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On a magnetic confinement of femtosecond laser pulse plasmas

V.S. Lisitsa[a] and A.A. Skovoroda

Nuclear Fusion Institute of RRC "Kurchatov Institute", Moscow, Russia

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Abstract. Perspectives of magnetic confinement for the increase of life times of laser plasmas generated by femtosecond laser pulses are considered. Possibilities that are provided by miniature magnetic cusp configurations with magnetic fields of moderate intensities (of order of Teslas) are investigated. The construction of micro-traps with permanent magnets, making it possible to increase neutron yield, seems to be very simple and possible for most modern "table top" laser experiments.

PACS. 52.50.Jm Plasma production and heating by laser beams (laser-foil, laser-cluster, etc.)

1 Introduction

Applications of laser plasmas for both thermonuclear synthesis and neutron sources are limited by small plasma confinement times. In the last decade special attention has been devoted to ultra short laser pulses in the pico- and femtosecond regimes where high light intensity densities (of the order of 10^{19}–10^{21} W/cm^2) provide large ion energies (temperature), sufficient to overcome a thermonuclear reaction threshold. The problem of plasma confinement under such extreme conditions (plasma density is more than 10^{19} cm^{-3}) becomes even more complicated compared with nanosecond laser plasmas. This problem leads to interest in the problem of plasma confinement by external magnetic fields, as a way to increase plasma confinement time. It is clear however that a straightforward solution of the problem on the basis of known magnetic configurations will be faced with the problem of many applications requiring superstrong (of the order of a hundred Teslas) magnetic fields. It was suggested in [1,2] that the plasma lifetime could be increased by an application of a strong magnetic field (>50 T) in order to increase neutron yield. Large values of the magnetic field are connected with the goal of generating a magnetic pressure of the same order as the plasma pressure.

New possibilities provided by miniature magnetic configurations with magnetic fields of moderate intensities (of order of some Teslas) for femtosecond laser plasma confinement are under investigation in the present paper. The magnetic traps under consideration are very simple and available for most modern "table top" laser experiments.

[a] e-mail: lisitsa@nfi.kiae.ru

2 The principle of adiabatic confinement of femtosecond laser plasmas

The general idea of magnetic confinement of femtosecond laser plasma pulses is based on peculiarities of the plasma dynamics. These peculiarities are connected with a sharp difference in the evolution of electron and ion temperatures under the action of laser radiation on targets. The difference is due to the fact that electrons move in the laser field undergoing intense energy exchange with one another, whereas their energy exchange by collision with ions is a relatively slow process due to large mass difference between electrons and ions. For example, the electron-electron Coulomb collision time is of the order of 10^{-9} s for plasma density $\sim 10^{19}$ cm^{-3} and temperature $\sim$10 keV, three orders of magnitude less then the energy relaxation time in collisions between ions and electrons. Energy exchange within the ionic component is essentially zero compared to the electronic component [3]. Ionic motion in the absence of a magnetic field is ballistic with rare collisions. Interaction between the electronic and ionic subsystems arises due to a space separation of their charges and a creation of correspondingly strong electric fields.

The dynamics of electronic and ionic subsystems described above has been observed many times in laser radiation interaction both with thin metallic foils and cluster targets [3,4]. In both cases electrons captured by the laser field have been extracted from the target's material. Further ion acceleration is due to a space charge of extracted electrons or/and due to Coulomb repulsion between ions in a cluster (the Coulomb explosion [1–4]).

The evolution of electron and ion subsystems mentioned above makes it possible to look for a magnetic confinement of femtosecond laser plasmas based on the adiabatic nature of electron expansion and their magnetic confinement. The ions are confined by the electric field arising due to charge separation.

