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

INFN

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.

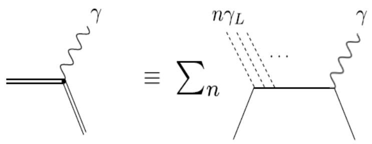
Q&A Session

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.

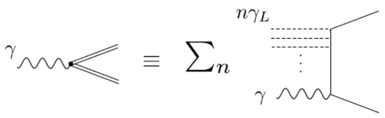
Scientific goals

- 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



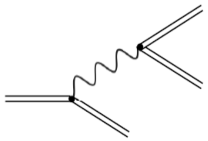
Non-linear (inverse) Compton

$$e^{\pm} + n\gamma_L \to e^{\pm} + \gamma.$$



Breit-Wheeler production

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



Non-linear Trident process

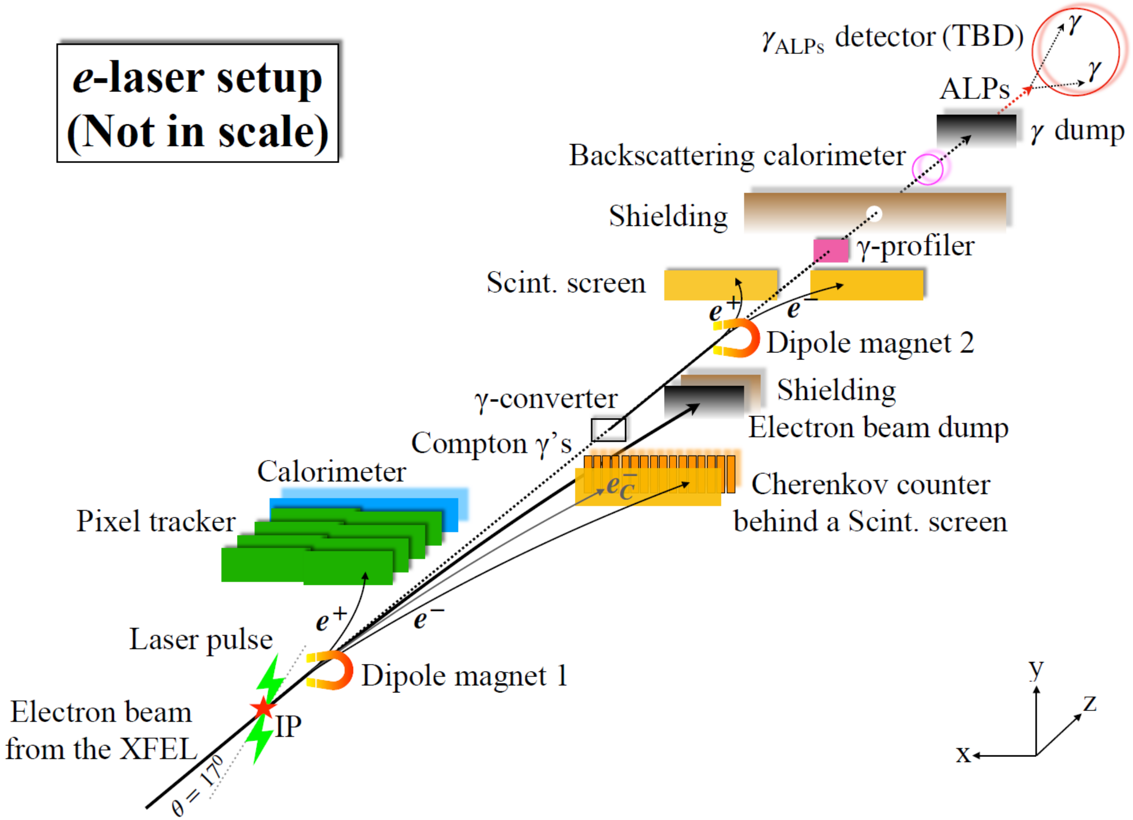
- Probe parameter-space edge of natural models of axion-like-particles (ALPs) coupling to photons, by using an optical+solid beam dump and an EM calorimeter.

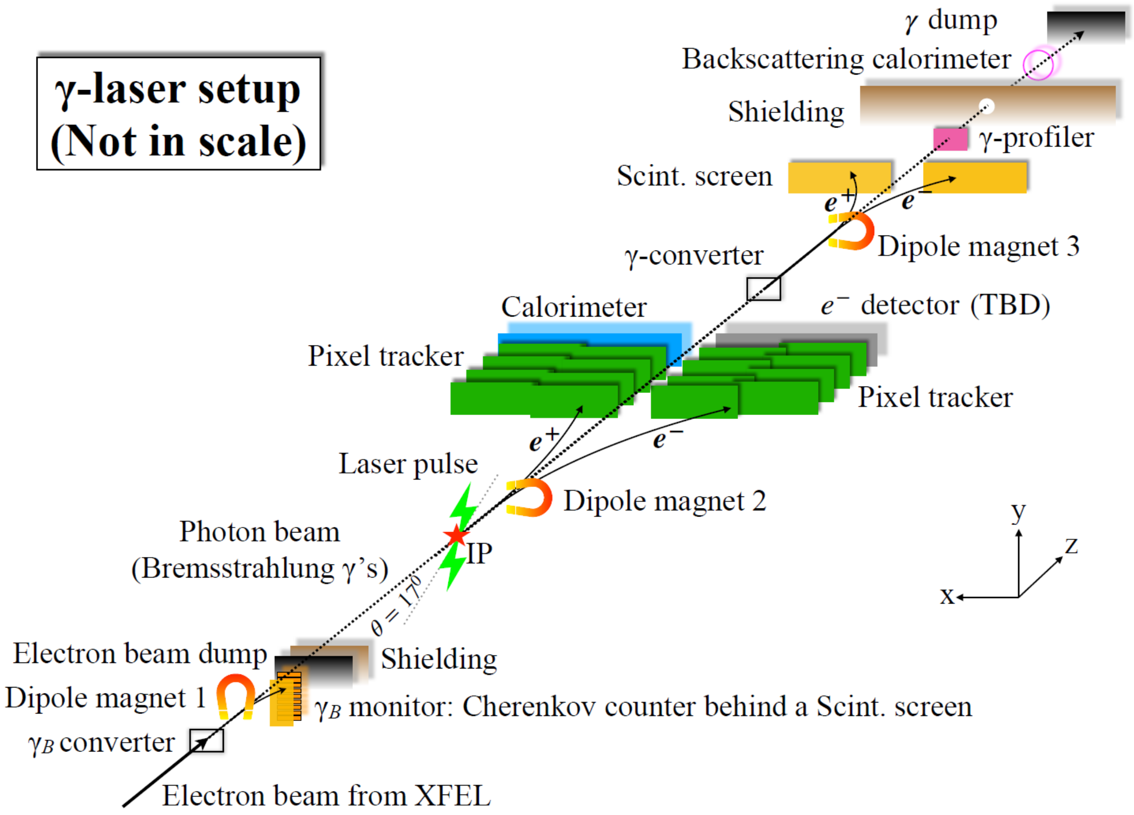
LUXE

LUXE. Experimental setup

Strong field QED (SFQED) phyics 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.





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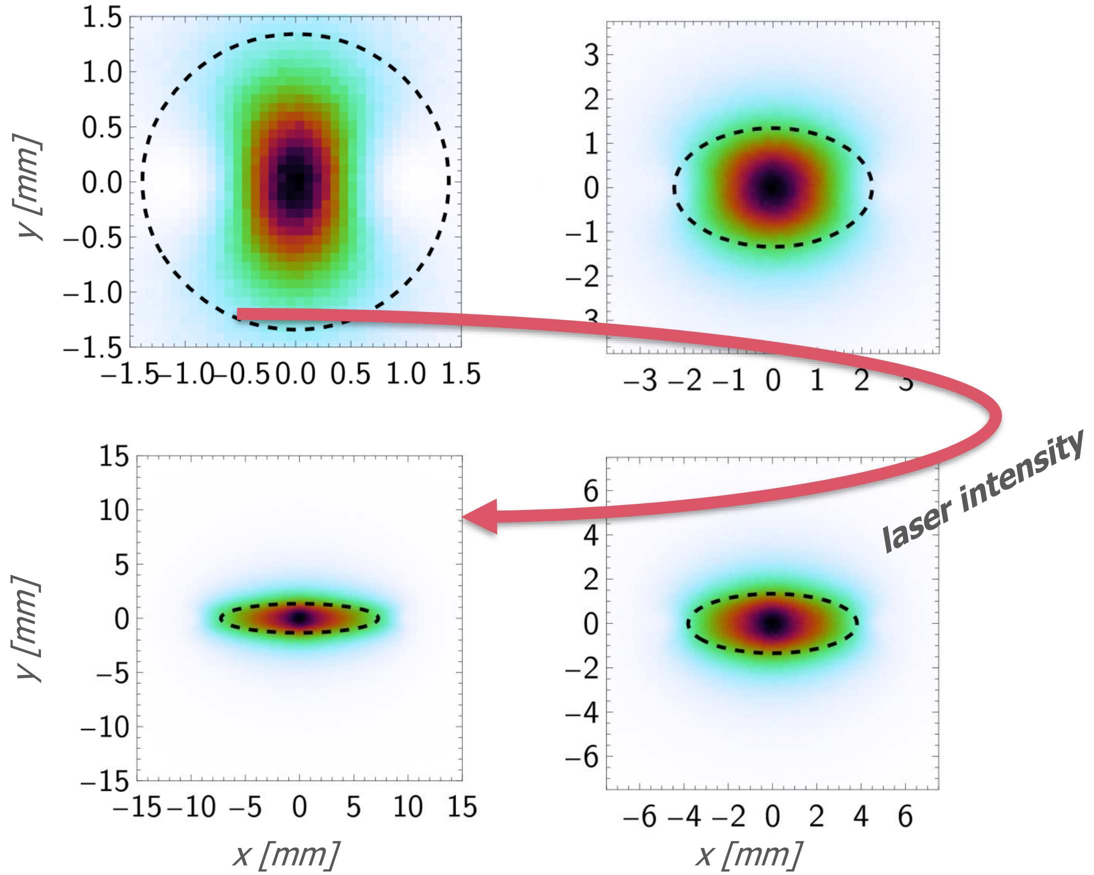
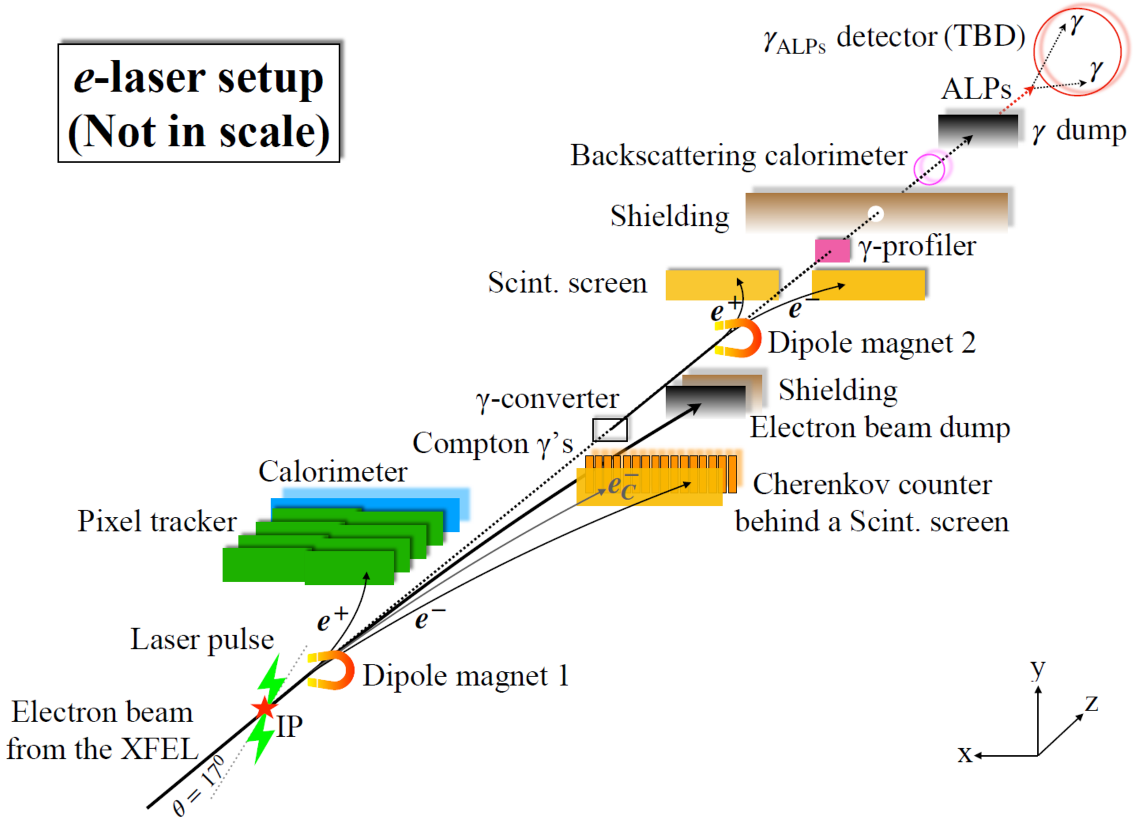


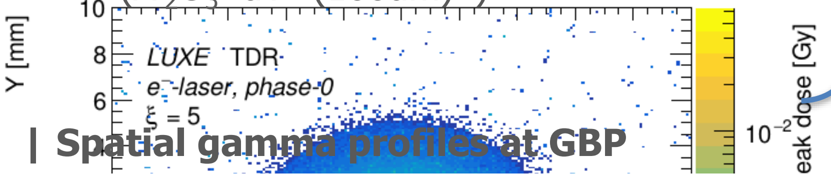


LUXE. Requirements for the Gamma Profiler

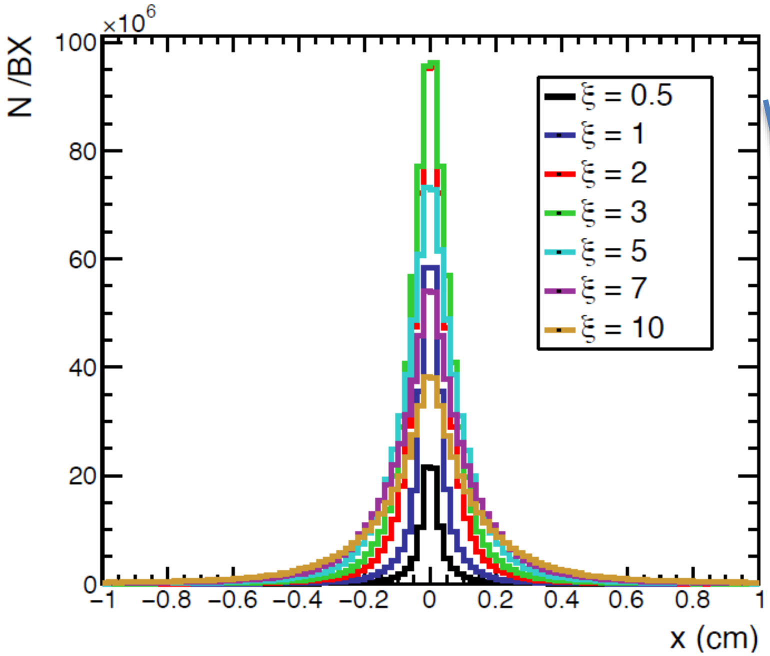
| Spectrum of primaries at GBP (ξ=5)

