Biweekly GBP meeting

Fringe effects simuation with Allpix^2

Università degli Studi di Padova

INFN

In this presentation

- Summary of Frascati data analysis with systematics
- Tutorial
  Simulating fringe effects for the sapphire pad detectors with Allpix^2

Summary of Frascati data analysis with systematics

Summary Frascati data analysis - 1/2

Systematic uncertainties are divided in two categories, contributing to

- CCE's numerator,
  1. min(CH)
- CCE's denominator
  - beam misalignment
  - beam sigma
  - monte-carlo beam sigma

Fit model

$$\mathrm{CCE}(V) = f_d\, k\, V \left[1 + k\, V \left(\exp\left(-\frac{1}{k\, V}\right) - 1\right)\right]$$

$$k \equiv -\frac{\mu_e \tau_e}{d^2}$$

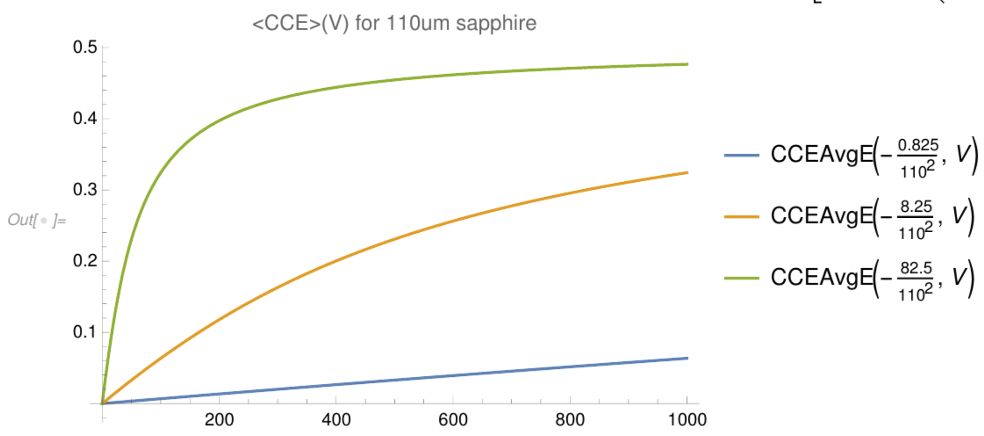


Figure 14: Plot of the eq.(18) for a 110um planar detector with $-(\mu\tau)_e$ products of $0.825\ \mathrm{um}^2\,\mathrm{V}^{-1}$, $8.25\ \mathrm{um}^2\,\mathrm{V}^{-1}$, $82.5\ \mathrm{um}^2\,\mathrm{V}^{-1}$ with $f_d = 1$.

Summary Let us collect in the following table the beam-related systematic uncertainty in the form of a relative error on the charge deposited for the small/large pad. We shall stick to the 'method 2' to evaluate the deposited charge.

- As estimator for the systematic uncertainty in the alignment, I shall use half the step size. This is analogous to the resolution error of 0.5mm I attach to the measure of a length with a cm ruler. Let us ignore statistical subtleties related to the fact that it's unlikely to have both axes misaligned and attach a (0.5, 0.5) mm absolute error to the beam alignment procedure. Relative variation in the energy deposited is given by

Method2 - Evaluation of systematic for a) offset of (0.5,0.5)mm										Relative variation	
filename	sigmaX	sigmaY	charge	triggers	pad	edep110 pad [MeV]	stddev edep1	edep150 pad [MeV]	stddev edep150 [MeV]	edep110 pad	edep150 pad
'X0.5_Y0.5_	2.11	1.46	507	962	'LP'	22.16893893	1.09100763	30.21729836	1.41028207	-3.8%	-4.0%
'X0.5_Y0.5_	2.14	1.6	500	977	'LP'	20.79405152	1.10592308	28.46727207	1.40002497	-4.0%	-3.9%
'X0.5_Y0.5_	2.14	1.65	504	832	'LP'	20.69349493	1.10080435	28.34388997	1.45465422	-3.9%	-3.7%
'X0.5_Y0.5_	2.13	1.66	500	587	'LP'	20.49328919	1.0937238	28.0561368	1.39575629	-4.1%	-3.9%
'X0.5_Y0.5_	1.9	1.3	427	980	'LP'	20.60553089	1.02198008	28.17858947	1.34658543	-4.0%	-4.0%
'X0.5_Y0.5_	2.04	1.3	471	987	'LP'	21.86801726	1.12446535	29.82717817	1.3302368	-3.9%	-4.0%
'X0.5_Y0.5_	2.13	1.84	1014	1032	'SP'	4.892047046	0.6756799	6.698805283	0.86048805	-6.9%	-6.0%
'X0.5_Y0.5_	2.13	1.84	1028	1050	'SP'	4.989268808	0.66618729	6.820166481	0.8553191	-6.3%	-5.9%
'X0.5_Y0.5_	2.13	1.84	1017	1334	'SP'	4.91959688	0.67807913	6.7372965	0.88102298	-6.1%	-6.0%
'X0.5_Y0.5_	2.13	1.87	1012	892	'SP'	4.825117365	0.68619097	6.641246152	1.45120757	-6.4%	-5.5%
'X0.5_Y0.5_	2.13	1.88	1016	959	'SP'	4.824790026	0.67041755	6.587978399	0.90795423	-6.6%	-6.5%
'X0.5_Y0.5_	2.13	1.86	1048	495	'SP'	5.034477032	0.70520484	6.852867957	0.88462855	-6.8%	-6.5%
'X0.5_Y0.5_	2.18	1.73	915	681	'SP'	4.574295253	0.64890255	6.243109341	0.88106619	-7.0%	-6.9%
'X0.5_Y0.5_	2.18	1.73	490	681	'LP'	19.43633587	1.09948847	26.62696543	1.36424228	-3.9%	-3.8%

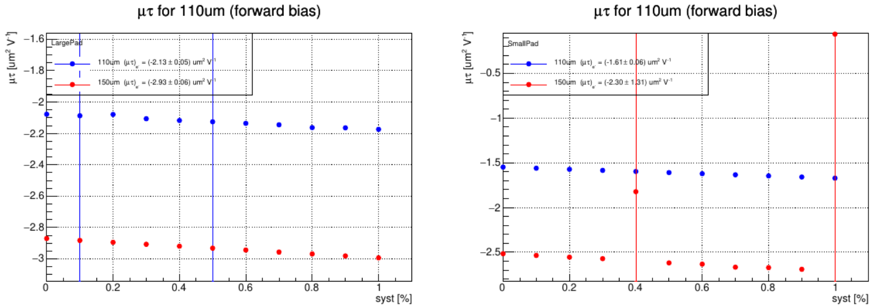
Table 5: MC table of energy deposited if a beam misalignment of (0.5, 0.5) mm between the beam-pad centers is present.

- Possible variations in the beam transverse parameters are neglected for two reasons: first, for each measure set I've already accounted for the different (σ_x, σ_y) beam; second, in most cases I was writing down the most updated value for the beam parameters and in the meeting with Foggetta turned out that he was monitoring the beam stability over time. Therefore, this contribution is assumed to be completely negligible.

Summary Frascati data analysis - 2/2

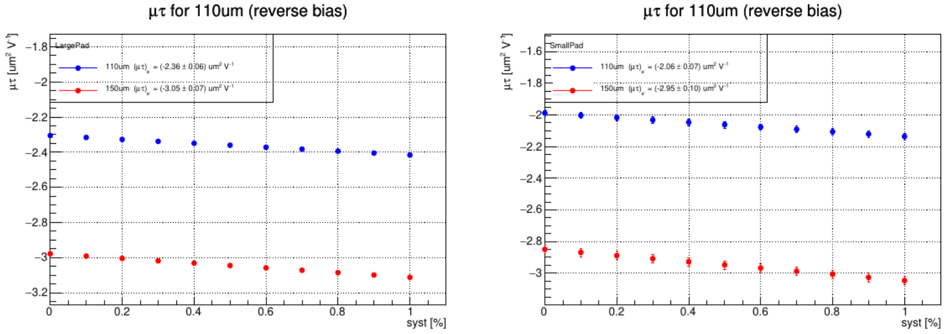
Summary All the systematic uncertainties can be reduced to be negligible for any of the measures, with the only exception of beam misalignment. This one matters from 5% to 7%, causing smaller charge deposited hence higher charge collection efficiency that the 'real' one. In order to provide a first estimate for the uncertainty in the fit parameters $\mu\tau$ we proceed in the following way

1. Estimate a realistic value for the uncertainty in the beam-pad alignment procedure. I considered a misalignment of (0.5,0.5)mm
2. Evaluate the table of charge deposited using the MC (see 4) using such a misalignment -> Table 5
3. Assume this systematic effect to be partially $0 < p < 1$ or fully $p = 1$ present.
4. Repeat the fits 15-16 and get the fit parameters as a function of the p variable.
5. Each fit parameter, say forward bias large pad 110um, now vary in a certain interval as a consequence of the variation of the p percentage. We consider this interval as the one spanned by the true value for the fit parameter in the presence of systematic uncertainty. As best value we consider the mean value and as uncertainty to this one the half the width of the interval.



(a) Large Pad (b) Small Pad

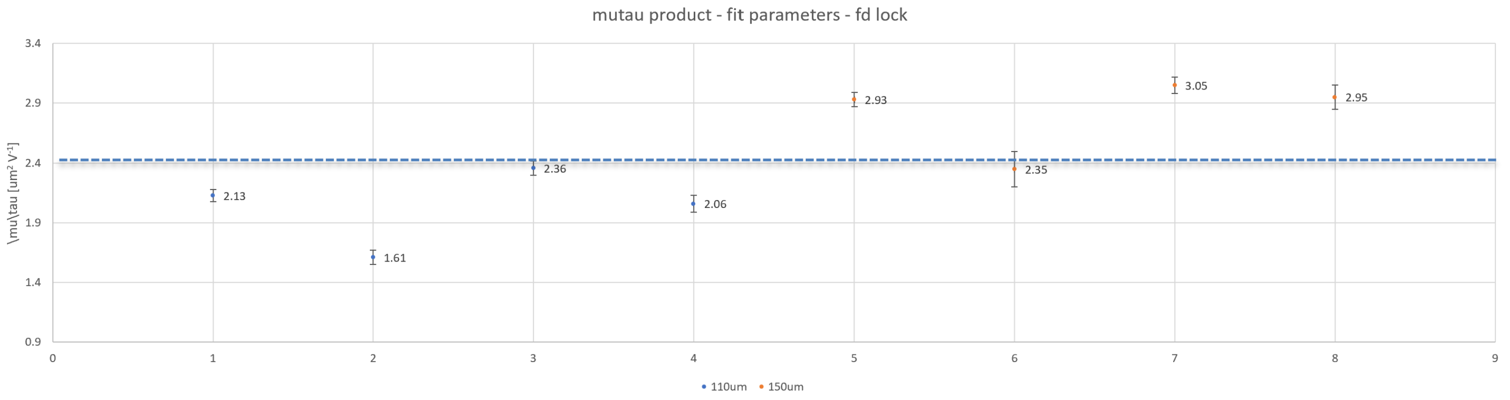
Figure 17: Behavior of the fit parameter $\mu\tau$ for the forward bias measures as a function of the variable p, which determines the presence of systematic shift from zero to the highest (when full beam misalignment of (0.5,0.5)mm is present. There are p for which fit does not converge properly - i.e. in (a) for $p = 0.1$, 0.5 in the 110um sample.



(a) Large Pad (b) Small Pad

Figure 18: Behavior of the fit parameter $\mu\tau$ for the reverse bias measures as a function of the variable p, which determines the presence of systematic shift from zero to the highest (when full beam misalignment of (0.5,0.5)mm is present. There are p for which fit does not converge properly - i.e. in (b) for $p = 0.4$, 1 in the 150um sample.

