Calibration with water for track-based multiple scattering tomography at the DESY II Test Beam Facility

Tetiana Povar, Taras Shevchenko University of Kyiv, Ukraine

September 4, 2019

Abstract

Track-based multiple scattering tomography is based on the measurement of impact position and kink angles of gigaelectronvolt electrons that pass through objects under study. As a result, this technology allows us to reconstruct the material budget distribution of samples. In this work, corresponding measurement for metallic boxes of different length with distilled water were performed at DESY II Test Beam Facility using electron energies of 1 and 2 GeV. The reconstruction of the electron tracks was carried out with help pixel beam-telescope DATURA. From the measured data the full width at half maximum (FWHM) of the kink angle distributions was calculated for all samples with water. Finally, a calibration with water was obtained as dependence between the thickness of water and the FWHM.

Contents

1. Introduction

Track-based multiple scattering tomography is a new method of material tomography which builds on the measurement of the impact point and deflection angles of gigaelectronvolt electrons that traverse a sample under test. It has significant advantages over other types of tomography such as no restrictions on the type of material. Like any new method, it requires a calibration to accurately determine the thickness of the material under study. The purpose of this work is to calibrate water as a test sample, since water is an important part of living organisms and some materials. This work will serve as an incentive for further research on the possibility of using this tomography method in medicine and industry.

2. Theory

2.1. DESY II Test Beam Facility

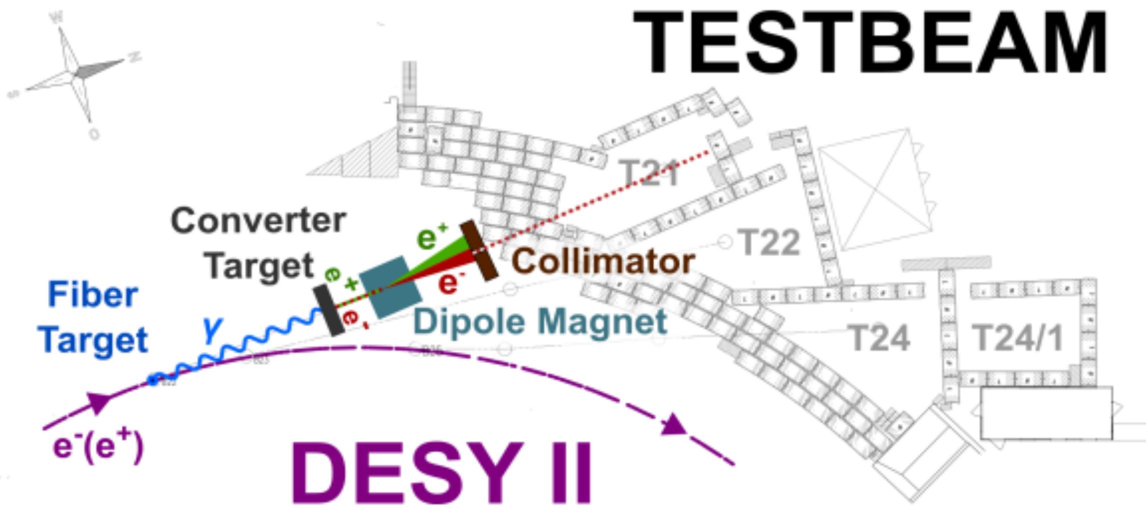


Figure 1: Schematic layout of a Test Beam Facility at DESY

The main purpose for the electron-syncrotron DESY II is acceleration of electrons which are then injected into PETRA III. Their energy reaches up to 6.3 GeV. Also this synchrotron serves as a source for the generation of electrons for four beam areas (T21, T22, T24, T24/1), located in building 27 at DESY [1]. Scientists use those areas for test of detector prototypes and calibration of detector components.

The formation of the electron beam for the test beam areas is as follows. Firstly, bremsstrahlung photons are generated by a carbon fiber in the electron beam that circulates in the ring of the electron-synchrotron DESY II. Then the photons are transformed to electron/positron pairs by a metal plate (converter). The beam of particles enter a variable magnetic field. The final beam is shaped by a collimator which allows particles with certain energy and charge.

2.2. EUDET-type beam telescope

Areas T21 and T22 has been equipped with high-precision pixel beam telescopes for particle tracking.

Figure 2: The DURANTA beam telescope with its sensor planes on aluminium rails.

