Appendix A.3. Out-of-plane beam deflection

A transmission irradiation experiment was performed to ensure that the beam was not deflected out of the film (x-y-) plane by magnetic field components pointing along the y-axis. For this purpose, the phantom was removed and a pixelated scintillation detector with a resolution of 0.5 mm (Lynx, IBA Dosimetry, Schwarzenbruck, Germany) was placed behind the magnet assembly in a distance of 24 cm. As depicted in Extended Data Figure A.9a, the out-of-plane deflection due to the magnetic field was within measurement uncertainty.

The deflection in y-direction observed on the scintillation detector y_{Lynx} is depicted in Extended Data Figure A.9b. We note that, assuming a uniform magnetic flux density $B = 0.95\,\mathrm{T}$ between the magnet poles and no magnetic field outside, y_{Lynx} can be easily approximated by trigonometric considerations from the length of the magnet poles x_{pole} and the distance between the magnet and the scintillation device d_{air} as

$$y_{\mathrm{Lynx}} = r - \sqrt{r^2 - x_{\mathrm{pole}}^2} + \frac{d_{\mathrm{air}}}{\sqrt{r^2 - d_{\mathrm{air}}}}\,. \tag{A.3}$$

Neglecting relativistic effects and beam energy loss in air, the radius of the beam path inside the magnetic field is $r \approx 14.4\frac{\sqrt{E_0}}{B_0}\,\mathrm{T\,cm\,(MeV)^{-\frac{1}{2}}}$, and a function of the initial proton energy E_0 [16]. Values for y_{Lynx} obtained with this approximation for a nominal distance between magnet and detector screen of $d_{\mathrm{air}} = 26\,\mathrm{cm}$ show excellent agreement with the measured positions (see Extended Data, Figure A.9b). The difference of d_{air} to the measured distance between the magnet and the detector can be ascribed to the distance between the active scintillation layer and the detector's surface and the non-uniformity of the magnetic field.

Appendix A.4. Uncertainty estimation

The influence of the measurement uncertainties on the Bragg peak lateral deflection Δy_{80} and range retraction ΔR_{80} was assessed as follows (see Table A.1).

Statistical uncertainties such as the robustness of the ΔR_{80}- and Δy_{80}-determination, and possible remaining displacement of the film relative to the phantom and to the scanner have been assessed by repeating the measurement for 180 MeV three times. Mean absolute deviations were used as statistical uncertainties.

Film-to-film variations and the film calibration are subject to percentual dose uncertainties. The calibration has a relative dose uncertainty of 5 % [28]. Dose uncertainties due to film and scanner variations add up to 0.5 % [29]. Being proportional to the dose, these uncertainties were considered to have negligible