		Forward		Reverse		Forward		Reverse		
		LargePad	SmallPad	LargePad	SmallPad	LargePad	SmallPad	LargePad	SmallPad	
110	\mu\tau	2.13	1.61	2.36	2.06	2.93	2.35	3.05	2.95	150
	err	0.05	0.06	0.06	0.07	0.06	0.15	0.07	0.1	
		1	2	3	4	5	6	7	8	

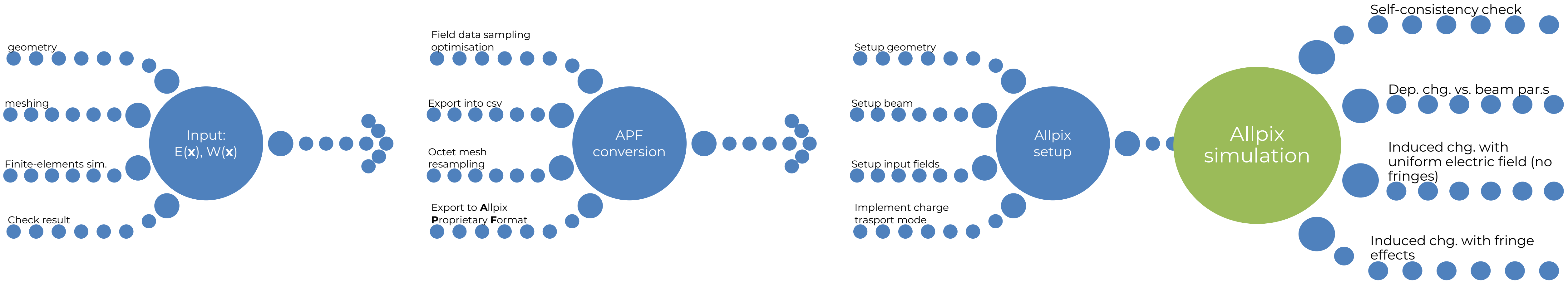


Simulating fringe effects for the sapphire pad detectors with Allpix^2

Sim. pipeline

GeometryBuilderGeant4 + DepositionGeant4 → ElectricFieldReader **(electric field $E(x)$)** → WeightingPotentialReader **(weighting field $\varphi(x)$)** → DopingConcentrationReader **(carrier lifetimes τ)** → TransientPropagation → Output

Sim. pipeline (detailed)



The Allpix2 simulation takes

- the electrostatic field,
- the weighting field,
- the chg. transport model
  (in the simplest case, mobility & lifetime)

as external input quantities.

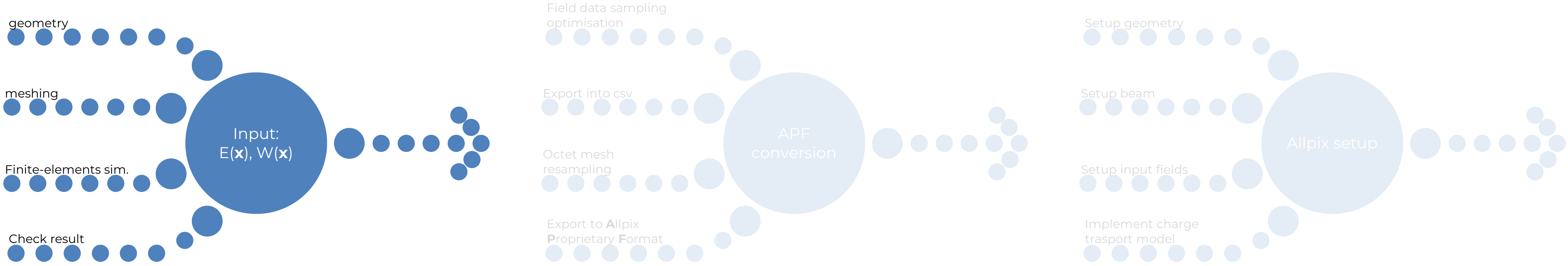
The simulation strategy is therefore oriented in first calculate these input quantities, then run the Allpix simulation and finally compare with Frascati experimental data.

Allpix2 default output observables allow for a quick sim. debugging and data extraction of simplest observables like

- generated charge by initial ionizing particles
- electric/weighting field visualization
- induced current/charge from e-/h+ at the electrodes
- drift time, recombination fraction, step length
- pulse profile

Access to such data (generated charge + induced charge) is enough to calculate the charge collection efficiency (CCE)

Electrostatic & Ramo fields

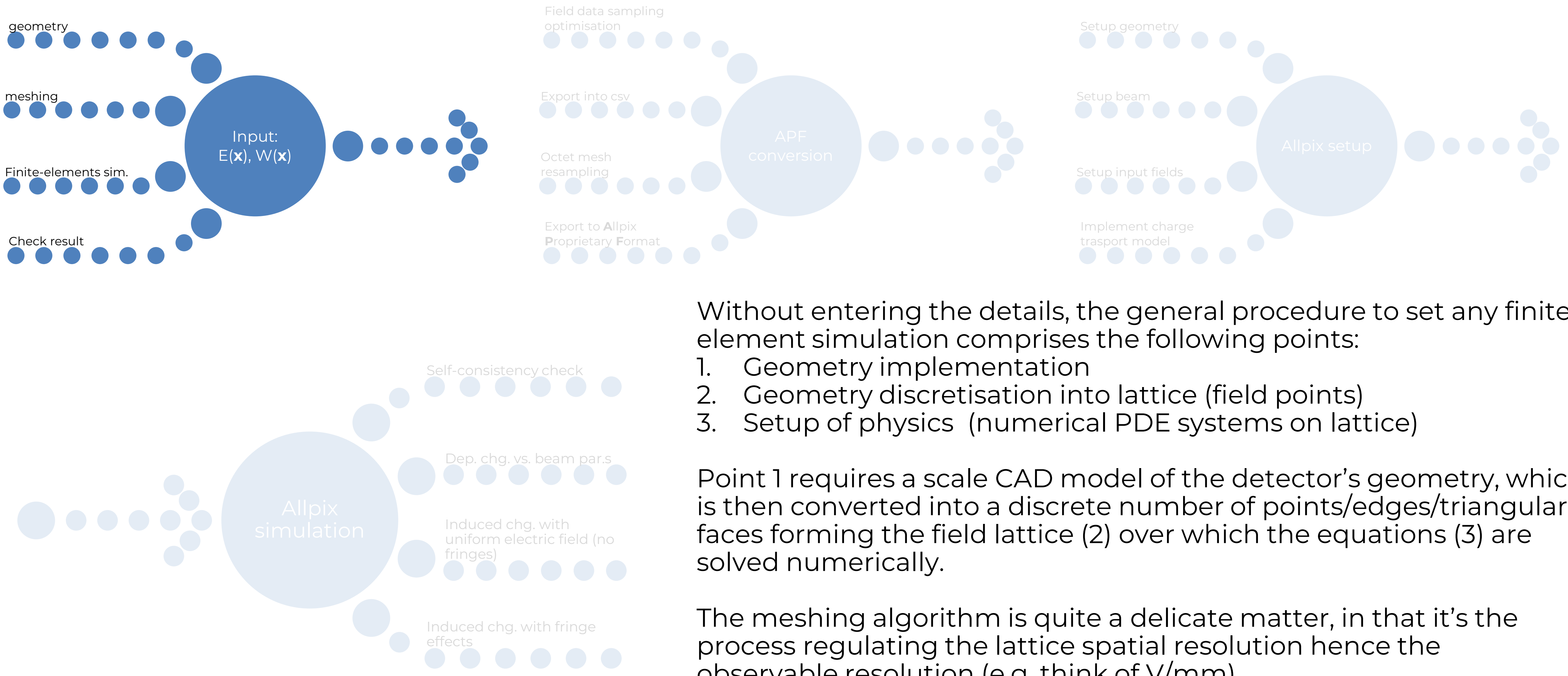


The evaluation of the electrostatic field configuration require the solution of the Laplace equation in the detector's geometry, with the boundary conditions given by the electrodes at a given V_bias voltage.

'Gold standard' for such finite-element simulations is **Synopsis-TCAD**, whose output format is compatible with Allpix2 and can be imported easily. However, TCAD requires both a valid *licence* and *training* to be used properly.

An alternative **free open-source** solution is adopted, based on the Finnish's **ELMER** tool.

Electrostatic & Ramo fields



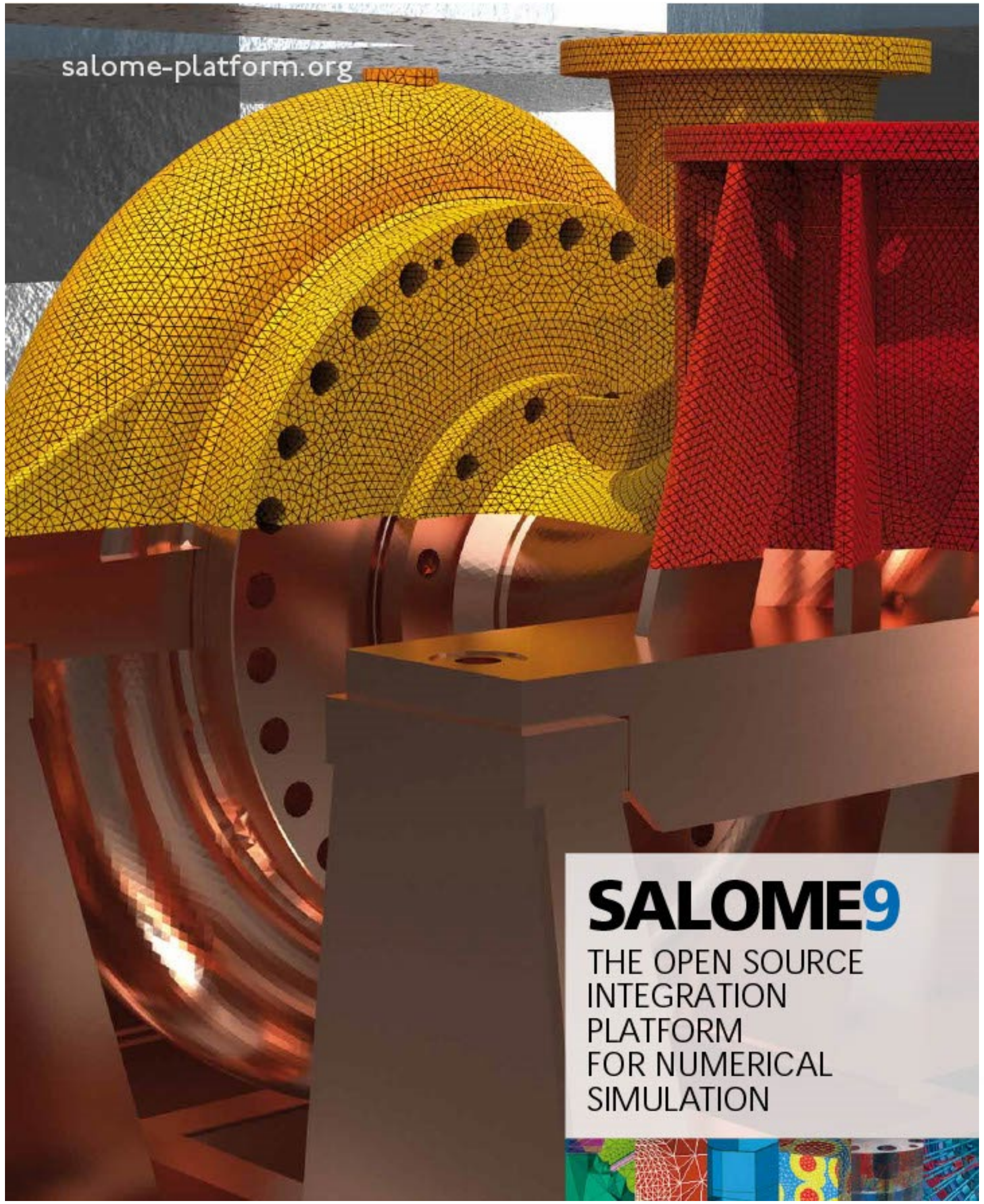
Without entering the details, the general procedure to set any finite-element simulation comprises the following points:

