Hydrogen analysis depth calibration by CORTEO Monte-Carlo simulation

M. Moser[a,*], P. Reichart[a], A. Bergmaier[a], C. Greubel[a], F. Schiettekatte[b], G. Dollinger[a]

[a] *Universität der Bundeswehr München, Institut für Angewandte Physik und Messtechnik LRT2, Fakultät für Luft- und Raumfahrttechnik, 85577 Neubiberg, Germany*
[b] *Université de Montréal, Département de Physique, Montréal, QC, Canada H3C 3J7*

Abstract

Proton-proton (pp) scattering has proven to be the most sensitive ion beam method for hydrogen analysis [1] due to the unique signature of the two protons emitting from the point of scattering with 90° angle to each other. Provided that the proton energy is large enough, a huge solid angle of detection of few sr can be used in transmission geometry and hence, for microscopic hydrogen imaging in 3 dimensions it is in fact the only method because of its low radiation damage potential [2]. For proton energies below 5 MeV the sample thickness is limited to few microns. At the nuclear microprobe SNAKE up to 25 MeV are possible and samples of more than 100 μm thickness can be investigated.

Depth information is evaluated from the energy sum signal with respect to energy loss of both protons on their path through the sample. In first order, there is no angular dependence due to elastic scattering. In second order, a

*Corresponding author
Email addresses: marcus.moser@unibw.de (M. Moser), guenther.dollinger@unibw.de (G. Dollinger)

path length effect due to different energy loss on the paths of the protons causes an angular dependence of the energy sum. Therefore, the energy sum signal has to be de-convoluted depending on the matrix composition, i.e. mainly the atomic number Z, in order to get a depth calibrated hydrogen profile. Although the path effect can be calculated analytically in first order, multiple scattering effects lead to significant deviations in the depth profile. Hence, in our new approach, we use the CORTEO Monte-Carlo code [3] in order to calculate the depth of a coincidence event depending on the scattering angle. The code takes individual detector geometry into account. In this paper we show, that the code correctly reproduces measured pp-scattering energy spectra with roughness effects considered. With Mylar-sandwich targets (Si, Fe, Ge) we demonstrate the deconvolution of the energy spectra on our current multistrip detector at SNAKE. As a result, hydrogen profiles can be evaluated with an accuracy in depth of about 1 % of the sample thickness.

Keywords:

proton-proton scattering, hydrogen analysis, hydrogen depth profiling, monte-carlo simulation, multiple scattering, multi strip detector

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1. INTRODUCTION

For quantitative detection of hydrogen by coincident elastic proton-proton (pp) scattering has to be proven as one of the most sensitive methods with a detection limit in the sub-ppm range [1]. Due to the lowest damage potential of all ion beam probe methods for hydrogen analysis [2], this method is the only one to analyze hydrogen distributions with μm resolution by using proton microprobe imaging [4]. The scattering analysis has to be performed in transmission geometry (Fig. 1a) so that the scattered protons can be detected in coincidence with an angular sum of 90° to each other as a unique signature. At SNAKE we use two pairs of matrix structured detector to look for this pattern as described in [5]. Due to the energy loss which is described by the stopping power $S = \mathrm{d}E/\mathrm{d}z$ for protons, the depth of the detected hydrogen atom scattered from the sample is correlated to the energy sum $E_{\mathrm{sum}} = E_1 + E_2$ of the two scattered protons from each event. Thus a depth distribution of about 5–10 % of the total thickness is obtained, this usually corresponds to few μm resolution, even sub-μm resolution is possible for lower energies.

The de-convolution of the energy sum signal to a depth value is a non-trivial task because the energy signal from equal depths is affected by the path length effect and hence depends on the scattering angle or the energy difference. This causes bending of the depth lines as visible in Fig. 1b and is described in detail in [2]. It has to be addressed in particular for transmission geometry, where we use huge solid angle of detection of about 2 sr in order to get the optimum ratio of signal to damage events [2]. Up to know we solved this deconvolution by a first order approximation: The energy sum signal

from front and back surface is extracted for each scattering angle/energy difference value and the depth is approximated by linear decrease from front and back surface value. Even for low hydrogen content the surface signal is clearly visible due to natural surface contamination, otherwise it can be prepared by adding Mylar to front and back. However, of course this approximation adds uncertainties to a quantitative evaluation of the depth profiles.

