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Diamagnetic Cavity of Plasma Clouds Expanding in Magnetized Media

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Abstract

Basic properties of the diamagnetic cavity created by spherically expanding clouds of exploding plasma in various magnetized media are studied as a result of the series experiments at large-scale ***"KI-1"*** facility with laser-produced plasma clouds of energy up to 300 J in the magnetic fields up to 2 kG. The cases of uniform and dipole fields were investigated to simulate an explosive-type cosmophysical phenomena and some schemes of the direct conversion of ICF-energy.

Keywords:

laser-produced plasma, magnetic fields, space and ICF-phenomena

1. Introduction

Diamagnetic cavity (DC) of exploding plasmas formed during their expansion into magnetic field plays a crucial role in the most key processes of interaction between plasma and surrounding magnetized media. Such plasmas with kinetic energy $\boldsymbol{E}_0$ could be decelerated by magnetic pressure $\boldsymbol{B}^2/8\pi$ and stopped in vacuum uniform magnetic field $\boldsymbol{B}_0$ at the radius $\boldsymbol{R}_b \approx (3\boldsymbol{E}_0/\boldsymbol{B}_0^2)^{1/3}$, equal to the maximum cavity size R_{cm} in this case [1], namely due to DC creation and fields' exclusion by plasma. The unique parameters of ***"KI-1"*** facility allowed us to study the general 1D-properties of diamagnetic cavity in uniform magnetized media (MM) in the experiments [2,3] on spherically-symmetrical expansion of Laser-produced Plasma Clouds (LPC) with a number of ions N_i (of the mass-$\boldsymbol{m}$ and charge-$\boldsymbol{z}$) under the condition of rather strong ion magnetization $\varepsilon_b = \boldsymbol{R}_h/\boldsymbol{R}_b \le 1$ (for ion Larmor $\boldsymbol{R}_h = \boldsymbol{m}c\boldsymbol{V}_0/\boldsymbol{z}e\boldsymbol{B}_0$), which is needed for effective plasma-MM interaction and LPC deceleration at $\boldsymbol{R}_{cm} \approx \boldsymbol{R}_b$. Also an influence of ionized MM background and its density gradient $\nabla \boldsymbol{n}_*(\parallel$ or $\perp \vec{\boldsymbol{B}})$ have been investigated [4]. Some preliminary data on the 2D-structure of diamagnetic cavity in both uniform and dipole vacuum magnetic field $\boldsymbol{B}_d$ were obtained in a series of ***«Cavity»*** experiments [5-10] and here we will present their completed results in more details.

2. «*KI-1*» Laser Facility and Magnetic Field Measurements

The multi-purpose ***"KI-1"*** laser facility [2,11] consists of a large-scale (∅1.2m * 5m), high-vacuum interaction chamber and the system of CO_2-lasers with output energy ~ 1 kJ for producing quasi-spherical LPC with moderate velocity $\boldsymbol{V}_0$ ~ 100–200km/s, $\boldsymbol{m}/\boldsymbol{z}$ ~ 2–3 amu and energy $\boldsymbol{E}_0$ up to 300 J needed for simulation of space [2,6,11] and ICF [5,9] phenomena at small values of $\varepsilon_b \le 0.3$. The optical system provides two-sided and multi-staged irradiation of small-size spherical or filament Nylon6 pellets. The chamber is supplied by

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sources of an axial uniform $\boldsymbol{B}_0$-field (up to 1 kG), dipole $\boldsymbol{B}_d$-field (with $\boldsymbol{M} \geq 10$ MG* cm^3) and Θ-pinch type source of background plasma with $\boldsymbol{n}_*$ up to $5*10^{13}$cm^{-3}. The ***«Cavity»*** experiments were done with LPC ($\boldsymbol{E}_0 \sim$ 10J) expanding into the dipole [6,10] and uniform [6-9] magnetic fields ($\boldsymbol{B}_d$ = 1–2kG and $\boldsymbol{B}_0$ = 40–800G) with $0.7 \leq \varepsilon_b \leq 2$. For magnetic field measurements we used 3-component $\vec{B}$-dote probe with high-frequency (50 MHz) coils of diameter 3–5mm with electrostatic [3,10] shielding, inserted into (5–7)mm-diam isolators. A set of such probes with digitalization system allow us to obtain the grid (~ 1 cm* 1 cm) of 2D-distributions of vectors $\Delta\vec{B}$ or $\vec{B} = \vec{B}^0 + \Delta\vec{B}$ and the levels of $\alpha = |\vec{B}|/B_0^0$ or $\alpha_d = |\vec{B}(r)|/B_d^0(r)$ of the fields' exclusion inside of plasmas and of its disturbance $\beta = |\Delta\vec{B}|/B_0^0$ outside the LPC (for initial field $\vec{B}^0$). The suitability of the whole measurements' procedure was tested by the control of magnetic flux conservation and by comparison of the $\vec{\mu}_d$-values of DC currents determined from the data on $\Delta\vec{B}$, obtained both inside and outside (see below) of LPC.