1. Geometry implementation
2. Geometry discretisation into lattice (field points)
3. Setup of physics (numerical PDE systems on lattice)

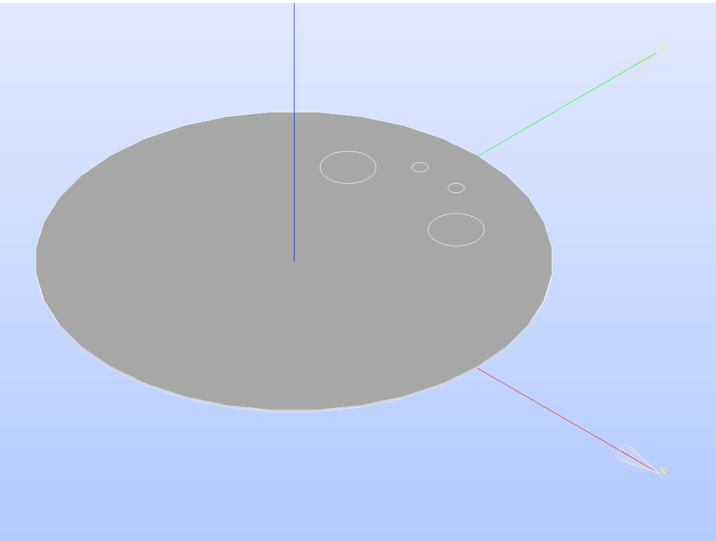
Point 1 requires a scale CAD model of the detector's geometry, which is then converted into a discrete number of points/edges/triangular-faces forming the field lattice (2) over which the equations (3) are solved numerically.

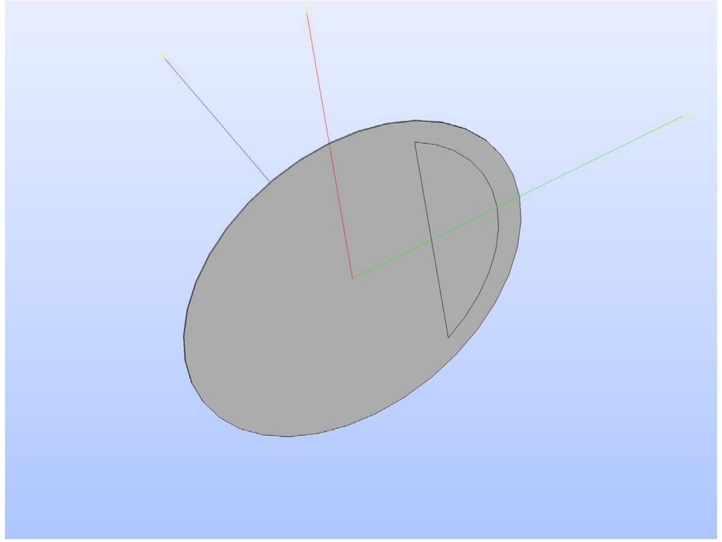
The meshing algorithm is quite a delicate matter, in that it's the process regulating the lattice spatial resolution hence the observable resolution (e.g. think of V/mm)

Geometry implementation



Geometry is implemented using the **open-source** SALOME9 software. The CAD model is defined parametrically allowing for trivial modification of revelant parameters (thickness, pad radii, etc.). Detector geometry is shown below





Although the entire sapphire wafer is implemented in the geometry, the simulation area is limited to few mm2 around the pad under consideration. This is necessary both to speed up the simulation - removing unnecessary memory wastes - and to reduce the amount of data to be post-processed.

Geometry and meshing

‘Meshing’ is the process of converting the abstract geometry into a set of vertices, edges and triangualted faces. This process creates the discretized spatial points field where the finite-element simulation runs.

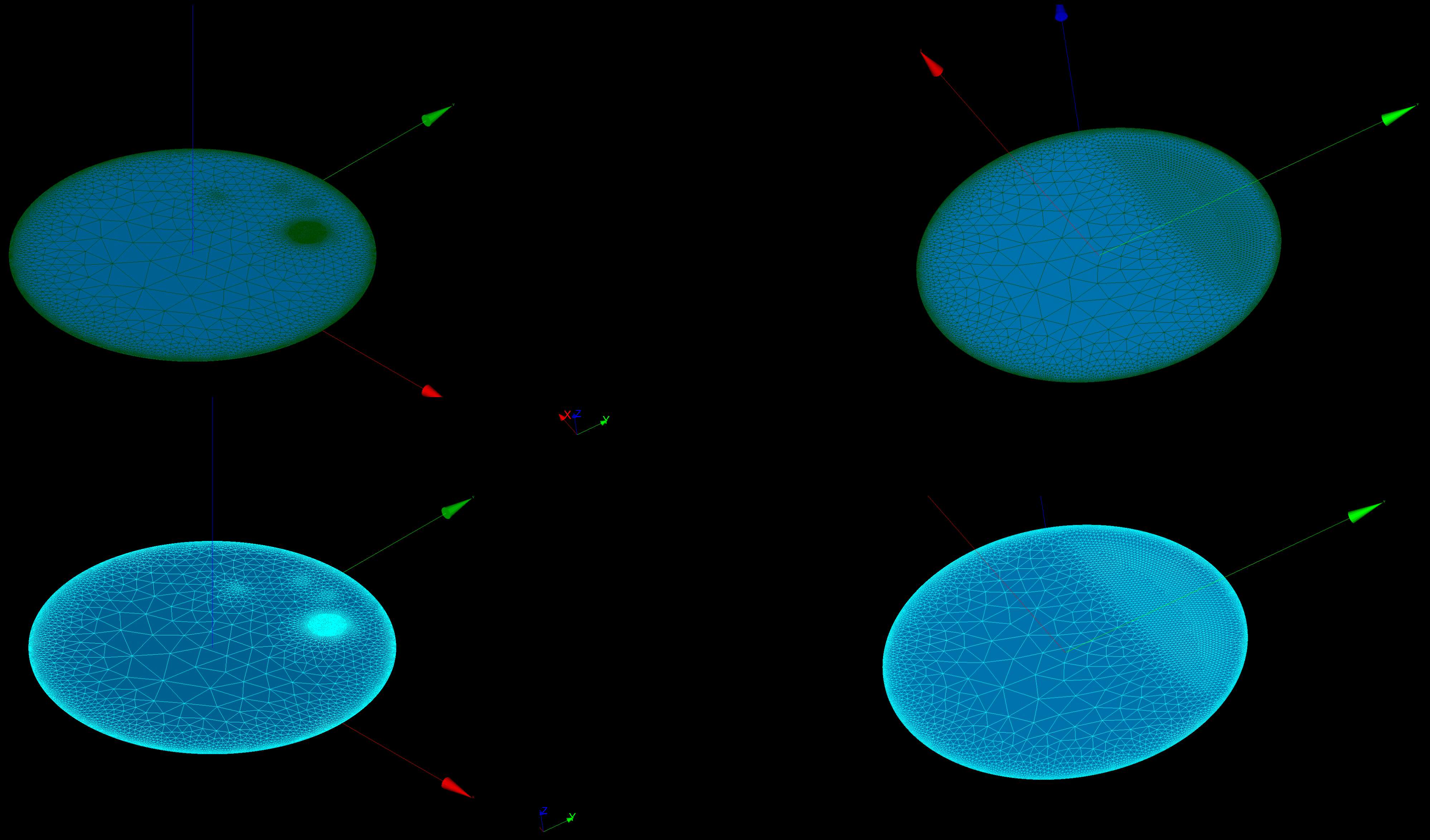
Mesh generation typically must be optimised by means of (geometric/physical) prior symmetries both to speed up computational time and keep accuracy goals over the lattice.

A very important point is that

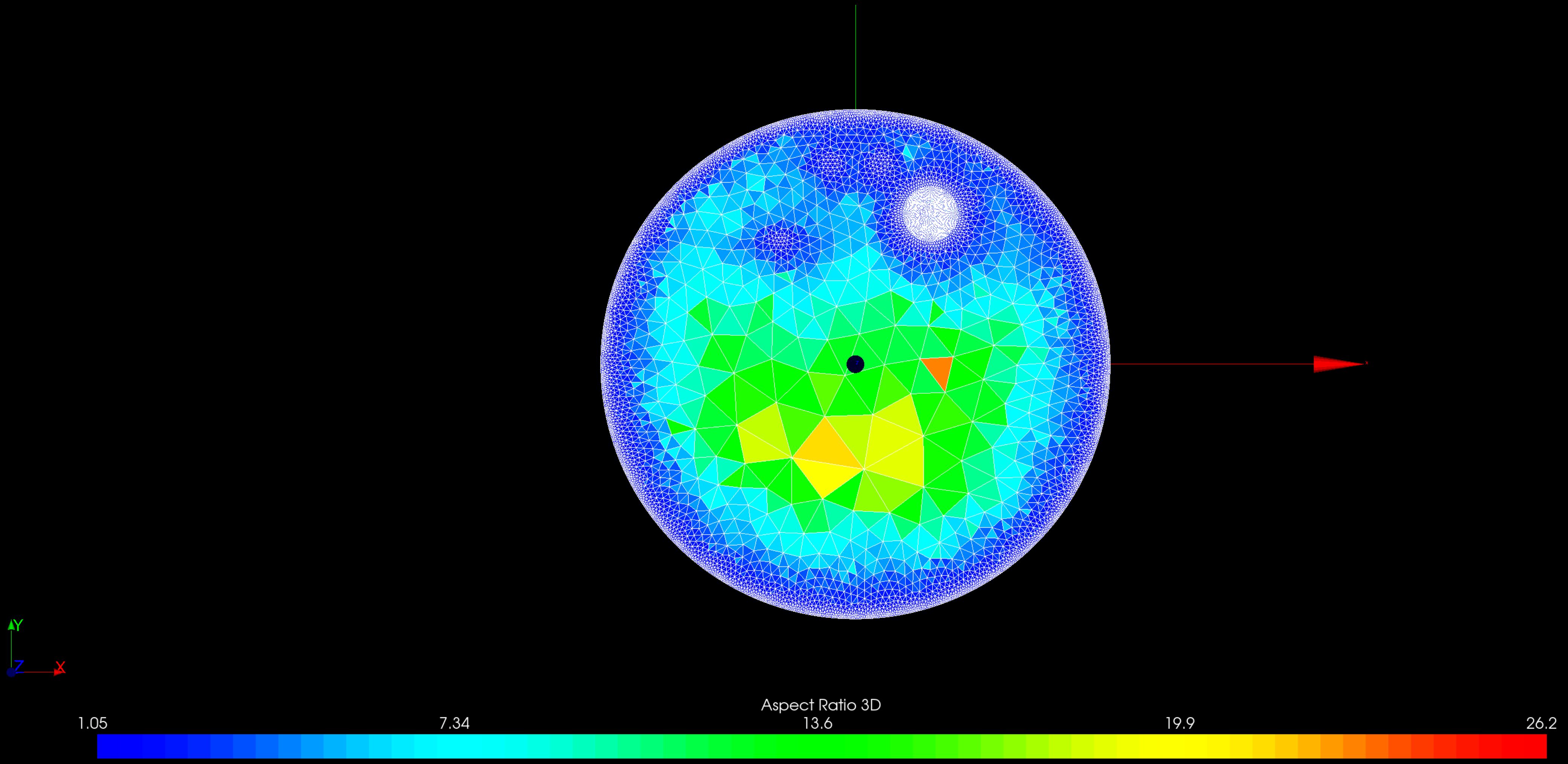
- the lattice spatial resolution determines electric/weight field spatial resolution

Hence, good compromises between performance/accuracy must be met on edges and regions one is most interested to look at.

