Nuclear Physics Mid Term Plan in Italy

LNF – Session

Frascati, December 1st - 2nd 2022

Future facilities for experiments with intense stable and radioactive beams at LNS

Diana Carbone

INFN - Laboratori Nazionali del Sud, Catania, Italy

INFN LNS

Three years upgrade project of the LNS Cyclotron and infrastructures

funded by national grant (PON) for 19.4 M€

Triggered by the NUMEN physics case

- **Much higher beam current will be available (from 100 W to 5-10 kW)**
- **FRAISE: a new FRAgment In-flight SEparator**

POT lns

The NUMEN physics case

(NUclear **M**atrix **E**lements for **N**eutrinoless double beta decay**)**

F. Cappuzzello et al., EPJA 54, 72 (2018)

Cross section measurements of heavy-ion induced **Double Charge Exchange (DCE)** reactions

F. Cappuzzello et al., Prog. Part. Nucl. Phys. 128, 103999 (2023)

Extraction from measured cross-sections of "*data-driven*" information on NME for all the systems candidate for 0νββ

- Constraints to the existing theories of NMEs (nuclear wave functions)
- Model-independent comparative information on the sensitivity of half-life experiments
- Complete study of the reaction mechanism

NUMEN phases			
Phase 1	**Phase 2**	**Phase 3**	**Phase 4**
Feasibility study	Study of few cases + development of theory + R&D activity	Shutdown & Upgrade of LNS facilities	Systematic study of all the targets
2013-2015	2015-2020	2020-2022	2023-...

Upgrades of the MAGNEX magnetic spectrometer

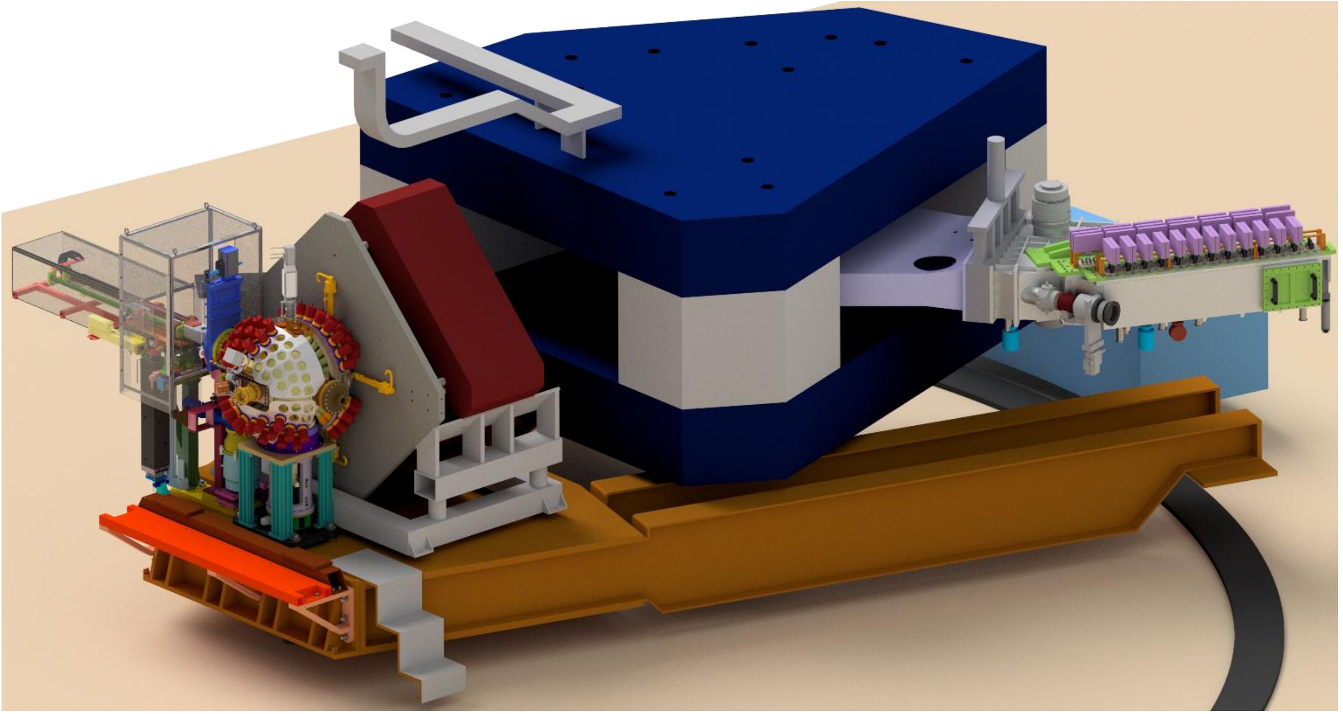
MAGNEX spectrometer

Optical characteristics	Current values
Maximum magnetic rigidity (Tm)	1.8
Solid angle (msr)	50
Momentum acceptance	-14%, +10%
Momentum dispersion (cm/%)	3.68

Performances

- Energy $\Delta E/E \sim 1/1000$
- Angle $\Delta\theta \sim 0.2°$
- Mass $\Delta m/m \sim 1/300$
- From H to Zn ions detected

F. Cappuzzello et al., Eur. Phys. J. A (2016) 52: 167
M. Cavallaro et al., NIM B 463 (2020) 334
G. Souliotis et al., NIM A 1031, 166588 (2021)



F. Cappuzzello et al., Int. Jour. Mod. Phys. A 36, 2130018 (2021)
C. Agodi et al., Universe 7, 72 (2021)

Major upgrades

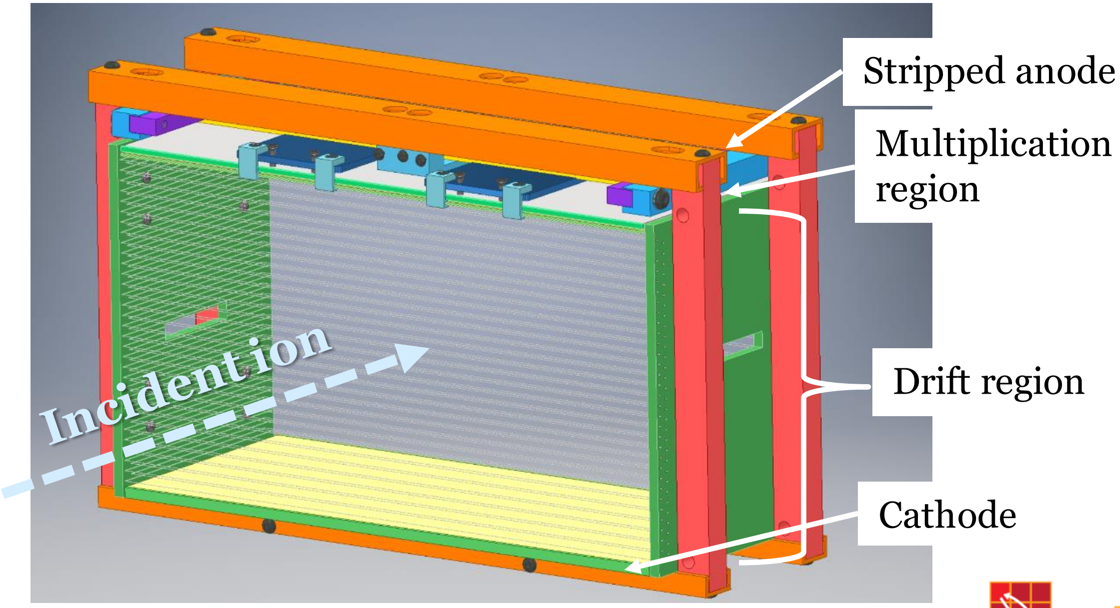
- New focal plane detector (gas tracker and pid wall)
- New gamma detector array (G-NUMEN)
- New exit beam lines and beam dump (for 0° measurements)
- Higher magnetic rigidity (up to 2.2 Tm)
- Suitable targets

WG5 Target development
F. Pinna talk

Measure the three-dimensional track (X, Y, θ, φ) of the reaction ejectiles reaching the focal plane

Requirements for new gas tracker

- Ability to cope the **rates** of particles as high as **MHz**
- **Low pressure** operation
- **High resolution measurement** of the track coordinates
  - horizontal position X_{foc} resolution **0.6 mm** (FWHM)
  - horizontal angle θ_{foc} resolution **0.3°** (FWHM)
  - vertical position Y_{foc} resolution **0.7 mm** (FWHM)
  - vertical angle φ_{foc} resolution **0.7°** (FWHM)



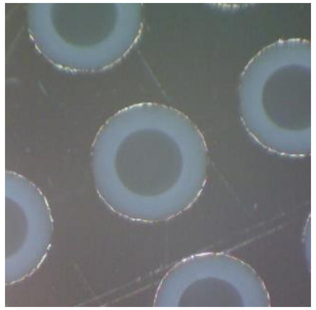
Same working principle of the present FPD tracker

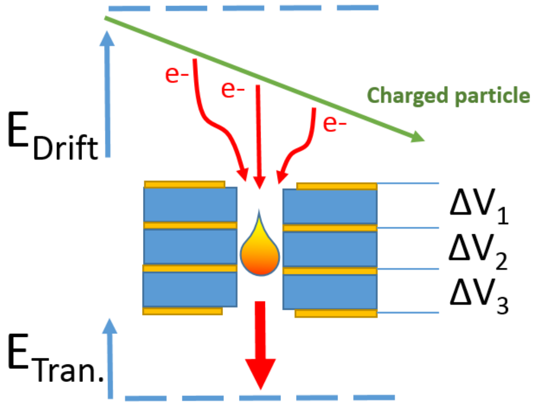
Filled with isobutane at low pressure (tens mbar)

Multiple Thick Gas Electron Multiplier (THGEM)