In our new approach we use the CORTEO code as a very fast Monte-Carlo-Simulation [3]. The simulation includes all geometric properties of the individual detection setup as it has been used before similarly in the case of coincident carbon-carbon scattering [6]. With this we simulate a spectra for the requested matrix composition with a defined homogeneous depth distribution of hydrogen. The output parameters of the scattering events are fed into the coincidence analysis like measured data with the same filter settings of the coincidence analysis. The point of origin of the scattering event is known from the simulation code and is then assigned by a fitting routine to the energy sum for each scattering angle. This gives the de-convoluted energy signal as a calibrated depth profile. Additionally, with the inclusion of all coincidence filters, we are also able to calibrate the depth dependent efficiency of the filters caused by multiple scattering effects. This will be addressed in a forthcoming paper.

In Section 2 we will at first proof that the generated energy signal from the code is in agreement with the measured data as well as analytical functions for energy loss and energy spread. Later we will describe the deconvolution of the energy spectra to gain depth profiles and give some examples using our current pp-detector setup.

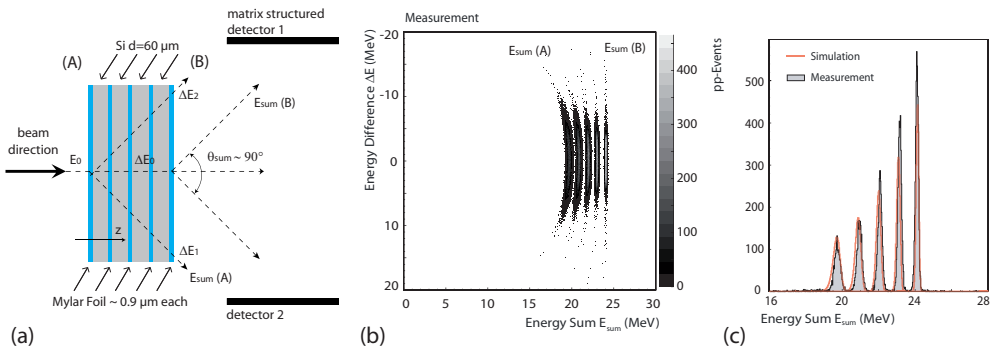

Figure 1: (a) Principle of the scattering geometry for coincident pp-scattering analysis with a position sensitive detector system. Furthermore, the sample exists of four $(60 \pm 10)\,\mu$m thick Si-wafer in a sandwich configuration of 900 nm thick Mylar layers in order to get a clear hydrogen signal with defined hydrogen content ($3 \times 10^{18} H - \mathrm{at/cm}^2$ each) as illustrated. (b) The measured energy sum E_{sum} in dependence on the energy difference ΔE of the both detected protons for the sample (see (a)), incident proton energy of $E_0 = 25\,\mathrm{MeV}$. (c) Projection of the pp-events onto the energy sum axis compared with the CORTEO simulation (red line).

2. SIMULATION OF ENERGY SPECTRA

Experimental setup

In a first study we used a simple pp-detector setup in order to compare the simulated CORTEO energy spectra with experimental data. As illustrated in Fig. 1a, the setup consists of two $1000\,\mu$m thick Silicon detectors with 7 horizontal strips each (Micron semiconductor Design I) covering a solid angle of detection of $\Delta\Omega \approx 2{\cdot}65\,\mathrm{msr}$. The energy resolution was determined by elastic scattering on a single Mylar foil with a incident proton energy of $25\,\mathrm{MeV}$ to $\delta E_\sigma / E \approx 0.17\,\%$ for each proton of about $12.5\,\mathrm{MeV}$ and each detector side, i.e. $\delta E_\sigma = 20\,\mathrm{keV}$ (1σ width) or $\delta E_{\mathrm{FWHM}} = 50\,\mathrm{keV}$ (FWHM

width).

For testing CORTEO we use a sandwich sample of four 60 μm thick one-side polished Si-wafers (as received) with 0.9 μm thick Mylar layers in between. This gives a clear hydrogen signal with defined hydrogen density of $\rho_{\mathrm{H}} dz = 3 \times 10^{18} H - \mathrm{at/cm^2}$ each. The sandwich construction was prepared by stacking some 5×10 mm large fragments. The planarity of the wafer is specified better than 1° and the tolerance in thickness was given as $d_{\mathrm{Si}} = (60 \pm 10)\,\mu$m, but found to be better by profilometer measurements.

