Quantum Electronics 45 (3) 224–227 (2015)

PACS numbers: 52.50.Jm; 52.38.Fz
DOI: 10.1070/QE2015v045n03ABEH015366

Magnetic-field generation by pulsed irradiation of aluminium in air

A.N. Chumakov, P.V. Chekan

Abstract. **Magnetic-field generation arising under irradiation of an aluminium barrier in the air by a series of laser pulses is studied experimentally. It is found that the magnetic field increases nonlinearly from 10^{-5} to 10^{-3} T with increasing laser power density from 10^7 to 10^9 W cm^{-2}, the degree of nonlinearity being different for single nanosecond pulses, for a series of such pulses with a repetition rate of 100–150 μs and for a combination of a millisecond laser pulse and a series of nanosecond laser pulses. The dependences of the magnetic-field induction on the power density of laser radiation in the above-mentioned regimes are established.**

Keywords: *laser plasma, magnetic-field induction, laser radiation.*

1. Introduction

Near-surface laser plasma obtained under pulsed irradiation of materials generates electromagnetic fields that can affect the dynamics of plasma expansion [1–20]. The studies on magnetic-field generation by the laser-plasma action on isolated objects in air and vacuum are of particular importance in connection with the design and development of different laser-plasma engines for spacecrafts [21–26]. These studies have shown that a high-efficiency laser thrust is provided by nanosecond repetitively pulsed laser radiation with a power density of $\sim 10^{10}$ W cm^{-2} [23, 25]. The efflux of the laser plasma jets formed under these conditions into surrounding space causes the accumulation of significant charges on the spacecraft surface [27, 28], which may be accompanied by a number of undesirable processes that interfere with the operation of electronic components of individual devices and lead to the failure of part of those components [29]. An increase in currents and separation of charges in plasma can be seen from the rise of pulsed magnetic fields; therefore, studying the processes of generation of electromagnetic fields induced by laser plasma as well as related processes of accumulation and dynamics of electric charges on the objects that are in contact with plasma is of great scientific and practical importance.

The studies performed previously have shown that the magnetic field induced by laser plasma decreases in some cases with distance according to the law $B \propto 1/r^2$ [2], the current source that determines the magnetic field generation being located in the region where plasma is in contact with a target actively participating in the process of the current flow [3]. The magnetic-field pulses generally consist of two components: fast component $\dot{B}_1$ and slow component $\dot{B}_2$; here, the electron emission is responsible for the origin of $\dot{B}_1$, while generation of $\dot{B}_2$ is stipulated by the interaction of expanding plasma with aresidual gas [4]. With increasing gas pressure, in addition to the positive component of magnetic-field pulses, a negative component appears which is generated inside the plasma [5]. The magnetic field of laser plasma depends nonlinearly on the residual air pressure, reaching a maximum at a pressure of $\sim$0.1 Torr, and is reduced by two to three orders of magnitude when the pressure is by many times increased or reduced [6], which may be due to a change in the contribution of ions from in the air components to the current flowing through the plasma and target.

In a number of papers, different mechanisms related to the generation of magnetic fields have been discussed: thermoelectric currents arising from the temperature gradients near the target [7–9] and currents caused by the electromotive force of the double layer localised near the laser plasma boundary [10]. Some of the mechanisms proposed are related to the violation of the axial symmetry in the distribution of gradients of the electron temperature and density, their collinearity [11, 12], formation of fast photoelectrons in photoionisation of the background medium by plasma radiation [13–15], effective contact electromotive force and inhomogeneity of the double-layer potential [16, 17]. The abundance of the models proposed is indicative of the complexity of the processes and the lack of available experimental data. Experimental studies of magnetic fields inside the laser plasma are severely hampered due to small size of the plasma plume, and so the calculations of the magnetic field inside the plume are mostly based on the measurements performed outside the plume [18–20].

