TRACS : Transient Current Simulator

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Summary

1) Motivation for creating TRACS
2) Simulation Overview and Applicability
3) Characteristics and GUI
4) Transient Currents
5) Example: e-TCT Microstrip Detector
6) TPA-TCT modeling
7) Future Improvements
8) Conclusions

Motivation

- We wanted something that allowed us to study:
  - <u>**Shape of transient current pulses in TPA-TCT technique**</u>
    - More info on technique: *Rogelio's talk (introduction)* & Ivan's talk (proof of concept measurement)
  - **Effect of microstrip geometry in e-TCT scan technique for the experimental determination of electric field (effective weighting field approximation)**
- **Result → TRACS (*Transient Current Simulator)***
  - Open source tool for fast simulation of drift dynamics inside detectors with complex geometries (e.g. microstrip detector or pixel detector) based on **Ramo's theorem**.
- **Aim** → *calculate weighting and electric field and obtain transient detector response for an arbitrary charge carrier distribution.*
  - Less rigorous than TCAD simulation (carrier transport not coupled with Poisson solvers) but useful for interpreting experimental measurements .
  - Other alternatives, as Weightfield2, did not a allow easy simulation of TCT techniques (including new TPA-TCT) or other type of detectors.
  - Some characteristics are still on development. However, the software is already working and avaliable.

Simulation Overview

SOLVING FIELDS IN THE DETECTOR → **CHARGE CARRIER TRANSPORT** → **FRONT-END EMULATION**

SOLVING FIELDS IN THE DETECTOR

Detector properties and operative characteristics

Finite Element Meshing

Laplace's Equation	Poisson's Equation
$\nabla^2 \Phi_W = 0$	$\nabla^2 \Phi = -\rho(\vec{r})/\epsilon$
Set BCs	***Set BCs***
Solve Φ_W	***Solve*** Φ
Weighting Field $\vec{E}_w = -\nabla \Phi_W$	***Electric Field*** $\vec{E} = -\nabla \Phi$
Solve $\vec{E}_W$	***Solve*** $\vec{E}$

FEM SOLVER - *FENICS*

CHARGE CARRIER TRANSPORT

An arbitrary charge carrier distribution (e.g. laser simulator or GEANT4)

Ramo's Theorem

$$I(t) = \sum i(t) = \sum q \vec{v}(t) \vec{E}_W$$

Drift of Carriers

$$\vec{v}_{drift} = \mu(E) \vec{E}$$

Diffusion

Thermal gen. / recomb.

Trapping (Monte Carlo)

Charge Gain

Differential Equation

$$\frac{d\vec{x}}{dt} = \vec{v}(t)$$

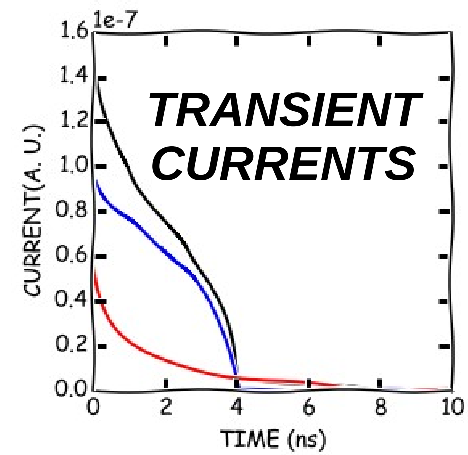
RK4 SOLVER - *ODEINT2*

FRONT-END EMULATION

RC shaping

Amplifier and Readout System Effect

Instrumental Noise



RED → NOT IMPLEMENTED YET

Applicability

- The approach taken here could also be useful for other detectors and techniques, so we decided to allow arbitrary charge carrier distributions:
  - ➔ **All TCT techniques: simulate laser supposing gaussian beam propagation and optical absorption coefficients → α (SPA) or β (TPA)**
  - ➔ Particle crossing / test beam: getting charge profile from GEANT4 or an approximate model of charge carriers generated
- So far we have simulated planar diodes and microstrip detectors (i.e. 2D)
  - ➔ Plans to do the same for 3D simulations (e.g. Planar Pixel Detectors)
- This simulator should only be accurate in the low carrier generation limit, when Ramo's theorem is applicable → electric field inside the detector is not importantly altered by the carriers drifting inside
- **The electric field could be imported from a TCAD (e.g. Sentaurus TCAD) for improved accuracy on the details of the doping profile / irradiation effect.**

Characteristics

- Open Source
- **Developed in C++** (C++11)
- **Based on powerful open source libraries**
  - ***Fenics*** **(FEM solver)**
  - ***ODEINT2***
  - **Visualization**
    - ***2D*** → ***QCustomPlot***
    - ***3D*** → ***VTK libraries***
- **Extensible and Adaptable**
- **A graphical user interface has been developed to study the particular case of microstrip detectors and diodes**

FEniCS PROJECT

"automated, efficient solution of differential equations"

