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Comparison of Charge Deposition Profiles in Polymers Irradiated With Monoenergetic Electrons: Pulsed Electroacoustic Measurements and AF-NUMIT3 Modeling

Zachary Gibson
Utah State University

JR Dennison
Utah State Univesity

Brian Beecken
Bethel University

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Zachary Gibson,[1] JR Dennison,[1] and Brian Beecken[2]

[1]*Materials Physics Group, Physics Department, Utah State University*

[2]*Physics Department, Bethel University*

APPLIED SPACE ENVIRONMENTS CONFERENCE 2021

UtahStateUniversity

MATERIALS PHYSICS GROUP

Overview

- Goals and Importance
- Simulations: AF-NUMIT3
- Measurements: Pulsed Electroacoustic Method
- Experiment
- Results
- Conclusions
- Future Work

Goals and Importance

Goals:

- Investigate spacecraft charging
- Improve deep dielectric charging predictions (AF-NUMIT3)
- Validate our PEA system

Why?

- Better modeling and experimentation allow for more accurate determination of deep dielectric charging and predictions of catastrophic breakdown in dielectric materials

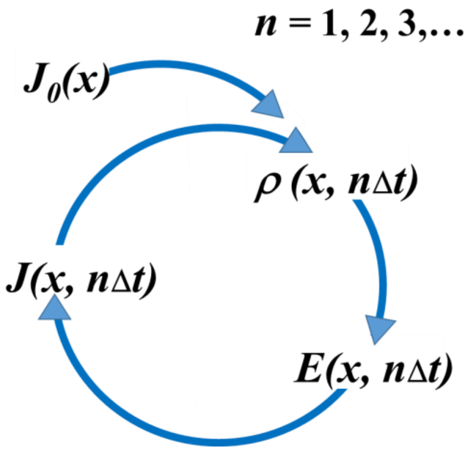
Simulation of Charge Deposition: AF-NUMIT3

I. What is AF-NUMIT3?

- **NUMIT = Num**erical **It**eration
- Goal: predict dangerously high Electric Fields within dielectric
- Simulation (1D) of charge build-up and transport deep in dielectric
- Material Input parameters: thickness, effective atomic number and weight, density, relative permittivity, dark conductivity, RIC coefficients

II. Simulation Steps for NUMIT

1) *Input Electron Flux* Spectra (time dependent!)
2) *Determine Deposition Profile* of incident Charge *and* Energy
   - Charge required to determine Electric Field
   - Energy required to determine Radiation Induced Conductivity (RIC)
3) *Model charge transport* using electrodynamics and material characteristics



Continuity Eq. $\frac{\partial J(x,t)}{\partial x} = -\frac{\partial \rho(x,t)}{\partial t}$

Gauss's Law $\frac{\partial E(x,t)}{\partial x} = \frac{\rho(x,t)}{\epsilon}$

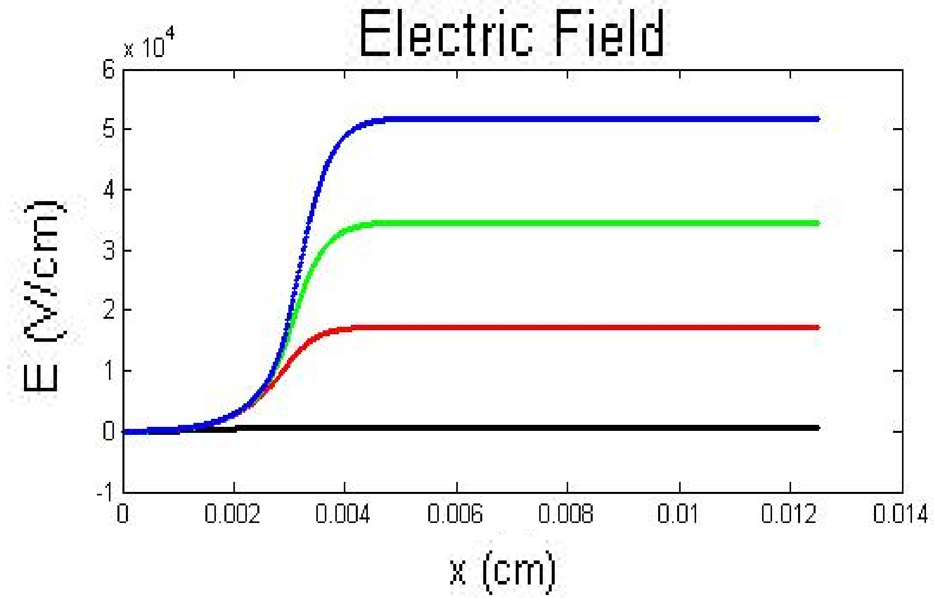
- Dielectric is divided into ~ 1000 spatial bins
- As incident electron current decreases with depth charge is deposited in bins
- *Algorithms* required for $J_0(x)$ and $\dot{D}(x)$

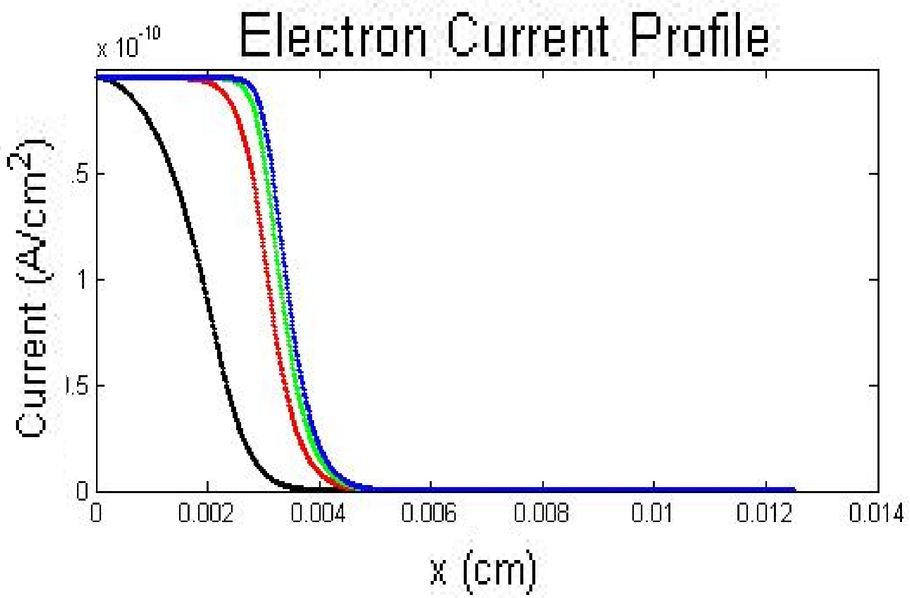
Total Current Eq. (Fowler Model)

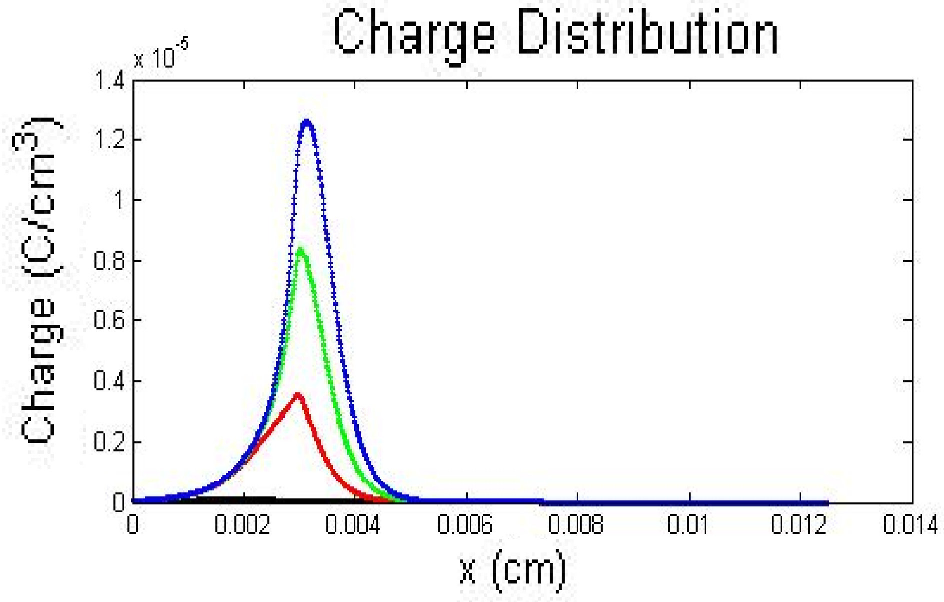
$$J(x,t) = J_0(x) + \left[g_0 + k\dot{D}(x)\right] E(x,t),$$

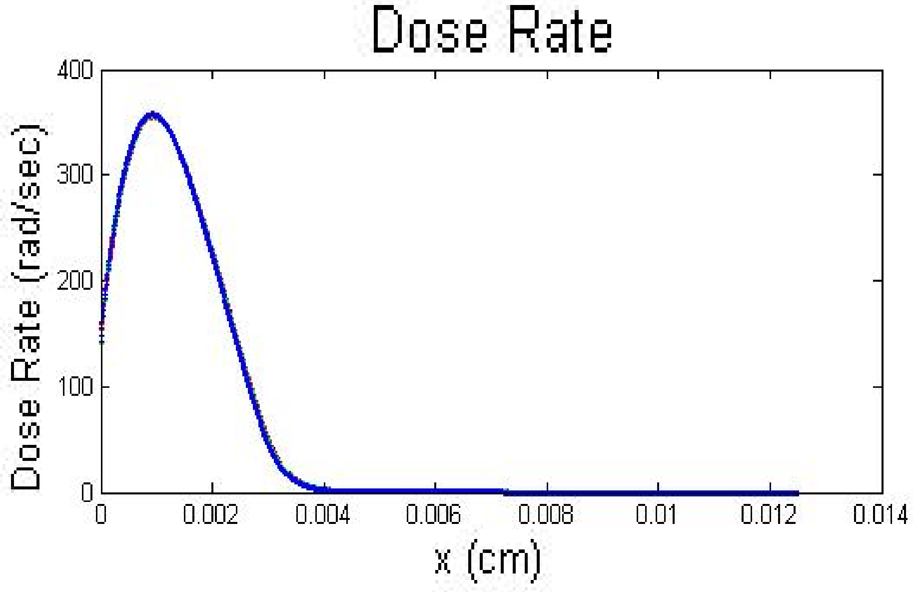
Incident Electron Current → $J_0(x)$; Dark Conductivity → g_0; Coef. of RIC → k; Dose Rate → $\dot{D}(x)$

AF-NUMIT3 Sample Output









The Experimental Set-up: What is PEA?

