SIGMA Update

Jonathan Wright
University of Liverpool

Outline

- Introduction
- Simulations
- Prototype update
- Summary

Introduction

High performance γ-ray tracking and imaging detector

Excellent energy resolution especially at low energies

SIGMA

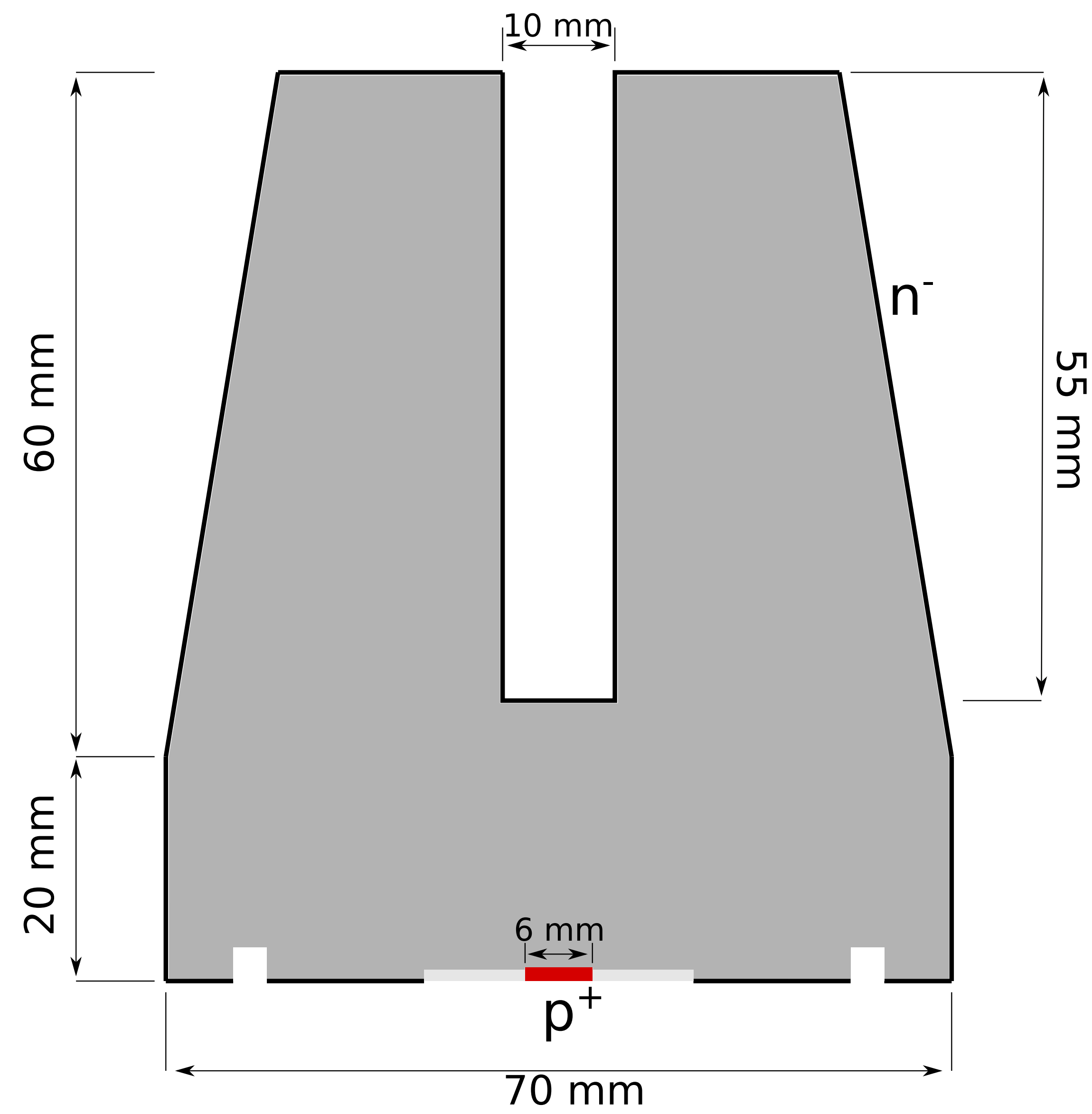
The Segmented Inverted-coaxial GerMAnium Detector

State-of-the-art position sensitivity

Large volume, high efficiency HPGe detector

Detector Design

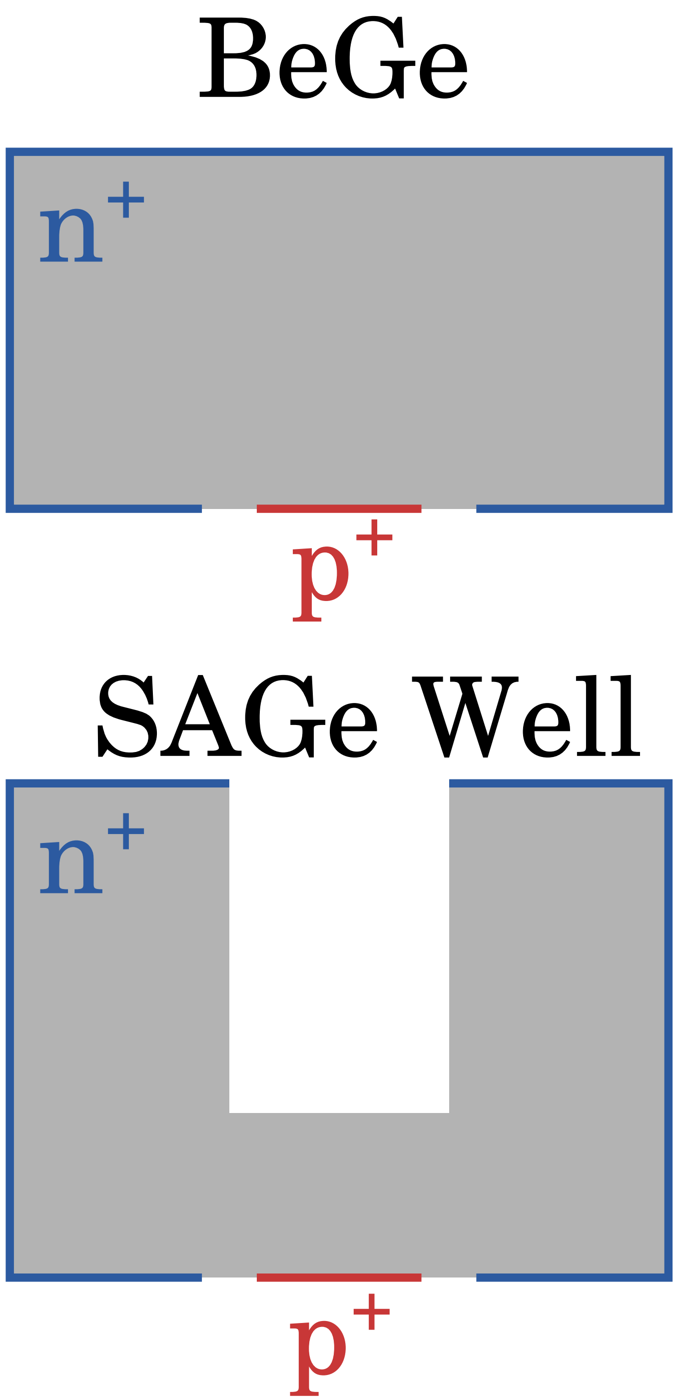
- P-type germanium inverted-coaxial detector
- Large volume detector for high efficiency
- Point contact technology
- Manufactured by MIRION
- N-type being investigated by LBNL/ORNL *



* M. Salathe et. al, Nucl. Instr. Meth. A 868 (2017) 19-26

Point Contact Technology

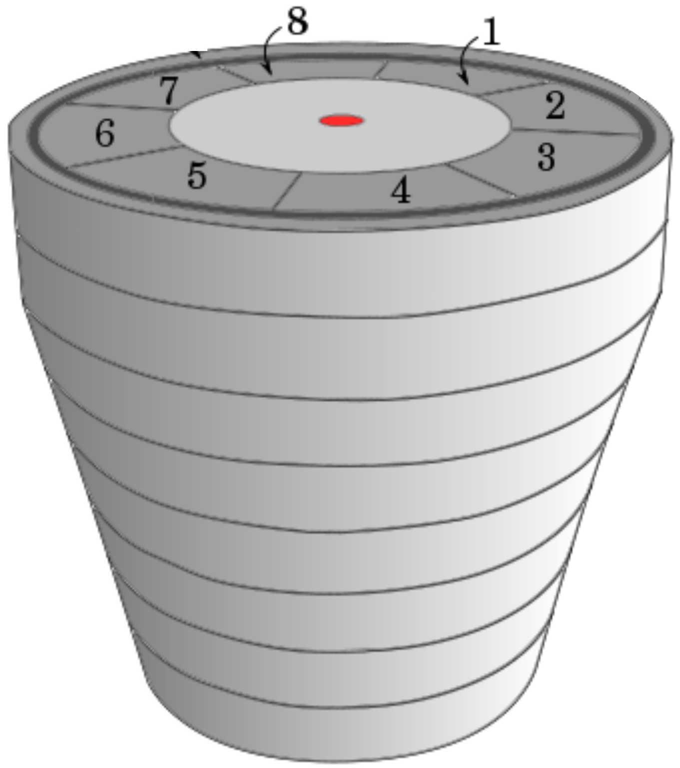
- Small, point-like contact with wrap around outer contact
- Low capacitance (~1 pF) due to small physical size of point-like contact
- Low C ⇒ low noise ⇒ improved ΔE
  - ~0.5 keV at E_γ = 122 keV*
  - 1.6 keV at E_γ = 1332 keV*
- Examples ⇒ BeGe, SAGe-well, etc

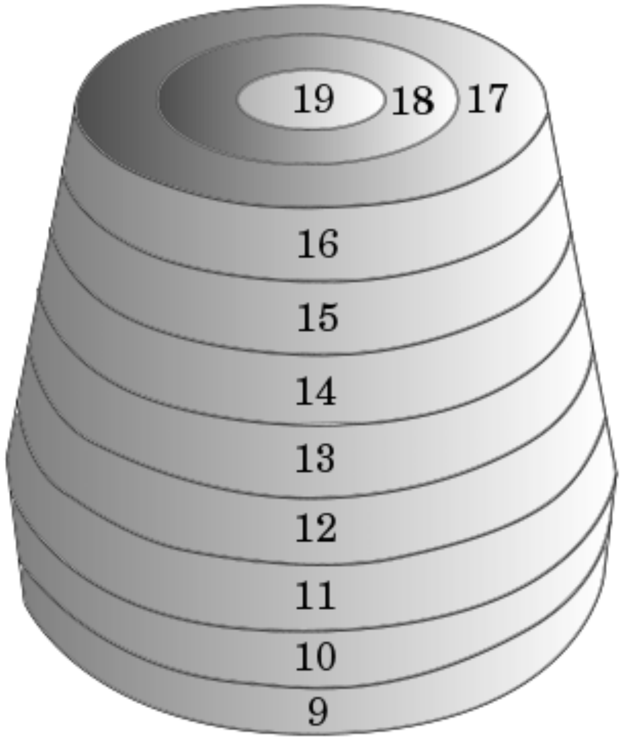


* L.J. Harkness-Brennan et. al, Nucl. Instr. Meth. A 760 (2014) 28-39

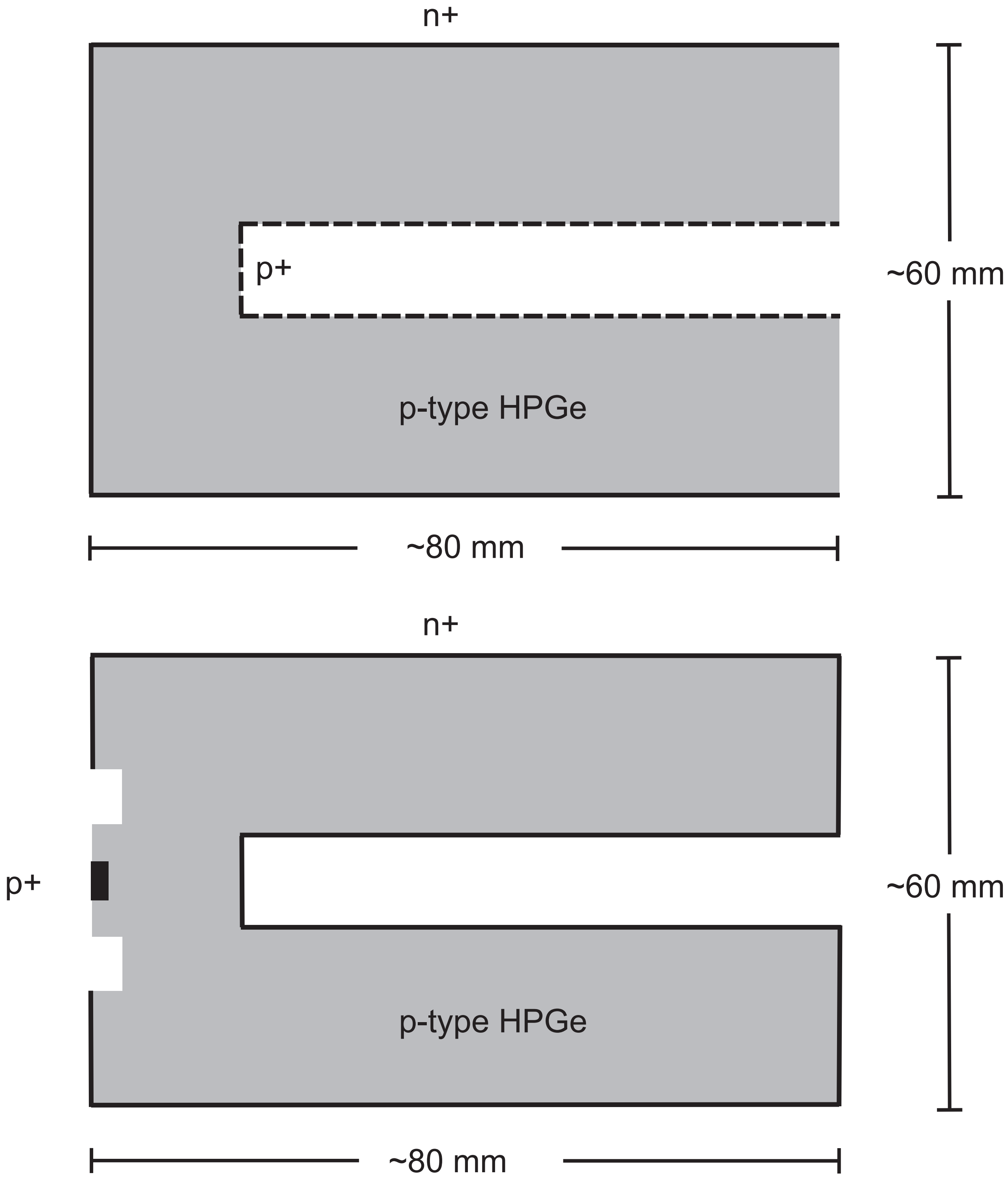
Segmentation Scheme

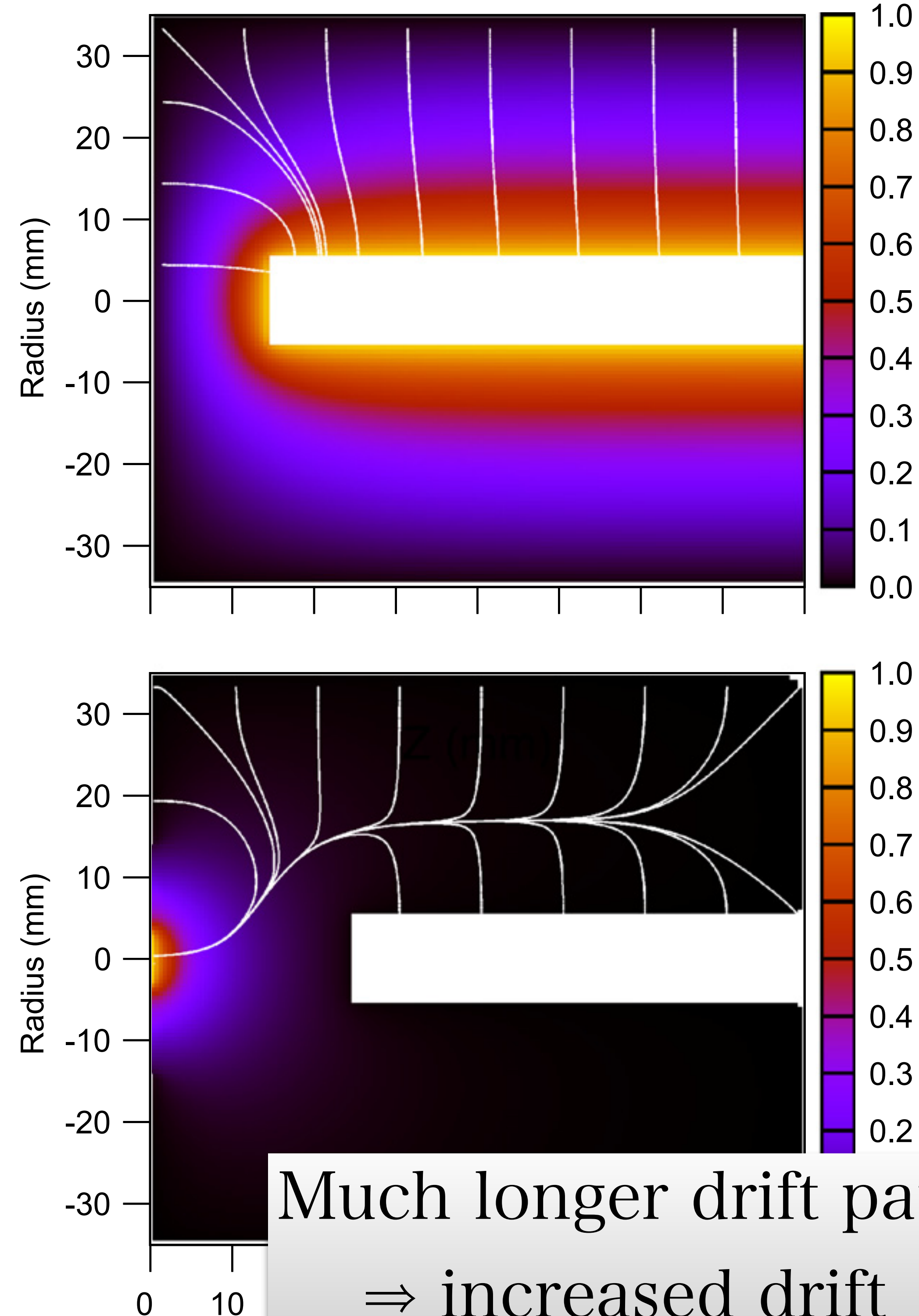
- 19 segments with 20 signals per event
  - Outer segments improve timing capabilities
- 8 azimuthal segments (1-8) ⇒ φ resolution
- 8 longitudinal rings (8-16) ⇒ z resolution
- 2 concentric segments (17, 18) ⇒ r resolution
- Core (19) and point contact (red)





Inverted-coaxial





Much longer drift paths

⇒ increased drift

times upto 2 μs

* R.Cooper et. al, Nucl. Instr. Meth. A 665 (2011) 25-32

Simulations

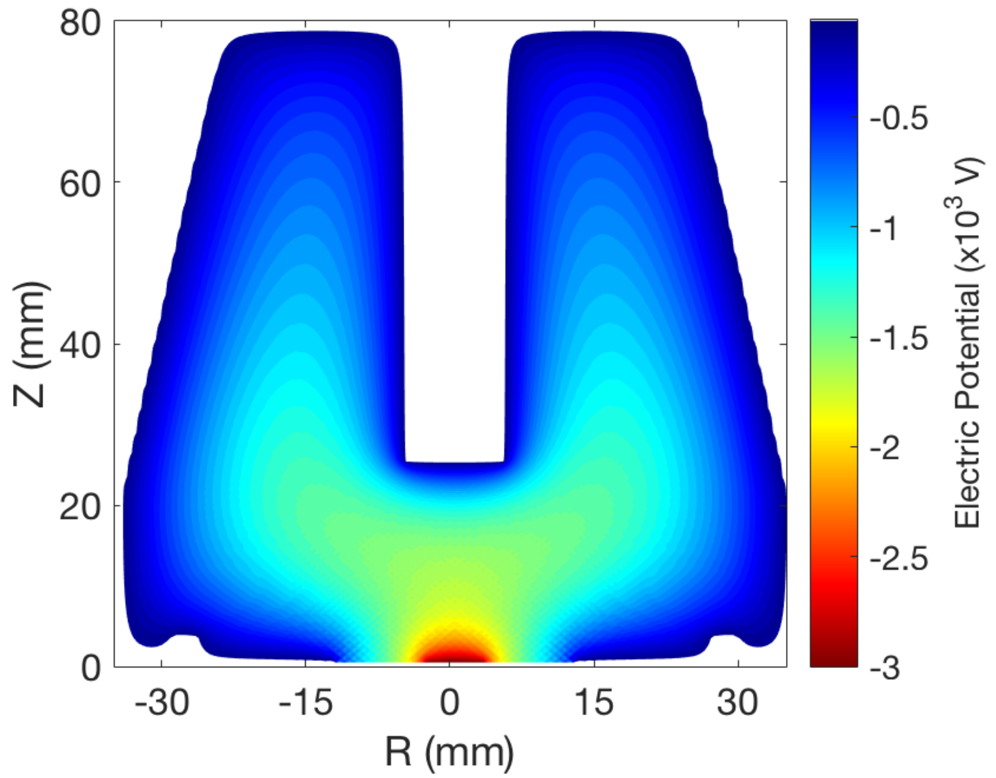
Field Simulations

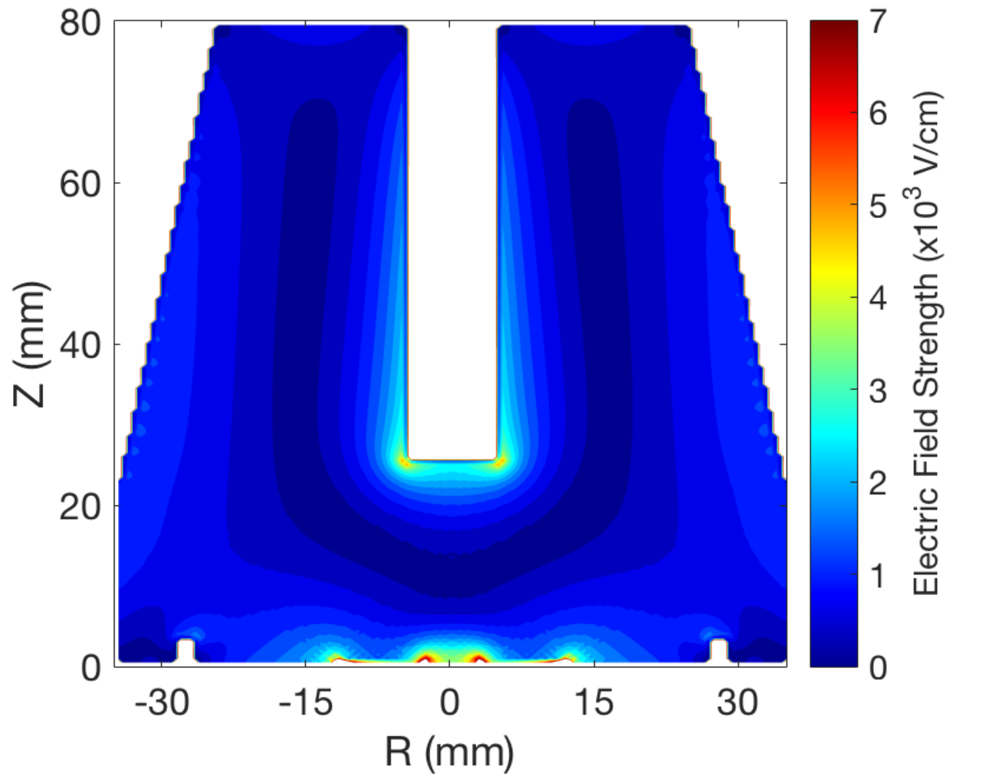
- Electric field simulations done using an adaptation of the FieldGen software

- Fields calculated by solving the Poisson equation

$$\frac{d^2\Phi}{dx^2} + \frac{d^2\Phi}{dy^2} + \frac{d^2\Phi}{dz^2} = \frac{-\rho(x,y,z)}{\epsilon_0}$$

- Weak fields & long drift paths $\Rightarrow$ long drift times to point contact



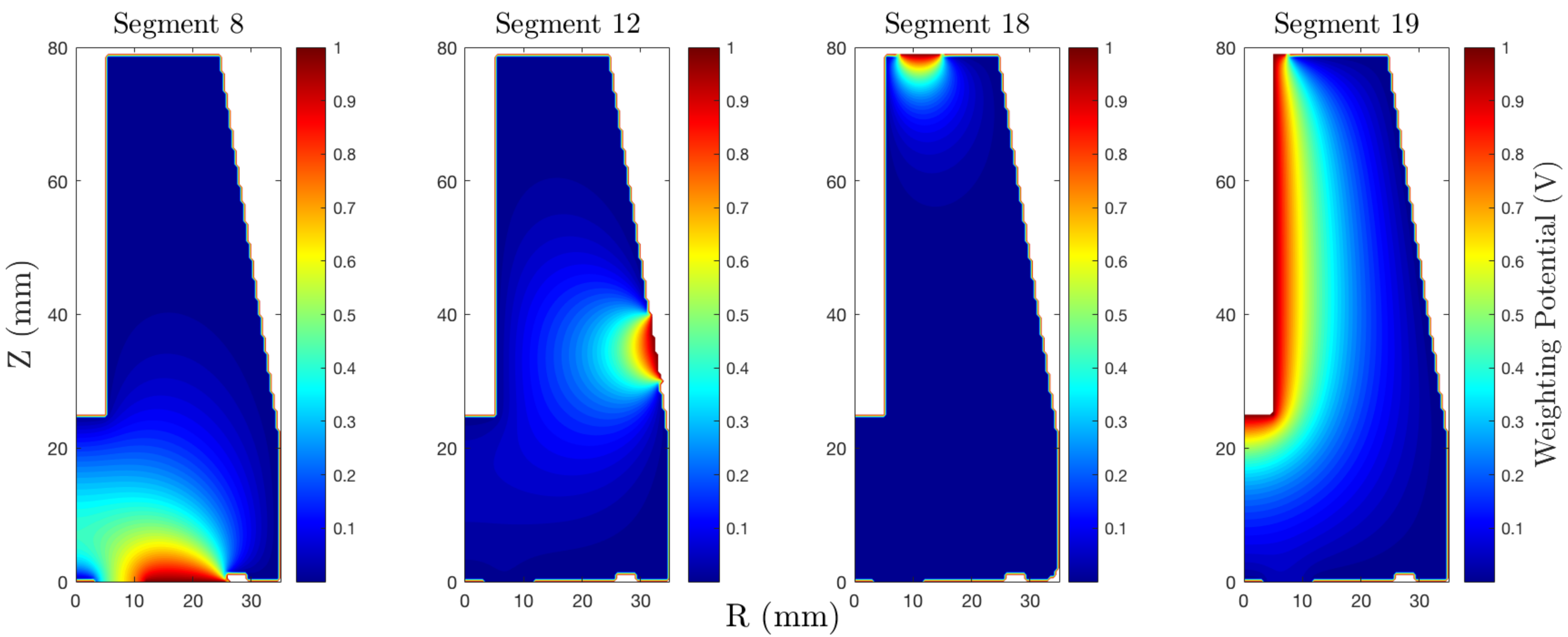


Weighting Potentials

- Enables theoretical charge pulses to be generated
- Electrode of interest set to 1 V -> all other set to 0 V