Let us consider a magnetic cusp trap of a small size (of order of some millimeters) which is however essentially larger than the size of laser spots in modern experiments (of order of hundred microns). The structure of the magnetic field in the cusp looks like a magnetic wall, that is, the field takes the zero value in the center of the cusp with its growth at the periphery. Let us describe this growth by the relation $B = B_m\,(V/V_m)^{1/3}$, where V is a plasma volume, V_m is a maximum volume of the trap. If a target is placed in the center of the trap, the magnetic field doesn't produce any strong effect on the plasma dynamics described above. The plasma expansion stops at the magnetic wall. So three general steps corresponding to different times can be defined, namely: (0) plasma creation during the action of a laser pulse, (1) plasma expansion up to the magnetic wall and (2) quasi-steady state confinement.

A description of the expansion step is a rather difficult kinetic problem. We suppose here an extremely simple expansion scenario, that can be considered as a pessimistic one. The expansion is a two-step process. At the first step the electronic motion is described by the adiabatic law (adiabatic cooling) whereas ions don't change their energies, moving in a ballistic manner. Naturally the density drops inversely proportionally to the increase of the plasma volume, that is, the conservation of total particle numbers is supposed. The electron expansion continues up to the moment when the electron pressure will be equal to the magnetic field pressure. At this moment the electron Larmor radius becomes smaller then the plasma size (magnetized electrons) whereas the ion Larmor radius remains larger then the plasma size (nonmagnetized ions). After this moment, electrons confined by the magnetic field break away from the nonmagnetized ions. This results in the appearance of an electric field due to the charge separation, which confines the ions as well. Electron heating is also possible in the process followed by further displacement of the magnetic field [5]. It is difficult at present to describe the process in detail. However, being interested in the plasma parameters of the final step of the process, let us suppose that an adiabatic evolution of the total plasma pressure takes place at the step with equalizing of electron and ion temperatures. The expansion will be finished when the total plasma pressure is equal to the magnetic pressure.

Let us suppose that there was a plasma generated at the initial moment of time with a volume V_0, electron pressure $p_{e0} = n_0 T_{e0}$ and partial ion energy $p_{i0} = n_0 E_{i0}$ (the density n_0 of electrons and ions is taken to be the same). The first step of the plasma expansion will be completed when the plasma volume is increased up to V_1

$$p_{e1} = p_{e0}\left(\frac{V_0}{V_1}\right)^{\gamma} = \frac{B_m^2}{8\pi}\left(\frac{V_1}{V_m}\right)^{2/3}. \tag{1}$$

The second step of the plasma expansion will be completed when $V_2 = V_m$ and

$$p_2 = \left(p_{i0}\frac{V_0}{V_1} + p_{e1}\right)\left(\frac{V_1}{V_m}\right)^{\gamma} = \frac{B_m^2}{8\pi}. \tag{2}$$

Here γ is an index of the adiabatic expansion. The total plasma pressure after the first step is generally determined by ions because of the electron cooling. Putting $p_{e0} = p_{i0} = p_0$ and neglecting the term p_{e1} in equation (2) we arrive at

$$\frac{V_0}{V_1} = \left(\frac{B_m^2}{8\pi p_0}\right)^{\frac{3\gamma+2}{3\gamma^2+2}}, \quad \frac{V_0}{V_m} = \left(\frac{B_m^2}{8\pi p_0}\right)^{\frac{6\gamma-1}{3\gamma^2+2}}. \tag{3}$$

The relationship for the energy change takes the form

$$\frac{T_{e1}}{T_{e0}} = \left(\frac{V_0}{V_1}\right)^{\gamma-1} = \left(\frac{B_m^2}{8\pi p_0}\right)^{\frac{(\gamma-1)(3\gamma+2)}{3\gamma^2+2}},$$
$$\frac{T_{e2}+T_{i2}}{E_{i0}+T_{e1}} = \left(\frac{V_1}{V_m}\right)^{\gamma-1} = \left(\frac{B_m^2}{8\pi p_0}\right)^{\frac{3(\gamma-1)^2}{3\gamma^2+2}}. \tag{4}$$

The indices 0, 1, 2 mark the steps described above.

