*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-2.018 (2004)*

Pinch-effect in Laser Produced Plasma

V.S. Belyaev

Central Research Institute of Machine Building of Federal Space Agency, Korolev, Moscow Region, Russia

Abstract.

The phenomenon of pinch-effect in plasma produced by super-intense laser radiation was investigated. Criterion of such laser pinch-effect realization was obtained. Lifetime of huge magnetic fields generated in laser produced plasma was estimated. D-D reaction neutron yield under the pinch condition was established. Principle possibility of break-even thermonuclear reaction realization (Lawson criterion fulfilment) was shown.

INTRODUCTION

The anisotropy of the high density electron fluxes borne by the laser field action leads to the development of instabilities, for example, the Weibel instability that generates super-strong magnetic field. The magnetic pressure or magnetic energy density of these fields $B^2/8\pi$ grows linearly together with the laser radiation intensity [1] and at some intensity may exceed the plasma kinetic pressure $(n_i + n_e)kT$, limited by temperature T and total densities of ions n_i and electrons n_e. When the magnetic pressure is larger than the kinetic pressure, the pinch effect develops and, therefore, the plasma density and temperature grow. In case of laser plasma, density and temperature are determined by the laser radiation intensity and they may significantly exceed the values obtained with different plasmas. It is important that the life time of the vortical pinch structures may be much greater than the duration of the laser pulse action. All this gives laser plasma a chance to meet the Lawson criterion, that is, the conditions for self-sustaining fusion. The justification of this possibility is the goal of this work.

The results of the laser plasma temperature measurements (T > 10 keV) and the D-D reaction energy (ε = 2,45 MeV) and the neutron yield ($Y>10^5$) are given. The Neodim set used (Korolev, Moscow region, CRIMB) gives the intensity of 10^{17}-10^{19}W/cm^2 ($\tau = 1{,}5\cdot10^{-12}$sec, λ = 1,053 μm, ε_{PULSE} = 5-15 J). The magnetic field $B>10^7$Gs was measured by a method described in [2], which is based on resonance interaction of the magnetic field energy levels (Landau levels) with the adjacent levels of the excited plasma atoms (ions).

These measurements were controlled by measuring the fast electron cut-off energy, that is, the maximal energy of the electrons exiting plasma at the given laser radiation intensity. This way to control the magnetic field is justified in [1]. This work also shows that in laser plasma, the fast electrons appear due to the strong magnetic field generation and the small part (tail) of the faster electrons are the result of pinching of the laser plasma magnetic field and the related local field increase.

THE BENNETT CRITERION FOR LASER PLASMA.

The Bennett criterion is the threshold condition for pinch effect in laser plasma. According to it, the magnetic and kinetic pressures must be equal

$$\frac{B^2}{8\pi} = (n_i + n_e)kT \ . \qquad (1)$$

Considering:

- $n_e = n_i(1+\alpha Z)$ is electron density when field ionization prevails, n_i is ion density, α is ionization degree, Z is nuclear charge of target matter atom;

- two-stage process of the pinch development, each of them has effective frequency and characteristic size: first stage has ω_0, $l_i = 2\pi / \omega_0$, ω_0 – laser radiation frequency, and second stage has ω_i, $\lambda = 2\pi / \omega_i$, ω_i – ionization frequency ($\hbar\omega_i = I_i$ - ionization potential);
- magnetic flux is conserved and characteristic size λ changes to l_i during the pinching: $B_0\lambda^2 = Bl_i^2$, where B_0, B_i are the magnetic fields generated in the plasma at the λ and l_i scales;
- pinch is linear two-dimensional structure: $n_0\lambda^2 = nl_i^2$;
- dependence of magnetic field on incident radiation intensity $B_0 \approx 10^{-1}\sqrt{J_0}$.

We get the pinch appearance and development criterion modified for laser plasma:

$$J_0\lambda_\mu^2 = 5{,}4 \cdot 10^{-13}\frac{n_0 T}{I_i^2}(1+\alpha Z) \qquad (2)$$

where J_0 [W/cm^2], λ_μ [μm], n_0 [cm^{-3}], T[^{o}K], I_i[eV].

For laser plasma and target from deuterated polyethylene $(CD_2)_n$ with n_0 = 4,5·10^{22}cm^{-3}, λ_μ = 1 μm, T = 10^8 ^{o}K, I_i = 10 eV, αZ = 5 we get $J_0\lambda_\mu^2 = 1{,}5 \cdot 10^{17}$ W/cm^2[μm]^2 the value easily achievable at the modern laser sets.

