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COLLECTIVE ACCELERATION OF LASER PLASMA IN NON-STATIONARY AND NON-UNIFORM MAGNETIC FIELD

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Abstract

This paper provides new experimental results of the research on the acceleration of laser deuterium-containing plasma in a quickly growing maximally symmetrical non-uniform magnetic field for the purpose of initiation of nuclear reactions D(d, n)^{3}He and T(d, n)^{4}He. As it was in the previous series of experiments for the laser plasma generation, the Nd: YAG laser (λ = 1.06 μm) was used with the impulse power of W ≤ 0.85 J and duration of τ ≈ 10 nsec. During its radiation focusing at a dielectric target made of deuterated polyethylene $(CD_2)_n$ in a vacuum of ~ 10^{-4} torr, the power density of about $5 \cdot 10^{15}$ W·m^{-2} was reached. A quickly growing magnetic field with the values to 10^8 T/sec was formed during the capacitive discharge after being charged to the voltage of ~ 100 kV with the current to 5 kA for a conical nichrome coil of 3 cm long and with the 45° vertex angle. The ion velocity was determined as per the time-of-flight method with the help of a collector made as a Faraday cylinder. Within the framework of this paper, the method of collective plasma acceleration was realized, and the maximum ion flow velocity of $2 \cdot 10^8$ cm/sec was reached, i.e. deuteron flows up to 10^{12} ions with the energy of ~ 100 keV were obtained.

INTRODUCTION

Laser-plasma ion source becomes more and more widespread among different types of ion sources. Some reasons it its advantages: high density of ion flow (to 1 kA/cm^2), high resource (target mass consumption of ~ 10^{-7} g per 10^{14} ions). An efficient ion flow in such a source is formed due to the expansion of plasma bunch, formed on the surface of solid target in a vacuum with the laser radiation pulse with the power density of more than 10^{10} W/cm^2.

The papers [1, 2] described the principle of laser plasma acceleration in a quickly growing non-uniform magnetic field formed during a discharge of reserve capacity to a thin ring circuit (Fig. 1).

Plasma is formed in a moment t_0, counted from the beginning of the reserve capacity discharge as a result of focusing of impulse laser radiation at a deuterium-containing solid target. As a result of magnetic field growing, the plasma excites azimuthal current. When this current interacts with the magnetic field, the ponderomotive force occurs, and its longitudinal component can accelerate the laser plasma bunch towards the system axis. The circuit creating the magnetic field usually is a coil of *N* turns.

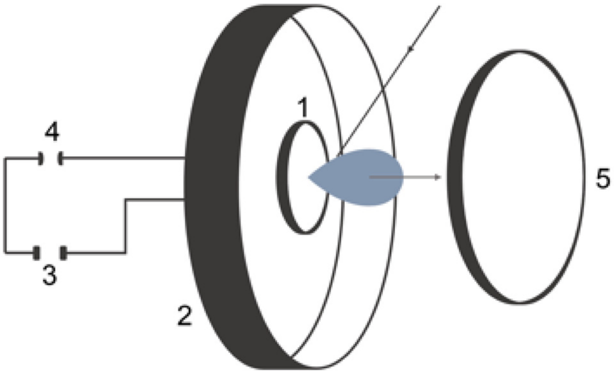

Figure 1: Accelerations of laser plasma bunch in moment of its formation: 1 – plasma-forming target; 2 – live ring circuit; 3 – capacitive energy storage; 4 – arrester; 5 – neutron-forming target.

The papers [3-6] experimentally showed the principal possibility of such acceleration. A laser generating radiation impulses with the wavelength of 1.06 μm, power of W ≤ 0.85 J and duration of τ ≈ 10 nsec were used for getting plasma. An Arkadyev-Marx circuit of high-voltage pulse oscillator (U ~ 400 kV) with load current limitation to I ≤ 1.5 kA was applied for the current excitation in an inductance coil. The power flow density per q ≈ $5 \cdot 10^{15}$ W/m^{-2} was provided at a target of deuterated polyethylene. The pulsed magnetic field with the growing speed to $2 \cdot 10^7$ T/s was created when a surge with the amplitude of U ≈ 300 kV and duration of τ ≈ 30 ns was inputted to the coil with the inductance of L ≈ 0.65 μH.