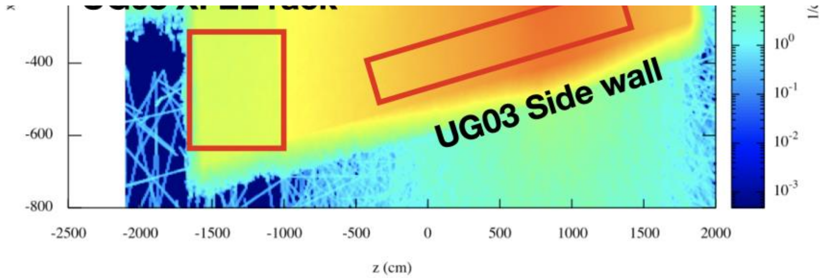
| Dose/bunch [Gy]

(Al_2O_3 $dV=(100um)^3$)



| Spatial gamma profiles at GBP





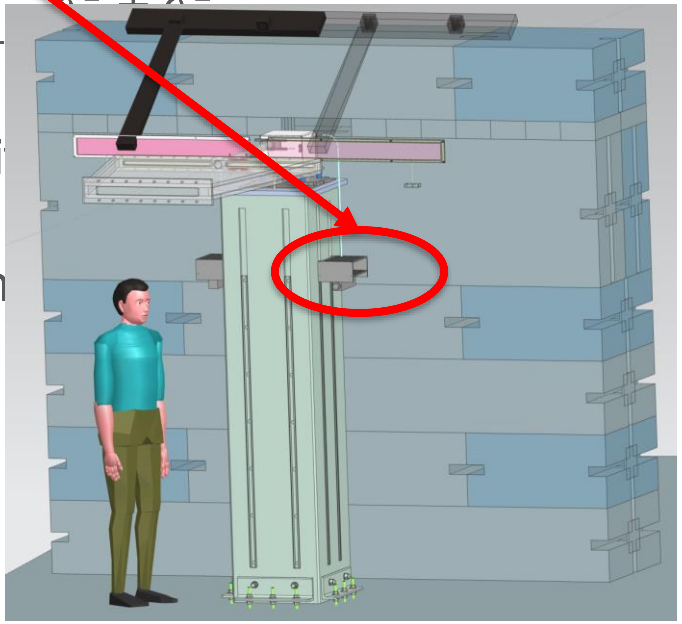
Detector requirements

- High flux ($\sim 10^9\ s^{-1}$) of high energy ($\sim$ 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 $300\ \mu m - 5\ mm$

$$\frac{\delta\xi}{\xi} \simeq \sqrt{2 \cdot 10^{-5} + \ldots \sigma^2 + \sigma^2}$$

To determine laser intensity wi
resolution of 5 um

- **High dynamic range** very im
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^2 vs pCVD 3 k€/cm^2) 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 hitti detector.

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

i.e. as BHM at FLASH

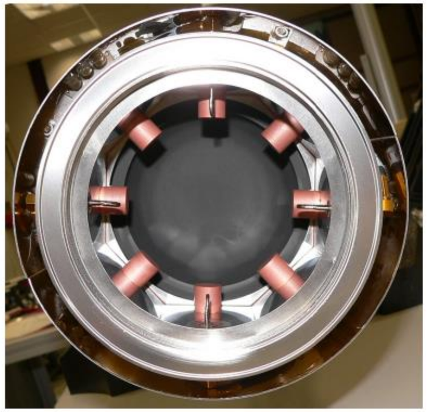
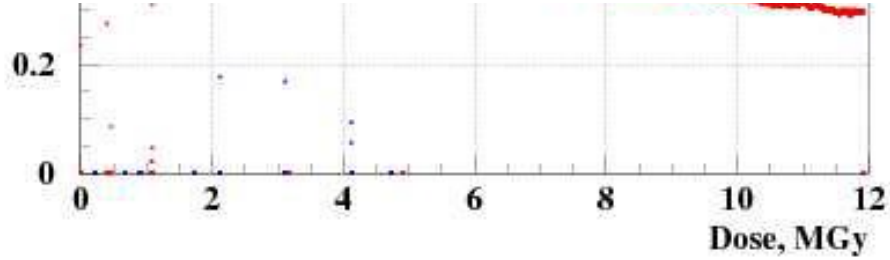
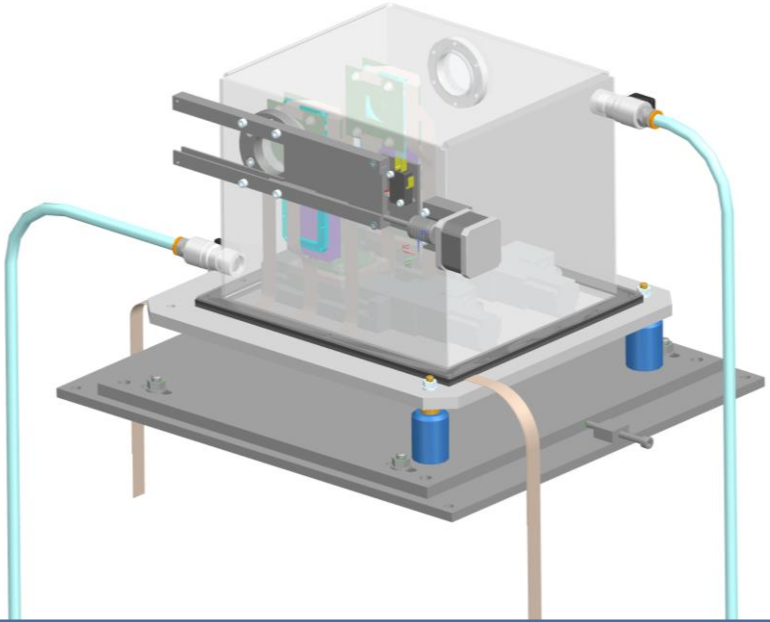


Figure 1: View of the BHM from the dump. The BHM sensors are inside the caps. Four loops of the magnetic-coupled BPM are right in front of the BHM sensors.

Material properties			
density [g/cm3]			
bandgap [eV]			
mean energy to create an			
dielectric constant	9.3-11.5	5.7	11.7
dielectric strength [MV/cm]	0.4	1.0	0.3
resistivity [Ohm cm] at 20^o C	1.0E+16	1.0E+16	1.0E+05
electron mobility [cm2/(V s)] at 20^o C	600	2800	460
MIP eh created [eh/μm]	22	36	73



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

SALOME9 THE OPEN SOURCE INTEGRATION PLATFORM FOR NUMERICAL SIMULATION

1. Parametric geometry
2. Meshing

Elmer

3. Finite-element Electrostatic/Ramo field calculation

ParaView

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

ap² allpix squared — mesh_converter +CSVParser

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

ap² allpix squared

8. Ad-hoc sapphire implementation
9. Simulate

Features

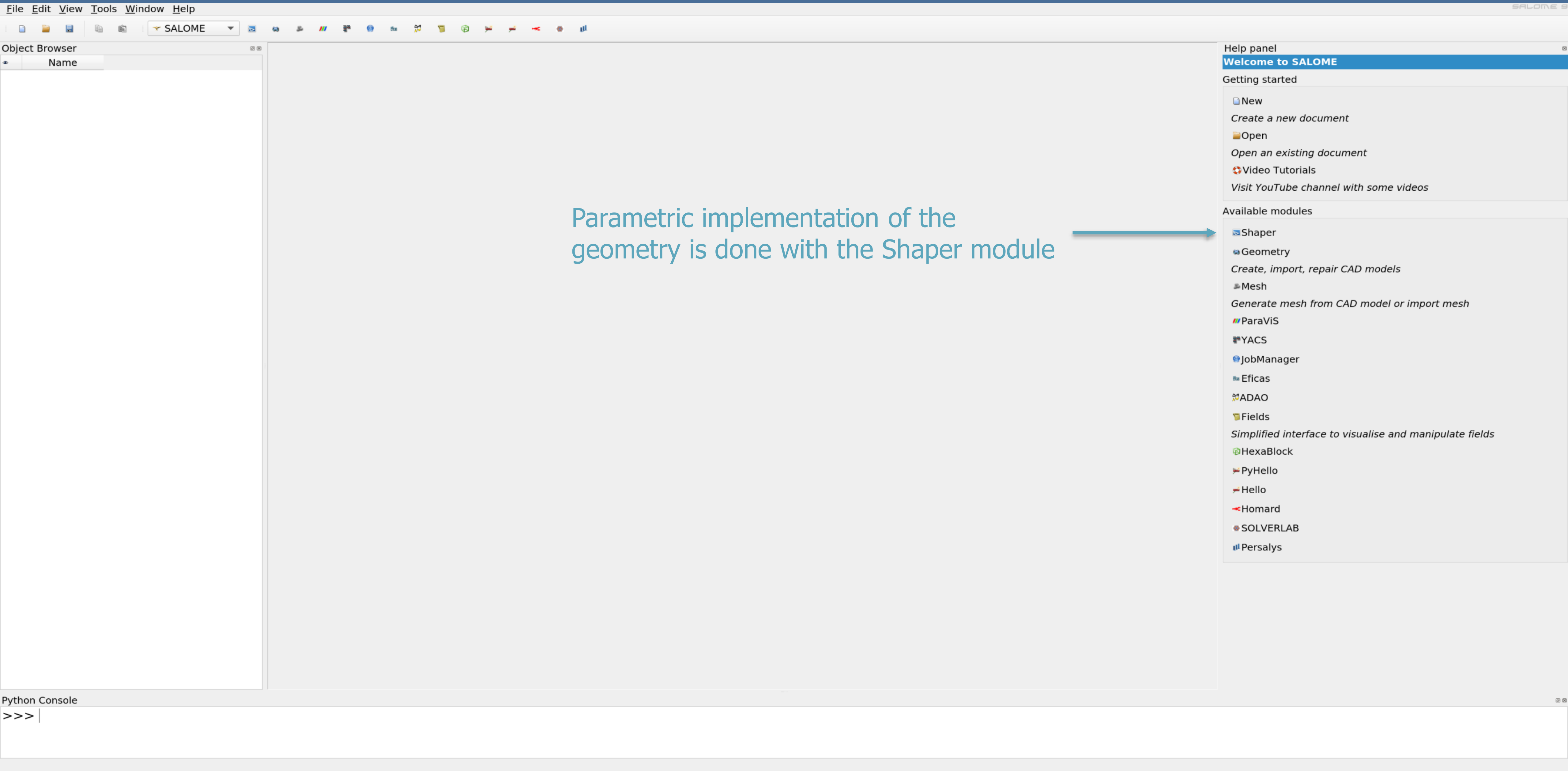
- Parametric design is excellent for detector design optimization (i.e. with ML alg.)
- Advanced meshing alg.s

- 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

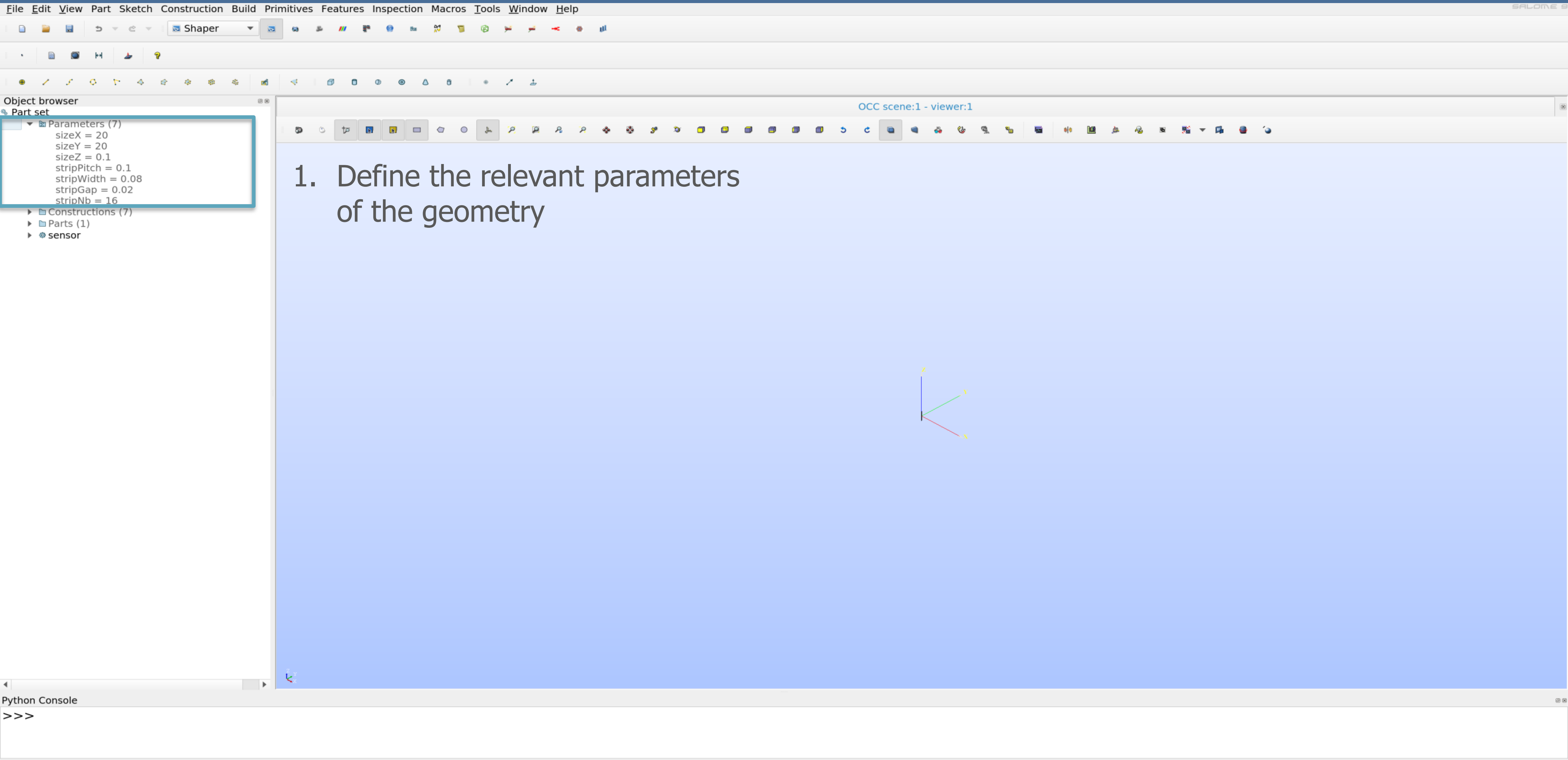
- Conversion of CSV/ROOT file to Allpix Proprietary Format (APF)
- MeshMap coordinate offset and scaling
- Automatic Ramo potential renormalization feature

