ELITPC – a TPC detector for photonuclear reaction studies using intense, monochromatic gamma-ray beams at the ELI-NP facility

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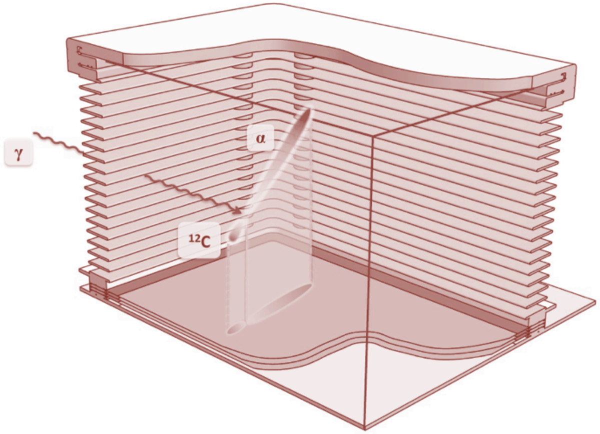
for ELITPC collaboration: UW, ELI-NP / IFIN-HH, Univ. of Connecticut

Gas-Filled Detection System Topical Meeting:
GDS coupling to auxiliary detection systems

25-27 January 2017 – INFN/LNL, Legnaro, Italy

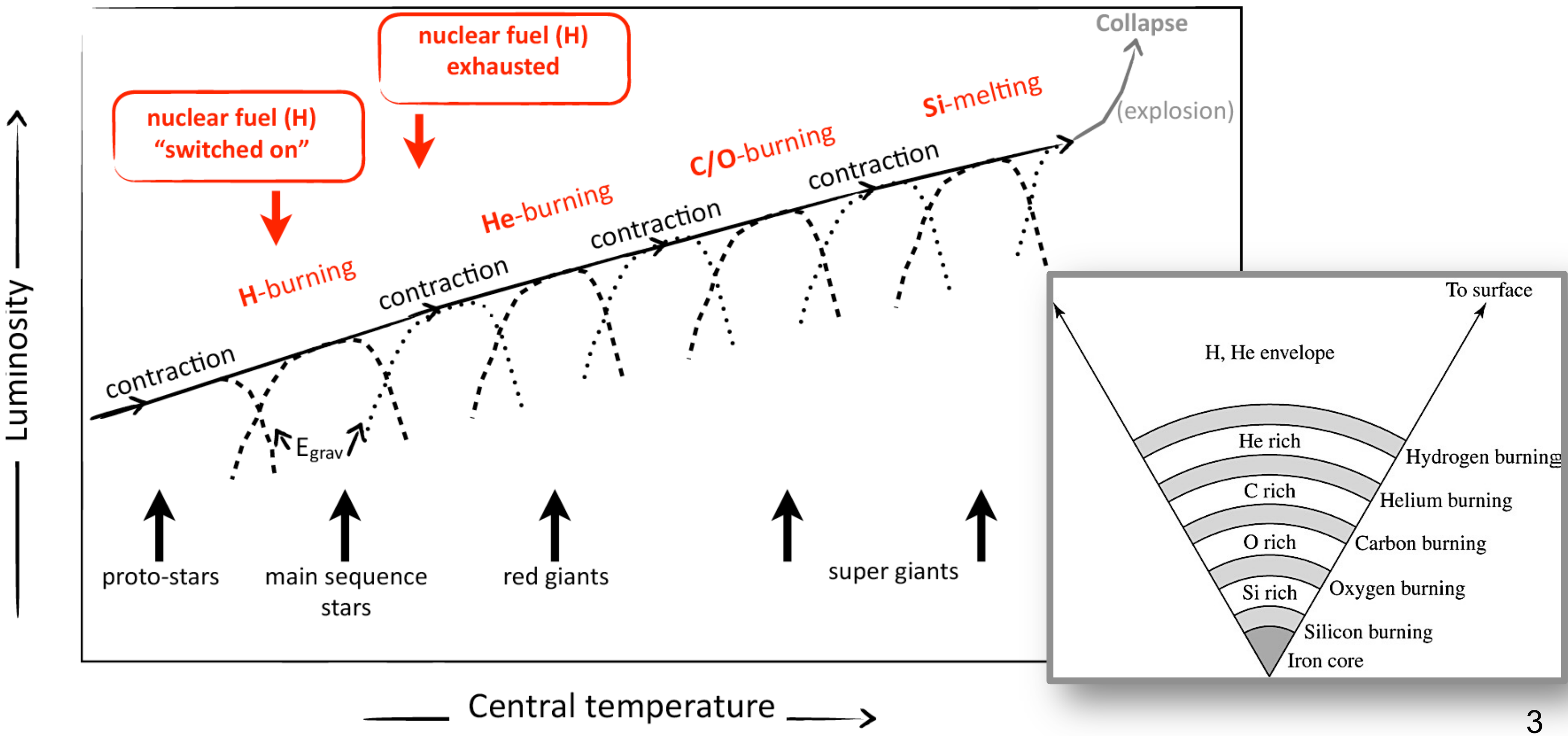
Outline

1. Physics motivation
2. ELITPC concept (**ELI**-NP **T**ime **P**rojection **C**hamber)
3. Status of R&D
4. Summary & outlooks

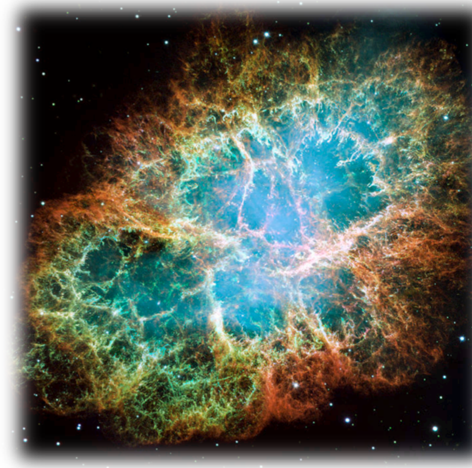


Stellar Nucleosynthesis

- **H** - burning: **p-p** & **CNO** cycles, Hot-CNO, Ne-Na, Mg-Al → synthesis of **He**
- **He** - burning: $3\alpha \rightarrow {}^{12}C$, ${}^{12}C(\alpha,\gamma){}^{16}O$, … → synthesis of: **C, O, Ne**
- Subsequent burning of: **C, O, Ne, Si** → synthesis of elements with **16 ≤ A ≤ 60**
- ***s***, ***r***, ***p*** - processes → synthesis of elements with **A ≥ 60**



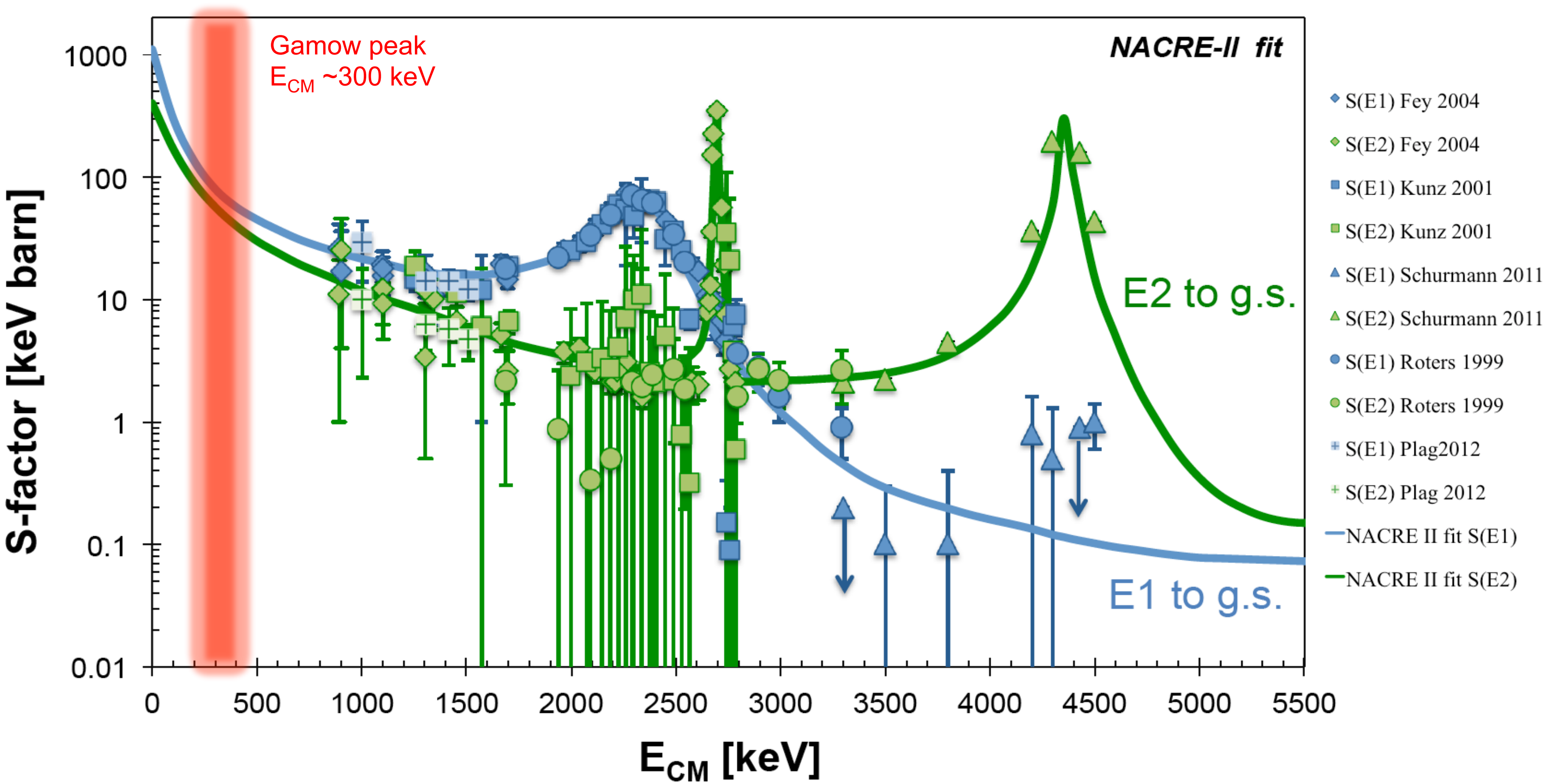
Carbon / Oxygen Ratio


Crab Nebula - HST/NASA

- 4 most abundant elements: *H, He,* **O, C**
- Observed **C/O ratio = 0.6**
- Reactions that regulate **C/O ratio** in the universe:
  - Bulk of **^{12}C** abundance: 3α-process
  - **^{16}O** is the "ash" of subsequent α-capture reaction: **^{12}C(α,γ)^{16}O**
- Significance of C/O ratio:
  - **Stars with M > 8 M$_\odot$:** modelling of **C/O** ratio during the final phase of He-burning in **red giants** remains **unsolved for 30 years**
  - **Stars with M ~ 1.4 M$_\odot$:** explode as ***Ia*-type supernovae**
    thanks to these **"standard candles"** accelerated expansion of the Universe and existence of the dark energy have been discovered
    precise modelling of of **C/O** ratio is needed to describe **production of ^{56}Ni**, which in turn modifies **light-curves** of these important "standard candles"

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

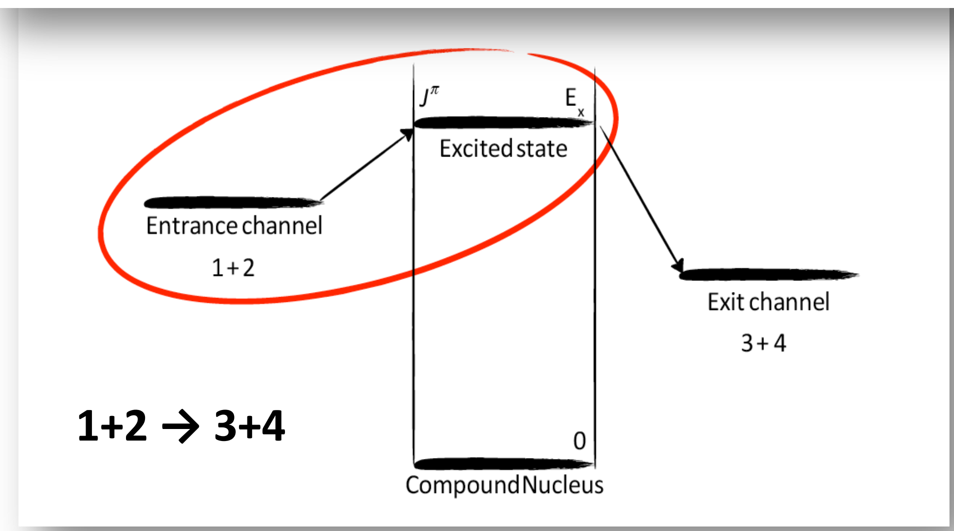
- Extrapolated p-wave (E1) & d-wave (E2) astrophysical **S-factors** to the Gamow peak in red giants: **40 – 80% uncertainty**



How to improve accuracy?