Time-of-flight measurements showed that the velocities of accelerated deuterons in experiment reached the values of $3 \cdot 10^6$ m/s what corresponds to the kinetic energy of T_d~100 keV.

The main disadvantage of these studies is the high level of electromagnetic interference. This interference is associated with the breakdown of air spark gaps. This sharply reduced the accuracy of the measurements.

PHYSICAL MODEL

A model, which allows the representation of the expansion of plasma formed during the interaction of a short laser impulse with a solid-state target as an expanding spherical plasma cloud, which center moves towards the perpendicular surface of laser target with the plasma front expansion velocity is used for valuating physical calculations.

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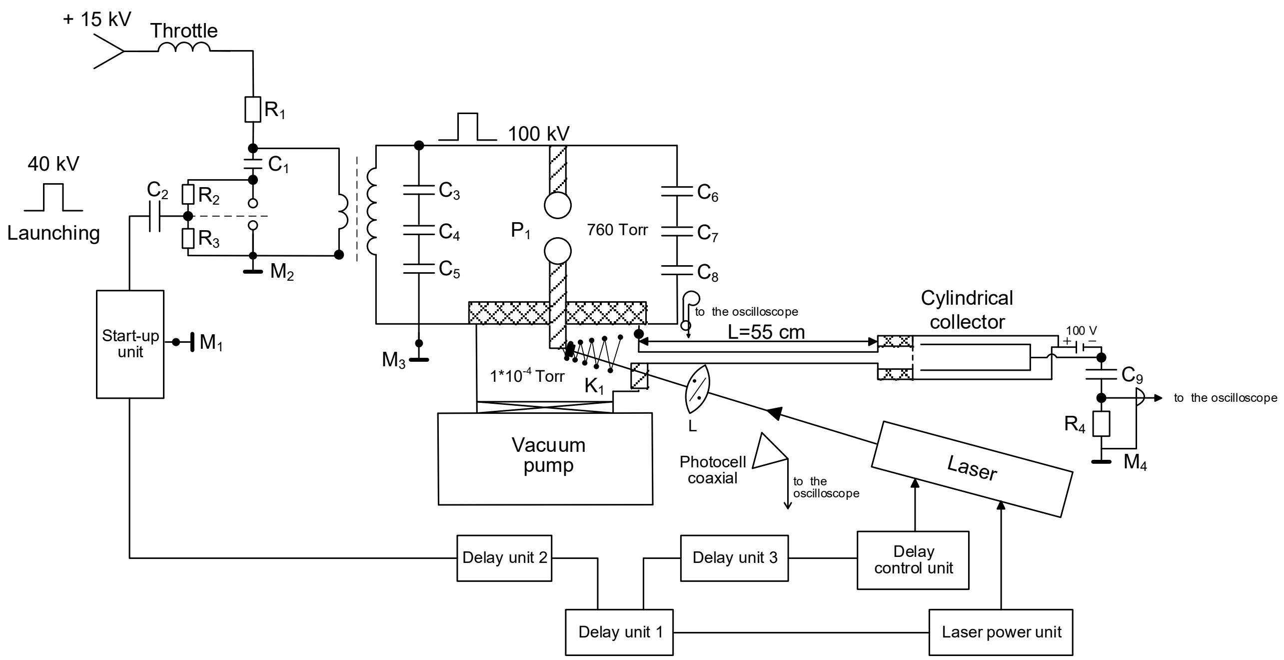

Figure 3: Scheme of experiment on collective acceleration of laser plasma ions in non-standard magnetic field (R_1 = 100 kΩ, R_2-R_3 = 220 MΩ, R_4 = 50 Ω, C_1 = 0,6 μF, C_2 = 470 pF, C_3-C_8 = 5.3 nF, C_9 = 0.1 μF, M_1-M_4 – weight, L – lens, P_1 – air gap, K_1 – nichrome coil, 7 turns).