How it works:

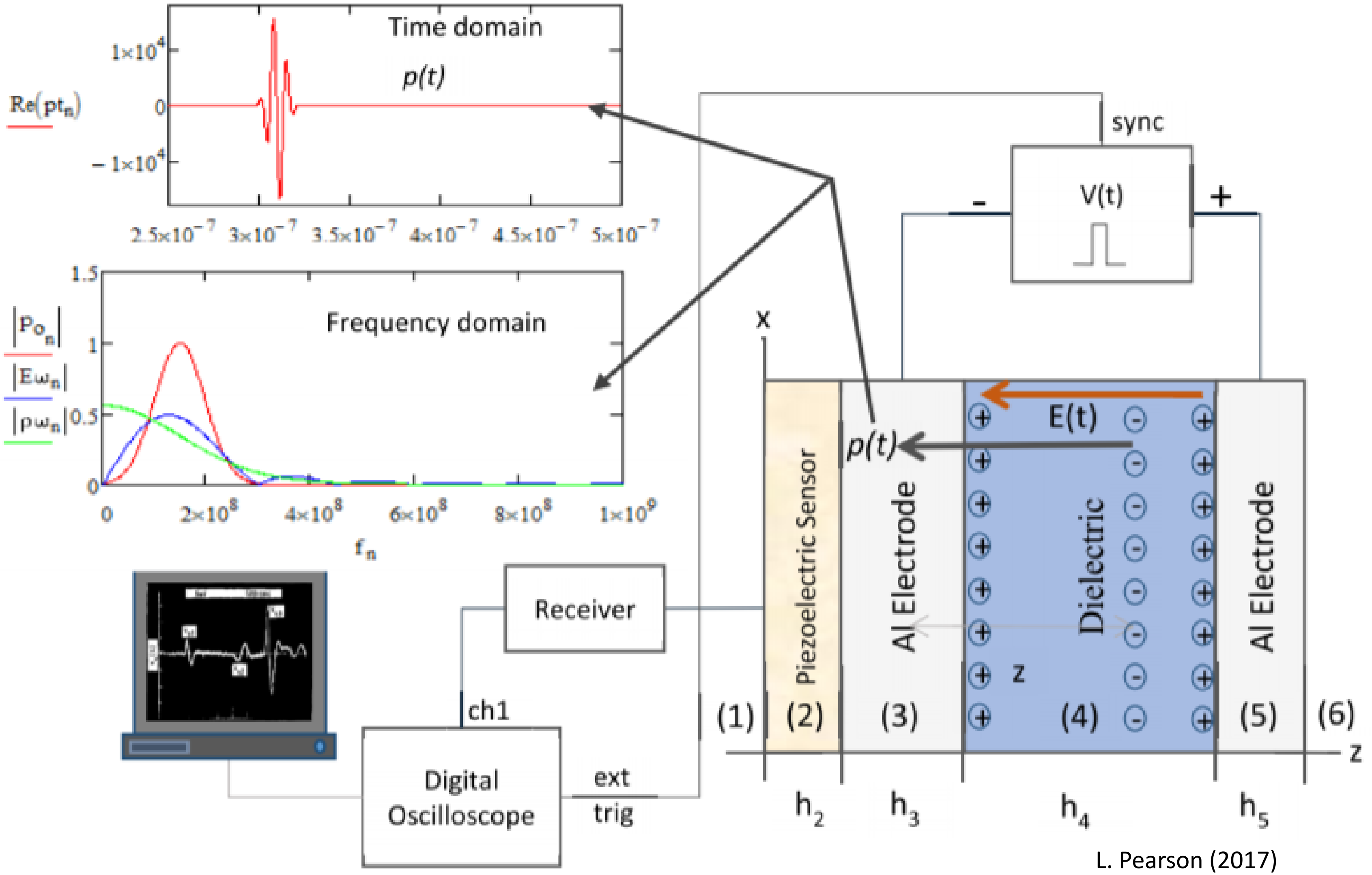
- Pulsed voltage probes embedded charge
- Time of flight indicates position of charge

Benefits:

- Nondestructive measurement
- Low cost

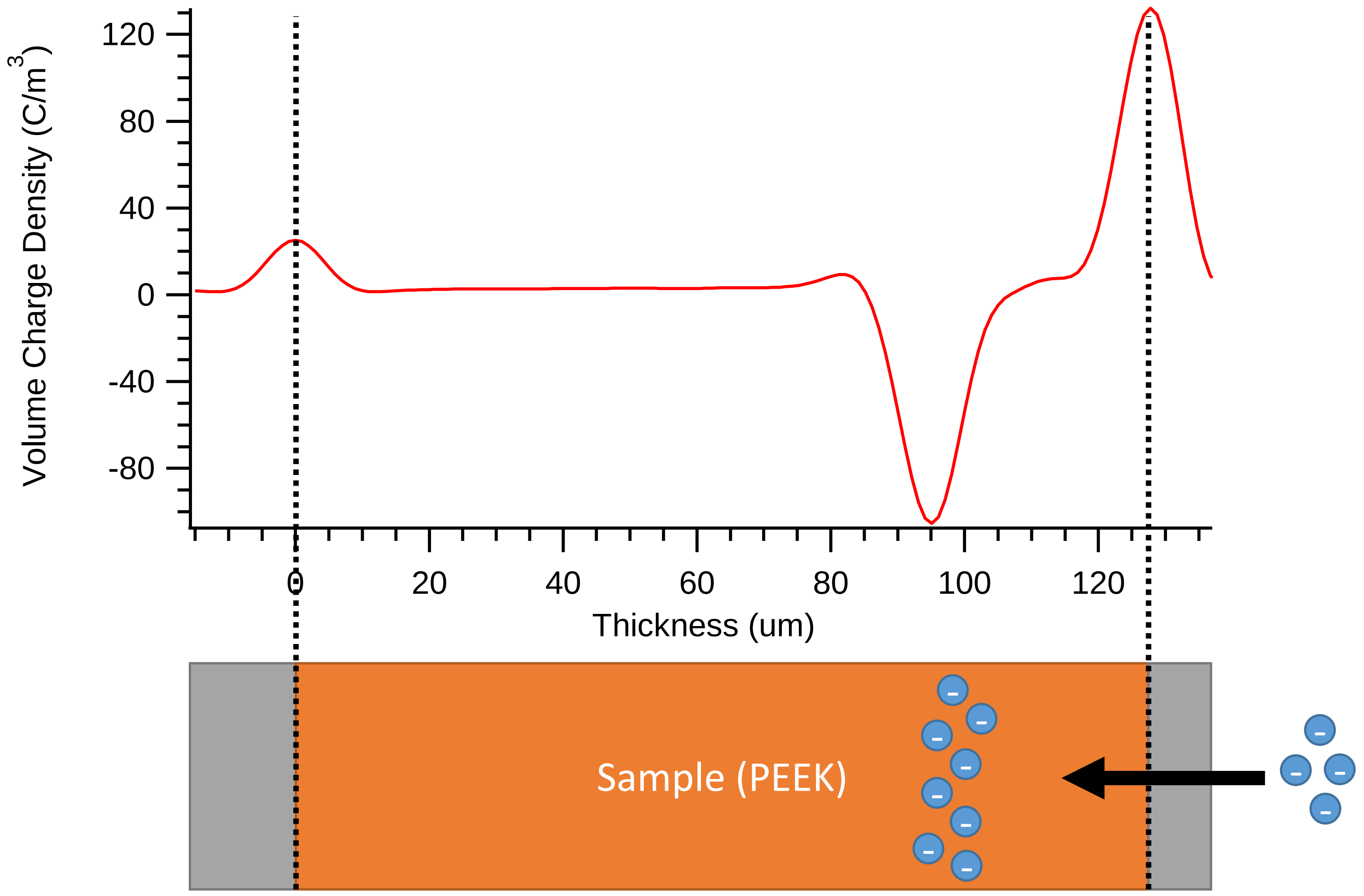
Limitations:

- Hard to increase resolution
  - High cost electronics
  - Difficult sensor fabrication