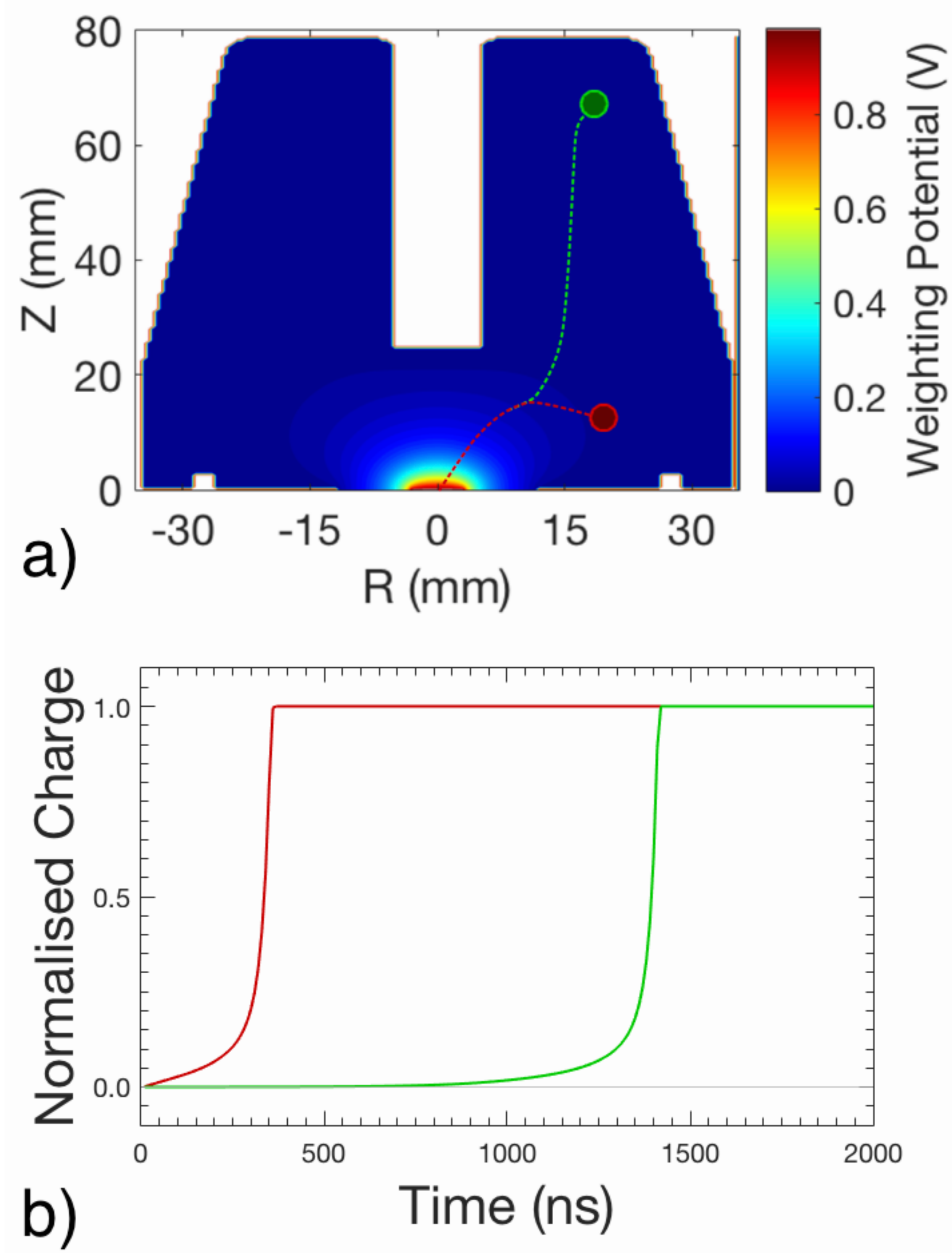
$$i = q\vec{v}\cdot\vec{E}$$

$$Q = q\Delta\varphi_0$$

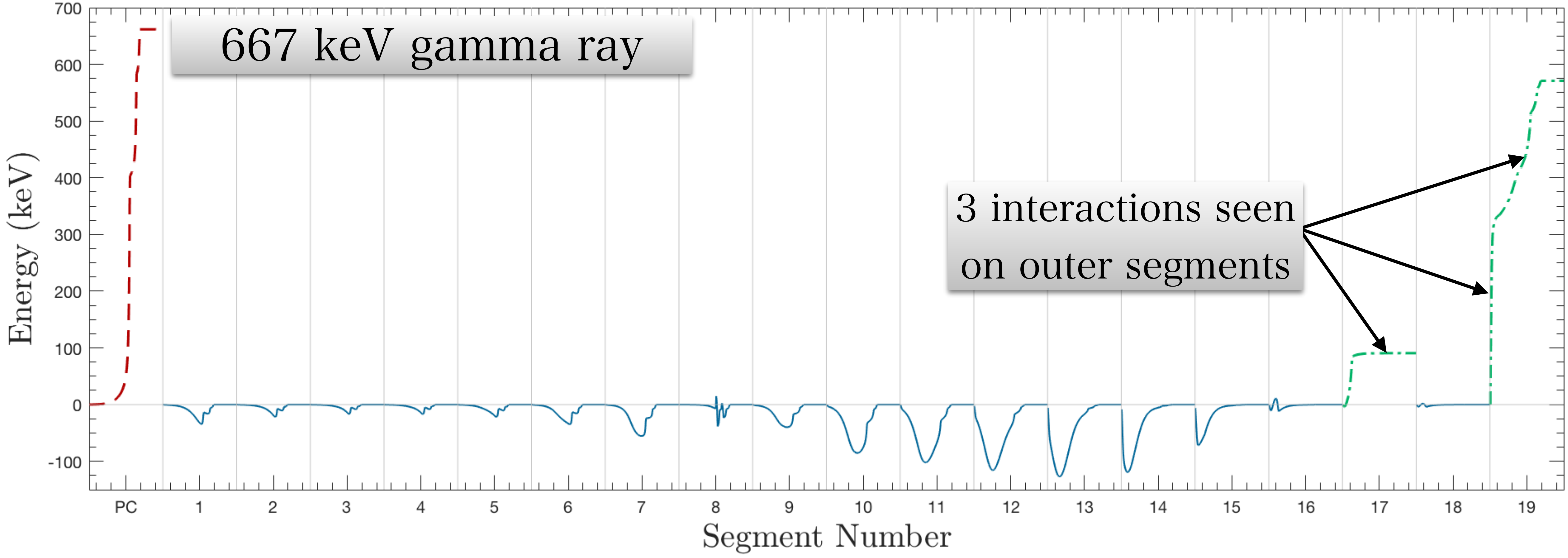


Charge Transport

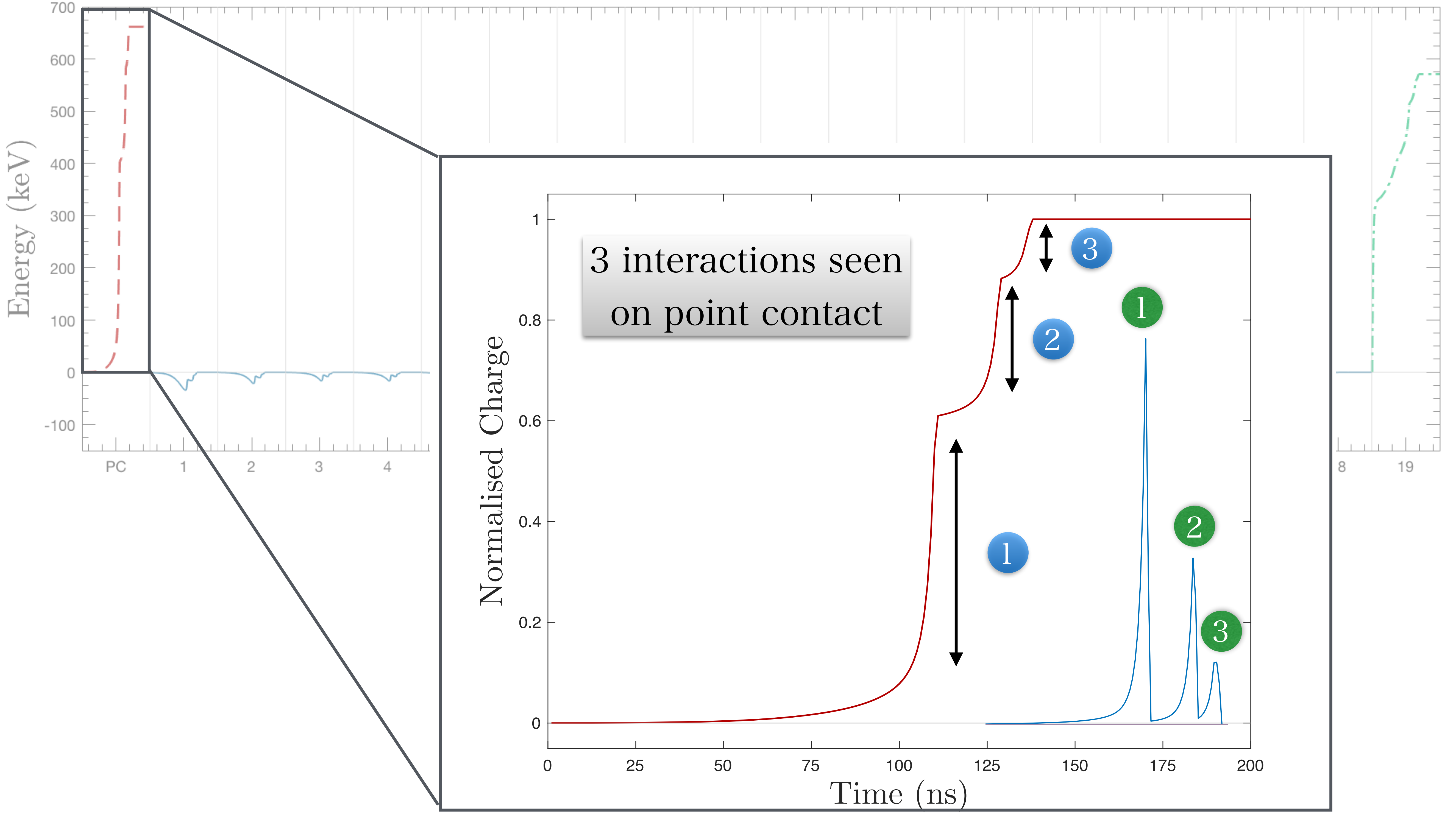
- Charge transport calculated using adaptation of SigGen software
- Calculations account for polarity, temperature, crystallographic axis, crystal impurity, etc
- Short range field near point contact gives sharp rise in charge pulses
- Similar signal shapes with clear temporal variation
- Easier to distinguish multiple interactions than standard coax



Example Superpulse

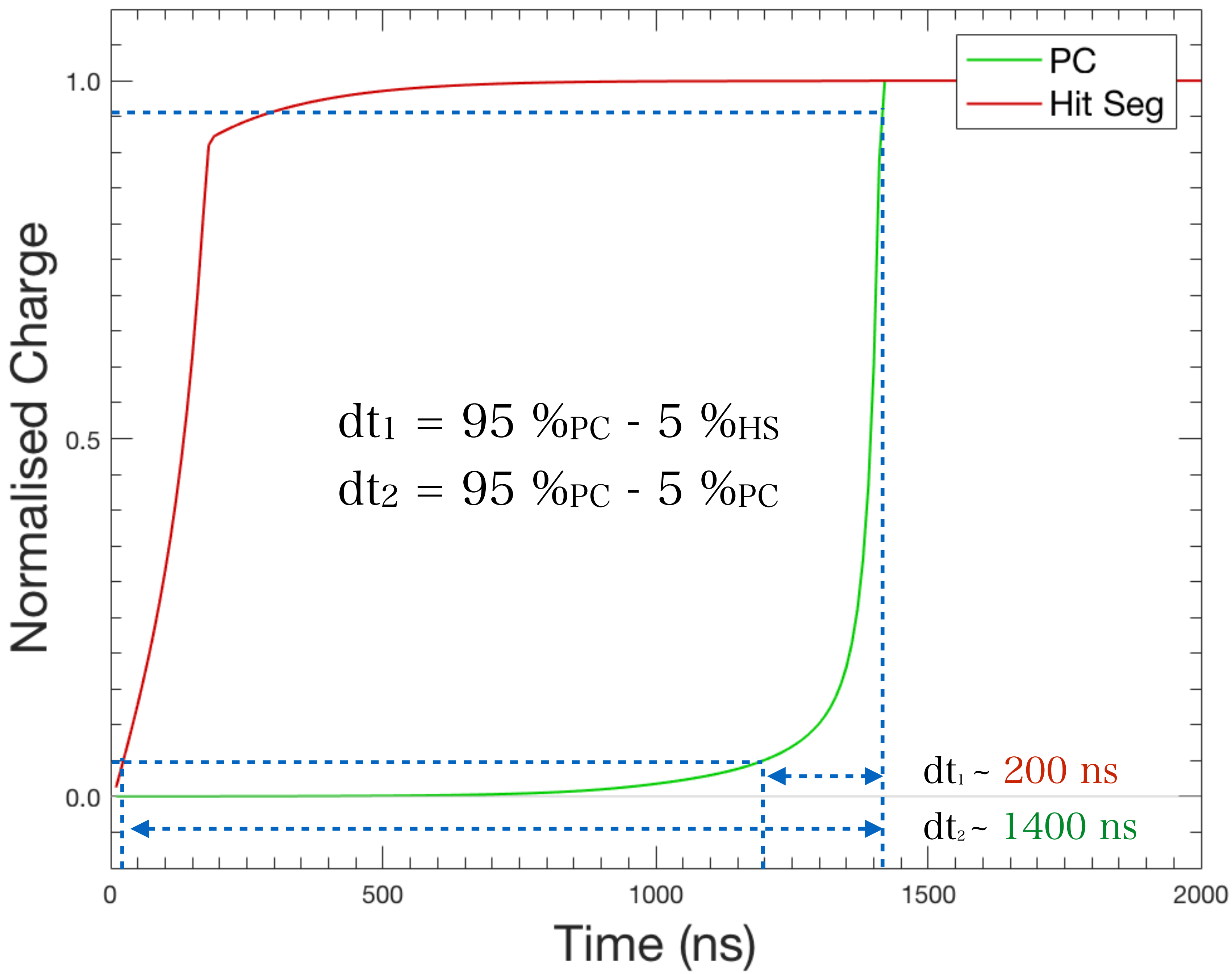


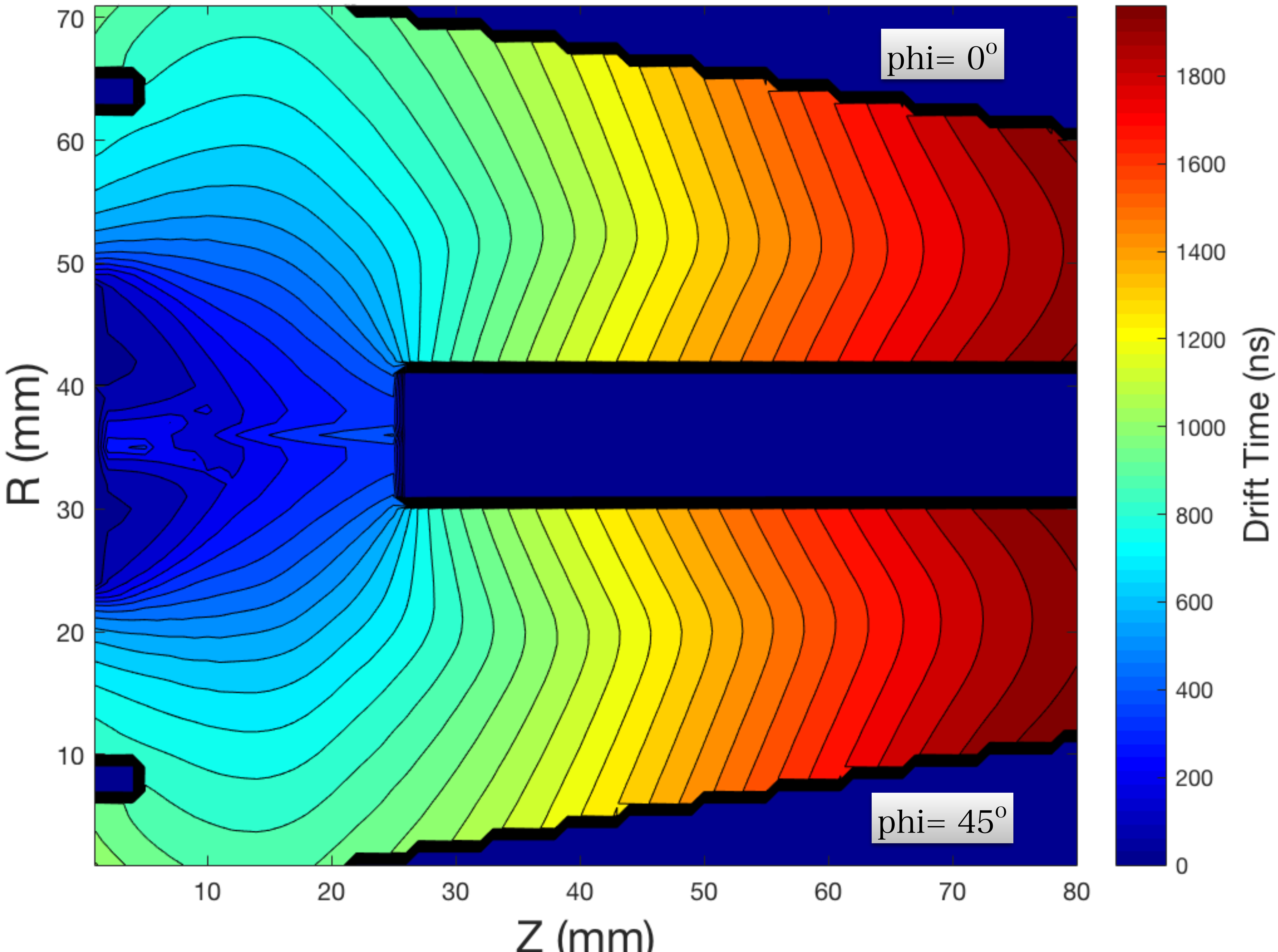
Example Superpulse



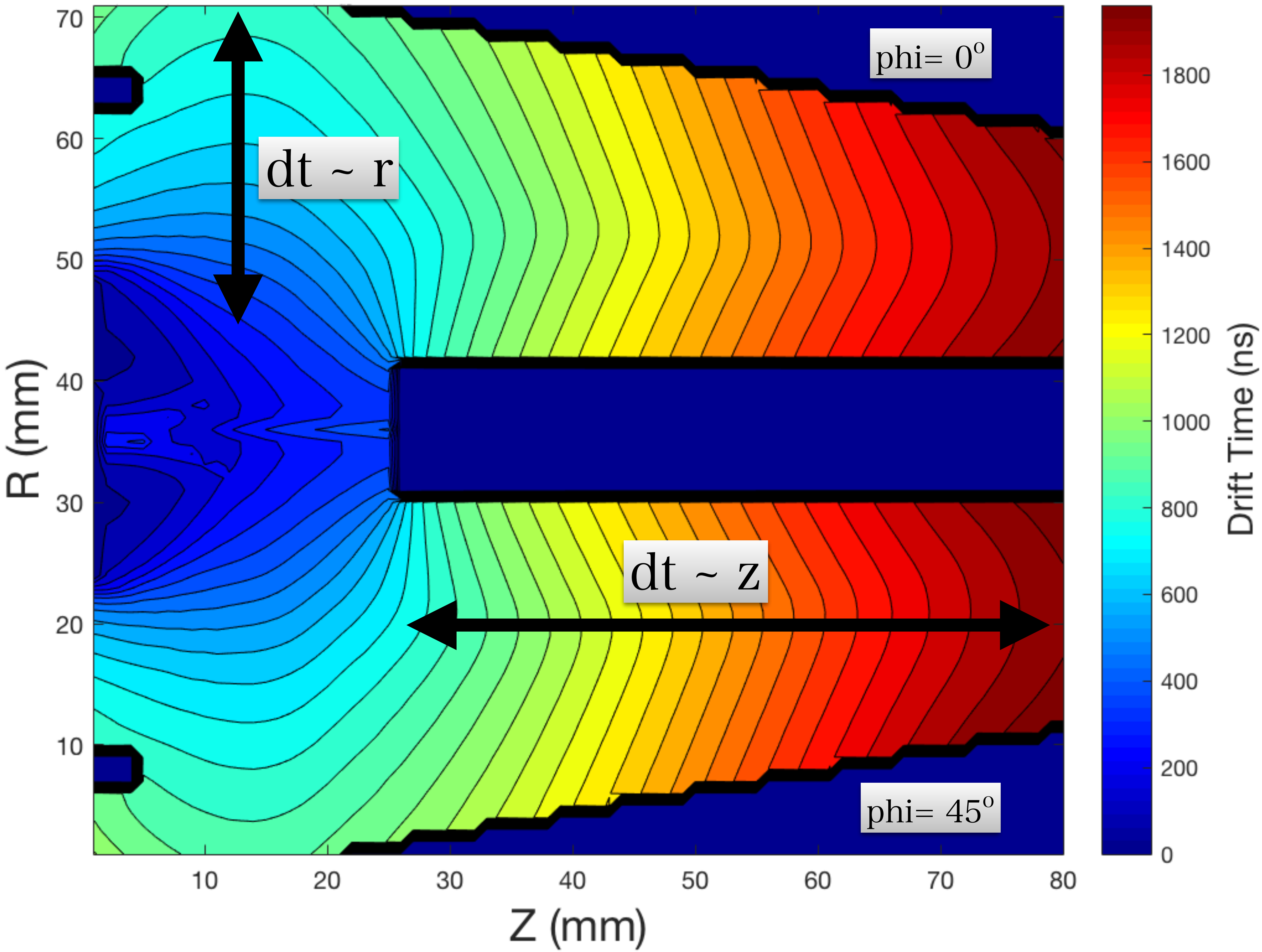
Drift time calculation

- Point contact trace flat for most of trace
- Enormous error in drift time when using PC only
- Hit segment rises early -> enabling better determination of t_0
- Drift time calculated as time from 5% of hit segment to 95% point contact



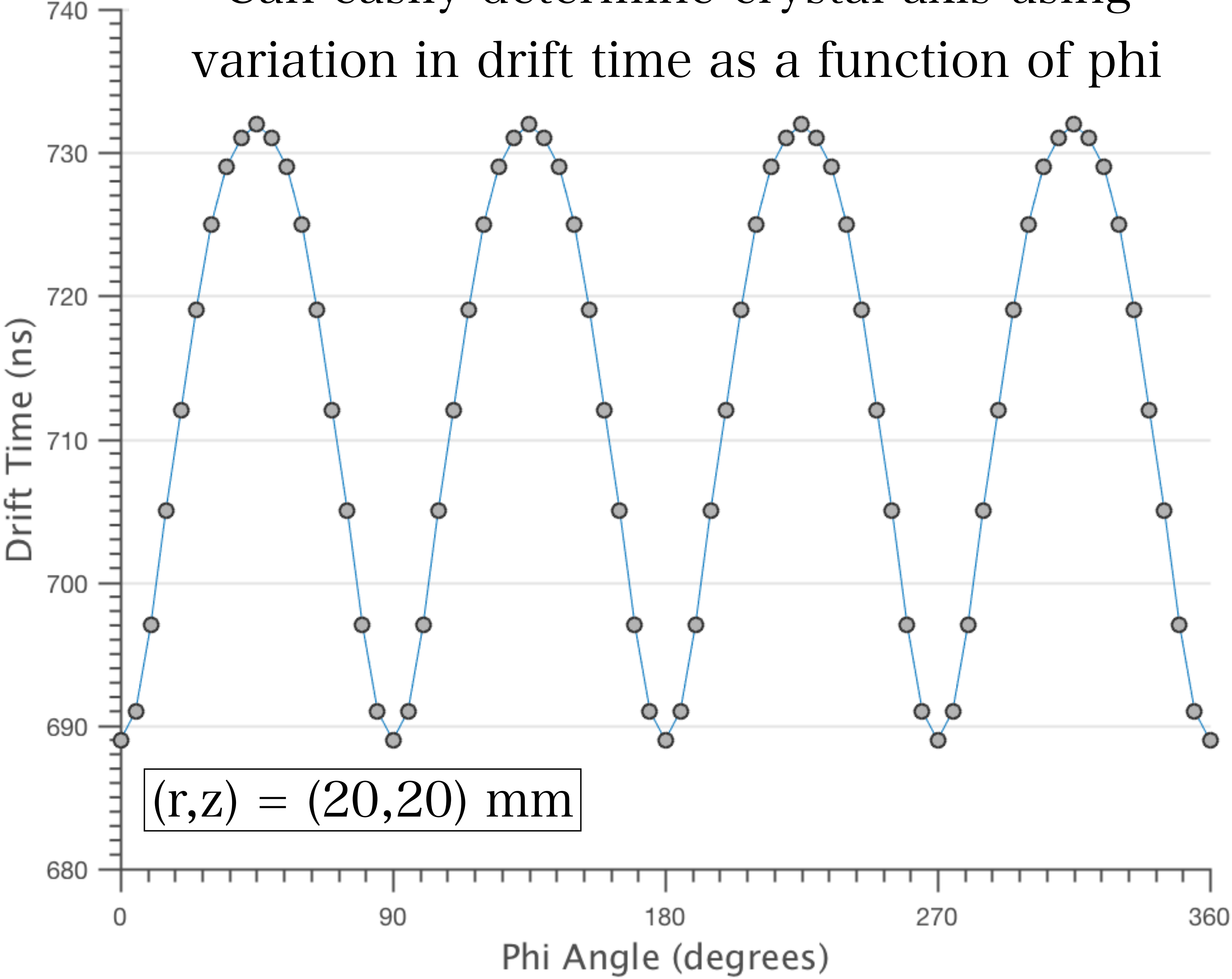


phi= 0°
phi= 45°
R (mm)
Z (mm)
Drift Time (ns)
70
60
50
40
30
20
10
10
20
30
40
50
60
70
80
0
200
400
600
800
1000
1200
1400
1600
1800

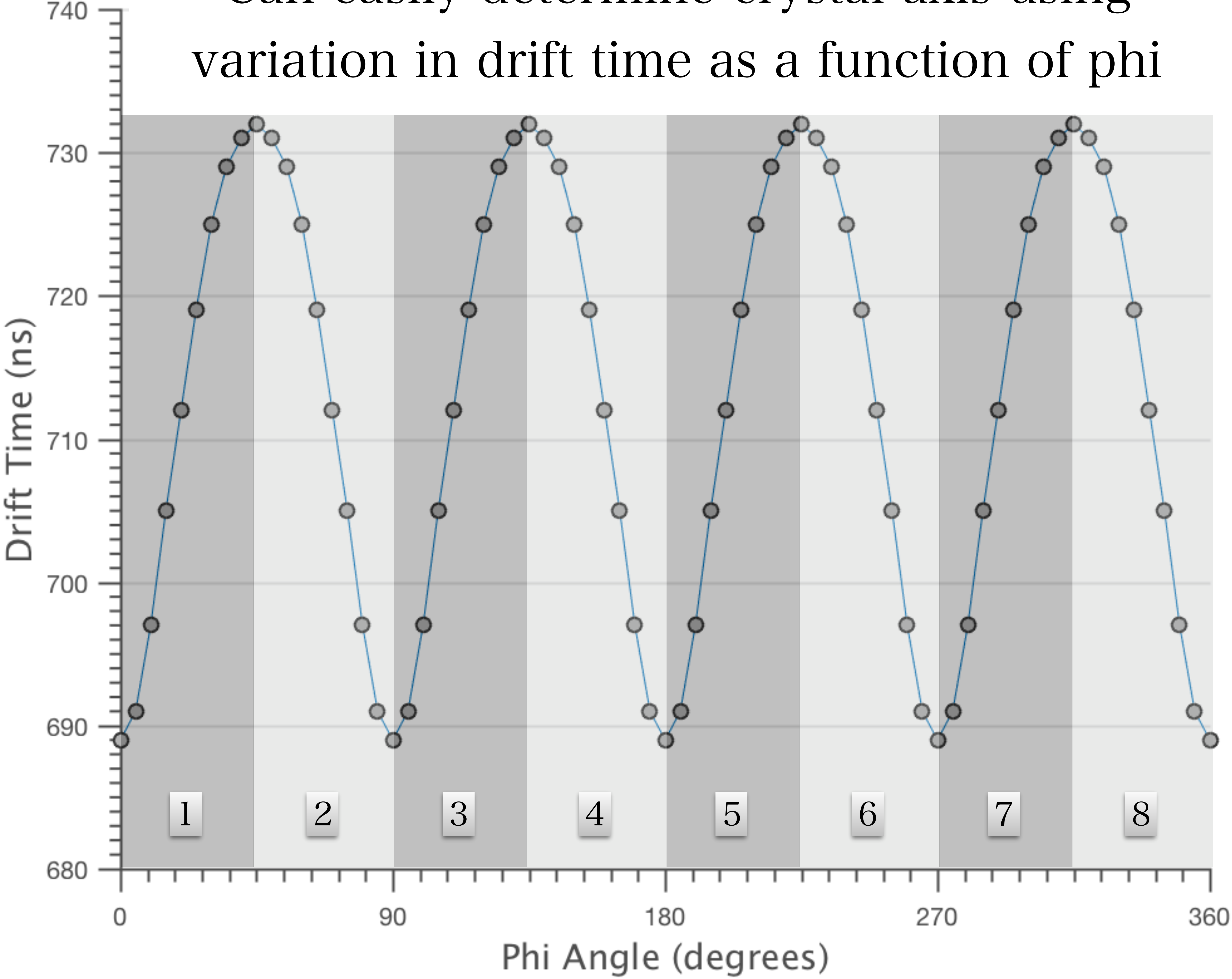


dt ~ r
phi= 0°
dt ~ z
phi= 45°
R (mm)
Z (mm)
Drift Time (ns)
70
60
50
40
30
20
10
10
20
30
40
50
60
70
80
1800
1600
1400
1200
1000
800
600
400
200
0

Can easily determine crystal axis using variation in drift time as a function of phi

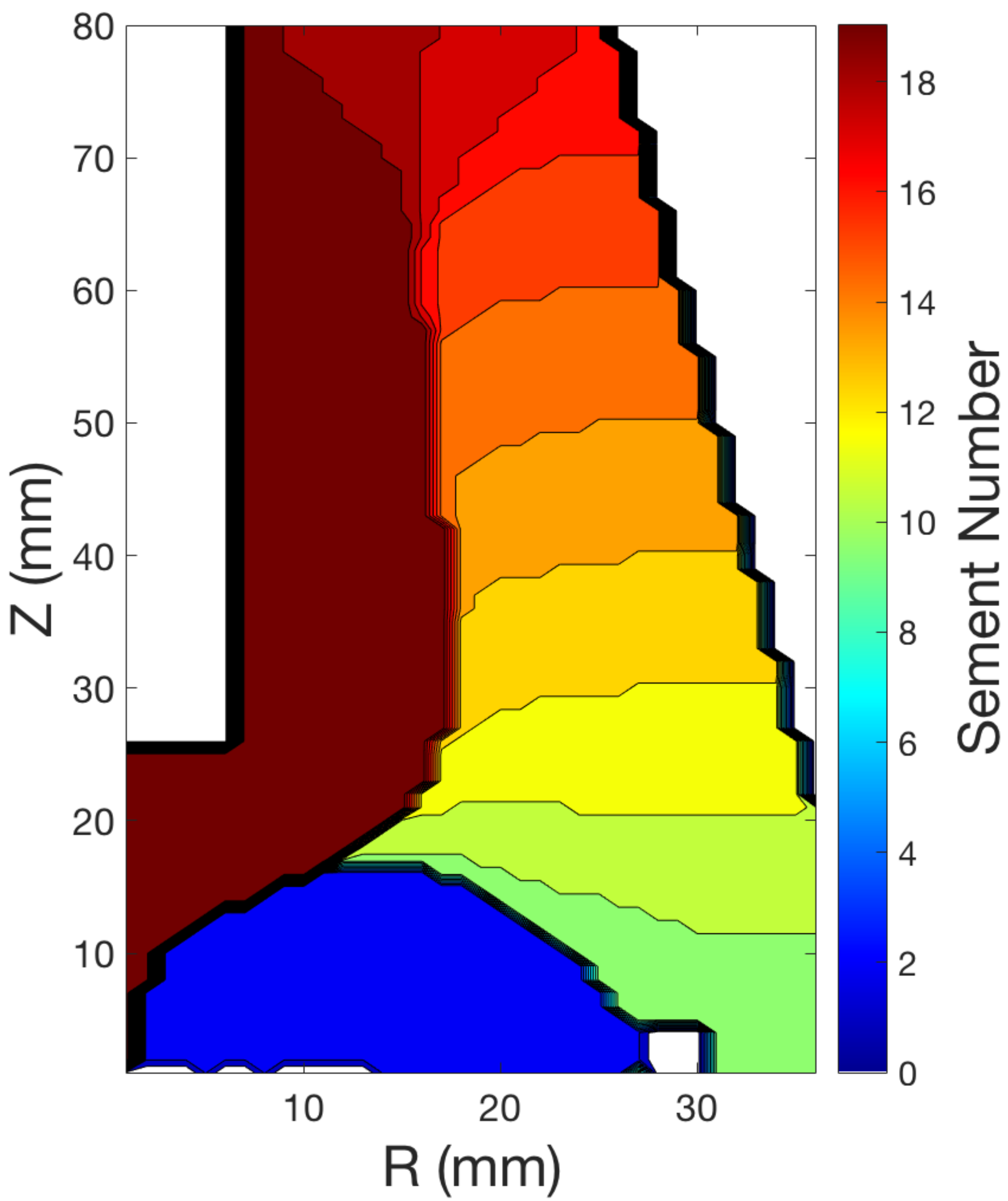


Can easily determine crystal axis using variation in drift time as a function of phi

