Physics of the X-Ray Sources Based on Laser-Induced Discharges[1]

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Abstract – The results of experimental and theoretical investigation of a new type of pulsed point-like sources of the X-ray radiation based on laser induced discharges at applied voltages $U_0 \le 2.7$ kV are considered.

1. Introduction

In this paper we continue our investigation of short pulse X-ray generation from point-like sources of laser-induced discharges in vacuum [1, 2]. Here we consider concrete case of discharge induced by picosecond laser beam under applied voltage $U_0 = 2.7$ kV (note, that as predicted theory [3] the analogous physical effects can take place under low applied voltages up to $U_0 = 12$ V). The unique experimental device RFR-4 [4] had been used in our work for X-ray diagnostics with high spatial (~ 2 μm) and temporal (30 ps) resolutions. In computer simulation the mathematical model [5] (in r-z geometry) was used as in [1, 3].

2. Mathematical Model

A mathematical model of vacuum breakdown induced by picosecond laser beam (with the same parameters as in experiments [1, 2]) in the presence of electric fields is based on the 2-D electro-hydrodynamic and heat transfer equations, with taken into account an electron emissive processes and radiation transfer, including self-consistent calculation of the electric field and current distributions. The system of hydrodynamic equations was solved by using method of "big particles", completed by equations of state in a wide range and semi empirical relationships for thermal and electric conductivity calculations (including states of strongly coupled plasmas).

3. Discussion of Results

Computer simulations have been carried out for the following conditions: applied voltage $U_0 = 2.7$ kV, an inter electrode gap distance $D_g = 50$ μm, the initial temperature of hot spot in cathode $T_0 = 20$ eV, in all other parts of copper electrodes the initial temperature equals to the room temperature under low inductance $L \approx 0$, for two cases of active resistance of external circuit: a) $R_c = 0.03$ Ω and b) $R_c = 50$ Ω. The evolution of main matter parameters for both cases is represented in Figs. 1–9. In case of low resistance (at mode of the shorting) the initial energy input approximately in twice grater then in case of 50 Ω (see Fig. 1).

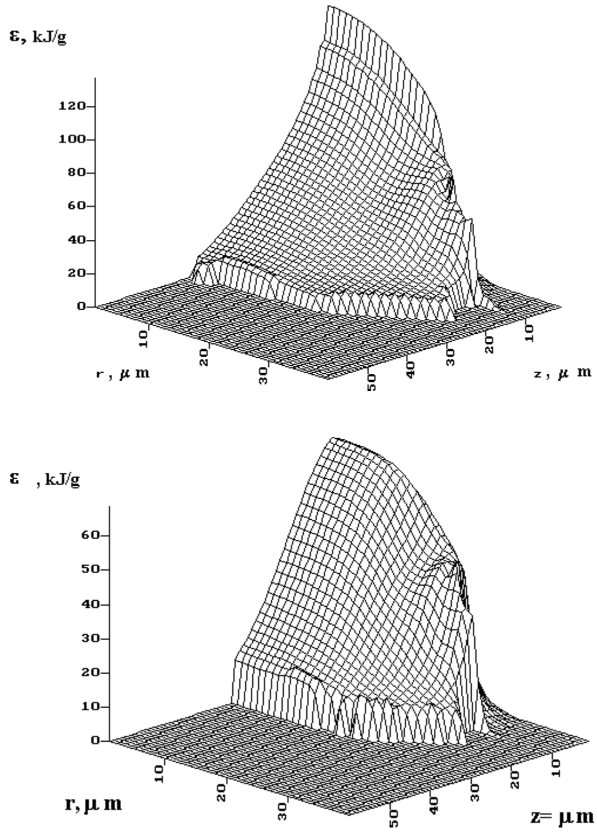

Fig.1. The specific internal energy at t =1.0 ns in cases a) and b) correspondingly

