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Diagnostics of Fast Processes by Charged Particle Beams at TWAC–ITEP Accelerator–Storage Facility

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Abstract—A new setup for the experimental investigation of rapid dynamic processes using proton radiography techniques has been created at the TWAC–ITEP terawatt accelerator–storage facility. A set of equipment for conducting shock-wave experiments has been designed, constructed, and tested, and an instrumentation–software complex has been developed for the automation of experiments. The first series of experiments with dynamic targets representing high explosives have been carried out, in which the density distribution in detonation waves initiated in these explosives has been measured.

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Investigations of the physical (in particular, mechanical) properties of materials subjected to intense dynamic loading are of both basic significance and considerable practical interest. However, most of the available experimental methods do not provide direct (absolute) information on a number of important characteristics of substances, including density and microstructure, immediately in the course of dynamic experiments. These possibilities are offered by radiographic methods, in which the sample is probed by a beam of high-energy particles (e.g., protons) [1] or X-rays [2]. The proton radiography is superior to the X-radiography in many respects, in particular by ensuring high spatial and temporal resolution, high transmission ability, and a large dynamic range of imaging. In addition, the proton radiography makes possible a multishot monitoring of dynamic processes and thus provides the possibility of tracing the evolution of the state characteristics of a substance.

The present investigation was aimed at developing the experimental setup for studying shock-wave and detonation phenomena by proton radiography techniques at the TWAC–ITEP terawatt accelerator–storage facility.

The proton radiography setup was based on a high-energy proton beamline of the TWAC–ITEP facility. The methods and results of magnetic optics calculations and the scheme of the experimental setup have been described in detail elsewhere [3]. The magnetic optics system comprises a set of seven quadrupole lenses ML-15 (Fig. 1, positions *1*–*7*), which enable the formation of an object image in the monitor plane and ensure the matching of a proton beam to the radiographic measurement system. The three magnetic lenses that constitute the matching system ensure the optimum proton beam parameters in the object plane and provide for a partial compensation of chromatic aberrations in the setup. The other four magnetic lenses, which feature magnetic fields of the same magnitude (~0.258 T), constitute a measuring system with an image transmission coefficient of –1. The length of the measuring system from the target (T) plane to the image (I) plane is 14.3 m. The magnetic channel is designed so as to form the so-called Fourier plane at the middle of the measuring system, which ensures the spatial separation of protons with different total angles of multiple Coulomb scattering in the target. In the vicinity of the Fourier plane, usual collimators (C) and anticollimators (continuous rods oriented along the beam axis) are arranged in order to increase the contrast of the radiographic image.

In order to ensure the safety during the dynamic experiments with high explosives (HEs), a special protection chamber was designed, constructed, and tested, which could withstand multiply repeated experiments with HE masses of up to 0.1 kg TNT equivalent. This chamber consisted of two steel hemispheres with an inner diameter of 520 mm and two coaxial windows in the walls for passing the proton beam. The object studied was positioned in plane T inside the chamber. The chamber was rendered hermetic by closing the windows with 1-mm-thick alumi-

