GEMPix detector as beam monitor at CNAO Hadrontherapy Center: Geant4 simulation and measurements

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Outline

- GEMPix detector for hadrontherapy
- GEMPix layout
- CNAO measurements: experimental setup and first results
- GEANT4 simulation
- Conclusions and future developments

A possible detector for hadrontherapy (I)

Fundamental Requirements

- High rate capability and Radiation hardness → High fluxes (10^8 particles/s) of carbon ions, protons, oxygen…
- Good spatial resolution → Beam diagnostic for daily quality controls and dosimetric measurements of treatment plans.

Good candidate → GEMPix detector – a Timepix based GEM detector

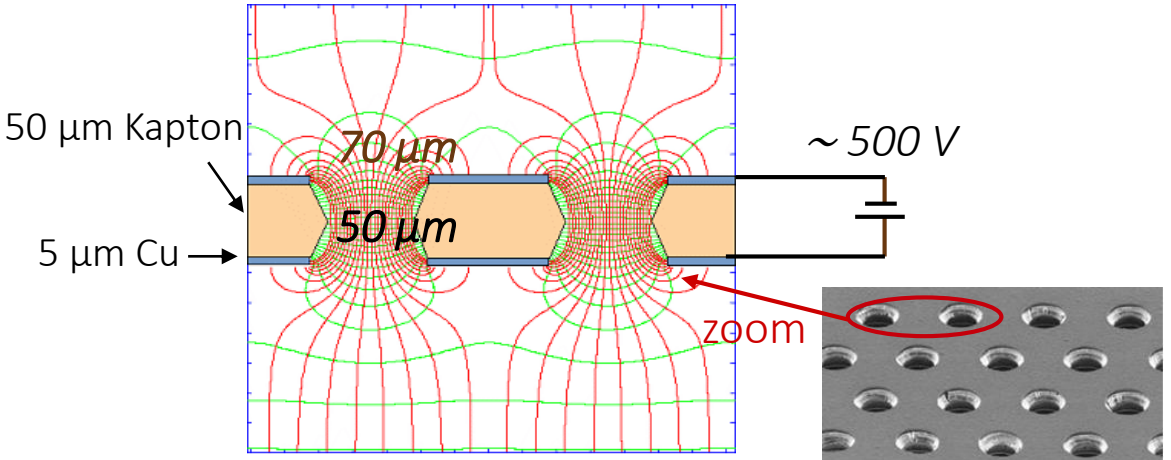
Already used for: Radioactive waste/ Microdosimetry/ Radiotherapy / Radon monitoring @ CERN
(http://ardent.web.cern.ch/ardent/ardent.php?link=publications)

A possible detector for hadrontherapy (II)

What is a GEM detector?

GEM foil → Kapton sheet (50 µm thick) metallized at both sides (5 µm of Cu) with 70 µm holes etched inside

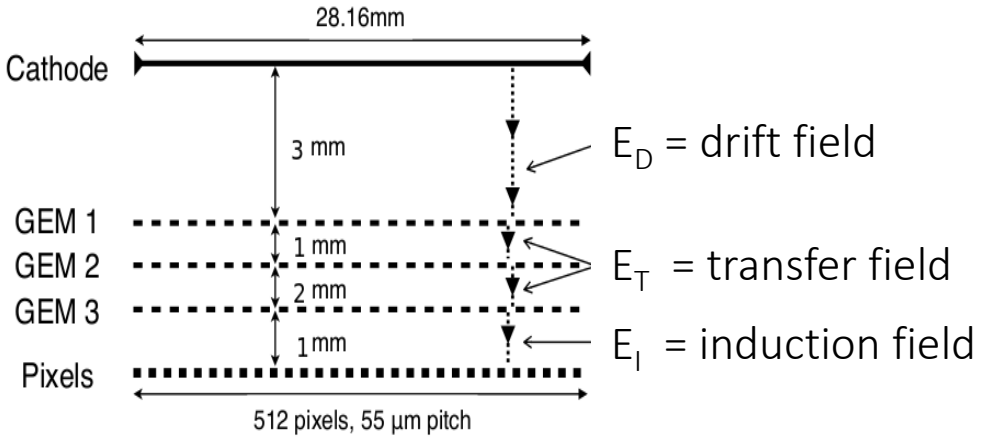
Electrical field ~100 kV/cm inside the holes
→ **localised** electron avalanche



http://www.physi.uniheidelberg.de/Forschung/ANP/Cascade/Konzept/

Image CERN GDD Group (2001)

How does the GEMPix work ?



Primary particle interaction in the Drift gap

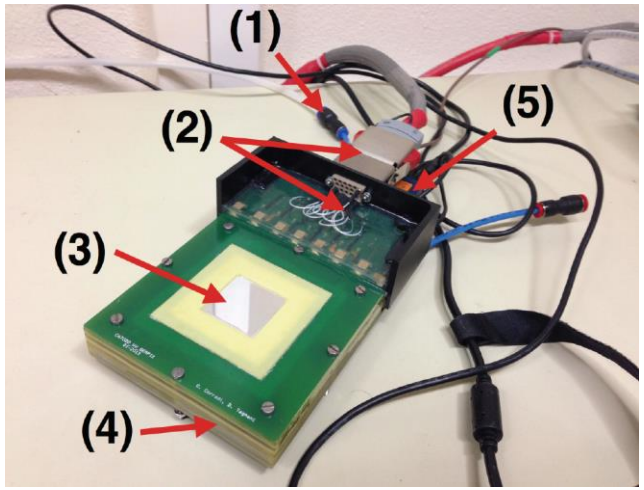
⬇

Electrons multiplication: up to 40 output electrons for each electron in. Three GEM foils give gains up to 10^5 → *f*(gas)

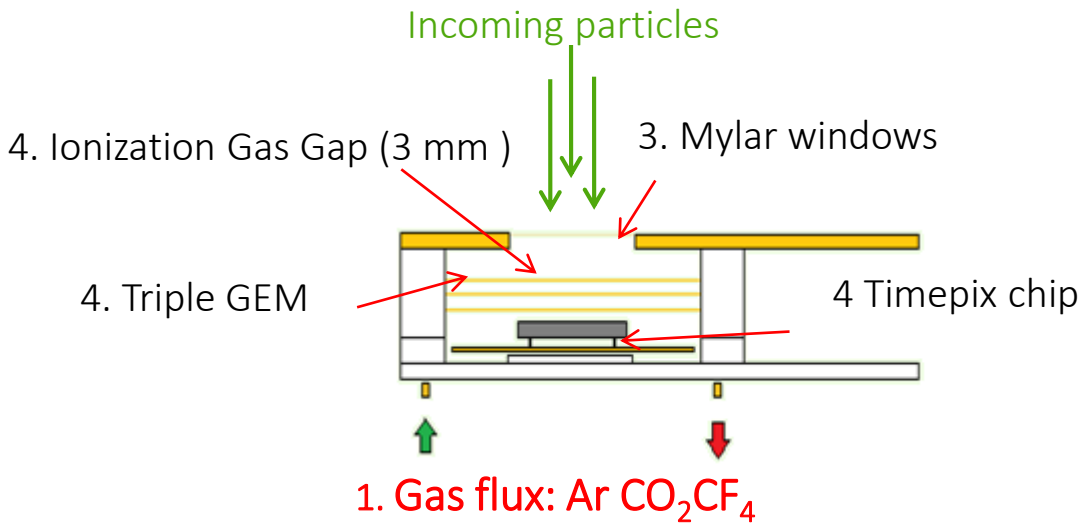
⬇

Readout: electrons are collected by the Timepix chip

GEMPix: detector and readout system



2. HV Conntector / 5. **Timepix Readout**



Layout

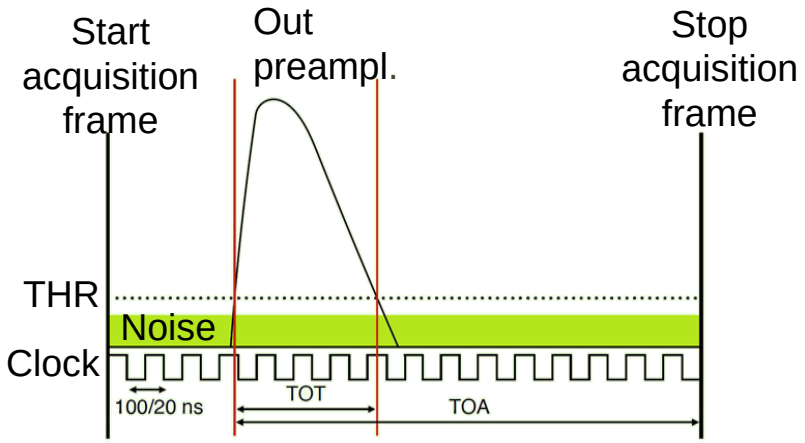
Developed by ARDENT project (CERN – INFN).