- Measure **time-reverse** *(photo-dissociation)* reaction → **^{16}O (γ,α) ^{12}C:**
  - strong and e-m interactions invariant w.r.t. time reversal
  - cross sections from detailed balance principle
  - LOW experimental background

$$\frac{\sigma_{12}}{\sigma_{34}} = \frac{m_3 m_4}{m_1 m_2}\frac{E_{34}}{E_{12}} \times \frac{(2J_3+1)(2J_4+1)}{(2J_1+1)(2J_2+1)} \times \frac{(1+\delta_{12})}{(1+\delta_{34})}$$



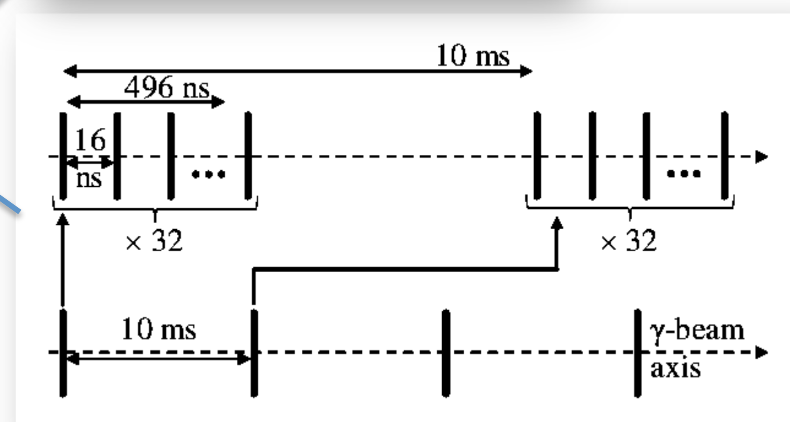
REQUIREMENTS:

- **Intense, monochromatic** γ-ray beams
- **Detection of low-energy charged products** of photo-dissociation reaction

Gamma-ray beam @ ELI-NP

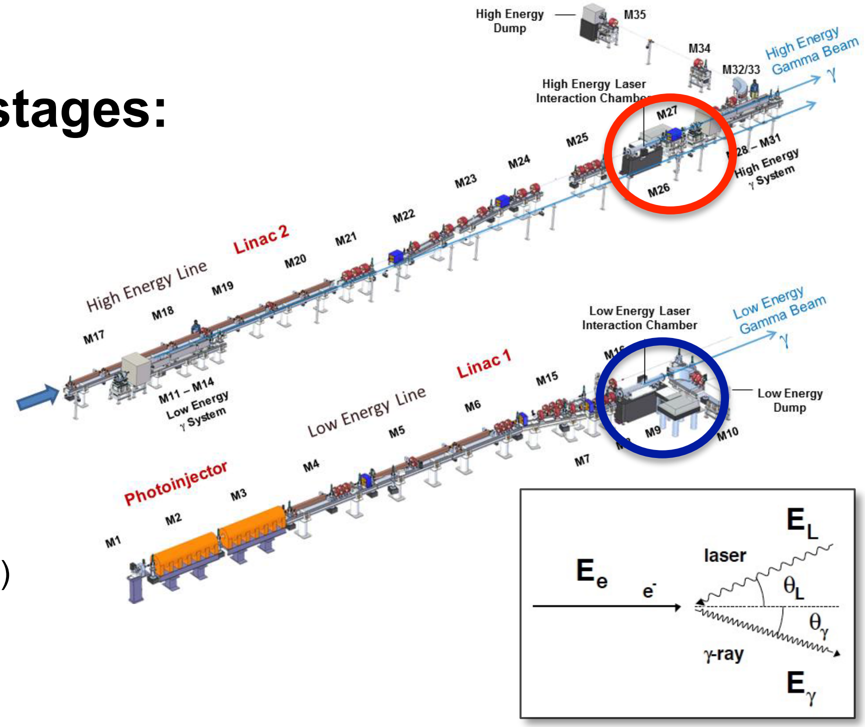
- **Compton Back Scattering**
- High-brilliance, narrow bandwidth, good collimation
- To be commissioned in 2018

Energy range	**0.2 – 19.5 MeV**
Energy BW (rms)	**< 0.5 %**
Spectral density	**> 0.5 10^3 γ/s/eV**
Peak brilliance	**10^{20} – 10^{23} γ/(s mm² mrad² 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

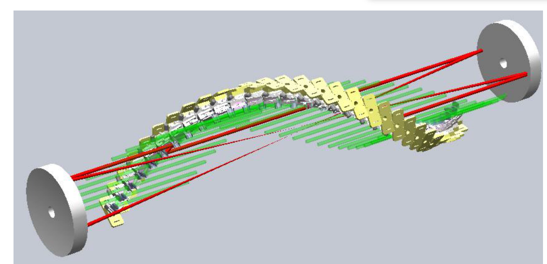


- **Gamma Beam System (GBS) has 2 stages:**
  - low energy (E_γ<3.5 MeV)
  - high energy (E_γ<19.5 MeV)

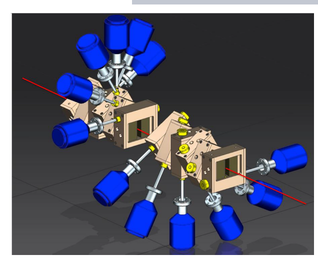
- **GBS components:**

1. Electron LINAC:
- tunable energy: E_e = 80 – 720 MeV
- laser photo-injector (32 pulses, 100 Hz rate)
- 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

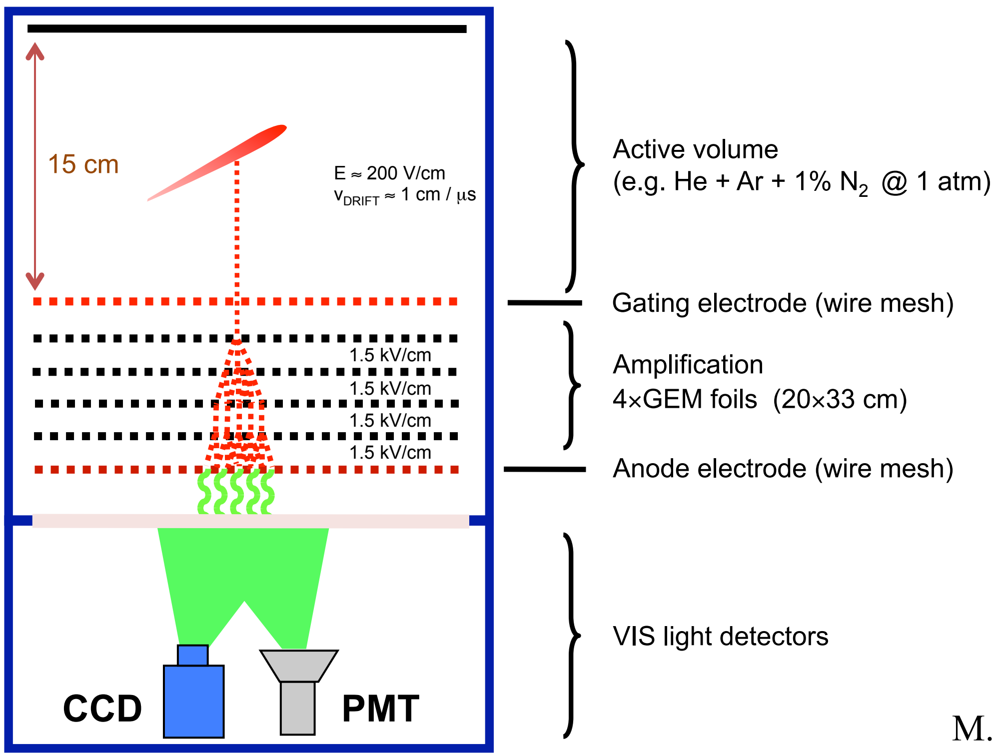


O. Adriani et al., arXiv:1407.3669 [physics.acc-ph], July 2014

GEM-based TPCs from Warsaw (1)

- **Active-Target TPCs – suitable for 3D kinematic reconstruction of photodisintegration reaction products @ ELI-NP**

- Univ. of Warsaw has long-time expertise in developing TPCs based on Gas Electron Multiplier (GEM) amplification structures

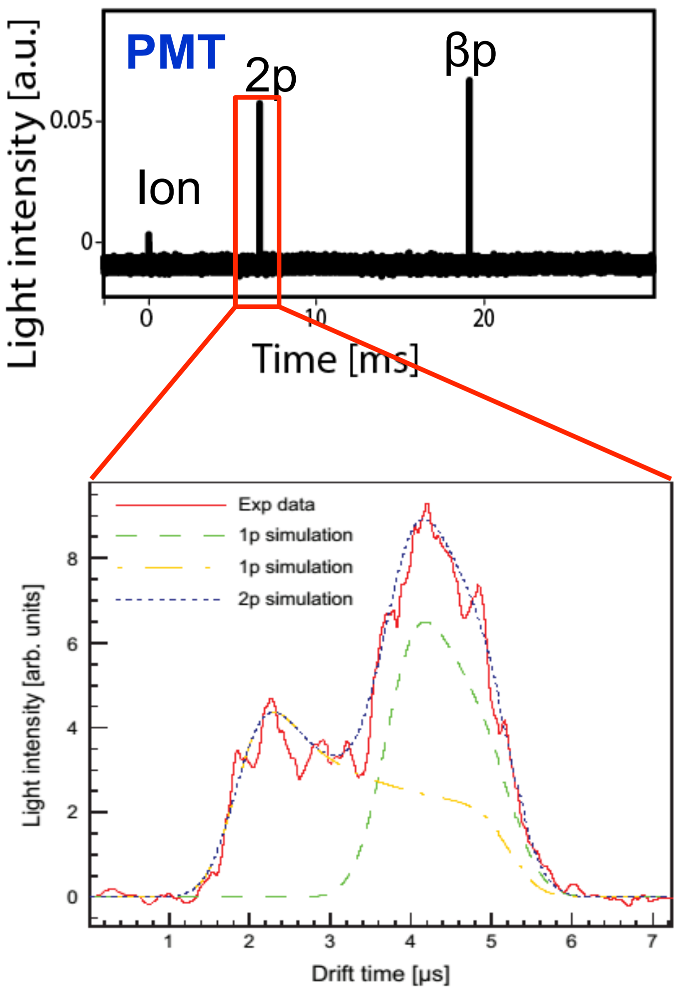


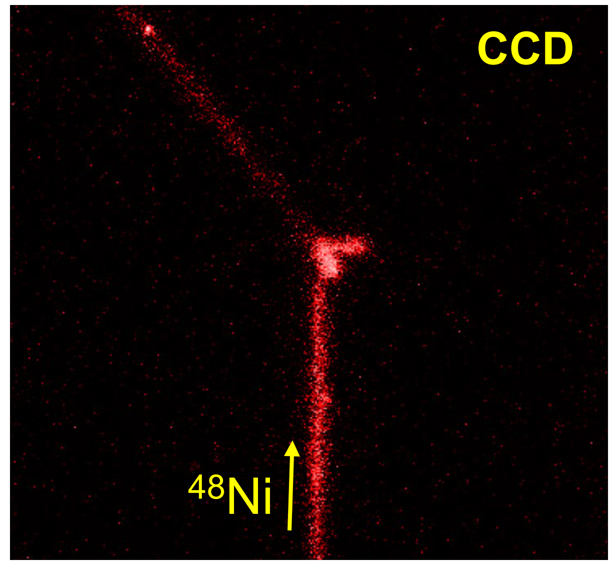
- Several TPCs with optical readout constructed since 2004:
  - two-proton radioactivity
    2p of ^{45}Fe, ^{48}Ni @ NSCL/MSU
  - β-delayed multi-particle emissions
    β3p of ^{31}Ar @ FRS/GSI
  - rare decays of He isotopes
    ^{6}He → α+d @ Isolde/CERN
    ^{8}He → α+t+n @ Acculinna/JINR

M. Ćwiok et al., IEEE TNS 52 (2005) 2895
K. Miernik et al., NIMA 581 (2007) 194

GEM-based TPCs from Warsaw (2)

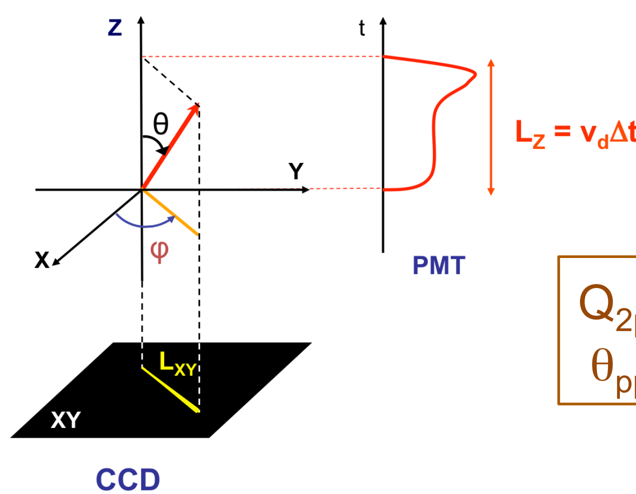
- Reconstruction of 2p decay event of ^{48}Ni:





E_{p2}= 665(50) keV
θ_{p2}= 150(6)°
φ_{p2} = -60(7)°

E_{p1}= 580(60) keV
θ_{p1}= 117(7)°
φ_{p1} = 0



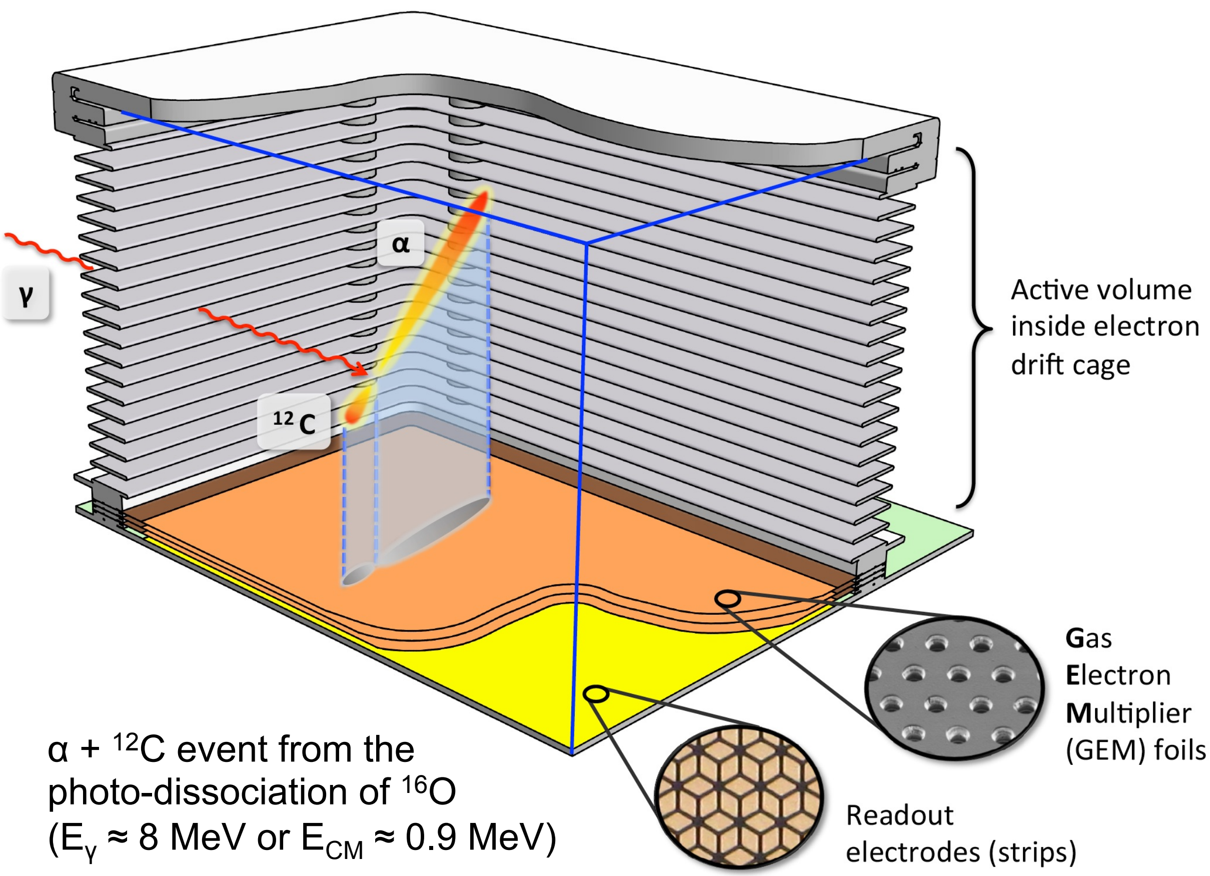
Q_{2p} = 1287(80) keV
θ_{pp} = 51(8)°

M. Pomorski et al., PRC 90 (2014) 014311

ELITPC detector concept (1)

Active volume:

- **35 x 20** cm^2 (readout) **x 20** cm (drift)
- gas pressure **~100 mbar** to increase track lengths



α + ^{12}C event from the photo-dissociation of ^{16}O ($E_\gamma \approx 8$ MeV or $E_{CM} \approx 0.9$ MeV)

Charge amplification:

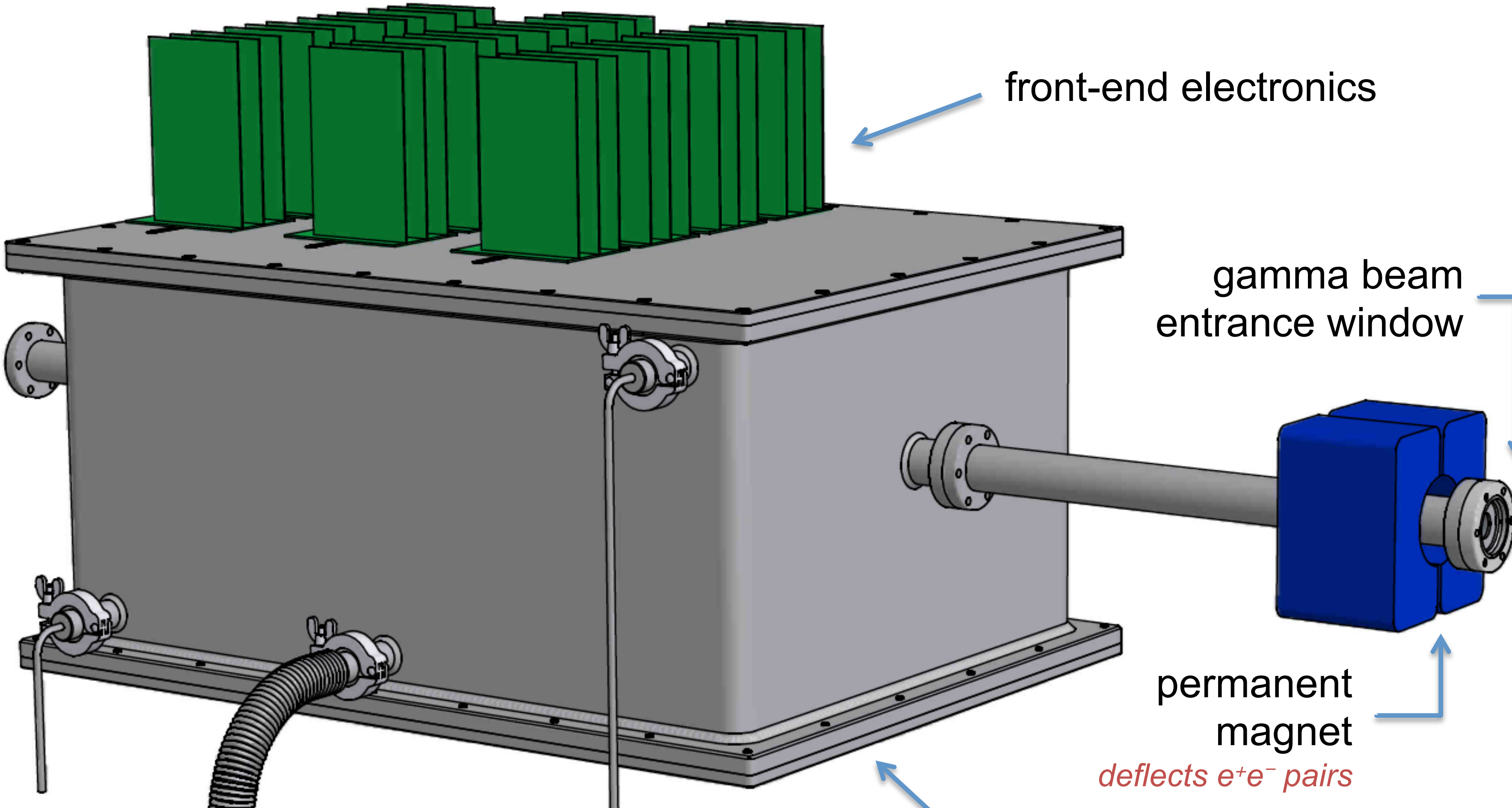
- **3 GEM** foils
  (or Thick-GEMs)

Readout:

- **3-coordinate, planar, redundant** strips (***u-v-w***)
- **1.5 mm** strip pitch
- about **1000 channels**
- **GET** electronics for signal amplification & digitization
- external trigger (100 Hz)

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

ELITPC detector concept (2)



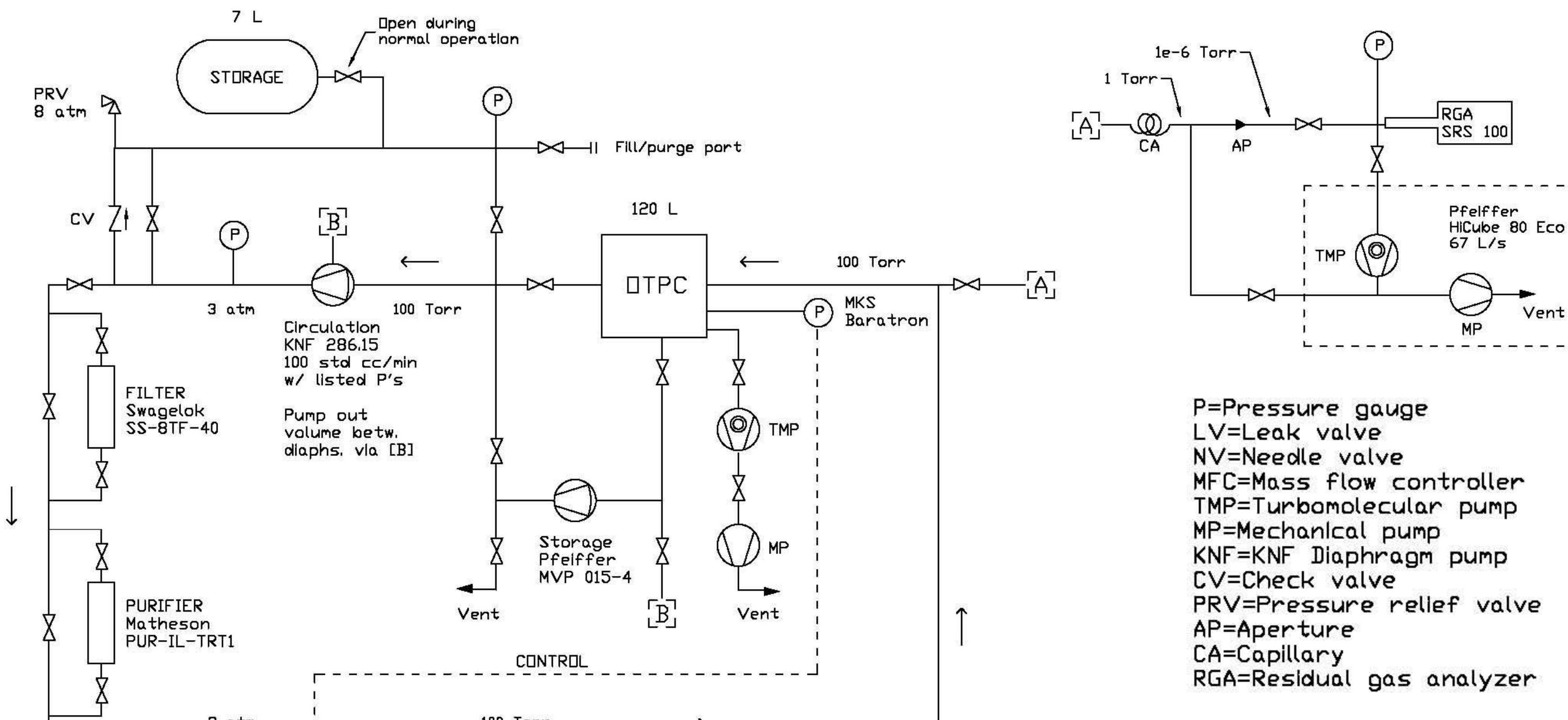
Location:	E8 experimental vault
Beam footprint:	$\phi < 2$ mm

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

ELITPC detector concept (3)

Low-pressure gas system:

- **non-recirculating** & **recirculating** (for isotopically enriched gases) operation modes
- design based on OTPC detector @ HIGS/TUNL (Duke University, NC, USA)



