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Directional-sensitive wide field-of-view monitoring of high-intensity proton beams by spectral tracking of scattered particles with scattering foil and miniaturized radiation camera

C. Granja^{a,*}, R. Uhlir^b, D. Poklop^{b,c}, P. Alexa^b, V. Zach^c, C. Oancea^a and L. Marek^a

^aAdvacam, U Pergamenky 12, 170 00, Prague 7, Czech Republic

^bVSB-Technical University of Ostrava, 708 00, Ostrava, Czech Republic

^cNuclear Physics Institute, Czech Academy of Sciences, 250 68, Rez near Prague, Czech Republic

E-mail: carlos.granja@advacam.cz

ABSTRACT: Monitoring and characterization of particle beams in wide-range is often necessary in research and many applications with particle accelerators. The quantitative measurement and evaluation of composition especially of high-intensity beams are limited and can become a challenge with conventional methods especially with simplified instrumentation for ease of deployment. For this purpose, we developed a novel technique based on high-resolution spectral-sensitive tracking of single particles scattered from the beam path by a thin foil. We use a compact radiation camera equipped with the semiconductor pixel detector Timepix3 together with dedicated Monte-Carlo simulations. Particle-event type discrimination and directional information are produced by the detector spectral-tracking response together with particle-type resolving power derived from experimental calibrations. Directional- and spectral-sensitive components can be resolved in wide field-of-view. Quantification of the primary beam intensity is extrapolated by numerical calculations. Demonstration and evaluation of the technique are provided by measurements with 33 MeV protons from a light ion cyclotron accelerator. Scattered particles originating from the thin foil, the accelerator beam nozzle, and the air space along the beam path are detected and evaluated.

KEYWORDS: Beam-line instrumentation (beam position and profile monitors, beam-intensity monitors, bunch length monitors); Particle tracking detectors (Solid-state detectors); Instrumentation for particle accelerators and storage rings - low energy (linear accelerators, cyclotrons, electrostatic accelerators); Models and simulations

*Corresponding author.

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1 Motivation, aims

Measurement, characterization and monitoring of delivered particle beams by particle accelerators [1–3] are valuable and often necessary for operation of the facilities and their use in a broad range of applications from basic research (nuclear and high-energy physics) to applied research such as particle radiotherapy. Particle beams are usually produced with high beam intensities ($> \text{nA}$) which can be directly monitored by conventional beam monitors such as current-integrating devices and gas-based detectors [1]. These devices provide namely the integrated beam current intensity and time profile with limited information on beam composition, beam size and directionality including beam divergence. When the beam intensity may be significantly decreased, quantitative and more complete information can be provided by placing an imaging detector directly on the beam path. Detailed and high-spatial resolution information on the beam can be thus directly measured for example on particle micro-beams [4].

For high-intensity beams however, positioning an active high-sensitive imaging detector on the beam path is no longer feasible. In this case, other systems, of limited resolution, are used such as gas-based detectors [2]. Alternatively, we make use of a thin scattering foil to detect the scattered beam particles by a high-resolution detector placed away from the primary beam axis. We examine and analyze the scattered particles in detail with spectral-sensitive tracking response in wide field-of-view (FoV). This is made possible by use of the pixel detector Timepix3 [5] assembled as a compact radiation camera [6] which can be easily placed in arbitrary proximity to the foil and safely away from the primary beam axis.

For the quantitative evaluation of the particle scattering yield and derivation of primary beam flux, we make use of dedicated Monte-Carlo (MC) simulations. Such numerical calculations can valuably provide the probability or flux normalization factors between the scattered protons experimentally

detected and the primary beam intensity. Moreover, the detector resolving power enables to selectively analyze spectral-tracking particle groups associated to the directional location of interaction — at the scattering foil but also at the accelerator beam exit nozzle. The simulations also provide information on the composition and energy spectrum of the beam particles across the foil and beam path which help to evaluate the experimental results.