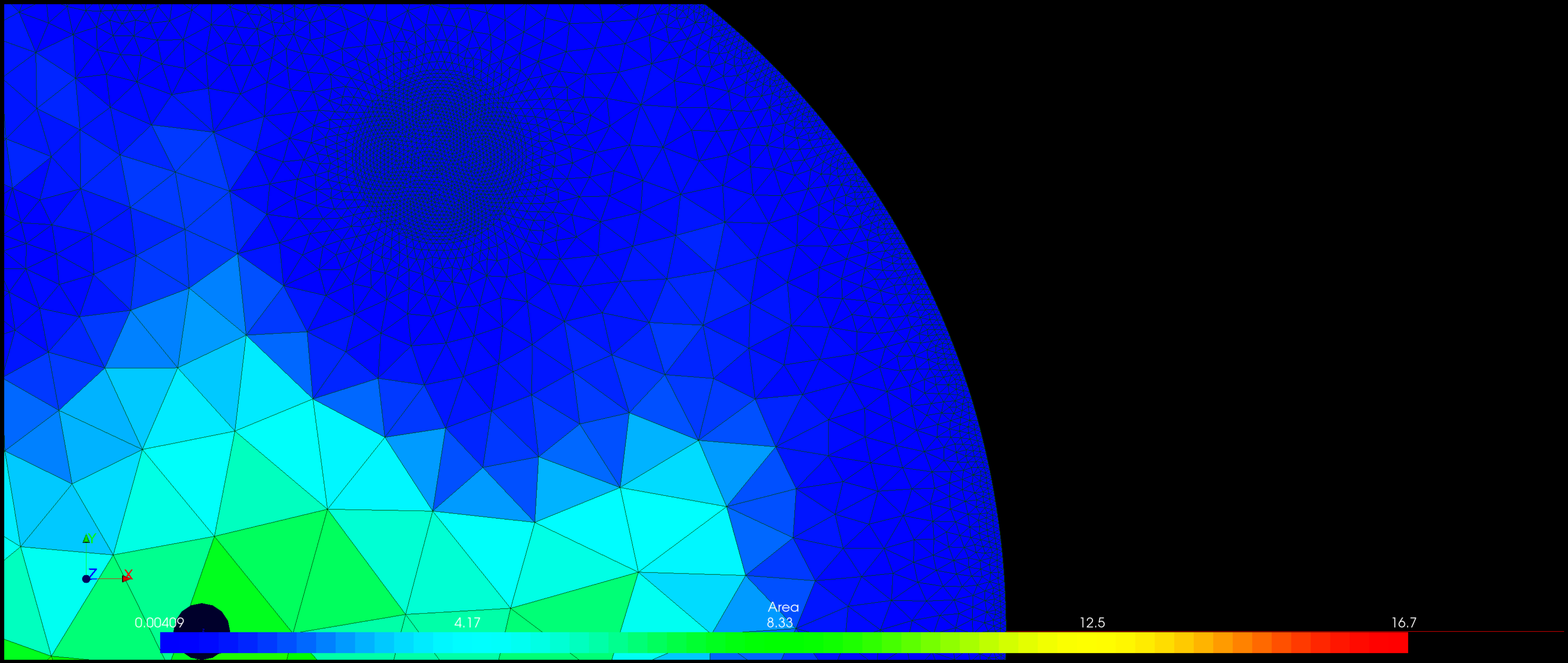
Mesh results



Lattice resolution. Aspect ratio

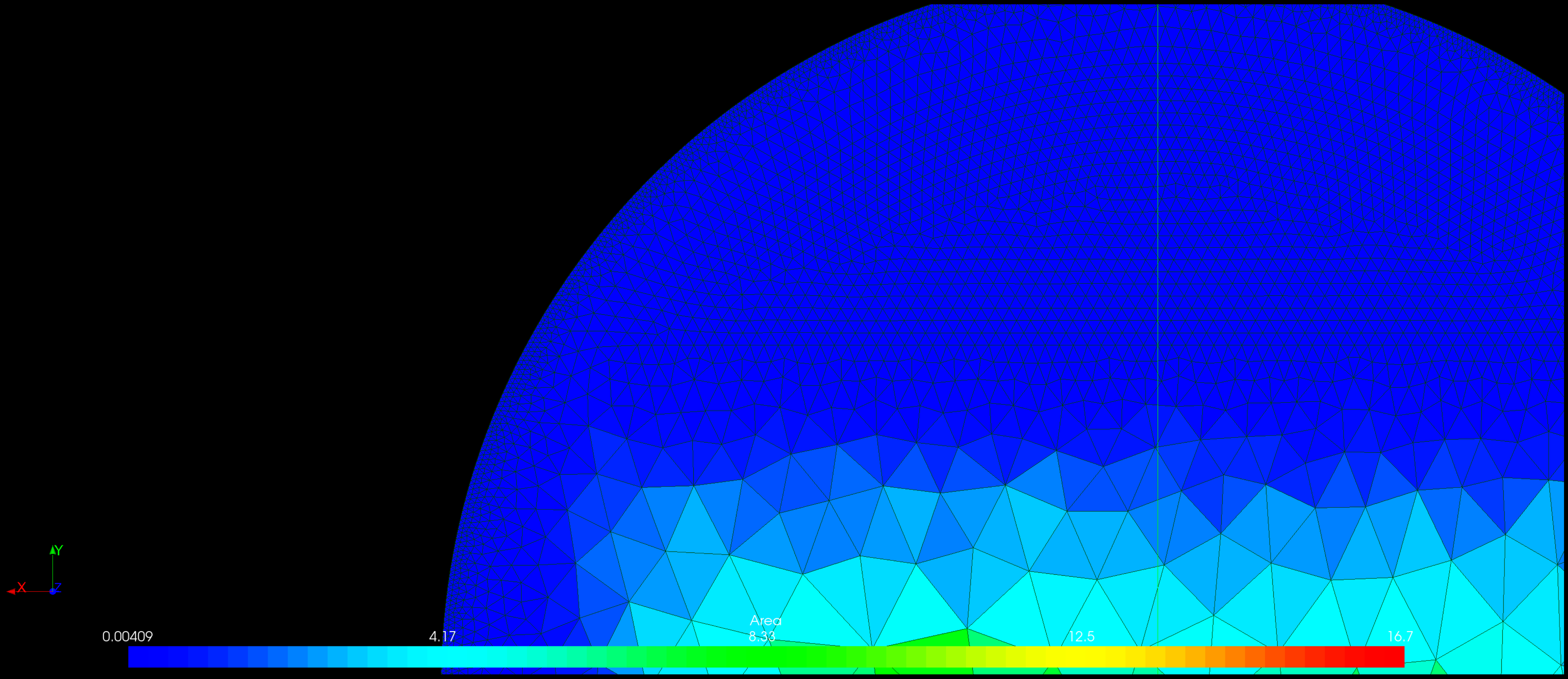


Lattice resolution. Surface (front)



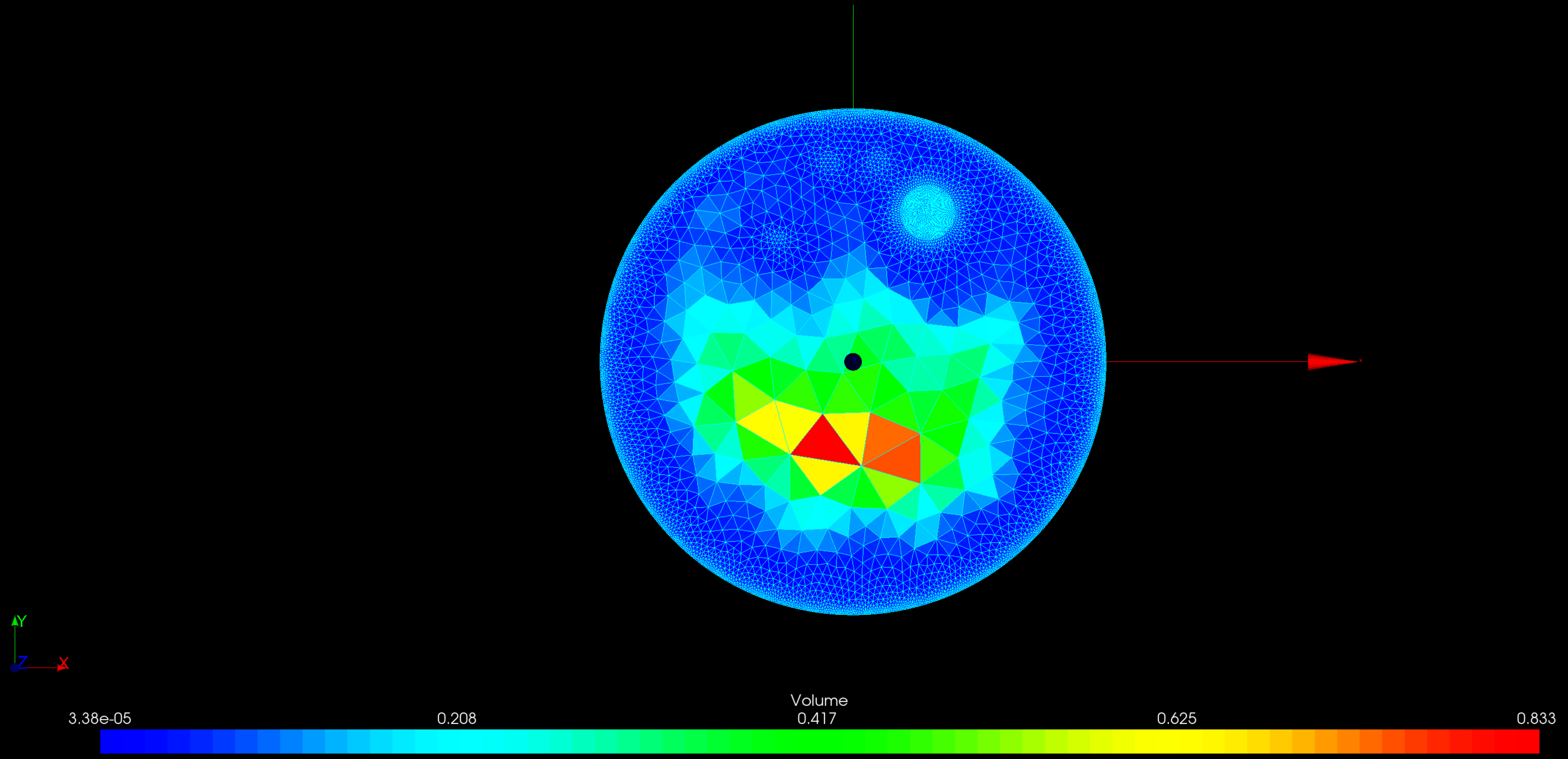
units in mm^2

Lattice resolution. Surface (rear)