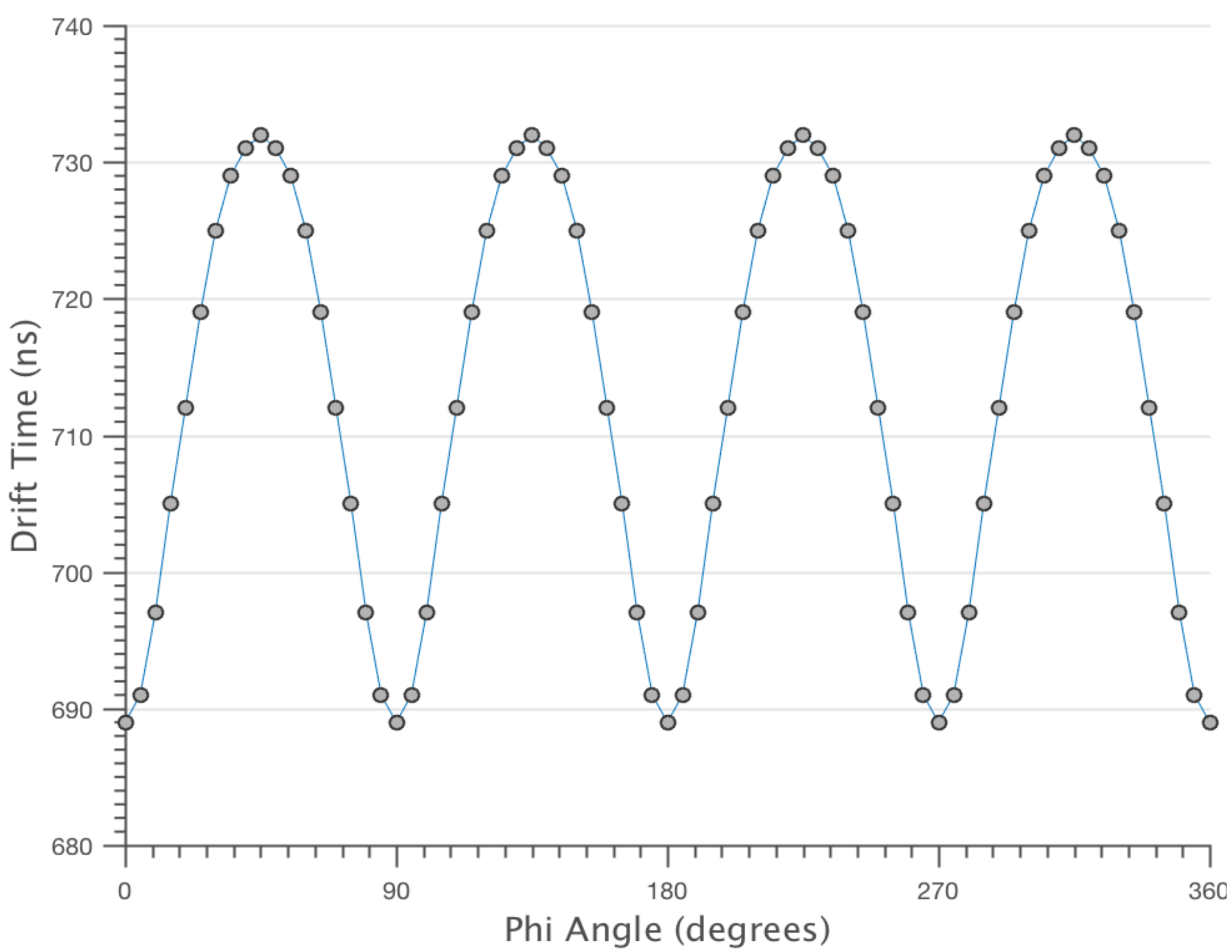


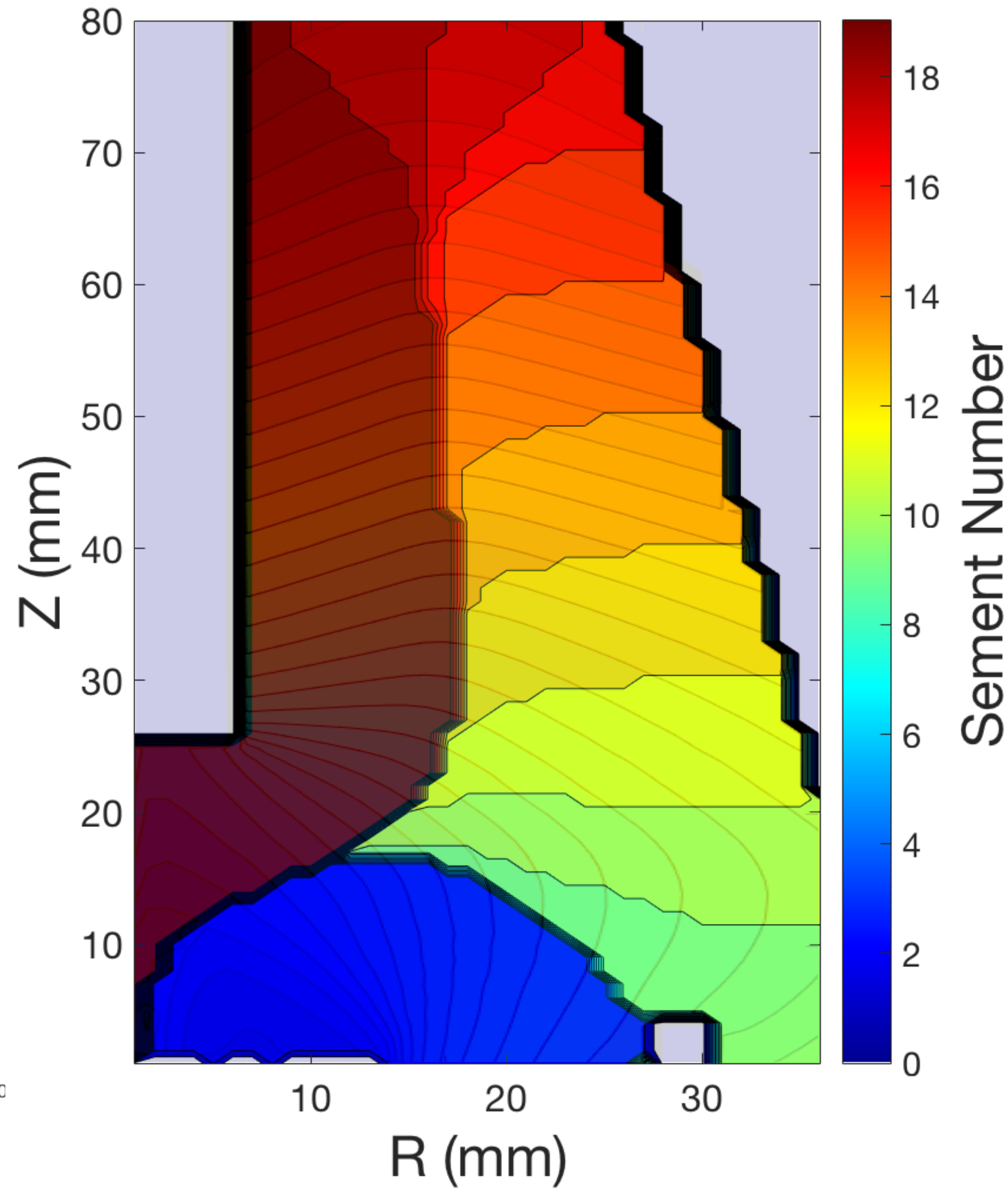
Drift Paths of Electrons

- Final terminating electrode of electrons as function of position
- “Effective segmentation”
- Gates on hit segment and drift time enable interaction positions to be localised to narrow region



- Lots of information available from just studying the drift times





Nuclear Inst. and Methods in Physics Research, A 892 (2018) 84–92

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Position resolution simulations for the inverted-coaxial germanium detector, SIGMA

J.P. Wright [a,*], L.J. Harkness-Brennan [a], A.J. Boston [a], D.S. Judson [a], M. Labiche [b], P.J. Nolan [a], R.D. Page [a], F. Pearce [a], D.C. Radford [c], J. Simpson [b], C. Unsworth [a]

[a] University of Liverpool, Oliver Lodge Building, Liverpool, L69 7ZE, UK
[b] STFC, Daresbury Laboratory, Daresbury, Warrington, WA4 4AD, UK
[c] Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

ARTICLE INFO

Keywords:
Point contact germanium detector
γ-ray imaging
γ-ray tracking
Position sensitivity
Pulse shape analysis

ABSTRACT

The SIGMA Germanium detector has the potential to revolutionise γ-ray spectroscopy, providing superior energy and position resolving capabilities compared with current large volume state-of-the-art Germanium detectors. The theoretical position resolution of the detector as a function of γ-ray interaction position has been studied using simulated detector signals. A study of the effects of RMS noise at various energies has been presented with the position resolution ranging from 0.33 mm FWHM at $E_\gamma = 1$ MeV, to 0.41 mm at $E_\gamma = 150$ keV. An additional investigation into the effects pulse alignment have on pulse shape analysis and in turn, position resolution has been performed. The theoretical performance of SIGMA operating in an experimental setting is presented for use as a standalone detector and as part of an ancillary system.

Nuclear Inst. and Methods in Physics Research, A 892 (2018) 84–92

sts available at ScienceDirect

lethods in Physics Research, A

ge: www.elsevier.com/locate/nima

Compares the variation in pulse shapes as a function of interaction position to get an idea of the position sensitivity

Position resolution simulations for t
detector, SIGMA

J.P. Wright [a,*], L.J. Harkness-Brennan [a], A.J.
R.D. Page [a], F. Pearce [a], D.C. Radford [c], J. Sin

[a] University of Liverpool, Oliver Lodge Building, Liverpool, L69 7ZE, UK
[b] STFC, Daresbury Laboratory, Daresbury, Warrington, WA4 4AD, UK
[c] Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

Δt_0 (ns)	Mean deviation (°/mm)			ε_{recon} (%)	FWHM (mm)
	r	φ	z	<1 mm	
0	0.000	0.000	0.000	100.0	0.00
10	0.327	5.597	0.253	57.9	3.10
20	0.698	7.744	0.573	40.2	4.85
30	0.968	9.228	0.859	30.7	6.11
40	1.208	10.138	1.132	24.9	7.18

Normalised RMS noise	Mean deviation (°/mm)			ε_{recon} (%)	FWHM (mm)
	r	φ	z	<1 mm	
0.00	0.0000	0.000	0.0000	100.0	0.00
0.01	0.0004	0.576	0.0004	100.0	0.11
0.02	0.0025	1.205	0.0026	100	0.28
0.05	0.0696	3.535	0.0531	93.0	1.33
0.10	0.3277	7.637	0.2359	40.6	3.52

ARTICLE INFO

Keywords:
Point contact germanium detector
γ-ray imaging
γ-ray tracking
Position sensitivity
Pulse shape analysis

ABSTRA

The SIGMA Ge
and position r
The theoretica
using simulate
the position r
investigation into the effects pulse alignment have on pulse shape analysis and in turn, position resolution has
theoretical performance of SIGMA operating in an experimental setting is presented for use
ctor and as part of an ancillary system.

Position resolution expected to be under 1 mm, ~4-5 x better than current large volume coax detectors

Prototype Update

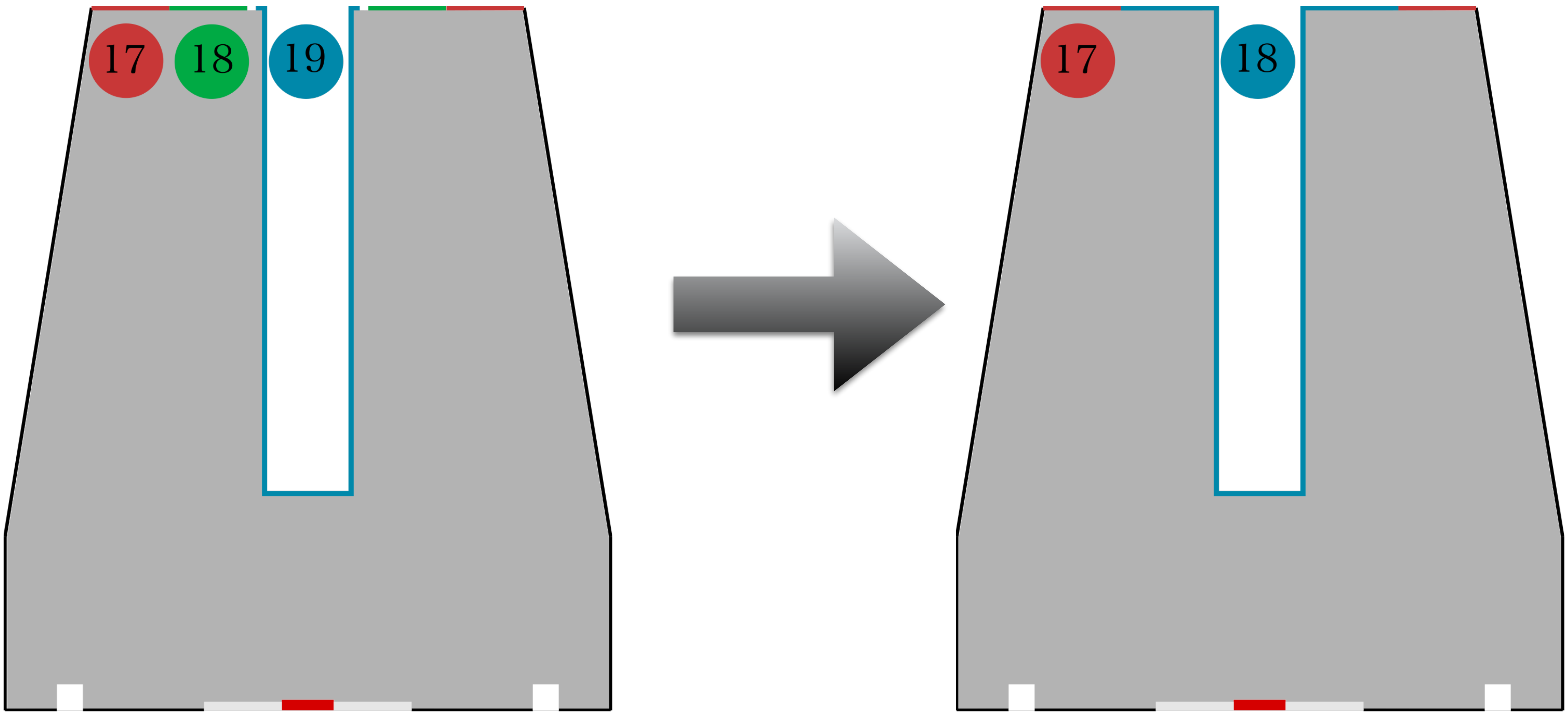
Prototype Status

- Segmentation has been a challenge
- Most recent reprocessing successful
- Crystal has been mounted in test cryostat
- Passed manufacturer acceptance test
- Delivery expected by mid April
- Detector as expected with minor change in segmentation scheme

