

# Sapphire strip detector with Allpix-squared: the Gamma Beam Profiler for the LUXE experiment at DESY

4th Allpix Squared User Workshop  
22-23 May 2023 at DESY, Hamburg



UNIVERSITÀ  
DEGLI STUDI  
DI PADOVA



*Speaker:* P. Grutta  
INFN and University of Padua

# Overview of the presentation

## 1. Introduction

- Brief overview of the LUXE experiment at DESY and its objectives.
- The importance of gamma beam monitoring in the context of the experiment.
- Requirement for the gamma profiler. Motivation for a strip detector.

## 2. Sapphire strip detector

- General background on sapphire detectors and their relevance in this scenario.
  - Advantages of a sapphire over diamond.
- GP design and the role of MC simulations.

## 3. Allpix-squared for sapphire

- Simulation pipeline
- Built-in capabilities and ad-hoc development for sapphire simulations.
- Integration of Sapphire Strip Detector and Allpix-squared
- Challenges faced in the integration process and how they were overcome.

## 4. Results and Findings

- Validation of the Allpix-squared for sapphire with the literature..
- Discuss the accuracy, precision, and reliability of the results, showcasing their significance for the LUXE experiment.

## 5. Conclusion

- Key points of the presentation.
- Outlooks. Future developments and applications.

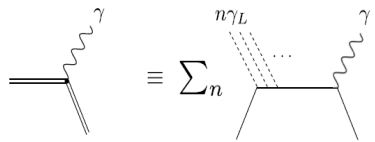
## Q&A Session

# LUXE. Introduction

Laser **U**nd **X**FEL **E**xperiment is a new experiment at DESY to perform precision measurements of the transition into the non-linear regime of quantum electrodynamics (QED), and to search for new particles beyond the Standard Model coupling to photons.

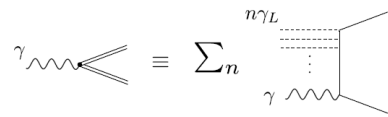
## Scientific goals

- First experimental observation of Sauter-Schwinger pair production of  $e^\pm$  by strong background field.
- Study the onset of the strong-field QED transition of the processes



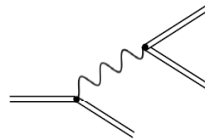
Non-linear (inverse) Compton

$$e^\pm + n\gamma_L \rightarrow e^\pm + \gamma.$$



Breit-Wheeler production

$$\gamma + n\gamma_L \rightarrow e^+e^-$$



Non-linear Trident process

- Probe parameter-space edge of natural models of axion-like-particles (ALPs) coupling to photons, by using an optical+solid beam dump and an EM calorimeter.

# LUXE



TECHNISCHE  
UNIVERSITÄT  
DARMSTADT

HELMHOLTZ  
Helmholtz-Institut Jena



QUEEN'S  
UNIVERSITY  
BELFAST

SUSTech  
Southern University of Science and Technology



AGH

m-psd  
Max-Planck-Institut für  
Struktur und Dynamik der Materie

TEL AVIV UNIVERSITY

HZDR  
HELMHOLTZ ZENTRUM  
DRESDEN ROSSENDORF



université  
PARIS-SACLAY



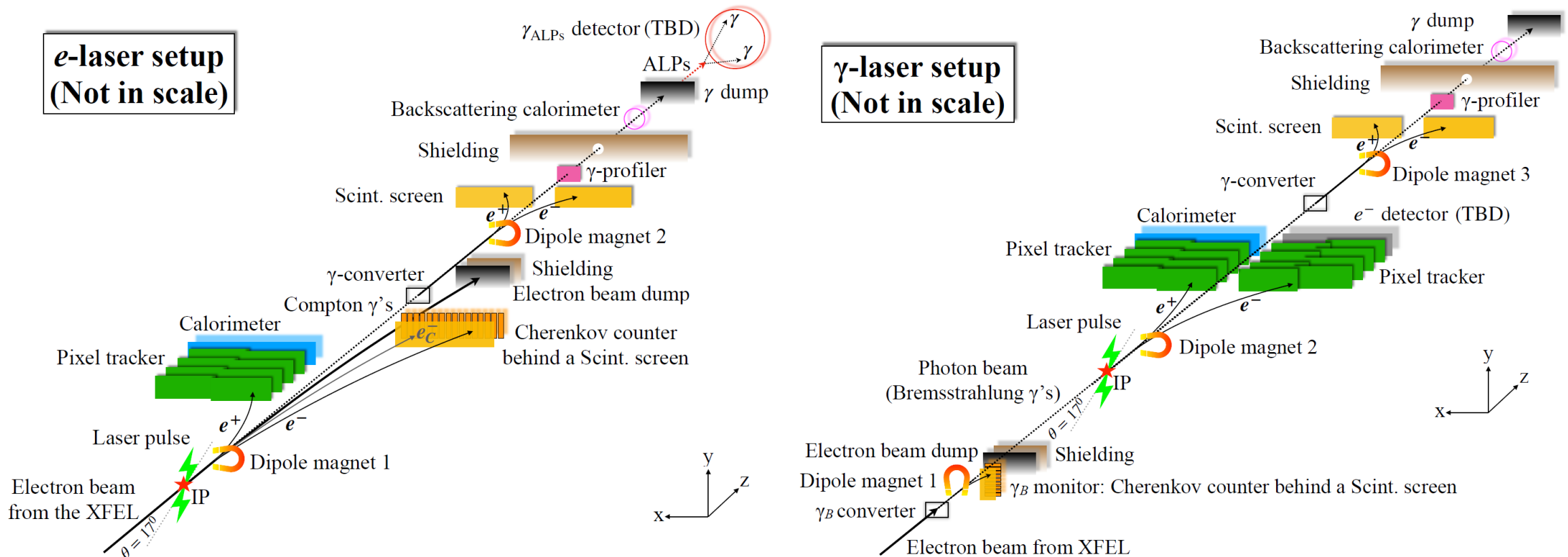
UNIVERSITY OF  
PLYMOUTH

# LUXE. Experimental setup

Strong field QED (SFQED) physics is probed using the two configurations

- electron-laser
- gamma-laser collisions

by colliding the 16.5 GeV electrons (XFEL) with a 800nm 40 TW laser beam.

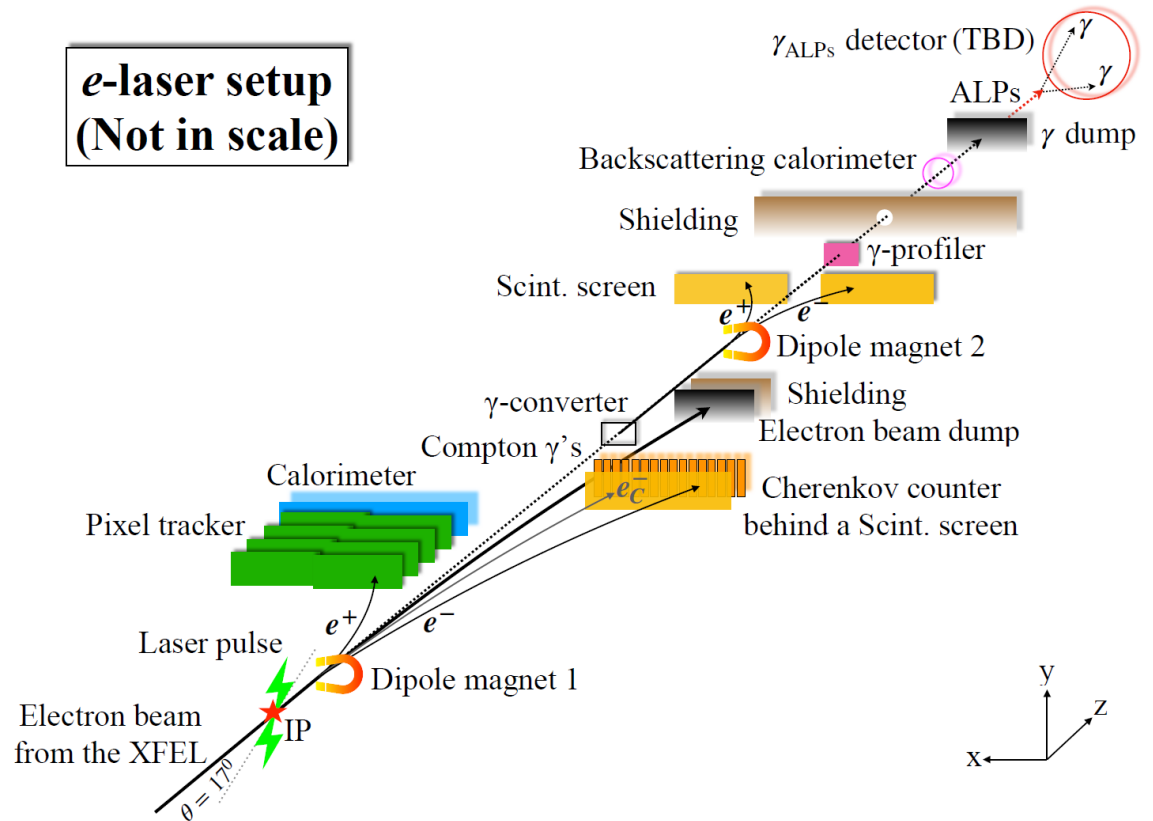
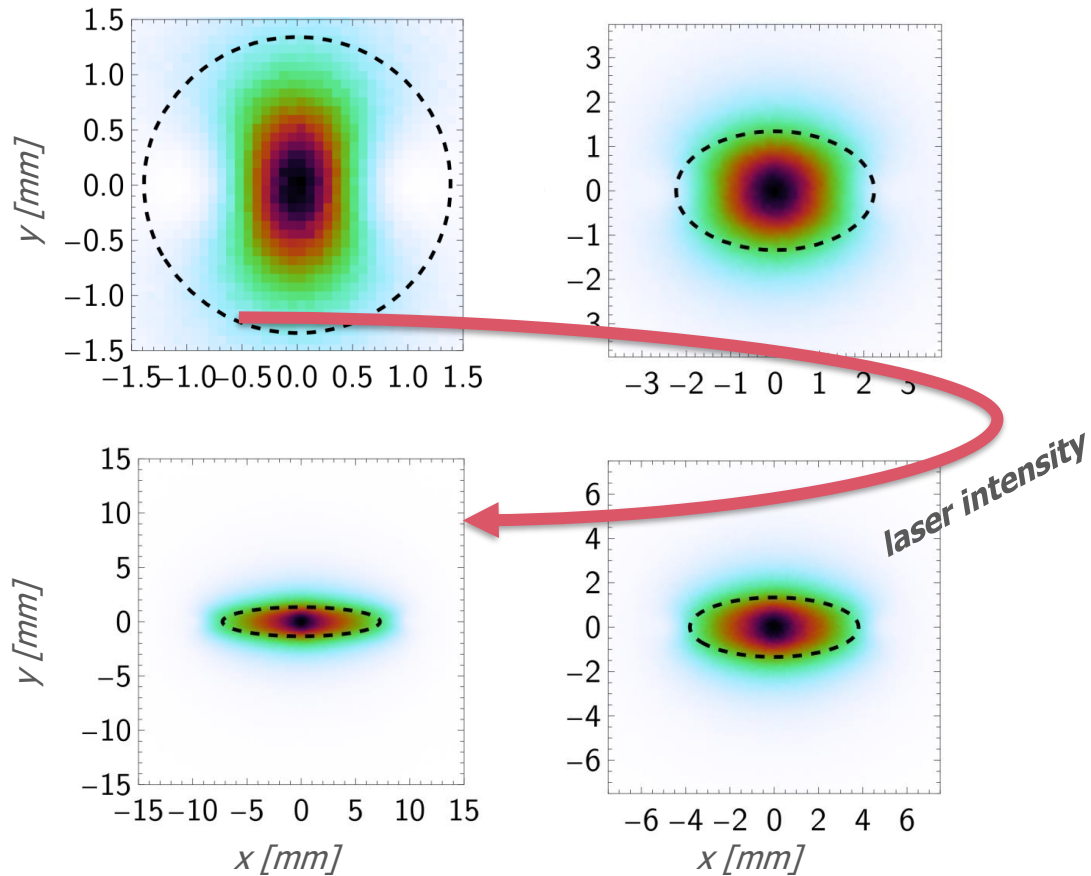


# LUXE. Experimental setup

Strong field QED (SFQED) physics is probed using the two configurations

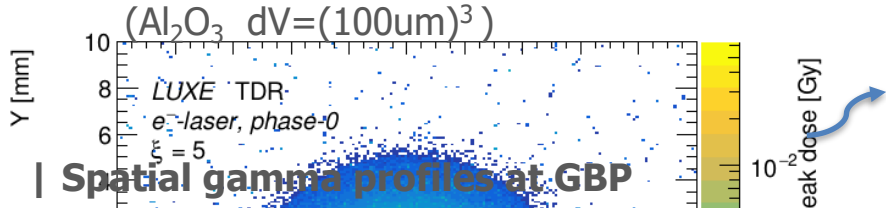
- electron-laser
- gamma-laser collisions

by colliding the 16.5 GeV electrons (XFEL) with a 800nm 40 TW laser beam.

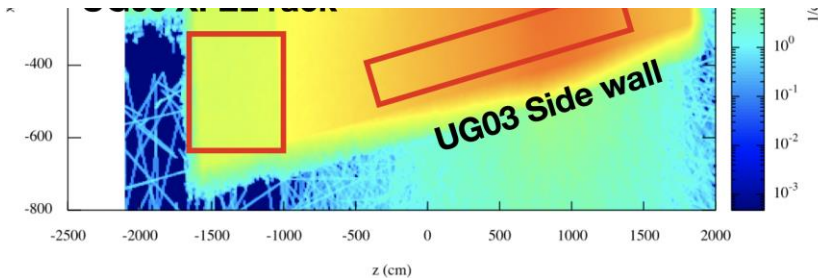
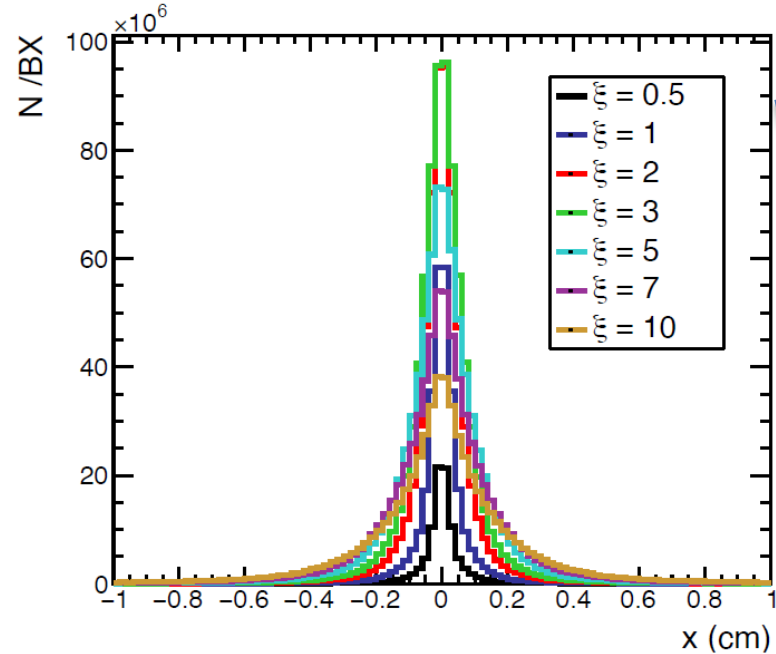


# LUXE. Requirements for the Gamma Profiler

## Spatial gamma profiles at GBP ( $\xi=5$ )



## Spatial gamma profiles at GBP



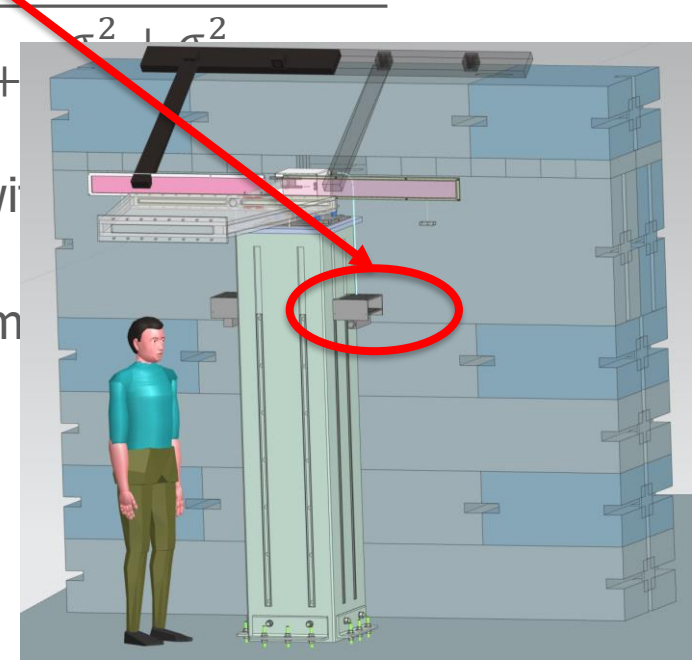
## Detector requirements

- High flux ( $\sim 10^9 \text{ s}^{-1}$ ) of high energy ( $\sim \text{GeV}$ ) photons. Dose of several MGy/yr -> **radiation-hardness**
- High radiation flux in the surrounding -> **strip-readout** (to keep electronics in low irradiated area)
- Gamma profile width is in the range  $300 \mu m - 5 \text{ mm}$

$$\frac{\delta\xi}{\xi} \approx \sqrt{2 \cdot 10^{-5} + \dots}$$

To determine laser intensity with **resolution of 5  $\mu m$**

- **High dynamic range** very important for gamma profile





# LUXE. Sapphire relevance in this scenario

- Artificial sapphire is a wide band-gap insulator which gained some interest as active material in radiation detector in harsh environments.
- It is industrially produced in large amount at a low **cost/** (1 €/cm<sup>2</sup> vs pCVD 3 k€/cm<sup>2</sup> ) and variety of custom shapes.
- Excellent mechanical and electrical properties.
- Extremely-low leakage current (< 10 pA) at room temperature, even after several MGy of irradiation -> it is practically **noiseless**.
- Superior **radiation hardness**.
- Low collection efficiency (<10%) but **suitable for detection of fluxes** of particles simultaneously hitting detector.