Read by *4 naked Timepix chips*

Active area → 9 cm^2

Readout System

- Each pixel can measure the deposited charge and count the single particle.
- Detection threshold around 1000 electrons (noise ~ 100 electrons)
- Readout configuration with 4 chip (512x512) → 2.6 x 10^5 pixels

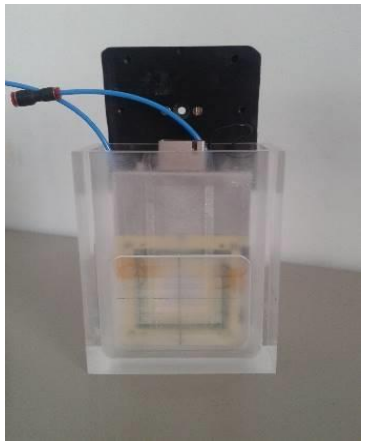


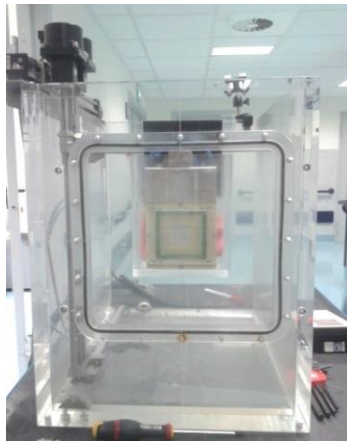
TOA -> Time Of Arrival (3D single track reconstruction)

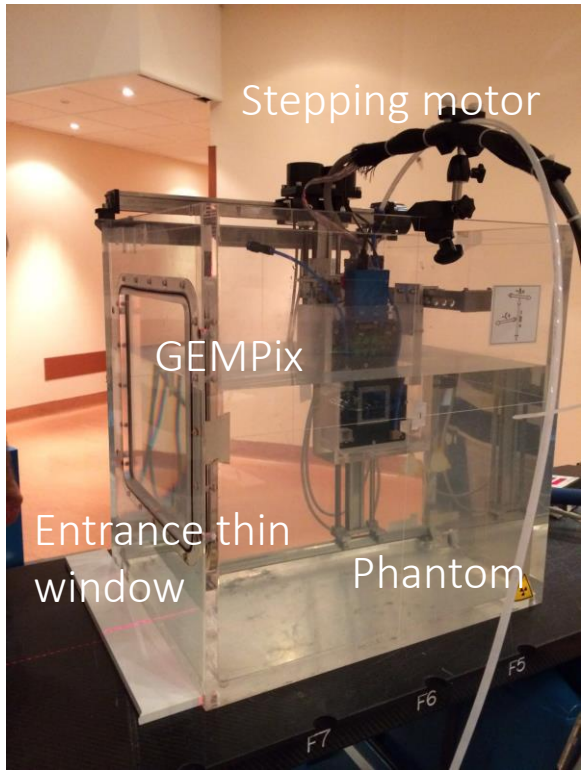
TOT -> Time Over Threshold (Charge and dE/dX)

→ TOA and TOT clock up to 100 MHz, but stable at 50 MHz

GEMPix: *experimental setup at CNAO*





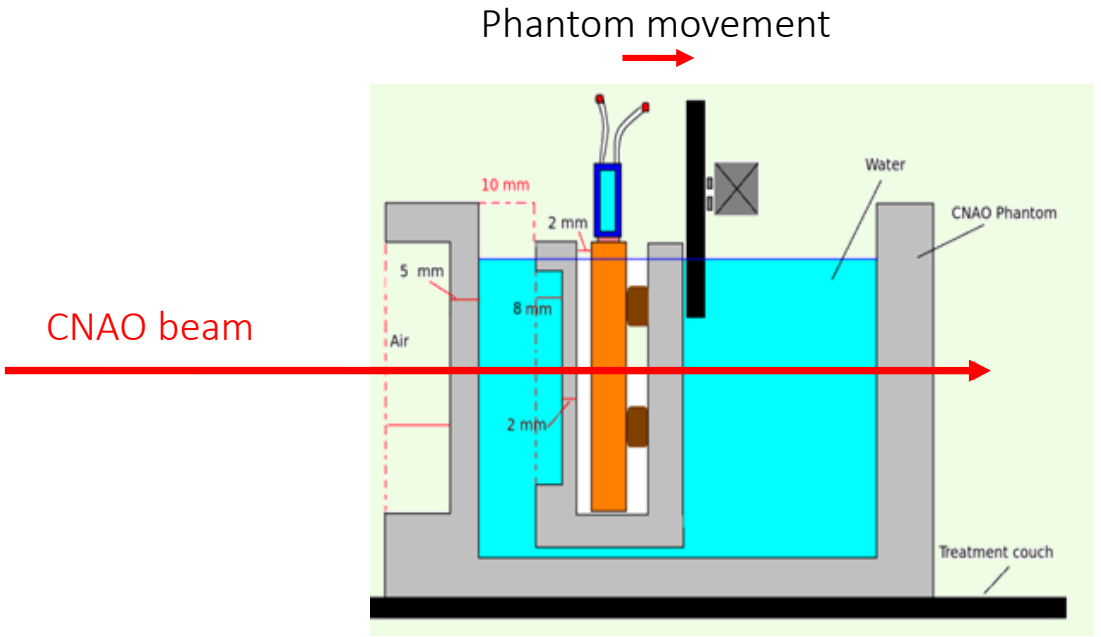


Particles type: carbon ions (single beam spot and scanned field)

Beam Energy: 3.9 GeV and 3.4 GeV

Particles per *spill*: 8 x10^5

Measurements: *Linearity, homogeneity and energy measurements* at different water depths



Motorized 3D water phantom

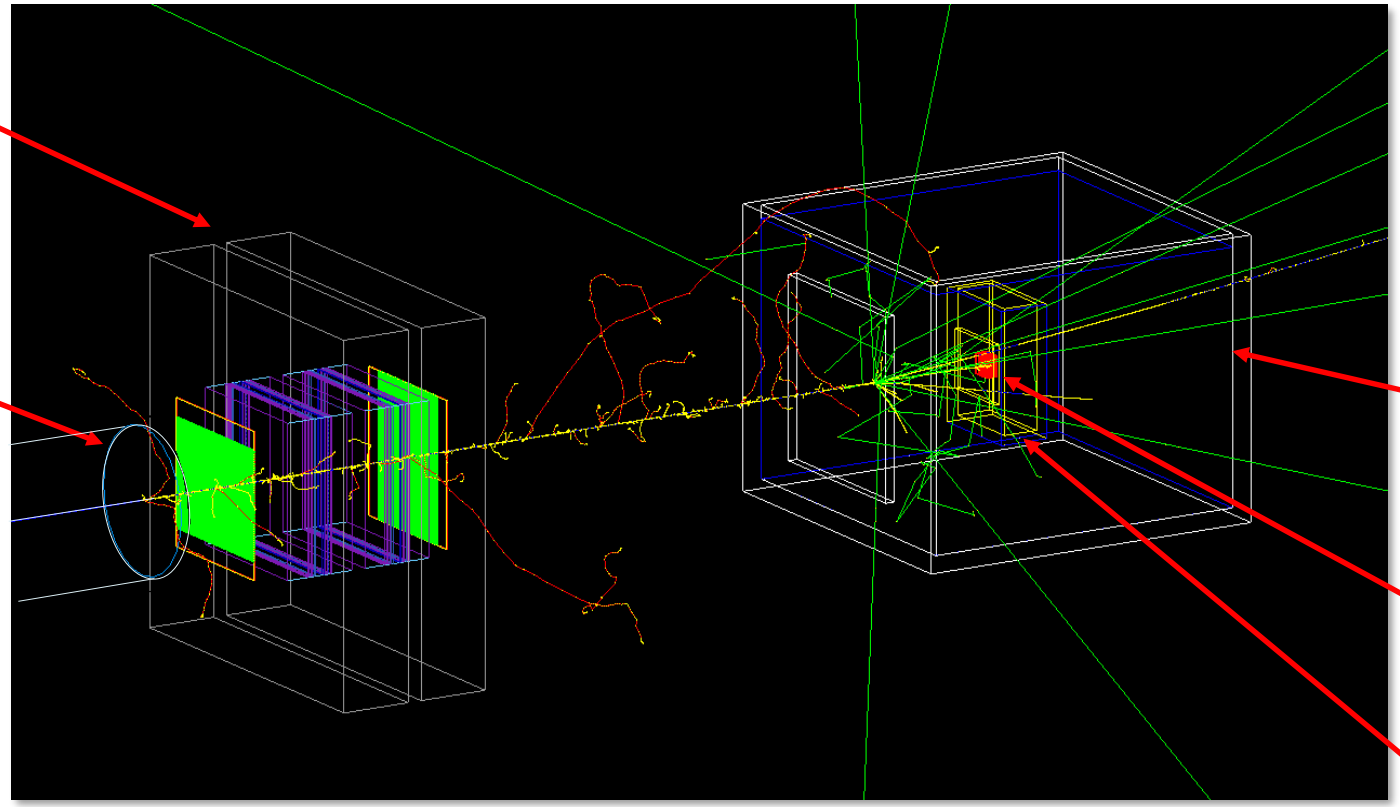
GEANT4 simulation: *experimental setup*

The CNAO extraction beamline and the experimental setup are fully simulated

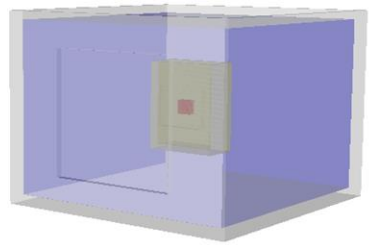
Dose delivery chambers

Vacuum Beam Pipe

CNAO Beam



3D view phantom + GEMPix



PTW PMMA water phantom

GEMPix active area

PMMA box for GEMPix

All the layers of the GEMPix active area are simulated with the corresponding materials