The coincidence events are filtered by Mesytec multistrip detector readout electronics[7] within a time window of $2 - 3$ ns in which both protons have to hit opposite strips that define a scattering plane. The angular sum $\theta_{\mathrm{sum}} = \theta_1 + \theta_2$ is defined simply by the detector itself. Hence, the angular filter condition for $\theta_{1,2} = 45° \pm 5°$ is fixed only to an angular sum of $\theta_{\mathrm{sum}} = 90° \pm \mathcal{O}(10°)$.

Experimental data

In Fig. 1b the energy difference ΔE of each coincident proton pair is plotted in dependence of the energy sum E_{sum}. The energy difference ΔE gives an additional angle information due to scattering kinematics. Therefore Fig. 1b is a depth profile with scattering angle information. The layers of hydrogen from Mylar are represented as lines of same depth. These are bend due to the mentioned path length effect [8]. Fig. 1c gives the projection onto the energy sum axis and can be interpreted as a hydrogen depth profile without correction of the path effect. The hydrogen peaks from Mylar are broadened at lower energies due to the path effect, but also due to energy

spread of the protons on their way through the sample. This is now directly compared to the energy data output of the CORTEO simulation (red line). The simulated yield is normalized to the measured yield.

One can see that the energy resolution δE_{sum} improves with the depth z. The integrated peak content of each layer (gray areas) shows a decrease of the coincident events due to the fact that multiple scattering destroys the angular signature of "good" events with increased path length z. Correction of this effect is not the topic of this paper, but we already want to point out that CORTEO is in total agreement with the data within our specifications of sample and setup geometry. Now, we use two parameters to evaluate the quality of the simulation data: The position of the hydrogen layers and the spreading of the Mylar layers (peak width).

Layer position

First, we compare the simulated and measured layer position. In order to eliminate systematic uncertainties, we fit the first and last peak to the optimum correlation as done in Fit. 1c. This compares to a simple thickness evaluation by energy loss and gives a mean Si thickness of $d_{\mathrm{Si}} = 4 \times 63.5\,\mu\mathrm{m}$, nominal thickness of Mylar assumed. A fit uncertainty of 10 keV has been determined corresponding to only $0.6\,\mu\mathrm{m}$ in thickness. The result is within the tolerance of the specifications for the Si thickness and wafer planarity with respect to our beam size diameter of about 0.5 mm. This is probably also the reason for the layer position of the three peaks in between showing a significant systematic shift of about 70 keV, corresponding to about $4\,\mu\mathrm{m}$. It doesn't make sense to evaluate the individual layer thickness and its deviation due to the unknown planarity and unprecise thickness specification. Hence,

we evaluate the spread function δE_{sum} of each layer and its width $\sigma_{\delta E_{\mathrm{sum}}}$ in the following.

Layer width

The widths $\sigma_{\delta E_{\mathrm{sum}}}$ of the Mylar layers are caused by the path effect but also of course by the energy spread due to energy loss scattering and multiple scattering effects that increases with path length of the protons in the sample.

In Fig. 2, the measured width $\sigma_{\delta E_{\mathrm{sum}}}$ of each Mylar peak (black squares) is plotted in dependence to the energy sum E_{sum}. The simulated width (red stars) shows a good agreement with the measured data (black squares) when we consider a variation for the one-side roughness of $\approx 1\,\mu$m and and additionally for the non-planarity of the wavers. In the case of CORTEO, the latter morphologic properties cannot be included, therefore we include a total roughness R_σ of $2 \times 1\,\mu$m for each layer. In fact, this is an assumption that is not representing the physical properties, but with this assumption the $\sigma_{\delta E_{\mathrm{sum}}}(E_{\mathrm{sum}})$ shows the best agreement and we get a mean deviation to the measured data of $\mathrm{Res}(\sigma_{\delta E_{\mathrm{sum}}}) = (18 \pm 11)\,\mathrm{keV}$ (residuum by quadratic substraction). Assuming a mean stopping power this corresponds to a deviation for the depth spread of $(1.1 \pm 0.6)\,\mu$m that can be interpreted as the accuracy for determining a depth resolution.