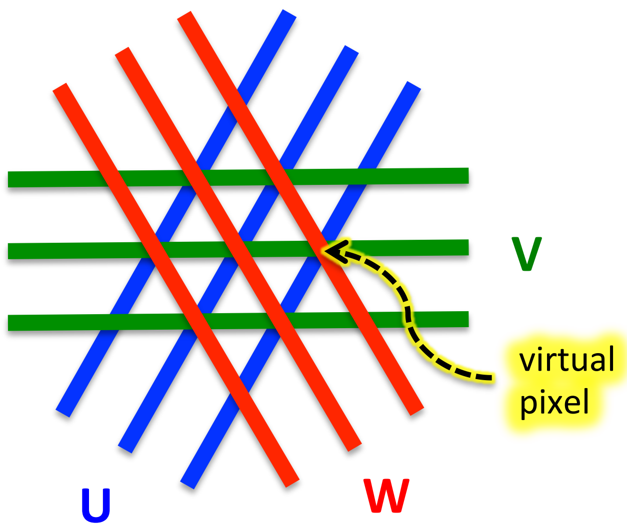
Gas recirculating mode is shown

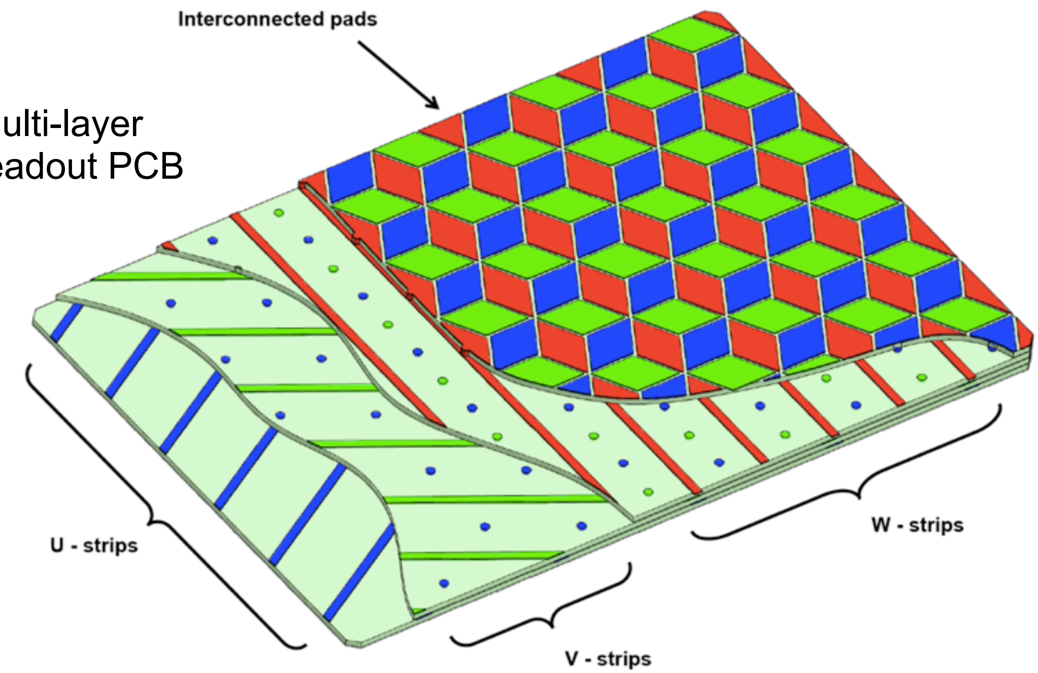
O.Tesileanu et al., Romanian Rep. in Phys. 68, Supplement (2016) S699

ELITPC detector concept (4)

3-coordinate, planar, redundant electronic readout:

- ***u-v-w*** strip arrays for hit disambiguation in 2D → virtual pixels
- ***z***-coordinate from timing information
- aimed for relatively simple event topologies → few tracks per event
- need only ***O*(10³)** channels → moderate cost of electronics

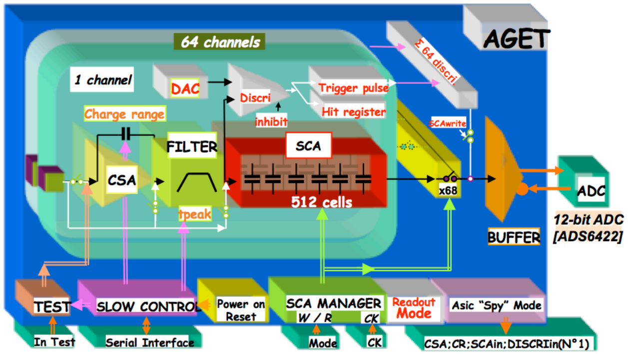




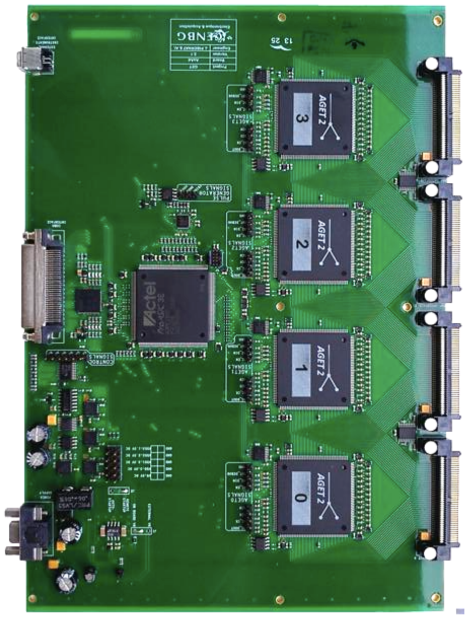
S. Bachmann et al., NIMA 478 (2002) 104
V. Ableev et al., NIMA 535 (2004) 294
M. Ćwiok, Acta Phys. Pol. B 47 (2016) 707
J. Bihałowicz et al., Proc. of SPIE 9290 (2014) 92902C

Generic Electronics for TPCs

- **Developed by: CEA/IRFU, CENBG, GANIL, MSU/NSCL**
  - in use over **20 labs** worldwide
- **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



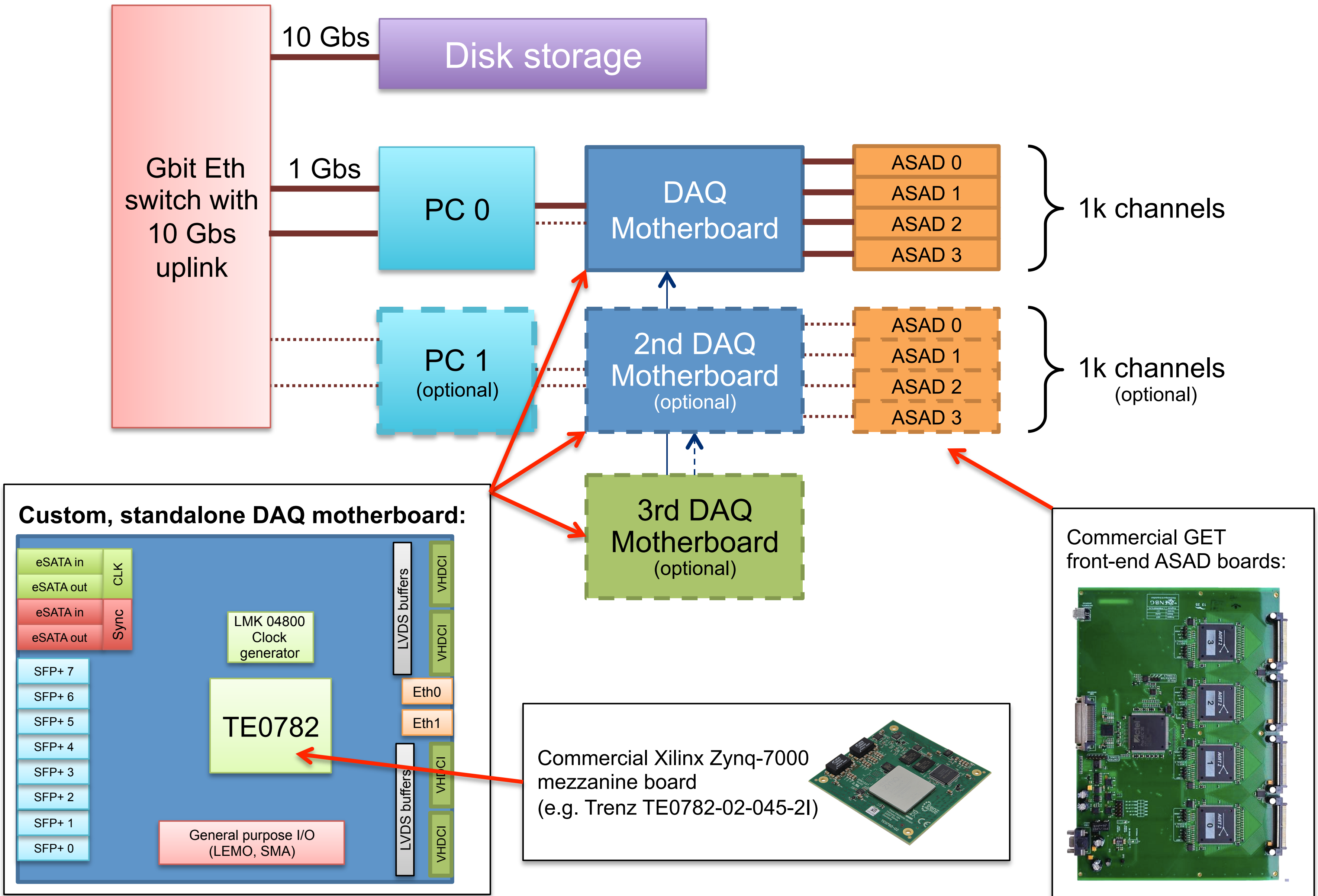
- **1024-ch front-end board (*AsAd* = *ASIC & ADC*):**
  - hosts 4 AGET chips
  - **12-bit ADC**, one channel per AGET chip



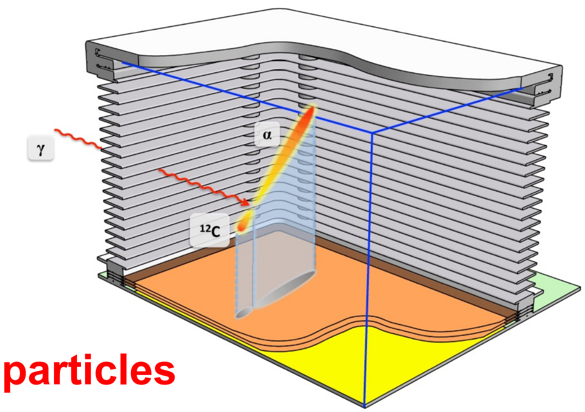
- **Data concentration, timing & trigger boards:**
  - big systems: **uTCA** crate, **CoBo** boards, **MuTant** boards (up to 32,000 channels)
  - small systems: standalone FPGA board (up to 256 channels)

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

ELITPC – final DAQ concept



ELITPC – event yields



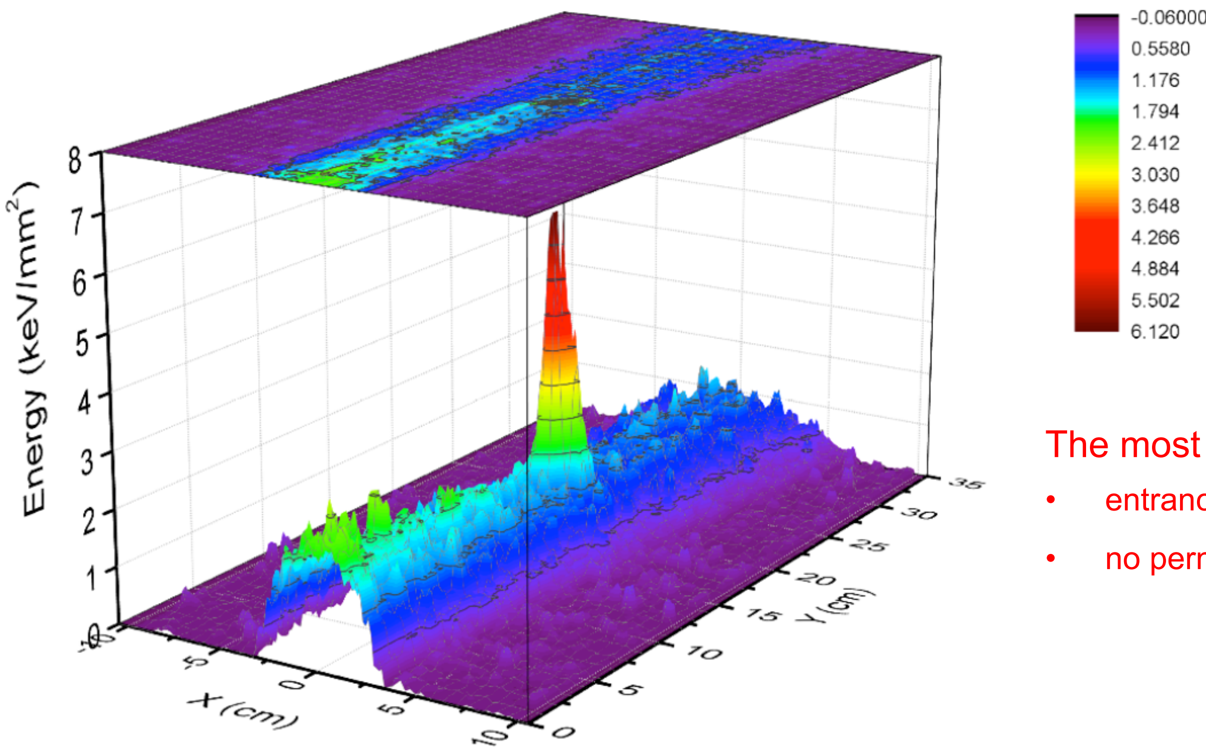
Time-reverse reaction → $^{16}O(\gamma,\alpha)^{12}C$:

- **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**
- **Background:**
  - main sources of background: Compton electrons & e^+e^- pairs in gaseous target and in a thin mylar/kapton entrance window
  - very small w.r.t. direct (α,γ) reaction experiments

ELITPC – background

GEANT4 simulation of a single ELI-NP macro-pulse:

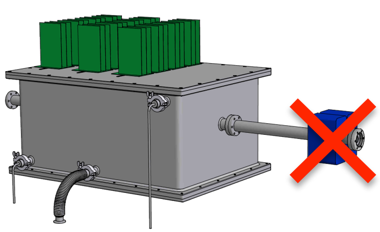
- 10^7 γ-rays of 8 MeV
- CO_2 at 100 mbar
- 0.5 MeV α-particle track added artificially to mimic ^{16}O photo-dissociation



