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The experimental setup for optical probing of high-voltage laser spark gap plasma

A.I. Lipchak[*], *N.B. Volkov*

Institute of Electrophysics UB RAS, Yekaterinburg, Russia
[*]*lipchak@iep.uran.ru*

Abstract. The article presents a recently developed technique and apparatus for synchronized optical probing of pulsed plasma initiated by Q-switched YAG: Nd^{3+} laser radiation in a high-voltage gas gap commutator. The latter is usually used as a primary switch of a high-current pulsed e-beam RADAN-type accelerator, and its properties notably define the synchronization accuracy of such devices. The investigation was performed in the natural atmosphere. The initial measurement results and the absorption coefficient dynamics of laser radiation in the plasma obtained on the developed apparatus are presented. These measurements have shown the appearance of plasma illumination phenomenon for energy densities higher than 2 MJ/m^2. Also, the threshold-like behavior of absorptivity jitter in dependence on the laser pulse energy densities was found.

Keywords: Laser-induced plasma, gas gap, e-beam accelerator.

1. Introduction

Laser-induced plasma (LIP) seems to be the most important component defining high-pressure gas gap operation mode with optical control, determining the stability and accuracy of its transition time to a conducting state [1, 2]. Despite decades since their development, the interest in its improvement is sustained by the unique features of these devices, such as the complete isolation of controlling circuits from controlled ones or the possibility of preliminary creation of a plasma long channel with high conductivity having different configurations [3, 4]. It stimulates the activity in the LIP studying in various conditions, even nowadays [5, 6].

2. Apparatus and measurement technique

The gas gap, which we used as the core of setup, consists of two polished stainless electrodes, having a Rogowski profile and spaced 3–10 mm apart, with a 2 mm diameter axial hole in the cathode for an entrance of the laser radiation. The 100 mm focal distance lens to concentrate laser radiation on the anode (see red arrow in Fig. 1) was used.

The point is that this configuration supplies the minimal switch–on jitter at a gas gap voltage level of 90–95 % of the self–breakdown [7]. We used the dynamical charging of the gas gap of a few microseconds, typical for a double forming line of RADAN–type accelerators [8]. Fig. 2 presents the schematic diagram of measurements. We used the fundamental harmonic (FH) wavelength radiation of the YAG:Nd^{3+} laser with $\lambda = 1064$ nm to ignite plasma on the anode. Along with it, the second harmonic (SH), $\lambda = 532$ nm was used to probe LIP in the transverse to the igniting pulse direction. The reason to use the SH is in the following known relationship (1) [9]:

$$n_{cr} = \frac{\omega^2 \cdot m_e \cdot \varepsilon_0}{e^2}, \tag{1}$$

where ε_0 is permittivity, m_e is electron mass, e is the elementary charge, and $\omega = 2\pi c/\lambda$ where c is the speed of light in vacuum, λ is laser radiation wavelength. This relationship lets one evaluate the critical concentration of electrons above which electromagnetic waves do not pass through a plasma. So, the SH gives a broader range of concentrations for LIP probing than the FH. Another problem that should be solved in the proposed experimental setup is the account of the instabilities of laser pulses from pulse to pulse. Mainly, this effect is caused by the beating of longitudinal modes in the multimode laser radiation generation mode [10, 11]. It occurs distinctly at a low power of the laser active medium pumping we observed. Thus, one should have reference copies of each pulse that was not perturbed by the plasma to compare them with those that passed through it. For this purpose, the beam splitter (BS) of the probe pulse was added to the setup scheme (the lower BS, Fig. 2). The probe and reference pulses were to be registered by the single UPD-50-UP photodetector with a rise time of 50 ps to exclude the account of the difference in instrument response functions if the signal would registered by different ones. This also allowed us to reduce the cost of the experimental setup. However, it would require an optical delay line with a time of about 100 ns to separate two laser pulses with a duration of about 45 ns. To achieve this delay using the air line, a distance of about 30, m is required, i.e., it is necessary to increase significantly the installation size. Another way is to use of twelve — fourteen retroreflectors bearing a typical optical bench size of 2.5–3 m. Each of then gives laser beam distortion and increases the its divergence. One can apply the optical fiber to delay the laser beam. For a 100 ns delay, it should have a 20 m length.

