The acceleration of laser plasma in a strong non-stationary magnetic field

A. Shikanov, E. Vovchenko, K. Kozlovskii, A. Isaev, A. Plekhanov and M. Lisovskii
National Nuclear Research University “MEPhI”, 115409, Russia, Moscow, Kashirskoe highway, 31
edvovchenko@mail.ru

Abstract. Based on experimental and computer simulation the acceleration of deuterons from laser plasma in a strong non-stationary magnetic field was studied. The possibility of reaching an energy of ~100 keV, corresponding to the effective course of the nuclear reactions $^3$D $(d, n) ^3$He and $^4$T $(d, n) ^4$He, was demonstrated. YAG: Nd$^{3+}$ laser ($W \leq 0.85$ J, $\tau \approx 10$ ns) was used in the experiment with focusing laser radiation on a deuterated polyethylene target. The high voltage pulse generator with a conical spiral coil was used to generate a high-speed magnetic field ($2 \times 10^7$ T/s). A mathematical model of the process is proposed. According to this model, the acceleration of a laser plasma is analyzed by means of a computer. The algorithm is based on a numerical solution of the system of Newton-Lorentz equations.

1. General
It is possible to use various methods of accelerating deuterons to create portable pulse neutron generators (PNG) based on the nuclear reactions $^3$D $(d, n) ^3$He and $^4$T $(d, n) ^4$He. The most popular methods so far are methods of direct acceleration of deuterons, in which the additional increase energy is realized in a single pass in an electric field. This field is formed with the help of high voltage pulse generators. In this case, the main efforts are aimed at reducing the influence of the space charge and the electron emission current, respectively, which limit the deuteron current density and the efficiency of their acceleration.

An alternative method of the acceleration of deuterons without these shortcomings, based on the expansion of a quasineutral laser plasma in a nonstationary strong magnetic field, is considered in the article. Experimental results and theoretical estimates are given. The prospect of such studies is related to the possibility of their application in development of PNG, plasma engine and ion injection systems for accelerators. The main goal of the research is to accelerate the deuterons of the laser plasma to velocities of $\sim 3 \times 10^6$ m/s and more. This corresponds to deuteron energies $\geq 100$ keV and allows efficient initiation of the nuclear reaction $^3$D $(d, n) ^3$He and $^4$T $(d, n) ^4$He.

The idea of such acceleration is not new and was known at the end of the last century [1]. Later, it was developed in works [2, 3], where the principle of the acceleration of a laser plasma in a high-speed ($\sim 100$ ns) inhomogeneous magnetic field is used. It field is formed when a storage capacitance is discharged onto a conducting ring with a radius of $\sim 0.01$ m. At that time, a qualitative model of an acceleration of laser plasma is proposed. Based on it the requirements for the experimental design is formulated. A new interest in such studies is caused by the appearance and availability of a compact high-power lasers which provide wider experimental possibilities.
2. Physical principle and experiment

The induction mechanism of acceleration is based on the interaction of an external variable magnetic field with a laser plasma, as a conducting medium. Laser plasma is created by the action of intense laser radiation on a solid-state dielectric target. The laser target is surrounds by an induction coil with a current passes through it. This current pulse is synchronized with the laser pulse.

A rapidly increasing magnetic field $\mathbf{B}$ induces an eddy current $\mathbf{j}$ in a laser plasma. The azimuthal component of this current $j_\varphi$ interacts with the radial component of the magnetic field $B_r$, and creates the electromagnetic Ampere-Lorentz force $F_x \approx [j_r \times B_r]_z = j_\varphi \cdot B_r$. This force accelerates the plasma in the axial direction. We note that in this physical model the laser plasma is consider as a continuous medium in which a quasineutrality violation does not occur at a macroscopic level. This removes the limitations associated with the space charge. Ions are accelerated in the presence of electrons. However, at the same directed velocity, the main energy of the flow due to the mass difference is determined by the ions. The energy of accelerated deuterons in such a system can reach ~100 keV, which is necessary for efficient neutron generation.