L. Pearson (2017)

Measuring Charge Distributions – An Example



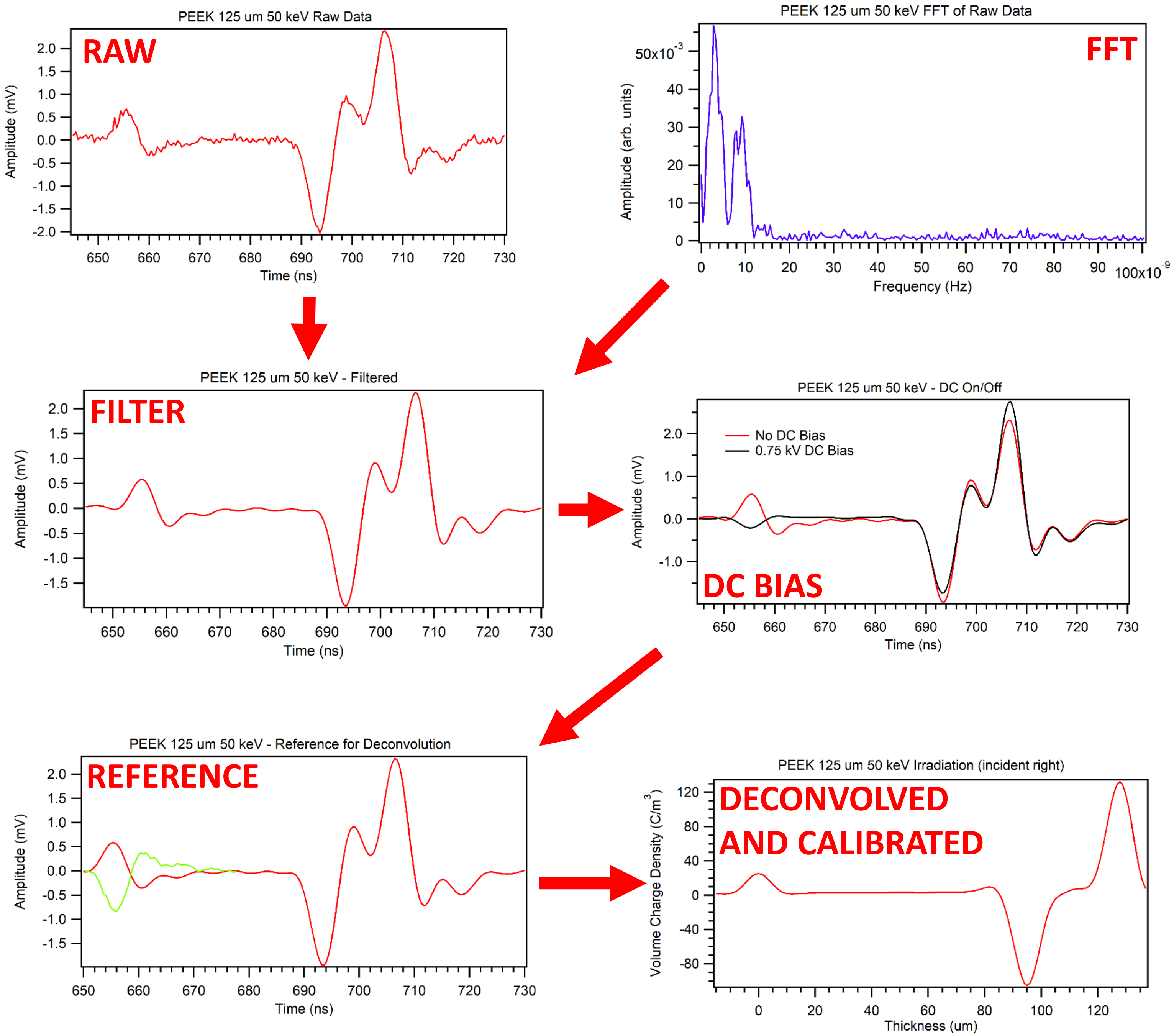
Signal Processing

Processing Steps:

- Average multiple measurements and compute statistics (not shown)
  - The rest of the processing is done on the averaged measurement
- Compute FFT to determine filter parameters
- Modified Gaussian filter used on data
- Take difference of DC on – DC off to obtain reference wave
  - Refer to (Chen 2006)
- Use system response to perform deconvolution

Calibration

- Multiply by calibration factor
  - $Calibration\ Factor = \dfrac{\epsilon_r \epsilon_o V_{DC}}{d \int V_{RefSignal} dx}$
- Calibrate x-axis to distance using the speed of sound calculated from the measured thickness and peak-to-peak time difference of the two interfaces



Electron Irradiation of Polymers

Goals:

Simulate deposited charge via AF-NUMIT3

Measure deposited charge via PEA method

Compare the results

Experiment:

Samples

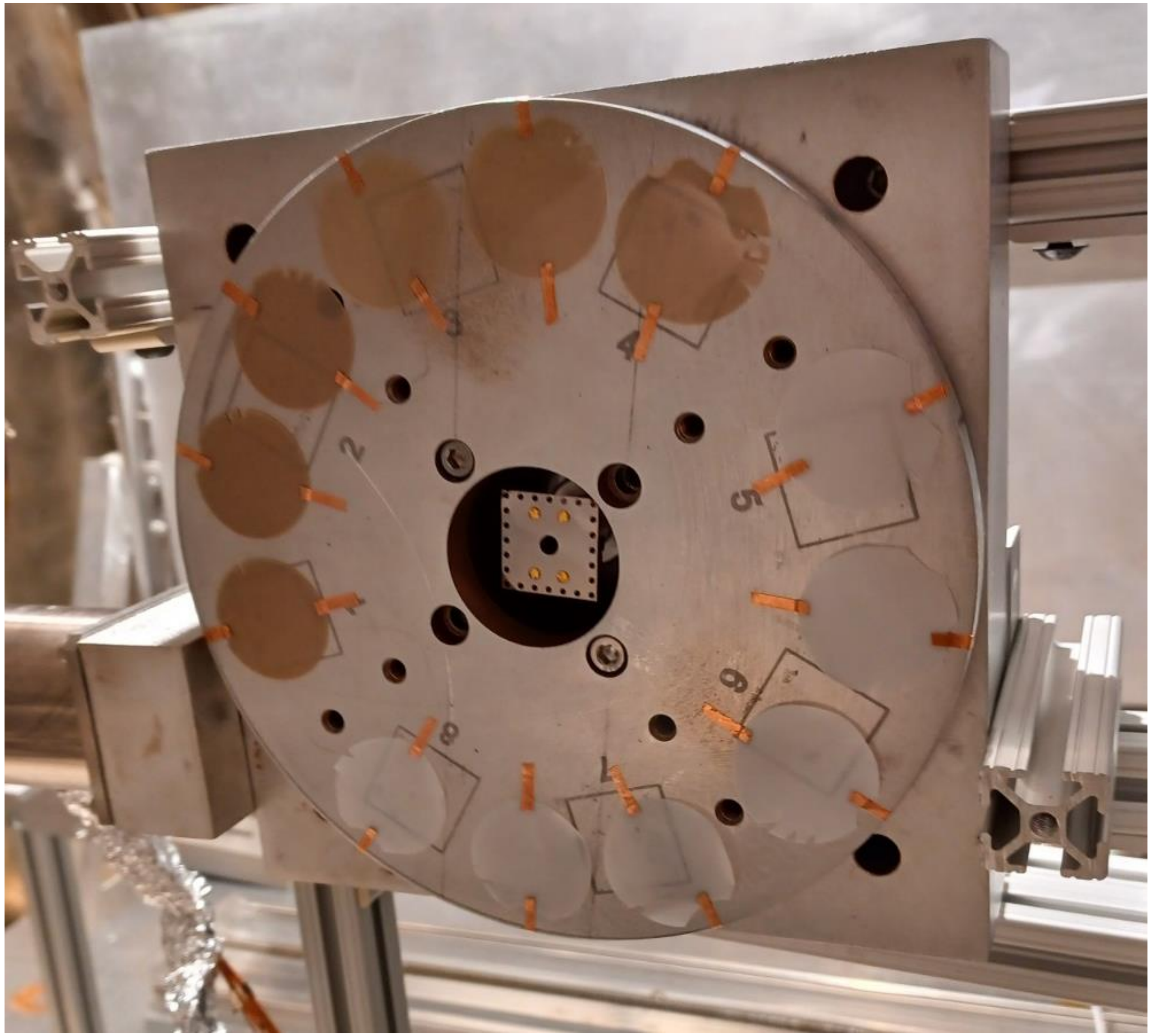
- Polyether-etherketone (PEEK)
- Polytetrafluoroethylene (PTFE)