Geant4 simulation parameters

- ✓ Release version: **Geant4 10.0 patch 03**

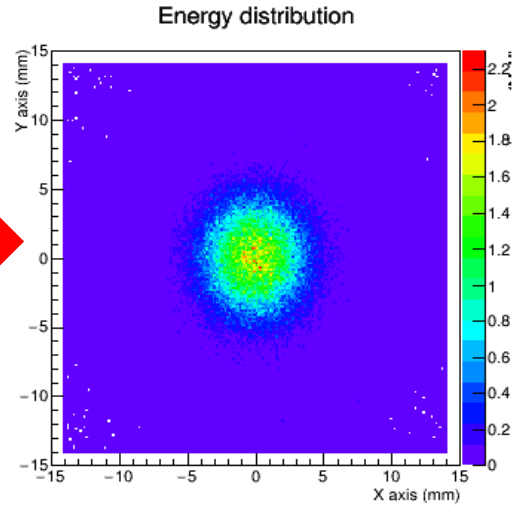
- ✓ Physics Lists (for Carbon Ions): G4EMStandardPhysics_option4, G4RadioactiveDecayPhysics, G4IonBinaryCascadePhysics, G4EmExtraPhysics, G4HadronElasticPhysicsHP, G4StoppingPhysics, G4EmPenelopePhysics, G4NeutronTrackingCut, G4HadronPhysicsQGSP_BIC_HP

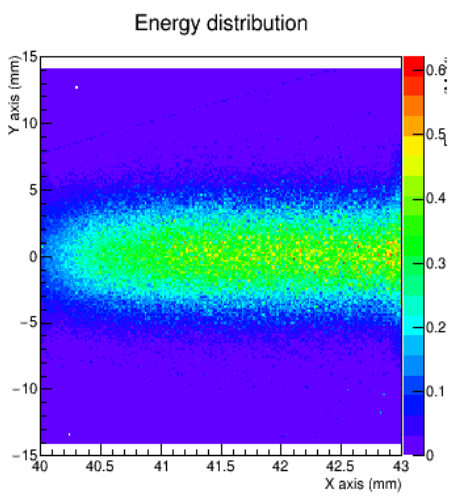
- ✓ Parallel geometries for scoring purposes (3D mesh) and sensitive detectors

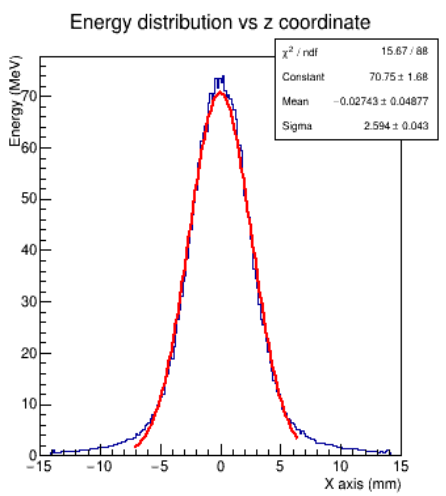
- ✓ Single spot and scanned beam irradiation methods implemented

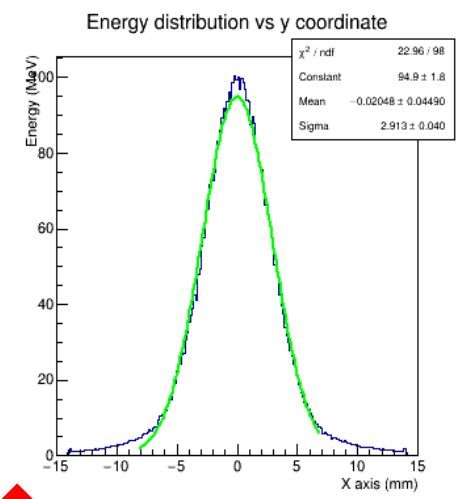
GEANT4 Simulation: *Lateral Profiles*

Carbon ion beams: 2D transversal and longitudinal view

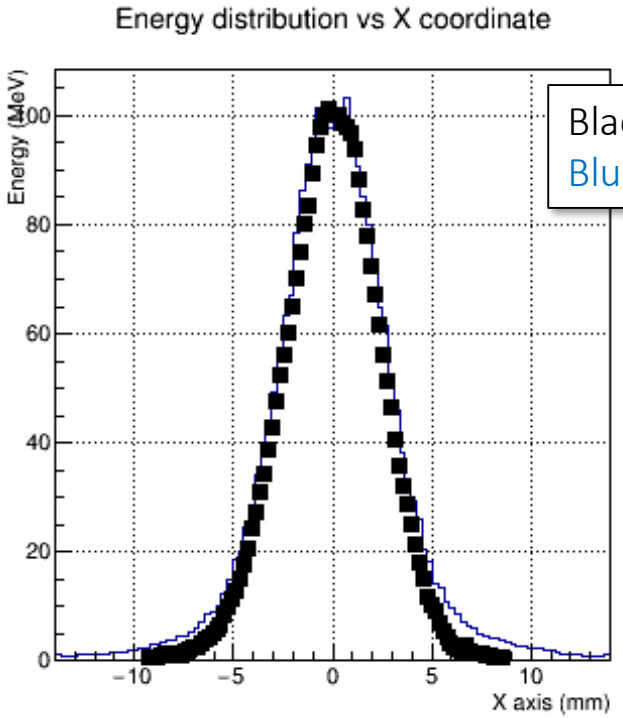








Beam vertical (y) and lateral (z) profile.



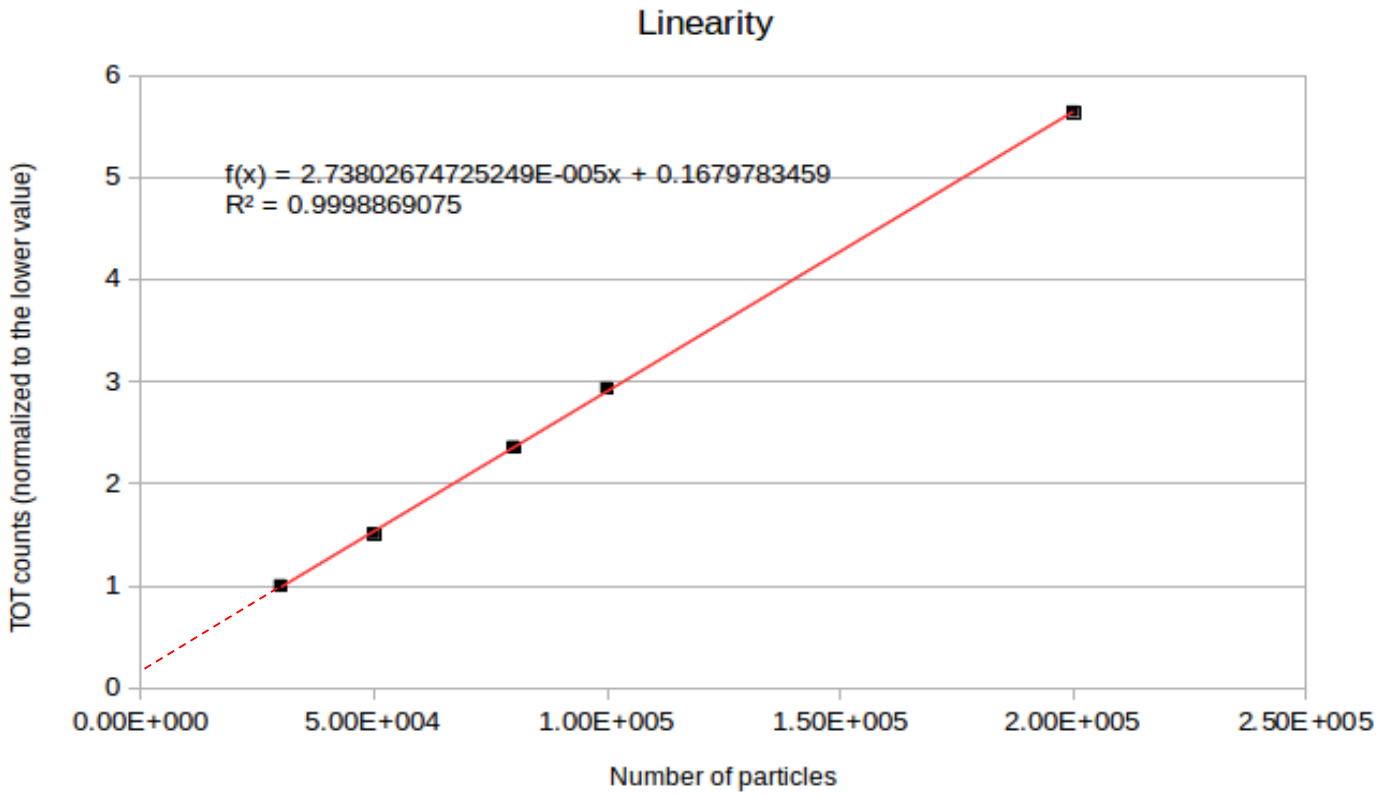
Black dots: EBT3 film
Blue line: Geant4 simulation