In order to describe the confinement step let us use the expression for the plasma confinement time τ_c in a cusp with a displaced magnetic field [5]:

$$\tau_c \sim \tau_{ee}\frac{2Na}{\alpha\rho_0}, \tag{5}$$

where τ_{ee} is the electron-electron collision time, $\rho_0 = c/\omega_{pe}$, ω_{pe} is the plasma frequency, $a \sim V_m^{1/3}$ is a typical size of the confined plasma, $N \sim$ 5–10 is a number of Larmor radii at the half width of the magnetic cusp slit, $\alpha \sim$ 2–5.

The values of plasma parameters calculated from relationships above for a deuterium plasma with $B_m = 1$ T, $\gamma = 5/3$, $T_{e2} = T_{i2}$ and $N/\alpha = 2.5$ are presented in the Table 1. The same data for $B_m = 3$ T are shown in Table 2. The size a of the plasma is $a = 0.5\,V^{1/3}$, time of flight is $\tau_f = a/\sqrt{2E_i/m_i}$, confinement time is $\tau_c[\mathrm{s}] = 0.15a[\mathrm{cm}]T_e^{3/2}[\mathrm{eV}]n^{-1/2}[\mathrm{cm}^{-3}]$, and number of neutrons is $N = n^2 V \tau_{f,c}\langle\sigma v\rangle_{DD}$.

There are a lot of modern experiments on neutron generation during the interaction of femtosecond laser pulses with both thick and cluster deuterium targets, see [1,2]. Let us make more specific estimations of plasma parameters for experimental cluster plasma conditions [1]. The number $\sim 1.5\times 10^4$ of thermonuclear neutrons was obtained in irradiation of a thin stream (diameter 2 mm) of deuterium clusters by a laser beam (820 nm, 0.12 J, 35 fs). The neutron yield is in agreement with the measured plasma parameters (the length is 2 mm, the diameter is 0.2 mm, plasma volume is <0.1 mm^3, plasma density is 1.5×10^{19} cm^{-3}, the average electron and ion temperatures are 2.5 keV). Plasma lifetime 0.2 ns was determined by the ion flight time of the plasma diameter [1].

The neutron yield (as well as possible approach to the Lawson criterion) is determined by the multiplication of the confinement time on the reacting ion density

Table 1. Deuterium plasma parameters for maximum magnetic field $B_m = 1$ T.

Step	0		1		2	
n, cm^{-3}	10^{17}	10^{19}	1.7×10^{15}	7.7×10^{15}	5.4×10^{14}	9.9×10^{14}
$T_{e,i}$, keV	$T_{e0} = 10$	$T_{e0} = 10$	$E_{i1} = 10$	$E_{i1} = 10$	$T_{e2} + T_{i2} =$	$T_{e2} + T_{i2} =$
	$E_{i0} = 10$	$E_{i0} = 10$	$T_{e1} = 0.67$	$T_{e1} = 0.083$	4.62	2.55
V, cm^{-3}	10^{-4}	10^{-4}	5.9×10^{-3}	0.13	0.02	1.01
a, cm	0.023	0.023	0.09	0.25	0.13	0.5
τ_f, s	2.35×10^{-10}	2.35×10^{-10}	10^{-9}	2.7×10^{-9}		
τ_c, s					10^{-4}	1.1×10^{-4}
N	2.4×10^2	2.4×10^6	2×10^1	2×10^4	5.1×10^3	1.06×10^5

Table 2. Deuterium plasma parameters for maximum magnetic field $B_m = 3$ T.