SALOME - Parametric geometry



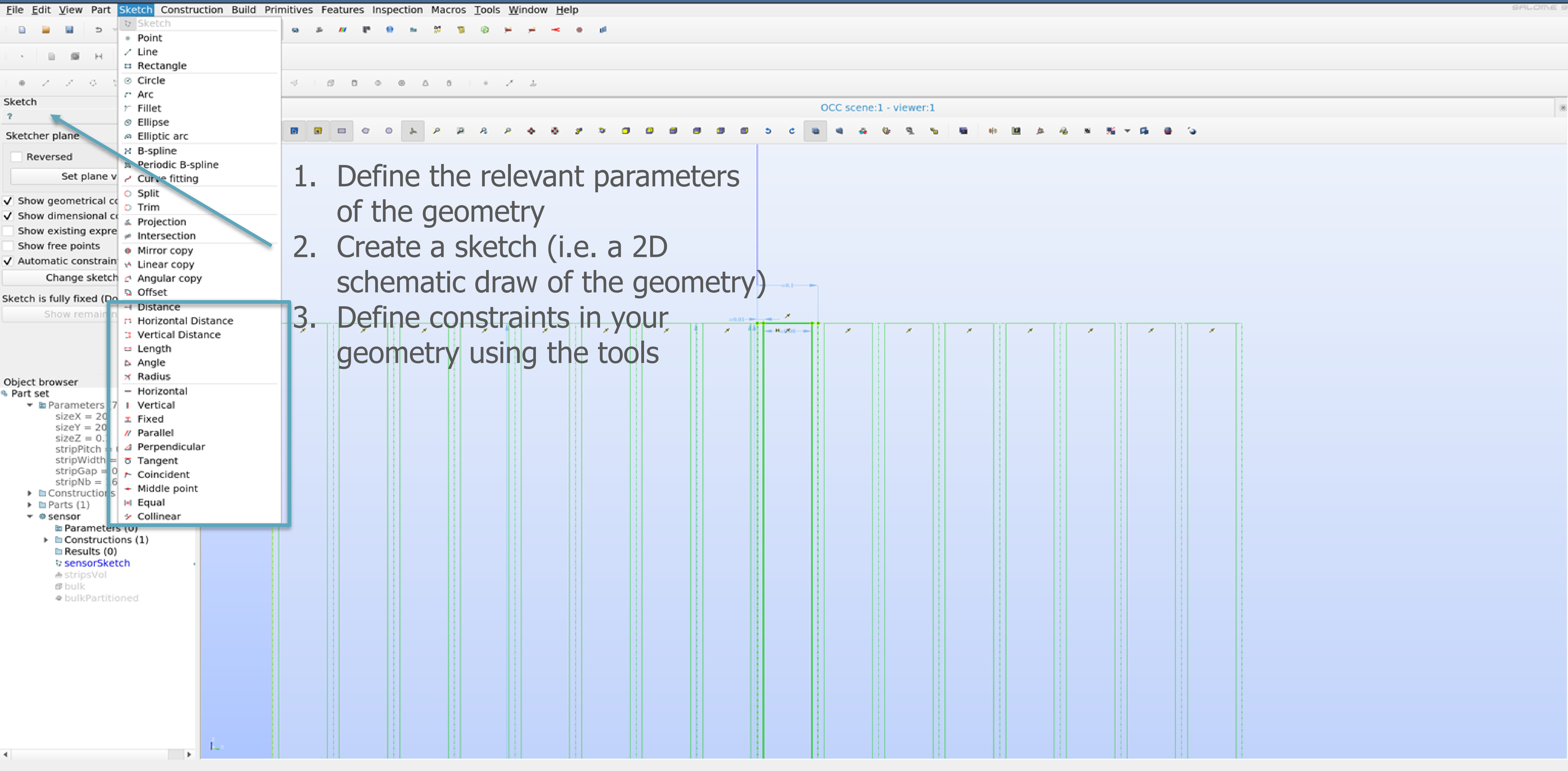
Parametric implementation of the geometry is done with the Shaper module

SALOME - Parametric geometry



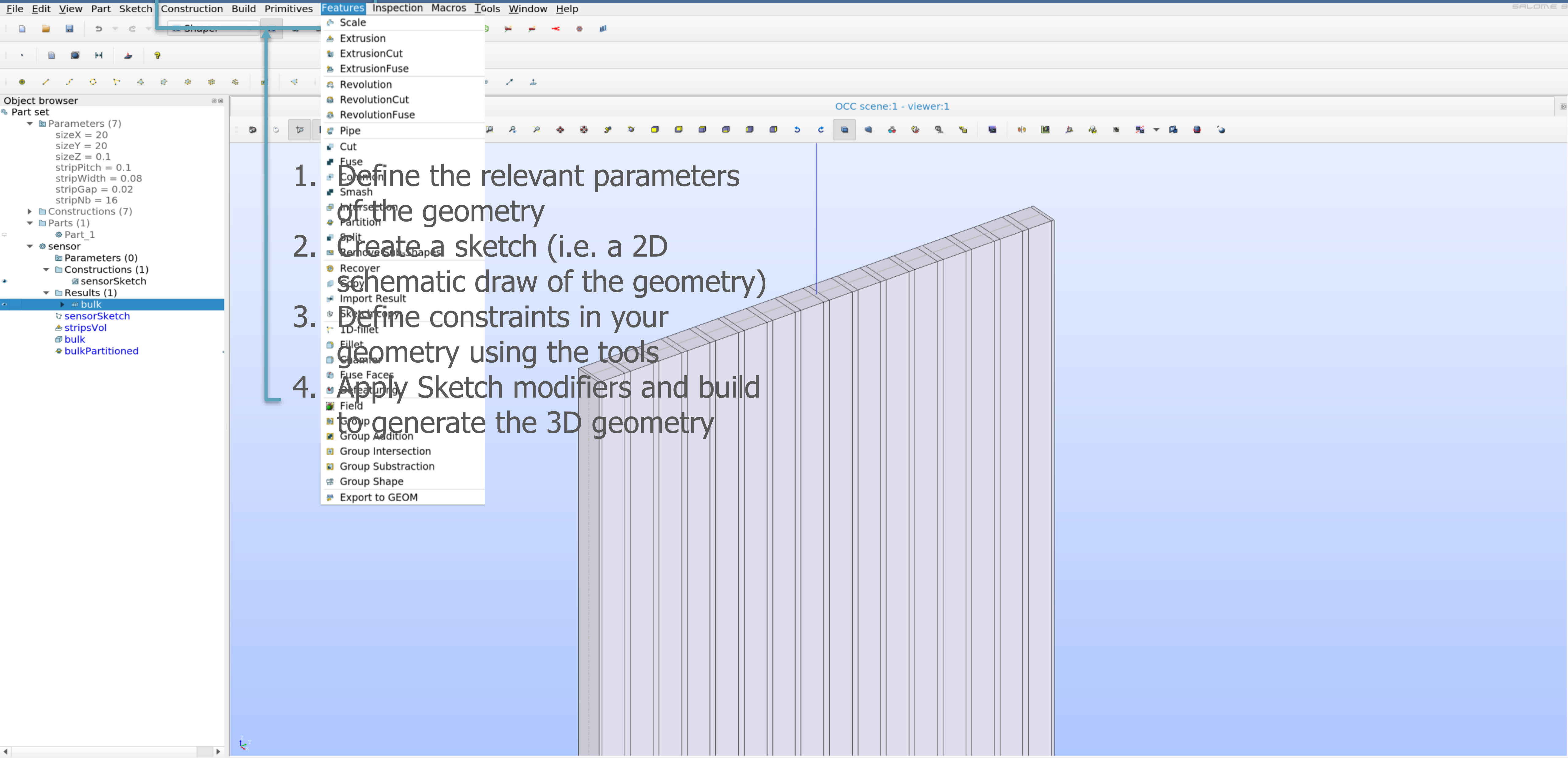
1. Define the relevant parameters of the geometry

SALOME - Parametric geometry



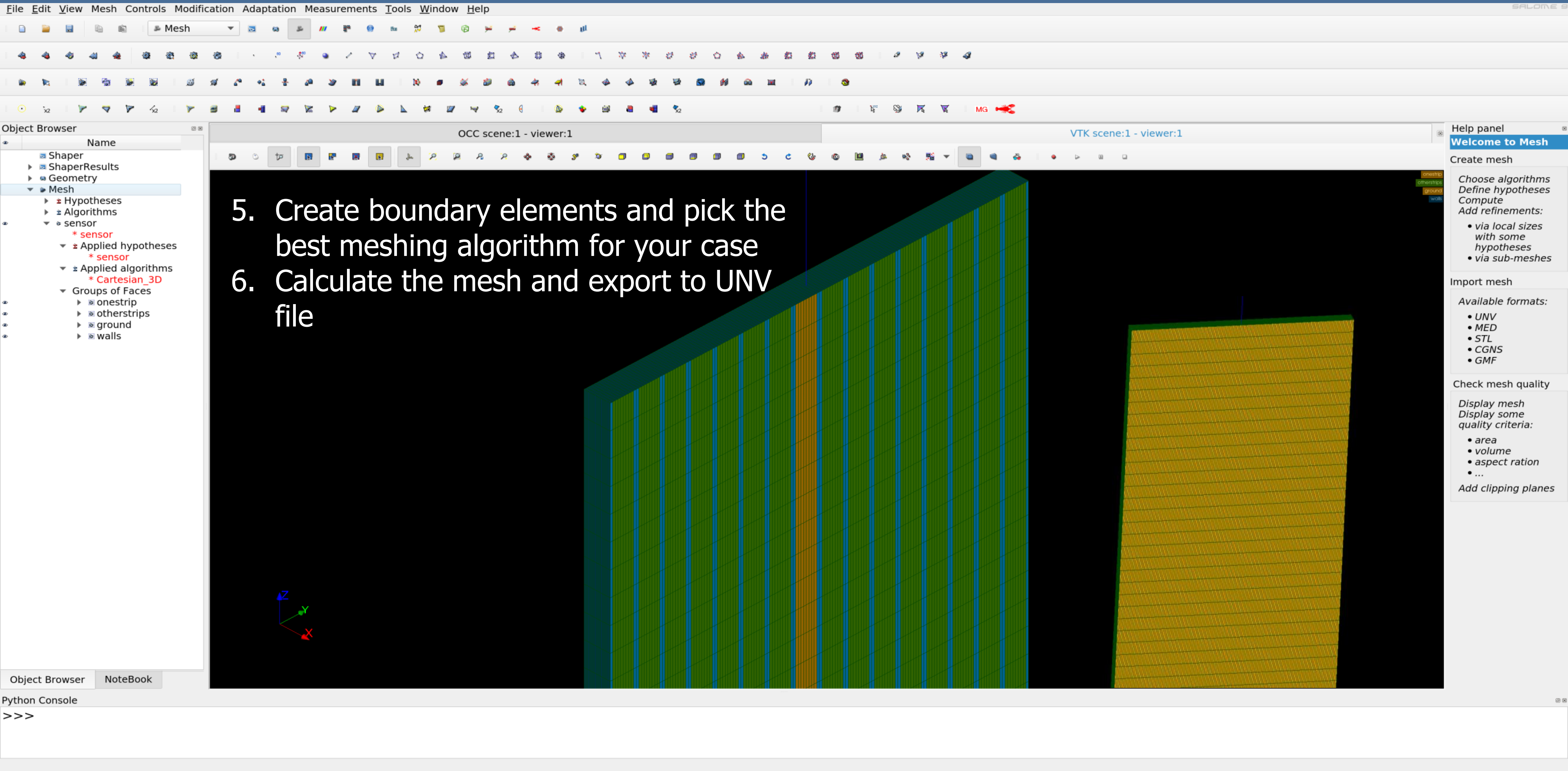
1. Define the relevant parameters of the geometry
2. Create a sketch (i.e. a 2D schematic draw of the geometry)
3. Define constraints in your geometry using the tools

SALOME - Parametric geometry



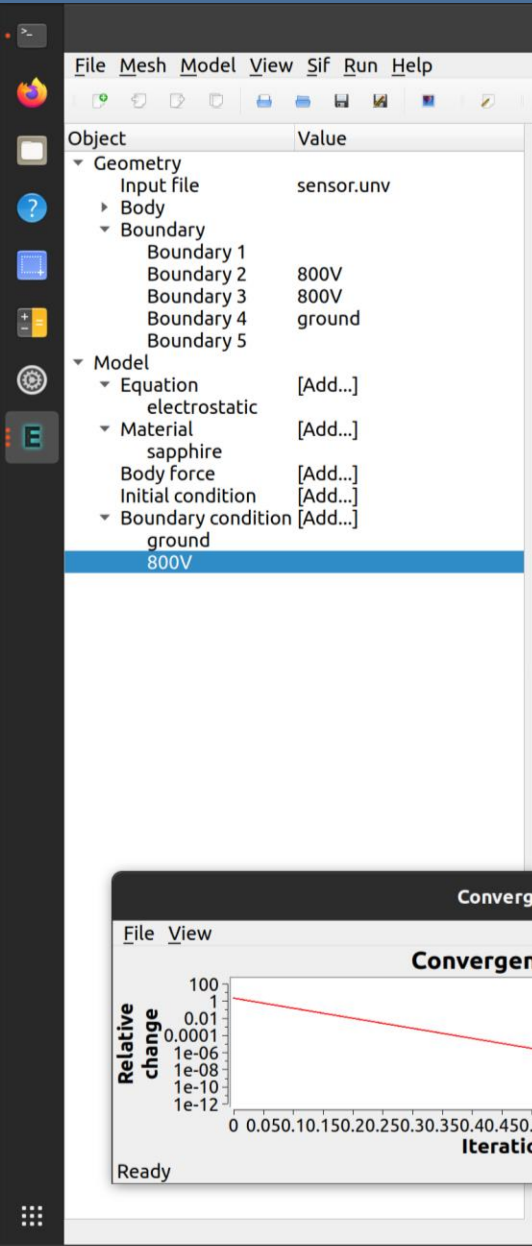
1. Define the relevant parameters of the geometry
2. Create a sketch (i.e. a 2D schematic draw of the geometry)
3. Define constraints in your geometry using the tools
4. Apply Sketch modifiers and build to generate the 3D geometry

SALOME - Meshing



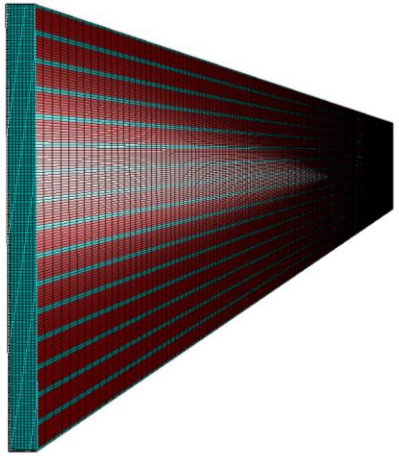
5. Create boundary elements and pick the best meshing algorithm for your case
6. Calculate the mesh and export to UNV file

