of plasma electrodynamic pulse acceleration consisting in introduction of working substance into interelectrode space and initiating of pulse high-current discharge between the electrodes via introduced working substance. At this discharge the substance is ionized and transformed into plasma, and the interaction between the discharge current through plasma and current magnetic field through the electrodes leads to plasma acceleration. However, plasma creation by means of the breakdown process in gas and the presence of a large portion of neutral component in these methods of plasma acceleration do not allow achieving of high efficiency and stable acceleration of dense homogeneous bunches with large number of ions up to high speeds.
Paper [1] considers the model of laser plasma acceleration in rapid-growing magnetic field formed at the discharge of a capacitor \( \text{C} \) charged up to voltage \( \text{U} \) to circuit in the form of conducting ring. Plasma is created at an instant of time \( t \) counted off from the beginning of capacitor discharge, as a result of pulse laser beam focusing on target of dielectric deuterated material. As the result of magnetic field growth, the eddy current in plasma is induced. At interaction of this current with the magnetic field a longitudinal ponderomotive force occurs that accelerates the plasma bunch.

In early theoretical works [2] the probability of acceleration of laser plasma spread from \( 10^7 \) to \( 3 \cdot 10^7 \) cm/s created with portable lasers emission was calculated. Experimentally the rate of magnetic field growth reached \( 10^5 \)–\( 10^6 \) T/s.

This paper reports new experimental data on the research of plasma ion component by means of laser plasma bunch acceleration and generation of intense beams of accelerated ions under influence of rapid-growing magnetic field. In order to analyze the ion acceleration mechanism a model of laser plasma collective acceleration with nonstationary magnetic field [3] generated at the discharge of capacitor to circuit ring with current was discussed.

2. Experimental model

In order to resolve the set tasks an experimental model was developed that consists of: vacuum post and vacuum chamber with high-voltage and optical entries; the chamber contains the dielectric deuterium-containing laser target located within the helical line, small-size pulse laser, high-voltage generator of pulsed voltage (PVG) according to Arkadyev-Marx scheme and the system for time-of-flight recording of ion flux parameters.

Figure 1 presents the section of vacuum camera with the system for time-of-flight recording of ion flux parameters.

![Figure 1. Illustration of test bench in section.](image)

Rapid-growing magnetic field at laser target was created by means of PVG discharge to conical coil with the inductance of \( L_1 = 0,65 \, \mu\text{H} \). Characteristic dimensions of conical coil amounted about 3 cm, cone opening was \( 20^{\circ} \). The discharge time was about 30 ns. Maximum and average velocity of ions was determined with the time-of-flight technique. Recording of ion bunch arrival time was performed by means of a collector – Faraday cylinder installed at the distance of 0,5 m from conical coil.
PVG allows obtaining of strong pulse of accelerating voltage with the amplitude of up to 400 kV at accumulated energy of up to 50 J, low-resistance load current of up to 1.5 kA with the discharge duration of up to 30 ns. Herewith, both PVG and laser can operate with the frequency of 1 Hz.

In order to obtain plasma a laser on yttrium-aluminum garnet activated with neodymium that generates in Q-switched mode the pulses of infrared radiation (\(\lambda = 1.06 \mu m\)) with the energy \(W \leq 0.85\) J and duration of \(\approx 10\) ns was used. 10\% of laser radiation power was focused on laser-controlled discharger commutating the first PVG cascade, thus providing a strict synchronization of pulse of rapid-growing magnetic field and creation of laser plasma bunches of required size.

Maximum and average velocity of ions was determined with the time-of-flight technique [4] by means of a collector in the form of a Faraday cylinder.

3. Schematic diagram of collective acceleration

Figure 2 presents the method schematic diagram. Laser radiation by means of focusing device was directed to dielectric laser target made of deuterated polyethylene. At this dielectric target a power density of about \(5 \times 10^{15}\) W \(\text{m}^{-2}\) was created.

\[\text{solenoid}\]
\[\text{dielectric laser target (CD}_2\text{)}_n\]
\[\text{collector}\]

Figure 2. Method schematic diagram.

