electronCT Simulations with Allpix Squared

electronCT

Malinda de Silva,
K. Dojan, P. Schütze, S. Spannagel, H. Wennlöf
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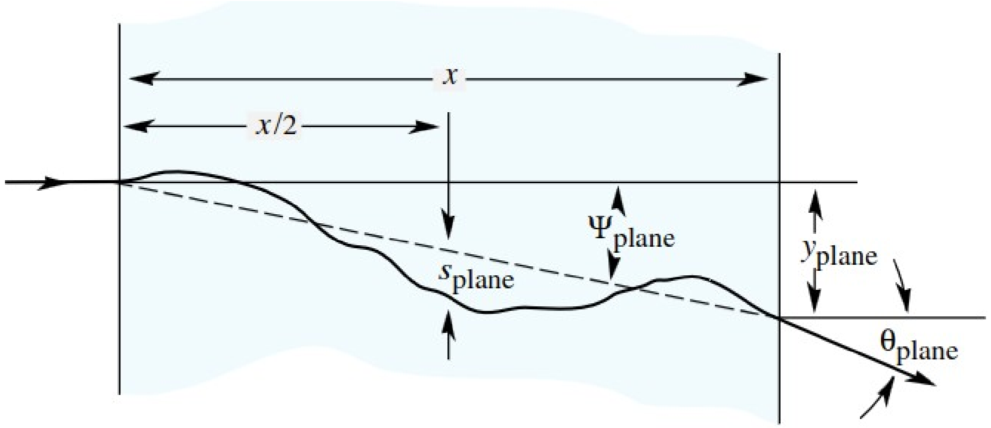
HELMHOLTZ

DESY.

Multiple Coulomb Scattering

Introduction

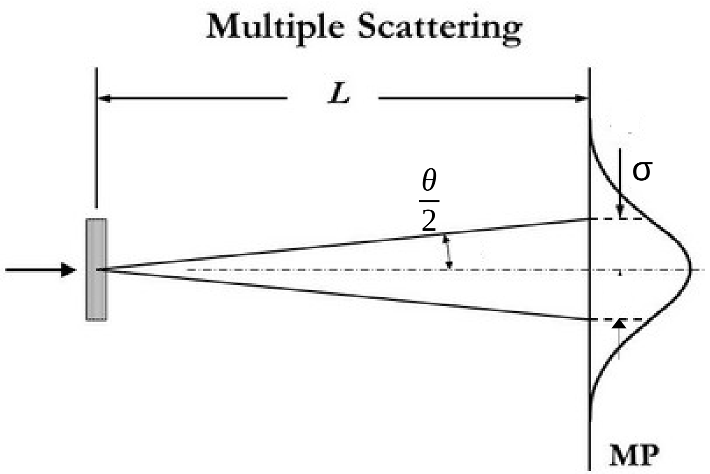
- High energy charged particles undergo multiple coulomb scattering (MCS)
  - Due to electric fields of nuclei in matter
  - Particles are deflected stochastically producing a scattering angle distribution



- Highland's formula describes how the scattering angle varies with material budget

$$\theta = \left(\frac{13.6\ MeV}{\beta c p}\right) \times \sqrt{\varepsilon} \times [1 + 0.038 \log(\varepsilon)]$$

where ε = material budget (thickness/radiation length)
p = momentum
βc = velocity



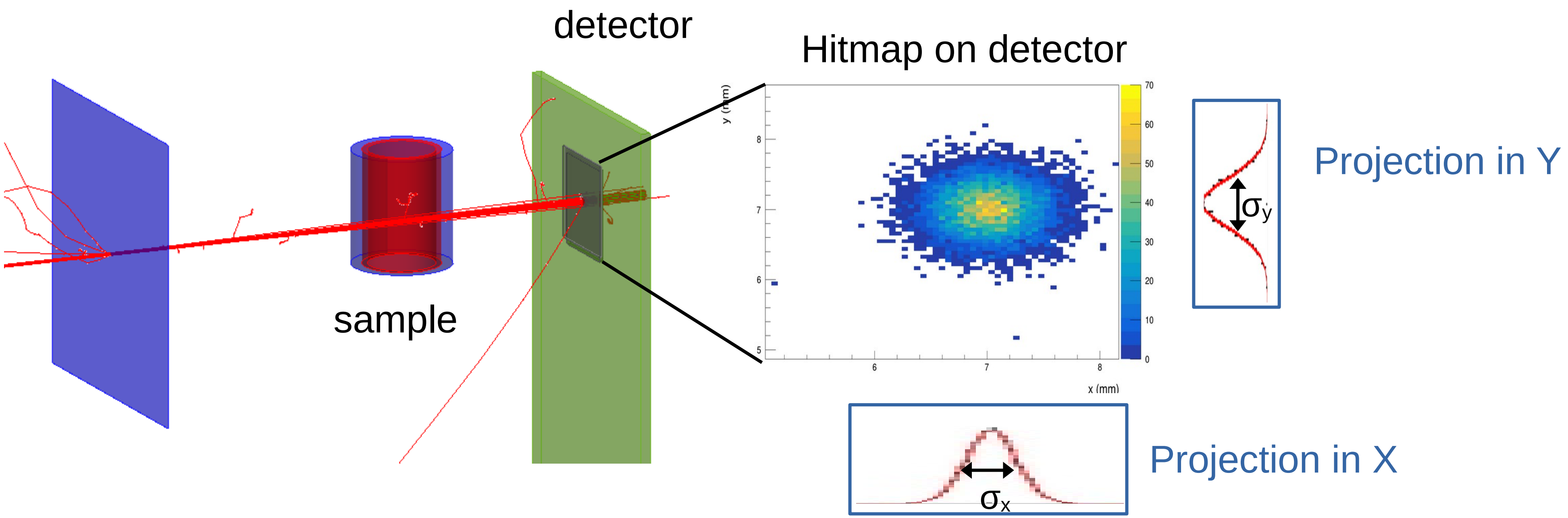
- The scattering angle distribution will contain information about the traversed material

- **electronCT: Perform imaging of macroscopic objects using the deflection distribution of electrons**

Methodology

Introduction to electronCT

- Use pencil beam to scan the sample and perform beam profile measurement downstream of the sample



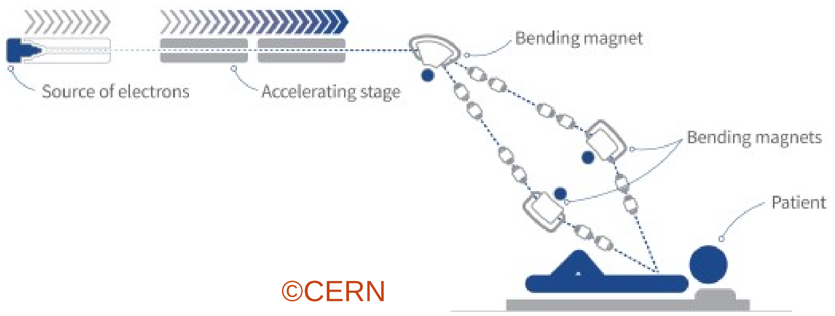
- Measured quantity from projections: from Gaussian fit
  - **width of beam profile** for given beam position

$$w = \frac{1}{2}(\sigma_x + \sigma_y)$$

Motivation

Introduction to electronCT

- **Imaging for Radiotherapy:**
  - Radiotherapy using Very-High Energy Electrons (VHEE, 100 – 250 MeV) is under wide investigation powerful tool when combined with FLASH therapy
  - Conventional CT or MRI used currently for imaging which requires a change in reference system
  - With electronCT :
    - Use the same accelerator for imaging and treatment
    - no change of reference system or patient relocation needed
    - Can be used to locate the tumor immediately before treatment



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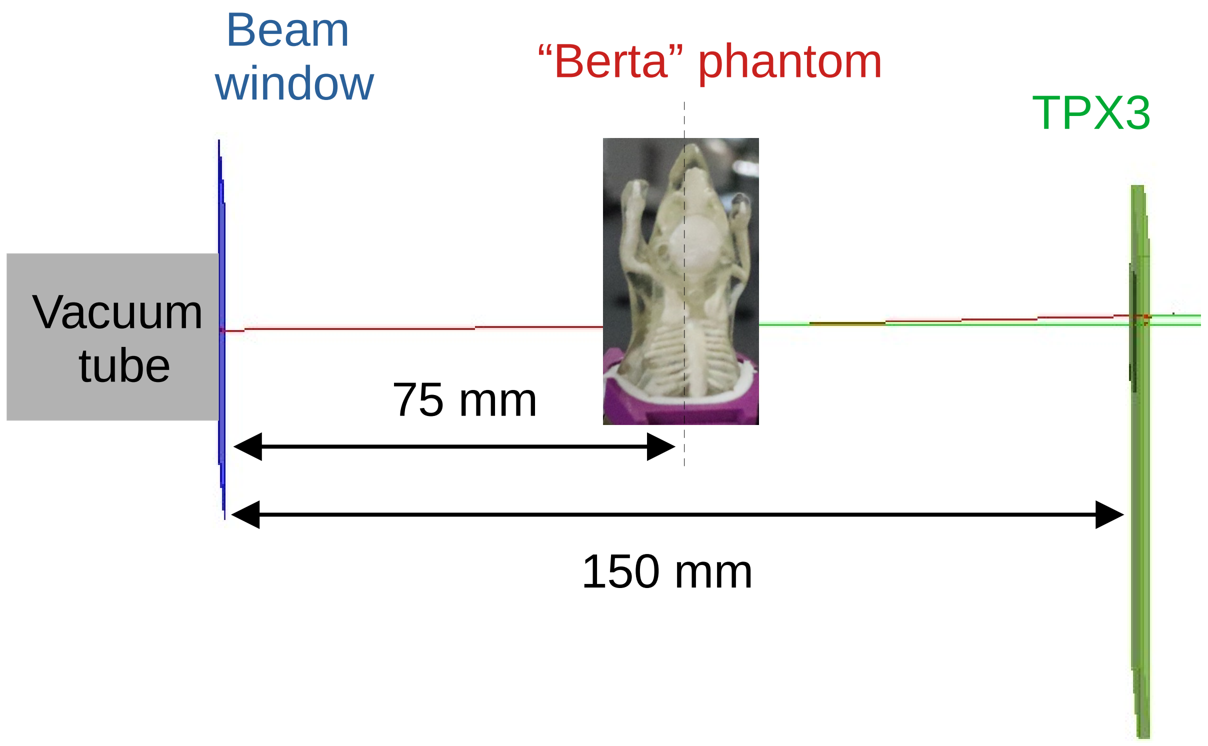
- **Industrial Imaging:**
  - Scattering angle distribution due to MCS depends on material budget (ε)
  - electronCT can be used:
    - to determine material properties of unknown materials
    - to image microelectronic components

Proof of Principle

electronCT

- Proof of principle of electronCT was established at the ARES accelerator facility at DESY
- **Test beam Setup:**
  - 155 MeV electron beam with width of ~300um at origin
  - Timepix3 sensor placed 150mm away from origin
  - Titanium beam window separated the vacuum beam pipe from the rest of the setup
  - Medical rat phantom on x-y-φ motion/rotation stage
    - “Berta”: solid (resin), detailed skeleton
  - Katherine readout module used for DAQ
- Around 3000-8000 electrons produced per bunch at 10 Hz rate
- Typical scan currently takes a few hours to complete