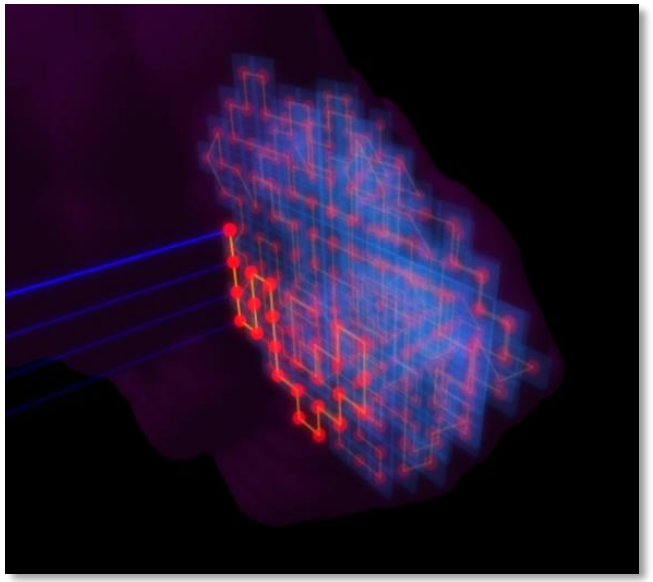
Lateral profile of the energy deposited by 3.9 GeV carbon ions beam spot along the beam axis (x) within the 3 mm *drift gap*

Cross-check with CNAO data from EBT3 radiochromic films

CNAO measurements: *linearity*

- Irradiation method: 60x60 mm^2 **scanned field -** 3.4 GeV carbon ions
- 5 fluxes: $3x10^4$ - $5x10^4$ - $8x10^4$ - 10^5 - $2x10^5$ total particles delivered



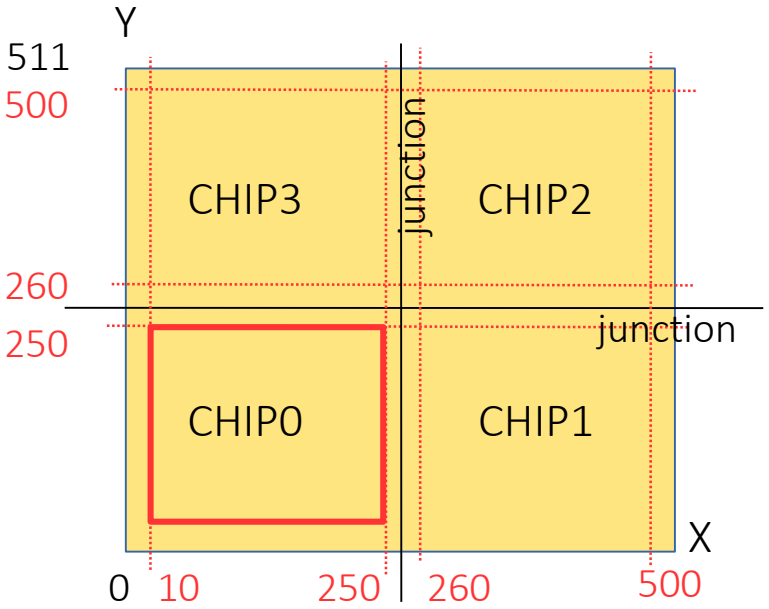


Active scanning

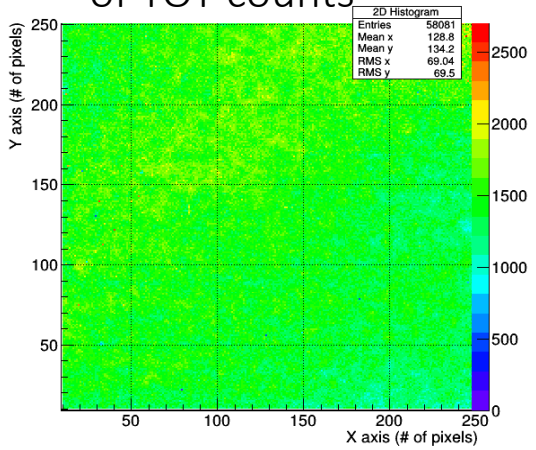
The scanned field dimensions allow to neglet side effects by including all the detector's sensitive area

CNAO measurements: *homogeneity*

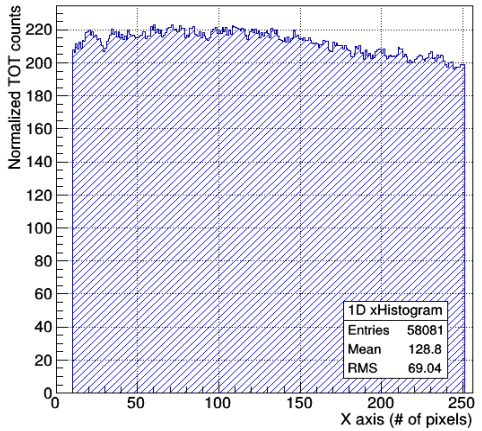
PRELIMINARY RESULTS



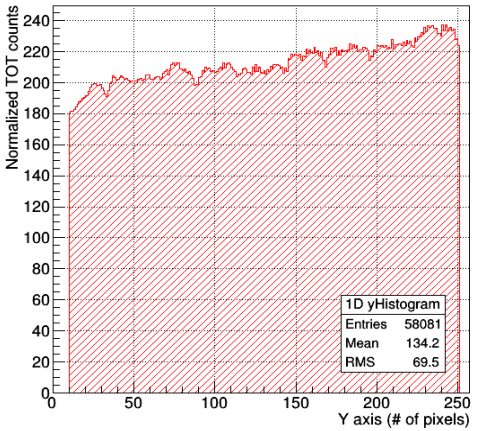
2D histogram of TOT counts



X projection (from pixel 0 to pixel 250)



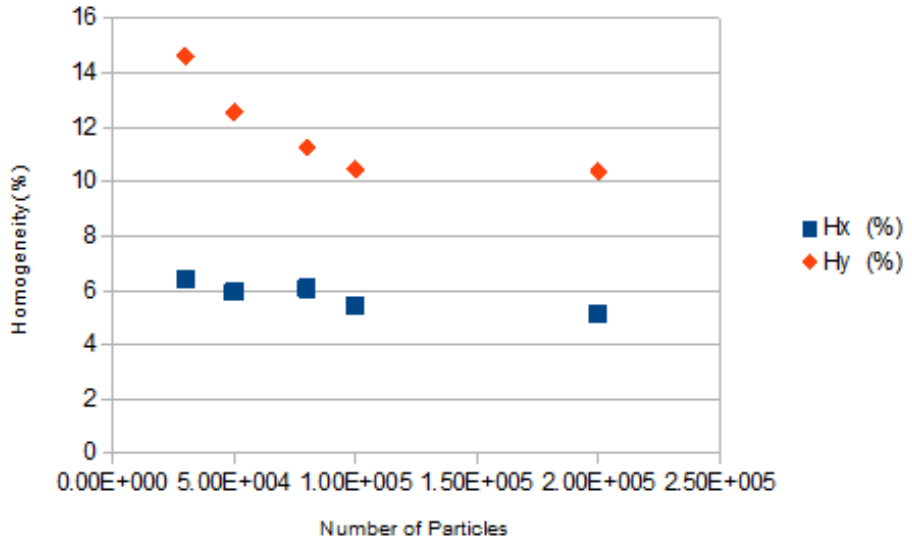
Y projection (from pixel 0 to pixel 250)