![Fig. 1. The scheme of the deuterons accelerating experiment](image)

The scheme of the deuterons accelerating experiment with using laser plasma in high-speed magnetic field and the time-of-flight collector measurements of the velocity of these deuterons is shown in Fig. 1. Nd: YAG laser ($\lambda = 1.06 \, \mu$m) with energy per pulse $W \leq 0.85 \, J$ and pulse duration $\tau \approx 10 \, \text{ns}$ was used to generate laser plasma. A power density of the order of $5 \times 10^{15} \, \text{W/m}^2$ was achieved by focusing its radiation on a dielectric target of deuterated polyethylene ($\text{CD}_2)_n$. The moment of appearance of the laser pulse on the target was registered with a coaxial photocell FEK–22SPU.

A high-speed magnetic field in the laser target was created using a pulsed current through an induction coil. The coil was made in the form of a conical helix with the vertex angle of the cone $2\alpha \approx 20^\circ$. Coil parameters: $r_{\text{min}} = 7.5 \times 10^{-3} \, \text{m}$, $r_{\text{max}} = 12.5 \times 10^{-3} \, \text{m}$, length $3 \times 10^{-2} \, \text{m}$, number of turns $N = 6$, inductance $L = 0.65 \, \mu\text{H}$. Two type of pulse high voltage generators were used to excite current in the induction coil: "fast" generator with high voltage ($U \sim 400 \, \text{kV}$) and current in load less then 1.5 kA; "slow" generator with more lower voltage ($U \sim 100 \, \text{kV}$) but a current up to 10 kA. The ion velocity was determined by the time-of-flight method with registration of the ion current on the collector as Faraday cylinder. The collector was installed at a distance of 0.5 m from the laser target.

In the first series of experiments, the Marx generator [4] was used. This device allows receiving a high voltage pulse with an amplitude of up to 450 kV with a stored energy of up to 50 J and, as noted above, a current in the load up to 1.5 kA. The results of these preliminary experiments was described in [5] and are given here for comparison and analysis. The pulse duration of the current flowing through the induction coil is 30 ns. The velocity of increase of the magnetic field reached up to $2 \times 10^7 \, \text{T/s}$. For these conditions, the velocity of the fastest component of the ion flux was $\sim 10^6 \, \text{m/s}$, but the bulk of the deuterons had a lower velocity of $\sim 5 \times 10^5 \, \text{m/s}$. In this case, up to $10^{13}$ ions arrive at the collector, and the total number of accelerated ions is $10^{15}$. It should be noted a high level of electromagnetic interference, caused by a cascade breakdown of air spark gaps in the scheme Marx generator. Since this markedly limited the accuracy of the measurements, all the measured values should be considered only an estimate. As an illustration, Fig. 2a shows the oscillogram of the current from the collector (upper beam) and the current in the induction coil (lower beam).
New results were obtained using a more powerful generator, performed based on pulse charging of the storage capacitance from a high-voltage pulse transformer. When the voltage is reached the value about 100 kV, a breakdown of the spark gap and the discharge of the capacitance onto the induction coil generating a magnetic field occurs.

The maximum current can be estimated by neglecting the active resistance using the ratio \( I_{\text{max}} = \frac{U}{(C_n/L)^{1/2}} \approx 10 \, \text{kA} \), where \( C_n = 4.4 \, \text{nF} \) is the total capacitance of high voltage storage and \( L = 0.65 \, \mu\text{H} \) is the coil inductance. The capacitance \( C_n \) has 12 sections, and each section consists of six 2.2 nF capacitors connected in series. The sections are arranged symmetrically with respect to the axis of the cylinder, on which the spark gap is installed. This design has significantly reduced the level of electromagnetic interference.

The oscillogram of the current from the collector (upper beam) and the laser pulse (lower beam) are shown in Fig. 2b. It can be seen that a sufficiently large group of fast deuterons (~30% of the total number) reaches the collector trough 500 ns after the laser pulse is has come to the (CD\(_2\))\(_n\) target, and the slowest group of deuterons – is no later than 1000 ns. Their velocities are respectively is equals to \(~10^6\) m/s and \(5\times10^5\) m/s. The second maximum on the collector current pulse is due to a group of slower carbon ions.

3. The model of acceleration of ring current

A mathematical model of the behavior of an axially symmetric laser plasma in a nonstationary magnetic field for the purpose of analyzing and selecting the optimal conditions for a physical experiment was developed. Axial symmetry makes it possible to represent a laser plasma as a superposition of toroidal plasmas.

