INTRODUCTION

This study involves investigation of high-power pulsed discharges in a high-density gas at an initial working-gas (hydrogen) pressure of up to 35 MPa, a deposited energy of $10^4$–$10^6$ J/pulse, and an amplitude of the discharge current of $10^5$–$10^6$ A with a rise rate of $10^9$–$10^{11}$ A/s. The electric discharge at such energy inputs is accompanied by considerable erosion of electrodes. Studying the ingress of metal vapors into the discharge volume and their mixing with a working gas under such conditions is a rather complex diagnostic problem.

The main fundamental difficulties in diagnosing such a discharge are associated with the high plasma density [1–5]. Optical methods yield information only on peripheral discharge regions where the absorption is not too strong. X-ray flash radiography makes it possible to perform the diagnostics of internal regions of the discharge channel with a high time resolution.

X-ray flash radiography using sources with effective photon energies of $\geq 10^2$ keV has become widespread. However, to study objects with relatively low concentrations of absorbing substances, softer X-rays are required [6].

The absorption of a beam of monochromatic X-rays can be calculated from the formula $I = I_0 \exp(-\mu \rho d)$, where $I_0$ is the initial beam intensity; $\rho$ and $d$ are, respectively, the density and thickness of the absorbing layer in the probing direction; and $\mu$ is the mass absorption coefficient, the approximate expression for which is $\mu = c Z^3 \lambda^3$. Here, $Z$ is the atomic number of the element, $\lambda$ is the wavelength, and $c$ is a constant depending on the position of the wavelength $\lambda$ relative to the element’s $K$ absorption edge [7]. The density measurement error is estimated as $\Delta \rho = \frac{1}{\rho} \frac{\Delta I}{I} \mu \rho d$, where $\Delta I$ is the absorption measurement error [6]. In this case, the highest sensitivity and a quite high measurement accuracy are observed, if the condition $\mu \rho d \sim 1$ is met [8].

To satisfy this condition in a discharge with copper and/or iron vapors (corresponding to the material of the electrodes and/or the initiating wire in our experiments) X-rays must be sufficiently soft. According to the estimates in [3–5], metal vapors in the discharge are concentrated in the central region of the 1- to 2-cm-long interelectrode gap with a concentration of $10^{19}$–$10^{20}$ cm$^{-3}$. The optimal wavelength of probing radiation is correspondingly $\lambda \sim 1$–$2$ Å near the $K$ absorption edge (with photon energies of $5$–$10$ keV).

Pulsed X-ray sources with a low effective photon energy are being applied in X-ray radiography of implosive processes [9], gas-dynamic experiments [10], and diagnostics of various plasma devices (in which, currently, an X-pinchar waist is successfully used as a source of soft X-rays) [11–13].

At the same time, studying a high-power discharge in a high-pressure dense gas accompanied by a large energy deposition is complicated by the impossibility of placing diagnostic instrumentation in the discharge volume. The considerable thickness of the diagnostic windows necessitates the use of harder radiation and requires a more powerful X-ray source. To design an
efficient diagnostic system, a compromise between different requirements must be sought for.

Until recently, the development of such radiography systems was very difficult. We know only a few such systems. In [8], a system for diagnosing a pulsed arc in a high-pressure gas at relatively low energy deposition is described, and paper [14] presents a method of induced X-ray fluorescence possessing a considerable potential for diagnosing internal regions of high-current discharges in high-pressure gases but requiring a very powerful source of soft X-rays, highly sensitive receivers, and a high computational power.

This paper describes an X-ray radiography system for diagnosing discharges in high-density gases at high energy depositions, which is based on an X-ray CCD camera and a compact high-power explosive-emission X-ray source with a high spatiotemporal resolution.

**EXPERIMENT**

A discharge in hydrogen initiated by an electric explosion of a 0.5-mm-diameter iron or copper conductor was studied. The distance between hemispherical steel or copper electrodes (20 mm in diameter) was varied from 5 to 25 mm. The experiments were performed at an initial hydrogen pressure of 2.5 kPa–35 MPa. Before the experiment, the discharge volume was evacuated to a pressure of 2.5 kPa and blown through with hydrogen to ensure the necessary purity of the working gas. The maximum pulsed pressure in the discharge chamber was 450 MPa. The experimental bench is described in more detail in [15].

Figure 1 shows the scheme used to perform the X-ray radiography of the discharge. The elements of the diagnostic system have been calculated as applied to the experimental condition for a medium with metal vapors, hydrogen, and for the case of radiation passage through the diagnostic windows manufactured from different materials of different thicknesses. For simplicity, it was assumed that, apart from the hydrogen-containing region $L_1 = 13$ cm (this size was determined by the design of the discharge chamber [15]), a region with a length $L_2 = 1$ cm with metal vapors was added at a pressure of 10 MPa. The total thickness $L_3$ of the diagnostic windows for each material considered was chosen proceeding from the required strength permitting them to withstand the operating pressure. The data on the X-ray absorption for different energies were taken from [16–18]. It occurred that, according to its aggregate characteristics—the impact strength, transparency in the X-ray region, easiness to manufacture, biological safety, and cost—polycarbonate surpasses other materials considered. The sufficient absorption of X-rays optimal for measuring metal-vapor concentrations of $10^{19}–10^{21}$ cm$^{-3}$ against an absorption background in diagnostic windows is ensured in the range of photon energies of ~30–40 keV (Fig. 2).

The total X-ray absorption in the system was estimated for different spectra of the source for X-ray radiography.

To approximate the spectrum of the actual device, a model spectrum was simulated for various potentials at the X-ray tube using the SpekCalc [19]. To measure the concentrations in the range $10^{19}–10^{21}$ cm$^{-3}$, the