SINGLE CHIP homogeneity:

H(%) = (Max Count-Min Count)*100/(Max Count+Min Count)

Homogeneity CHIP0

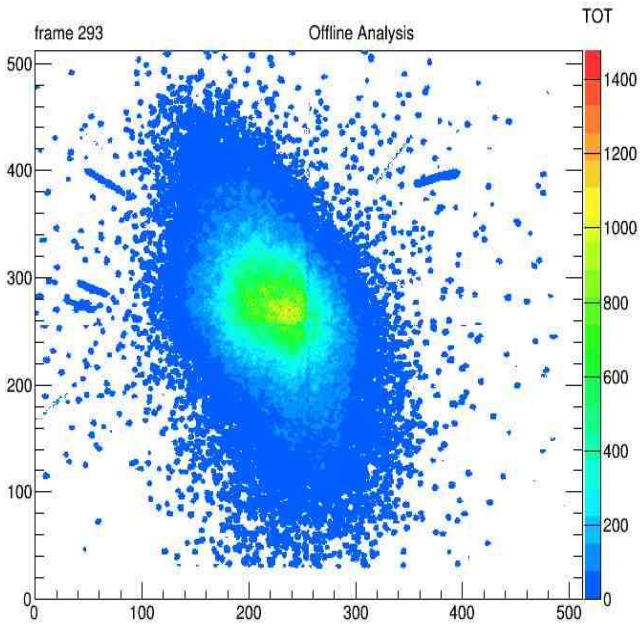


CNAO measurements: *Bragg Peak (I)*

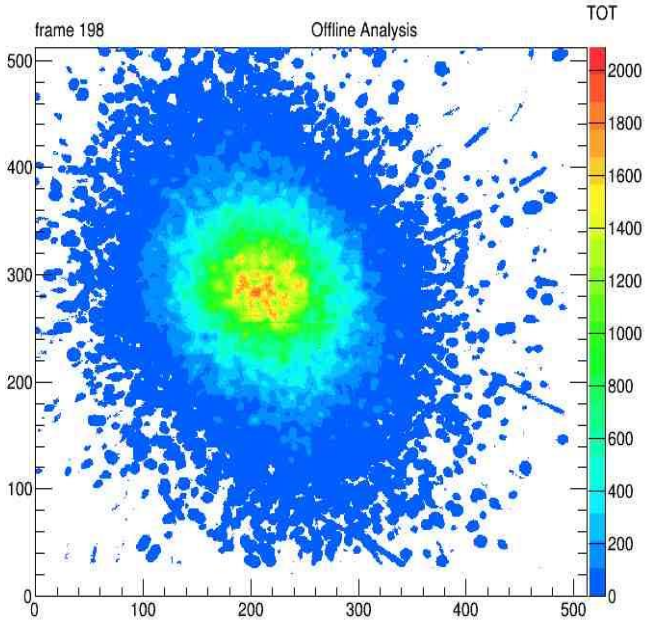
PRELIMINARY RESULTS

2D histograms of TOT counts obtained with 3.9 GeV carbon ions beam spot as a function of the GEMPix position in water

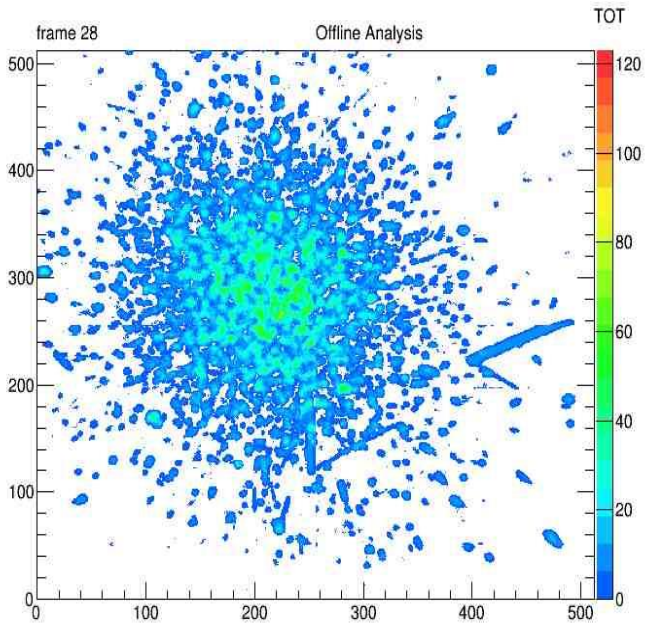
Plateau



Peak



Tail

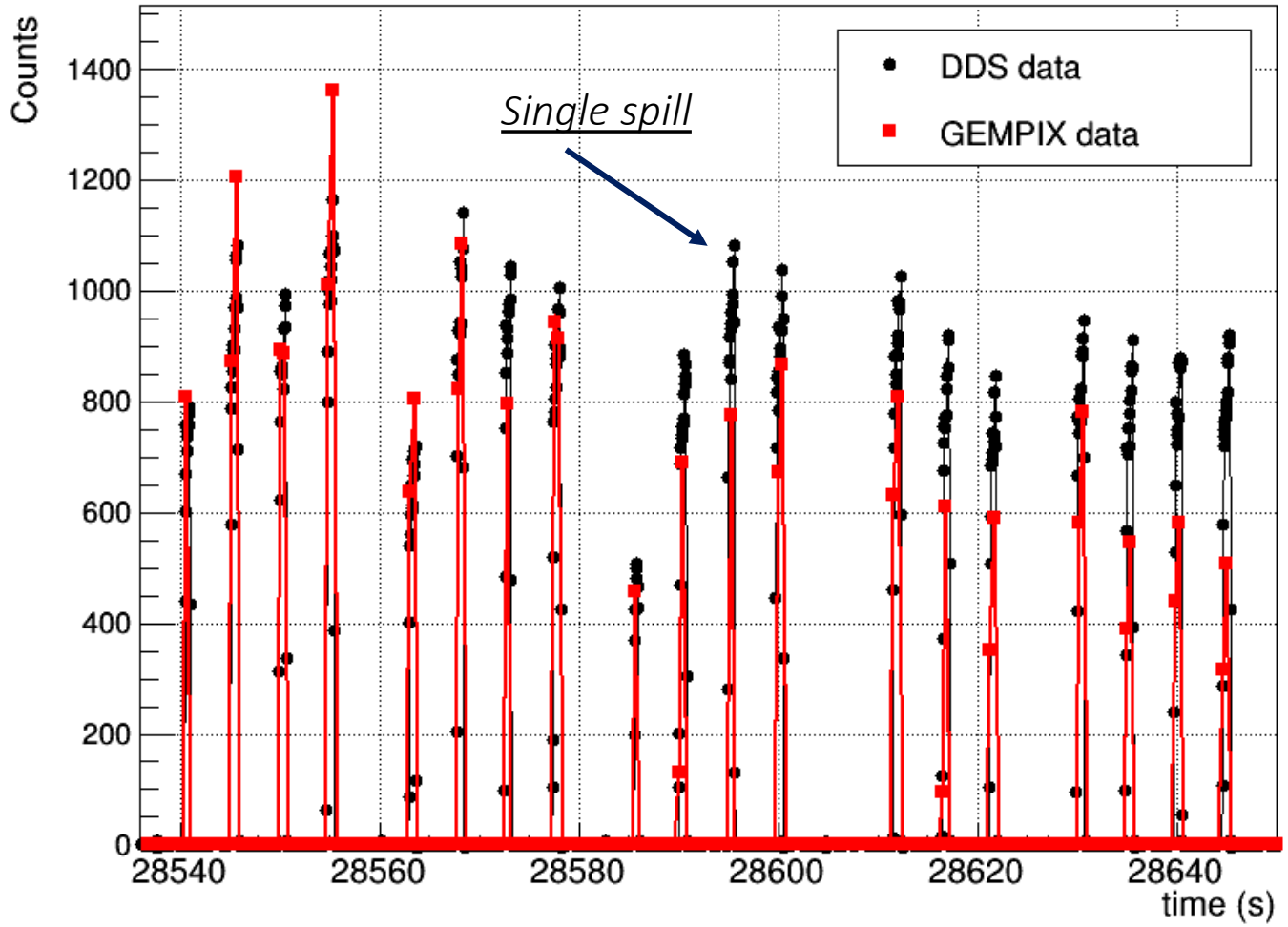


Further studies are currently ongoing to determine the origin of lateral clusters.

