Low-pressure TPC detector for studying photonuclear reactions at astrophysical energies with gamma-ray beams at ELI-NP

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*for **ELITPC** collaboration*

(UW, ELI-NP / IFIN-HH, Univ. of Connecticut)

ELITPC

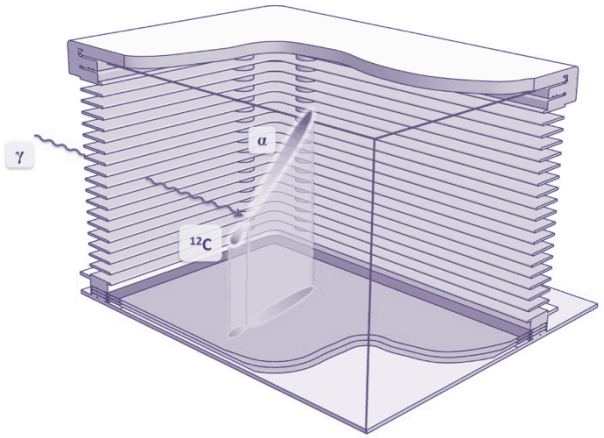
Workshop on Active Targets and Time Projection Chambers for High-intensity & Heavy-ion beams in Nuclear Physics

17-19 January 2018 – Santiago de Compostela, Spain

GDS

Outline

1. Nuclear photo-disintegration reactions.
2. ELITPC detector concept:
   - detector structure
   - toy Monte Carlo signal simulations
3. R&D studies:
   - gas gain at low-pressures
   - small scale prototype tests



Motivation

1. Physics goals:
   - study **(α,γ)** and **(p,γ)** reactions of current astrophysical interest:
     - **burn helium** → regulate **C / O** ratio in the Universe
     - **burn ^{18}O** → regulate **^{16}O/^{18}O** ratio in the Universe
   - particular effort on **^{12}C(α,γ)^{16}O** reaction at E_{cm} ~1 MeV

2. Approach:
   - capture vs. photo-disintegration reactions
   - monochromatic gamma-ray beams @ ELI-NP
   - *active-target* Time Projection Chamber for ELI-NP (ELITPC)

Nuclear Astrophysics studies with monochromatic γ–ray beams

- use detailed balance principle for time-reverse reactions
- measure decay products of nuclear photo-dissociation reactions

Time-reverse reaction	Detector type	Target	Astrophysical relevance
$^{16}O(\gamma,\alpha)^{12}C$	TPC	**CO_2**	**ratio C/O**
$^{19}F(\gamma,p)^{18}O$	TPC	CF_4	ratio $^{16}O/^{18}O$, CNO-cycle
$^{21}Ne(\gamma,\alpha)^{17}O$	TPC	^{21}Ne	role of ^{16}O as neutron poison
$^{22}Ne(\gamma,\alpha)^{18}O$	TPC	^{22}Ne	ratio $^{16}O/^{18}O$, CNO-cycle synthesis of ^{22}Ne (source of *n* in *s*-processes)
$^{24}Mg(\gamma,\alpha)^{20}Ne$	SSD	^{24}Mg	Si-burning
$^{96}Ru(\gamma,\alpha)^{92}Mo$	SSD	^{96}Ru	synthesis of elements with A>73 in *p*-processes

O.Tesileanu et al., Romanian Rep. in Phys. 68, Supplement (2016) S699

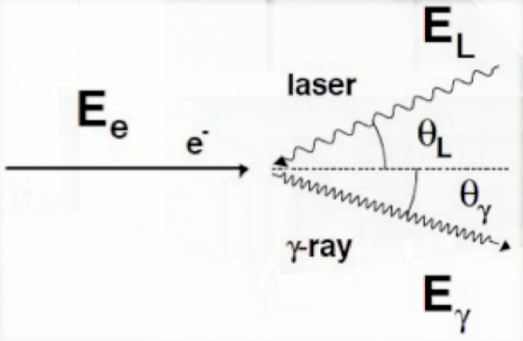
Gamma-ray beam @ ELI-NP

Extreme Light Infrastructure – Nuclear Physics

Bucharest-Magurele, Romania

Compton Back Scattering:

- high-brilliance
- narrow energy bandwidth



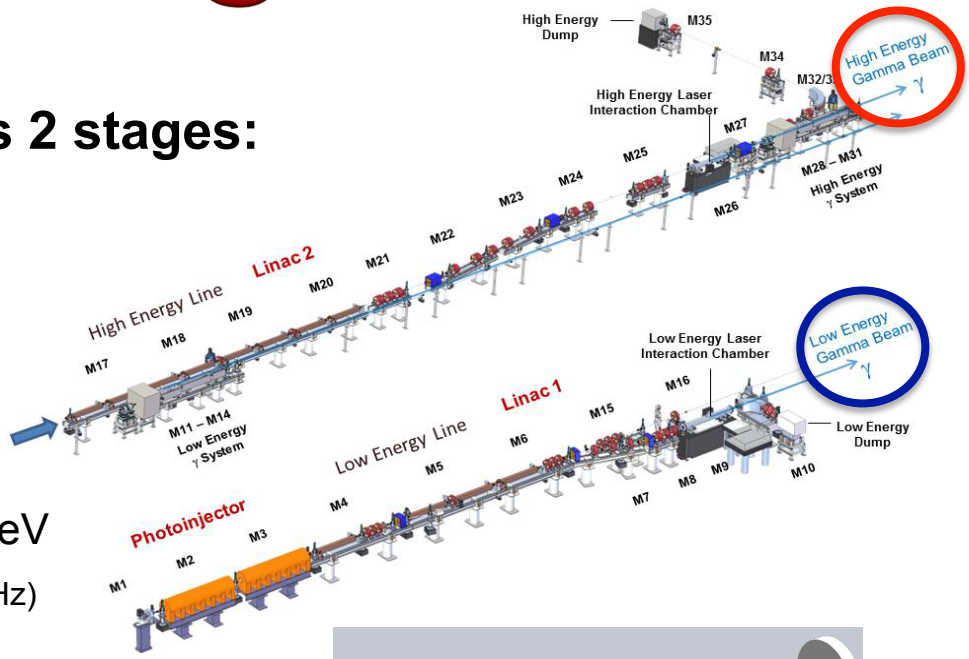
First beams expected in 2018

Gamma energy range	**0.2 – 19.5 MeV**
Energy bandwidth (rms)	**< 0.5 %**
Spectral density	> 0.5 10^3 γ/s/eV
Peak brilliance	10^{20} – 10^{23} γ/(s mm^2 mrad^2 0.1%BW)
Angular divergence (rms)	25 – 200 μrad
Macro-pulse rate	100 Hz
Linear polarization	> 95%

S.Gales et al., Phys. Scr. 91 (2016) 093004
D.Filipescu et al., Eur. Phys. J. A 51 (2015) 185

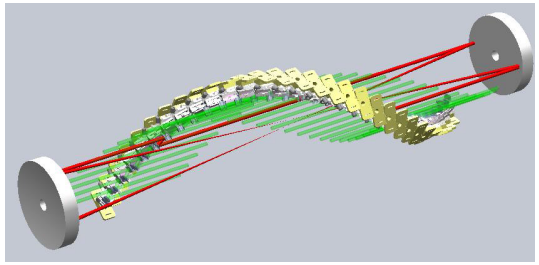
Gamma-ray beam @ ELI-NP

- **Gamma Beam System (GBS) has 2 stages:**
  - **low** energy (E_γ<3.5 MeV)
  - **high** energy (E_γ<19.5 MeV)

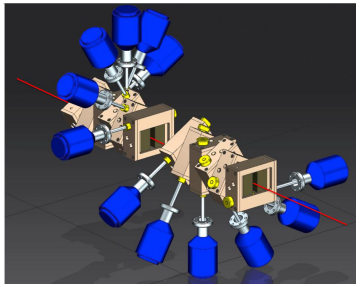


- **GBS components:**

1. **Electron LINAC:**
   - tunable energy: E_e = 80 – 720 MeV
   - laser photo-injector (32 pulses, 100 Hz)
   - two stages (Linac1, Linac2)
   - total length: 90 m



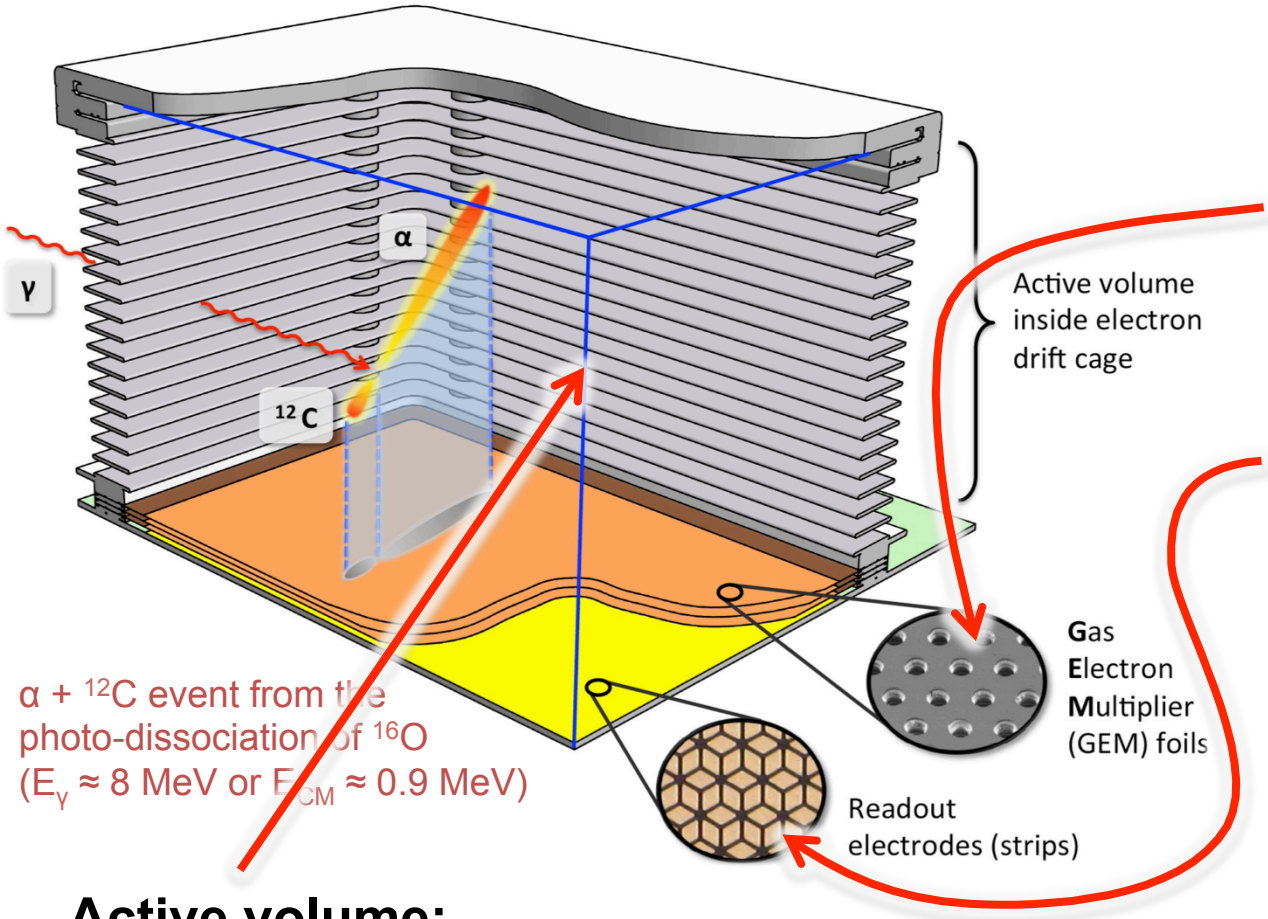
2. **Laser system:**
   - green light (E_L=2.4 eV, λ=515 nm, 500 mJ / 3.5 ps)
   - fixed electron-photon crossing angle (θ_γ=7.5°)
   - multi-pass laser beam recirculation



3. **Collimation & diagnostics systems**

O. Adriani et al., arXiv:1407.3669 [physics.acc-ph], July 2014

ELITPC : low-pressure Active-Target TPC



Charge amplification:

- *Gas Electron Multiplier* (GEM) structures

Readout:

- Planar, 3-coordinate, redundant strip arrays
- about 1000 channels
- *GET* electronics for signal amplification & digitization
- external trigger (100 Hz)

Active volume:

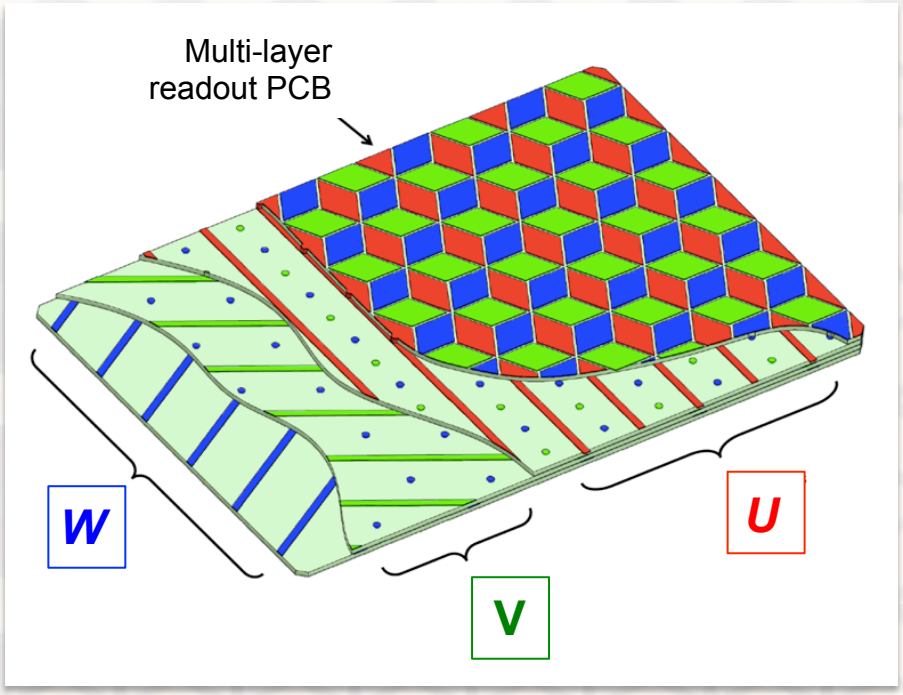
- 33 x 20 cm^2 (readout) x 20 cm (drift)
- gas pressure ~100 mbar ⇒ increase track lengths

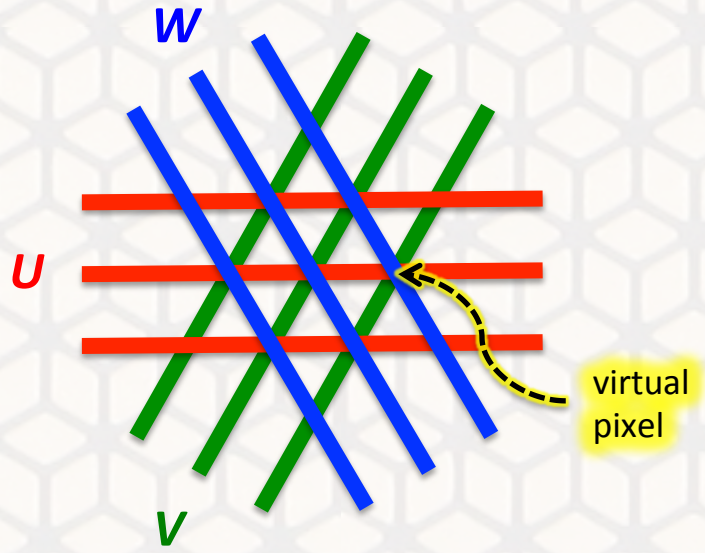
O.Tesileanu et al., Romanian Rep. in Phys. 68, Supplement (2016) S699

ELITPC readout concept

3 grids of strips, crossed at 60° with each other:

- 3-coordinate, planar, redundant readout, strip pitch ~ 1.5 mm
- Simple event topologies → only few tracks per event
- Moderate cost → only ***O*(10^3)** channels of digitized channels
- ***U*-*V*-*W*** strip arrays on XY plane + Z-coordinate from drift time → virtual 3D pixels

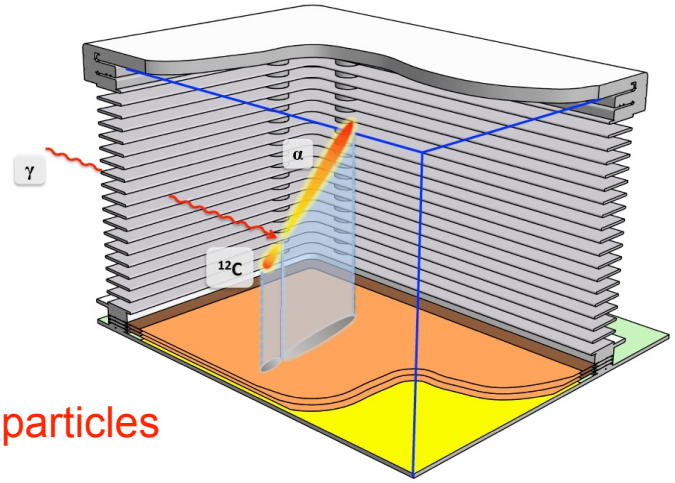




S. Bachmann et al., NIMA 478 (2002) 104
V. Ableev et al., NIMA 535 (2004) 294
M. Ćwiok, Acta Phys. Pol. B 47 (2016) 707
J. Bihałowicz et al., Proc. of SPIE 9290 (2014) 92902C

Monte Carlo event yields

- **Reaction case $^{16}O(\gamma,\alpha)^{12}C$:**

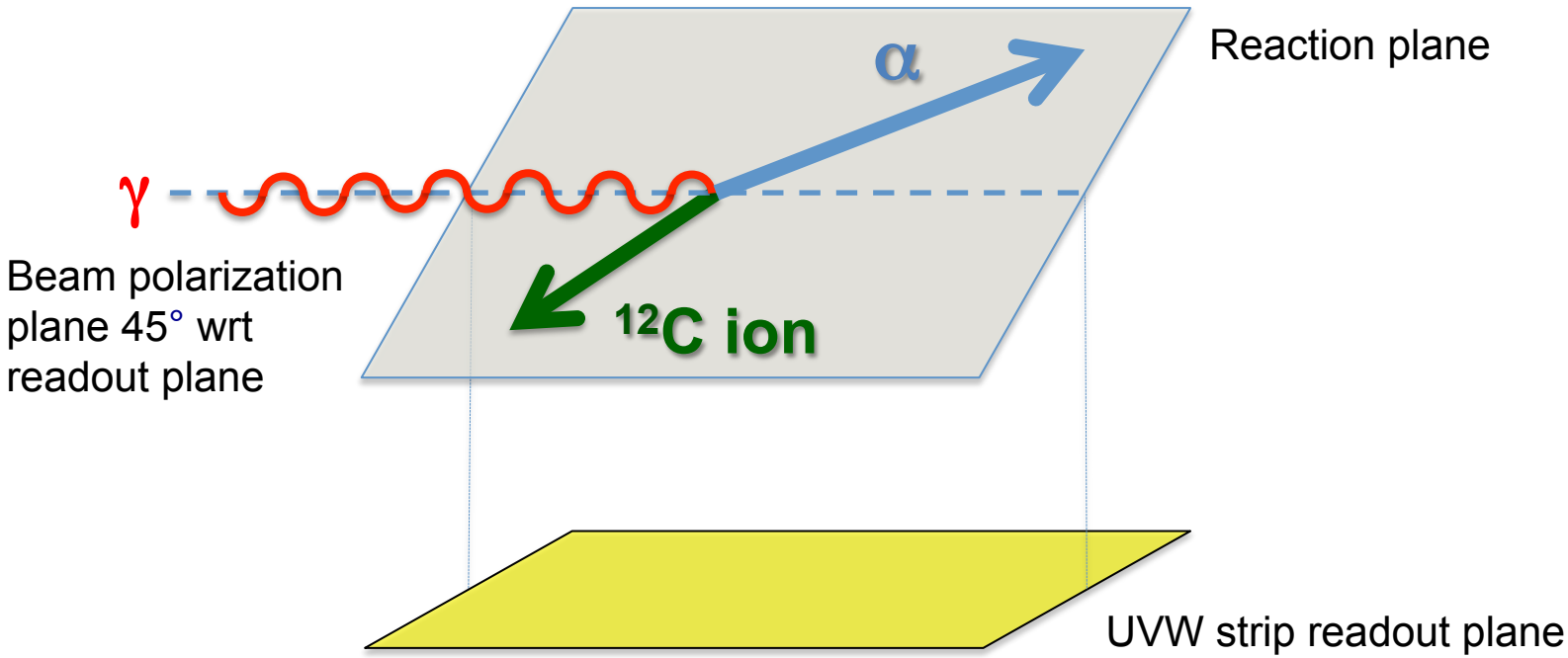


  - **Method:**
    - measure energy & angular distributions of charged particles
    - obtain accurate values of E2 / E1 components

  - **Efficiency** (example for CO_2 @ 100 mbar):
    - beam energy: **E_γ=8.26 MeV → E_{cm}=1.1 MeV** [Q=7.162 MeV for **$^{12}C(\alpha,\gamma)^{16}O$**]
    - beam intensity on target: 2.5 × 10^4 γ/s/eV, 0.5% bandwidth → **10^9 γ/s**
    - **1500 events** to measure angular distributions → **21 days of beam time**

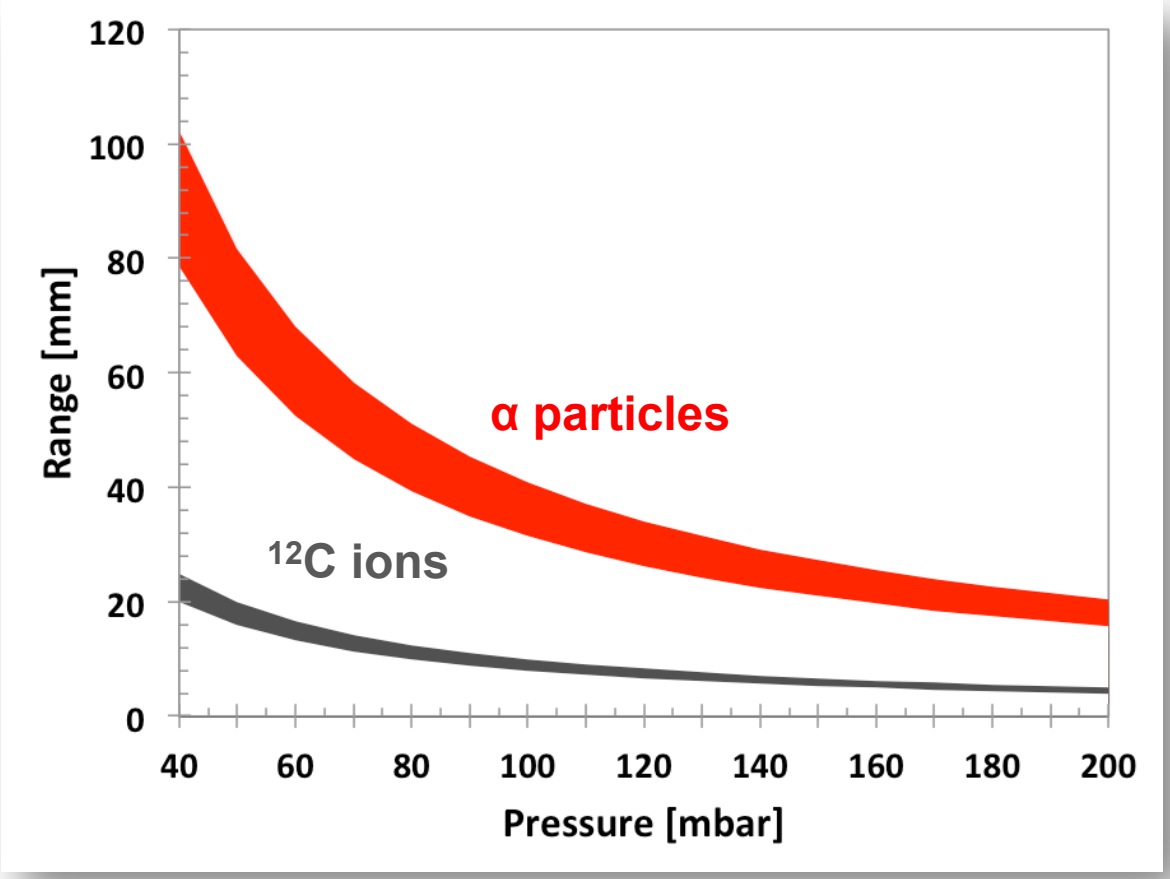
Monte Carlo: signal topology

- **Reaction case $^{16}O(\gamma,\alpha)^{12}C$:**



Monte Carlo: track lengths

- **Reaction case $^{16}O(\gamma,\alpha)^{12}C$:**



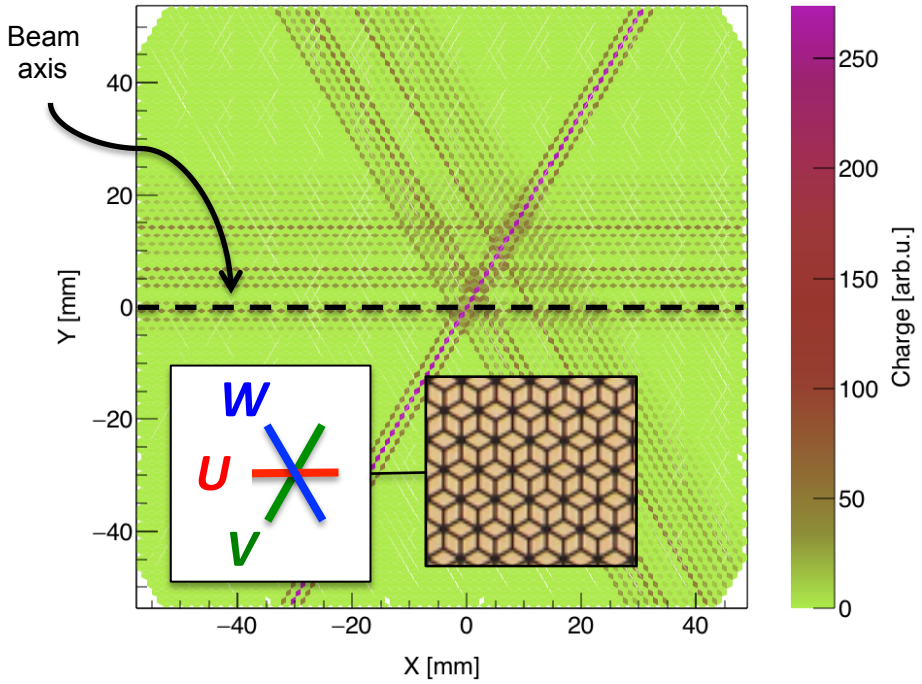
- SRIM-simulated ranges of charged particles vs. CO_2 pressure