2 Rutherford scattering

Rutherford scattering is the elastic scattering of charged particles, in our case protons, by the Coulomb interaction with target nuclei [7]. It represents the dominant interaction channel on the selected configuration (thin tantalum foil). The use of a high-density material minimizes the change of direction and the energy spread of the scattered proton. Its differential cross section $d\sigma/d\Omega$ depends on the proton incident kinetic energy E_k according to the formula

$$\frac{d\sigma}{d\Omega} = \left(\frac{Ze^2}{16\pi\epsilon_0 E_k} \right)^2 \cdot \frac{1}{\sin^4 \frac{\theta}{2}},$$

where Z is the proton number of the target nuclei, e the proton charge, ϵ_0 the vacuum permittivity and θ the proton scattering angle. The probability p that a proton from the proton beam scatters on the tantalum foil and arrives to the detector position can be estimated as

$$p = nd \frac{d\sigma}{d\Omega} \frac{\Delta S \cos \varphi}{r^2},$$

where n is the density number of atoms in the target foil (tantalum), d is the target thickness, ΔS is the detector area, φ is the angle between the normal to the detector area and the direction of the scattered proton and r is the distance between the center of the foil and the center of the detector surface. Because the protons interact and lose energy along their path through the foil volume, the differential cross section of the Rutherford scattering increases with the penetration depth. In the simulation we have to divide the target into a set of thin layers of $1 \mu\text{m}$ equal thickness d_0 to take this effect into account. The proton kinetic energy E_{ki} in the i -th layer is calculated with the SRIM code [8]. The formula for the probability p then becomes:

$$p = nd_0 \frac{\Delta S \cos \varphi}{r^2} \sum_i \frac{d\sigma}{d\Omega}(E_{ki}).$$

For 33 MeV protons at the experiment performed (section 3.2) the probability p is 1.16×10^{-5} . A more accurate estimate of the probability can be provided by MC simulations (section 5).

3 Instrumentation, experimental setup, measurements

3.1 Miniaturized radiation camera MiniPIX-Timepix3

We use the miniaturized radiation camera MiniPIX-Timepix3 [6] equipped with the Timepix3 ASIC chip [5] bump-bonded to a $500 \mu\text{m}$ thick silicon sensor (figure 1a). The camera operates at room temperature with integrated power, control and data readout enabled via single USB 2.0 connector to standard PC. The integrated cross-platform (Windows, Linux, MacOS) software tool PIXET [9] provides complete control, online response and visualization of the registered particle tracks.

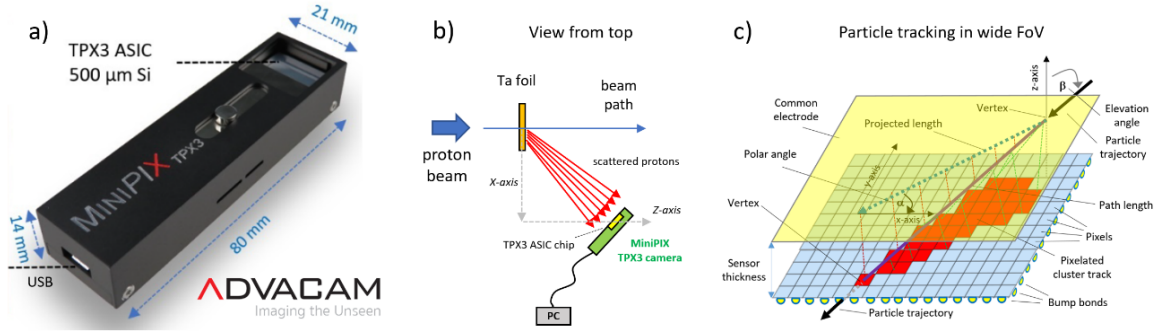


Figure 1. (a) Radiation camera MiniPIX-Timepix3. Reproduced from [6]. © 2022 IOP Publishing Ltd and Sissa Medialab. All rights reserved. (b) Setup geometry for detection of scattered beam particles from a high-Z thin foil placed on the beam axis. The pixel detector is placed away from the beam axis at 45° . (c) Illustration of spectral tracking in wide FoV of a proton in Timepix3. The particle direction is derived in 3D with components along (polar angle α) and perpendicular (elevation angle β) directions to the detector sensor plane.