The transition from single-pulse to double-pulse or multiple-pulse laser action on materials is, in some cases, accompanied by a significant increase in the efficiency of laser plasma formation [30, 31], which should lead to a change under the conditions for magnetic-field generation. Indeed, experiments have shown that the efficiency of magnetic-field generation increases in transition from single-pulse to double-pulse air breakdown [14, 15]. This phenomenon also takes place in the near-surface plasma formation under the action of a series of laser pulses on different materials in air [32] and substantially depends on the laser power density, irradiation spot size and target material. The aim of this work is to study the peculiarities of magnetic-field generation under the plasma formation conditions, when metals in air are exposed to the action of a series of nanosecond laser radiation pulses following with a

A.N. Chumakov, P.V. Chekan B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, prosp. Nezavisimosti 68, 220072 Minsk, Belarus,
e-mail: chumakov@dragon.bas-net.by

Received 13 December 2013; revision received 17 October 2014
Kvantovaya Elektronika **45** (3) 224–227 (2015)
Translated by M.A. Monastyrskiy

time interval of ~100 ns, and also to the combined action of millisecond and nanosecond pulses of laser radiation.

2. Experimental setup and measurement techniques

The studies were performed on an experimental setup utilising a modified GOS-301 Nd : glass laser (the wavelength λ = 1.06 μm) with controlled generation regime. In the free generation regime, the laser with a hemispherical resonator provides a quasi-stationary pulse with a duration of 1 ms. By using a LiF : F_2 optical shutter, the passive *Q*-switching regime was implemented and two regimes of generation were obtained: repetitively pulsed with a countable number of laser pulses and combined regime in which different parts of the resonator generate simultaneously in free and repetitively pulsed regimes. The latter allows implementation of the combined action of short and long laser pulses on the target. In the repetitively pulsed regime, a series of several 80-ns laser pulses is generated (Fig.1). The energy and shape of the laser pulses were measured by means of standard methods of pulse photometry. The power density of laser radiation in the irradiation spot on the target surface was varied with the use of calibrated filters.

The pulsed flows of laser plasma were formed under the action of laser radiation on the barrier representing a hollow aluminium cylinder 0.5 mm in thickness, placed in the air at an atmospheric pressure. The laser beam was focused onto the flat face end of the cylinder at a distance of no less than 5 mm from the face end, the spot diameter of irradiation constituting 1.2 mm.

To register the magnetic field, a magnetic probe of induction type (coil winding diameter of 1.7 mm), manufactured and calibrated using the Helmholtz coils [33], was used. Since the magnetic field of erosion plasma possesses cylindrical symmetry [1 – 5], the probe was located close to the target at a distance of 1 mm from the beam spot centre. The axis of the coil probe was oriented perpendicular to the direction of the laser plasma motion to detect the azimuthal component of the magnetic field generated by moving charged particles of plasma. The magnetic probe signal, which is proportional to the magnetic flux in the probe coil, generally represents a single bipolar pulse. The magnetic induction, which is calculated on its basis, is a single unipolar pulse. In the case of a strong decrease in the laser power density, the magnetic induction pulse may be distorted, acquiring the double and bipolar form, which can be attributed to the approach to the plasma formation threshold.

The signals obtained from the magnetic probe were fed into a Tektronix DPO4104 digital oscilloscope and maintained in digital form for further processing. The magnetic field and the power density of laser radiation in individual pulses were calculated by means of numerical integration using the MathCAD 11 package.

The experiments were aimed at investigating the magnetic-field generation under irradiation of an aluminium target in two regimes: repetitively pulsed and combined ones. In the repetitively pulsed regime, the resonator was completely overlapped by a passive shutter and the radiation energy constituted ~8 – 9 J, while the maximum peak power density in the pulses reached 1×10^9 W cm^{-2}. In the combined regime, the laser energy was ~7 – 8 J, with the maximum laser power density reaching 1.8×10^7 W cm^{-2} and 1.4×10^8 W cm^{-2} in millisecond and nanosecond pulses, respectively.

3. Experimental results and their discussion

Figure 2 demonstrates the experimental dependences of the maximum magnetic field induction *B* on the laser power density *q* in various regimes of laser action on aluminium for the first three pulses of a periodic series of pulses. The dependences have a power form and can be described by the expression

$$B(q) = Cq^{\alpha}, \quad (1)$$

where α varies from 0.9 to 2.4.

