Advanced study of ICF-energy direct conversion for Laser Fusion Rocket with quasi-dipole field in the laser-plasma experiments and PIC–simulations

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Abstract. We had studied by the methods of numerical and laboratory simulations an important problem of direct inductive conversion of the ICF-plasma’ energy into electric one, under conditions of promising space propulsions with magnetic nozzle. For such kind of Laser Fusion Rocket, like a VISTA, with the strong and dipole-like magnetic field, a minimal 5%-level of conversion efficiency is required to supply a need power for laser system etc. As a result of calculations by 3D/PIC-code of KU a real opportunity to achieve this value was confirmed for the first time with taking into account a data of simulative experiments at KI-1 facility of ILP. A schemes and results of “VISTA-KI” experiments with Laser-Plasma clouds is discussed to verify this opportunity under real conditions of flute-like plasma instability and the geometry of plasma expansion (versus the main and pick-up coils) close to VISTA.

1. The problem of the efficiency of direct energy conversion in Laser Fusion Rocket schemes

VISTA is a well-developed design [1,2] of Laser Fusion Rocket (LFR) with the magnetic field’ nozzle [3] formed during asymmetrical expansion of plasma cloud along the X-axis of strong and dipole-like magnetic field supplied by SCM-coil, combined with the additional pick-up coil for EMF-generation of electric energy Eₐ spent to laser driver. Design of its nozzle’ part with a 10 m – scales and kinetic plasma energy E₀~ 500 MJ (per shot of ICF-microexplosion, see table 1) was explored by LLNL for ≤ 1 year roundtrip to Mars on the base of rather optimistic values of the conversion efficiencies both for energy ηₑ=Eₑ/E₀ ~ 5 % and momentum ηₚ=Pₚ/P₀ ~ 60 %. The latter value of ηₚ was successfully confirmed by the methods of numerical [4], laboratory [5] and joint [6] simulations in wide range of dimensionless parameters (criteria) of the problem: energetic – æ and ion magnetization – υ₀ (table 1).

But for the energy conversion efficiency ηₑ situation is not so clear [2], because nobody, except first LFR-project [3] never do its quantitative estimations (based on physical processes of direct inductive conversion of energy), while the result of this LLNL work on the level of ηₑ ~ 15% was obviously overestimated for the given geometry of LFR (with the pick-up coil suited along to X far away from plasma). For example, our special studies [7-11] of such kind maximum efficiency for more suitable case (of uniform field and more close plasma-coil geometry) show, that in this case nor
more than limit ~ 30% could not be obtained, even in absence of dissipation or any instabilities and with “good matching” in plasma/ pick-up coil system, that means not only evident condition of $\Delta = 0$ (see figure 1), but the optimal radius $R_c$ of coil, comparable [8-10] with the maximal size $R_c$ (~ $R_b$, see table 1) of plasma diamagnetic cavity. While indeed, due to effects of flute-like instabilities [11,12] at plasma boundary, the real value of energetic efficiency should be in two-fold lower [8] than this limit.

**Table 1. Main parameters of Laser Fusion Rocket VISTA and experiments for its simulations**

| Parameters and criteria | Project VISTA [1,2] | VISTA test, planned at NIF [4] | “Impulse” [5] | “VISTA-KI” (S) |
|-------------------------|---------------------|-------------------------------|--------------|---------------|
| Plasma energy, MJ $E_0$ | 500±1000            | 4                            | (3±4) $\times 10^{-6}$ | ~ 30$\times 10^{-6}$ |
| Expansion velocity, km/s $V_0$ | 300                        | 300                          | 140          | 170           |
| Plasma ions, a.m.u. $m_i$ | 1                        | $\sim 10$                    | 2.5          | 2.5           |
| (m$_i$=m/m$_p$, in average) $z$ | (H$_2$-expellant)       | (Au-shell)                   | (CH-plastic) | (CH-plastic) |
| Ejection point, m $X_0$ | 11                      | 1                             | 0.15         | ~ 0.057       |
| Current in main coil, MA $J_t$ | 17                      | 4                             | $\sim 0.1$ (MA-turn) | ~ 0.05 (MA-turn) |
| Coil radius, m $R_t$ | 13                      | 1                             | $\sim 0.05$  | 0.0675        |
| Dipole moment, G*cm$^3$ $\mu$ | $10^{13}$             | $10^{10}$                    | $10^6$       | $8 \times 10^5$ |
| Magnetic field (at $X_0$), kG $B_d$ | 4                        | 9                             | 1            | 2.25 (up to 5) |
| Scale $(3E_0/B_d)^{1/3}$ of plasma deceleration by field $B_d$, m $R_b$ | $\sim 11$                  | $\sim 1$                     | $\sim 0.05$  | ~ 0.055       |
| Geometric factor $\alpha = X_0/R_t$ | 0.85                    |                               | 3            | 0.85          |
| Ion magnetization criterion $\varepsilon_0 = R_t/R_b$ | ~ 0.001                 | 0.02                          | 0.75 (< 1)   |               |
| for Larmor $R_l$=mc$V_0$/ze$B_d$ ($<< \varepsilon_0 \sim 1$ / critical value) | ($\sim 1$ for direct irradiation) | for $R_b \approx 4.7$ cm and $R_t \approx 3.5$ cm | 0.34          |               |
| Energetic criterion $\alpha_0 = 3E_0X_0^3/\mu^2$ | 0.2~0.4                 | ($\leq \alpha = 0.4$)         | ~ 1 ($\geq \alpha$) | ~ 0.1         | 0.26          |