Typical CCE values in range from 1 ÷ 15% (for field 1-10 V/um).

## Material properties

density [g/cm<sup>3</sup>]

bandgap [eV]

dielectric constant

dielectric strength [MV/cm]

resistivity [Ohm cm] at 20° C

electron mobility [cm<sup>2</sup>/(V s)] at 20° C

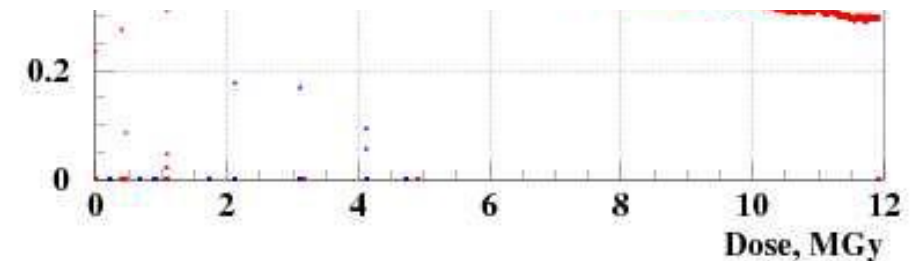
MIP eh created [eh/μm]

i.e. as BHM at FLASH

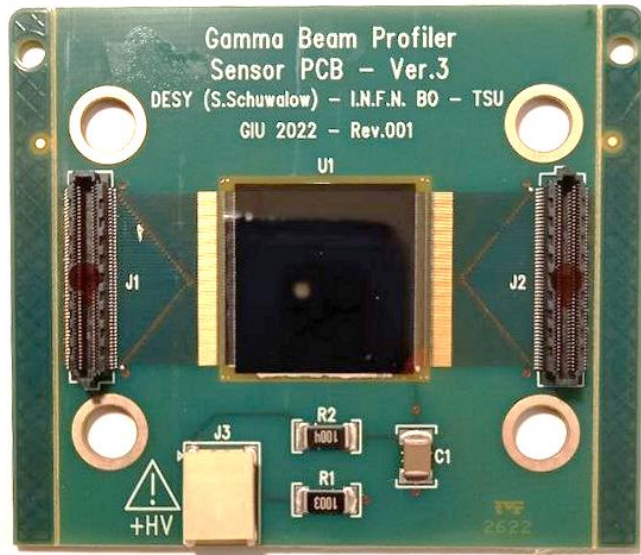


Figure 1: View of the BHM from the dump. The BHM sensors are inside the caps. Four loops of the magnetic-mean energy to create an coupled BPM are right in front of the BHM sensors.

density [g/cm <sup>3</sup> ]	9.3-11.5	5.7	11.7
bandgap [eV]	0.4	1.0	0.3
dielectric constant	1.0E+16	1.0E+16	1.0E+05
dielectric strength [MV/cm]	600	2800	460
resistivity [Ohm cm] at 20° C	22	36	73
electron mobility [cm <sup>2</sup> /(V s)] at 20° C			
MIP eh created [eh/μm]			



# GP and the role of simulations



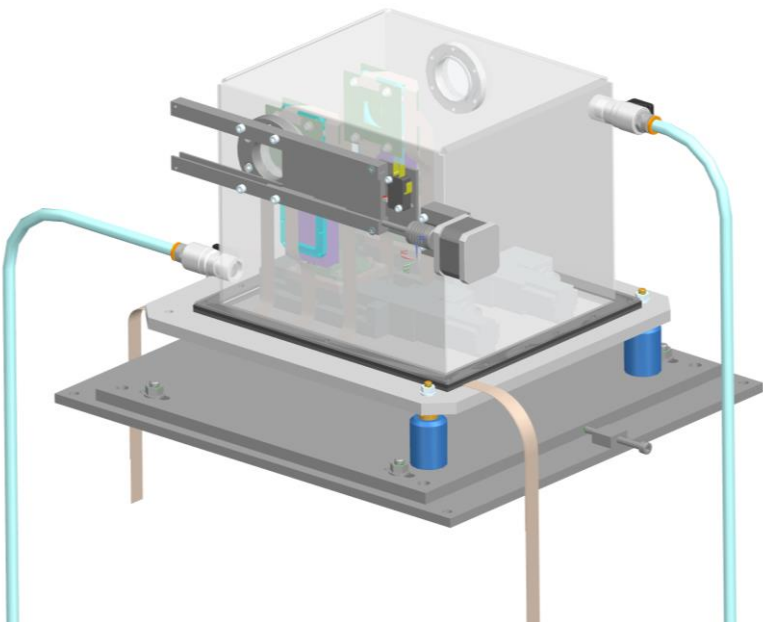
## The Gamma Profiler

Detector requirements are met with two orthogonally-oriented **100um-thick 192-strips sapphire** detectors of with **strip-pitch 100um**.

## The importance of the simulations

- Harsh environment -> dosimetry constrains
- Relatively new material -> lack of characterization
  
- Design optimization
  - Detector geometry
  - Front-end electronics
- Detector-dependent modelling
  - Extract sapphire characteristics from test-beams
  - Estimate systematic uncertainties
  - Develop improved beam-reconstruction algorithm

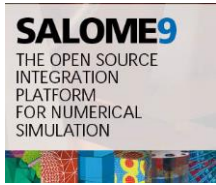
**Allpix-squared is a fundamental tool for sapphire.**





# Allpix-squared for sapphire

A full open-source approach based on Salome, Elmer, Paraview is developed to simulate sapphire strip detector with Allpix-squared



1. Parametric geometry
2. Meshing



3. Finite-element Electrostatic/Ramo field calculation



4. Fields interpolation and resampling over uniform structured grid
5. Export to CSV



mesh\_converter  
+CSVParser

6. Import CSV (single or multiple observables)
7. Convert to APF



8. Ad-hoc sapphire implementation
9. Simulate

## Features

- Parametric design is excellent for detector design optimization (i.e. with ML alg.)
- Advanced meshing alg.s
- User has complete control on solver settings.
- MT by default.
- Different simulation models available (i.e. one can simulate thermal stresses for free)
- Powerful visualization tools
- Advanced interpolation alg.s
- Data filtering (i.e. rejection of odd regions)
- Resampling over different meshes/datasets
- Conversion of CSV/ROOT file to Allpix Proprietary Format (APF)
- MeshMap coordinate offset and scaling
- Automatic Ramo potential renormalization feature

# SALOME - Parametric geometry

The screenshot displays the SALOME software interface. At the top, there is a menu bar with 'File', 'Edit', 'View', 'Tools', 'Window', and 'Help'. Below the menu bar is a toolbar with various icons. On the left side, there is an 'Object Browser' panel with a 'Name' column. The main central area is a large, empty workspace. On the right side, there is a 'Help panel' with the following content:

- Help panel
- Welcome to SALOME
- Getting started
  - New
    - Create a new document
  - Open
    - Open an existing document
  - Video Tutorials
    - Visit YouTube channel with some videos
- Available modules
  - Shaper
    - Geometry
      - Create, import, repair CAD models
    - Mesh
      - Generate mesh from CAD model or import mesh
  - ParaVIS
  - YACS
  - JobManager
  - Eficas
  - ADAO
  - Fields
    - Simplified interface to visualise and manipulate fields
  - HexaBlock
  - PyHello
  - Hello
  - Homard
  - SOLVERLAB
  - Persalys

In the center of the workspace, there is a text box that reads: "Parametric implementation of the geometry is done with the Shaper module". A blue arrow points from this text box to the 'Shaper' module in the 'Available modules' list on the right.

At the bottom left, there is a 'Python Console' panel with the prompt '>>>'.

# SALOME - Parametric geometry

File Edit View Part Sketch Construction Build Primitives Features Inspection Macros Tools Window Help

Shaper

Object browser  
Part set

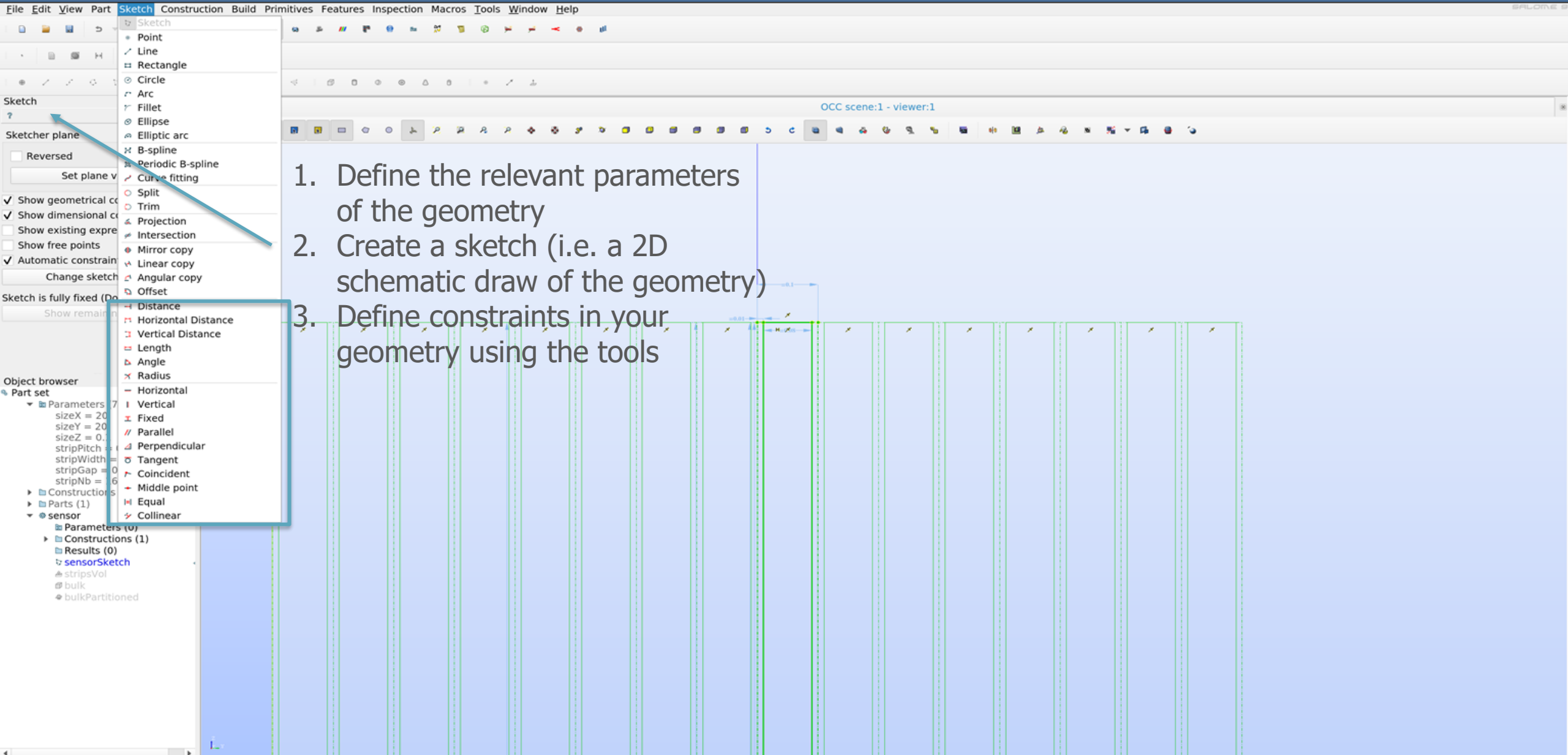
- Parameters (7)
  - sizeX = 20
  - sizeY = 20
  - sizeZ = 0.1
  - stripPitch = 0.1
  - stripWidth = 0.08
  - stripGap = 0.02
  - stripNb = 16
- Constructions (7)
- Parts (1)
- sensor

OCC scene:1 - viewer:1

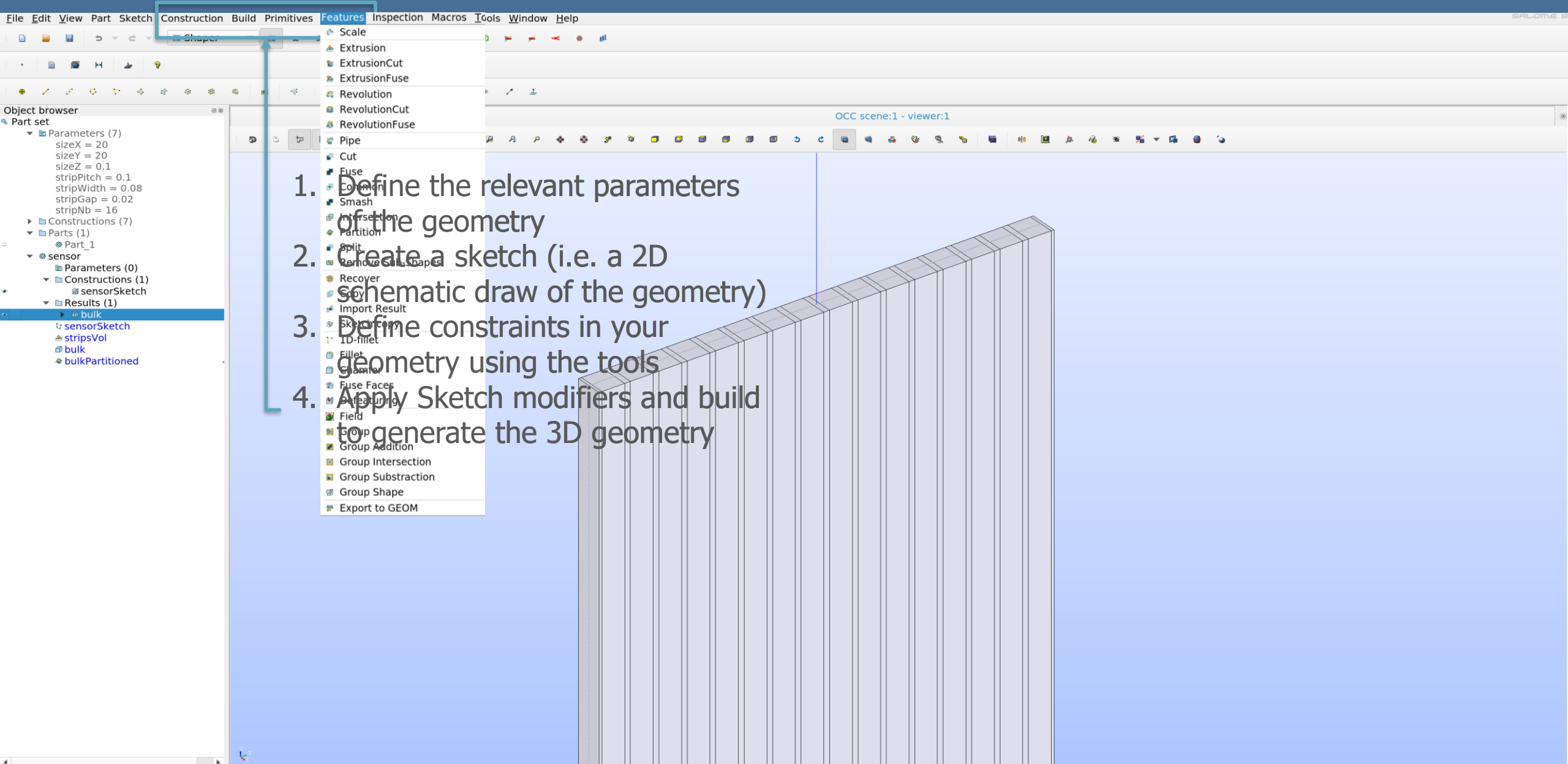
1. Define the relevant parameters of the geometry