Step	0	1	2
n, cm^{-3}	10^{19}	$3.4{\times}10^{16}$	6.6×10^{15}
$T_{e,i}$, keV	$T_{e0} = 10$, $E_{i0} = 10$	$E_{i1} = 10$, $T_{e1} = 0.22$	$T_{e2} + T_{i2} = 3.45$
V, cm^{-3}	10^{-4}	0.03	0.15
a, cm	0.023	0.16	0.27
τ_f, s	2.35×10^{-10}	1.7×10^{-9}	
τ_c, s			4×10^{-3}
N	2.4×10^6	1.2×10^4	10^6

$n\tau_c \langle \sigma v \rangle_{DD}$. Plasma volume increases up to the magnetic trap volume during the expansion, the plasma density, temperature and (as a consequence) neutron yield decreasing correspondently. The only factor responsible for the neutron yield increase is the essential increase of the confinement time.

The data presented in Tables 1 and 2 demonstrate that a significant increase in neutron yield can be seen even in the case of relatively weak magnetic fields. The strong dependence of DD reaction cross-section on ion temperature results in a smaller increase in the case of more dense plasmas. Remember that the isothermal model used for the estimations above results in the strongest decrease of the ion temperature in the expansion (the ion energy in the initial step of the magnetic confinement can in reality be significantly larger than the electron temperature). However the general conclusion is obvious, namely the more dense and hot the plasma obtained after the laser pulse action, the stronger the magnetic fields that must be applied in order to remove the ion cooling effect. The stronger the magnetic field, the more dense and hot plasmas (ions) are confined.

The examples presented above point to possibilities optimistic enough for selection of laser plasma parameters in order to obtain magnetic confinement conditions. It is clear however that the variation of possible values of the plasma parameters is broad enough, so from a practical point of view one has to look for experimental verification of the conditions identified above.

3 A magnetic trap for a confinement of femtosecond laser pulse plasmas

The main problem in the construction of such traps is a combination of miniature size of the trap (see Tab. 1) with large values of magnetic fields ($\sim$T). This is the case for the cusp used in the estimations above with a spatial increase of the magnetic field $\sim$10 T/cm. Construction of such traps seems at first view to be a hard technical problem. There exists however a very simple solution.

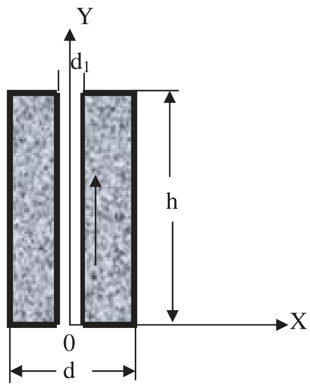

Fig. 1. Permanent magnet with a width d, a height h and a slit with thickness d_1. The arrow indicates the magnetic induction direction.

Let us demonstrate a method of miniature cusp trap construction on the basis of permanent magnets Nd–Fe–B (the magnetization is 1.2 T). In order to obtain the cusp geometry it is enough to make a hole of millimeter diameter in the magnet along the magnetic induction direction. Due to the fact that the field is directed along the magnetic induction vector inside the hole whereas it is directed in the opposite sense outside the magnet, one obtains a zero magnetic field at the surface of the magnet that is just the necessary condition for a miniature cusp. Naturally the cusp sizes are determined by the diameter of the hole and they can easily be chosen to correspond with specific experimental conditions.

One can obtain an image of the field geometry and the magnetic field values using known analytical expressions for plane magnet geometry (see Fig. 1). Analytical relationships are obtained by a solution of equations

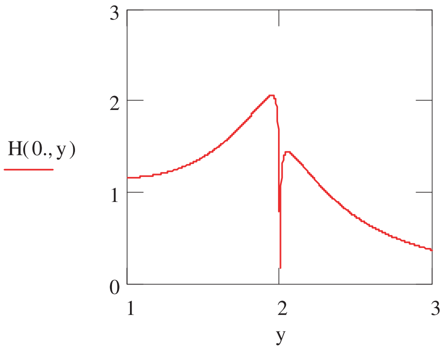

Fig. 2. A magnetic field strength distribution along Y-axis at $x = 0$ in the magnet shown in Figure 1; ($d = 1$ cm, $h = 2$ cm) with a slit diameter $d_1 = 0.01$ cm. The field strength is normalized to the value 0.6 T.