→ Simple and Robust

Assembly of several THGEM elements stacked together



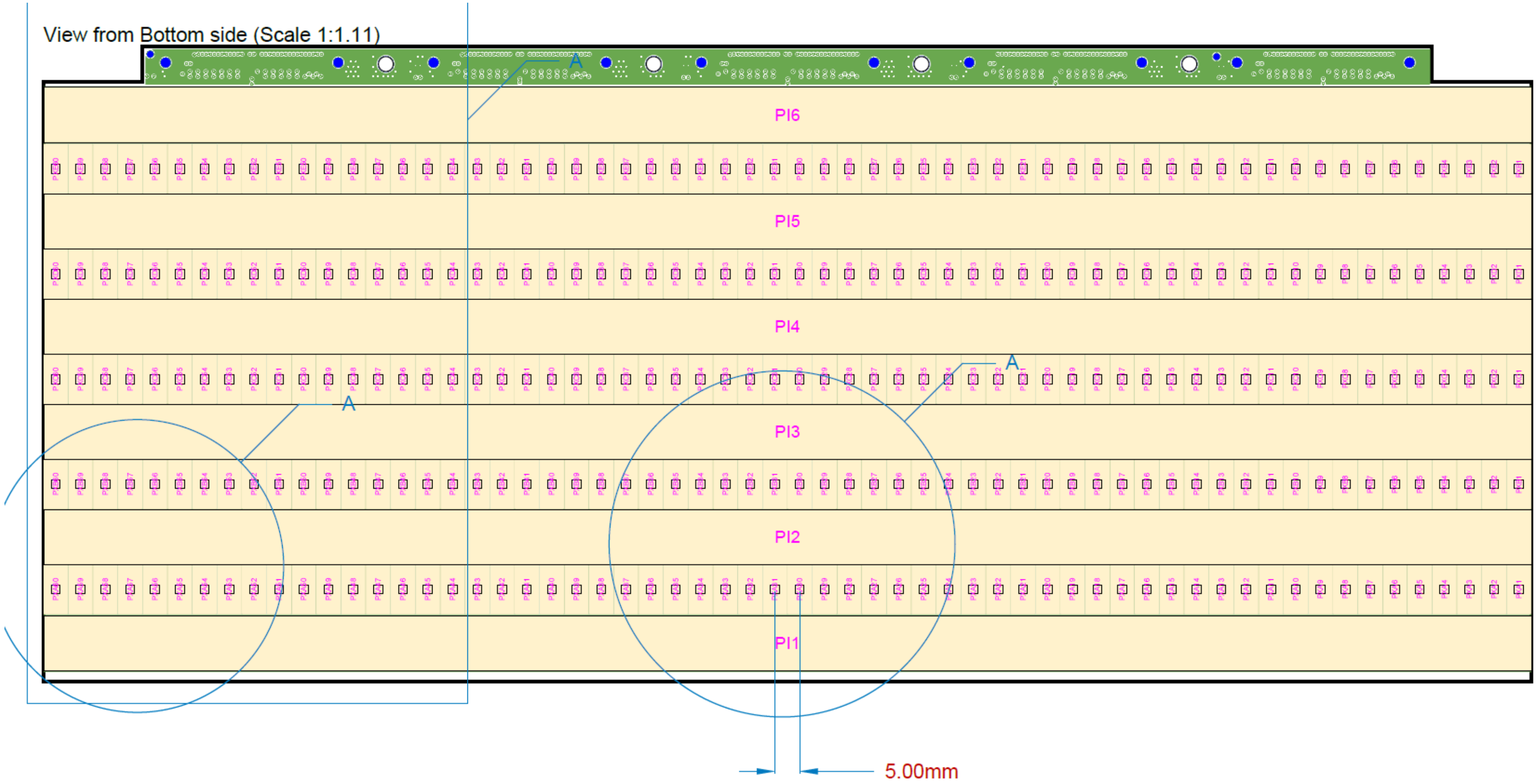


3-layer THGEM

Large gain at low pressure

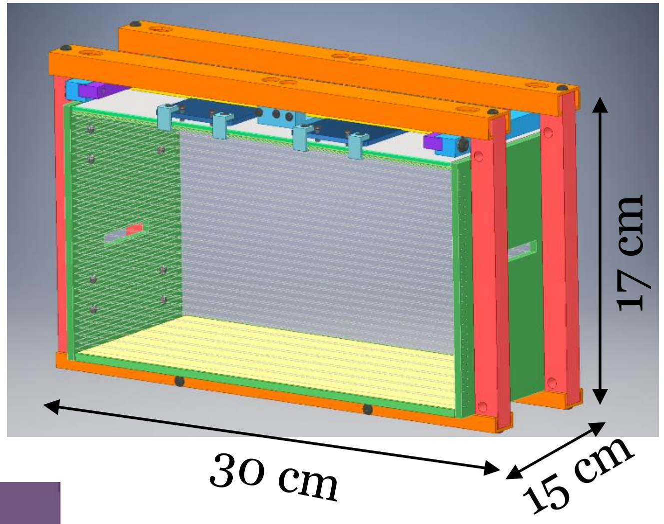
The stripped anode

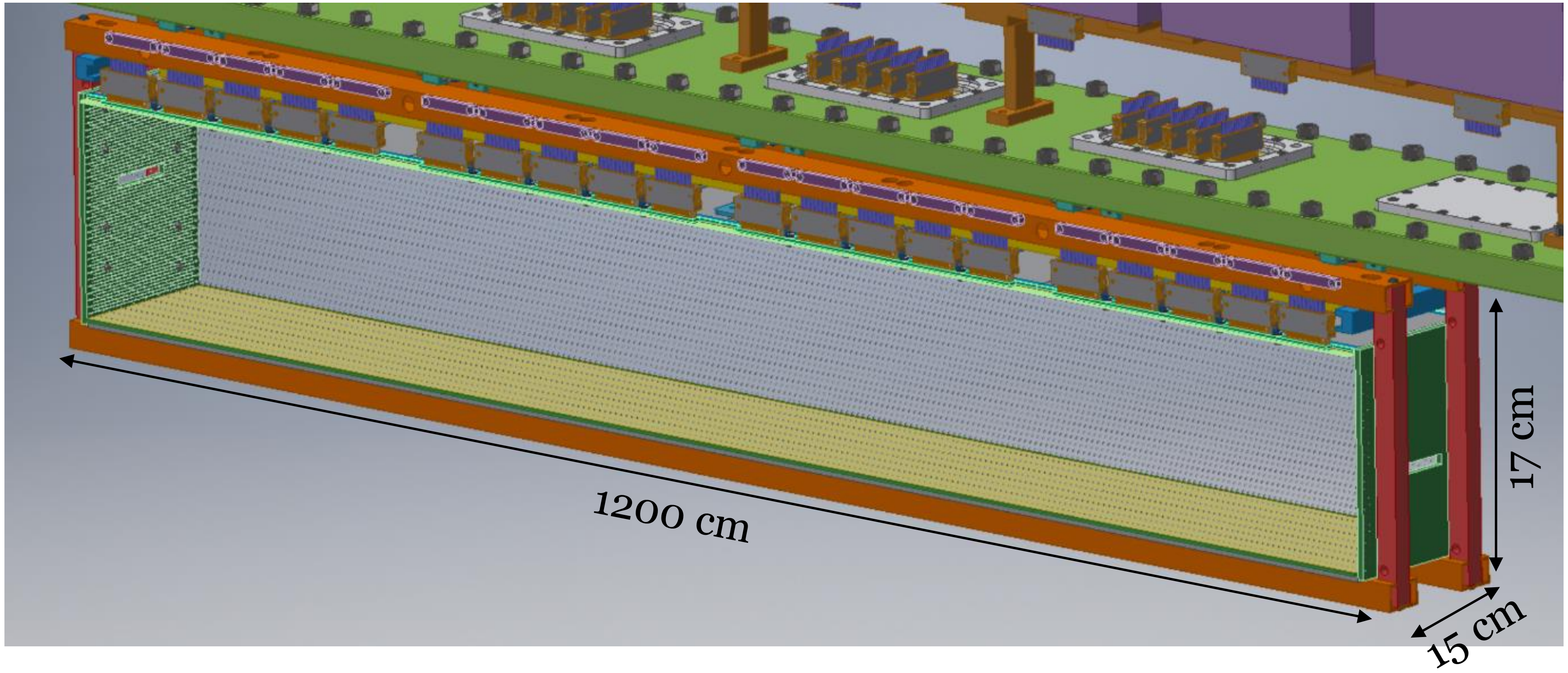
- 60 pad in 30 cm (1/4 of the full tracker)
- 5 mm x 10 mm pads
- 6 strips (11 mm height)
- Active region ≈ 110 mm

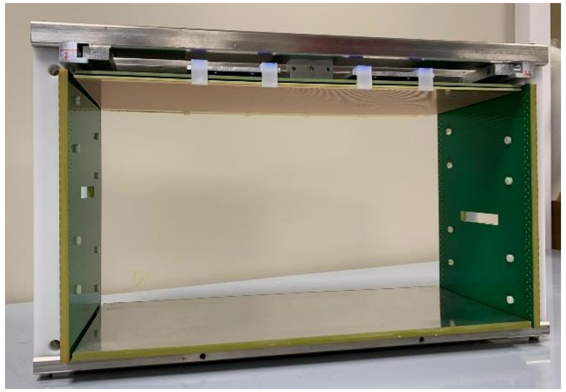


The prototype

- Same design of the final tracker, just scaled in size
- 30 cm lenght (1/4 of the full tracker lenght)
- Important test bench for the final detector (performances, mechanical and electrical choices)

