Laser spark as a source of electric and magnetic fields in the ambient gas

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A laser spark initiated by a high energy laser in a gas mixture of a composition imitating the primordial terrestrial atmosphere models the effect of energetic events (e.g. meteorite impacts) supposed to play a role in the synthesis of chemical compounds, such as simple amino acides, [1],[2], which are the building stones of life substances. Those molecules which are optically active are, however, not naturally racemized and there is thus no symmetry between the concentrations of L- and R-species. Since the synthesis is initiated in the gaseous environment by processes (either a burst of short wave radiation or a shockwave propagation) which in no reasonable way might induce an imbalance between both the optical isomers, the asymmetry must be imprinted by an external cause. An explanation put forward recently suggests that the spontaneous electric and magnetic fields induced by the dynamics of the laser spark in its vicinity might be responsible for the observed asymmetry. Such fields during an optical breakdown in the air have actually been directly measured, [3]. Their interpretation is unfortunately not straightforward. Namely, the electric dipole formed in the plasma channel, which is caused by the polarization due to the plasma radial expansion in the self-generated magnetic field, seems, at a first glance, to have an opposite polarity than the observed one. The aim of the present contribution is to apply an adequate model of laser spark formation and to determine the physical conditions under which the agreement between the observed and calculated quantities is achieved. This might have implications for a better understanding of processes in the terrestrial reductive atmosphere and their possible influence on the organic synthesis.

Mechanism of the laser spark

The process crating the laser spark in a gas at the atmospheric pressure into which a high power laser beam is focused is the optical breakdown. The optical discharge starts inside the focal conus in the place where the focused intensity attains the breakdown value characteristic of the gas mixture and its pressure. The breakdown intensities are tabled for some gases, generally they are higher if the mixture contains an electronegative component (with a tendency for the electron capture by forming negative ions, such as CO or CO_2). For a sufficient power of the laser beam the breakdown thus occurs inside the focusing cone still before the optical focal point. The phenomena which follow the breakdown are described in detail in the book [4]. The absorbed energy at the plasma front is driving a shockwave called “light detonation wave” with the charateristic velocity $D \sim (I_L/\rho)^{1/3}$ of propagation against the laser beam, 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 thanks to the breakdown temporal delay described in [4] the laser energy can penetrate initially much closer to the geometrical focus and only then the plasma is formed by the "breakdown wave". If we ignore the the taping of the focal cone, a cylinder of plasma is formed filling the space between the focus and the nominal breakdown intensity surface inside the focal cone with the perpendicular dimensions comparable to the width of that surface. It is a remarkable property of this initial plasma formation that the plasma density is rising from the focal side towards the laser, where a sharp drop in the density occurs, [5]. This slope should be due to the plasma expansion, since any recombination process would be too slow to cause such a density gradient. After this initial formation stage the plasma keeps expanding. The density profile assumes more and more symmetric shape first in the longitudinal direction, with a less pronounced maximum in the centre of the former cylinder, but also in the perpendicular direction, so that gradually a plasma sphere is formed, as it is often observed in the experiments, [6]. It is also interesting that even in an under-dense plasma, unless the laser power is quite low, the inhomogeneity in the refraction index inside the spark scatters the laser power causing a total defocusing of the beam so that there is no propagation and plasma creation at the far end of the spark (with respect to the driving laser), it is beyond the point of the initial breakdown. There is no simple similarity solution describing the just mentioned laser spark properties and its temporal evolution, but the numerical solution found in the literature combining all the important factors like the plasma formation and composition together with its optical properties, seem to reproduce the above notion quite well, at least for a ns spark in the air, [5]. An important feature of the propagating spark is also a pre-ionization glow observed during the stage of the spark formation in its path and generally also in its closed vicinity, which is interpreted as a photoionization of the ambient gas by the UV and X-ray radiation emanating mainly from the propagating plasma front. These hard photons are no doubt also responsible for the synthesis of chemical products found after a series of repeated shots inside the interaction chamber.

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. 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

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

(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 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 both the radial and axial dependence of the density and temperature with simple parabolas

$$n(r,z) = n_0(1-(\frac{r}{r_s})^2)(\frac{z}{z_s}+1)^2, \quad T(r) = T_0(1-(\frac{r}{r_s})^2)(\frac{z}{z_s}+1)^2, \quad (2)$$

where r_s and z_s are the radius and the length of the spark channel extending over the intervals $0s < r < r_s$ and $-z_s < z < 0$. A simple estimate renders

$$B_\varphi = \frac{4c}{e}\frac{k_B T}{(r_s z_s)^2}\tau_L r(z+z_s), \quad (3)$$

where r_s is the radial and z_s longitudinal dimension of the spark. 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

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

$$d_z = \int dV\, z\rho_c = \frac{(k_B T_0)^{3/2}}{3e\sqrt{m_i}}\tau_L(r_s + z_s/3) \quad (5)$$

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 dipole moment has now a 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 $B \simeq 54$ G and from (5) for the electric dipole moment $d_z \simeq 6.8 \times 10^{-3}$ [CGS units].

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