$$\nabla^2 u = f(\vec{r}) = -\rho(\vec{r})/\epsilon$$

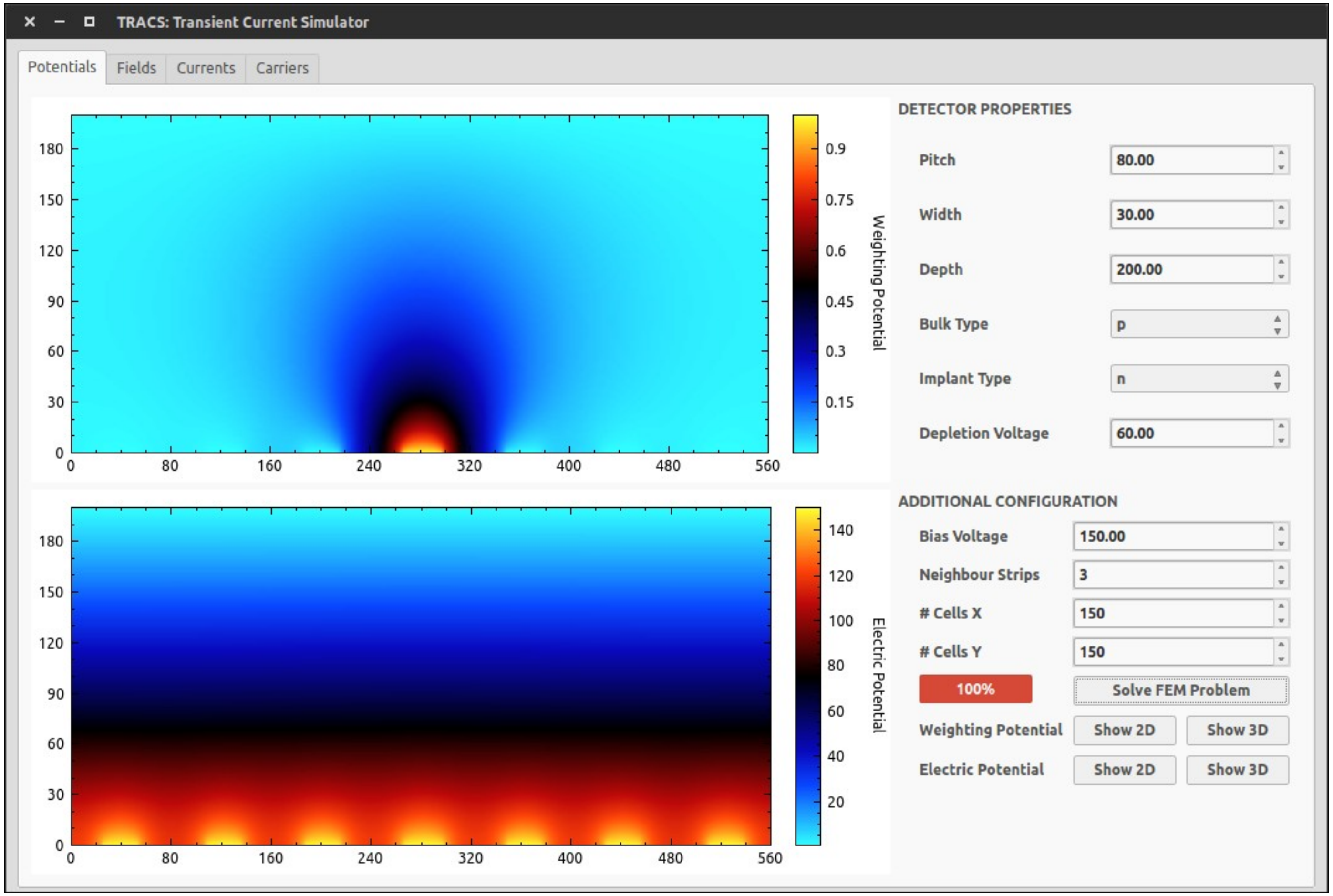
BCs and FEM Mesh

Variational form of Poisson's eq.

$$\underbrace{\int_\Omega \nabla u \cdot \nabla v \, \mathrm{d}x}_{a(u,v)} = \underbrace{\int_\Omega f v \, \mathrm{d}x}_{L(v)} \quad \forall v \in V$$

Solve for u (automatic)