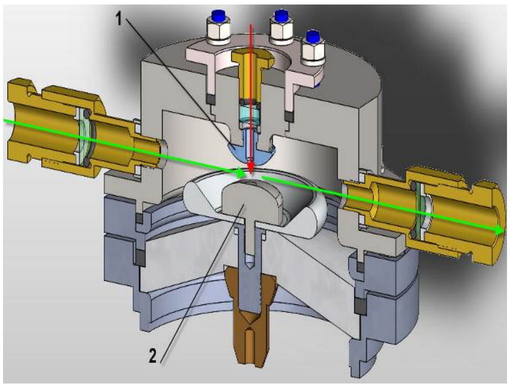

Fig. 1. Red arrow – plasma forming laser pulse, green arrow – probe laser pulse, 1-cathode, 2-anode.

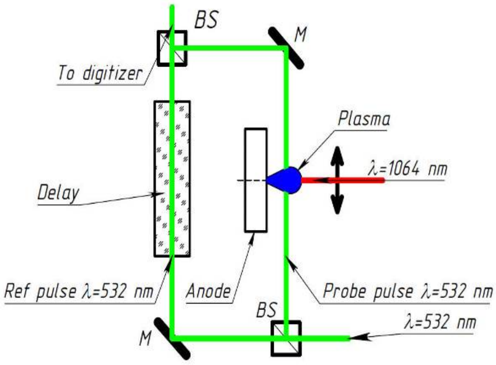

Fig. 2. The schematic diagram of measurements: BS – beam splitters, M – mirrors. The cathode is not shown.

The overall size may be diminished by wrapping fiber into a ring. The fibers for the transmission of multimode laser pulses have limitations. It is known that modal dispersion is the dominant factor of distortion of such laser pulses in fibers [12]. It occurs because the optical path length varies for different modes. The higher modes pass the longer path than the lower ones. The combined approach was proposed to overcome these limitations. The air 15 m delay line along with 12 m quartz fiber was used. Probe and reference pulses are combined to be registered by the photodiode (the top BS, Fig. 2). The pulse energy E_i can be varied in the range of 50–100 mJ.

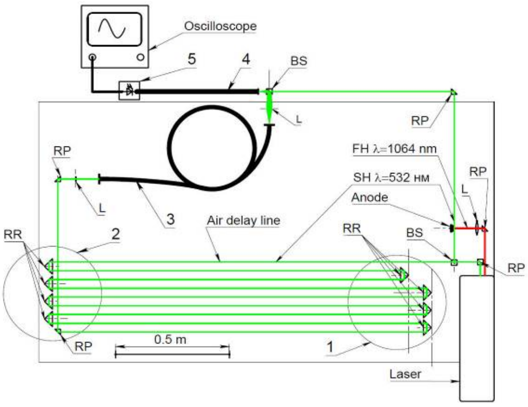

Fig. 3. The experimental setup:1, 2 – arrays of retroreflectors, 3, 4 – optical fibers, 5 – photodiode, BS – beam splitters, RP – reflecting prism, L – lenses.

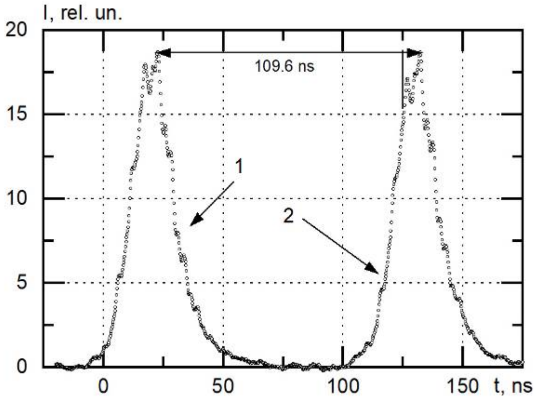

Fig. 4. The waveforms of probe (1) and delayed reference (2) pulses without LIP in the gas gap.

Finally, the design of the experimental setup is to be as follows (Fig. 3). The result of testing the probing system without igniting the LIP is shown in Fig. 4. It manifests the operation of the combined delay line. Fig. 5 shows the ratio of the reference pulse to the probe one in the absence of LIP. Excluding of the initial part with a low signal-to-noise ratio, the measurements give an absorption coefficient approximately equal to one (red curve *3* in Fig. 5). Thus, the distortion of the probing signal passing through the delay line seems to be satisfactory, especially in comparison with the case when LIP is formed in a gas gap by a laser pulse with energy E_i = 55 mJ (Fig. 6).

