RASER – A python package for solid-state radiation detector simulation

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On behalf of RASER team

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Outline

- The motivation of RASER
  - Why Python?
  - Why another software?
- Device simulation for electric properties
  - electric field, weighting field, IV&CV, irradiation
- single event simulation for prototypes
  - energy deposition, carrier transport, signal generation, electronics
- single event for strip detectors
  - signal generation for detectors with electrode array, cross talk
- multiple events
  - batch job, statistics from waveform, resolution calculation
- various application situations
- Conclusion, Next steps & More

The Motivation of RASER – Why Python?

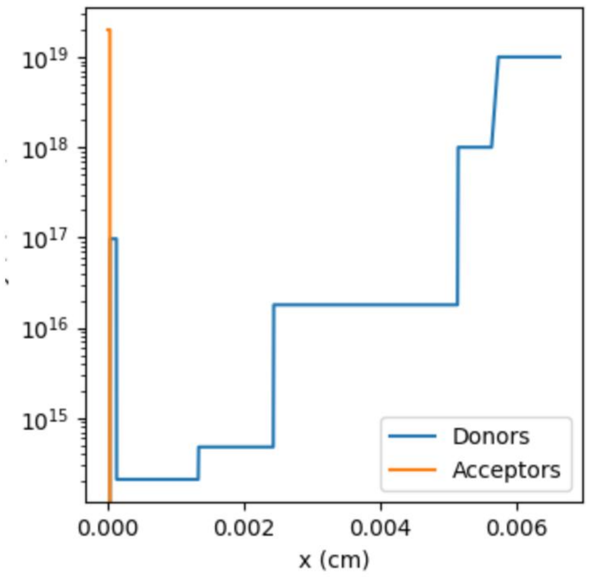
- Utilizing great Python packages from the open-source community
  - Scientific calculating & plotting: Numpy, Scipy, Matplotlib
  - Python interfaces from HEP community: PyROOT, Geant4-pybind
  - Devsim by Juan Sanchez for electric field and weighting field calculation
- Make it full open-sourced
  - Easy to distribute by Pypi
  - No limitations from commercial software licenses
- More user-friendly, especially for those who have less experience in programming
  - Easy to start with than C++ based softwares
  - Python package management is easier than C++ library management

The Motivation of RASER – Why another software?

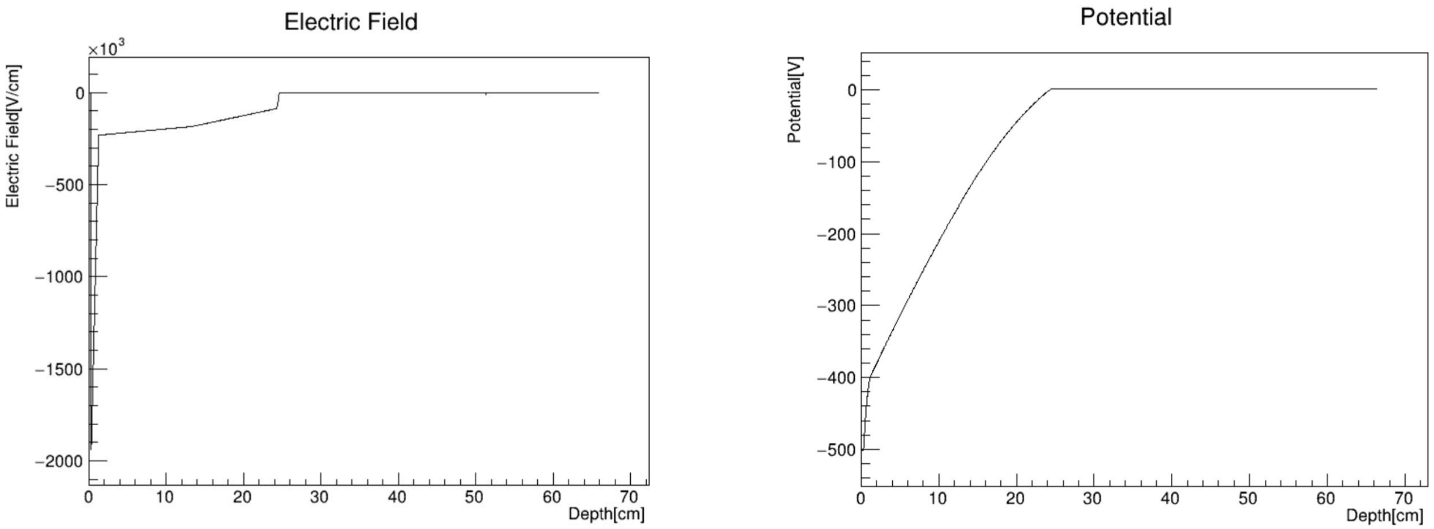
- Establish a comprehensive understanding of detectors fabricated by other materials like 4H-Silicon Carbide
- Better support for detector prototypes, especially those with multiple electrodes
- Multiple simulated experiments
  - alpha/beta source injection
  - test beam
  - transient current technique
  - luminosity monitoring
- For further information, refer to Suyu's talk (https://indico.cern.ch/event/1507215/contributions/6537319/)

Electric Property Simulation – Electric Field

- Solving the Poisson equation and the carrier continuous equations in steady state
    - Using Scharfetter – Guemmel framework provided by Devsim
        - git repo: http://github.com/devsim/devsim
    - Necessary for non-planar like devices (like 3D) under non-depleted voltage