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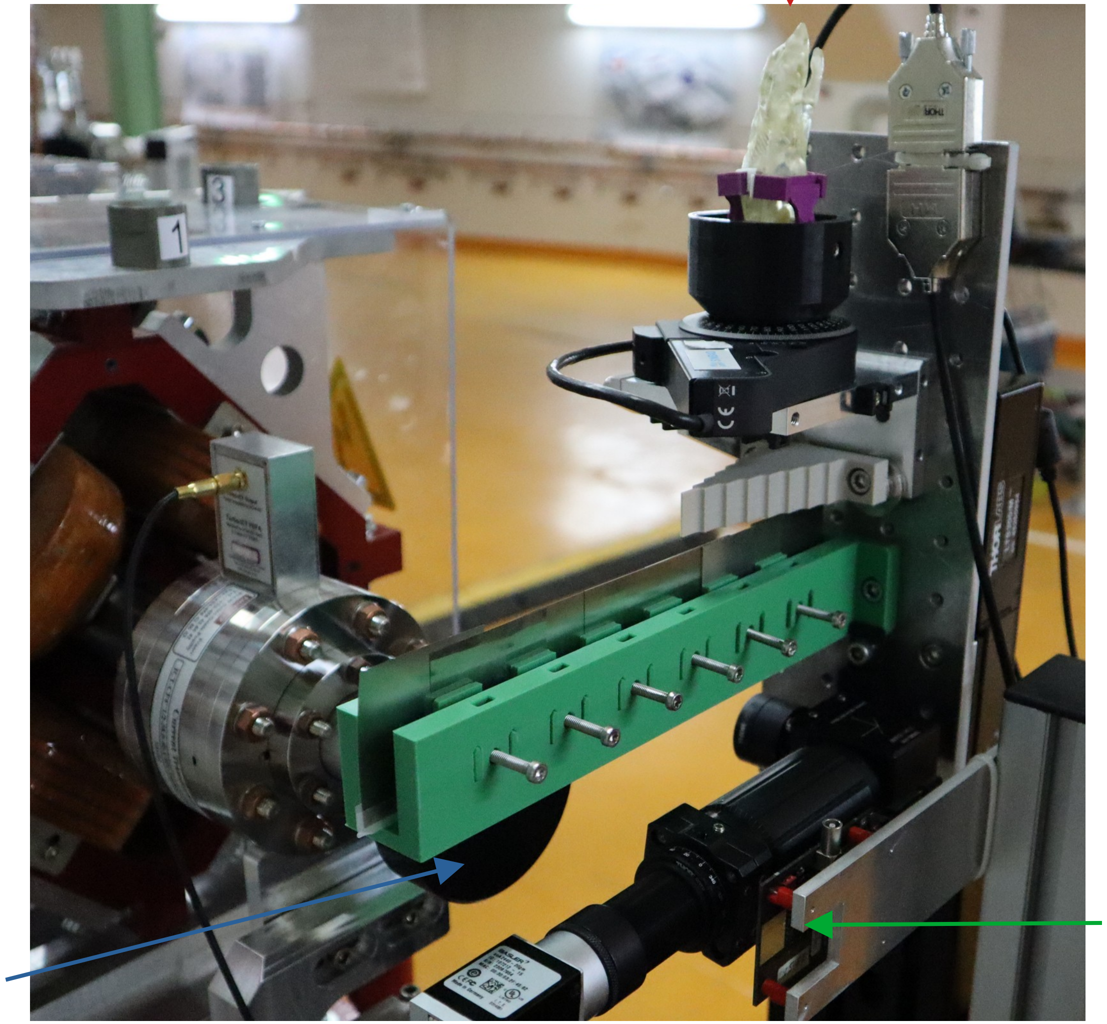

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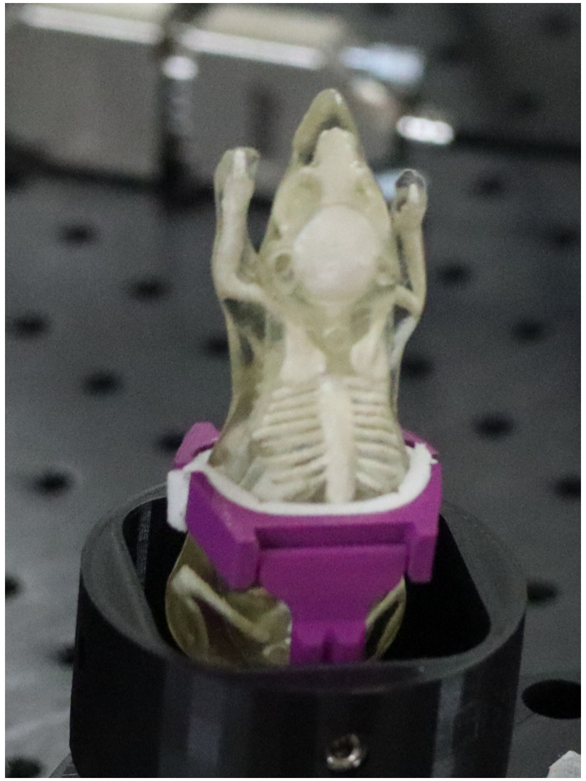

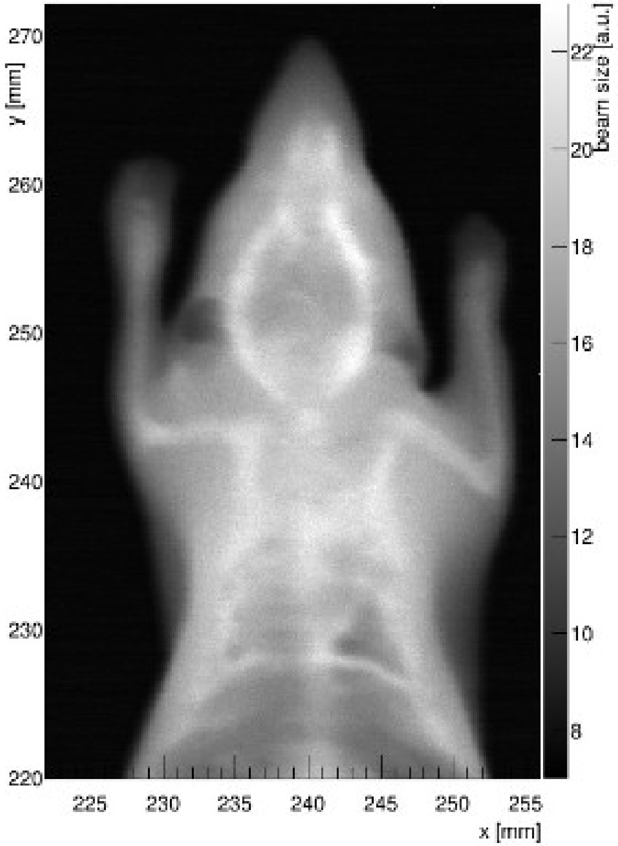

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- Typical scan currently takes a few hours to complete

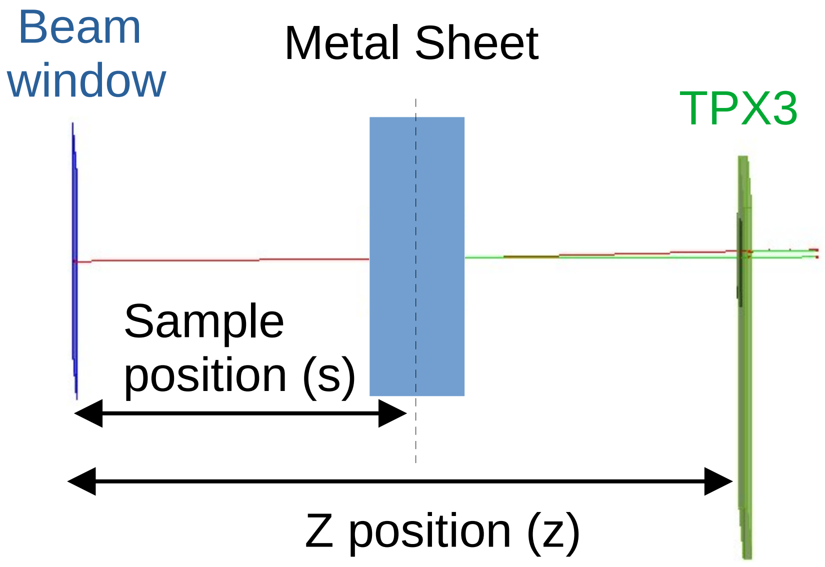
Simulations with Allpix Squared

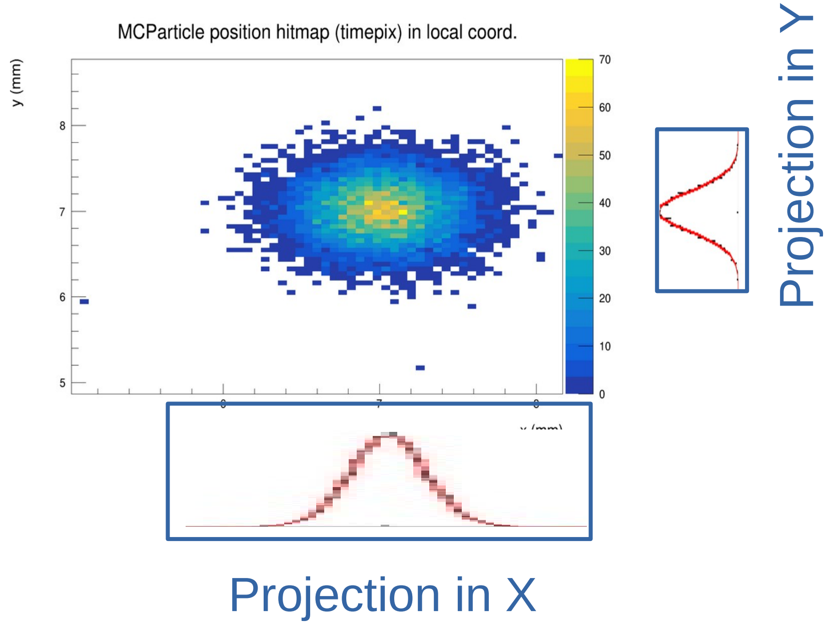
electronCT

- It is important to simulate the beam setup in order to understand the strengths and limitations of this novel method
  => Using Allpix Squared

- **Simulation with Allpix Squared:**
  - One event with 10,000 electrons
  - Only MCParticle object used for analysis, detector response not used
    - Reason: Some properties of the Timepix3 assembly used were unknown at the time of the initial studies (eg: electronic noise, threshold smearing, QDC parameters)

- **First Goals:**
  - Replicate the exact beam conditions using Allpix Squared including beam profile in z direction
  - Reproduce the width of the beam with simulations under different conditions measured during test beam





Config Files

Using Allpix Squared

Main Config file

```
random_seed = 12345
number_of_events = 1

[GeometryBuilderGeant4]
world_material = "air"

[DepositionGeant4]
physics_list = FTFP_BERT_LIV
particle_type = "e-"
number_of_particles = 10000
source_energy = 155MeV
source_position = 0mm 0mm -200um

source_type = "beam"
focus_point = 0mm 0mm 220mm
beam_size = 300um
beam_direction = 0 0 1
max_step_length = 5um
record_all_tracks = true

[ROOTObjectWriter]
file_name = "data.root"
include = "MCParticle" "MCTrack"
```

