# Electric and magnetic fields generated in the vicinity of laser sparks

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Focusing a high power nanosecond laser into a gaseous medium simulates the effect of energetic events (e.g. meteorite impacts) supposed to drive in the ancient terrestrial atmosphere a number of chemical reactions leading to the origine of primitive organic species such as simple amino acides, [1]. It is interesting that many of thus created molecules which are optically active are not naturally racemized and there is an asymmetry observed between the yields 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. A popular explanation points out to the existence of spontaneous electric and magnetic fields induced by the dynamics of the laser spark in its vicinity. A synthesis in the presence of slowly varying fields might, indeed, be responsible for the observed asymmetry. Such fields accompanying an optical breakdown in the air have actually been directly measured, [2] and interpreted. The aim of the present contribution is to determine analogous phenomena occurring during a breakdown in the early Earth reductive model atmosphere to be able to assess their possible influence on the organic synthesis.

**Laser spark**

The process crating the laser spark in a gas 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 very intense laser pulse and a relatively long focusing caustic, such as used in [3], a volume breakdown mechanism was suggested in [4] called the breakdown wave since the delay of the breakdown goes up with the diminishing light intensity along the focal conus. This mechanism should form a larger plasma than the more conventional mechanism also described in [4] of absorption just at a sharp boundary of initial breakdown and its propagation in the form of light energy driven detonation wave (ionization front) at a speed of hundreds km per second till the laser pulse dies down. The just mentioned detonation wave mechanism is likely to have operated in [2], where the ionization front was actually observed. After its formation the plasma still keeps expanding at the thermal speed of about the same magnitude. Two cases must be distinguished

either, if the electron critical density is exceeded the laser light is reflected from the over-dense plasma, which especially in the case of the breakdown wave regime screens off the focal conus volume behind the focus. Then further plasma formation beyond the critical surface is given by the thermal conduction only. The plasma keeps expanding against the laser beam in the form of an breakdown wave until the laser intensity of the heating pulse goes down, so that the plasma cloud assumes an asymmetric form with respect to the laser focus,

or, if the plasma remains under-dense it still remains asymmetric but the passing light may contribute to a partial expansion of the plasma rear surface. It is, however, clear that even in the case of under-dense plasma the full symmetry cannot survive. The refraction in a relatively long plasma cloud will divert the rays away from the plasma and defocus the beam so that the far end of the plasma will not resemble the near wing formed in front of the focus by an unimpeded breakdown wave.

For the first harmonics $\lambda = 1.315$ $\mu$m of the iodine laser $n_{e(crit)} = 6\times 10^{20}$ cm$^{-3}$. With the assumed composition of the primordial atmosphere there are enough electrons around to make the plasma just slightly under-dense the second case would mostly apply. The break-down power density, which for most examined compositions of the premordial atmosphere ($CO_2$/CO-$N_2$-$H_2O$, 1:1 plus saturated $H_2O$ vapour, total 1 atm) can be estimated at $10^{11}$ Wcm$^{-2}$ and the parameters of the focusing system used in the experiment [3] (lens diameter 15 cm, focal length 25 cm, pulse energy about $10\times 100$ J - 87 J in the example shown - and pulse length $\tau_L = 0.5$ ns) imply that the breakdown occurs about 2.5 cm from the ideal focus, as seen in [3]. In this way a certain relatively small volume of plasma within the original gas filling is formed, which is, as a whole, electrically neutral, but it is not entirely homogeneous and thus it may generate an electric dipole field in its vicinity. The higher terms of the multipole expansion contribute in larger distances much less.

**Origin of fields around the laser spark**

This dipole moment $\vec{d}$ due to the plasma cloud representing the laser spark is defined as

$$\vec{d} = \int dV\vec{R}\rho, \tag{1}$$

where the integration is over the plasma volume, $\vec{R}$ is the position vector and $\rho$ is the charge density. Paper [2] examines the reasons how such a charge inhomogeneity may be generated.

1. Polarization due to the light pressure - the electrons are pushed in the direction of the heating beam and thus shifted with respect to the ions. The resulting charge separation creates an electric dipol oriented against the beam, which agrees with the dipole field observed experimentally. However, for the ns pulses the available power density is too low to account for the magnitude of the observed dipole field and another mechanism should be sought.

2. Dipole originating due to the plasma polarization caused by fast axially expanding electrons causing a charge separation and an ambipolar electric field holding the plasma together. The resulting dipole is oriented on the laser side parallel to the beam, which is contrary to what is really measured. It the plasma remains under-dense a dipole on the far side should compensate due to the symmetry the dipole on the laser near side and the contribution would be zero, as claimed in [2]. We, however, surmise that due to the clear asymmetry of the plasma cloud with respect to the focus such a compensation cannot occur. Rather, the estimated contribution of this axial polarization process to the overall dipole moment is also much too small, similar as in the previous case.

3. Another possible source of the electric dipole is the presence of azimuthal magnetic field, which winds around the plasma plume [5] in the clockwise direction with respect to the beam propagation. It is assumed in [2] that this field is generated in a narrow region close to the focus on the laser side by the $[grad\ T \times grad\ n]$ process ($T$...plasma temperature with a radial gradient and $n$...plasma density with an axial gradient parallel to the laser beam) is supposed to diffuse symmetrically from the point of its origin, which gives a finite dimension of the charge separation zone. This is somewhat inconsistent with the assumption of the supposed plasma symmetry with respect to the focus as considered in

the previous point. Also, in the case of [3], with a much shorter pulse, there would be not much time left for the field to diffuse. Nevertheless, in an ideally conducting plasma expanding radially across the clockwise magnetic field a charge separation occurs in the axial direction, with electrons shifted parallel to the laser beam, which may be a source of the dipole field. This dipole is tied to the active part of the plasma in front of the focus and is supposed to be absent on the focus far side.