Graphical User Interface

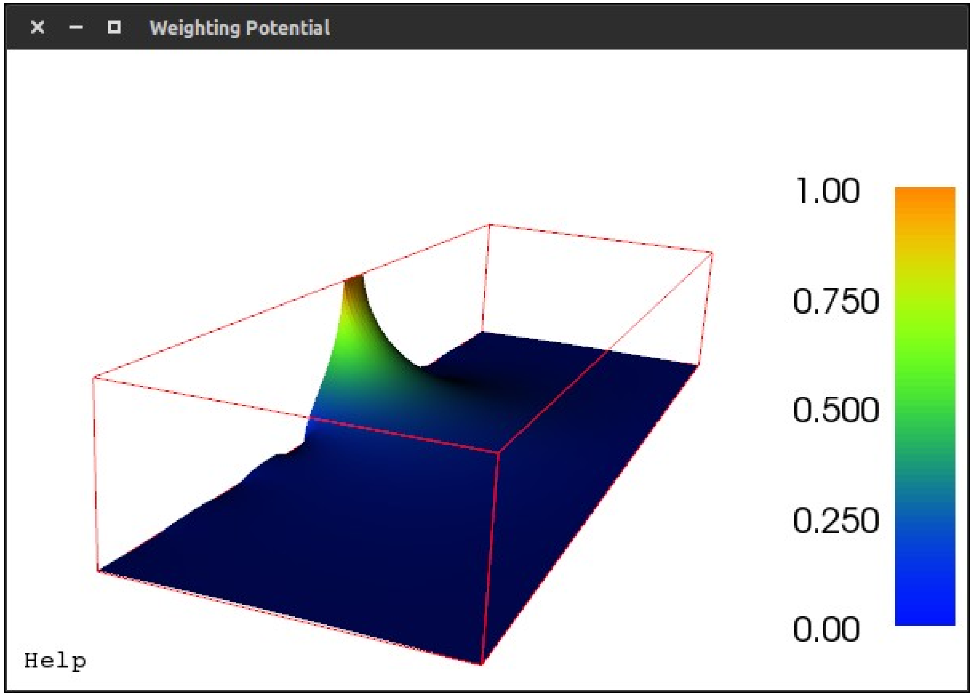


Allows basic simulation on microstrip detectors and planar diodes

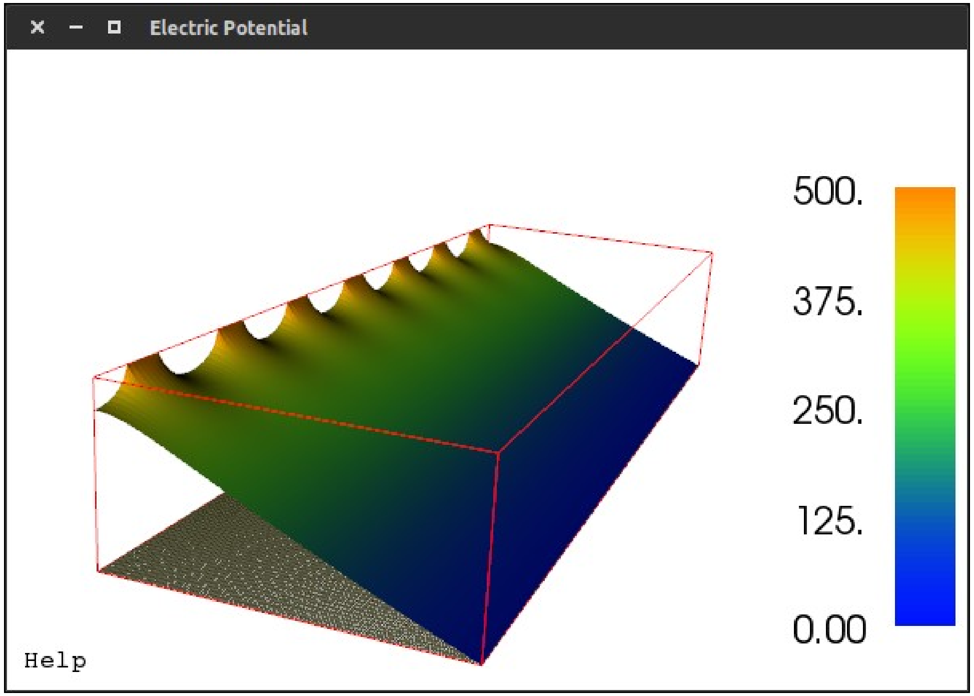
Set detector characteristics and meshing accuracy

Inspect fields and currents produced by arbitrary carrier distributions

Interactive 3D Visualization



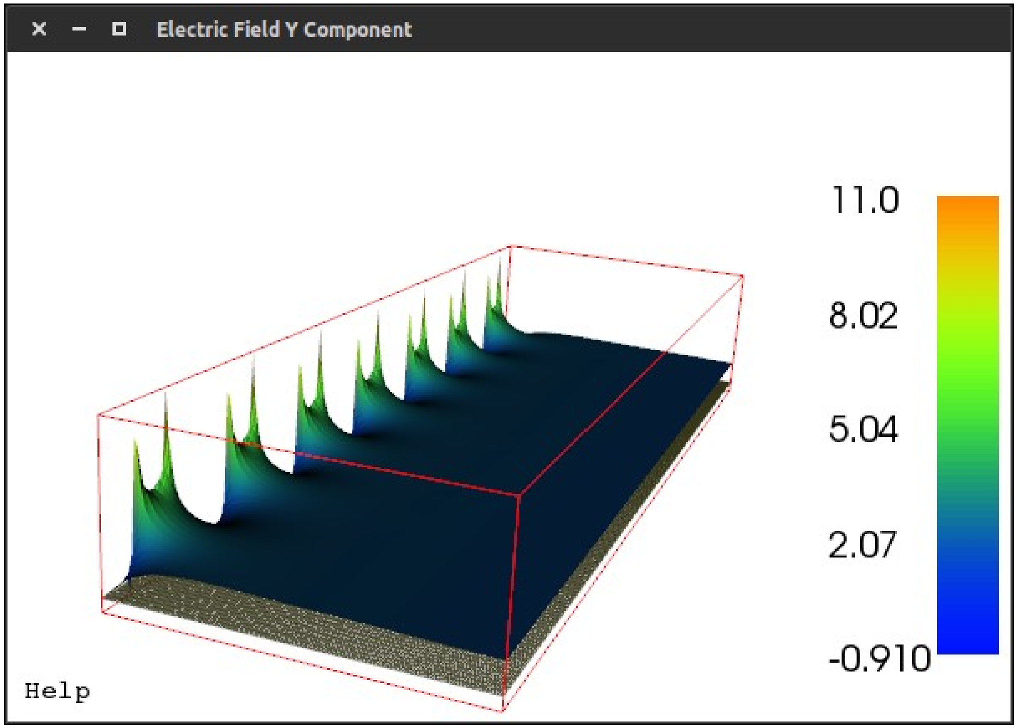
Weighting potential of the readout electrode of a 200 µm thick microstrip detector



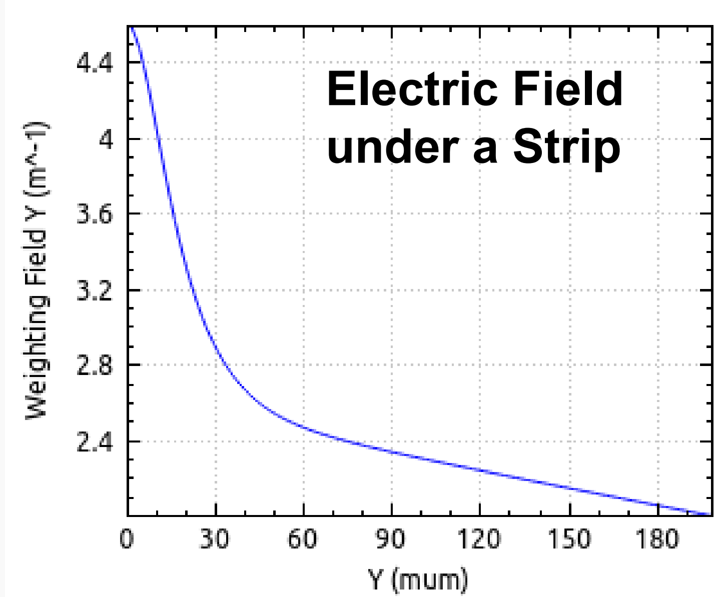
Electric potential for a 200 µm thick microstrip detector whose V_{dep}= 50 V and V_{bias}= 500 V