The basis of the computational model was the problem of accelerating an individual plasma toroid surrounded by a single conductive ring with a current that creates a magnetic field [6]. To estimate the energy, we use the notion of the acceleration field \( f(r, z, t) \). Variable parameters: \( r \) is the transverse size of the plasma; \( z \) is the distance between the conductive ring and the laser target with displacement toward the incident laser radiation; \( t \) is the time delay of plasma formation in relation to magnetic field build-up.

The time-increasing magnetic field produced by the current \( I(t) \) when the capacitor is discharged to the single conductive ring can be determined through the components of the magnetic induction vector [7]

\[
B_r(r, z, t) = I(t) \cdot B_{or}(r, z) \quad \text{and} \quad B_z(r, z, t) = I(t) \cdot B_{oz}(r, z),
\]

where

\[
B_{or}(r, z) = \frac{\mu_0}{2\pi r} \left[ E(k) \frac{a^2 + r^2 + z^2}{(a - r)^2 + z^2} - K(k) \right] \frac{z}{\sqrt{(a + r)^2 + z^2}},
\]

\[
B_{oz}(r, z) = \frac{\mu_0}{2\pi} \left[ E(k) \frac{a^2 - r^2 - z^2}{(a - r)^2 + z^2} + K(k) \right] \frac{1}{\sqrt{(a + r)^2 + z^2}},
\]
\( \mu_0 \) is the magnetic constant, \( a \) is the radius of the conductive ring with current, \( K(k) \) and \( E(k) \) are complete elliptic integrals with argument

\[
k(r, z) = \frac{4ar}{\sqrt{(a+r)^2 + z^2}},
\]

(4)

and the current in the discharge circuit with capacitance \( C \), resistance \( R \) and inductance \( L \) is equal to

\[
l(t) = \frac{C}{2L} \exp \left( -\frac{R}{2L} t \right) \sin \left( \frac{t}{\sqrt{LC}} \right).
\]

(5)

The azimuthal vortex electric field arises because of a temporal changing of the magnetic field. This vortex field is primarily determined by the rate of current rise in the circuit

\[
E_\phi(r, z, t) \approx -\frac{d}{dt} \frac{F_L(r, z, t)}{B_L(r, z, t)}.
\]

(6)

In this case, an azimuth current with a density \( j(r, z, t, \theta) = \sigma(\theta) \cdot E_\phi(r, z, t) \) is excited in the plasma, which interacts with the radial component of the field \( B_r(r, z, t) \) and creates ponderomotive force, that acts on an element of unit volume of the plasma

\[
F_L(r, z, t) = \sigma(\theta) E_\phi(r, z, t) B_r(r, z, t),
\]

(7)

where \( \sigma(\theta) \) is the conductivity of the plasma, which depends on the temperature \( \theta \). The relation determines the acceleration field corresponding to this force

\[
f(r, z, t) = \frac{\sigma(\theta) E_\phi(r, z, t) B_r(r, z, t)}{M_n},
\]

(8)

where \( M \) is the deuteron mass, and \( n \) is the electron density.

The algorithm for calculating the acceleration field \( f(r, z, t) \) was developed on the basis of a mathematical model, a numerical experiment was performed to determine the optimal conditions for the acceleration of a laser plasma in a rapidly growing magnetic field, and recommendations were obtained for setting up a real physical experiment. The main conclusions are given below:

- optimal conditions for interaction of the plasma with the magnetic field are achieved when the plasma-forming target is located at a distance \( z_0 \approx (0.15 - 0.20)a \) from the plane of the conductive ring with a current in the direction of the plasma expansion;
- the acceleration of deuterons increases monotonically with increasing radius of the focusing ring and reaches a maximum at \( r_0 \approx 0.9a \);
- the decrease in the transverse dimension of the plasma, due to the focusing properties of the magnetic field, leads to reducing the influence of \( B_r(r, z, t) \), and means to reduction of acceleration force \( F_L(r, z, t) \) in the axial direction and the decreasing of characteristic length of acceleration;
- the acceleration of deuterons increases monotonically with increasing parameter \( (U^2C^{1/2})/L^{3/2} \).