The generated magnetic field $\vec{B}$ may, however, influence the environment in the interaction chamber in its own right, just as the dipole electric field. Its generation equation is derived by combining the electron equation of motion, where the electron mass has been neglected, Faraday's law and the Ampere's law of the Maxwell's equations to obtain

$$\frac{\partial \vec{B}}{\partial t} = rot\,[\vec{V} \times \vec{B}] + \frac{c^2}{4\pi\sigma} \triangle \vec{B} - rot[\frac{\vec{j}}{ne} \times \vec{B}] + c\, rot(\frac{grad\ p_e}{ne}), \tag{2}$$

$\vec{V}$...plasma flow velocity, c...speed of light, $\sigma$...plasma conductivity, $\vec{j}$...current density, $p_e = nkT$...electron scalar pressure ($T$...temperature, $k$...Boltzmann constant). The first term on the right-hand-side of (2) describes the field-line freezing effect (dynamo), the second one field-line diffusion and the third is the Hall effect. All the three need not be considered at this stage, since they represent no source terms. As the source term only the last term can be identified, especially if (2) transcribed as

$$\frac{\partial \vec{B}}{\partial t} = \frac{ck}{en}[grad\ T \times grad\ n]. \tag{3}$$

The solution of (3) can be found in model cases, for our purposes it is sufficient to take over an approximate solution from [5]: the field is an azimuthal one $\vec{B} = (0, B_\varphi, 0)$, winds around the beam direction in the clockwise sense and its only non vanishing component equals (the cylindrical coordinate system $[r, \varphi, z]$ has the $z$-axis oriented against the laser beam and the azimuth $\varphi$ is oriented anti-clockwise with respect to $z$, it means clockwise to with respect to the direction of the beam propagation)

$$B_\varphi = -\frac{2c}{e}\frac{kT}{rl_p}\tau_L, \tag{4}$$

where $r$ is the cylindrical radial coordinate. With the magnetic field known, we can proceed to the evaluation of the electric dipole moment. Using the Ohm's law in an ideally conducting plasma and the Poisson equation the charge density is obtained as $\rho = -\frac{1}{4\pi c} div([\vec{V} \times \vec{B}])$, so that $\vec{d} = (0, 0, d_z)$ of (1) can be evaluated as

$$d_z = \frac{1}{4\pi c}\int_0^{2\pi} d\varphi \int_0^{r_p} dr\, r \int_0^{l_p} dz\, z \frac{d(v_r B_\varphi)}{dz}. \tag{5}$$

Substituting from (4), ignoring the radial contribution, assuming that the radial velocity scales as the sound speed and modelling the breakdown wave regime by the assumption that the plasma temperature $T$ diminishes quadratically when going away from the focus we obtain

$$d_z = -\frac{(kT)^{3/2} r_p \tau_L}{4e\sqrt{m}} \tag{6}$$

In the last expression the numerical factor is, of course, uncertain. More accurate calculations would require a detailed knowledge of the laser spark hydrodynamics. Also, the plasma dipole is oriented in the negative $z$-direction, parallel to the laser beam (negative charge nearer to the laser), which is contradicting the experiment of [2]. We surmise that the resolution of this contradiction should be understood in terms of different regimes of laser spark origin. In the case of large under-dense plasma formed by a short energetic pulse focused by the lens with a long focal caustic as described in [3] the breakdown wave regime of [4] applies and the maximum of laser energy would thus be deposited near the focus, with no marked influence of the detonation wave (ionization front) regime. On the other hand, in [2] the propagation of an ionization front after the breakdown was actually observed. Most of the energy was thus likely to be deposited at the laser side of the plasma and the longitudinal temperature gradient might thus be reversed changing also the sign of (6). The magnitude of the dipole moment is, however, well within the experimental findings.

**Evaluation of the fields for the conditions of the spark in the model primordial atmosphere**

The dipole electric field as well as the circulatory magnetic field generated for the condition of the experiment [3] will be evaluated using the expressions (4) and (6). The focused laser energy propagates forward in the taping focal conus until the break-down intensity is reached. Assuming the breakdown intensity for the mixture 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 in the focus $T = 500$ eV it is obtained from (4) for the magnetic field on the plasma surface $B \simeq 30$ G and from (6) for the electric dipole moment $d_z \simeq -2.5\times10^{-3}$ [CGS units]. The same evaluation would give for the situation of [2] (air, pulse energy 0.2 J, duration 30 ns, focal length 5 cm, breakdown intensity $10^{12}$ Wcm$^{-2}$, estimated temperature 150 eV) $B \simeq 40$ MG and $d_z \simeq -4.5\times10^{-5}$ [CGS units] as against assumed 1.5 MG and measured $3 \div 7\times10^{-4}$ [CGS units]. A more realistic breakdown intensity of $10^{11}$ Wcm$^{-2}$ would, however, yield $B \simeq 4$ MG and $d_z \simeq -1.5\times10^{-5}$ [CGS units] closer to the experimental numbers.

**Acknowledgements**

This contribution was written in a partial fulfilment of the project “Research Center of Laser Plasma" No. LC528 of Ministry of Education of the Czech Republic and a support by the grant No. IAAX00100903 of the Grant Agency of the Academy of Sciences of the Czech Republic is also gratefully acknowledged.

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