MAYORANA

Multi-Aspect Young-ORiented Advanced Neutrino Academy

Modica, Italy

June 16-18th 2025

Experimental Challenges and Construction Status of the NUMEN Project

Dimitra Pierroutsakou

INFN, Sezione di Napoli, Italy

for the **NUMEN Collaboration**

NUMEN

Outline

- Scientific motivation for the NUMEN Project
- Upgrade of the INFN-LNS Superconducting Cyclotron and beam lines
- Upgrade of the MAGNEX spectrometer
  - Gas Tracker
  - PID Wall
  - G-NUMEN
  - Target system
- Conclusions and perspectives

The NUMEN project

Neutrinoless double beta decay (0ν2β): a **never observed** isobaric transition of a parent nucleus (A,Z) to a daughter nucleus (A,Z+2) with emission of two electrons, but with no electron antineutrinos

$$X(Z,A) \rightarrow Y(Z+2,A) + 2e^-$$

- a direct probe of lepton number violation with implications for our understanding of the evolution of the Universe
- neutrino nature (**Majorana or Dirac**): an open problem in modern physics
- information on the absolute mass scale of **neutrino**

In the light-neutrino exchange model the half-life of the decay is related to the neutrino effective mass:

$$(t_{1/2}^{0\nu\beta\beta})^{-1} = G_{0\nu\beta\beta}(Q_{\beta\beta}, Z)\,|M_{0\nu\beta\beta}|^2 \left(\frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}\right)$$

$t_{1/2}^{0\nu\beta\beta}$: the half-life of the decay

$G_{0\nu\beta\beta}(Q_{\beta\beta}, Z)$: **well established phase space factor**

$M_{0\nu\beta\beta}$: **Nuclear Matrix Element (NME)**

$\langle m_{\beta\beta}\rangle = \left|\sum_i U_{ei}^2 m_i\right|$: neutrino effective mass

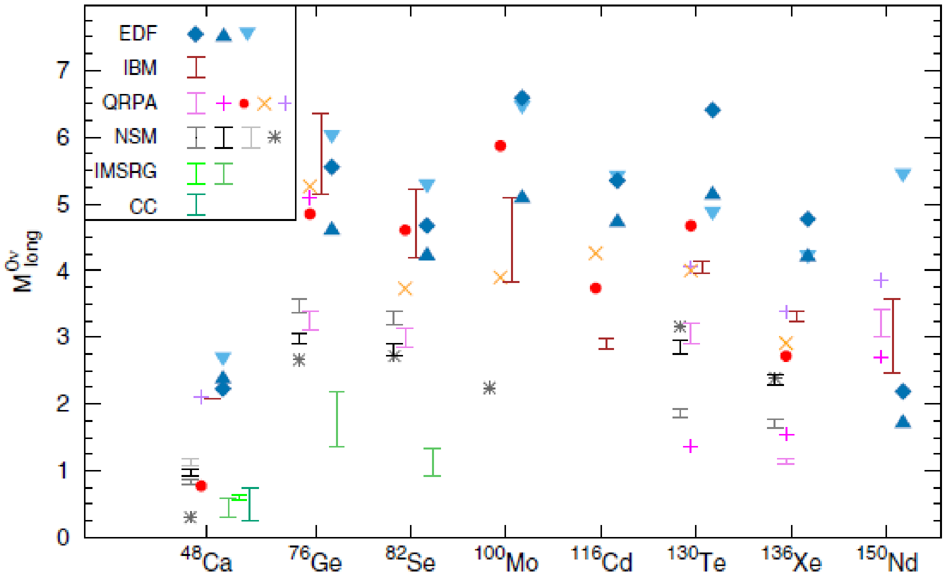
m_i : **neutrino mass**

U_{ei} : **elements of the neutrino mixing matrix**

m_e : **electron mass**

The NUMEN project

- NMEs are not physical observables
- NMEs evaluated from calculations based on different models of nuclear structure (Quasi-particle Random Phase Approximation, Large scale shell model, Interacting Boson Model, Energy Density Functional theory, ab-initio …..): **large uncertainties**



M. Agostini et al., Rev. Mod. Phys. 95 025002 (2023)

If a discovery is made, in order to infer the **neutrino mass**, or to **design next-generation experiments**, it is **essential** to obtain **accurate NMEs** for all isotopes of experimental interest.