The EUDET-type beam telescopes consist of six pixel detector planes, where MIMOSA 26 sensors are located, the mechanics for precise positioning of the device under test (DUT) and the telescope planes in the beam, a Trigger Logic Unit (TLU) and a Data Acquisition System (DAQ). The sensors consist of 1152 columns and 576 rows of pixels with size of 18.4 µm × 18.4 µm. This telescope design satisfies the most important requirements of users such as easy integration capabilities, good spatial resolution, and high trigger rates. Such a simple construction of telescope`s planes was created in order to achieve a minimal material budget and to get a good track resolution at the particle energies of up to 6 GeV at the DESY test beam facility [2].

2.3. Track-based multiple scattering tomography

In track-based multiple scattering tomography the reconstruction of material budget distribution is based on the impact point and kink angles of electrons traversing the sample. When electrons pass through the sample, they are scattered off the electric fields of the nuclei. As a result of such multiple scattering, they change the direction of their movement, leading to an effective angular deflection. This angle between the incoming and the outgoing electron and its impact position on the sample are determined by the measurement of the electron's trajectory using pixelated charged-particle sensors before and after the sample (Figure 3).

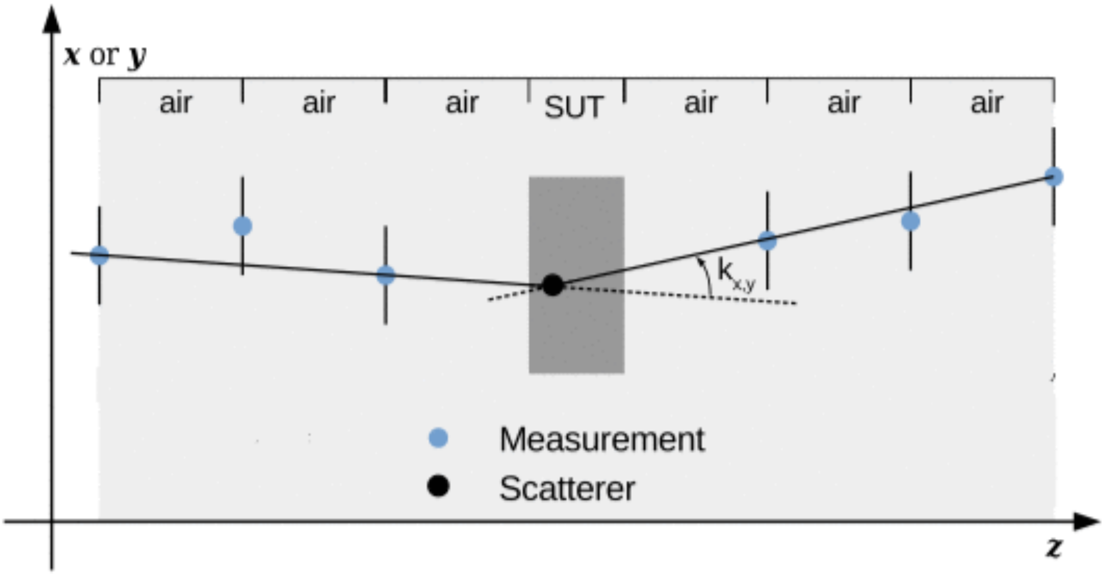


Figure 3: Kink angle between electron`s track before and after sample under test (SUT)

The width of the angular distribution for electrons traversing an object is related to the projected material budget $\varepsilon = \frac{l}{X_0}$, where l is the thickness of objects and X_0 is the radiation length, which is a function of the atomic number.

The angular distribution is approximately Gaussian for small angles but eventually tends to form tail at the ends of the distribution. This effect was well understood by many investigators who worked on multiple scattering but Molière united the Gaussian region with the large-angle region for his theory. Highland proposed simple formula which used as a proxy for Molière theory in the Gaussian approximation.

In Highland's approximation, Θ for a single scatterer ε is calculated [3]:

$$\Theta^2 = \left[\frac{13.6\text{MeV} \cdot z}{\beta \cdot c \cdot p}\right]^2 \cdot \varepsilon \cdot \left[1 + 0.038 \cdot \ln(\varepsilon)\right]^2, \quad (1)$$

where βc , p and z is the velocity, the momentum and the charge number of traversing electrons.