2. **Simulation of conversion processes in “VISTA-KI” experiment with Laser-Plasma clouds**

In figure 1 a general layout of “VISTA-KI” experiment is shown with the using of additional pulsed magnetic coil (1), inserting into the center of target chamber of KI-1 laser facility [11,12], and with applying of perlon filament. From such target, an axially-symmetrical plasma cloud is generated due to its irradiation by two laser beams of CO$_2$-laser with the 100 ns duration of pulses [12]. The angular distribution of the kinetic energy $E_k$ in such Laser-Plasma Clouds (LPC) could be presented roughly by function like $dE_k/d\theta$: $vS\theta$ (for the usual angle $\theta \approx 90^\circ$ into direction of Z-axis in figure 1), so for the real total LPC-energy $E_k$ near 20 J, its effective value $E_0=4\pi(dE_k/d\theta)_{max}$ could reach 30 J [12].

Therefore to estimate a maximal size $R_c$ of the LPC diamagnetic cavity (into Z-direction) we need to use namely $E_0$ in both the general expression of $R_c$ as $R_c \approx (3E_0/B_d)^{1/3}$ and to determine $\alpha$-criterion, listed in the table 1 together with the main parameters of discussed cases of LFR and its simulations.

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**Figure 1.** A scheme of “VISTA-KI” experiment: 
1 – main coil; 2 – pick-up [7] coil at $\Delta = 4.5$ cm (with Rogowsky coil to register EMF-induced current $J$); 3 – two laser beams (near 300 J totally); 4 – Laser-Plasma cloud in a form of toroid in the absence of dipole field ($B_d^{max} \sim 5$ kG for $X_0 \approx 5.7$ cm); 5 – Langmuir and magnetic probes; 6 – target in a form of plastic filament $\varnothing 0.3$ mm (or spherical target $\varnothing 4$ mm); 7 – glass tube to support it. $B_i$ is the field $\sim 10$ kG of main coil (near pick-up one)
Experimentally, the real efficiency of direct energy conversion is determined [8] as \( \eta_{ex} = E_e/E_k \), where \( E_e = L J^2/2 \) is the energy of electric current \( J \) (see figure 1) induced in pick-up coil (imitating Be-shield, of radius \( R_s \) for SCM-coil in VISTA) by rising LPC’ cavity at point \( X_0 \). The same data on current \( J(t) \) was used to control the efficiency (\( \eta_p > 50\% \)) of direct momentum transfer \( \Delta P_d \propto J x B_b \tau \) from ICF-plasma to VISTA via magnetic disturbances (with life-time \( \tau \)) outside of cavity [5,9,10].

3. Estimations and PIC-simulations of the efficiency under real conditions of plasma and coils

For study real opportunity to achieve a necessary 5%-level of the efficiency \( \eta_e \) we had analysed earlier [10] a processes of inductive generation of current in pick-up coils by expanding blob of diamagnetic ICF-plasma in quasi-dipole magnetic field. So in the case of spherical cloud, expanding (with velocity \( V_0 \)) from the point at distance \( X_0 \) near dipole \( \mu \), the shape of boundary for plasma’ deceleration by field is described by energetic criterion \( \alpha = 3E_0X_0^3/\mu^2 \) of MHD-model (Nikitin S.A. and Ponomarenko A.G., 1994) and the ideal efficiency of one-turn pick-up coil could be estimated as \( \eta_{ex} (\%) \approx 13\alpha/\alpha^2 \) [10]. The only main geometric coil-factor \( \alpha = X_0/R_s \) is used, for the usual condition of VISTA case, that pick-up coil is almost coincided with the main \( \mu \)-coil, so \( \eta_e \) is “independent” upon \( X_0 \).

