Investigation of Pressure Pulse Formation in Target Exposed by Stream of Relativistic Electrons and Hot Plasma[1]

A.V. Arzhannikov, V.V. Boldyrev*, A.V. Burdakov, I.A. Ivanov, V.S. Koidan, S.V. Polosatkin, V.V. Postupaev, A.F. Rovenskikh, A.A. Shoshin, S.L. Sinitsky, S.V. Tsybulja**

Budker Institute of Nuclear Physics of Russian Academy of Science, Lavrentev av. 12, Novosibirsk, 630090 Russia, Phone 7(3832)341031, Fax 7(3832)342163, A.A.Shoshin@inp.nsk.su
** Institute of Solid State Chemistry of Russian Academy of Science, Kutateladze st. 18, Novosibirsk, 630090, Russia,*
*** Institute of Catalysis of Russian Academy of Science, Lavrentev av. 5, Novosibirsk, 630090, Russia,*

Abstract – On the GOL-3 facility it was carried out the researches of generation of high-pressure pulse in solids at interaction by pulse relativistic electron and hot plasma stream. Technique of high-pressure pulse measurements on detecting the shift of ruby fluorescence lines R1 (694.23 nm) and R2 (692.8 nm) was developed. Calibration of technique was performed by strike to ruby crystal. The measured pressure was up to 1.1 kBar in the experiments, and this value is well agreed with numerical modeling [4].

1. Introduction

On the GOL-3 facility in the Budker Institute of Nuclear Physics we carry out the researches of plasma confinement in the multimirror trap when the plasma is heated by microsecond relativistic electron beam with power up to 200 kJ [1]. In these conditions the beam of relativistic electrons and a stream of plasma with power up to 30 MJ/m^2 fell on a target installed in chamber. Heating and evaporation of a target surface occur in the result. This process may be accompanied by producing a compression wave with high amplitude in substance. Interest in studying on such short-term wave of pressure is connected with opportunity to use results of this investigations for updating properties of various substances at pulse influence. These properties have importance not only in fundamental sense, but also for practical applications, for example, in the choice of a material for divertor plates of reactor ITER.

For studying of formation and time behavior of a pressure wave in a solid body and study of substances updating, the cell of a high pressure was created. The probe for pulse pressure measurement is mounted inside it. Principle of the probe operation is based on shifting the fluorescence lines of ruby R1 (694.23 nm) and R2 (692.8 nm) in red area at action of pressure on the ruby crystal. In the paper we present the description of diagnostics, its calibration and results of measurement of pressure arising in a solid body at influence of a powerful electron beam and plasma stream.

2. Method of Pressure Measurement

The method for calculating the value of tension by measuring wavelength shift of fluorescence spectral lines in crystals is well known [2, 3]. As usual this method was used for obtaining of permanent value tension and some modification of this technique is required for measuring of pressure pulses.

The scheme of experimental set up is shown in Fig. 1. The ruby crystal has been used as an active element of the pressure probe. The crystal is placed in the high-pressure unit that is exposed by relativistic electron beam on the GOL-3 facility. The excited levels in the ruby are pumped by radiation from pulsed krypton gas-discharge lamp through specially designed light guide. Duration of lamp luminosity is established shore then characteristic time of fluorescence of ruby in order to reduce background light in the registration system. Re-emitted light is collected by quartz lightguide and directed to spectral analysis system. This system includes high-resolution spectrometer (spectral resolution 0.05 nm) equipped by two independent recording units. The first one consists of photodiode array with intensity amplifier and is used for accurate measuring of fluorescence spectrum that is required for adjustment and calibration of system. The second includs three-channel ligthguide collector with PMTs applied for light registration. This unit provids high sensitivity and temporal resolution required for real experiments.

Measuring spectrum of the ruby fluorescence is shown in Fig. 2. It contains two spectral lines: R1 694.23 nm and R2 692.8 nm. Compression of the crystal causes change in dimensions of crystal lattice and therefore shifting the wavelengths of fluorescence. On the same figure the spectral range of registration for each channel of three-channel detector is marked.

