The detector for the PRIOR proton microscope

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Abstract

While the idea to use charged particles for radiography is known since 1960's, the technique was not widely used because scattering in the radiographed sample caused a substantial image blur. A way to overcome this blur was discovered in the 90's at the Los Alamos National Laboratory by using a set of magnetic quadrupole lenses to image the object on the detector, and to correct chromatic aberrations.

Based on this experience, the proton microscope PRIOR (Proton Microscope for FAIR) is currently under construction at GSI. Its spatial resolution of less than 10 μm will by far exceed the capabilities of other proton radiography systems available at LANL (Los Alamos) and ITEP (Moscow).

Here we present a first design of the designated detector system for future dynamic experiments with PRIOR, which consists of a scintillator screen and a high resolution CCD camera. Geant4 Monte Carlo simulations have been carried out for optimizing the detector performance.

Challenges in Proton Radiography

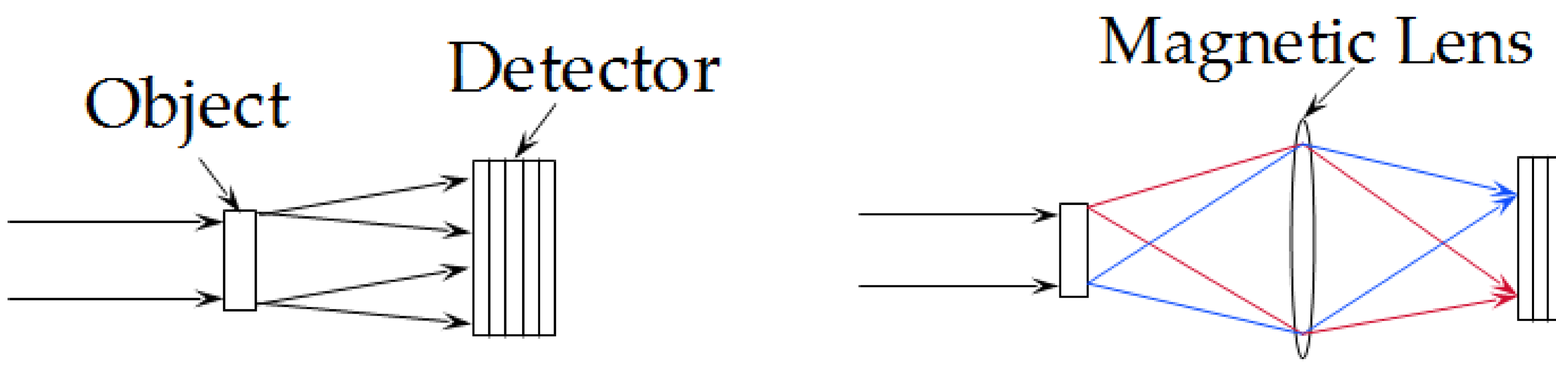

FIGURE 1: The principle of proton radiography. the left image shows a basic setup with a proton beam irradiating a target. Behind the target, the scattered protons are detected on a scintillator screen. This method has one major disadvantage: The Multiple Coulomb Scattering (MCS) within the object causes a substantial image blurring. As pointed out on the right side, this can be overcome by using a magnetic lens to correct the chromatic aberrations, similar as it is done in optics.