Colors correspond to integrated energy deposits on the 2D readout plane

The most unfavourable scenario is shown:

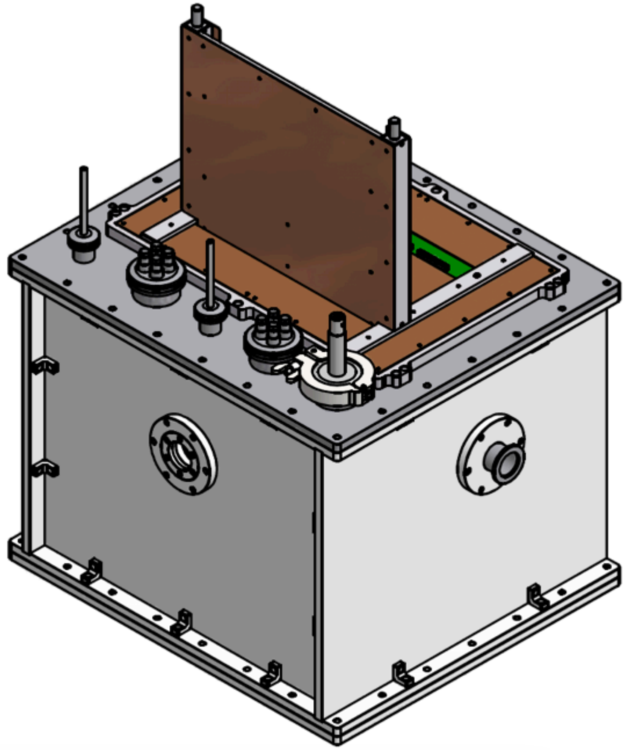
- entrance window very close to the active volume
- no permanent magnet after the entrance window

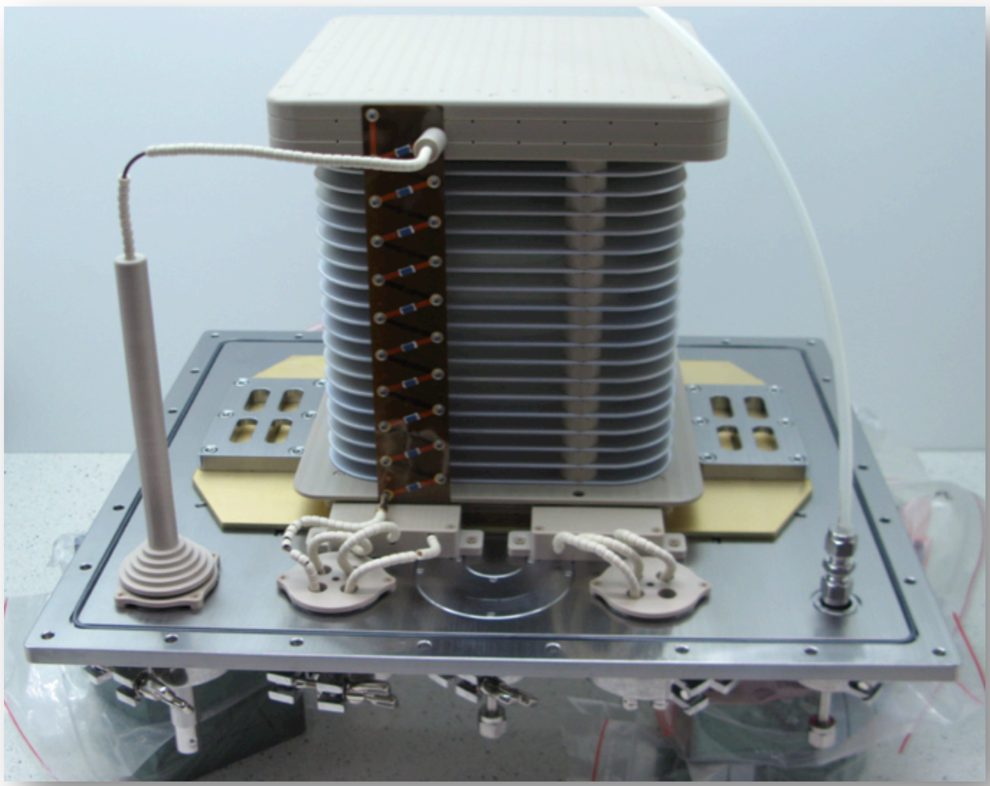


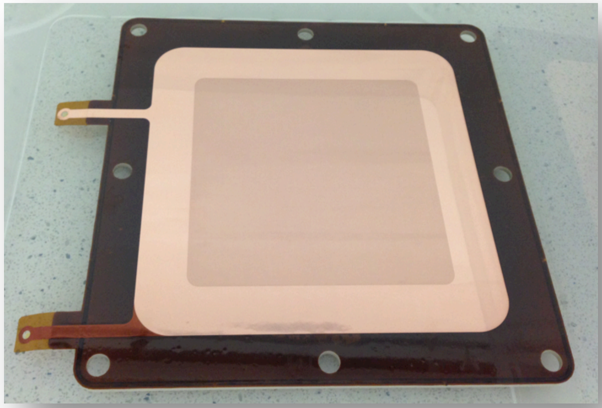
O.Tesileanu et al., Romanian Rep. in Phys. 68, Supplement (2016) S699

Demonstrator detector (1)

- Readout area: **10 × 10 cm²**, drift: **20 cm**
- GET electronics: **256 channels**
- Operating at atmospheric pressure

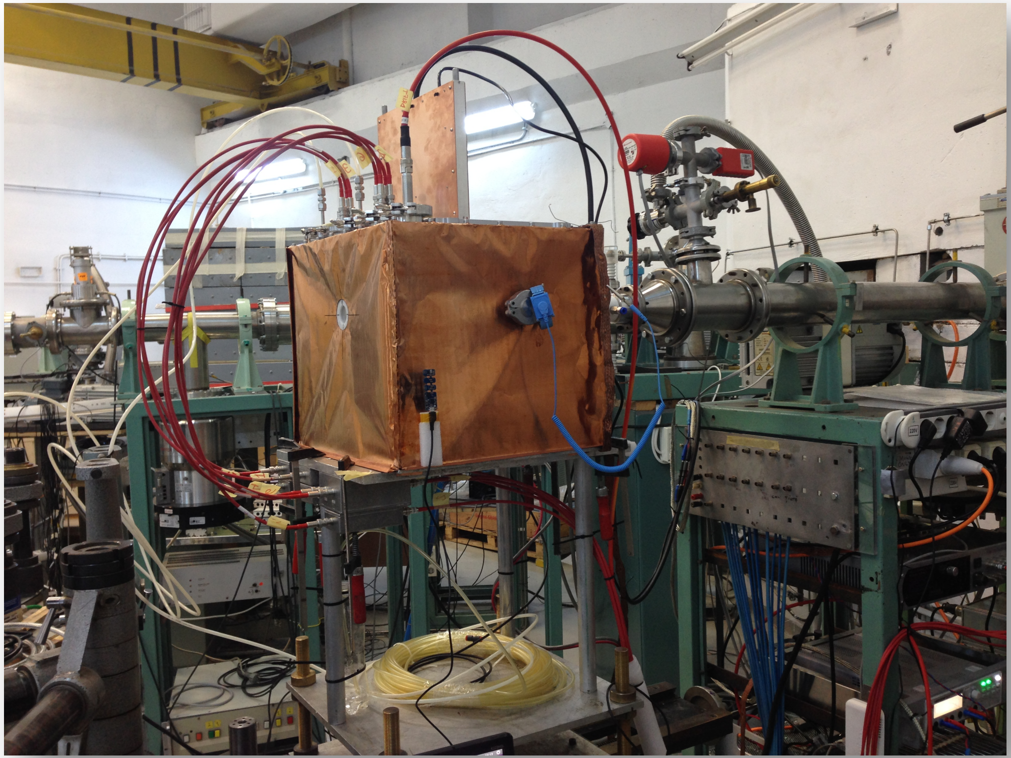


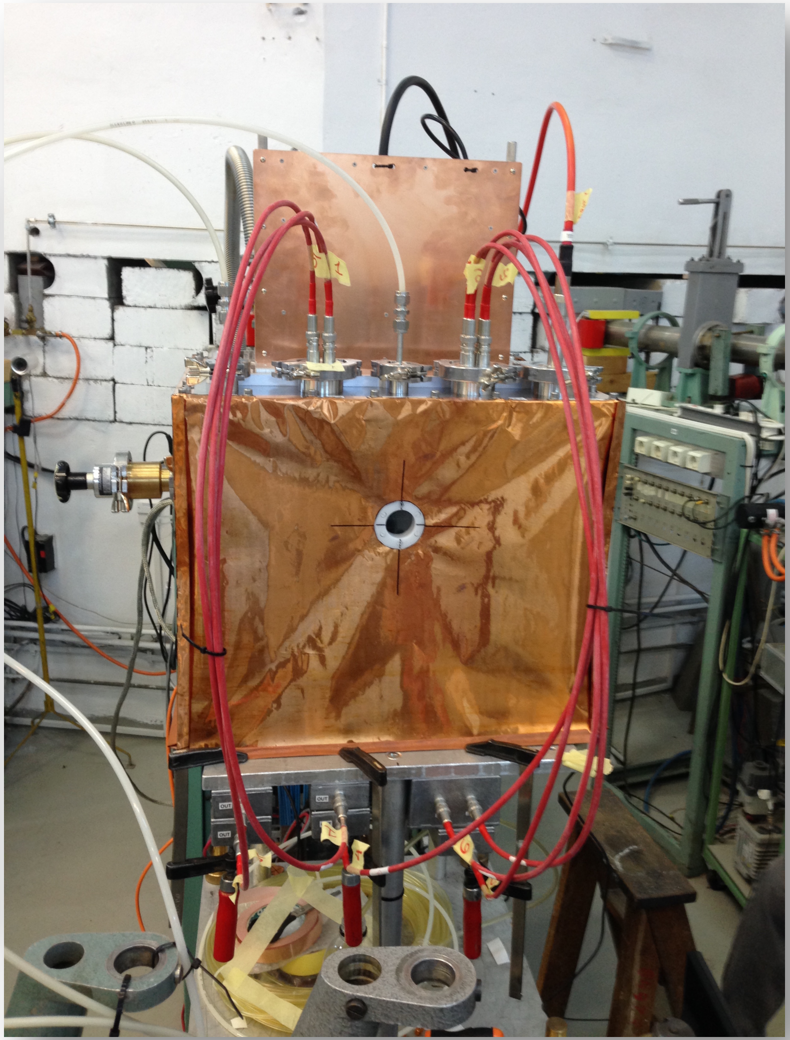




Demonstrator detector (2)

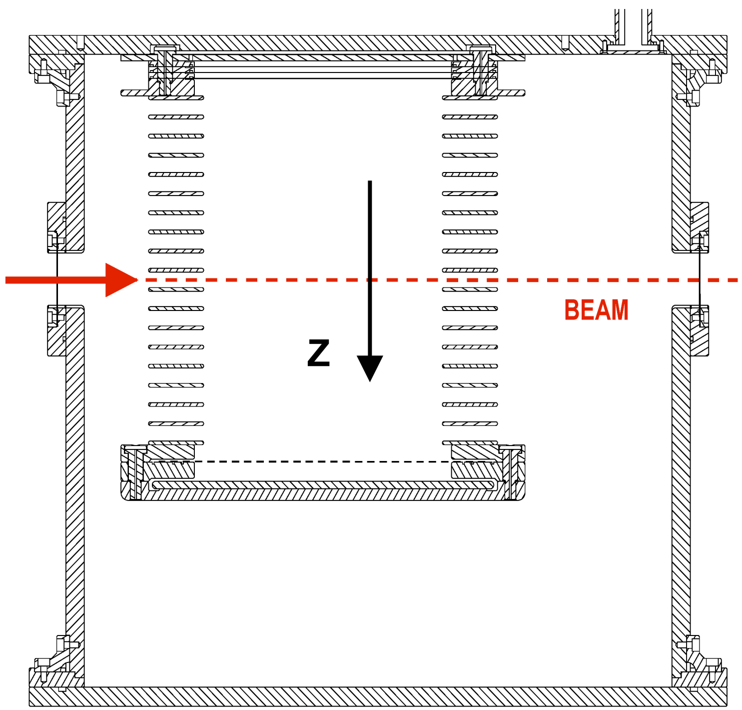
- Tests @ 9 MV Tandem (IFIN-HH, Romania) with **15 MeV α-particle beam** in April 2016