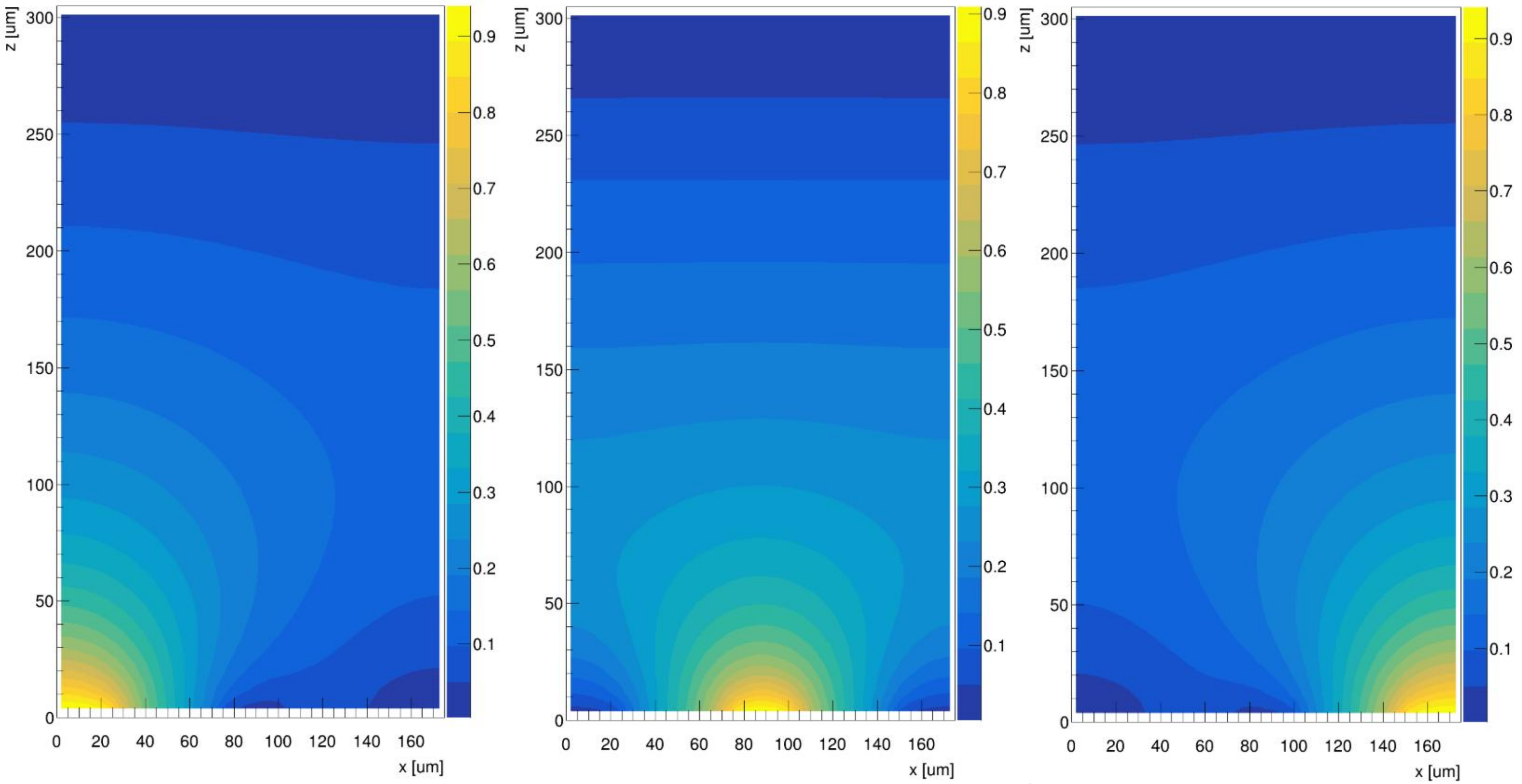
The doping profile of an 1D 4H–SiC LGAD prototype, total thickness 66.4um, active thickness 25.1um.



The Electric field and the potential of the 4H–SiC LGAD, bias voltage –500V on the top. Under bias voltage enough to deplete the device, the electric field and the potential look just the same as one could obtain from barely the Poisson equation, with doping as charge.

Electric Property Simulation – Weighting Potential

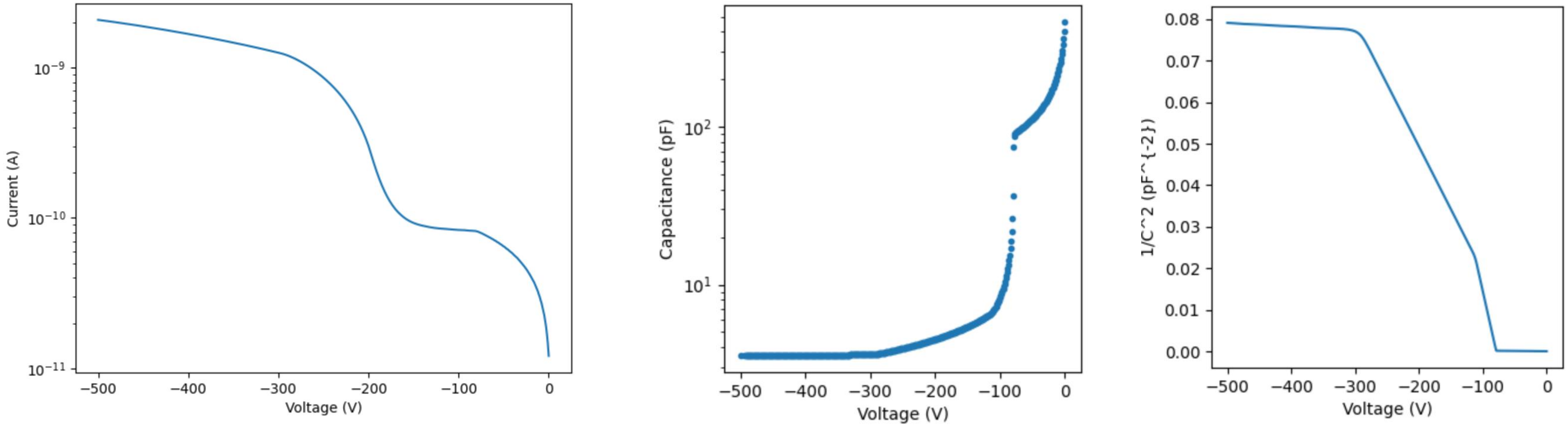
- Two approaches
  - 1: calculate the electric potential of the original system which the charges are all removed and a bias voltage of 1V is set onto the specified electrode
  - 2: after the original electric potential is calculated, add another 1V bias voltage onto the specified electrode, obtain a new electric field and take the substraction between the new potential and the old potential



The weighting field of a silicon strip sensor prototype with 3 strips (thickness 300um, total width 175um, pitch 75um, strip width 25um).

Electric Property Simulation – IV & CV

- IV data obtained from the continuous equations
- Additional AC simulations are done for CV data
- Both are considered of area factors



Simulated I–V, C–V and C^{-2}–V relations of the 4H–SiC LGAD. The area factor is set to be 0.01 cm^2.