In the combined regime of laser action, a close-to-quadratic dependence of the magnetic induction on the laser power density is observed. This dependence is almost identical for the first and second pulses of the series, while for the third pulse a slight decrease in magnetic induction is observed, which may be associated with a decrease in the power density of the quasi-continuous component of the combined pulse;

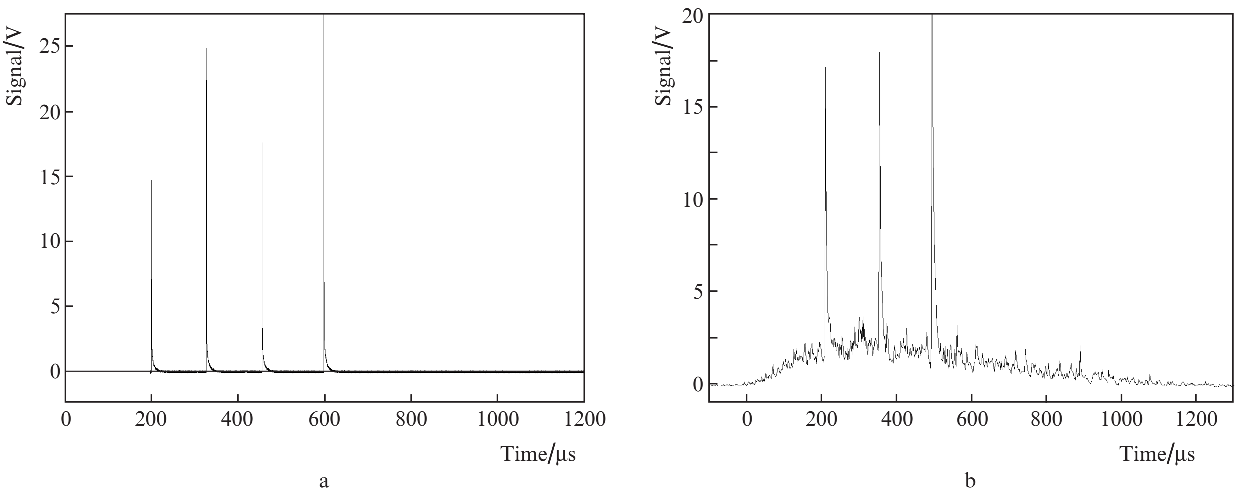

Figure 1. Typical oscillograms of a periodic series of laser pulses (a) and a combined laser pulse (b).