Python Console  
>>>

# SALOME - Parametric geometry



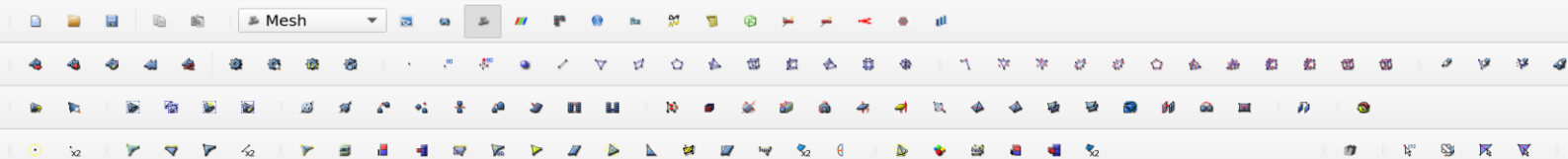
# SALOME - Parametric geometry



1. Define the relevant parameters of the geometry
2. Create a sketch (i.e. a 2D schematic draw of the geometry)
3. Define constraints in your geometry using the tools
4. Apply Sketch modifiers and build to generate the 3D geometry

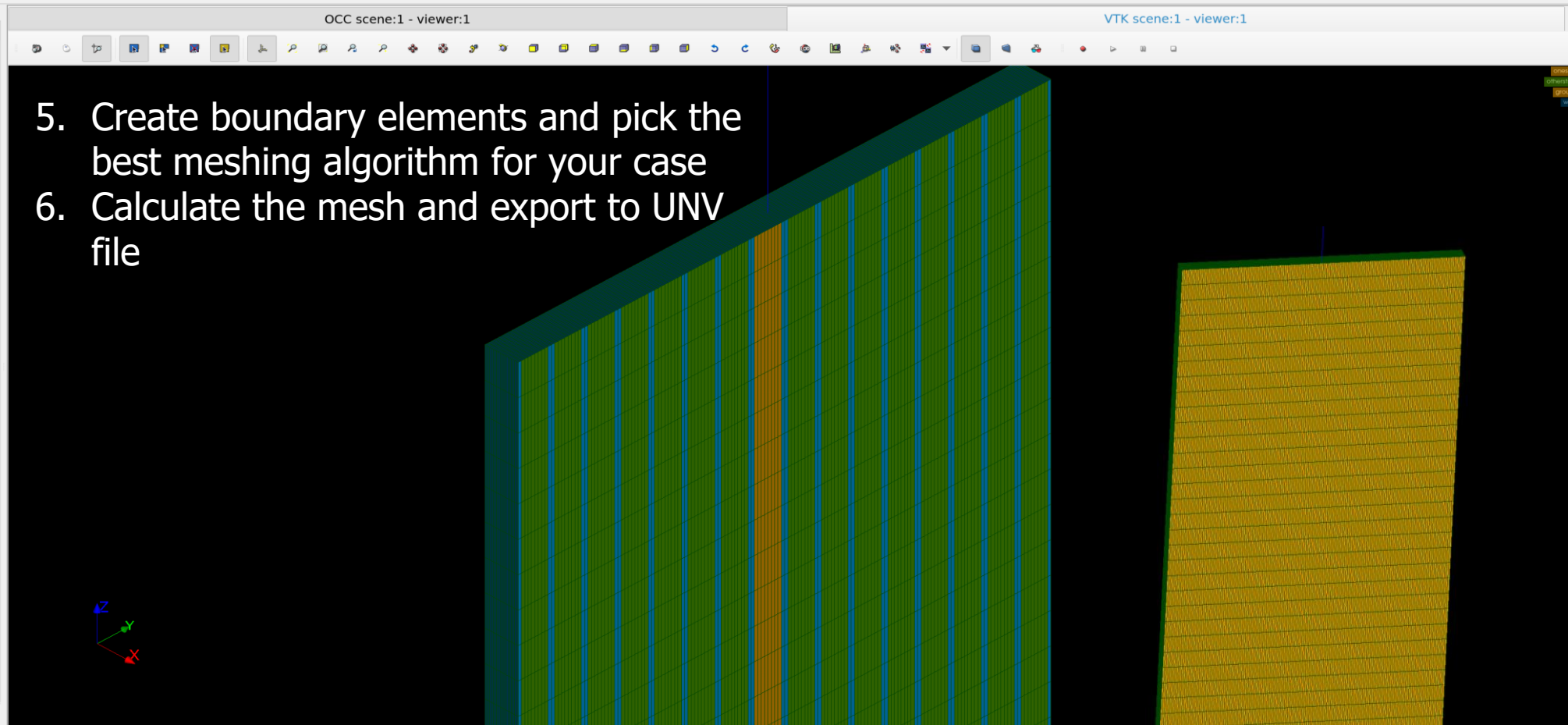
# SALOME - Meshing

File Edit View Mesh Controls Modification Adaptation Measurements Tools Window Help



Object Browser

- Name
- Shaper
- ShaperResults
- Geometry
- Mesh
  - Hypotheses
  - Algorithms
  - sensor
    - \* sensor
    - Applied hypotheses
      - \* sensor
      - Applied algorithms
        - \* Cartesian\_3D
  - Groups of Faces
    - onestrip
    - otherstrips
    - ground
    - walls



5. Create boundary elements and pick the best meshing algorithm for your case
6. Calculate the mesh and export to UNV file

Help panel

Welcome to Mesh

Create mesh

- Choose algorithms
- Define hypotheses
- Compute
- Add refinements:
  - via local sizes with some hypotheses
  - via sub-meshes

Import mesh

Available formats:

- UNV
- MED
- STL
- CGNS
- GMF

Check mesh quality

Display mesh

Display some quality criteria:

- area
- volume
- aspect ration
- ...

Add clipping planes

Object Browser Notebook  
Python Console  
>>>



# ELMER – Electrostatic / Ramo field solver

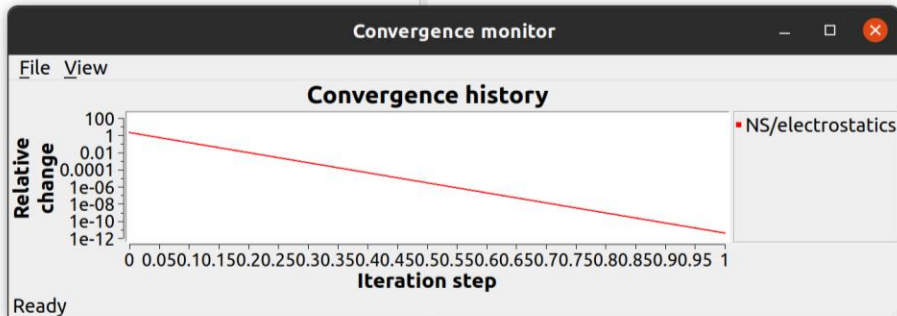
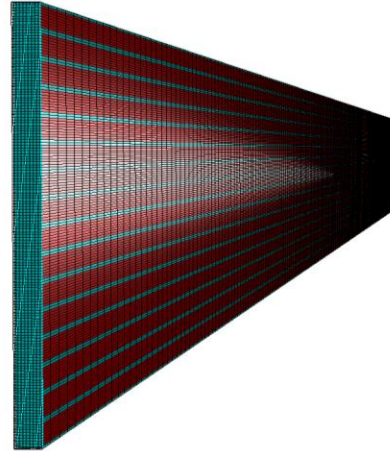
ElmerGUI - /media/sf\_shared\_folder/sensor192

File Mesh Model View Sif Run Help

Object	Value
Geometry	
Input file	sensor.unv
Body	
Boundary	
Boundary 1	
Boundary 2	800V
Boundary 3	800V
Boundary 4	ground
Boundary 5	
Model	
Equation	[Add...]
electrostatic	
Material	[Add...]
sapphire	
Body force	[Add...]
Initial condition	[Add...]
Boundary condition	[Add...]
ground	
800V	

7. Import the UNV.
8. Set the electrostatic solver.
9. Assign boundary conditions and compute.

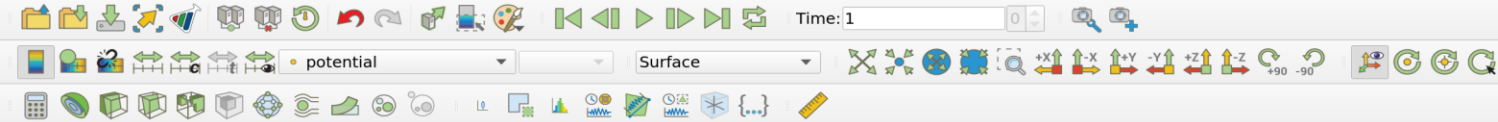
Fields are stored with  
**VTK Unstructured Grid Files**



```
Solver log
File Edit Preference
StatElecSolve:
StatElecSolve: Electrostatic iteration: 2
StatElecSolve: Starting Assembly...
StatElecSolve: Assembly: 34 % done
StatElecSolve: Assembly: 69 % done
StatElecSolve: Assembly (s) : 3.0857600000000005
1 0.1446E-10
ComputeChange: NS (ITER=2) (NRM,RELC): ( 462.83966 0.40387546E-11 ):: electrostatics
StatElecSolve: Solve (s) : 0.297309000000000027
StatElecSolve: Tot. Electric Energy : 8.9746599119634625E-003
StatElecSolve: Capacitance : 2.8045812224885820E-008
StatElecSolve: Result Norm : 462.83966015977251
StatElecSolve: Relative Change : 4.0387546490476096E-012
StatElecSolve:
ComputeChange: SS (ITER=1) (NRM,RELC): ( 462.83966 2.0000000 ):: electrostatics
ResultOutputSolver: -----
ResultOutputSolver: Saving with prefix: case
ResultOutputSolver: Creating list for saving - if not present
CreateListForSaving: Field Variables for Saving
ResultOutputSolver: Saving in unstructured VTK XML (.vtu) format
VtuOutputSolver: Saving results in VTK XML format with prefix: case
VtuOutputSolver: Saving number of partitions: 4
ResultOutputSolver: -----
ElmerSolver: *** Elmer Solver: ALL DONE ***
ElmerSolver: The end
SOLVER TOTAL TIME(CPU,REAL): 16.03 19.17
ELMER SOLVER FINISHED AT: 2023/05/21 14:49:04
```

# Example. E-field for 800V/100um

File Edit View Sources Filters Extractors Tools Catalyst Macros Help



Pipeline Browser

- builtin:
  - FastUniformGrid1
  - Transform1
  - ResampleWithDataset1
  - case\_t0001.pvtu
    - ResampleWithDataset1
    - Slice1
    - StreamTracer1
    - Slice2
  - ResampleWithDataset1
  - CSV1
  - PlotOverLine1

Properties Information

Properties

Apply Reset Delete ?

Search ... (use Esc to clear text)

**Properties (case\_t0001.pvtu)**

- Cell/Point Array Status
- GeometryIds
- electric energy density
- electric field
- potential