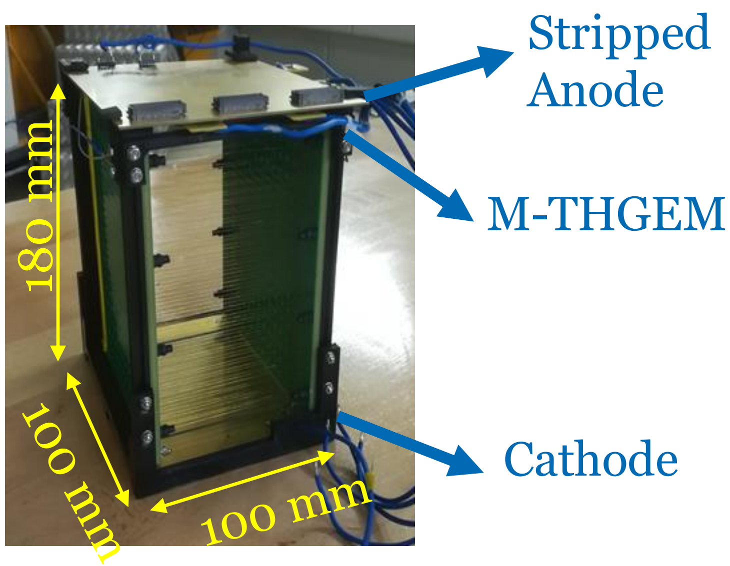


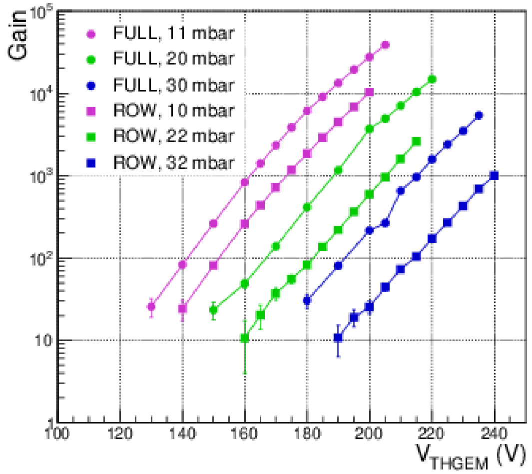




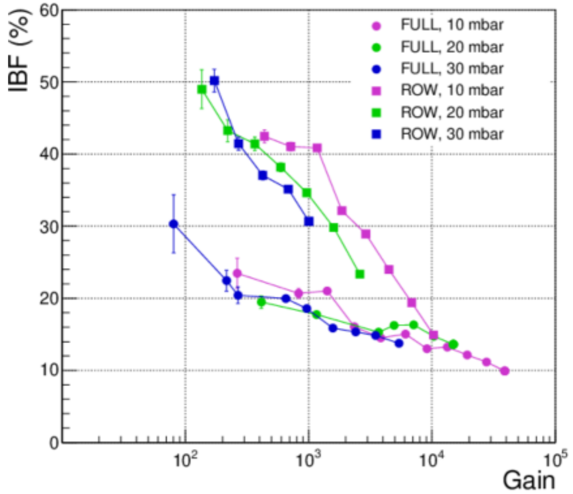
Prototype ready

The prototype characterizations





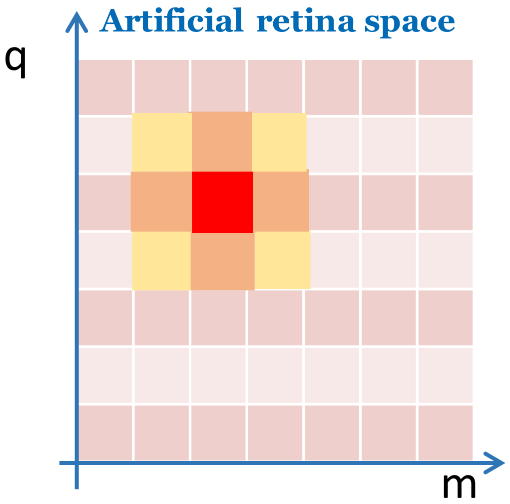
High gain at low voltage and pressure



Ion Back Flow

I. Ciraldo, G.A. Brischetto et al., accepted

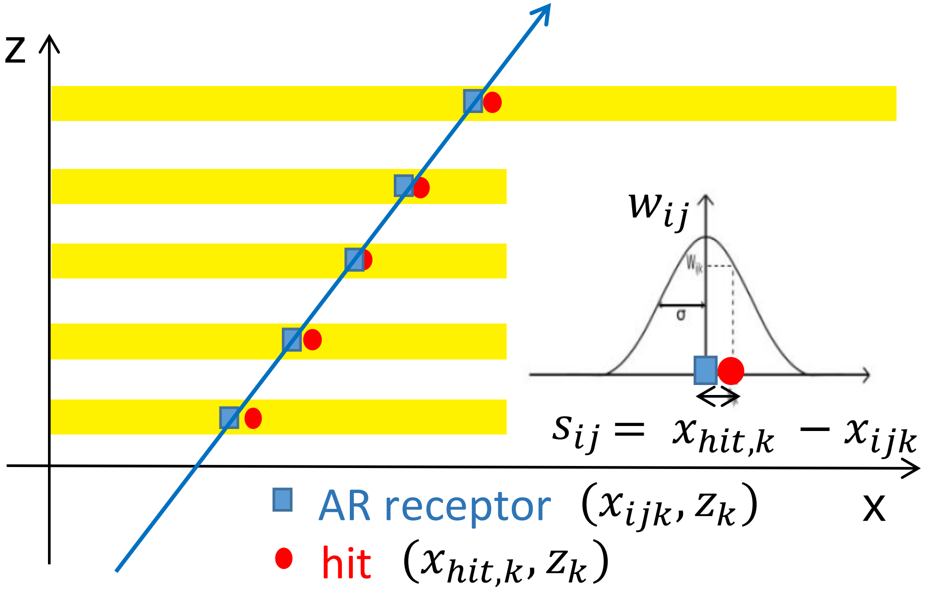
Track reconstruction



Artificial retina algoritm

Inspired by INFN RETINA project

- A AR cell represents a track in the anode
- Weight proportional to the distance beetween receptor and hit
- Real track parameters from weighted sum of nearby AR cells



Determine the atomic number (Z) of the reaction ejectiles and provide, in connection with the gas tracker, the isotopic species (A) and its atomic charge state (q)

Requirements for new PID system

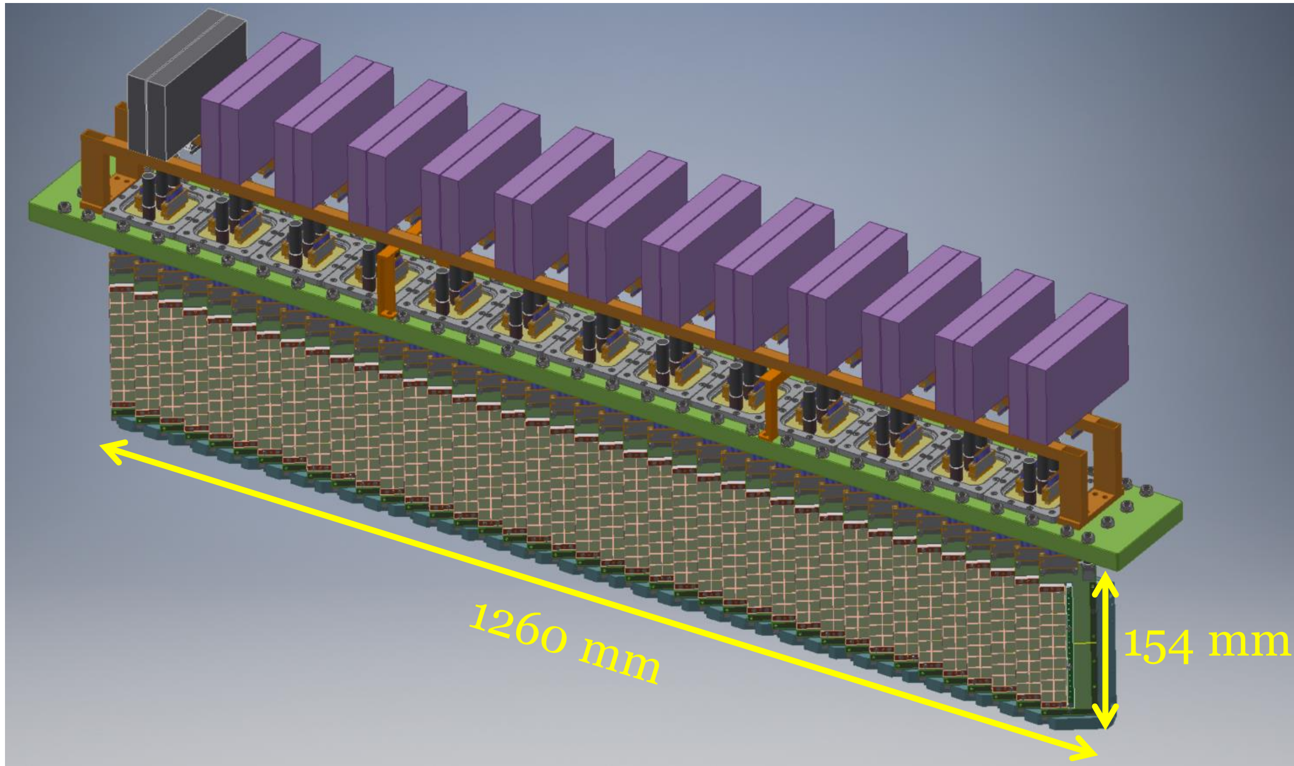
- **Radiation Hardness** of the order of 10^{11} ions/(cm^2/yr)
- Particle identification capability for identification of **Z ≈ 10 and A ≈ 20**
- **Time resolution** better than 2-3 ns
- **Double-hit** event probability **below 3%** in the whole FPD
- Woking in low pressure (tens mbar) gas environment

PID wall

720 SiC-CsI telescopes arranged in 36 towers

Obtained performances

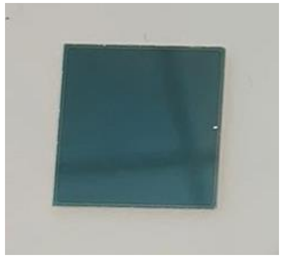
- ✓ Radiation hardness 10^{13} ions/cm^2 for SiC
- ✓ Radiation hardness larger than 7.5 x 10^{11} ions/cm^2 for CsI
- ✓ $\Delta Z/Z \approx 1/24$ and $\Delta A/A \approx 1/47$
- ✓ Time resolution hundreds of ps for SiC
- ✓ Double hit less than 2.5 % with the chosen granularity



The particle identification system

ΔE stage SiC

Thickness 100 μm
Dead layer 10 μm
Area 1.54 x 1.54 cm²
Bias -300/-1000 V



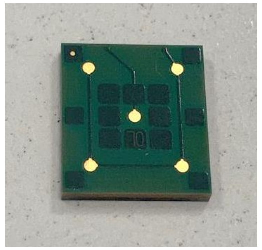
WG2 Charged particle detectors
G. Pasquali talk

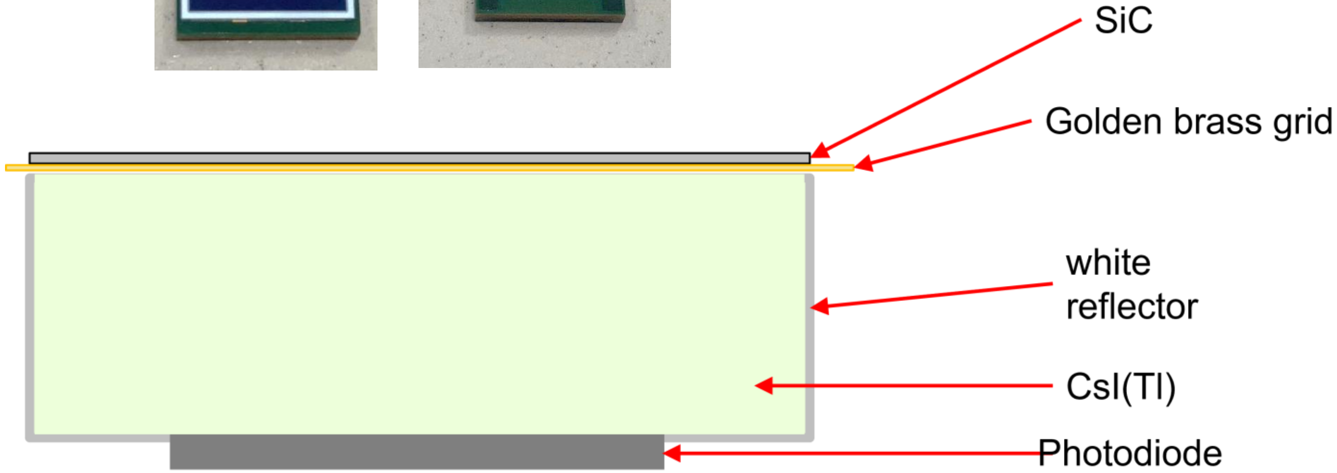
E stage CsI (Tl)