It is connected with the more high current densities in a first case, Fig. 2. The electrical potentials in plasma torches for both cases are approximately the same and reach to few V. The current distributions at later times are shown in Figs. 3, 4. We can see that in plasma torches the "shooting" solitons generation [1] takes place accompanying by increasing of temperatures in different micro volumes (Figs. 5, 6). The electric potential in a case b) at $t \approx 1.96$ increases up to 60–300 V, at this time a multiple charged ions creation and high

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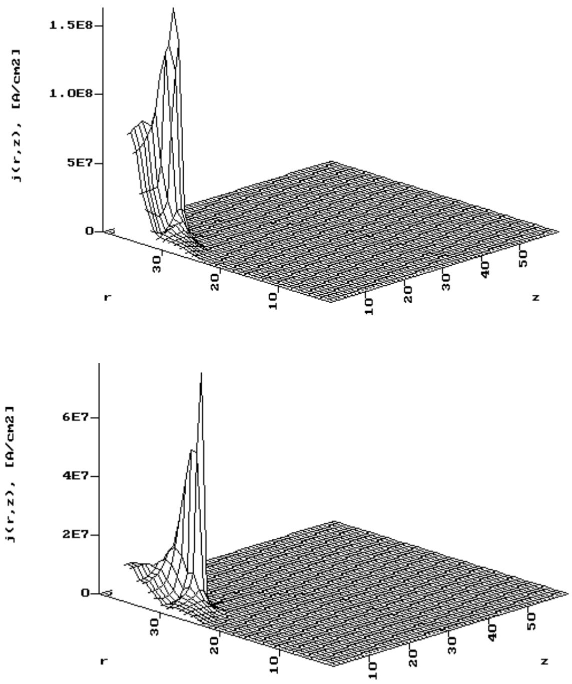
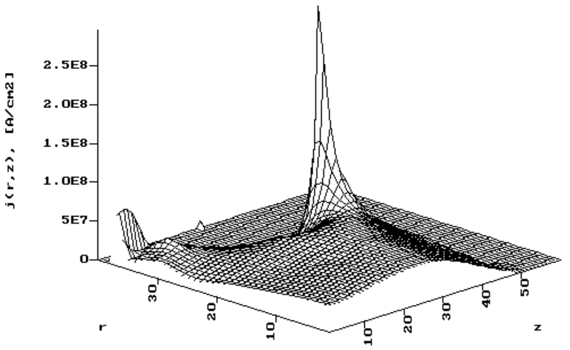
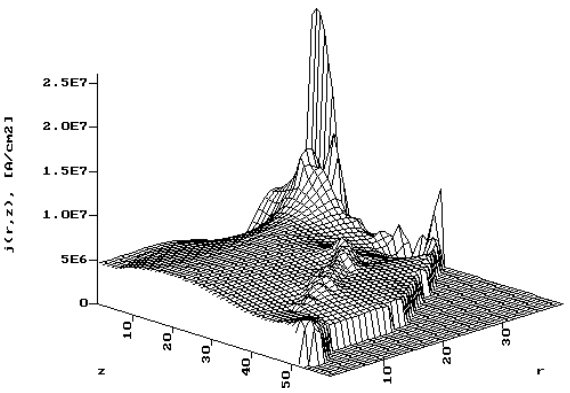