The peak widths are also in agreement with analytical models from energy loss straggling [9] and small angle scattering [10]. Taking these contributions on all paths of the protons and also the detector energy resolution as independent, we get

$$\delta E_{\mathrm{sum}}(E_{\mathrm{sum}}) = \sqrt{2\delta E_{\mathrm{det}}^2 + \delta E_{\mathrm{stragg}}^2(E_{\mathrm{sum}}) + \delta E_{\alpha}^2(E_{\mathrm{sum}}) + \delta E_{\mathrm{path}}^2(E_{\mathrm{sum}})} \quad (1)$$

with δE_{det} being the energy resolution of the detector (1σ), $\delta E_{\mathrm{stragg}}$ the energy loss strangling, δE_{α} the small angle scattering (multiple) path effect and δE_{path} the correlated path length effect as derived in detail in [8].

The theoretical model of Eq. (1) is plotted in Fig. 2 (bold black dash line). Additionally for the specified non-planarity of the wavers we add $\delta E_{\parallel}$ in order to count for a misalignment of each layer that is statistically distributed. This misalignment results in a thickness variation $R_{\parallel}$ similar to a roughness. With this, the theoretical model (bold black dashdot line) is in agreement to the measurement, with $R_{\parallel} = (0.9 \pm 0.1)\,\mu$m where the given uncertainty is drawn as a confidence interval (grey shade). Thus, the modified analytical model show the same agreement as the CORTEO simulation within a mean deviation to the measured data of $\mathrm{Res}(\sigma_{\delta E_{\mathrm{sum}}}) = (20 \pm 3)\,\mathrm{keV}$. This again corresponds to a spread in depth values of $(1.1 \pm 0.2)\,\mu$m. The particular contributions of Eq. (1) are separately plotted (thin black lines) in Fig. 2, showing that energy loss straggling $\delta E_{\mathrm{stragg}}$ in fact gives the major contribution to the total energy spread δE_{sum}.

With the agreement of both (Monte-Carlo and analytical) approaches with the experimental data we justify the use of CORTEO to de-convolute the measured energy to a depth scale.

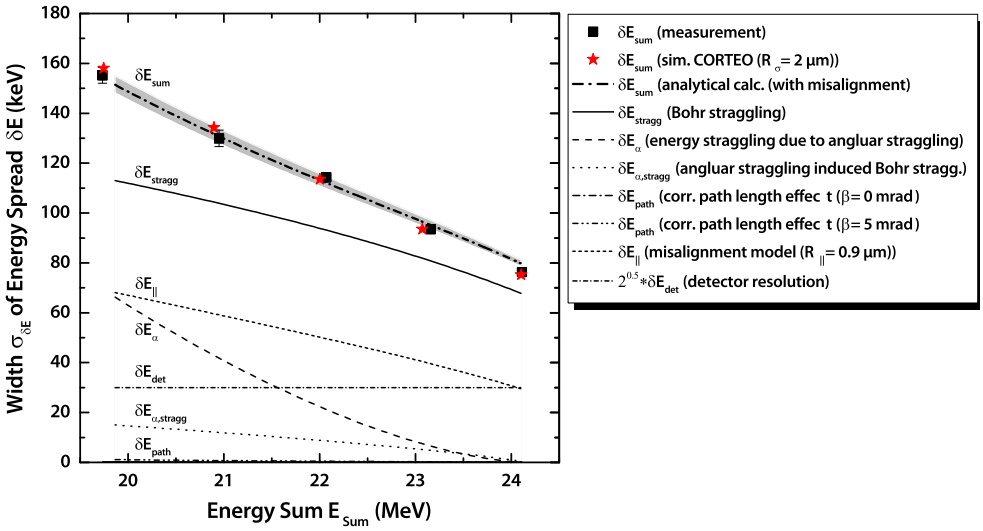

Figure 2: Comparison of the of the energy spread $\delta E_{\rm sum}$ in dependence on the energy sum $E_{\rm sum}$. For CORTEO simulation (red stars) and the measured data (black squares) the width $\sigma_{\delta E_{\rm sum}}(E_{\rm sum})$ of each Mylar peak is plotted. The results of the simulation with CORTEO (red stars) are plotted with a roughness $R_\sigma \sim 2\,\mu$m of the single sample that counts for the assumed misalignment of the single wavers. The theoretical model (bold black dash line) includes all contributions of Eq. (1) with the separately plotted contributions for the energy spread model $\delta E_\parallel$ that accounts for the thickness variations $R_\parallel$, the detector resolution $\delta E_{\rm det}$, the energy loss strangling $\delta E_{\rm stragg}$, the small angle scattering path effect δE_α and the correlated path length effect $\delta E_{\rm path}$. The confidence interval (grey shade) give the uncertainty due to $R_\parallel = (0.9 \pm 0.1)\,\mu$m.