$\nabla \times \mathbf{H} = 0$, $\nabla \cdot \mathbf{B} = 0$ where the magnetic induction $\mathbf{B}$ and magnetic field strength $\mathbf{H}$ are connected with the magnetization I by the relationship $\mathbf{B} = \mu\mathbf{H} + 4\pi\mathbf{I}$. Here μ is magnetic conductivity. The value $\mu = 1$ for Nd–Fe–B magnets is due to the magnet saturation inside the sample. Introducing the scalar magnetic potential U according to the equation $\mathbf{H} = -\nabla U$ one arrives at the equation $\Delta U = 4\pi\nabla \cdot \mathbf{I}$, which is transformed into a Laplace equation under the homogeneous magnetization conditions, $\nabla \cdot \mathbf{I} = 0$. So one can use an electrostatic analogy in the solution where there is a "charge" with a surface density modulus I at the boundary of the magnet perpendicular to the vector I. The following expression follows for the magnetic field distribution in the magnet without a slit:

$$H_x = -\frac{1}{2\pi} \ln \left\{ \frac{[(y-h)^2 + (x-d/2)^2][y^2 + (x+d/2)^2]}{[(y-h)^2 + (x+d/2)^2][y^2 + (x-d/2)^2]} \right\},$$
$$H_y = \frac{1}{\pi} \left(\text{arctg} \frac{x+d/2}{y-h} - \text{arctg} \frac{x-d/2}{y-h} - \text{arctg} \frac{x+d/2}{y} + \text{arctg} \frac{x-d/2}{y} \right). \quad (6)$$

The field is normalized on the value $2\pi I$, that is, on 0.6 T for magnets Nd–Fe–B. If a slit with a width d_1 is extracted from the center of the magnet then the magnetic field can be calculated with the help of relationships $H_x = H_x(d) - H_x(d_1)$, $H_y = H_y(d) - H_y(d_1)$ using the solution (6). The variation of the field modulus along the Y-axis at $x = 0$ for the magnet with the slit is shown in Figure 2. A comparison of numerical calculations of the magnetic field in the cylindrical hole geometry with the slit hole geometry is presented in Figure 3.

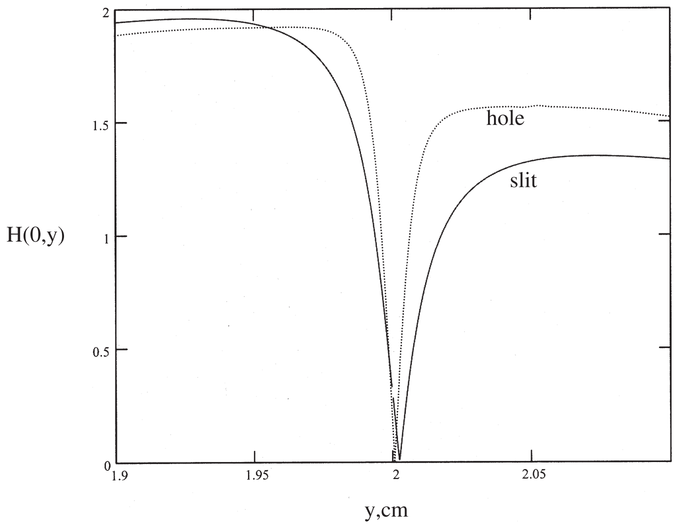

Fig. 3. A comparison of magnetic field strength distribution in a cylindrical hole and a plane slit.

4 Conclusion

We present an attractive proposal for magnetic confinement in order to increase the life time of laser plasmas generated by subpicosecond laser pulses. Estimations of the neutron yield corresponding to real laser plasma parameters also appear hopeful.

The construction of a magnetic micro-trap making it possible to increase neutron yield seems to be very simple and cheap as it follows from the considerations above. The results above suggest it should be possible to find efficiency improvements of experiments on magnetic confinement of laser plasmas with the application of micro-traps built with permanent magnets.

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