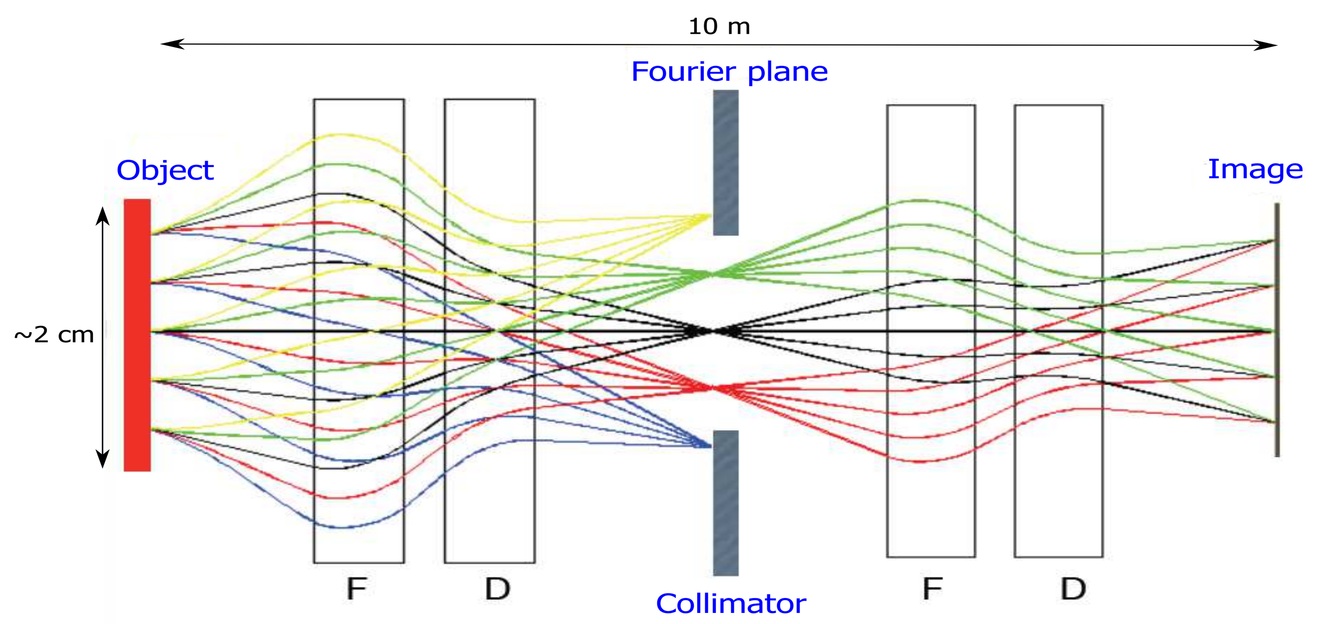

FIGURE 2: Using a set of four matched magnetic quadrupole lenses (Q1-Q4), it is possible to correct the blurring caused by MCS and even magnify the image. In the fourier plane between Q2 and Q3 a collimator can be added as an additional filter for protons with a large scattering angle. The resulting system is called a proton microscope and was first developed in the Los Alamos National Laboratory in the 90's to study dynamic material properties under extreme pressures.

The PRIOR setup

Currently PRIOR is under construction at the HHT experimental area at GSI. It is designed to provide a unique setup with a high spatial resolution (less than 10 μm), a high time resolution ($\sim$10 ns) and a magnification factor of 4.5.

The protons will be provided by the GSI SIS-18 with a maximum energy of 4.5 GeV and up to 5×10^{10} protons per pulse.

FIGURE 3: The setup for the four magnetic quadrupoles as designed for PRIOR. Each magnet has a pole tip field of 1.8 T. They are mounted on high precision adjustment stages to align the magnets to the beam axis.

Requirements for a scintillator

Scintillators are known since quite a long time. Today there are dozens of different types used in research (plastic, liquid, crystals, etc.). They all have their specific advantages and disadvantages. For the PRIOR detector there are several important aspects a scintillator has to fulfill:

- high light yield (for high energy protons)
- fast decay time (regarding the proton pulse structure provided by the accelerator)
- high spatial resolution ($\sim$ 10 μm)
- radiation hardness for GeV protons

A common scintillator material in proton radiography is LSO (cerium-doped lutetium oxyorthosilicate), which is a good compromise concerning all these factors. Its fast decay time of 47 ns (compared to most other crystals) is in the range of a typical pulse length of the proton beam used for PRIOR. A quite new material, YaP, has an even faster decay time of 27 ns and still fulfills the other criteria, but is hard to handle due to its mechanical an optical properties. For the first non-dynamic experiments with PRIOR also the widely used CsI is a possibility.

The scintillation light is then reflected away from the beam axis in order to preserve the fast CCD camera used for the observation of the screen from radiation damage. Gating the detector makes it possible to achieve a high time resolution by selecting a single proton bunch from the SIS-18 (typical pulse length $\sim$50 ns).