Time Array None

**Display (UnstructuredGridRepresentation)**

Representation Surface

**Coloring**

potential

Scalar Coloring

- Map Scalars
- Interpolate Scalars Before Mapping

**Styling**

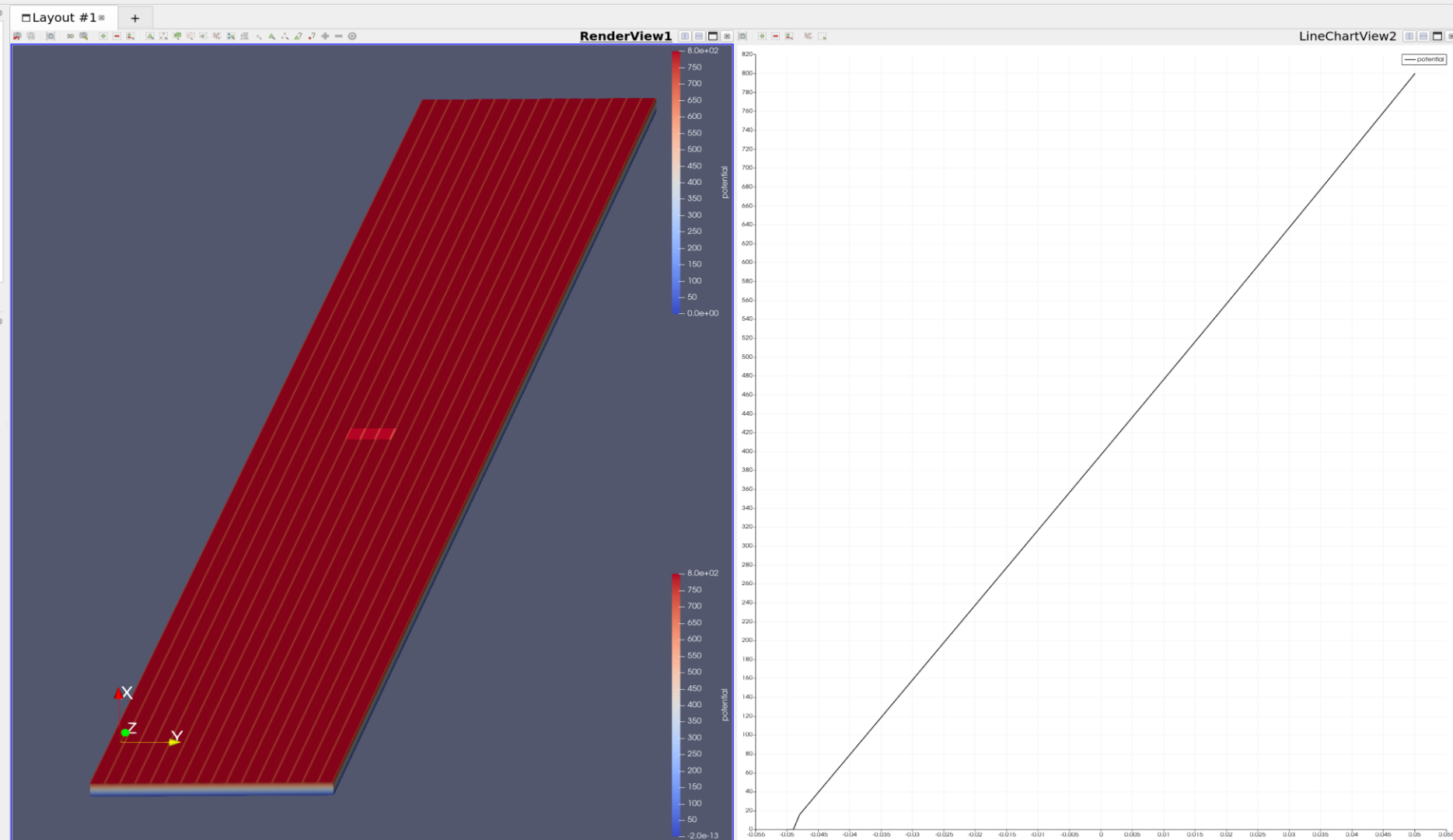
Opacity 1

Point Size 2

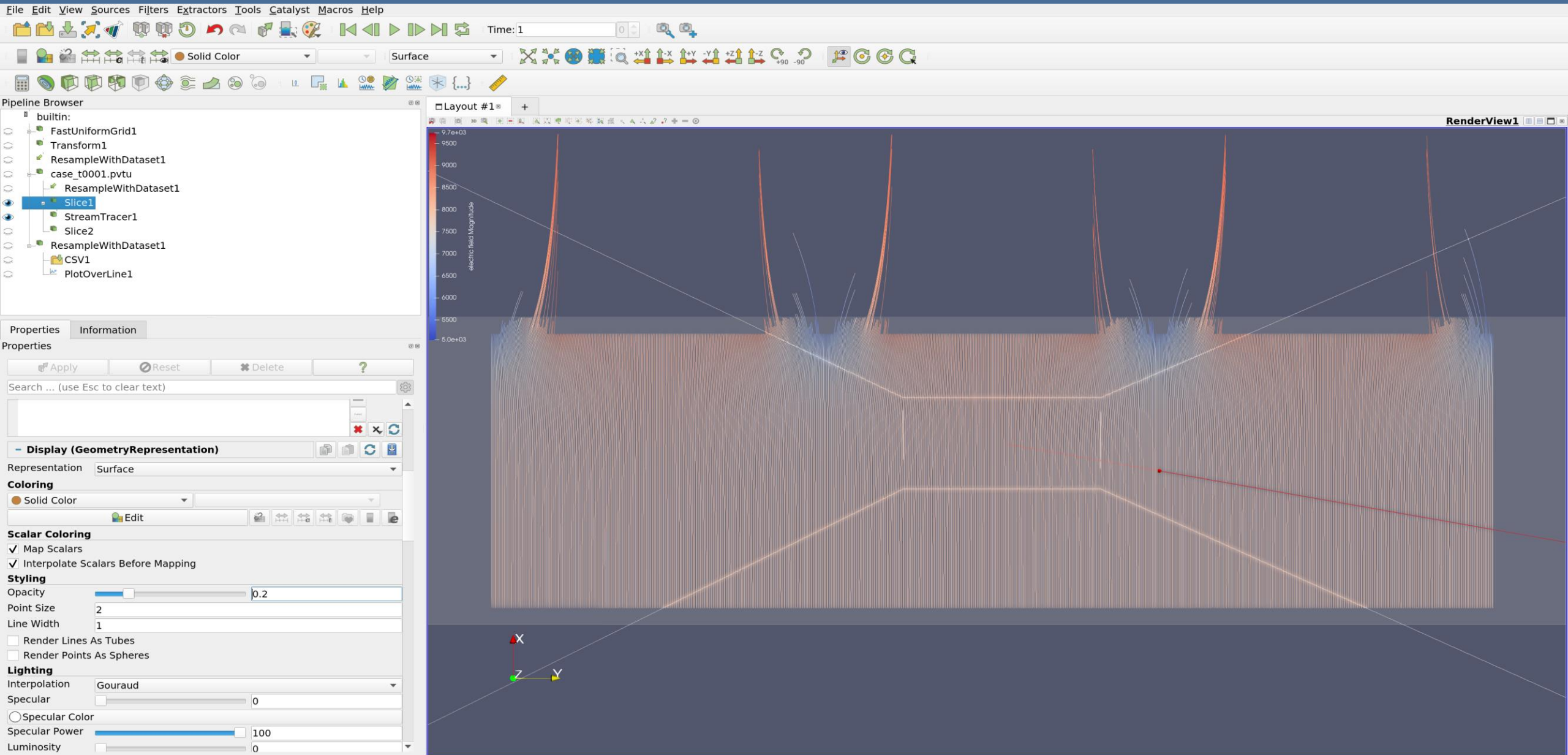
Line Width 1

- Render Lines As Tubes
- Render Points As Spheres

**Lighting**



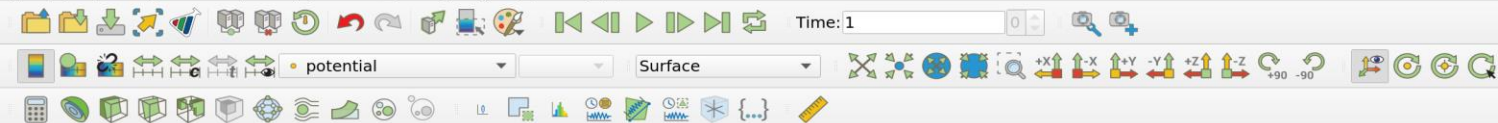
# Example. E-field for 800V/100um





# Example. E-field for 800V/100um

File Edit View Sources Filters Extractors Tools Catalyst Macros Help



Pipeline Browser

- builtin:
  - FastUniformGrid1
  - Transform1
  - ResampleWithDataset1
    - case\_t0001.pvtu
      - ResampleWithDataset1
      - Slice1
      - StreamTracer1
      - Slice2
    - ResampleWithDataset1
  - CSV1
  - PlotOverLine1

Properties Information

Properties

Apply Reset Delete ?

Search ... (use Esc to clear text)

**Properties (PlotOverLine1)**

**Line Parameters**

Length: 0.1

Show Line

Point1	-0.05	0
Point2	0.05	0

**Note: Use 'P' to place alternating points on mesh or 'Ctrl+P' to snap to the closest mesh point. Use '1'/Ctrl+1' for point 1 and '2'/Ctrl+2' for point 2.**

X Axis	Y Axis	Z Axis

Sampling Pattern **Sample Uniformly**

Resolution 1000

Pass Partial Arrays

Pass Cell Arrays

Pass Point Arrays

Pass Field Arrays

Compute Tolerance

**Display (GeometryRepresentation)**

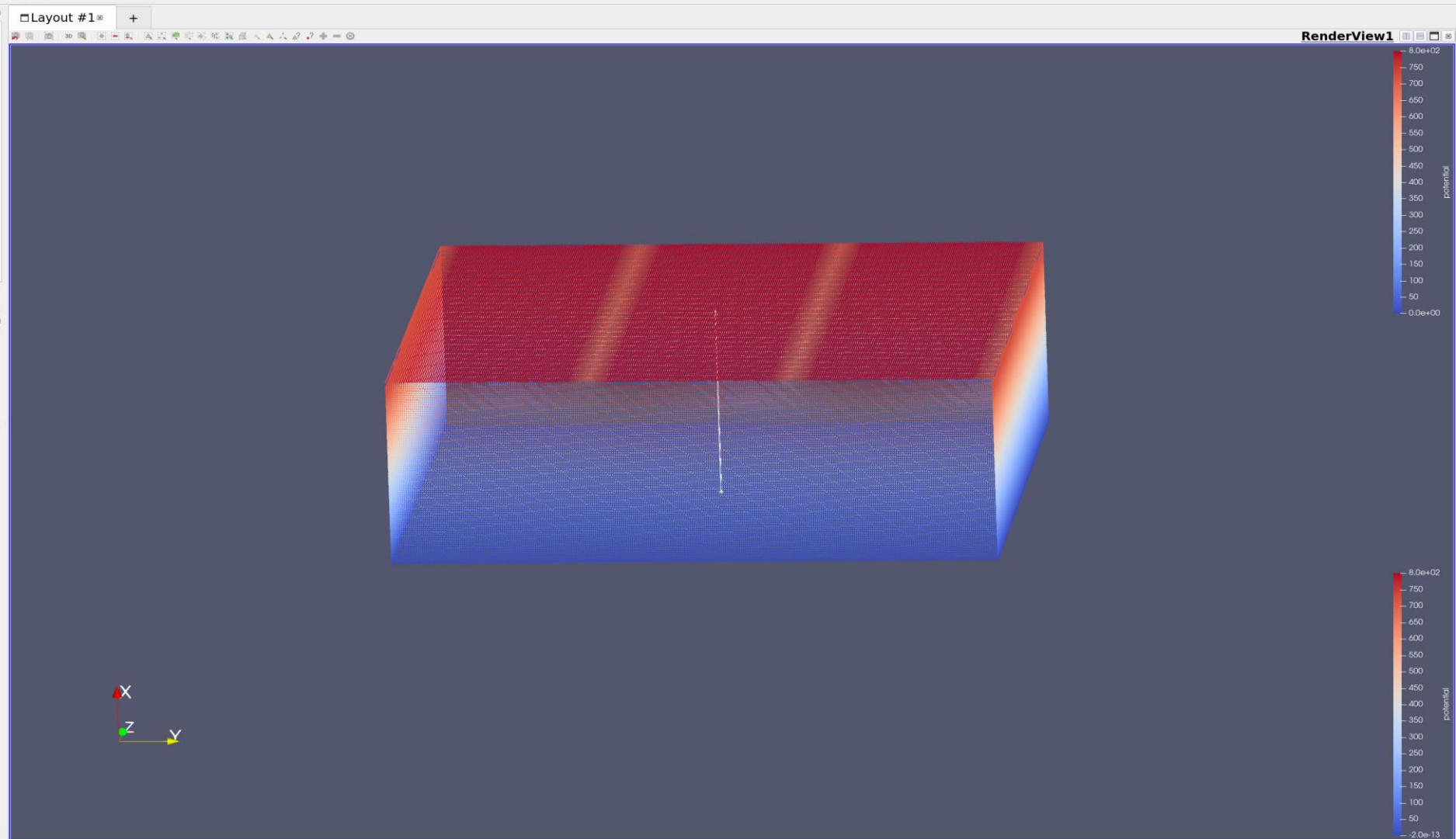
Representation Surface

**Coloring**

potential

Edit

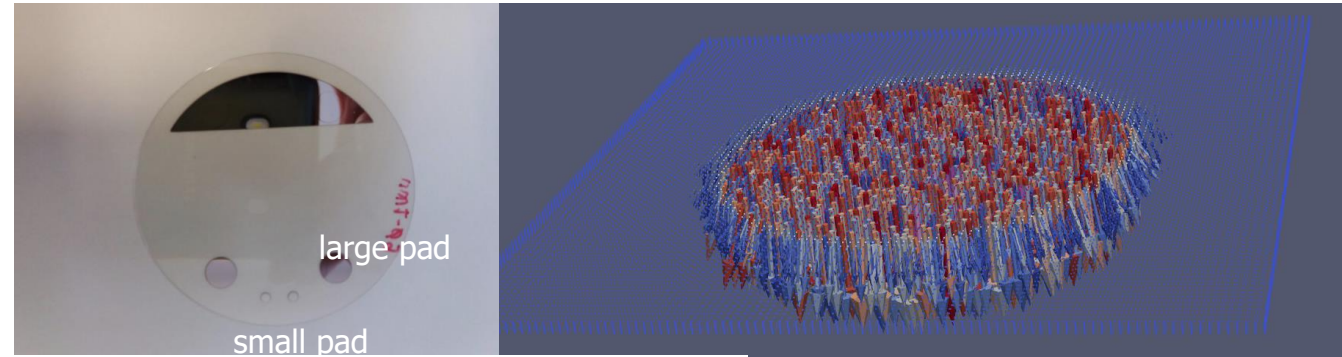
**Scalar Coloring**



# PARAVIEW - Field interpolation

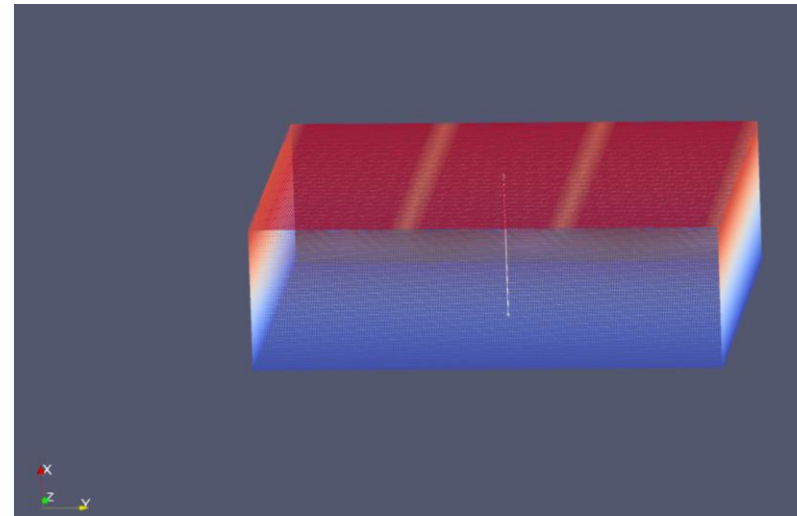
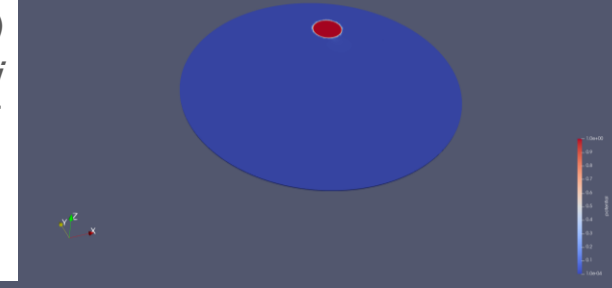
## Preparation for APF conversion

- Field data is interpolated with a gaussian kernel and resampled to a regular mesh grid with higher spatial-resolution.
- If fringe effects are relevant, fields over the entire sensor volume are exported.
- Otherwise, a 3x3 pixel volume is used.
- Data for the Electrostatic and Ramo fields is exported to CSV file.



### Sapphire pads (May 22)

Simulation for test beam at *INFN-Frascati*  
Two sapphire pads ( $d=1.6, 5.5$  mm) of  
thickness 110um, 150um



### Sapphire strip detector LUXE

Simulation for test beam at *CERN*  
of the LUXE 192-strip prototype

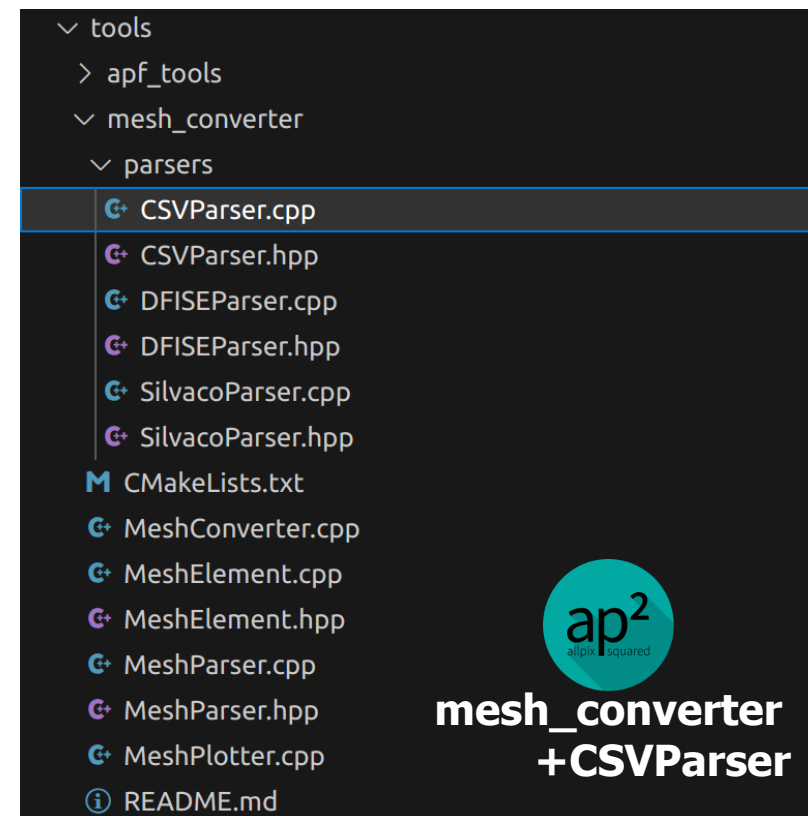


# ALLPIX – From CSV to APF

The Allpix-squared mesh\_converter tool is modified with the addition of a CSV parser that converts the fields from Paraview to Allpix-squared File Format (APF).

## Features

- Convert field from CSV to APF format, with or without mesh interpolation.
- Possibility to set ref. frame for mesh coordinates.
- Multiple observables (i.e. E-field, Ramo, Doping...) in the same file
- Renormalization of Ramo field (in range [0,1])



### #### Parameters for the CSV parser (only)

- \* ``coodiante_origin``: Reference position from which the coordinate are expressed. Defaults to ``coodiante_origin = 0 0 0``.
- \* ``coordinate_units``: Units in which the coordinate points in the CSV file are expressed. Required parameter (i.e. like ``mm``).
- \* ``coordinate_scale``: Scaling vector to rescale coordinates. Defaults to ``coordinate_scale = 1 1 1``.
- \* ``both_phi_E``: Specify whether the file contains both the electric field and the weighting field. Default to ``false``. If true is used, the header should be in the form of ``x,y,z,Ex,Ey,Ez,phi``.