The detector sensor was fully depleted with an applied bias voltage $+80$ V. The detector was operated in frame mode with acquisition time, and consequent detection live time, of 10 ms. The detector readout deadtime, defined as the time interval following each measured frame, was about 40 ms. The duty cycle was thus 20% with overall frame rate of 20 fps. The Timepix3 pixels were operated in integrated energy (iTOT) and counting (CNT) configuration. Prior to the measurements, the pixel detector was per-pixel energy calibrated using discrete-energy X ray and low-energy gamma rays from radionuclide sources [10].

3.2 Scattering foil, proton cyclotron, high-intensity beam

The process exploited is the Rutherford elastic scattering of protons by a high-density thin foil (section 2). For this purpose, we used a homogeneous and thin (0.86 mm thick) Ta foil which was chosen based on estimate for a relatively high yield of scattered particles, limited energy loss and small change of proton energy at the scattered angle (45°). The foil was placed at 40 cm from the accelerator beam nozzle. The detector was placed in the forward direction at 10 cm transversal and 10 cm along the beam axis (see figure 1b). In addition, the detector-sensor plane was tilted to the direction of the arriving particles in order to enhance the spectral-tracking resolving power [11].

Measurements were performed at the proton/light ion cyclotron U-120M [12] of the NPI-CAS Rez near Prague. We used proton beams of 33 MeV (at the foil position) of varying beam intensity from the $\approx \mu\text{A}$ level down to the $\approx 10^{-2}$ nA level.

4 Detection and spectral-tracking of scattered protons

4.1 Quantum imaging detection and track visualization of single particles

The quantum-imaging detection [13] and spectral-sensitive tracking [11, 14] of single particles with the Timepix3 detector are illustrated in figure 1c. Together these techniques enable to detect single particle, selectively discriminate and analyze in high-resolution the deposited energy and direction of trajectory.

The radiation field registered by Timepix3 at the detector position (figure 1b) is shown in figure 2a. The per-pixel deposited energy is displayed by the color scale. Most of the apparent event pile-ups were recorded as isolated tracks of individual particles. The data are shown integrated over many