units in mm^2

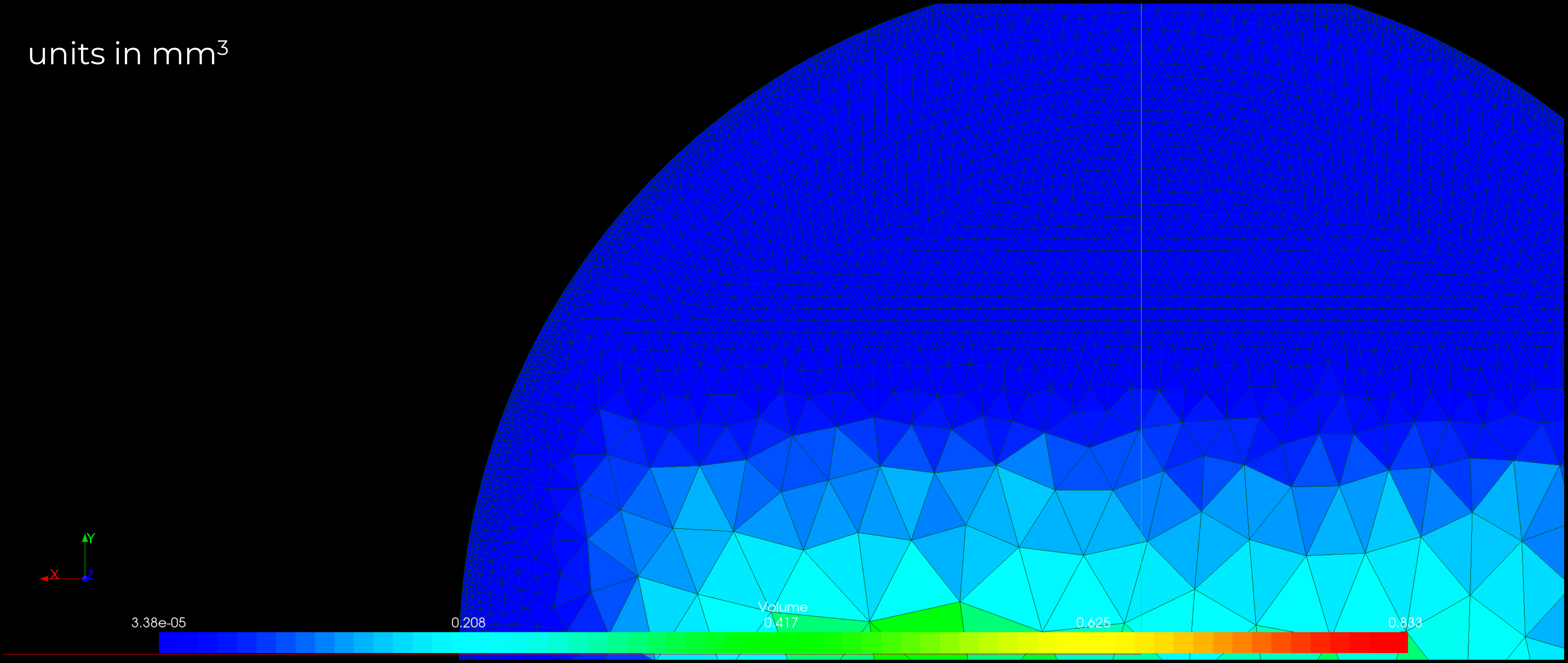
Lattice resolution. Volume



units in mm^3

Lattice resolution. Volume

units in mm^3

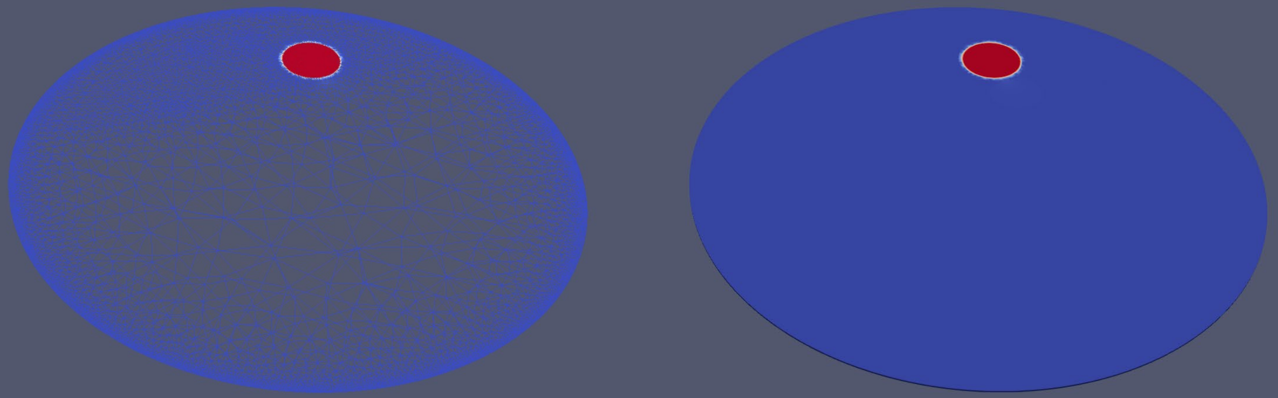


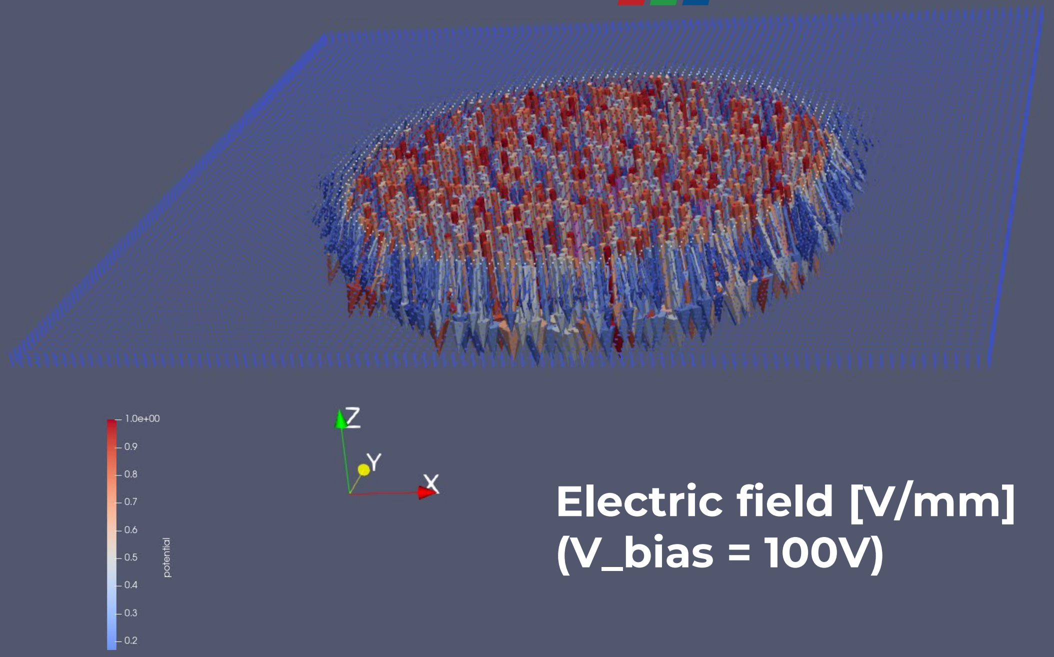
- Lattice linear resolution along the z-axis in the inner pad region is about 7.5 um
- Uniform 3d aspect ratio in the pad region means that points are spaced with the same order of sizes along the orthogonal directions x,y,z.

Finite-element simulation with Elmer

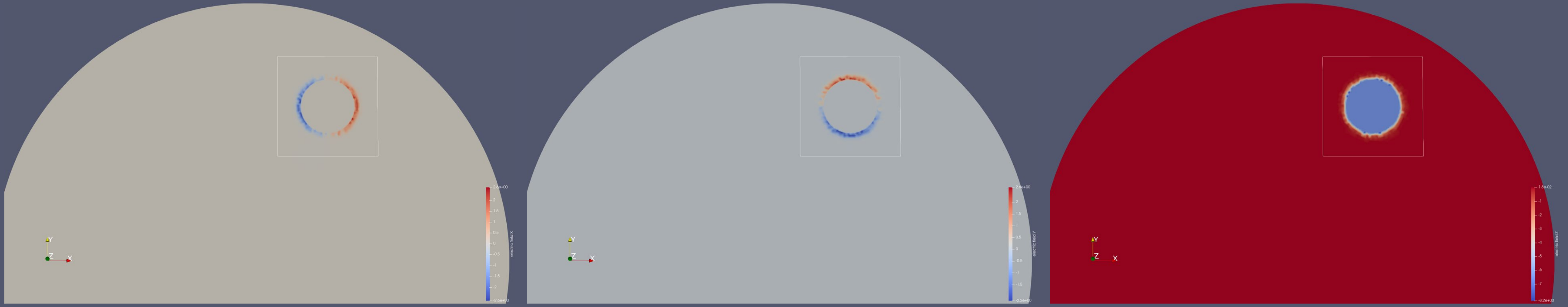
Data visualization with ParaView

potential [V]
(V_bias = 100V)

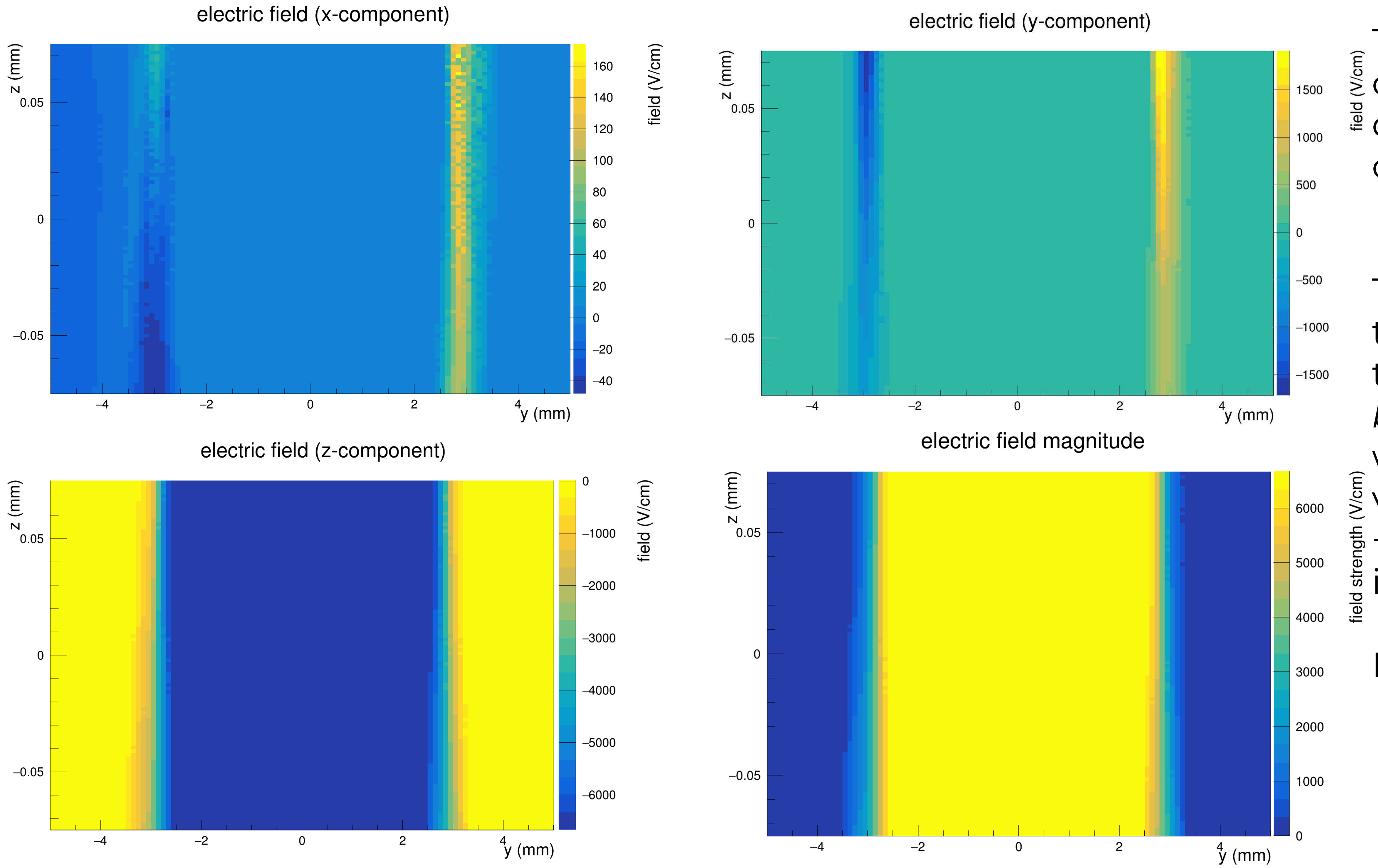




Electric field [V/mm]
(V_bias = 100V)