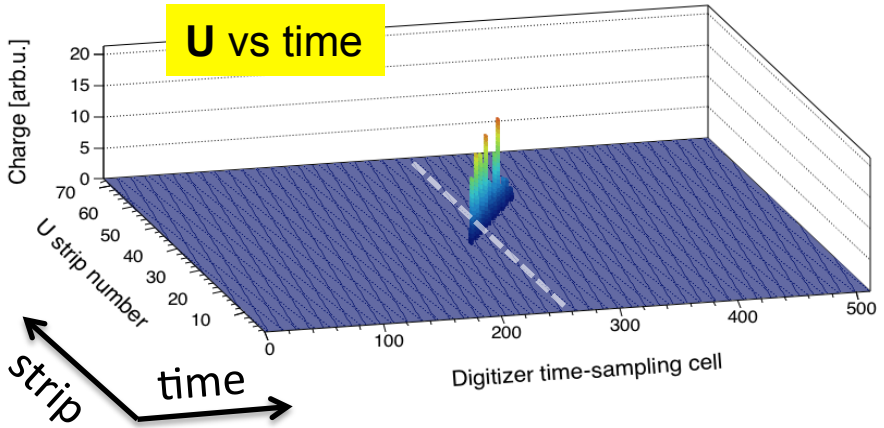
- Bands correspond to:
  - E_γ range: 8.26 - 8.67 MeV
  - 90° emission angles w.r.t. γ-beam axis

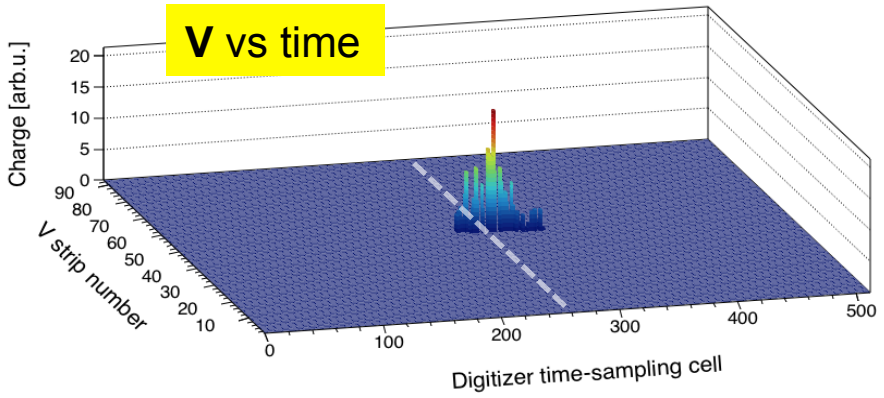
O.Tesileanu et al., Romanian Rep. in Phys. 68, Supplement (2016) S699

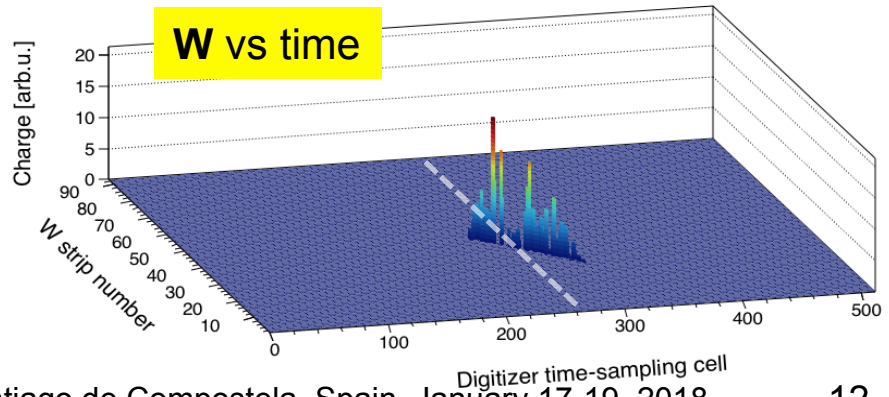
Pure signal event

Time-integrated UVW signals





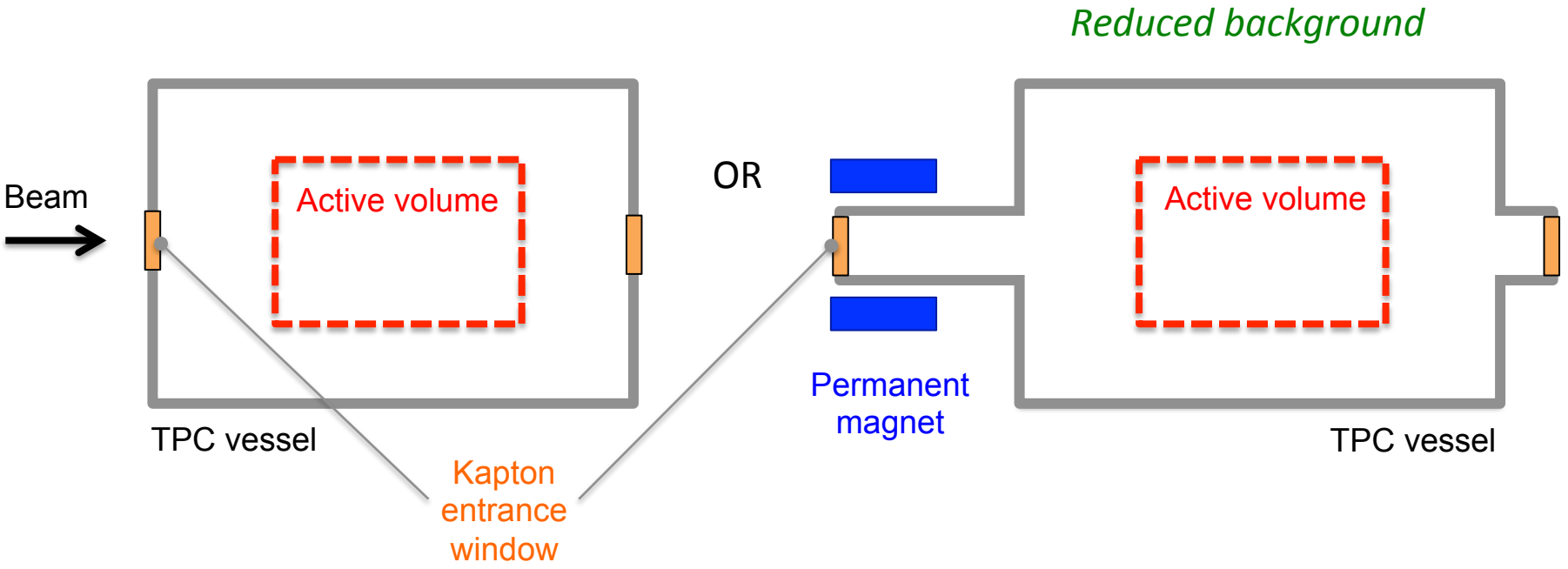




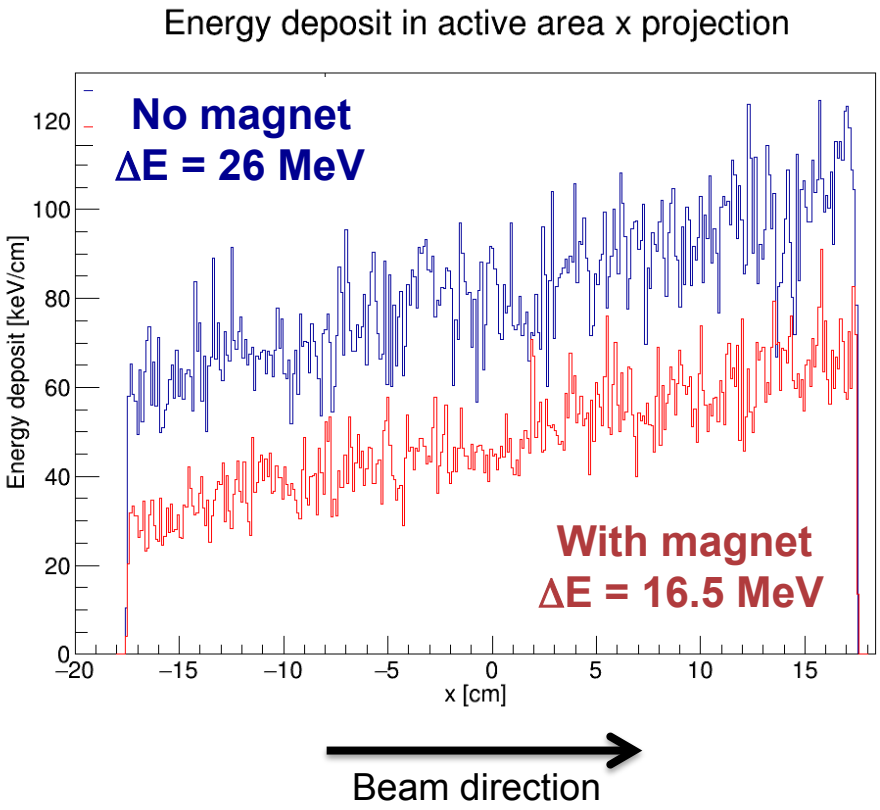
- **E_γ = 8.3 MeV** (i.e. E_{cm} = 1.1 MeV)
- E(α) = 0.85 MeV, E(^{12}C) = 0.25 MeV
- **100 mbar CO_2** / no diffusion & gas gain
- 10 x 10 cm^2 area / 1.5 mm strip pitch
- GEANT4

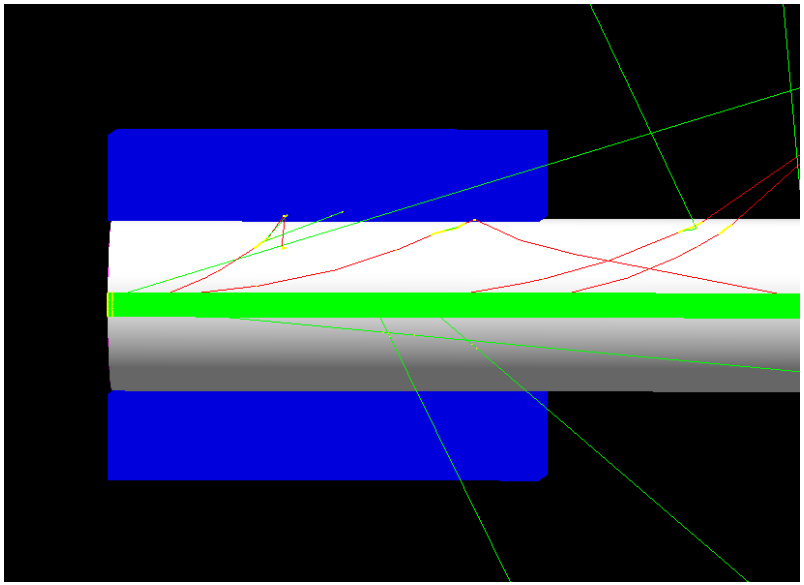
Monte Carlo: background

- **Compton electrons, e^+e^- pairs** from: Kapton window + gas target
  - Small in comparison with direct (α,γ) reaction experiments
- Single ELI-NP macro-bunch: **~10^7 photons**
- Macro-bunch rate: **100 Hz** (10 ms apart)