THE ESTIMATE FOR THE LIFETIME OF THE MAGNETIC FIELD GENERATED IN LASER PLASMA

Consider the vortical magnetic structure as an autonomous system appearing in laser plasma, whose decay is characterized as some transition process. The measure of this time is the normalized rate of the Lyapunov function change, which is generally proportional to the system energy. Given this, the transition time T is determined by the normalized rate of the system energy change $\frac{d\varepsilon/dt}{\varepsilon} = \frac{2}{T}$. From here, the duration of the arbitrary transition process, involving energy loss by an autonomous system, that is, the system lifetime, is equal $T \approx 2\frac{\varepsilon}{\Delta\varepsilon}\Delta t$, where ε is the starting energy of the system, $\Delta\varepsilon$ is the energy loss for time Δt. The system considered here is a vortical electronic structure, an inductive accumulator of the magnetic field energy accepting the energy of the laser radiation hitting the target. Let us assume these energies are equal.

Considering:

- plasma scattering takes place with the maximum rate determined by the anomalous Bohm diffusion; for any diffusion process, the following is true $D = L^2/t$, where D is the diffusion coefficient, L and t are the characteristic scale and time of diffusion. In our case, $L = \lambda$ is the wavelength, thus $\Delta t = \frac{\lambda^2}{D}$; energy loss from the area of the magnetic field is determined by the particle scattering and the associated kinetic energy $\Delta\varepsilon = \frac{Nmv^2}{2}$, where N is the number of particles with mass m exiting the area with the magnetic field $N = n_0V_0$, n_0 and V_0 are the starting density and volume of the magnetic energy area; $v = \frac{\lambda}{\Delta t}$ - average velocity of particles; $V_0 = \pi d_f r^2$ is the size of the focusing spot, $r = \lambda$ is the skin-layer thickness.

- number of particles remains the same during pinching, $mn_0 = n$, where n [kg/m^3] is the matter density, we get

$$T = 1{,}3 \frac{\varepsilon \cdot \lambda^2}{n \cdot d_f D^3} \qquad (3)$$

- for the laser pulse energy ε = 1 J, λ = 1 μm = 10^{-6} m, n = 1 g/cm^{-3} = 10^3 kg/m^3, $d_f = 10\,\mu\text{m} = 10^{-5}\,\text{m}$, D = 1 m^2/sec we get $T = 1{,}3 \cdot 10^{-10}$ sec. For a picosecond action, the magnetic field lifetime is two orders of magnitude greater.

THE D-D REACTION NEUTRON YIELD UNDER THE PINCH-EFFECT CONDITIONS

The yield of the neutrons formed in laser plasma as a result of reaction $^2H(d,n)^3He$ can be estimated $N_n \approx 0{,}25 n_D^2 < \sigma\upsilon >_{DD} \tau \cdot V$, where n_D is the deuteron density in the target material, $< \sigma\upsilon >_{DD}$ is the fusion rate averaged by the ion distribution, τ is the dense plasma lifetime, and V is the plasma volume.

Considering:

- density depends on magnetic field as following $n \sim p_B \sim B^2 \sim J$, where p_B is the magnetic field pressure, J is laser radiation intensity;
- the multiplier $< \sigma\upsilon >_{pp}$ is proportional to the incident radiation intensity;
- plasma scattering after pinch "stop" is unstable and is determined by anomalous Bohm diffusion. This diffusion coefficient is inversely proportional to magnetic field $D \sim 1/B$, from here time Δt, a multiplier in formula for the magnetic field lifetime τ will be proportional to B: $\Delta t \sim B$. Given $\varepsilon \sim \Delta\varepsilon$ at the exponentially changing energy, we get $\tau = 2 \frac{\varepsilon}{\Delta\varepsilon} \Delta t \sim B$; pinching volume V is $V \sim r^2$. From the conserved magnetic flux F = $\pi r^2 B = Const$, we get $r^2 \sim 1/B$ or $V \sim \frac{1}{B}$, and thus the product $\tau \cdot V$ is magnetic field independent and we get for neutron yield $N_n \sim J^3$.

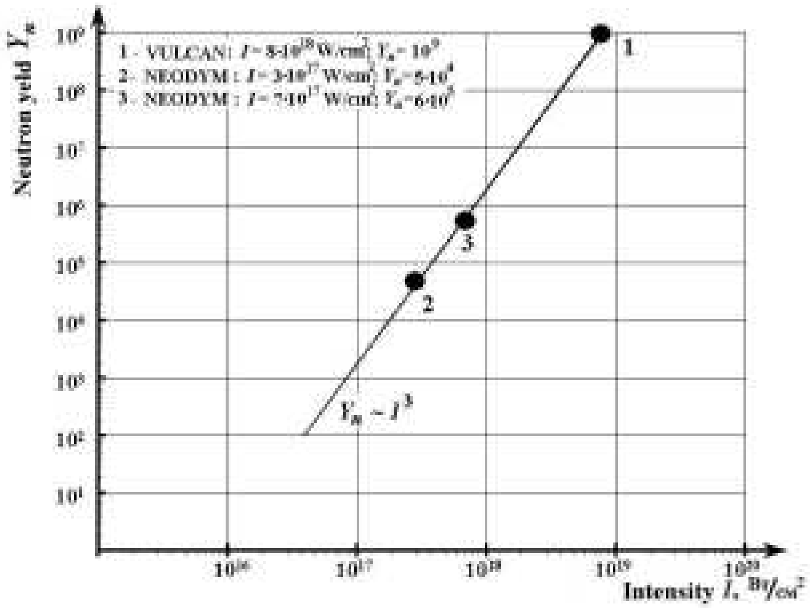

Figure 1.