*Courtesy of MIRION Technologies

Segmentation Change

Issue arose due to reprocessing -> should be avoidable in future iterations

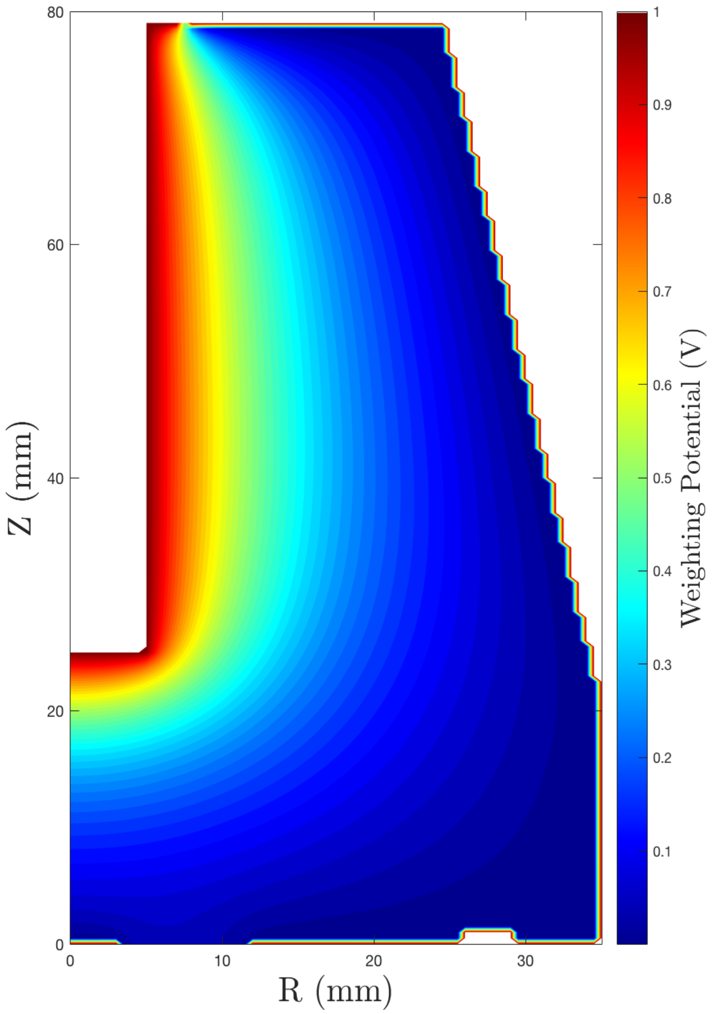


Published Simulations

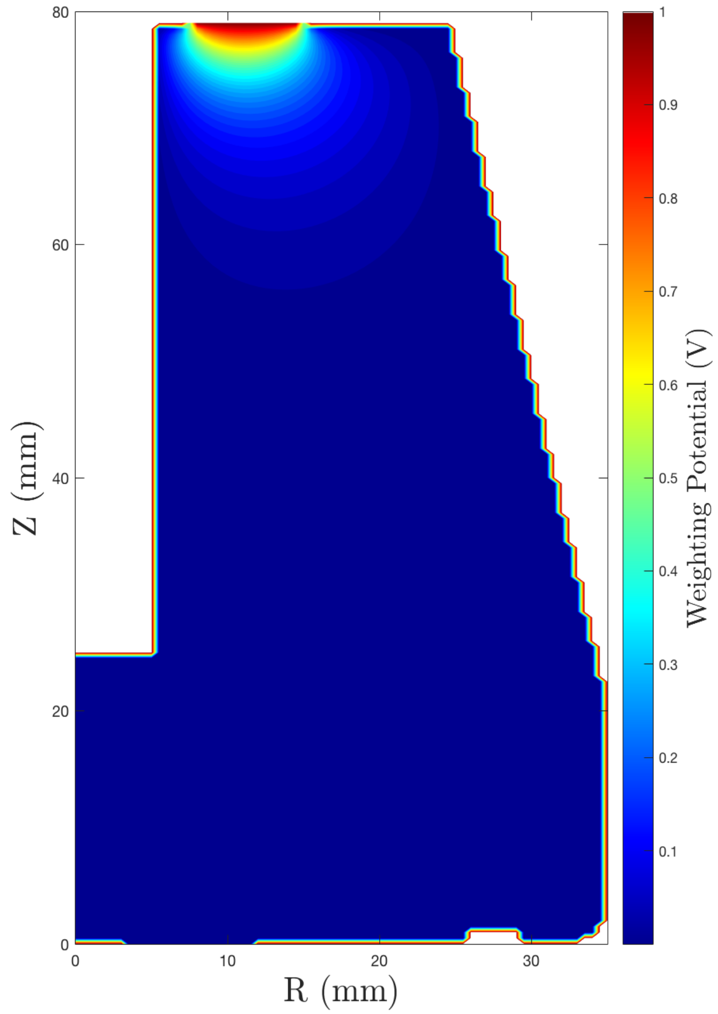
Prototype Detector

Weighting Potentials

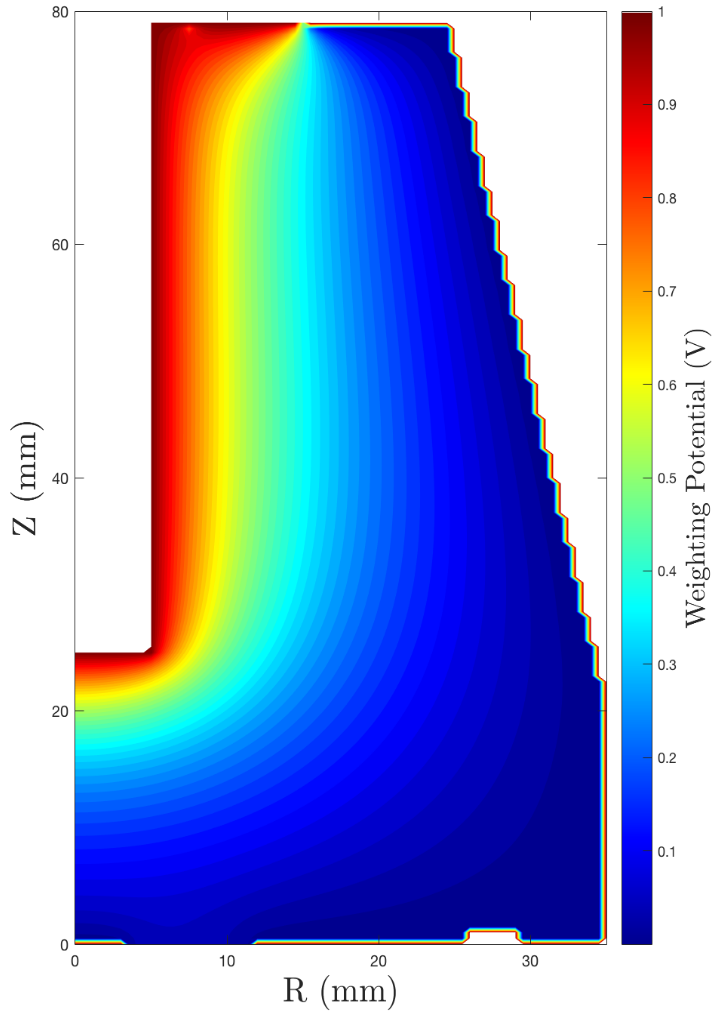
Segment 19



Segment 18



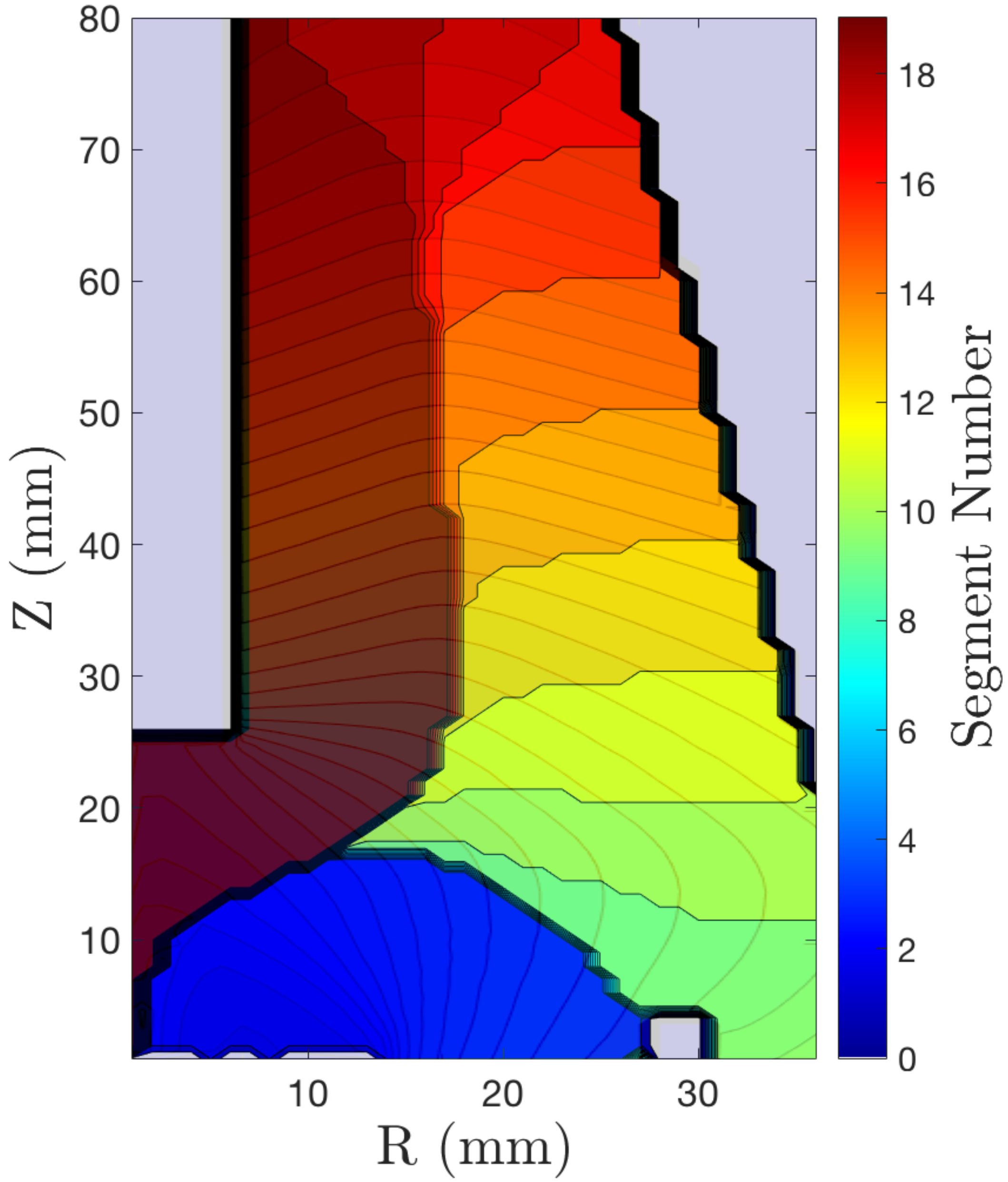
Segment 18/19



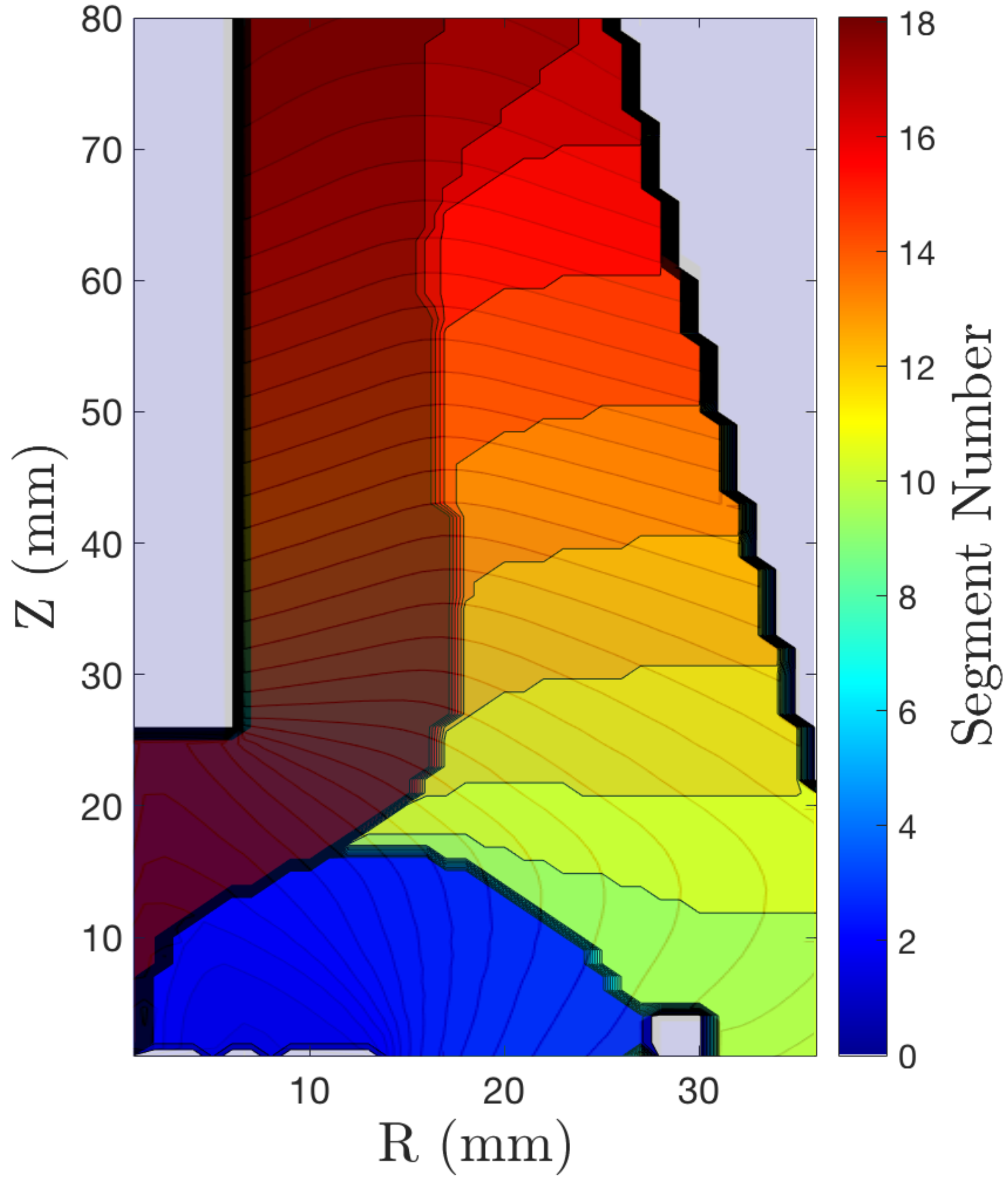
Published Simulations

Prototype Detector

Native Resolution



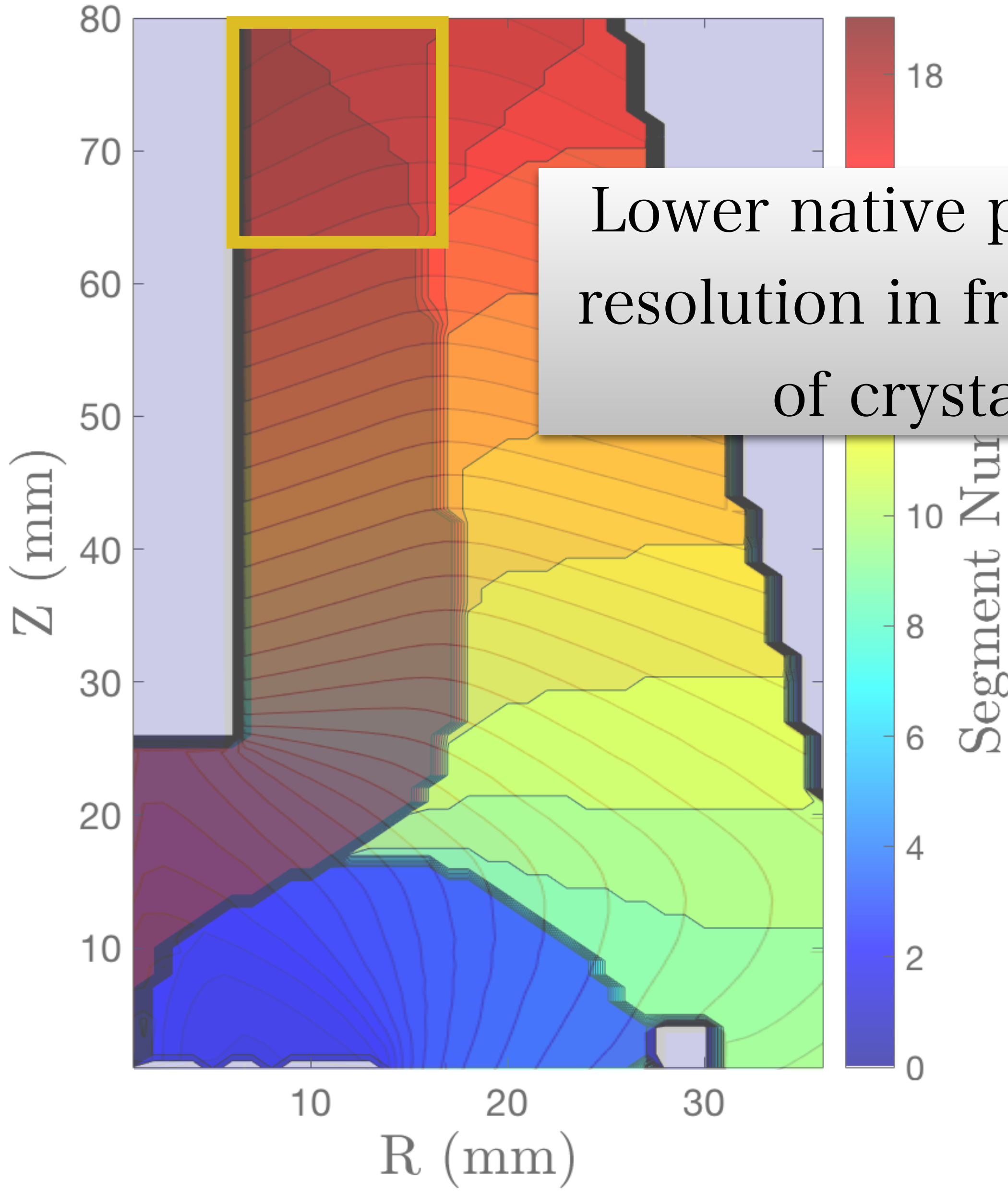
Published Simulations



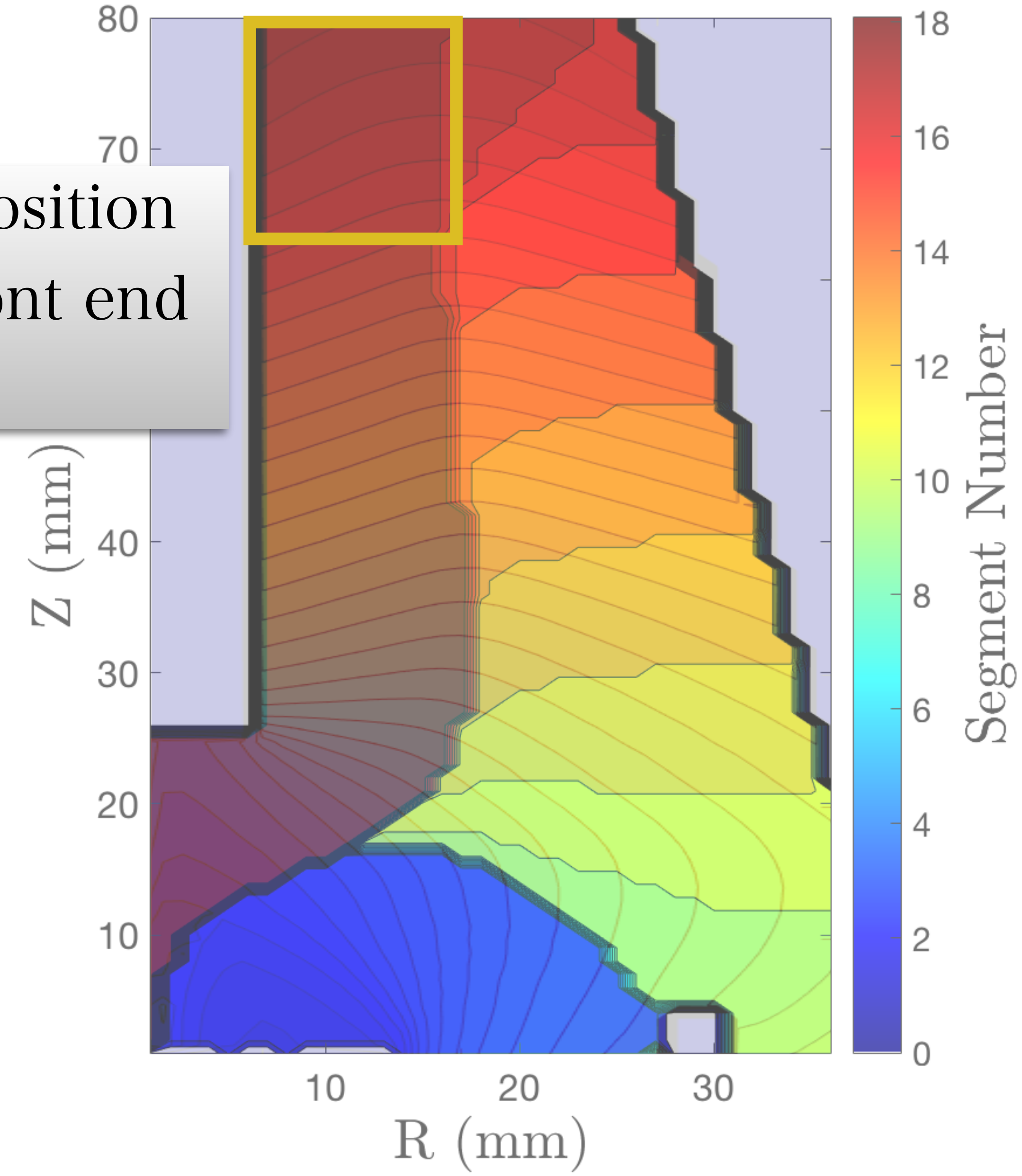
Prototype Detector

Native Resolution

Lower native position resolution in front end of crystal



Published Simulations



Prototype Detector

Manufacturer Spec

Full volume performances				
Depletion voltage	-	800	V	
Operating high voltage (negative)	-	2500	V	
Energy resolution FWHM at 1.33 MeV (Co-60)		2.37	keV	
Efficiency		41	%	
Peak / Compton ratio		41		
FWHM at 122 keV (Co-57)		0.89	keV	

*Preliminary values from manufacturer

Outer contact performances

Segment number		Energy resolution (FWHM in keV) 122 keV (Co-57)	Energy resolution (FWHM in keV) 1.33 MeV (Co-60)	
1		1.20	2.64	
2		0.90	2.44	
3		0.88	2.33	
4		0.87	2.43	
5		0.92	2.28	
6		0.89	2.33	
7		0.92	2.40	
8		0.92	2.40	
9		1.90	2.45	
10		1.03	2.02	
11		1.14	2.04	
12		1.13	2.08	
13		1.09	2.15	
14		1.09	2.36	
15		1.10	2.15	
16		1.08	1.90	
17		1.04	2.01	
18		1.16	To be measured	

Manufacturer Spec

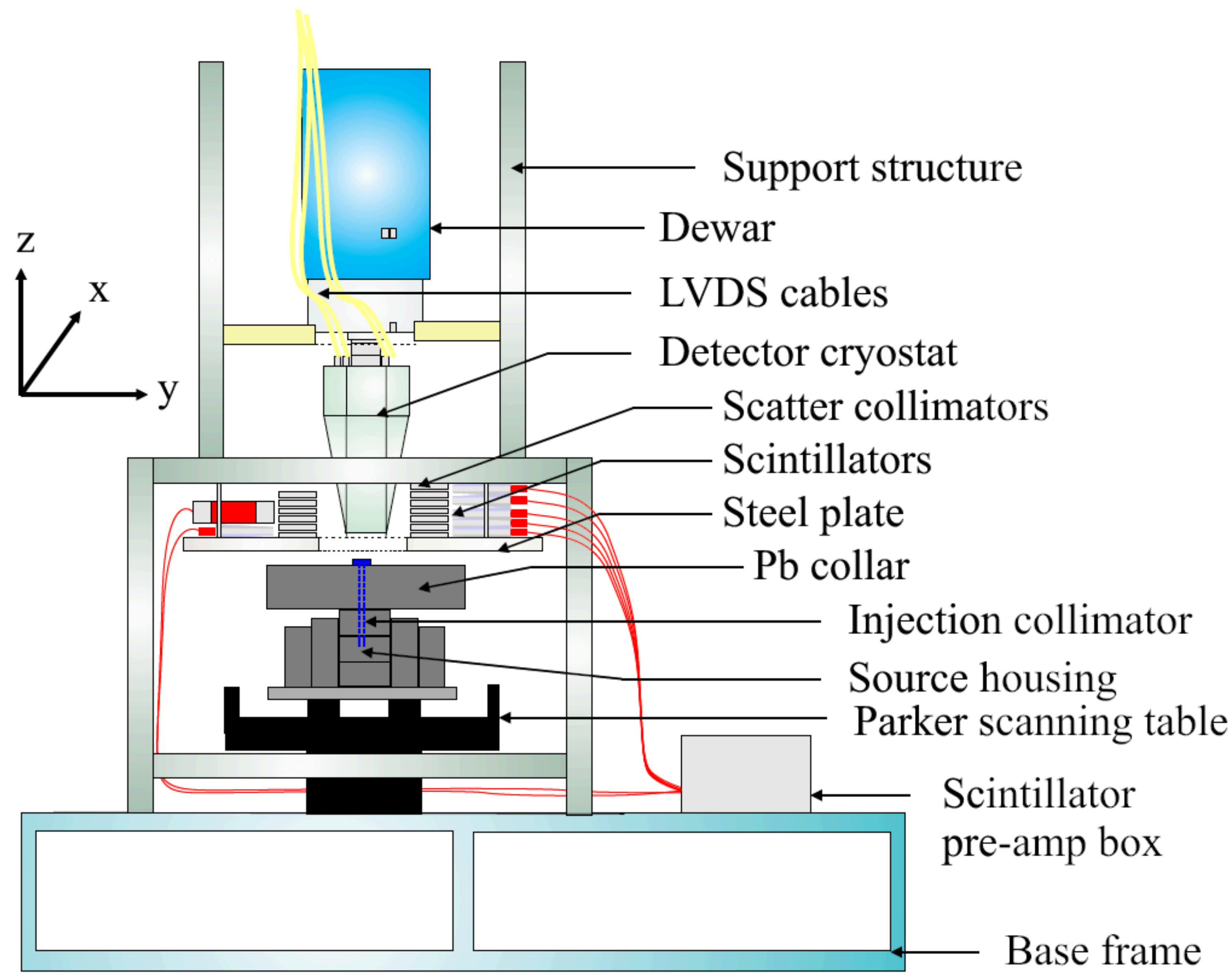
Full volume performances			
Depletion voltage	- 800	V	
Operating high voltage (negative)	- 2500	V	
Energy resolution FWHM at 1.33 MeV (Co-60)	2.37	keV	
Efficiency	41	%	
Peak / Compton ratio	41		
FWHM at 122 keV (Co-57)	0.89	keV	

*Preliminary values from manufacturer

Outer contact performances			
Segment number		Energy resolution (FWHM in keV)	
		122 keV (Co-57)	1.33 MeV (Co-60)
1		1.20	2.64
2		0.90	2.44
3		0.88	2.33
4		0.87	2.43
5		0.92	2.28
6		0.89	2.33
7		0.92	2.40
8		0.92	2.40
9		1.90	2.45
10		1.03	2.02
11		1.14	2.04
12		1.13	2.08
13		1.09	2.15
14		1.09	2.36
15		1.10	2.15
16		1.08	1.90
17		1.04	2.01
18		1.16	To be measured

Next Steps

- Acceptance tests at Liverpool
- Digital electronics parameter optimisation
- Set up on scanning table
    - ~2-3 months
- Refinement of pulse shape basis to match experimental observations



Summary

- A novel detector has been designed and characterised through simulation
- Sub-mm position resolution predicted
- The 1st prototype has been successfully manufactured
- Delivery expected within the coming weeks
- Acceptance testing and basis validation to begin upon arrival

Collaborators

J.P.Wright[1], L.J.Harkness-Brennan[1], A.J.Boston[1], D.S.Judson[1], M.Labiche[2], P.J.Nolan[1], R.D.Page[1], F.Pearce[1], D.C.Radford[3], J.Simpson[2], C.Unsworth[1]

[1] University of Liverpool, UK
[2] STFC Daresbury, UK
[3] Oak Ridge National Laboratory, USA

UNIVERSITY OF LIVERPOOL

Science & Technology Facilities Council

OAK RIDGE National Laboratory

Thank you

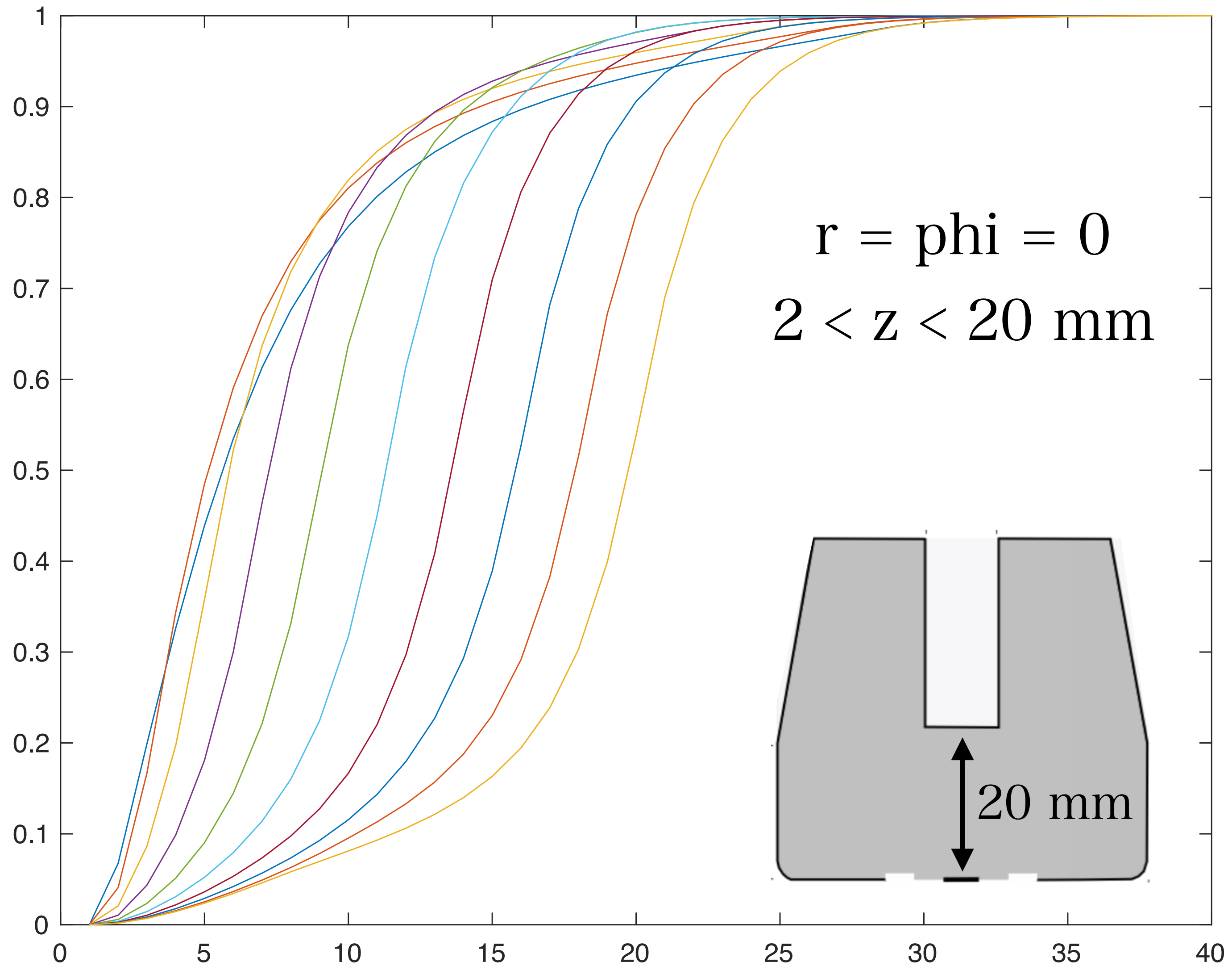
Any Questions?

Additional Slides

Position Sensitivity Study

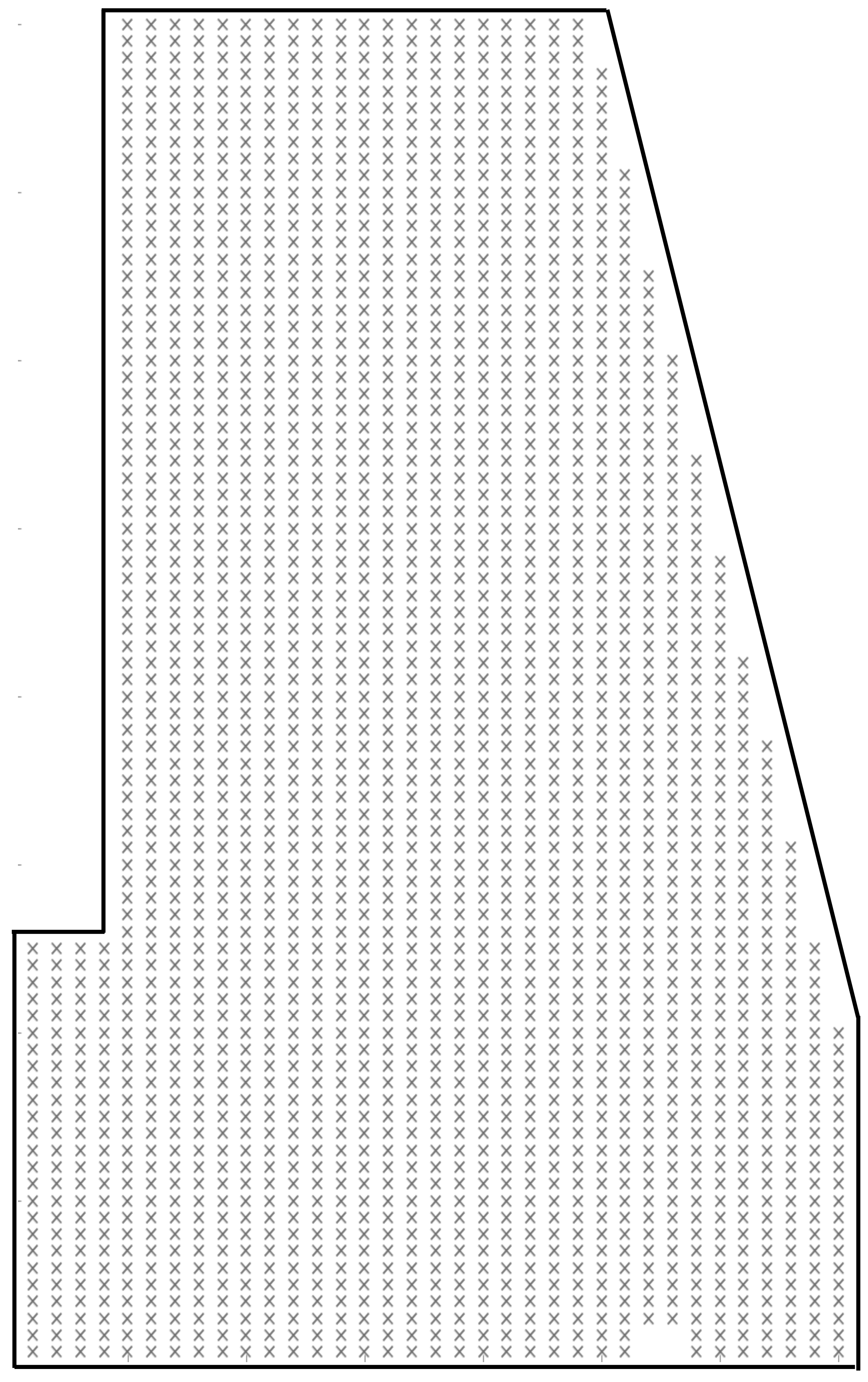
Pulse Shape Analysis

- Interactions occurring in different locations result in different charge pulses
- Comparing experimental pulses to a simulated database enables better position sensitivity



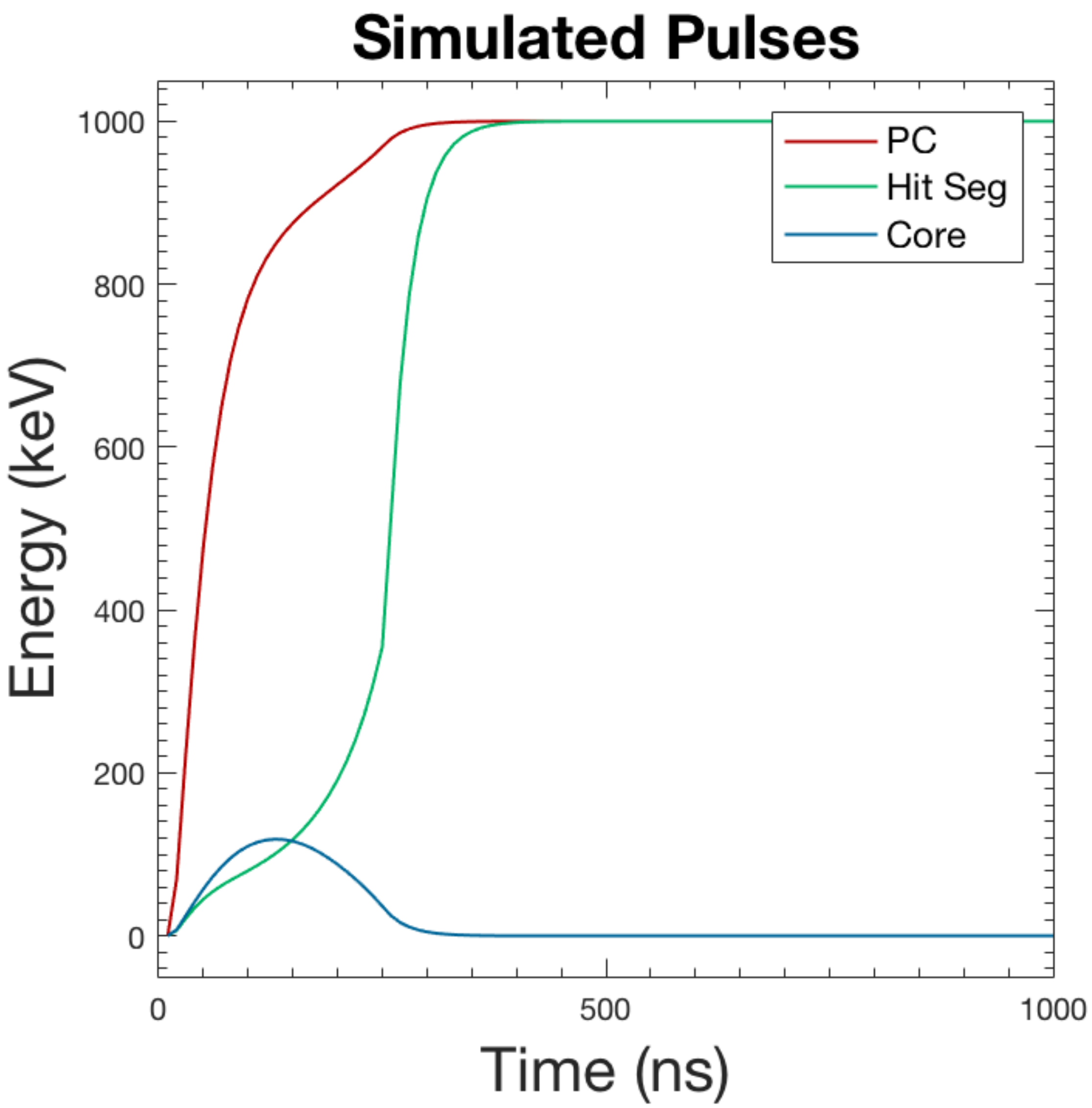
Pulse Shape Database

- Pulses generated for every position on a 1 mm x 1 mm x 3 degree grid
- 200 x 10 ns samples per pulse
- Data output at each position contains
  - 20 pulses
  - Drift times
  - x,y,z & r,phi,z coords
  - Hit segment number



Position Resolution Study

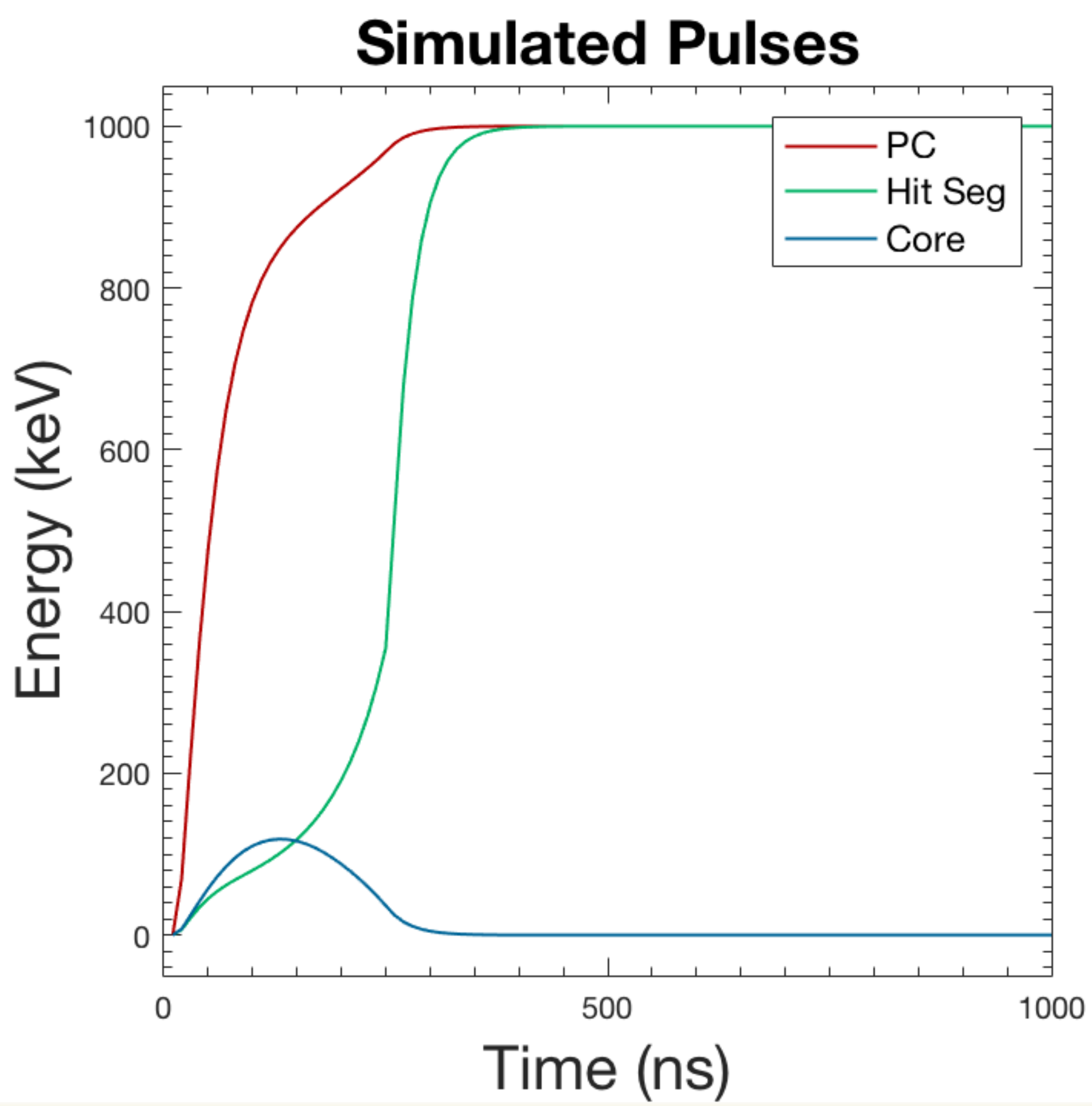
1. Select pulse from basis

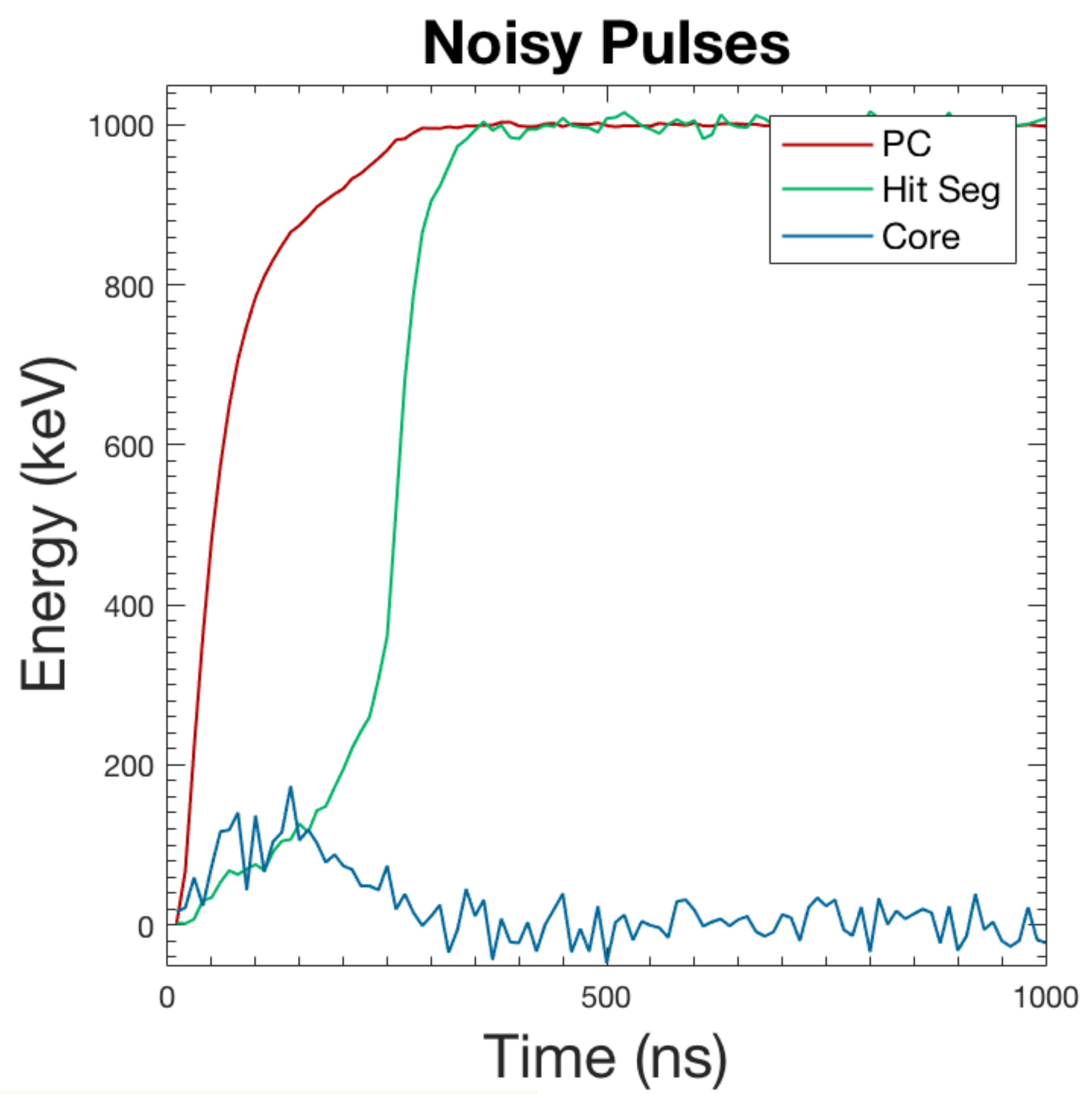


Position Resolution Study

1. Select pulse

2. Add realistic noise to all pulses - $V_{p\text{-}p}$ ~ 1 mV* for point contact, $V_{p\text{-}p}$ ~ 5-20 mV for outer segments,



