X-RAY RADIATION FROM MICROPINCHES IN LASER-INDUCED DISCHARGES

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1. Introduction

Although physics of vacuum spark discharges and vacuum arcs are subject of investigations in many research groups since many decades their real nature is not yet understood well until now. One of the most important questions is how the electrode material from the cold cathode surface transforms into plasma being able to carry out current in vacuum by a magnitude of some kA. The experimental and theoretical efforts have revealed recently [1-4] many interesting effects in laser-induced vacuum discharges. Among them are: (i) generation of non-stationary emission centers - „shooting solitons“ - at the moving boundary of an expanding cathode plasma with current densities in the range of 10^6 - 10^{11} A/cm^2 [1-3], (ii) aperiodic focusing and defocusing of electrical current in the dense cathode plasma within characteristic time of 1 - 4 ns [3], caused by a phase transition from a metal to a non-ideal plasma, , (iii) development of overheating instability with a consequence of plasma temperature in low voltage discharges increasing up to 200 eV [1-3] and (iv) plasma erosion interruption when in small local volume of plasma torch the voltage drops up to 10’th kV and higher [2]. All these processes must be accompanied by x-ray radiation, which at first had been predicted in [1- 4].

The present work was aiming to perform an experimental study of x-ray generation occurring in vacuum pulsed discharges initiated by intense laser beams (100 ps pulse duration, 30 - 60 mJ pulse energy, 1064 nm wave length) and possessing low voltage between used Cu-electrodes (U = 150 V - 2.7 kV). The radiation of the laser-induced breakdown was investigated just after ignition by IR laser beam as well as for a long time period after the ignition pulse in order to eliminate the x-ray radiation coming from the laser-produced plasma.

2. Experimental

In described below experiments, time resolved x-ray emission from vacuum discharge plasmas was picked up by the help of a x-ray streak camera FRF-4 [5]. The cathode consisted of a solid plane target, which had been mounted inside a vacuum chamber maintained at a pressure of about 10^{-5} Torr. The anode had a needle-shaped form with a central hole through which a laser pulse was directed onto the cathode surface for spot ignition. The cathode and anode material was copper, the gap distance had a size of 50 µm. The discharges were fed by a 50 Ohm coaxial cable charged up to 150 V -2.7 kV the inductance was about 150 nH. In this case the discharge time was determined by cable length and lasted up to 750 ns. The oscilloscope for current measurements was triggered by a signal from a fast diode illuminated by the IR ignition -laser pulse.

The laser pulses have an energy of 30 - 60 mJ, a duration of 100 ps and a peak focused intensity of about $(1 - 3)\cdot 10^{13}$ W/cm^2. The radiation from small electrode gap was registered by x-ray streak camera with an Au -photo cathode, which is sensitive in the spectral range of the order of 0.1 -10 keV. According to [5] the temporal resolutions as small as 10 ps, and generally is determined by a different time of flight for photo electrons moving from different parts of the photo cathode to the deflecting plates of the streak tube (time dispersion due to photo electron energy distribution). A sweep time of about 3 ns or 30 ns was used to investigate plasma radiation closely to the ignition of breakdown by the laser pulses, as well as in a later state, when a typical vacuum spark and arc discharge exists.

3. Temporally and spatially-resolved x-ray emission

We investigated the temporal behavior of the emission from low-voltage pulsed vacuum arcs with two different regimes: (i) if the amplitude of the mean current increases up to 54 A and some simultaneously active emissive centers of x-ray radiation exist, and (ii) if a single one occurs, when the mean current is below 2 A.

In the first mentioned case a voltage between 1.3 kV and 2.7 kV was applied for copper electrodes separated from each other by a distance of approximately 50 µm. The current discharge has an amplitude of 26 - 54 A and a duration of 750 ns.

If we initiated a laser-produced plasma without any external voltage between the electrodes, then the image of streak-recording has a very homogeneous structure. The broadband emission (spectral width determinate by Au photo cathode sensitivity 0.1- 10 keV) lasts only 250 ps and is not sufficient longer than the laser heating pulse (100 ps). For intensities used in this study (10^{12} - $3{\cdot}10^{13}$ W/cm^2) the typical plasma temperature was estimated to be in the range of 200 eV exhibiting hot components up to 1 keV [6].

The spatial distribution of x-ray emission changes radically if the voltage between electrodes is switched on. In Fig. 1a a streak-photograph of x-ray emission from pulsed vacuum discharge with an applied voltage of 2.7 kV just after ignition by laser beam is represented. The x-ray sources selected in the frame by a dot-and-dash line give an examples of triple- point-like emissive center (Fig. 1b). Two of them move with a velocity of $2.5 \cdot 10^5$ cm/s relative to an entrance slit of streak camera in an opposite direction to each other, and the middle one is motionless. During their life-time (see Fig. 1b) the intensity of x-ray emission varies with a typical time of 30 - 200 ps. The size of an intensive x-ray emission consists 0.6 - 3 µm, therewith it is evident that the middle point-like center splits after 600 ps into two sources. Besides, there are some sources with a typical life-time of 1- 6 ns and sizes of 10 -20 µm. Most probable that the region of an intensive x-ray emission above the marked area represents also an other point-like sources, which are strong connected with each other but not resolved in this streak image.

Besides two mentioned above mechanisms of soft and hard x-ray generation caused by the overheating instability and plasma erosion interruption [1-4] we can consider an additional one. Namely, the highly localized x-ray sources observed in our experiments can be explained by the electron beam heating in a constricted micropinch. As it had been shown [3] extremely high current density in plasma channels of cathode torch can be reached ($J > 10^{10}$ A/ cm^2). This spontaneous increasing of current density causes immediately a generation of high magnetic field in plasma fragments up to values of order of 10^5 - 10^{6} Gauss. Now we have a situation when a fast contraction in plasma channel occurs similar to well-known „hot spots“ in low-inductive vacuum sparks [7]. The plasma channel contraction on the other side is connected with an intensive x-ray emission. The point-like x-ray sources observed in our experiments can be interpreted as a small contracting plasma fragments. As long as current density and also self-generated magnetic field exceeds the kinetic pressure in plasma fragments, we can investigate contracted channel with the x-ray emission in form of horizontal lines in our streak photographs.

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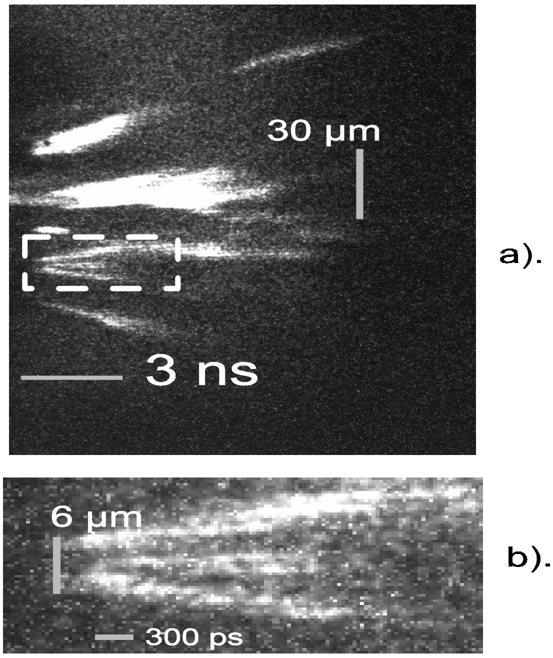

Figure 1. a) A streak picture of x-ray emission of laser-induced vacuum discharge with a voltage of U = 2.7 kV taken with a delay time of t = –3 ns. b) Magnified detail from the streak picture marked by a broken line.