Electrostatic field

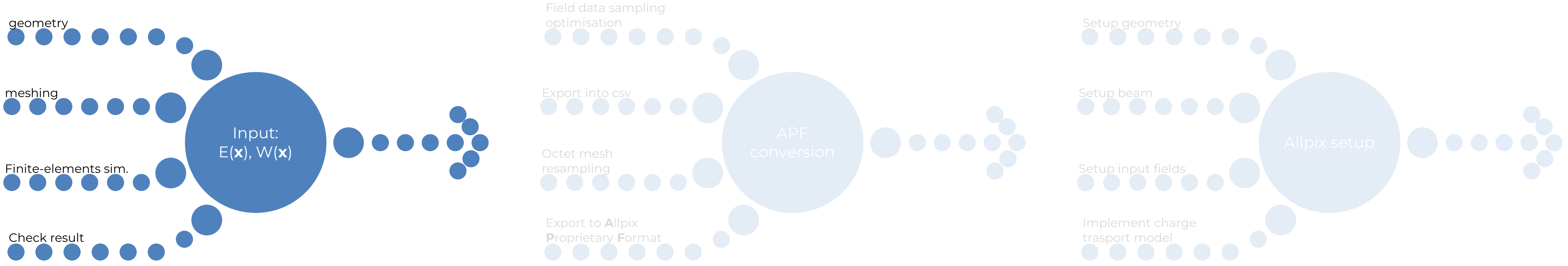


The plots show slices centered at the detector’ s geometric origin of coordinates.

The E-field shown on the left corresponds to the so-called *reverse bias* configuration, where a positive voltage of +100V is applied to the pad.

E =100V/150um
= 6666 V/cm

Weighting potential



The Shockley-Ramo theorem allows to evaluate the induced charge Q_{qi} on electrode i by a point charge q located at position x_0. This is written in terms of the weighting potential ϕ_i which is defined as to satisfy (a) the Laplace equation with (b) boundary condition that a unit electrostatic potential is present only on the conductor i.

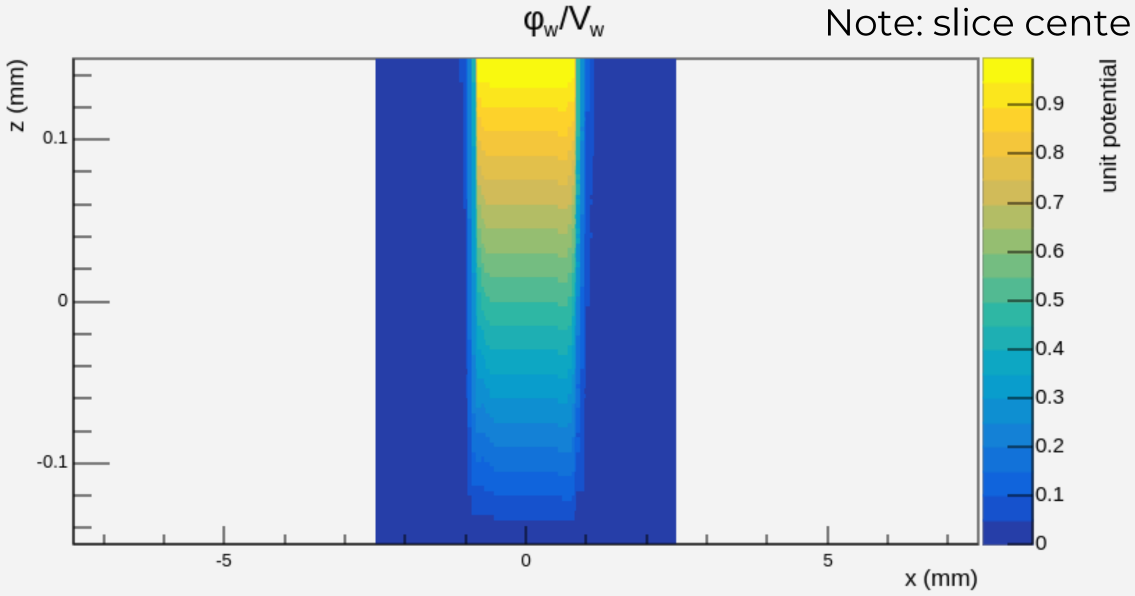
The field $E=-\nabla\psi_i$ is called weighing field.

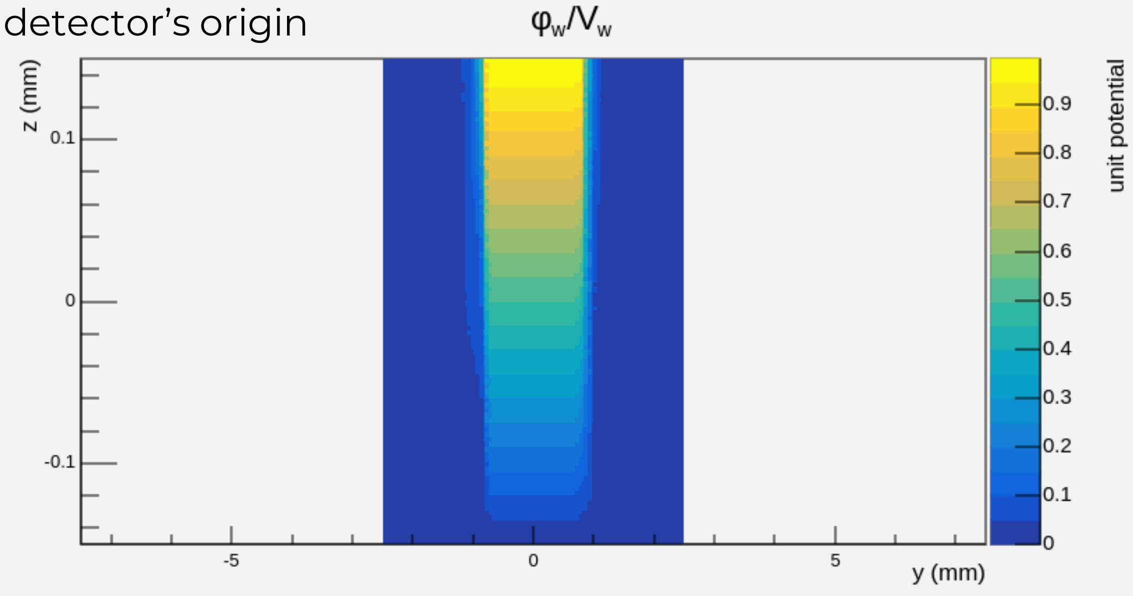
It is a weighting field because it satisfy the property that the sum of all the weighting potentials ϕ_i (for every conductor i) is 1 everywhere in the volume enclosing the detector*.

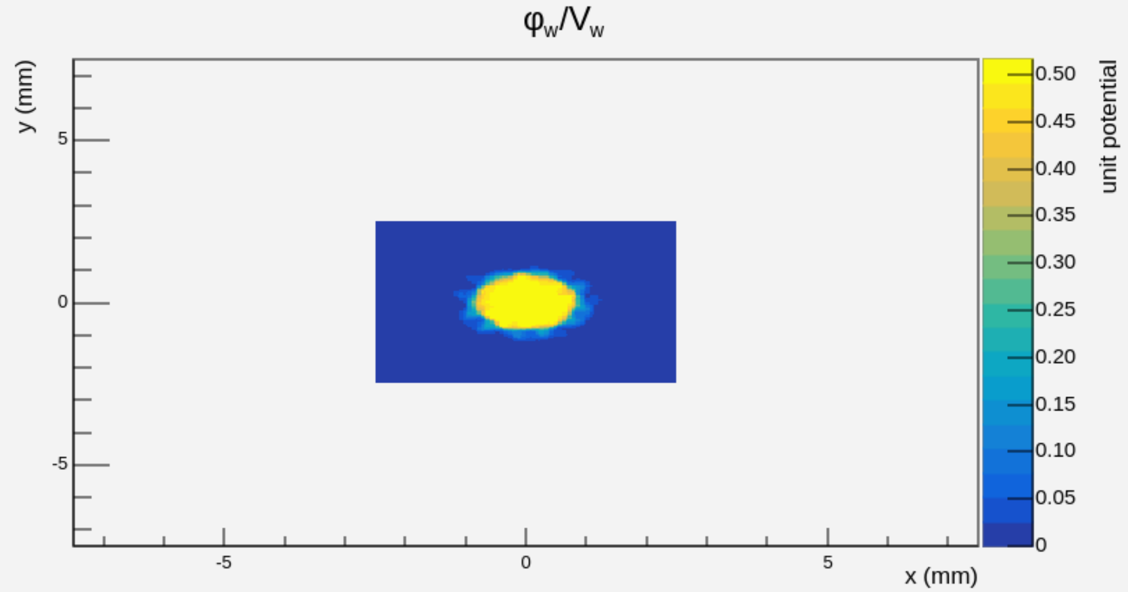
(a)+(b) give operative prescription to calculate the weighting field