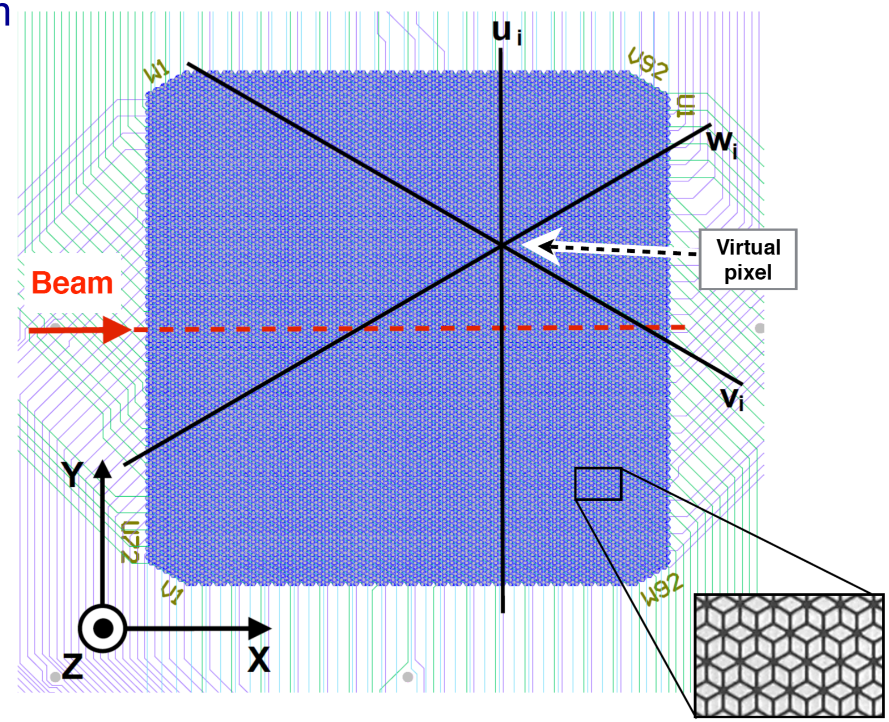


Demonstrator detector (3)

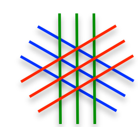
- Tests @ 9 MV Tandem (IFIN-HH, Romania) with **15 MeV α-particle beam** in April 2016
  - gas mixture: He+CO_2 (70:30) @1 atm
  - entrance window: 3μm Mylar



SIDE view - XZ plane along beam axis



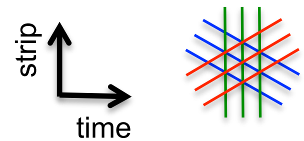
# of channels: U=72, V=92, W=92



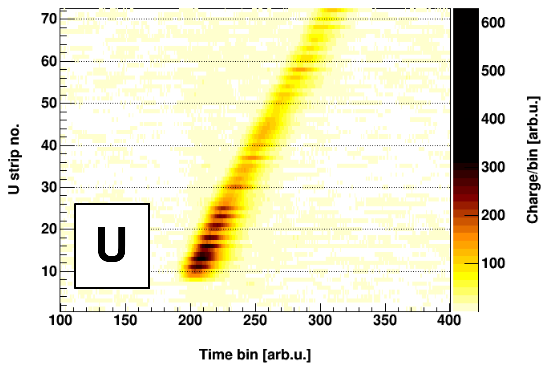
TOP view – XY readout plane

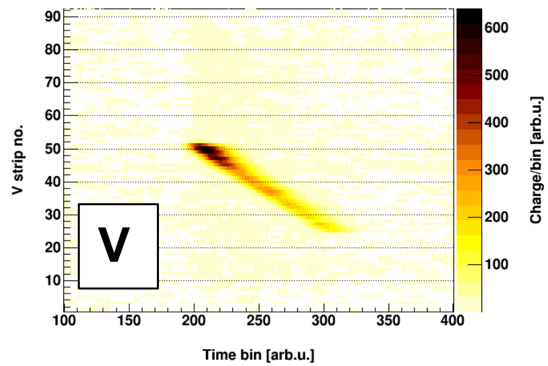
Demonstrator detector (4)

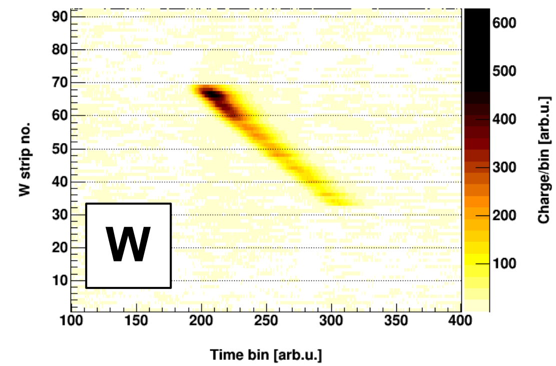
- **Example #1: Single track** from α-particle beam:
  - Gas mixture: He+CO_2 (70:30) **@1 atm**



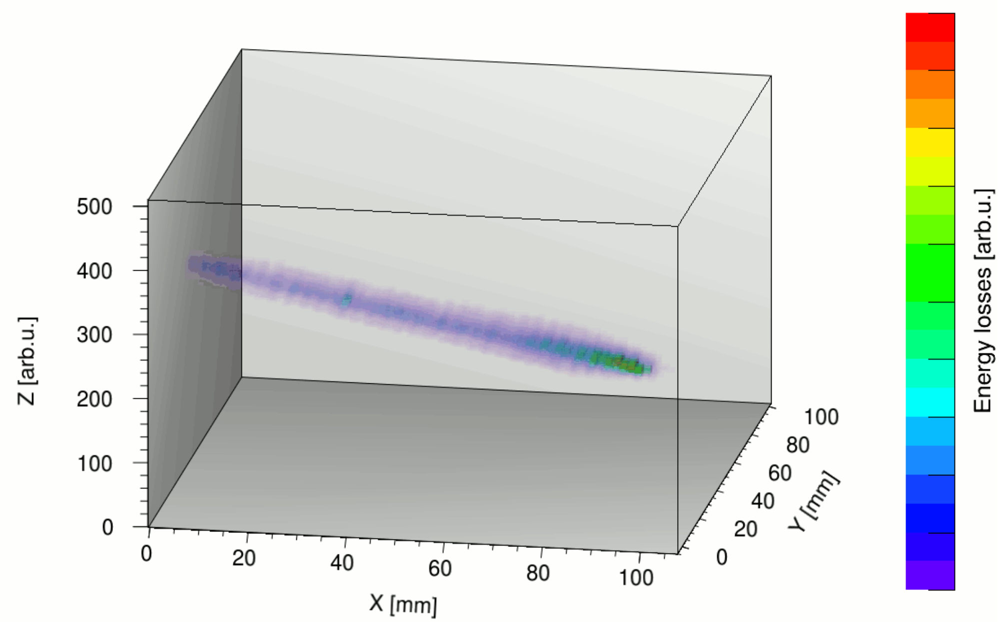
Raw data





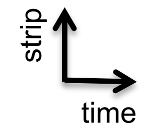


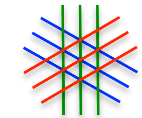
Reconstructed α-particle track in 3D



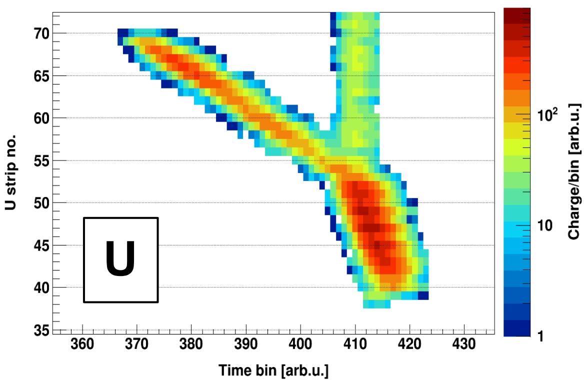
Demonstrator detector (5)

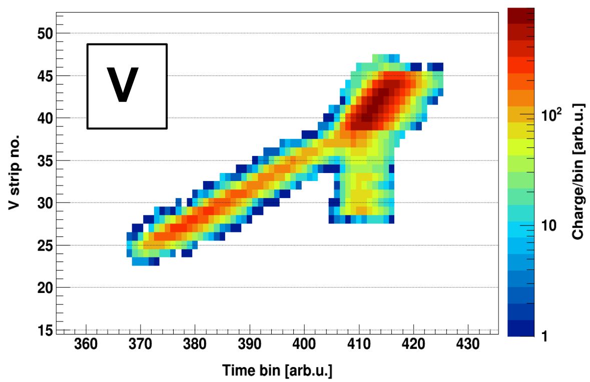
- **Example #2:** event with **3 tracks** from ^4He + ^{16}O scattering:
  - Gas mixture: $He+CO_2$ (70:30) **@1 atm**

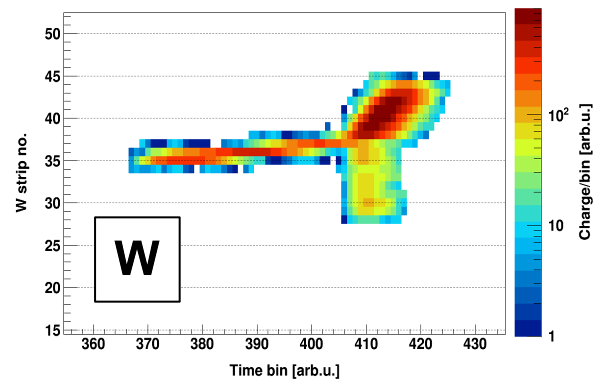




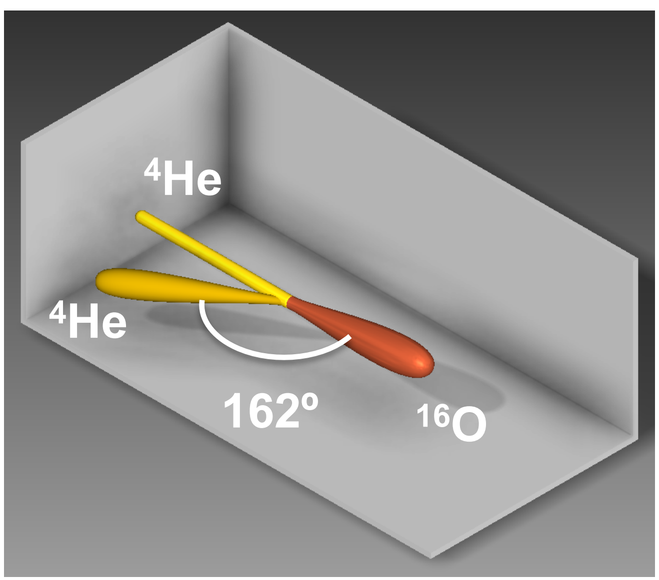
Raw data

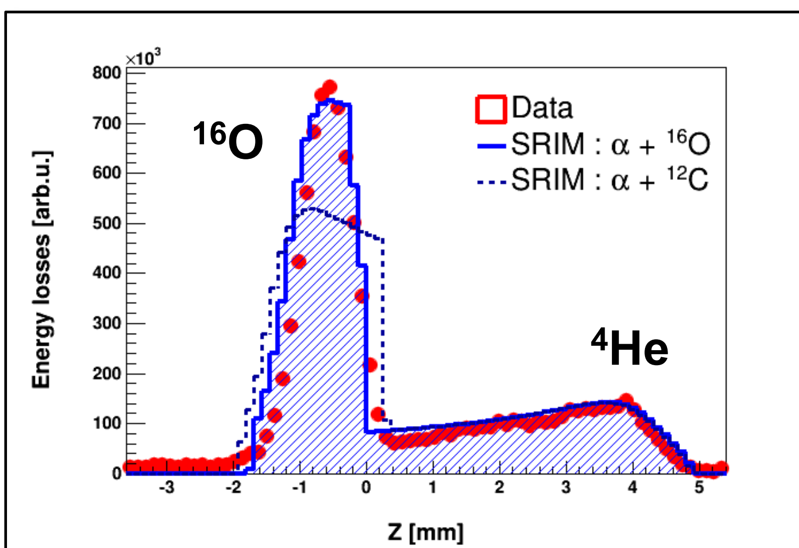






Reconstruction



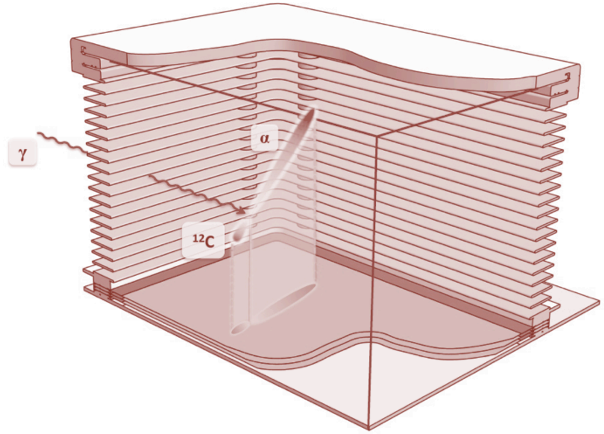


Summary

- **ELITPC detector approved as one of DAY-1 experiments for ELI-NP.**

- **256-ch demonstrator detector is operational:**
  - first beam tests (with charged particles) done in 2015 and 2016
  - proof-of-principle of the readout method
  - detector works with GET electronics

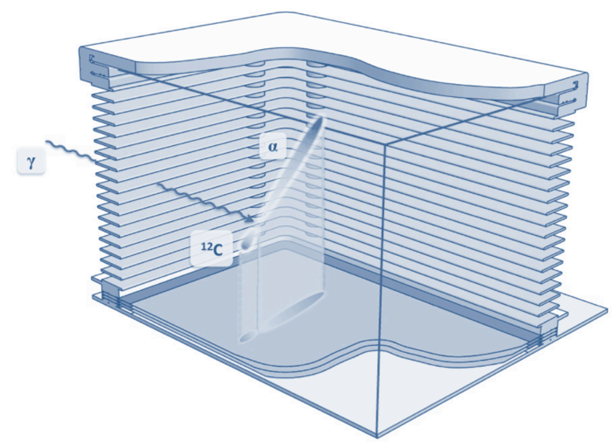
- **UW and ELI-NP signed a 2-year R&D contract for designing a full-scale, low-pressure detector (Oct 2016 – Oct 2018):**
  - in time for beam commissioning at end of 2018