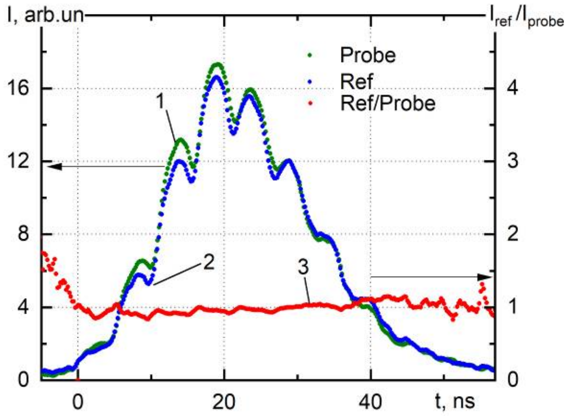

Fig. 5. (1) – not delayed probe pulse, (2) – delayed reference pulse (left *Y* axis), (3) – ratio of reference to probe pulse (right *Y* axis), no plasma in gas gap.

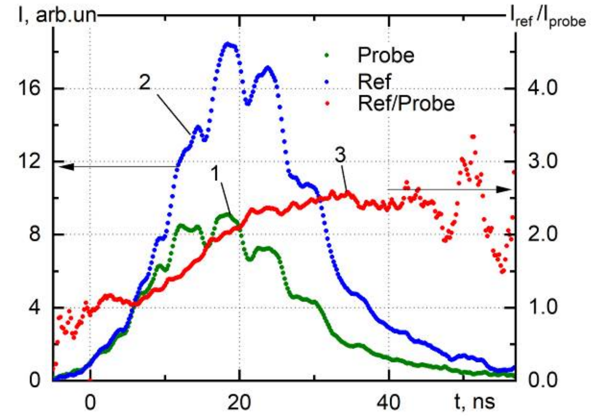

Fig. 6. (1) –probe pulse passed through the plasma, (2) – reference pulse (left *Y* axis), (3) – ratio of reference pulse to probe pulse (right *Y* axis), E_i = 55 mJ.

3. Results and discussion

The obtained data statistical processing was done using 20 waveforms. The ratio of the reference signal to probing one, i.e., absorption coefficient $K(t) = I_{ref}/I_{probe}$, is shown in Fig. 7. The averaged over 20 shot $K_m(t)$ value and the confidence intervals of the random error ΔK were determined for the confidence probability $p = 0.95$ and $\Delta t = 0.4$, ns [13] for pulse energy number E_i = {55, 65.5, 76, 85.5, 95.5} mJ, Figs. 8–12. The procedure to evaluate ΔK is similar to that one we used to calculate a jitter of switch-on delay of gas gap [14], and the mean value was determined as follows (2):

$$K_m = \left(\sum_{i=1}^{N}\left(K_i\right)\right)\cdot N^{-1},\ N{=}20. \tag{2}$$

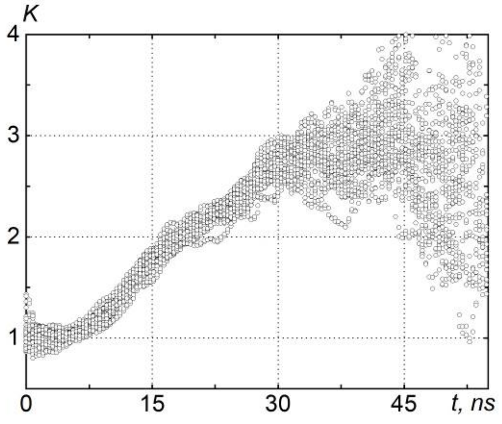

Fig. 7. The overlay of 20 waveforms at E_i=65.5 mJ.

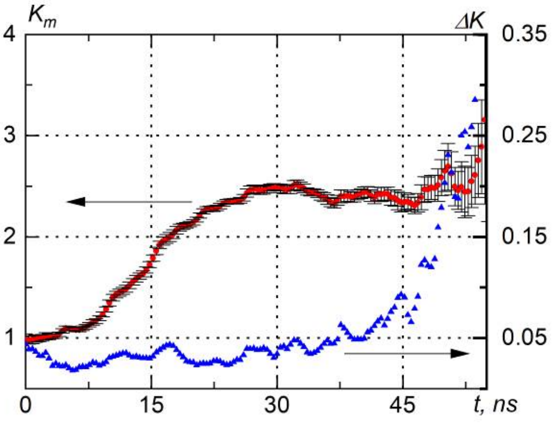

Fig. 8. Mean absorption coefficient K_m and confidence interval ΔK for pulse energy E_i = 55 mJ.

