Influence of the laser spark generation mechanism on electric and magnetic fields in its vicinity

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A laser spark formed by the focused beam of a ns high energy laser in a gas filled interaction chamber can mimic energetic events in the early Earth atmosphere, which are thought to be instrumental in the synthesis of simple chemical compounds, such as some amino acides, [1, 2], which later might have participated in more complex organic syntheses leading to the origin of terrestrial life. Some of these molecules are optically active and it is an experimental fact that the model experiments in the gas-filled chamber yield an unequal ratio of right-handed (R-) and left-handed (L-) optical isomers. It has been conjectured that this asymmetry between the R- and L- species is induced by the synthesis going on under the action of superimposed electric and magnetic fields occurring in the spark vicinity as a consequence of its polarization and internal currents. Such fields during an optical breakdown in the air have actually been directly measured, [3]. The orientation of the electric dipole formed in the plasma, which is caused by the polarization due to the plasma radial expansion in the self-generated magnetic field, has the polarity, which very much depends on the disposition of electron density and electron temperature gradients inside the plasma. These gradients depend, in turn, on the mechanism of the laser spark formation. In the literature essentially three different mechanisms can be tracked down: (1) light detonation wave, [4], (2) radiation hydrodynamics supersonic propagation, [5], and (3) delayed breakdown action, also described in [4]. The present contribution is aiming at an assessment of the mentioned spark formation models and their comparaison with the experimental findings.

Mechanism of the laser spark

The laser spark in a gas at the atmospheric pressure is initiated by an optical breakdown in a gas into which a high power laser beam is focused. The optical discharge starts inside the focal cone in the place where the focused intensity attains the breakdown value characteristic of the gas mixture and its pressure. The propagation of the ionization front from the break-down point, due to which the laser spark is formed may occur in three different regimes in dependence on the duration and intensity of the driving laser pulse. They are described in [4]. For long pulses the most fundamental mechanism is the “light detonation wave” with the characteristic velocity

$D \sim (I_L/\rho)^{1/3}$ of propagation against the laser beam, see [4], where I_L is the local laser beam intensity and ρ_m the initial mass density of the ambient gas. The speed of the plasma front may reach 100 km/s, but it is not enough for short pulses to form a large spark plasma as it is observed experimentally. The propagation may still be enhanced by the second mechanism of supersonic radiative wave propagation driven by x-ray radiation emanating from the forming plasma in both longitudinal and radial directions, [5], but even this mechanism needs a longer time of several ns to form a sizable plasma. For very short pulses as produced by a subnanosecond iodine laser the most likely mechanism seems to be the delayed break-down action equally described in [4]. A short pulse with a steep leading edge easily reaches the steady-state intensity break-down value somewhere on its way down the focal cone, but before the actual break-down occurs, the front end of the pulse moves farther on still closer to the focus undisturbed by any plasma effects. As the intensity keeps rising the initial break-down eventually takes place closer to the focus than given by the nominal break-down intensity and the resulting break-down front travels very fast against the laser beam to the point where the nominal break-down intensity was first reached. In this way a large plasma formation is created in the form of a truncated cone with the narrow side facing the focus. It is a remarkable property of this initial plasma formation that the plasma density is rising from the focal side towards the laser, with a sharp drop in the density on the laser side. Only after the plasma is formed the propagating beam is defocused and scattered by the resulting refraction index inhomogeneities thus blocking any further plasma creation on the focal side of the spark.

Electric and magentic fields around the laser spark

The laser spark is an energetic phenomenon capable of forming the electric and magnetic fields in its vicinity. Here we shall be interested primarily in the evaluation of the fields generated by the spark in its active stage or shortly after. We shall thus consider a plasma cloud in the form of taping truncated cone partially filling the focal cone with the geometrical focus placed in the origin of coordinates and the laser light propagating against the $z-$axis. The mechanism creating an azimuthal magnetic field $\vec{B} = (0, B_\varphi, 0)$ winding around the spark plasma is well known. Its generation equation is derived by combining the electron equation of motion with the electron inertia neglected, Faraday's law and the Ampere's law of the Maxwell's equations. Keeping the source term only it is obtained

$$\frac{\partial \vec{B}}{\partial t} = \frac{ck_B}{en}[grad\ T \times grad\ n]. \tag{1}$$