# ALLPIX - Ad-hoc implementation for sapphire

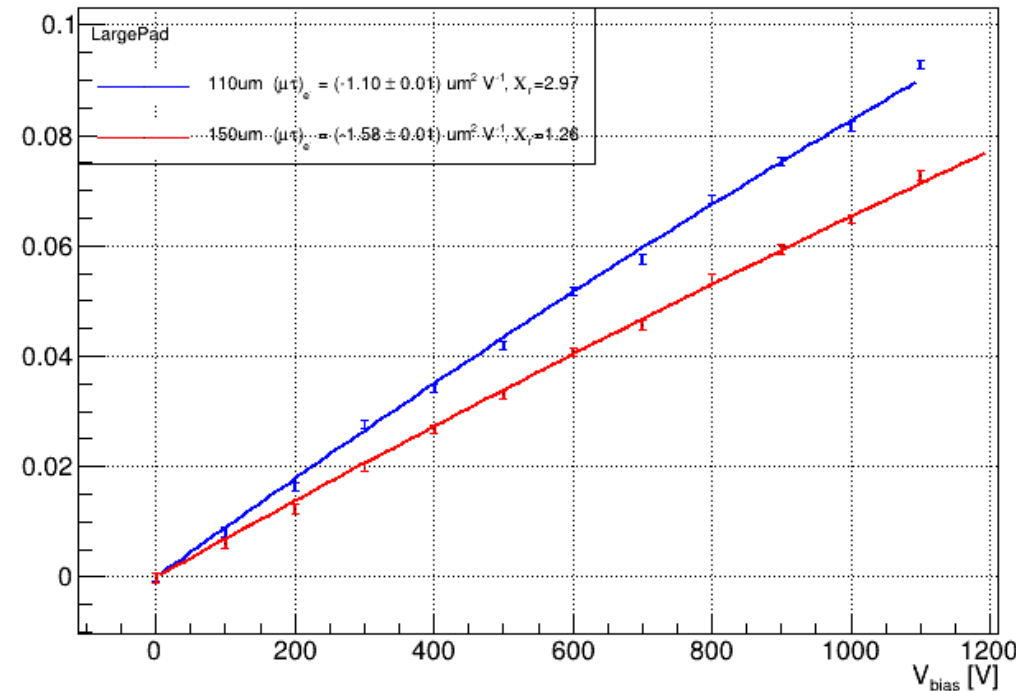
## Ad-hoc implementation for sapphire requires

- Add G4\_ALUMINIUM\_OXIDE in *GeometryBuilderGeant4*
- Add SAPPHIRE in physics/MaterialProperties with 27eV average pair-creation energy and 0.382 Fano factor (educated guess from diamond)
- Chg. Transport dominated by contribution from electrons.
- Transient Propagation with 'custom' model with electron/hole mobilities of

$$\mu_e \sim 600 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$$

$$\mu_e \sim 30 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1} \quad \text{CCE}$$

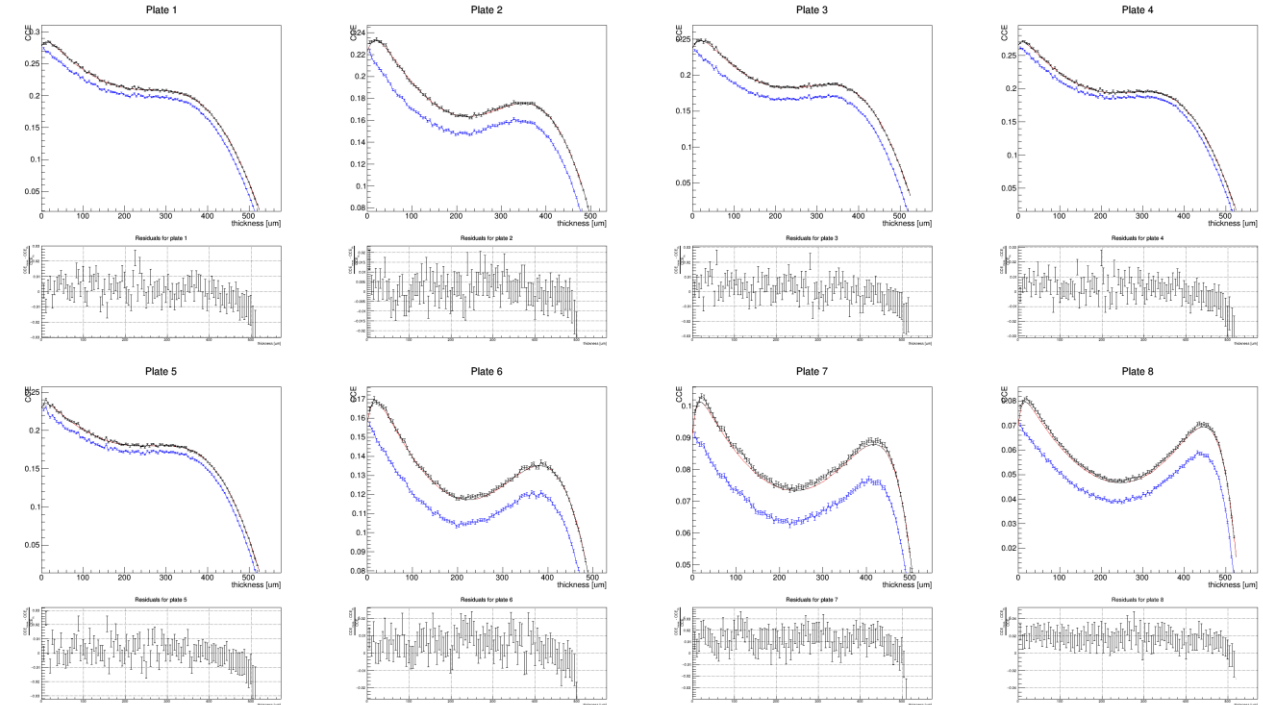
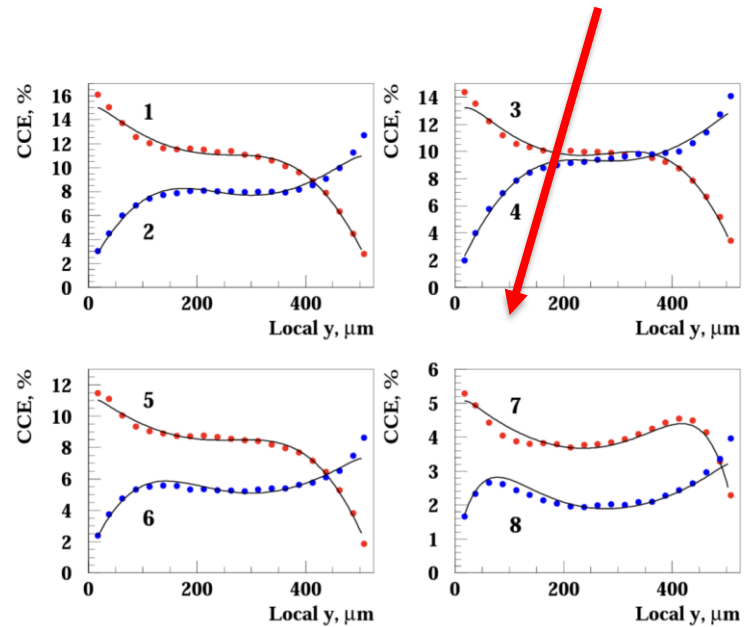
- Dominant trap-release mechanism is recombination
- Low charge collection efficiency implies short distance of collection: linear regime  $CCE(V) \propto V$
- Linear response to beam charge up to  $61 \text{ ke} (200\text{ns})^{-1}$



## Conclusions and outlook

# Validation of Allpix-squared for sapphire with the literature

- The ad-hoc implementation for sapphire in allpix-squared has been validated by comparing simulation results with experimental data from a test-beam available in the literature



good agreement (<4%) for simulation and data

Figure 7: The CCE measured as a function of the local  $y$  coordinate inside a plate in slices of  $25 \mu\text{m}$  for all plates of the sapphire stack. Blue dots are for the electric field in the direction of  $y$  and red dots for the opposite field direction. The lines are the result of a fit including both electron and hole drift. The fit parameters are given in Table 3.

# Case study. Fringe effect for sapphire pad sensor

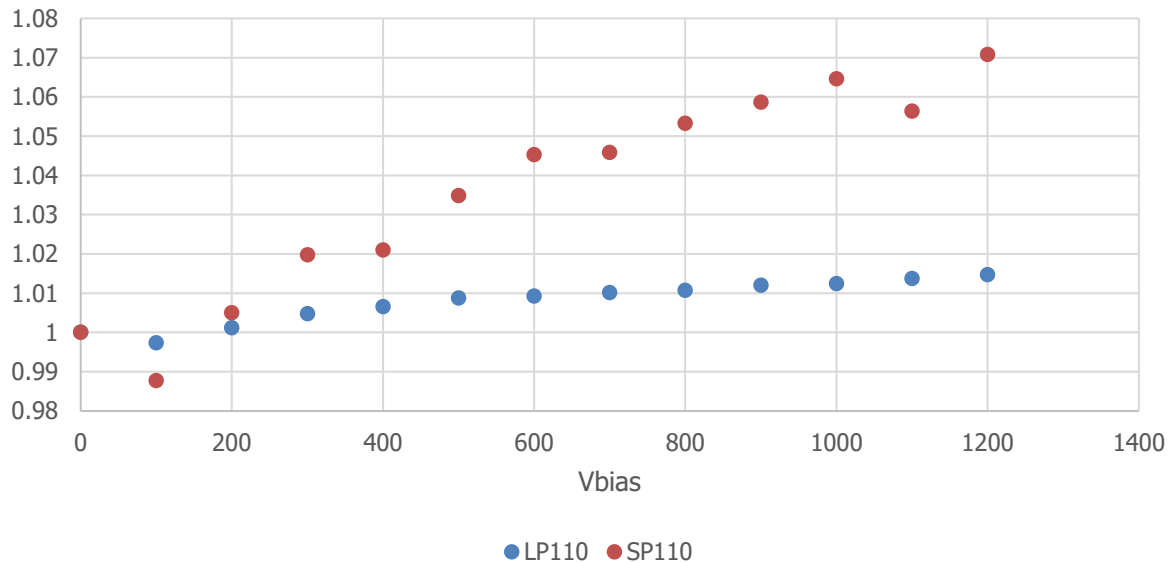


What is the difference in the detector's collected charge if

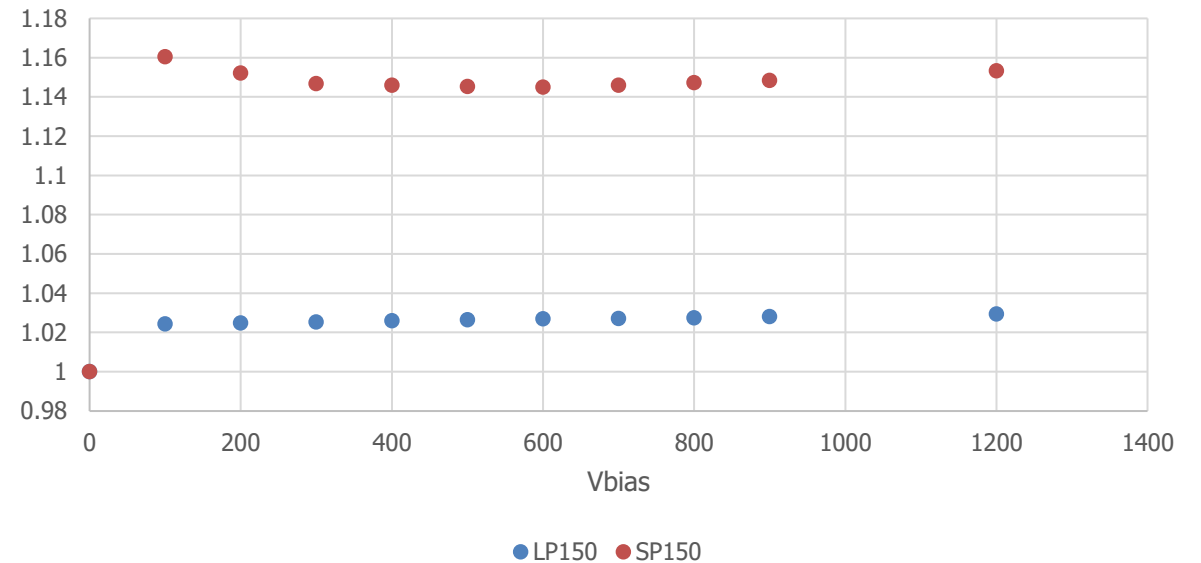
1. a uniform field along z-axis  $E=V/d$  is applied in the pad disk, or
2. the realistic simulated field (with fringe effects)

is used?

$Q_{ind|fringe} / Q_{ind|uni.}$   
(upstream 110um - typical BTF beam par.s)



$Q_{ind|fringe} / Q_{ind|uni.}$   
(downstream 150um - typical BTF beam par.s)



- Small effect in the large pad (beam spot within most of the pad diameter)
- Uniform effect for the 150um while linear increase of the fringe contributions for the 110um
- Overall, negligible effect for LargePad while 8-16% increase of charge collected for the SmallPad

# Allpix-squared for sapphire. Applications so far

## Applications

- TB1-pad - Alpha source. Sapphire pad sensor tested with alpha source.
  - Investigation of charge collection efficiency as a function of the biasing field.
  - Signal formation at the preamplifier stage.
- TB2-pad – Electron beam. Sapphire pad sensor tested with electron beam.
  - Investigation of CCE. Systematic uncertainties in the experiment.
  - Evaluation of the fringe effects contributing to the charge collected.
- TB3-4 – Electron beam. Sapphire 4-strip sensor tested with electron beam at high dose rates.
  - Systematic uncertainties in the CCE as a function of the dose during irradiation.
- TB4-192 – Electron beam. Sapphire 192-strip sensor at high dose
  - Work in progress: investigation of the signal formation with the strip as a transmission line.
- (next) LUXE – Detector performance goals review with the simulation of the front-end chain response.

**Sapphire pads**  
(May 22, INFN-LNF)



**Sapphire 4-strip**  
(Sep. 22, CERN)



**Sapphire 192-strip**  
(Dec. 22, CERN)



# Key points and outlook

## Key points

Open-source parametric simulation of a (sapphire) detector

- Excellent for automated design optimization-algorithms (e.g. ML)
- Full control over field computation resolution and simulation time
- Essential tool for characterizing sapphire properties (e.g. from test beams)
- Fundamental tool to estimate detector-dependent systematic uncertainties
- Mesh\_converter's CSVParser bypass the need for TCAD simulations

## Outlook

- Merge CSVParser to Allpix-squared repository
- Strip-crosstalk from custom module treating the strip as transmission line