In general, the quickly growing magnetic field is formed with the help of a spiral line of K turns, expanding along the axis, z according to the following geometrical relations:

$$b_i = b_0 + \frac{i}{K-1} b_{K-1}, \quad h_i = \frac{i h_{K-1}}{K-1}$$

where b_i is the radius of the i-th turn, h_i is the distance from the focal point to the i-th turn.

The current impulse is supplied to the spiral

$$I(t) = I_0 \sin(\pi \frac{t + \tau_з}{\tau})$$

where $\tau_з$ is a delay of laser impulse relative to the current impulse.

The components of induction vector are defined by the following equations:

$$B_z(r,z,t) = I(t) \sum_{i=0}^{K-1} B_{zK}(b_i, r, z - h_i)$$

$$B_r(r,z,t) = I(t) \sum_{i=0}^{K-1} B_{rK}(b_i, r, z - h_i)$$

where $B_{zK}(a, r, z, t)$, $B_{rK}(a, r, z, t)$ are the components of induction vector of the magnetic field created by single direct current.

Eddy current appears in the process of magnetic field growing in the area of plasma formation. The azimuth component of this current with the volumetric density of

$$j(r,z,t) \approx \frac{\pi I_0}{\tau} \cos(\frac{t + \tau_з}{\tau}) \sum_{i=0}^{K-1} B_{zK}(b_i, r, z - h_i)$$

interacts with the radial component of the magnetic field and creates the Ampere-Lorentz electromagnetic force of $F_z \sim [\vec{j}\vec{B}]_z = j_\varphi \cdot B_r$, accelerating the plasma in the axial direction (Fig. 2).

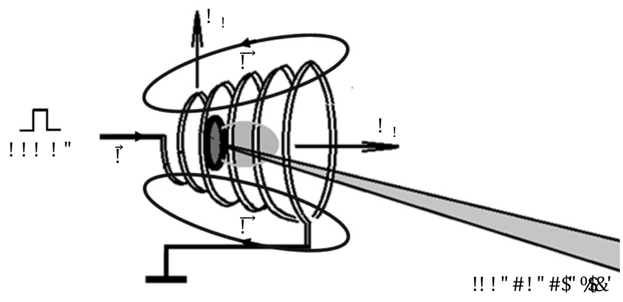

Figure 2: Accelerating magnetic field (I=5 kA, B_z = 6 T, B_r = 1 T).

EXPERIMENTAL RESULTS

Figure 3 specifies a new scheme of experiment on collective acceleration of laser plasma ions in a non-standard magnetic field. A laser on the neodymium-activated yttrium aluminum garnet which generates impulses of infrared radiation (λ = 1.06 μm) with the power of W ≤ 0.85 J and duration of τ ≈ 10 nsec in the modulated storage factor mode was used for getting deuterium plasma. Angular divergence of laser radiation $3 \cdot 10^{-3}$ rad. When its radiation was focused at a dielectric target of deuterium polyethylene $(CD_2)_n$, the power density of about $5 \cdot 10^{15}$ W·m^{-2} was reached. A ~ 100 kV, 5 kA high-voltage impulse oscillator with a forming line, which discharged at a conical coil with the vertex angle of 45°, was used for the purpose of generation of a quickly growing magnetic field. The minimal coil has the 0.8 cm diameter, 3 cm length, 6 turns, inductance of L = 0.65 μH.

The ion speed was determined as per the time-of-flight method with the registration of ion current at a collector made as a Faraday cylinder, which is installed at a distance of 0.5 m from the laser target. The synchronization of laser impulse and plasma bunch formation, and the moment of magnetic field growing were obtained within the framework of the experiment (Fig. 4). In this case, it is possible to change the synchronization with the help of delay blocks.