Detector geometry file

```
[vacuum]
type = "cylinder"
length = 300um
outer_radius = 3mm
position = 0mm 0mm -150um
orientation = 0deg 0deg 0deg
material = "vacuum"
role = "passive"

[beamwindow]
type = "cylinder"
length = 45um
outer_radius = 3mm
position = 0cm 0cm 127.5um
orientation = 0deg 0deg 0deg
material = "ti5"
role = "passive"
mother_volume = "vacuum"
```

```
[timepix]
type = "timepix"
sensor_thickness = 100um
position = 0um 0um 200mm
orientation_mode = "xyz"
orientation = 0deg 0deg 0deg

[DetectorLayer]
position = 0 0 75mm
```

Modeling the ARES Beam Profile

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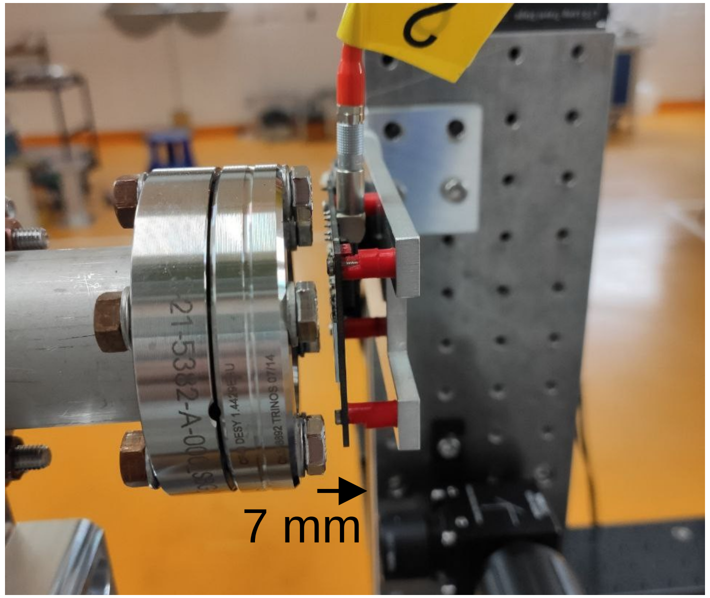
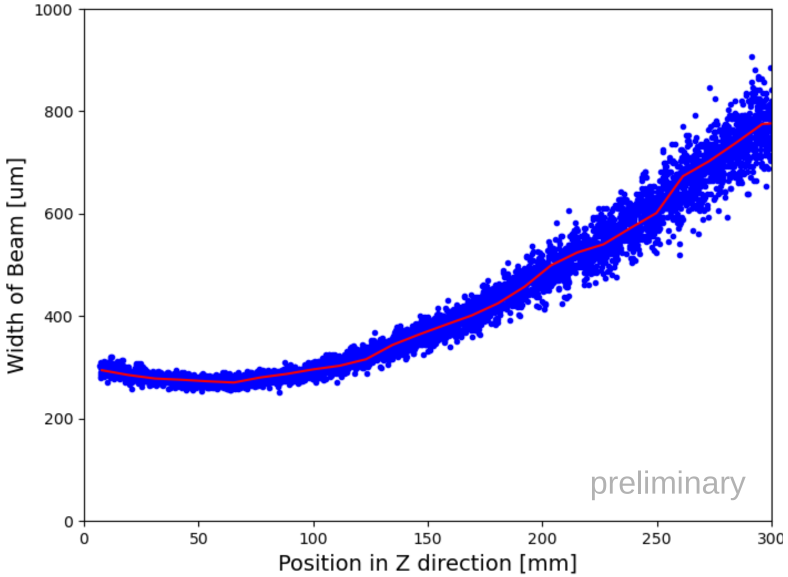
Beam Profile in Z Direction: Test Beam Data

Data from April 2024 Test Beam in ARES



- Beam profile was measured by changing distance between beam window and stage holding the timepix3
  - No sample placed in between
- Observation:
  - Beam converges until ~75 mm and diverges from that point onward
- **Challenge:**
  - **Allpix Squared did not contain a method to focus a Gaussian beam to a point**



Focused Beam Implementation

Allpix Squared : Merge Request !1104

- Following changes were made to GeneratorActionG4.cpp
  - Added new variable “focus_point” to source_type=“beam”
  - Usage in config file:

```
[DepositionGeant4]
source_type = "beam"
focus_point = 0mm 0mm 220mm
```

  - focus_point and beam_divergence are mutually exclusive. Only one of the two should be defined and not both.

```
if(config_.count({"beam_divergence", "focus_point"}) > 1) {
    throw InvalidCombinationError(config_,
                                  {"beam_divergence", "focus_point"},
                                  "Beam divergence and beam focus point are mutually exclusive!");
}
```

```
if(config_.has("focus_point")) {
    // Set beam to focus
    single_source->GetAngDist()->SetAngDistType("focused");
    auto focus_point = config_.get<G4ThreeVector>("focus_point");
    single_source->GetAngDist()->SetFocusPoint(focus_point);
} else {
```

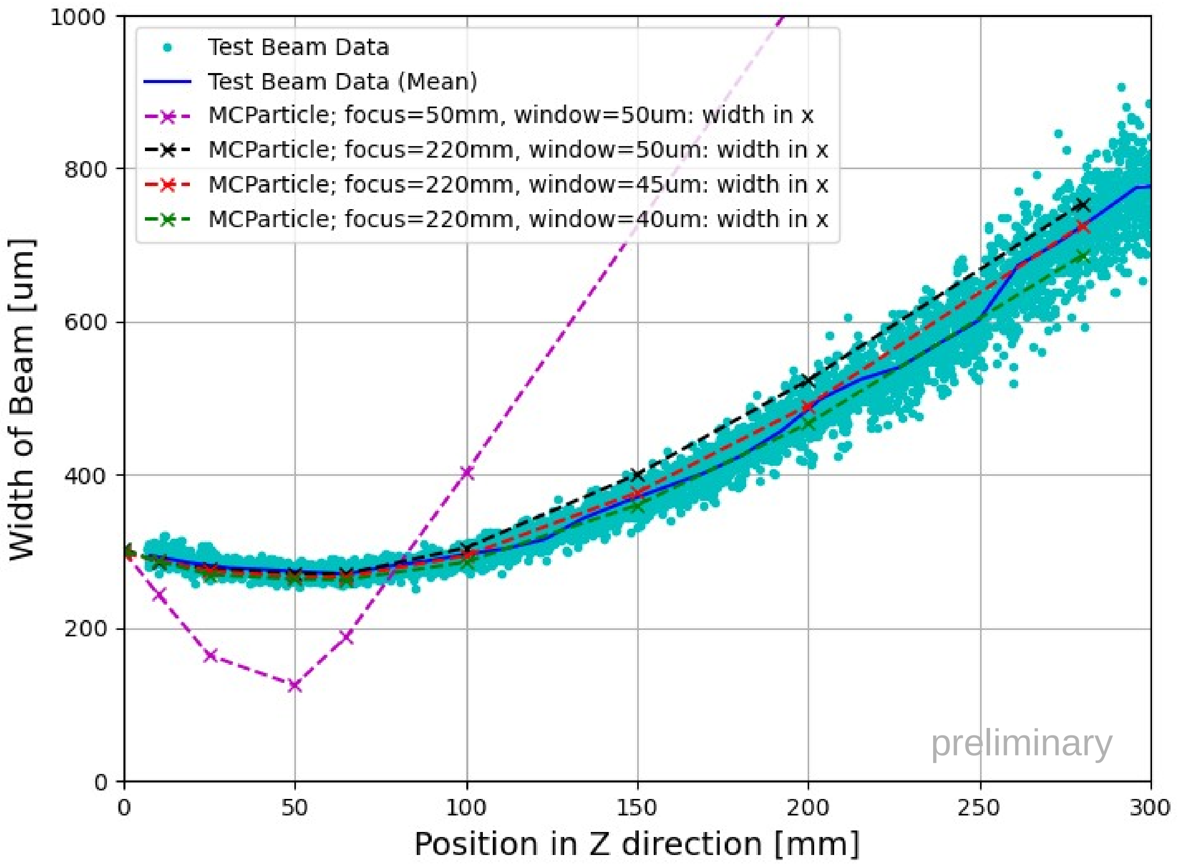
  - Merged with Master branch

Simulating the Beam Profile in Z-Direction

Allpix Squared Simulation

- **Geometry Implemented on Allpix Squared**
  - World volume : Air
  - Particle gun at z= -200um (placed in a vacuum)
  - With Ti5 beam window placed at origin (varying sizes)
  - Focused beam at point z=220mm

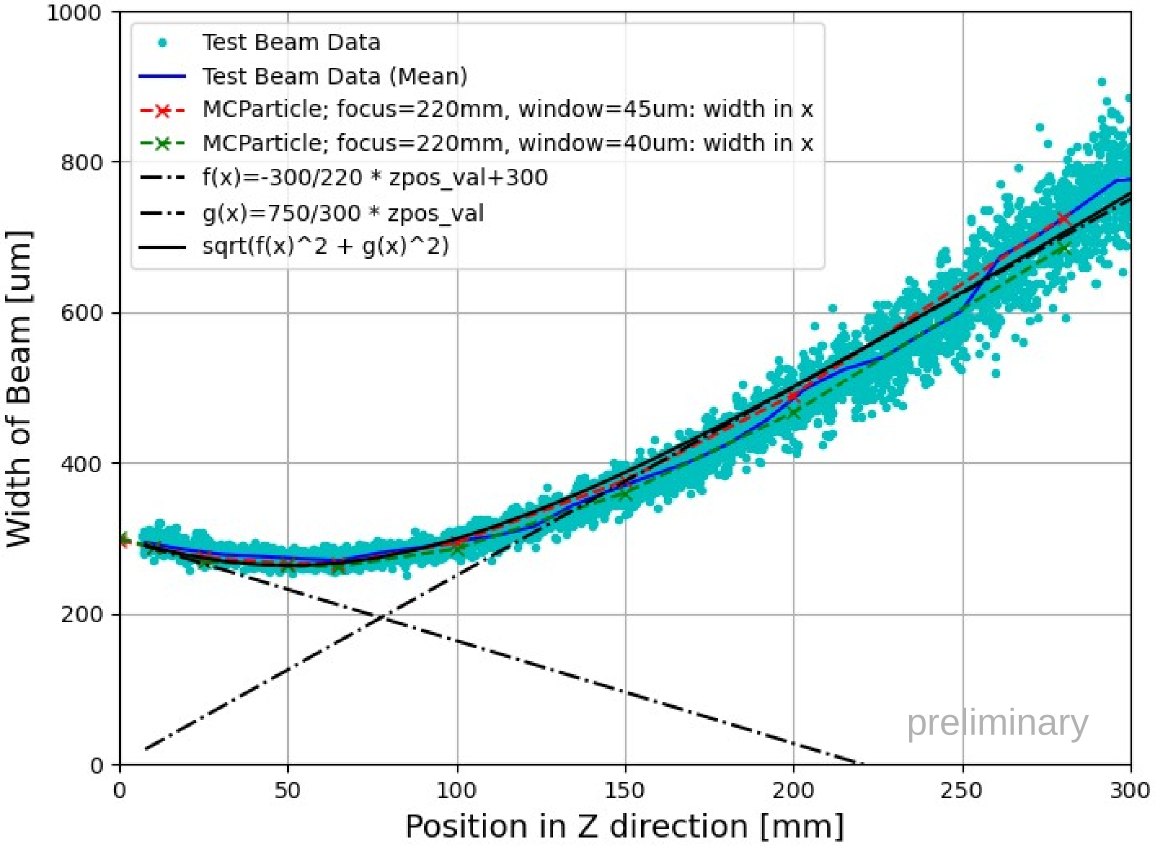
- **Results:**
  - Beam can be modeled assuming a window of ~45um.
  - Titanium beam window used at ARES claims to be (50 +/- 5) um thick.