**Thank you for your attention!**



**Thank you for your attention!**

**Q&A session**

# Backup

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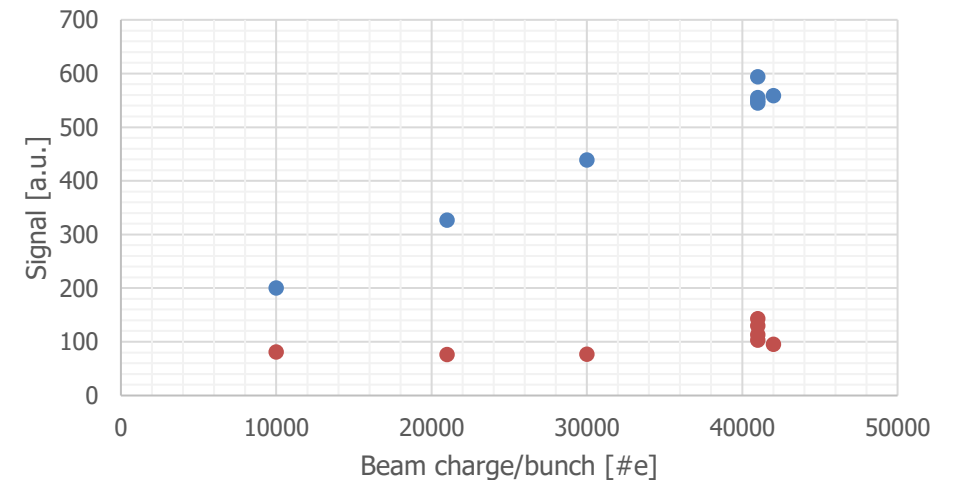
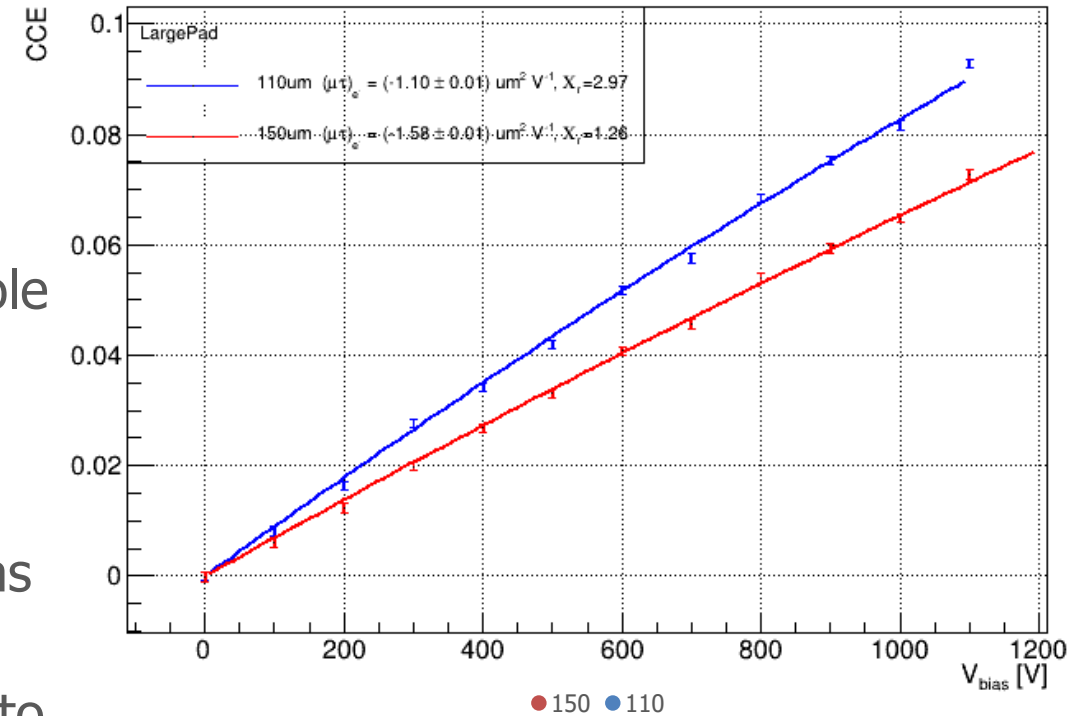
UNIVERSITÀ  
DEGLI STUDI  
DI PADOVA



# Sapphire characteristics

## Sapphire charge transport properties

- Dominant contribution to charge transport from electrons
- Electron mobility ( $\mu_e \sim 600 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$ ) and low hole mobility
- Dominant trap release mechanism is recombination
- Low charge collection efficiency (<15%) imply small collection distance: linear regime of charge collected as function of the bias voltage
- Linear response function with beam charge tested up to 61k e<sup>-</sup>/bunch (at BTF-INFN Frascati)

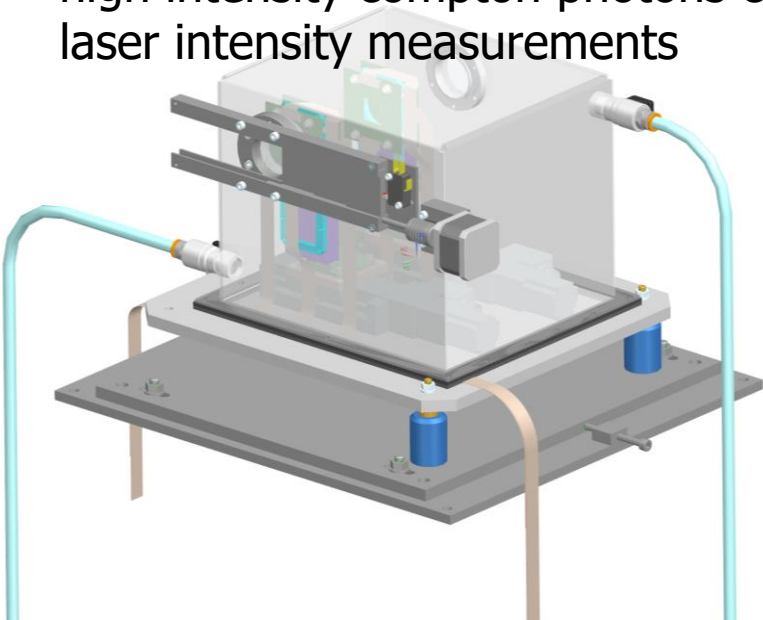


# Sapphire micro-strip detector for high intensity gamma beam monitoring for the LUXE experiment at DESY

## LUXE

is a new experiment at DESY to perform precision measurements of the transition into the non-linear regime of quantum electrodynamics (QED), and to search for new particles beyond the Standard Model coupling to photons, by colliding 16.5GeV electrons (XFEL) with a powerful laser beam (up to 350TW)

**Gamma Beam Profiler (GBP)** is a beam line monitor for high intensity compton photons crucial for shot-by-shot laser intensity measurements



### Keypoints

- radiation-hardness
- 192-strip readout
- low leakage current (<10pA)
- 5um resolution
- high dynamic range

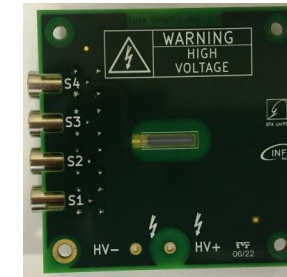
## R&D on sapphire detectors

- Test beams

**Sapphire pads**  
(May 22, INFN-LNF)



**Sapphire 4-strip**  
(Sep. 22, CERN)



**Sapphire 192-strip**  
(Dec. 22, CERN)

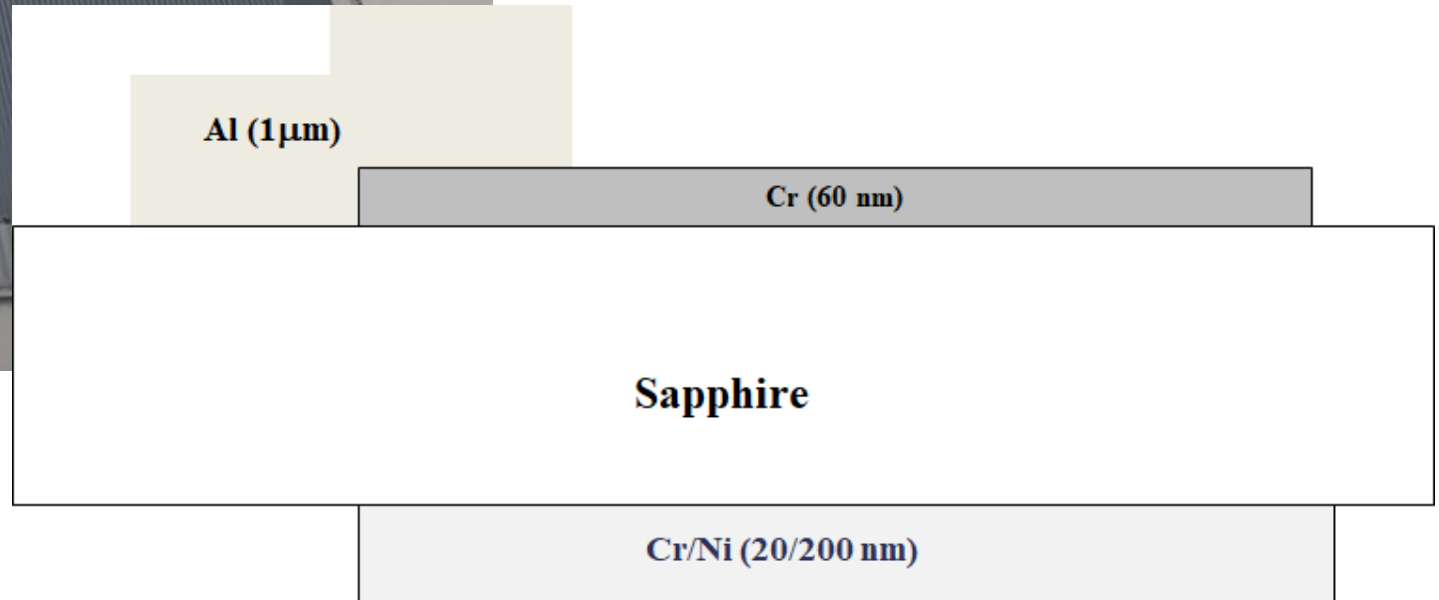
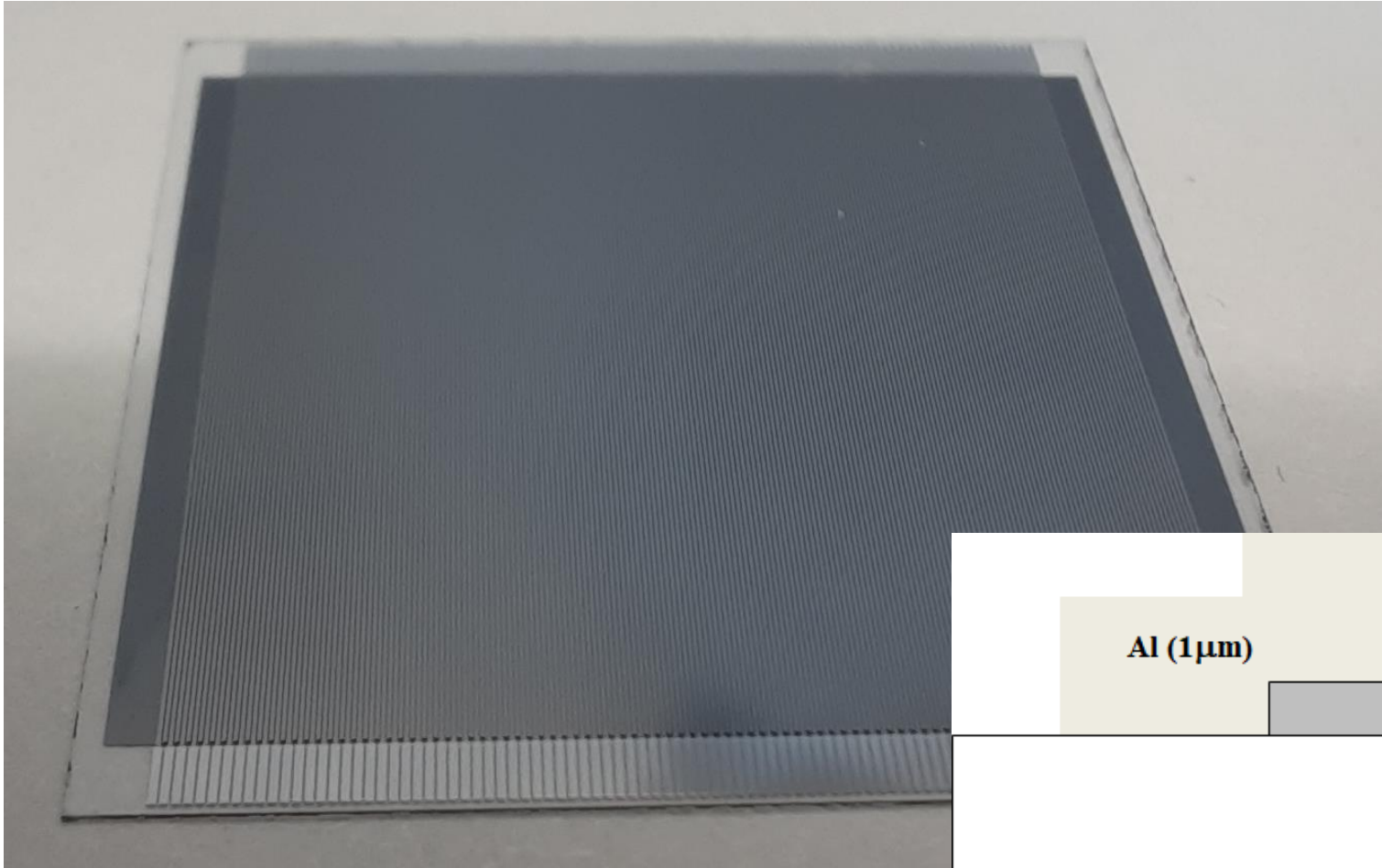


- Simulations

## Open-source sapphire detector simulator



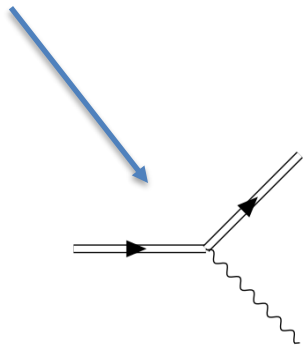
# Metallization



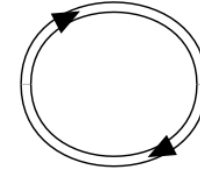
# LUXE *in a nutshell*

## Scientific goals

- Landmark for the first experimental observation of **Sauter-Schwinger pair production** of  $e^+/e^-$  by strong background field
- Study the onset on non-perturbative strong field QED transition in a clean environment, by considering the processes:
  - non-linear Compton

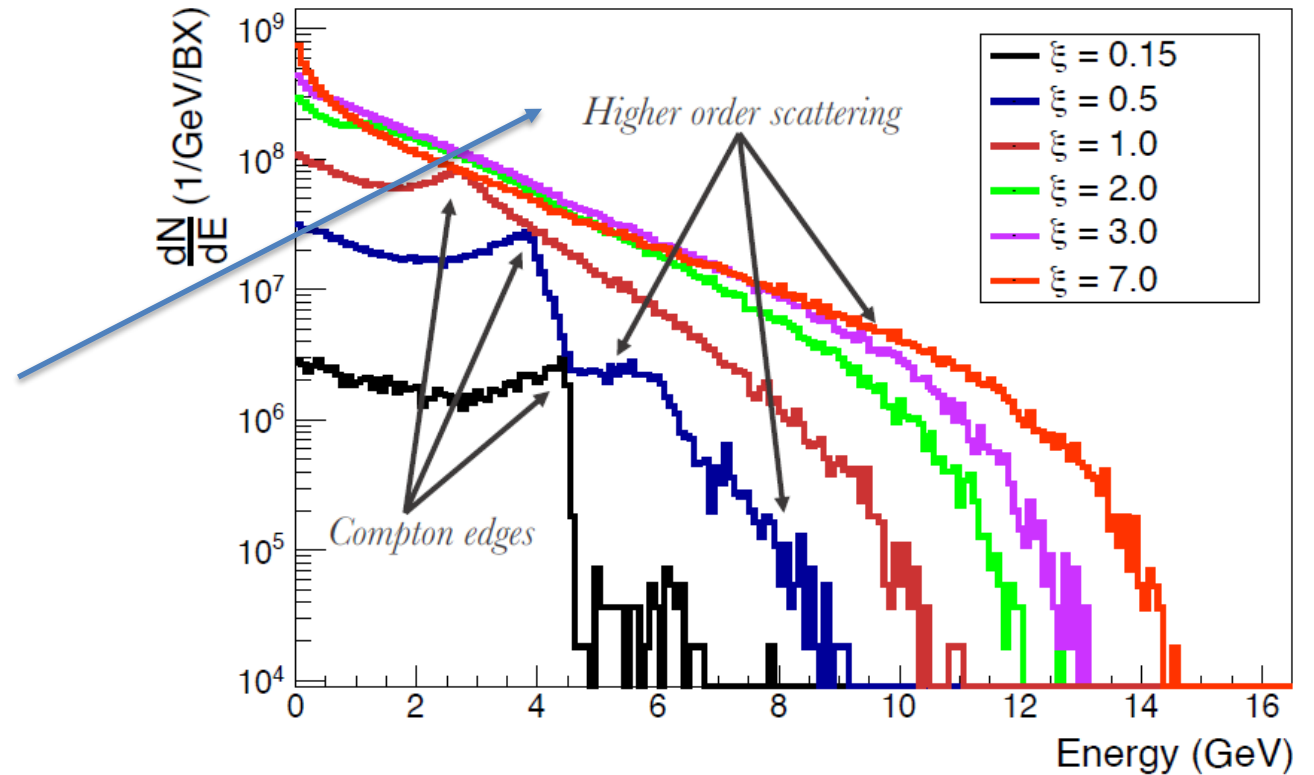


$$\xi = \frac{e}{m} \langle A^2 \rangle$$



$$N_{pairs} = 2VT \frac{e^2 E^2}{(2\pi)^3} \exp\left(-\pi \frac{m^2}{eE}\right)$$

