NUCLEAR ASTROPHYSICS WITH CHARGED PARTICLE DETECTORS AND GAMMA-BEAMS AT THE ELI-NP IN ROMANIA

The Charged Particle Working Group/ ELI GammaTDR#4

M. Gai, D.P. Kendellen, O. Tesileanu, C. Balan, S. Gales, D.G. Ghiță, C. Matei, C. Petcu, V. Zamfir, J.S. Bihalowicz, M. Cwiok, W. Dominik, Z. Janas, T. Matulewicz, C. Mazzocchi, K. Mikszuta, M. Pfützner, M. Zaremba, A. Anzalone, M. La Cognata, C. Spitaleri

http://astro.uconn.edu, moshe.gai@uconn.edu

1. **The Charged Particle Working Group (CPWG) Gamma-TDR#4**
   Silicon Strip Detector: ELISSA
   Electronic Readout TPC: ELITPC

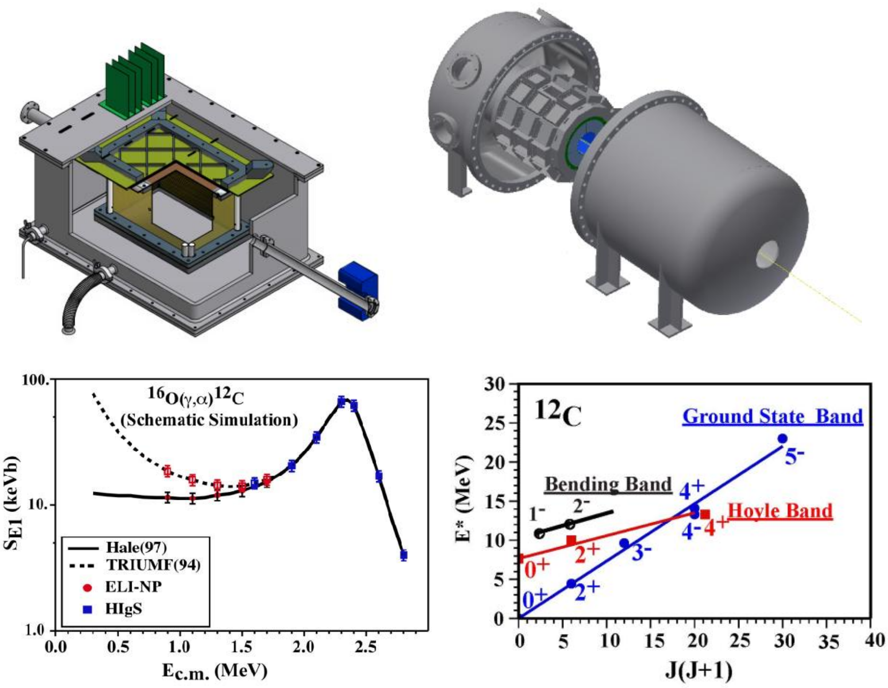
2. **The Physics Case**
   The $^{12}C(\alpha,\gamma)^{16}O$ Reaction: C/O Ratio

INPC 2016, Adelaide, September 13, 2016

Charged Particle Detection at ELI–NP

Technical Design Report

RA4 – TDR 4



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April 2015

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GBS-TDR4: CHARGED PARTICLE DETECTION AT ELI–NP.

O. Tesileanu, M. Gai, A. Anzalone, C. Balan, J.S. Bihalowicz, M. Cwiok, W. Dominik, S. Gales, D.G. Ghita, Z. Janas, D.P. Kendellen, M. La Cognata, C. Matei, K. Mikszuta, C. Petcu, M. Pfuetzner, T. Matulewicz, C. Mazzocchi, C. Spitaleri.

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CHARGED PARTICLE DETECTION AT ELI–NP

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Abstract. We propose charge particle detectors to be used in measurements utilizing intense gamma-ray beams from the newly constructed ELI-NP facility at Magurele, Bucharest in Romania. We consider a large area Silicon Strip Detector (SSD) and a gas Time Projection Chamber detector read by an electronic readout system (e-TPC). We intend to use the SSD and e-TPC detectors to address essential problems in nuclear structure physics, such as clustering and the many alpha-decay of light nuclei such as ^{12}C and ^{16}O. The e-TPC detector may be also used for studies in nanodosimetry and radiation damage to DNA (research described in the Medical Applications TDR of ELI-NP, RA4-TDR5). Both detectors (SSD and e-TPC) will be used to address central problems in nuclear astrophysics such as the astrophysical cross section factor of the ^{12}C(α,γ) reaction and other processes central to stellar evolution. We identify the infrastructure required in Romania and other countries to facilitate the construction of these detectors as well as the required budget and personnel. Memorandums of Understanding (MOUs) between the ELI-NP facility and the collaborating institutes have been signed in order to permit the realization of this Technical Design Report (TDR).

Key words: silicon-strip detectors, TPC, charged particle, photon-induced, gamma beam.