Some experimental approaches to shed light on $0\nu\beta\beta$ NMEs:

- Nuclear structure observables
- Ordinary muon capture
- Pair transfer amplitudes
- $2\nu\beta\beta$ decay
- $\gamma\gamma$ decays
- **Heavy-ion double charge exchange reactions**

The NUMEN project: a Double Charge Exchange Experiment

The NUMEN project proposes to provide insights into the 0νββ NMEs by measuring **cross-sections** of Heavy-Ion Double Charge Exchange (**DCE**) reactions for various systems candidates for 0νββ.

F. Cappuzzello et al, Progress in Particle and Nuclear Physics 128 (2023) 103999

DCE reactions as surrogate process of the 0νββ decay

$$a(Z_1, A_1) + X(Z, A) \rightarrow b(Z_1 \mp 2, A_1) + Y(Z \pm 2, A)$$

DCE reactions can proceed through:

1)One-step DCE with exchange of two correlated charged mesons between target and projectile (related with nn short range interactions): **Majorana DCE** resembling **0νββ decay**

H. Lenske et al., Progress in Particle and Nuclear Physics 109 (2019) 103716 and H. Lenske et al., Universe (2024), 10, 93

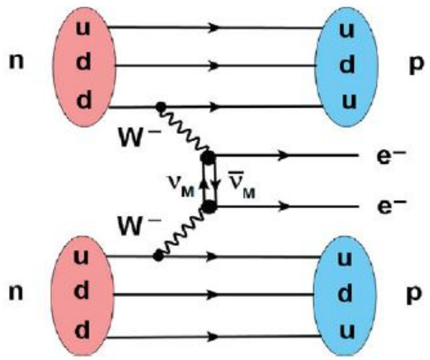
2) **Two-step DCE**: 2 consecutive **Single Charge Exchange** steps, with exchange of two uncorrelated charged mesons between target and projectile resembling **2νββ**

J. I. Bellone et al., Phys. Let. B 807 135528 (2020), H.Lenske et al., Universe (2024), 10, 93

3)**Sequential multi-nucleon transfer** mechanism: found to be **negligible**

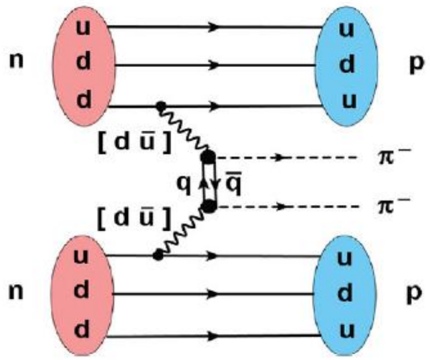
J.L. Ferreira et al., PRC 105, 014630 (2022) and J. L. Ferreira et al., PRC 111, 054609 (2025)

0νββ decay



$X(Z, A) \rightarrow Y(Z + 2, A) + 2e^-$

Majorana DCE



$a(Z_1, A_1) + X(Z, A) \rightarrow b(Z_1 - 2, A_1) + Y(Z + 2, A)$

See talk of M. Colonna

Weak *vs* strong interaction
Decay *vs* nuclear reaction

Similarities

- initial and final nuclear states;
- The transition operators are a superposition of short-range Fermi, Gamow-Teller and rank-two tensor components with a high available momentum in the virtual intermediate state;
- both processes take place in the nuclear medium;
- non local with two vertices localized in a pair of valence nucleons;
- Off-shell medium propagation through virtual intermediate channels.

The NUMEN project: a Double Charge Exchange Experiment

Beams of interest: (^{20}**Ne**,^{20}O) for $\beta^-\beta^-$ and (^{18}**O**,^{18}Ne) for $\beta^+\beta^+$ at energies from 15 AMeV to 70 AMeV. Examples of candidate isotopes of interest are ^{48}Ti, ^{76}Se, ^{116}Sn with (^{18}**O**, ^{18}Ne) reaction, and ^{116}Cd, ^{130}Te, ^{76}Ge using (^{20}**Ne**, ^{20}O) reaction