3. Diamagnetic Cavity in Vacuum Uniform Magnetic Field

According to the model [1] of plasma cloud as «superconducting sphere» (SSM) the magnetic field should be excluded down to $\boldsymbol{B} = 0$ inside of DC (and plasma) boundary $\boldsymbol{R}_c$ and should have outside it the dipole-like disturbance $\Delta\vec{B} = \vec{b}_d$, which is described by the magnetic moment of DC currents $\vec{\mu}_d = -\vec{B}_0^0 R_c^3/2$. So, along the $\vec{r} \perp \vec{B}_0^0$ direction ($\theta = \pi/2$) the field compression should be $\beta_\perp = 0.5(r/R_c)^3$ and in others $\beta = \beta_\perp(1 + 3\cos^2\theta)^{1/2}$. Earlier we have obtained for the first time [3] a very thin width of skin-layer $\delta \approx 2c/\omega_{pe}$ and $\beta_\perp^{max} \approx 0.5$ while in other experiments [12,13] it was not more than 0.3. In ***"Cavity"*** experiments a real spherical shape of DC (Fig. 1) was registered at early times of expansion as well as a whole $\vec{b}_d$-character of its $\beta(r, \theta)$-disturbances. It allowed us to develop contactless method [8] of «Remote Magnetic Probe» (RMP) to determine the size $\boldsymbol{R}_c$ of DC via measurements of RMP-signal $\beta_{\perp p}(r_p)$ at distances $r_p > R_c$ and calculation of R_c as $R_c = r_p(2\beta_{\perp p})^{1/3}$. The results of direct measurements of $\boldsymbol{R}_{cm}$ (for level $\alpha = 0.5$ at $r_p < R_c$) agree rather well with those of RMP (Fig. 2). But both of them become very different from the corresponding SSM's cavity data ($R_{cm} = R_b$) in the range of $\varepsilon_b \geq 1.5$ ($B_0 \leq 100$G, $E_0 \approx 8$ J). The reason is a fast $\boldsymbol{B}$-field penetration into plasma [3] with very high effective collision frequency of electrons $\nu_{eff} \approx \xi\omega_{ce}$($\xi \sim 0.3$ in DC skin-layer) probably related to observed lower-hybrid turbulence (LHT). Due to this reason only at early-stage of DC expansion the law of $\boldsymbol{R}_c(t)$ dynamics could coincide with the plasma radius $\boldsymbol{R}(t)$ and both of them could be described [9] in the range $\varepsilon_b \leq 1$ by SSM deceleration law in the dimensionless [11] form:

$$\tau_b = \int_0^{s_b} dx \Big/ \left(\sqrt{1-0.8x^3} - \sqrt{0.2x^3}\right) \text{ for}$$

$$s_b = R/R_b < 1 \text{ and } \tau_b = tV_0/R_b \qquad (1)$$

After the time $\tau_b \approx 1.5$ the boundaries of plasma and DC begin diverge as $\boldsymbol{R}$ goes over $\boldsymbol{R}_b$ (due to flute instability [2,12,13] of plasma) and as $\boldsymbol{R}_c$ stops at $R_{cm} \approx (0.8–0.9)$ $\boldsymbol{R}_b$ (due to δ-broadening [3,8,9]) and further collapses.

