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Investigation of emission of multiple-charged ion flows from plasma of the laser-induced vacuum discharge

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Abstract

The possibility of using plasma of the laser- induced vacuum discharge as a source of multiple-charged ions is considered. To this end, a sequence of measurements of the ion emission from discharge plasma was made. The laser radiation was focused on the anode surface in the focal spot with diameter $D \leq 250$ µm and with intensity on the target $q \approx 5 \times 10^9$ W/cm^2. The laser energy $E_l = 50 \div 60$ mJ. The choice of given geometry in this experiment has allowed us to successfully detect the ions emitted at a small angle ($\alpha \approx 21^0$) with respect to the discharge axis. We have already established earlier that the ion yield, in the case of focusing laser radiation on the cathode of discharge system, is significantly less.

The use of the storage capacitor of C=0.22 µF enabled us to vary the amount of discharge energy in the range of E_{dr} =5÷24 J. Depending on the discharge energy the intensity of ion emission and the spectrum of charge states changed. Our measurement results allowed us to make an assumption that the work in the range of discharge energies E_{dr} = 10÷14 J is the most effective from the point of view of the quantity of emitted multiple-charged ions. The average ion flux density was $Wp = (1.5 \div 3) \cdot 10^{14}$ Ions/sr.

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1. Introduction

In recent years, an interest in studying combined systems of plasma generation has grown. These systems, as shown in [1, 2], can form the basis of creation of new sources, both X-ray radiation and multiple-charged particles with high intensity of flow. Technological progress requires the creation of small-sized, simple-to-operate and reliable sources of ions and X-ray, which will occupy their own niche in the market of new technologies and industry. The combined system of plasma generation based on laser-triggered vacuum discharge [3] can meet such requirements.

In this paper, we consider the possibility of using plasma of the laser- induced vacuum discharge as a source of multiple-charged ions. The analysis of the dependence of emission properties of the laser- induced vacuum discharge on the amount of energy put in the discharge, for the chosen geometry of electrode system, has been carried out.

2. Experimental setup

The experimental investigation of the laser-induced discharge in vacuum was conducted at the facility "Alligator" (Fig.1) consisting of a vacuum chamber (pressure $P \approx 1.2 \cdot 10^{-5}$ Torr, volume $V \approx 0.1$ m^3), a pulsed Nd:YAG laser, discharge system and diagnostic system. The pulsed Nd:YAG laser was operating at the Q-switched mode (wavelength λ = 1,06 μm, pulse energy E_l = 50÷60 mJ, duration $\tau \approx$ 17 ns, the focal length of the lens $F \approx$ 10 cm.)

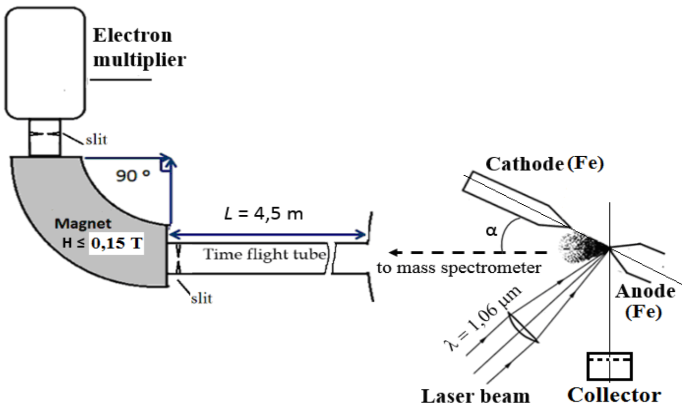

Figure 1: Experimental set-up

The discharge system consists of an energy storage capacitor (C = 0,22 μF), a low-inductive vacuum current lead and a set of conical electrodes located in the vacuum camera. Electrode materials: the anode - Fe, the cathode - Fe. The distance between electrodes d= 5.2 ± 0.2 mm. In order to initiate the discharge the laser beam was focused on the conical surface of anode close to the tip. The discharge current was measured with a Rogowski coil. For registration of pulses the digital oscilloscope *Lecroy "WaveAce2024"* was used.

In order to investigate the component and charge composition of the laser- induced discharge plasma we used the combination of time-of-flight mass analyzer (TOF) with magnetic-sector instruments [4]. Ions emitted from the discharge plasma at a small angle to its axis ($\alpha \approx 21^0$) were detected by the vacuum electron multiplier of the TOF mass analyzer (Fig.1).