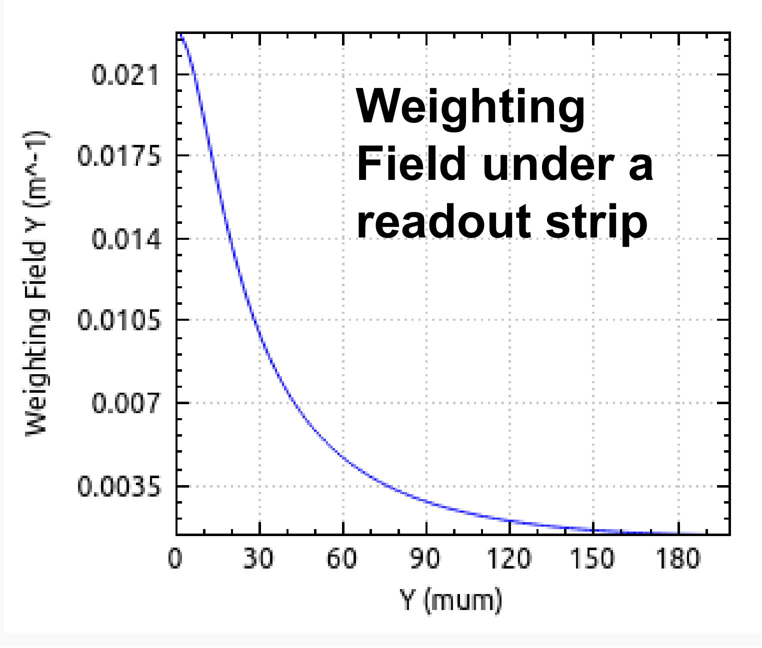
In this case, simulating 7 strips with 22500 finite element cells in 2D

Field Visualization / Slicing



Electric field for a 200 µm thick microstrip detector whose V_{dep}= 50 V and V_{bias}= 500 V





Transient Currents

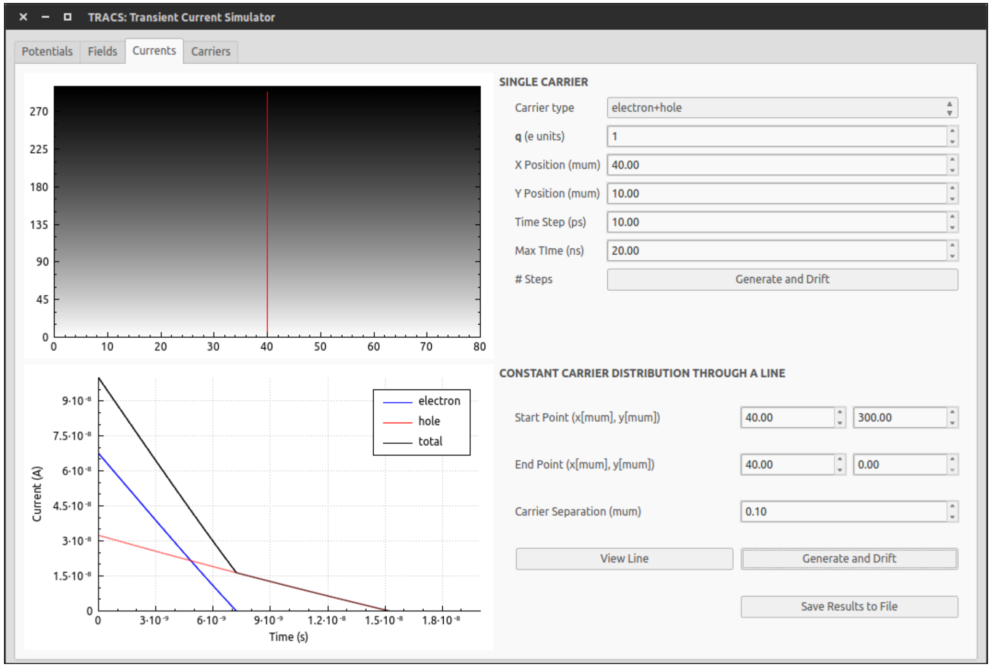


Fig: transient currents and electron/hole contributions in a 300 µm diode when carriers are generated along a uniform line across the detector ~ IR TCT