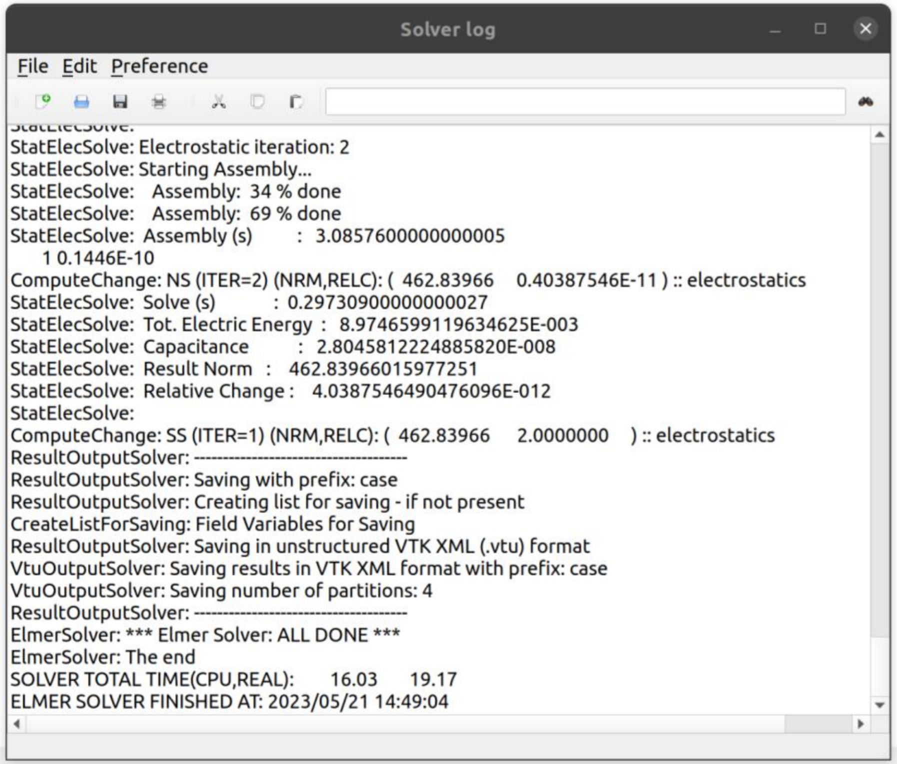
ELMER – Electrostatic / Ramo field solver

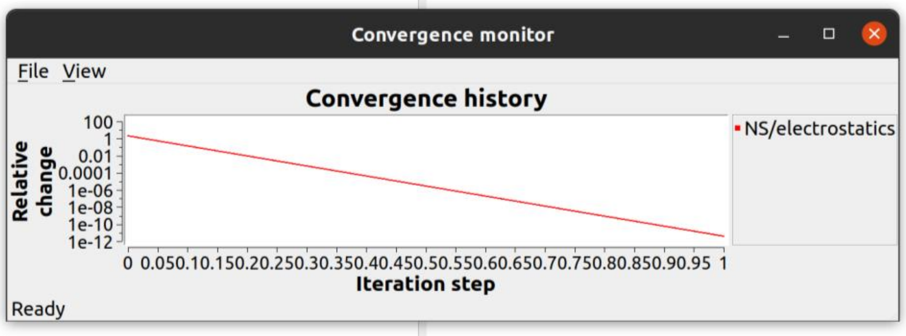


7. Import the UNV.
8. Set the electrostatic solver.
9. Assign boundary conditions and compute.

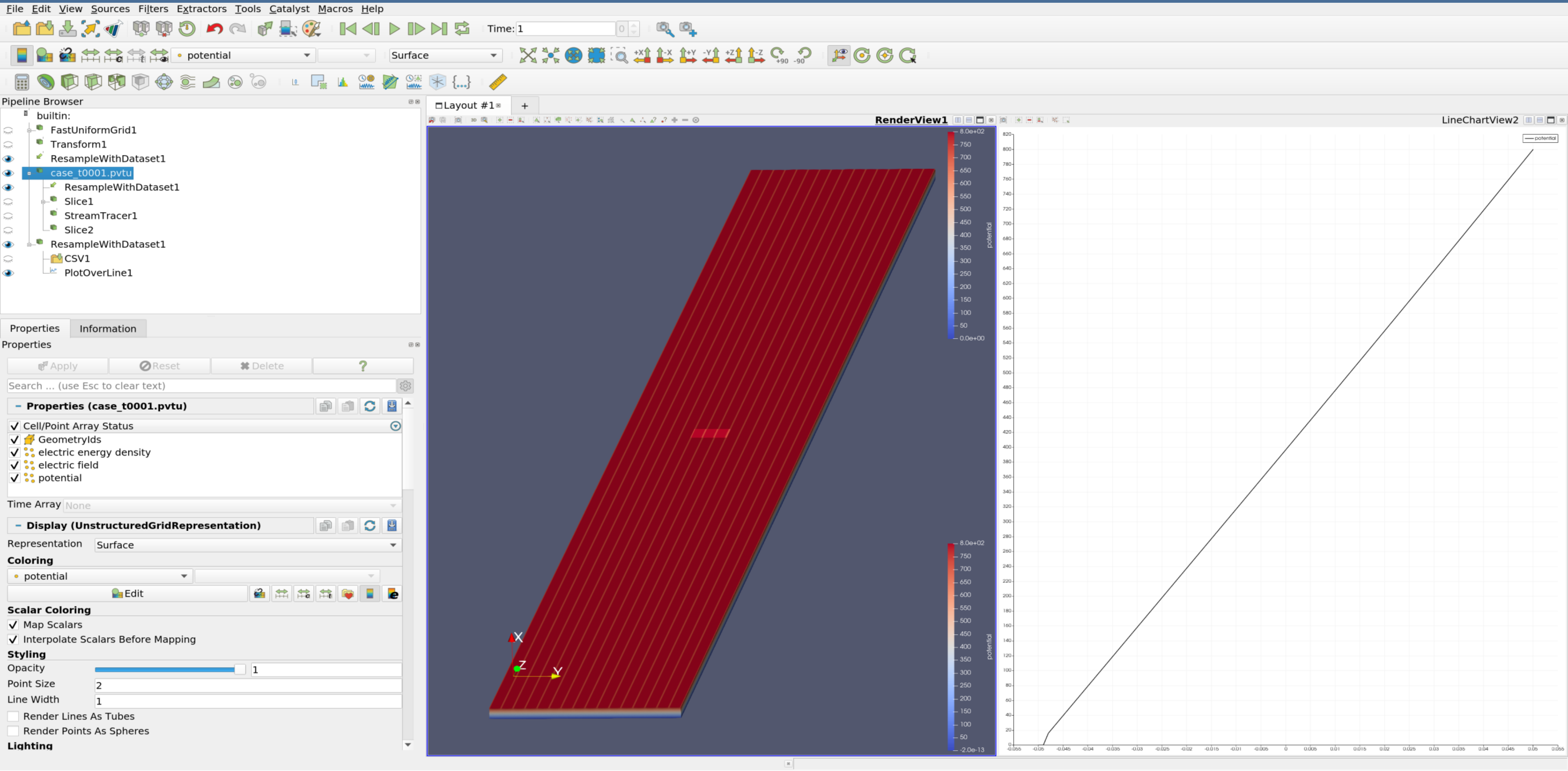
Fields are stored with
VTK Unstructured Grid Files







Example. E-field for 800V/100um



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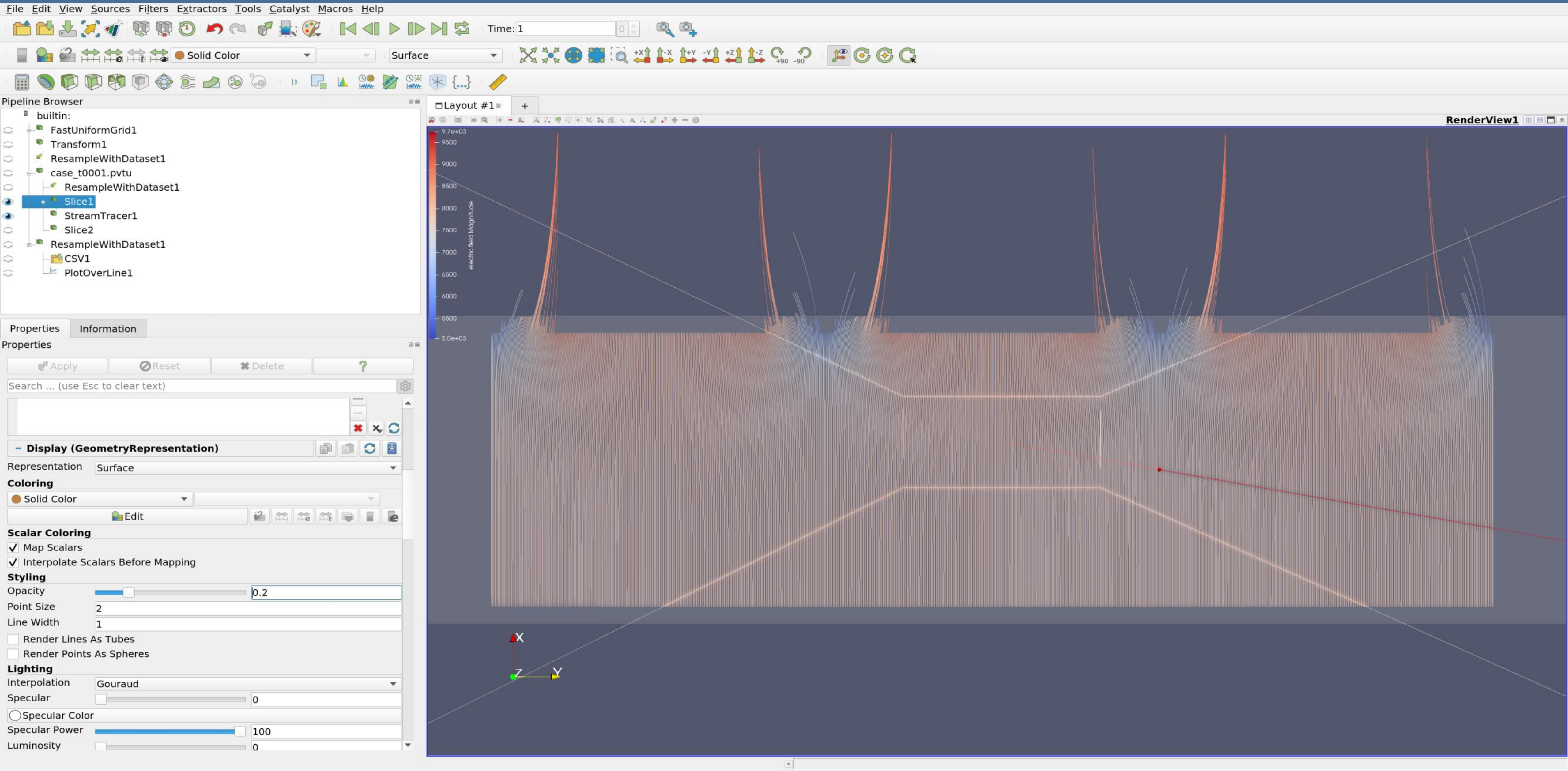
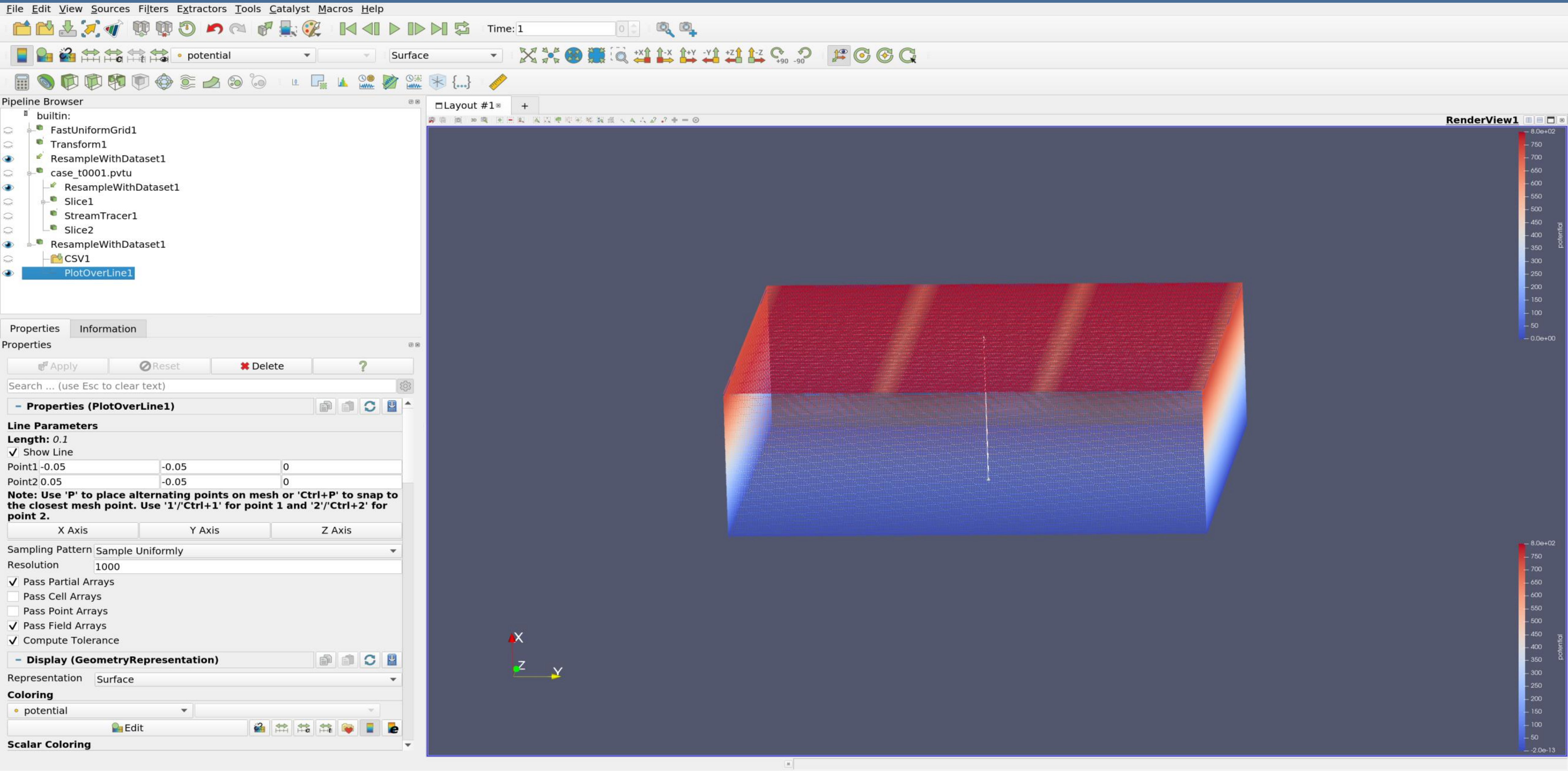


Example. E-field for 800V/100um



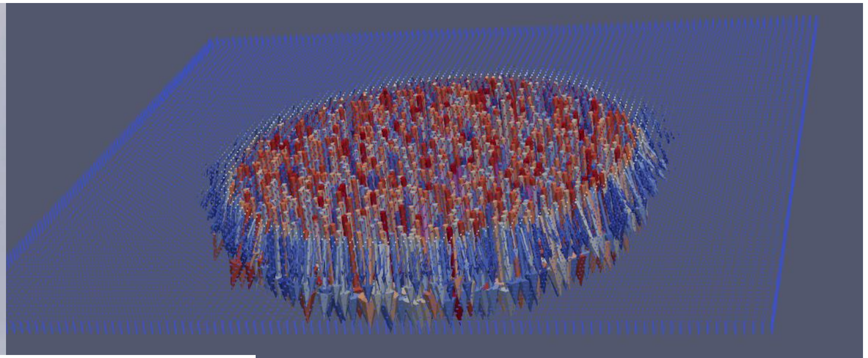
PARAVIEW - Field interpolation

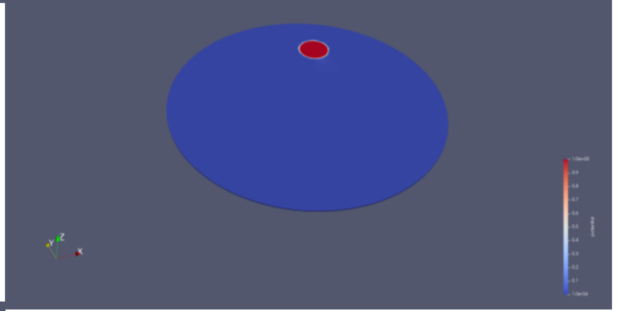
Preparation for APF conversion

- Field data is interpolated with a gaussian kernel and resampled to a regular mesh grid with higher spatial-resolution.