3. Measurement

3.1. Setup

For calibration measurement (Figure 4) 8 metallic boxes were made with the length ranging from 5 to 400 millimeters, which are sealed on both sides with a 125 µm layer of kapton, as samples under test (SUT). A hole was made on top of each box for filling water. The width and height of the box corresponds to the size of the sensor which is 21.2 mm $\times$ 10.6 mm. A thin kapton layer was chosen due to the small contribution of multiple scattering ($\varepsilon = 0.00056$) in it and the strength of the material.

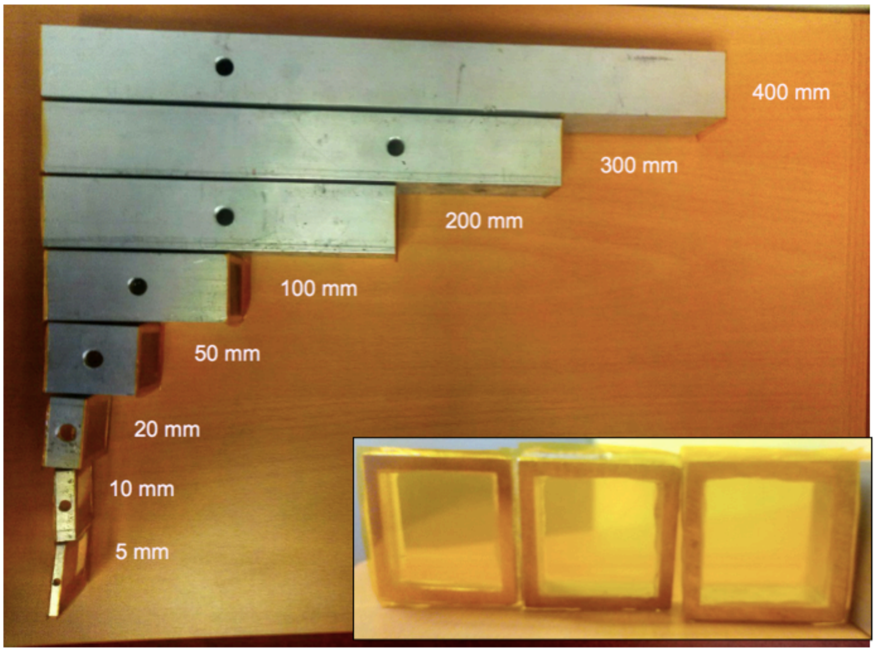


Figure 4: 8 Metallic boxes filled with water.

The setup used in the measurement is shown in Figure 5. A right-handed coordinate system was used with the z-axis along the beam and the y-axis facing down. A configuration of the beam telescope was chosen with different distances between the planes before (dz = 150mm) and after (dz^* = 30 mm) the SUT. The distance between the third plane and the center of the sample was 230 mm and remained unchanged during measurements for all samples.

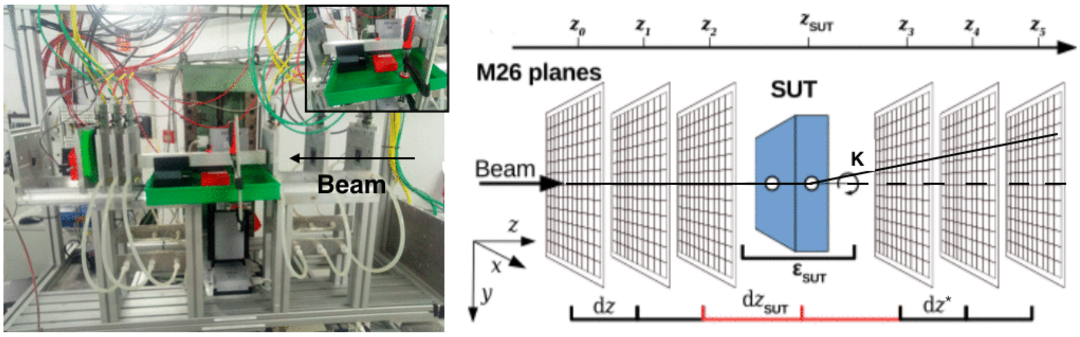


Figure 5: Setup of telescope used for the measurement

3.2. Measurement and analysis of the kink angle distribution

It takes several steps to get a calibration for the material budget. Firstly, data was collected, 2 million events for all of water samples and 1 million events for without samples have been recorded. Then tracks reconstruction was performed using the EUTelescope analysis framework. Analysis procedure includes 5 steps: noisypixel (search for hot pixel), clustering (data clustering and hot pixel deletion), hitmaker (creation of hits and prealigment), alignGBL (updating telescope geometry) and fitGBL (fit telescope tracks using GBL algorithm). In result a root-file with data containing the impact position and the kink angle was created. Afterwards a distribution of kink angle in X and in Y was built (Figure 7). Identical distributions were observed for kink angle in X and in Y. Hence using only one of them is sufficient for the calculation.