Mathematical Modeling the Beam Profile in Z-Direction

Parametrization of Beam Profile

- Beam can be further mathematically modeled by using two linear functions
- Function 1: Effect due to focused beam
  - $$f(z) = \frac{beam\,width\,at\,origin}{focal\,point} \times z + beam\,width\,at\,origin$$
- Function 2: Effect due to 45um titanium window
  - $$g(z) = gradient\,at\,tail \times z$$
- **Quadratic sum of two functions models the beam profile in z direction in the range 0<z<300mm**
  - $$P(z) = \sqrt{f(z)^2 + g(z)^2}$$

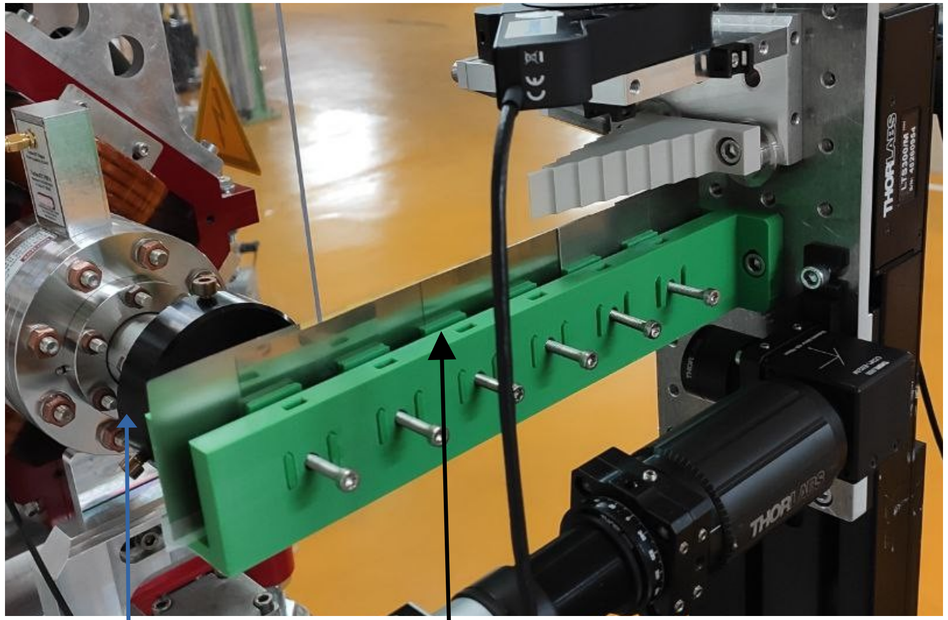


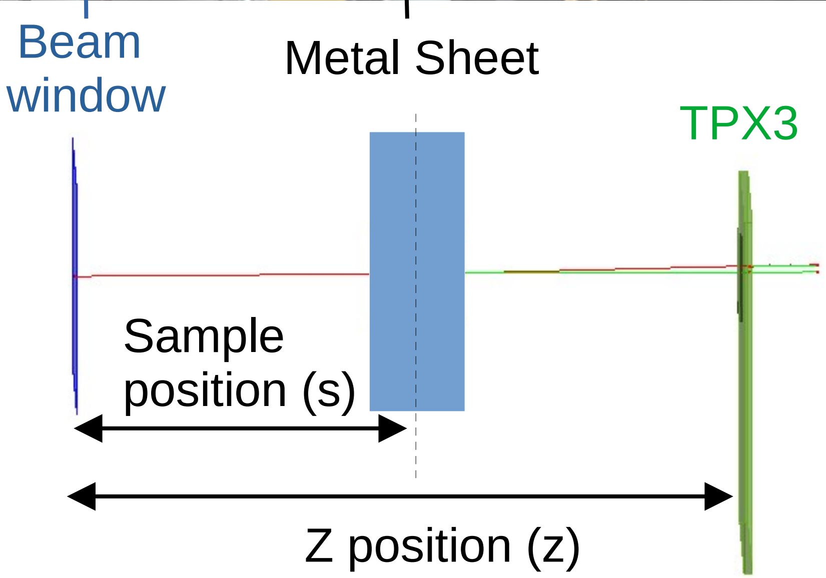
Variation of Width with Material Thickness

Material Thickness vs Beam Width:

Test Beam Data

- Two metals of different thicknesses were used as samples to further characterize the beam width
  - Nickel sheets of thicknesses ranging between 0.025 mm and 3 mm
  - Aluminum sheets of thicknesses ranging between 0.025 mm and 4 mm
- Nickel and Aluminum sheets were placed on a mechanical holder such that there are overlaps to produce more thicknesses.

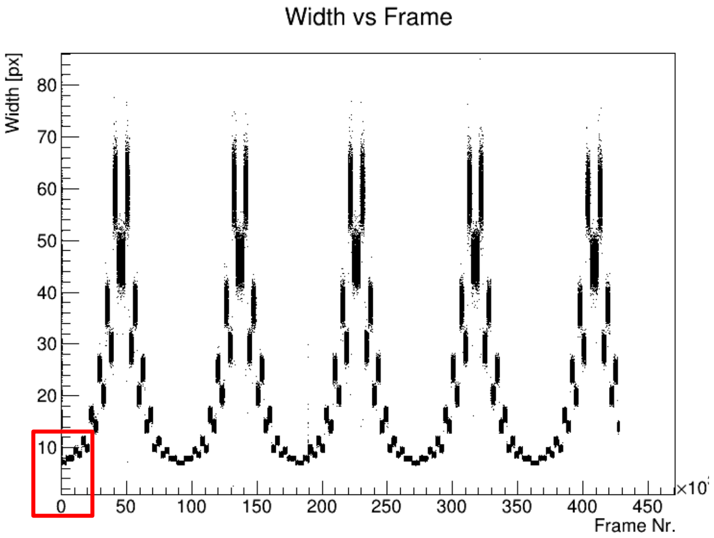


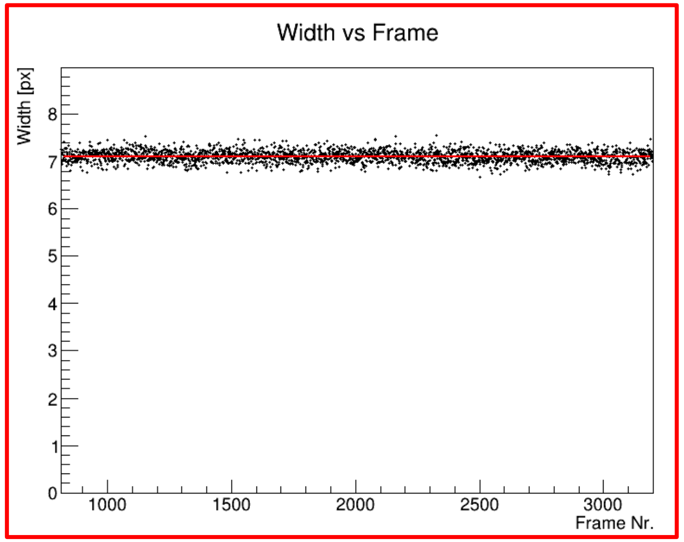


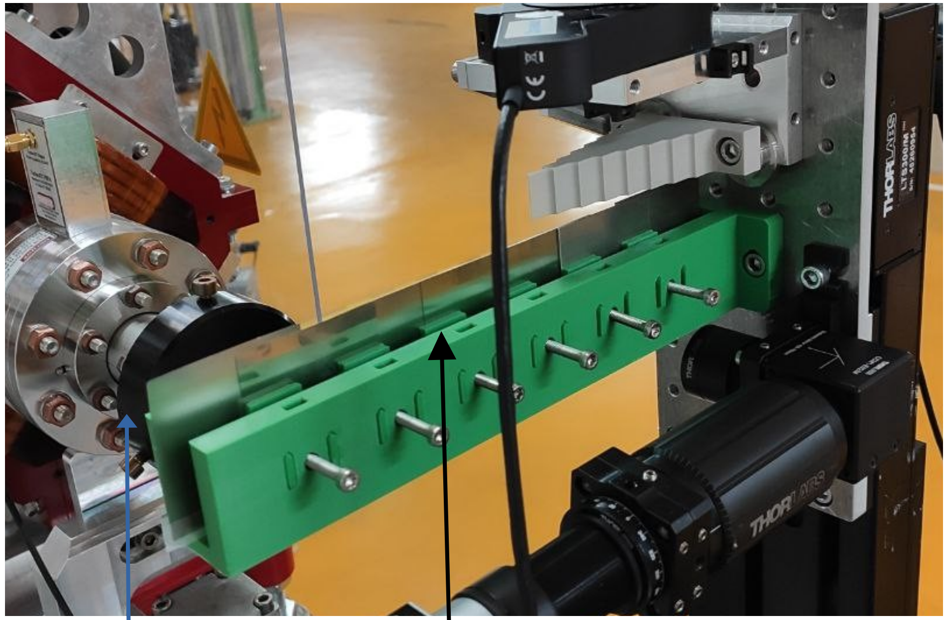
Nickel Thickness vs Beam Width

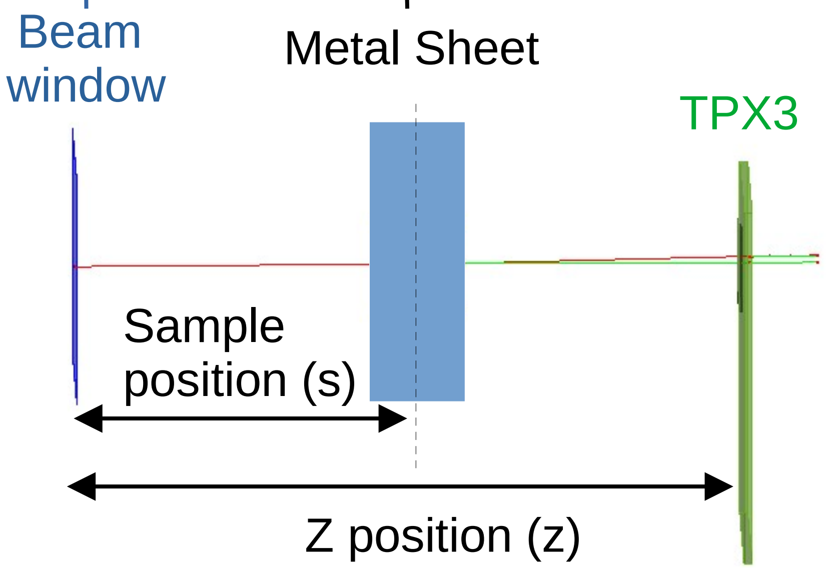
Analysis of Test Beam Data

- Mean width of nickel sheets were calculated by:
  - Selecting data for a given thickness
  - Calculating the mean of measured widths [in px] for a given thickness
  - Converting width to µm by multiplying by 55µm (TPX pitch size)