Monte Carlo: background

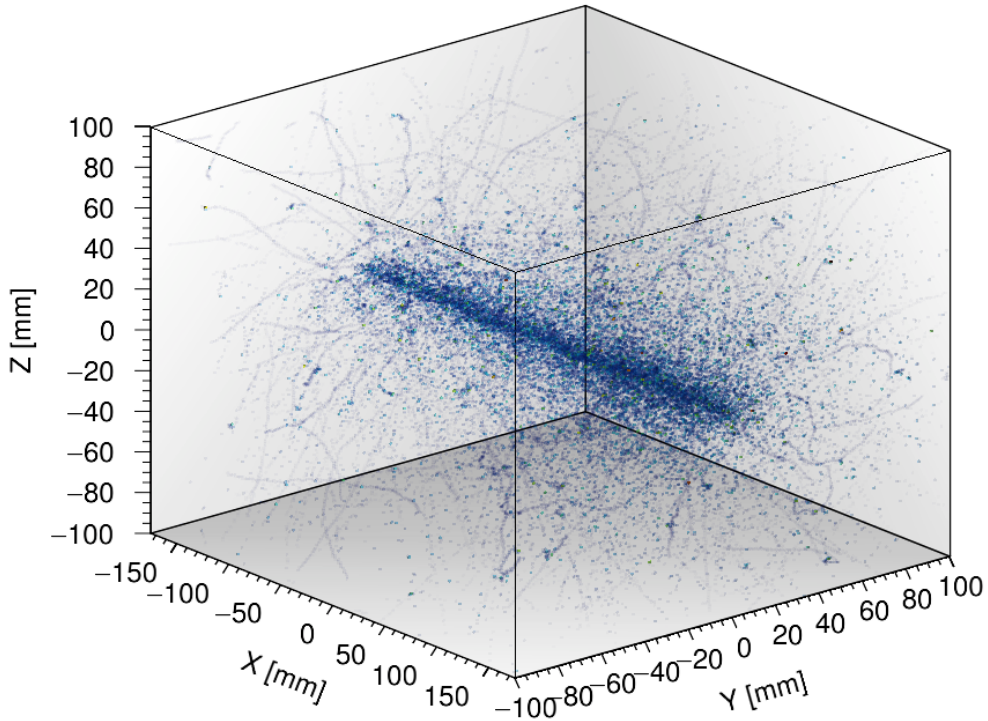


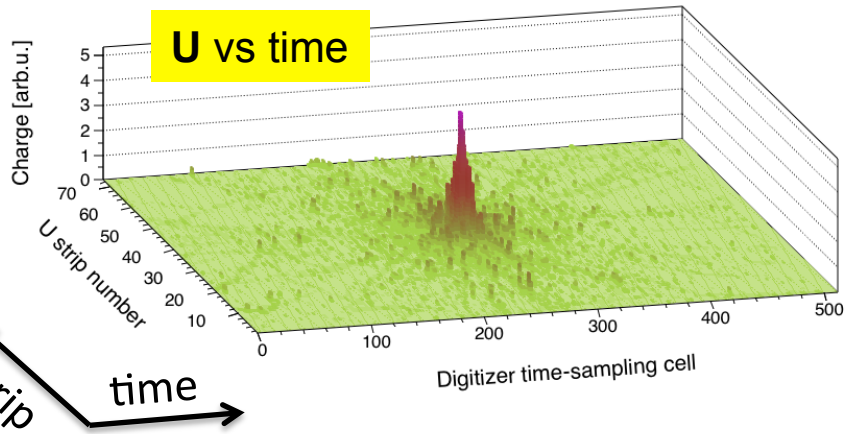


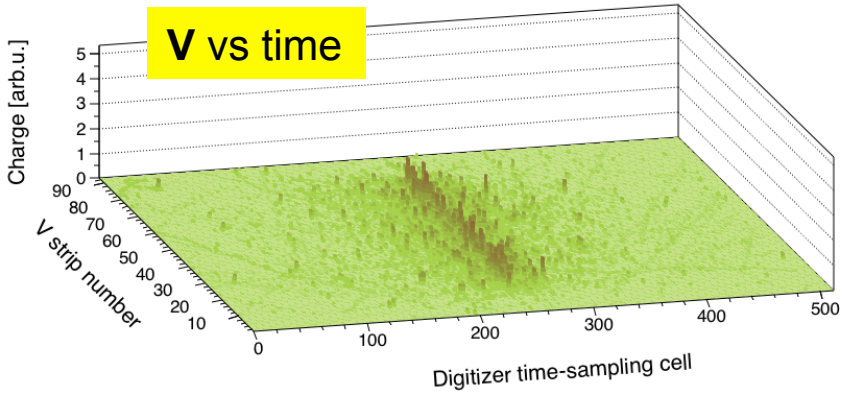
- **E_γ = 8.3 MeV**
- **100 mbar CO_2**
- 35 x 20 cm^2 active area, 20 cm drift
- GEANT4 / 10^7 photons

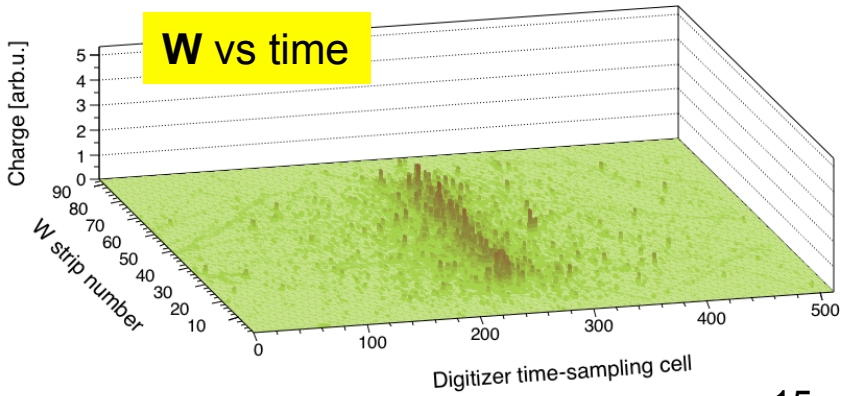
Pure background event

- E_γ = **8.3 MeV**
- **100 mbar CO_2** / no diffusion & gas gain
- 10 x 10 cm^2 area / 1.5 mm strip pitch
- GEANT4 / 10^7 photons



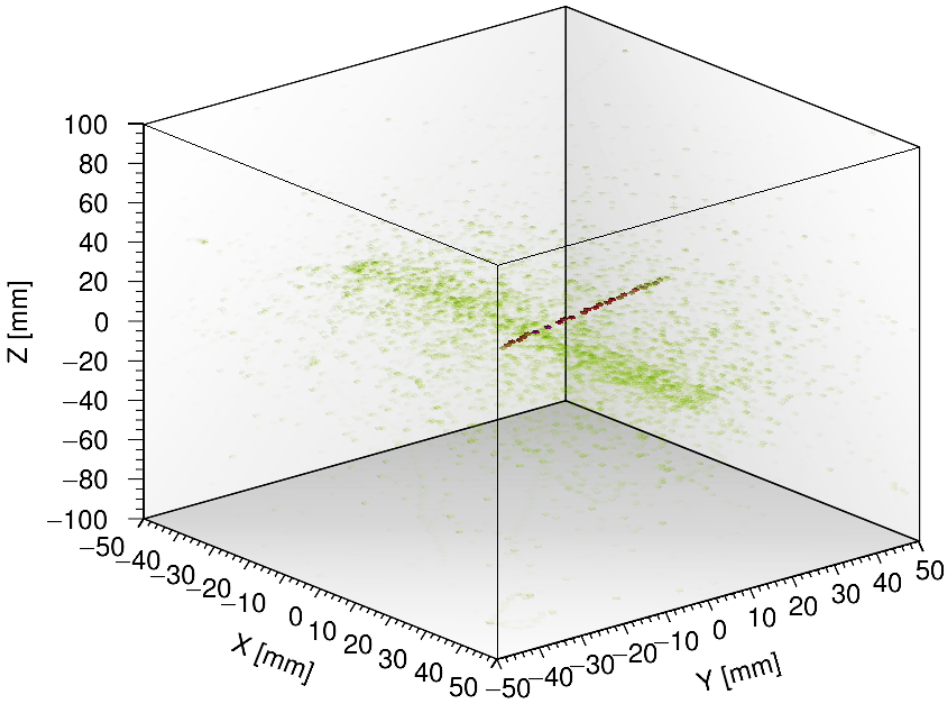


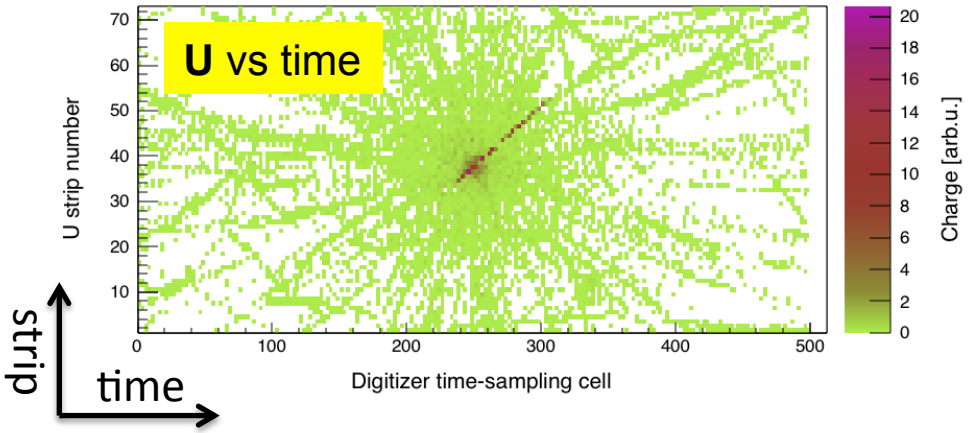


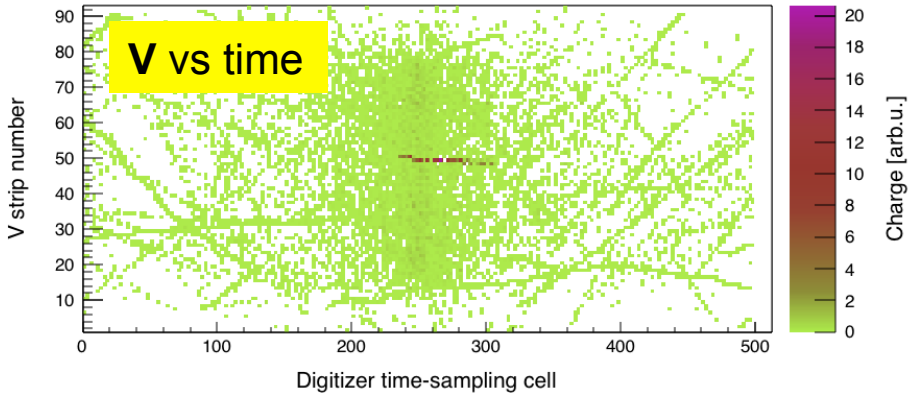


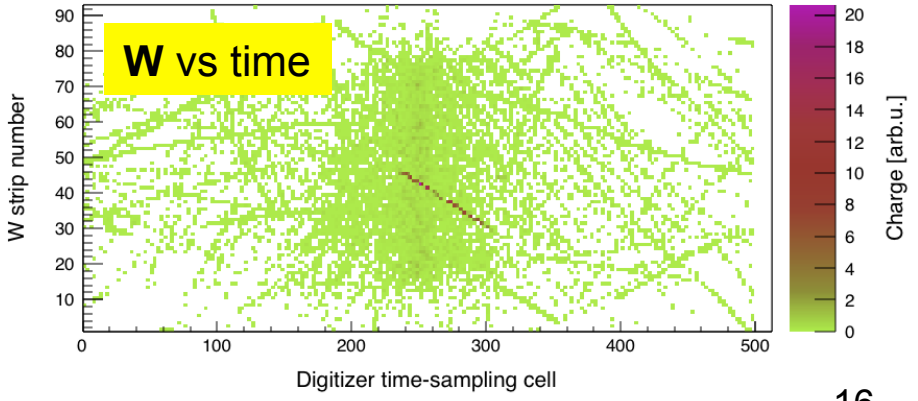
Combined SIG + BKG event

- **E_γ = 8.3 MeV**
- E(α) = 0.85 MeV, E(^{12}C) = 0.25 MeV
- **100 mbar CO_2** / no diffusion & gas gain
- 10 x 10 cm^2 area / 1.5 mm strip pitch
- GEANT4