The signal registration from the TOF and collector was carried out by two single-channel 12-bit ADC with sampling speeds of up to f = 40 MSPS, i.e. the time resolution of registered mass spectra Δt = 0.025 µs.

3. Experiment

A feature of the investigated plasma formation is a substantial instability of time delay τ between the laser impulse initiating discharge and the moment of initiation of the discharge current. In certain cases, at the same energy stored in capacitor, after initiation of discharge the ion emission was much less. For a large number of discharge impulses the range of delay variation τ = 0.1-1.3 µs was determined. The registered synchro (TTL) pulses and signals from the Rogowski coil for two discharges received under the same conditions are given in Figure 2.

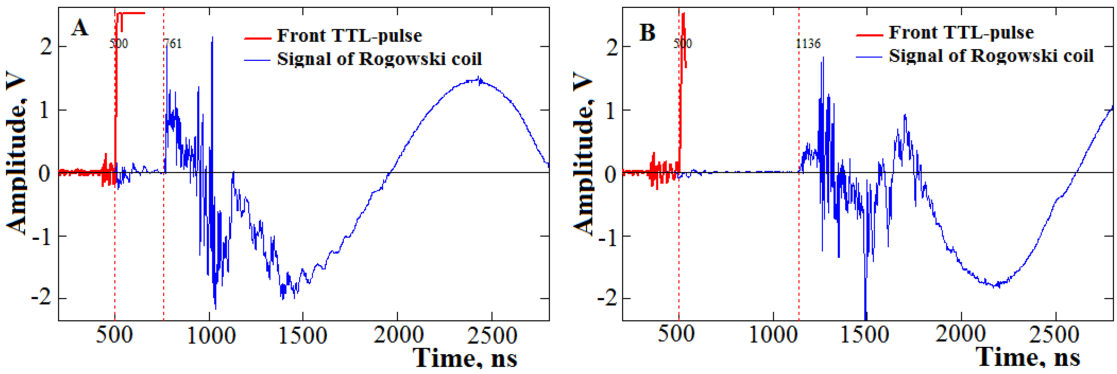

Figure 2: An oscillogram of the TTL-pulse synchronous to the laser impulse(red curve) and a signal from the Rogowski coil(blue curve). A) τ = 0.25 µs and B) τ = 0.65 µs.

Since the ADC, processing signal from the Electron multiplier of mass-spectrometer, is started by the TTL-pulse synchronous with the laser impulse, and discharge ions appear with some unstable delay in time, the analysis of the mass spectra obtained becomes considerably complicated. The computer data processing allowed us to determine the mass spectra obtained with satisfactory accuracy, including the fastest ions ($E_{ion} \geq$ 80 keV) with small *m/z.*

The typical registered mass spectrum of ions was obtained under following conditions: the fixed voltage of capacitor U= 8 kV ($E_{dr} \approx 7$ J) and the magnetic field intensity of analyzer $B \approx$ 0.08 T (Fig.3).

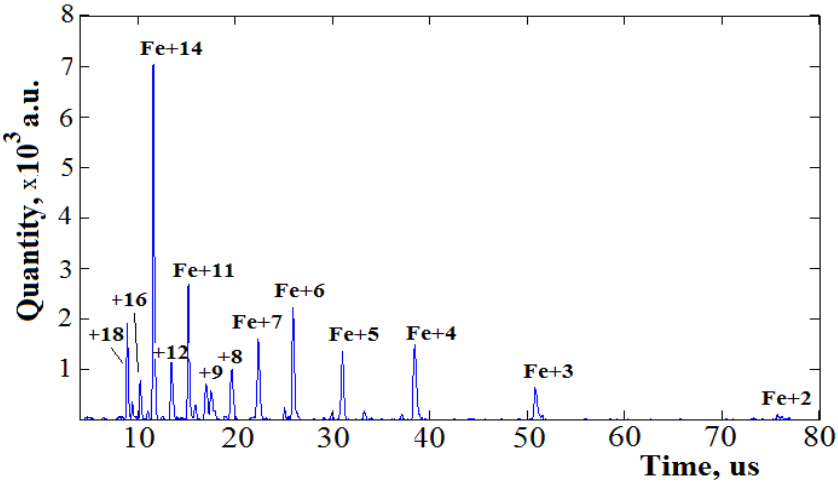

Figure 3: The typical mass spectrum of ions emitted from plasma of the laser -induced vacuum discharge. Capacitor voltage U = 8 kV ($E \approx 7$ J). The induction of the magnetic field of analyzer $B \approx 0.08$T.