CNAO measurements: *Bragg Peak (II)*

PRELIMINARY RESULTS

Beam time/space evolution



3.4 GeV carbon ions beam spot

DDS (Dose Delivery Sistem)

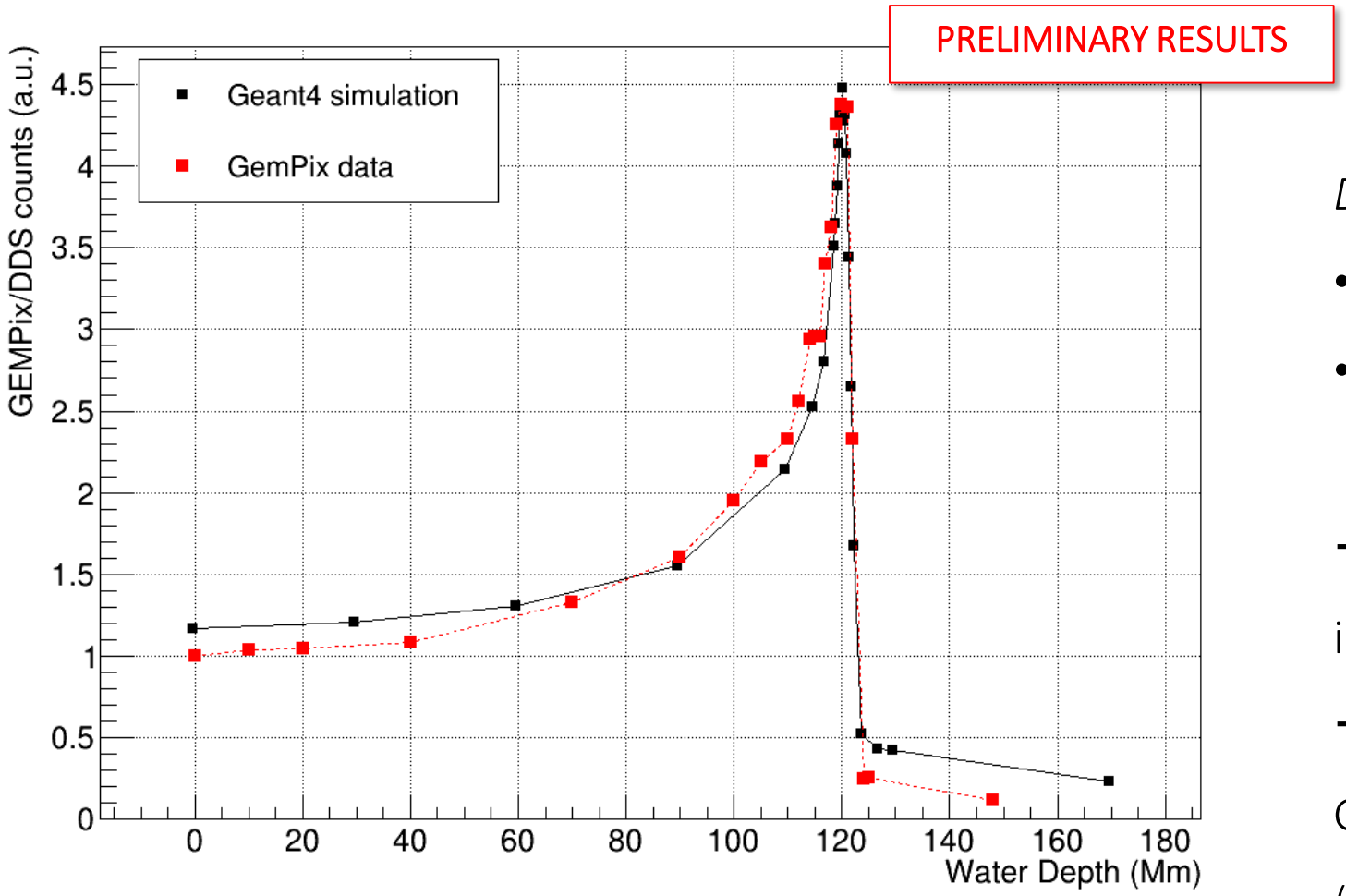
↓

CNAO beam control system

(Ionization and pixels chambers)

Med Phys. 2015 Jan;42(1):263-75. doi: 10.1118/1.4903276.

CNAO measurements: *Bragg Peak (II)*



The curves are normalized at the peak

3.4 GeV carbon ions beam spot

Deposited dose underestimated:

- **Plateau region**
- **Fragmentation tail**

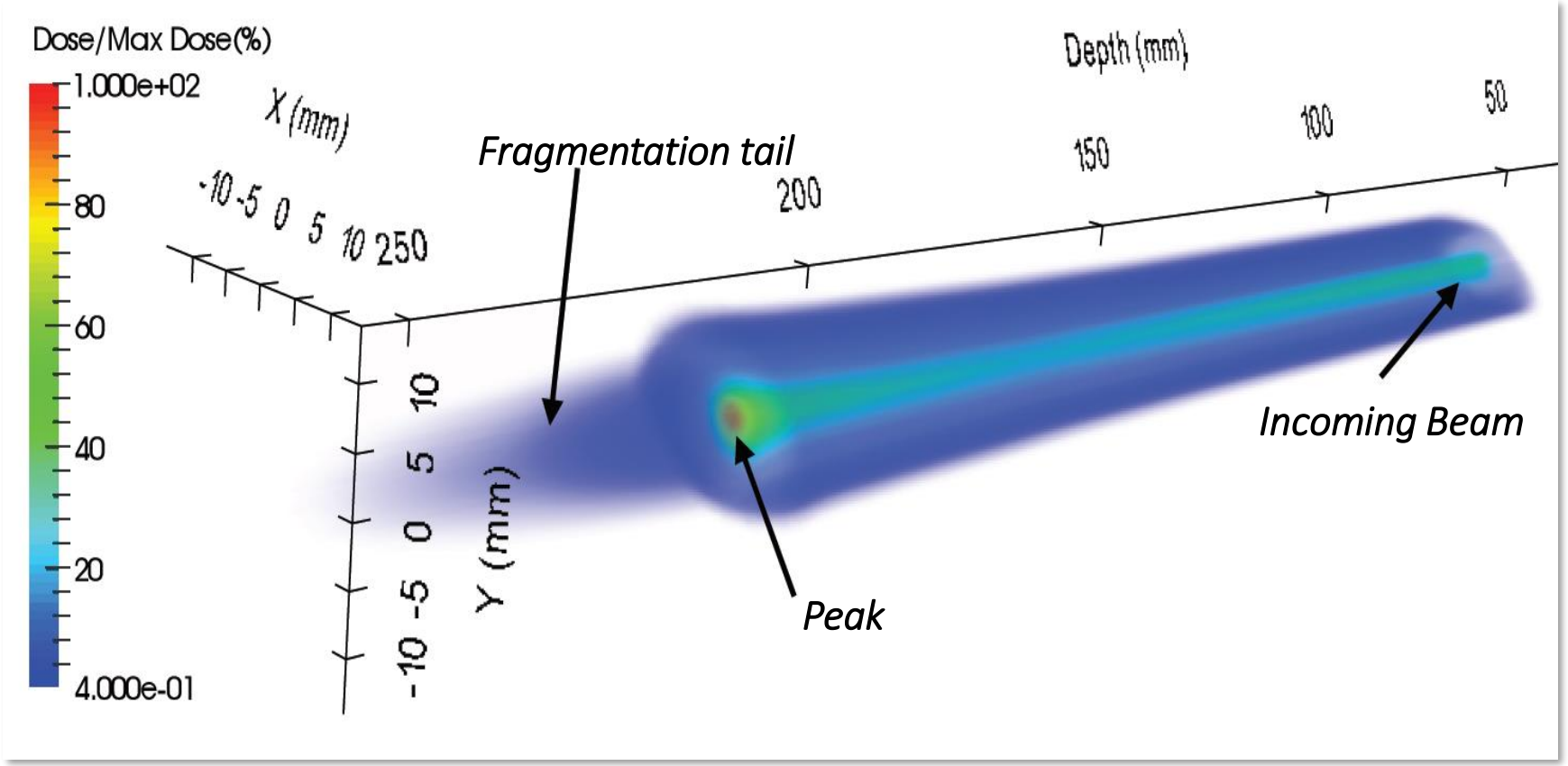
→ Ongoing studies on physics lists and interaction processes in Geant4.

