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## Investigation of spectral lines broadening in femtosecond laser plasma generated on the surface of the barium water solutions

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### Abstract

The spectral lines broadening in femtosecond laser plasma generated by the 45 fs Ti:Sa laser pulses on the surface of the water solutions of Ba is investigated. Under the experimental conditions, determined the temperature of femtosecond laser plasma is 3000K. The contribution of the Doppler broadening for spectral lines width is minimal and amounts 0,0022 nm for Ba. The main mechanism of Ba spectral line broadening in experimental conditions is resonance. The resulting values of resonance broadening constitute 0,0349 nm for Ba I (413,24 nm), 0,0563 nm for Ba I (553,54 nm), 0,0241 nm for Ba II (455,41 nm), 0,0437 nm for Ba II (614,17 nm).

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*Keywords:* femtosecond; laser; plasma; spectral line width; broadening; LIBS; spectroscopy

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### 1. Introduction

Nowadays femtosecond laser plasma is promising for use in the laser-induced breakdown spectroscopy (LIBS) of liquids (Labutin, T.A. et al. (2016), Ilyin A.A. et al. (2013), Golik S.S. et al. (2015a), Golik S.S. et al. (2015b), Golik S.S. et al. (2015c), Ilyin A.A. and Golik S.S. (2014), Ilyin A.A. et al. (2015)). It is known, LIBS is a powerful technique for in-situ analysis (Labutin T.A. et al. (2016), Ilyin A.A. et al. (2013), Cremers D.A. and Radziemski L.J. (2006), Miziolek A.W. et al. (2006)). Even though LIBS has obvious advantages, the limits of detection (LOD) of

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the LIBS method with nanosecond laser excitation are at the ppm level (Labutin T.A. et al. (2016), Ilyin A.A. et al. (2013)) which is not satisfactory for applications that require high sensitivity such as seawater monitoring. But the application of the laser excitation with femtosecond pulse duration in LIBS leads to LOD down to  $10^{-6}$  g/L (Labutin T.A. et al. (2016), Golik S.S. et al. (2012)). It is known when the optical breakdown is induced by femtosecond laser pulses, the mechanical and thermodynamic parameters of the laser-produced plasma are considerably different from those of plasma produced by nanosecond laser pulses (Noack J. et al. (1998), Sirven J.B. (2004)). The temperature and electron density in plasma produced by femtosecond laser pulses are significantly lower. As a result the continuous background plasma radiation is relatively weak for the femtosecond laser pulses case (Sarpe-Tudoran C. et al. (2006), Ilyin A.A. et al. (2015)).

The time evolution of continuous and line spectra of plasma also changes with switching from the nanosecond to the femtosecond laser excitation (Labutin T.A. et al. (2016), Cremers D.A. and Radziemski L.J. (2006), Miziolek A.W. et al. (2006)). The choice of parameters of time-resolved laser plasma spectra detection such as gate delay  $t_d$ , gate width  $t_g$  and signal accumulation has a great importance in order to improve LIBS sensitivity (Cremers D.A. and Radziemski L.J. (2006), Miziolek A.W. et al. (2006)). Strong continuum emission occurs during and just after laser-induced breakdown and hides the line emission. As a result the detection has to be started after gate delay ( $t_d$ ) on the order of hundreds of nanoseconds to microseconds when the plasma has sufficiently cooled and the emission lines have emerged from the background. The optimal values of  $t_d$  and  $t_g$  usually depend on the elements to be researched (Labutin T.A. et al. (2016), Cremers D.A. and Radziemski L.J. (2006)). So, plasma excitation by the femtosecond laser pulses and time-resolved spectra registration in LIBS leads to increase a signal-to-background ratio and improve the limit of detection (Labutin T.A. et al. (2016), S.S. Golik et al. (2012)). In this work we have studied the spectral lines broadening in femtosecond laser plasma generated by the Ti:Sa laser pulses on the surface of the water solutions of Ba and plasma temperature in dependence of the gate delay.

## 2. Experimental setup

The layout of the LIBS experimental setup is shown in Figure.1. The Spitfire Ace Ti: Sapphire laser system (Spectra-Physics) (1) was used as the source of femtosecond laser pulses (with the central wavelength 800 nm, pulse width <45 fs, pulse energy up to 7 mJ, repetition rate from 4 Hz to 1 kHz and initial beam diameter 10 mm). Laser radiation was directed by the system of the mirrors (2) and telescope (3) on a plano-convex lens (5) with 100 mm focal length (KPX094AR.16, NewPort) and was focused on the surface of the investigated solution. The samples with water solution were placed into 3 mL cylindrical glass cell (6). The cell was mounted on a 3-axis (XY-horizontal, Z-vertical) translation stage with micrometer drives (MT3/M, Thorlabs). Plasma radiation emitted from the cell (6) was imaged by the quartz lens (7) ( $f=100$  mm) on the 50- $\mu$ m input slit of the 300 mm focal length spectrometer (8) (Spectra Pro 2300, Princeton Instruments) equipped with a 1,200 groove/mm grating. A 14 bit gated ICCD camera (9) (Pi-MAX 3, 1024\*1024 pixels, Princeton Instruments) was used as a detector. An internal Super SYNHRO time delay generator of the Pi-MAX 3 ICCD camera (9) was used to provide the gate delay  $t_d$  of the ICCD camera (10) with the pulses of laser system (1). The experimental setup was controlled by a computer (10).

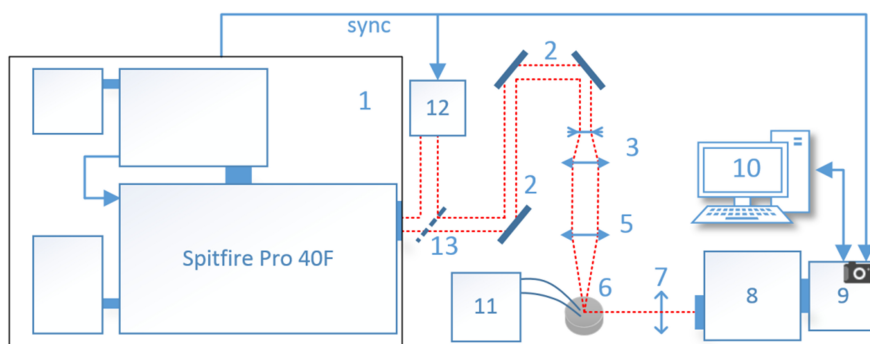


Fig.1. The layout of the LIBS experimental setup.

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