3. DE–CONVOLUTION OF THE ENERGY SPECTRA

In the previous section we have shown that the CORTEO code is valid for a quantitative description of the measured coincident pp-events with the depth correlated energy sum E_{sum}. However, the energy sum E_{sum} has to be de-convoluted due to the path length effect for quantitative hydrogen profiles. In the following we demonstrate how to use CORTEO to calculate this de-convolution function using our current pp-detecotr setup.

Experimental setup

The current setup consists of 4 double sided silicon strip detectors (DSSSD, Micron Semiconductor Design W1) with an active area of $50 \times 50\,\mathrm{mm}$ and 16 strips on each side (back and front). The detectors energy resolution has been determined to $\delta E_\sigma / E = 0.23\,\%$ with $\delta E_\sigma = 15\,\mathrm{keV}$ for each proton of about 6.5 MeV and each detector side [11]. The detectors are arranged in a box like structure and each pair of detectors facing each other [11].

For a demonstration of the de-convolution procedure we use a similar Si-Mylar-sandwich, but this time we used two, on both side polished Si-wafers with in total three $0.9\,\mu\mathrm{m}$ thick Mylar layers. Due to the polishing process, the thickness is reduced to about $56\,\mu\mathrm{m}$. In Fig. 3a we show the original energy signal of the coincident pp-events (energy sum E_{sum} vs. energy difference ΔE) using an incident proton energy $E_0 = 13\,\mathrm{MeV}$. Three lines of pp-events from the Mylar layers are clearly visible. These are separated by the (nominally anhydrous) area of Si-wafers and bent by the path length effect.

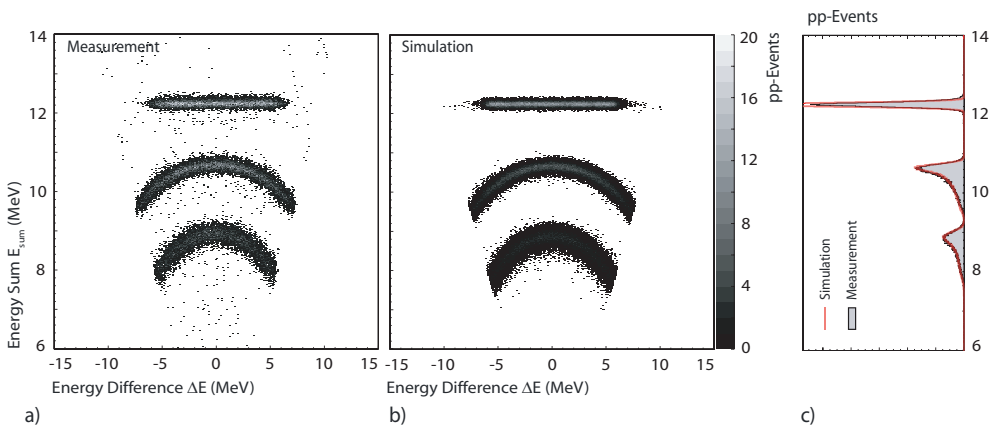

Figure 3: "As received" pp-coincidence spectra of $2 \times 56\,\mu$m Si-wafer sandwich with $0.9\,\mu$m Mylar in between and on top (hydrogen content 3×10^{18} at/cm^2 each). (a) Experimental data with current pp-detector setup as described using 13 MeV incident protons. (b) Simulated by CORTEO with same filter conditions and geometry. Note that pixels are filled weighted here due to the applied scattering cross section and give a wrong impression of the content compared to (a). (c) Projection onto energy sum E_{sum}, comparing measurement (black line) and simulation (red line).