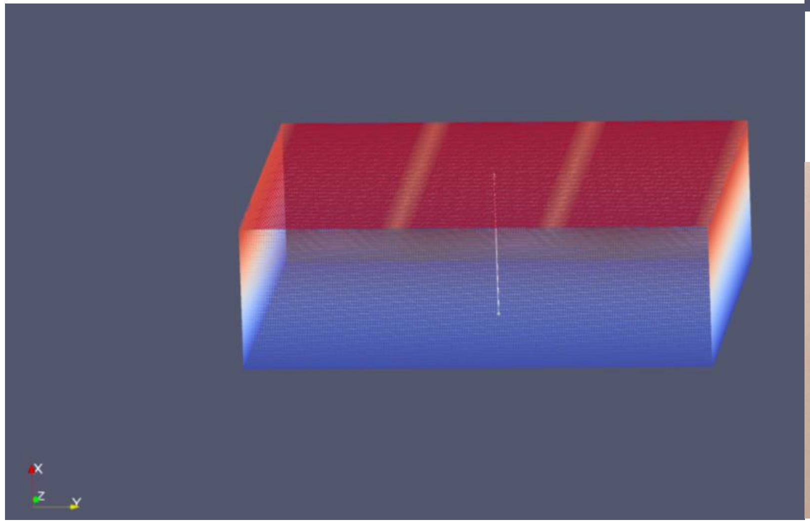
- If fringe effects are relevant, fields over the entire sensor volume are exported.
- Otherwise, a 3x3 pixel volume is used.

- Data for the Electrostatic and Ramo fields is exported to CSV file.





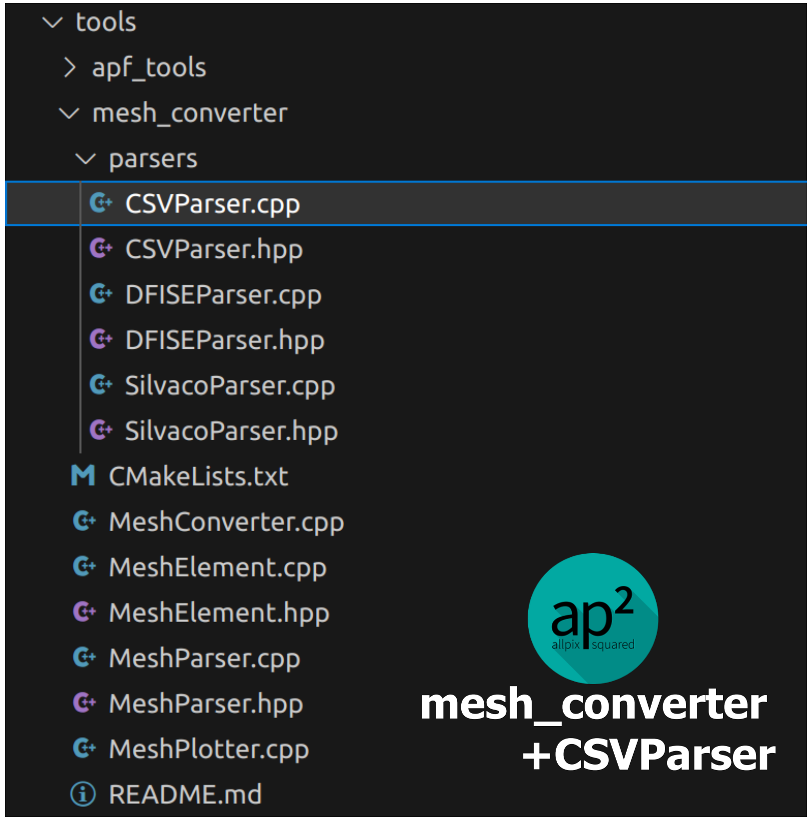
Sapphire pads *(May 22)*
Simulation for test beam at *INFN-Frascati*
Two sapphire pads (d=1.6, 5.5 mm) of thickness 110um, 150um



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

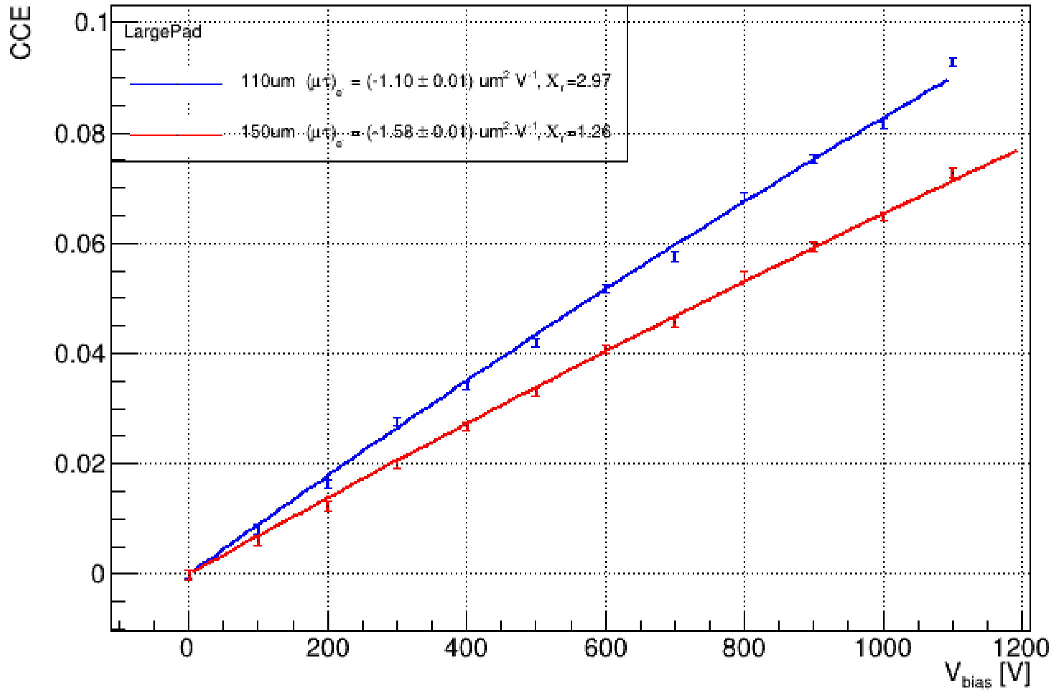
- Convert field from CSV to APF format, with or without mesh interpolation.
- Possibility to set ref. frame for mesh coordinates.
- Multiple observables (i.e. E-field, Ramo, Doping…) in the same file
- Renormalization of Ramo field (in range [0,1])

Parameters for the CSV parser (only)
* `coordiante_origin`: Reference position from which the coordinate are expressed. Defaults to `coordiante_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.
- TransientPropagation with 'custom' model with electron/hole mobilities of
  $\mu_e \sim 600 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$
  $\mu_e \sim 30 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$
- 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 $61\ ke\ (200ns)^{-1}$



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

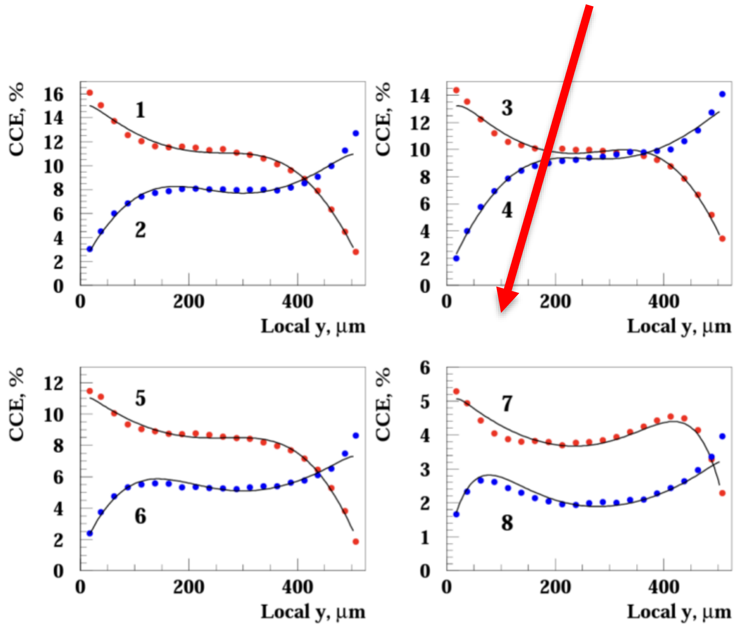
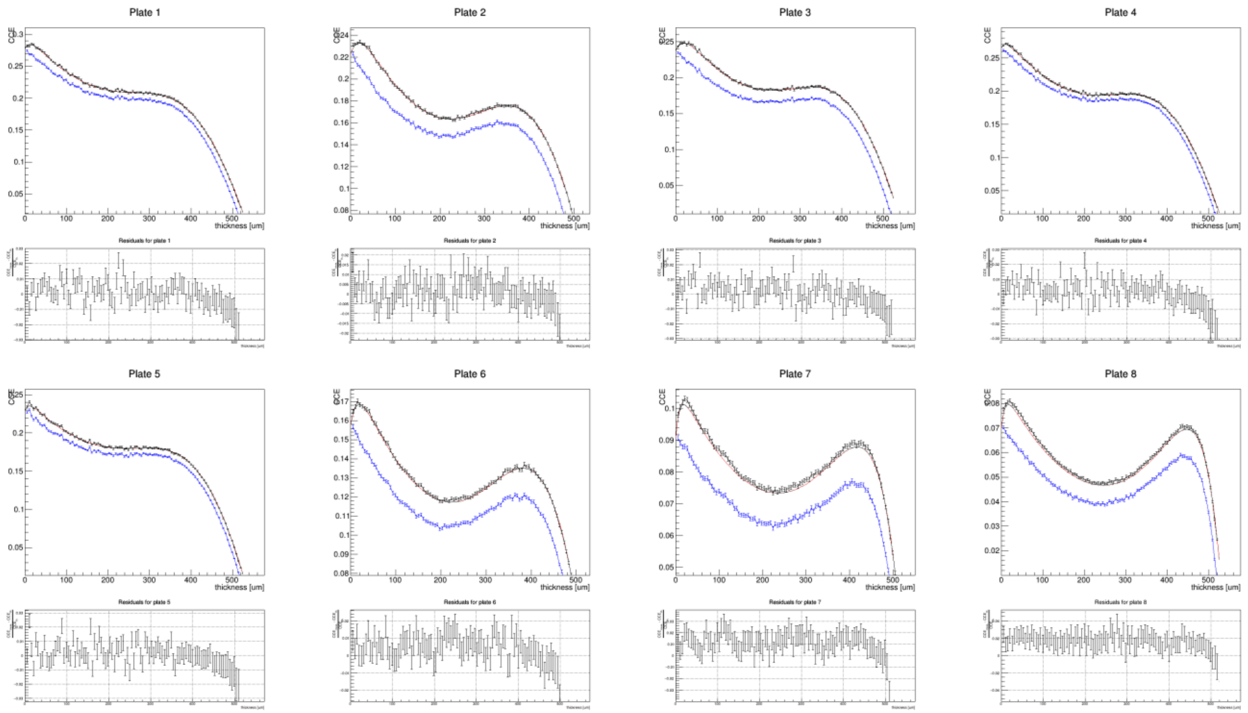


Figure 7: The CCE measured as a function of the local y coordinate inside a plate in slices of 25 μm for all plates of the sapphire stack. Blue dots are for the electric field in the direction of y and red dots for the opposite field direction. The lines are the result of a fit including both electron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



good agreement (<4%) for simulation and data

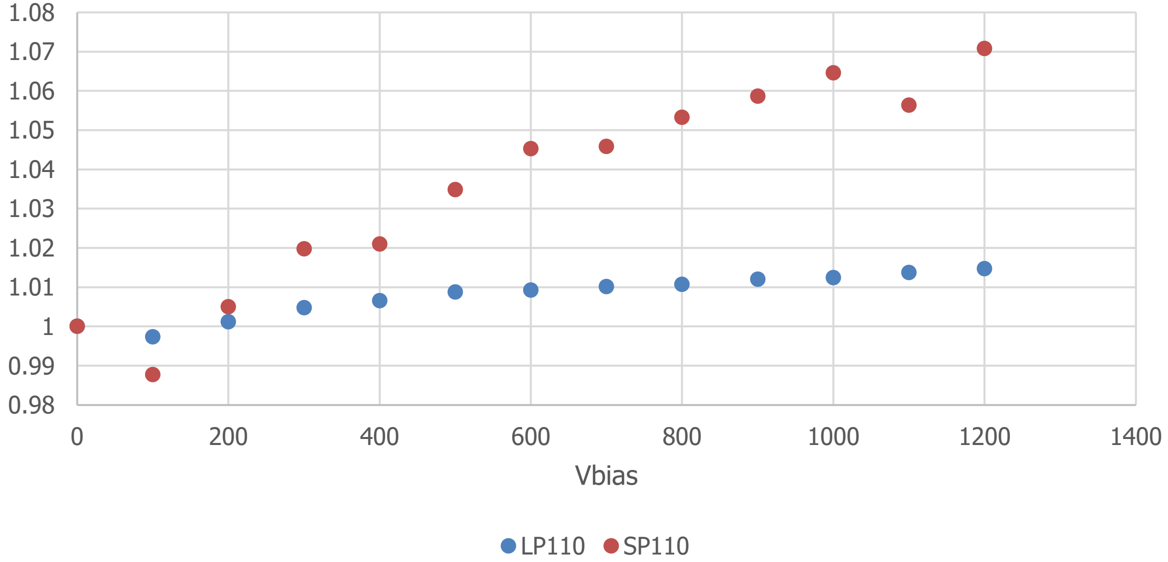
Case study. Fringe effect for sapphire pad sensor