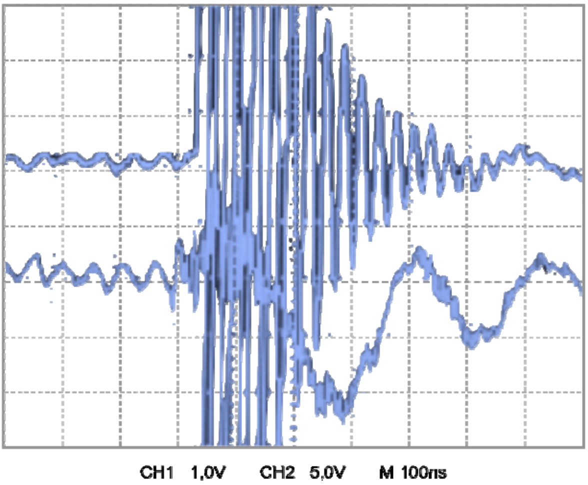

Figure 4: Synchronization: the photocell pulse of a coaxial (laser, channel 1), the current of the forming line (channel 2).

In this case, it is possible to change the synchronization with the help of delay blocks. In Fig. 5 and 6 show the characteristic oscillograms of the experiments performed. In Fig. 5 shows the photocell signal of the coaxial (the beginning of laser radiation) and the ion current in the collector in the absence of a rapidly increasing magnetic field.

One of the advantages of this series of experiments is the absence of interference on the collector. We note that the electronic component in the Faraday cylinder was removed by a transverse magnetic field. In Fig. 6 shows the ion current on the collector when a fast-growing magnetic field is applied.

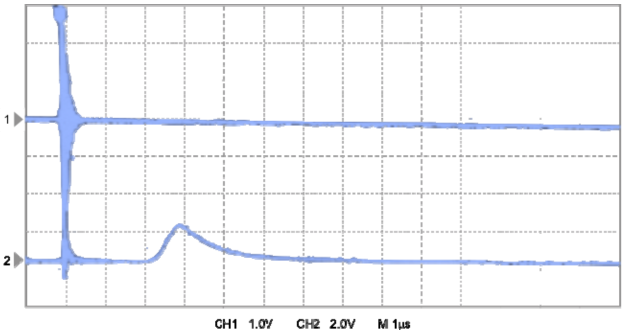

Figure 5: The photocell of the coaxial (laser) pulse (channel 1), the ion current on the collector in the absence of a rapidly increasing magnetic field (channel 2).

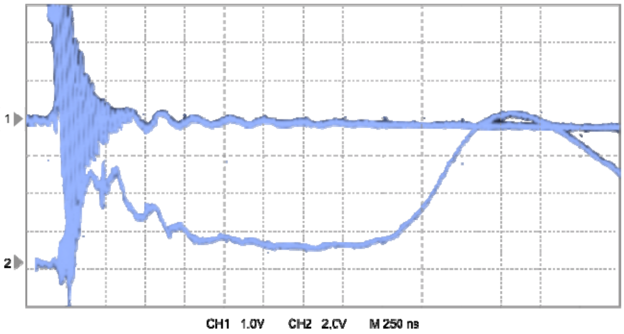

Figure 6: The photocell of the coaxial (laser) pulse (channel 1), the ion current on the collector when a rapidly increasing magnetic field is applied (channel 2).

On the oscillogram, you can see that the plasma breaks into a fast and slow part. The slow part increases by 3.5 times because of the heating of the plasma by a rapidly increasing magnetic field. The velocity of accelerated ions of the "fast" part was $2 \cdot 10^8$ cm/sec, "slow" – $1.7 \cdot 10^7$ cm/sec. An estimate for the "fast" ions shows that 10^{12} pieces are accelerated with a total number of 10^{15} ions.

CONCLUSION

Within the framework of this paper, the method of collective plasma acceleration by a quickly growing magnetic field was realized, and the maximum ion flow velocity of $3 \cdot 10^8$ cm/sec was reached, that is the power of about ~ 100 keV for deuterons. The measured total quantity of accelerated deuterons is about 10^{12} with the magnetic field growing speed of 10^8 T/s. So, when a bunch of accelerated deuterons is directed at a deuterium-containing target located near the coil, the output of 10^5 neutr./imp. can be reached. Further studies require the study of the angular distribution of the expansion of fast ions, including in order estimating their number.

The proposed system allows the neutron generation mode including, perhaps, the thermo-nuclear one, at counter fluxes of collectively accelerated laser plasmas when using two similar accelerators located coaxially and face to face.

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