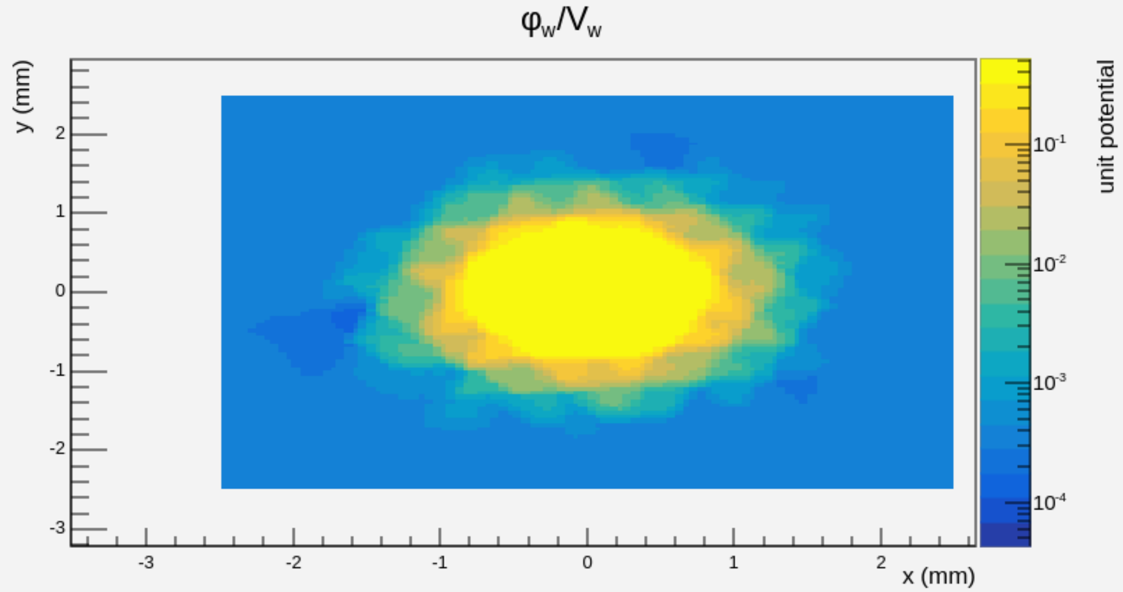
Weighting potential

Note: slice centered at detector's origin









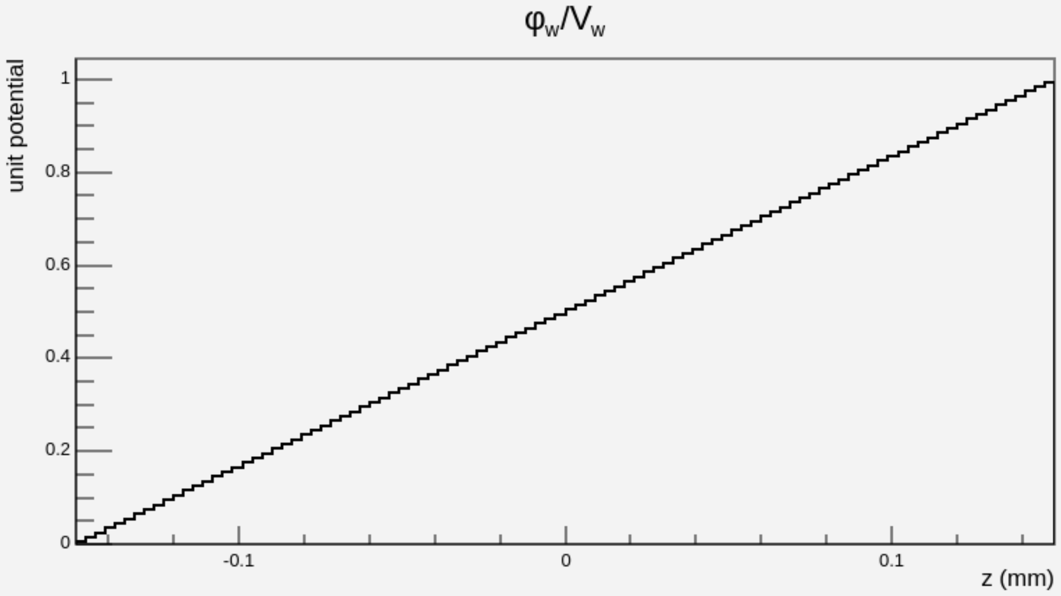
Weighting potential

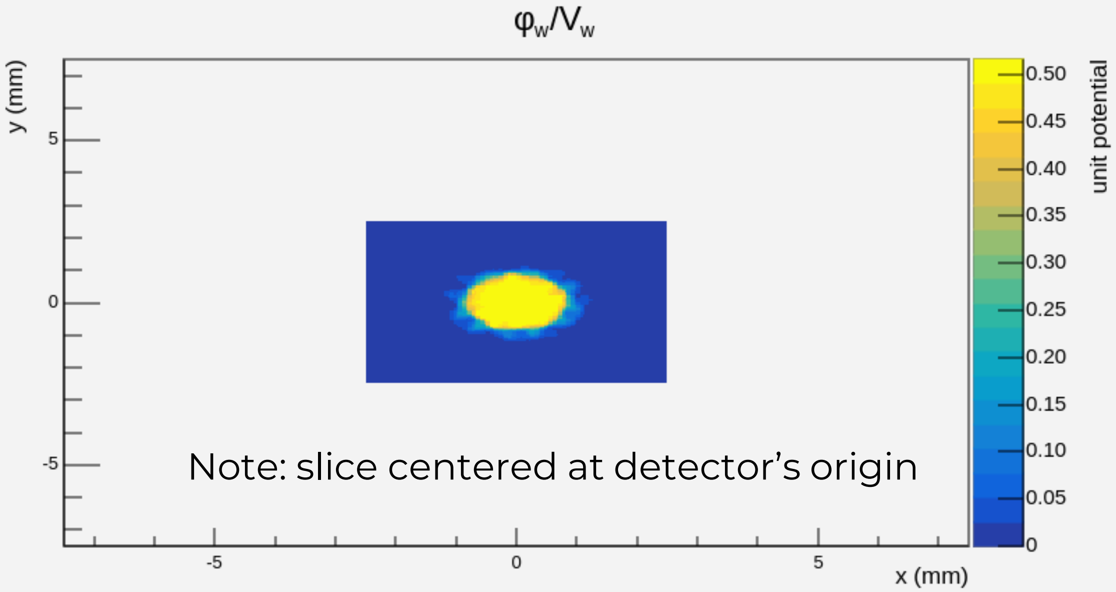
The weighting potential is calculated using Elmer. It is the electrostatic scalar field from the laplace equation with boundary condition that the smallpad is at unit potential 1V and the other conductors (LargePad, ground plane) grounded.

An accuracy goal of relative convergence 1e-10 was set in Elmer.

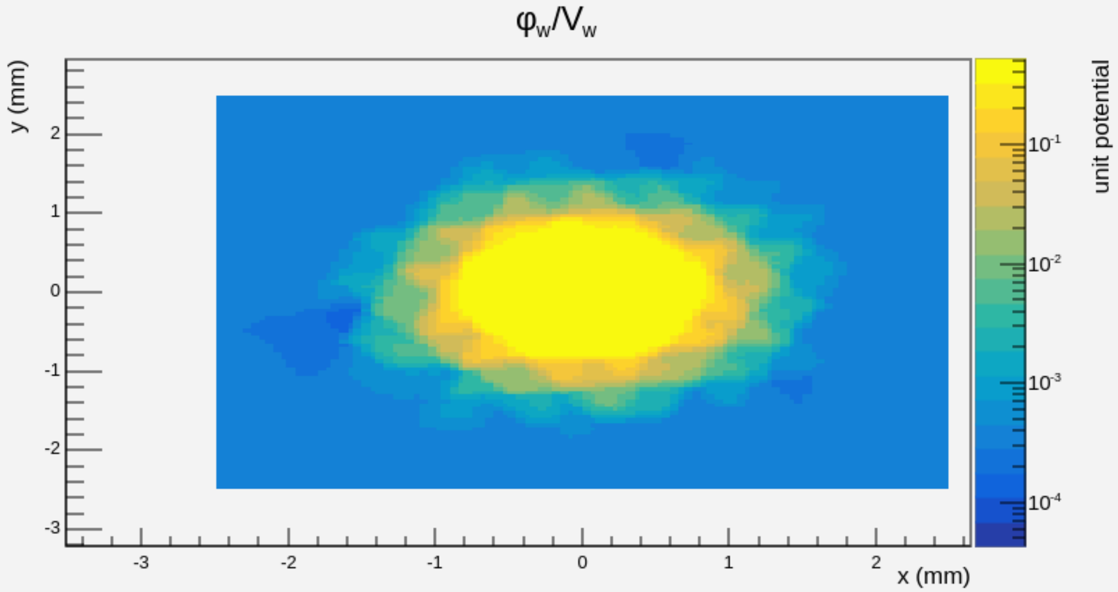
Slicing of the initial mesh around the pad resulted in an weighting scalar field with negative values and not properly bounded $|\varphi| <= 1$ but rather $|\varphi| <= 1 + O(1e\text{-}3)$

Therefore, it was necessary to rescale the field to positive [0,1]

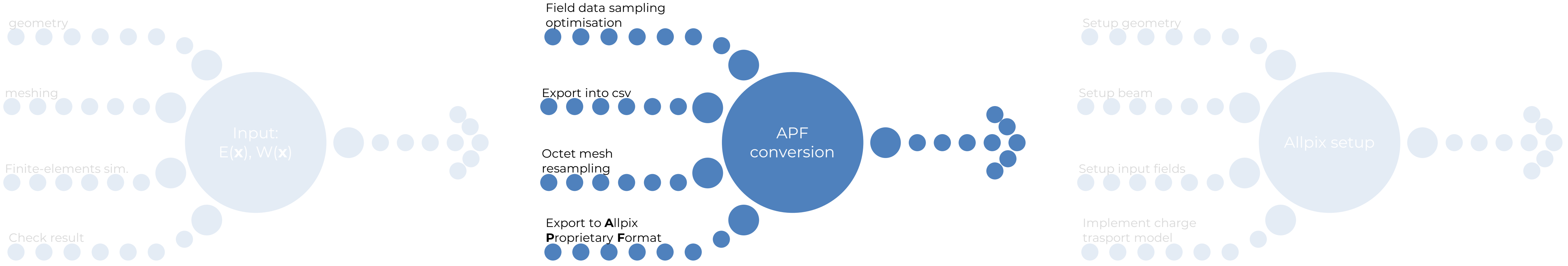




Note: slice centered at detector's origin



APF conversion



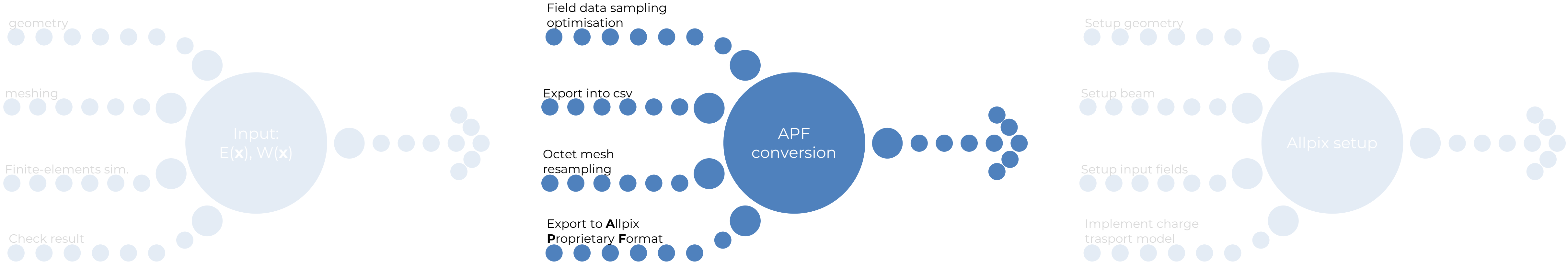
Allpix^2 takes input electrostatic/Ramo field in **APF** (Allpix Proprietary File format) and **INIT** (legacy TCAD format).

Data post-processing with Paraview allows to save field data in many format, but not INIT.

A 'patch' code is developed with the purpose to read the field in tabular (csv) format and export it in the APF format. Features

- multi-thread execution csv->apf
- resampling over regular grid lattice + field interpolation
- open source - will be merged in the Allpix2 CERN-git project

APF conversion



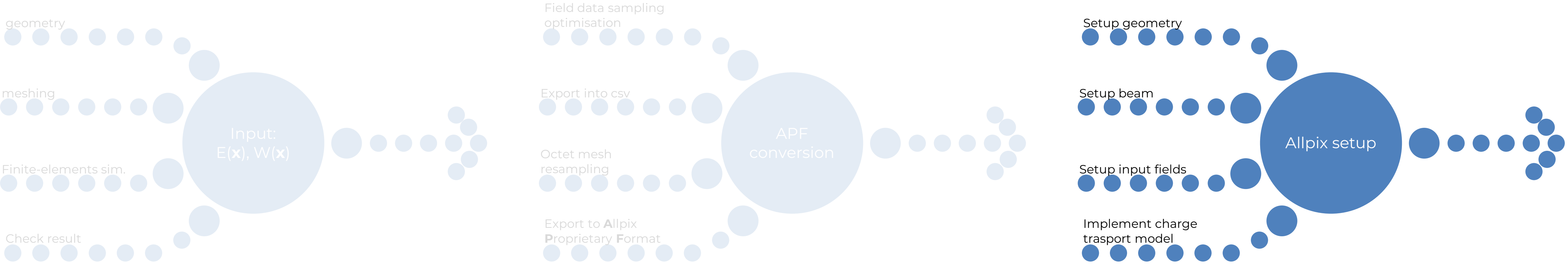
The typical file size of a csv file with the electric field (Ex, Ey, Ez) at each point (x,y,z) – e.g. using a regular sampling grid of 100x100x150 points aroung pad center – when written with 5 digits precision in scientific notation is **47.7 MB**