Thickness 5 mm
Area 1.5 x 1.5 cm²

Hamamatsu Photodiode S3590-0887

Area ~ 1 x 1 cm²
Bias -70 V

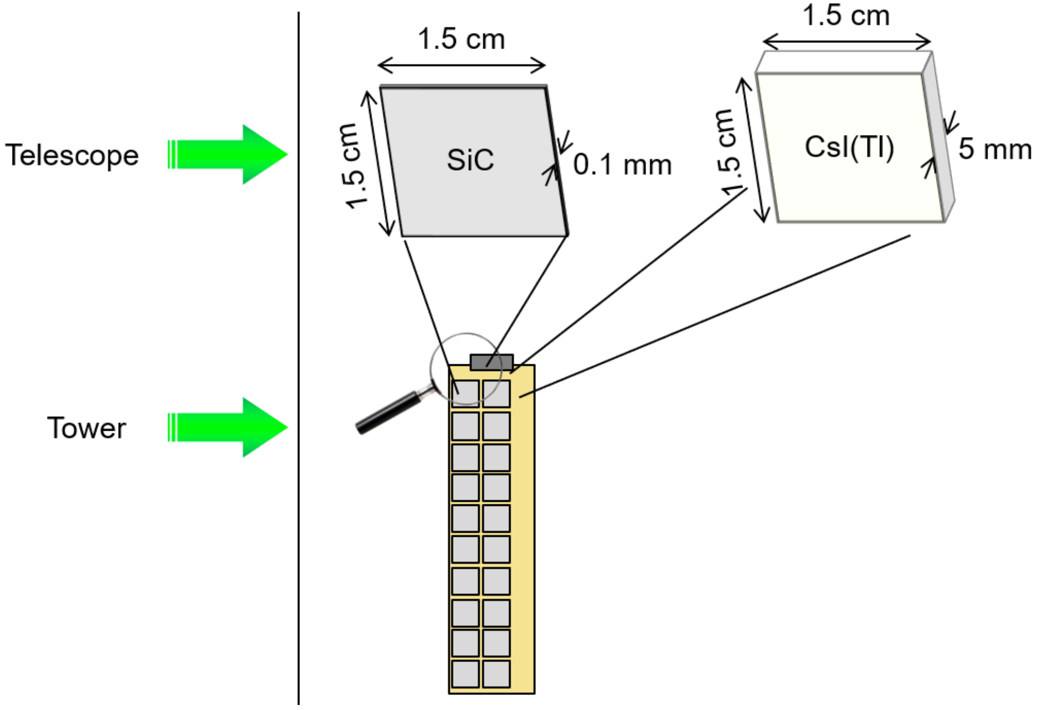


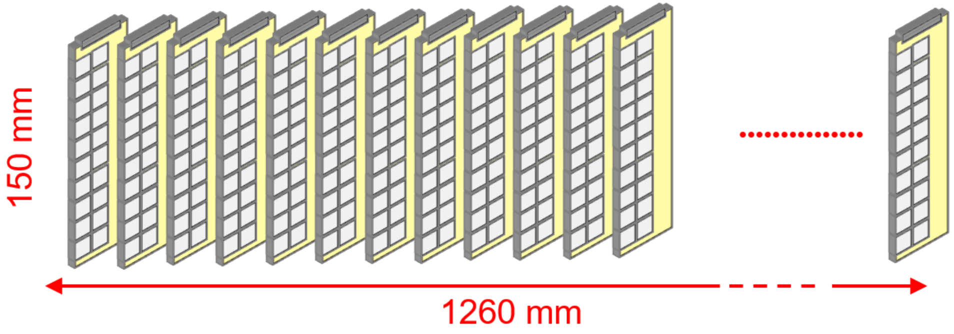


Front view

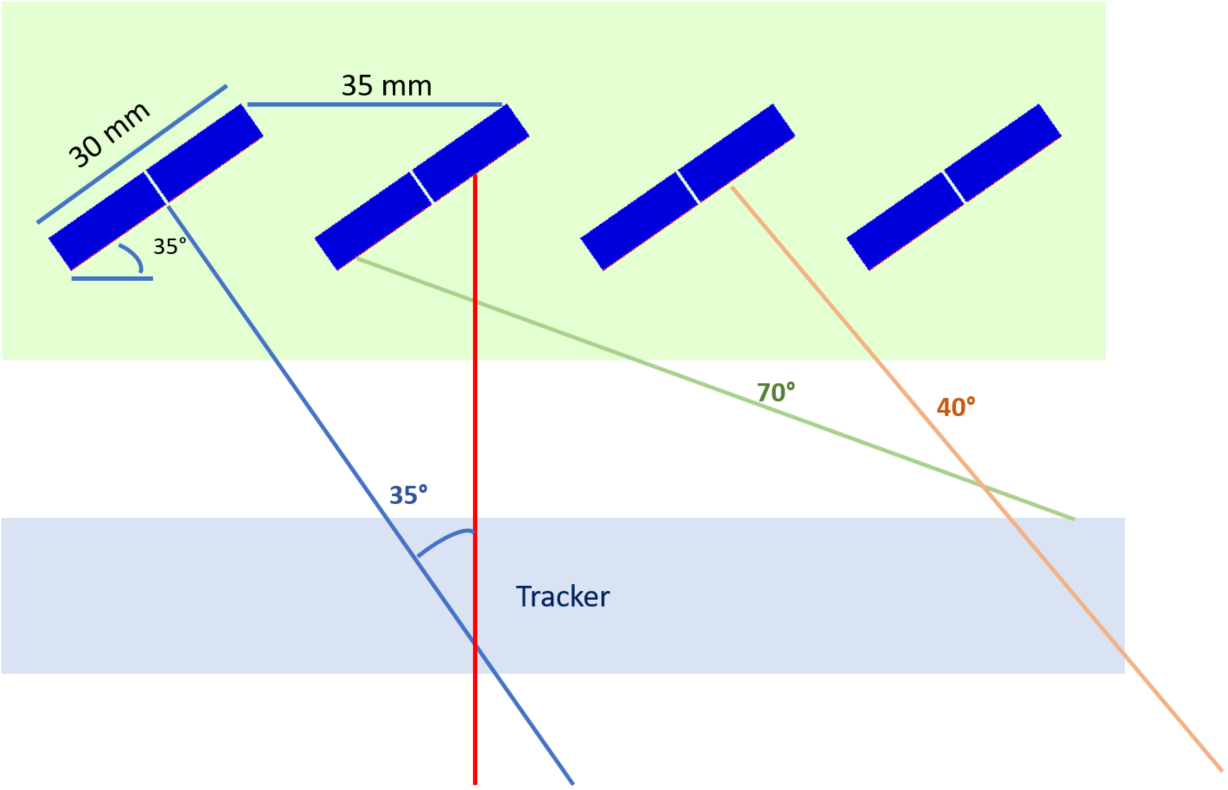
Back view

The PID tower

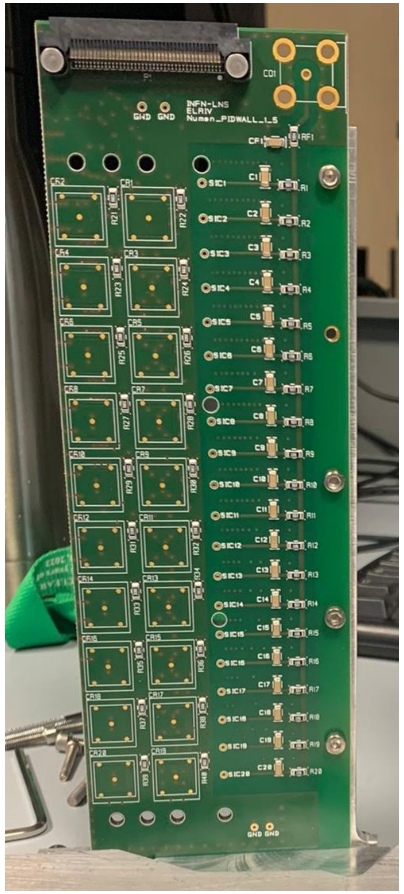




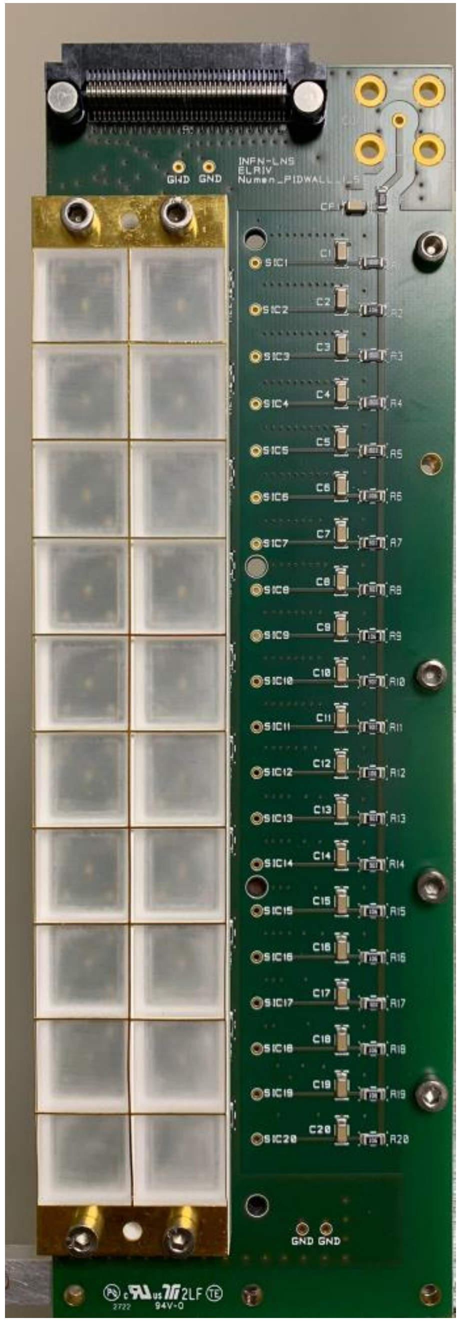
20 elements in each tower
35° angle of the towers

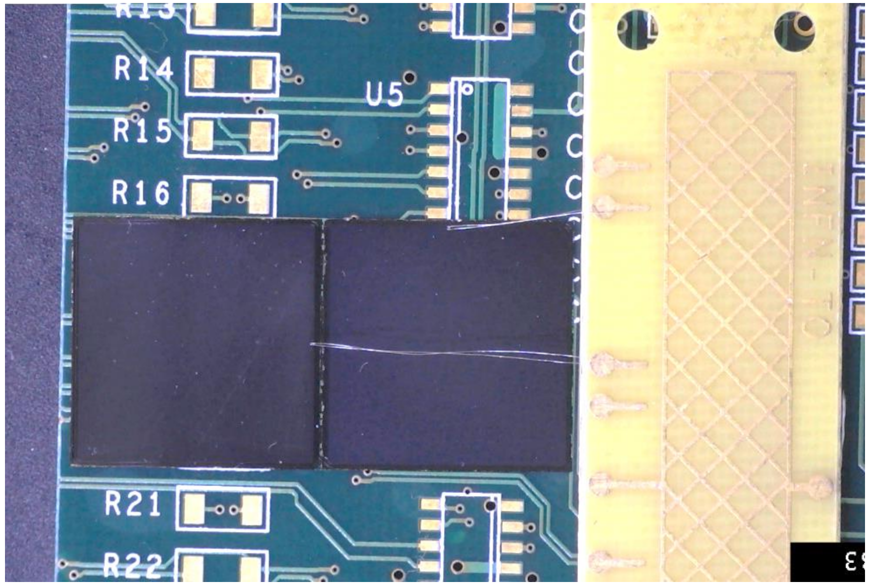


The PID tower



Main PCB for the readout of the detectors



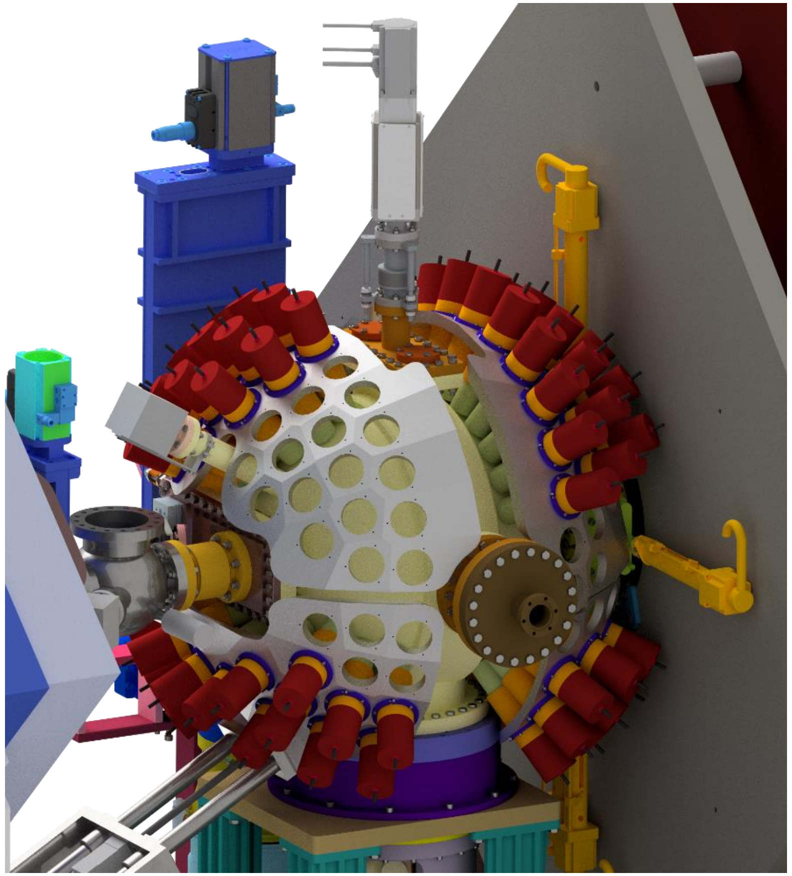


Long wire bonding (performed at INFN-To)

Measure the low-lying gamma-ray transition in coincidence with the DCE FPD events when the MAGNEX energy resolution is insufficient to isolate the g.s. to g.s. transition

Requirements for gamma array detector

- **Energy resolution** < 3-25 % (FWHM) depending on the nucleus
- **Time resolution** better than 5 ns (FWHM)
- Observational limit σ_{DCE}/σ_R less than 10^{-8}
- Radiation tolerance 10^{10} n/cm²