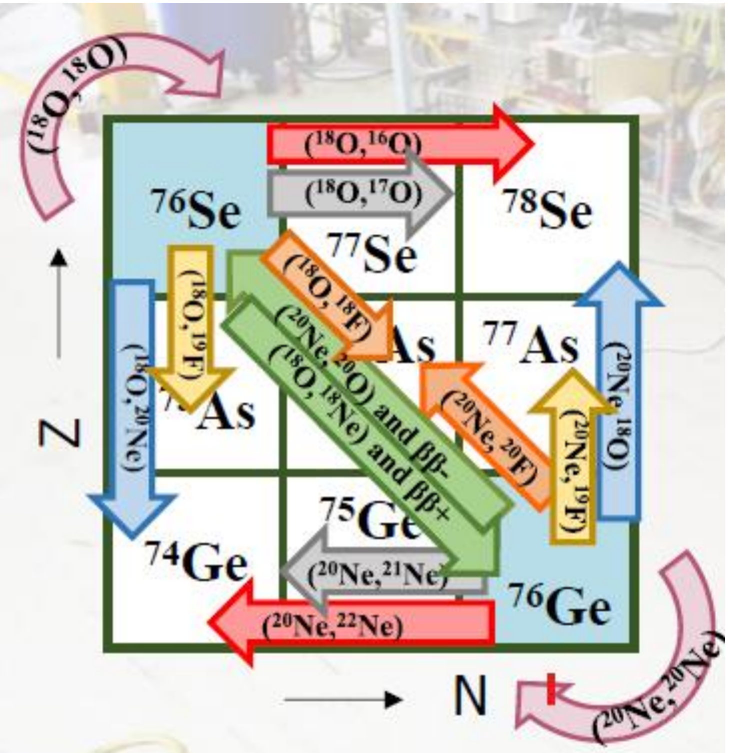
Use of the **K800 Superconducting Cyclotron at LNS-INFN** and the **MAGNEX** large acceptance magnetic spectrometer.

See talk of O. Sgouros

E_{lab}= 15 AMeV
^{20}Ne + ^{76}Ge
^{18}O + ^{76}Se

To isolate the MDCE process from other reaction mechanisms, both nuclear structure and reaction dynamics aspects must be properly addressed.

All the open channels (elastic, inelastic, nucleon transfer, Single Charge Exchange, DCE) will be simultaneously investigated to fully explore the reaction mechanism in a **multi-channel approach**, allowing to build a **constrained analysis** of the nuclear states of interest for DCE and 0νββ decay.



A. Spatafora et al., PRC 100, 034620 (2019)
L. La Fauci et al., PRC 104, 054610 (2021)
I. Ciraldo et al., PRC 105 (2022) 044607
I. Ciraldo et al., PRC 109, 024615 (2024)

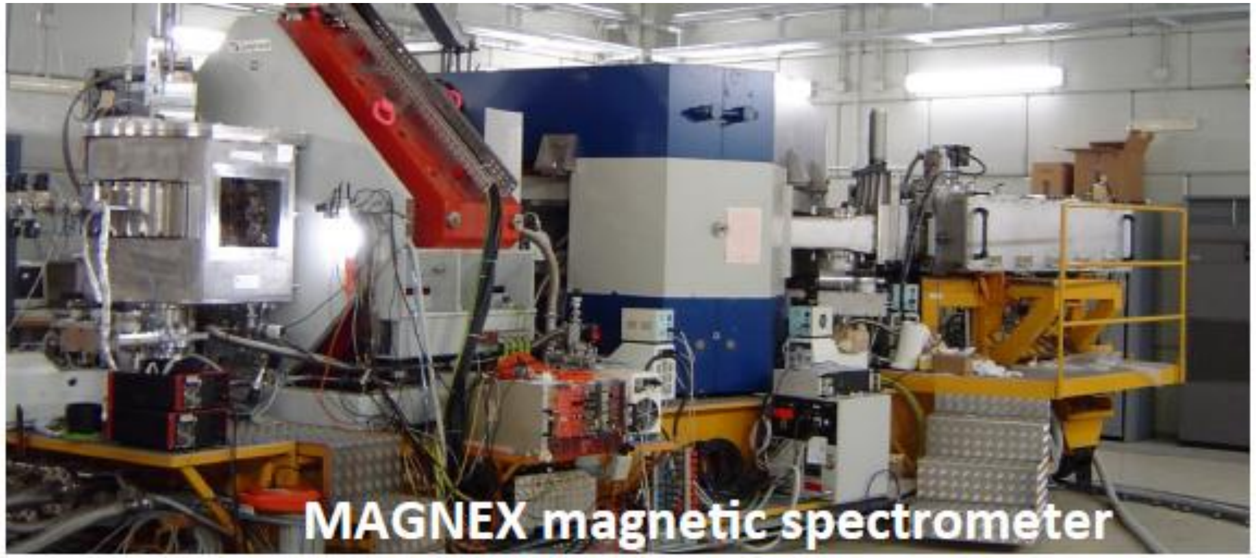
- **First experimental runs** for few nuclei show that competing channels and DCE absolute cross sections can be measured at 0° and suitable information can be extracted.