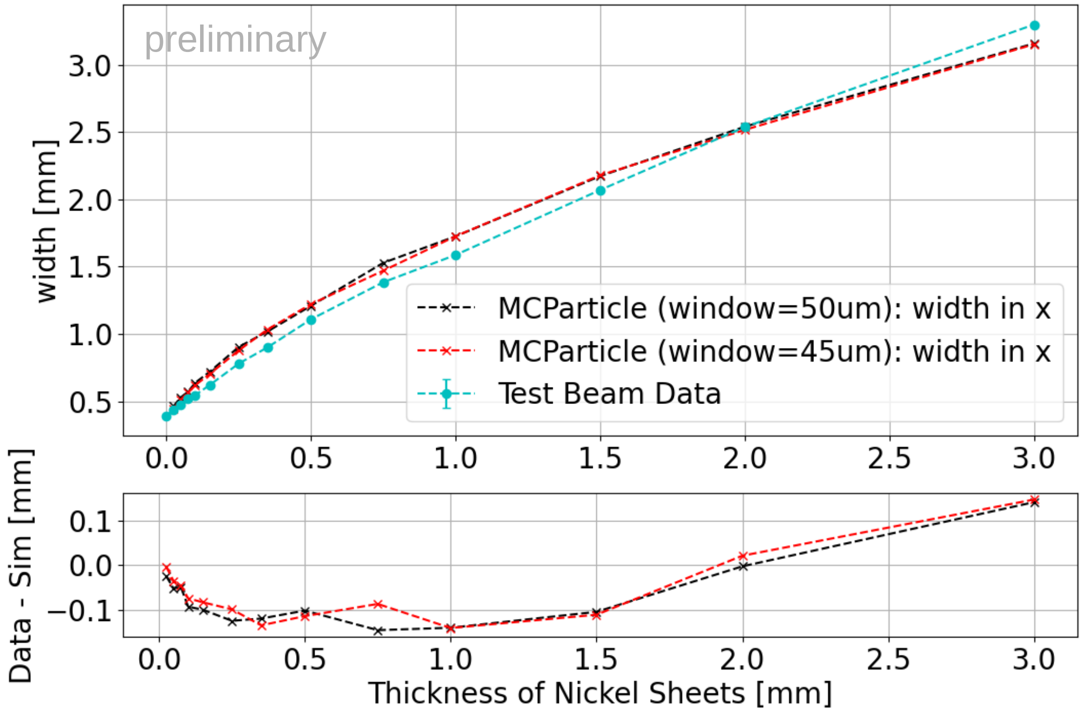






Comparison of Test Beam Data with Allpix Squared Simulation

Variation of Width vs Nickel Thickness

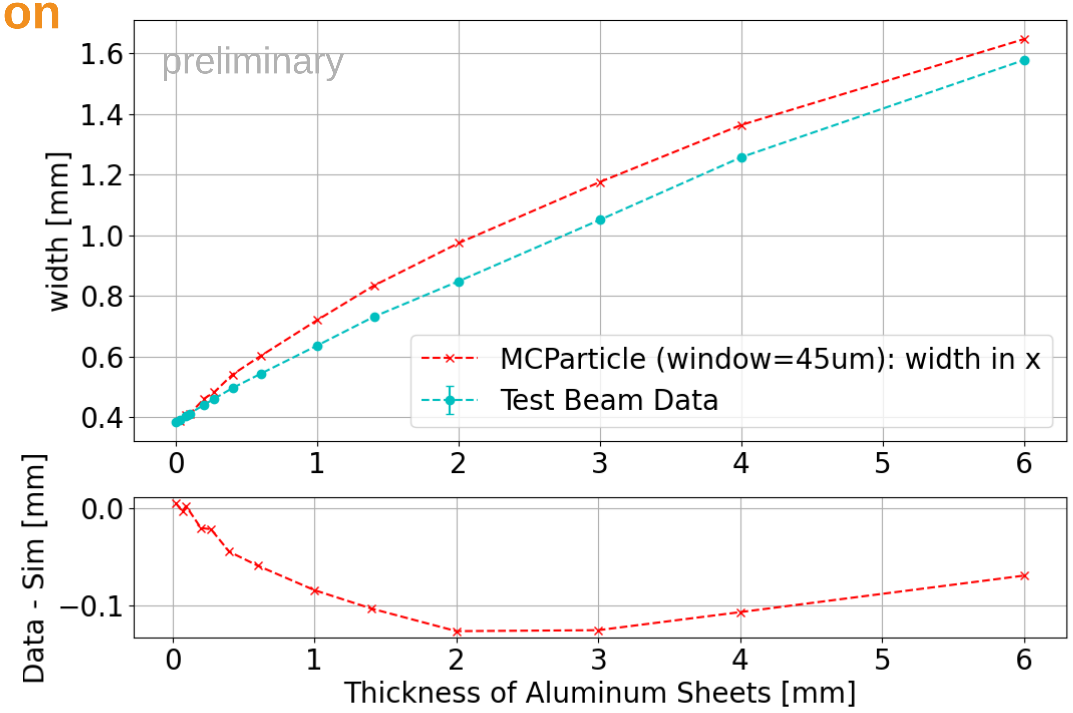


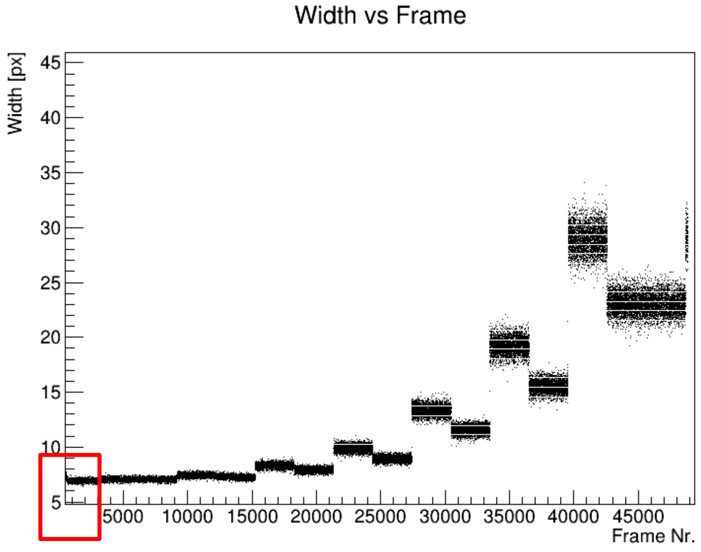
- In the range give, data and simulation results agree relatively well
  - Up to 5% difference between simulation and data
- Differences could be:
  - Due to the use of MCParticle “truths” instead of the TPX charge map
    - Due to non-linear gain of Timepix3
  - Due to multiple scattering model used in “FTFP_BERT_LIV”
- Further investigations necessary

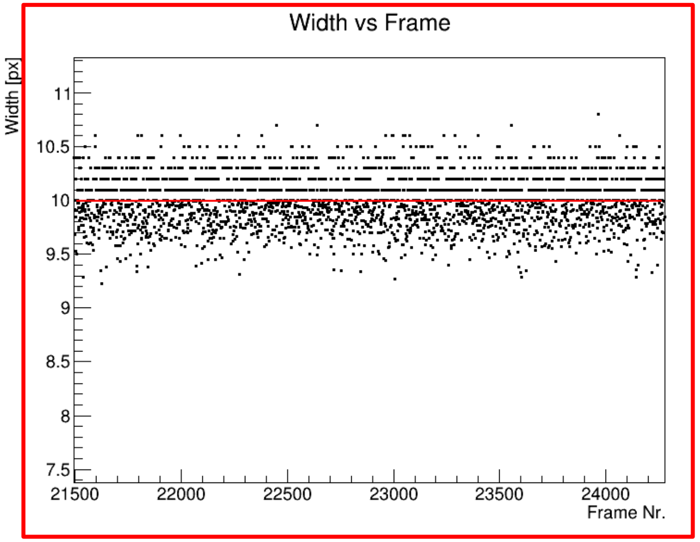
Aluminum Thickness vs Beam Spread

Comparison of Test Beam Data with Allpix Squared Simulation

- Mean width of aluminum sheets were calculated the same way the width of nickel sheets were calculated.
- In the range give, data and simulation results agree relatively well
  - Up to 10% difference between simulation and data
  - Purity of Aluminum sheets is unknown: Could be the potential reason for the difference
  - Further investigations necessary



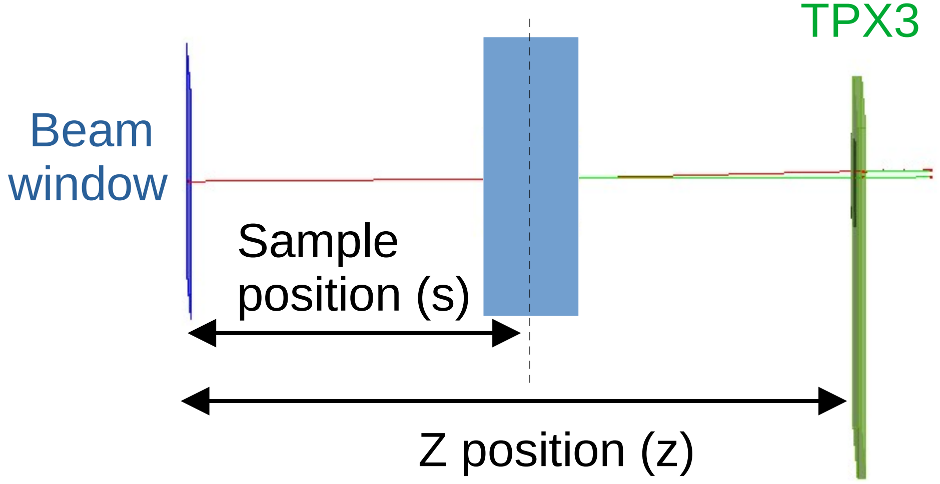




- Note: The change in least count observed at 10px is due to a rounding error. Will be fixed in the coming weeks

Mathematical Description of Multiple Coulomb Scattering

Comparison of Test Beam Data and MCParticle Data with Highland's Formula



- Highland's formula describes how the scattering angle varies with material budget

$$\theta=\left(\frac{13.6\,MeV}{\beta cp}\right)\times\sqrt{\varepsilon}\times[1+0.038\log(\varepsilon)]$$

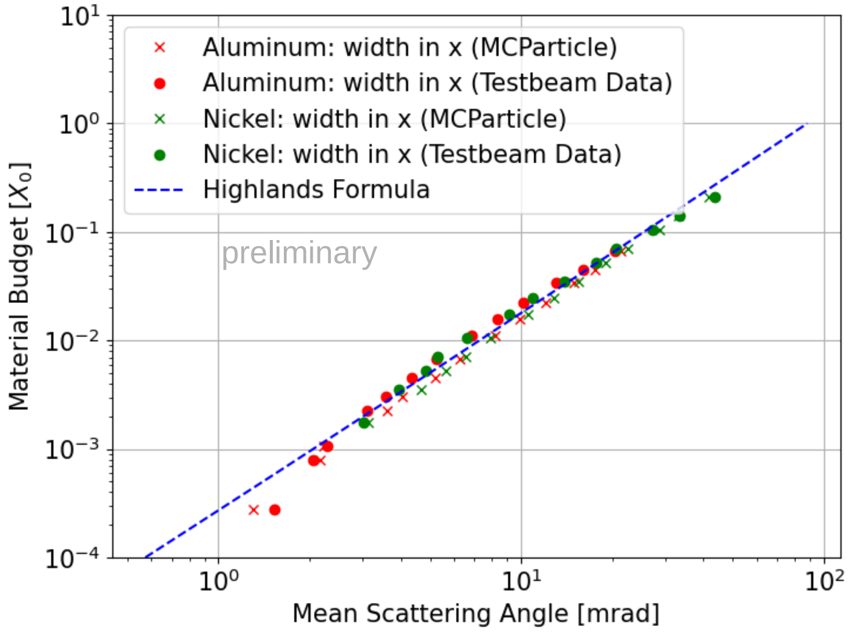
where ε = material budget (thickness/radiation length (X_o))
p = momentum
βc = velocity