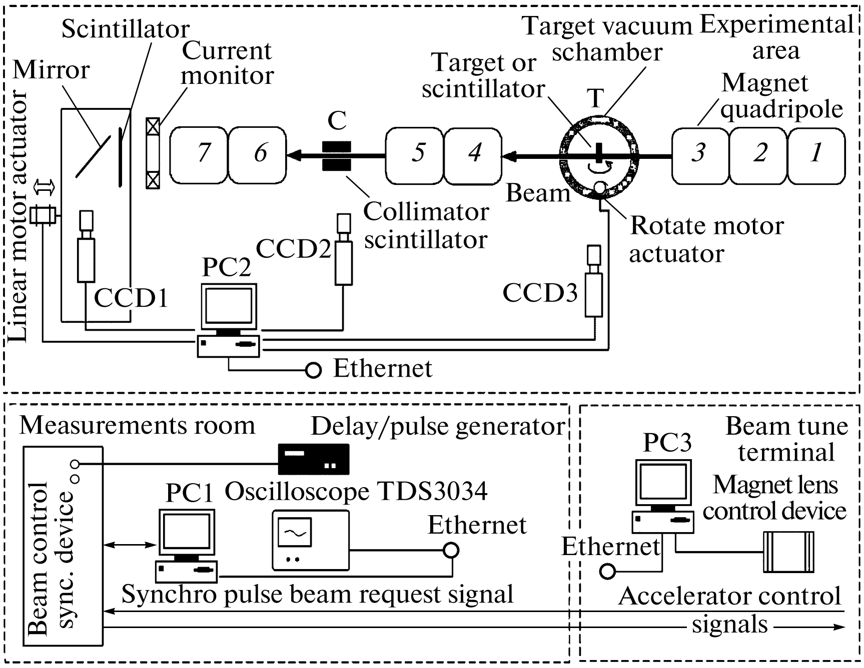

Fig. 1. Schematic diagram of experimental setup and instrument–software complex.

num protection plates with an aperture diameter of 20 mm. Prior to each experiment, the chamber was evacuated in order to decrease the action of the shock wave on the chamber walls.

We have developed an instrumentation–software complex (ISC) for automating experiments. Automated systems ensure the synchronization of all diagnostic means and instruments involved in the experiment with the cycles of the TWAC–ITEP facility operation; the control of all parameters of the experimental setup; and the acquisition, storage, and processing of experimental data on computers (Fig. 1). The proton beam parameters (intensity, temporal matching) are controlled using a beam current transformer-monitor, which is positioned in front of the image plane. The proton beam image was formed on scintillation converters and recorded using a high-speed optical digital camera. Working parameters of the magnetic optics system (current and temperature of electromagnets) and radiation safety system are also monitored and controlled. All data from the instruments are collected and stored in computers.

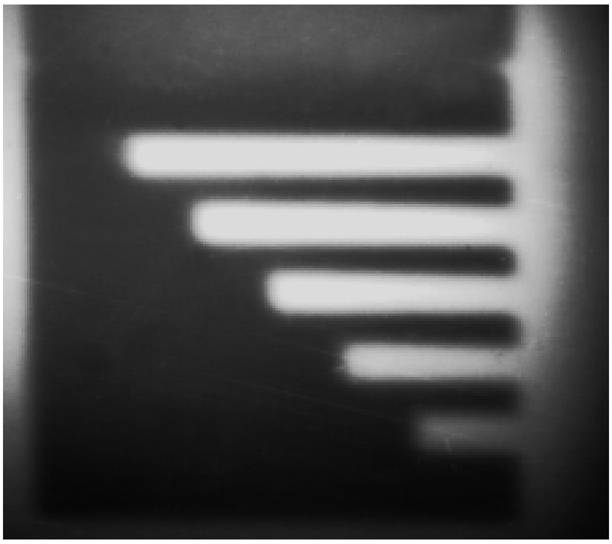

Fig. 2. Radiographic image of static TO.

The software consists of program packages for all components of the experimental setup, including digital CCD cameras, translation manipulators, digital oscilloscopes, radiation meters, etc. These program perform the primary analysis of the experimental data. The data exchange in the computer network is performed using a TCP/IP protocol in agreement with the experimental schedule.

In order to determine metrological parameters of the proton radiography setup, we have performed a series of experiments with static test objects (TOs). The typical TO represent a brass cube with 20-mm edges and mutually perpendicular 1.6-mm-wide cut channels. Using this TO design, it was possible to measure the spatial resolution by evaluating the degree of smearing of a sharp edge. Figure 2 shows the typical radiographic image of a static TO, where bright bands correspond to the channels. The spatial resolution determined from this image is $\sigma = 300 \pm 10$ μm, which well agrees with an analytical estimation of σ_t = 293 μm [3].

The possibility of using the proposed setup for tracing the evolution of the state of a substance involved in a fast dynamic process was demonstrated in dynamic experiments with HEs. The samples for investigation were made of pressed trinitrotoluene (TNT) with a density of $\rho_0 \sim 1.32$ g/cm^3. With this initial HE density, the duration of a chemical reaction in pressed TNT is ~200–250 ns [4], which corresponds to a width of the region of elevated pressure and density within ~1.2–1.5 mm. The TNT charges in the form of 32-mm-long cylinders with a diameter of 20 mm were mounted inside the working chamber. The HE detonation was initiated by a point source (electrodetonator).