However: the DCE cross section is a **very small part** of the reaction cross section: need to perform a **high statistical significance** and **high sensitivity** measurement**->Much higher beam intensity and new detection system**

The NUMEN project

Experimental challenge: measurement of very **small** DCE cross sections with **high statistical significance** and **high sensitivity** to distinguish the DCE signal from the background **-> Higher beam intensity and new detection system**

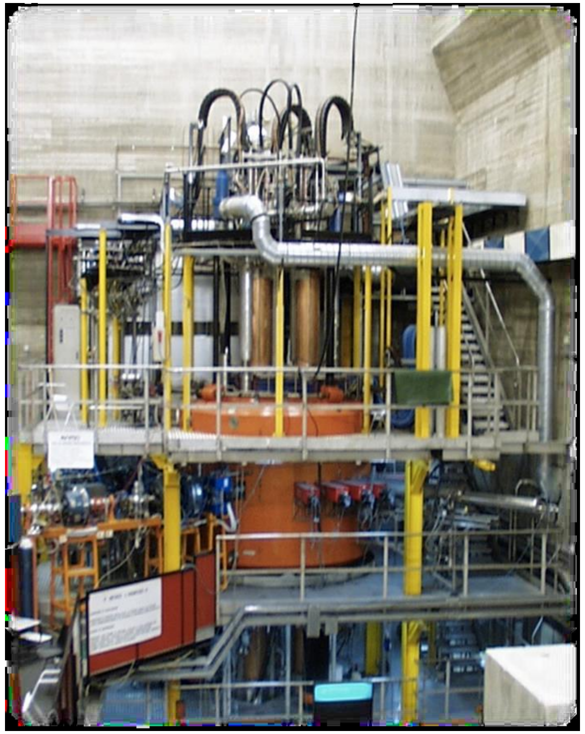
- Upgrade of the CS cyclotron to produce **high intensity heavy-ion beams** up to 10^{13} pps (from 100 W to 5-10 kW)
- Upgrade of the focal plane detectors of MAGNEX spectrometer with **novel detectors** to identify and track heavy ions at an expected rate of **5.10^6 Hz** at full intensity able to work in **harsh environment**
- Introduction of a γ-ray spectrometer
- Development of the **technology** for **suitable targets** to be irradiated with **intense ion beams**



"The NUMEN technical design report", F. Cappuzzello et al., International Journal of Modern Physics A 36, 30 (2021)

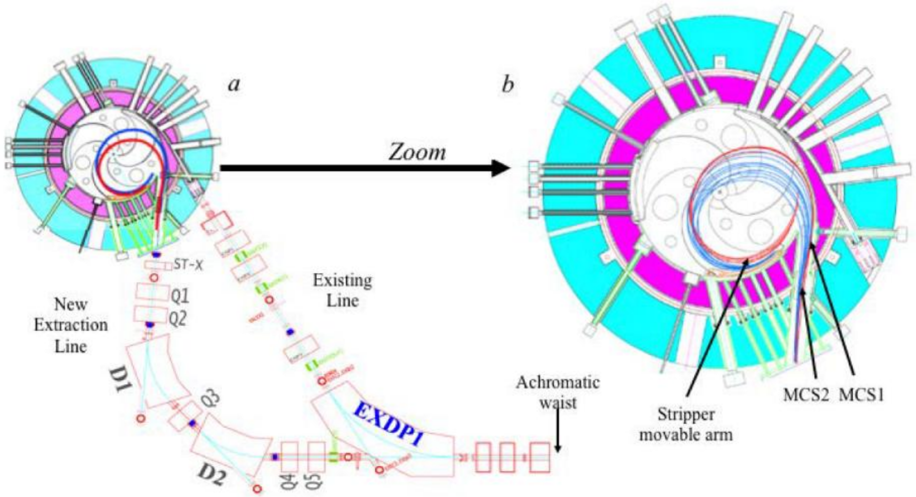
Superconducting Cyclotron: UPGRADE

In operation since 1996.
•Accelerates from H to U ions
•Maximum energy 80 AMeV
Very compact -> max extraction efficiency 60%
Thermal issues for power > 100 W