The use of the TOF method has allowed us to obtain the energy distributions of ions emitted from plasma of the laser- induced vacuum discharge. Energy distributions for typical charges of ions emitted from plasma at the discharge energy E_{dr} = 10÷12 J are given in Figure 4.

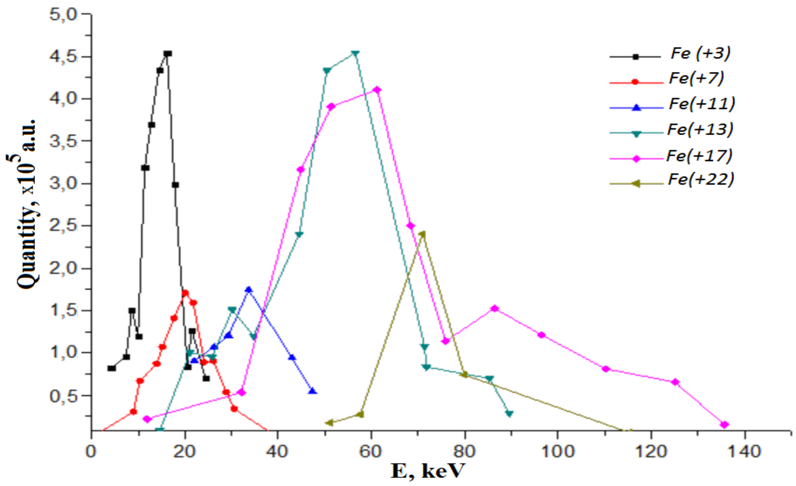

Figure 4: Energy distributions for typical charges of ions emitted from the plasma of vacuum discharge.

The data shown in Fig. 3 and 4 demonstrate that there are primary ions of the laser pre-plasma with charge states up to Fe^{+4} in the spectrum. Highly charged ions with charge states up to Fe^{+22} and energies up to $E_{ion} \leq 130$ keV are formed at a stage of the discharge formation which has either a form of avalanche ionization (Fig. 2a) or chaotic narrow pulses at the beginning of the harmonic current signal (Fig. 2b). Dependences of the quantity of ions on the ion charge, i.e. the charge distributions, for different stored energies E_{dr} are presented in Figure 5.

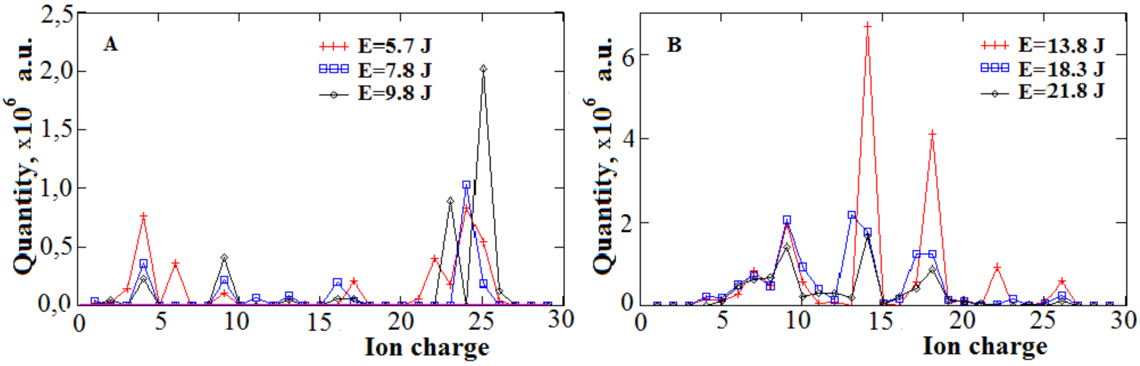

Figure 5: Charge distributions of ions of vacuum discharge for different stored energies: a) $E_{dr} < 10$ J; b) $E_{dr} > 10$ J.

As seen from Figure 5, the total number of ions grows at the stored energy $E_{dr} = 5 \div 10$ J, it reaches maximum at the energy about $E_{dr} = 10 \div 14$ J and then decreases with the subsequent energy increase in the storage capacitor.

4. Results and discussion

In earlier works [5,6] it has been shown that an increase in storage capacitor energy considerably affects the emission characteristics of discharge and defines the degree of its pinching. Thus, at the stored energy over $E_{dr} \geq 15$ J, the flux of multiple- charged ions goes down because the degree of pinching is already rather high, and multiple-charged ions are shielded by the dense plasma constriction, and it is possible to determine only ions of the laser pre-plasma.

