THE PROTON RADIOGRAPHY FACILITY AT THE U-70 SYNCHROTRON

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Abstract

The results on operation and development of proton radiography facility (PRGC-100) at the U-70 synchrotron are presented. PRGC-100 is designed to look inside the objects with mass thickness from 10^{-1} g/cm^2 up to 450 g/cm^2 and the field-of-view up to 220 mm at proton beam energy 50÷70 GeV. The measured spatial resolution is 90 µm for thin objects and less than 500 µm for the objects of 350 g/cm^2 thickness. The development of the beam extraction systems for PRGC-100 as well as the first results on testing the proton microscope mode is presented.

FACILITY DESCRIPTION

The proton radiography facility PRGC-100 was created with partial use of the existing infrastructure - injection tunnel (IT) of accelerator storage complex UNK [1].

The extraction of the accelerated proton beam in IT is performed by the fast extraction system which includes the kicker magnet KM-16 and the two septum magnets EM-62 and EM-64 [2]. The single-turn extraction mode provides up to 29 proton bunches with intervals between bunches 165 ns and extraction duration up to 5 µs. The bunch intensity is (2÷4) $\times 10^{11}$ proton. The width of beam relative momentum distribution on the basis of $\pm 2\sigma$ is $\pm 0.8\times 10^{-3}$ and corresponds the bunch duration about 20 ns.

The magnetic structure of the PRGC-100 includes a beam transport line from the proton synchrotron U-70 and the optics of PRGC-100 itself, consisting of three quartets of quadrupole lenses. Each quartet is constructed of four pairs of quadrupole lenses 30Q180-6,7 (Fig. 1) [3] and provides image transmission coefficient –1.

The facility has rich diagnostic equipment for beam monitoring consisting of 12 profile detectors and 7 television stations.

At the beginning of the first quartet, a subsystem for initial beam image registration is established. The objects are installed before the second quartet. A proton beam passing through an object is formed by the second and third quartets for registration and obtaining the image of the object under study.

The length of each quartet is 65.2 m.

Figure 1: Section of PRGC-100 with quadrupole lenses and radiation protection blocks.

The beam collimators are located in the middle of the second and third quartets (the focus points). The quartet structure of PRGC-100 is schematically shown in Fig. 2.

PRACTICAL RESULTS

The facility was commissioned in 2014. At present the capabilities to provide the required beam parameters are significantly expanded.

The facility allows to study inside of various static and dynamic objects with thickness from 10^{-1} g/cm^2 to 450 g/cm^2 with field of view up to 220 mm at proton beam energy 50-70 GeV [4].

The magnetic system of the beam transport line allows controlling the diameter of the proton beam from 30 mm to 240 mm depending on the size of the object under study and the required proton flux density.

There were created wide-aperture multi-frame image recording systems and quality monitoring of each proton bunch [4].

The total exposure time for dynamic radiography was increased in several times due to the use of "portional" fast resonant extraction (FRE) with pauses between the extracted bunches. In this mode, the beam is ejected by a kicker magnet KM-16 beyond the separatrix of the betatron motion on the third order resonance $3\times Qr=29$