Simulation

In Fig. 3b, the energy signal of the same sample configuration but simulated by CORTEO is plotted. Again, the front and back layer is fitted and we obtain a thickness for Si of $2 \times 55.7\,\mu$m (fit uncertainty $0.7\,\mu$m). The simulated pp-events are filtered by the same analysis routine as the experimental data, using the full geometry of the multistrip detection system as well as its energy and angular resolution. Also, the same dead time corrected charge Q_{corr} from the experiment was applied to the simulation. CORTEO uses the pp-scattering cross section data of [12]. Therefore, an equal number of coincident pp-scattering events appear in the spectrum. This is not visible

due to weighted filling of the bins from the scattering cross section value, but it gets clear in the E_{sum} projection as plotted in Fig. 3c. Also for the complex structured low energy tails we find a perfect agreement of the both spectra.

Depth map

The de-convolution function is a mapping of each ΔE-E_{sum} coordinate to a unique depth value. This map is generated by simulating a sample of same composition with a homogeneous hydrogen content and plotting the z-coordinate of the main collision as depth value to the z-axis. This is plotted in Fig. 4 for 115 μm thick silicon. One can see that the depth values of the events are directly correlated with the path length effects. With this map we assign each detected pp-event from the measured $(\Delta E, E_{\mathrm{sum}})_{\mathrm{exp}}$ value a depth z. In detail, we use for this procedure a 2-dimensional fit function in order to assign depth values to events that have energy coordinates outside the simulated spectra.

De–convolution

The result of the applied de-convolution function is demonstrated in Fig. 5 with the depth z of each event assigned to the ΔE-E_{sum} coordinate, while ΔE was kept so that $(\Delta E, E_{\mathrm{sum}}) \rightarrow ((\Delta E, z(\Delta E, E_{\mathrm{sum}}))$. The original bent lines representing hydrogen from same layer induced by the path length effect are fully corrected. Fig. 5c shows the corrected spectra with perfect agreement of measurement (black line) and simulation (red line). The complex structured low energy tails as shown in Fig. 3c are fully corrected by the

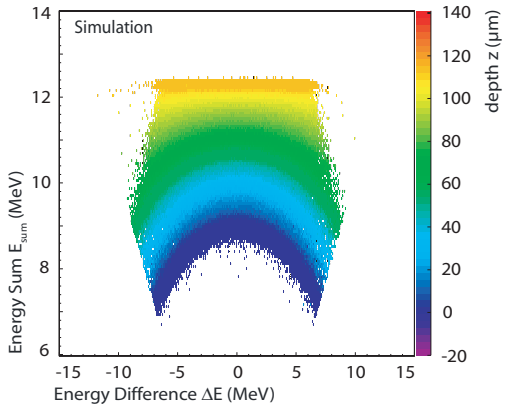

Figure 4: CORTEO simulation of 115 μm silicon with a homogeneous hydrogen content. Plotted is the energy sum depending on the energy difference as a function of the depth z of the main collision $(\Delta E, E_{\mathrm{sum}})(z)$ of the both simulated protons for an incident proton energy of 13 MeV.

de-convolution resulting in a homogeneous gaussian distribution of the peak layers.

Heavy materials

At last we show in Fig. 6 that the de-convolution as well as the CORTEO algorithm also works for heavier material in same quality as well as lower proton energies of $E_0 = 13\,\mathrm{MeV}$. Here we used Fe- and Ge-sandwich samples in same way as above. The thickness of the Fe-layers is specified with $(25 \pm 2)\,\mu$m by the manufacturer (Goodfellow) and the simulation of the energy spectra (Fig. 6a) gives agreement with the experimental data as well as the de-convoluted depth profile (Fig. 6b). From simulation we find the Fe-layers in fact to be 24.2 μm thick, respectively, with an accuracy for the fit of 0.2 μm. Hence, we claim a deviation of 3.2 % from the nominal value but within the