TABLE 1: A list of possible scintillators. CsI is a relatively cheap possibility for non-dynamic experiments, that do not require a good time resolution. YaP is a new alternative currently under investigation. A typical plastic scintillator (BC-408) is listed for comparison. Its lack of radiation hardness would make it necessary to exchange the scintillator very often.

Material	Decay Time [ns]	Light Yield [Ph/MeV]	Density [g/cm^3]	LY·Density [10^3·Ph/MeV·g/cm^3]	Radiation hardness
CsI:Tl	1000	54.000	4.51	243.5	✓
LSO:Ce	47	25.000	7.40	176.0	✓
YaP:Ce	27	15.200	5.37	81.6	✓
BC-408 (plastic)	2.1	10.500	1.03	10.8	×

Estimates on the spatial resolution

As information about the achievable spatial resolution or the point spread function (PSF) of scintillator materials are rare and defining the parameters for 4.5 GeV protons in an experiment is extensive, the Geant4 Monte Carlo simulation toolkit has been used to simulate this. We tested different configurations for the scintillator crystal by variing the thickness and the surface parameters.

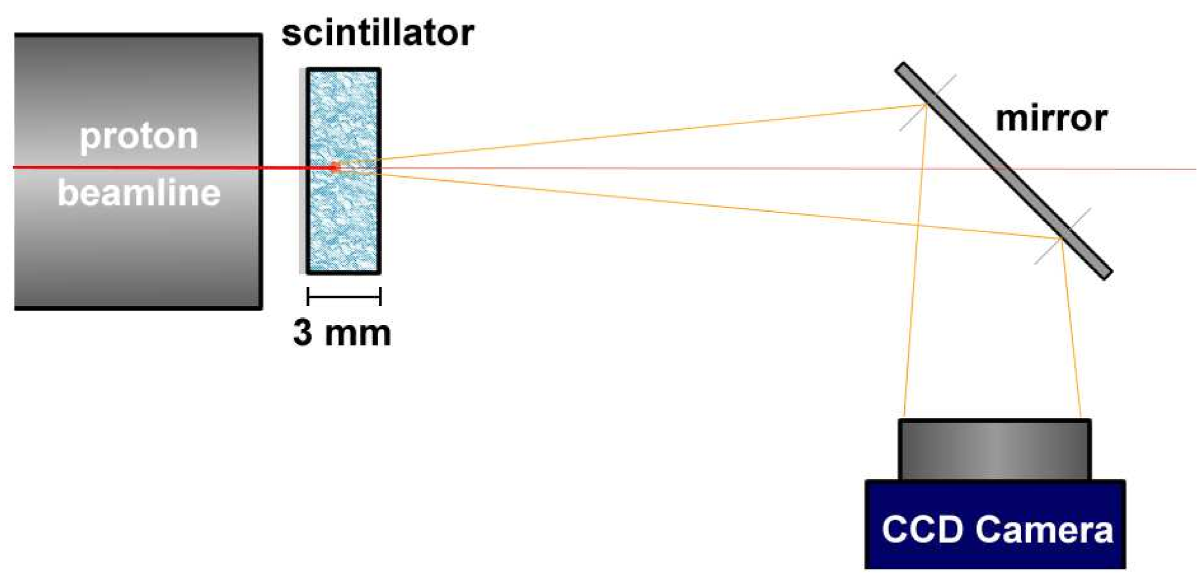

FIGURE 4: The detector geometry. the protons hit the scintillator mounted at the end of the beamline. The scintillation photons leave the crystal and are reflected away from the beam direction by a mirror to a CCD camera. For the simulations below the assumed maximum exit angle is 10°, which is realistic for a camera positioned around 40 cm away from the scintillator. Photons with a wider exit angle do not hit the camera. This influences the PSF because the crystals surface is not assumed to be perfectly polished and the thickness of the crystal itself causes a spread.