G-NUMEN

≈ 110 LaBr3(Ce) crystal scintillator detectors

Expected performances

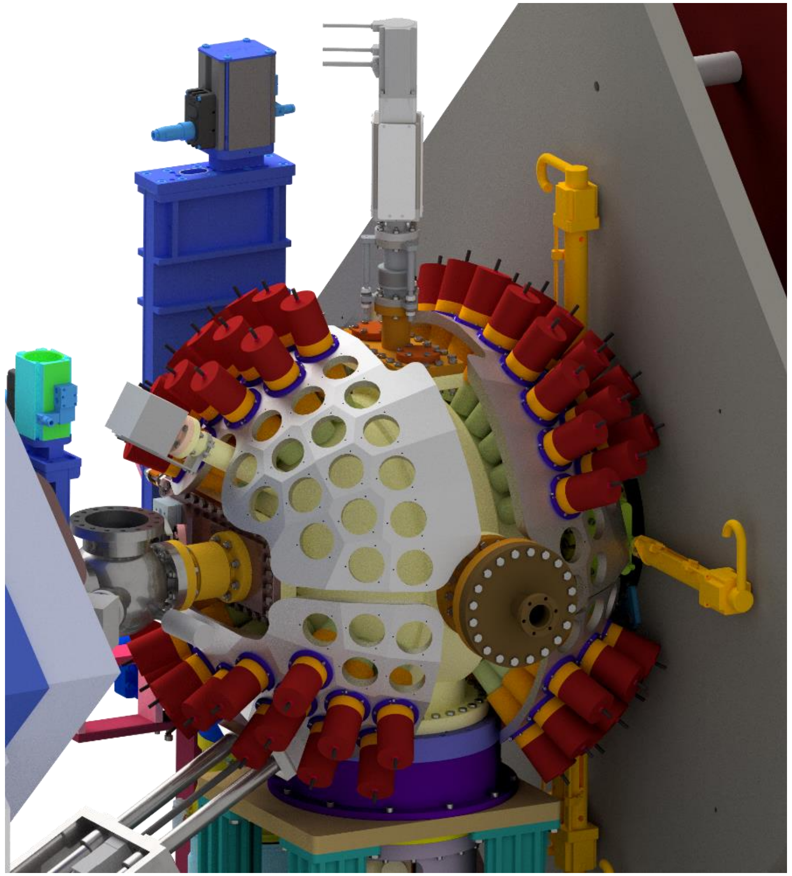
- ✓ Total photopeak efficiency of ≈ 4% at 1 MeV
- ✓ Energy resolution up to 2% (FWHM)
- ✓ Time resolution better than 1 ns (FWHM)
- ✓ Observational limit 0.3 x 10^{-8}
- ✓ Radiation tolerance better than 10^{10} n/cm²

Very high rate of signals over which distinguish very few good DCE events in the region of interest

J.R.B. Oliveira et al, EPJA 56, 153(2020)

G-NUMEN

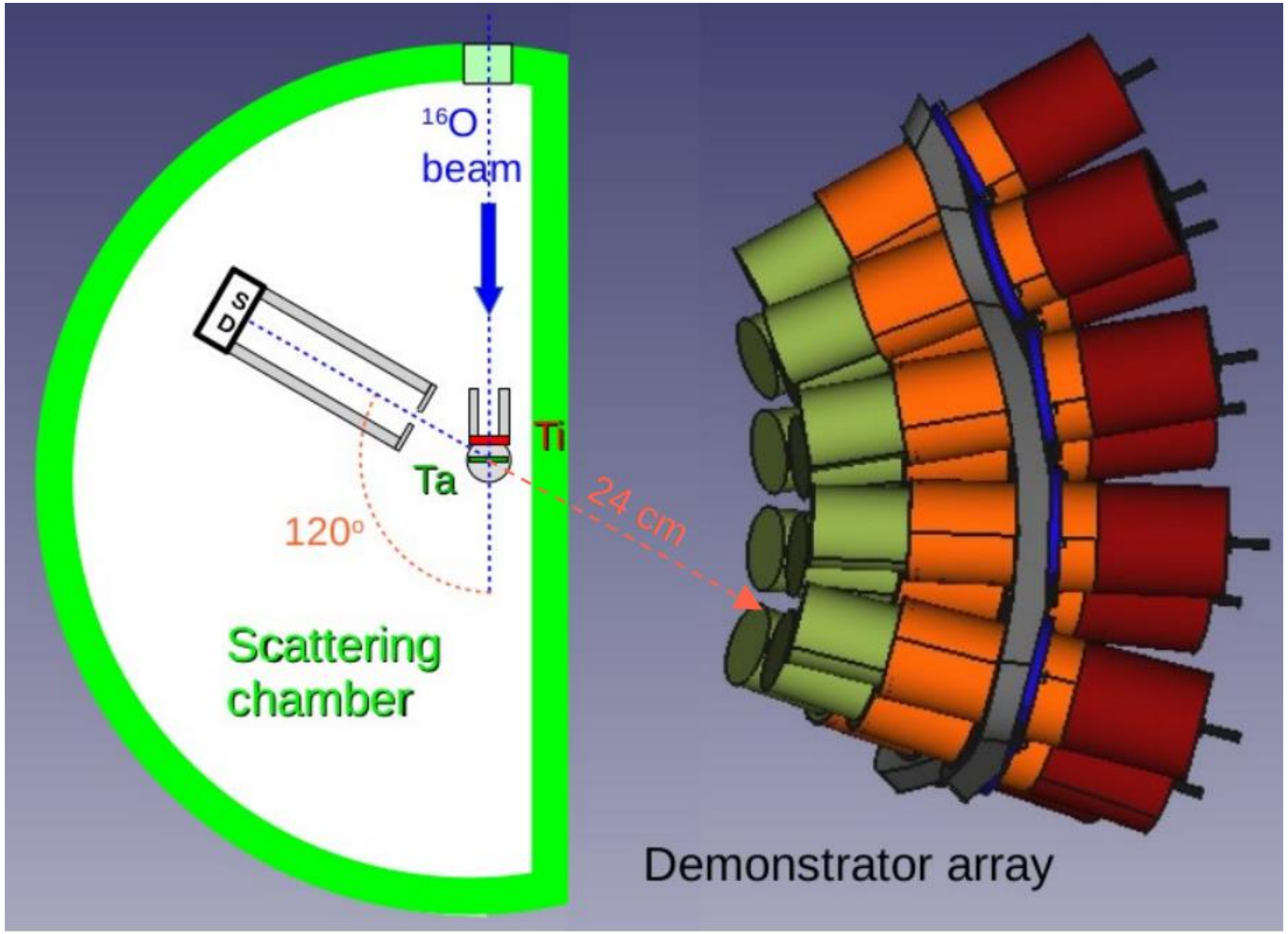
- ≈ 110 LaBr3(Ce) crystal scintillator detectors
- distributed in 7 rings around the beam axys
- 24 cm distance from the target
- Single crystal size 38 mm diameter and 50 mm length (compromise of increasing the photopeak efficiency while keeping the count rate per detector limited, to avoid excessive pile up)



New MAGNEX scattering chamber

- Aluminum sphere of ≈ 500 mm diameter, 6 mm thickness and 6 apertures
- Aluminum shell, 15 mm thick, surrounding the scattering chamber that opens up in five pieces

G-NUMEN demonstrator

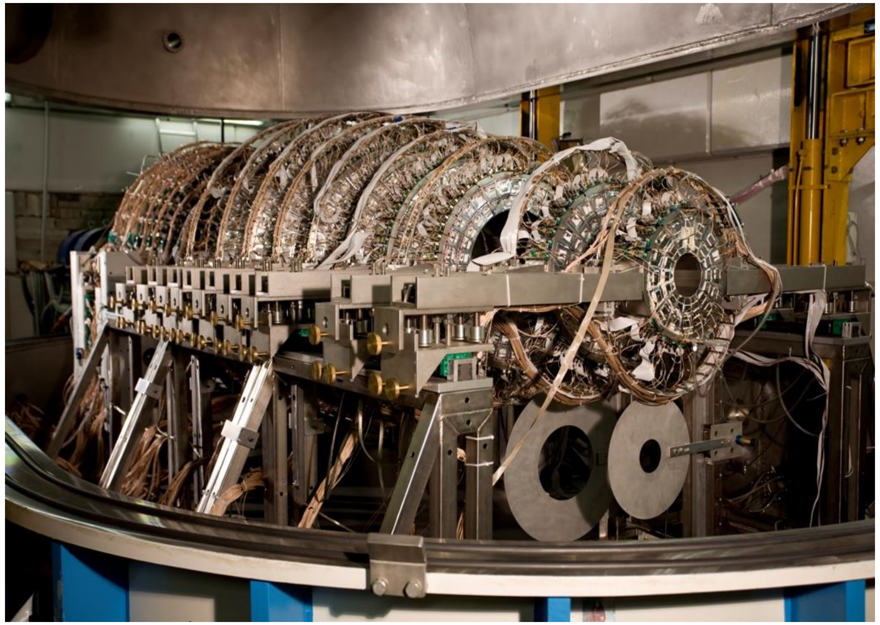


15 LaBr3(Ce) crystal scintillator detectors

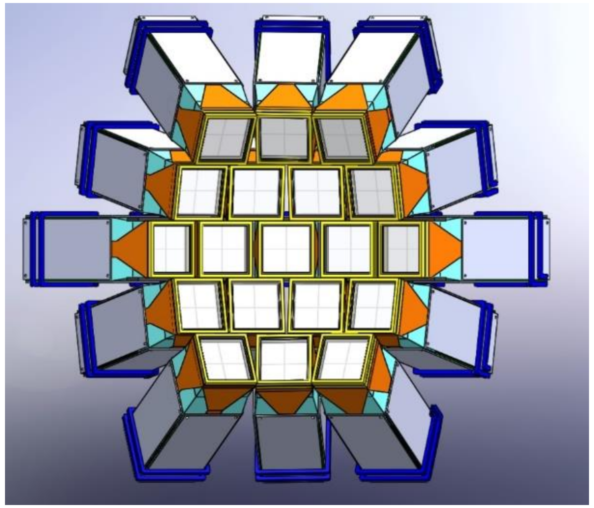
Ready to be assembled and tested

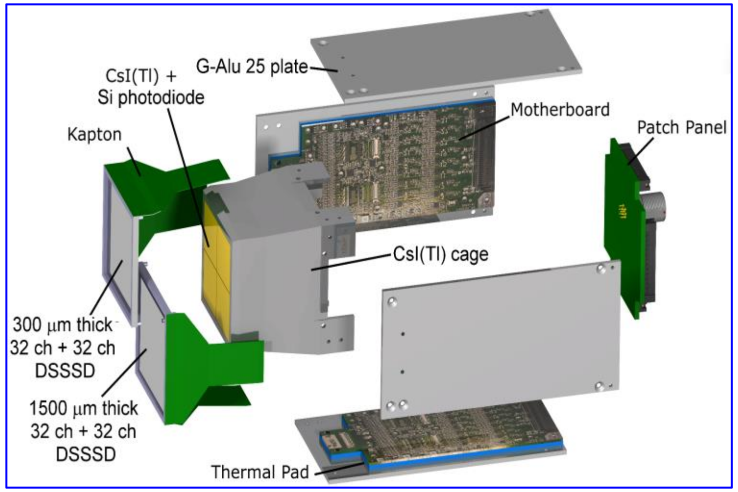
CHIRONE EXPERIMENT
RN Sara Pirrone(INFN-CT) & Paolo Russotto(INFN-LNS)
RL C.Guazzoni (INFN-MI) E.V.Pagano (INFN-LNS) G.Politi (INFN-CT)