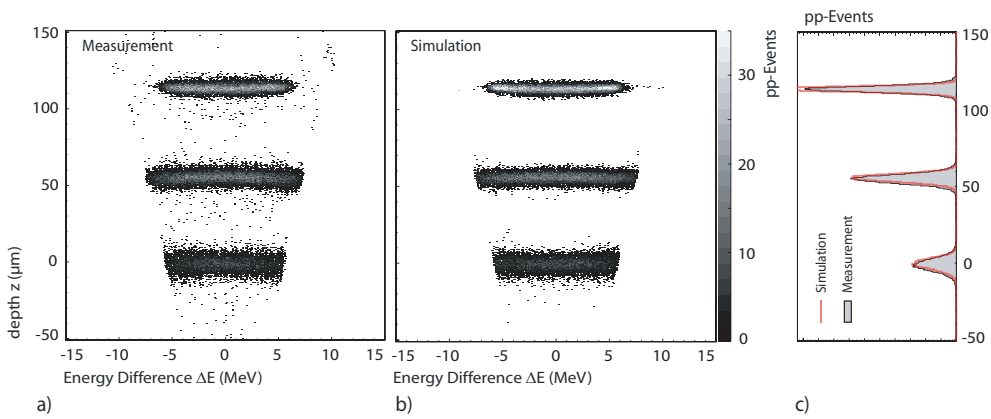

Figure 5: De-convoluted pp-scattering spectra of of the same sample like Fig. 3 using 13 MeV incident protons. The depth z of each event was assigned to the ΔE-E_{sum} coordinate by the de-convolution function, while ΔE was kept so that $(\Delta E, E_{\mathrm{sum}}) \rightarrow ((\Delta E, z(\Delta E, E_{\mathrm{sum}}))$. (a) Experimental data and (b) Simulated data (c) Projection onto depth z, comparing measurement (black line) and simulation (red line).

manufacturers specification.

In the case of Ge in Fig. 6c and d, we have used polished fragments of a waver with different thickness around 50 μm. We used this experiment to fit the unknown thickness by CORTEO simulation and find best agreement to the experimental data with 57 μm and 46 μm, respectively, with a fit uncertainty of 0.4 μm. These examples together with the above show for pp-scattering at energies of 13–25 MeV that determination of layer thickness by CORTEO fitting is possible even with less than μm-accuracy, although the depth resolution of the method is limited to few μm.

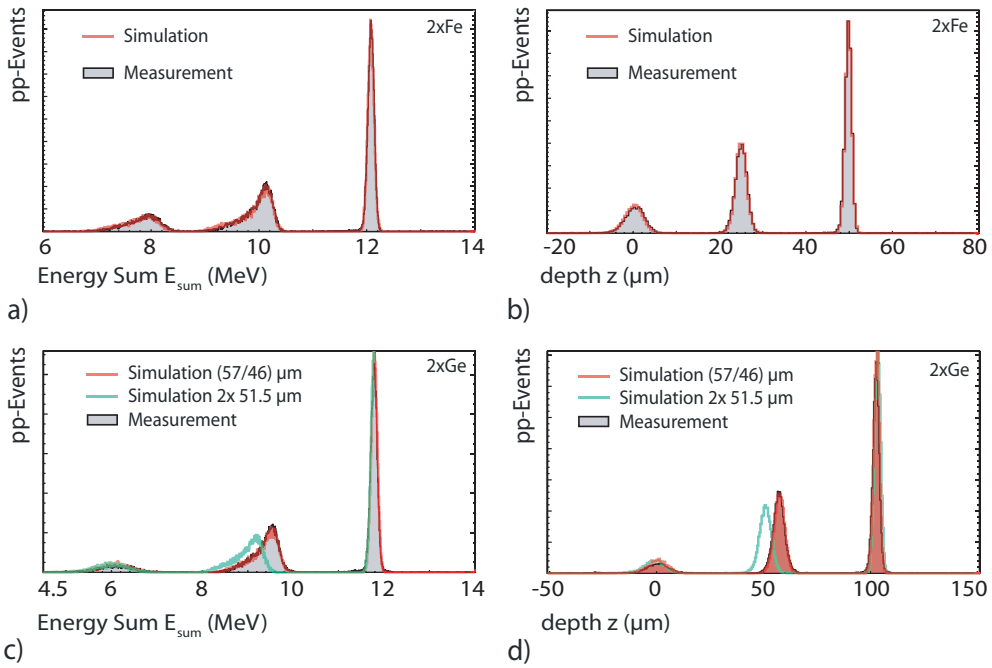

Figure 6: Coincident pp energy sum spectra and (corrected) hydrogen depth profile of 2×Fe sandwich sample and 2×Ge-sandwich sample with 0.9 μm thick Mylar layers in between and on top. Incident proton energy $E_0 = 13\,\mathrm{MeV}$. (a),(b) For the Fe-sandwich with $(25 \pm 2)\,\mu$m thickness the simulation and measurement are in perfect agreement. (c),(d) The unknown thickness of the polished Ge wavers has been determined by a best fit of the simulated data with 57 μm and 46 μm thickness.