$$E_S \equiv \frac{m^2}{e} \approx 10^{18} \text{ V/m}$$





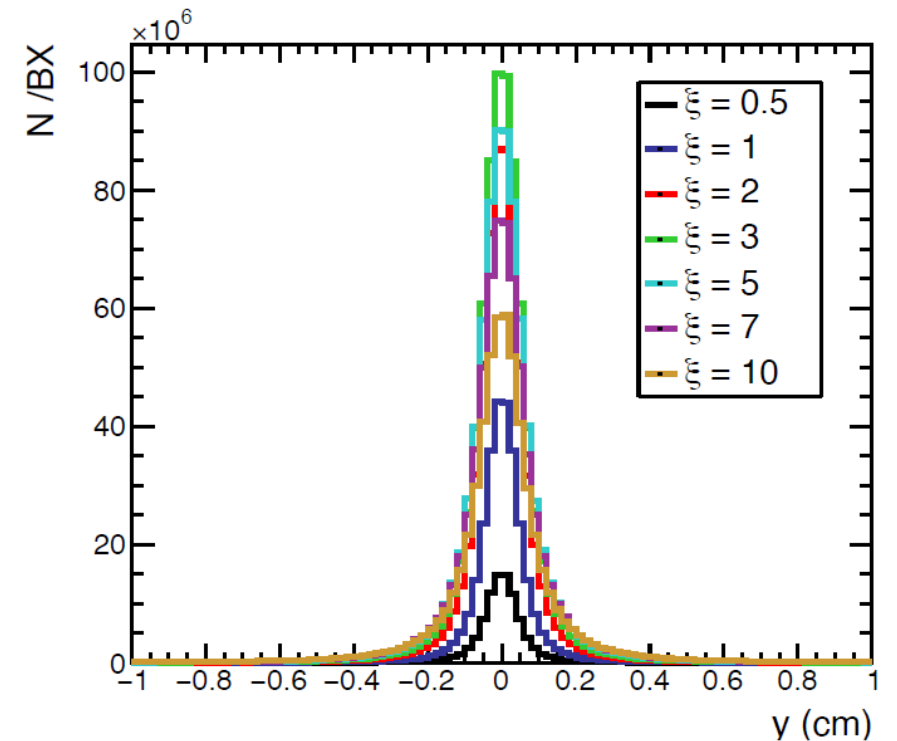
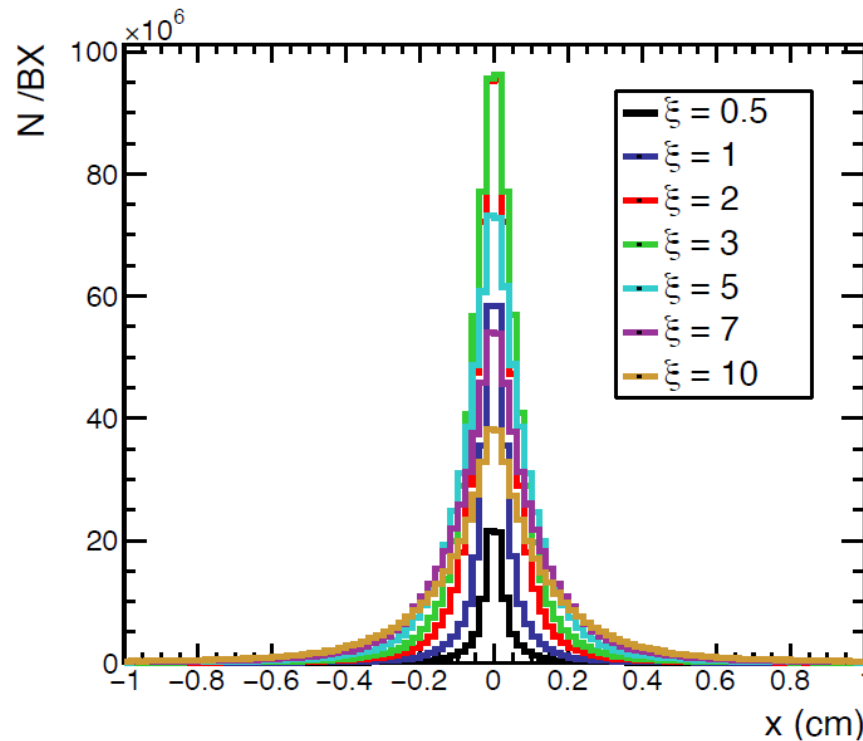
# LUXE. The gamma beam monitor

The angular distribution of Compton photons is strongly dependent on the laser intensity ( $\xi$ ) **locally** experienced by the initial electron during the electron-laser interaction **at the time of emission**.

Photons angular distribution contains valuable information allowing to infer *shot-by-shot* the  $\xi$  value

$$\xi^2 \sim (\sigma_{\parallel}^2 - \sigma_{\perp}^2)$$

| **Spatial distribution of  $\gamma$   
11m downstream the IP**

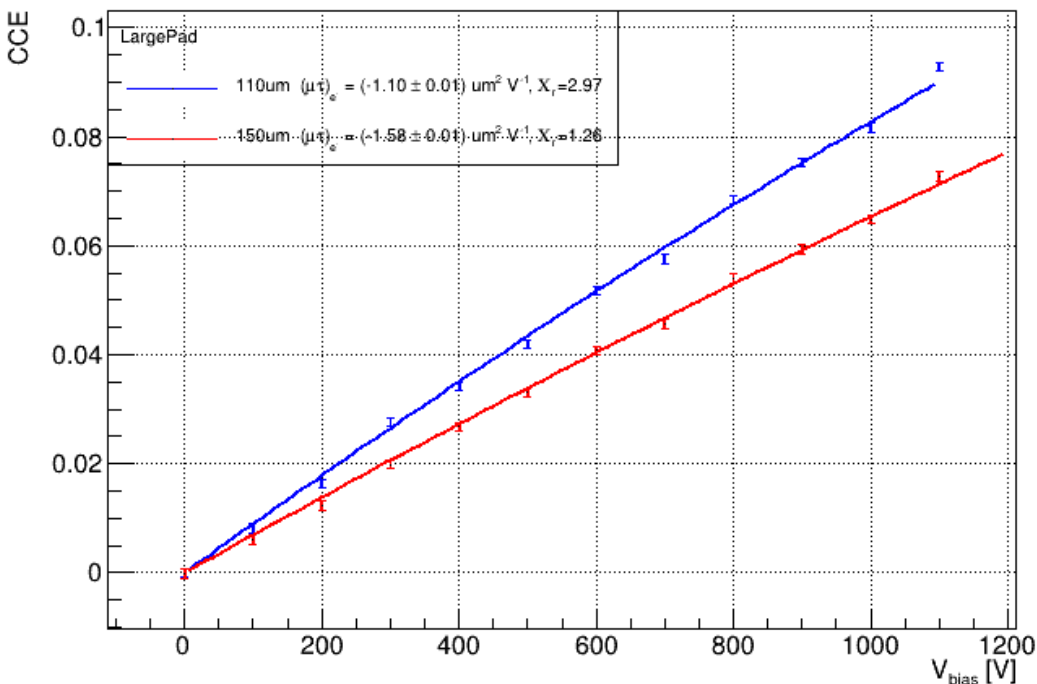


The **Gamma Beam Profiler (GBP)** is envisaged for this task – i.e. beam monitoring the gamma beam.

# Sapphire detection efficiency with MIPs

## What is a MIP?

A *minimum ionizing particle* (MIP) is a particle whose mean energy loss rate through matter is close to the minimum. As a consequence, this implies that the charge deposited in the material is roughly uniform along the material thickness in the direction of the initial ionizing particle.



## Sapphire Charge Collection Efficiency with MIPs

The passage of an ionizing MIP particle through an active material generates a certain amount of *deposited charge*, which for sapphire is of the order of

$$E_{dep}^{MIP} \sim \frac{50 \text{ keV}}{100 \text{ um}}$$

In the literature, the average sapphire pair excitation energy is 27 eV, corresponding to about 22 e/h-pairs per um.

The charge collected at the implants is typically lower, due to recombination of carriers. It is determined by the *charge collection efficiency*

$$CCE(V) \equiv \frac{Q_{collected}(V)}{Q_{deposited}}$$

which in general depends on the external biasing field. Typical CCE values for sapphire range from 1% to 15%, for field values in range 1-10 V/um.

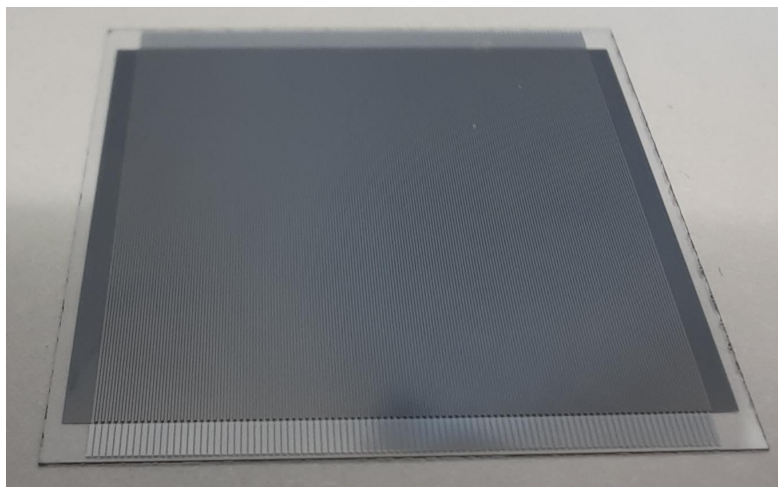
# GBP detection efficiency in LUXE



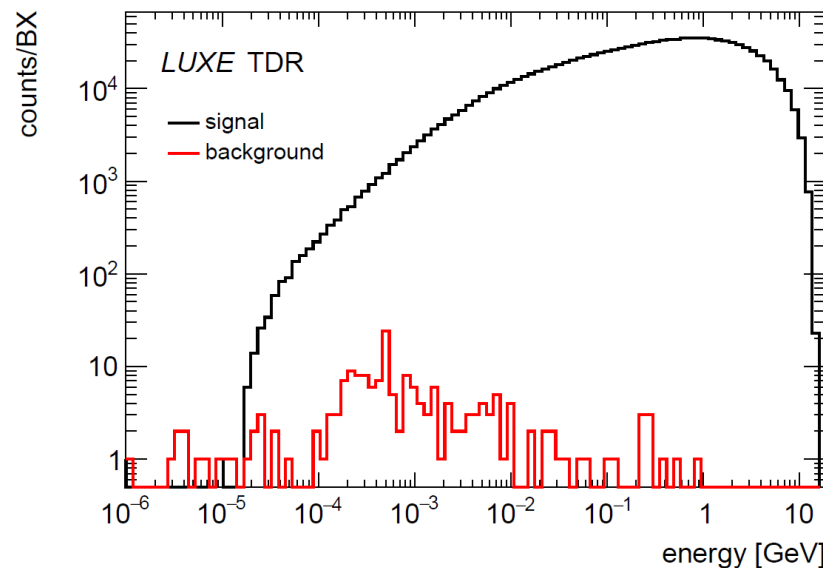
## Interaction mechanism in LUXE: gamma conversion

Typical interaction of the HE Compton's photon beam with sapphire is by means of photon conversion into electron/positron pairs. This occurs with a probability of roughly 1/1000.

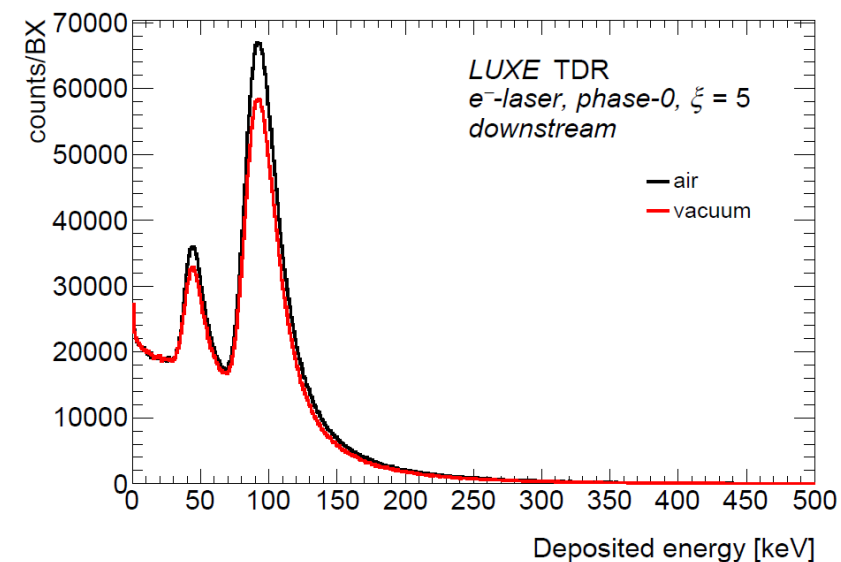
For example, an electron/laser interaction at  $\xi = 5$  generates a typical stream of  $O(10^9)$  high energy photons crossing the GBP. The charge deposited in the 100um-thick sapphire sensor is of the order of  $4.4 \cdot 10^6$  ke.



## | Spectrum of primaries at GBP ( $\xi=5$ )



## | Spectrum of depositions in $Al_2O_3$



# Typical signal at LUXE's GBP

For example, an electron/laser interaction at  $\xi = 5$  generates a typical stream of  $O(10^9)$  high energy photons crossing the GBP. The charge deposited in the 100 $\mu$ m-thick sapphire sensor is of the order of  $4.4 \cdot 10^6$  ke.

From the previous example, the charge collected in the whole sensor is at most  $4.4 \cdot 10^5$  ke  $\simeq$  0.07 pC

If the strip charge is 2%, then the strip charge collected is 1.4 fC

Over a strip capacity of 2pF, this means a signal with peak amplitude at about 2.8 mV

# Luxe physics

# LUXE. Scientific motivation

## LUXE main aims are

- Measure the interaction of real photons with electrons/positrons at field-strengths where the coupling becomes non-perturbative
- Make precision measurements of the transition between perturbative to non-perturbative regime of QED
- Use strong-field QED processes to design a sensitive search for BSM particles coupling to the photons

## What is '*strong field*'?

- QED constants lead to a natural EM field one can build, called the *Schwinger field*

$$\mathcal{E}_{\text{cr}} \equiv \frac{m^2 c^3}{e\hbar} \approx 1.32 \times 10^{18} \text{ V/cm}$$

which is orders of magnitudes above artificially producible EM field.