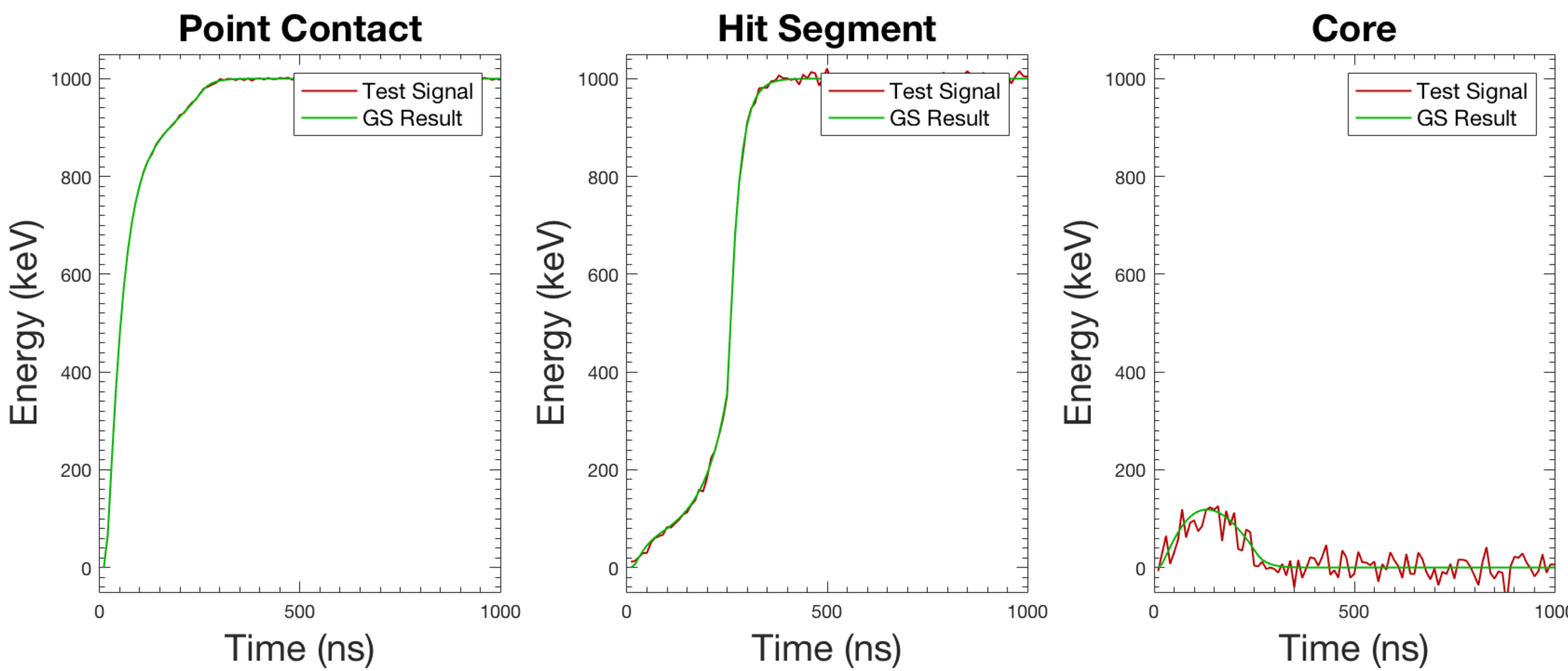


* L.J. Harkness-Brennan et. al, Nucl. Instr. Meth. A 760 (2014) 28-39

Position Resolution Study

$$\chi^2 = \sum_{i,j} |S^m_{i,j} - S^s_{i,j}|^2$$

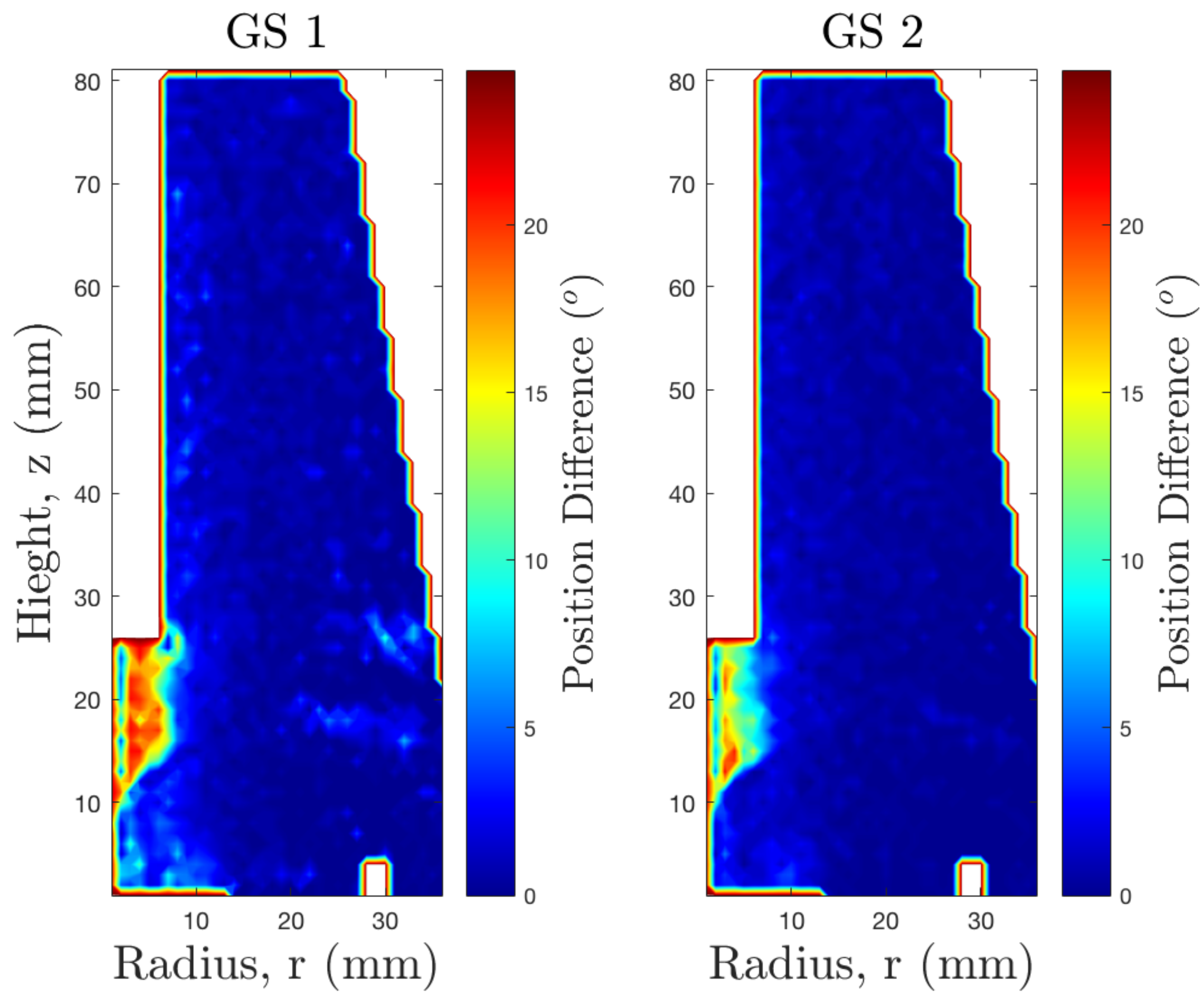
1. Select pulse
2. Add noise
3. Run through grid search algorithm, performing chi² minimisation to find most likely interaction position



Position Resolution Study

- Addition of azimuthal segs significantly improves phi resolution
- Addition of remaining sigs slightly improves resolution but increases time to perform search
- Drift time and hit segment cuts help reduce search time

Phi deviation as a function of interaction position



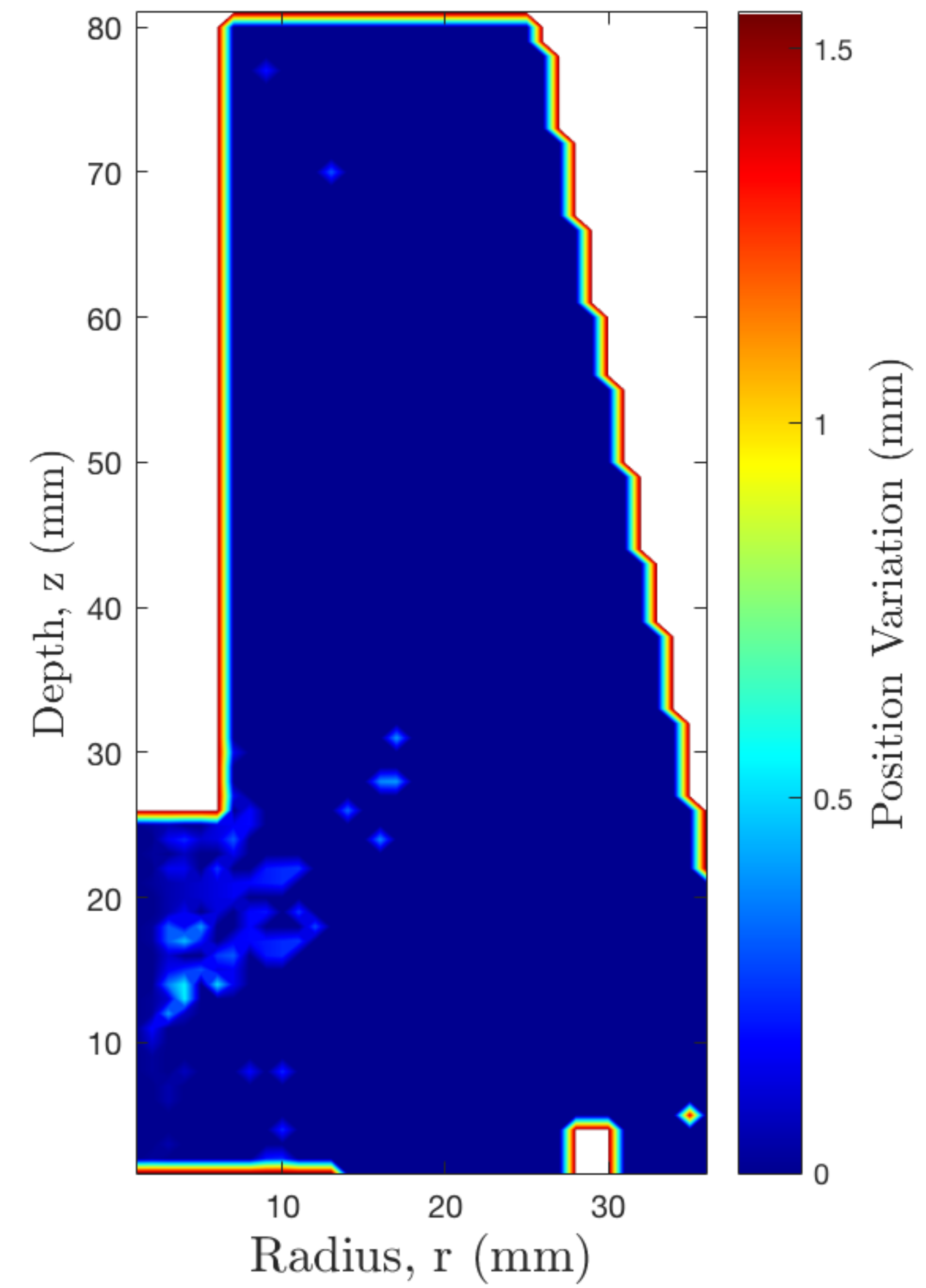
GS 1 = PC + HS + Core
GS 2 = GS 1 + 8 x Azimuthal

Position Resolution Study

1. Select pulse
2. Add noise
3. Grid search algorithm
4. Measure average deviation from known position for 10 independent samples per basis position
   FWHM = **0.41 mm** averaged throughout detector

$$FWHM = 2.35\sigma = 2.35\sqrt{\frac{\sum_N \Delta^2_{x,y,z}}{N}}$$

FWHM as a function of interaction position

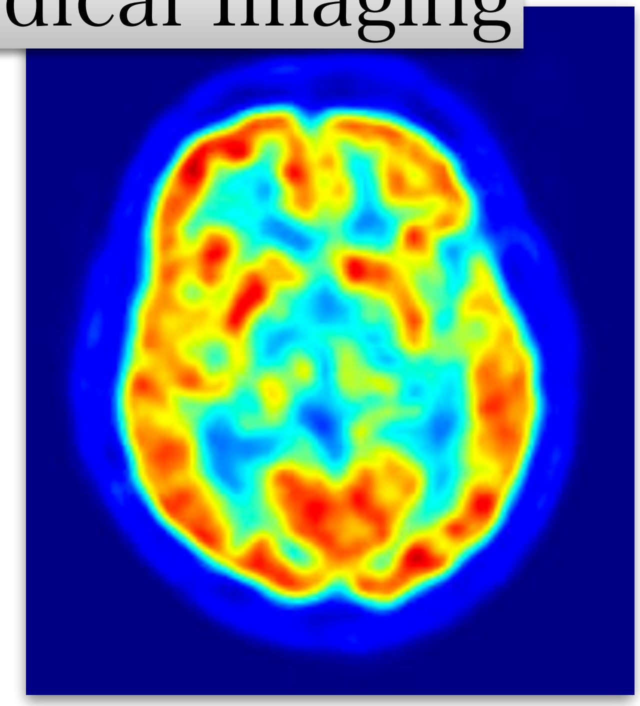


GS 5 = All segs + dt cut + hit_seg cut

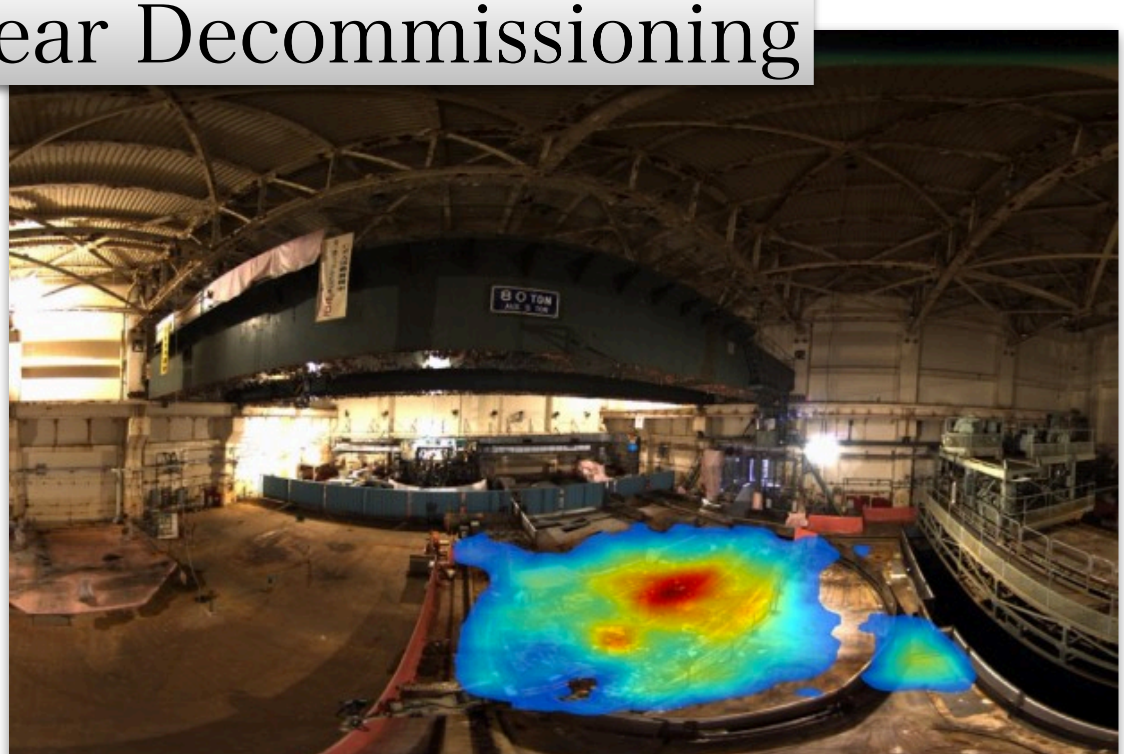
Applications

Research

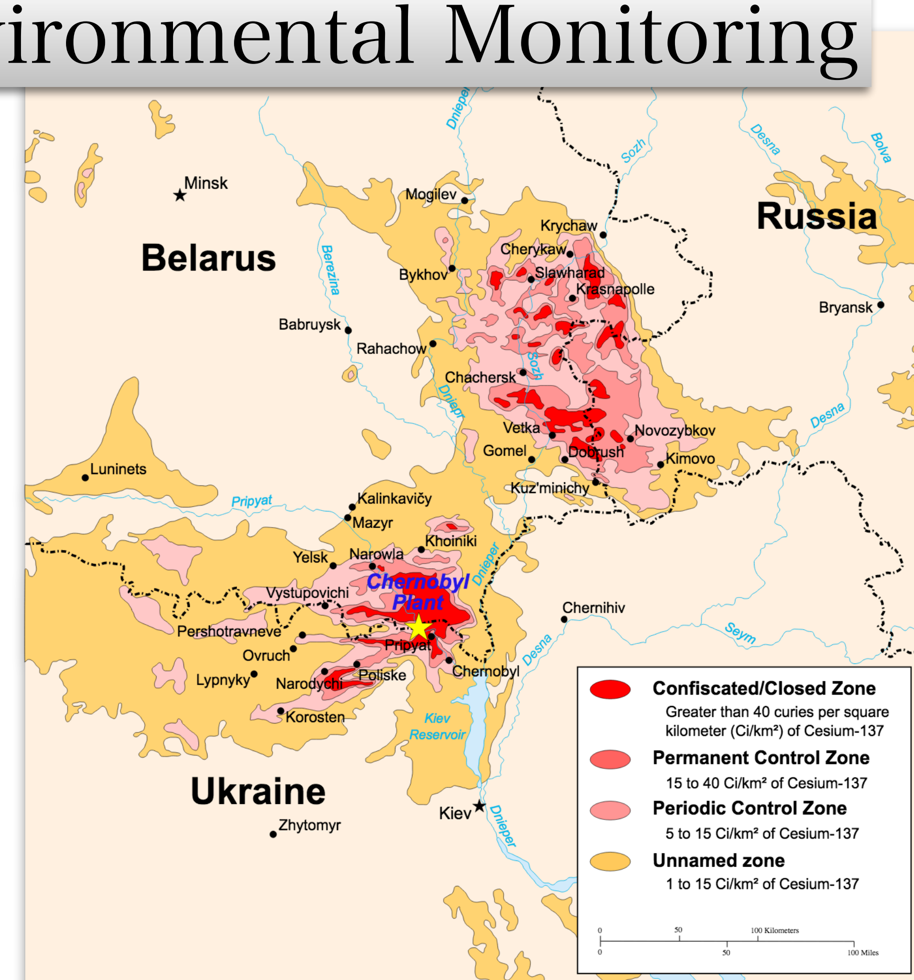
Medical Imaging



Nuclear Decommissioning



Environmental Monitoring



Ongoing Work

- Design different array configurations to test efficiency
- Compare potential SIGMA arrays to other DEGAS Phase III options
- Test imaging potential of fully operating SIGMA tracking array

Published by IOP Publishing for Sissa Medialab

Received: *March 21, 2015*
Accepted: *May 13, 2015*
Published: *June 17, 2015*

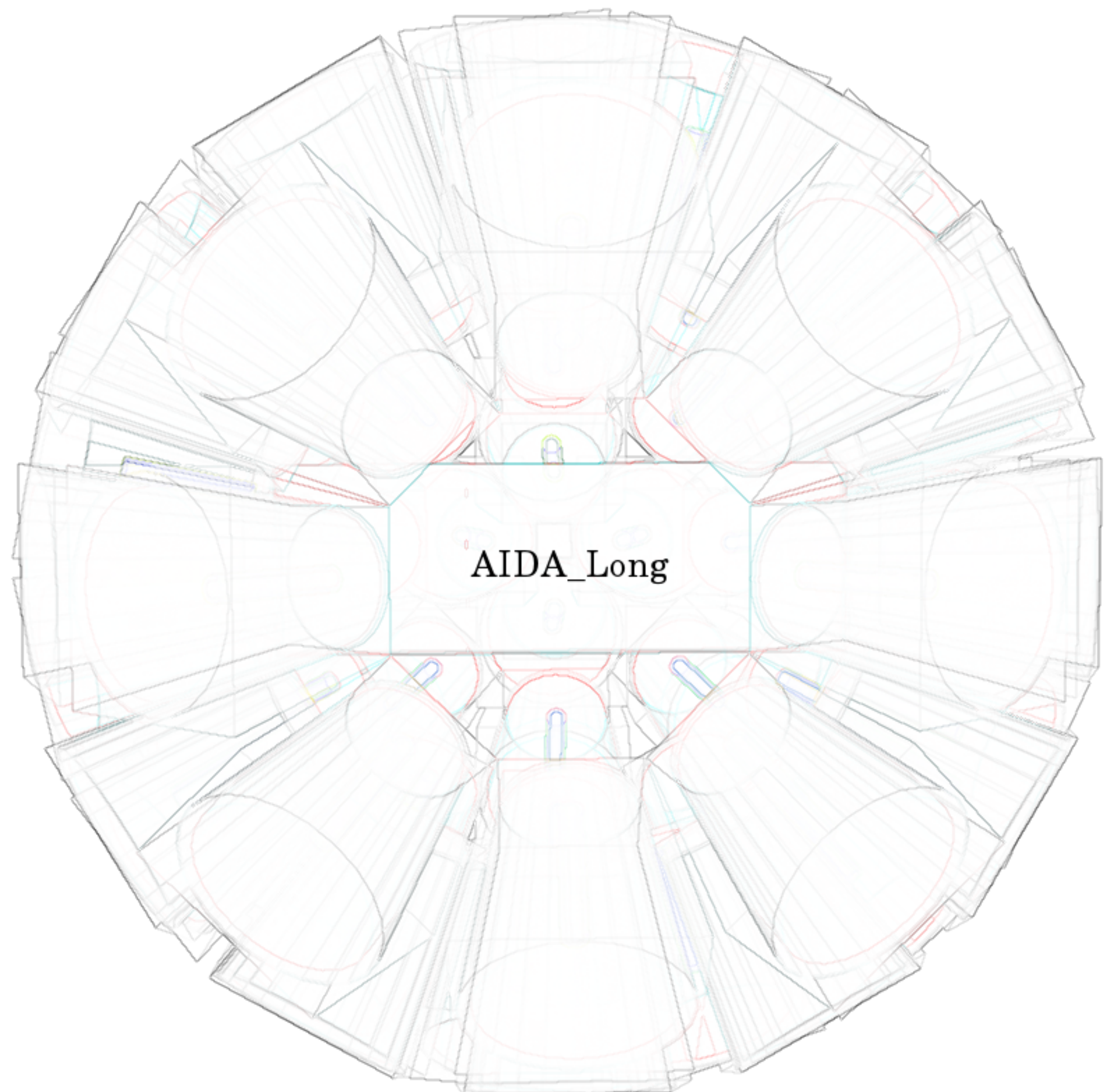
Conceptual design of a high resolution Ge array with tracking and imaging capabilities for the DESPEC (FAIR) experiment

M. Doncel,[a,b,1] **B. Cederwall,**[a] **S. Martín,**[b] **B. Quintana,**[b] **A. Gadea,**[c] **E. Farnea**[d] **and A. Algora**[c,e]

Abstract: We present results of Monte Carlo simulations for the conceptual design of the high-resolution DESPEC Germanium Array Spectrometer (DEGAS) proposed for the Facility for Ion and Antiproton Research (FAIR) under construction at Darmstadt, Germany. The project is carried out in three phases, although only results for the two first phases will be addressed in this work. The first phase will consist of a re-arrangement of the EUROBALL cluster detectors previously used in the RISING campaign at GSI. The second phase is based on coupling AGATA-type triple-cluster detectors with EUROBALL cluster detectors in a compact geometry around the active ion implantation target of DESPEC.