Thicknesses

- 125 µm
- 250 µm

Irradiation Energy

- 50 keV
- 80 keV



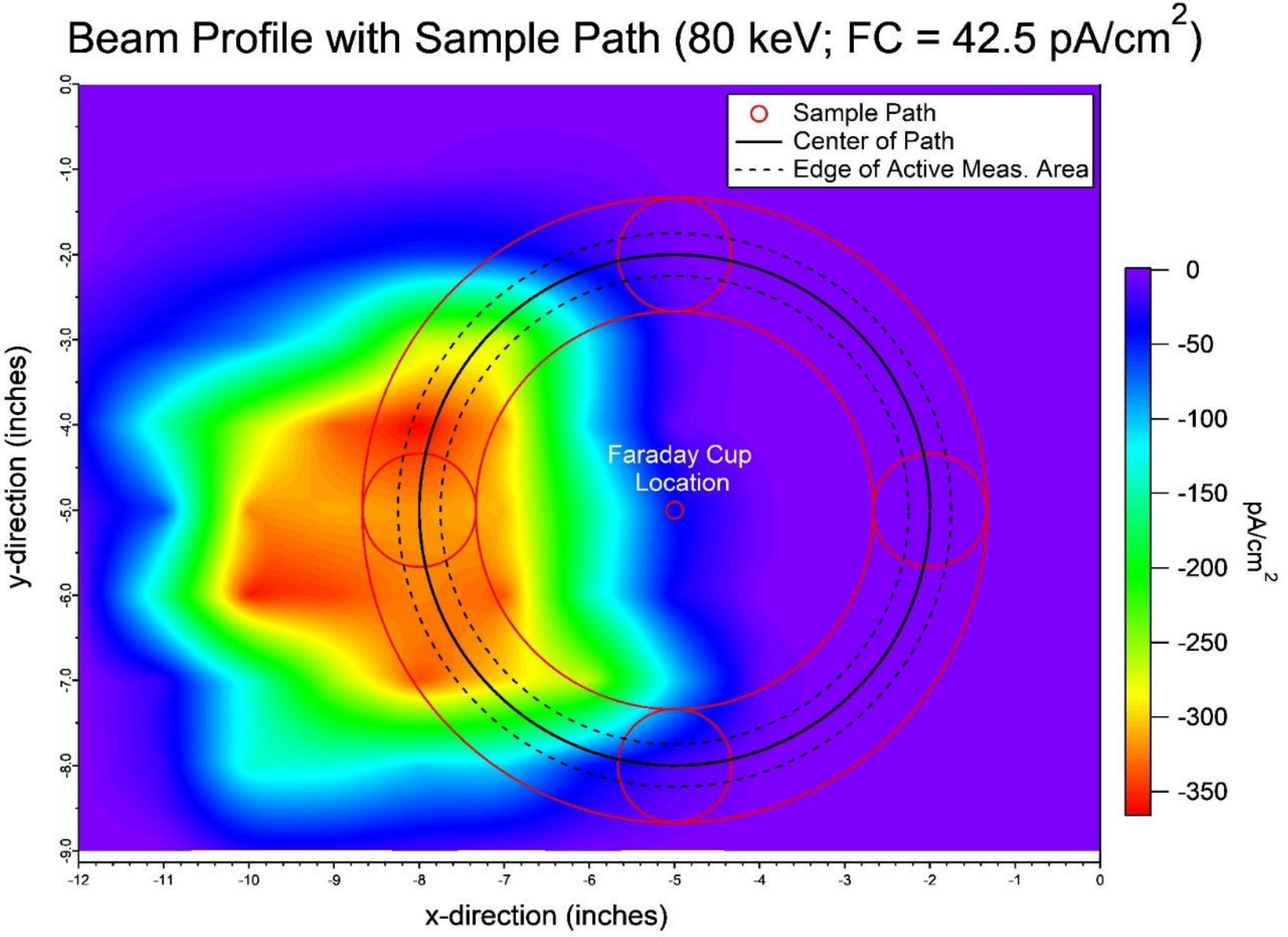
The Experiment – Irradiation Details

Average Flux

- For 80 keV, 210 pA/cm^2
- For 50 keV, 220 pA/cm^2

Irradiation time

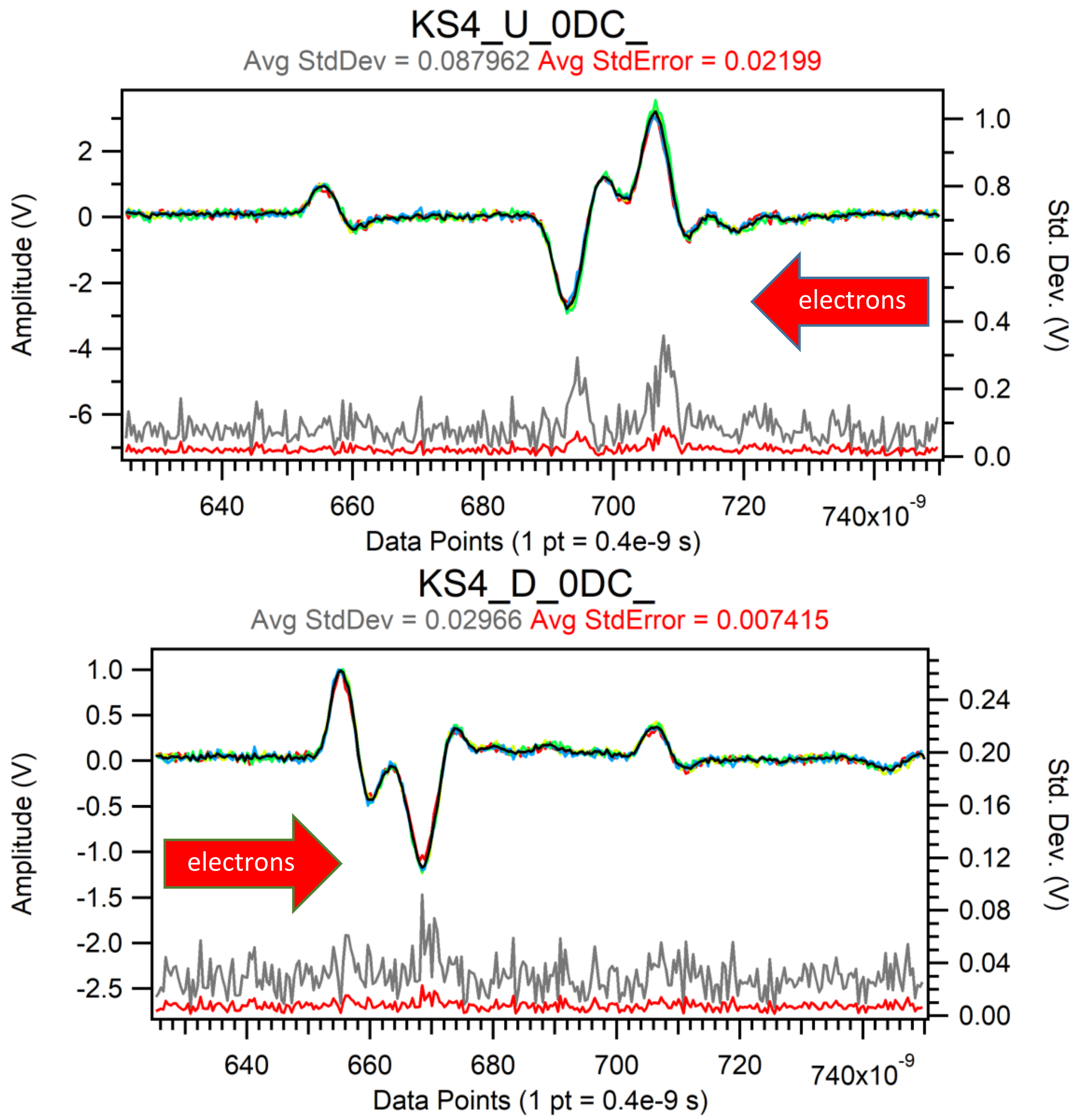
- 150 s
- 75 s in beam
- 75 s out of beam
- 30 s per rotation (2 RPM)



Typical Raw PEEK Measurement

- Low attenuation
- Low dispersion

- Deconvolution of this dataset is straightforward
- Calibration of data is straightforward



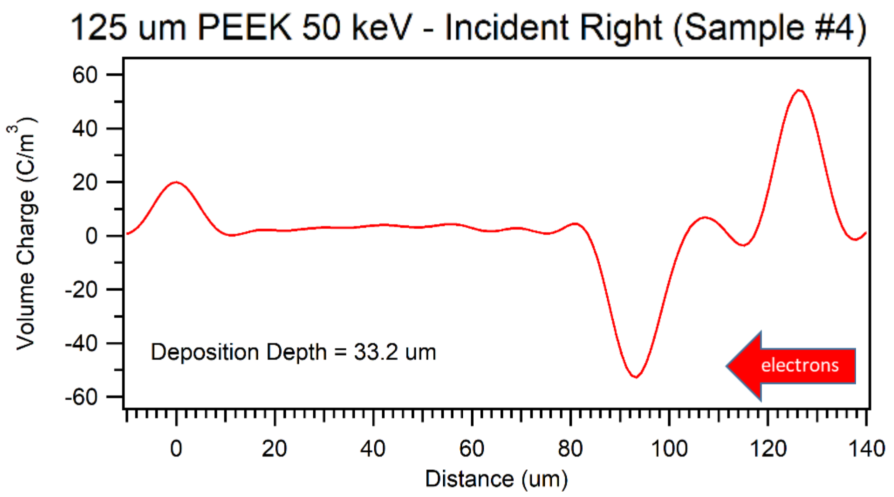
Results: PEEK 125 µm at 50 keV

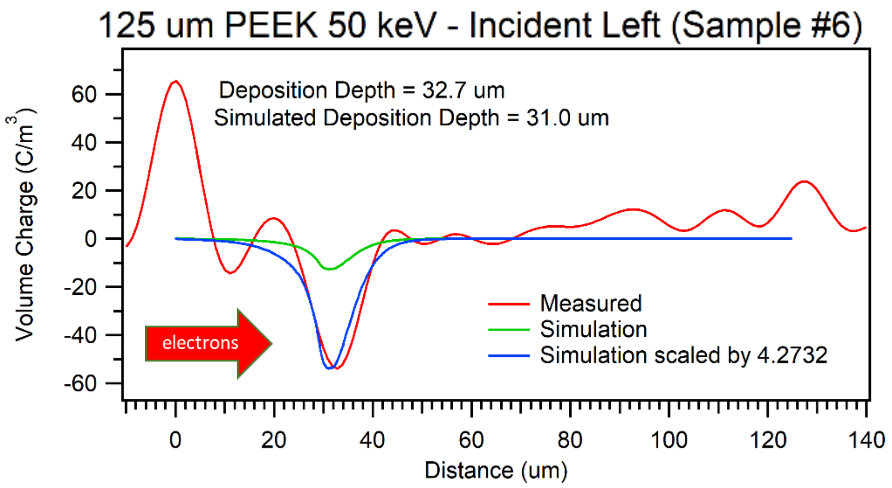
125 um PEEK 50 keV - Incident Left (Sample #4)