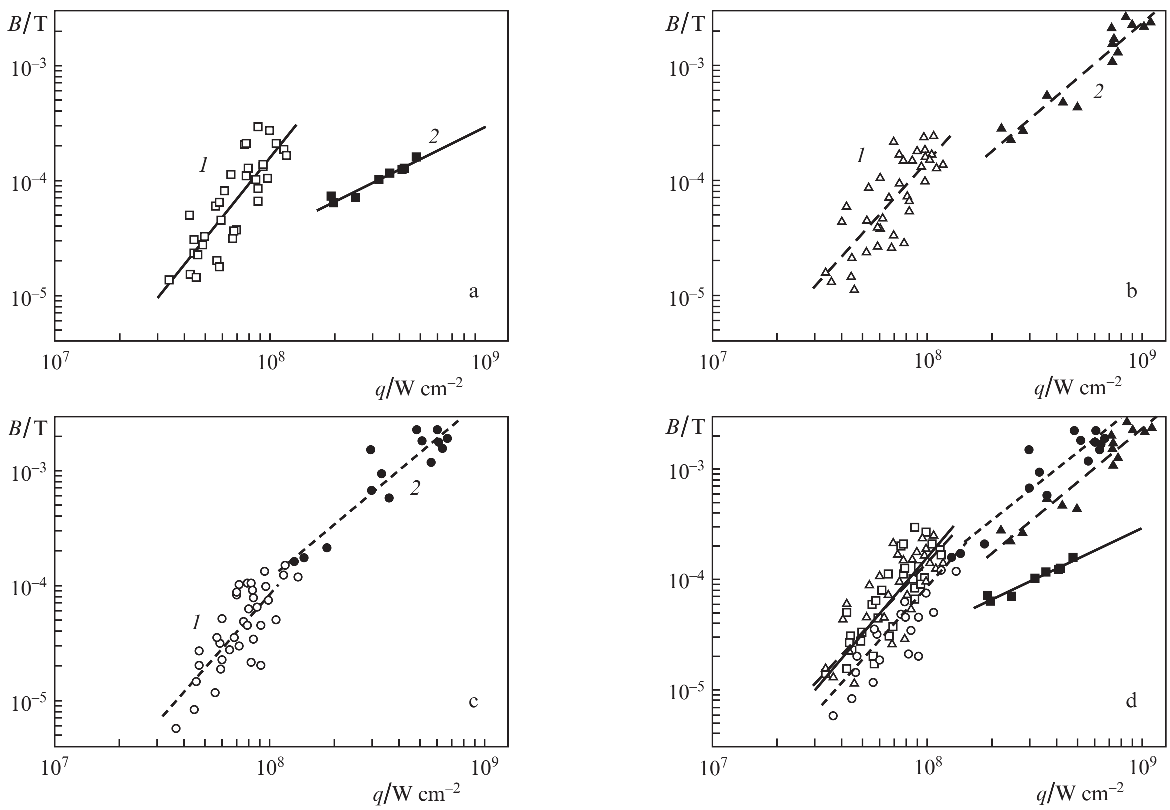

Figure 2. Fragments of the dependence of the magnetic-induction amplitude B on the laser power density q under irradiation of an aluminium cylinder in the combined (*1*) and repetitively pulsed (*2*) regimes of laser action for the first (a), second (b) and third (c) laser pulses of a series, and a full dependence $B(q)$ (d).

herewith, the rate of a magnetic induction increase does not change with increasing power density. Taking into account the dependence established, one should expect that the magnetic induction would increase up to several Tesla with increasing power density of pulsed laser radiation merely by an order (up to 1×10^{10} W cm^{-2}), which may result in a significant influence of the magnetic field on the structure and dynamics of laser plasma formation [34, 35].

In the repetitively pulsed regime, the magnetic induction amplitude depends not only on the laser power density, but also on the sequential number of the laser pulse in the series. In this case, the dependence of the magnetic induction growth rate with increasing power density varies from a linear function (Fig. 2a) to a quadratic one (Figs 2b, c) for each subsequent pulse. For the third laser pulse of the series, this dependence virtually coincides with that for the combined regime of irradiation (Fig. 2c).

These peculiarities can be attributed to the fact that the action of a high-frequency series of laser pulses on the target material induces not only intensification of the erosion plasma formation, but also a change in the plasma-forming medium [30, 31]. The air plasma prevailing in the laser plume formed by the first pulse is gradually pushed out by erosion plasma under the action of subsequent pulses. When irradiating the same target in the combined regime, the quasi-continuous component of the laser pulse produces and maintains an erosion steam plasma plume, in which plasma is formed under the action of modulated laser pulses. This leads to an increase in the contribution of erosion plasma to the processes of plasma formation and magnetic-field generation under the action of short high-intensity laser pulses.

The conclusion on the contribution of different components of a combined pulse to the plasma formation is confirmed by the laser plasma spectra in the repetitively pulsed and quasi-cw regimes (Fig. 3). It can be seen that erosion plasma makes the main contribution to the radiation in the quasi-cw regime, while the excitation of spectral lines of nitrogen of the atmospheric air in the repetitively pulsed regime is observed.