Electric Property Simulation – Irradiation

- Based on SRH model and trap assisted tunnelling
- For Silicon, HPTM model is referred and adjusted
  - https://arxiv.org/abs/2504.20463
- For Silicon Carbide, $Z_{1/2}$ and EH_3 are considered
  - Details in Zaiyi's talk: https://indico.cern.ch/event/1507215/contributions/6540484/

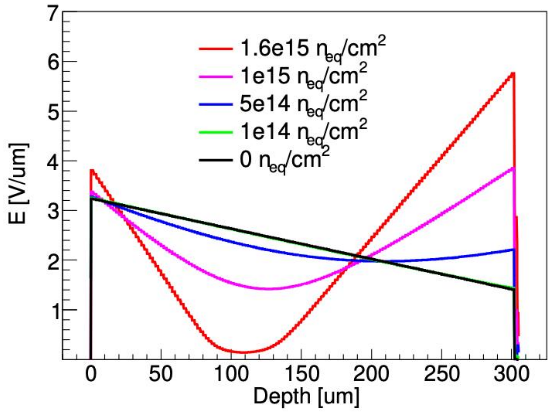


Fig. 3 Simulation results of electrical field distribution with different fluences at 700 V

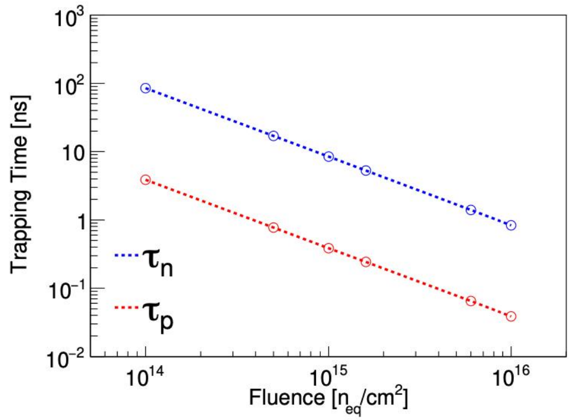


Fig. 4 Simulation results of trapping time with different fluences

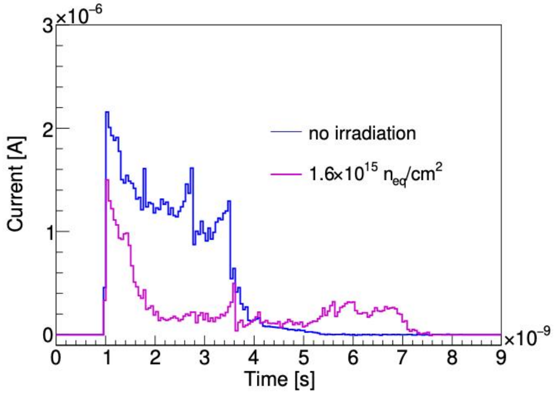
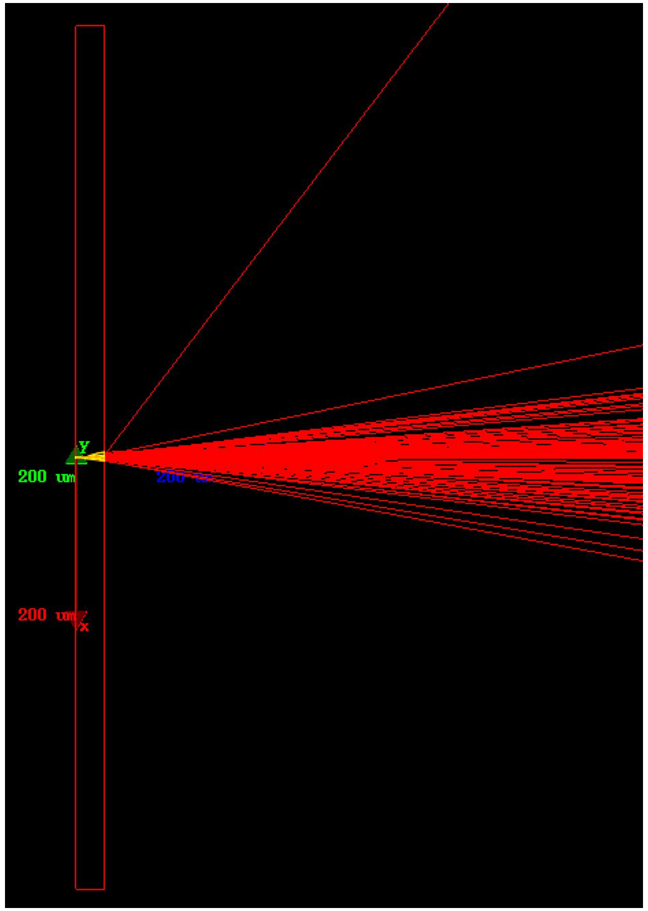


Fig. 5 Simulation of induced current waveform with non-irradiation and 1.6×10^{15} n_{eq}/cm^2 fluence at 500 V