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

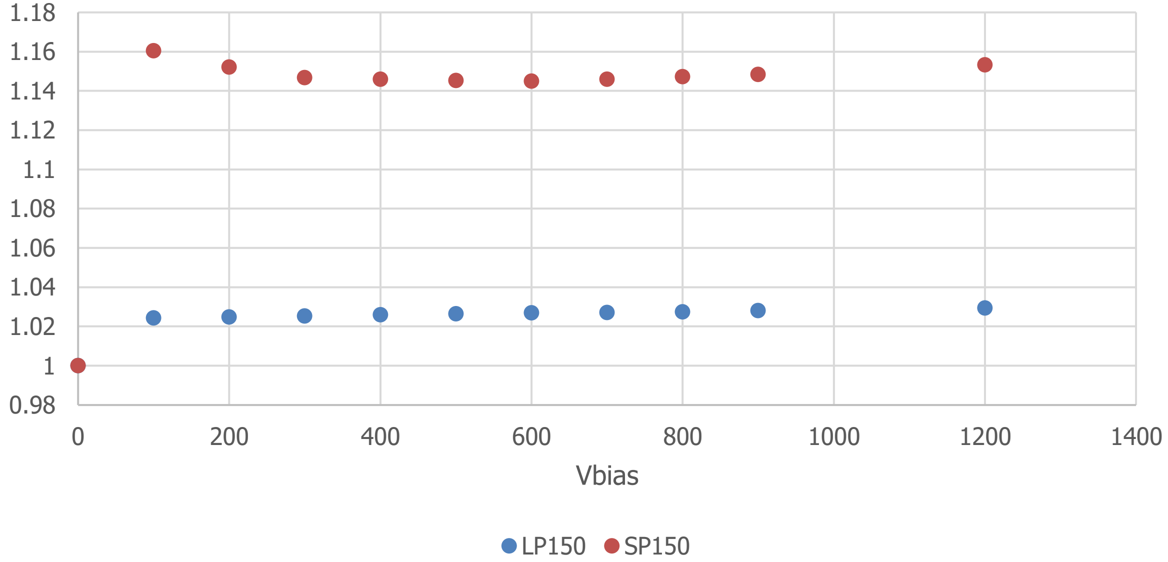
1. a uniform field along z-axis E=V/d is applied in the pad disk, or
2. the realistic simulated field (with fringe effects)

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

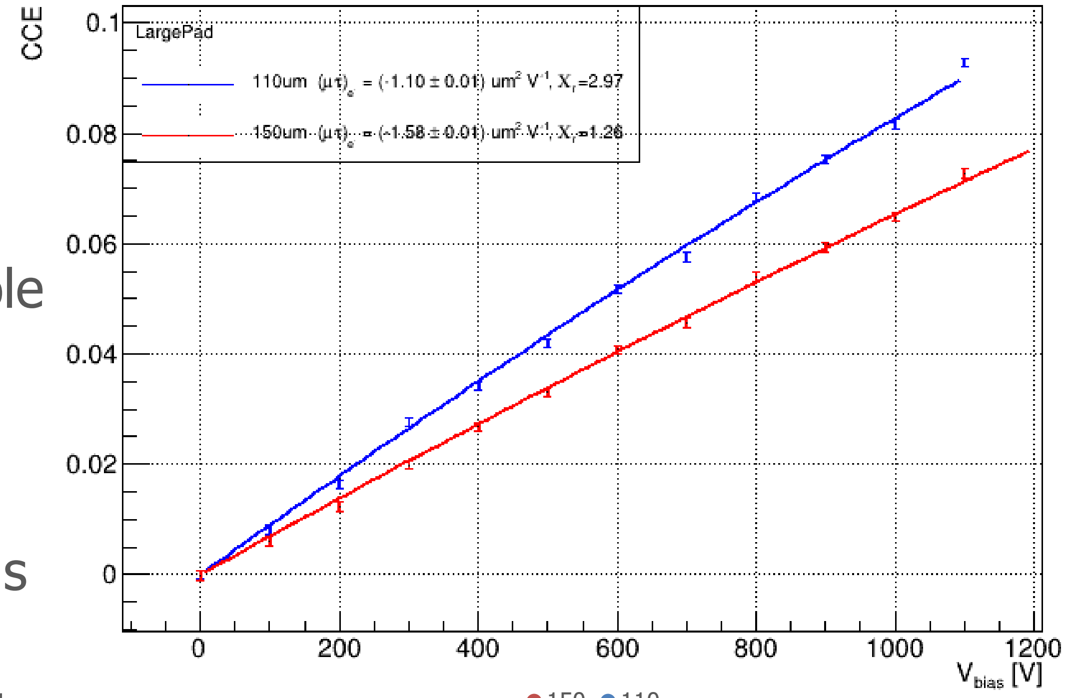
Backup

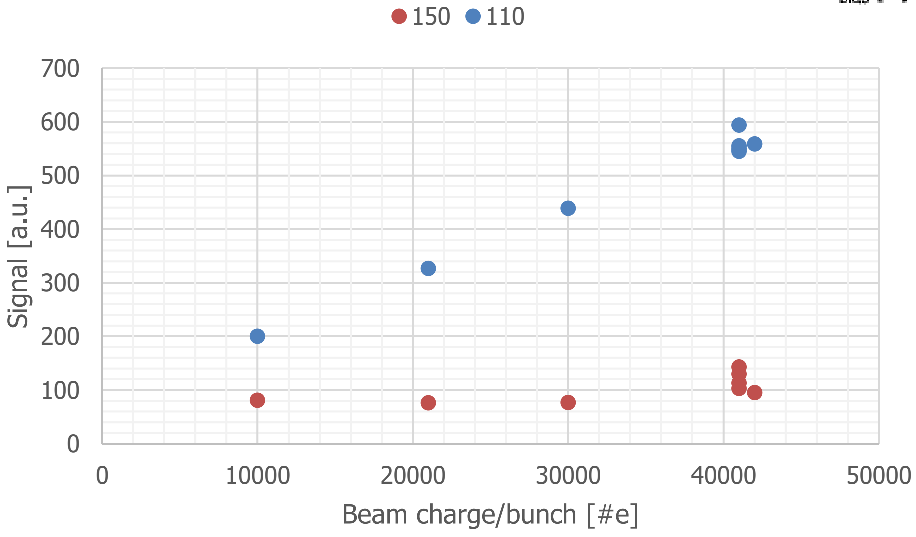
Università degli Studi di Padova

Sapphire characteristics

Sapphire charge transport properties

- Dominant contribution to charge transport from electrons
- Electron mobility ($\mu_e \sim 600\ \mathrm{cm}^2\ \mathrm{V}^{-1}\ \mathrm{sec}^{-1}$) 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$^-$/bunch (at BTF-INFN Frascati)

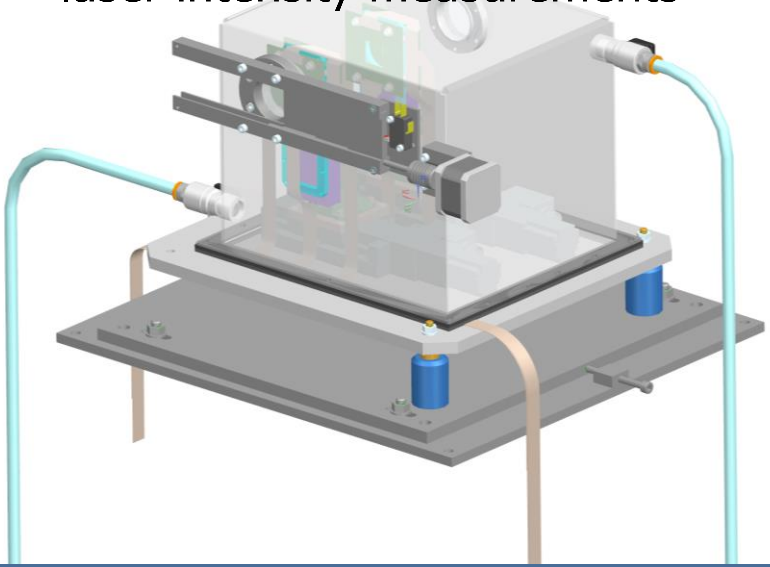




Sapphire micro-strip detector for high intensity gamma beam monitoring for the LUXE experiment at DESY

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



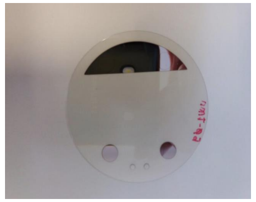
Keypoints

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

R&D on sapphire detectors

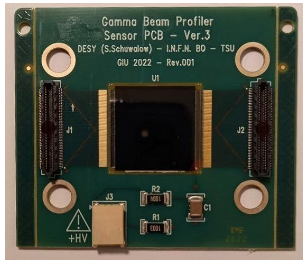
- Test beams

Sapphire pads
(May 22, INFN-LNF)



Sapphire 4-strip
(Sep. 22, CERN)

Sapphire 192-strip
(Dec. 22, CERN)