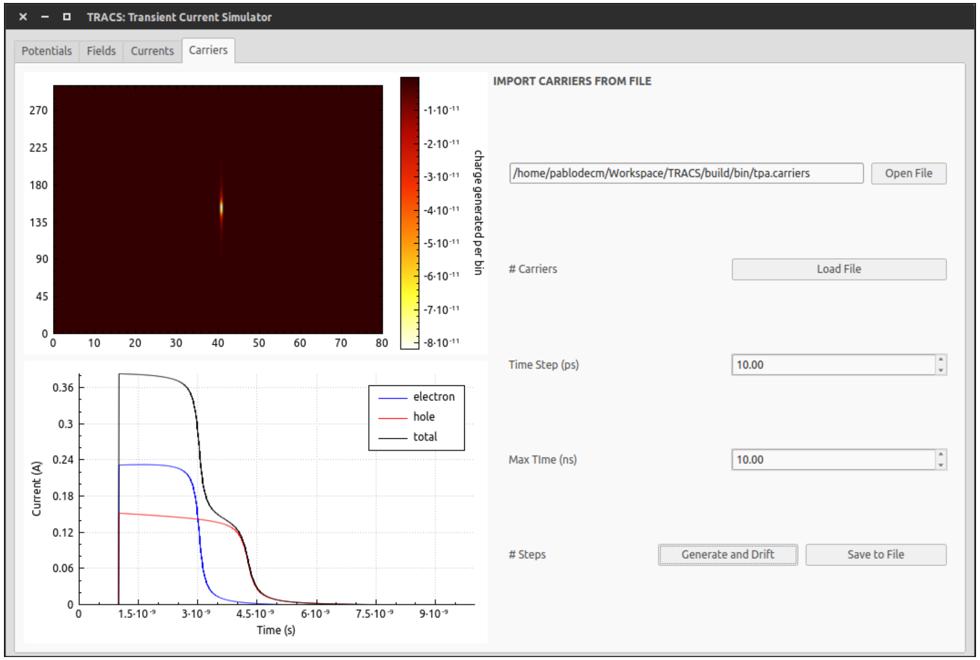


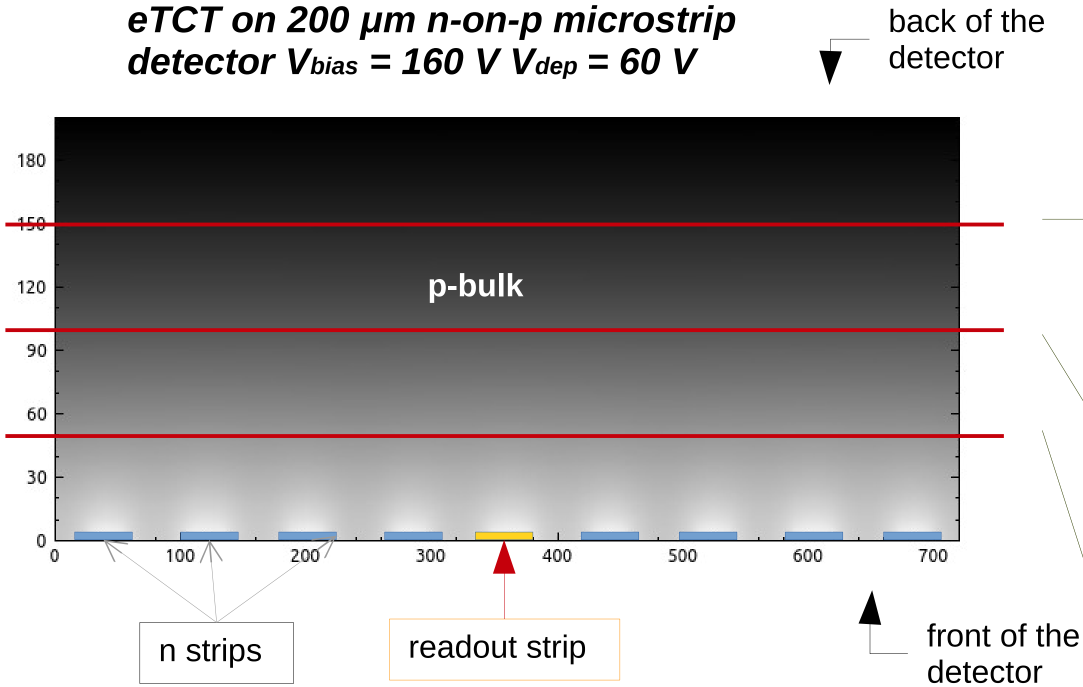
Fig: transient currents and electron/hole contributions in a 300 µm diode when carrier are generated by TPA-TCT

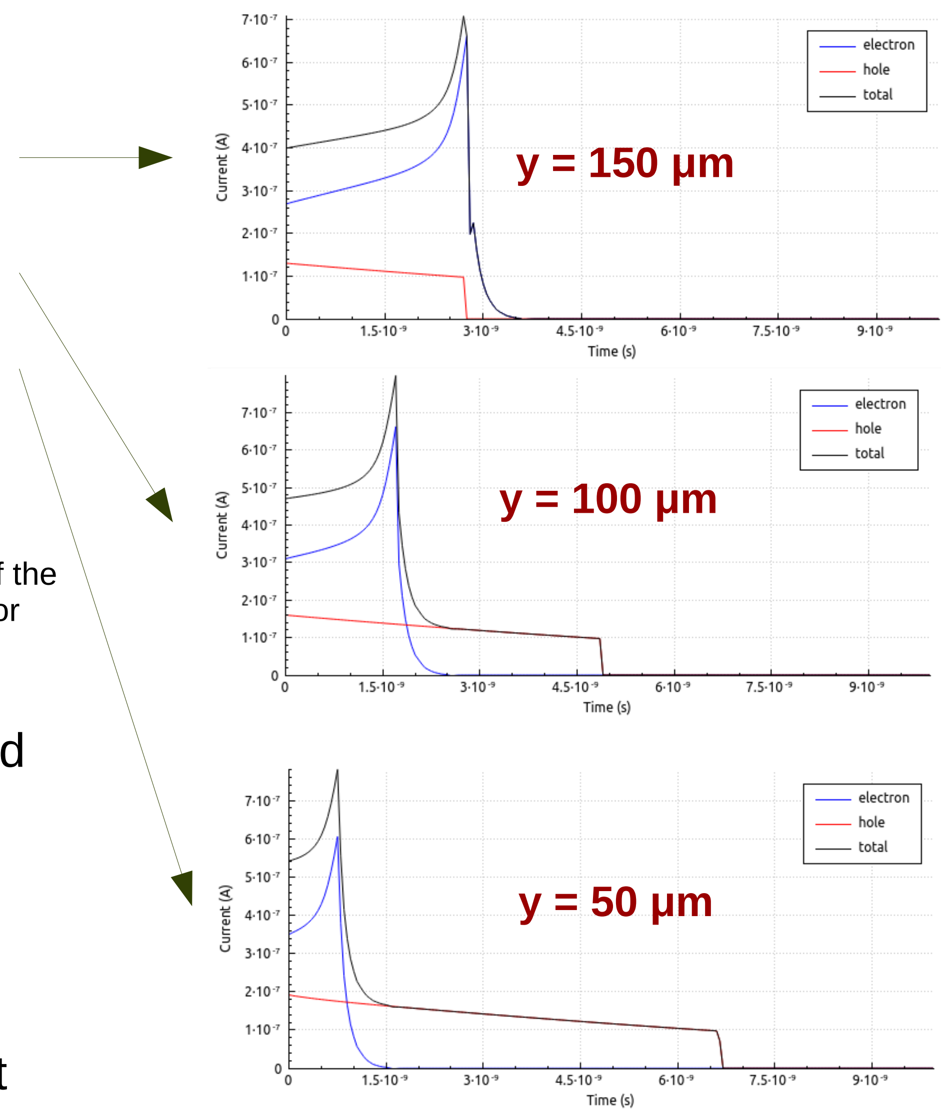
- **Generation of a probe carrier at a certain point of the detector ~ click & drift**
- **Generation of carriers uniformly along a line inside the detector (any direction)**