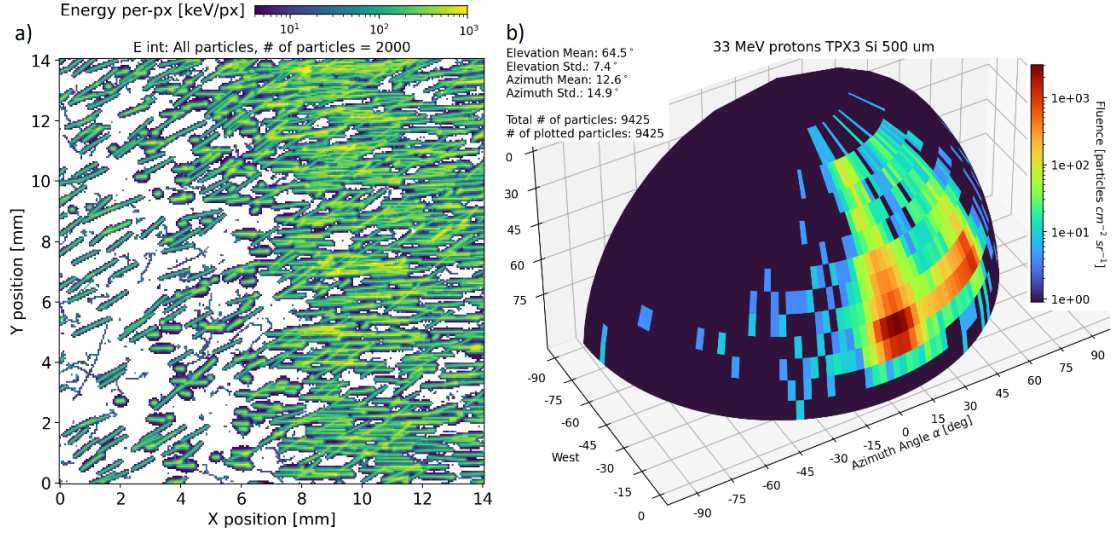


Figure 2. Spectral- and directional-sensitive tracking of scattered 33 MeV protons at the Ta foil measured by Timepix3 at the detector position: (a) Quantum-imaging detection and track visualization of the scattered beam particles by Timepix3. The per-pixel registered deposited energy is displayed by the color bar (log scale). The full detector-sensor matrix is shown = 256×256 pixels = $14.1 \text{ mm} \times 14.1 \text{ mm} = 1.98 \text{ cm}^2$. (b) Angular proton flux displayed in log scale (color bar) as particle directional map in 3D for the data in (a) with a larger set of data processed (40 k events). See text.

frames each of which was collected in a short acquisition time (see below). The measured count rate at the detector position, expressed in terms of particle flux, was $2.08 \times 10^2 \text{ particles} \times \text{cm}^{-2} \times \text{s}^{-1}$.

The loss of events on part of the sensing region (left half) is due to partial shielding by the detector’s casing edge (Al 2 mm thick, see figure 1a). This shielding effectively stops protons of lower energy which scatter on the foil. The beam was incident onto the detector from the left side. The detector-sensor plane was tilted to the beam-foil-detector plane at an angle $\beta = 60^\circ$ (elevation angle). The proton events exhibit distinct signals — large mostly elongated tracks of many pixels.

Figure 2a shows a total of 2000 particle tracks which were collected in 540 frames, each lasting 10 ms, with an integrated live time of 5.4 s. All particles are displayed without any event filtering or selection. Most of the tracks registered (large elongated tracks) are produced by protons which are incident onto the detector from the left and bottom-left directions. Along the sensor plane two directionally distinct proton components are thus resolved: broad straight tracks parallel to the horizontal X axis at $\alpha \approx 0^\circ$ (protons coming from the scattering foil) and at $\alpha \approx 40^\circ$ (protons coming from the accelerator beam nozzle).

4.2 Directional flux of scattered protons

The direction of trajectory of the registered tracks is derived from the morphology of the single particle tracks [11]. The resulting angular flux for the resolved protons incident on the detector is given in figure 2b. The data (9425 proton tracks shown) is displayed as a 3D map. The particle angular flux is displayed by the color bar in log scale. The detector sensor plane is displayed on the horizontal plane over which the track polar angle α is registered. The elevation angle β is displayed by the vertical Z axis. Two distinct directional components are resolved (see also figure 2a) at $\alpha = 0^\circ$, $\beta = 60^\circ$ and $\alpha = 45^\circ$, $\beta = 60^\circ$ which correspond to scattered protons from the Ta foil and from the accelerator beam nozzle, respectively.

4.3 Mixed-radiation field decomposition, particle-tracking groups

Particle-event types on the detector are analysed and classified by experimental calibrations in well-defined radiation fields [15] using high-resolution pattern recognition analysis [15, 16] of the pixelated tracks. This serves for decomposition analysis of mixed-radiation fields [17]. Scattered protons can be resolved and selected for further analysis with enhanced discrimination as given in figure 2b (see also section 4.4). For this work, we analysed and resolved several event groups in terms of particle-tracking classes as shown in figure 3.