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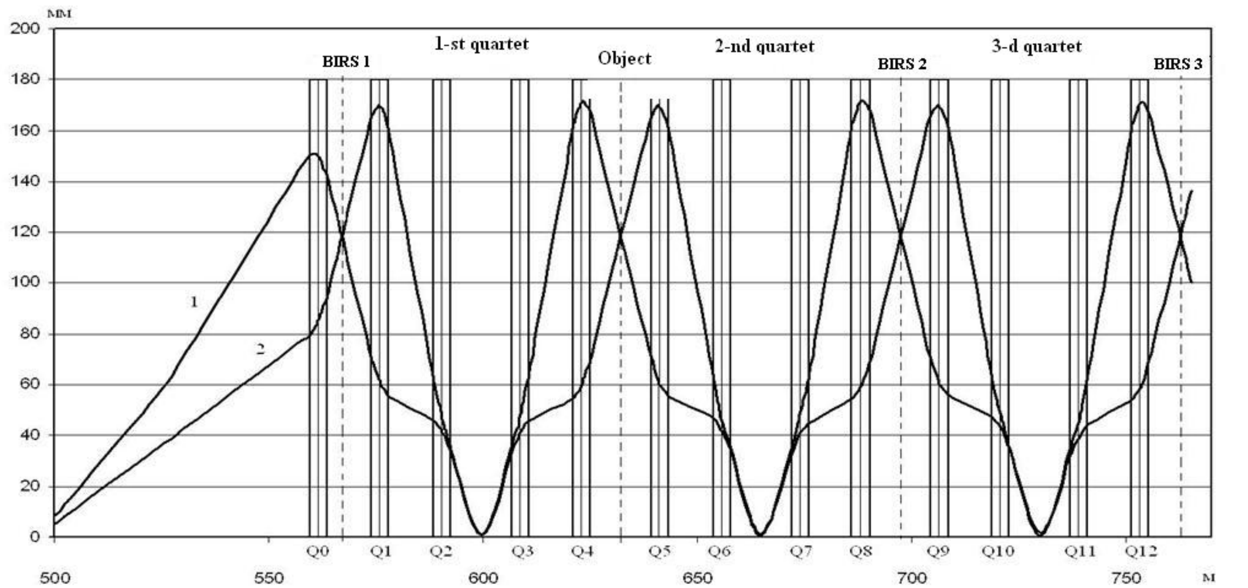

Figure 2: The structure of the quartets (shown beam envelopes in the horizontal (1) and vertical (2), Q1-Q12 quartet lenses).

formed by the U-70 sextupole lenses. Further, in the process of motion, the amplitude of the beam increases and eventually the beam is thrown into the aperture of the electrostatic deflector ED-106 and then to the aperture of the magnets EM-24, EM-62 and EM-64. There formed 2 or 3 groups of the extracted bunches separated by intervals of 10 µs. The total duration of extracted beam is 20 or 35 µs (Fig. 3).

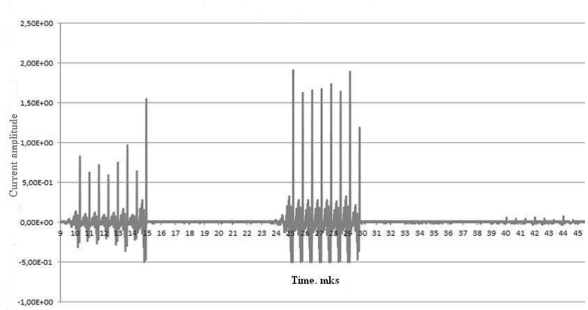

Figure 3: Current signal of the extracted beam in the FRE mode.

A multi-turn proton beam fast extraction was also developed [5]. This mode is carried out by means of two fast bump magnets located near the electrostatic deflector ED-106 that excite local distortion of a closed orbit and transfer the beam through a thin partition ED-106. Next, the beam enters the apertures of EM-24, EM-62 and EM-64. The duration of extracted beam in this mode can be up to 50 µs (up to 10 groups of extracted bunches). Accordingly, the intensity of a single bunch is also shared on parts.

A special resolution essentially depends on the thickness of the radiography object. The image blur of a thin object is determined by the following significant effects (in descending order of importance): the system of registration, blur on the vacuum chamber diaphragms, chromatic aberration, the variation of the currents in lenses. For thick objects these are chromatic aberration, object scattering, registration system.

The measured spatial resolution for a 10 mm thick static steel object (≈ 8 g/cm^2) is 90 µm (standard deviation). The spatial resolution in the case of the object with thickness of 350 g/cm2 is 450±50 µm (Fig. 4). Proton images were recorded by TV cameras with a matrix of 2048×2048 pixels.

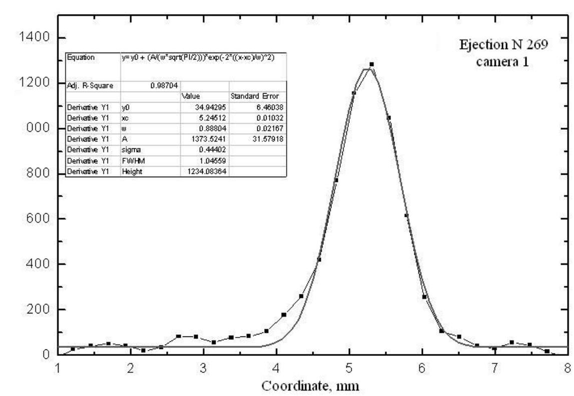

Figure 4: Measured blur function of the boundary for object with a thickness of 350 g/cm^2.