- **Import carriers according to any distribution (they can account for several e or h ~ charge packages)**
- **Import the distribution from a text file, results can also be exported**

Example: e-TCT Microstrip Detector

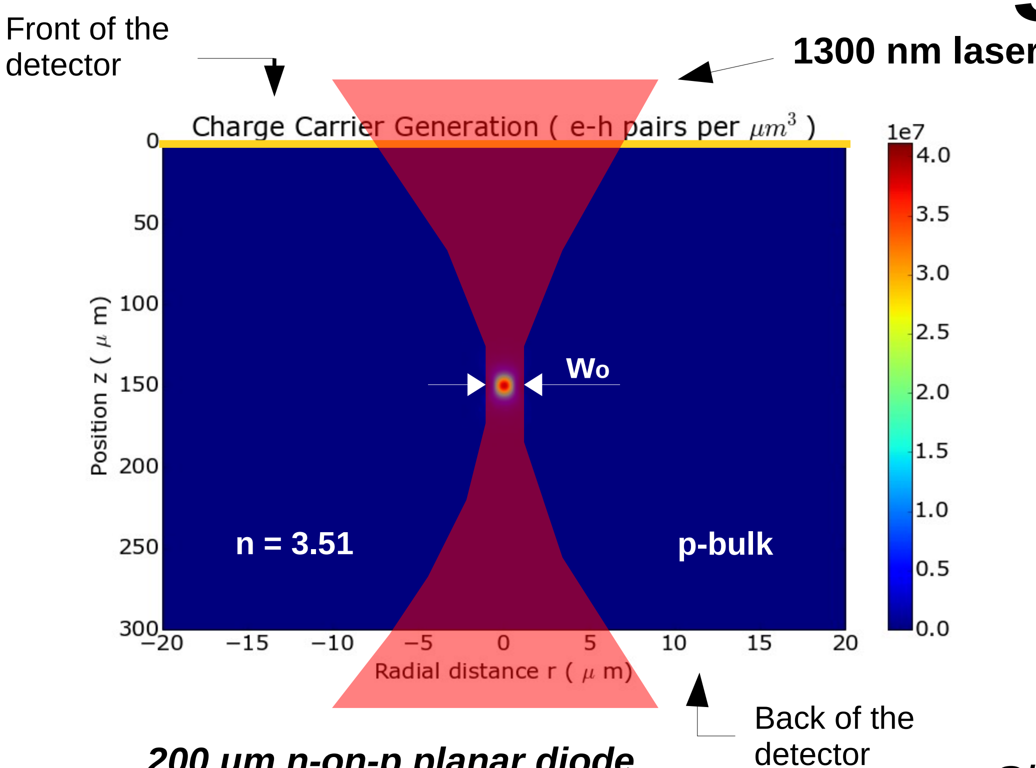
eTCT on 200 µm n-on-p microstrip detector V_{bias} = 160 V V_{dep} = 60 V



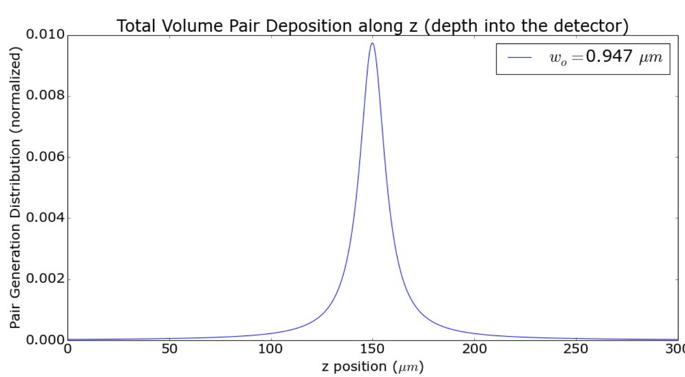


- Effect of detector capacitive shaping or amplifier not included, which will be required for experimental comparison
- Using naive approximation for an eTCT IR beam, a Gaussian beam profile and linear attenuation can be added.
- Future work: comparison between a simulated and experimental measurement of a full eTCT scan in a non-irradiated microstrip detector