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THE EUROPEAN PHYSICAL JOURNAL A

Review

Perspectives for photonuclear research at the Extreme Light Infrastructure - Nuclear Physics (ELI-NP) facility[⋆]

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Communicated by N. Alamanos

Abstract. The perspectives for photonuclear experiments at the new Extreme Light Infrastructure - Nuclear Physics (ELI-NP) facility are discussed in view of the need to accumulate novel and more precise nuclear data. The parameters of the ELI-NP gamma beam system are presented. The emerging experimental program, which will be realized at ELI-NP, is presented. Examples of day-one experiments with the nuclear resonance fluorescence technique, photonuclear reaction measurements, photofission experiments and studies of nuclear collective excitation modes and competition between various decay channels are discussed. The advantages which ELI-NP provides for all these experiments compared to the existing facilities are discussed.

⋆ Contribution to the Topical Issue "Perspectives on Nuclear Data for the Next Decade" edited by Nicolas Alamanos, Eric Bauge, Stéphane Hilaire.

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Gamma Beam System experiments for charged particles detection @ ELI-NP

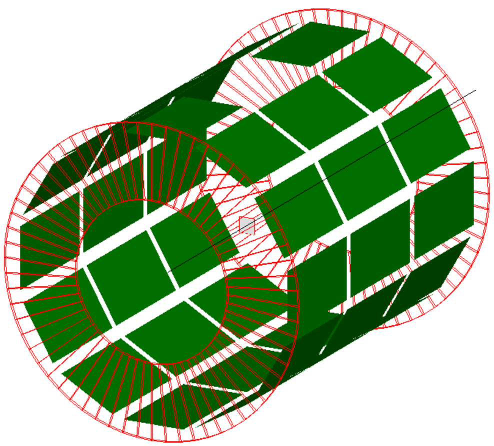
Day-1 experiments approved under framework of GBS TDR4:

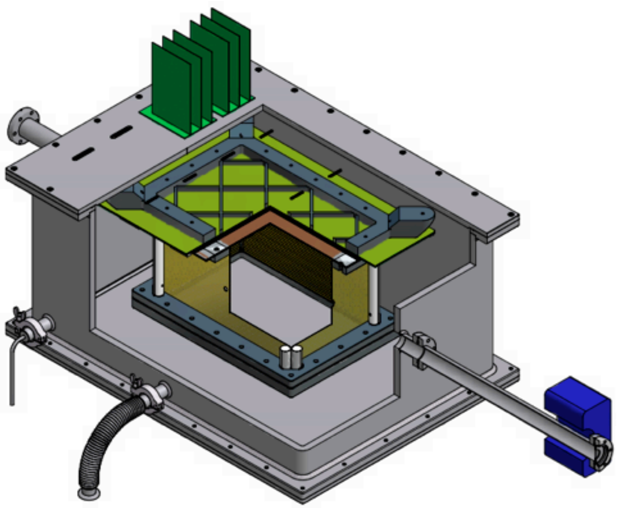
ELISSA: Silicon Strip Detector array with removable **solid target** in vacuum

INFN-Catania, ELI-NP/IFIN-HH

ELITPC: **active gaseous target**, low-pressure Time Projection Chamber

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





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

Catania - ELI SSD Array
Now ELISSA, Catalin Matei, ELI-NP

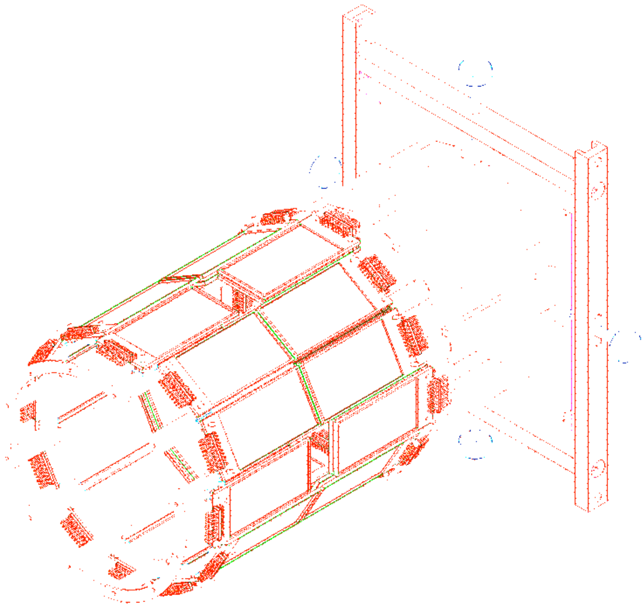


Fig. 3.1.1: Drawing of the ORRUBA silicon array.

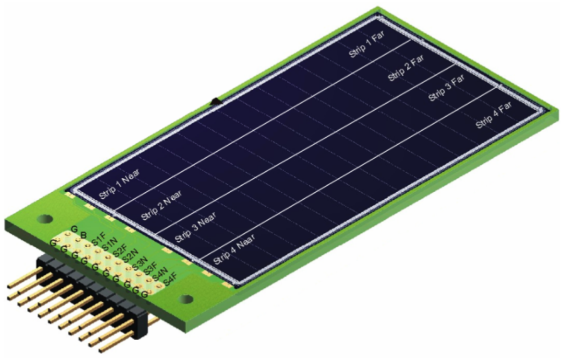


Fig. 3.1.2: Picture of a Super X3 position sensitive detector.