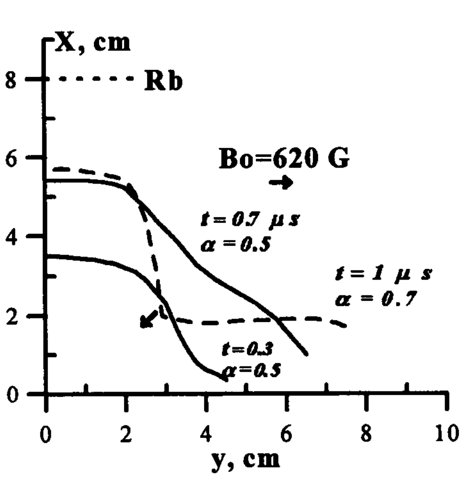

Fig. 1 Diamagnetic cavity evolution in uniform $\boldsymbol{B}_0$-field.

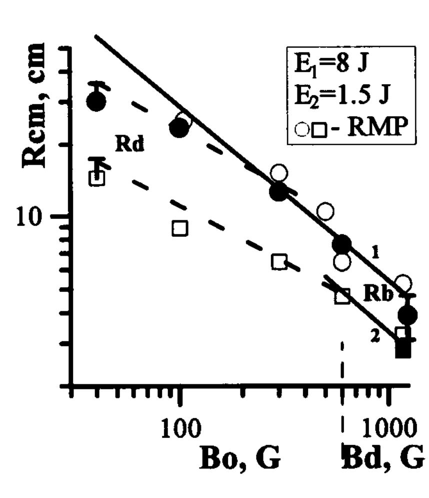

Fig. 2 Dependence of maximum cavity size $\boldsymbol{R}_{cm}$ upon the plasma energy $\boldsymbol{E}_0$ and various magnetic fields $\boldsymbol{B}$.

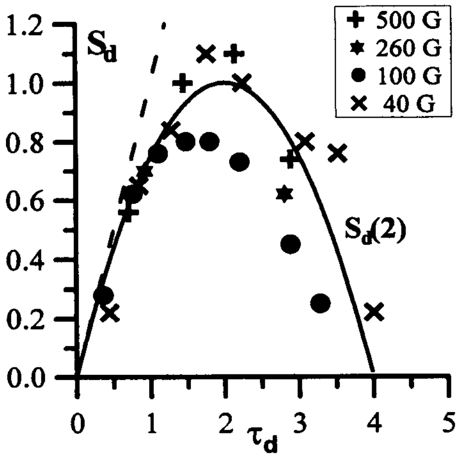

Fig. 3 Dynamics of cavity boundary across B_0-field.

The whole measured DC dynamics in the range $\varepsilon_b \geq 1$ could be roughly described by the usual field diffusion model with $\delta \approx \sqrt{c^2 t/4\pi\sigma}$ and $\sigma = n_e e^2/m_e \nu_{eff}$. Using the simple formulae [3] $R_c(t) = V_0 t\text{-}\delta(t)$ we obtain a new, diffusion law of DC evolution:

$$s_d = \tau_d - 0.25\tau_d^2$$
$$\text{for } \tau_d = tV_0/R_d \leq 1 \text{ and } s_d = R_c/R_d \qquad (2)$$

That gives another maximum size of DC [3] $R_{cm} \approx R_d$ via a new scale of the problem $R_d = (3ezN_iV_0/16c\xi B_0)^{1/2} \equiv R_b/\sqrt{\varepsilon_b}$ and corresponding DC «lifetime» $T_{cd} \sim$ 3–4 R_d/V_0 (determined only by turbulent diffusion). The formulae (2) agrees rather well with all data on DC dynamics at $\theta = \pi/2$ in ***«Cavity»*** experiment if one takes $\xi = 0.25$ (Fig. 3). But along $\theta = \pi/4$ (Fig. 1) we had observed more faster field penetration which may be caused by the Hall-effect, that could appear namely here with the same $\nu_{eff} \approx \xi\omega_{ce}$. In general, the «lifetime» T_c of DC, defined in dimensionless form as $\gamma_c = T_cV_0/R_b$ and determined by the level $\alpha \approx 0.5$ of field penetration inside of $r \approx R_{cm}/2$ could be expressed for the diffusion regime (2) by the relation like $\gamma_{cd} \approx 3/\sqrt{\varepsilon_b}$. While for MHD-case in the range $\varepsilon_b \ll 1$ we could use the scale of «Alfvenic» frequency [14] which describes the DC evolution as stopping (1) at R_b and following inward motion with Alfven velocity that gives us [7] the limiting value $\gamma_{cb} \approx 3$. Therefore, in the intermediate range $\varepsilon_b \approx 1$ the curves γ_{cb} and γ_{cd} should transit into each other. The ***«KI-1»*** results (see ● at Fig. 4) and other laboratory (○) or space experiments (★) and computer simulations (□) could be described by such DC «lifetime» ($\gamma_{cb} \rightarrow \gamma_{cd}$) relation in a wide range of conditions of exploding natural (or ICF) plasmas that provides the base to simulate them by LPC.