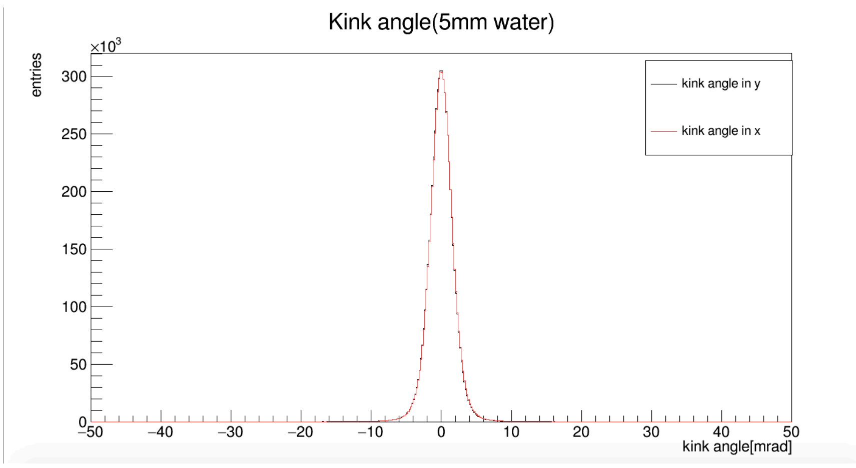


Figure 7: Kink angle distribution in X and Y

A program has been created that calculates the width of the inner 97% quantile of the kink angle distribution:

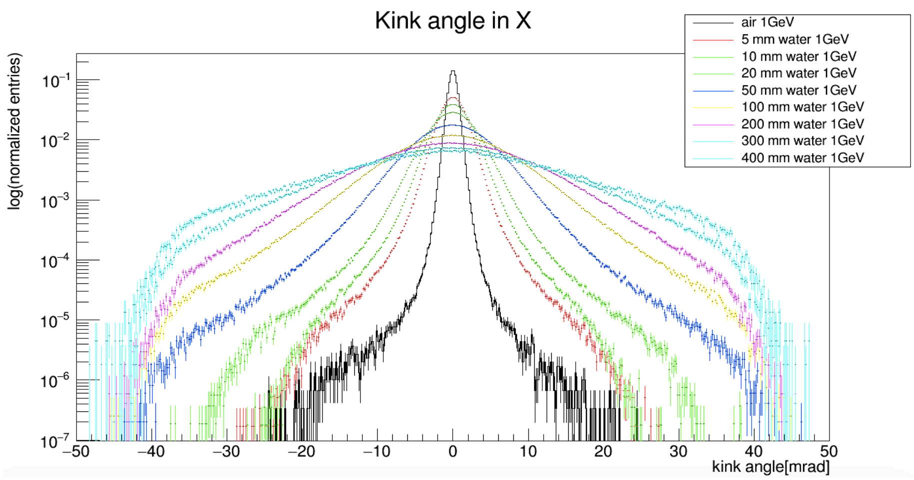
1. Find mean value (μ)
2. Calculation of standard deviation (σ)
3. Calculation of full width at half maximum (FWHM) as a function of σ

$$W = 2 \cdot \sqrt[2]{2 \cdot \ln(2)} \cdot \sigma \quad . \tag{2}$$

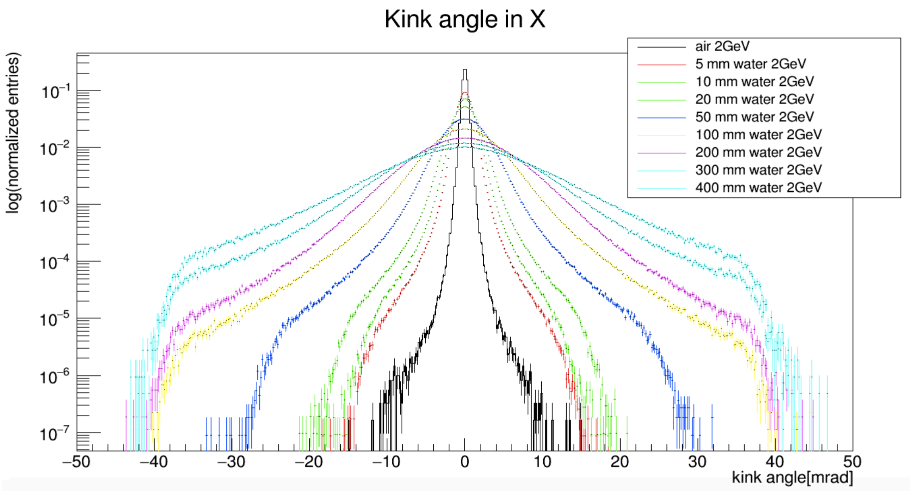
The measurement was performed without samples in order to exclude the contribution of scattering in air and the sensors and take into consideration the resolution of the sensors. As correction of the width of the kink angle distribution for water, the following formula was used:

$$W_{water*} = \sqrt{W_{water}^2 - W_{air}^2} \ , \tag{3}$$

where W_{air} is the width of the kink angle distribution without samples.



(a)



(b)

Figure 7: Normalized kink angle distribution with log y-axis for beam energies of 1GeV(a) and 2 GeV(b) for all of water samples and without samples.

3.3. Determination of calibration

A calibration line for water was obtained for 1 GeV and 2 GeV beam energy (Figure 8). The width of the kink angle distribution is increasing as a function of water's thickness. Also, an increasing width was observed with decreasing beam energy of probing electrons. These effects can be very simply explained. There is less multiple Coulomb scattering in a sample with increasing energy of the probing electrons resulting in a lower width of kink angle distribution.

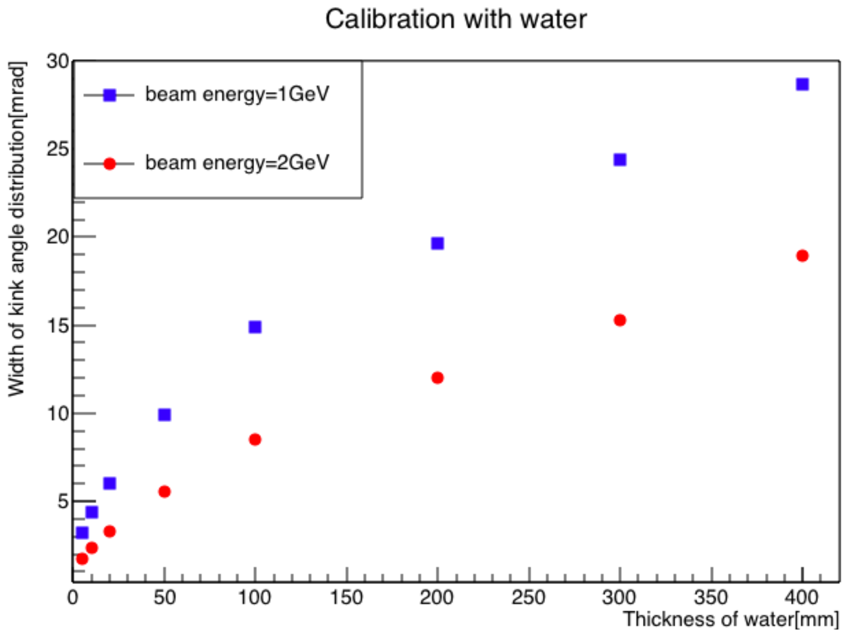


Figure 8: Calibration with water

A calibration was derived by fitting to the Highland approximation with free parameter K (Figure 9):

$$\Theta = \frac{K}{E} \cdot \sqrt{\frac{l}{X_0}} \cdot \left[1 + 0.038 \cdot ln\left(\frac{l}{X_0}\right) \right] \quad . \tag{4}$$

The measured data is generally well described by this formula. Highland proposed to use $\frac{K}{E} = \left[\frac{13.6\text{MeV} \cdot z}{\beta \cdot c \cdot p}\right]$. For used beam energies 1 GeV and 2 GeV $\frac{K}{E} = 21.78$ and $\frac{K}{E} = 10.88$ were calculeted respectively. The systemetic difference between the calculated parameter and fit parameter are observed:

$$[\frac{K}{E}]_{fit} = F \cdot [\frac{K}{E}]_{Highland} \ , \tag{5}$$

where F is systematic factor. Some clarification is needed for correct comparison of this values.