Single Event Simulation – Energy Deposition

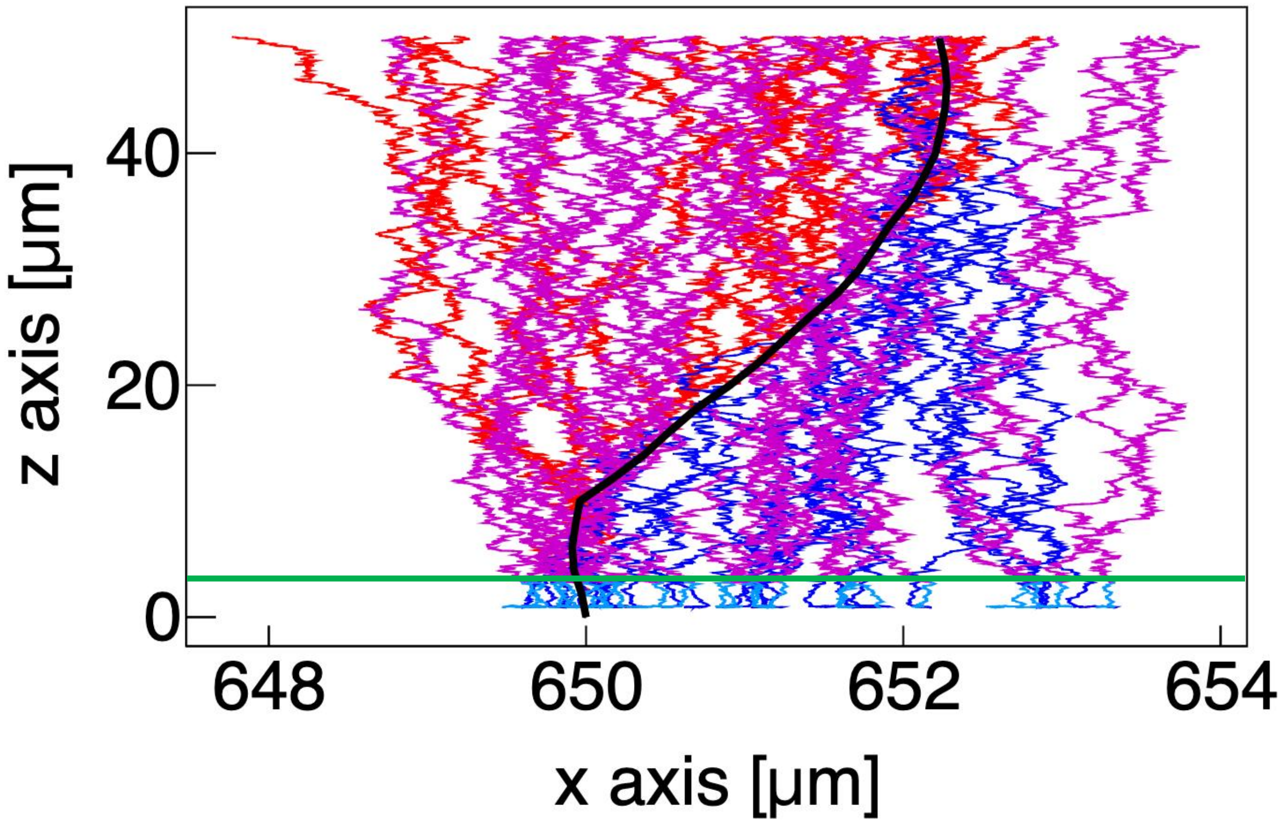
- The detector geometry need to be constructed in Geant4
- After the materials and the geometrys are defined, a particle gun is appended to the system
- Several events are generated with different track and energy deposition
- The deposited energy is converted to excited carriers, which drift inside the detector and generate signal (next page)



A Sr90 beta source is placed on the left of the DUT (the red rectangle). After passing through the DUT, the beta rays are greatly scattered.

Single Event Simulation – Carrier Transport

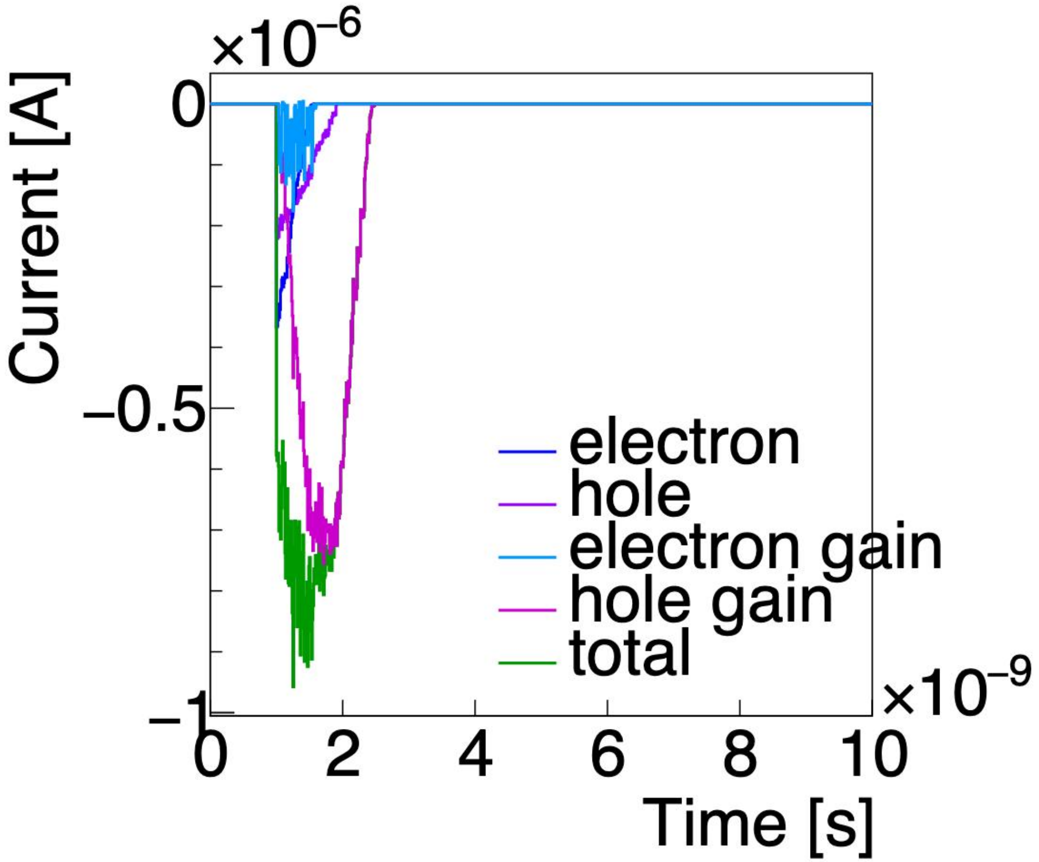
- Starting at where the injected particle depleted its energy, several pairs of electrons and holes start to drift under the electric field of the device
- Drift will end when the carrier reaches the border of the device or enters an area with low electric field intensity (except for non-full-depletion MAPS)
- For LGADs, after an carrier reached the gain layer, M (equal to the gain) carriers with opposite sign will be released at the gain layer and start to drift



The black line illustrates how an incoming beta ray passes through a silicon LGAD. The original carriers (red for holes, blue for electrons) start to drift immediately after generated, and when the holes touch the gain layer (the green line), the gain carrier pairs will be generated from avalanche (magenta for holes, cyan for electrons).