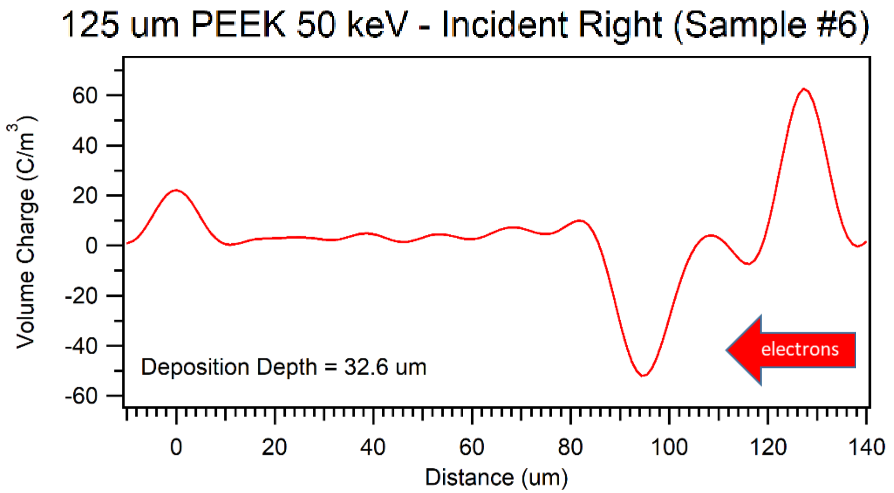
Measured: 33 ± 0.5 µm

Simulated: 31 µm

electrons



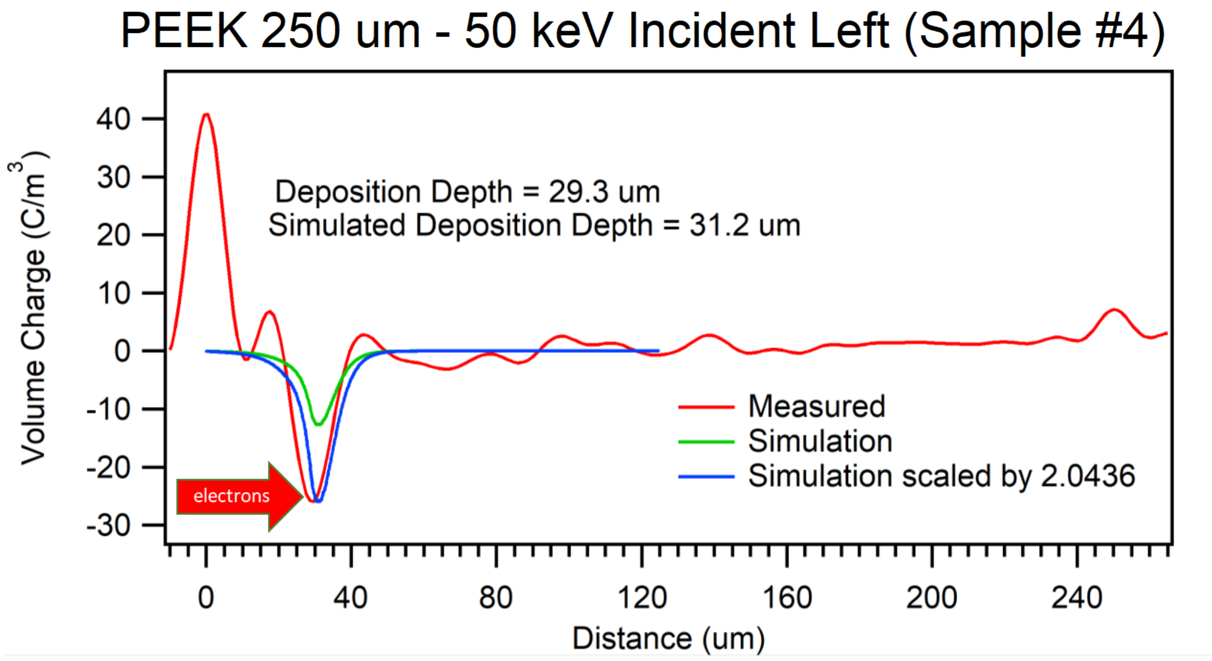


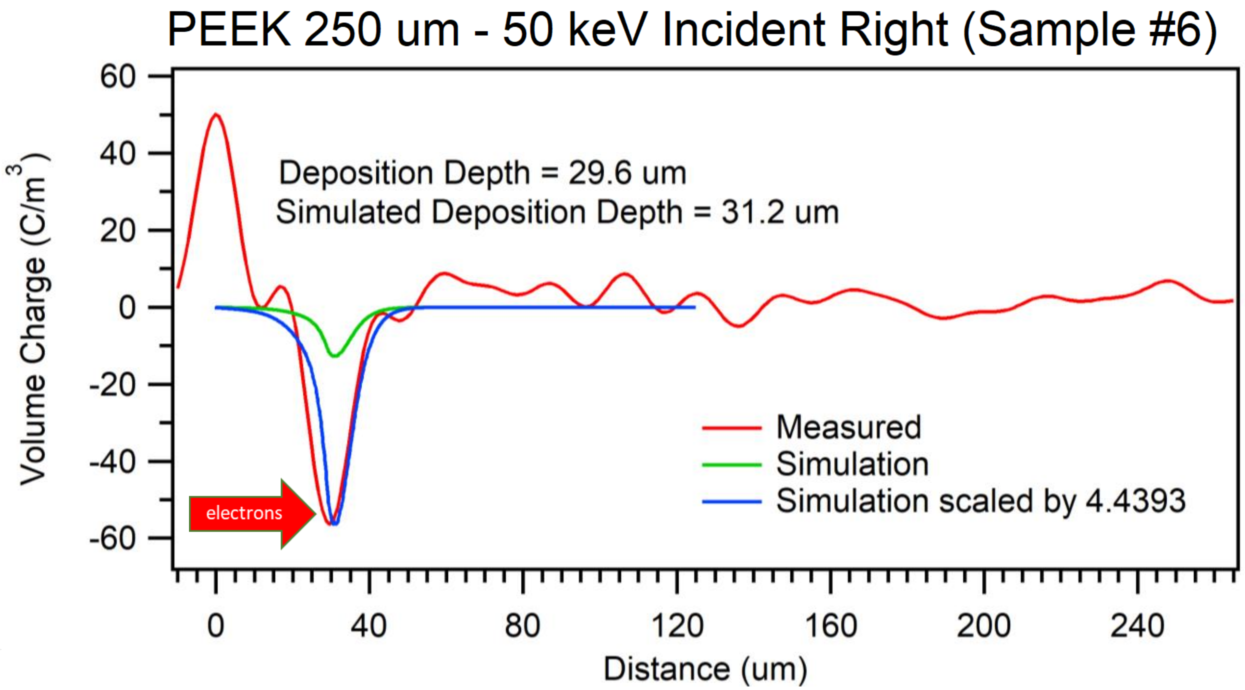


Measured: 33 ± 0.5 µm

Simulated: 31 µm

Results: PEEK 250 µm at 50 keV

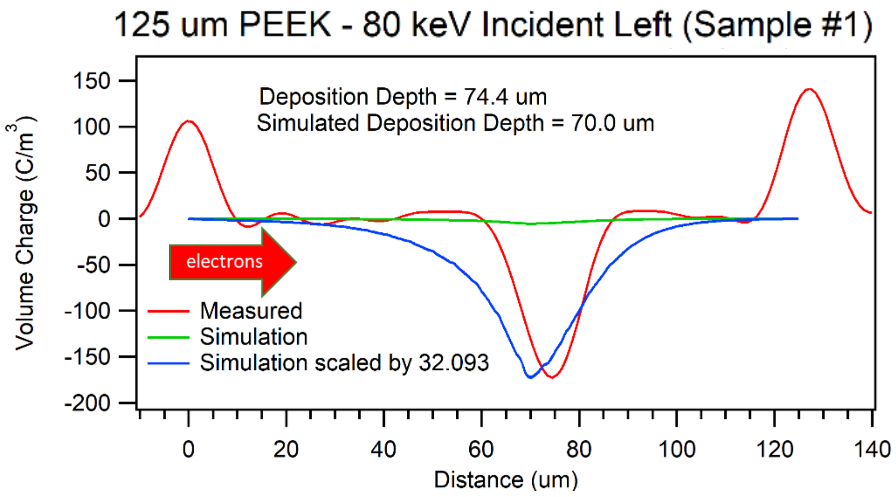


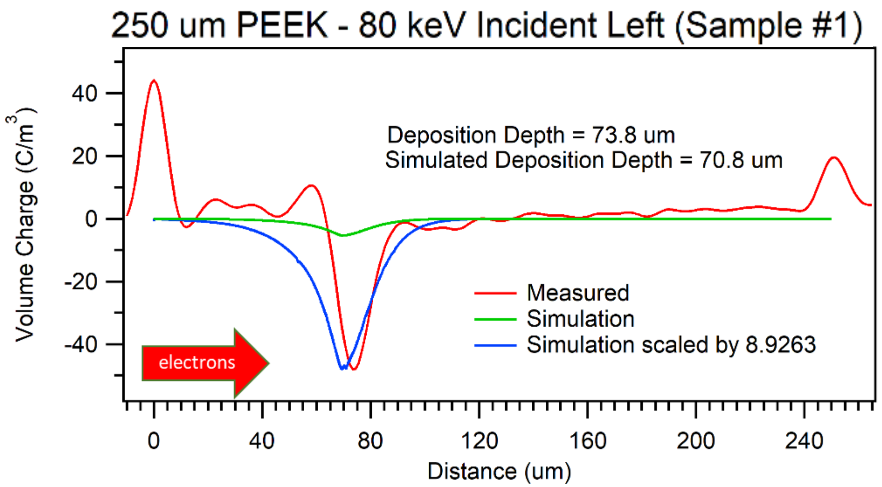


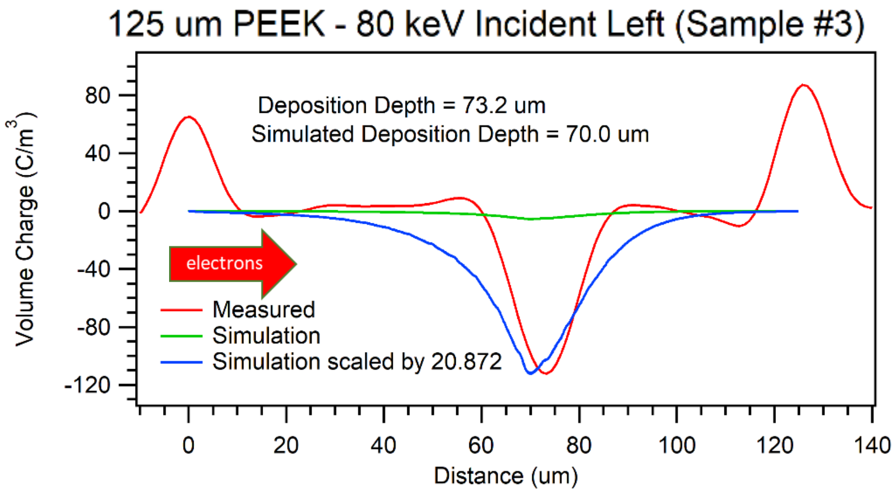
Measured: 29.5 ± 0.5 µm

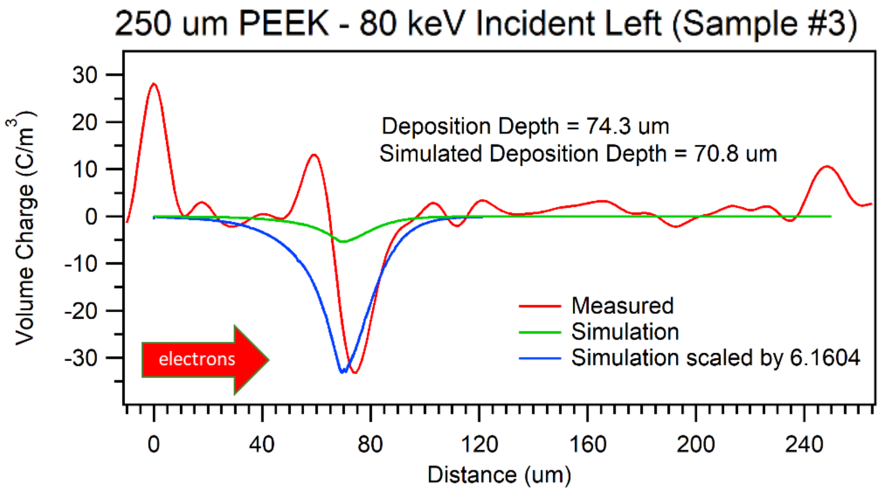
Simulated: 31.2 µm