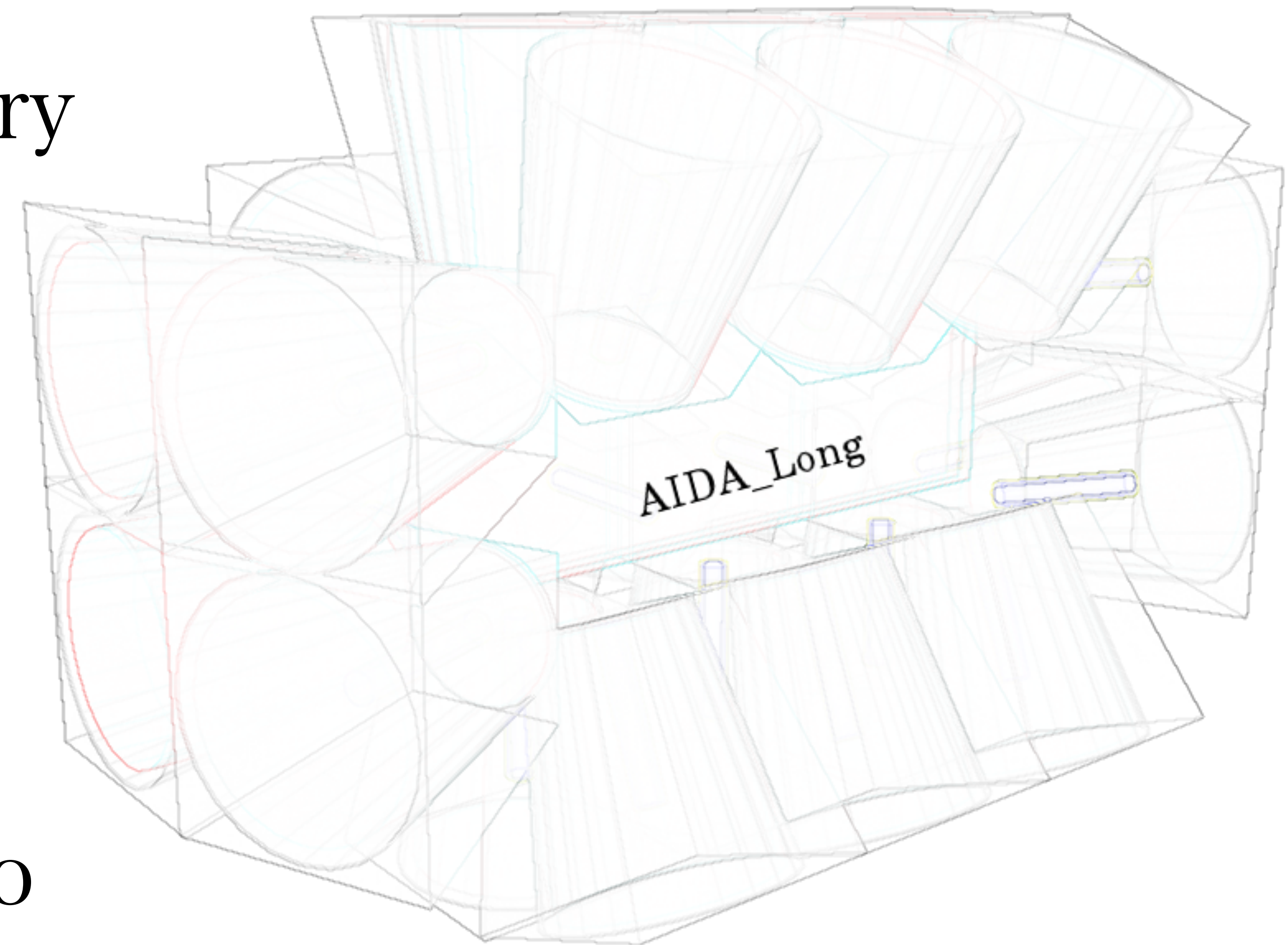
Spherical Configuration

- Half-sphere design
- Enables larger dewar
- Compactness limited by front end size

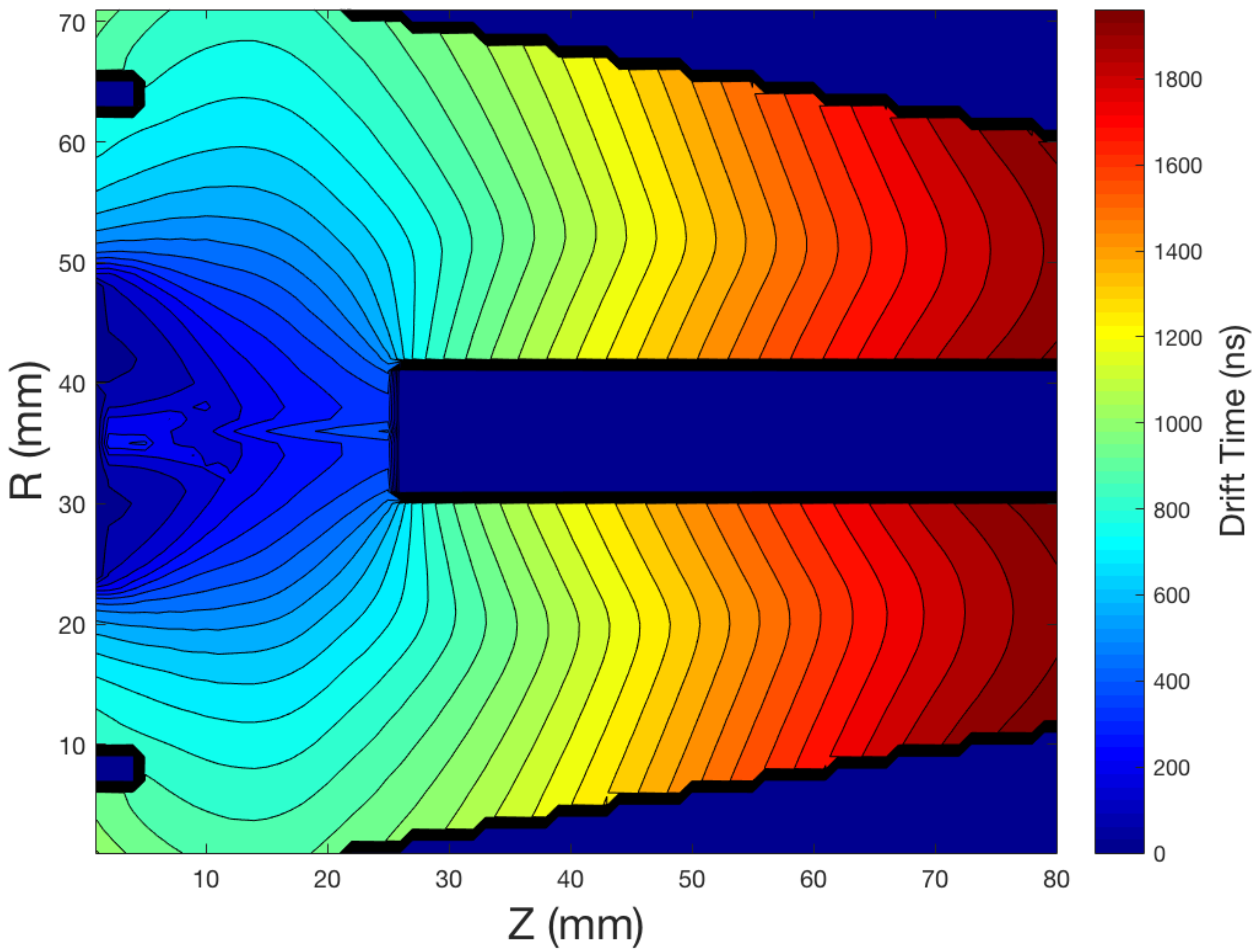


“Box” Configuration

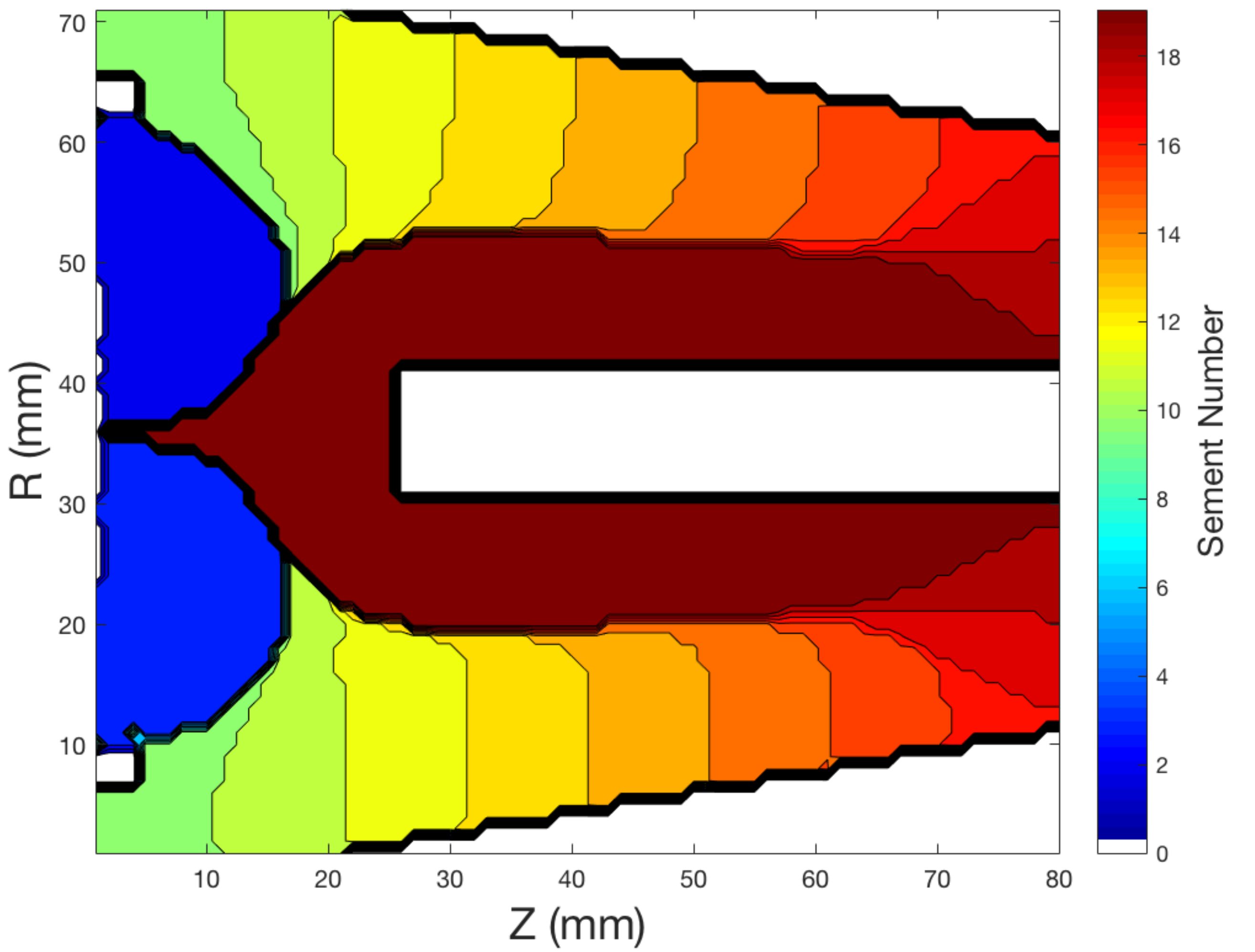
- Cubic / “Box” geometry
- Limited by width of dewar
- Can theoretically be more compact than Sphere
- Smaller dewar leads to practical complications



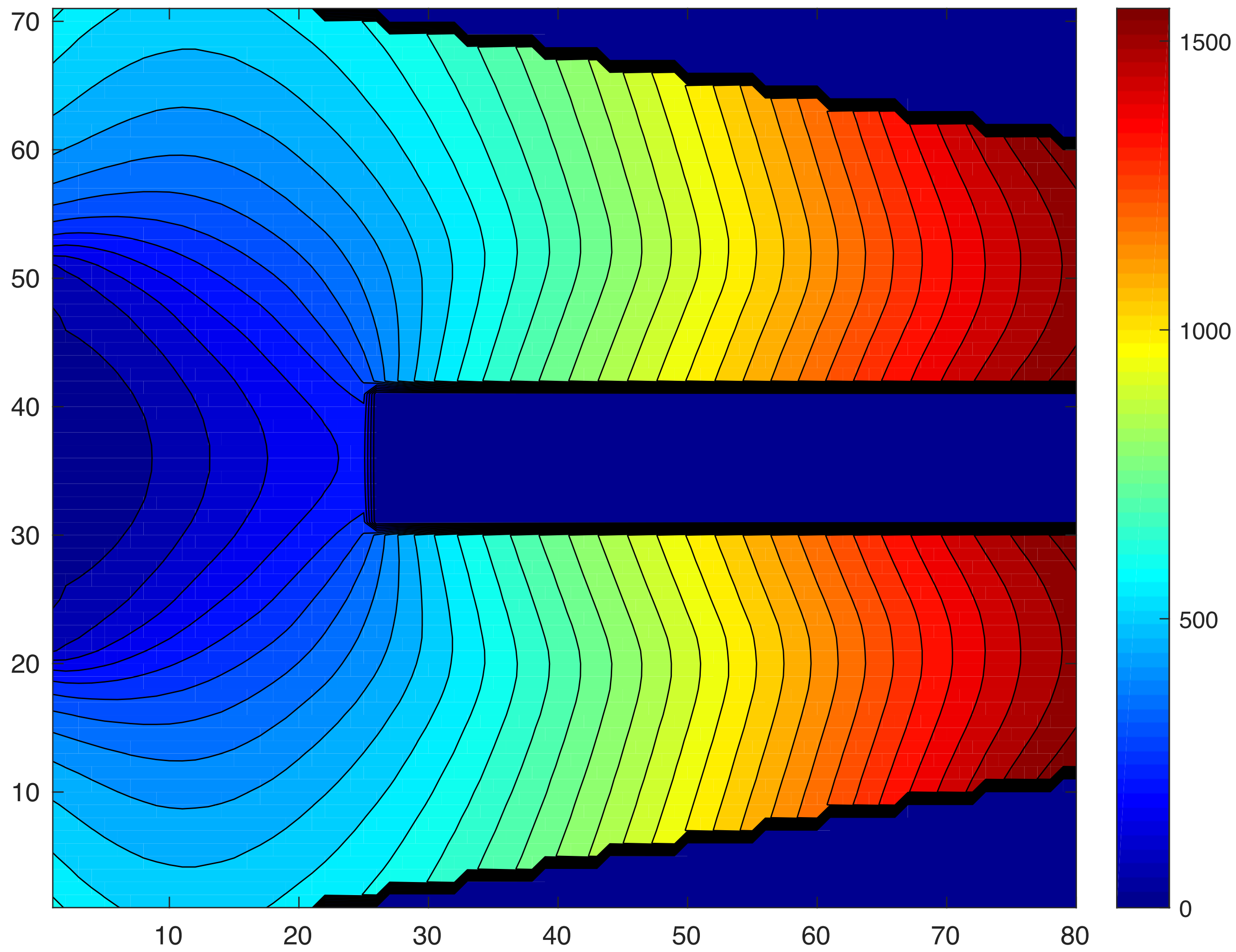
Drift time distribution as a function of R and Z



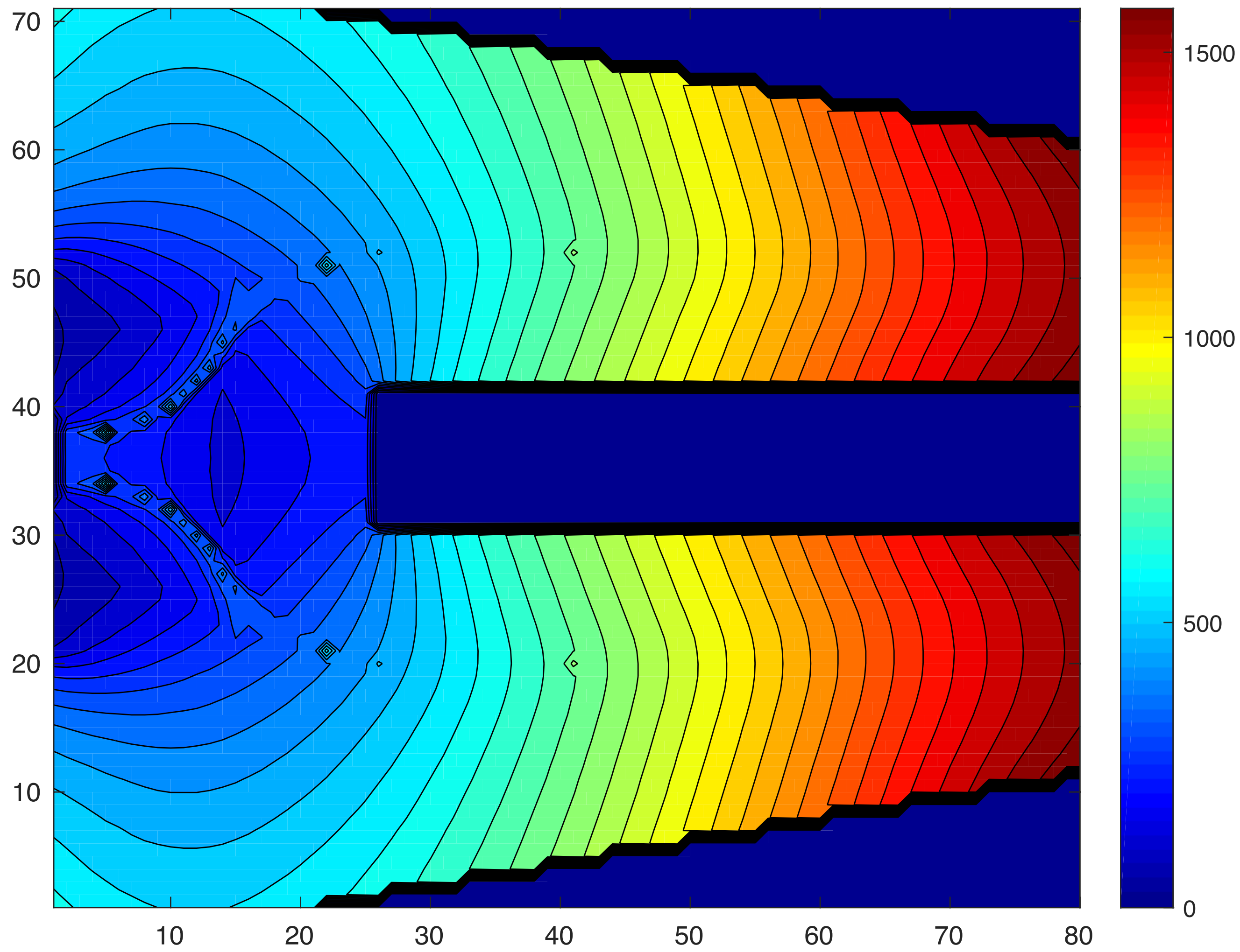
Distribution of hit segment as a function of R and Z



Drift time 0 - 50%

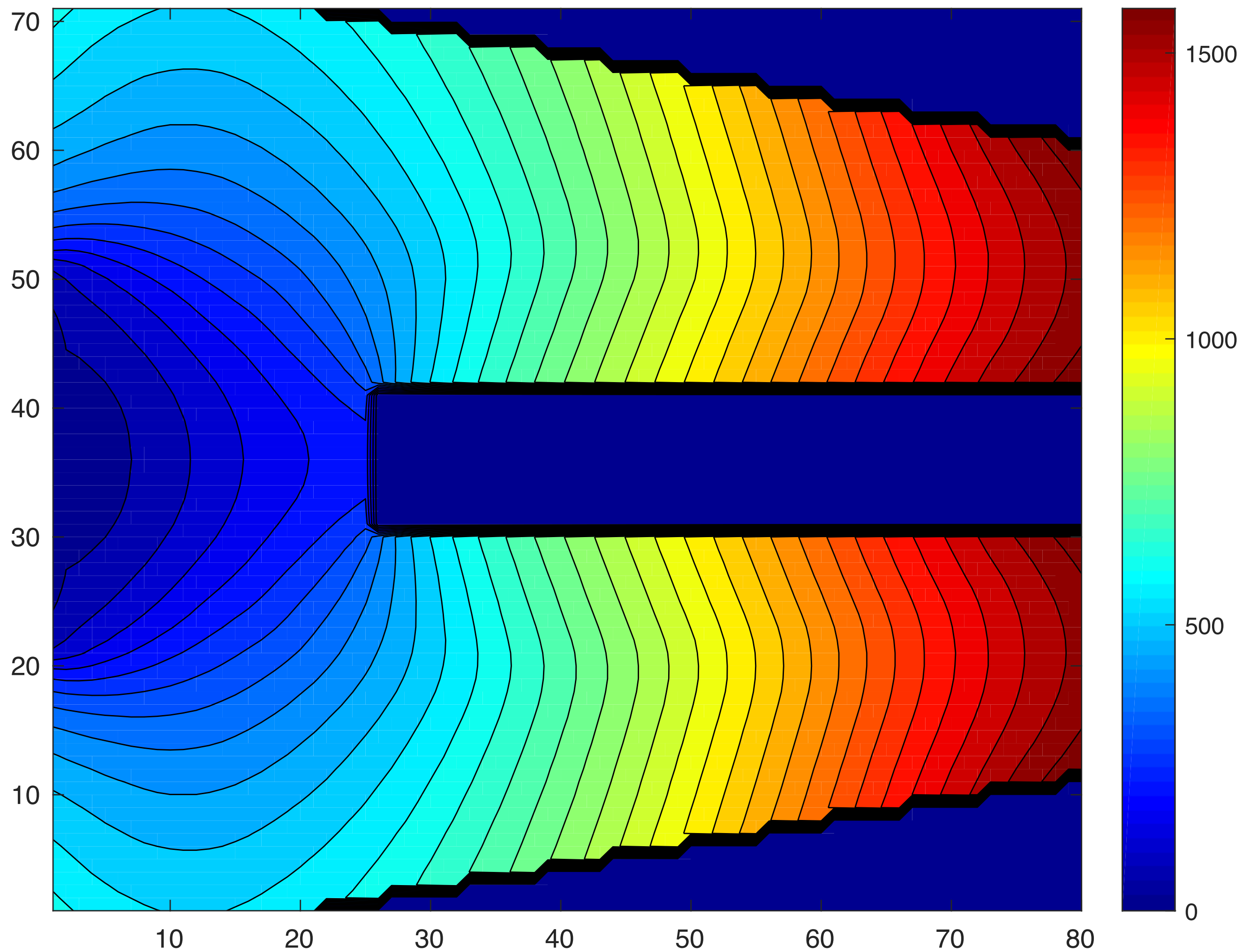


Drift time 0 - 100%

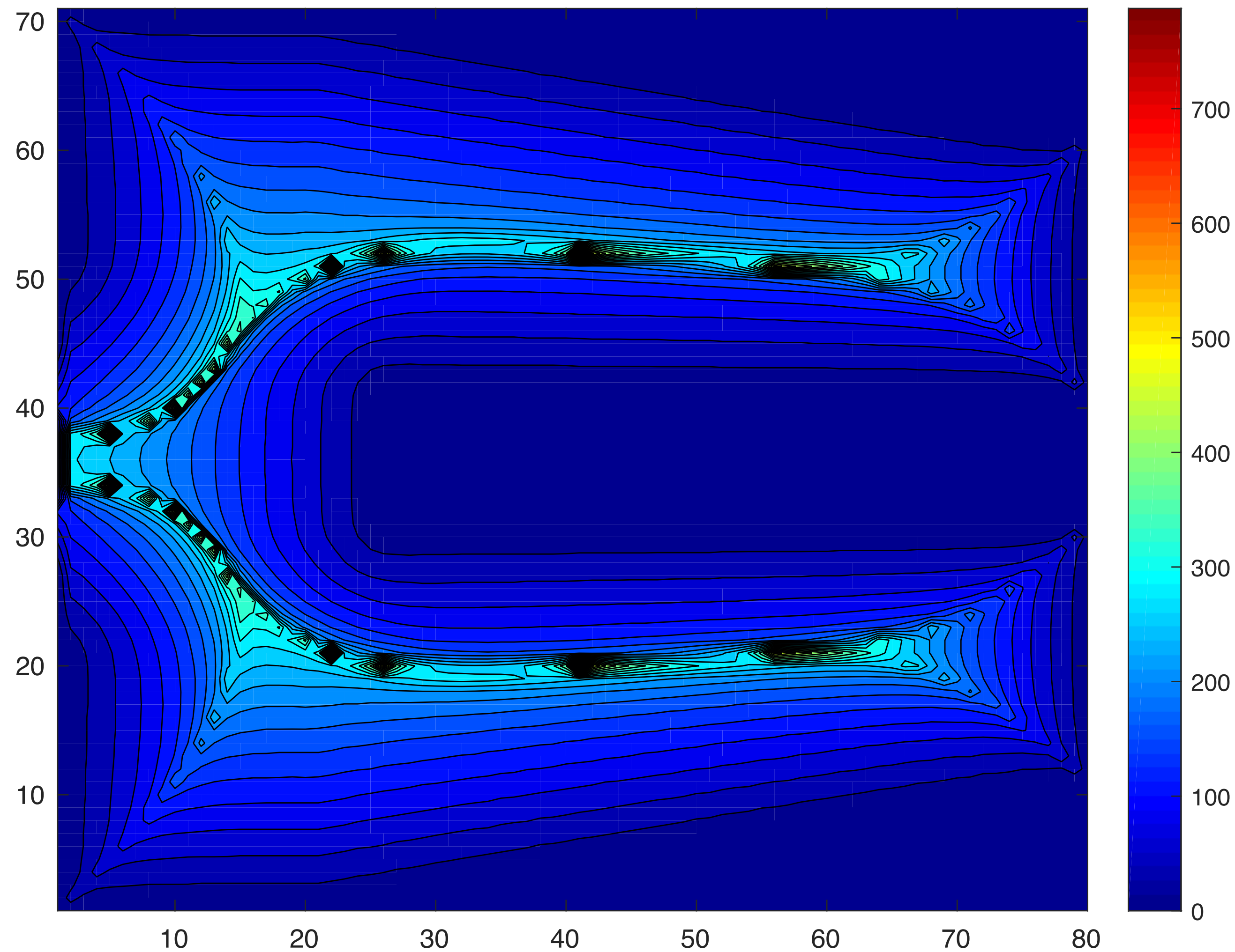


- Localised increases disappear
- Localised increases more prevalent

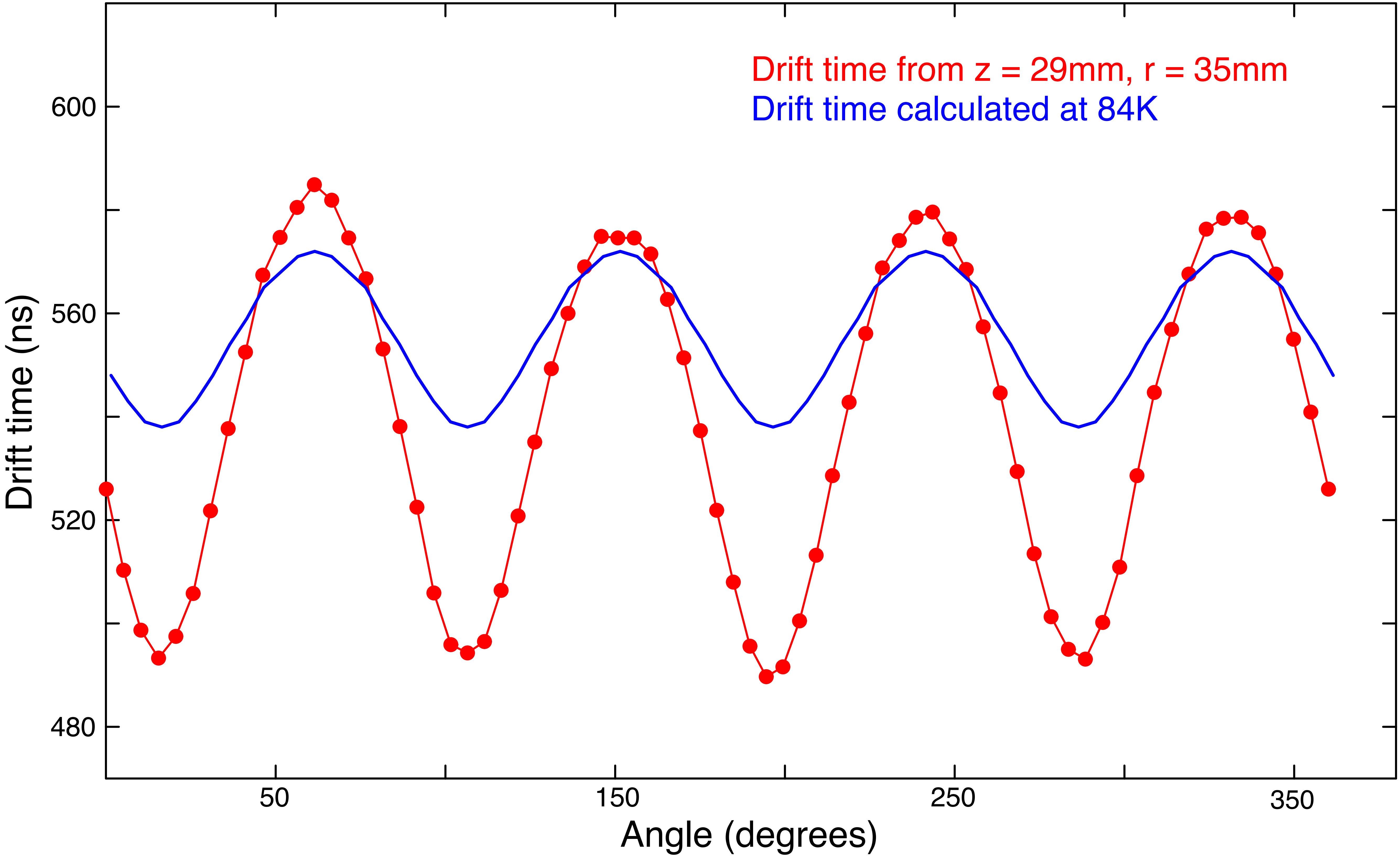
Drift time for electrons



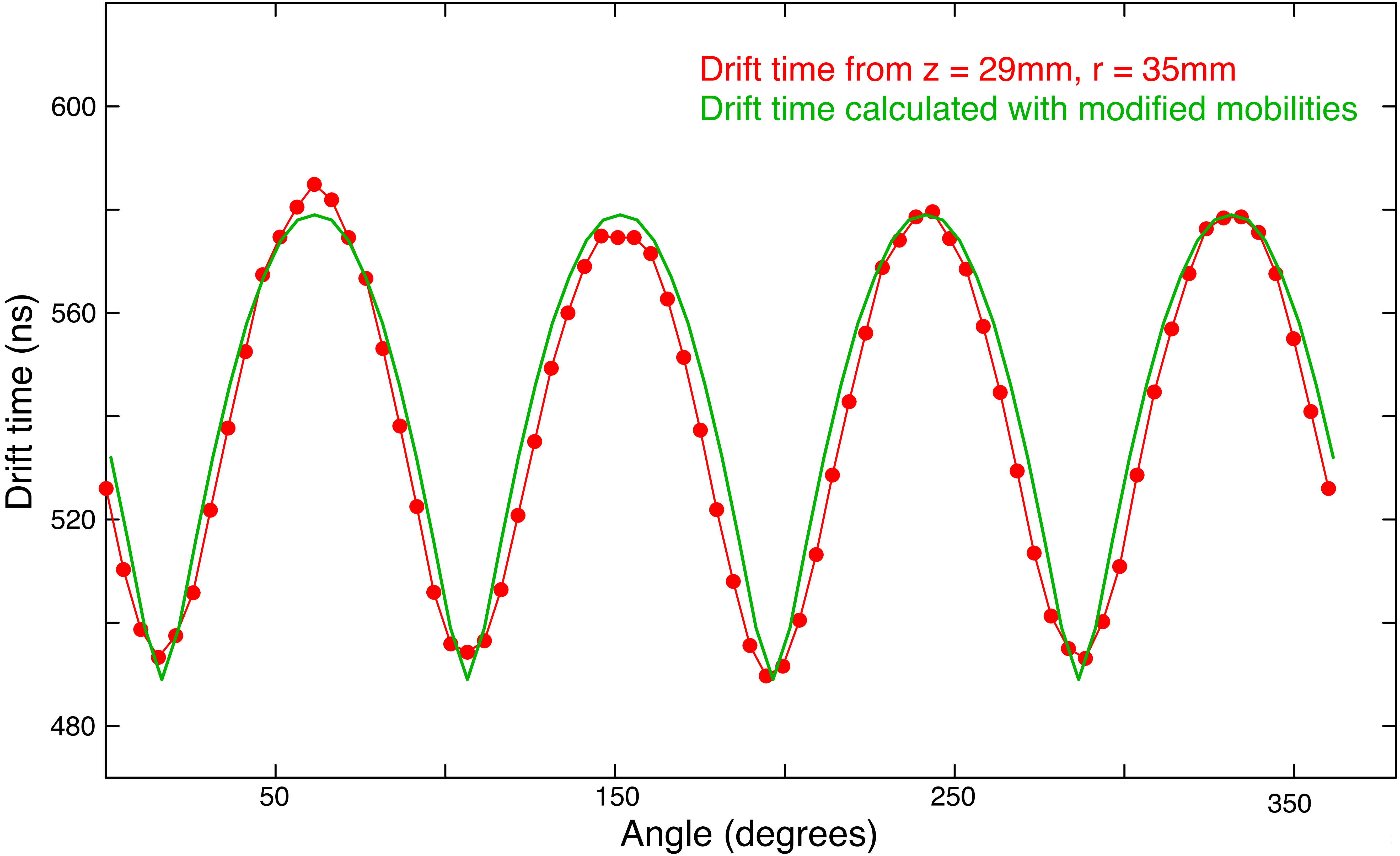
Drift time for holes



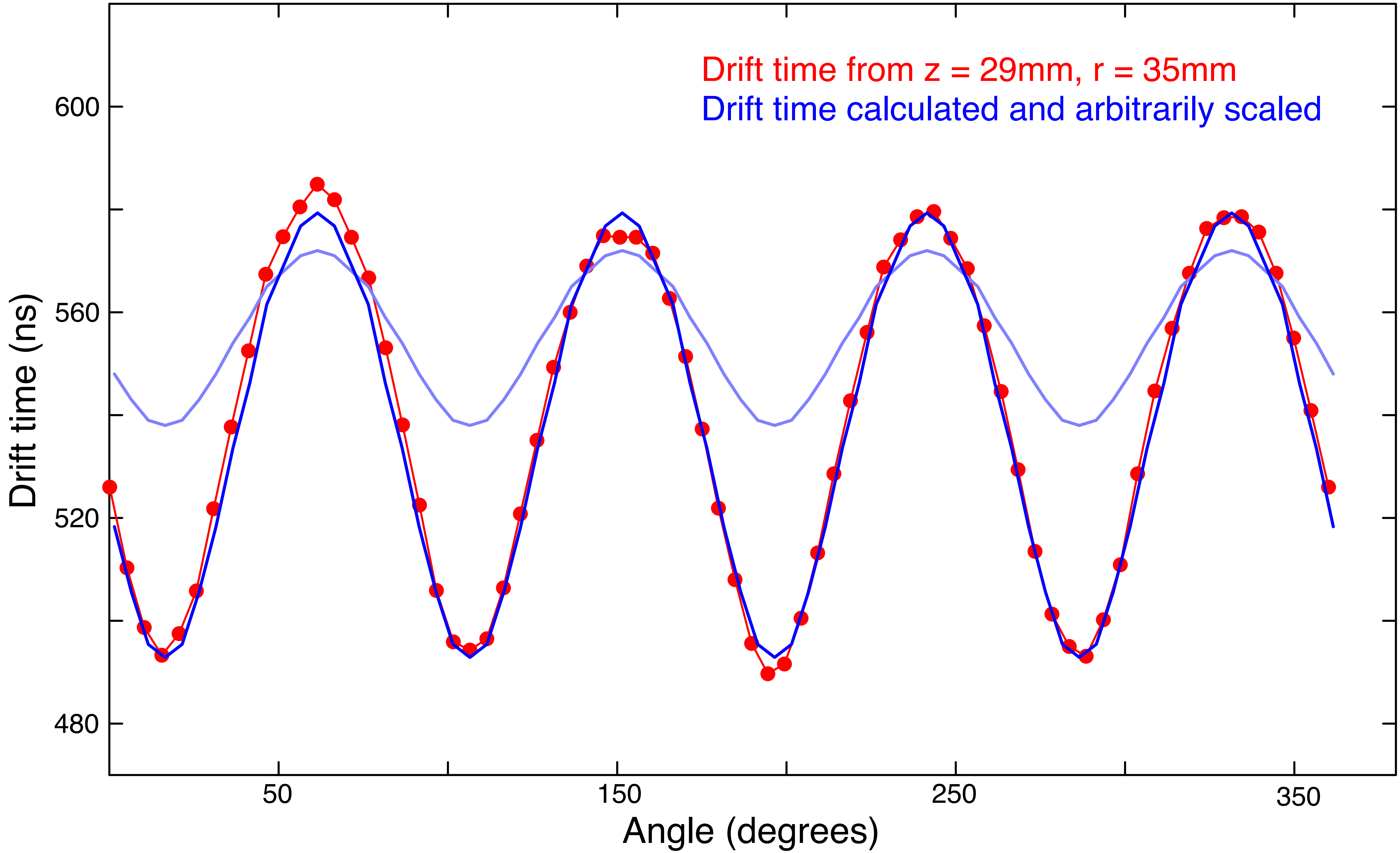
- Localised areas of long hole drifts causes artefacts in total drift plot
- Can be seen in hit segment plots