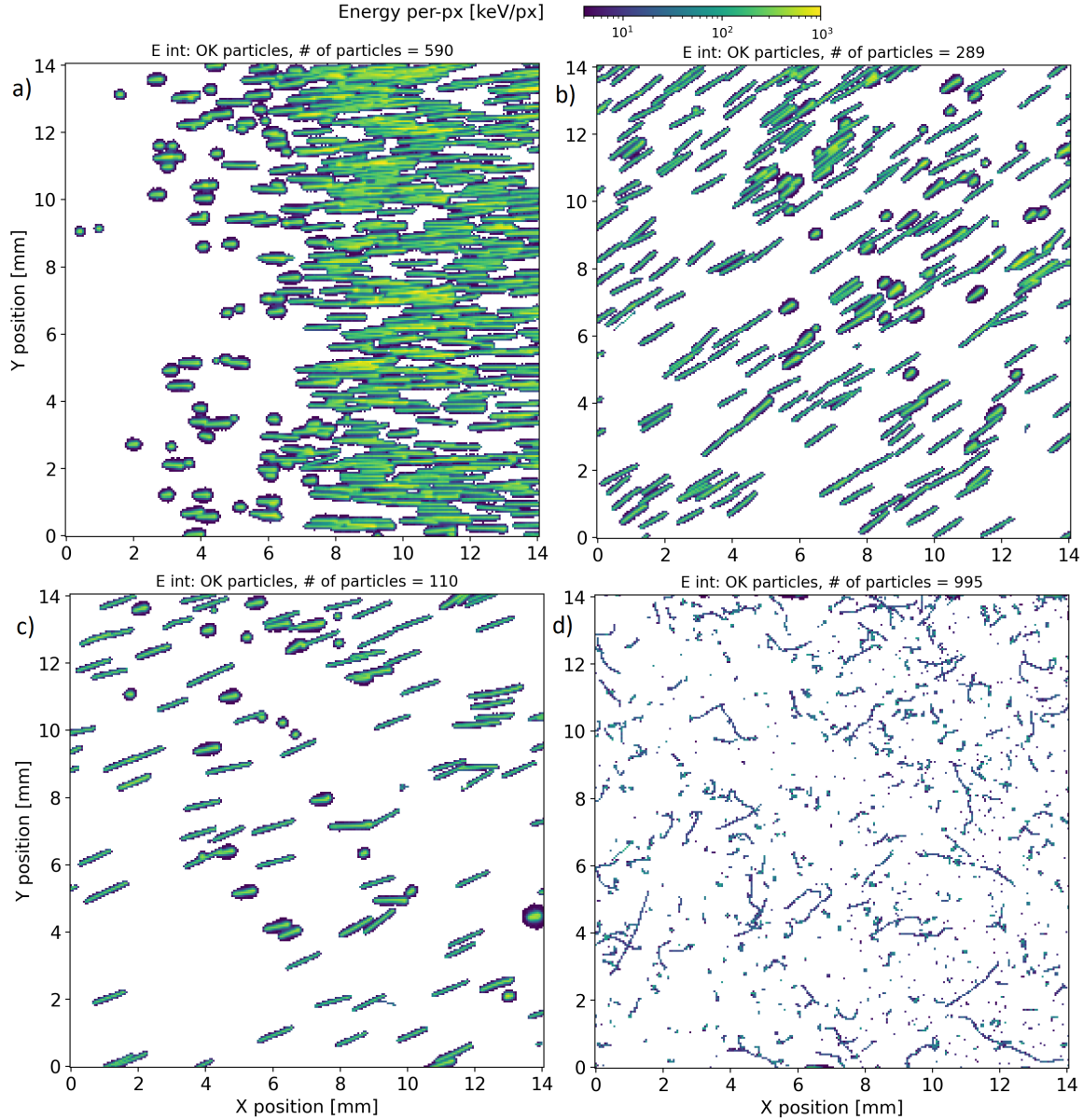


Figure 3. Similar to figure 2a showing the decomposition of the mixed-radiation field into three particle-tracking groups: (a) scattered protons from the Ta foil, (b) scattered protons from the accelerator beam nozzle and (c) scattered protons from the beam path between the beam nozzle and the foil. (d) Unwanted/background tracks produced by secondary radiation such as electrons, X rays and gamma rays.