Results: PEEK 125 and 250 µm at 80 keV









Measured: 74 ± 1 µm

Simulated: 70 µm

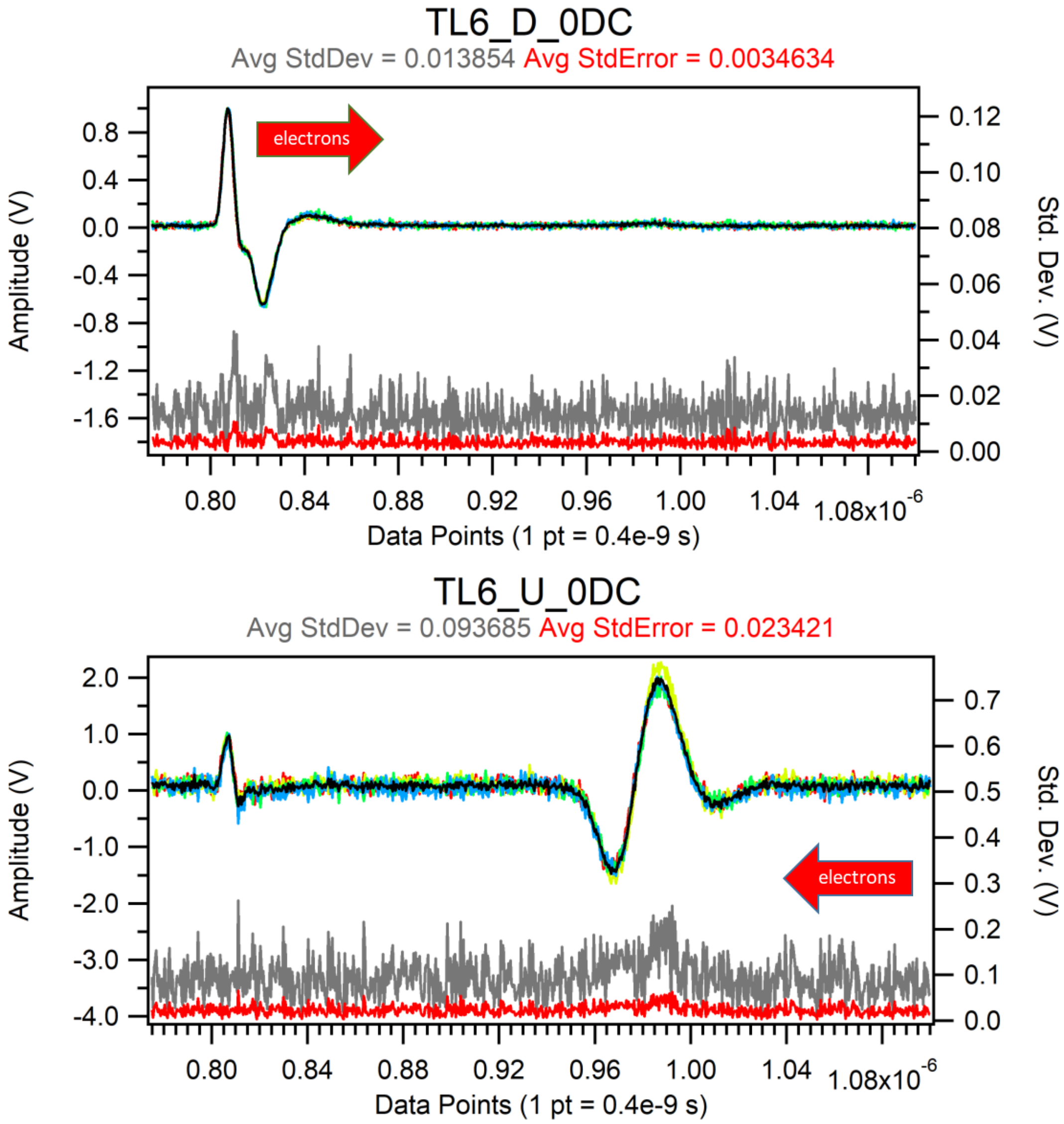
Measured: 74 ± 0.5 µm

Simulated: 70.8 µm

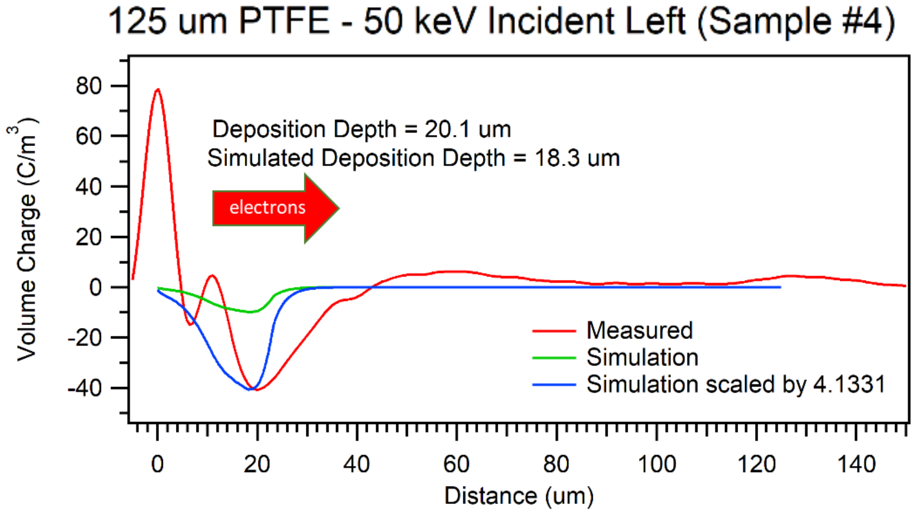
Typical Raw PTFE Measurement

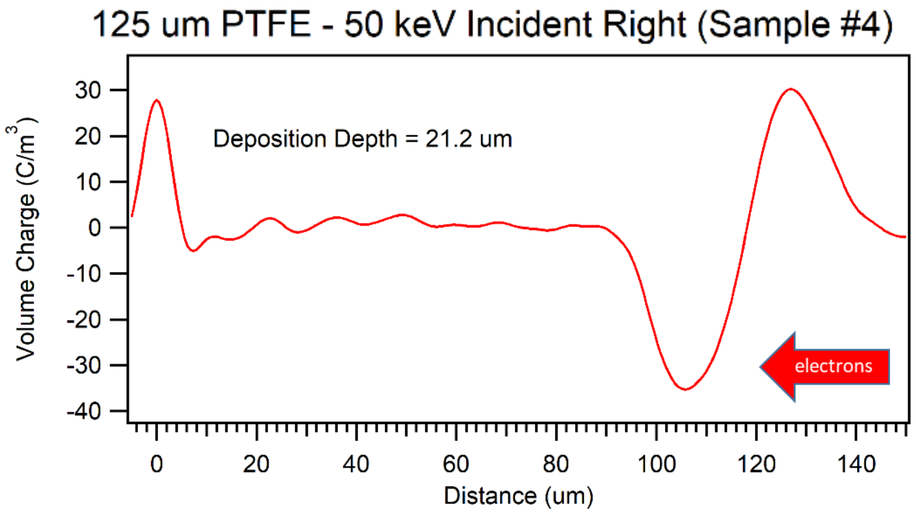
- Strong attenuation
- Strong dispersion

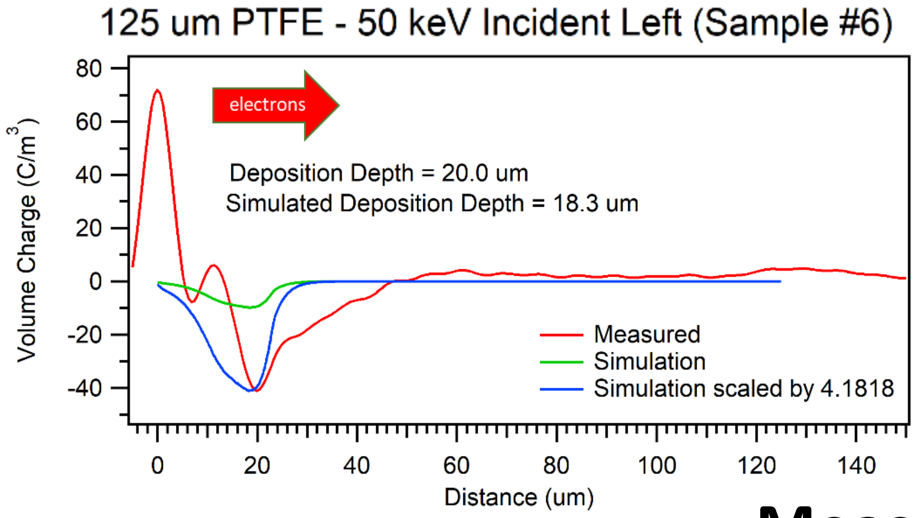
- Deconvolutions do not work as well on this dataset
- Calibration of data is difficult