In terms of the development of the functional capabilities of the PRGC-100 a high spatial resolution mode (proton microscope) for beam energy of 50 GeV is being developed. Relatively small magnetic field gradients in the lenses, as well as their fixed positions impose certain restrictions on the optimization of this regime. Experiments were carried out in the proton microscope mode with the image magnification factor equal to 5.

The static measuring object of steel (Fig. 5) with a thickness of 10 mm and diameter of 50 mm was irradiated with a beam of diameter of ~ 60 mm.

The image registration area was 150×150 mm^2 (Fig. 6).

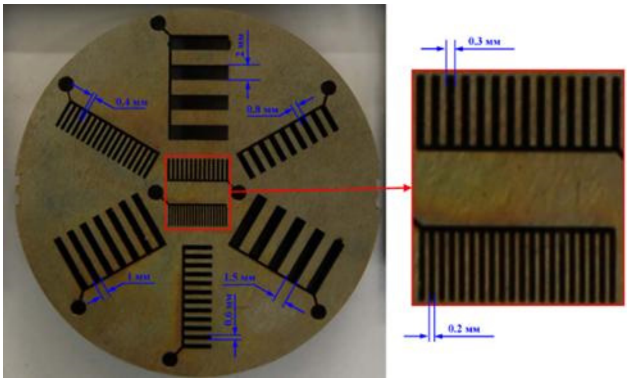

Figure 5: The radiography object.

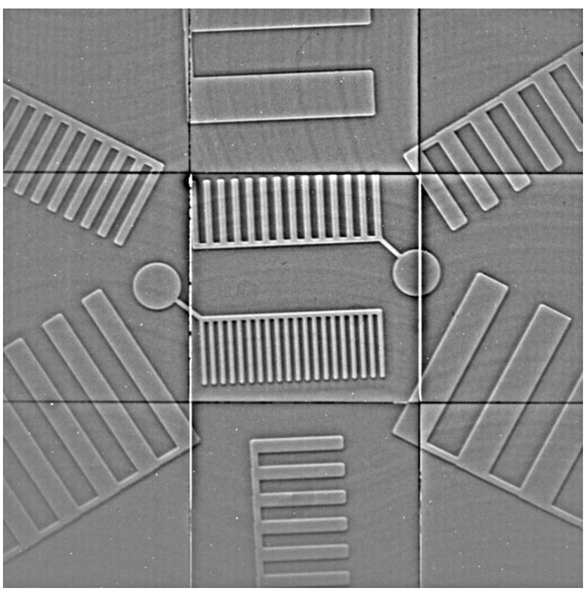

Figure 6: Proton radiography image of the object in microscope mode.

The spatial resolution in the horizontal plane was measured as 26 µm (Fig. 7). The chromatic aberration in the vertical plane has not yet been suppressed.

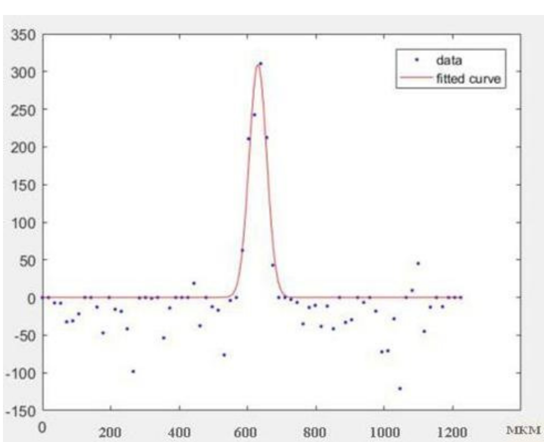

Figure 7: Measured blur function in the horizontal plane.

CONCLUSION

The status, operational results and development of a proton radiographic facility were presented. Constructed in 2014 on the basis of the U-70 the facility PRGC-100 was designed for the study of structure and dynamics of various objects with the mass thickness from 10^{-1} g/cm^2 up to 450 g/cm^2 with the field-of-view up to 220 mm. Facility is used for material science research at proton beam energy of 50÷70 GeV.

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