- Mean widths measured in mm at test beam and using MCParticle object was converted to scattering angles θ using:

$$w_{high}=\sqrt{w_{tot}^2-h_{beam}^2}$$

$$\theta=\tan^{-1}\left(\frac{w_{high}}{(z-s)}\right)$$

where w_{total} = beam width measured at detector
h_{beam} = beam width of background measured at detector
w_{high} = background subtracted beam width at detector



- **Results: With minor fluctuations the test beam and MCParticle data follow Highland's formula**

Story So Far...

eCT with Allpix Squared

- electronCT is a novel imaging method with many potential applications in medical and industrial imaging
- With the proof of principle established, a well developed simulation study is required to further characterize and improve the imaging technique
- Implementation of beam focusing on Allpix Squared has helped model the profile of the beam width in z-direction
- **Preliminary Results:**
  - Increase in width due to materials: Simulations agree to some extent with test beam data and with theoretical values obtained from Highlands formula
  - Mathematical modeling of beam: Quadratic addition of multiple linear functions for different effects model the beam width relatively well

Next Steps...

eCT with Allpix Squared

- Move from “ideal scenario” to an even more realistic scenario:
  - MCParticle object was used in all studies conducted so far.
    - Reason: Properties of the timepix used were unknown at the time on the initial studies (eg: electronic noise, threshold smearing, QDC parameters)
  - Once parameters have been estimated, repeat study with Timepix charge map instead of MCParticle hitmap
- Once this has been implemented successfully, one can do a comprehensive simulation study with “rats”
- **Studies have just begun. Exciting times ahead!**

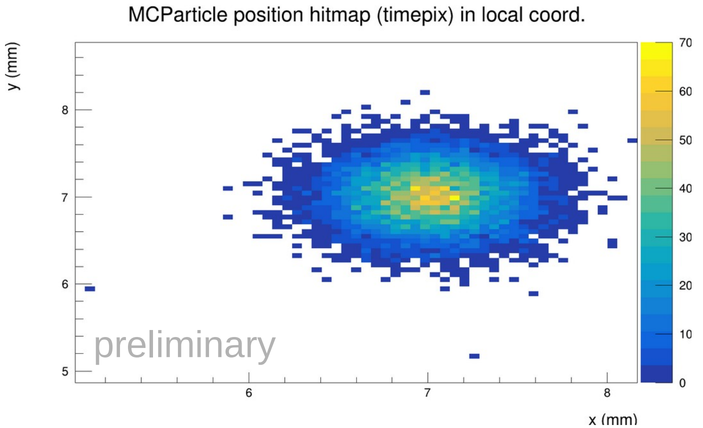
Thank You for Listening!

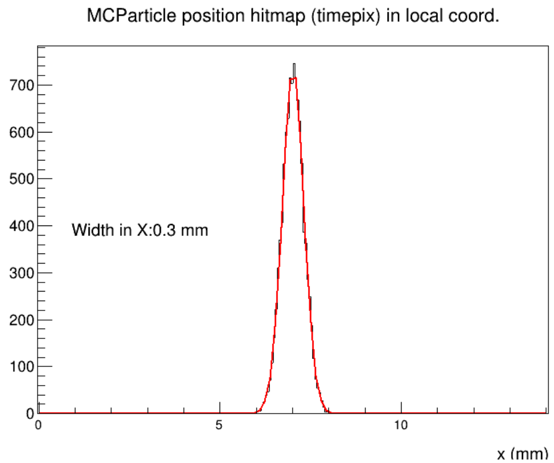
Backup

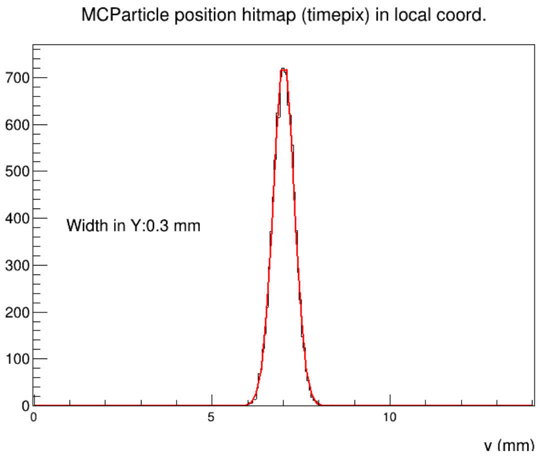
MCParticle Hitmap vs Charge Hitmap

Using Allpix Squared

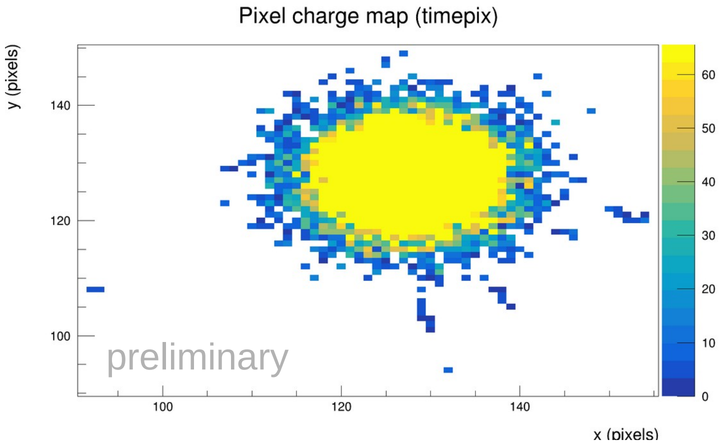
- **Geometry: 300um beam**
  - World volume : Vacuum
  - TPX3 detector placed at z=0.1 mm from gun
  - No beam window present

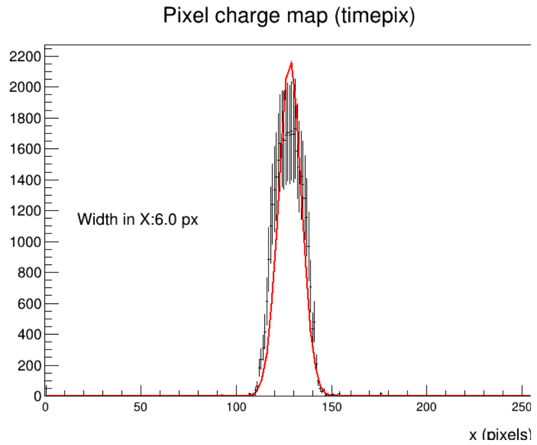


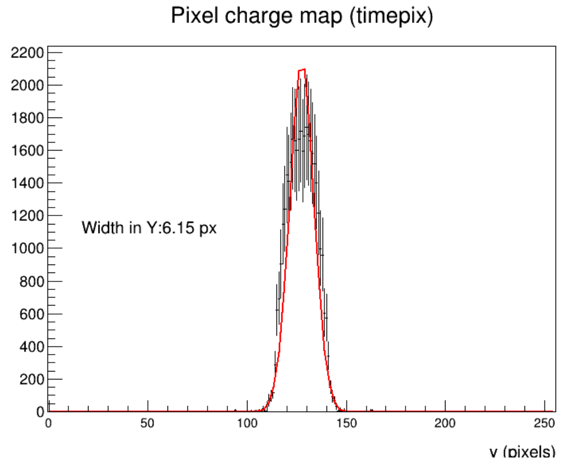




- **Results:**
  (based on timepix charge map)
  - Width = 6.0 px and 6.15 px or 330 um and 338 um







- Beam width is in the correct range at very short distance

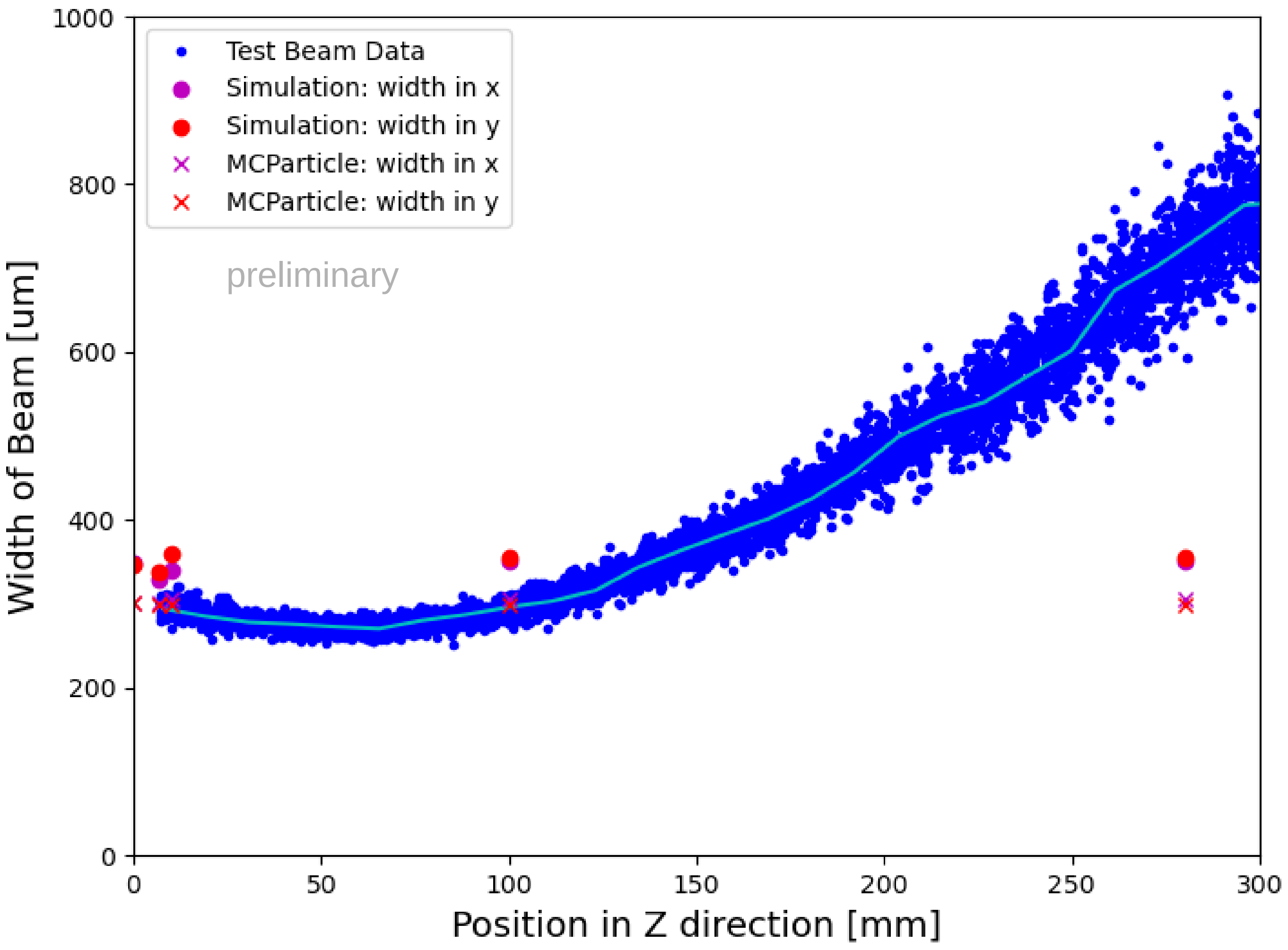
- But pixels at the center seem to be saturating