4. CONCLUSION

The energy sum spectra of coincident pp-scattering events corresponds to a hydrogen depth profile. However, this is convoluted by energy spread from energy loss straggling, multiple scattering effects and a strong path length effect, in particular when investigating thick samples or heavier material. The lower the energy, the better is the depth resolution but also the larger becomes the spread effect. We have shown that CORTEO Monte-Carlo simulation code reproduces the scattering physics very well, so that it can be used to describe material dependent the pp energy spectra. It is also in agreement with analytical description from Bohr straggling and small angle scattering theory. In our demonstration of a Si-sandwich sample, we introduced an additional spread due to misalignment of the sample layers, equivalent to a roughness value. We found that fitting by CORTEO-simulation gives the possibility to evaluate layer spread or roughness with better than μm-accuracy at 13–25 MeV proton energy.

The data output of CORTEO can be adapted to the individual detector geometry of a coincidence detector setup and fed into the filter analysis of the data acquisition, giving the same filtered coincidence signal as the experimental data. With this, the depth dependent efficiency loss due to loss from multiple scattering effects in the specified angular filter can be simulated and hence corrected for individual matrix compositions. This will be the topic of a forthcoming paper. In this paper we have shown to use CORTEO to generate a de-convolution function to correct the energy spectrum and get a calibrated hydrogen depth profile. With this method, the uncertainty of the depth scale can been reduced to better than 1 % of the sample thick-

ness. This is of course a essential requirement for quantification of hydrogen concentration in the depth profile, that is now been solved for any material composition, sample thickness and proton energy combination.

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References

[1] P. Reichart, G. Datzmann, A. Hauptner, R. Hertenberger, C. Wild, G. Dollinger, Three-dimensional hydrogen microscopy in diamond, Science 306 (2004) 1537.

[2] P. Reichart, G. Dollinger, A. Bergmaier, G. Datzmann, A. Hauptner, H.-J. Körner, Sensitive 3d hydrogen microscopy by proton proton scattering, Nucl. Instrum. Methods B 197 (2002) 134.

[3] F. Schiettekatte, Fast monte carlo for ion beam analysis simulations, Nucl. Instrum. Methods B 266 (8) (2008) 1880 – 1885.

[4] G. Dollinger, P. Reichart, G. Datzmann, A. Hauptner, H.-J. Körner, Three–dimensional hydrogen microscopy using a high–energy proton probe, Appl. Phys. Lett. 82 (2003) 148.

[5] K. Peeper, M. Moser, P. Reichart, E. Markina, M. Mayer, S. Lindig, M. Balden, G. Dollinger, 3d-microscopy of hydrogen in tungsten, Journal of Nuclear Materials 438, Supplement (0) (2013) S887 – S890.

[6] I. Bogdanovic-Radovic, M. Jaksic, F. Schiettekatte, Technique for sensitive carbon depth profiling in thin samples using c-c elastic scattering, J. Anal. At. Spectrom. 24 (2009) 194–198.

[7] MESYTEC GbR, Putzbrunn, Germany, www.mesytec.com.

[8] P. Reichart, G. Dollinger, Hydrogen analysis by proton proton scattering, in: Y. Wang, M. Nastasi (Eds.), Handbook of Modern Ion Beam Material Analysis, 2nd Edition, Materials Research Society, 2009.

[9] N. Bohr, Mat. Fys. Medd. an. Vid. Selstr. 8 (1948) 18.

[10] P. Sigmund, K. B. Winterbon, Small-angle multiple scattering of ions in the screened coulomb region : I. angular distributions, Nucl. Instrum. Methods 119 (1974) 541–557.

[11] P. Reichart, C. Greubel, M. Moser, K. Peeper, G. Dollinger, Deuterium microscopy using 17 mev deuteron-deuteron scattering, NIMB these proceedings (**Note to the Editor: Plese reference to this paper that will be submitted at IBA2015.**).

[12] M. Moser, P. Reichart, C. Greubel, G. Dollinger, Differential protonproton scattering cross section for energies between 1.9 mev and 50 mev, Nucl. Instrum. Methods B 269 (20) (2011) 2217 – 2228.