Single Event Simulation – Signal Generation

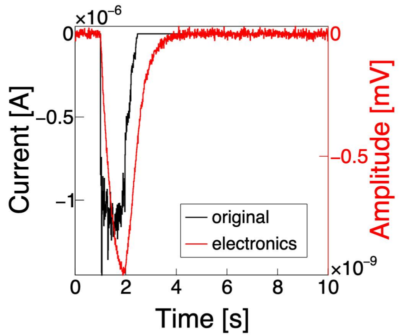
- According to the Shockley–Ramo theorem, a drifting charge will induce a current on certain electrode, the value of which is $I = q*v*E_w$
- As there are a great number of carriers, we turn to calculate $I*dt = q*dx*E_w = q*dU_w$ instead
  - avoids differentiating the weighting potential
  - shows good compatibility with TH1F format, because we can just Fill() the signal generated by one carrier into the total signal



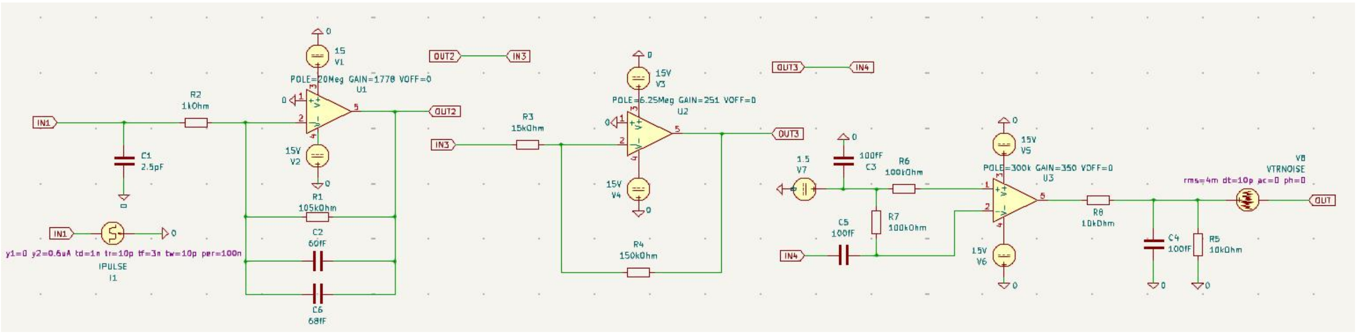
The generated signal by beta ray in a silicon LGAD. The four components and the overall signal are shown in the legend. The gain of the LGAD is 3.3.

Single Event Simulation – Electronics

- Original signal needs to be amplified to be observed or further processed
  - Noise are considered too
- Two approaches:
  - Convoluting the signal with pulse response functions modelled from an amplifier
  - Using NGSpice by sending the signal into a .cir netlist file
    - NGSpice: https://ngspice.sourceforge.io
    - KiCad: https://www.kicad.org



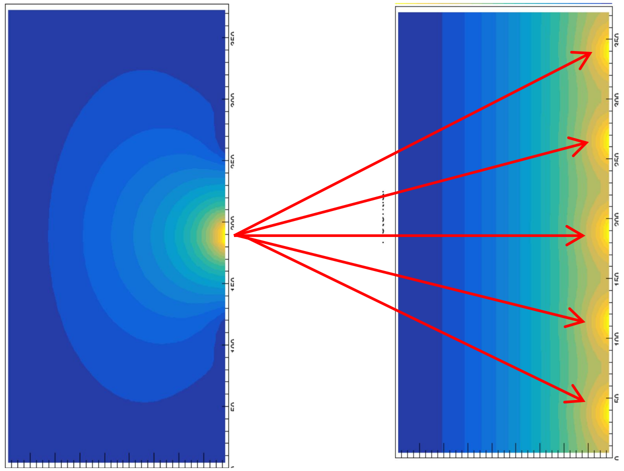
Approach 1: the signal (black line) is convoluted into an amplificated waveform (red line).



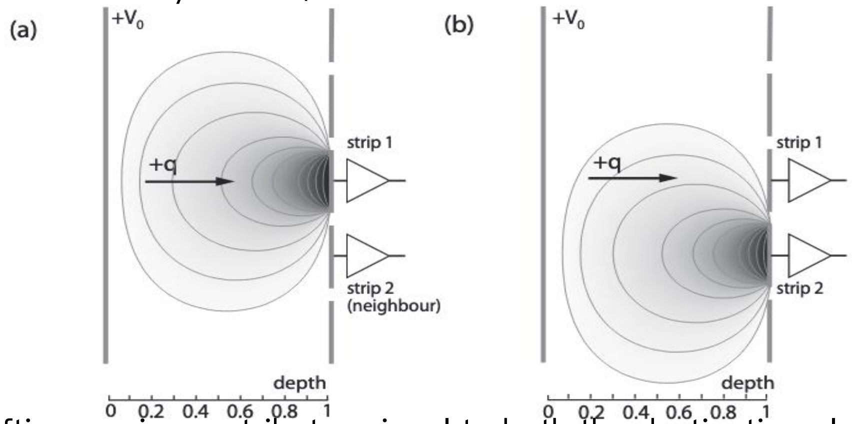
Approach 2: an amplifier circuit drawn in KiCad, which could easily converted into an NGSpice netlist, which could be utilized by RASER as the front end electronics.

Strip detectors – Adjustments on the Electric Field and Weighting Field

- For detectors with many readout electrodes (say > 10), it is hard and unnecessary to solve the fields across the whole detector
- After considering the effect from neighbouring electrodes, all the electrodes could be assigned with the same fields because of periodicity
- Carriers will not only induce signal on the nearest electrode, but also on other electrodes with non-zero weighting potential at the place of the carrier



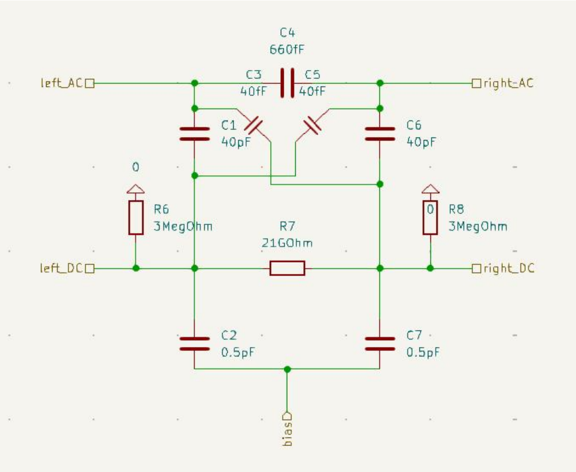
For each electrode, the electric nearby is periodic but the weighting field is not, while the weighting field of every electrode looks the same. That is why we could assign the same weighting field into every channel, avoiding calculate them many times. (But this is also true for the real electric field)