Fig. 2.The current density at t = 1.0 ns for a), b)-cases



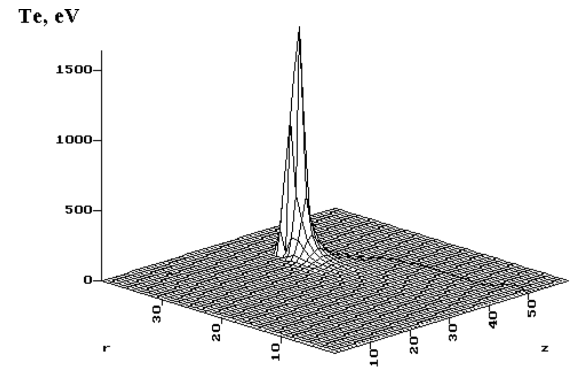
t = 1.44 ns



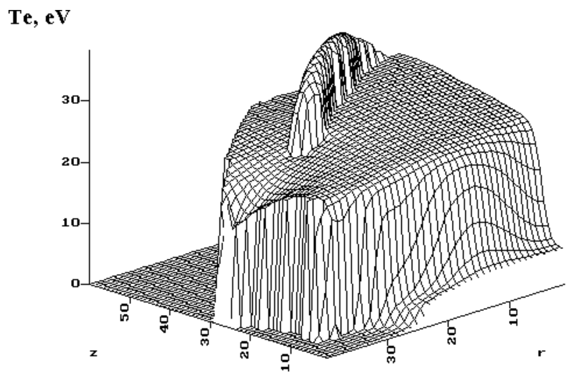
t = 1.49 ns

Fig. 3.The current density, case a)

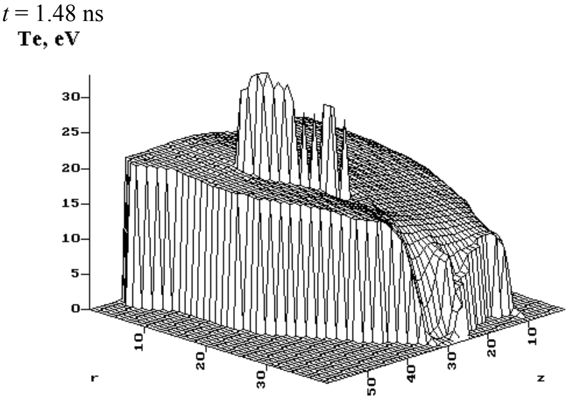
pressures occurs (see Fig. 7). At later time for this case we have peaks in spatial distributions of electrical generation (Fig. 5) as well as electrical potential increasing (Fig. 9,a) and growth of ratio ionization and generations of micro beams of multiple charged ions from plasma region with extremely high Z (a mean potential and temperature (Fig. 8). In a case a) we also have ultrafast nonlinear phenomena accompanying matter transition into extreme states and hot spots generation (Fig. 5) as well as electrical potential increasing (Fig. 9,a) and growth of ratio ionization and generations of micro beams of multiple charged ions from plasma region with extremely high Z (a mean ion charge) in front of shock wave (Fig. 9,b). Such generation of micro ion beams is accompanied by the generation of micro electron beams too. Its pulse duration as well as X-ray pulse time can be higher then time life of single hot spot τ. A few hot spots can generate the one pulse of X-ray radiation or particle beam. In a case a) the time τ is very short ($\tau \sim 10$ ps). In a case b) the value τ can be higher (at considered conditions).



t = 1.44 ns

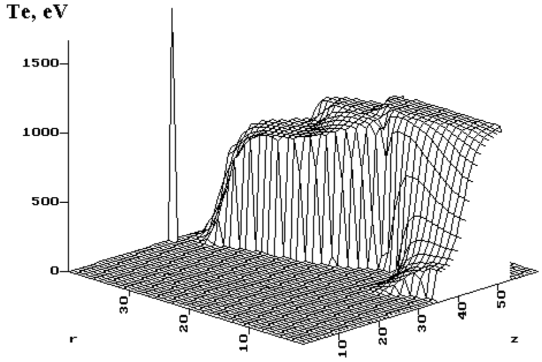


t = 1.48 ns

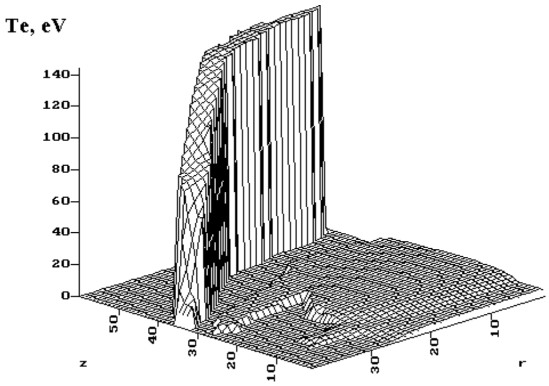


t = 1.49 ns

Fig. 4. The electron temperature in plasma, case a)