So, we can name the ΔK as jitter of absorption coefficient (blue curves in Figs. 8–12). One can see that the plasma absorption coefficient changes its dependence on time by increasing the igniting laser pulse energy. At the pulse energy level of more than 76 mJ (which corresponds to the energy density value of ~2 MJ/m^2), it appears to be non-monotonic.

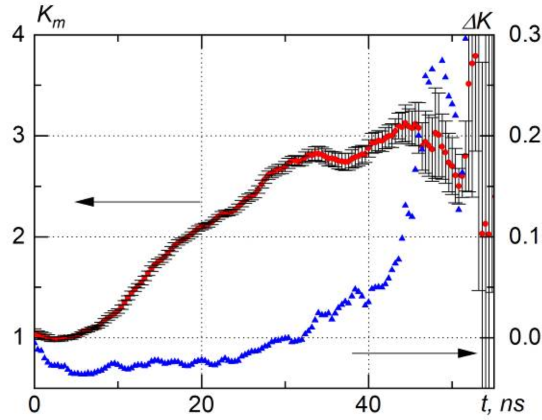

Fig. 9. Mean absorption coefficient K_m and confidence interval ΔK for pulse energy E_i = 65.5 mJ.

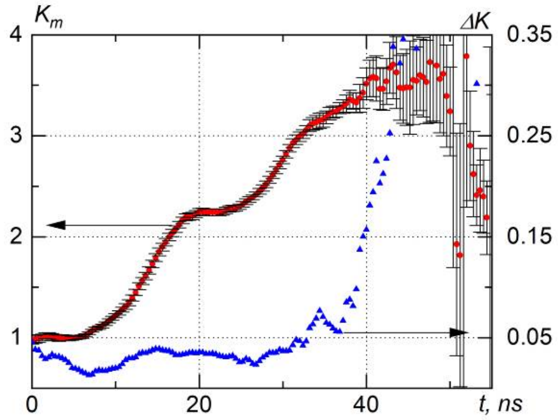

Fig. 10. Mean absorption coefficient K_m and confidence interval ΔK for pulse energy E_i = 76 mJ,

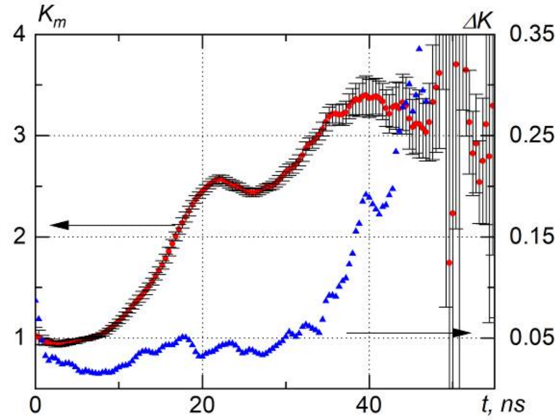

Fig. 11. Mean absorption coefficient K_m and confidence interval ΔK for pulse energy E_i = 85.5 mJ.

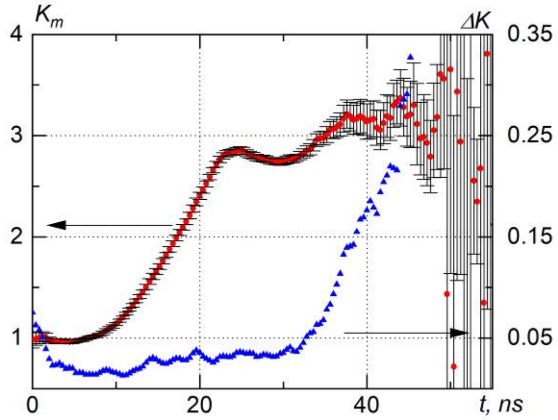

Fig. 12. Mean absorption coefficient K_m and confidence interval ΔK for pulse energy E_i = 95.5 mJ,

Fig. 13 shows the absorption coefficient dependence at the initial phase of the laser pulse for pulse energy variation. Thus, the absorption coefficient does not depend on pulse energy for approximately the first 15 nanoseconds for any pulse energy under the investigated range of energies.