4.4 Monitoring of scattered protons, event discrimination

The measurement and detailed monitoring at the ms level of scattered protons in terms of particle flux [14] and particle dose rate [13] is given in figure 4. Results can be provided for all particles (black data points) and for particle-tracking groups such as scattered protons at the Ta foil (green data points, see figure 3a) and at the accelerator beam nozzle (blue data points, see figure 3b). Unwanted/background events from secondary electrons, X rays and low-energy gamma rays (red data points, see figure 3d) are included. Resulting mean values and standard deviations are indicated — see values within brackets in the plot label inset.

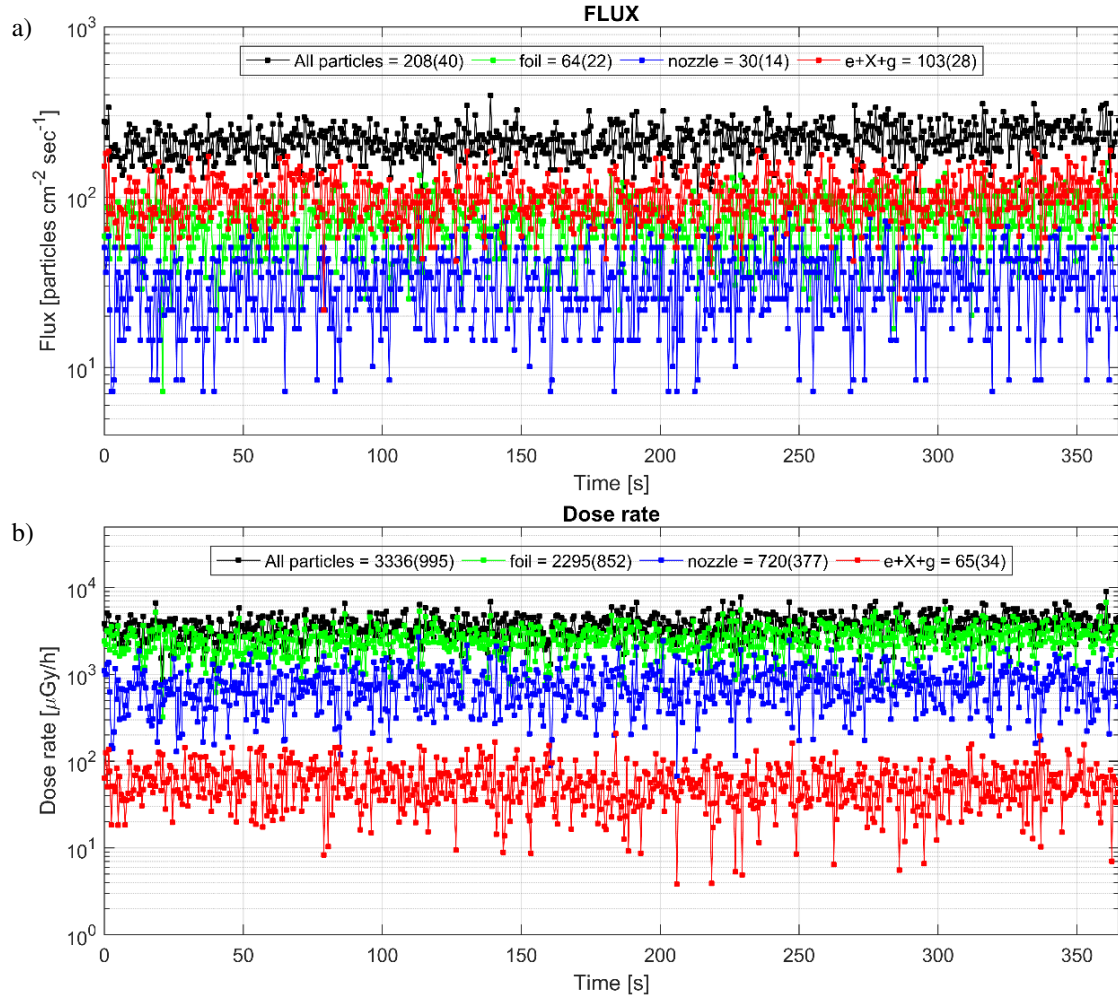


Figure 4. Measured (a) flux and (b) dose rate of scattered 33 MeV protons by Timepix3 at the detector position. Data shown for a 6 min beam delivery interval. Results given for all particles (black data points) and the resolved particle-tracking groups of protons scattered at the foil (green data points) and at the accelerator beam nozzle (blue data points). Unwanted events, produced by secondary and background electrons, X rays and gamma ray are included (red data points).

5 Monte-Carlo simulations

Dedicated MC simulations were performed using the MCNP6.2 code [18, 19] with the ENDF/B-VII.1 nuclear data library [20]. Transported particles were: protons, neutrons, electrons and photons.

Particle physics options on PHYS card were kept default. In the simulation the tantalum foil ($5\text{ cm} \times 5\text{ cm} \times 0.86\text{ mm}$) was irradiated by a homogeneous parallel beam of 33 MeV monoenergetic proton beam with the size diameter of 1 cm. Incoming and outgoing fluxes of protons interacting with the tantalum foil as well as fluxes from the direct beam and from the tantalum-foil scattered protons on the outer surface of the pixel detector were calculated using the tally F2 for selected energy bins (En card). In addition, to track the origin of the incoming protons on the outer surface of the Timepix3 detector angle bins for the tally F2 were applied (Cn card). In the MC simulation a homogeneous Si detector of dimensions as Timepix3 was used and the aluminum detector's casing was taken into account. To achieve plausible relative errors of the total flux in the angle bins (less than 0.5%) a total of 10^9 particle histories were performed.