- Simulations

Open-source sapphire detector simulator

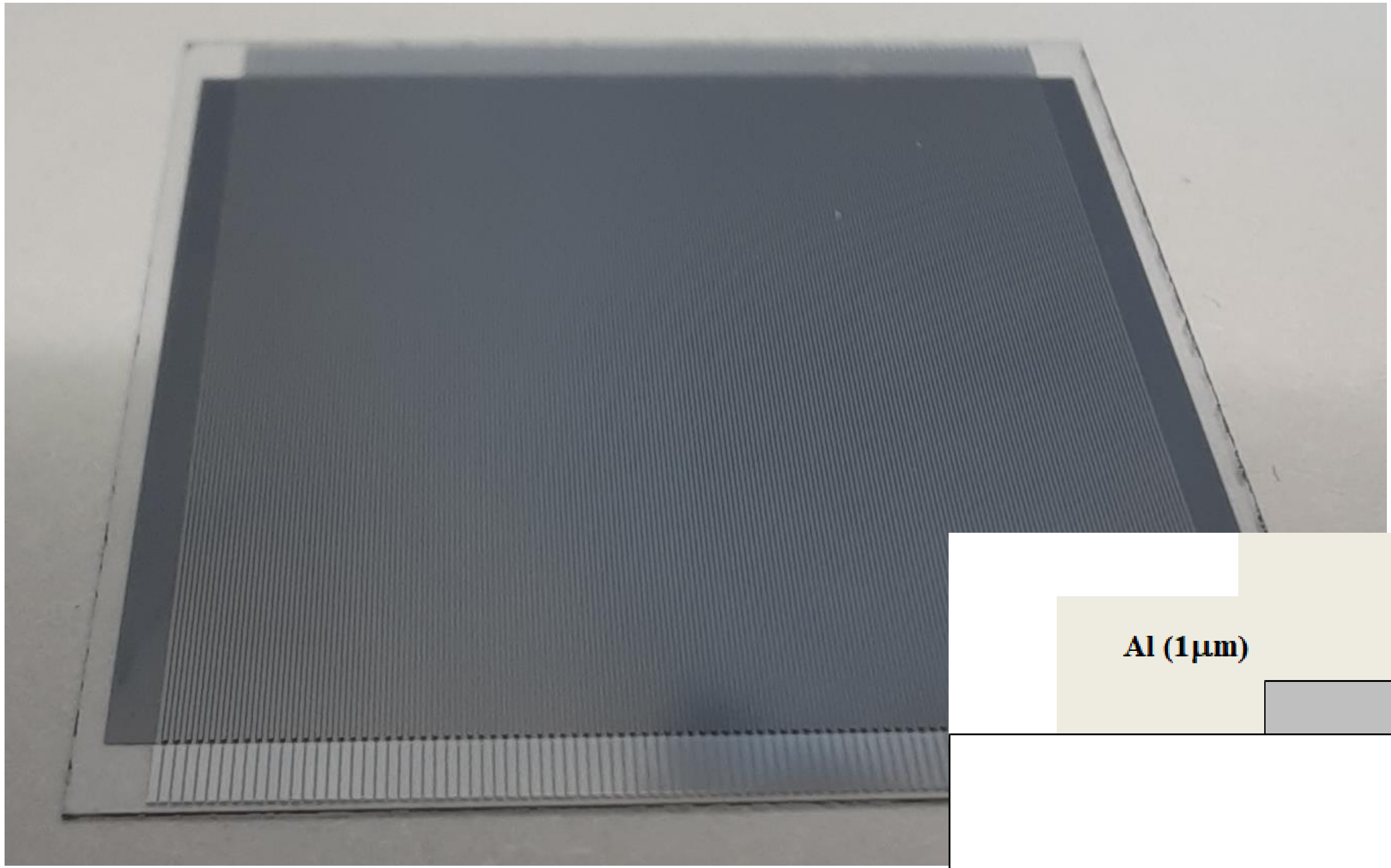
ap² allpix squared

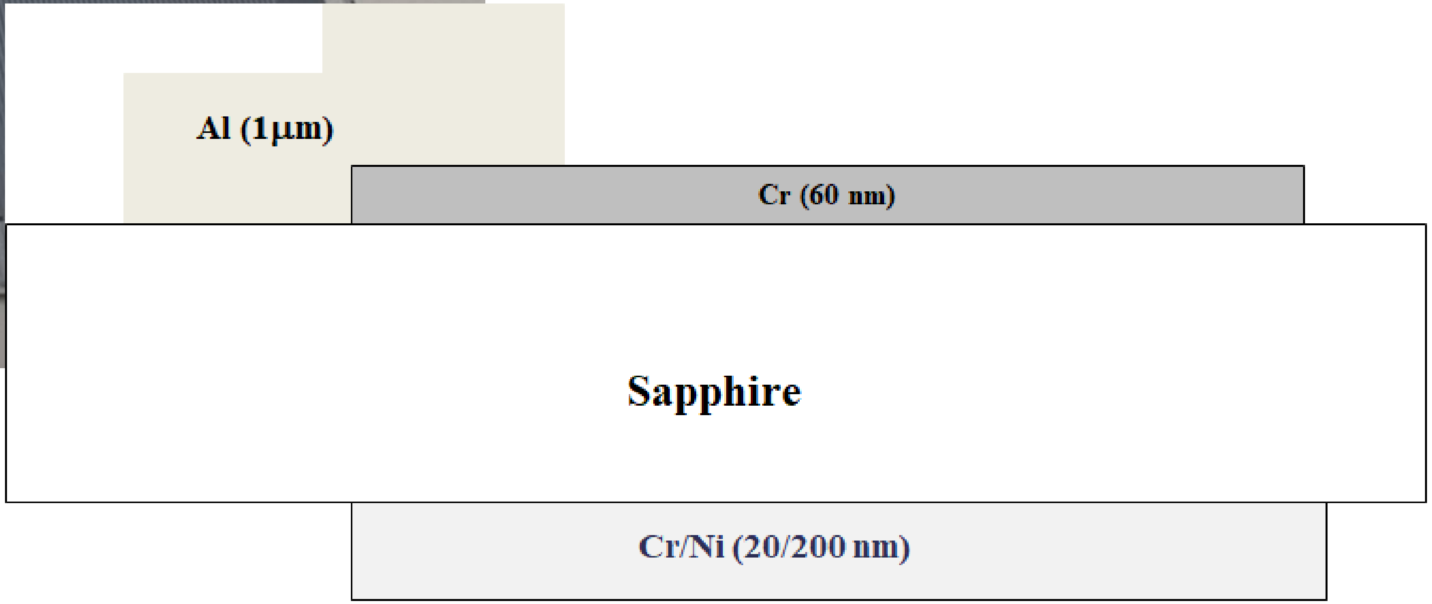
SALOME9 THE OPEN SOURCE INTEGRATION PLATFORM FOR NUMERICAL SIMULATION

ParaView

Elmer

Metallization

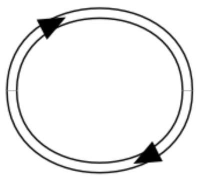




LUXE *in a nutshell*

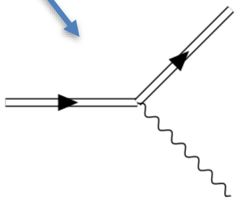
Scientific goals

- 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

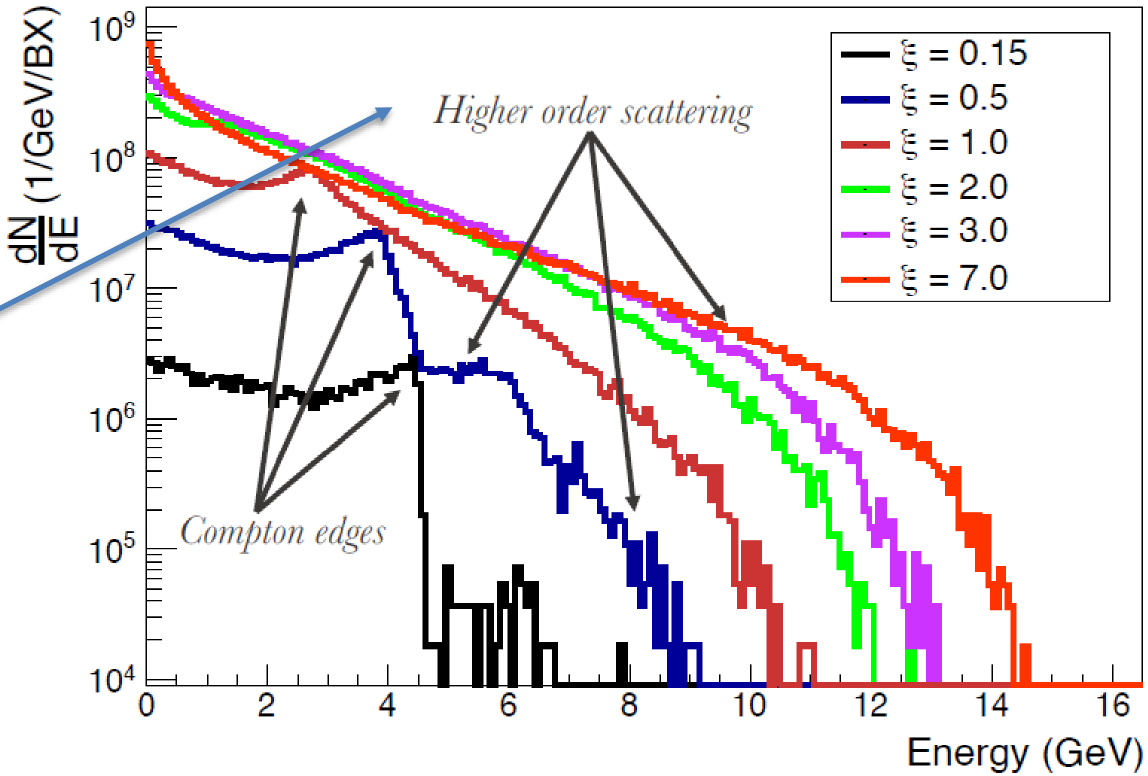


$$N_{pairs} = 2VT\frac{e^2E^2}{(2\pi)^3}\exp\left(-\pi\frac{m^2}{eE}\right)$$

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



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



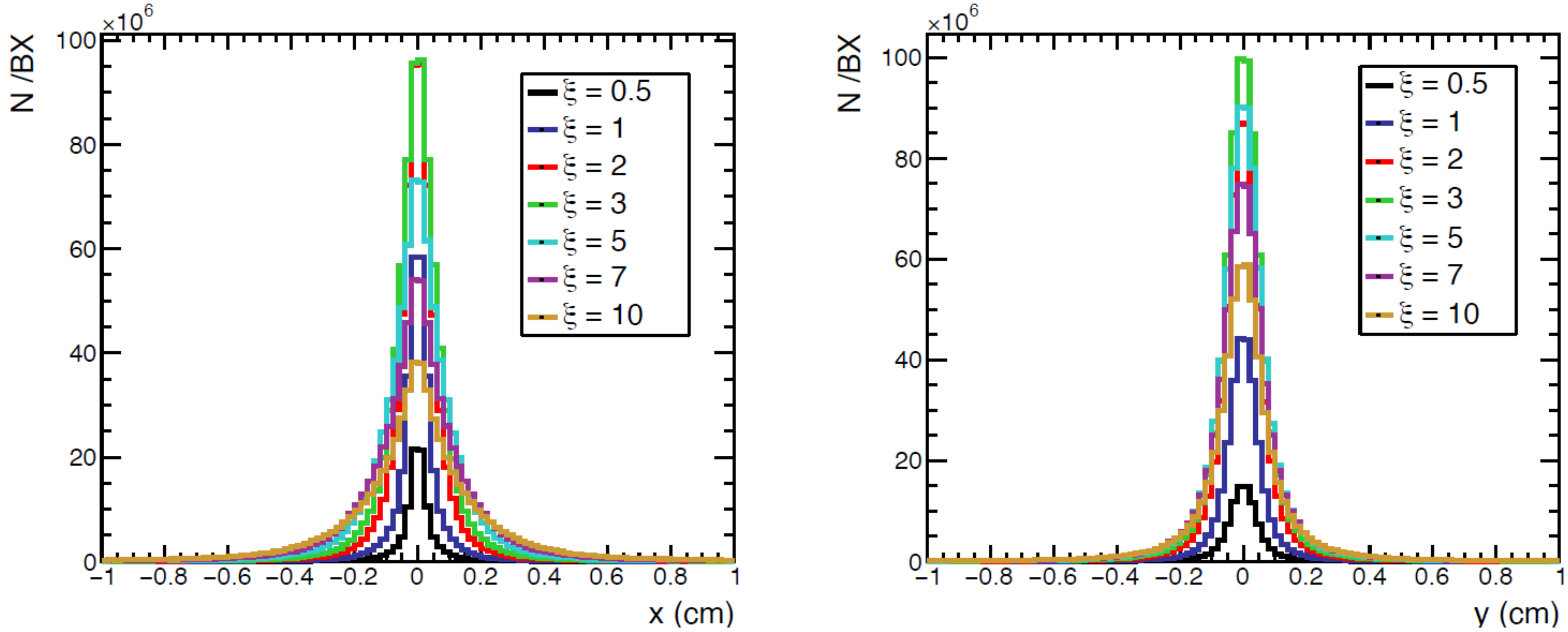
LUXE. The gamma beam monitor

The angular distribution of Compton photons is strongly dependent on the laser intensity (ξ) **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 ξ value

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

| Spatial distribution of γ 11m downstream the IP

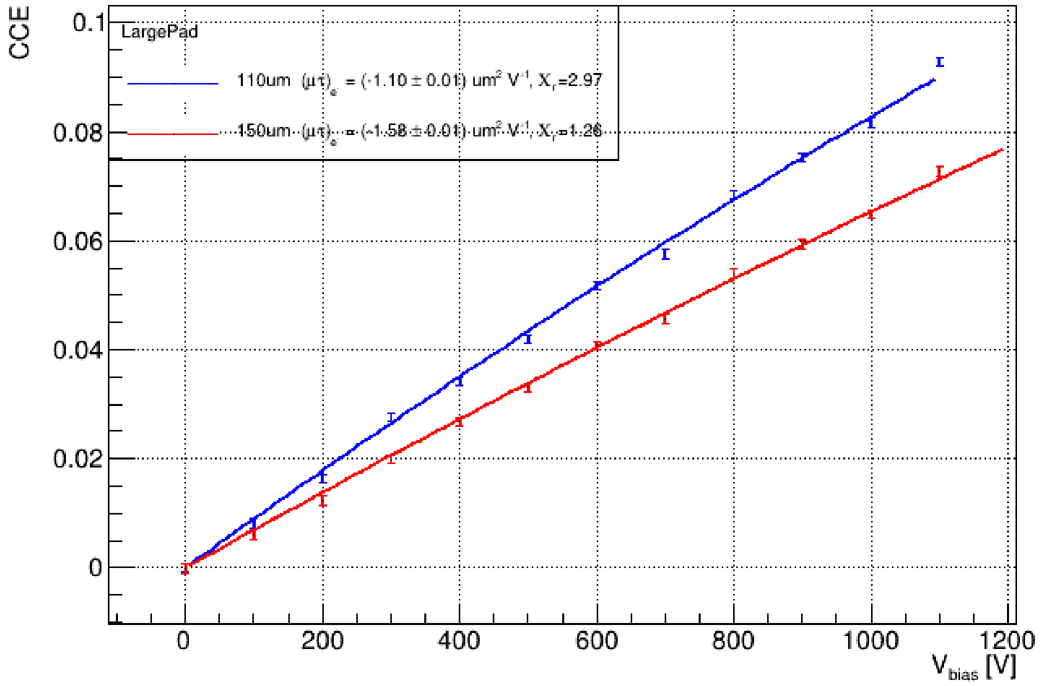


The **Gamma Beam Profiler (GBP)** is envisaged for this task – i.e. beam monitoring the gamma beam.

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

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

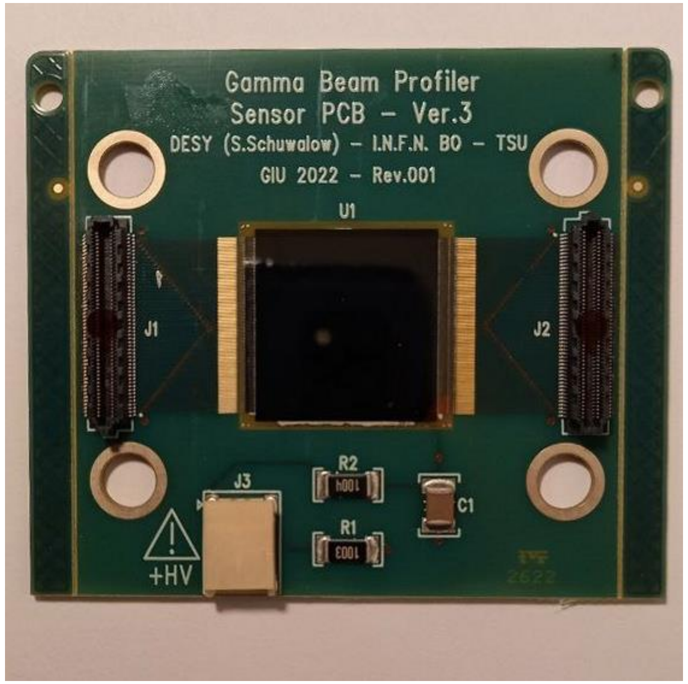
In the literature, the average sapphire pair excitation energy is 27 eV, corresponding to about 22 e/h-pairs per um.

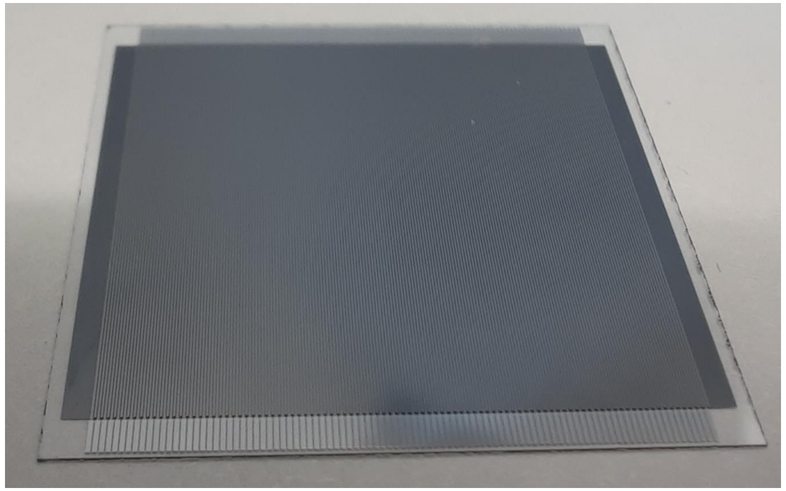
The charge collected at the implants is typically lower, due to recombination of carriers. It is determined by the *charge collection efficiency*

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

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



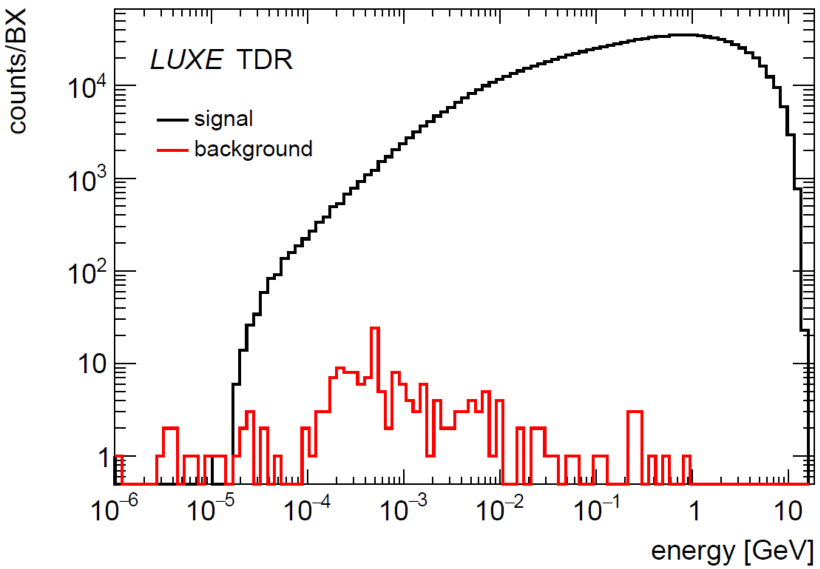


Interaction mechanism in LUXE: gamma conversion

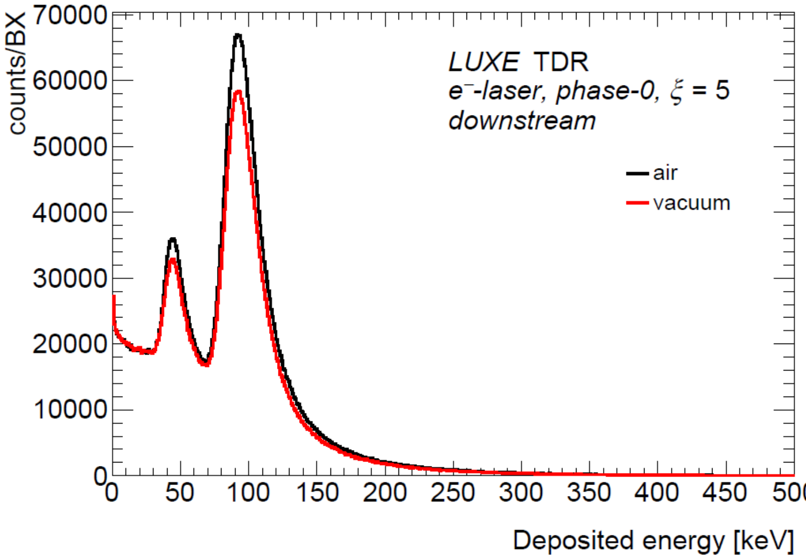
Typical interaction of the HE Compton's photon beam with sapphire is by means of photon conversion into electron/positron pairs. This occurs with a probability of roughly 1/1000.