Although the results presented above are obtained at atmospheric pressure, they also hold true at a reduced pres-

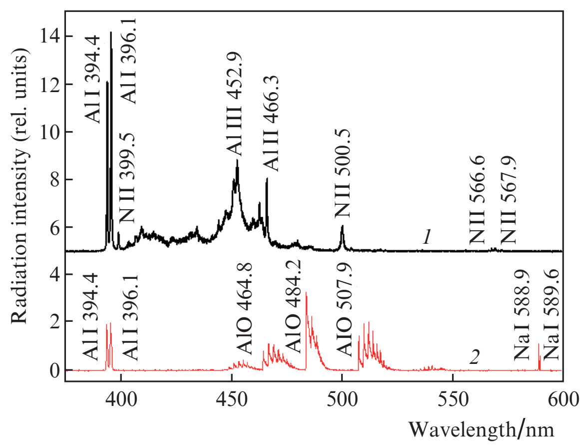

Figure 3. Emission spectra of the near-surface laser plasma produced in the repetitively pulsed (*1*) and quasi-cw (*2*) regimes.

sure, with regard to the fact that the laser plasma magnetic field reaches its maximum at an air pressure of ~0.1 Torr and is reduced by 1–2 orders of magnitude when the pressure is by many times increased or decreased [6].

4. Conclusions

The results obtained show that the magnetic-field induction in laser plasma depends not only on the laser power density, but also on the regime of laser action, and in the case of multi-pulse generation – even on the sequential pulse number in a series. This is due to the changes in the plasma formation conditions and increase in the contribution of erosion plasma to the combined and multi-pulse laser action, which is manifested at transition to the second and subsequent laser pulses.

The results of studies on the laser plasma magnetic field are of importance in selecting the optimal regimes of laser-plasma engines for the space purposes, because they indicate the existence of general laws in the laser-plasma generation of a pulsed magnetic field and to the interrelation between the magnetic field and the regime of laser action on the target. Taking into account the relatively large values of the laser plasma magnetic field (~1 T), which can be achieved at typical laser power densities (~10^{10} W cm^{-2}), it is advisable to explore in the future the peculiarities of the laser plasma magnetic-field generation in vacuum and its effect on the dynamics and parameters of erosion laser plasma.