In our work, for the analysis of development of the laser- induced vacuum discharge for the given geometry of the experiment, we have presented graphically the experimental data obtained (Fig. 6). The data shown in Figure 6 demonstrate the dependence of the total quantity of emitted ions on the discharge energy and the dependence of the share of highly charged ions of Fe^{+z} ($Z \geq 21$) on the quantity of all emitted ions for different discharge energies. These results are obtained at the fixed laser energy and the change of energy in storage capacitor within the range of $E_{dr} = 5 \div 24$ J.

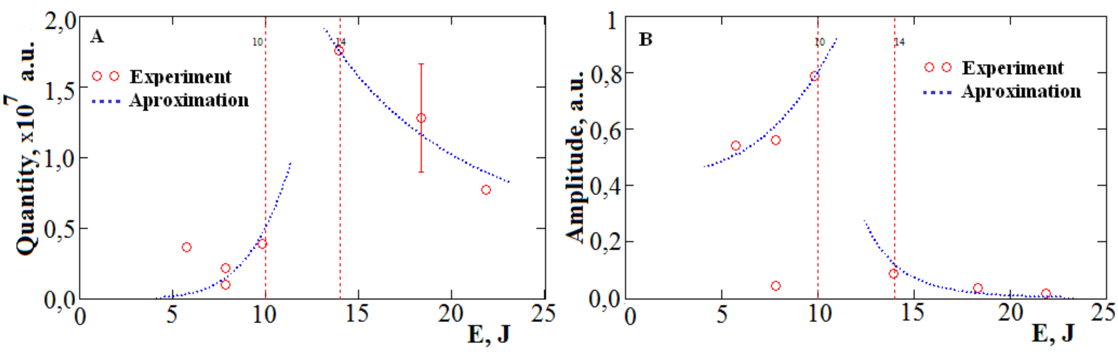

Figure 6: Dependence of the total quantity of emitted ions on discharge energy (a). The share of highly charged ions of Fe^{+z} ($Z \geq 21$) on the quantity of all emitted ions for different discharge energies (b). The blue dashed line, in both plots, shows the polynomial approximations of experimental data.

As seen from Figure 6a, when stored energy is within the range of E_{dr}= 5÷13 J the discharge develops with the gradual increase in compression ratio of the plasma jet by the internal magnetic field. This leads to the intensive growth of ion flow and the growth of the maximum (Z ≥ 21) and average ion charges (10 ≤ Z ≤ 20). The latter can be seen from Figure 5b. The energy range of storage capacitor E_{dr} = 10÷14 J can conditionally be called the optimum operating mode of the discharge as a source of highly charged ions with $Z \geq 21$. For these energies the ion flux density in the direction to the collector (Fig. 1) varies within the range of $W_p = (1.5 \div 3)\cdot 10^{14}$ ions/sr , and the maximum share of highly charged ions Fe^{+Z} *(Z ≥ 21)* (Fig. 6b) is obtained. The further increase in energy of the storage capacitor (E_{dr}> 14 J) leads to a reduction in ion flux density and sharp decrease in highly charged ion yield. We assume that this occurs owing to the shielding of ion yield during the plasma pinching. For comparison, it should be noted [6] that for a high-current micropinch discharge in vacuum the highly charged ions produced in the hot dense plasma can be registered only by methods of X - ray spectroscopy.

5. Conclusion

We have shown the possibility of using plasma of the laser- induced vacuum discharge as an effective source of multiple-charged ions with density up to $W_p = (1.5 \div 3)\cdot 10^{14}$ Ions/sr and the maximum charge states up to Fe^{+26}. The geometry with focusing of a laser beam on the anode of discharge system was used in these experiments. In so doing, some substantial instability of parameters of the laser-induced vacuum discharge takes place. This is possibly caused by the development of instability in the extending laser plasma in the electric field inhibiting electrons. It has been noted that the process of plasma pinching interferes with the yield of multiple-charged ions and brings about essential restrictions in the possibility of further increase in the ion flux density and maximum ion charge only by increasing the capacitor energy. One may draw a conclusion that the further increase in the source power of multiple-charged ions on the basis of the laser-triggered vacuum discharge is possible by the selection of the laser radiation parameters and the optimization of geometry of the electrode system. We are going to investigate these issues in the near future**.**

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