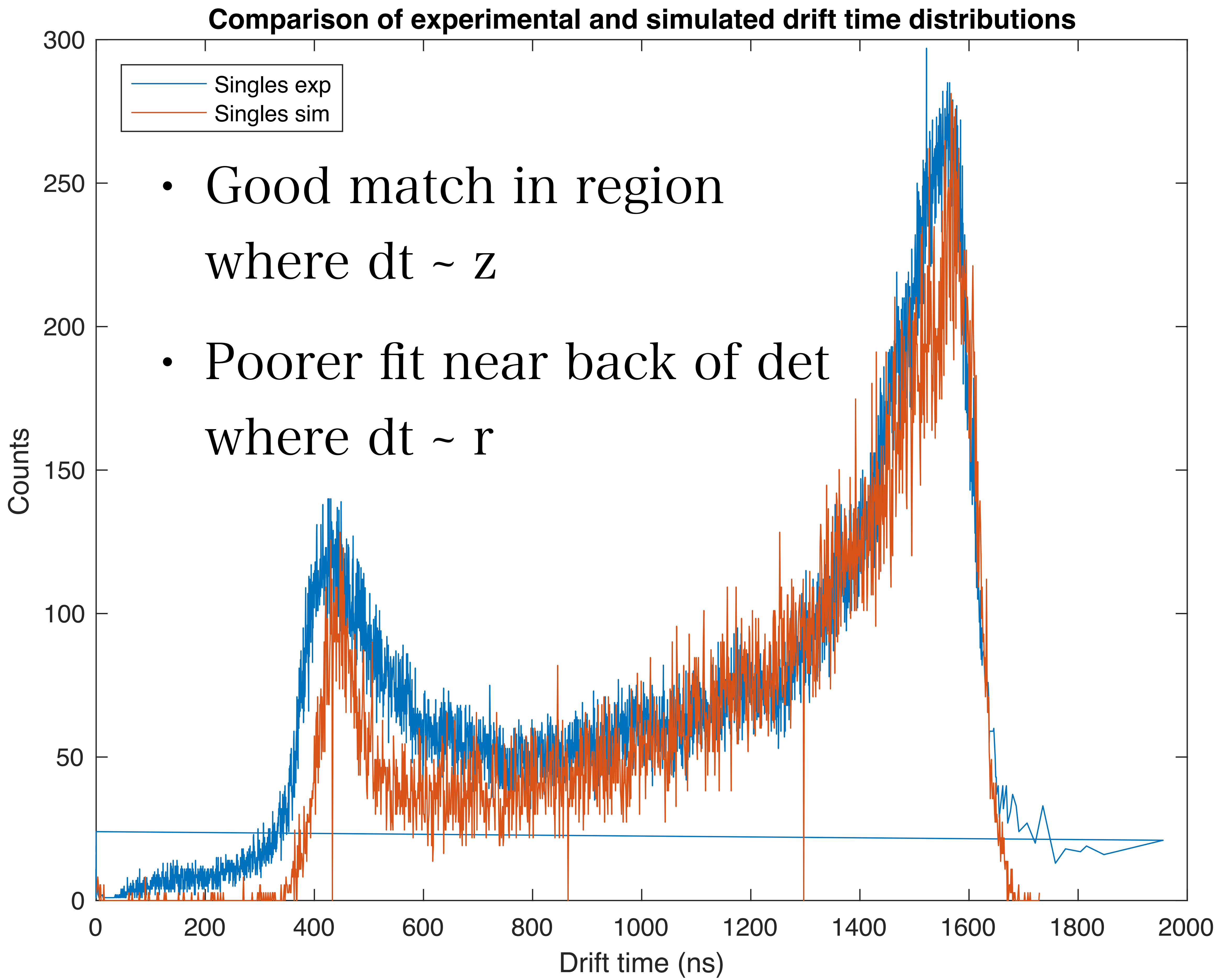
standard drift times give too small variation in dt with angle



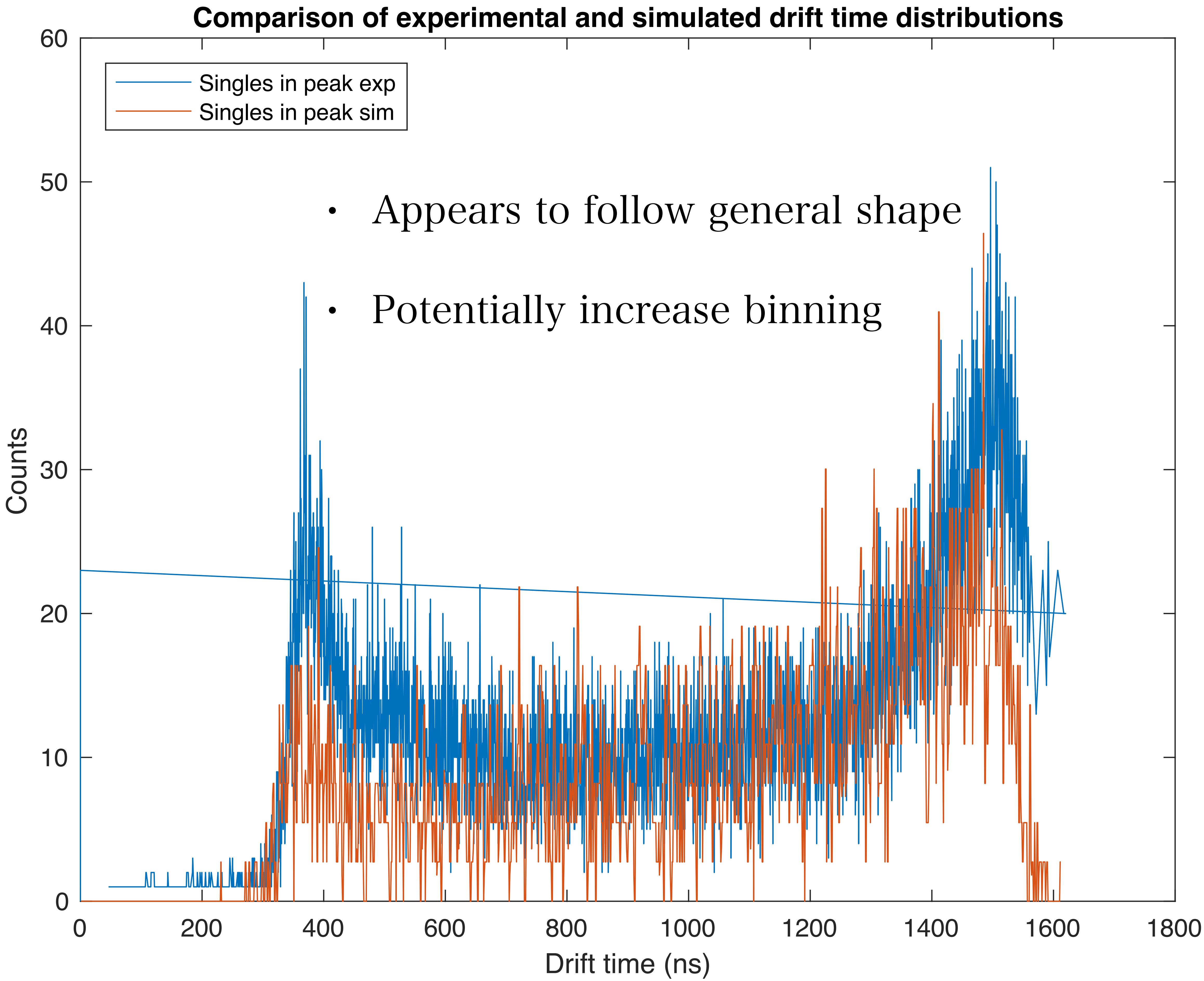
altering mobilities gives incorrect shape but correct amplitude



‘fudged’ values to give correct shape and amplitude

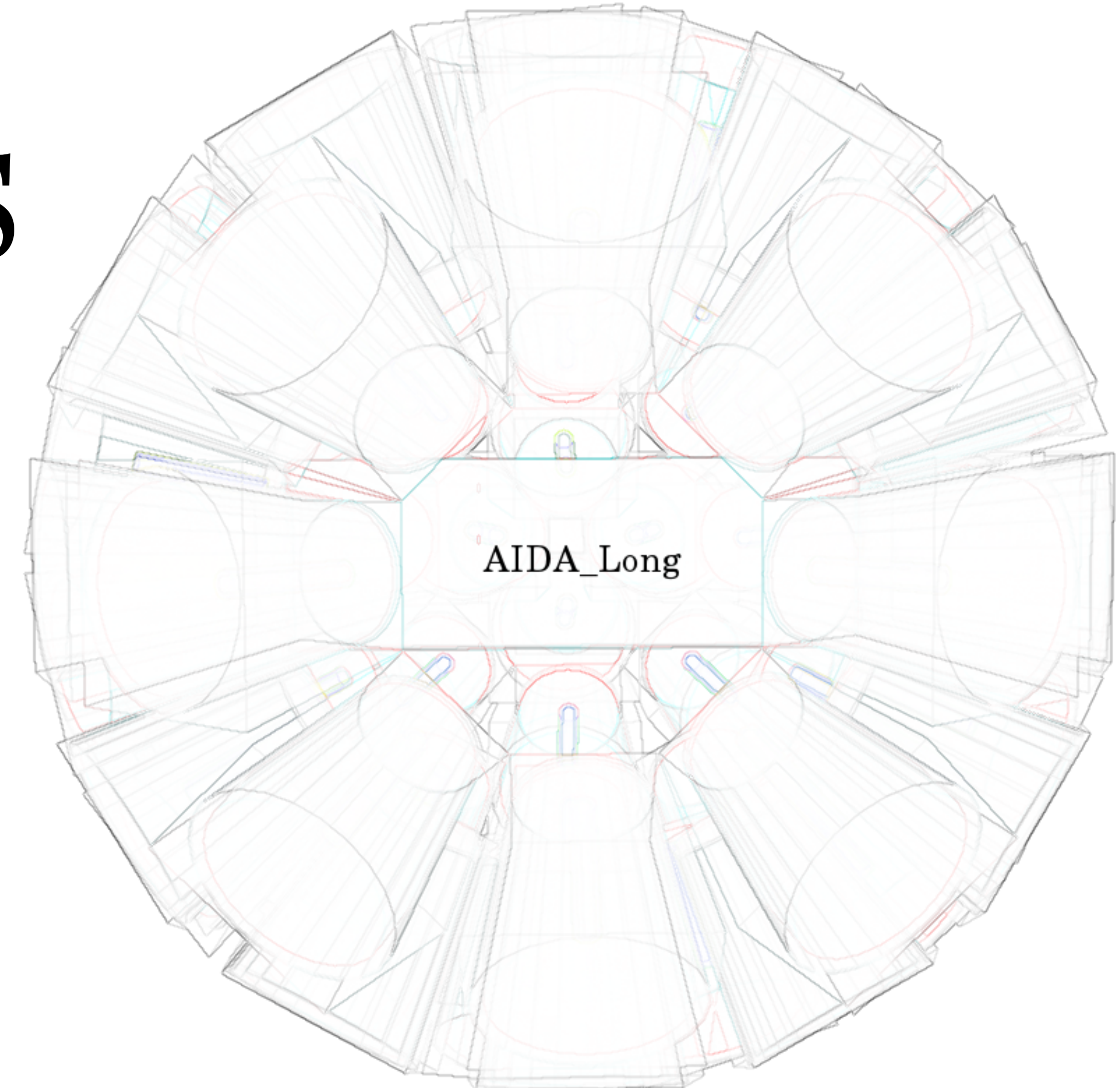


- Good match in region where dt ~ z
- Poorer fit near back of det where dt ~ r

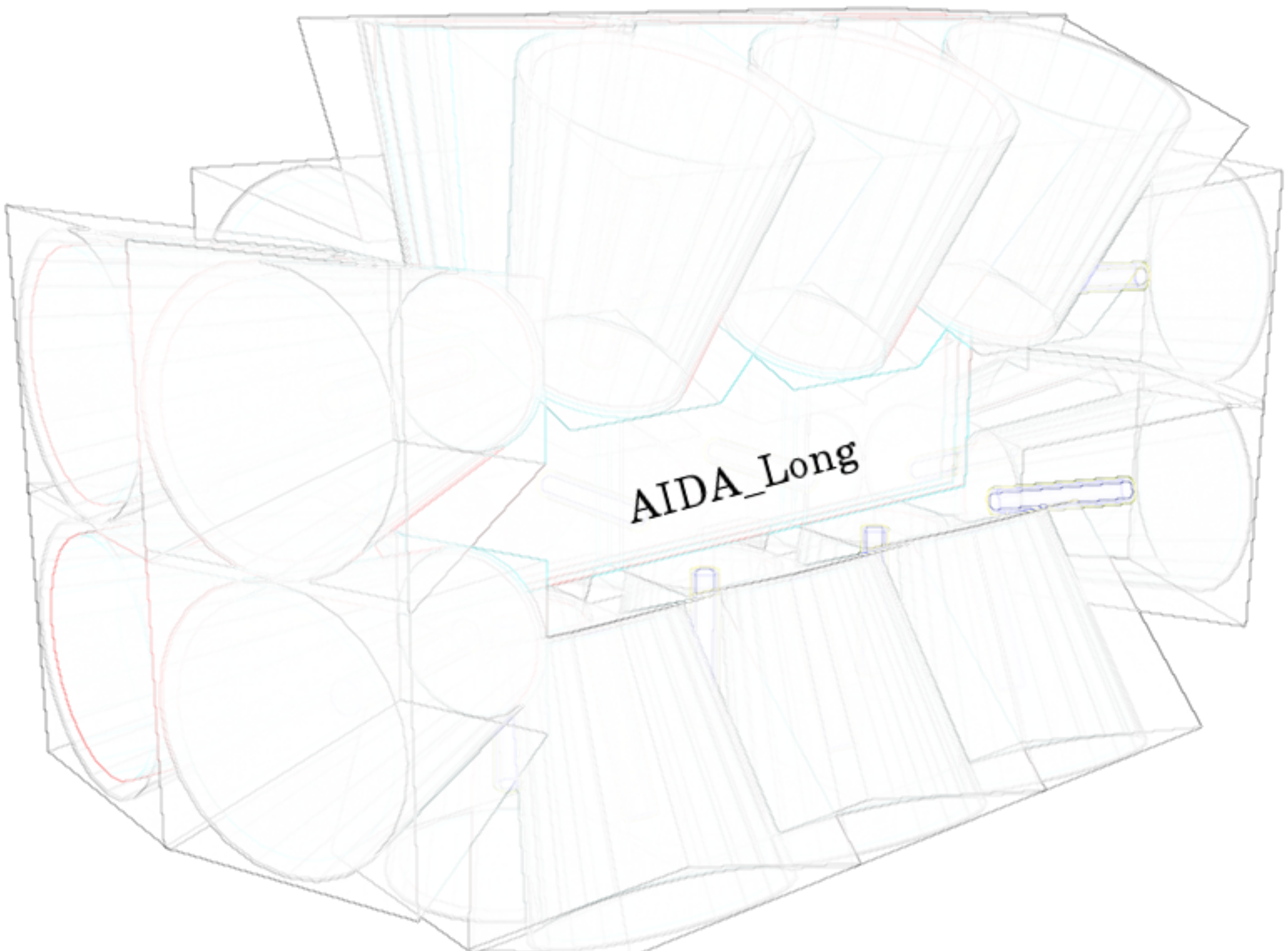


Comparison of experimental and simulated drift time distributions
Singles in peak exp
Singles in peak sim
• Appears to follow general shape
• Potentially increase binning
Counts
Drift time (ns)
0
10
20
30
40
50
60
0
200
400
600
800
1000
1200
1400
1600
1800

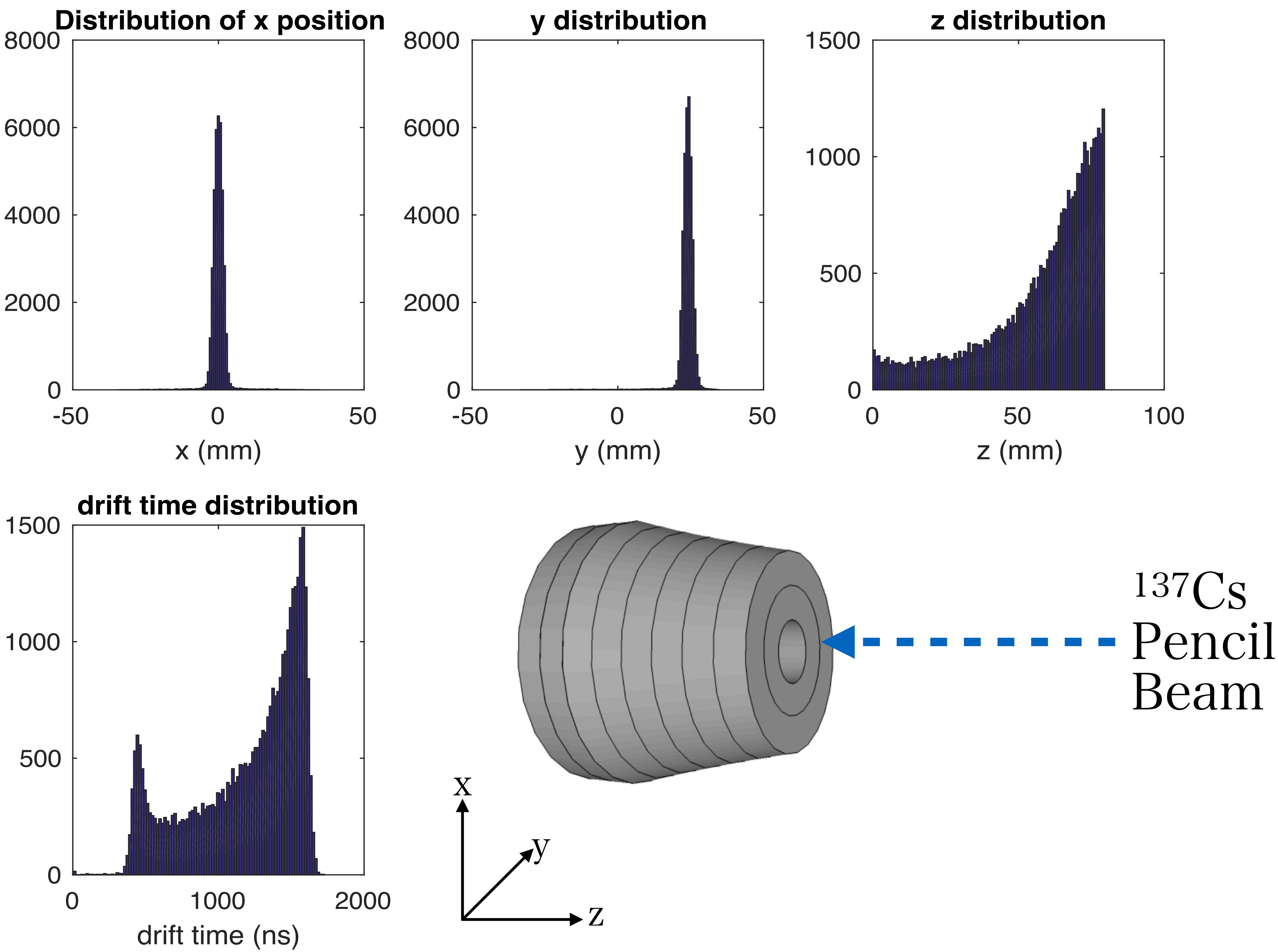
Array Designs



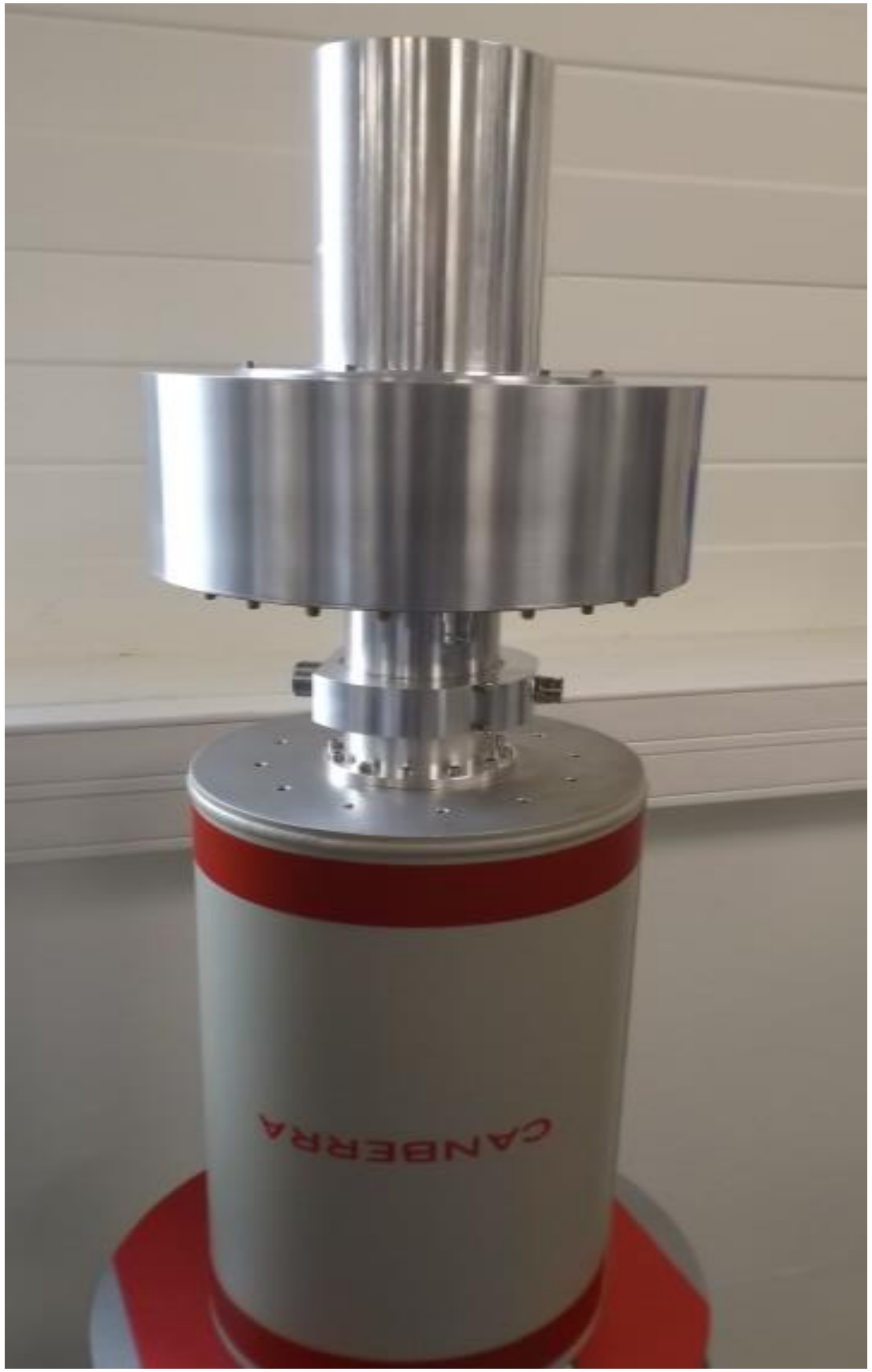
Spherical Geometry can accommodate dewar width of any size



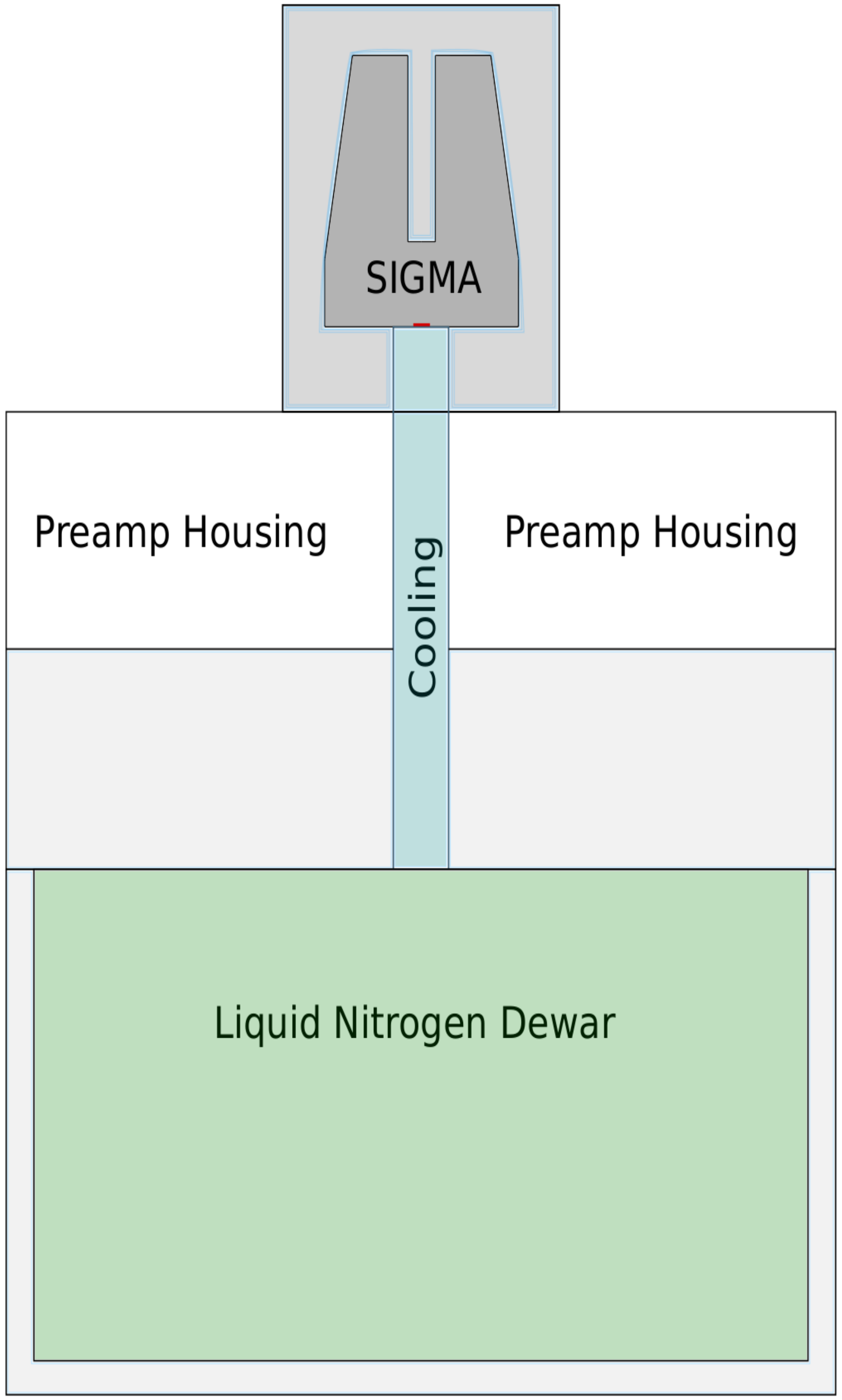
Box Geometry requires dewar width to be no wider than detector head size

