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Physics of Exploding Plasma in Magnetic Fields and Oppotunity of Direct Conversion of ICF-Energy

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Abstract

The processes of direct energy conversions of the ICF microexplosion in magnetic fields are discussed and investigated by both the methods of their simulations in the experiments with usual Laser-Produced Plasma Clouds and via their numerical PIC-modelling in 3D-schemes. The problems of additional energy losses of exploding plasmas which could prevent to achieve more than 50/% efficiency of such electrical conversion in uniform magnetic field are studied by comparison of experimental and numerical data.

Keywords:

ICF simulation experiment, magnetized parameter, 3D hybrid code

1. Introduction

Due to recent progress in ICF study carried out by "NOVA" or another high-power lasers as well as in development of related programs of ICF ignition at NIF, LMJ and KONGOH facilities a new possibility is now opened to realize rather old idea [1-4] of ICF application based on interaction of D-^{3}He fusion plasma with various magnetic B-field systems. Such systems could provide a direct conversion of fusion energy into electrical [1,3-6] or mechanical [2,4,9] ones due to the diamagnetic effect, i.e. complete exclusion of the external magnetic field by the thermonuclear plasma cloud. On the other hand, it is known that instabilities such as Rayleigh-Taylor instability would occur at the surface of expanding plasma cloud under the external magnetic field and they would lead to degradation of energy conversion efficiency.

The magnetized parameter $\varepsilon_b = R_h/R_b$ is an important one for understanding the behavior of expanding plasma into a magnetic field, where $R_h = V_0/\omega_{ci}$ is direct ion Larmour radius, V_0 being initial plasma expansion velocity and ω_{ci} cyclotron frequency [7]. R_b is magnetic confinement radius at which the kinetic energy of the expanding plasma balances the excluded magnetic energy and defined as $R_b = (3\,\mu_0\,E_p/2B_0^2\pi)^{1/3}$ where μ_0 is the vacuum permeability, E_p initial plasma kinetic energy, and B_0 initial magnetic field strength. In the case of $\varepsilon_b > 1$, the expanding plasma behaves as the large Larmor radius (LLR) Rayleigh-Taylor instability, while in the case of $\varepsilon_b \ll 1$, it does as the conventional one.

In this paper, the influences of instabilities are discussed by comparing experiments carried out at KI-1 facility with numerical study.

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2. Experimental Setup and Numerical Model

The multi-purpose KI-1 simulation facility [9,10] consists of a large-scale (diameter 1.2m × 5m), high-vacuum interaction chamber and system of CO_2-lasers with output energies ~1 kJ for producing quasi-spherical laser plasma cloud (LPC) with moderate velocity V_0 ~ 100–200km/s, m/z ~ 2–3amu (with main kinds of H^+ and C^{+4}-ions) and initial plasma energy $\boldsymbol{E}_0$ up to 300 J needed for ICF simulation. The chamber is supplied by systems of two-sided and multi-staged irradiation of small-size spherical or filament Nylon 6 pellet and sources of an axial uniform $\boldsymbol{B}_0$-field (up to 0.1 T). In these conditions, the magnetized parameter $\varepsilon_b = R_h/R_b$ ~ 0.2–0.3. The number is close to our calculation conditions for an ICF energy conversion scheme [6].

To calculate the ICF-plasma behavior under the magnetic field, we have developed a 3D hybrid PIC-code based on the model in ref. [11], which treats electrons as inertialess fluid (with electron's temperature $Te = 0$ here) and ions as particles for taking into account their finite Larmor radius for some ICF-conditions. The Darwin limit or non-radiative Maxwell equations are used for electromagnetic field calculation.

We are now developing a modified version of the code to take into account diffusion of magnetic field due to observed turbulence in the skin layer of the expanding plasma [8].

3. Comparison between Experimental and Numerical Results

The basic processes of interaction between exploding plasma with uniform magnetic field $\boldsymbol{B}_0$ were studied in a series of our "Cavity" experiments [10,12-14] at "KI-1" facility under conditions of the Laser Plasma Cloud (LPC) expansion ($\boldsymbol{E}_0$ ~ 10 J) into the field $\boldsymbol{B}_0$ = 0.05–0.06 T. As results of this investigations the detailed and direct 3D-data about evolution of plasma cloud (Fig.1, 2, 3) and its diamagnetic cavity [12] of radius-R_c with sheath's width-d (i.e. the region with $\boldsymbol{B} < \boldsymbol{B}_0$ inside of plasma) were obtained for the first time. Measurements are also made on the spatial-temporal characteristics of the external magnetic disturbances $\boldsymbol{b}$ of exploding plasma which is very important for ICF. It was found [14] that at the initial stage (at $t \leq 2R_b/V_0$ = 1 s) both R_c and $\boldsymbol{b}$ rather well correspond to idealized theoretical model [15] of plasma cloud's interaction with $\boldsymbol{B}_0$-field and that at the same time the influence of a flute instability could not seem to be very important. It means that at this initial stage one could expect an effective electromotiveforce-generation and possible high efficiency of plasma energy recovery if we could