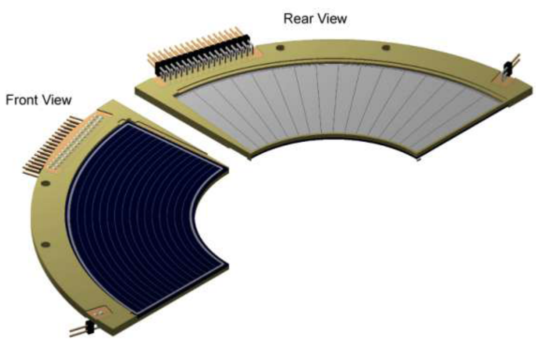
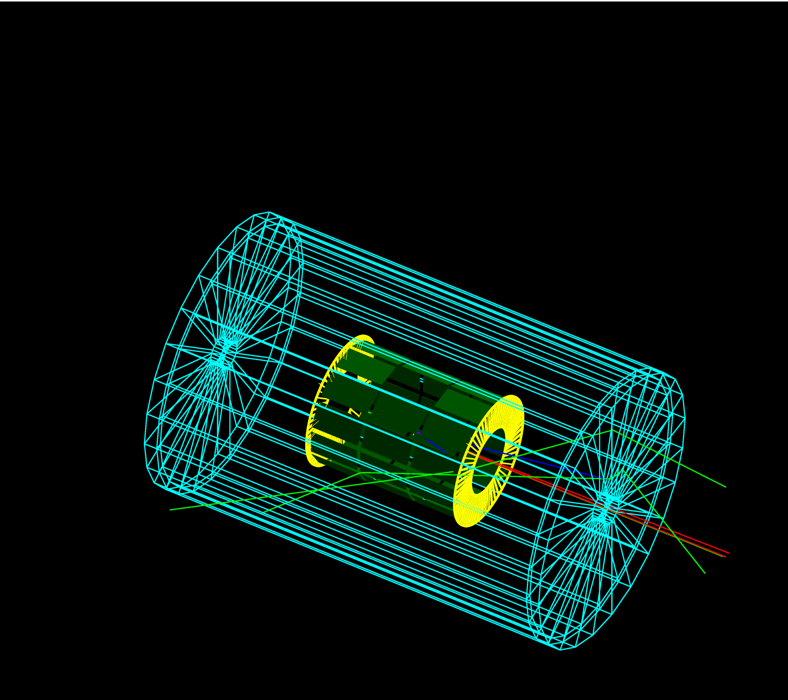


Fig. 3.1.3: The QQQ3 end cap detector assembly.

<u>Marco La Cognata, Catania</u>
(April 16, 2014)



Gamma beam experiments for charged particles detection @ ELI-NP

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**
$^{24}Mg(\gamma,\alpha)^{20}Ne$	SSD	^{24}Mg	Si-burning
$^{96}Ru(\gamma,\alpha)^{92}Mo$	SSD	^{96}Ru	synthesis of elements with A>73 in *p*-processes
$^{22}Ne(\gamma,\alpha)^{18}O$	TPC	^{22}Ne	ratio $^{16}O/^{18}O$, CNO-cycle synthesis of ^{22}Ne (source of *n* in *s*-processes)
$^{19}F(\gamma,p)^{18}O$	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

ELITPC Collaboration (June 2016)

Univ. of Warsaw, Poland

M. Bieda, J.S. Bihałowicz, M. Ćwiok, W. Dominik, Z. Janas, Ł. Janiak, J. Mańczak, T. Matulewicz, C. Mazzocchi, M. Pfützner, P. Podlaski, M. Zaremba

IFIN-HH / ELI-NP, Romania

D. Balabanski, C. Balan, D.G. Ghita, O. Tesileanu

Univ. of Connecticut, USA

M. Gai, D.P. Kandellen

ADMINISTRATIVE SUMMARY:

NSF: Partnership for International Research & Education

Title of the project:

"PIRE US-Romania Collaboration on Studies Using the Extreme Light and Extreme Matter Infrastructures"