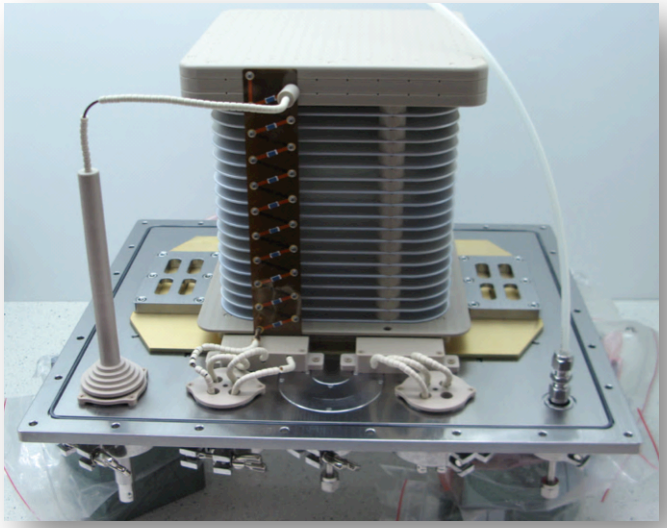


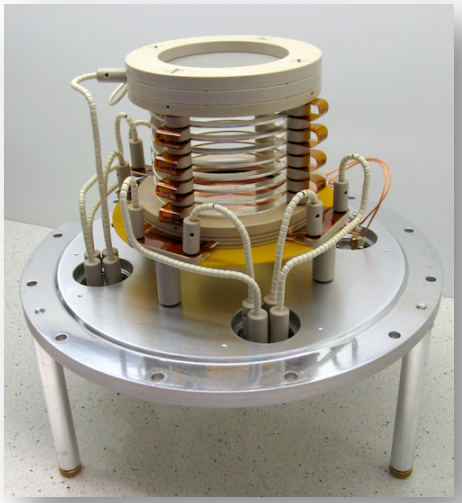






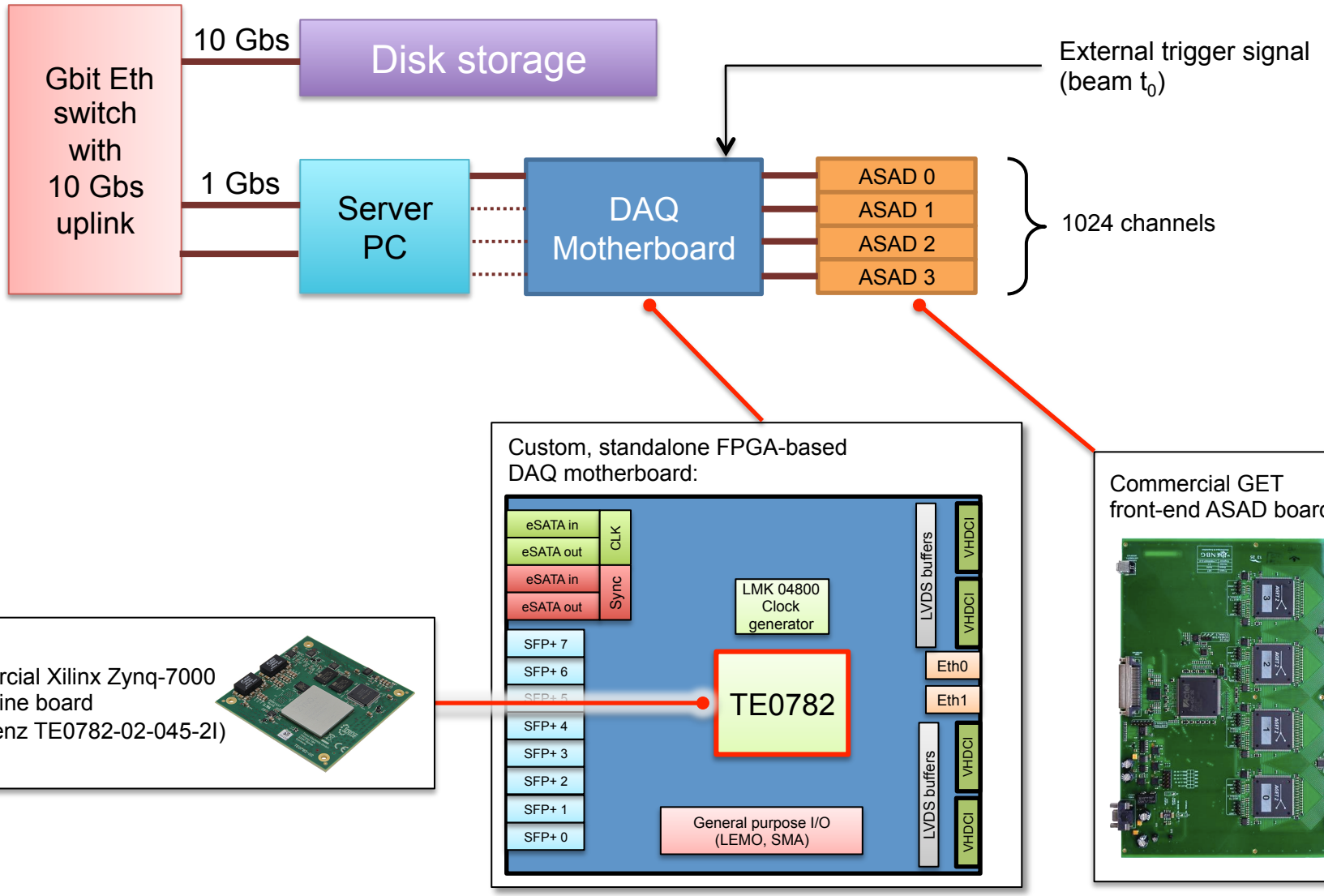
ELITPC – R&D status





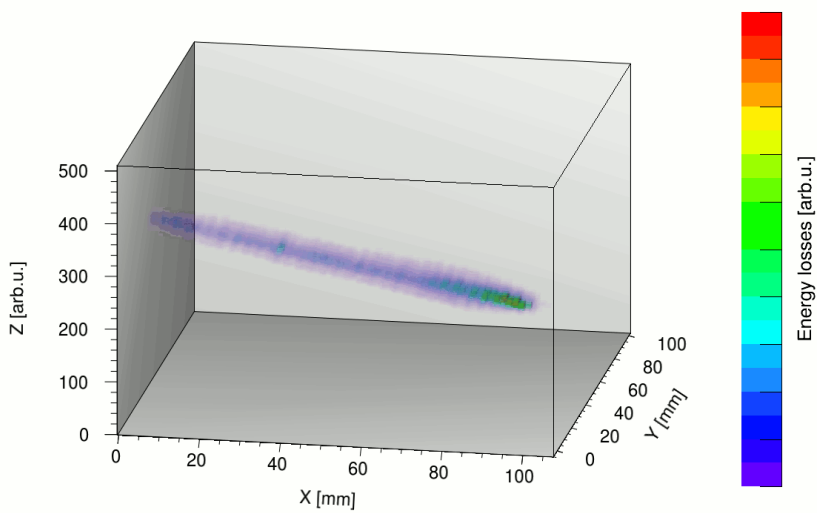
- **Customized FPGA-based DAQ:**
  - using GET front-end boards
- **Proof of principle studies:**
  - demonstrator detector: 10 x10 cm^2 area, 20 cm drift @ 1 atm
  - tested with charged particles
- **Optimization studies:**
  - test bench for low-pressure gas-gain studies with X-rays
  - amplification structures, He+CO_2 gas mixtures, etc...

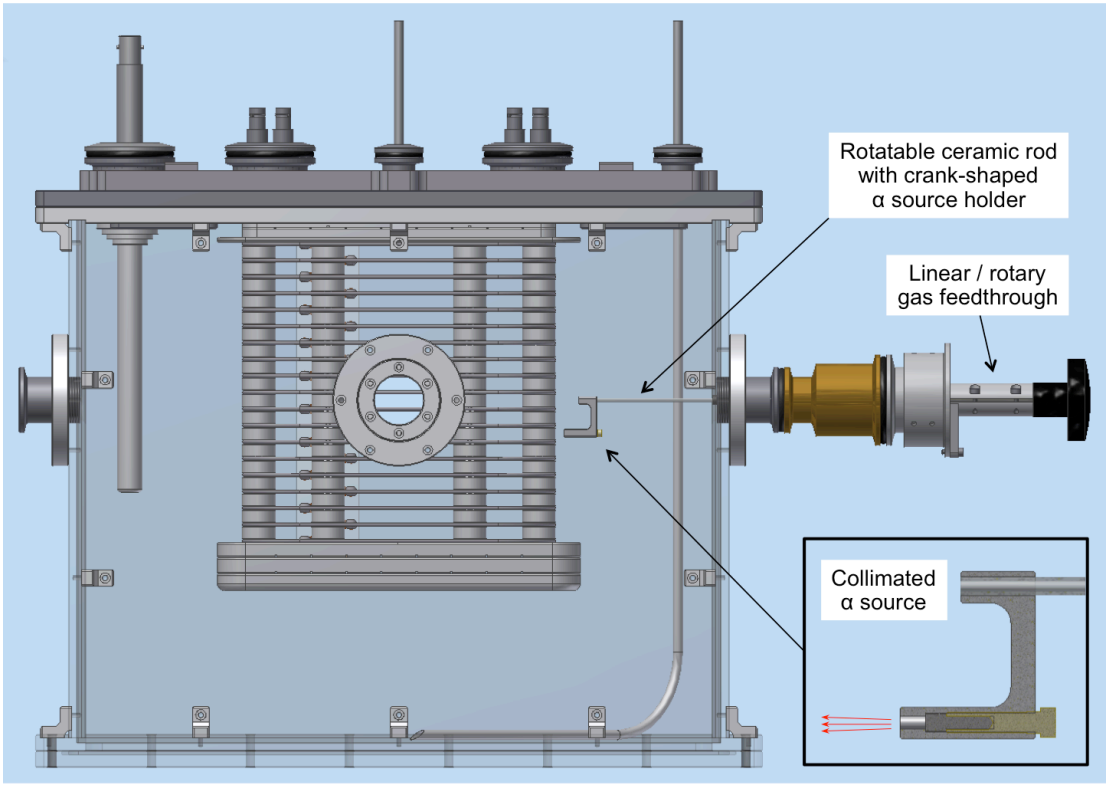
ELITPC – DAQ system



Demonstrator detector

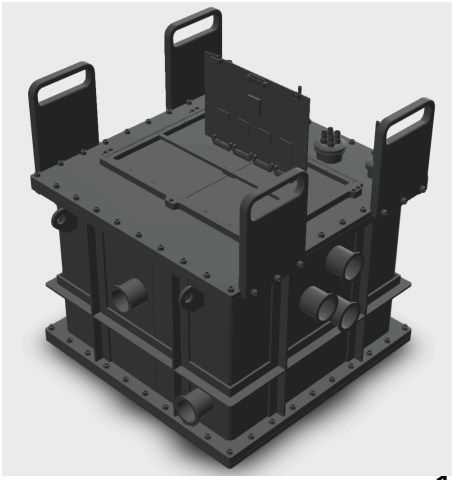
- Readout area: **10 × 10 cm²**, drift: **20 cm**
- GET electronics: **256 channels**
- **He+CO_2** gas mixtures **@ 1 atm**
- Tested with α-particles (rad. src, beam)



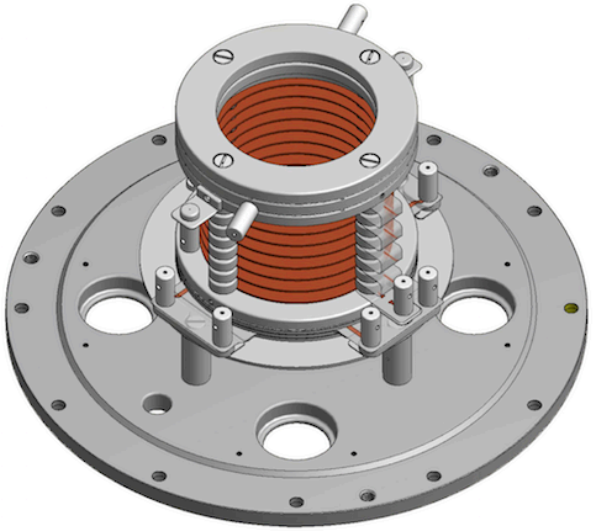


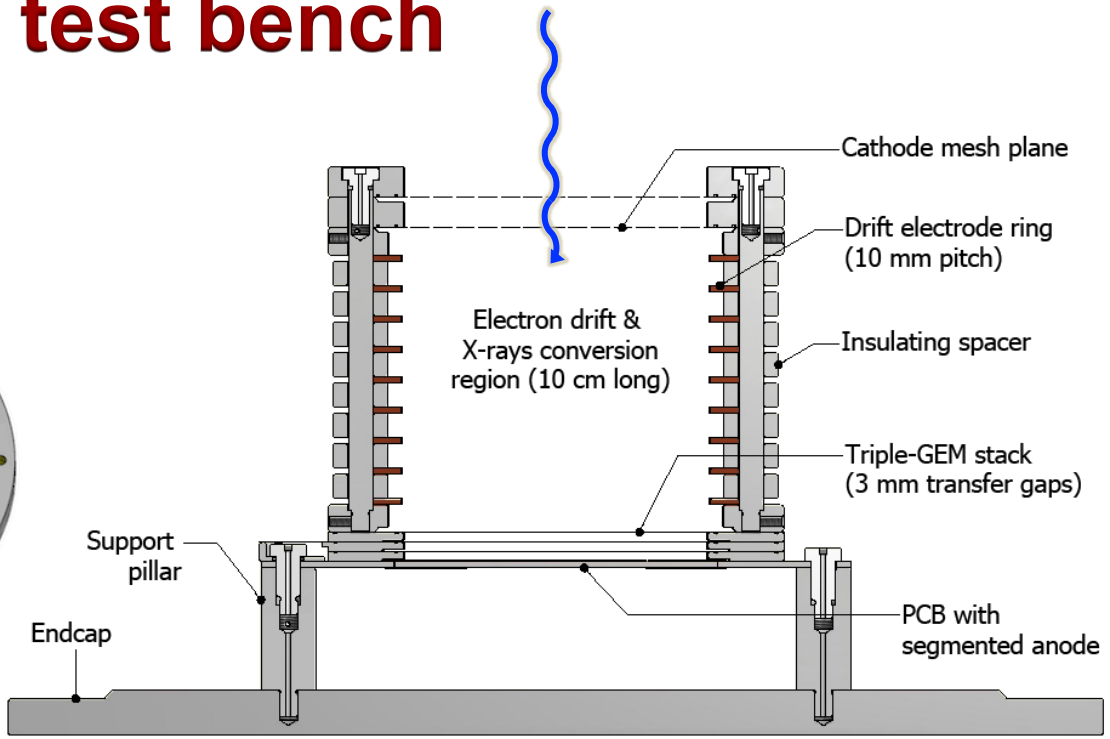
NEXT STEPS:

- migrate to a vacuum vessel
- tests with CO_2 and He+CO_2 at 100-200 mbar



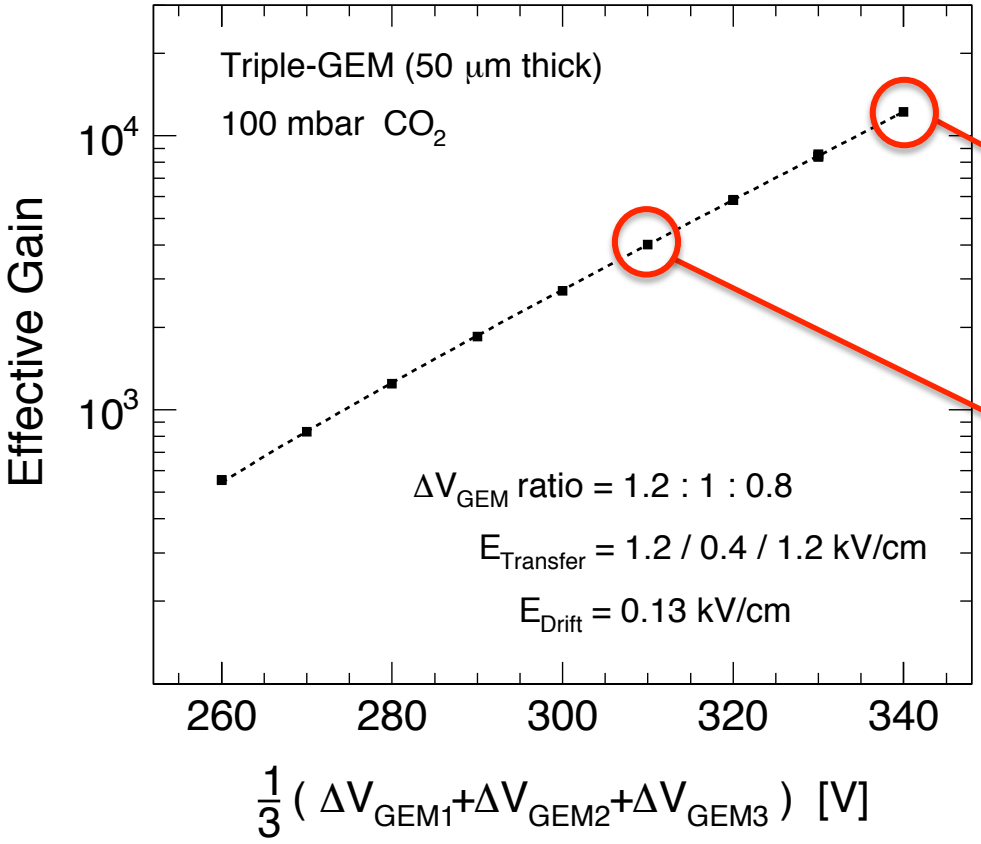
Low-pressure test bench

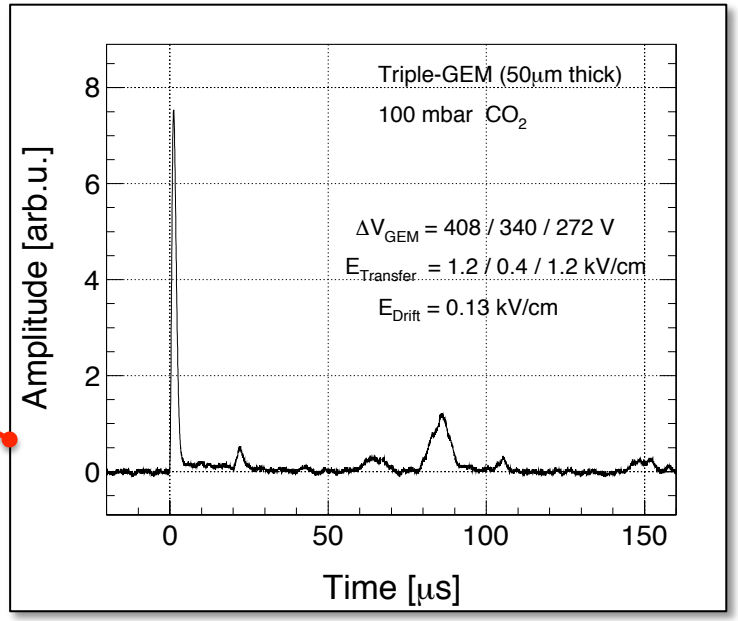


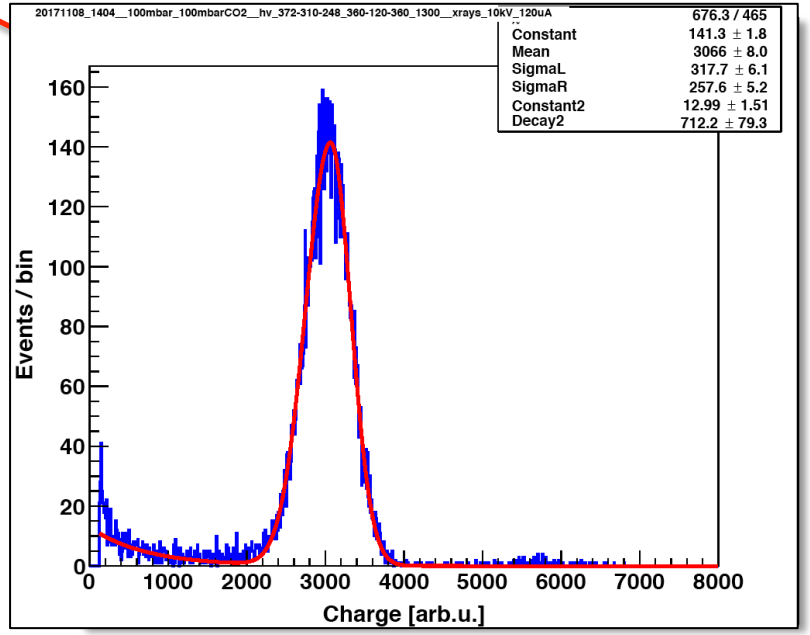


- **Gas gain** & **energy resolution** measured by soft X-rays conversion
- X-rays from Ag lamp filtered through: Ti + Kapton foils
  - quasi-monochromatic input energy spectrum: peak @ 5 keV, FWHM 9% from SiDet
- **Pure CO_2** and different **He+CO_2** gas mixtures (50-200 mbar total pressure)
- **Standard 50-μm GEMs** made by CERN / RD51

Pure CO_2 @ 100 mbar





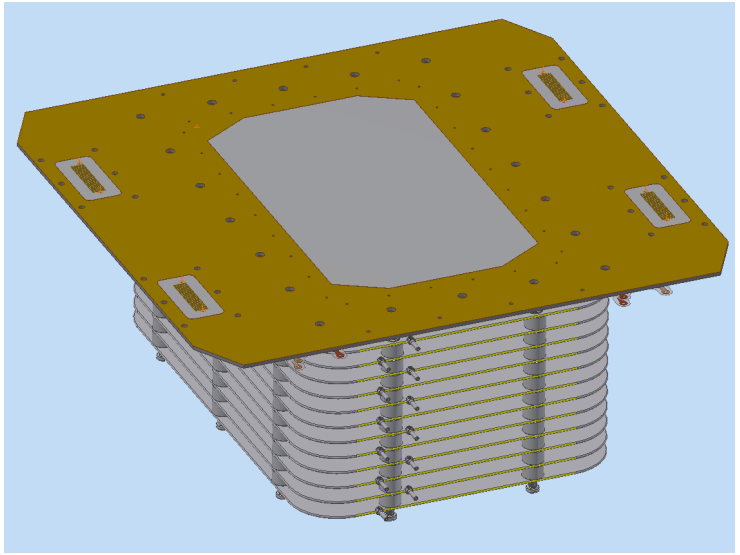


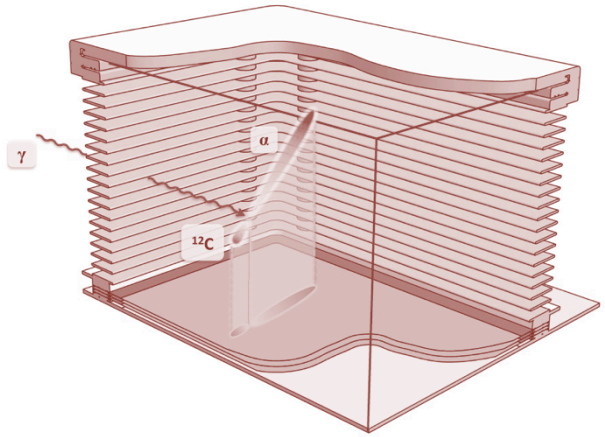
- Max gain **~10^4** : limited by positive ion feedback!
- Gain **~$5 \cdot 10^3$** : feedback OK, FWHM ~25% @ 5 keV

NEXT STEPS: measure diffusion, test 125-μm GEMs...

Summary & outlooks

- MC techniques used to optimize ELITPC detector structure.
- Low-pressure studies will be continued with 256-ch demonstrator detector for various He+CO_2 pressures.
- Mechanical design and strip segmentation – to be fixed by Mar 2018.
- 1024-ch customized GET electronics – to be ready by Oct 2018.





Thank you for your attention !!!

The ELITPC collaboration:

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2) IFIN-HH / ELI-NP, Romania
3) Univ. of Connecticut, USA

