Peculiarities of proton microscope development for the aims of proton radiography

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Abstract. Proton radiography facility based on a GeV-energy beam is expected to be useful to study the dynamic processes in matter under extreme conditions. The main factors affecting pRad facility spatial and temporal resolutions and general peculiarities of proton microscopy are described. The results of the microscope simulation for GeV-energy facility are presented.

1. Introduction
Proton radiography is one of numerous radiographic methods used for the research of matter. Well-known methods such as X-ray radiography, electron and positron radiography, neutron radiography and muon radiography as well as proton radiography have a specific range of their applicability. For particular physical tasks the applicability of a specific radiographic method is mainly determined by the task requirements as well as by the experimental conditions and the costs of the implementation of the method. The method of proton radiography is useful for dense and superdense objects study, both static and dynamic [1-3] because of the specific interaction of energetic proton with matter, namely because the curve of the energy release during the complex proton-matter interaction has a significant “plateau” range and the final peak (Bragg’s peak). For instance, such a shape of the energy release distribution allows to carry out the experiments for cylindrical shock wave observation and investigation. The existence of the Bragg’s peak allows to carry out some static experiments when the energy release should be in a localized area. This property is especially useful in medicine for proton therapy and tomography coupled.

Another benefit of proton radiography are the excellent proton transmission characteristics, for instance, the proton penetration through the substance having an optical thickness 350 g/cm is ~15%, in contrast to γ-ray transmission estimated as ~ 10⁻⁷, so such a tool will be useful for extensive objects study.

The applicability of proton radiography is restricted due to resolution limitations. The spatial resolution limit appears to be due to a few reasons, such as the scattering of the particles inside the object investigated, the interaction of transmitted protons with the detector substance (the “device” function) and accelerator technology limitations. The respective impacts of these reasons are different and may be reduced by means of additional technologies and treatment. One of the methods to improve spatial resolution is to increase the beam energy.

Proton radiography with high energy beam requires full accelerator technique involvement instead of low-energy proton radiography devices, working at tens of MeV energies. The GeV-energy facility

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should include telescopic ion-optical system or proton microscope [4] to obtain the best spatial resolution.

Spatial resolution is of great importance to study both the dynamic processes and static objects. The study of the dynamic processes requires additionally the appropriate temporal resolution. Temporal resolution doesn’t depend on the properties of the microscope. The factors affecting the facility temporal resolution are temporal structure of the beam and temporal characteristics of the registration system (detector).

In this paper the properties of proton microscope and their influence on spatial resolution as well as the peculiarities of the microscope development in the GeV-energy range are described.

2. Peculiarities of proton microscope development
To develop an appropriate ion-optical system serving as proton microscope one should fulfill the following basic principles. Proton microscope should consist of the “forming” part and the “measuring” part, and the target chamber should be placed between them.

The main mission of the “forming” optics is to make an effective illumination of the target (or the object under investigation) with possible intensity profile uniformity. The mission of the “measuring” optics is to form an image corresponding to the object studied at the plane of registration (detector plane). Note that in proton imaging experiments typically the radiochromic film (one or more) is used as a detector, placed in the plane of the image. The detector placement with respect to the object position corresponds to the optical system magnification.

One of the possible proton microscope schemes is shown in Figure 1, where the magnetic quadrupole lenses in triplet configuration serve as a “forming” microscope part, and four magnetic quadrupole lenses in “Russian quadruplet” configuration serve as a “measuring” part.

To operate high energy proton beam the microscope scheme should consist of quadrupole magnetic lenses, providing the sufficient dynamic aperture to decrease the possibility of the image distortion.

The optical scheme of the proton microscope should be based on electromagnetic lenses. The microscope based on the electromagnetic lenses has flexible tuning and is easily operated in contrast with the scheme based on permanent magnets. The ion-optical system built on the basis of electromagnetic lenses has the highest long-term stability. Such a scheme doesn’t require the mechanical displacement of the optical elements to tune the optics for the specific object, so it avoids the probable element shifts, turns and following optics mismatches, hence it doesn’t require the additional time during the experiment or before it for the mismatch elimination. Such a scheme does not require the replacement of the lenses caused by the lens parameter degradation under the radiation exposure during the long period due to the easy tuning ability. In contrast, the scheme based on the permanent magnets requires lens re-magnetization after a rather short operation time. Recent investigations have demonstrated that strong-field permanent magnets of pRad microscope are significantly degraded in a short time [5]. It was found that under the exposure of equivalent dose of $10^{14}$ protons the decrease of the field level achieves up to 20%. Besides the level diminution the field shape became distorted with significant deviation from the linear character. In addition, the field inside the permanent quadrupole lenses became significantly asymmetric, that may be caused by the specific lens construction and the technological principle of its manufacturing. In the case of the proton microscope the lens field nonlinearity appeared not to be a dominant or even significant factor deteriorating the image. The dominant factor is the field diminution leading to the optical system focus displacement and requiring the perpetual tuning. This is a strong reason to avoid the permanent magnet application for the aims of radiography facility development.