Principal investigator: **Moshe Gai**

Length of study (maximum 5 years): **Five Years**

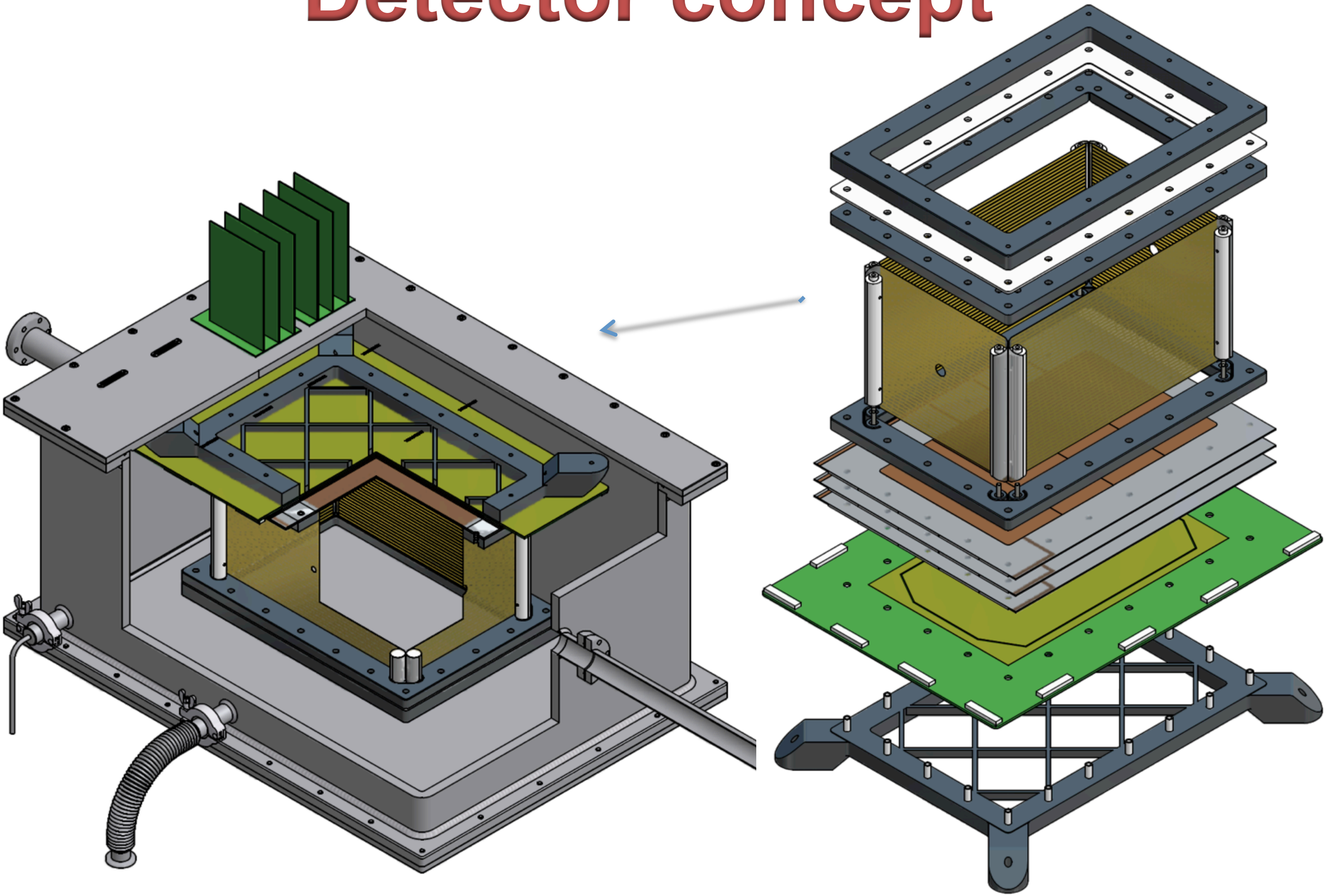
Estimated total budget (does not need to be itemized):

Lead institution: **University of Connecticut**

List of partner institutions and key researchers:

Johns Hopkins University, Baltimore, MD, Dan Stutman, Maria Pia Valdivia
University of Michigan, Ann Arbor, MI, Karl M. Krushelnick
Texas A&M University, College Station, TX, Aldo Bonasera
Yale University, New Haven, CT, John W. Harris