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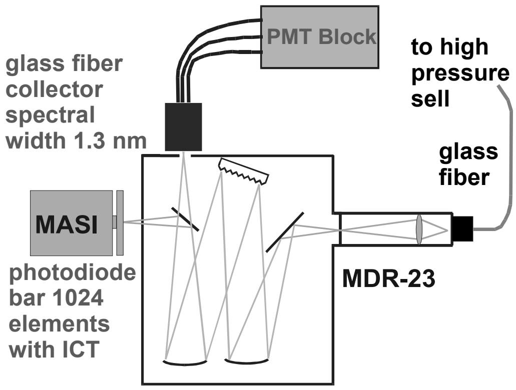

Fig. 1. Schematic of spectral analyzer for registration of ruby R1 spectral line shift

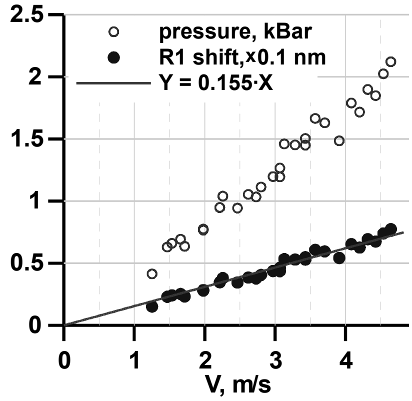

Fig. 2. The results of pressure measurements on shifting of ruby R1 line at strike of two solid body. The one body stands and the other moves with the velocity V

For slight shifts of spectral lines the line shift can be found as a difference of intensities in the channels “A” and “B” normalized to full intensity of the fluorescence. Cannel “C” is used for exclusion of background radiation produced by the source of pumping. The resulting formula for line shift calculation is

$$\Delta\lambda \ [\text{nm}] = 0.5 \cdot \frac{I_b - I_a - 0.5 \cdot I_c}{I_b + I_a - 0.5 \cdot I_c}. \qquad (1)$$

where I_a, I_b, I_c – intensities of corresponding channels. Numerical coefficients in the formula have been found with taking into account spectral width of channels, their sensitivity and the spectrum of the fluorescence.

Testing of high-pressure measuring unit

In order to test and calibrate high-pressure measuring unit we created a special test bench. In this facility pressure wave in the unit is generated by gravitationally accelerated striker. Ruby crystal mounted on a massive steel basis in this bench. For providing of flat pressure wave in the crystal the shock from the striker is delivered through a conical steel transmitter. The pressure behind the front of the wave is defines as

$$P = \frac{k}{2 \cdot V_s} \cdot V, \qquad (2)$$

where V – velocity of striker: V_s – sound velocity in the basis: k – elastic modulus.

We assume that the wavelength shift linearly depends on pressure in the crystal with a coefficient

$$\Delta\lambda = 0.365 \cdot P. \qquad (3)$$

This coefficient was measured in [2] for quasestationary regime with a pressure rise time about 1 min. Such steady-state approximation is proper if the characteristic frequencies of interaction less than shift of emission frequency:

$$\omega << \frac{2\pi c}{\Delta\lambda} = 1.456 \cdot 10^3 \cdot P \ [\text{Pa}].$$

In our conditions the steady-state approximation can be used for pressure pulses with rise time up to 1 μs.

Linearity of the system was verified by measuring of pressure in the crystal on the dependence velocity of the striker. This dependence is presented in Fig. 3. It is well fitted by linear function

$$P \ [\text{kBar}] = (0.425 \pm 0.006) \cdot V \ [\text{m/s}]$$

with residual mean square $\sigma = 0.012$.

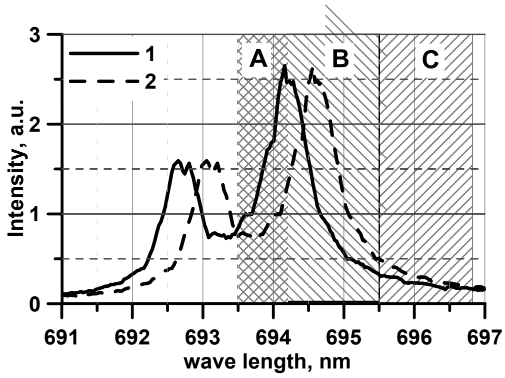

Fig. 3. Contour of R1 (right), R2 (left) lines (curve 1) and its shifting at pressure influence (curve 2). A, B, C – channels of glass fiber collector for registration of shifting R1 line

The calibration of the system was performed in the tests with flattening of the vertex of the conical transmitter. Since a pressure in the vertex can't exceed creep strength

$$\sigma_{cr} = (6 \pm 0.5) \cdot 10^8 \ \text{N/m}^2,$$

maximal pressure in the crystal can achieve

$$P = \sigma_{cr} \frac{S_v}{S_{cr}},$$

where S_{cr} – area of crystal, S_v – flatten area of vertex after interaction. In test experiments we found $P_{max} = 2.12 \pm 0.1$ kBar. In the same time estimation in accordance to (3) gives 2.1 ± 0.2 kBar.