References

1. Korobkin V.V., Serov R.V. *Pis'ma Zh. Eksp. Teor. Fiz.*, **4**, 103 (1966).
2. Serov R., Richardson M.C. *Appl. Phys. Lett.*, **28**, 115 (1976).
3. Droet M.G., Bolton R., Saint-Hilaire G., et al. *Appl. Phys. Lett.*, **29**, 469 (1976).
4. Korobkin V.V., Motylev S.L., Serov R.V., Edwards D.F. *Pis'ma Zh. Eksp. Teor. Fiz.*, **25**, 531 (1977).
5. Ananyin O.B., Bykovskiy Yu.A., Novikov I.K., et al. *Kvantovaya Elektron.*, **11**, 1471 (1984) [*Sov. J. Quantum Electron.*, **14**, 995 (1984)].
6. Drouet M.G., Bolton R., Saint-Hilaire G., Kieffer P., Szili Z., Pe-pin H., Grek B., Thibaudeau A., Trepanier K. *Appl. Phys. Lett.*, **29**, 469 (1976).
7. Stamper J.A., Papadopoulos K., Sudan R.N., et al. *Phys. Rev. Lett.*, **26**, 1012 (1971).
8. Afanasiev Yu.V., Gamaliy E.G., Lebo I.G., et al. *Zh. Eksp. Teor. Fiz.*, **74**, 516 (1978).
9. Gorbunov V.A., Nikol'skaya L.S., Petrukhin A.I., et al. *Kvantovaya Elektron.*, **11**, 349 (1984) [*Sov. J. Quantum Electron.*, **14**, 238 (1984)].
10. Motylev S.L., Pashinin P.P. *Kvantovaya Elektron.*, **5**, 1230 (1978) [*Sov. J. Quantum Electron.*, **8**, 700 (1978)].
11. Korobkin V.V., Motylev S.L. *Pis'ma Zh. Eksp. Teor. Fiz.*, **29**, 700 (1979).
12. Gorbunov V.A., Kalmykov A.A., Petrukhin A.I., et al. *Kvantovaya Elektron.*, **9**, 130 (1982) [*Sov. J. Quantum Electron.*, **12**, 83 (1982)].
13. Ananyin O.B., Bykovskiy Yu.A., Zamyshlyaev B.V., et al. *Kvantovaya Elektron.*, **10**, 523 (1983) [*Sov. J. Quantum Electron.*, **13**, 307 (1983)].
14. Konov V.I., Nikitin P.I., Prokhorov A.M., Silenok A.S. *Pis'ma Zh. Eksp. Teor. Fiz.*, **39**, 501 (1984).
15. Konov V.I., Nikitin P.I., Prokhorov A.M. *Izv. Ross. Akad. Nauk, Ser. Fiz.*, **49**, 1208 (1995).
16. Afanasiev Yu.V., Ibraev R.A., Kanavin A.P., et al. *Kvantovaya Elektron.*, **12**, 392 (1985) [*Sov. J. Quantum Electronics*, **15**, 255 (1985)].
17. Afanasiev Yu.V., Gamaliy E.G., Kanavin A.P., Kiselev A.E. *Kvantovaya Elektron.*, **15**, 1862 (1988) [*Sov. J. Quantum Electron.*, **18**, 1162 (1988)].
18. Zakharov N.S., Rudenko V.V. *Izv. Ross. Akad. Nauk, Ser. Fiz.*, **63**, 1173 (1999).
19. Zakharov N.S., Rudenko V.V. *Izv. Vyssh. Uchebn. Zaved., Ser. Materialy*, (2), 32 (2000).
20. Zakharov N.S., Shainoga I.S. *Kvantovaya Elektron.*, **15**, 428 (1988) [*Sov. J. Quantum Electron.*, **18**, 271 (1988)].
21. Phipps C.R., Luke J.R. *AIAA J.*, **40**, 310 (2002).
22. Protasov Yu.S., Protasov Yu.Yu. *Izv. Vyssh. Uchebn. Zaved., Ser. Mashinostr.*, (5), 35 (2002).
23. Protasov Yu.S., Protasov Yu.Yu. *Izv. Vyssh. Uchebn. Zaved., Ser. Mashinostr.*, (8), 29 (2002).
24. Rezunkov Yu. *AIP Conf. Proc.*, **702**, 228 (2003).
25. Lubchenko F.N., Fedenev A.V., Bosak N.A., Chumakov A.N., Panchenko A.N., Tarasenko V.F. *Kosm. Raketostr.*, **56**, 62 (2009).
26. Phipps C., Birkan M., Bohn W., Eckel H.-A., Horisawa H., Lippert T., Michaelis M., Rezunkov Y., Sasoh A., Schall W., Scharring S. *J. Propul. Power*, **26**, 609 (2010).
27. Dmitriev I.A., Kiselevsky L.I., Shkurko V.V. *Zh. Prikl. Spektrosk.*, **48**, 909 (1988).
28. Dubois J.-L., Lubrano-Lavaderci F., Raffestin D., Ribolzi J., Gazave J., La Fontaine A.C., d'Humières E., Hulin S., Nicolaï Ph., Poyé A., Tikhonchuk V.T. *Phys. Rev. E*, **89**, 013102 (2014).
29. Woods A.J., Uinas E.P. *Aerokosm. Tekhn.*, **3**, 146 (1986).
30. Min'ko L.Y., Chumakov A.N., Bosak N.A. *Kvantovaya Elektron.*, **17**, 1480 (1990) [*Sov. J. Quantum Electron.*, **20**, 1389 (1990)].
31. Chumakov A.N., Avramenko V.B., Bosak N.A. *Zh. Prikl. Spektrosk.*, **79**, 279 (2012).
32. Chumakov A.N., Bykov I.M., Bosak N.A., Chekan P.V. *Vestnik Voen. Akad. Resp. Belarus*, **3**, 40 (2009).
33. Phillips R.C., Turner E.B. *Rev. Sci. Instrum.*, **36**, 1822 (1965).
34. Harilal S.S., Tillack M.S., O'Shay B., Bindhu C.V., Najmabadi F. *Phys. Rev. E*, **69**, 026413 (2004).
35. Pandey P.K., Thareja R.K. *J. Appl. Phys.*, **109**, 074901 (2011).