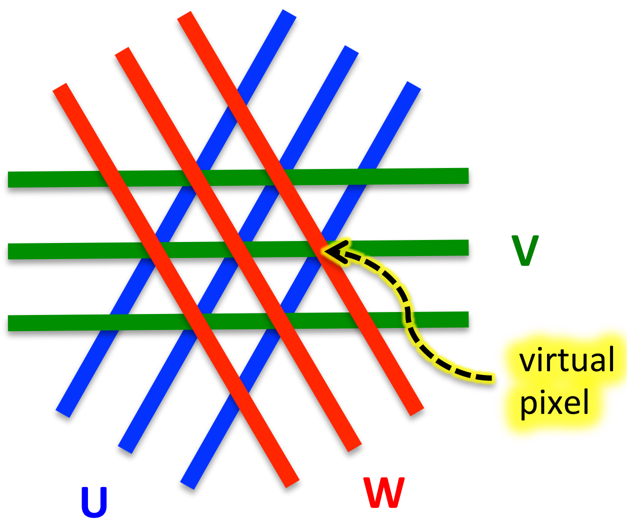
Detector concept

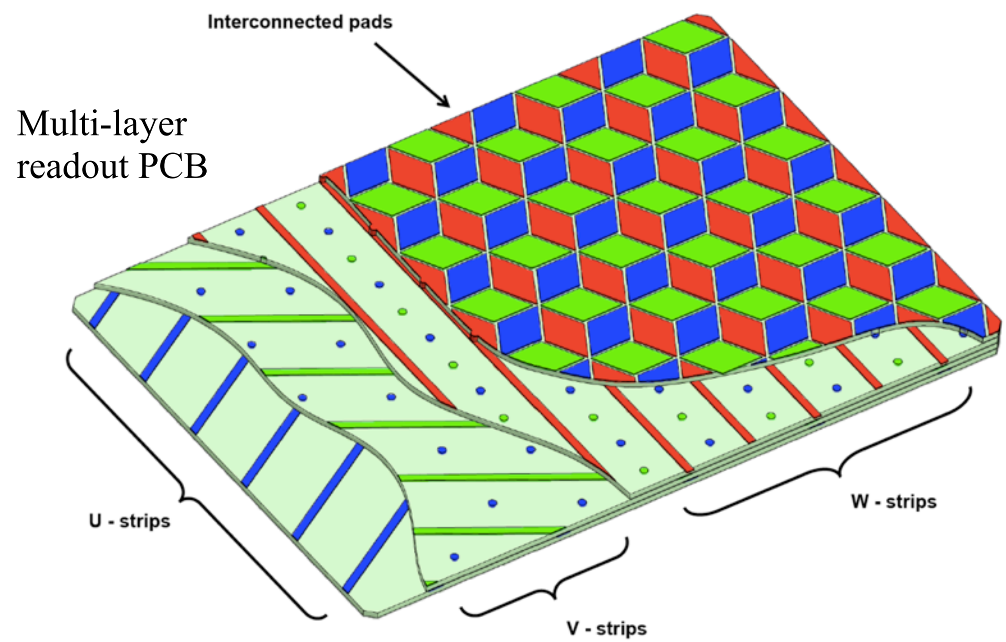


ELITPC detector (2)

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)
- need $O(10^3)$ channels → moderate cost of electronics

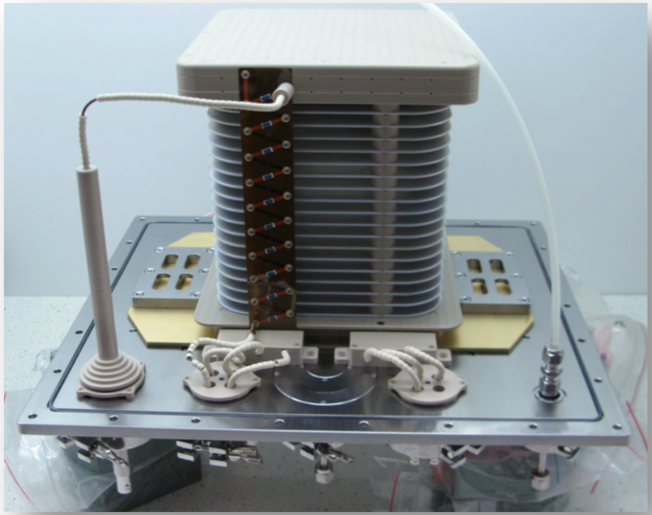




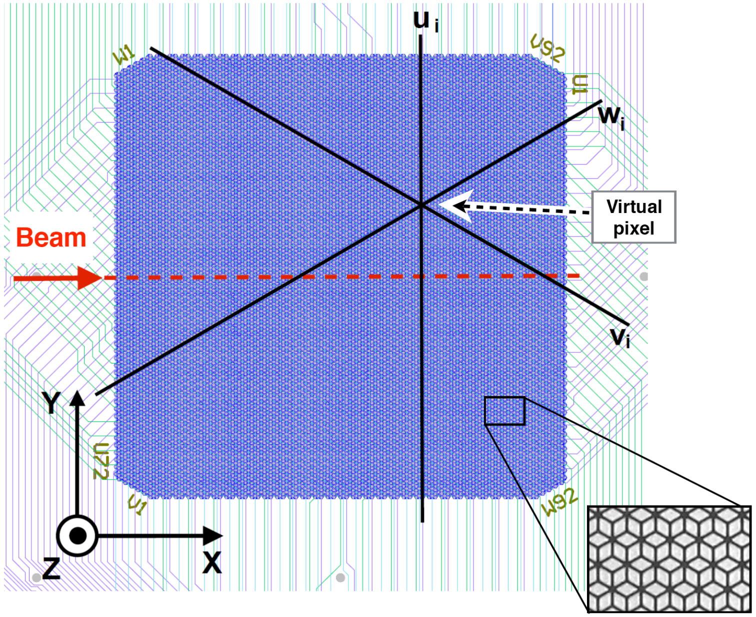
S. Bachmann et al., NIMA 478 (2002) 104
V. Ableev et al., NIMA 535 (2004) 294
M. Ćwiok, Acta Phys. Pol. B 47 (2016) 707
J. Bihałowicz et al., Proc. of SPIE 9290 (2014) 92902C