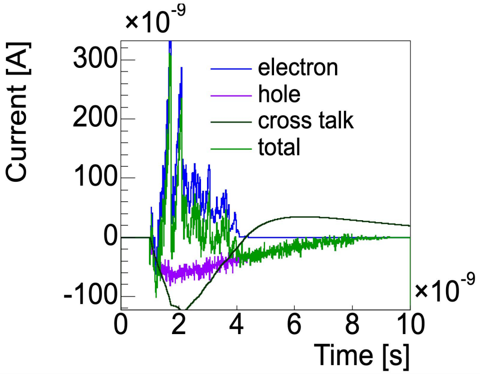
An drifting carrier contributes signal to both the destination electrode and its neighbouring electrode (figure from *Particle detectors: fundamentals and applications* by Hermann Kolanoski & Norbert Wermes)

Strip detectors – Cross Talk

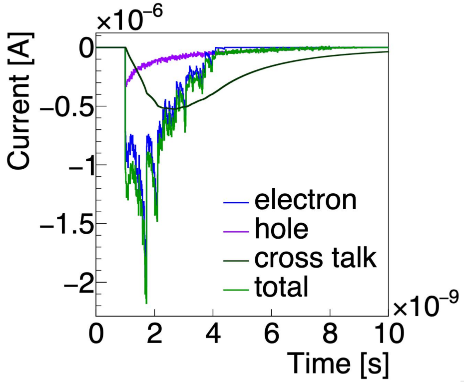
- Parasitic capacitances between neiboughing electrodes will change the output signal
  - Some strip sensor utilizes this feature to reduce readout channels while keeping the space resolution unchanged



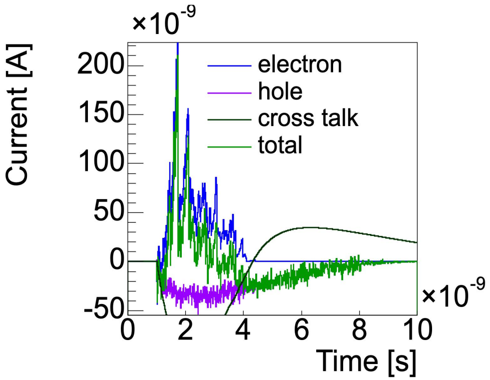
Resistances and capacitances between two readout strips in KiCad.



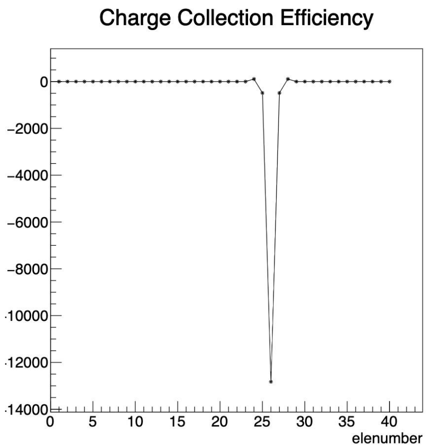
signal of electrode 25



signal of electrode 26



signal of electrode 27

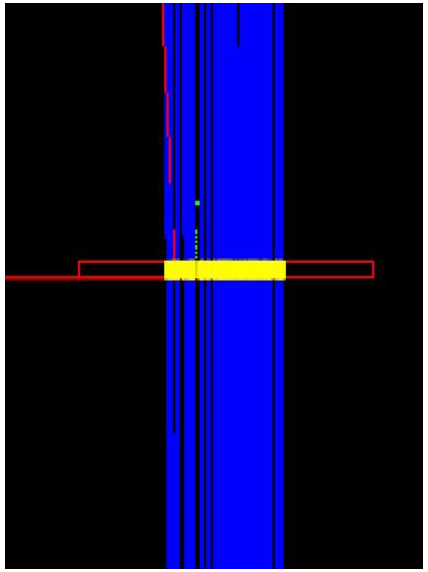


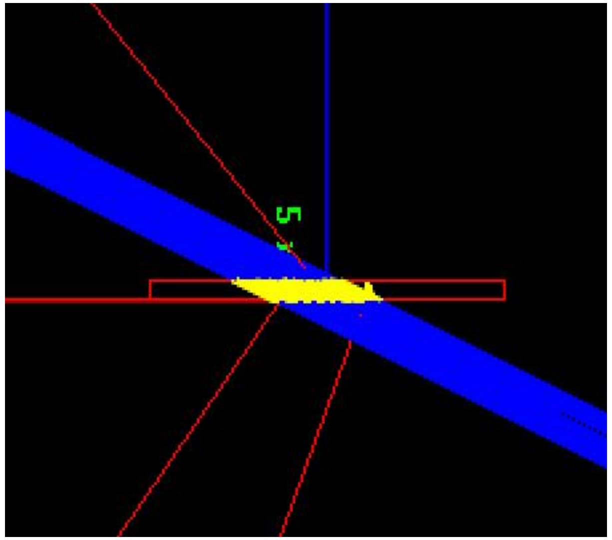
charge collection of the 40–channeled sensor

Signals induced on a 40–channel AC–readout strip sensor (left 3 figures) from a MIP hitting on electrode 26. Without cross talking (merely considering the expansion of the weighting field), the signs of the pulse on the neighbouring electrodes are opposite to the original one. But with cross talking, these signs appear to be the same, and lead to a charge collection with the same sign as the target electrode (right).