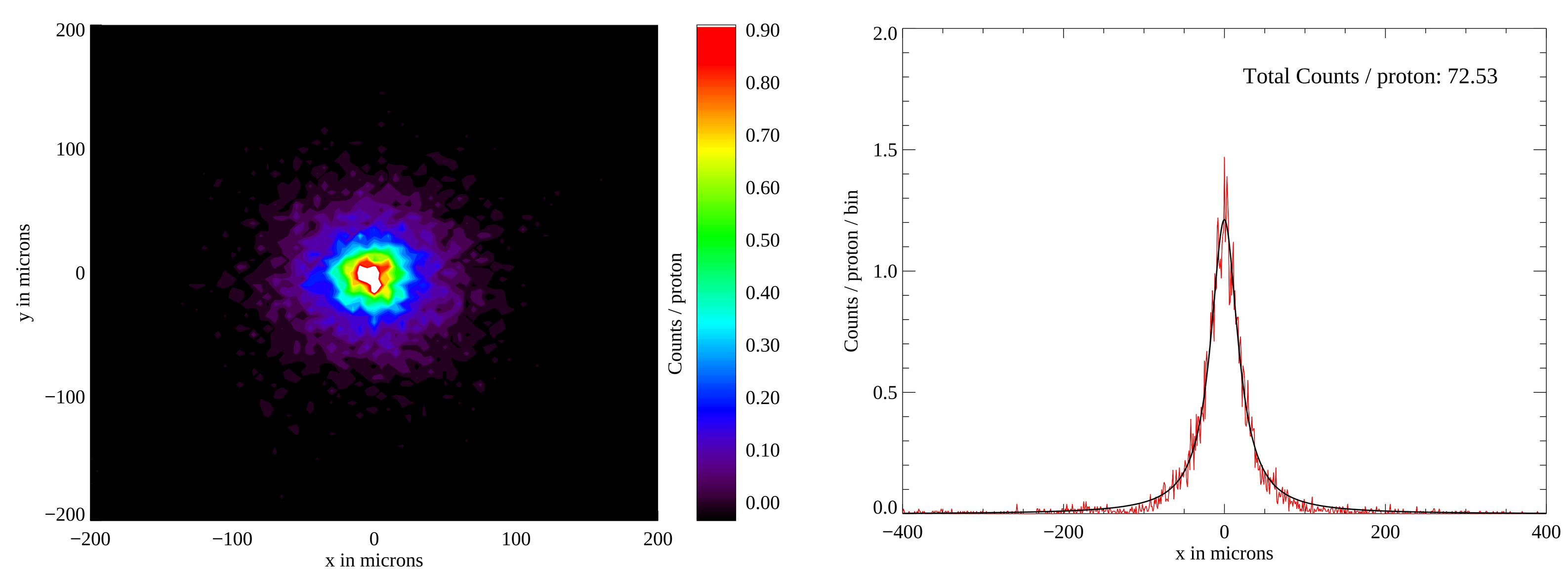

FIGURE 5: Left: View on the X-Y-plane of a simulated 3mm thick LaBr scintillator without any cover on the back side. Right: Spot size for a single proton in x-direction. The red points are simulated data, the black line is a Gaussian fit. The FWHM is 41 μm which is quite acceptable to achieve the goal of a 10 μm spatial resolution for the radiograph (considering the magnification).

For the simulations above, the camera itself is not considered as a limiting factor for the spatial resolution. This has to be included when the final parameters are known. Currently the development of a full Monte Carlo simulation of the whole microscope is also in progress.

Further quality tests

The maximum achievable resolution ist not only limited by the PSF of a single proton in an ideal crystal. Impurities, bubbles, cracks or a not perfectly polished surface can also have an influence. Depending on the conditions during the crystal growing process these can vary from producer to producer and thus have to be tested.

Ideally this could be done with a proton beam similar as in the final proton radiography experiment, but since beamtime is very limited it can only be done in offline experiments.

One diagnostic tool is a Schlieren setup which might provide the possibility to discover stresses and cracks in the crystal by the change of refractive index. Another option is the usage of a x-ray source to excite the scintillation process itself instead of looking at the transmission of visible light.

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