Demonstrator detector

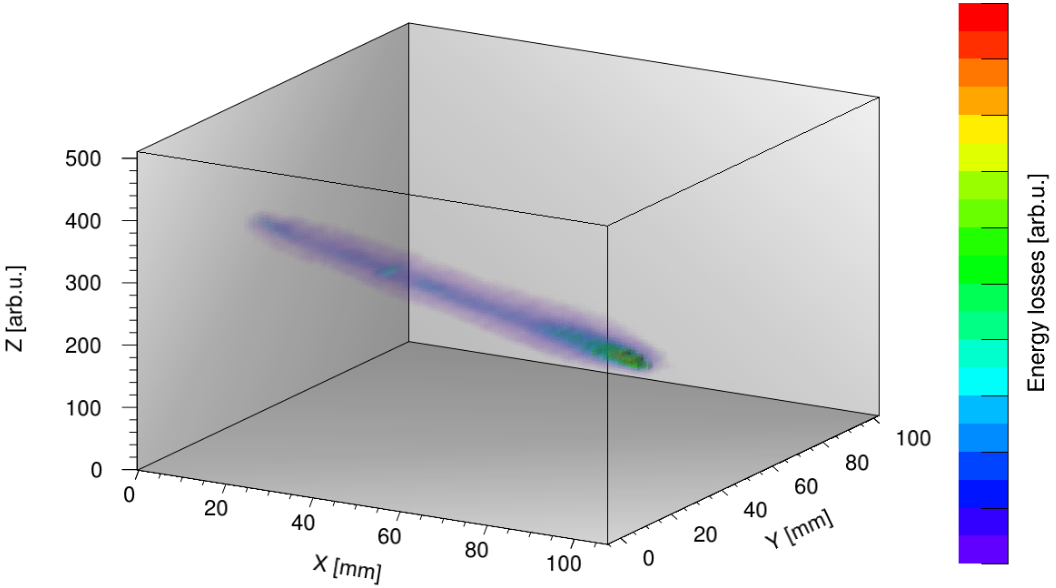
- Active area: **10 × 10 cm²**, drift: **20 cm**, He+CO_2 (70:30) gas mixture **@1 atm**
- GET electronics: **256 channels**
- Apr 2016: tested at **15 MeV α-particle** beam from 9 MV Tandem (IFIN-HH, Romania)



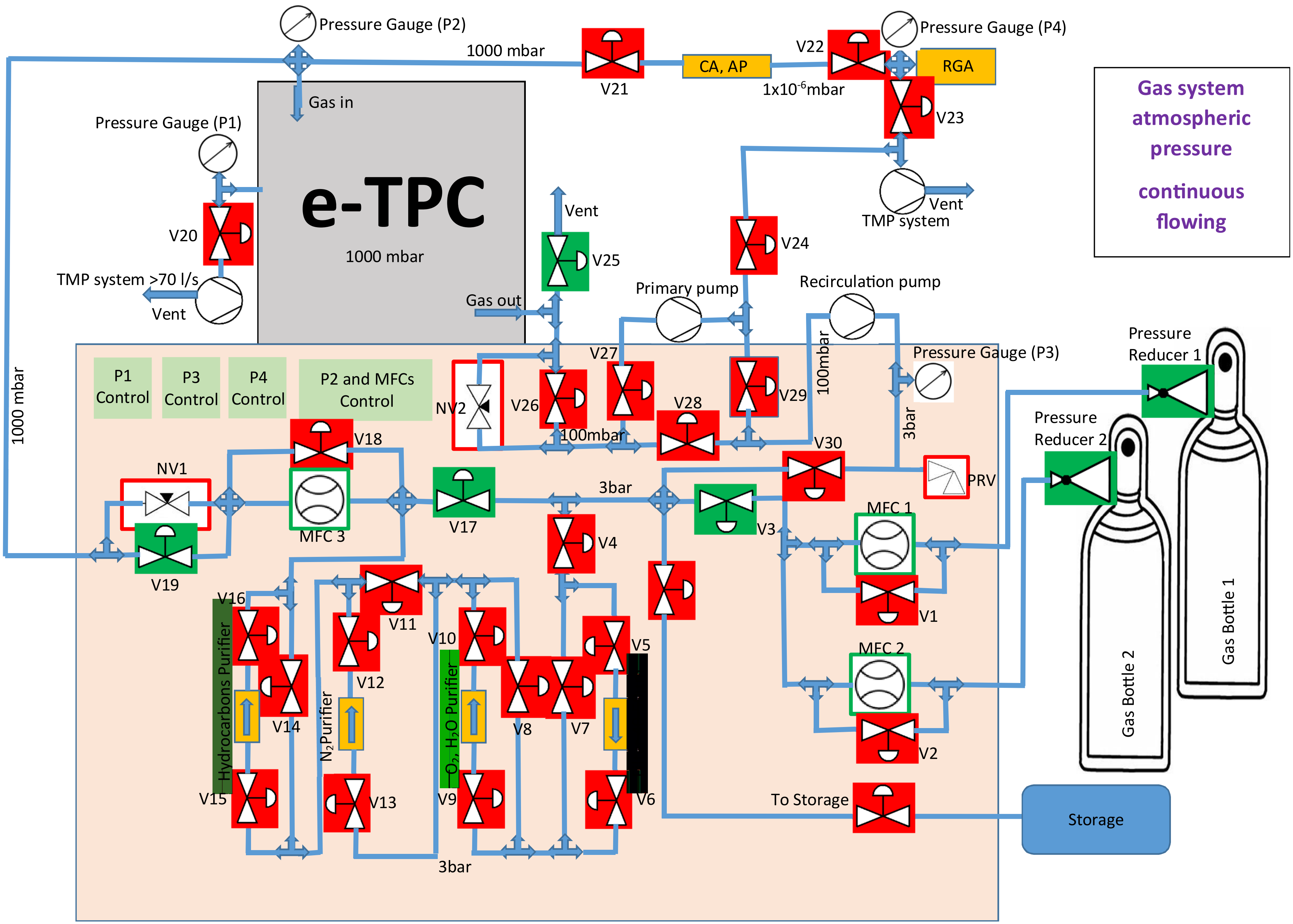
Beam axis projection onto UVW readout PCB