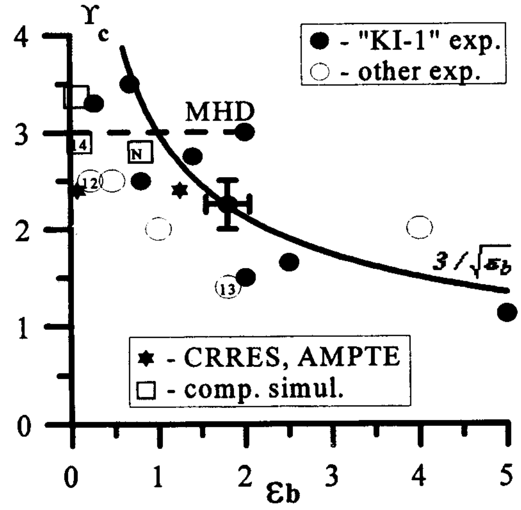

Fig. 4 Dimensionless scaling of the cavity «lifetime» in vacuum uniform magnetic field (N-data of H. Nakashima, 1998).

4. The Effects of Fields' Non-Uniformity and Ionized Background

SSM's based analysis and calculations [5,15] of the plasma stopping radius $R_m(\theta)$ in the dipole field shows that in sectorial approximation it depends only from the parameter $æ = 3E_0R_0^3/M^2 = (R_b/R_0)^3$ and angle $\varphi_{\vec{M}\vec{R}_0}$ (where R_0 is the radius between dipole M and explosion point) via unified equation $F(\varphi, R_m/R_0) = æ$. It gives $R_m = R_b(B_d)$ for $æ \ll 1$ while $R_m \rightarrow \infty$ (breakout of plasma into $-\nabla B_d^2$ direction) for $æ \geq 0.1$. In ***«KI-1»*** experiments [15] the main features of such plasma-dipole interaction were observed. Besides it, a «non-sectorial» effect of displacement of cavity (and plasma) as a whole were registered [6,10] at $\varphi = 30°$ even for $æ < 0.1$. DC structure for this regime at $\varphi = 0$ (Fig. 5) could be roughly described by sectorial approximation as quasi-stationary ovoid shape (with $R_c \sim R_m \sim R_b$). It is valid only from the initial interaction time $t_1 \sim R_b/V_0 \sim 0.3\ \mu s$ up to 1–1.5 μs, but after that DC goes away with velocity rather close to its estimation $V_0æ^{1/3}$ via the action of $(\vec{\mu}_d\nabla)\,\vec{B}_d$-force. In the case of plasma cloud expansion with super-Alfvenic velocity $V_0 \geq C_A = B_0/(4\pi m_* n_*)^{1/2}$ into background plasma [2,4,11] two other effects and DC scales became important: its spatial [2,11,16] one $\widetilde{R} = (3zN_i/4\pi n_*)^{1/3}$ and its T_c-value, reaching [7] the classical one $4\sigma_c R_c^2/\pi c^2$ (for Coulomb conductivity σ_c of background) due to suppression of

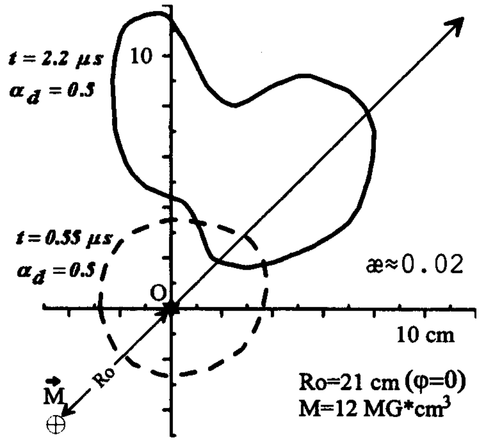

Fig. 5 Evolution of diamagnetic cavity in dipole field.