$t = 1.94$ ns



$t = 1.96$ ns

Fig. 5. The electron temperature in plasma, case b)

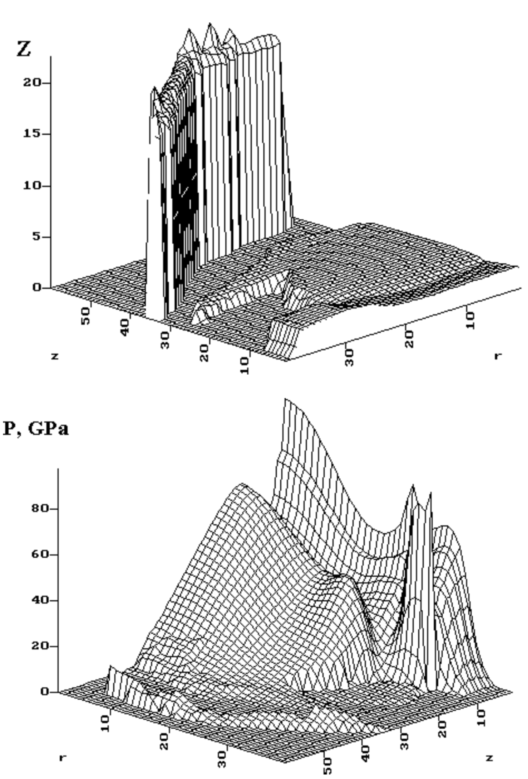


Fig. 7. The ratio ionization Z and pressure P, $t = 1.96$ ns

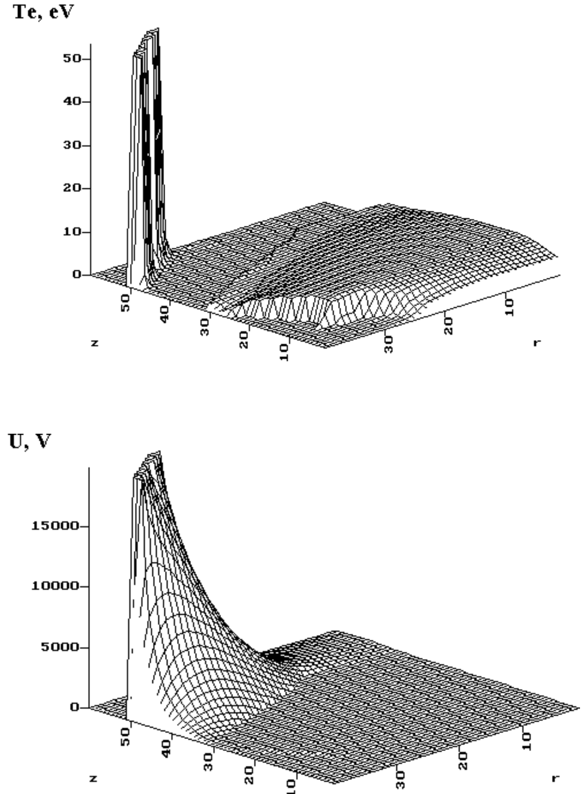


Fig. 8 The temperature T_e and potential U at $t = 2.01$ ns

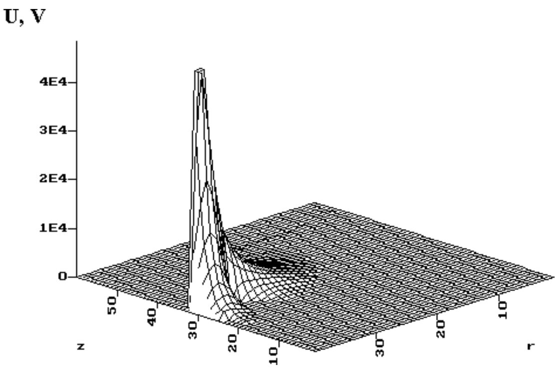


Fig. 9,a. The electric potential in plasma at $t = 1.54$ ns

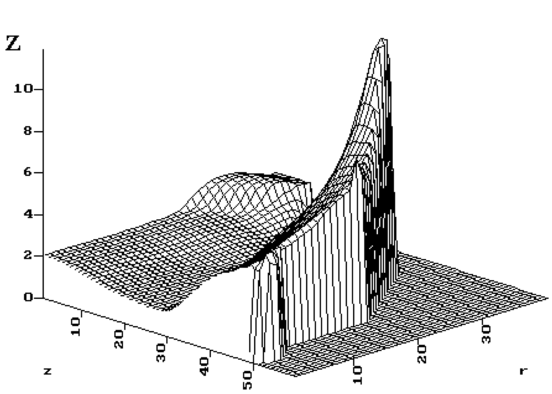
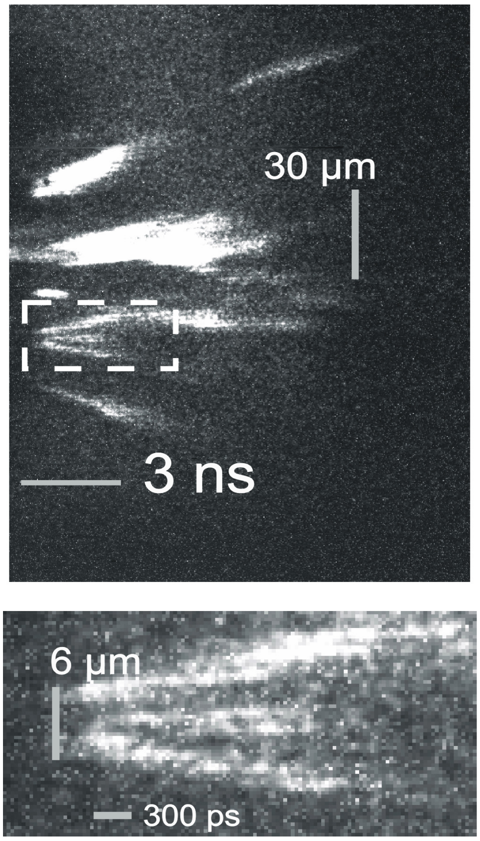


Fig. 9,b. The ratio ionization Z in plasma at $t = 1.45$ ns

The mentioned above ultrafast nonlinear phenomena take place in aperiodic mode on the background of "usual" dynamics of vacuum sparks or arcs.



a)

b)

Fig. 10. a) A streak picture of X-ray emission of laser-induced discharge in vacuum (under $U_0 = 2.7$ kV, with $R_c \sim 50\ \Omega$) taken with a delay time of $t = -3$ ns. b) Magnified detail from the streak picture marked by a broken line

In experiments we have also detection of electron beams and X-ray radiation generation (see, e.g., Fig. 11).

4. Summary

The most interesting results of present calculation are:

– it is possible to obtain an extreme states of matter in laser induced discharge at different values of active resistance (under applied voltages $U_0 \approx 1.7$–2.7 kV) ;

– the time life of hot spots τ increases with the resistance growth from 0.03 Ω to 50 Ω;

– in both considered cases it is possible to generate not only soft X-ray radiation owing shooting solitons generations and overheating instability, but also- a hard X-ray radiation due to initiation a peaks of electrical potentials in plasma torch;

– at lower applied voltages (for example, under $U_0 \sim 12$ V) the described above ultrafast nonlinear phenomena take place in mode of the shorting only.

References

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