- **Other physics cases with ELITPC @ ELI-NP:**
  - other astrophysical reactions (different gas targets)
  - nuclear structure physics (clustering phenomena)
  - nano-dosimetry & radiation damage to DNA

Some R&D outlooks

- **Compare 50-µm GEMs vs 125-µm Thick-GEMs at low pressures:**
  - selected He + CO_2 gas mixtures
  - pressure range: 100-500 mbar
- **Test demonstrator detector at low pressures:**
  - influence of diffusion, attachment & gas purity on charge collection efficiency
  - correcting for electronics effects → signal de-convolution, inter-channel calibration
  - different 3D reconstruction methods → clustering, Hough transform, SRIM simulations
- **Adapt GET electronics for specific needs of ELITPC:**
  - develop standalone Zynq FPGA readout board optimized for O(1000) channels
  - collaboration with: CEA-IRFU, CENBG, GANIL, MSU/NSCL
- **Realistic GEANT4 background simulations:**
  - optimization of readout structure & number of channels
  - better S/N ratio



ELITPC Collaboration (Jan 2017)

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IFIN-HH / ELI-NP, Romania

D. Balabanski, A. Bey, D.G. Ghita, O. Tesileanu

Univ. of Connecticut, USA

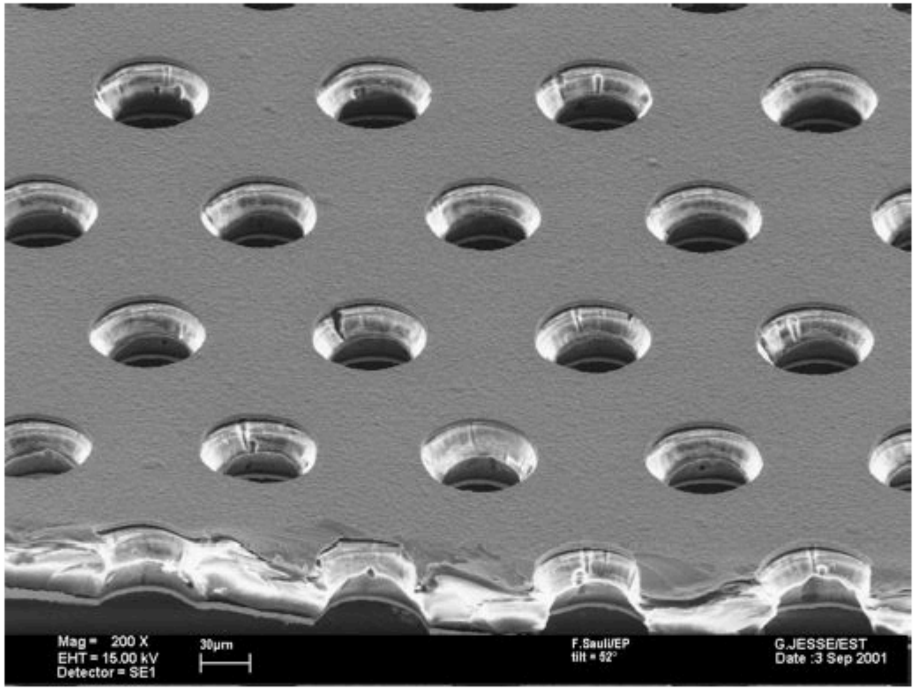
M. Gai, D.P. Kandellen

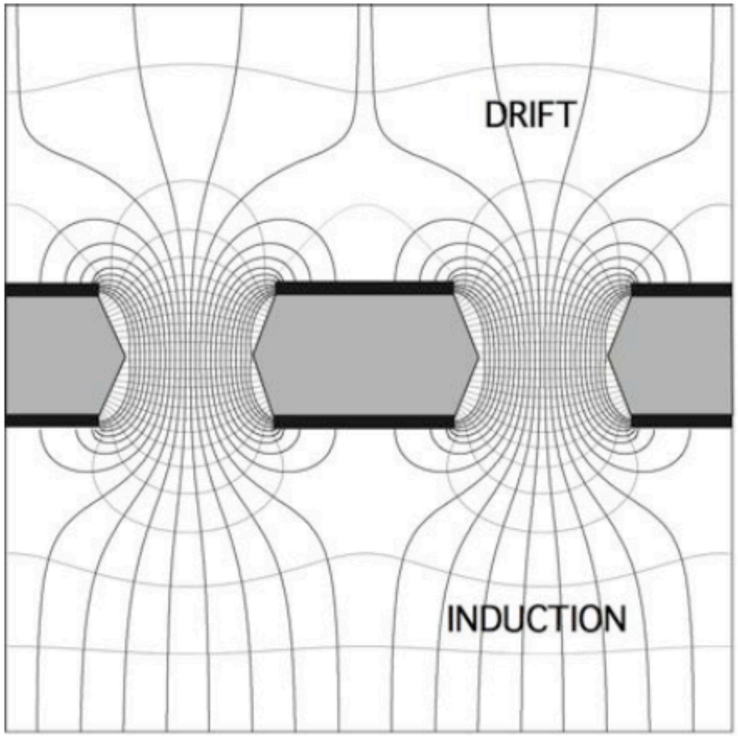
BACKUP SLIDES

Gas Electron Multiplier (GEM)

- **GEM charge amplification structures:**
  - developed at CERN in late 1990's
  - thickness: Kapton – **50 μm**, copper – 5 μm
  - electric fields **~40 kV/cm**, electron charge gain factors **~10^3**
  - several GEM foils can be stacked together

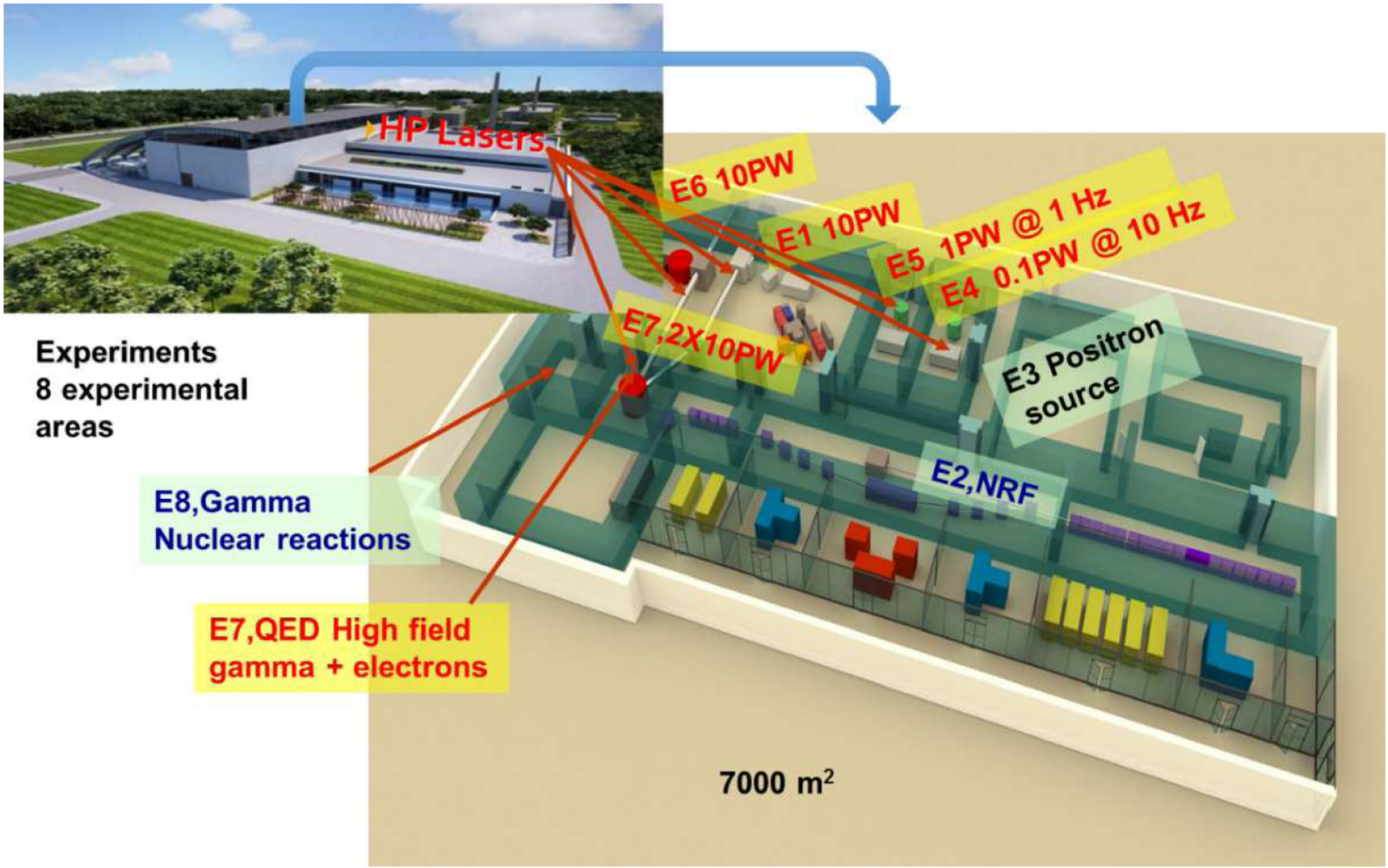
F. Sauli, NIM A386 (1997) 531





ELI-NP facility layout

nuclear physics



S.Gales et al., Phys. Scr. 91 (2016) 093004

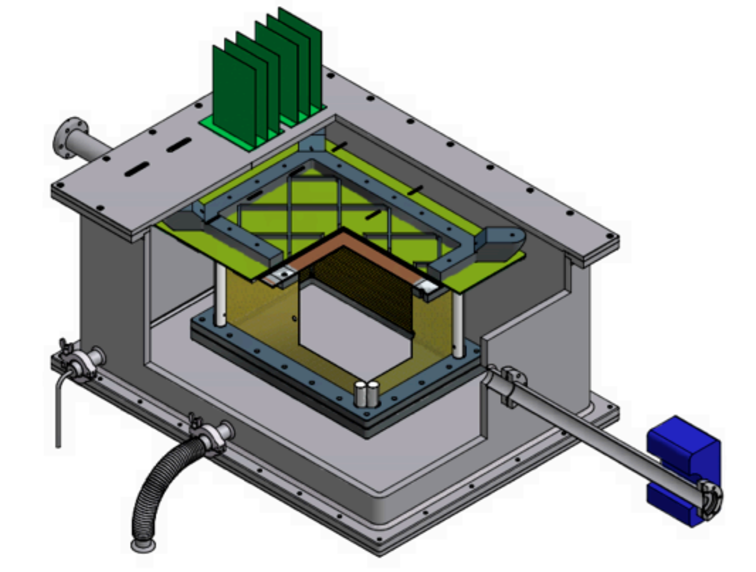
DAY-1 γ-ray beam experiments @ ELI-NP for charged particles detection

ELITPC

active gaseous target

low-pressure Time Projection Chamber

U. of Warsaw, ELI-NP/IFIN-HH, U. of Connecticut

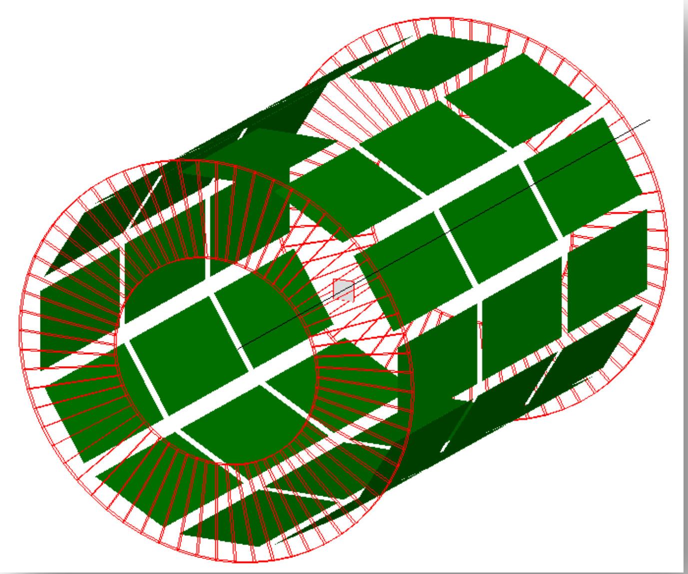


ELISSA

solid, removable target

Silicon Strip Detector array in vacuum

INFN-Catania, ELI-NP/IFIN-HH



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

Day-1 γ-beam experiments @ ELI-NP for charged particles detection

Nuclear Astrophysics studies:

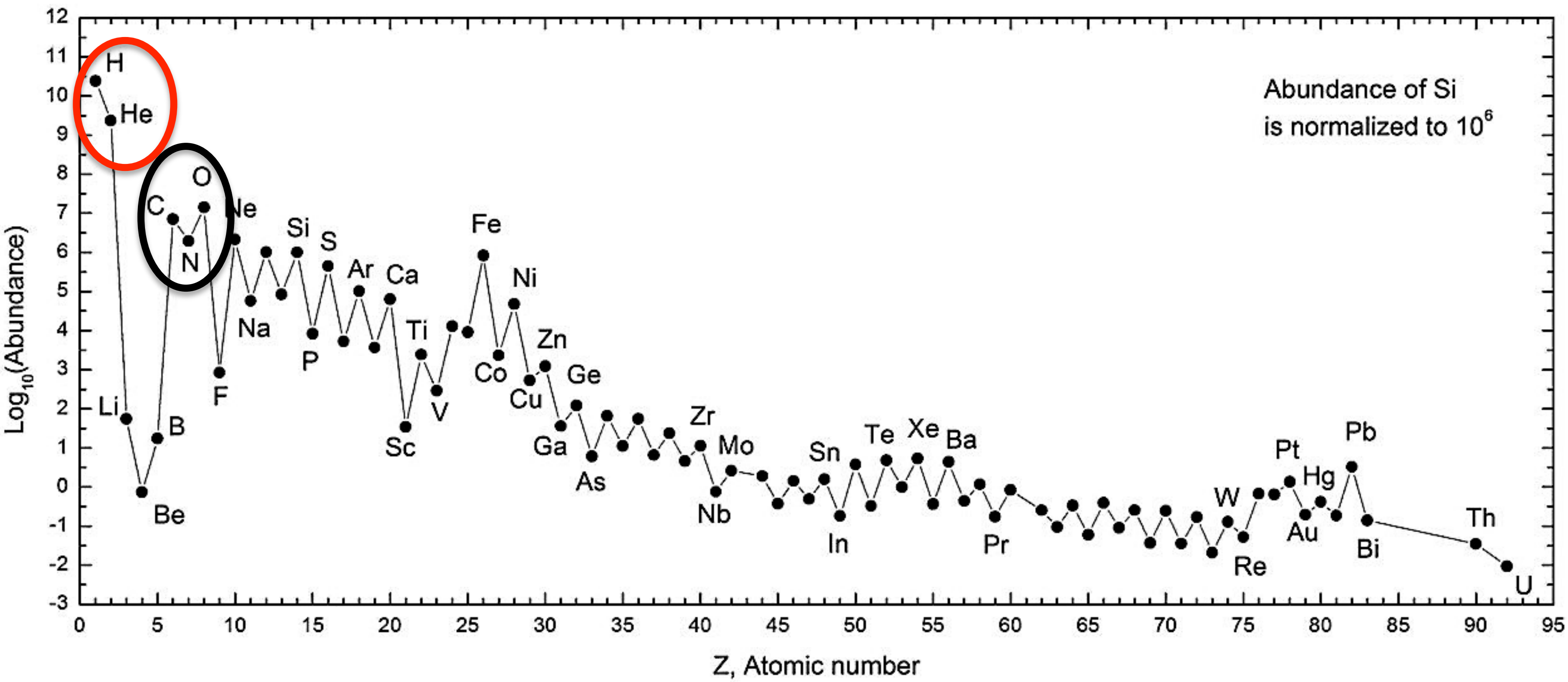
- use detailed balance principle for time-reverse reactions
- measure decay products of nuclear photo-dissociation reactions

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

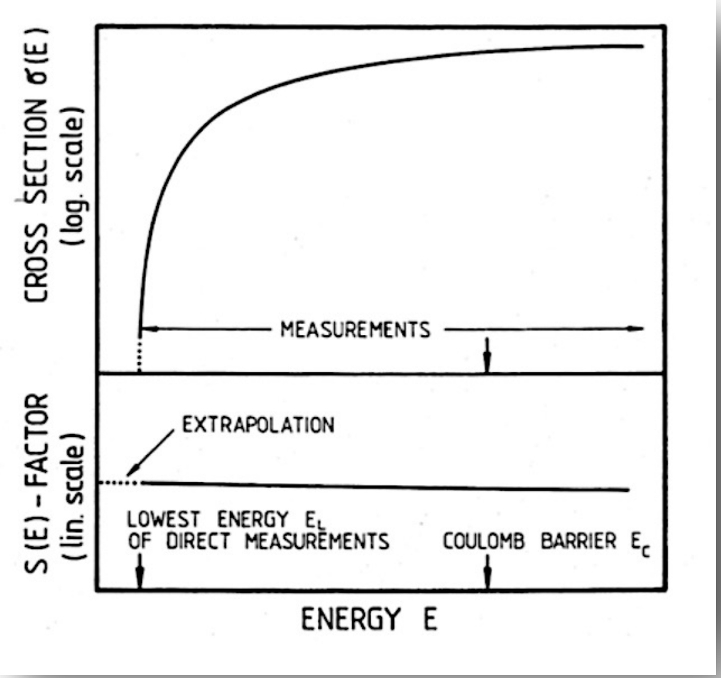
Abundance of chemical elements

- **Universe** (by mass): **H – 74%, He – 24%, O – 0.85%, C – 0.39%** + others (<1%)
- **Human body** (by mass): **O – 65%, C – 18%,** H – 10%, N – 3% + others (4%)

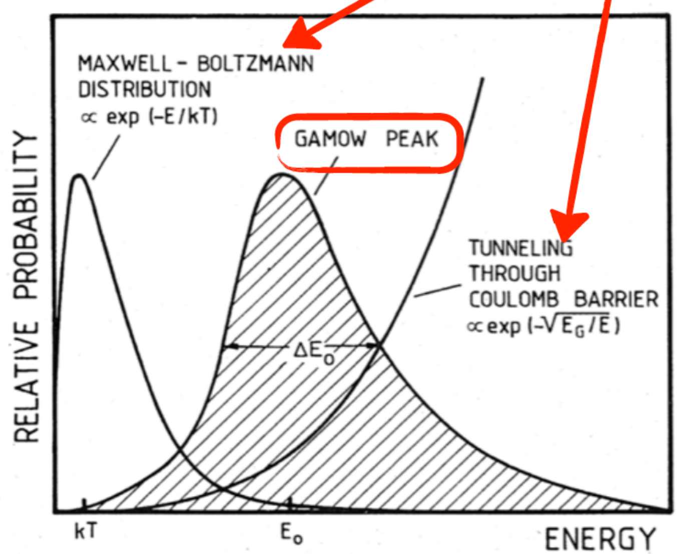


Stellar Nucleosynthesis

- **Problem of Coulomb barrier in direct α-capture (α,γ) measurements:**
  - in the interesting energy regime the cross sections are very small
  - exp. data need to be extrapolated to the Gamow peak
  - significant exp. background



$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \left(\frac{1}{K_B T}\right)^{3/2} \int_0^\infty S(E) \exp\left(-\frac{E}{K_B T} - \sqrt{\frac{E_G}{E}}\right) dE$$



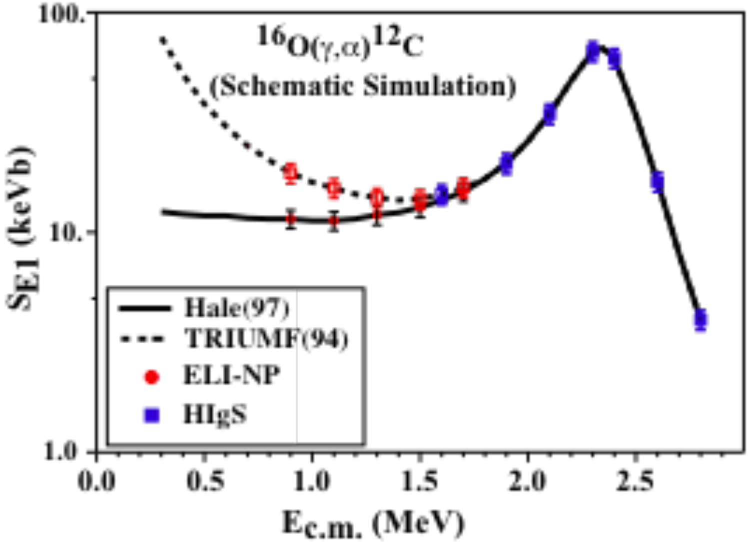
Gamow energy

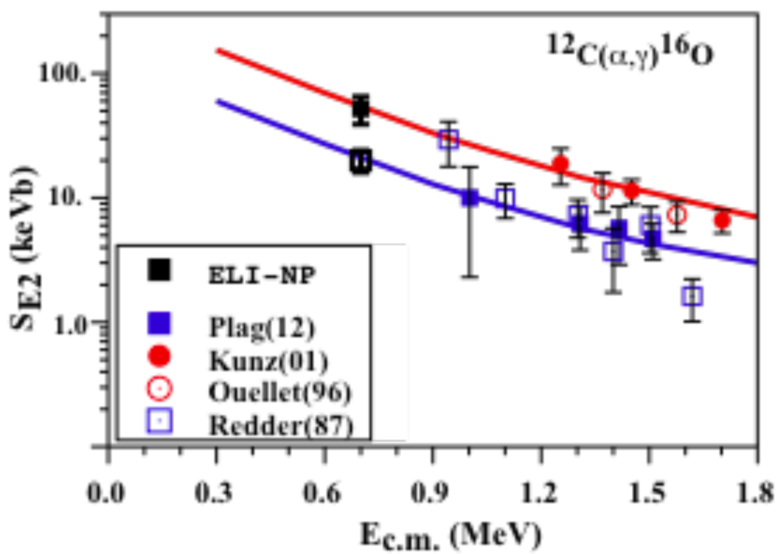
$$E_G = 2\mu \frac{\pi^2 e^4}{\hbar^2} (Z_1 Z_2)^2 \, MeV$$

Motivation for ELITPC @ ELI-NP

Studies of $^{12}C(\alpha,\gamma)^{16}O$:

- Present experimental data start from E_{CM} ~ 1 MeV
- **Goal:** measure astrophysical *S*-factor near the Gamow peak in red giants
  - E_{CM} ~ E_G **= 300 keV**
  - S_{E1}**(300)** and S_{E2}**(300)** corresponding to ***p*** and ***d***-waves
  - reduce uncertainty on *S*-factor from 40-80% to **10%**

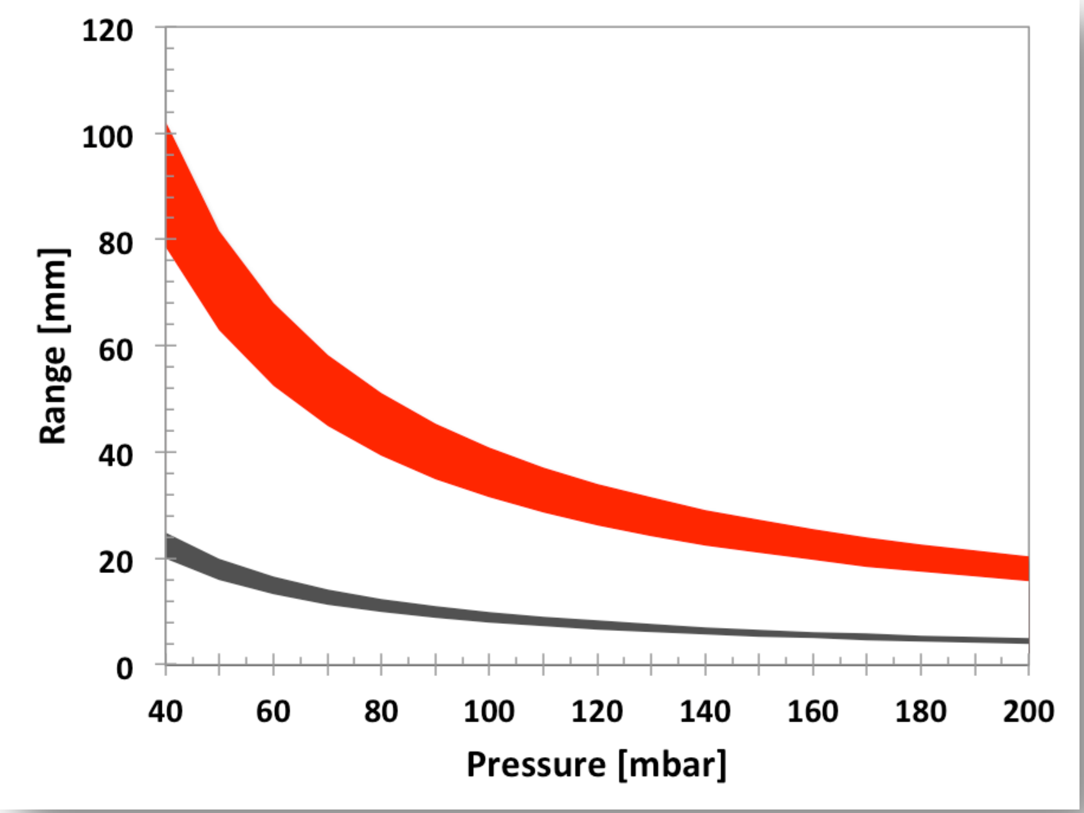




O.Tesileanu et al., Romanian Rep. in Phys. 68, Supplement (2016) S699

ELITPC – track lengths

- **Studies of $^{12}C(\alpha,\gamma)^{16}O$:**
  - SRIM-simulated ranges of charged particles as a function of CO_2 pressure



Red band : α particles

Grey band : ^{12}C ions

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