Commissioning of the PRIOR prototype*

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PRIOR (*Proton Microscope for FAIR*) is one of the three frameworks proposed by the HEDgeHOB collaboration for the future experiments at FAIR. This worldwide unique high-energy proton microscopy (HEPM) facility will be integrated into the HEDgeHOB SIS-100 beam line and employ high-energy $(3 - 10\,\mathrm{GeV})$, high-intensity $(2.5 \cdot 10^{13}\,\mathrm{ppp})$ proton beams for fascinating multidisciplinary research such as experiments on fundamental properties of materials in extreme dynamic environments generated by external drivers (pulsed power generators, high-energy lasers, gas guns or explosive-driven generators) prominent for materials research and high energy density physics as well as the PaNTERA (*Proton Therapy and Radiography*) experiment, with a great relevance to biophysics and medicine.

Recently, as a result of the international effort of a team of scientists from GSI, LANL, ITEP and TUD a PRIOR prototype has been designed, constructed and commissioned at the HHT area of GSI (Fig. 1 (left)). The PRIOR prototype employs high-gradient NdFeB permanent magnet quadrupole (PMQ) lenses developed by ITEP and provides a magnification of $\approx 4 - 5$ with a field of view of $\approx 15\,\mathrm{mm}$.

Figure 1: The PRIOR prototype PMQ lenses (left) and the pulsed power setup — four high-current generators placed around a small explosion chamber (right) followed by the four PRIOR lenses installed at the HHT area of GSI.

The detector (image collection) system developed by LANL was installed in the newly constructed concrete-shielded detector room $\approx 9\,\mathrm{m}$ downstream the target location. With a pellicle / mirror arrangement, the system employs two cameras simultaneously: a high resolution (4 Mp) CMOS camera (PCO DIMAX HS) used mainly for static experiments and a fast intensified CCD camera (PCO DICAM PRO) for dynamic measurements. $10 \times 10\,\mathrm{cm}$ columnar CsI and plastic BC-400 scintillators were installed for static and for dynamic measurements, respectively.

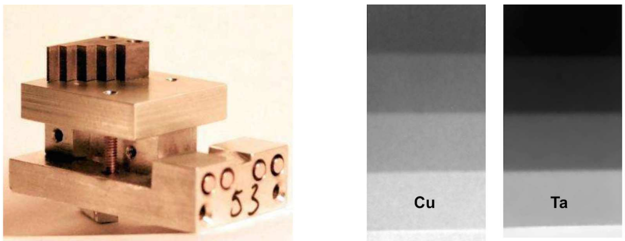

Figure 2: Tantalum step wedge object on a target table (left) and PRIOR proton radiographs (right) of the identical copper and tantalum step wedges $(0.56, 2.06, 4.07$ and $6.05\,\mathrm{mm}$ step thicknesses).

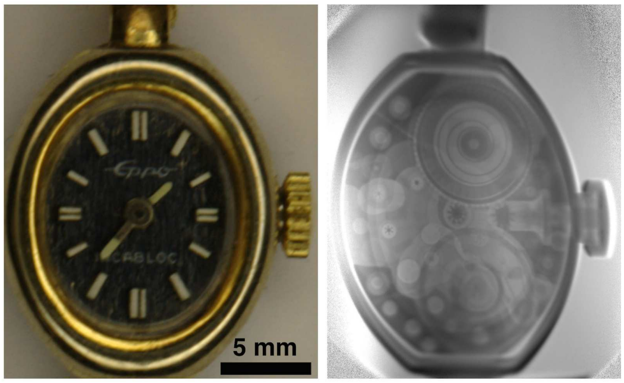

Figure 3: A small women mechanical wrist watch (left) and its proton radiograph (right) obtained with the PRIOR prototype using a 3.6 GeV SIS-18 proton beam at GSI.

In April 2014, an experimental campaign for the commissioning of the PRIOR prototype employing $3.5 - 4.5\,\mathrm{GeV}$, moderate $(10^8 - 10^9\,\mathrm{ppp})$ intensity proton beams from the SIS-18 synchrotron took place at GSI. In these experiments a large set of small static objects including step wedges (Fig. 2) and sets of wires made of different metals, resolution and matching tuning targets as well as some fancy objects (Figs. 3 and 4) were used in a vacuum target chamber equipped with a 6-axis manipulator. As a result of these experiments, an rms spatial resolution of the prototype of about $30\,\mu m$ with a remarkable density sensitivity has been demonstrated. It has also been shown that with

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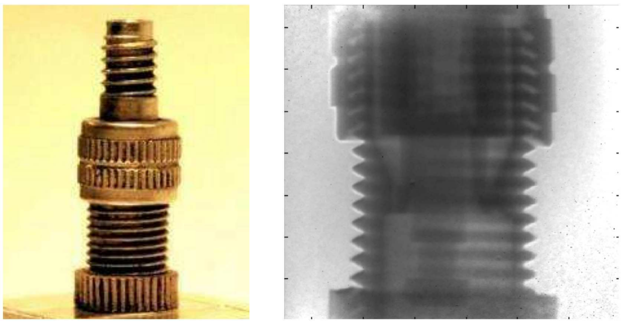

Figure 4: A presta valve from a bicycle inner tube (left) and a PRIOR proton radiograph of its central part (right). One can clearly see the engagement of the threads as well as the valve stem and the details of how this valve is seated.

a sufficient proton beam intensity ($10^{10} - 10^{11}\,\mathrm{ppp}$) and by using a fast plastic scintillator in the detector system, one can achieve $10\,\mathrm{ns}$ or better temporal resolution without significant degradation of the imaging properties.