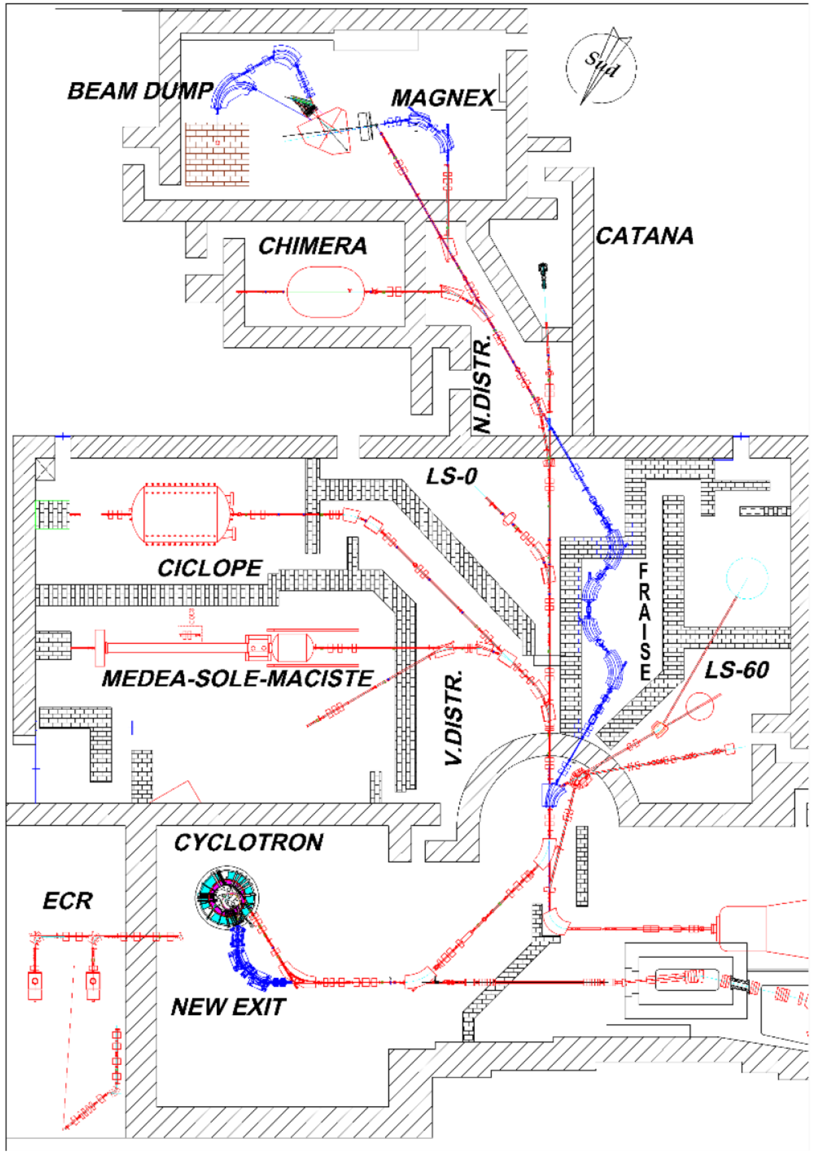


C. Agodi et al., Universe 7, 72 (2021)

- New beam extraction method based on stripping (instantaneous change of the magnetic rigidity of the accelerated ion after crossing of a thin stripper foil)
- New extraction channel
- **Efficiency 99% for A < 40 and E≥ 15 AMeV**
- **Intensity up to 10^{13} pps (10 kW)**