5.1 Primary beam and scattered proton flux

The MC simulations were used to calculate the flux of protons at the foil position and at the detector position relative to one delivered proton from the accelerator beam nozzle (table 1). Beam straggling and defocusing occur along the proton trajectory between the beam nozzle and the scattering foil (40 cm apart in air), between the foil and the detector (14.1 cm apart in air, see figure 1b) as well as through the foil material and the detector semiconductor sensor. The measured flux at the detector position can be thus extrapolated to derive the delivered beam flux at the accelerator beam nozzle.

Table 1. Probability coefficients of scattered proton flux normalized to one primary beam proton at the accelerator beam nozzle. Coefficients are calculated by MC simulation at various positions. The measured flux (scattered protons) at the detector position is extrapolated to the accelerator primary beam flux at the nozzle position.

<i>Position</i>	<i>Scattered proton flux [$\text{particles} \times \text{cm}^{-2} \times \text{s}^{-1}$] at detector position</i>	<i>Coefficient</i>	<i>Primary beam proton flux [$\text{particles} \times \text{cm}^{-2} \times \text{s}^{-1}$] at beam exit nozzle</i>
entrance surface of Ta foil		4.00×10^{-2}	
exit surface of Ta foil		4.03×10^{-2}	
entrance surface of TPX3	1.05×10^2	2.19×10^{-6}	4.78×10^7
exit surface of TPX3		1.68×10^{-6}	

The measured flux of scattered protons is moreover unfolded into the resolved particle-tracking components which originate selectively at the scattering foil and at the accelerator beam nozzle (section 4.3 and figure 3). The corresponding probability coefficients for the distinct scattered components are correspondingly calculated and selectively related to the primary beam intensity as given in table 2.

Table 2. Similar to table 1 listing the partial probability coefficients for the particle-tracking groups with directional vertex origin at the beam nozzle (blue data curve in figure 4a) and at the scattering foil (green data curve in figure 4a). The measured proton flux for each of the particle-tracking groups can be thus extrapolated to the primary proton beam flux.