ELITPC

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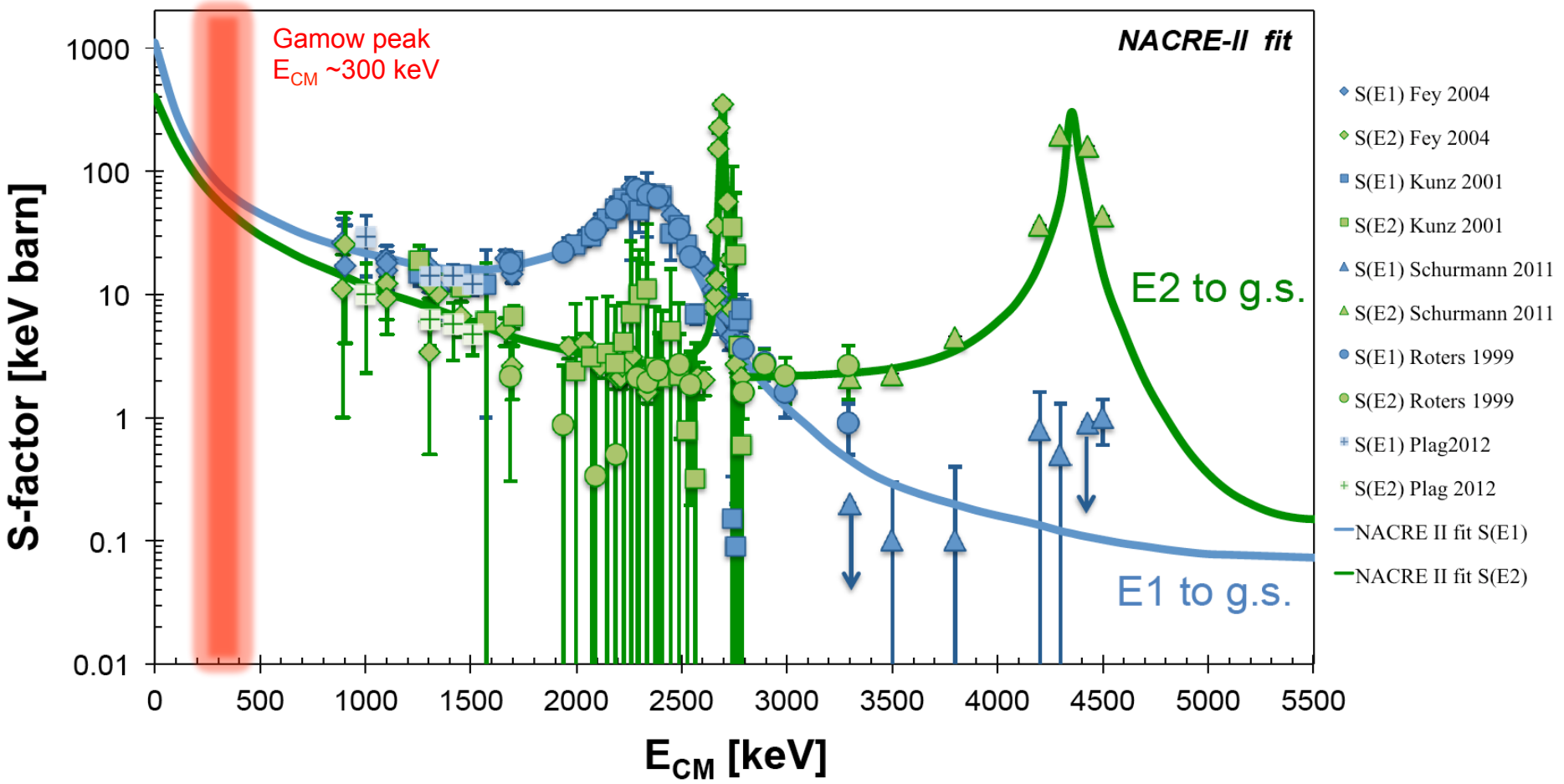
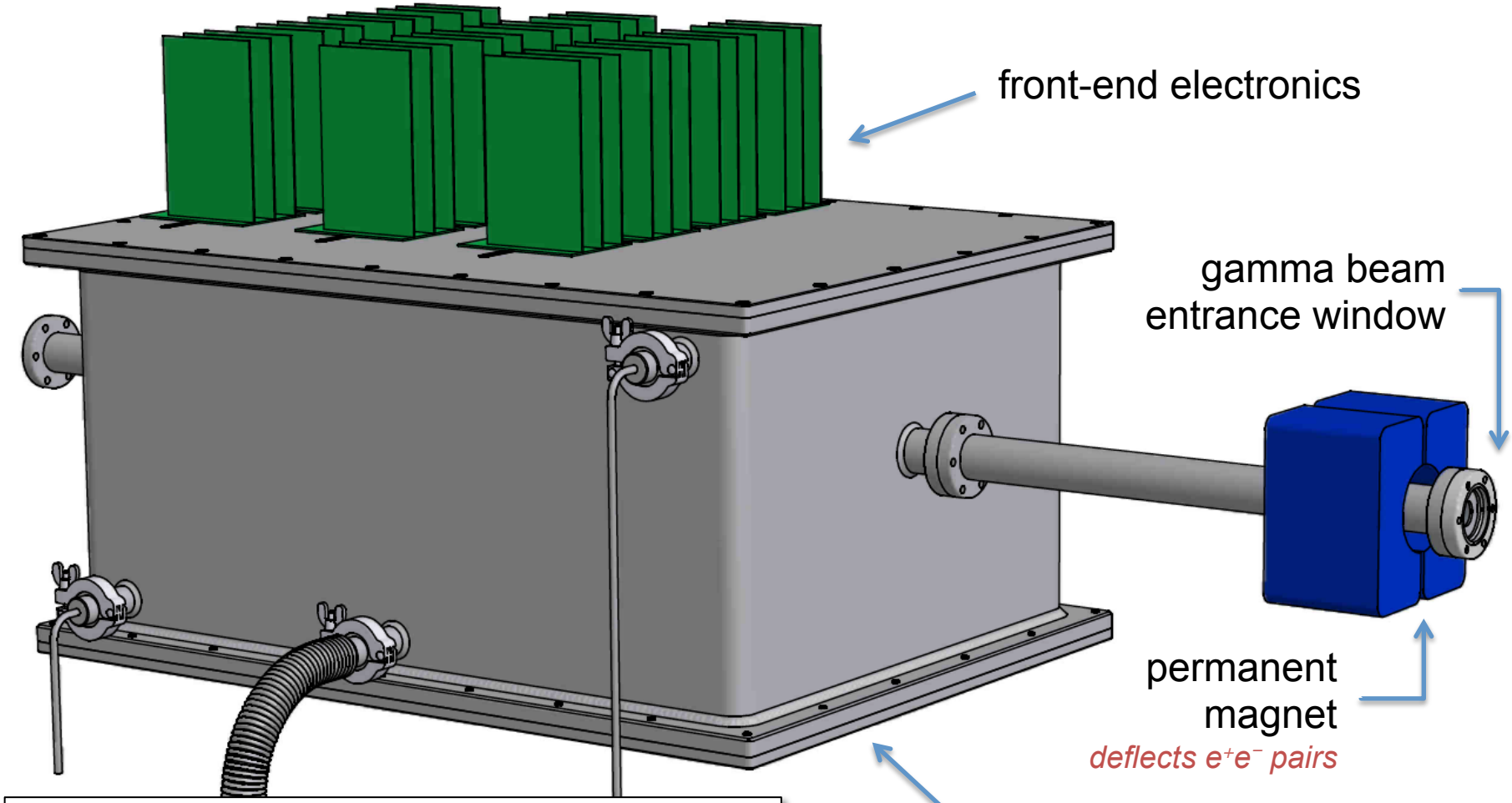
BACKUP SLIDES

Experimental data on $^{12}C(\alpha,\gamma)^{16}O$

- Extrapolated p-wave (E1) & d-wave (E2) astrophysical **S-factors** to the Gamow peak in red giants: **40 – 80% uncertainty**



ELITPC detector concept (2)

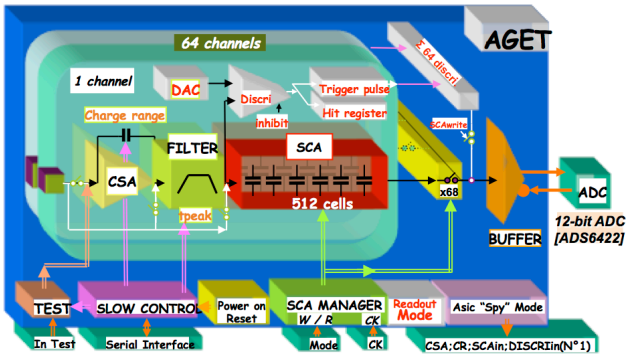


Location:	E8 experimental vault
Beam footprint:	ϕ < 2 mm

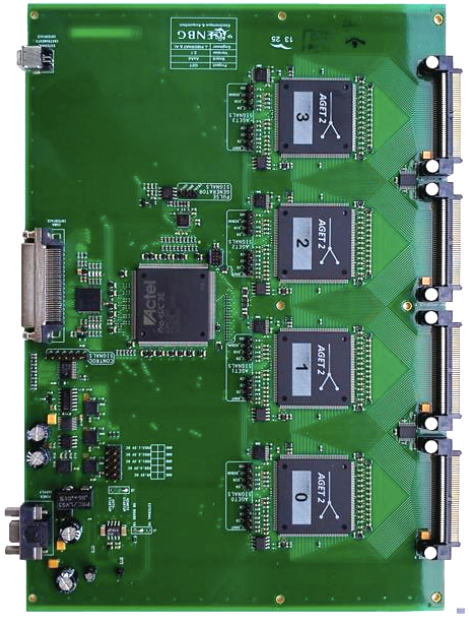
O.Tesileanu et al., Romanian Rep.
in Phys. 68, Supplement (2016) S699

Generic Electronics for TPCs

- **Developed by: CEA/IRFU, CENBG, GANIL, MSU/NSCL**
- **64-ch ASIC chip (*AGET* = *ASIC for GET*):**
  - flexible sampling frequency: **1-100 MHz**
  - **512 time-cells** per channel, analog SCA memory
  - adjustable gain & filtering per channel



- **1024-ch front-end board (*AsAd* = *ASIC & ADC*):**
  - hosts 4 AGET chips
  - **12-bit ADC**, one channel per AGET chip

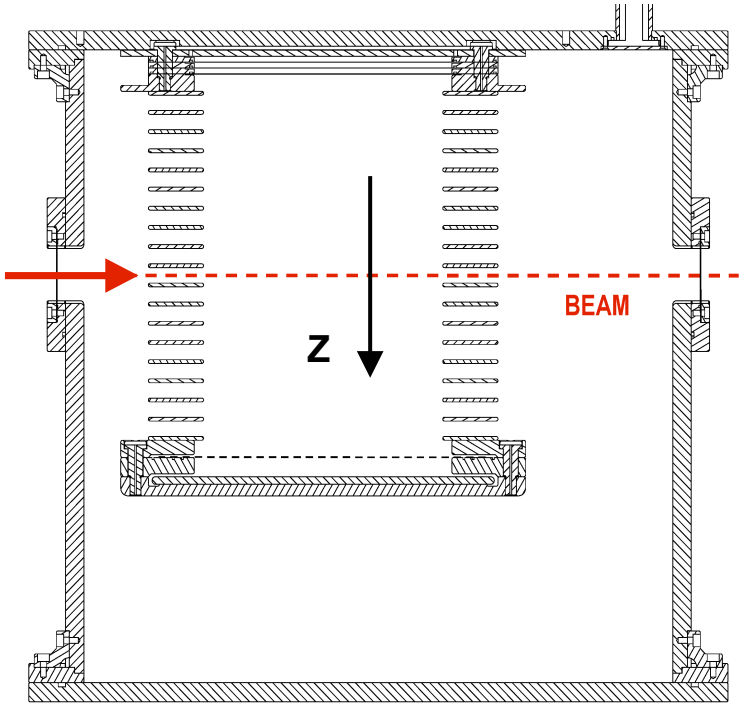


- **Data concentration, timing & trigger boards:**
  - big systems: **uTCA** crate, **CoBo** boards, **MuTant** boards (up to 32,000 channels)
  - small systems: standalone FPGA boards (usually 256 channels)

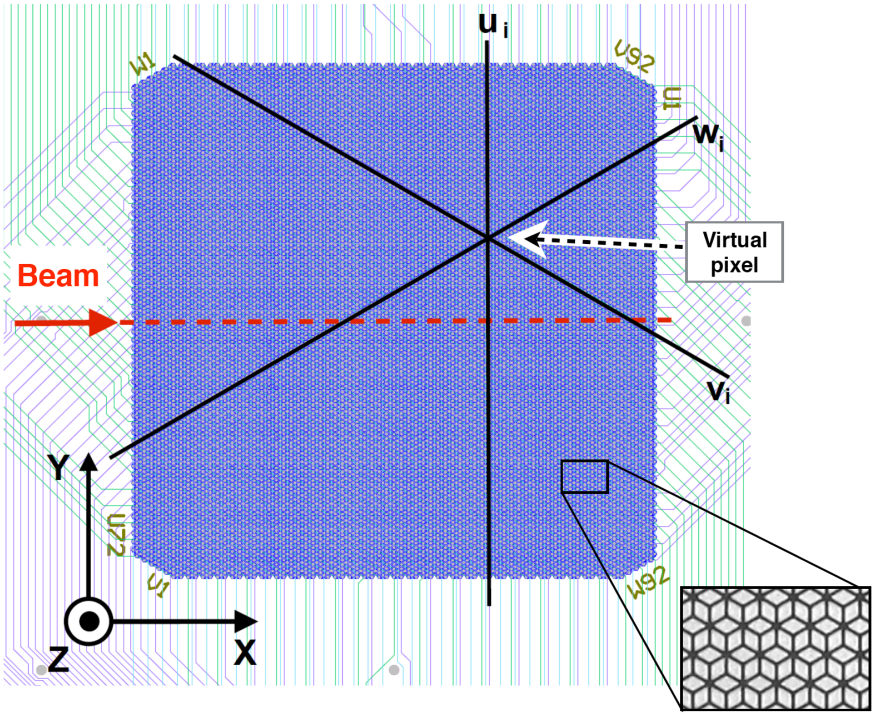
E. Pollacco et al., Physics Procedia 37 (2012) 1799

Demonstrator detector (1)

- Tests @ 9 MV Tandem (IFIN-HH, Romania) with **15 MeV α-particle beam** in April 2016
  - gas mixture: He+CO_2 (70:30) @1 atm
  - entrance window: 3μm Mylar