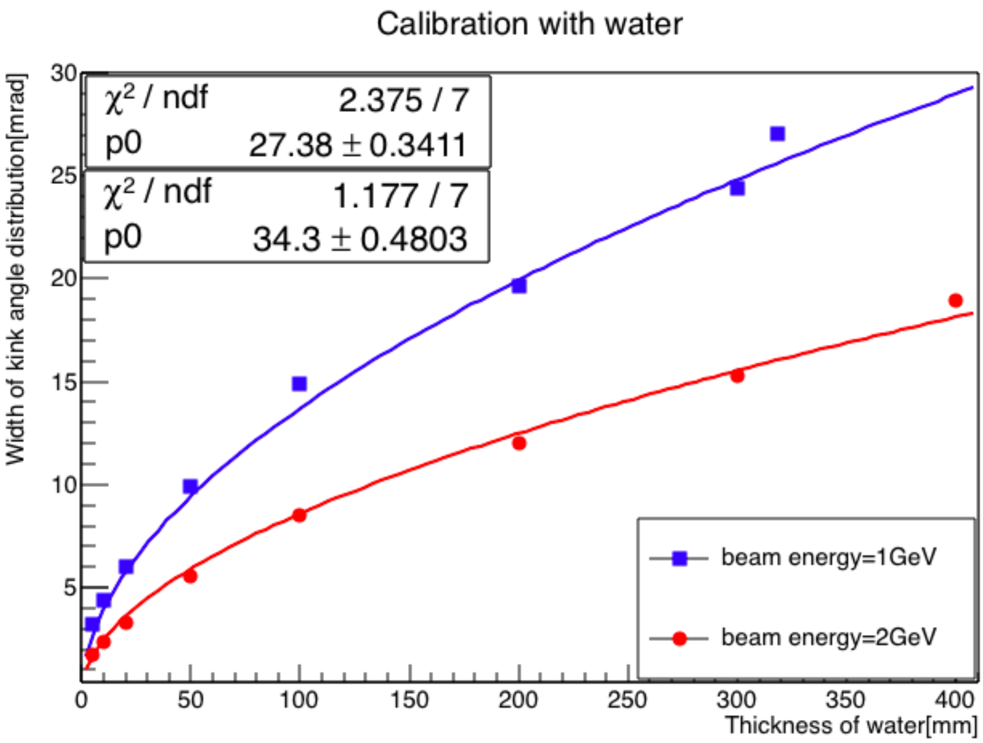


Figure 9: Calibration with water fitted by Highland approximation with a free parameter

4. Conclusion

In this work, measurements of kink angles were perfomed for different length of distilled water. This was done using the pixel beam-telescope DATURA which is located in test beam area TB21. For the measured data track reconstruction was made using the GBL algorithm within the EUTelescope analysis framework. Histograms for the kink distribution were created for all samples and the FWHM for water samples and without samples were calculated. Finally, a calibration line was obtained as dependence between the thickness of water and the FWHM for beam energies 1 and 2 GeV. The width is an increasing function of material thickness. Also, an increasing width was observed with a decreasing beam energy of the probing electrons. The calibration lines were fitted by Highland's approximation with a free parameter.

Acknowledgement

I would like to thank my three supervisors Hendrik Jansen, Jan-Hendrik Arling and Paul Schütze for for the opportunity to work on this project, help in every work related question and getting to know new skills. It was nice to work with you!

Thank you to Lennart Huth for helping with samples for my measurement.

Thank you to Jan Dreyling-Eschweiler, Gonzalo Morras, Robert Hammann, Giulio Bardelli, Lorenzo Cotrozzi, Andreas Löscheke Centeno for helping with test beam shifts.

Thank you to the whole organization teams for this program. It was very wonderful time in my life.

References

[1]. Description of the DESY Test Beam Attributes. Map of the DESY-II tunnel and the test beam lines. http://particle-physics.desy.de/e252106/

[2]Hendrik Jansen at al., Performance of the EUDET-type beam telescopes. EPJ Techniques and Instrumentation (2016)

[3] Hendrik Jansen and Paul Schütze, Feasibility of track-based multiple scattering tomography. Applied Physics Letters 112 (2018)

Appendix

Table 1. Width of the kink angle distribution

Thickness of water, mm	Beam energy 1 GeV	Beam energy 2 Gev
	Width of kink angle distribution [mrad]	
5	3.20663	1.75282
10	4.34548	2.38116
20	5.99462	3.30552
50	9.87375	5.52261
100	14.8921	8.49411
200	19.66	12.0209
300	24.4155	15.2722
400	28.6589	18.9343