Let us consider the possible optical solutions for GeV-energy proton microscopy based on electromagnetic lenses. The first scheme proposed has the “forming” part that consists of the quadrupole lenses in triplet configuration. The “measuring” part consists of four electromagnet quadrupoles in configuration called “Russian quadruplet” [6]. Such quadruplet configuration has reflection symmetry and allows the same particle excursion in both transverse coordinate planes. It is a preferable optical scheme for such a telescopic system. The layout of the scheme is shown in Figure 1.
The simulation of the scheme in the case of the beam with 1 GeV-energy was carried out with the help of G4Beamline [7]. In Figure 2 the particle trajectories are presented. Some scheme elements such as the microscope entrance window, the target chamber, the collimators as well as the virtual detectors are illustrated on probation, without their real dimensions, to simplify the illustration.

The scheme simulated has the “measuring” part with magnification coefficient equal approximately to “4”.

![Figure 1. Microscope with the “forming” triplet and the “measuring” Russian quadruplet.](image1)

![Figure 2. Particle trajectories for a beam with 1 GeV-energy simulated in the case of the scheme “triplet + Russian quadruplet”.](image2)

The geometry of the beamline depends on the initial experiment conditions, such as the delivered beam energy, the accessible length of the beamline or the accessible experimental area dimension, the size of the chamber which must contain the investigated object. The microscope design depends on the costs too, which affect the choice of the accessible lenses.

![Figure 3. Microscope with the “forming” doublet and the “measuring” quadruplet.](image3)

![Figure 4. Particle trajectories for a beam with 9 GeV-energy simulated in the case of the scheme “doublet + quadruplet”.](image4)

In Figure 3 another microscope scheme is presented. The scheme consists of the “forming” doublet and the “measuring” quadruplet [8]. Figure 4 corresponds to the case of 9 GeV energy beam simulation for the scheme illustrated in Figure 3. In this case the microscope with magnification coefficient “-1” is realized.

To simulate the beam dynamics in both the schemes the same initial beam parameters are considered. The following parameters are used during the calculation: the beam divergence at the entrance window of the microscope 5 mrad, the beam normalized rms emittances $32 \pi$ mm mrad and $11 \pi$ mm mrad for horizontal and vertical plane respectively, the beam momentum spread 1%, the beam intensity $10^7$ ppb, the beam size at the entrance of the microscope 3-10 mm.

Spatial resolution of the schemes is estimated with the help of the sharp-edge method and is used for the scheme optimization. The best spatial resolution in the cases considered above corresponds to second scheme.

Generally, the coefficient of the microscope magnification should be chosen proceeding from the basic experiment conditions, namely the accessible lens parameters and the accessible experimental area size. The increase of the coefficient improves the resolution in whole [4], but it is a subject of

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careful choice to satisfy all the requirements of the task. In any case, the results of preliminary calculations [8] have shown the possibility to obtain the scheme spatial resolution not worse than 10 μm in the case of the magnification coefficient “-1”.

The significant factor which affects the effectiveness of the microscope scheme is the angular acceptance of the system, so the shortest systems have the best spatial resolution under the same conditions. The angular acceptance is an important factor for the “forming” part of the scheme too, because it affects the microscope field-of-view.

Finally, let us estimate qualitatively the influence of the general task parameters on the image blur. The image distortion caused by the proton multi-scattering in the object may be characterized by the expression $\sigma \sim l^{3/2} / p$, where $\sigma$ is the dispersion, $l$ – the length of the object investigated in the direction of the beam inlet, $p$ – the beam momentum. The distortion caused by the chromatic aberrations of the microscope may be presented as $\sigma \sim (l / p^3)^{1/2}$, and the blur caused by the processes inside the detector may be characterized as $\sigma \sim l_{det}^{1/2} / p$, where $l_{det}$ – is the conditional “depth” of the detector. While fixing the distortions, caused by the Coulomb and nuclear scattering inside the object and in the detector, the external factors defining the image blurring are the beam energy and the size of the object studied. While the beam energy fixed, the best spatial resolution could be achieved for the microscope scheme with minimum chromatic length.

3. Conclusions

The applicability of proton radiography for the aims of the study of matter depends on the facility resolution. Spatial facility resolution is improving with increasing beam energy, so GeV-energy range is preferable to study dense objects and fast dynamic processes, and particularly the matter extreme states. Proton microscope is needed to operate the high energy beam for the object image creation. The microscope should be built with quadrupole electromagnets and consist of an “illuminating” or “forming” part and a “measuring” part. The microscope significantly contributes to the spatial resolution limitation. To avoid the image errors caused by the optical scheme the microscope should be carefully designed. Depending on the specific experimental conditions one should choose the ion-optical scheme with admissible highest angular acceptance, appropriate dynamic aperture, reflection symmetry of the “measuring” optics and minimum chromatic length.

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