Reconstructed 15 MeV α-particle track in 3D



UConn - ELI, Dave Kendellen, Dan Ghita, Gas System:
Now Catalin Balan, ELI-NP, Februray 23, 2016



W.A. Fowler; Rev. Mod. Phys. 56, 149 (1984)

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

C/O = ???

Reaching the Horizon, US Nuclear Physics Long Range Plan - 2015

[Some Claim Total S(300) ±12% or even ±4.5%]

Sidebar 4.1: The Carbon-to-Oxygen Ratio in Our Universe [$^{12}C(\alpha,\gamma)$]

A fundamental question for nuclear astrophysics is the ratio of ^{12}C to ^{16}O that emerges in the very first generations of stars. This ratio is not only important for the development of the chemical building blocks of life but also for the entire scheme and sequence of nucleosynthesis events as we imagine them now. The carbon-to-oxygen ratio determines the sequence of late stellar evolution phases for the massive stars that give rise to core collapse supernovae. It determines the ignition and burning conditions in Type Ia (thermonuclear) supernovae, and it dictates conditions for the ignition of so-called superbursts observed in accreting neutron stars. Carbon induced reactions are, therefore, of extreme importance for our entire understanding or interpretation of nucleosynthesis patterns and the identification of nucleosynthesis sites.

Present extrapolation of the reaction rates associated with the $^{12}C/^{16}O$ ratio from the presently existing data depends very much on the reliability of nuclear structure and reaction models, which introduce orders of magnitude uncertainty into the predictions. This problem has been well known for decades, and its solution requires new experimental efforts in a cosmic-ray-background-free (deep underground) environment to provide the necessary experimental conditions for putting to rest the question associated with low-energy carbon capture and fusion reactions.

Brief History of $^{12}C(\alpha,\gamma)$ Reaction
(42 Years later)

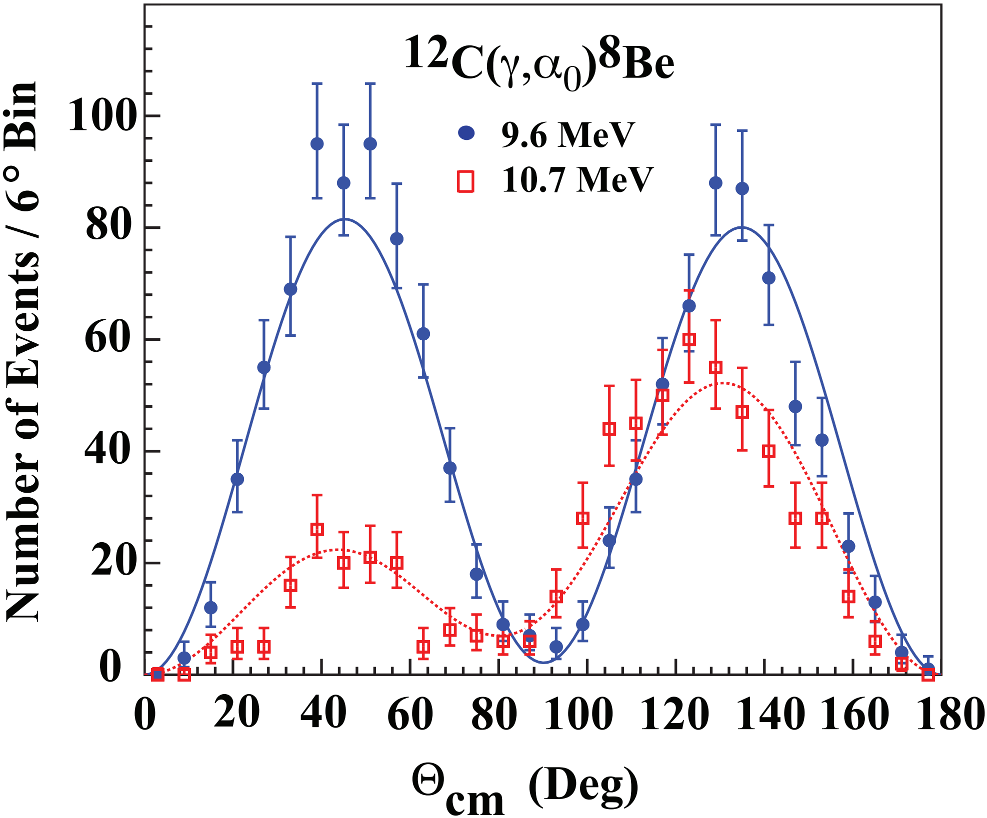
1974	Ph.D. thesis: Peggy Dyer & Charlie Barns
1984	Willie Fowler, Nobel Lecture
- - -	A Lot of Work, Many Measurements…
2013	Ambiguities in the $^{12}C(\alpha,\gamma)$ Reaction
	M. Gai; Phys. Rev. C 88(2013)062801(R)