CHIMERA



FARCOS

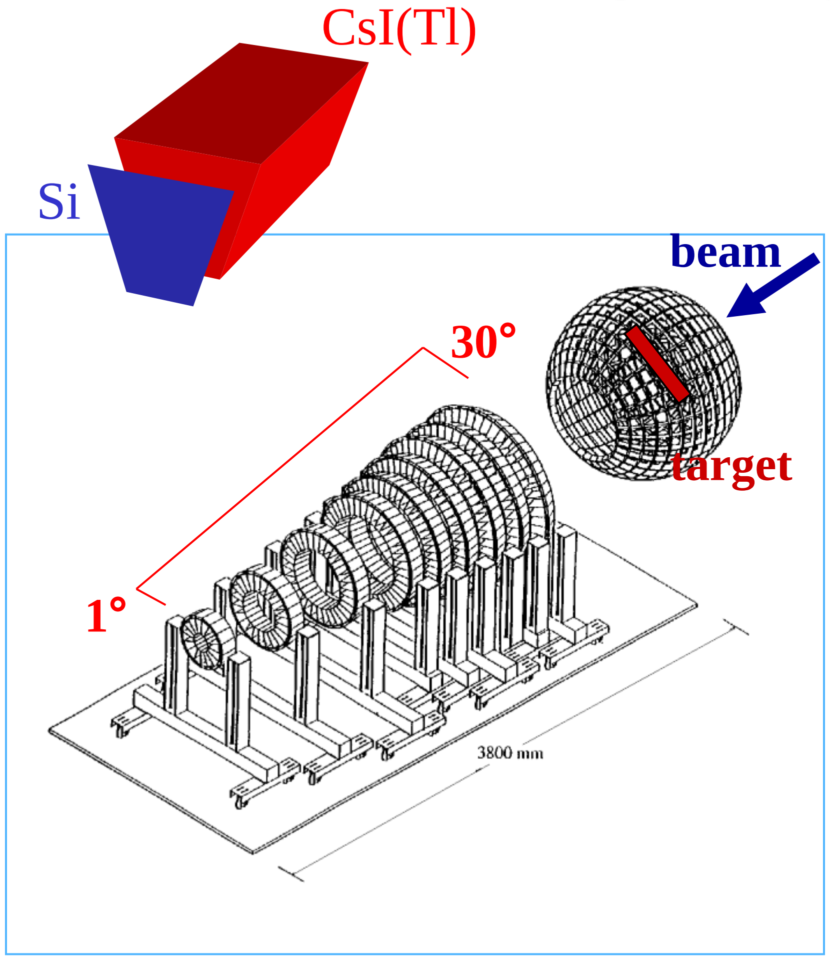




CHIMERA is going to be upgraded and renewed to be ready for the experimental activity that will be performed with the stable and radioactive beams, thanks to the relevant upgrade of the LNS Cyclotron and the installation of the FRAISE fragment separator

CHIMERA

Charge Heavy Ion Mass and Energy Resolving Array



Granularity	1192 telescopes Si (300μm) +CsI(Tl)
Geometry	RINGS: 688 telescopes 100-350 cm SPHERE: 504 telescopes 40 cm
Angular range	RINGS: $1° < \theta < 30°$ SPHERE: $30° < \theta < 176°$ 94% of 4π
Identification method	ΔE-E E-TOF PSD in CsI(Tl) PSD in Si
Experimental observables and performances	TOF $\delta t \leq 1$ ns $\delta E/E$ LCP (Light Charge Particles) $\approx$ 2% $\delta E/E$ HI (Heavy Ions) $\leq$ 1% Energy, Velocity, A, Z, angular distributions
Detection threshold	$\approx$ 1 MeV/A for H.I. $\approx$ 2 MeV/A for LCP

Dynamical range (HIC 10-100 AMeV) :

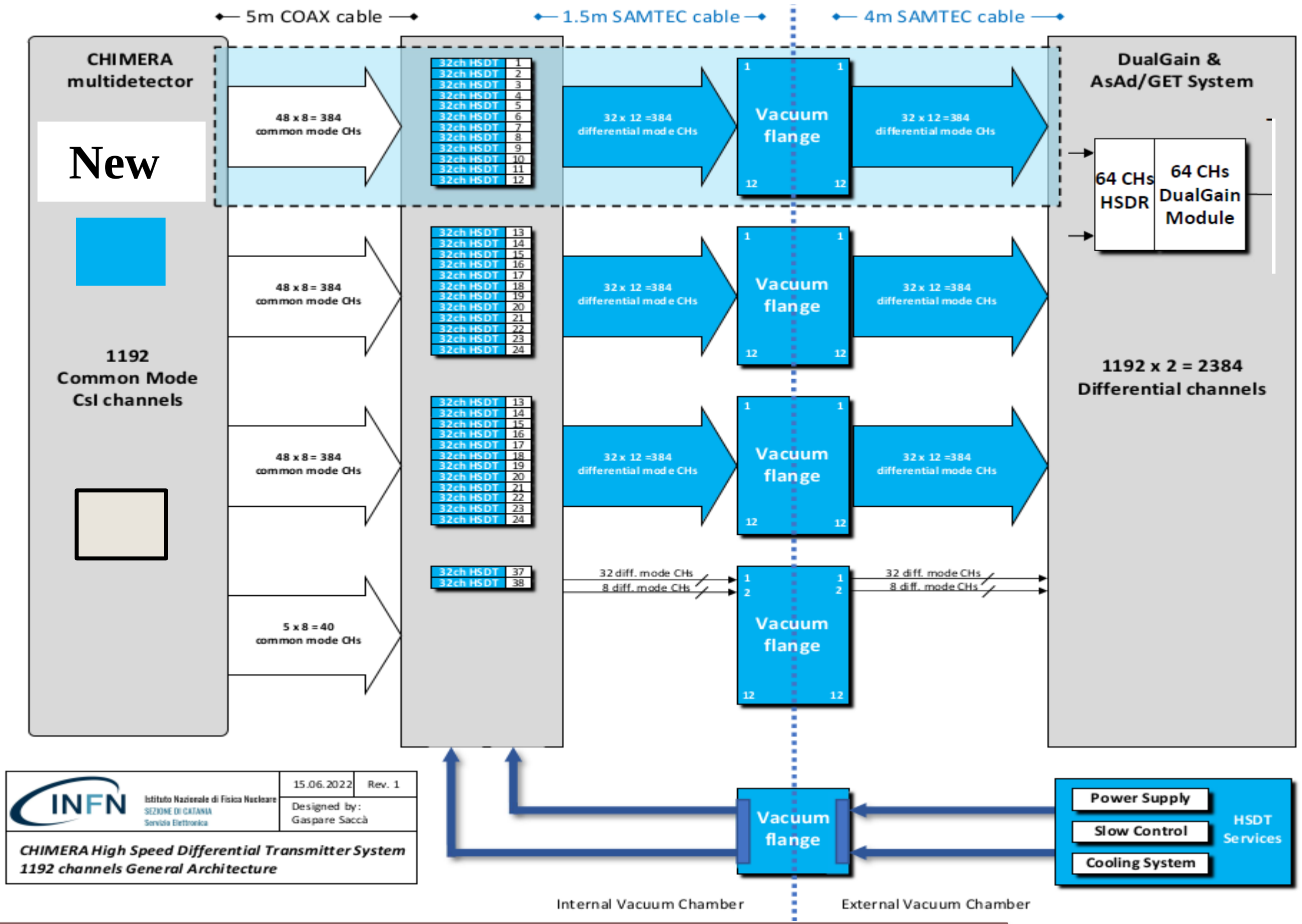
from fusion, fusion-fission to multifragmentation reactions

(TANDEM & CYCLOTRON Beams)

Improving on electronic system and digitalization of the signals

Conversion of the CHIMERA detectors signals from single-ended transmission into differential transmission system. This technique improves the signal integrity and the detector EMC performance (i.e. reducing the electromagnetic interferences).

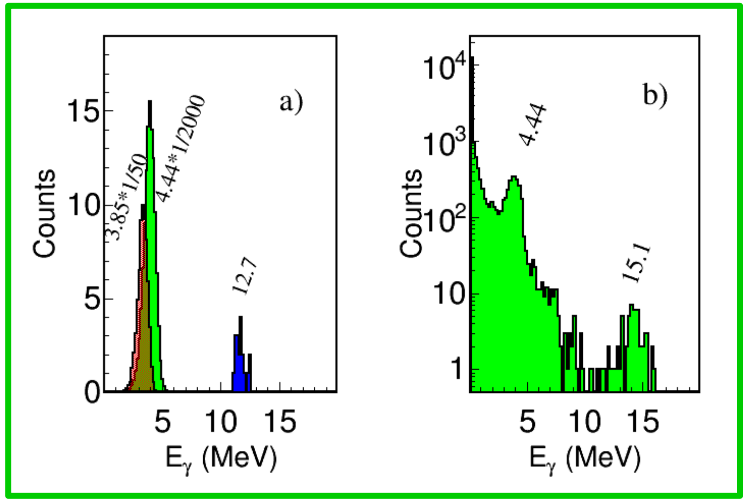
This upgrade needs new cables (COAX - SAMTEC) and flanges system; the realization of the single-ended to differential conversion system, the new
HSDT
High Speed Differential Transmitter
designed by the Electronic Service of
INFN - Catania.



Upgrade in two stages: the **first** working on the **CsI(Tl) detectors** system and the **second** one, on the **Silicon detector** system. We also plan an upgrading of the silicon chain with the full digitalization of the electronics, to improve the particle identification and energy resolution.

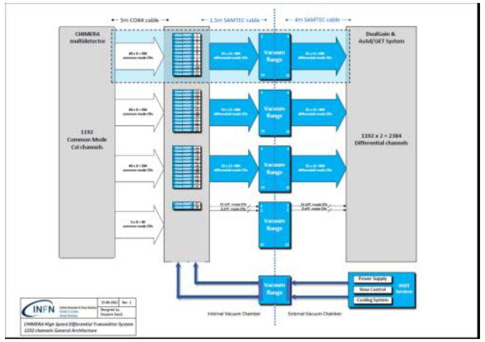
Improving of gamma detection on CsI(Tl)

Currently, the threshold of gamma detection of the CsI(Tl) crystals, coupled with photodiode is about 1.5 MeV. This will be reduced by using the differential transmission of the signals. An additional possibility to reduce the threshold is under study, adding a SiPM to the photodiode readout.



Gamma-particle coincidences are a powerful tool for the investigation of different topics as observed in experiments performed by using the CsI(Tl) crystals of the CHIMERA device. Currently the gamma detection threshold is around 1.5 MeV.

Thanks to the experience made with SiPMs used for the light reading of the prototype of the neutron detector, we are confident that it is possible to apply this technique to the reading of the CsI(Tl) scintillators.



With the differential transmission system, hopefully the noise will be reduced to 1 MeV.

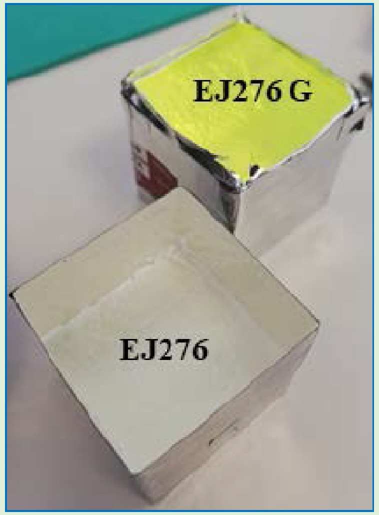
Development of an ancillary hodoscope for neutrons, gamma and charged particles detection

PRIN ANCHISE-2020

Period: 3 years starting June 2022
Fund: ~ 627KE MUR
Collaboration: INFN – UniCt – UniMe - PoliMI.
Coordinator and spokes: A.Pagano (INFN) – G.Politi (UniCt) - M.Trimarchi (UniME) - A.Castoldi (PoliMI).

Neutron detection - fully integrated with Charged particles detection - Reaction studies and spectroscopy with Stable and n-rich nuclei at Fermi energies.