This \( \eta_e \)-relation was tested preliminary under the same condition in the “MHD” experiment at KI-1 [11,12] with \( E_0 \approx 15 J \) (of quasi-spherical LPC) and uniform field \( B_0 \approx 8 kG \) (but with a shift of main-shield, of radius \( R_s \), for SCM-coil in VISTA) by rising LPC’ cavity at point \( X_0 \). The same data on current \( J(t) \) was used to control the efficiency (\( \eta_p > 50\% \)) of direct momentum transfer \( \Delta P_d \propto J x B_b \tau \) from ICF-plasma to VISTA via magnetic disturbances (with life-time \( \tau \)) outside of cavity [5,9,10].

These advanced estimations of energy conversion efficiency were confirmed in preliminary 3D/PIC-calculations of ILP with the using of Hybrid code of KU [4], that were done especially for the conditions of a new simulative experiment “VISTA-KI”, in which all main conditions of VISTA design for plasma – field and field – pick-up coil interactions will be realized (see table 1) for the first time, due to using of both axial-symmetrical (A) and spherical (S) LPCs (see figure 1,2 and 3).

Figure 2. Data of PIC-runs for “VISTA-KI” case (A), demonstrating the moderate levels of flutes’ growth (b) and their influence (c) onto energy conversion, which could achieve here a value up to \( E_e = (\Delta\Phi)^2/2L \approx 0.32 J \) (and \( \eta_{ex} > 2\% \)), on the base of calculated from (c) flux \( \Delta\Phi \approx 3.6*10^4 G*cm^2 \) and real \( L_{min} \approx 200 cm \) of short-circuited-pick-up coil. At the right a first results are shown: on the relevant LPC generation (at d – with the second, slow plasma peak LPC-2 of small energy \( E_0 \approx 1.5 J \) at levels \( \alpha \approx 0.3 \) and \( \alpha_s \approx 0.8 \) (< critical 1) in the field \( B_0 = 0.5 kG \) and (a) on its induced current \( J \) in the same coil at \( \Delta = 4.5 \) cm (with the probable efficiency \( \eta_{ex} \) up to 2.5 % of main peak J).
The observed non-MHD flutes (figure 2b) arise under conditions of finite-level magnetization $H_b$ of ions (see table 1), so they could be important at $\varepsilon_0 \sim 0.2$ for VISTA without expellant (around ICF-target), but not important – with it ($\varepsilon_0 \ll 1$). Nevertheless, even in the last MHD-case, during long-time plasma deceleration at $1.5R_0/V_0\sim 50\ \mu$s, a customary Rayleigh-Taylor flutes could develop and destroy plasma diamagnetizm. PIC-data at figure 2b show that when the non-MHD flutes are realized indeed by finer grid, than they could affect on plasma-field interaction, appearing in decreasing of $R_\alpha$, $\Delta B$ and $\Delta \Phi$-values (figure 2c). Because the energy of LPC $A$-type was limited by few Joules in the first simulative experiments with fiber target (figure 2d) we did both additional PIC-runs and experiments with the quasi-spherical LPCs ($S$) in the near 10 J-range of their energy $E_0$, but with the using of just the same scheme (figure 1). Now it was usually $E_0 \sim 6.5\ J$ while in the nearest future we plan to increase it up to need 30 J (see table 1) or more by using a flat-type solid targets, e.g.

![Figure 3](image-url)

Figure 3. Data (a,b,c) of PIC-run for “VISTA-KI” S (see Table), where at c – curve 1 is a total field’s change $\Delta B$ caused by LPC, 2 – $\Delta B$ due to its penetration (1 at 1) into coil and 3 is $\Delta B$ of LPC’s dipole $\mu_c=1.1*10^5\ G*cm^3$ in zero point (corresponding to $\eta_{ex}$ up to 3±4 %). At the right– a first experimental data with LPC ($S$) of energy $E_0 \sim 6.5\ J$ is presented with $\eta_{ex}$ up to 1.5 % (in the field $B_0=1.5\ kG$, in accordance with corresponding PIC-run at $z \sim 0.14$, $\varepsilon_0 \sim 0.6$ and grid 1,25 mm).

The data of PIC-modeling and first results of last “VISTA-KI” experiment (see figure 3) show that with these new schemes of simulative experiment we could confirm (at $z > 0.25$ and $\varepsilon_0 < 0.4\pm 0.5$) a possible real high level of energy conversion efficiency $\eta_{ex} \sim 4\%$ for the project of LFR VISTA [2].

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