1) Two Solutions: $S_{E1} \approx 10$ or ≈ 80 keVb
2) $S_{E2} \approx 60$ or ≈ 154 keVb
3) E1-E2 mixing phase (φ_{12}) Violates Unitarity
4) Cascade (6.05 MeV) Data Disagree by ≈ 25

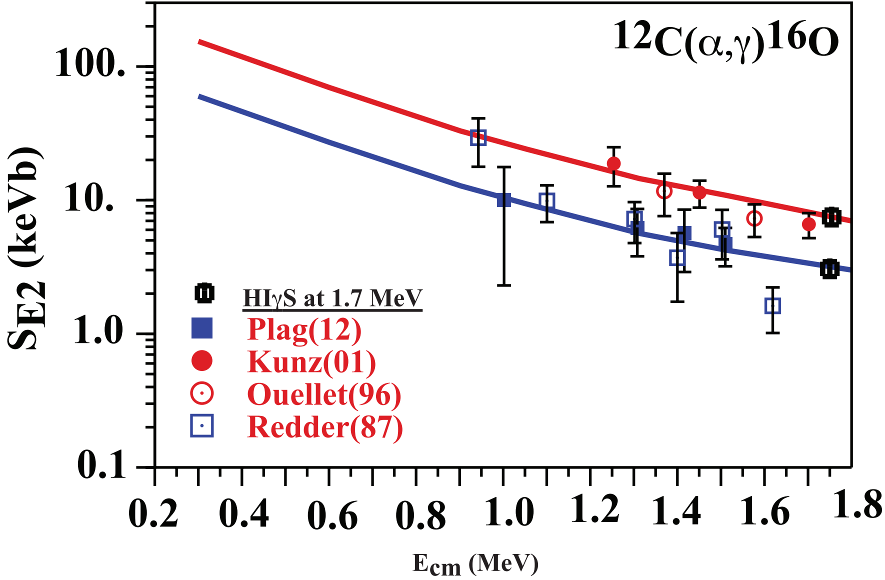
The “Inconveniet Truth” of $^{12}C(\alpha,\gamma)$

OTPC at HIγS: W.R. Zimmerman et al.; Phys. Rev. Lett. 110(2013)152502

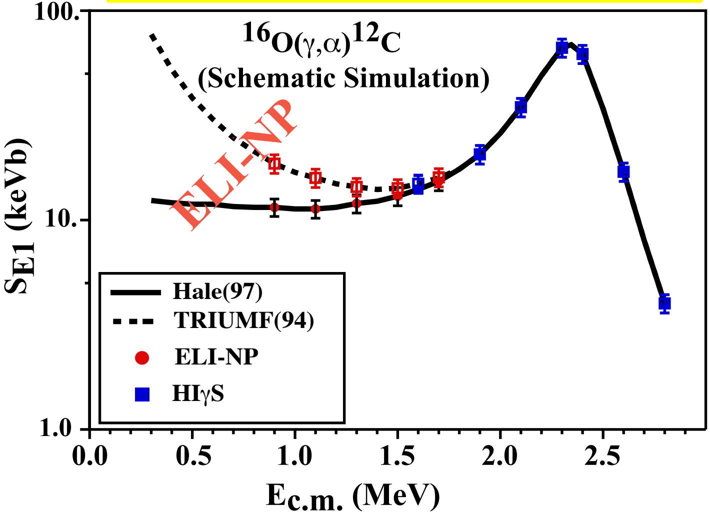
	9.6 MeV	10.7 MeV
E2/(E1+E2) =	0.97 ± 0.02	0.71 ± 0.05
ϕ_{12} =	80 ± 6°	132 ± 5°



M. Gai, Phys. Rev. C 88(2013)062801(R)



ELI-NP Anticipated Data
M. Gai, Nucl. Phys. A928, 313 (2014).



Conclusions:

Two Solutions:

1) SE1 ≈ 10 or ≈ 80 keVb

2) SE2 ≈ 60 or ≈ 154 keVb

3) φ_{12} Values Violate Unitarity

4) Cascade (6.05 MeV) Data Disagree by ≈ 25

Current Solutions Depend on the Choice of Data

Hope vis-à-vis $^{16}O(\gamma,\alpha)$ With Gamma-Beams

φ_{12} Measurement at HIγS

$S_{E2}(300)$: HIγS at Eγ = 8.8 MeV

$S_{E1}(300)$: ELI-NP at Eγ = 8.0 MeV