TPA-TCT charge generation



200 µm n-on-p planar diode
V_{bias} = 500 V V_{dep} = 50 V



<u>Carrier distribution along z axis when focused to the center</u>

<u>Gaussian Intensity Profile</u>

$$w(z)^2 = w_o^2\left[1 + \left(\frac{\lambda z}{\pi w_o^2 n}\right)^2\right]$$

$$I(r,z) = \frac{2P}{\pi w(z)^2}\exp\frac{-2r^2}{w(z)^2}$$

<u>TPA absorption (negligible attenuation)</u>

$$n_{TPA}(z) = \frac{\beta\tau}{2\hbar\omega} I(r,z)^2$$

- *Simple model for charge generation of carriers by TPA*
- *Longitudinal and transverse distributions are obtained by integrating*
- ***Beam waist in experiment w_o in Si is obtained** by fitting the experimental z-scan charge profile using this model:*
  - w_o = 0.95 ± 0.05 µm
  - **r spot size** → 1σ~0.8 µm & 2σ~3.4 µm
  - **z spot size** → 1σ~13 µm & 2σ~60 µm

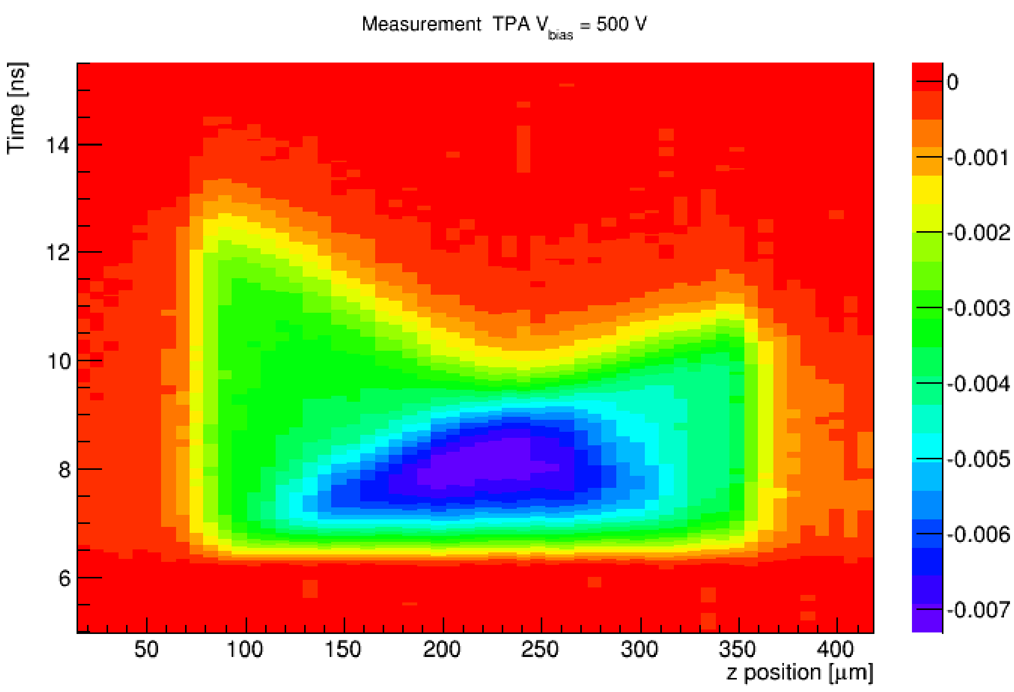
TPA-TCT Z-Scan

- **Carrier distribution from model on previous slide (Simple TPA model)**
- **Shift distribution along z axis to perform an scan (n change is important)**
- **Generation of carriers uniformly along a line inside the detector (any direction)**

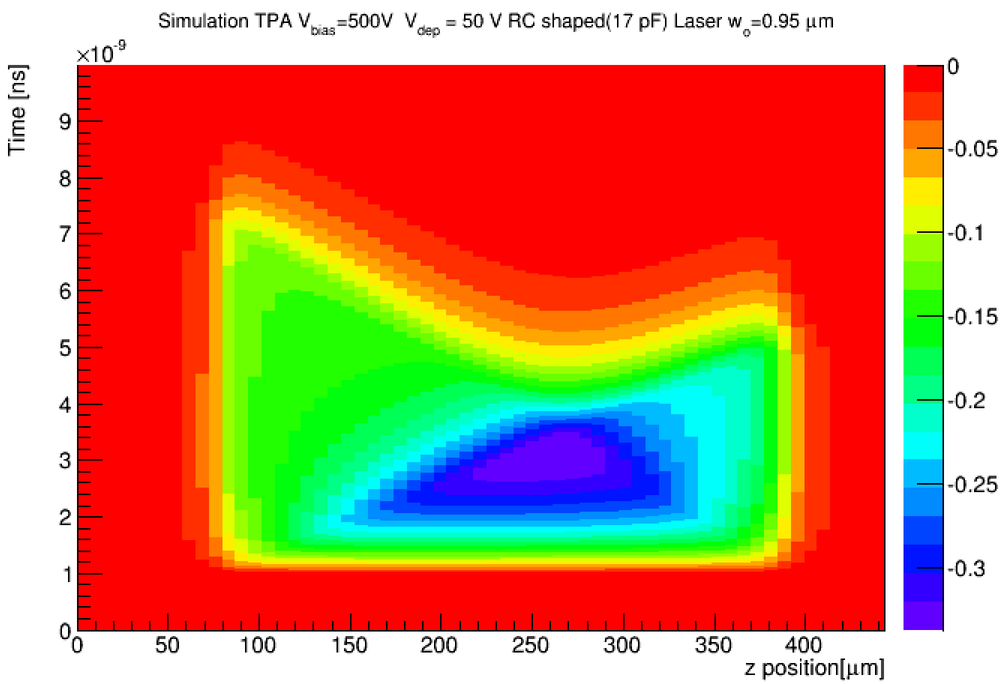
<u>Simulation parameters:</u>
Bias voltage: 500 V
Depletion voltage: 50 V
w_o = 0.95 µm
RC = 50 Ω * 17 pF

Agreement is very good!