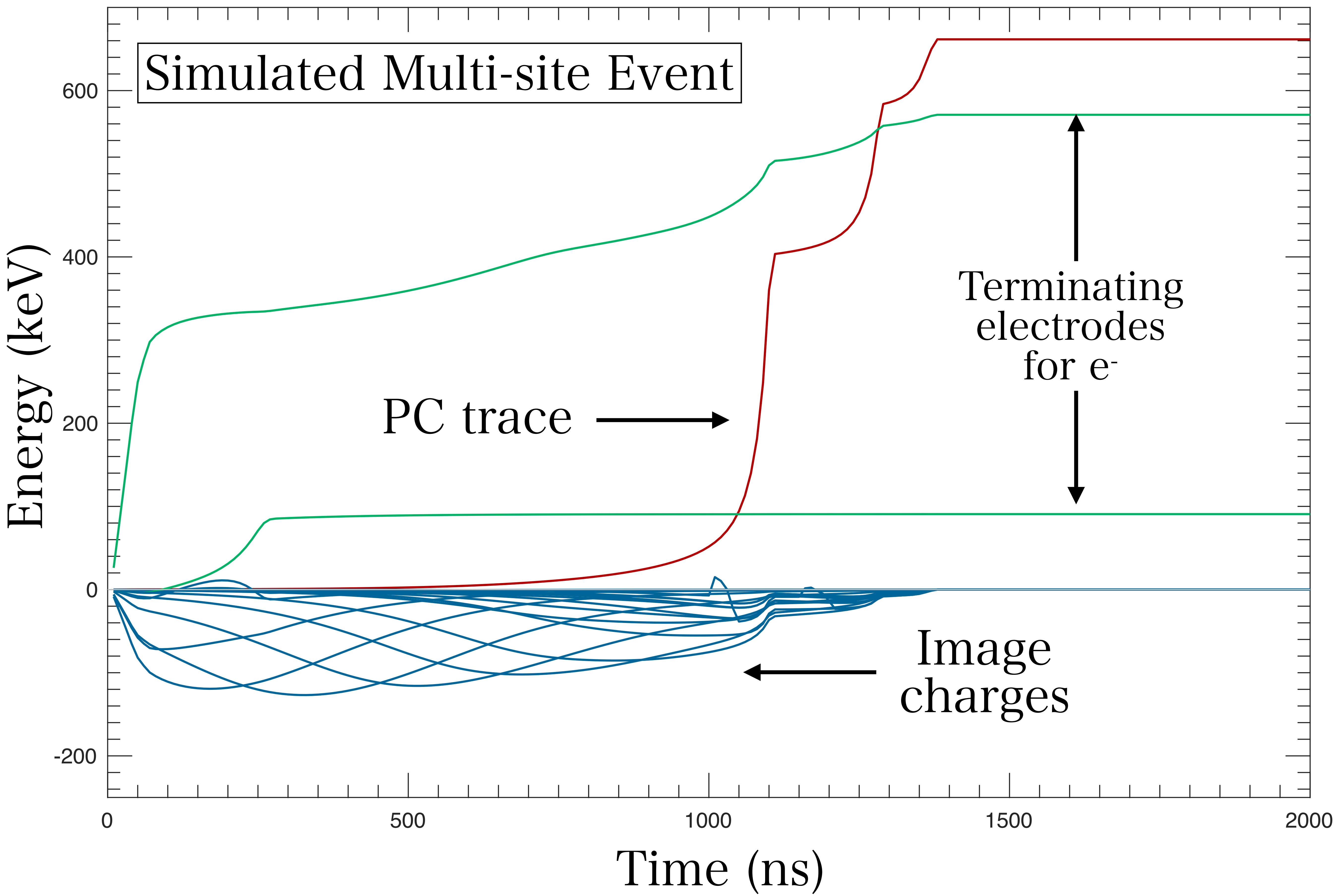


Distribution of x position
8000
6000
4000
2000
0
-50
0
50
x (mm)
y distribution
8000
6000
4000
2000
0
-50
0
50
y (mm)
z distribution
1500
1000
500
0
0
50
100
z (mm)
drift time distribution
1500
1000
500
0
0
1000
2000
drift time (ns)
x
y
z
^{137}Cs
Pencil
Beam

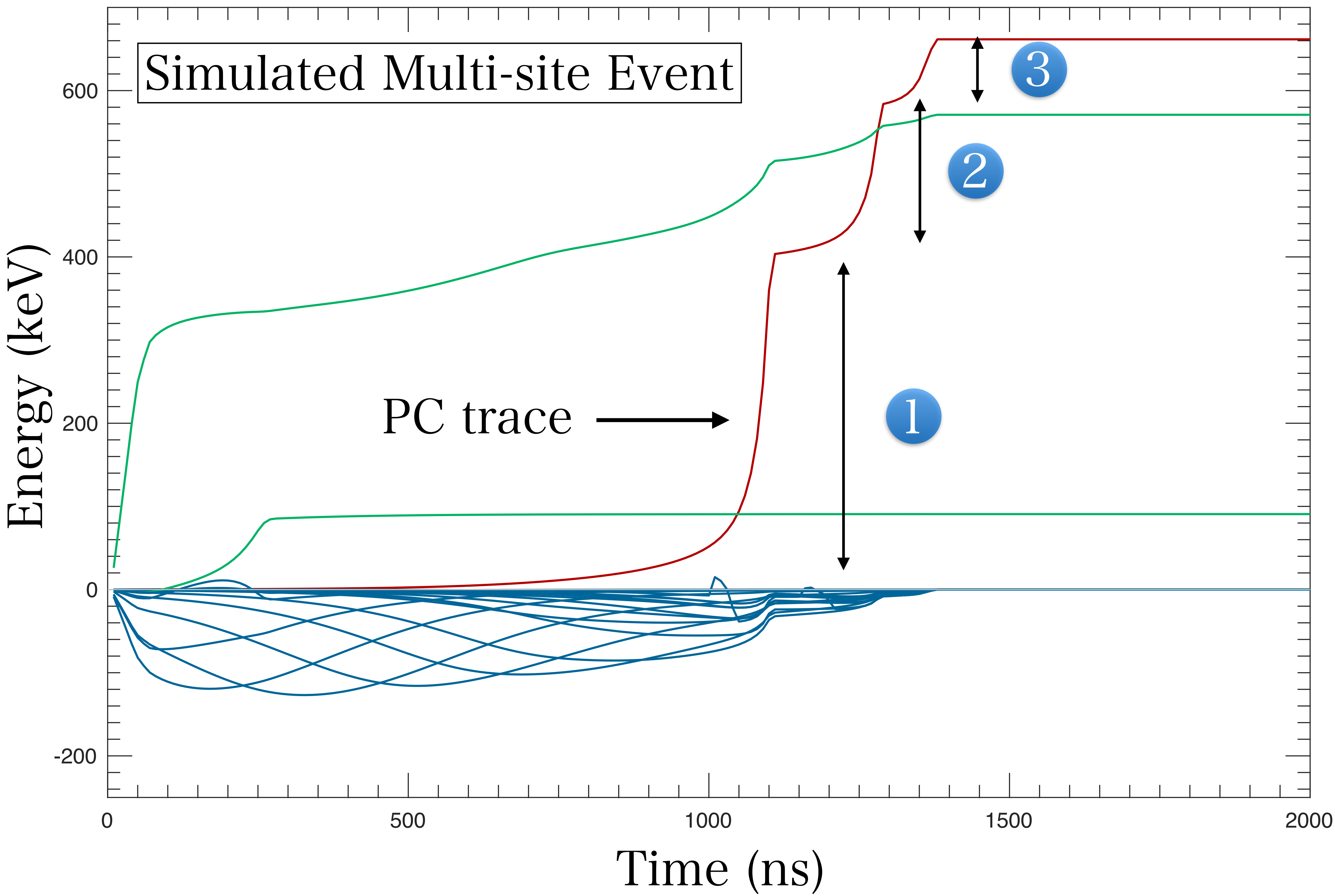


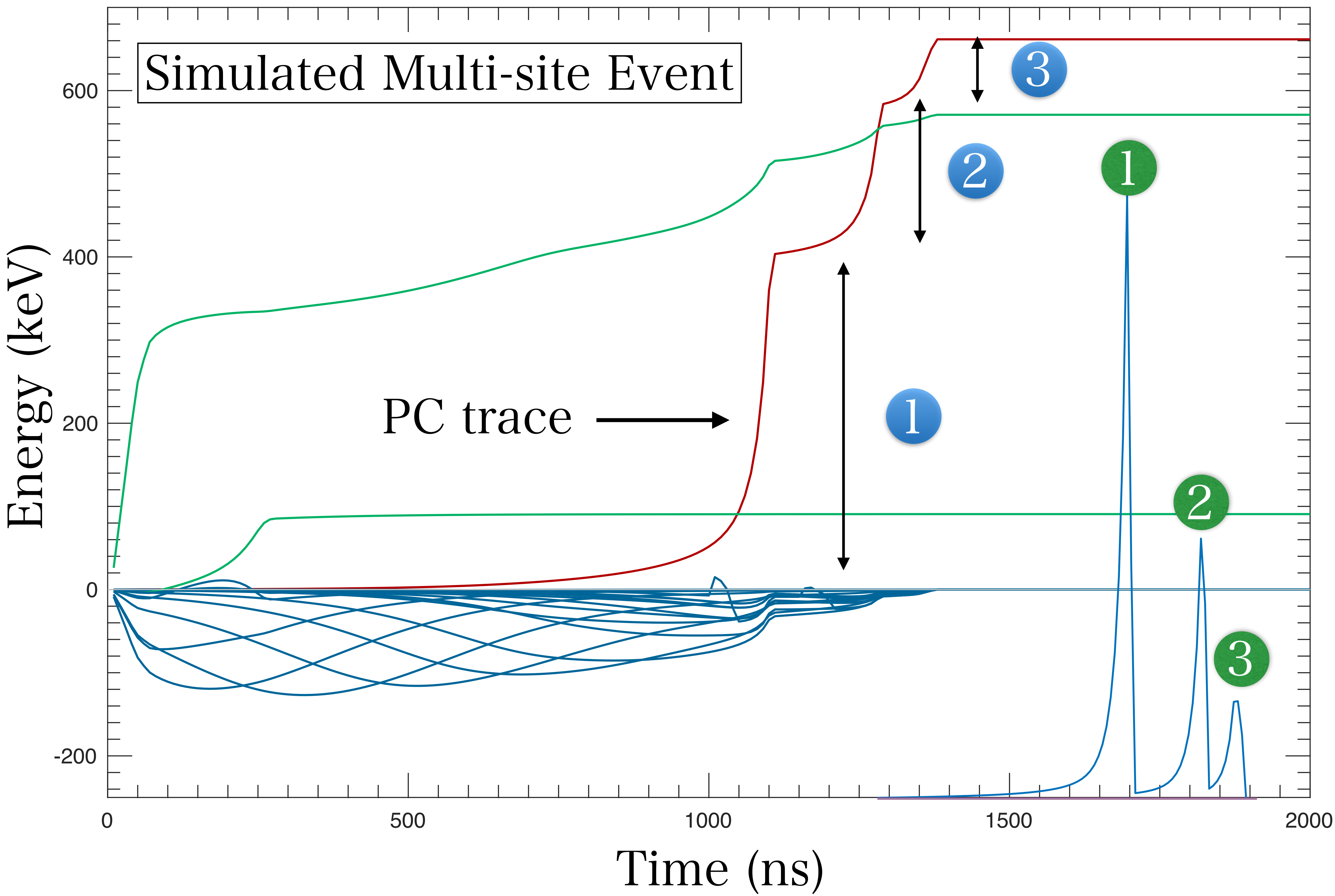
*Courtesy of MIRION Technologies



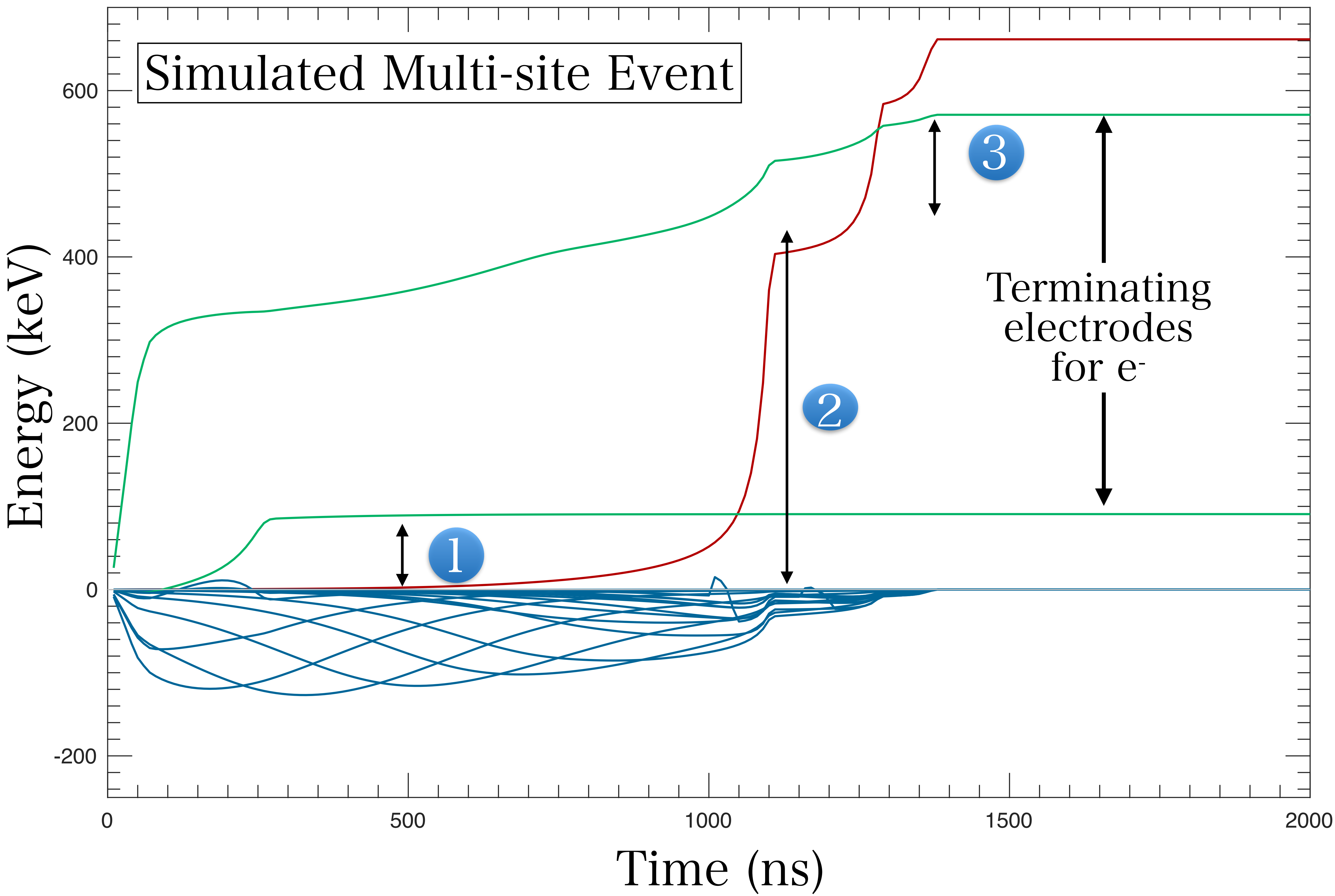


Simulated Multi-site Event
Terminating electrodes for e-
PC trace
Image charges
Energy (keV)
Time (ns)
600
400
200
0
-200
0
500
1000
1500
2000


Simulated Multi-site Event
PC trace
1
2
3
Energy (keV)
Time (ns)
600
400
200
0
-200
0
500
1000
1500
2000



Simulated Multi-site Event
PC trace
1
2
3
1
2
3
Energy (keV)
600
400
200
0
-200
0
500
1000
1500
2000
Time (ns)

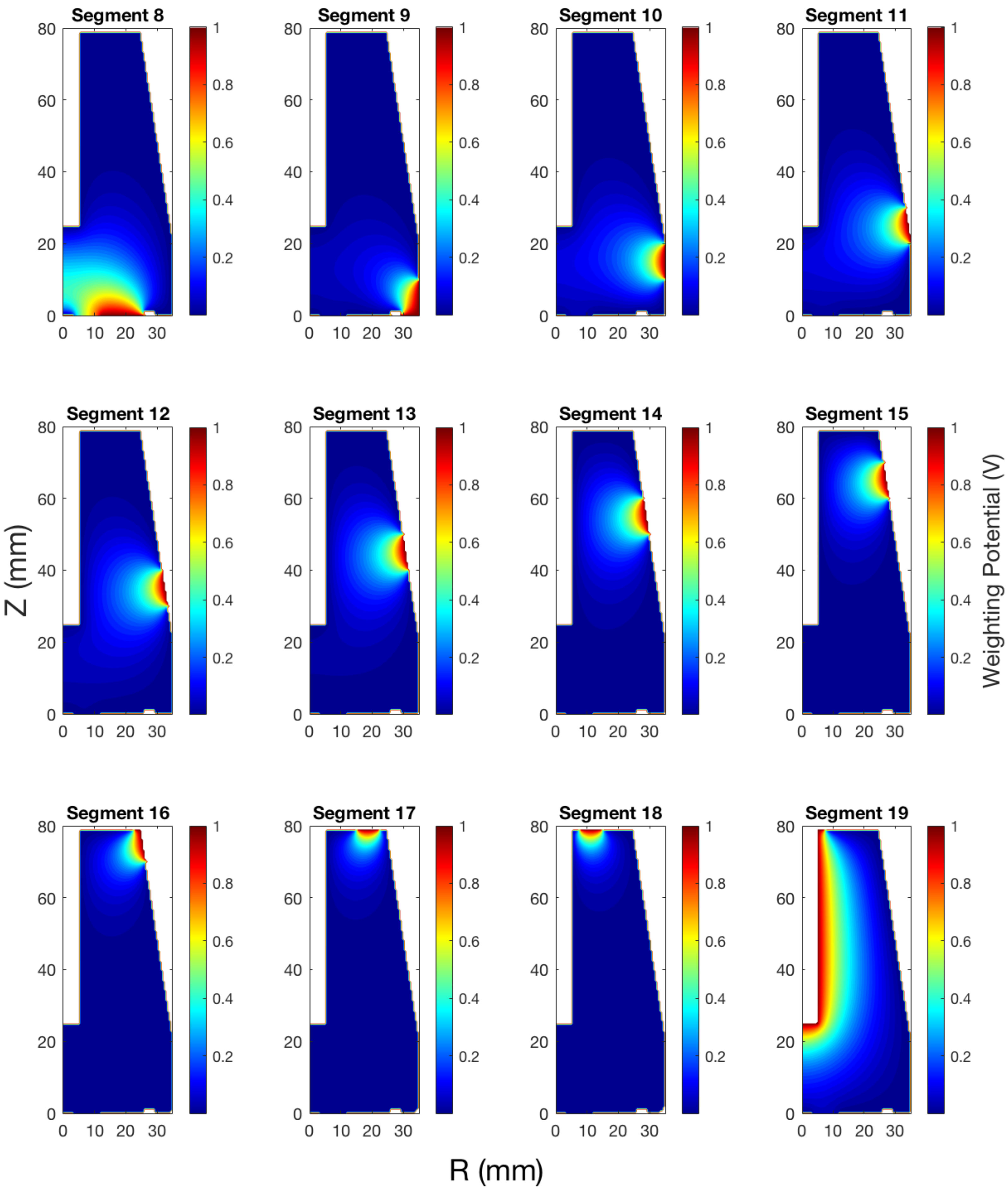

Simulated Multi-site Event
Energy (keV)
Time (ns)
600
400
200
0
-200
0
500
1000
1500
2000
1
2
3
Terminating electrodes for e-

Weighting Potentials

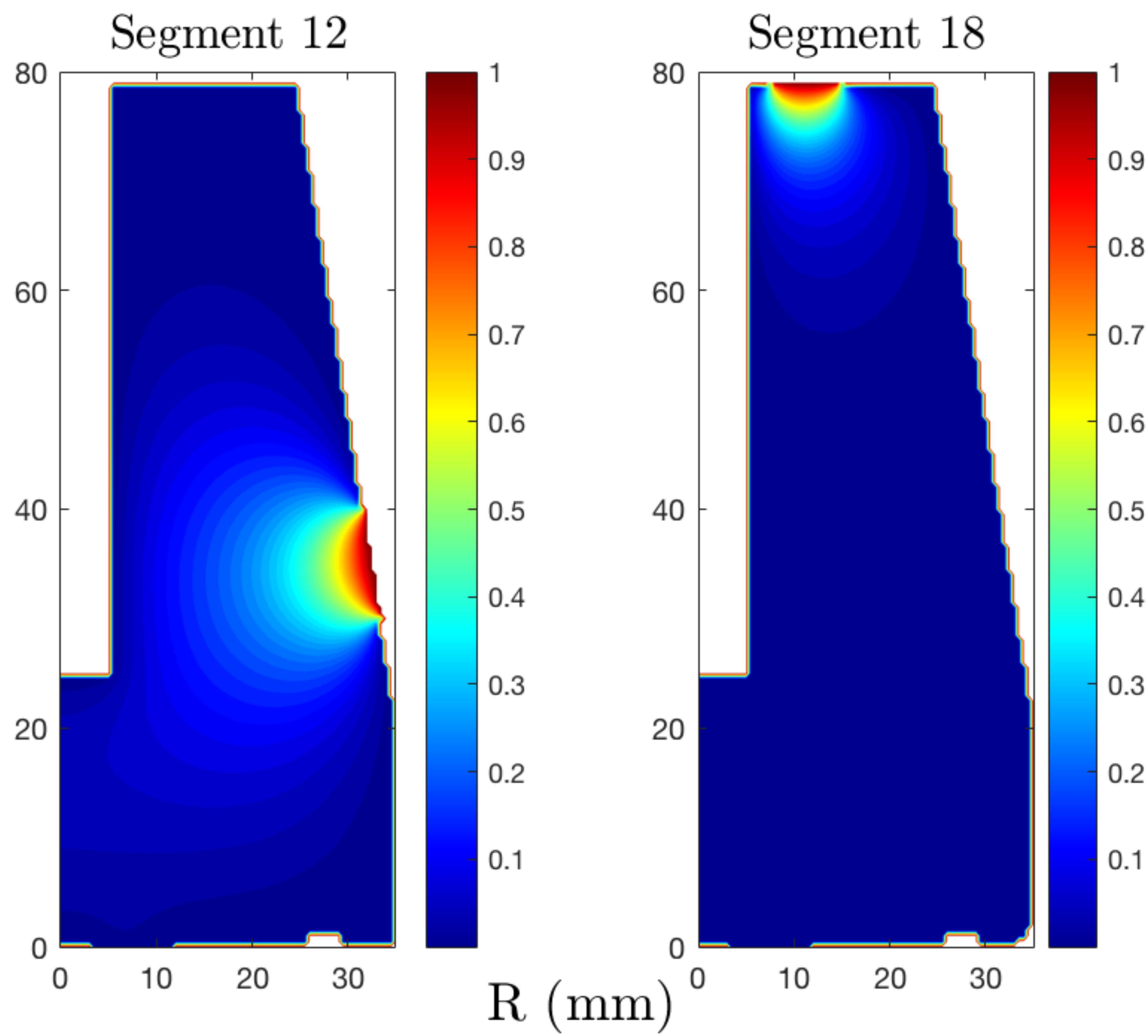
- Shockley-Ramo theorem
- Voltage on electrode of interest set to 1 V
- All other electrodes set to 0 V

$$i = q\overrightarrow{v} \cdot \overrightarrow{E}$$

$$Q = q\Delta\varphi_0$$

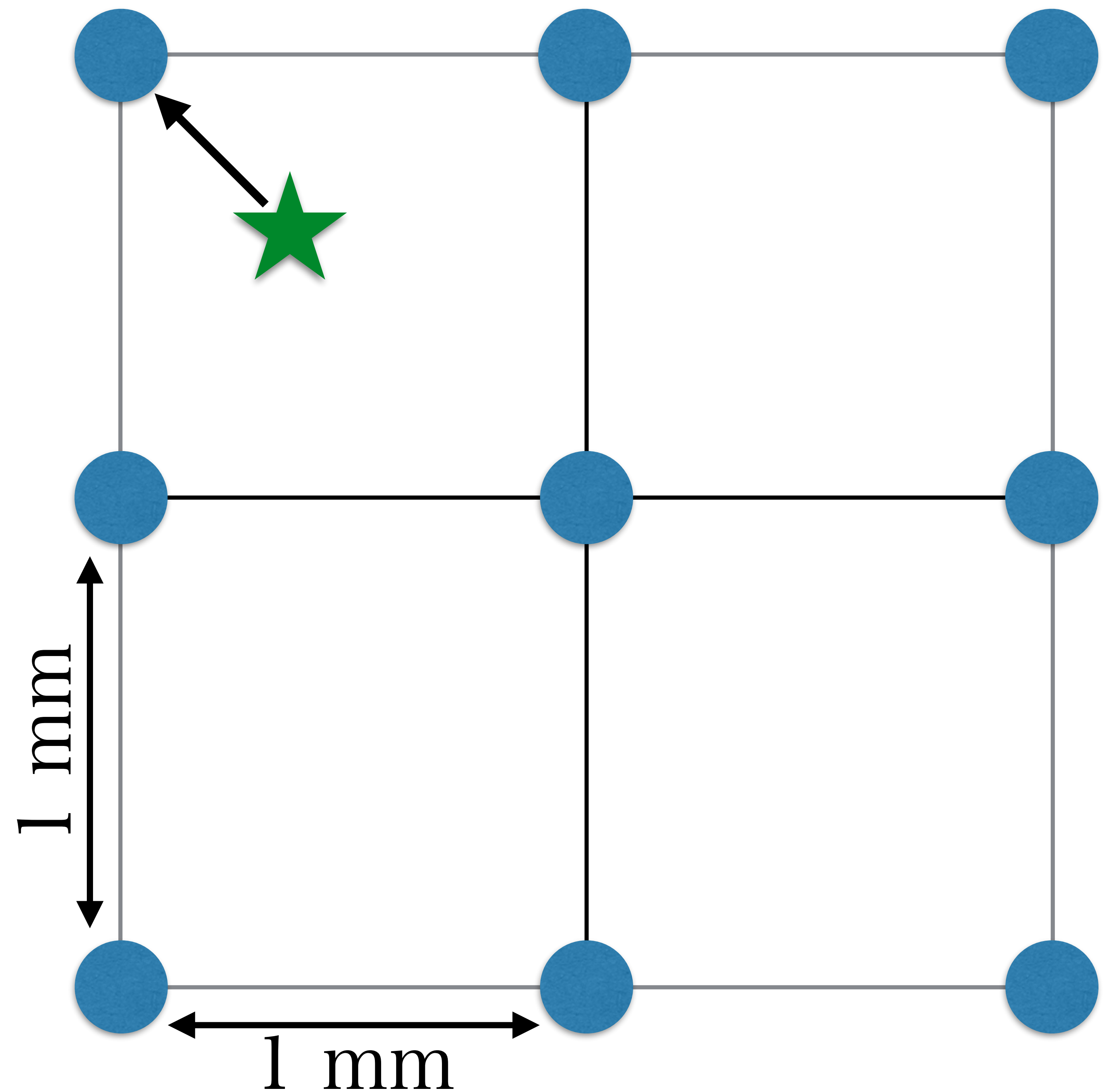


Signal generation



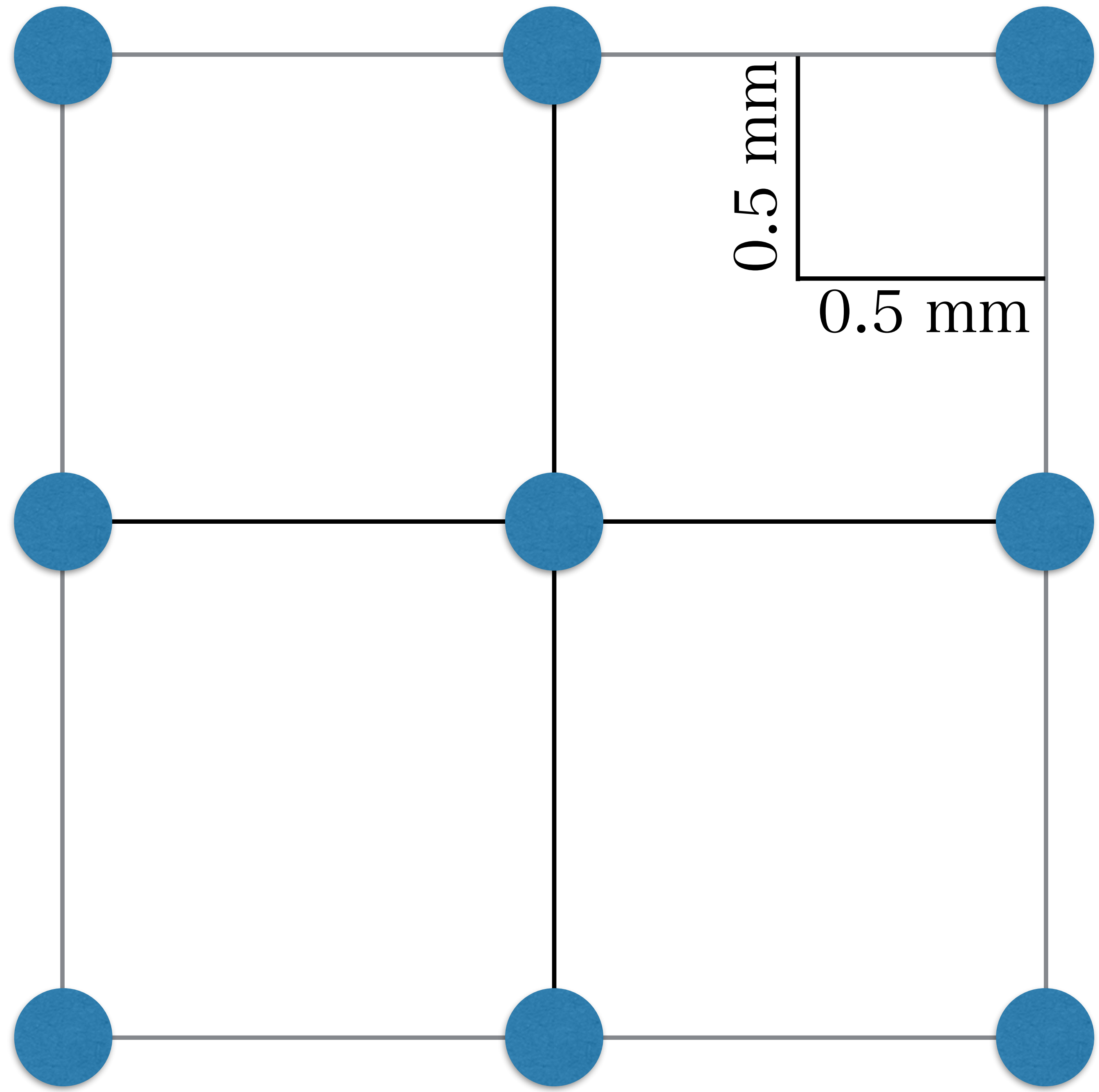
Grid Size Issue

- In reality, interactions can occur in between grid points
- Events will jump to nearest basis point



Grid Size Issue

- Max error when interaction occurs in centre of grid ~0.71 mm



Grid Size Issue

- Reducing basis grid size removes error
- FWHM remains ~0.4 mm with smaller grid size of 0.1 x 0.1 mm
- Resolution will then be governed by the size of the charge cloud