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 (ξ=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 100um-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 photos 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*

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

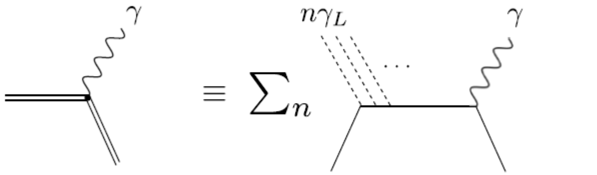
which is orders of magnitudes above artificially producible EM field.

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 γ to $\mathcal{E}_* = \gamma \mathcal{E}(1+\cos\theta)$ with θ the collision angle (which for LUXE is 17.5 deg)

LUXE. Scientific Goals

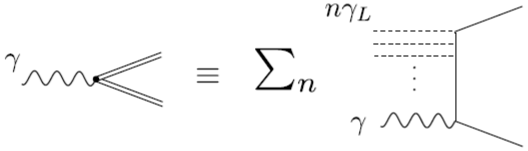
LUXE Scientific Goals

- 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:



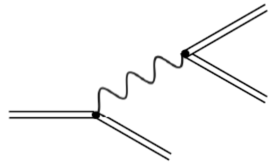
Non-linear (inverse) Compton scattering

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



Breit-Wheeler production

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



Non-linear Trident process

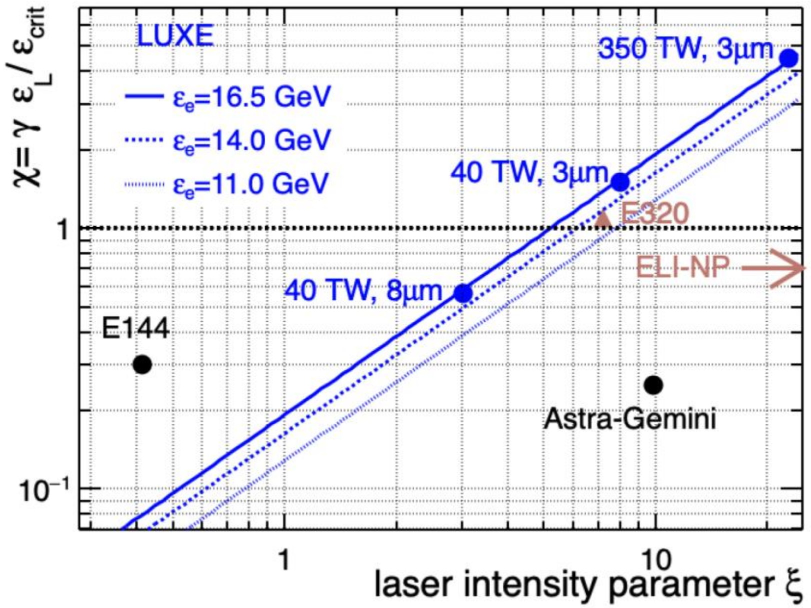
$$e^- + n\gamma_L \rightarrow e^- + \gamma \quad \text{and} \quad \gamma + n'\gamma_L \rightarrow e^+e^-.$$

Parameter space

The electron-laser interaction is characterised by the classical non-linearity parameter ξ, the quantum non-linearity parameter χ and the energy parameter η.

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

with ω_L, ϵ_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 ξ 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 ξ^{2n}
- In weak-fields probabilities of QED processes scale as $\sim \xi^2$ (n=1)

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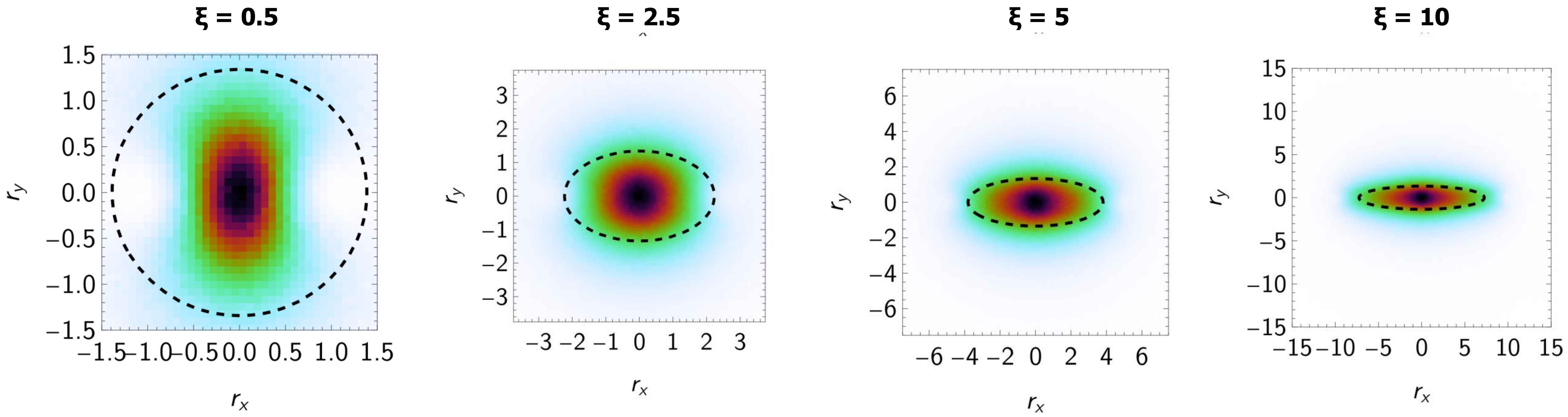
$$\xi^2 \sim (\sigma_{\parallel}^2 - \sigma_{\perp}^2)$$

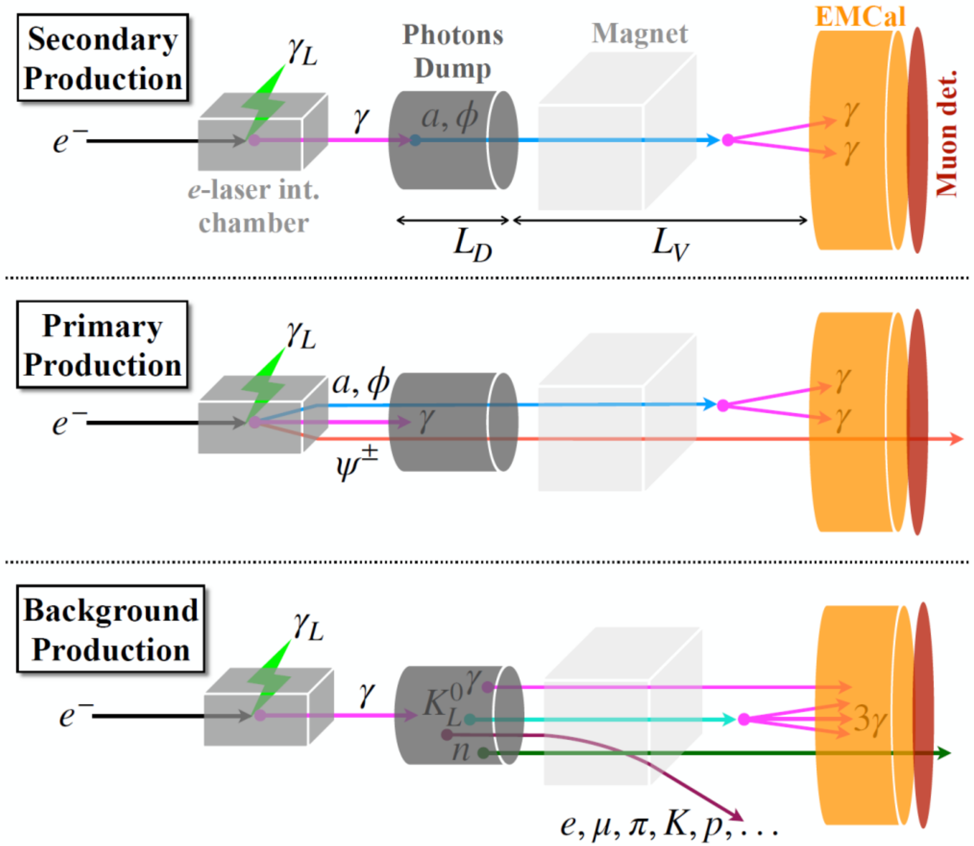
| Angular distribution of Compton scattered photons at different laser intensities

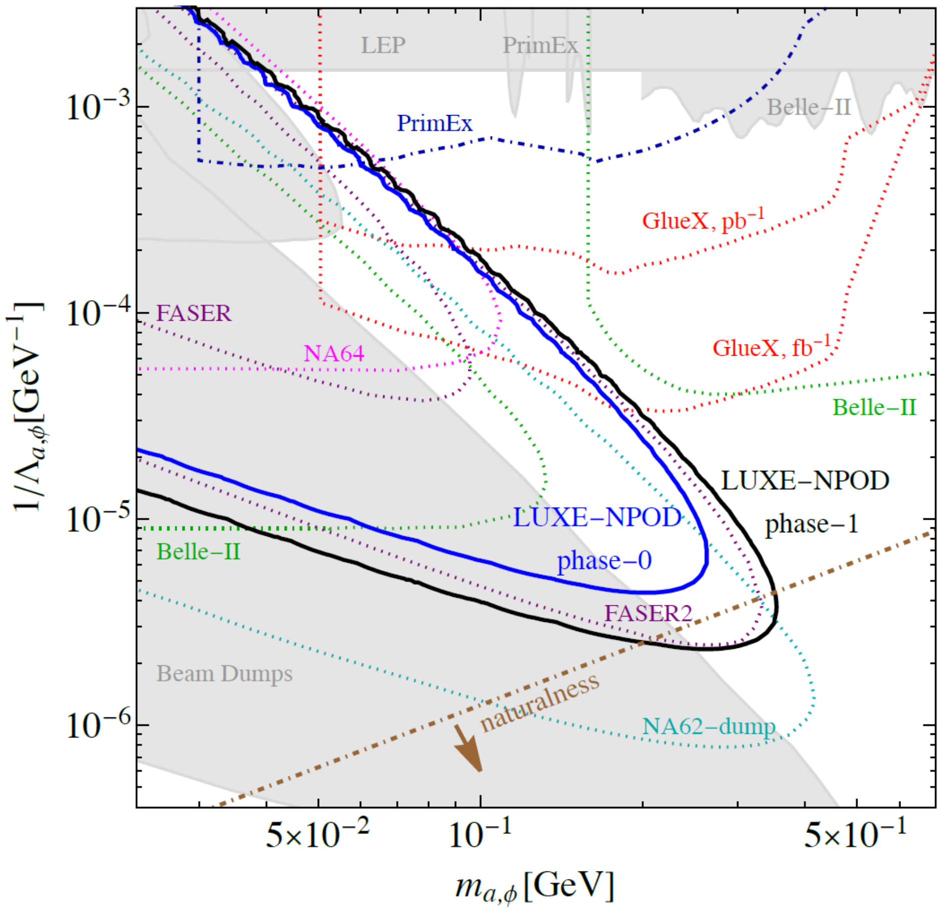


The **Gamma Beam Profiler (GBP)** is envisaged for this task – i.e. beam monitoring the gamma beam.

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 110um, 150um) 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 (100um, 150um, 150um)

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.

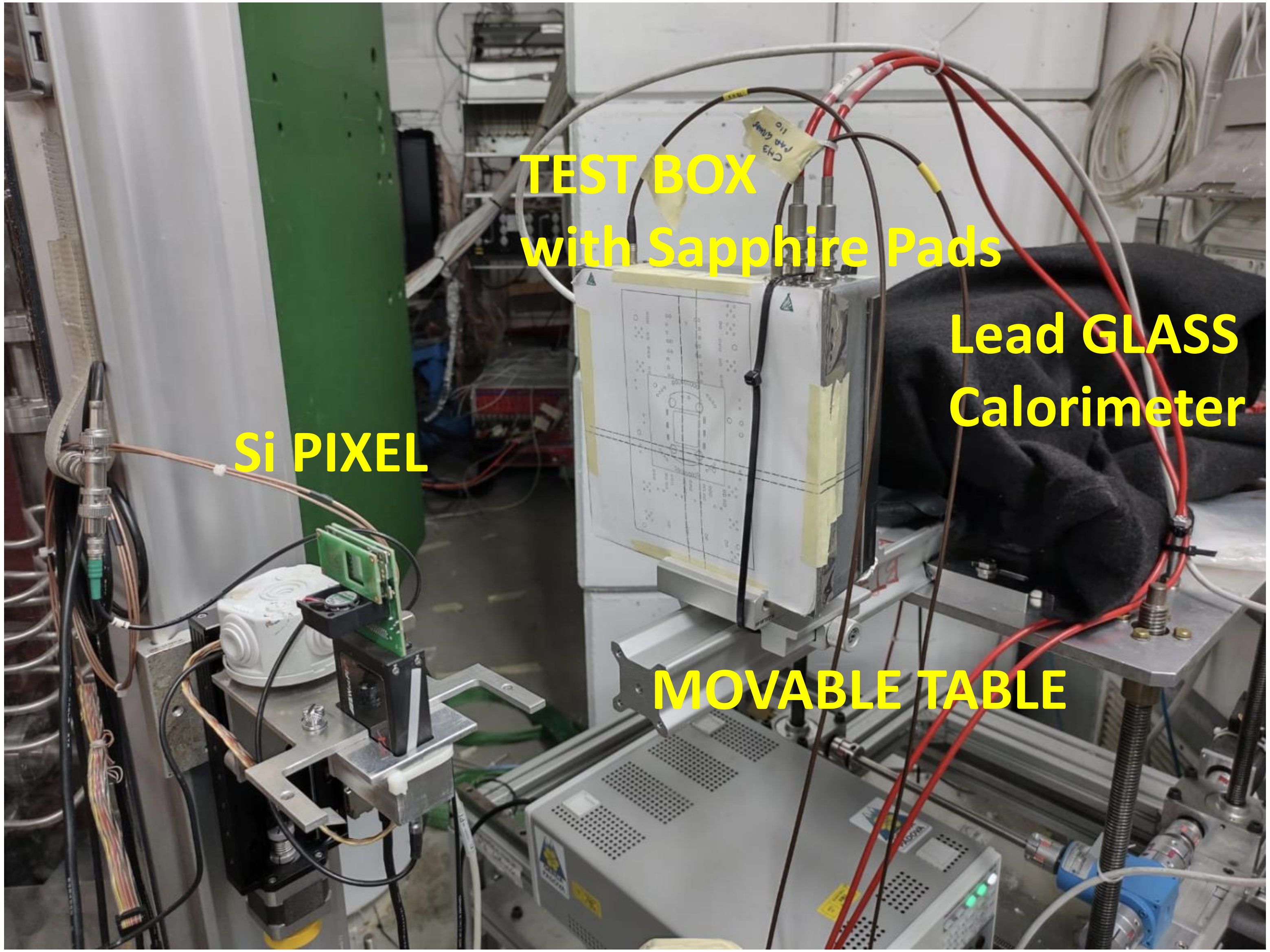
Measure programme
- Electronics
- Radiation damage
- Collected charge
- Profile reconstruction capability

R&D – test beam pads

Sapphire pads *(May 22)*
Test at BTF (*INFN-Frascati*)
of two sapphire pad (d= 1.6, 5.5 mm) detectors (thickness 110um, 150um) with 300MeV electron beam (up to 3e10 e-/s)

Measure programme

- Collected charge (V, beam, damage)



R&D – test beam 4-strip

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DESY.

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