The intensity of an 800-MeV proton beam was ~10^{10} particles per shot, which involved four (7 ± 5)-ns-long pulses with intervals of 250 ± 15 ns. This structure of the pulsed proton beam makes it possible to obtain up to four proton radiography images of the probed dynamic object. In our experiments, a series of pairs of these images of detonating TNT cylinders were obtained that corresponded to the second and third pulses. Figures 3a and 3b show the typical images of such a pair, in which the detonation wave propagates from left to right. The dark vertical band observed in the central part of the image corresponds to the zone of substance densification in the detonation wave. The evaluated velocity of motion of this band between the two shots was 5.7 ± 0.5 km/s, which coincides (to within the standard deviation) with the known velocity of TNT detonation (6 km/s) at the given charge density. The zone of substance densification is followed by a zone of unloading, which is observed in the right-hand part of the image and characterized by a gradual decrease in the density.

The proton transmission data obtained from the radiographic images are recalculated to the values if linear density (in the direction of beam propagation) in the target, based on which the volume density profiles at the beam axis can be reconstructed. The corresponding profiles, which were obtained using the images presented in Figs 3a and 3b, are depicted in Fig. 3c (dotted curves *1* and *3*, respectively) in comparison to the profile (dash-dot curve *3*) obtained by the numerical simulation of the detonation of an analogous TNT charge. In the region of the density drop, the profiles of radiographic images were fit to the Gauss function (solid curves). Note that profile *2* lies below profile *1*, which is probably related to a residual illumination of the CCD matrix by the first shot. For this reason, the subsequent analysis was performed with allowance for only the first profile.

The sharpness of brightness changes in radiographic images in the region of the detonation wave front for profile *1* is characterized by $\sigma_a = 450 \pm 15$ μm. This value is about 1.5 times worse (greater) than the spatial resolution evaluated above. This discrepancy is probably explained, first, by an uncertainty due to the wave propagation along the target during the exposure (i.e., for a proton pulse duration of ~7 ns). Another possible factor is an additional obstacle to proton transmission presented by aluminum plates in the two windows, which impair the setup resolution. Finally, additional smearing of the front of the observed detonation wave may be caused by lateral unloading at the charge–external medium interface, which significantly distorts the shape of the detonation front.

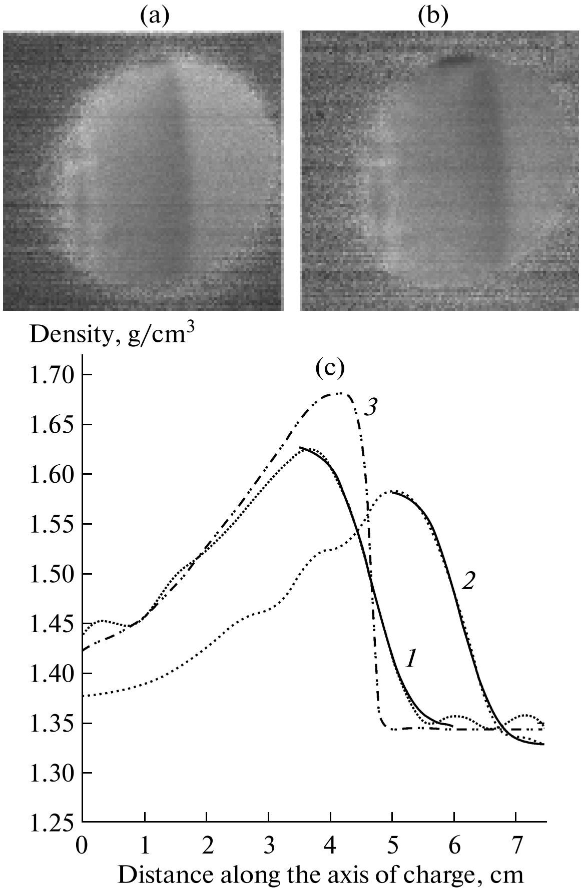

Fig. 3. Detonation wave in TNT charge: (a, b) radiographic images of two sequential proton pulses with an interval of about 250 ns; (c) volume density profiles at the charge axis according to images (a) and (b) (curves *1* and *2*, respectively) and the results of numerical simulation of the TNT detonation (curve *3*).

Nevertheless, the volume density profiles in the unloading zone presented in Fig 3s show both qualitative and good quantitative agreement with published data [4] and the results of numerical simulation of the detonation wave propagation in an analogous TNT charge of the same initial density. These results show evidence for the possibility of using proton radiography for determining the density of a substance in fast dynamic processes.

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