→ Further characterization tests of the GEMPix detector with carbon ion beams (different clock, gain, gas …)

CNAO measurements: *Bragg Peak (III)*

PRELIMINARY RESULTS

3D reconstruction 3.9 GeV carbon ions Bragg peak in water



Conclusions

Complete simulation of the CNAO extraction beamline, GEMPix detector and experimental setup

Linear response as a function of particle flux

Quite good homogeneity response → study of edge/junction effects

Good agreement between data and simulation

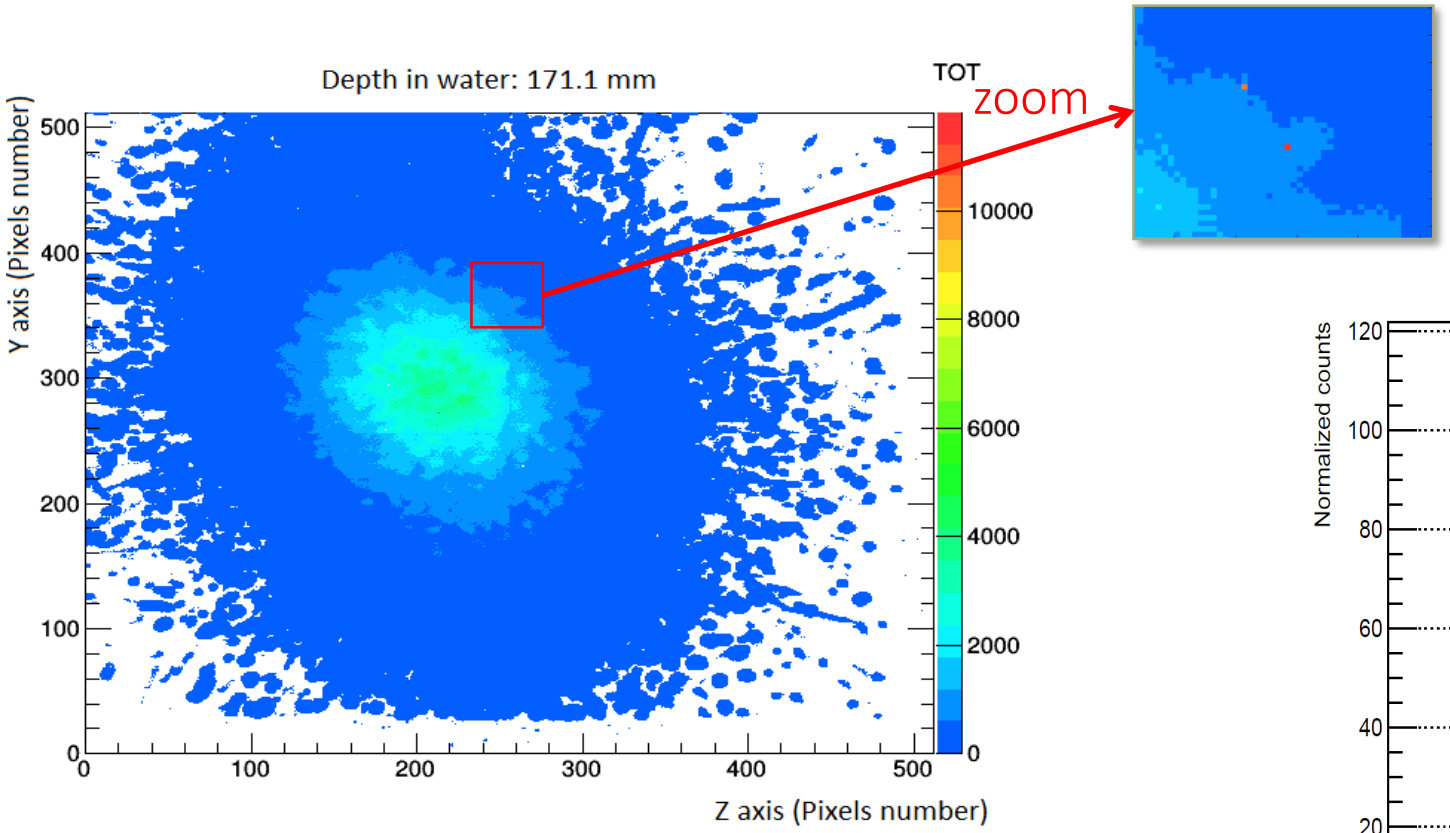
Further experimental measurements have been done at CNAO and are being analysed

Future developments

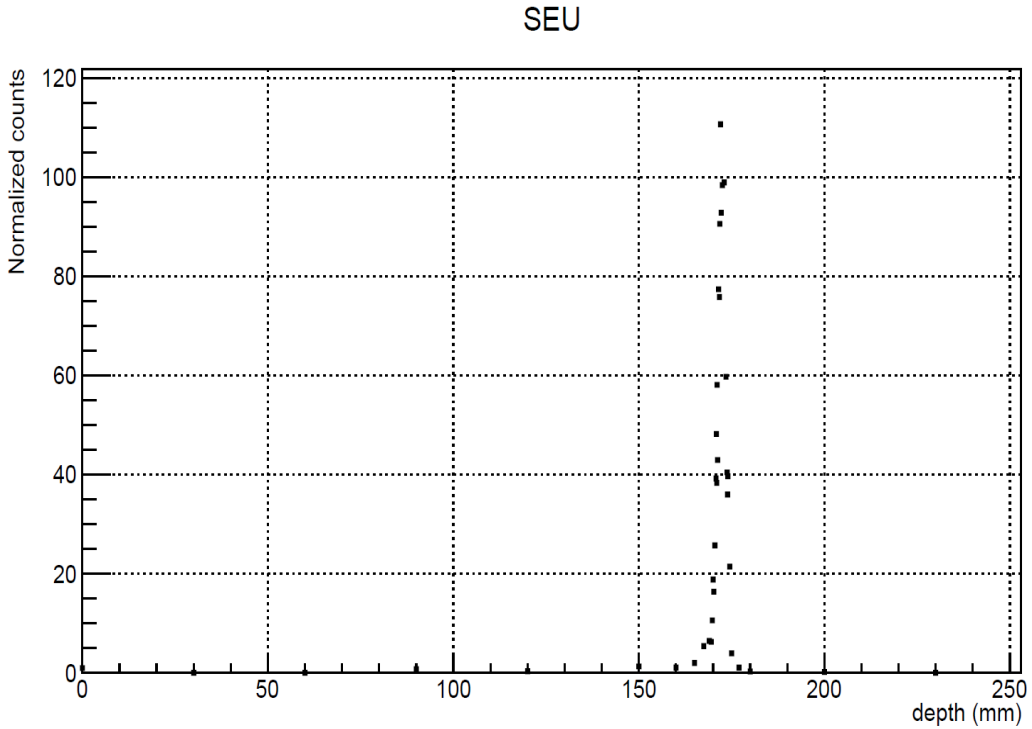
- More detailed simulation → electric field of GEM layers
- Advanced simulation study of secondary particle distrubution in water and in the GEMPix
- Study of the Bragg curve for different GEMPix setting parameters (gain, acquisition clock)
- Continuous monitoring of pressure and temperature inside the detector during the measurements
- Implementation of a better trigger system between GEMPix and DDS CNAO system
- New measurements at CNAO Centre

Backup
Ctrl

GEMPix and SEU *(Single Event Upset)*



SEU events above (red) and below (orange) the TOT saturation level (11000)

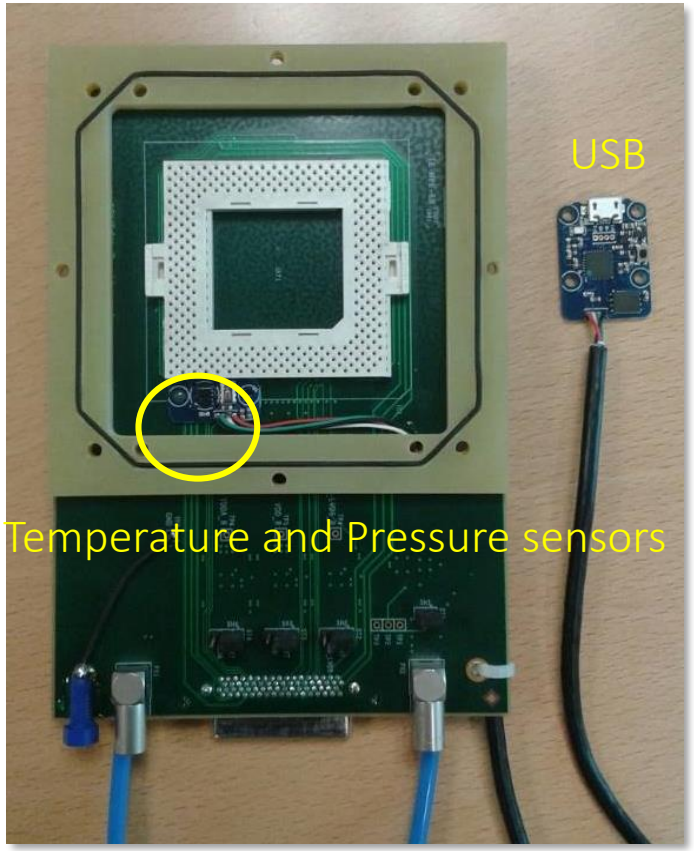


SEU is a function of water depth

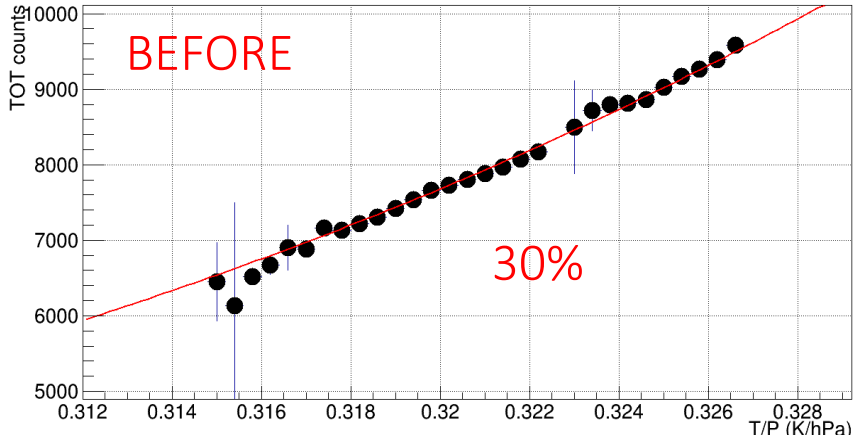
Maximum value of SEU at the Bragg peak → maximum dose release