(e...elementary charge, c...speed of light, k_B...Boltzmann constant, n...electron number density, T...electron temperature). The solution of (1) can be found in model cases, for our purposes it is sufficient to take an approximate solution. However, in contrast to the case of a solid target, the density gradient in the case of the laser spark is rising away from the breakdown point towards the laser (positive z-axis direction). The field has thus in the case of mostly flatter dependence of the electron temperature along the z-axis still a purely azimuthal direction $\vec{B} = (0, B_\varphi, 0)$, but it winds around the beam direction in the anti-clockwise sense and its only non vanishing component B_φ is thus positive. Modelling of the radial dependence of density and temperature is done with simple parabolas, respecting simultaneously the focal cone taping

$$n(r,z) = n_0\big(1 - (\frac{rf}{zR})^2\big)P_{(n)}(z/z_n), \quad T(r) = T_0\big(1 - (\frac{rf}{zR})^2\big)P_{(T)}(z/z_T), \tag{2}$$

where f is the focal distance and R the aperture radius, $P_{(n)}(z/z_n)$ and $P_{(T)}(z/z_T)$ are so far unspecified longitudinal profiles of density and temperature, governed by the scale lengths z_n and z_T, respectively. A simple estimate renders

$$B_\varphi = \frac{2c}{e} k_B T_0 \tau_L r \left(\frac{f}{zR}\right)^2 \left(\frac{P'_{(n)}P_{(T)}}{z_n P_{(n)}} - \frac{P'_{(T)}}{z_T}\right), \tag{3}$$

where τ_L is the laser pulse duration. Note that the magnetic field is now windig around the spark channel in the opposite sense than in the conventional laser experiments with solid targets. As for the origine of the electric field, it was conjectured in [3] that streaming of the expanding plasma across the magnetic field is causing a charge separation inducing a longitudinal electric dipole moment $\vec{d} = (0, 0, d_z)$ of the spark

$$\rho_c = -\frac{1}{4\pi c} div([\vec{v} \times \vec{B}]) \tag{4}$$

Assuming that the longitudinal temperature profile is flat $P_{(T)}(z/z_T) = 1$ and longitudinal scaling of density and temperature are equal $z_T = z_n$, it is obtained for d_z

$$d_z = \int dV\, z\rho_c = -\frac{\pi}{24\sqrt{2}} \frac{(k_B T_0)^{3/2}}{e\sqrt{m_i}} \tau_L \frac{z_n R}{f} \left[\left(\frac{z^2 P'_{(n)}}{z_n^2 P_{(n)}} - 3\frac{z \ln P_{(n)}}{z_n} \right) \Bigg|_{z_1}^{z_2} + \frac{3}{z_n} \int_{z_1}^{z_2} dz \ln P_{(n)} \right] \tag{5}$$

where m_i is the ion mass, ρ_c is the charge density and $\vec{v}$ is the plasma flow velocity given by the acoustic speed $v \sim \sqrt{k_B T / m_i}$. The last expression can be evaluated provided the longitudinal density profile is known. For instance, a linear dependence leads in (5) to a numerical factor of 2, a quadratic dependence gives 4 and an exponential density growth renders 1/2. The dipole moment has now the correct orientation along the z-axis (positive charge nearer to the laser) as, indeed, found experimentally, [3].

Evaluation of the fields for the spark in a model primordial atmosphere

The dipole electric field as well as the circulatory magnetic field generated for the condition of the experiment [6] will be evaluated using (3) and (5). The focused laser energy propagates down the taping focal cone until the break-down intensity is reached. Assuming the breakdown intensity for a $CO - N_2$ mixture 1:1 to be approximately equal to 10^{11} Wcm^{-2} we obtain after some elementary calculations for the parameters of the focusing system used in the experiment (lens diameter 15 cm, focal length 25 cm, pulse energy 87 J and pulse length 0.5 ns) the length of the spark (in front of the focus) about 2.5 cm and its diameter about 1.5 cm. Setting as an example the temperature $T_0 = 500$ eV it is obtained from (3) for the magnetic field near the plasma surface $B \simeq 27$ G and from (5) for the electric dipole moment $d_z \simeq 6.3 \times 10^{-4}$ [CGS units].

Acknowledgements

A support by the grant No. P205/11/0571 of the Czech Science Foundation is gratefully acknowledged as well as the Czech Ministry of Eduation project OP VK2 No. CZ.107/2.3.00/20.0087.

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