Measurements of pressure pulse in e-beam experiments

For experiments on pressure pulse generation in solid at its surface irradiation by stream of relativistic electrons and hot plasma in the vacuum chamber of the GOL-3 facility has been build device that schematically is shown in Fig. 4. The main part of the device is a hollow tube. On the top of the tube there is the high-pressure cell with the ruby inside. Quartz fiber transmits light from the ruby crystal to the spectral system. From below of the tube there is an illumination port and a lamp IFP-8000 for excitation of the ruby fluorescence.

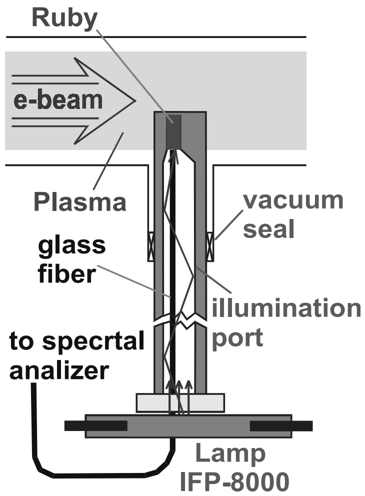

Fig. 4. Schematic of the high-pressure cell for measurement of pressure in solid substance at radiation treatment of its surface by stream of relativistic electrons and hot plasma

At the experiments the relativistic electron beam and hot plasma stream heat and evaporate the cell surface that produces a big reactive force and thermomechanical stresses. This process may be accompanied by occurrence of a wave of compression with high amplitude in the cell. Numerical simulations of such systems showed that the amplitude of the pressure wave could amount to tens kBar [4].

During the surface irradiation by the electron beam a bramstrahlung radiation exists that additionally pumps the ruby fluorescence. Intensity of the ruby fluorescence at the channel “b” of the spectral system during experiments with and without lamp is shown in Fig. 5. Hatching area in Fig. 5 shows the time of the electron beam passage. Measured value of the pressure are similar at additional pumping by the lamp and without it. Therefore, we provided some experiments without the additional pumping.

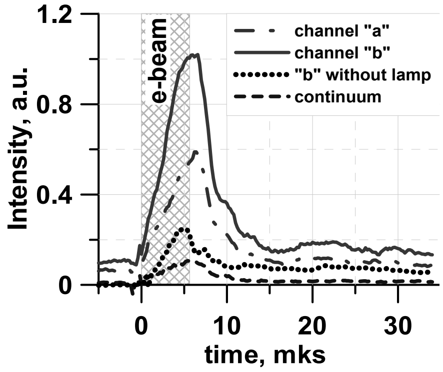

Fig. 5. Fluorescence of ruby R1 line at measurements of shifting of the line at interaction by relativistic electrons and hot plasma stream on the cell. By the points showed is the signal of channel “b” without pump of fluorescence by the lamp

Measured time behavior of the pressure inside the cell versus time is shown in Fig. 6. This result was obtained by averaging the results of several measurements. Maximum of the measured pressure is up to 1.1 kBar.

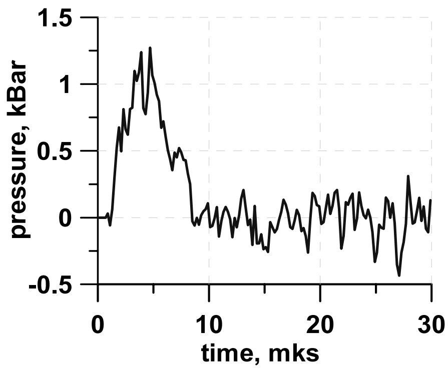

Fig. 6. Reconstructed pressure at interaction of stream of relativistic electrons and hot plasma on the target

Difference getting results from modeling [4] can be explained by that the length of high-pressure cell is only 17 mm and the time of sound passage though the cell is 3 μs. Therefore the measured pressure in ruby is the sum of the pressure wave coming on it from the left and the unload wave – from the right. It significant reduces the pressure created by the electron beam and plasma stream at surface of the cell.

3. Conclusions

The device for high-pressure pulse measurement was created. Its operation ability was checked up at strike.

Study of testing experiments forming the pressure in solids under its surface irradiation by electron beam and plasma stream is carried out. Experiments have shown that additional pumping of ruby crystal fluorescence by bramstrahlung radiation from the electron beam allows using the cell without the pumping lamp. The pressure inside the cell arises up to 1.1 kBar with the time duration 8 μs. This value agrees with the results of numerical modeling [4].

References

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