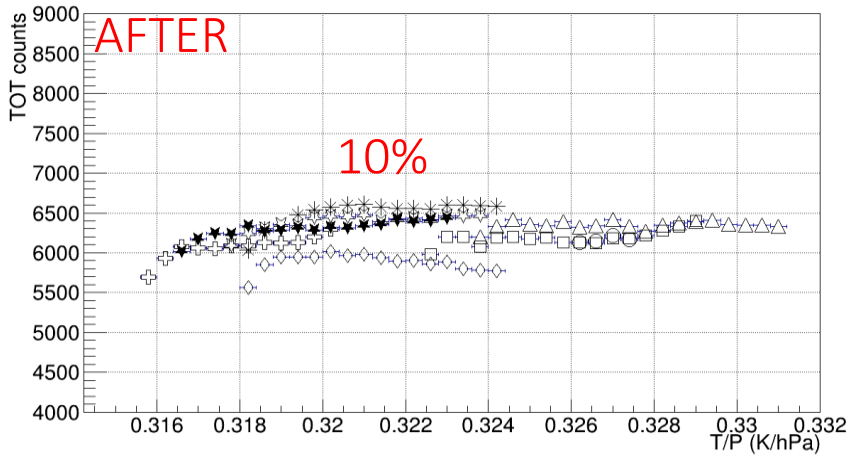
Energy calibration and T/P correction

The temperature and the pressure measured inside the detector allow the realtime HV correction to obtain gain stability



Online HV correctic



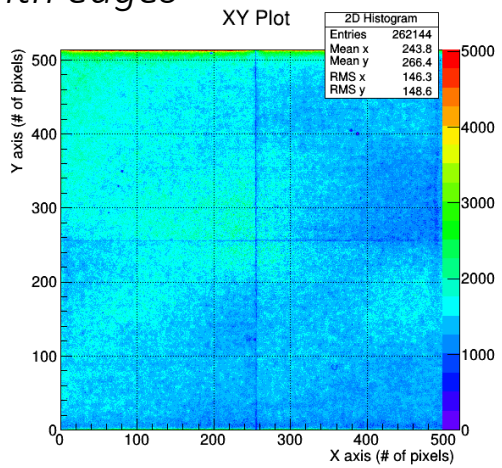


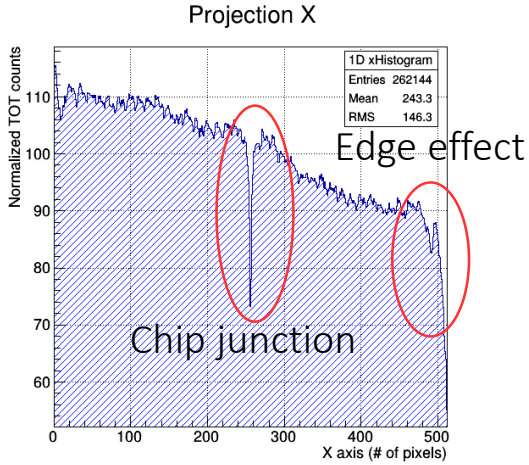
CNAO measurements: *homogeneity (I)*

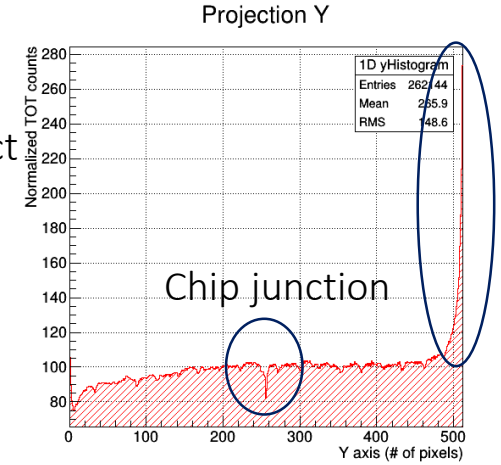
PRELIMINARY RESULTS

60 mm^2 carbon ions scanned field (3x10^4 total particles delivered)

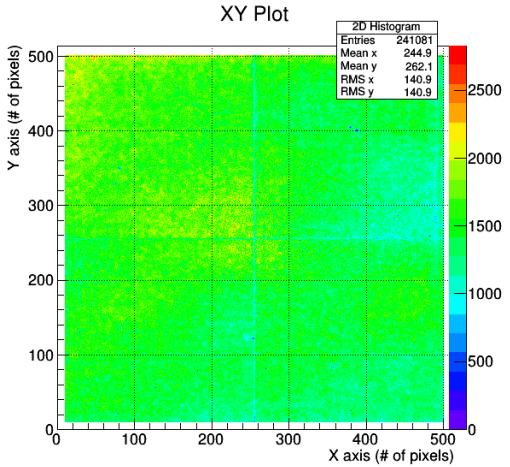
With edges

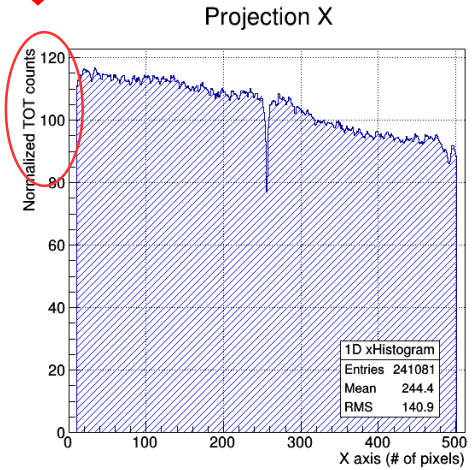


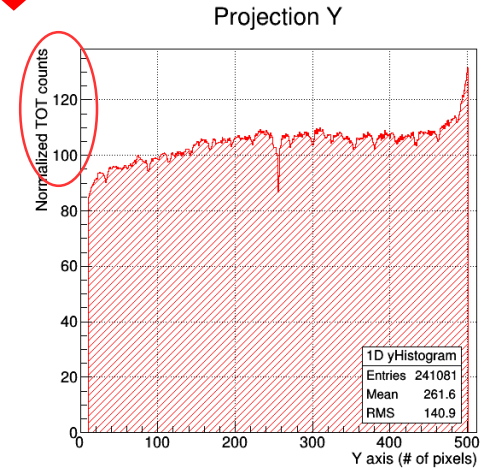


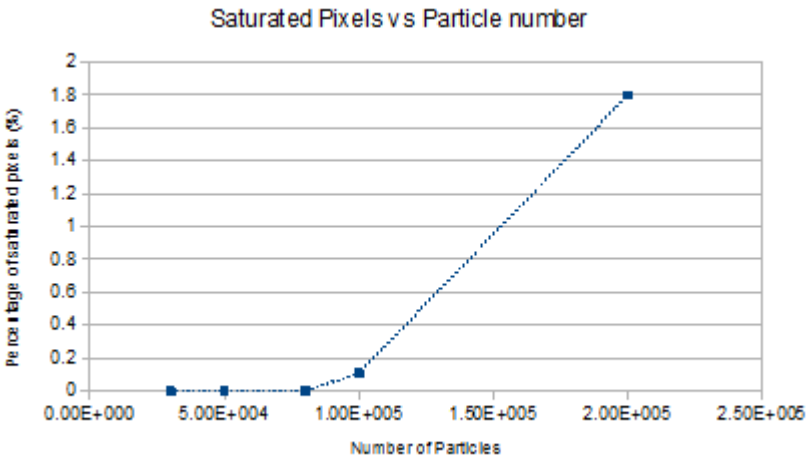


Without edges









Edge effects → 2% of saturated pixels at higher particle fluxes