Comparison of Beam Width with Test Beam

Using Allpix Squared : Vacuum

- **Geometry**
  - World volume : Vacuum
  - **Particle gun at z=-50 um**
  - No beam window present

- **Results:**
  - As expected, no interactions with surrounding
  - Width remains same with z distance



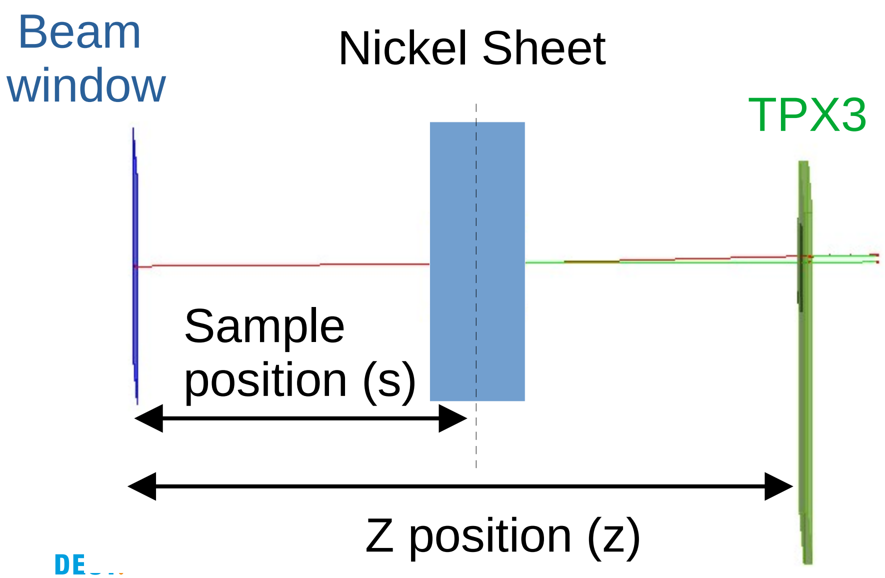
Mathematical Modeling of Deflection Distribution

Using Allpix Squared

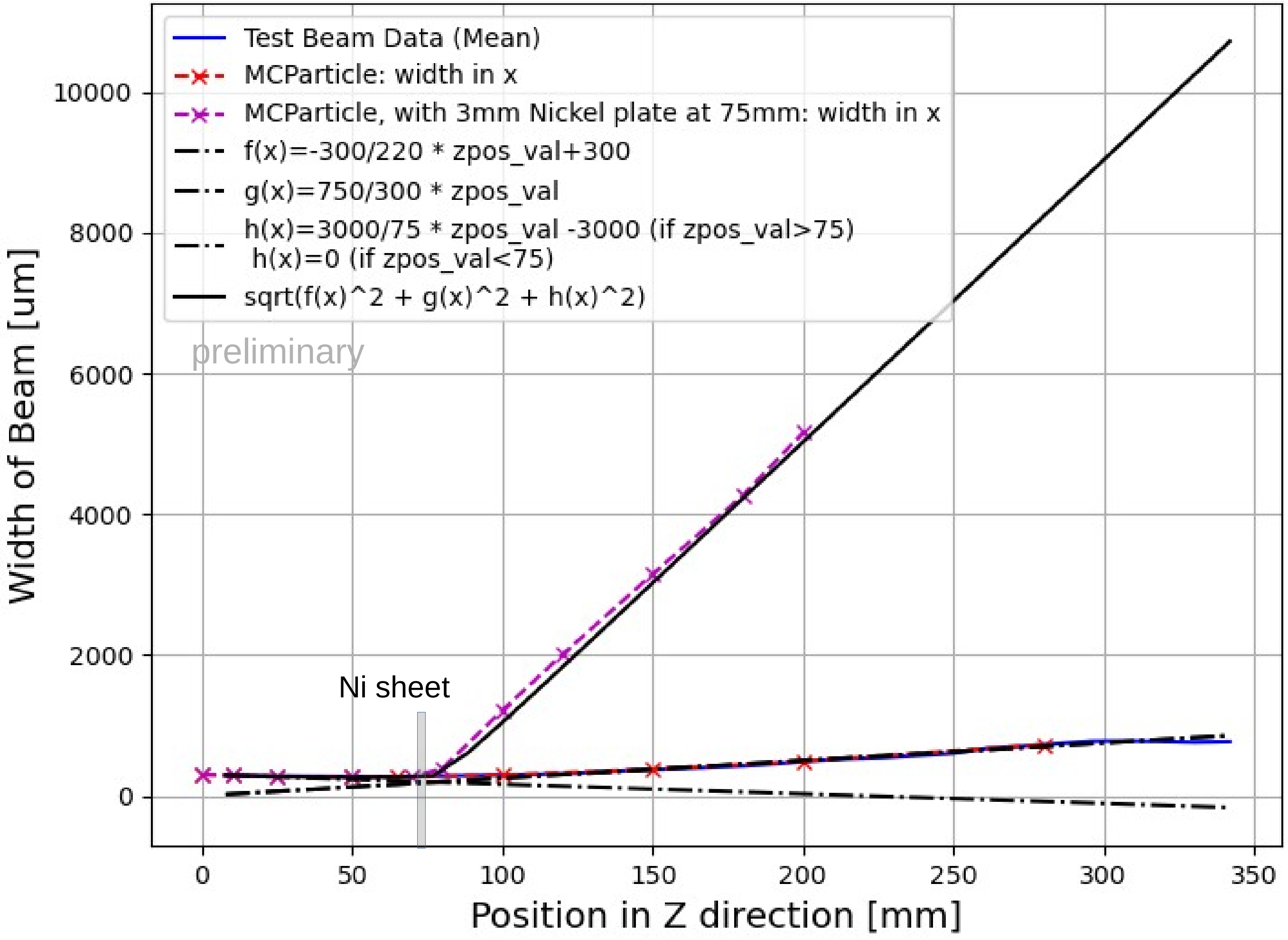
- Mathematically one can quadratically add a third function to model the increase in width with z position : $h(z)$

- $h(z)\begin{cases} 0(if\ z<s) \\ grad*(z-s)(else) \end{cases}$ $P(z)=\sqrt{f(z)^2+g(z)^2+h(z)^2}$

Where $grad$ = gradient of h(z)
depends on material properties



For sample position = 75 mm



Needs to be verified at test beam

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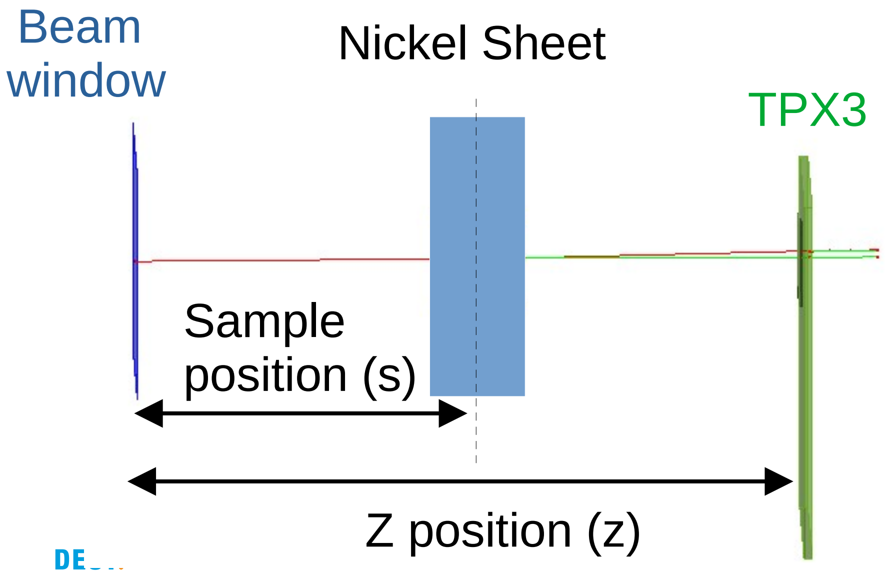
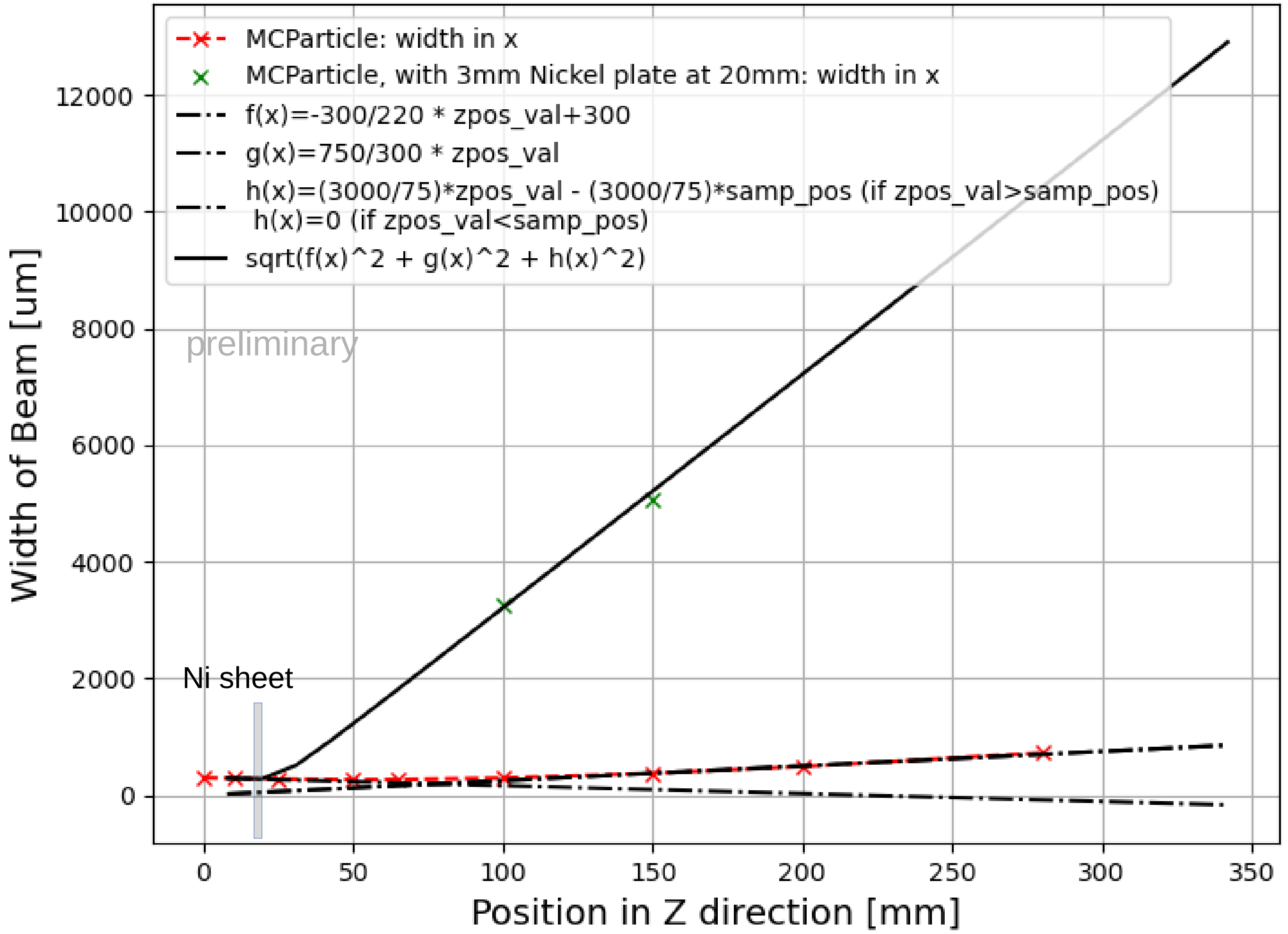