4. The theoretical model of acceleration in geometry of conical spiral

The next step in the development of the model (1) - (8) was the transition from the single conductive ring with a current to the model in which the magnetic field is formed by an induction coil in the form of a conical spiral of \( N \) turns. This coil expands along the \( Z \) axis in accordance with the following geometric with ratios:

\[
b_i = b_0 + \frac{i}{N-1}(b_{N-1} - b_0), \quad h_i = \frac{i}{N-1}h_{N-1},
\]

(9)

\( b_i \) is the radius of the \( i \)-th turn, \( h_i \) is the distance from the point of focusing to the plane of the \( i \)-th coil. In this case, to determine the components of the vector of induction instead of formula (1) is necessary to consider the total contribution of each coil

\[
B_x(r, z, t) = I(t) \sum_{i=0}^{N-1} B_{ix}(b_i, r, z - h_i) \quad \text{and} \quad B_y(r, z, t) = I(t) \sum_{i=0}^{N-1} B_{iy}(b_i, r, z - h_i)
\]

(10)
\(B_N(b_i, r, z - h_i)\) and \(B_zN(b_i, r, z - h_i)\) are defined by formulas (2) - (4), replacing the radius \(a\) by \(b_i\) and replacing the current coordinate \(z\) by \(z - h_i\). \(I(t)\) is the current in the induction coil. In contrast to (5), we will be considered current \(I(t)\) is harmonic in order to simplify the calculations

\[
I(t) = I_0 \sin \left( \frac{\pi t}{\sqrt{L/C}} \right);
\]

where \(\tau\) is the laser pulse delay relative to the beginning of the current in the induction coil. Vortex electric field \(E_{\phi}(r, z, t)\) (6) occurs as the result of high-speed increasing of the magnetic field. Due to this processes the azimuthal current is excited in the laser plasma. The density of current is

\[
f(r, z, t) \approx \sigma \left( \frac{t}{2} \right)^{N-1} b_i^3 \cdot \frac{\pi I_0}{\sqrt{L/C}} \cos \left( \frac{\pi t + \tau}{\sqrt{L/C}} \right).
\]

The corresponding magnetic moment is equal to

\[
L(r_c, z_c, t) = \frac{1}{2} \int [r, j] dV \approx \frac{1}{2} \int \int \int j \cdot r^2 dr \cdot dz \cdot dp \approx \pi \int \int \int j \cdot r^2 dr,
\]

where \(B_N(r, z, t)\) is the value of the longitudinal component of the magnetic field induction vector at the center of gravity of the plasma \[8\].

The system of equations of motion of the center of gravity of a deuteron avalanche with total mass \(\Delta m\) has the following form

\[
\frac{dV_c}{dt} = \frac{F(t, z_c, r_c)}{\Delta m},
\]

\[
\frac{dz_c}{dt} = V_c,
\]

\[
\frac{dr_c}{dt} = V_\perp(t),
\]

with the initial conditions \(V_c(0) = V_0; z_c(0) = r_0; r_c(0) = r_0\). The average energy of an accelerated deuteron in a bunch is determined by the following formula

\[
T(t) = \frac{10^{-3} M}{2e} V_c^2 [\text{keV}].
\]
The computer program is designed to solve the system of equations (16), (17) numerically, taking into account conditions (11) - (15). The calculated dependence of the average kinetic energy of an accelerated deuteron on time is shown in Fig. 3 as an illustration. These results correspond by time delay \( \tau = 60 \) ns between the laser pulse and the beginning the current in the induction coil. The calculation is made for \( N = 6; h_2 = 0.03 \) m; \( b_0 = 0.005 \) m; \( V_0 = 2 \cdot 10^5 \) m/s; \( I_0 = 10^4 \) A.

**Fig. 3.**
Modeling of kinetic energy of deuterons

5. Summary
Based on experimental and computer simulation the acceleration of deuterons from laser plasma in a strong non-stationary magnetic field was studied. The results of the modeling calculations showed that the energy of the directed motion of deuterons increases approximately by 40–50 times during a time of 60 ns. This corresponds to an increase in speed to \( 10^6 \) m/s. In this case, the deuterons have an energy of \( \sim 100 \) keV, and this agrees with the experiment. It is acceptable for the generation of neutrons in the synthesis reactions of heavy hydrogen nuclides.

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