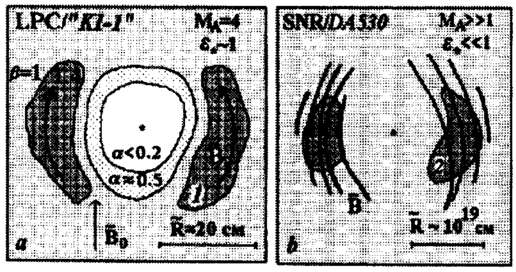

Fig. 6 Simulation of Super-Nova diamagnetic cavity at presence of ionized background.

LHT and flutes . In such kind of experiments at ***«KI-1»*** on simulation of Super-Nova Remnants (SNR) dynamics at numbers $M_A = V_0/C_A \gg 1$ we had realized for the first time in laboratory [2] the plasma-plasma collisionless interaction at $R \sim \tilde{R}$ due to the action of curl electric fields. It is possible only under condition $\varepsilon_* = \sqrt{R_h R_{h*}}/\tilde{R} \le 1$ of both kinds of ions magnetization and the formation of DC with $R_c \approx \tilde{R}$ (and B-field compression at its edge, see region ***1*** at Fig. 6a). The measured DC structure is very similar to the observed [17] SNR one (Fig. 6b with region ***2*** of plasma compression) if expressed in corresponding dimensionless time $\tau_* = tV_0/\tilde{R} \approx 1.5$–$2$ which is t = 2 μs for laboratory and 1500 years of SNR ***DA530*** age, expanding with $V_0 \sim 5000$km/s.

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References

[1] Yu.P. Raizer, J. Appl. Mech. Techn. Phys. N6, 19 (1963) - in Russian (see also *NASA TN F-239*: Washington DC, 1964, 20p.).

[2] Yu.P. Zakharov, A.M. Orishish, A.G. Ponomarenko *et al., ESA SP-251, Joint Varenna-Abastumany Intern. School & Workshop on Plasma Astrophysics*, Noordvijk (ESA, 1986) p.37.

[3] Yu.P. Zakharov, A.M Orishich, A.G Ponomarenko and V.G. Posukh, Sov. J. Plasma Phys. **12**, 674 (1986).

[4] V.M. Antonov, Yu.P. Zakharov, A.M Orishish *et al., ESA SP-311, Varenna-Abastumany-ESA-Nagoya-Potsdam Workshop on Plasma Astrophysics*, Noordvijk (ESA, 1990) p.189.

[5] Yu.P. Zakharov, S.N. Nikitin, A.M. Orishich and A.G. Ponomarenko, Book of Abstracts of Fourth Intern. Toki Conf. on Fusion and Astrophysical Plasmas (Toki, 1992) p.47.

[6] V.M. Antonov, Yu.V. Afonin, Yu.P Zakharov, A.M. Orishich *et al.*, UK Inst. of Physics Conf. Series N**140**, 167 (1995).

[7] Yu.P Zakharov, A.V. Melekhov and A.G. Ponomarenko, Abstr. of IEEE Intern. Conf. on Plasma Science (Santa-Fe, 1994) p.92.

[8] Yu.P Zakharov, A.V Melekhov, S.A Nikitin *et al., Proc. 1996 Int. Conf. on Plasma Physics* (Nagoya, 1997) v.2, p.1670.

[9] Yu.P. Zakharov, A.G. Ponomarenko, H. Nakashima *et al., Proc. 9th Int. Conf. on Emerging Nuclear Energy Systems*, Ramat Gan (Dan Knassim Ltd, 1998) v.1, p.384.

[10] I.F. Shaikhislamov, V.M. Antonov, Yu.P. Zakharov *et al.*, J. Appl. Mech. Techn. Phys. **36**, 488 (1995).

[11] Yu.P. Zakharov, A.M. Orishich and A.G. Ponomarenko, *Laser-Produced Plasma and Laboratory Simulation of Non-Stationary Space Processes* (ITAM, Novosibirsk, 1988) p.220 - In Russian.

[12] G. Dimonte and L.G. Wiley, Phys. Rev. Lett. **67**, 1755 (1991).

[13] B.H. Ripin *et al.*, Phys. Fluids **B5**, 3491 (1993).

[14] L.L. Lengyel, Phys. Fluids **31**, 1577 (1988).

[15] S.A. Nikitin and A.G. Ponomarenko, J. Appl. Mech. Techn. Phys. **34**, 745 (1994).

[16] T.P. Wright, Phys. Fluids **14**, 1905 (1971).

[17] D.K. Milne, Australian J. Phys. **40**, 771 (1987).