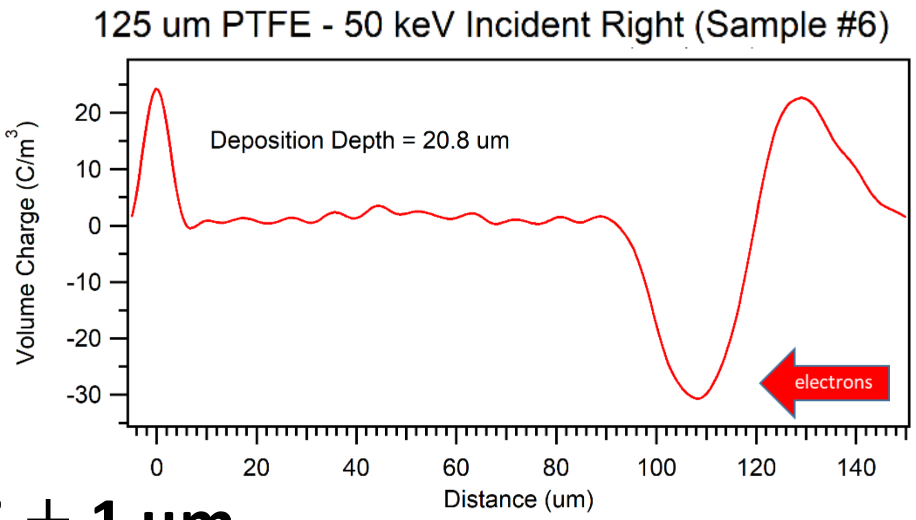


Results: PTFE 125 µm at 50 keV





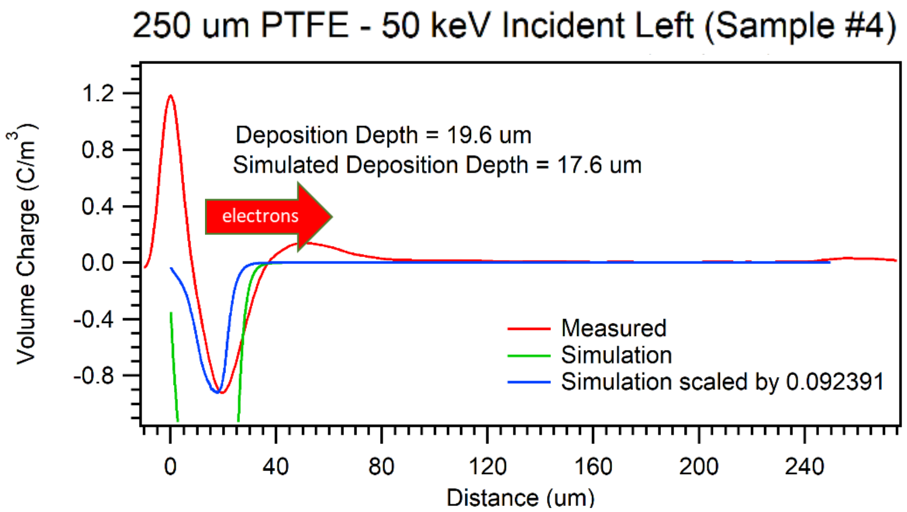


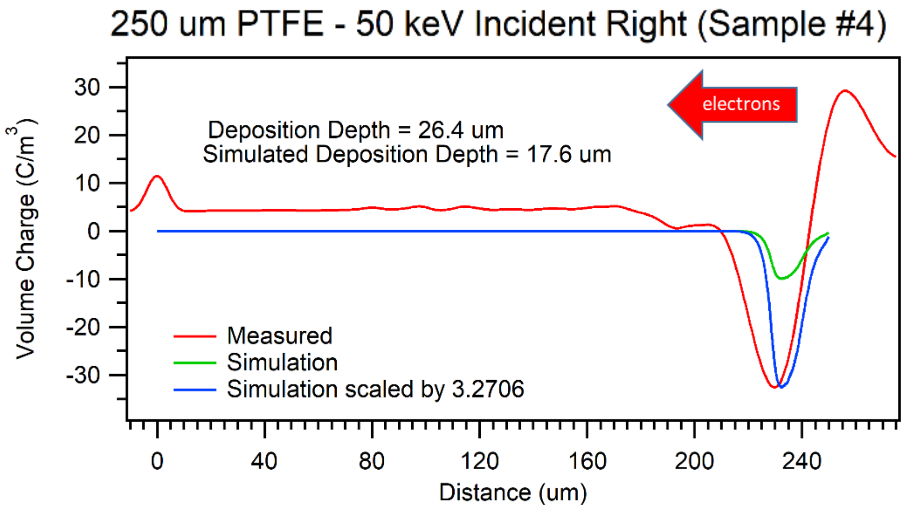


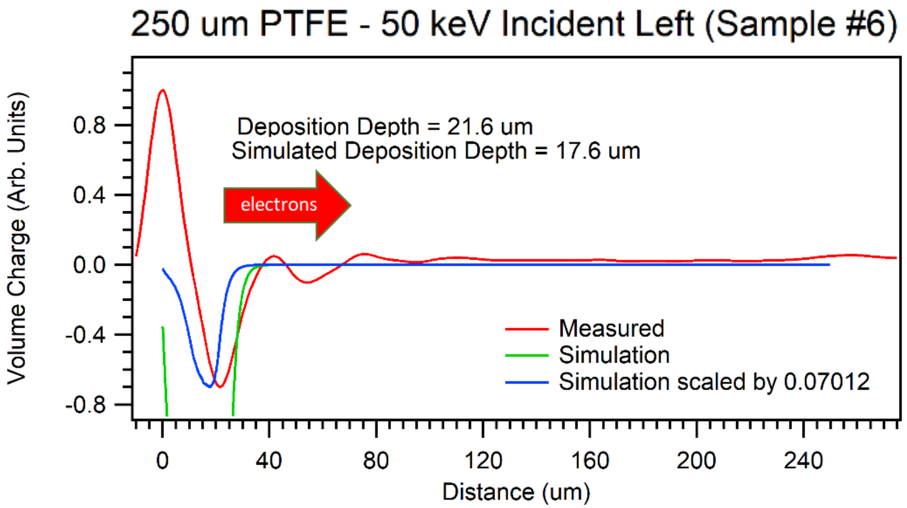
Measured: 20.5 ± 1 µm

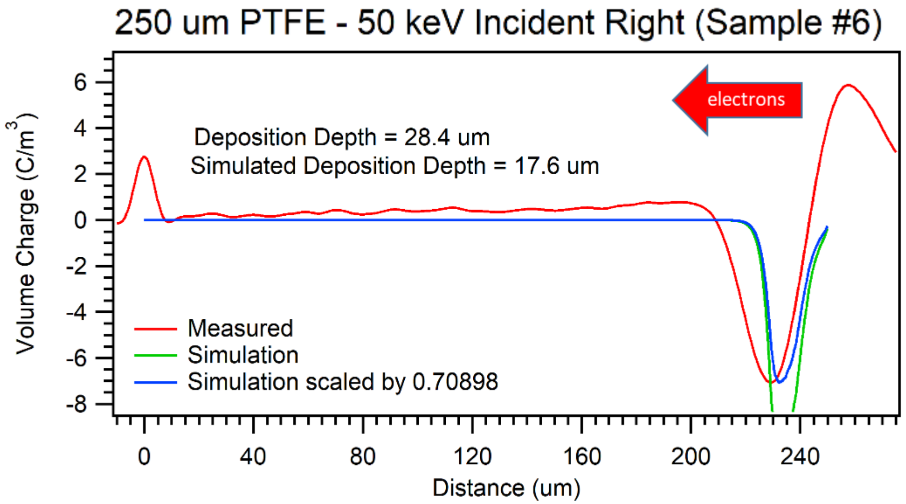
Simulated: 18 µm

Results: PTFE 250 µm at 50 keV









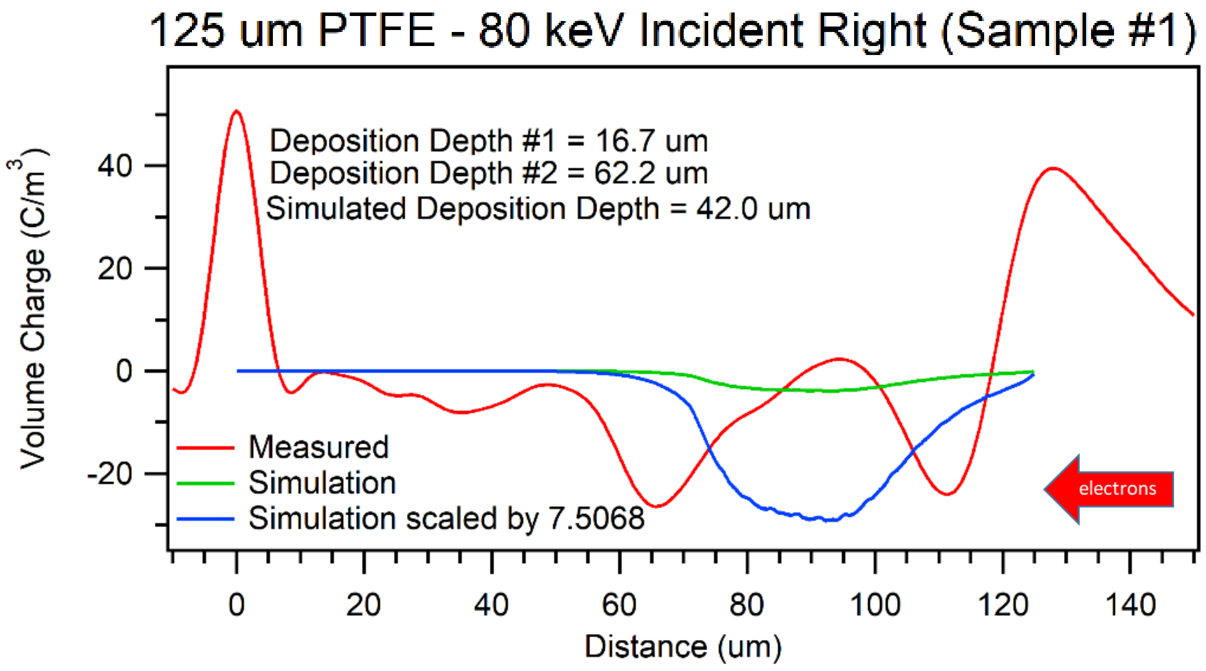
Measured: 20 $\pm$ 2 µm

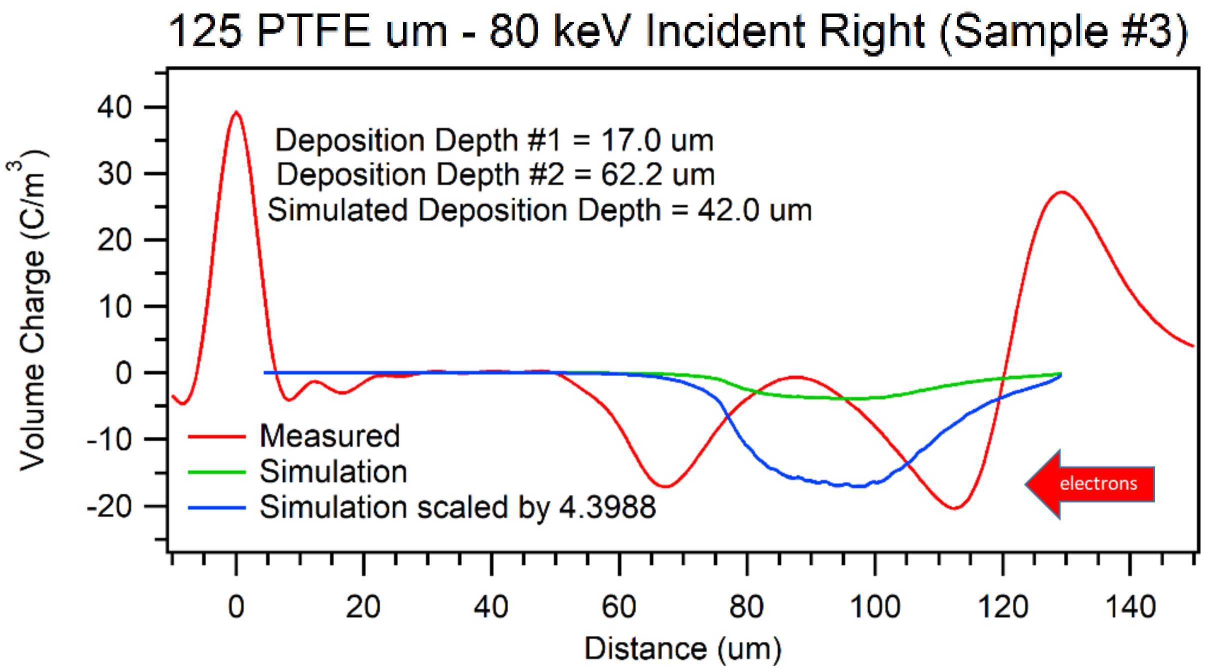
Simulated: 17.6 µm

Measured: 27 $\pm$ 3 µm

Simulated: 17.6 µm

Results: PTFE 125 µm at 80 keV

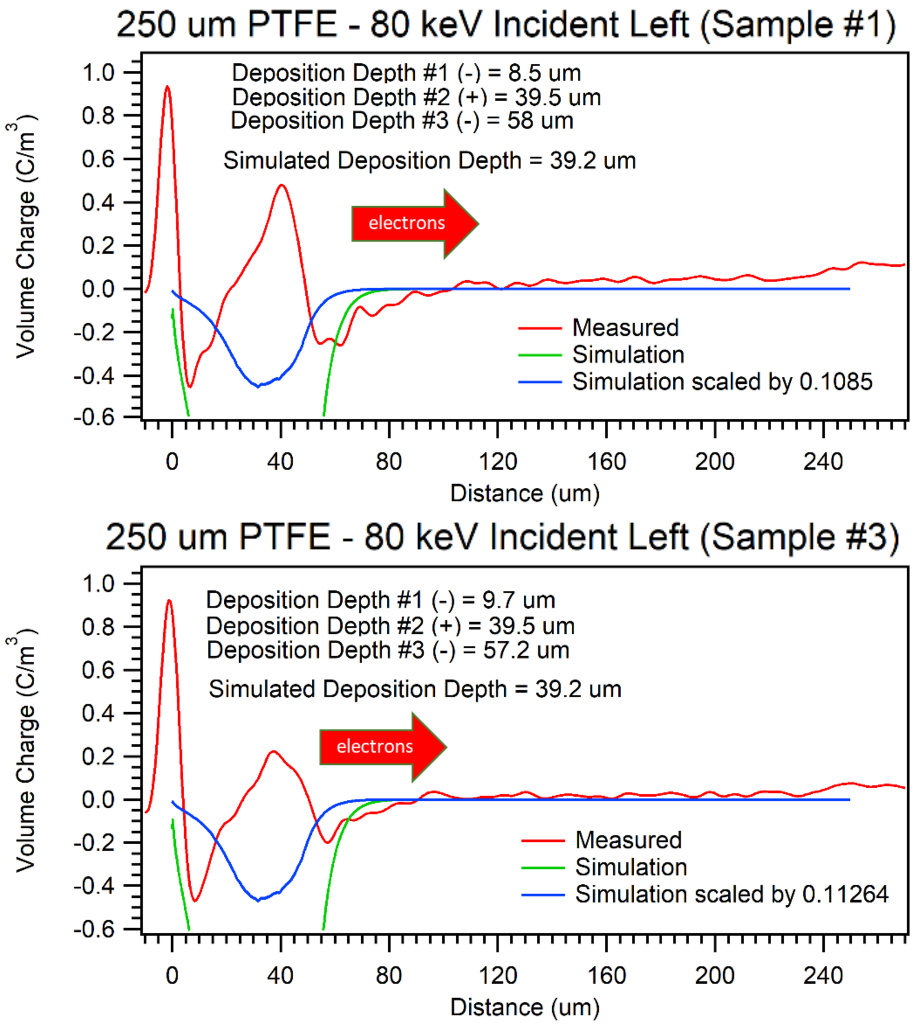


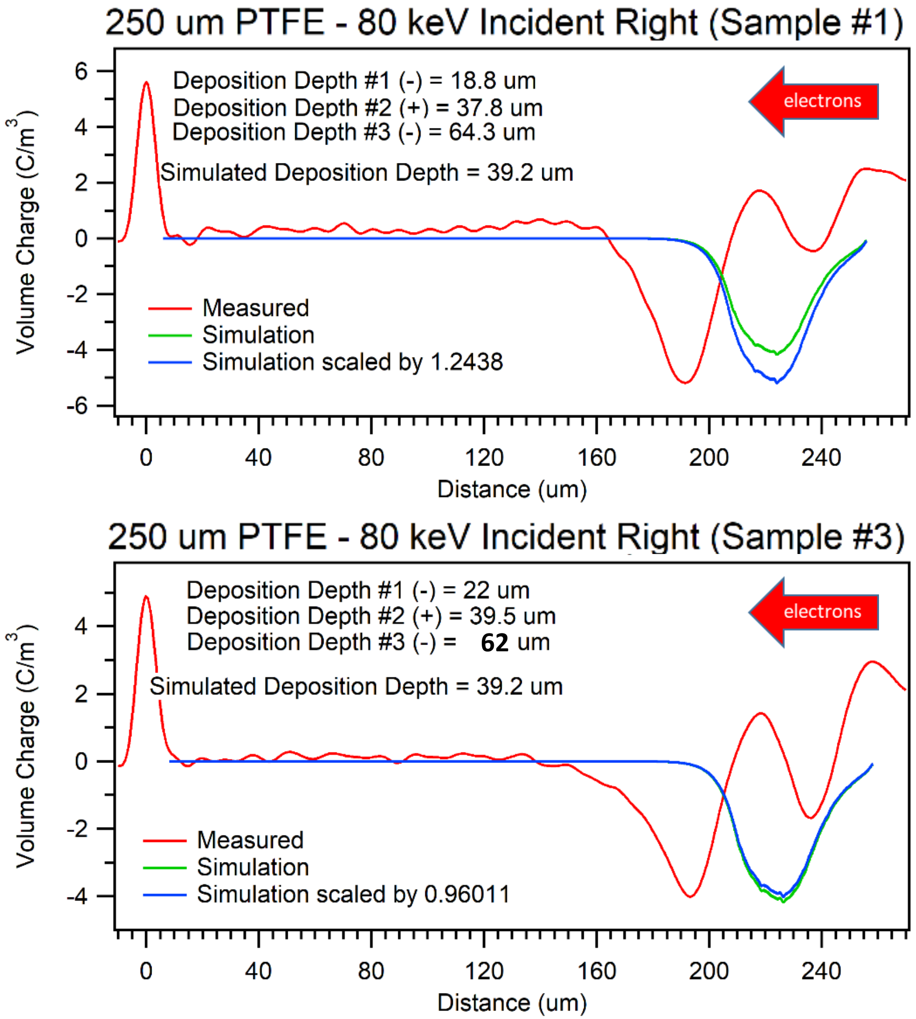


Measured: 17 $\pm$ 0.5 µm and 62 $\pm$ 0.5 µm

Simulated: 42 µm

Results: PTFE 250 µm at 80 keV





Measured: 9(-), 40 (+), and 58 (-) µm

Simulated: 39.2 µm

Measured: 20(-), 38 (+), and 63 (-) µm

Simulated: 39.2 µm

Conclusions

PEEK

- Measurements are self-consistent for a given sample when comparing orientations of measurements
- Measurements are mostly consistent with samples exposed to similar environments
- Measurements agree fairly well with predicted deposition depths from AF-NUMIT3
- Experimental deviations in deposition depths needs to be investigated to be sure this is “real” and not within error

PTFE

- Data is not always self-consistent for a given sample, varying by several or tens of microns between measurements in different orientations
- Multiple peaks were measured in 80 keV irradiated samples
- AF-NUMIT3 predicted a single peak in between the measured peaks for 80 keV irradiated samples
- Deposition depths for 50 keV irradiated samples were in relatively good agreement with simulations from AF-NUMIT3

Overall

- Attenuation and dispersion needs to be corrected for in the data
- More work is needed in determining the absolute error of the magnitude of charge measured
- AF-NUMIT3 agrees fairly well with the data, aside from the multiple peaks in PTFE irradiated at 80 keV

Future Work

- Determine error and validity of the calibration of the charge magnitude in PEA measurements
- Correct for attenuation and dispersion in PEA measurements
- Investigate effects of RIC/DRIC on charge accumulation and migration
  - AF-NUMIT3 predicts differences between no RIC/RIC/DRIC simulations
  - Accumulation of charge from pulsed/continuous beam and low/high dose rate
- Address relative and absolute errors in PEA measurements for insight into differences in deposition depths between measurements/different samples
  - Differentiation resolution appears to be ~ 0.5 µm or less

Acknowledgements

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