Given the assumption about the magnetic field influence, the $^2H(d,n)^3He$ reaction neutron yield in laser plasma is proportional to the incident laser radiation intensity cubed.
Let us estimate N_n for intensity $3\cdot10^{17}$ W/cm^2. At this intensity, which is twice the pinch development threshold we carried out experiments on definition of plasma temperature. We get 20% ions with $E_i > 10$ keV, and 5% ions with $E_i \sim 100$ keV [3]. According expression for plasma density in the pinch conditions (above) we have $n_D = 10^{25}$ cm^{-3} for $(CD_2)_n$ target. Take $n_D = 10^{24}$ cm^{-3}, $\langle\sigma v\rangle_{DD} = 10^{-18}$ cm^{3}sec^{-1} for $T = 10^8$ K (10 keV), lifetime $\tau = 1{,}3\cdot10^{-10}$ sec, volume v = $1{,}6\cdot10^{-4}$ cm^3 for $l = 10^{-3}$ cm, $r = l_i = 4{,}6\cdot10^{-6}$ cm. Considering all this, the neutron yield is $N_n = 5\cdot10^5$ for the parameters given. The obtained theoretical estimates fit the experimental data well. So, in [3], for the given intensity of $3\cdot10^{17}$ W/cm^2 the neutron yield achieved is $5\cdot10^5$. The results of experiments on the picosecond laser radiation action conducted in England (Vulcan set) and Russia (Neodim set) give the relationship between the neutron yield and the laser radiation intensity. Figure 1 shows that the cubic relationship between neutron yield and the laser radiation intensity is confirmed well by the experiments.
The line on figure 1 show the relationship $N_n \sim J^3$ in the logarithmic scale. The neutron yield of ~ $6\cdot10^5$ obtained on the Neodim set at the intensity of $7\cdot10^{17}$ W/cm^2 also fits the theory well.

ON POSSIBILITY OF FULFILMENT OF THE LAWSON CRITERION IN LASER PLASMA

The considered laser plasma characteristics under the conditions of the pinch effect development let us hope that the conditions for the self-sustaining fusion may be achieved. These conditions are determined by the known Lawson criterion, that says that, for instance, for the D-D synthesis $n\cdot\tau > 10^{15}$ cm^{-3}sec, where n is the high temperature ($T > 10$ keV) plasma density and τ is the lifetime of this density.Note that the product $n\tau$, the Lawson criterion for the pinch case, that is for received above expressions for n and τ is $n\tau = \frac{4}{\pi}\frac{\varepsilon\lambda^4}{d_f l_i m D^3}$ and is not dependent on the starting fusion fuel density. For the parameters above $\varepsilon = 1$ J, $\lambda = 10^{-6}$ m, $d_f = 10^{-5}$ m, $l_i = 4{,}6\cdot10^{-8}$ m, $m_{CO2}=2{,}6\cdot10^{-26}$ kg, $d_f = 10^{-5}$ m, D = 1,0 m^{2}сек$^{-1}$ we have $n\tau = 2{,}4\cdot10^{21}$ m^{-3}sec = $2{,}4\cdot10^{15}$ cm^{-3}sec.

CONCLUSIONS

The results obtained confirm the great and key role of the super-strong quasi-stationary magnetic field spontaneously generated in laser plasma during the plasma formation and during the atomic and nuclear processes taking place in it. The possibility of the pinch effect in these fields is shown under the laser parameters already achieved in many laboratories. The pinch effect development there gives rise to the vortical electronic structures. The magnetic pressure inside such structures leads to the considerable increases in temperature and density. The lifetimes of these structures are estimated to significantly exceed the duration of the plasma-forming laser radiation. These conditions are shown to make possible the fulfilment of the Lawson criterion for self-sustaining fusion in laser plasma. Using an example of $^2H(d,n)^3He$, the supposition on the key role of the magnetic field and pinch effect and the neutron yield estimates conducted on its basis are shown to be in good agreement with the experimental results.

Work was supported by International Science and Technology Center, project #2155.

References.

1. V.S. Belyaev, *Quantum Electronics* **34**(1), 41 (2004).
2. V.S. Belyaev et al., *Pis'ma Zh. Eksp. Teor. Fiz. Letters,* **78**(11), 1216 (2004).
3. V.S. Belyaev et al., *Zh. Eksp. Teor. Fiz.* **125**(6), 1265 (2004).