<i>Vertex origin of beam protons</i>	<i>Polar angle α [deg]</i>	<i>Proton flux [$\text{particles} \times \text{cm}^{-2} \times \text{s}^{-1}$] at detector position</i>	<i>Coefficient</i>	<i>Proton flux [$\text{particles} \times \text{cm}^{-2} \times \text{s}^{-1}$] at beam exit nozzle</i>
protons scattered by beam nozzle	(25° , 70°)	3.0×10^1	6.32×10^{-7}	4.74×10^7
protons scattered by Ta foil	(-10° , 10°)	6.4×10^1	1.24×10^{-6}	5.25×10^7

5.2 Proton energy spectra, energy loss

The MC simulations were also used to calculate the (kinetic) energy distribution of the delivered and scattered proton beam (figure 5a). Effects of beam straggling and energy loss can be quantified along the particle trajectory. For the 33 MeV protons, the energy loss through the foil is 14 MeV. At the detector position the extended energy spread is reflected by the broad spectral range of the protons tracks registered (see figure 3a). This information is valuable for validation and evaluation of the spectral information measured by the detector such as the deposited energy spectrum of the measured scattered proton field at the detector position (figure 5b).

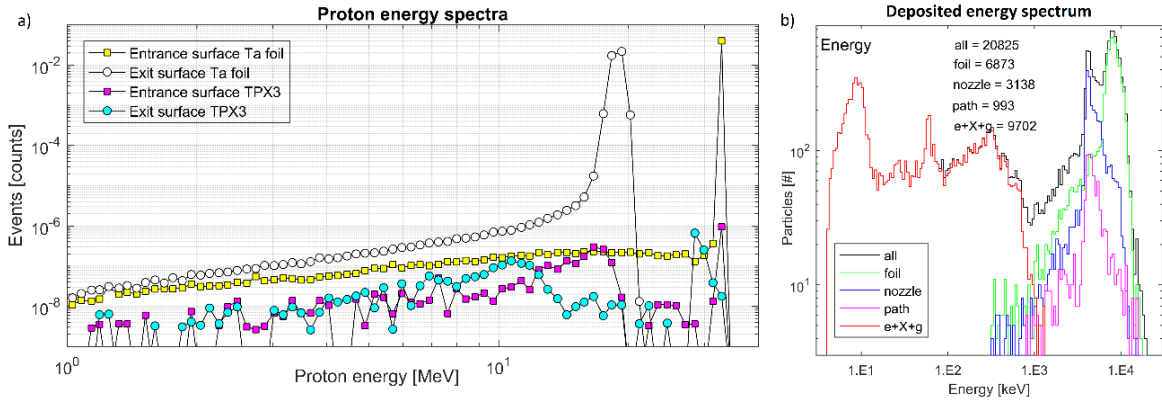


Figure 5. (a) Proton energy spectra calculated by MC simulations at the scattering foil and at the detector sensor. Values normalized to one proton delivered at the accelerator beam nozzle. (b) Deposited energy spectrum measured by Timepix3 at the detector position. Data shown for all particles (black curve) and the resolved particle-tracking components scattered at the foil (green curve), at the beam nozzle (blue curve) and at the beam path in between the foil and nozzle (purple curve). The background component from electrons, X rays and low-energy gamma rays is resolved (red curve). The number of events is included.

6 Conclusions, outlook

The principle of beam monitoring based on detection of scattered beam particles has been demonstrated. Results are provided on experiments performed with proton beams examined with various beam intensities. With the foil thickness used and relatively close detector-foil geometry configuration chosen, best results were achieved with low intensity beams ($< \text{nA}$). For higher beam currents, a thinner foil and greater distance are recommended. The sensitivity and dynamic range of the technique enable to detect and evaluate also particles scattered from the accelerator nozzle and even from the air space along the beam path. The spectral-sensitive tracking response of the detector enable to resolve directionally distinct components which can be correlated to localized positions along the beam path. Together with the detector quantum-imaging response, results and assignments are provided with enhanced discrimination. The spectrally resolved scattered protons can be further analysed to expand the information on the delivered particle beam and tentatively provide a tool sensitive to the energy of the primary beam.

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