At the first stage of plasma expansion, as the result of its intersection with the magnetic lines of force, within the volume of plasma bunch occurs an eddy electric field and electric current creating the magnetic moment. Magnetic field at certain distance from the center of magnetic system in the form of cone-shaped helix with current becomes nonuniform, so the acceleration of part of ions in the center of plasma bunch occurs (gyromagnetic acceleration). During further plasma spread its periphery ions come into magnetic field domain with the radial component and, as they herewith possess azimuthal component of velocity, they are also involved in acceleration process. In the first case the acceleration energy is gained at the expense of plasma bunch kinetic energy, and in the second case it is gained at the expense of external sources providing field and the mode of its growth.

For plasma effective acceleration it is provided that the time of bunch creation and acceleration is less than the time of discharge current magnetic field penetration into this plasma. Within the scope of this work the rate of magnetic field growth of \(2 \times 10^7\) T/s was achieved, which 1–2 orders of magnitude higher than in previous experiments [2–3].

4. Analysis of obtained results

Figure 3 presents the oscillogram of pulse of ions at collector with laser plasma, scanning is 1 \(\mu\)s, characteristic time was 3 \(\mu\)s. Figure 4 presents the oscillogram of focusing on the recording system in
the absence of laser plasma, reference is the laser pulse recorded with coax photocell ФЭКом, scanning is 25 ns.

Figure 5 presents the oscillogram with scanning of 250 ns, in which are distinguished the two groups of ions: first group consists of accelerated deuterons, and the second one consists of carbon, as more heavy ions, but with greater energy, herewith, lag time between ion packages amounts not more than 300 ns.

**Figure 3.** Oscillogram of signal from the collector with laser plasma, but without PVG.  
**Figure 4.** Oscillogram of signal from collector with PVG, without laser plasma.  
**Figure 5.** Oscillogram of signal from collector, with laser plasma and PVG.

Within the scope of work the method of plasma collective acceleration with rapid-growing magnetic field is implemented and the maximum speed of ion flux of $3 \times 10^8$ cm/s is achieved, which for deuterons corresponds to the energy of about 100 keV. The evaluation shows that the total number of accelerated deuterons amounts about $10^{15}$ (at collector, at the distance of 50 cm from coil, $10^{13}$ ions are recorded). Thus, at directing of accelerated deuterons beam to near-coil deuterium-containing target it is possible to achieve the emission of $10^8$ neutrons per a pulse. Herewith, the duration of neutron pulse is about 30 ns. Current density for accelerated deuterons reaches 1 kA/cm$^2$ at pulse duration of about 30 ns.

Consequently, by means of these neutron generators it is possible to implement the delayed neutrons method. Studied method of plasma acceleration with rapid-growing magnetic field may be used for development of neutron intense pulse generators, ion injectors for accelerators, plasma engines and other applications.

In order to optimize the system of laser plasma acceleration in rapid-growing magnetic field currently are performed works on modernization of test bench for provision of variation of synchronization of laser pulse initiation from start to maximum of magnetic field of coil with current.

5. Summary
In early works the increase of spread velocity of laser plasma created with radiation of portable lasers amounted from $10^7$ to $3 \times 10^7$ cm/s. Within the scope of the present paper a laser plasma deuteron accelerator to velocities higher than $10^8$ cm/s was created, which allows the initiation of nuclear reaction D+D, D+T by them. Within the scope of work the rate of magnetic field growth of $2 \times 10^7$ T/s was achieved, which is 1–2 orders of magnitude higher than in the previous experiments.

Calculations allow formulating of requirements to the experiment conditions and test plant design. They also allow compiling of recommendations on further experimental research. For example, it is necessary to provide a possibility of laser target motion along the magnetic system axis, as well as the possibility of laser and magnetic system independent startup. These activities allow selecting of optimal acceleration and neutron generation mode.

It is also worth noting that the developed system allows for mode of neutron generation (including thermonuclear ones) at counter fluxes during plasma generation and for locating of magnetic field generation systems in two different points of space on one axis. In this case the problem related to
degradation of solid neutron-generating targets is resolved. There also occurs a possibility of fast accumulated running time of packed solid targets at using of deuteron-tritium laser targets.

Acknowledgments
This work has been supported by National Research Nuclear University MEPhI in the framework of the Russian Academic Excellence Project (contract No. 02.a03.21.0005, 27.08.2013).

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