A radiographic facility, placed in the initial rectilinear part of the injection channel, which is intended for transporting a proton beam from U-70 into an accelerator-storage complex, is described. It is designed for energy 50 GeV with field of view 60 mm and makes it possible to obtain an image of objects with optical thickness to 400 g/cm$^2$ with resolution 100 µm. The first static and dynamic experiments performed in our country at 50 GeV have shown the advantages of pulsed radiography in studying fast processes in ultradense media.

This article is devoted to proton radiography – a new method of studying fast processes in media with high optical density.

For more than half a century, the main tool for studying fast processes was pulsed x-ray radiography. Its advantages are simplicity and relatively low cost of the facilities, the main element of which is an electron accelerator. The wide use of x-ray radiography is mainly due to these advantages. But γ-rays with high penetrating power (about 4 MeV) passing through an object engender photon showers which result in background noise in the recorded image. In thick objects, the photon noise can completely conceal the useful image. To increase the penetrating power of x-ray radiographic facilities, their power must be increased. In so doing, it becomes more difficult to provide acceptable target dimensions, which limits the power of x-ray facilities.

Proton radiography does not have these problems. In terms of penetrating power, protons significantly surpass x-rays. The average free path of high-energy protons is approximately 185 g/cm$^2$. For optical thickness 300 g/cm$^2$, 20% of the protons (versus $10^{-6}$ γ-rays) pass through an object. For this reason, a million times fewer protons than γ-rays are needed to form a radiographic image. Proton radiation can be used confidently to study the structure of thick objects, for example, objects containing 400 g/cm$^2$ steel or tungsten (uranium), which is almost impossible to do with γ-rays. Gamma radiation is attenuated 10-fold on passing through 50 g/cm$^2$ steel. High-energy protons are attenuated 10-fold on passing through 300 g/cm$^2$. In addition, the presence of charge makes it possible to control proton fluxes in order to obtain multiframe and multibeam photographs on the basis of a single accelerator.

The main requirement for proton radiography is the presence of high-energy protons with energy 50–70 GeV. Such a high energy is required not so much to guarantee penetration of optically thick objects as to obtain high image sharpness since the image blurriness owing to chromatic aberrations and multiple Coulomb scattering decreases with increasing proton energy. Special magnetic optics makes it possible to significantly decrease the effect of Coulomb scattering and obtain resolution less than 1 mm for objects with optical thickness greater than 300 g/cm$^2$ [1] (Fig. 1).
A powerful proton accelerator is the most expensive and technically complex part of a proton radiography complex. The presence of a 70 GeV proton accelerator and a developed extraction system made it possible in 2004–2006 to create in the U-70 a facility for studying objects with almost any thickness of practical interest by means of proton radiography [2–5]. Static and dynamic experiments were performed in the U-70 proton beams using objects of different complexity, the advantages of proton radiography were proved experimentally and a basis for its wide adoption and development was prepared.

Proton radiography on static objects with a single pulse and energy to 24 GeV was checked at the Brookhaven National Laboratory (USA) [6]. Proton radiography is used systematically for dynamic experiments on the LANSCE facility (USA) at proton energy 800 MeV, which greatly limits the possibilities of the method [7]. Experiments were performed at this energy using the TVN accelerator-accumulator complex [8].

In terms of the parameters, the facility described in the present article appreciably surpasses the other facilities enumerated. Research, development and modernization of the extraction system and other systems of the U-70 accelerator complex and the planned increase of the intensity of the proton beam open up new possibilities for increasing the frame multiplicity and exposure and thereby substantially expand the region of application of proton radiography for studying fast processes. The present work examines only the organization of the proton beam. The work in [9] is devoted to recording the image of an object and performing experiments.

**Some Characteristics of the Proton Synchrotron at the Institute for High-Energy Physics.** The U-70 proton accelerator complex contains a URAL-30 30-MeV linear accelerator with high-frequency quadrupole focusing, a rapid cycling (16.6 Hz) 1.5-GeV booster, and a 70-GeV proton synchrotron. The maximum intensity of the proton beam is $1.7 \times 10^{13}$ particles/pulse. The multiplicity of the hf accelerating field is 30.

The particles in large proton accelerators are bunched in compact bunches. Up to 29 proton bunches can be injected from the booster into the U-70 orbit for subsequent acceleration. Their minimum intensity for stable operation of the feedback system is $3 \times 10^{11}$ particles. The fast extraction system can extract 1 to 29 bunches once per cycle. Thus, the minimum intensity per pulse extracted is $3 \times 10^{11}$ protons and the maximum intensity reaches $1.5 \times 10^{13}$ protons.

The duration of single-revolution extraction of all bunches is ~5 μsec. In this time, twenty-nine frames and information about fast processes can be obtained. Multiframe recording of objects in a microsecond time interval must be implemented in order to study such processes. The duration of a single bunch of protons can be shortened to 5–15 nsec by special hf gymnastics. The interval between frames is ~167 nsec.

A packet of successive proton bunches formed in the accelerator is directed onto the object for radioscopy and obtaining a photographic image synchronized with it. The emittance of the accelerated beam at maximum intensity is 2 mm-mrad. At lower intensities ($3 \times 10^{12}$) it can be about 1 mm-mrad. For an object moving with speed $10^8$ m/sec, the objects moves a distance of only 100 μm over the passage time of a bunch, which is about $10^{-8}$ sec. Thus, proton radiography permits obtaining up to 29 frames of very fast processes with smearing ~100 μm.

**Proton Beam Forming System.** The foundation of the proton radiography facility based on the existing infrastructure – injection channel – is the optical system, consisting of four quadrupole magnetic lenses (quartet) with transfer matrix $-1$.