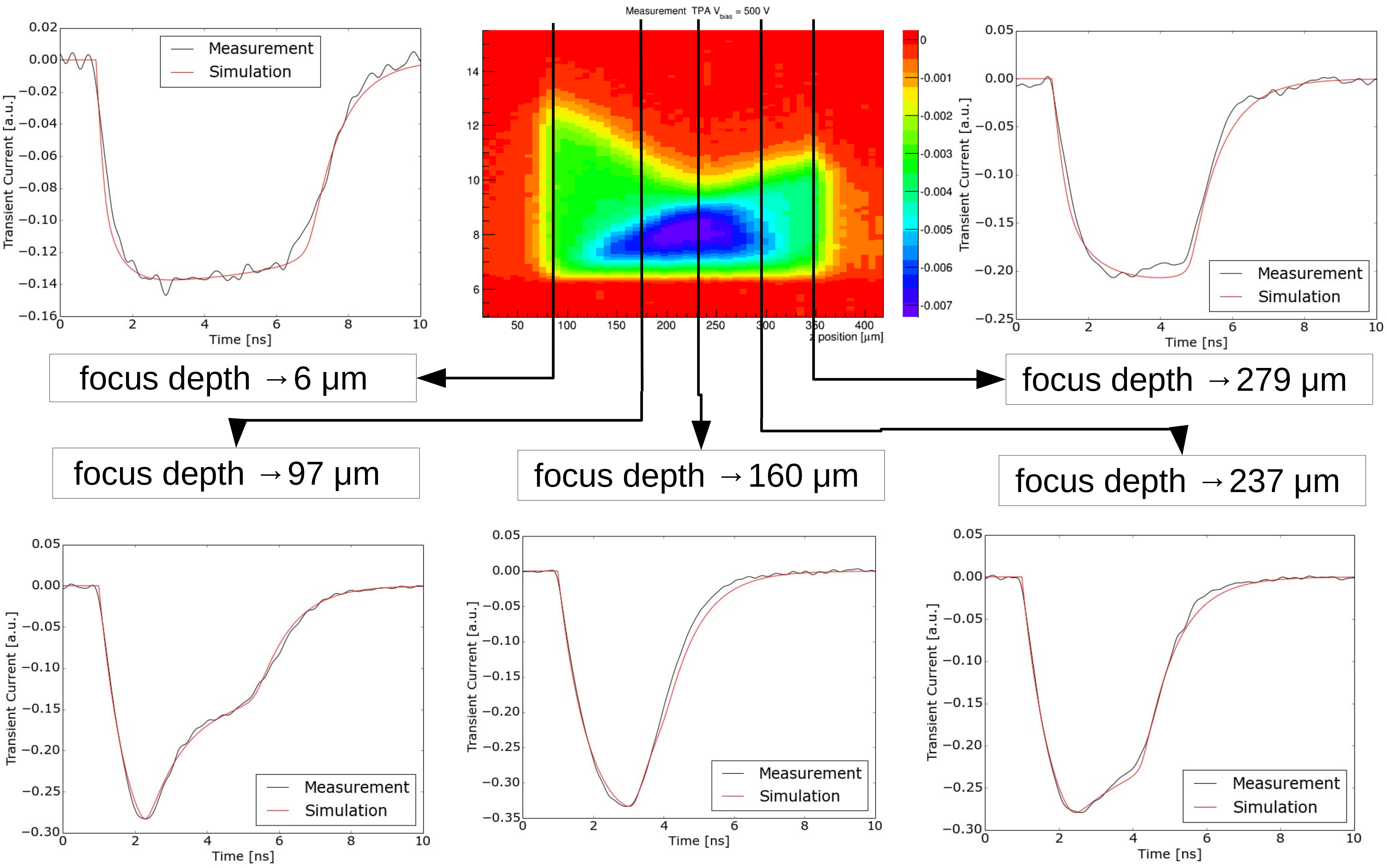
<u>Experimental Measurement</u>



<u>TRACS simulation (with RC shaping)</u>



Transient Current Shapes



Future Improvements

- Additional detector geometries
  - **Planar Pixel Detector** (3D simulation is not a problem!)
- Gaussian Laser simulator (SPA and TPA) built-in in the graphical interface
- Electric field
  - Try with charge density profiles from irradiated detectors
  - **Import from advanced TCAD simulators** (e.g. Sentaurus TCAD)
- Improved models
  - **Diffusion and Avalanche Gain**
  - **MC trapping and thermal carrier generation model**
  - **Read-out electronics shaping and noise**
- Performance improvements and optimization
  - Adaptive ODE step size
  - Threading and/or parallelization
  - Code cleaning and Doxygen documentation system

Conclusions

- A tool for the simulation of the drift dynamics of electron and holes inside a semiconductor detector of complex geometry has been successfully developed.

- Results obtained so far agree for simple (and non-irradiated) systems agree with the expected results and it has already been probed useful to **understand and predict some transient waveforms as the results of the new TPA-TCT characterization technique**.

- **Many extensions and improvements can be done. We are still working on this software.**

- Source code is openly available. **Feel free to try it and provide feedback, test it or improve it if you want.**

https://github.com/IFCA-HEP/TRACS

Thank you!

Any question?