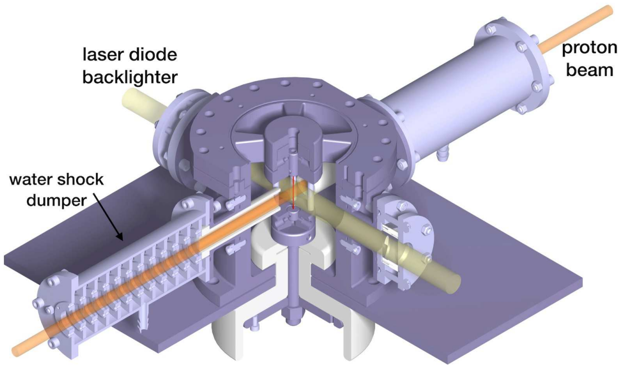

Figure 5: UEWE water filled target chamber. A thin exploding wire (red) in the center of the chamber is illuminated from one side by a proton beam for HEPM measurements, and from the other side — by an optical backlighter for shadowgraphy diagnostics.

For the dynamic commissioning of the PRIOR prototype, a new pulsed power generator had been developed by Technion and GSI (see Fig. 1 (right)). This generator (up to $50\,\mathrm{kV}$, $12.5\,\mathrm{kJ}$ stored energy) was designed to generate warm dense matter states of various metals by underwater electric wire explosions (UEWE) for equation of state studies. A metallic wire ($30 - 50\,\mathrm{mm}$ length, $0.1 - 1\,\mathrm{mm}$ diameter) is placed in the middle of a $\approx 11\,\mathrm{cm}$ diameter explosion chamber (Fig. 5). The wire is quickly heated by a pulsed electric current ($\approx 200\,\mathrm{kA}$, $1.5 - 2\,\mu\mathrm{s}$ rise time) to a dense plasma conditions with about $2 - 3\,\mathrm{eV}$ temperature.

In addition to the HEPM measurements with the PRIOR prototype, an optical shadowgraphy setup consisting of a 450-nm, 4-W fiber-coupled laser diode backlighter, two fast intensified CCD cameras and a streak camera has been installed for target diagnostics. A special effort has been taken to design water shock dumpers in order to minimize the amount of material used to separate the UEWE explosion chamber and the vacuum ($10^{-3}\,\mathrm{mbar}$) PRIOR beam line as well as the water layer thickness in the proton beam direction (see Fig. 5).

In July 2014, a new experimental campaign aiming commissioning of the PRIOR prototype for dynamic experiments took place at GSI. In comparison with the April 2014 run, the proton beam intensity has been increased by more than two orders of magnitude (up to 10^{11} protons per pulse) and a new beam diagnostics for high energy protons (scintillator screens and cameras) has been integrated into the HHT beam line to ensure a good beam alignment and matching.

The dynamic PRIOR experiments have been carried out using the developed UEWE setup. In these experiments, a pulsed current ($\approx 40\,\mathrm{MA/cm^2}$, $5\,\mathrm{GW}$ deposited power) run through a tantalum wire ($0.8\,\mathrm{mm}$ diameter and $40 - 50\,\mathrm{mm}$ length) generating this way warm dense matter states characterized by specific energy deposition level about $10\,\mathrm{kJ/g}$ and $\sim\mathrm{km/s}$ expansion velocities. An example of the proton radiography measurements of an exploding tantalum wire in shown in Fig. 6. In total, about twelve successful dynamic shots with the PRIOR prototype has been made. In these shots, we have varied the power deposited in the $0.8\,\mathrm{mm}$ Ta wires as well as the time moment of the proton radiography imaging. The obtained data is currently being processed and analyzed.

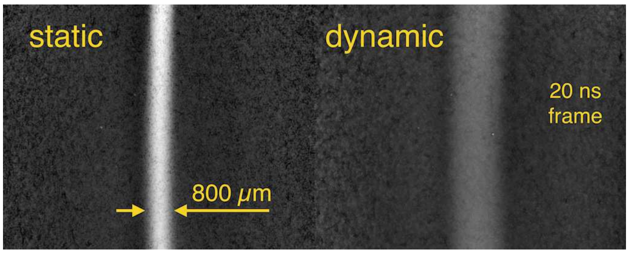

Figure 6: Proton radiographs (20 ns temporal resolution) of a tantalum wire in water before shot (left) and during the explosion (right) driven by the UEWE generator ($\approx 10\,\mathrm{kJ/g}$ specific energy deposition in Ta).

As an unexpected result of the commissioning experiments, we have observed a considerable image degradation caused by the radiation damage of the PMQ lenses (the reduction of the quadrupole strength and increased high-order multipole components) due to large fluences of spallation neutrons which are mainly produced in the tungsten beam collimator located in a close proximity to these permanent magnets. We have also performed special measurements and simulations to study this phenomenon. For the future applications of the PRIOR magnifier at FAIR where much higher proton beam intensities are expected we suggest to either consider using the samarium-cobalt (SmCo) PMQ lenses or, better, to design and employ high-gradient small-aperture radiation-resistant warm electromagnets. The corresponding design study on the final construction of PRIOR for experiments at FAIR has been started.

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