When laser radiation is absorbed, the electron component of the plasma heats up, and its temperature rises. This increase contributes to the ionization of excited atoms during collisions with electrons in times of 10^{-11} s (or even faster). An increase in temperature also intensifies the excitation acts of atoms from the ground state during electron impacts. For the nanosecond laser pulse case, the atoms' excitation from the ground state does not have time to occur. As a result, the population of atomic levels decreases, and a new quasi-equilibrium state in which there is equilibrium between the electronic component of the plasma and excited atoms is established. However, there is no equilibrium between excited and unexcited atoms.

In this state, the concentration of excited atoms, which appear to be the main absorbers of laser radiation, becomes smaller. This effect leads to a decrease in the absorption coefficient. The non-monotonic behavior of plasma absorption is a well-known effect that was described decades ago

[15] and also manifested in our experiments at higher levels of pulse energy used to ignite plasma (Figs. 10–12). Unlike the mentioned paper, the described experimental technique makes it possible to study this phenomenon in a single pulse without a probe pulse time integration. This phenomenon, named in [15] a plasma *illumination*, may play a substantial role in the formation of instability non-monotonic dependence of a laser-triggered gas gap we observed in [7]. In contrast to the plasma formation in a pure gas without a target, the absorption coefficient of radiation during its formation on the surface of a solid body plays the role of feedback. It is common knowledge that the N-shaped characteristic of such feedback is a necessary condition for the formation of oscillations [16]. As one can see in Figs. 10–12, such a shape of feedback appears to be as the intensity of laser radiation increases. Another issue use to pay attention is the statistical instability of absorption at the final pulse phase, which can be considered absorption coefficient jitter (Fig. 14). One can see that after the thirtieth nanosecond, the jitter shows sharply increase. Moreover, for laser pulse energies, when the conditions for *illumination* are not realized (curves *1*, *2*), the jitter is noticeably lower than for the ones for which *illumination* seems to be realized (curves *3*–*5*). This is also an additional confirmation of the above assumption about the significant contribution of the plasma *illumination* phenomenon to the instability of the operation of laser-controlled gas gaps, which, however, may not be the only phenomenon determining the instability of their triggering [17, 18].

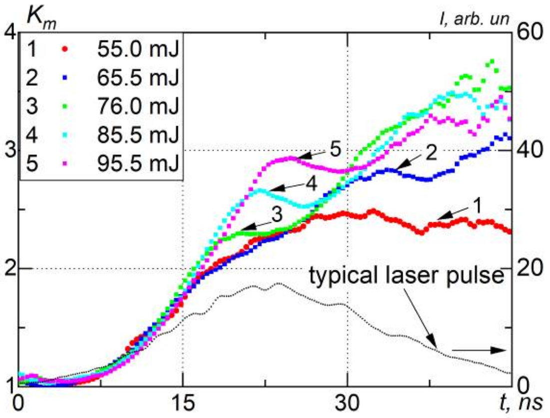

Fig. 13. Mean absorption coefficient K_m dependence on time and laser pulse energy.

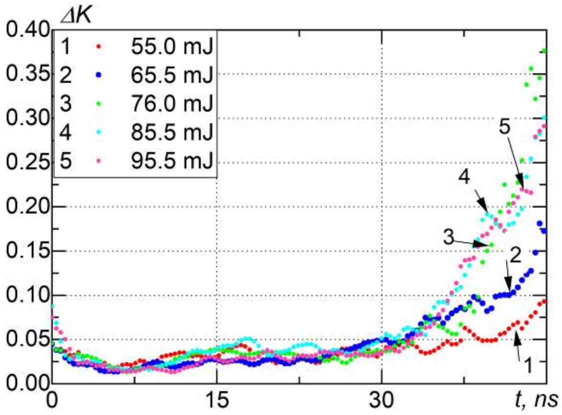

Fig. 14. Confidence interval ΔK – absorption jitter.

4. Conclusion

A study of the absorption of a nanosecond laser SH pulse at $\lambda = 532$ nm by a nanosecond LIP has been performed using a specific experimental setup. The experiments have been carried out in air at atmospheric pressure. The LIP absorption has been studied according to the following parameters: the absorption evolution time and the igniting pulse energy. To estimate qualitatively the relationship between pulse energy and plasma *illumination*, the absorptivity measurements have been performed. These measurements have put in evidence the appearance of this phenomenon for energy densities higher than 2 MJ/m^2. Also, the threshold-like behavior of absorptivity jitter in dependence on the laser pulse energy densities was stated, which is governed by the LIP *illumination* phenomenon appearance. New investigations, both theoretical and experimental, will be performed to verify this interpretation.

5. References

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