After conversion in the APF binary format is **24.0 MB**

Key points of the APF conversion/format are

- the conversion preserves absolute spatial resolution and
- it improves field accuracy by interpolating with a factor (100,100,100)
- much **faster lookup** than init/ascii formats

Allpix^2 setup



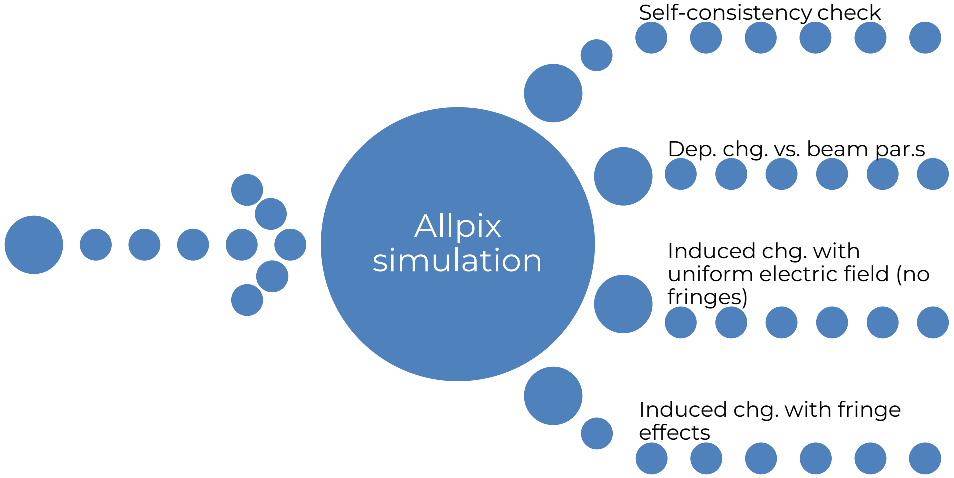
Allpix2 setup is advantaged by sharing geometry/beam description markup languange with Geant4:

- box assembly is implemented as in Frascati Geant4 sim.
- same for beam configuration: a 300MeV electron beam with gaussian distribution with sigma (2.18, 1.74)mm is generated 22cm upstream the device under test (DUT), at the position of the Fitpix sensor.

Input fields are verified with built-in allpix2 reporting histo.s

The chg. transport model implemented is simplest fixed uniform mobility + fixed uniform lifetime with a given product of $\mathbf{(\mu\tau)_e = 2.4\ um^2\ V^{-1}}$ **(**$\mathbf{\mu=30cm^2 V^{-1} s^{-1}}$**,** $\mathbf{\tau=800ps}$**)**

Allpix simulation. Results overview



SmallPad of the 110um detector is expected to receive largest deviation if fringe effects considered. The comparison consists in the following passages:

- Simulate a uniform V/d electric field along z localized in the region sqrt(x^2 + y^2) < r, extract the induced charge
- Repeat the simulation with the calculated E-field

The same random number generator seed is used evetytime, so to exclude missing induced charge from different initial beam depositions.

Perfectly aligned gaussian (2.18, 1.74)mm beam is used.

example – single pcb with 150um wafer upstream

Uniform vs. Fringe – LargePad 150um

- For 1000 initial electrons, that is for 1000 events in the simulation, the total number of charges deposited in the large pad of the 150um sensor is **5976130** charges (average of 5955 per sensor for every event) that is **2988065** electrons and **2988065** holes uniformly distributed along the 150um thickness (MIP).
- If a uniform electric field directed along z with magnitude E=100V/150um for the region sqrt(x^2 + y^2) < R=2.75mm is applied, the induced electronic charge at the electrode is **16374 e-** giving a charge collection efficiency of 16374/2988065 = **0.54%**
- Otherwise, if the simulated E field is used, the induced electronic charge is **17032e-** giving a collection efficiency of 17337/2977851 = **0.57%**

Same random number seed used (to exclude initial beam biasing)

LargePad 150um – beam (2.18, 1.74) mm

Simulated field

CCE at 100V is -17032.485960010337/2988065.0 that is 0.005700172506290973

CCE at 200V is -36312.06692269986/2988065.0 that is 0.01215236848017023

CCE at 400V is -73482.58315719888/2988065.0 that is 0.024592029677131817

CCE at 600V is -109687.92743664651/2988065.0 that is 0.03670868185151478

CCE at 800V is -144269.36628932963/2988065.0 that is 0.048281870136469465

CCE at 1000V is -176918.27818180484/2988065.0 that is 0.05920830978636838

Uniform in the r<2.75mm region, no outside

CCE at 100V is -16373.999822909771/2988065.0 that is 0.005479800413615424

CCE at 200V is -35053.42209701274/2988065.0 that is 0.011731144435282613

CCE at 400V is -71063.90455195686/2988065.0 that is 0.023782583227592725

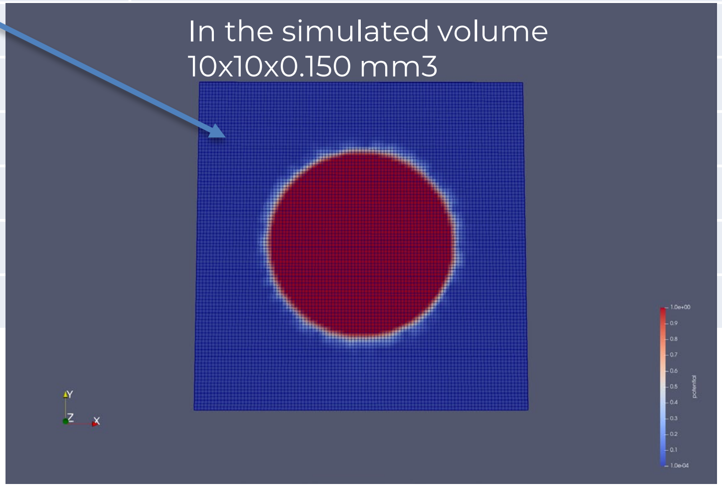
CCE at 600V is -106364.16127852381/2988065.0 that is 0.03559633451030142

CCE at 800V is -139771.00228168853/2988065.0 that is 0.04677642630989906

CCE at 1000V is -171160.14513275222/2988065.0 that is 0.05728126567954587

LargePad 150um – beam (2.18, 1.74) mm

Simulated					Relative variation of induced charge with respect to uniform case
Vbias	Charge ind. [#e]	Charge dep. [#e]			Ind.Sim/Ind.Uni
100V	-17032.48596	2988065			1.04021535
200V	-36312.06692	2988065			1.035906475
400V	-73482.58316	2988065			1.034035262
600V	-109687.9274	2988065			1.031248929
800V	-144269.3663	2988065			1.032183814
1000V	-176918.2782	2988065			1.033641786
Uniform r<2.75, no outside					
100V	-16373.99982	2988065			
200V	-35053.4221	2988065			
400V	-71063.90455	2988065			
600V	-106364.1613	2988065			
800V	-139771.0023	2988065			
1000V	-171160.1451	2988065			



Uniform vs. Fringe – SmallPad 150um

- For 1000 initial electrons, that is for 1000 events in the simulation, the total number of charges deposited in the small pad of the 150um sensor is **3892656** charges (average of 3892 per sensor for every event) that is **1946328** electrons and **1946328** holes uniformly distributed along the 150um thickness (MIP).
- If a uniform electric field directed along z with magnitude E=100V/150um for the region sqrt(x^2 + y^2) < R=0.8mm is applied, the induced electronic charge at the electrode is **2378 e-** giving a charge collection efficiency of 2378/1946328 = **0.122%**
- Otherwise, if the simulated E field is used, the induced electronic charge is **2659e-** giving a collection efficiency of 2659/1946328 = **0.136%**

Same random number seed used (to exclude initial beam biasing)

SmallPad 150um – beam (2.18, 1.74) um

Simulated E-field

CCE at 100V is -27818.019424831436/3078100.0 that is 0.0090373995077585
CCE at 200V is -59296.45729188814/3078100.0 that is 0.019263980147457244
CCE at 400V is -120131.77780470635/3078100.0 that is 0.03902789961492685
CCE at 600V is -178458.50019801405/3078100.0 that is 0.05797683642442222
CCE at 800V is -234841.37640912525/3078100.0 that is 0.07629426477668862
CCE at 1000V is -287959.8863399514/3078100.0 that is 0.09355117973423586

Uniform in the r<0.8mm region, no outside

CCE at 100V is -27887.654013225252/3078100.0 that is 0.009060022095846545
CCE at 200V is -59424.46169065795/3078100.0 that is 0.01930556567059483
CCE at 400V is -120396.49049767366/3078100.0 that is 0.03911389834562674
CCE at 600V is -178737.53092403666/3078100.0 that is 0.05806748673663515
CCE at 800V is -235274.4309657543/3078100.0 that is 0.07643495369408215
CCE at 1000V is -288492.5291278483/3078100.0 that is 0.093724222451463

Simulated					Relative variation of induced charge with respect to uniform case
Vbias	Charge ind. [#e]	Charge dep. [#e]			Ind.Sim/Ind.Uni
100V	-27818.01942	3078100			0.997503032
200V	-59296.45729	3078100			0.997845931
400V	-120131.7778	3078100			0.997801326
600V	-178458.5002	3078100			0.99843888
800V	-234841.3764	3078100			0.998159364
1000V	-287959.8863	3078100			0.998153703
Uniform r<0.8, no outside					
100V	-27887.65401	3078100			
200V	-59424.46169	3078100			
400V	-120396.4905	3078100			
600V	-178737.5309	3078100			
800V	-235274.431	3078100			
1000V	-288492.5291	3078100			

In the simulated volume 5x5x0.150 mm3

SmallPad 150um – beam (2.18, 1.74) mm

Simulated E-field

CCE at 100V is -2658.5462635728213/1946328.0 that is 0.0013659292080126378

CCE at 200V is -5762.337600044188/1946328.0 that is 0.0029606199982963755

CCE at 400V is -12110.842000122459/1946328.0 that is 0.006222405473343886

CCE at 600V is -18245.45797165257/1946328.0 that is 0.009374297637218686

CCE at 800V is -24229.292645809164/1946328.0 that is 0.012448720177590399

CCE at 1000V is -30144.16673084084/1946328.0 that is 0.015487711593750304

Uniform in the r<0.8mm region, no outside

CCE at 100V is -2378.4106364023255/1946328.0 that is 0.0012219988880148837

CCE at 200V is -5095.922805088091/1946328.0 that is 0.0026182240635124663

CCE at 400V is -10531.12811821504/1946328.0 that is 0.005410767413413895 5

CCE at 600V is -15760.80216328796/1946328.0 that is 0.008097711261045394

CCE at 800V is -20717.72547448786/1946328.0 that is 0.010644519050482682

CCE at 1000V is -25747.882071432152/1946328.0 that is 0.013228953224447344

SmallPad 150um – beam (2.18, 1.74) mm

Simulated				Relative variation of induced charge with respect to uniform case
Vbias	Charge ind. [#e]	Charge dep. [#e]		Ind.Sim/Ind.Uni
100V	-2658.546264	1946328		1.1177827
200V	-5762.3376	1946328		1.130774115
400V	-12110.842	1946328		1.150004241
600V	-18245.45797	1946328		1.157647801
800V	-24229.29265	1946328		1.169495786
1000V	-30144.16673	1946328		1.170743545
Uniform r<0.8, no outside				
100V	-2378.410636	1946328		
200V	-5095.922805	1946328		
400V	-10531.12812	1946328		
600V	-15760.80216	1946328		
800V	-20717.72547	1946328		
1000V	-25747.88207	1946328		

In the simulated volume 5x5x0.150 mm3

What’s next?

- Fringe effects with beam offset
- Turn on front-end modules