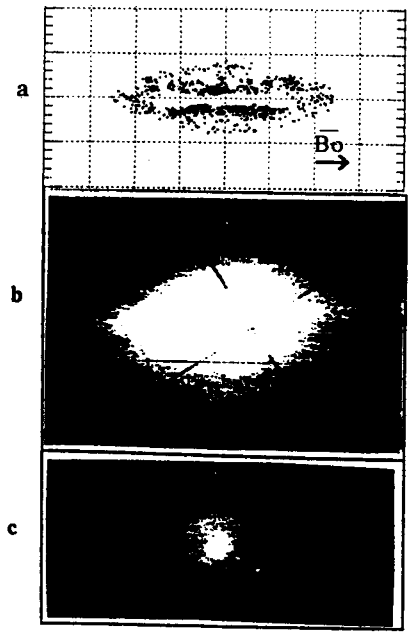

Fig. 1 Calculation data (a) and frame-photo (b, c) of the plasma configuration from the point of view across magnetic field $\boldsymbol{B}_0$ (in the same scale), data of KI-1 experiment Cavity:
- a) t = 1.4μs, vertical (X) large division and horizontal (Z along $\boldsymbol{B}_0$) ones are both equal to 0.1 m;
- b) t = 1.8μs, additional H_2-background pressure ~ 0.1 mT and registration in C^{+3}-line (λ = 5801A);
- c) t = 3.6μs, background pressure ~ 10^{-6} Torr.

Fig. 2 Calculation data (a) and frame-photo (b, with H_2-pressure ~ 0.1mT) of the plasma from the point of view along magnetic field (here one large division is equal 0.1m) at time $t \approx$ 1.3–1.75μs.

neglect electron heating and their pressure effects.

To check this situation and to test the applicability of developed 3D/PIC-model of ICF-energy conversions to the real plasma conditions we did a set of such calculations runs for the parameters of the Cavity experiment and have obtained rather good correspondence between them at initial stage (Fig.3). We are using ~ 10 hours of SX-4 computer's time for a typical run with 100000 ions (of one type ions with m = 6.5amu and z = 2.5) in 81 × 81 × 81 grid (X, Y, Z with Z-axis along $\boldsymbol{B}_0$-field). Initial plasma radius was taken to be R_0 = 0.02–0.04m (< R_b = 0.11m) with spherically-symmetrical expansion velocity at its front of V_0 = 170km/s (in spite of its asymmetry obserbed in the experiment by a factor of 1.5 into directions of laser beams).

Here we will discuss the first results of this calculations that in comparison with our experimental data at late stage reveal some rather new plasma/field-interaction features which could be very important not only for ICF-energy conversion task but also for general problem of the plasma confinement in magnetic fields. In our case the magnetic system with uniform magnetic field is extremely open in a sense of absence of any external sources of enhanced field along it (from both sides of a LPC). But during diamagnetic plasma's expansion it itself should create at its spherical boundary the field's geometry very similar to magnetic bottle one. So one could expect some effects of ion's trapping in such configuration and we had measured [13,14] indeed their evident compression (by factor ≥ 1.5 for C^{+4} ions, registered quantitatively via analysis of their charge-exchange luminosity [14] in line) at the ends of "bottle" along field (Fig. 1b). On the other hand the calculation results show that during plasma boundary's deceleration and stopping in the cross-field direction, the shell of enhanced plasma density could be formed (Fig. 1a), slightly similar to observed ones in experiment by usual photoregistration in a wide spectral range (Fig. 1c).

According to the calculation data on plasma dynamics (Fig. 3) and its cross-field (X,Y) energetics this cylindrical-like (due to free motion along field) shell evolves to collapse stage with inward radial motion (at $V \sim V_0$) and $\boldsymbol{E} \sim \boldsymbol{E}_0$ of the main part of plasma, that could be important for the processes of ICF-energy conversion. But at the same time other part of plasma (see Fig. 1a and Fig. 3) remains at radius $R \approx R_b$, which may be due to development of flute-like instability (Fig. 2a). It seems that mainly as result of more pronounced and fast growing of a small-scale flutes in experiment

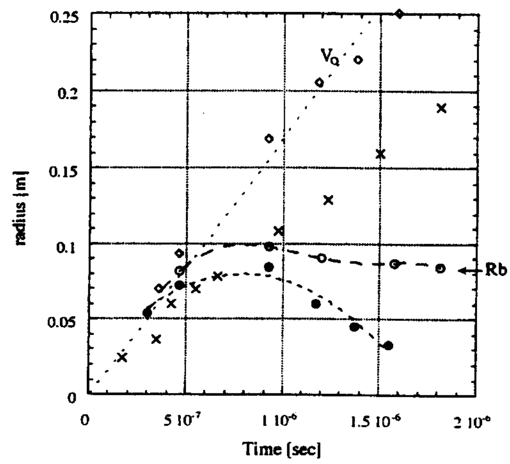

Fig. 3 Data on plasma cloud expansion in X, Z directions: -across magnetic field (x - experiment; ○ - calculation for the outer rare plasma; ● - calculation for plasma shell); -along field ◊ plasma front's motion according to the calculation.

(Fig.2b) in its real plasma conditions we had never observed such essential collapse effect during confinement of exploding plasma. Another very possible reason of this difference between experimental and calculation data could be an obvious absence in the last one of any gas-kinetic (electron) pressure inside of plasma cloud when it was stopped by the field.

4. Conclusion

All our experimental and PIC-simulation results proved that future ICF-based power station with magnetic fields could be rather perspective and that our common approach (LPC + PIC) is very productive for development of their design. In particular, unique experimental opportunities [14] of "KI-1" facility for realization of the value $\varepsilon_b \sim 0.1$ made possible such simulations of ICF-conditions.

Acknowledgments

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