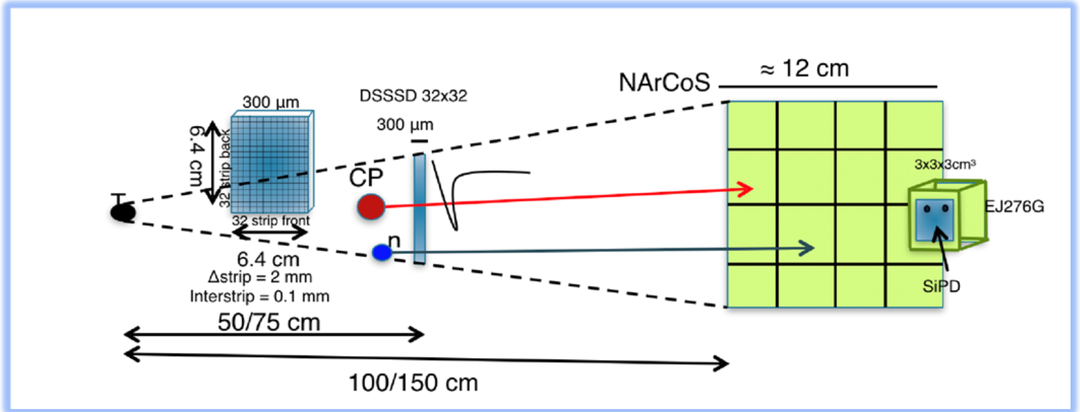
Highly segmented Hodoscope (new material such as EJ276 coupled with Si-PMT) important tool to master the crucial problems of Cross talk for neutron detections.



TOF, Pulse shaping (n,gamma, CP) and Digital Acquisition

- Candidate: The plastic scintillator EJ276-Green Type (ex EJ299-33) (3x3x3cm^3)
- 1 cluster: 4 consecutively cubes (stack configuration)-> 3x3x12 cm^3 (64 detection cells)
- Reading the light signal: Si-PM and digitalization
- Modular, reconfigurable (in mechanic and electronic)
- Discrimination of n/γ from PSD (but also light charged particles)
- Energy measurement from ToF (Δt≤1 ns with L_{ToF}≈1÷1.5m)

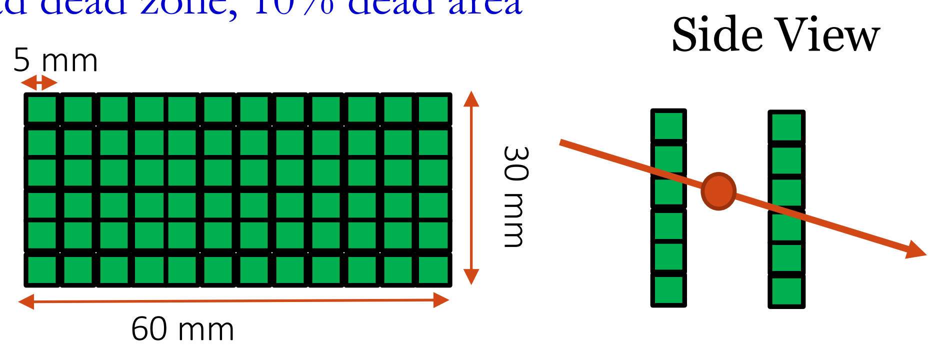
TOF measured using the RF of the CS or with an ancillary MCP (low intensity exotic beams)



Details in NEUTRON DETECTOR Section

Development of CHIMERA specialized tagging system

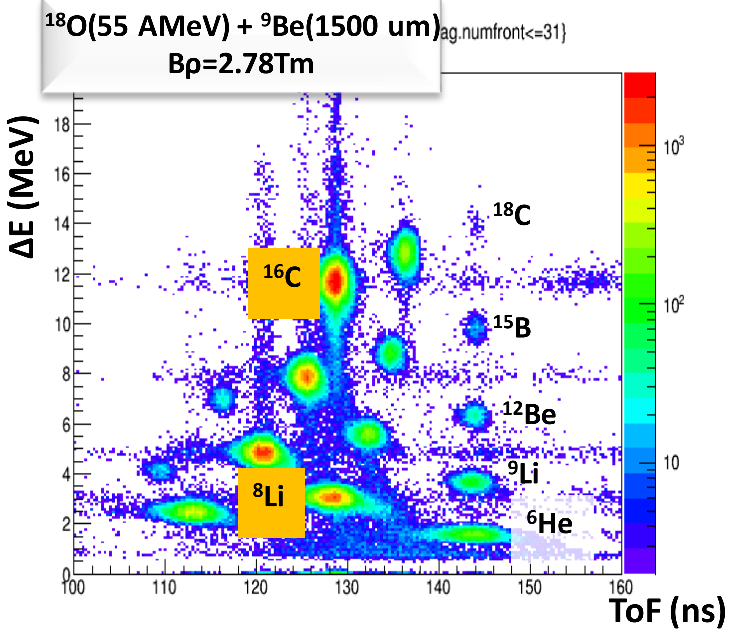
Future CHIMERA line tagging for FraISe beams: array of detectors based on **SiC technology**, single detection unity pad 5 × 5 mm2 and 100 μm thick, 72 channels with $\Delta t \approx 200$ ps (≈0.1% precision on energy for 20 m base-of-flight) with 200 μm inter-pad dead zone, 10% dead area



- Front-end: Custom multi/channel ASIC with charge preamplifier configuration and analog preprocessing optimized for amplitude and time measurements
- Full waveform digitizers and synchronization with CHIMERA/FARCOS DAQ

PRIN 2022: TORATHIB, development of a Test prOtotype of a RAdiation-hard Tagging detection system for High-Intensity radioactive Beams with ultimate time resolution (submitted)

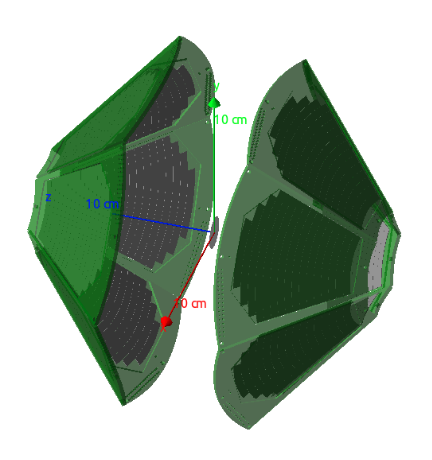
Current CHIMERA line tagging for FRIBs: event-by-event tagging of cocktail beam, ΔE-ToF with a MCP-DSSSD system



MCP: up to 10^5 pps, $\Delta t \approx$ 200-300 ps
DSSSD: max rate 200 kHz, but worsening of performances in ≈1 week with medium mass beam at 30 kHz; Overall $\Delta t <\approx 1$ ns
I. Lombardo et al., NIMB 215, 2011

Details in CHARGED PARTICLES DETECTORS Section

Large High-resolution Array of Silicon for Astrophysics

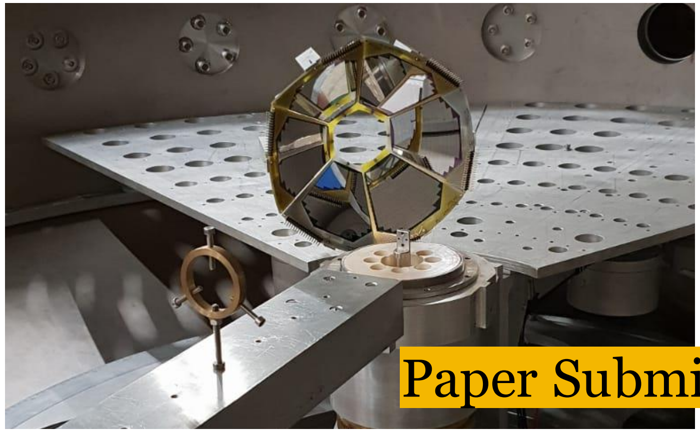


Characteristics:

- Wide angular range coverage (almost 80% of 4π in final configuration)
- Low energy threshold
- Compactness useful to couple it with ancillary detectors (neutron arrays)
- High energy resolution
- Angular resolution allows for kinetic identification of the reaction channels

Direct measurement of the ^{19}F(p,α)^{16}O reaction at E_{cm}=0.6-0.8 MeV using the LHASA detector array

G.L. Guardo[1], T. Petruse[2,3], D. Lattuada[1,4], M. La Cognata[1], D.L. Balabanski[2], E. Açıksöz[2], L. Acosta[5], L. Capponi[2], D. Carbone[1], S. Cherubini[1,6], D. Choudhury[2], G. D'Agata[1,6], A. Di Pietro[1], P. Figuera[1], M. Gulino[1,4], A. I. Kilik[7], M. La Commara[8], L. Lamia[1,6,9], C. Matei[2], S. Palmerini[10,11], R.G. Pizzone[1], S. Romano[1,6,9], P.-A. Söderström[2], R. Spartà[1], A. Tumino[1,4] and S. Viñals[12]



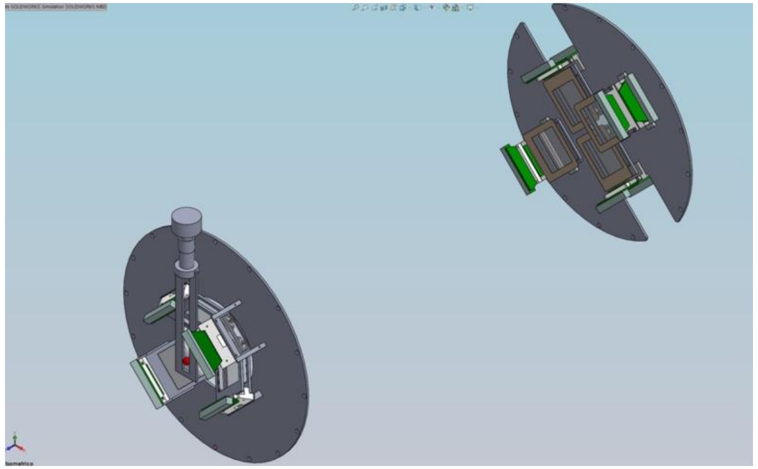
Paper Submitted

Upgrades & new developments:

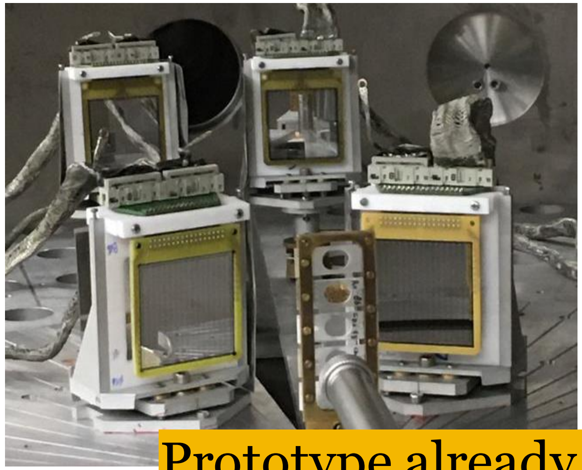
- Purchase of second lamp and/or different thickness detectors
- Exploring a possible double sided silicon configuration for increasing the position resolution
- Study of a pulse shape analysis at low energy range
- Developing digital ACQ

Perfectly suited for direct measurement in nuclear astrophysics!!

Near Far Silicon Telescope Array



Characteristics:
- 8 telescopes with DSSSD
- Measurement in a very forward direction
- Versatility & portability
- Optimized for reaction with 3-body in the exit channel
- High energy and position resolution



Prototype already tested

Upgrades & new developments:
- Purchase of different thickness detectors to increase the versatility
- Exploring the possibility to build a monolithic telescope to decrease the threshold
- Study of the maximum rate acceptable
- Developing of devoted simulations

Perfectly suited for Trojan Horse Method experiments!!