For sample position = 20 mm



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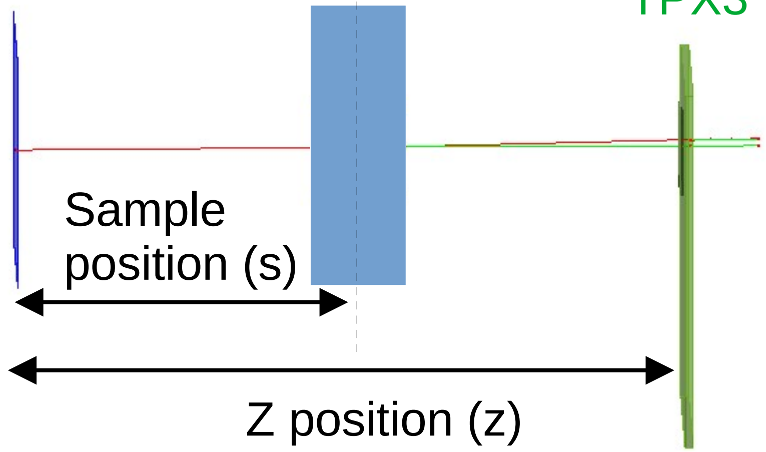
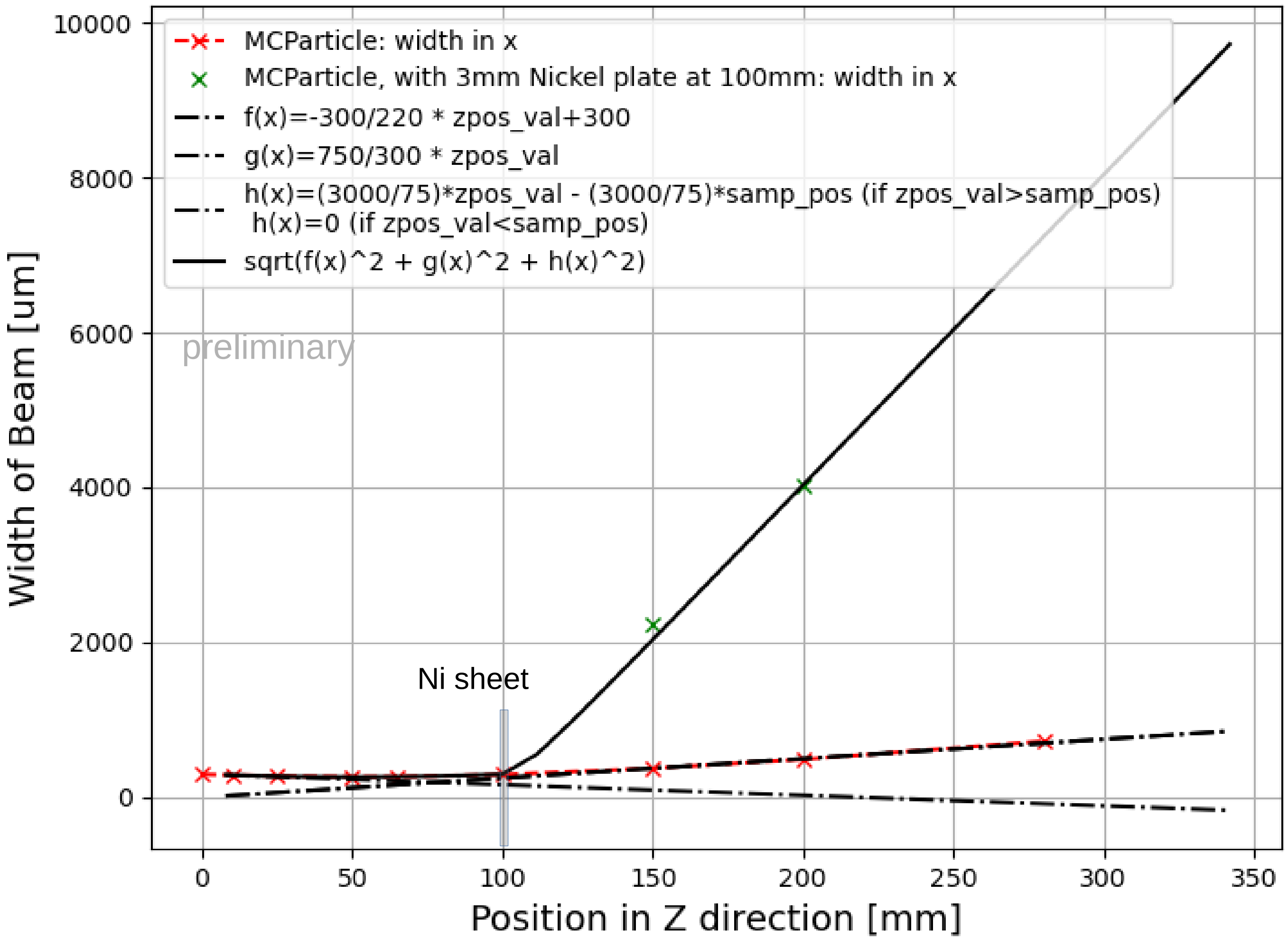


For sample position = 100 mm



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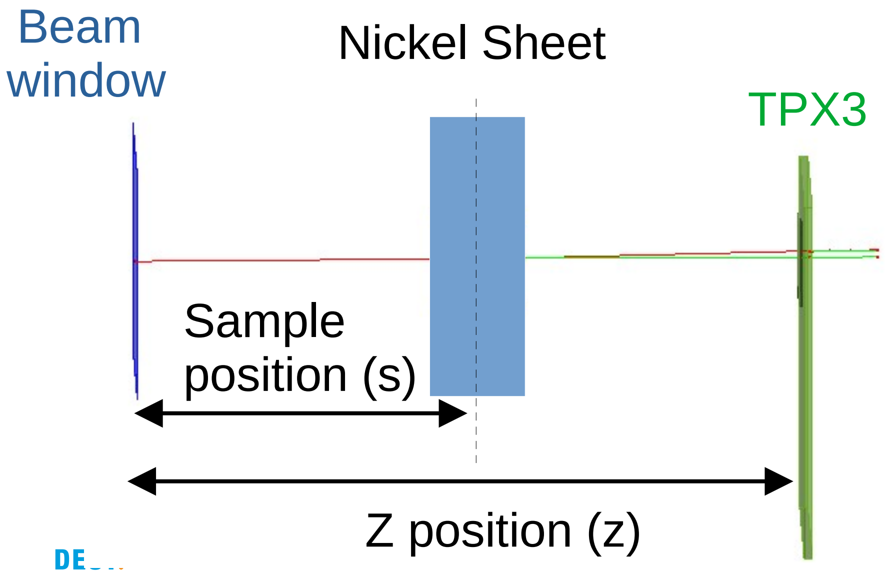
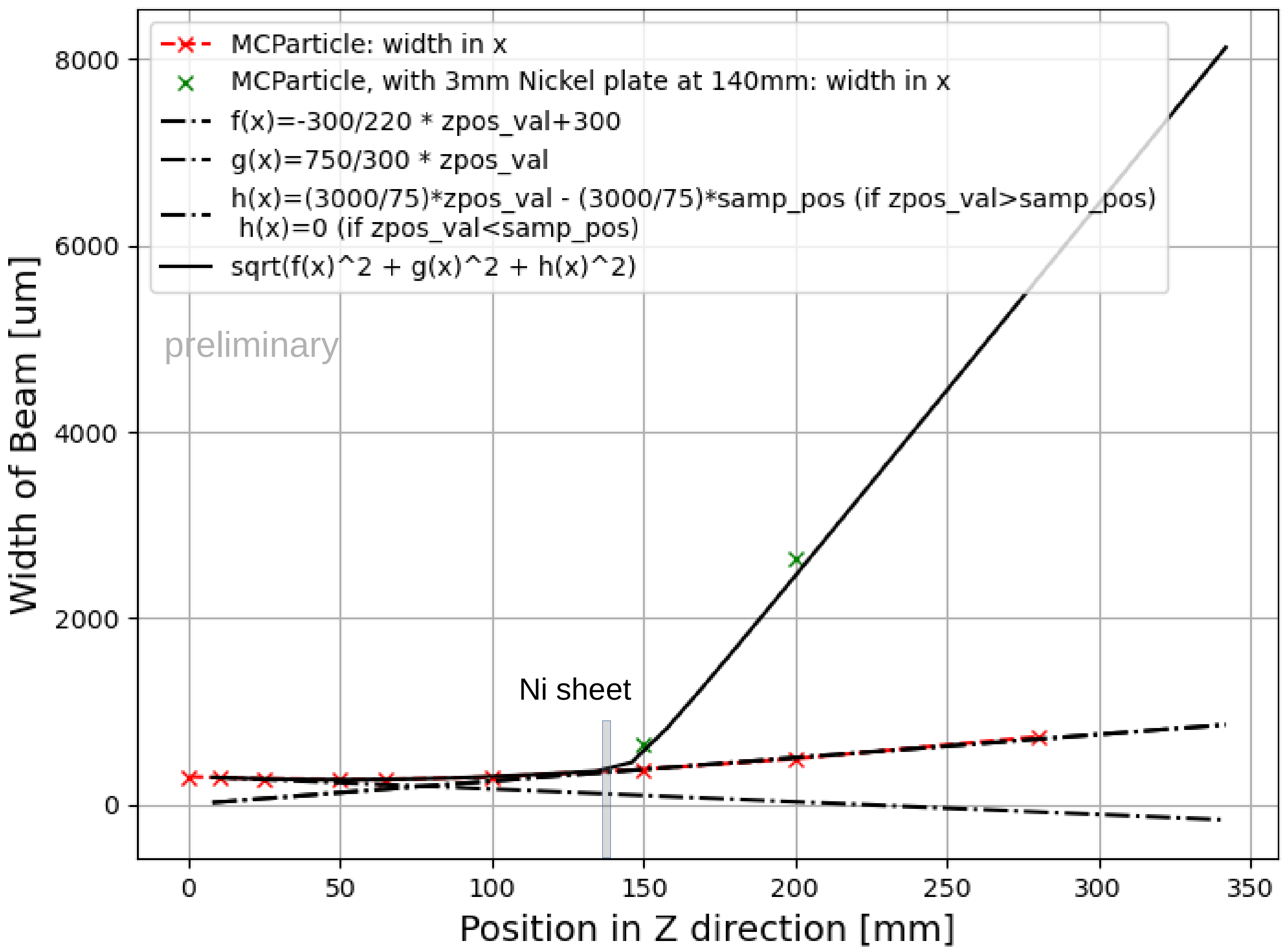
- $h(z)\begin{cases} 0 \, (if \; z<s) \\ grad*(z-s)\,(else) \end{cases}$ $\quad P(z)=\sqrt{f(z)^2+g(z)^2+h(z)^2}$

Where $grad$ = gradient of h(z) depends on material properties



For sample position = 140 mm



Needs to be verified at test beam