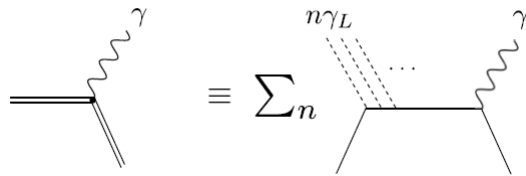
However, in the rest frame of a boosted high-energy probe charge, the EM field strength which it is subjected is boosted by the Lorentz factor  $\gamma$  to  $\mathcal{E}_* = \gamma \mathcal{E} (1 + \cos\theta)$  with  $\theta$  the collision angle (which for LUXE is 17.5 deg)



# LUXE. Scientific Goals

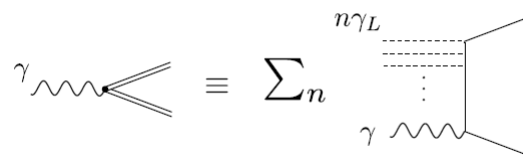
## LUXE Scientific Goals

- Landmark for the first experimental observation of Sauter-Schwinger pair production of  $e^+/e^-$  by strong background field
- Study the onset on non-perturbative strong field QED transition of the processes:



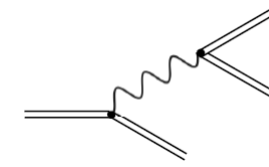
Non-linear (inverse) Compton scattering

$$e^\pm + n\gamma_L \rightarrow e^\pm + \gamma.$$



Breit-Wheeler production

$$\gamma + n\gamma_L \rightarrow e^+e^-$$



Non-linear Trident process

$$e^- + n\gamma_L \rightarrow e^- + \gamma \quad \text{and} \quad \gamma + n'\gamma_L \rightarrow e^+e^-.$$

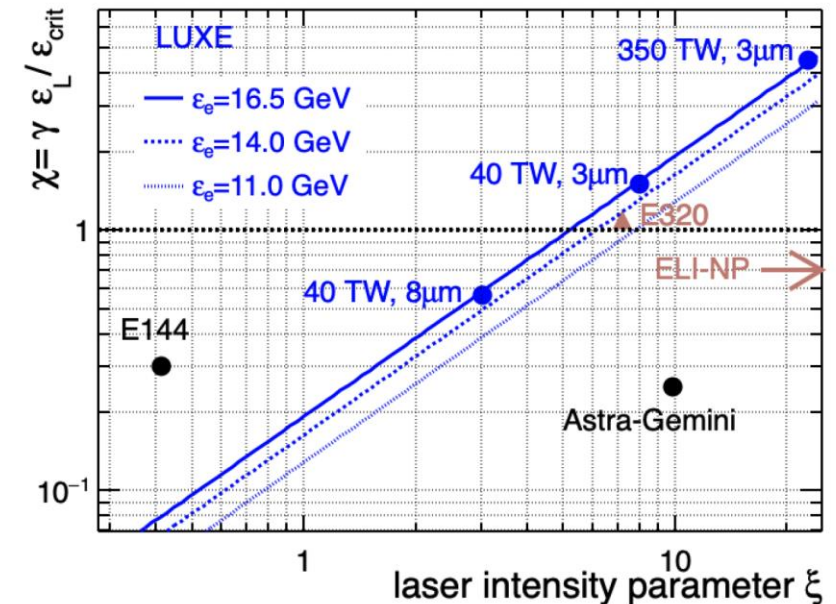
## Parameter space

The electron-laser interaction is characterised by the classical non-linearity parameter  $\xi$ , the quantum non-linearity parameter  $\chi$  and the energy parameter  $\eta$ .

$$\xi = \frac{m_e \epsilon_L}{\omega_L \epsilon_{cr}}$$

$$\chi = (1 + \cos \theta) \frac{E \omega_L}{m_e \epsilon_{cr}}$$

with  $\omega_L, \epsilon_L$  laser frequency and field-strength in lab. frame



# LUXE. QED in strong EM fields

## QED in intense EM fields can arise in

1. Gravitational collapse of black holes, where astrophysical pair creation can occur;
2. The propagation of cosmic rays;
3. The magnetosphere of strongly magnetised neutron stars;
4. Beam-beam collisions at future high-energy lepton colliders;
5. In heavy-ions collisions, e.g. where Coulomb field around nuclei (typically  $Z < 137$ ) is strong

## What separates strong-field QED from regular QED?

- The dimensionless charge-field coupling, which in plane wave EM backgrounds is described by the classical non-linearity parameter

$$\xi = \frac{e \mathcal{E} \lambda_e}{\hbar \omega_L}$$

work of the EM field over a (reduced) Compton wavelength  
*in units of*  
the background EM field photon energy

- The  $\xi$  quantifies how many laser photons interact with the charge in a given QED process, with the probability of interaction with  $n$  background photons scaling as  $\xi^{2n}$
- In weak-fields probabilities of QED processes scale as  $\sim \xi^2$  ( $n=1$ )

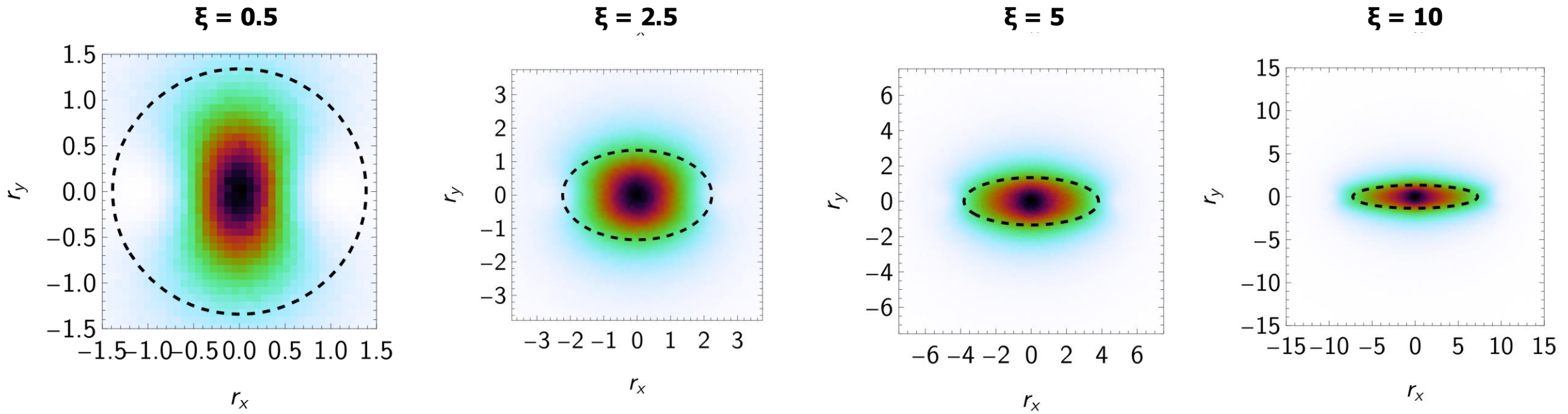
# LUXE. The gamma beam monitor

The angular distribution of Compton photons is strongly dependent on the laser intensity ( $\xi$ ) **locally** experienced by the initial electron during the electron-laser interaction **at the time of emission**.

Photons angular distribution contains valuable information allowing to infer *shot-by-shot* the  $\xi$  value

$$\xi^2 \sim (\sigma_{\parallel}^2 - \sigma_{\perp}^2)$$

## | Angular distribution of Compton scattered photons at different laser intensities

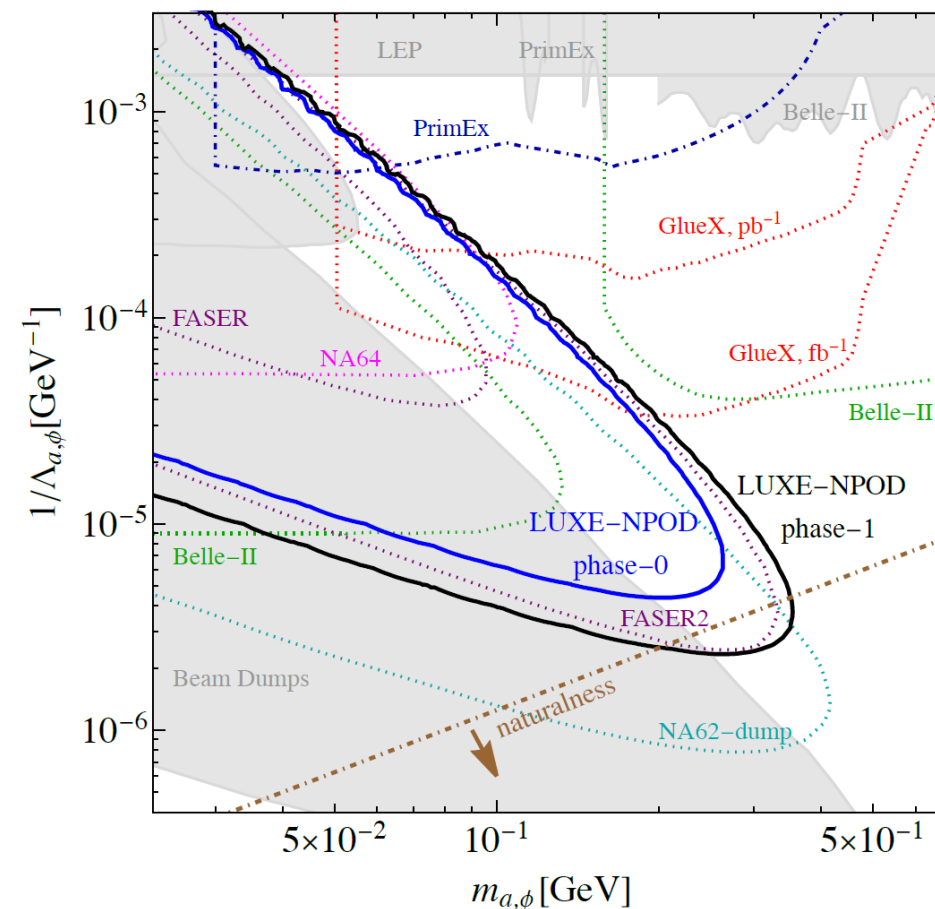
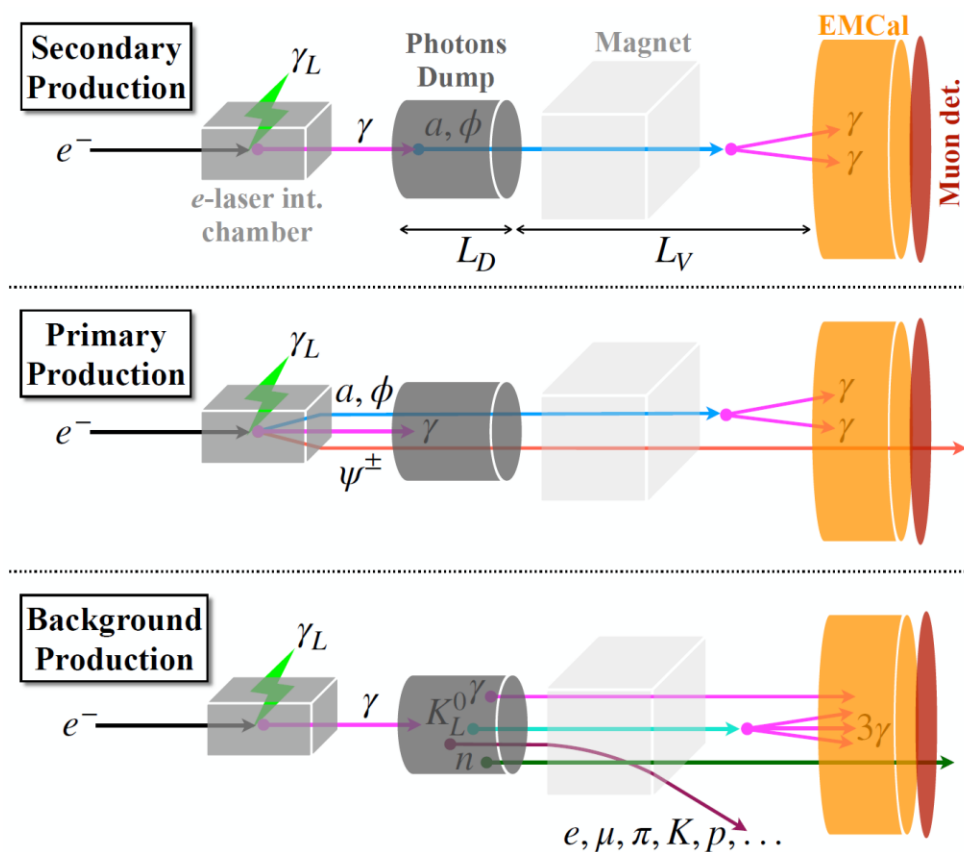


The **Gamma Beam Profiler (GBP)** is envisaged for this task – i.e. beam monitoring the gamma beam.

# LUXE in a nutshell

## New physics scenarios

LUXE (phase-1) is expected to reach the sensitivity required to probe the edge of the parameter space of natural models of axion-like-particles (ALPs) and scalars, by using an optical and solid beam dump and an EM calorimeter.



# Sapphire R&D

# R&D. Experimental campaigns



## **Sapphire pads** (May 22)

Test at BTF (*INFN-Frascati*)

of two sapphire pad ( $d= 1.6, 5.5$  mm) detectors (thickness 110 $\mu$ m, 150 $\mu$ m) with 300MeV electron beam (up to  $3e10$  e-/s)

### *Measure programme*

- Collected charge (V, beam, damage)



## **Sapphire 4-strip** (Sep. 22)

Test at CLEAR (*CERN*)

of a stack of three 4-strip detectors (100 $\mu$ m, 150 $\mu$ m, 150 $\mu$ m)

### *Measure programme*

- Radiation damage
- Signal shape (w/o shaping)
- Collected charge (V, beam, damage)
- Response uniformity(X,Y)



## **Sapphire 192-strip** (Dec. 22)

Test at CLEAR (*CERN*)

of a 192-strip detector with its final electronics (CAEN FERS) reading out 64 strips.

### *Measure programme*

- Electronics
- Radiation damage
- Collected charge
- Profile reconstruction capability



# R&D – test beam pads

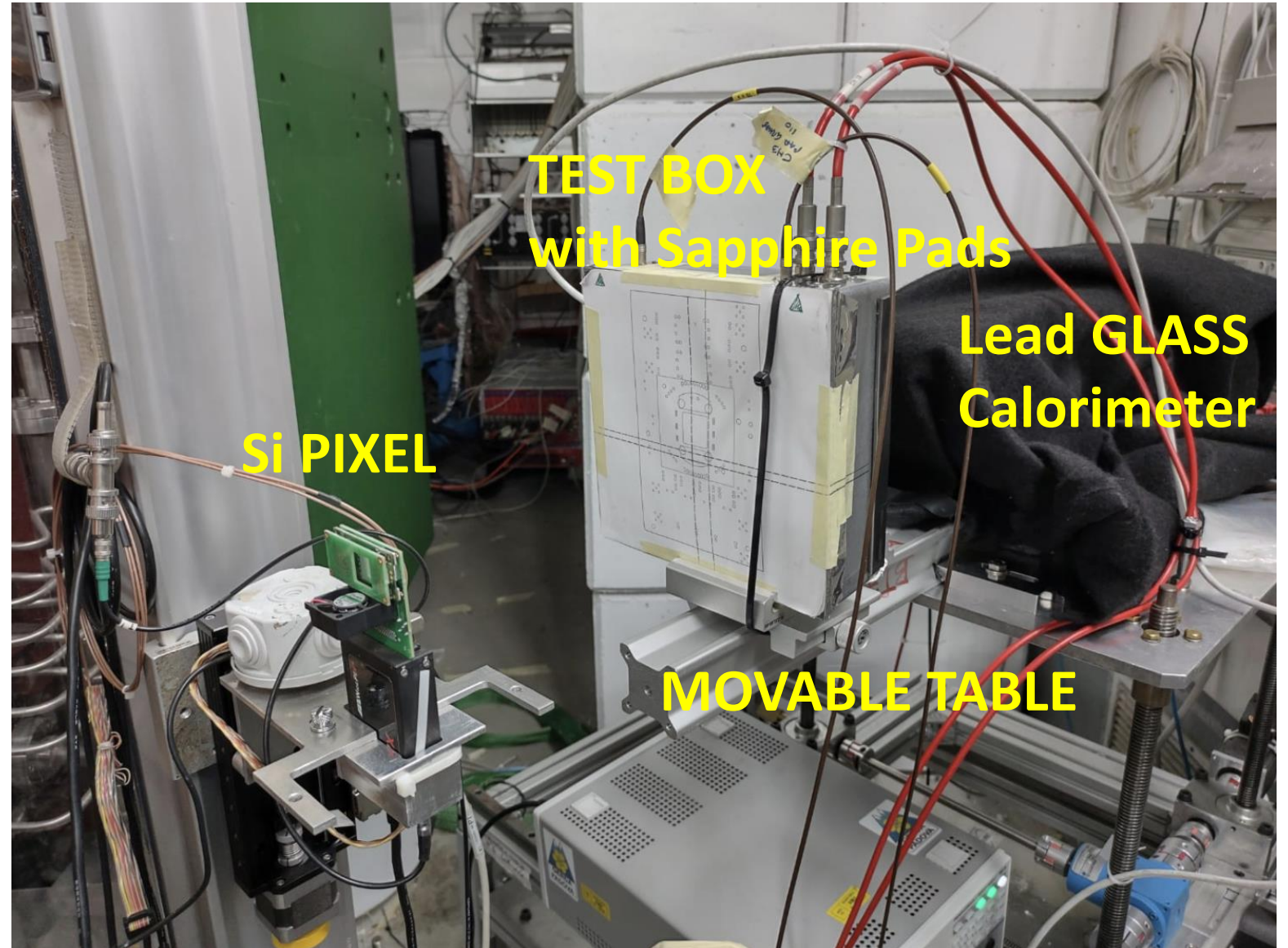


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### Measure programme

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# R&D – test beam 4-strip



**Sapphire 4-strip** (Sep. 22)  
Test at CLEAR (CERN)  
of a stack of three 4-strip detectors  
(100um, 150um, 150um)

## Measure programme

- Radiation damage
- Signal shape (w/o shaping)
- Collected charge (V, beam, damage)
- Response uniformity(X,Y)