Exploring the astrophysical energy range of the $^{27}Al(p,\alpha)^{24}Mg$ reaction: A new recommended reaction rate

M. La Cognata [a,*], S. Palmerini [b,c], P. Adsley [d,e], F. Hammache [f], A. Di Pietro [a], P. Figuera [a], R. Alba [a], S. Cherubini [a,g], F. Dell'Agli [h], G.L. Guardo [a,g], M. Gulino [a,i], L. Lamia [a,g,j], D. Lattuada [a,i], C. Maiolino [a], A. Oliva [a,g], R.G. Pizzone [a], P.M. Prajapati [a], S. Romano [a,g,j], D. Santonocito [a], R. Spartá [a,g], M.L. Sergi [a,g], A. Tumino [a,i]

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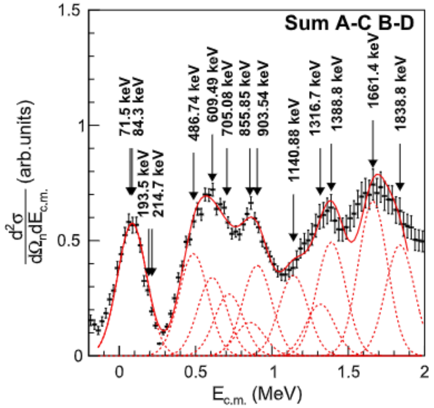
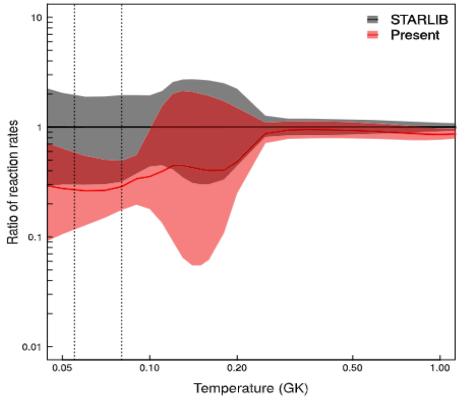




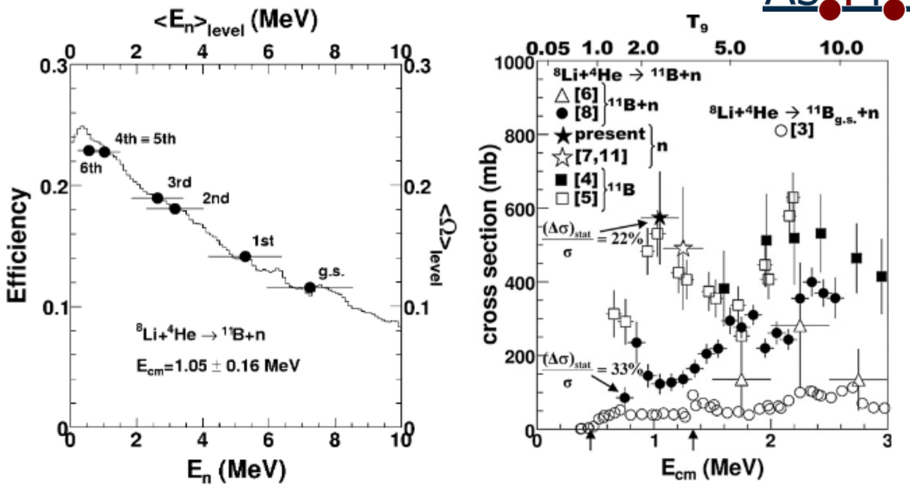
Polycube detector array For Experimental Multimessenger astrOnomy

Characteristics:

- 12 4bar ^{3}He counter
- Polyethylene moderators 40x40x40 cm^3
- Low energy range (<10MeV neutrons)
- Devoted Monte-Carlo simulation
- Almost 4π angular coverage

Upgrades & new developments:

- Developing of implantation chamber (design already performed)
- Purchase of 2 Silicon detector for RIBs tagging and electron detection
- Implementation of the devoted simulations with the chamber



On the magnitude of the ^{8}Li + ^{4}He → ^{11}B + n reaction cross section at the Big-Bang temperature

M. La Cognata [a], A. Del Zoppo [a,*], P. Figuera [a], A. Musumarra [a,b], R. Alba [a], S. Cherubini [a,b], N. Colonna [c], L. Cosentino [a], V. Crucillà [a,b], A. Di Pietro [a], M. Gulino [a,b], L. Lamia [a], M.G. Pellegriti [a,d], R.G. Pizzone [a], S.M.R. Puglia [a,b], G.G. Rapisarda [a,b], C. Rolfs [c,1], S. Romano [a,b], M.L. Sergi [a,b], C. Spitaleri [a,b], S. Tudisco [a], A. Tumino [a,b]

^{3}He counter perfectly working

Perfectly suited for Beta-delayed neutron emission processes using RIBs!!

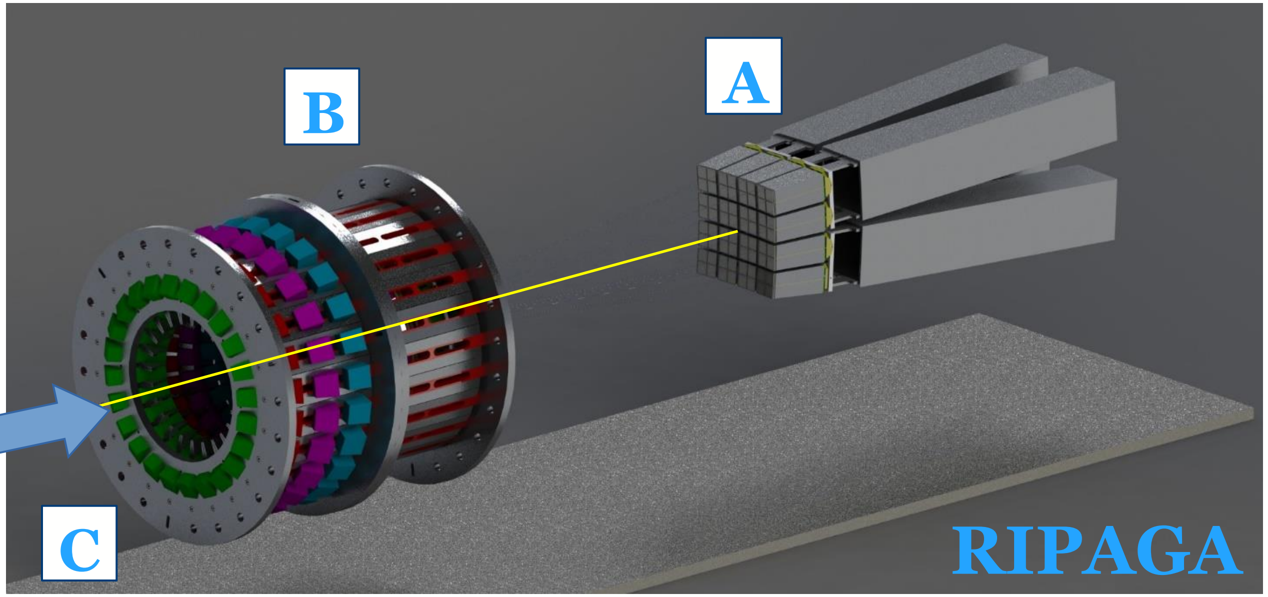
Nucl-ex FAZIA group:
S.Barlini, G.Casini, C.Ciampi, S.Piantelli INFN e Università di Firenze
D.Santonocito LNS Catania

Use of intense stable beams and medium-light unstable fragmentation beams from the FRAISE facility at LNS

Proposed physics cases

1. Cluster configurations and collectivity in nuclear systems at high excitation energies
2. Absolute reaction cross sections measurements for exotic reactions at Fermi energies measuring the branching ratio of the different reaction channels (fusion, break-up, binary collisions)
3. Excitation and decay modes of the reaction products far from the valley of stability

RIPAGA (RIvelatore per PArticelle e GAmma): A new array for charged products and hard gamma rays



C Gamma array detector

- Based on **MEDEA BaF_2 crystals**
- Good energy resolution and efficiency up to 30 MeV
- **SiPM** readout instead of PM

Monitor detector for the cross section normalization

- Plastic scintillators

A Charged particle detector at very forward angles

- Based on **FAZIA** three stage **telescopes** (Si + Si + CsI)
- Reasonable granularity
- Good charge and mass resolution
- Possibility to **measure at 0°** with low intensity exotic beams
- Possibility to use **SiC** detectors

GARFIELD

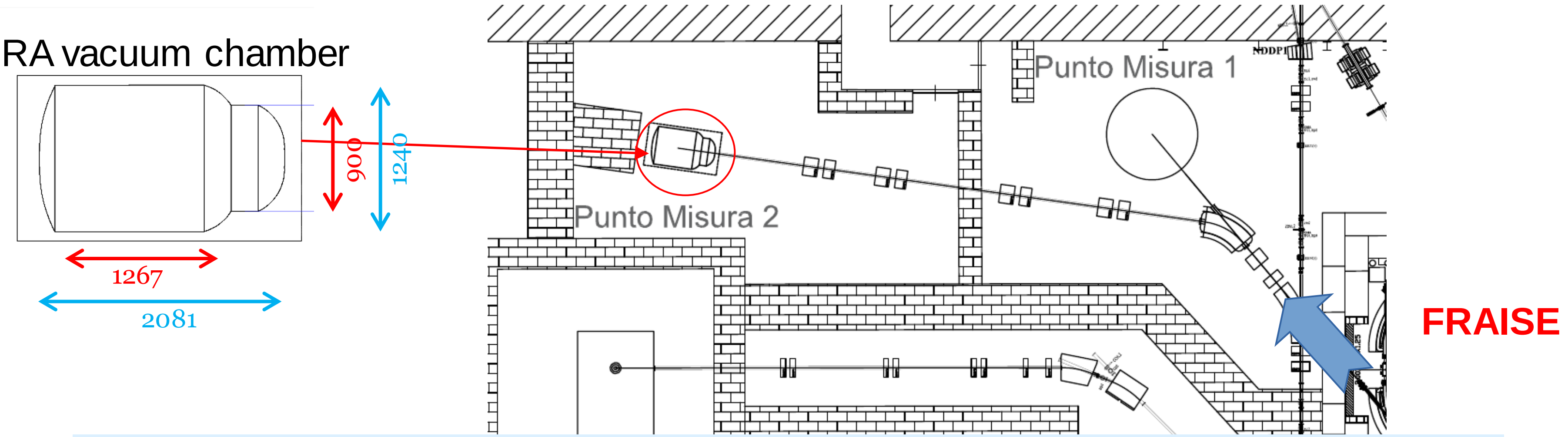
B Light charged particles (Z <= 4) detectors at larger angles

- Based on **Garfield CsI crystals**
- CsI crystals (low cost, versatility)

Experimental requirements

- Large and well-equipped scattering chamber (2500 mm lenght, 1000 mm wide)
- Good stable and radioactive beam quality at the measure point
- Beam diagnostic

GIRA vacuum chamber



Multipurpose experimental hall **(Punto Misura 2)** in which FRAISE beams will be delivered. Needs for a large scattering chamber for hosting the detectors

- **GIRA** scattering chamber

PROPOSAL (also for CSN3) : The GIRA chamber may be too small for the RIPAGA detector and the future developments. **Is it possible to equip a larger scattering chamber ?** (including vacuum system, remotely controlled target holder, beam diagnostic, etc.)

WG7 – New facilities at LNS

D. Carbone, C. Agodi, G.A. Brischetto, D. Calvo, F. Cappuzzello, M. Cavallaro, I. Ciraldo, F. Delaunay, P. Finocchiaro, M. Fisichella, J.R.B. Oliveira, D. Sartirana, O. Sgouros, A. Spatafora, V. Soukeras, D. Torresi, S. Pirrone, B. Gnoffo, E. De Filippo, G. Saccà, M. Trimarchi
G.L. Guardo, G. D'Agata, A.A. Oliva, M.L. Sergi,
S. Barlini, G. Casini, C. Ciampi, S. Piantelli, D. Santonocito

Thank you