SIDE view - XZ plane along beam axis

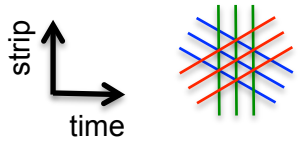


# of channels: U=72, V=92, W=92

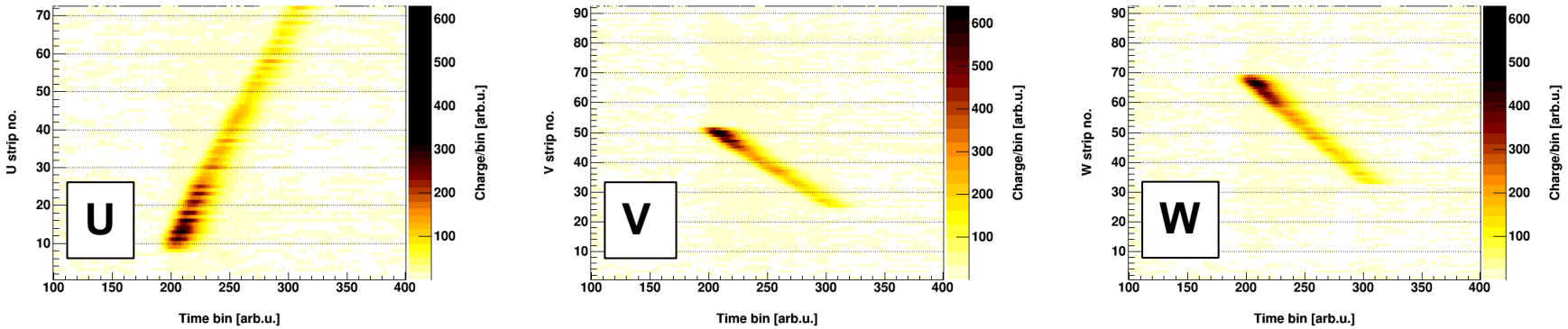
TOP view – XY readout plane

Demonstrator detector (2)

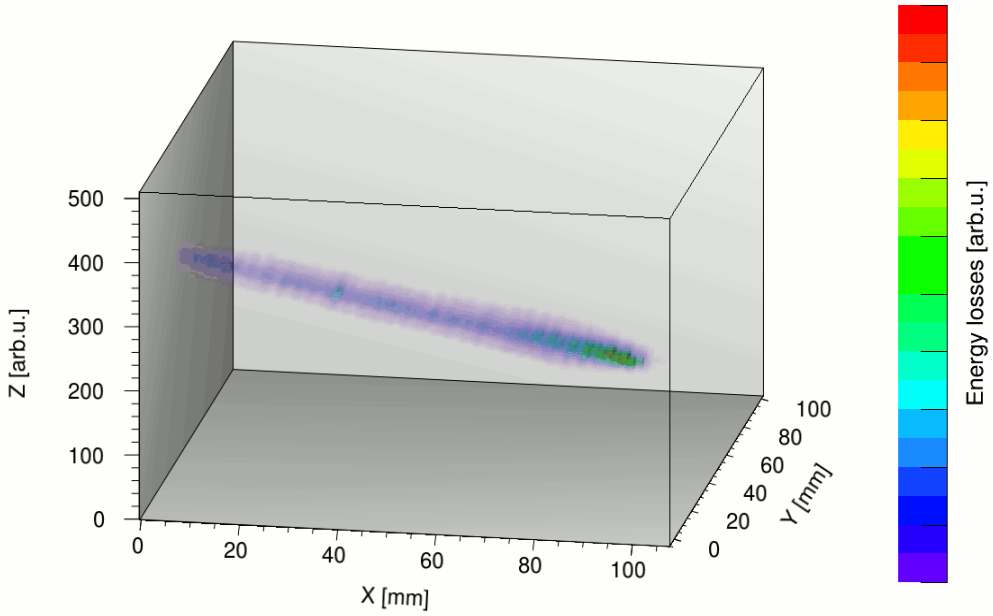
- **Example #1: Single track** from α-particle beam:
  - Gas mixture: He+CO_2 (70:30) **@1 atm**



Raw data

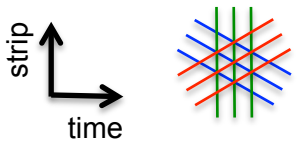


Reconstructed α-particle track in 3D

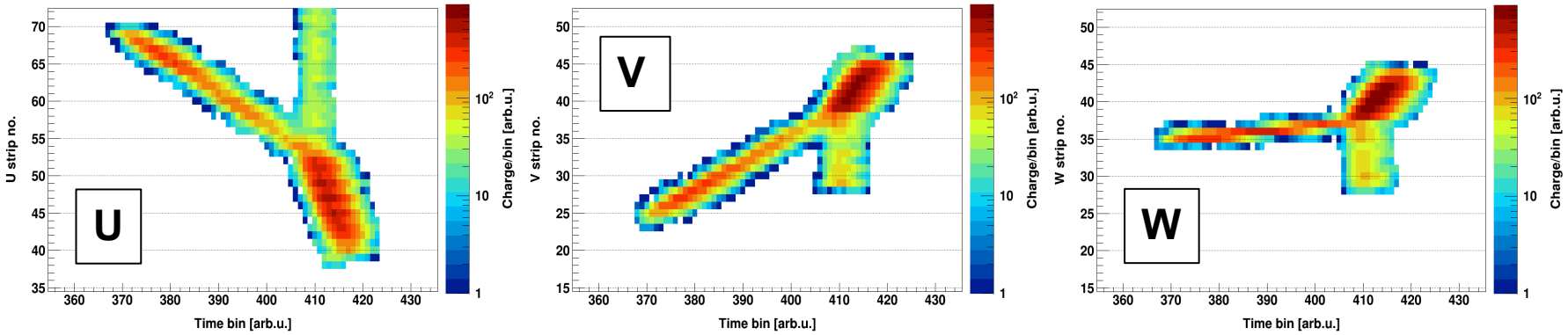


Demonstrator detector (3)

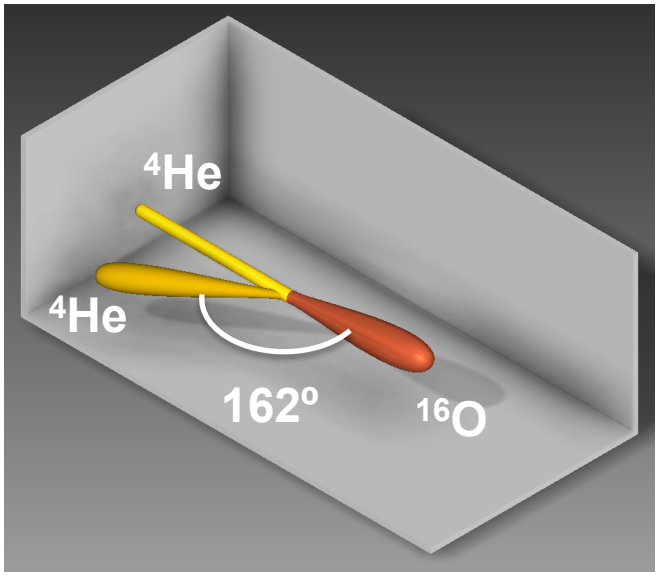
- **Example #2:** event with **3 tracks** from ^{4}He + ^{16}O scattering:
  - Gas mixture: $He+CO_2$ (70:30) **@1 atm**

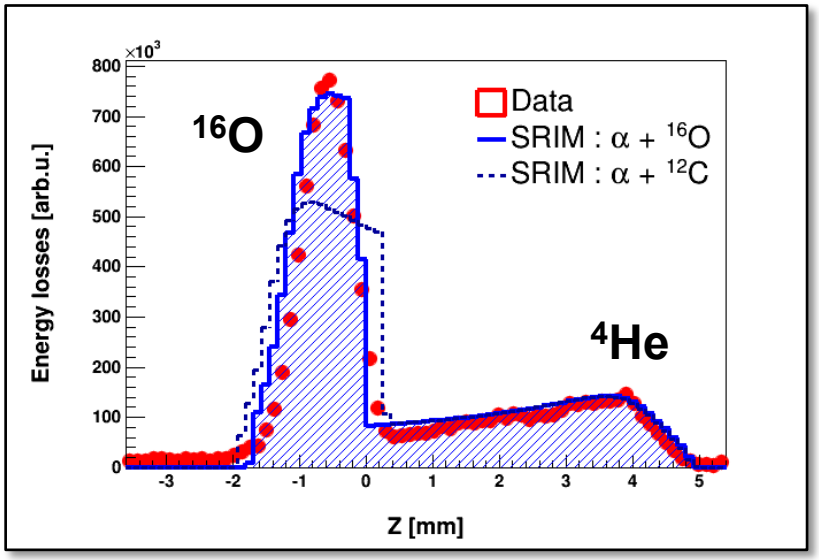


Raw data



Reconstruction

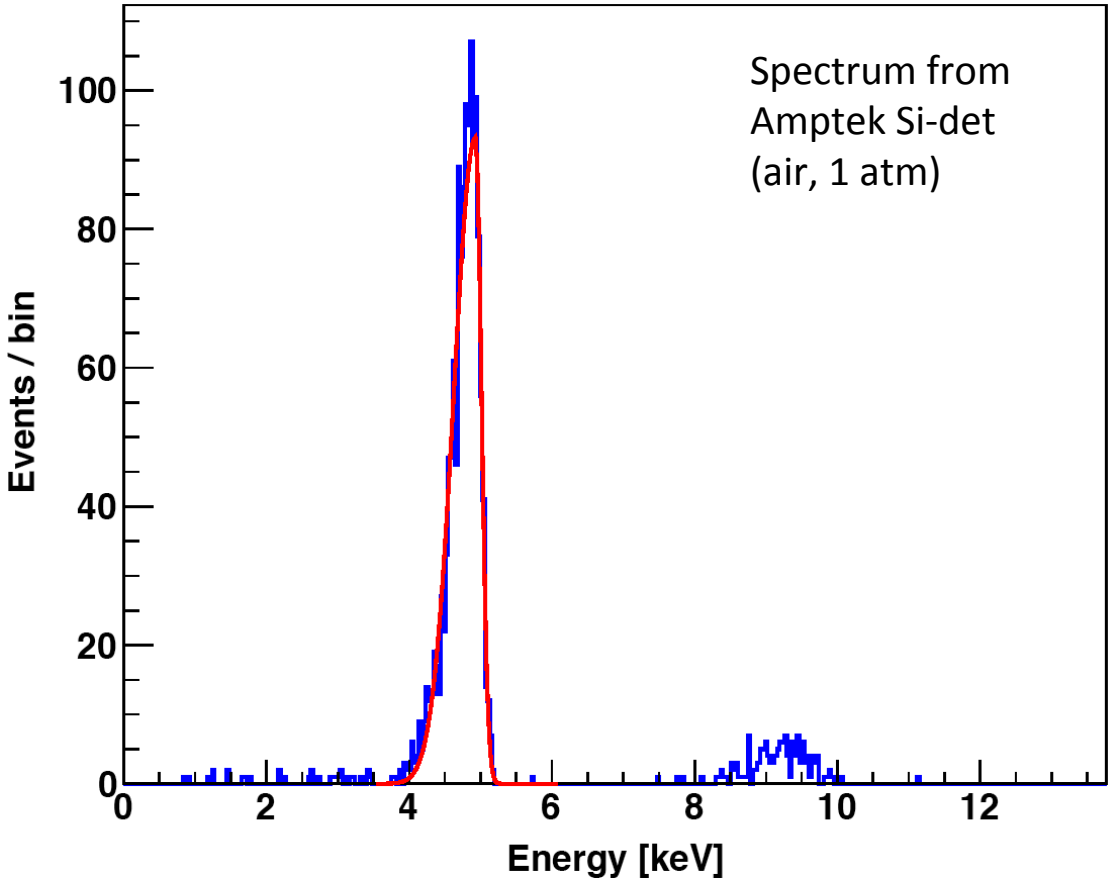




Low-pressure test bench: X-rays

✓ **Source of radiation:**

- Amptek MiniX generator : Ag target, Be window, U_{XRAY}=10 kV
- XRF fluorescence filters : 110 um Ti + 50 um Kapton
- Quasi-monochromatic X-ray spectrum : peak @ 4.9 keV (9% FWHM)
- Conversion rate @ 100 mbar CO_2 : 12–70 Hz for I_{XRAY} = 40 – 200 uA



χ^2 / ndf	58.54 / 37
Constant	93.24 ± 3.52
Mean	4.929 ± 0.012
SigmaL	0.3026 ± 0.0119
SigmaR	0.08447 ± 0.00821

Monte Carlo: background

- **E_γ = 8.3 MeV**
- **100 mbar CO_2**
- 35 x 20 cm^2 active area, 20 cm drift
- 10^7 photons → single macro-bunch
- simplified gamma-beam model