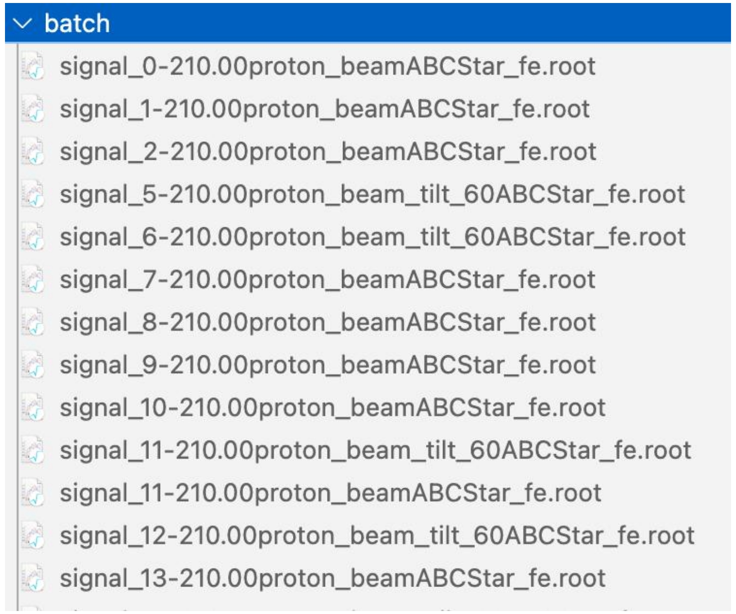
Multiple Events – Batch Job

- For obtaining the statistical performances (e.g. the space resolution, the time resolution) of a detector, a great amount of events need to be simulated
- HTCondor service is utilized (temporarily only available for IHEP users)





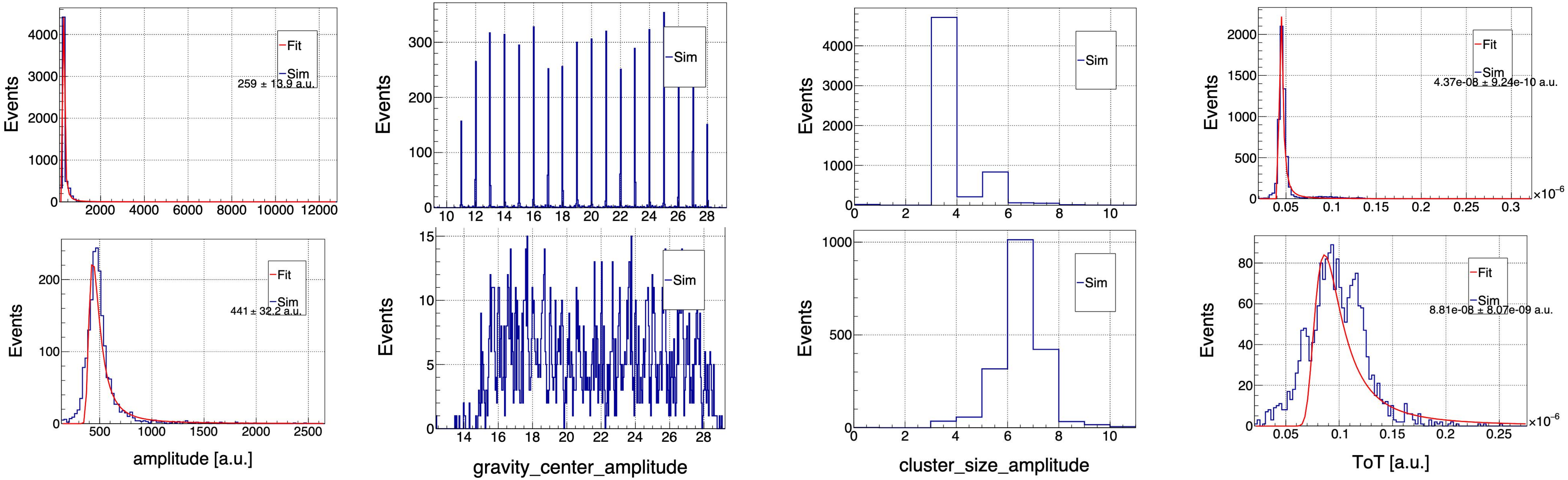
For calculating the space resolution of a strip sensor, about 10000 events are needed. We divide the events in to 100 jobs and send them to compute platforms by HTCondor service. The figures on the left and the right correspond to different injection angles.



Every running result of a job will be filled into an .root file by the form of ROOT TTree object. The TTrees are able to be further analysed.

Multiple Events - Statistics from waveforms

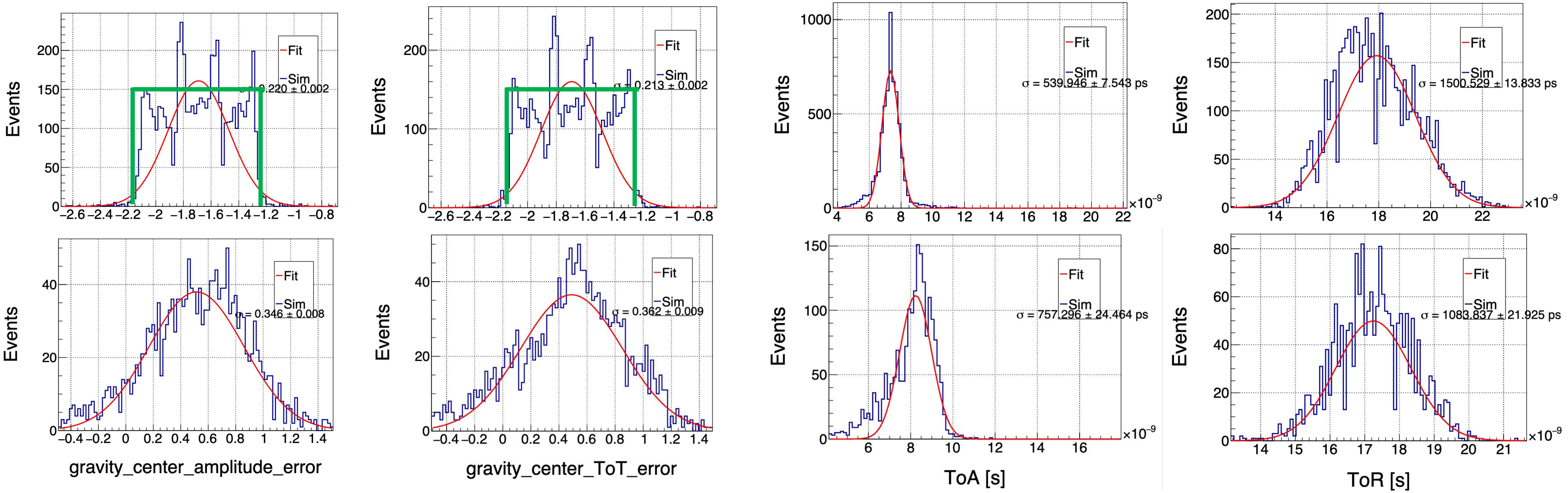
- Every event brings a list of characterized datas
  - total amplitude, gravity center, cluster size, time over threshold, etc.
  - their distributions reflect the procedure of particle-detector interaction



The amplitude, c.o.g., cluster size and ToT of an strip sensor under 3 GeV proton beam. The upper figures are for perpendicular injection, while the lower figures coresopnds to an injection tilted for 60 degrees. Beacuse of the existance of a strong cross talk, the cluster sizes tend to be bigger than other strip devices.

Multiple Events – Resolution Calculation

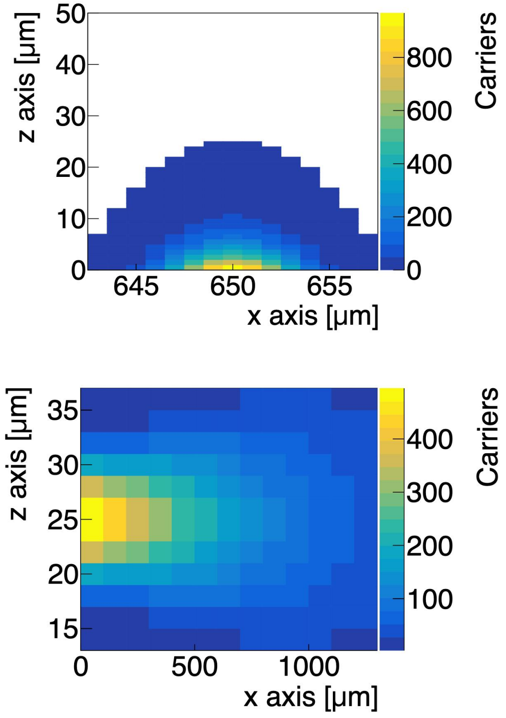
- With proper knowledge of the incoming particle, we could calculate the error of the measured datas from the real ones
  - in reality we use telescope or trigger, but in simulation we have already known it



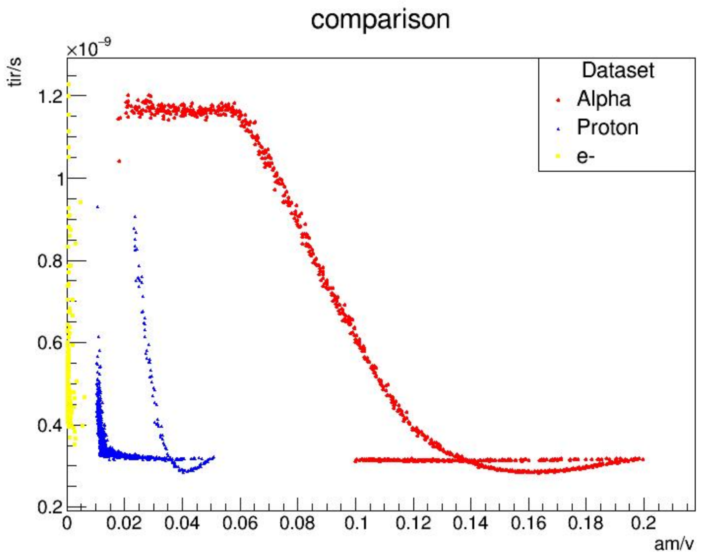
Two kinds of spacial resolution using amplitude and ToT (strip pitch as unit) and two kinds of time resolution using arrival time and constant ratio discriminator. The upper figures are for perpendicular injection (expected distribution of the gravity center error is drawn in green), while the lowers are for an injection tilted for 60 degrees.

Application situations

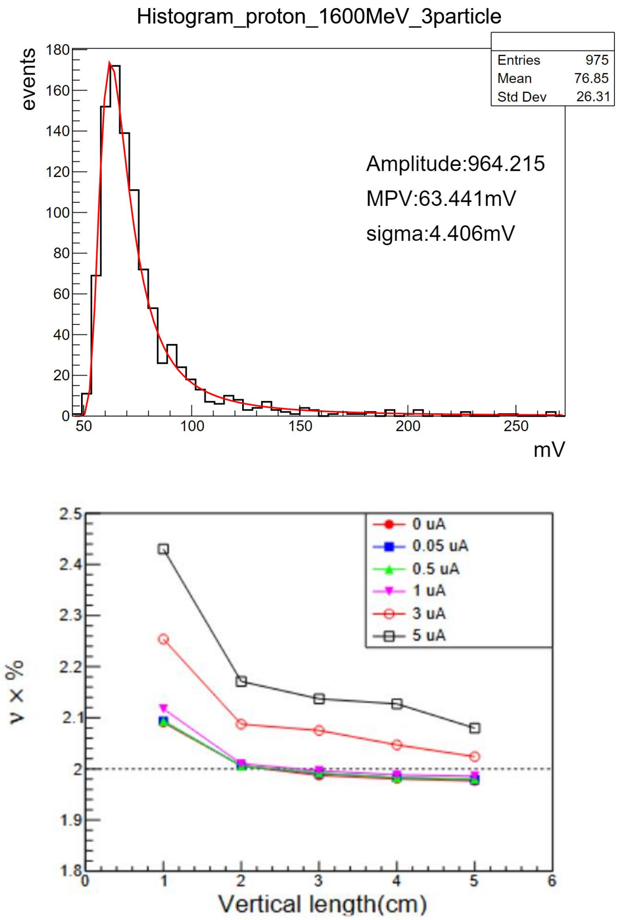
- See more in Suyu's talk (https://indico.cern.ch/event/1507215/contributions/6537319/)



Top & edge TCT for silicon and silicon carbide



Particle identification in TOKAMAK



Beam monitoring & Luminosity monitoring

Conclusion, Next steps & More

- Conclusion
  - A python-based package, RASER, is built for simulation of solid-state detectors, mainly focusing on novel designs and applications
  - Through a series of processes, one could obtain several properties of the new designed detector, including its responce to certain stimulation, its resolution, and its performance under irradiation
- Next steps
  - extend our simulation to pixel detectors, 3D detectors & resistive silicon detectors
  - include open-source PDK & fabrication simulation, digital front end, and so on
- Contacts
  - git repo: https://code.ihep.ac.cn/raser-team/raser
  - pypi: https://pypi.org/project/raser/

Thanks for listening and welcome to contribute!