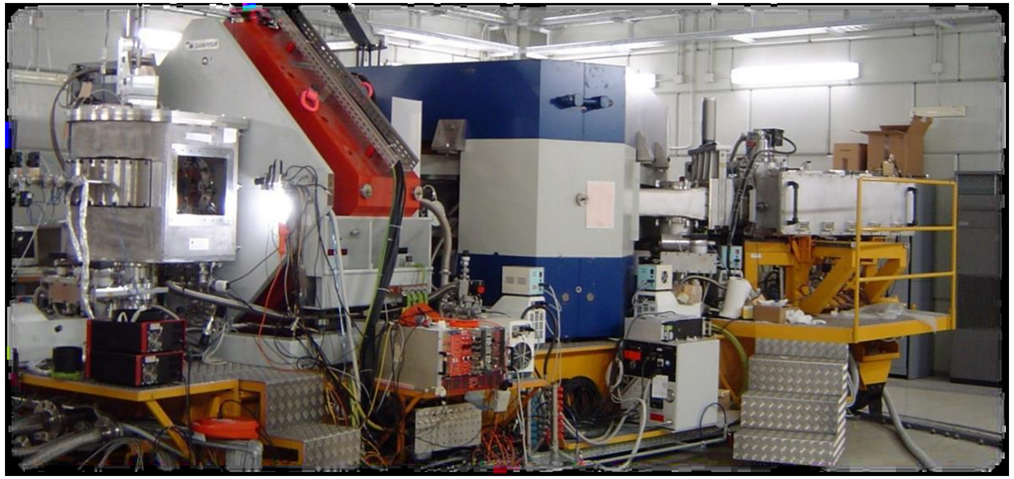


NUMEN beam requirements
- Beam spot x=1 mm, y=2.5 mm (FWHM)
- Horizontal divergence < 4 mrad (FWHM)
- Vertical divergence < 7.5 mrad (FWHM)
- Energy spread = 0.1% (FWHM)



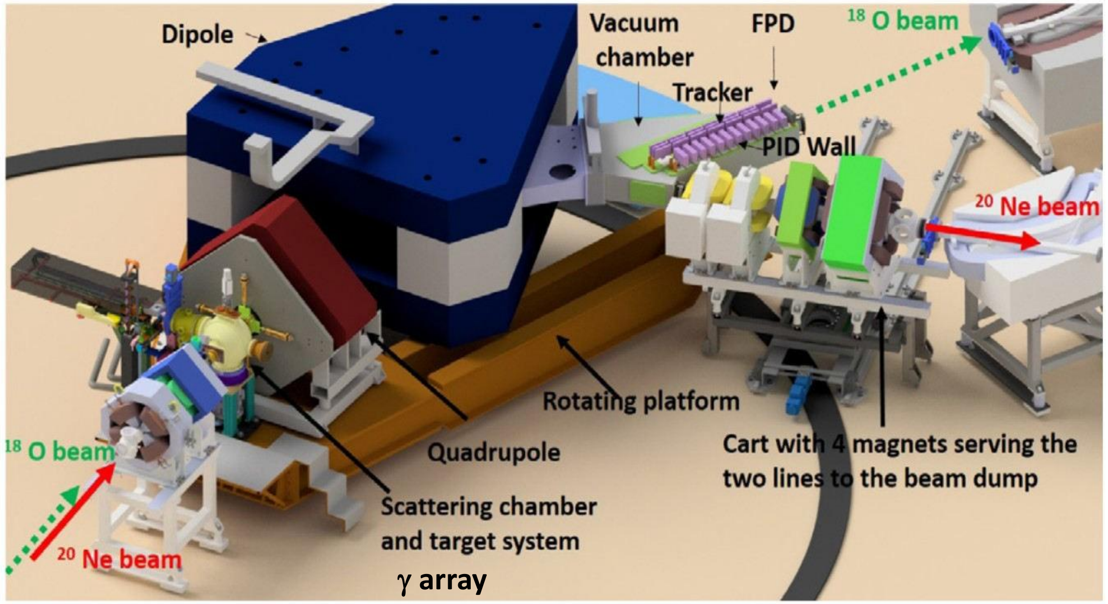
MAGNEX: Current status and UPGRADE

F. Cappuzzello et al., Eur. Phys. J. A (2016) 52: 167



NUMEN Technical Design Report

F. Cappuzzello et al., Intern. Jour. of Mod. Physics A36 (2021) 2130018



Large acceptance magnetic spectrometer consisting of a large aperture vertically focusing quadrupole and a 55° horizontally bending dipole.

Max magnetic rigidity (Tm): 1.8
Solid angle(msr): 50
Momentum acceptance: -14%, +10%
Momentum dispersion (cm/%): 3.68

Trajectory reconstruction

Energy $\Delta E/E \sim 1/1000$
Angle $\Delta\theta \sim 0.2°$
Mass $\Delta m/m \sim 1/160$

MAGNEX upgrade

Max magnetic rigidity (Tm) (new power supplies): 2.2 (15-70 AMeV)
New Focal Plane Detector
γ array (G-NUMEN)
Upgrade of the target system
New beam dump
New electronics

The old Focal Plane Detector

Two tasks to accomplish:

1) High resolution measurement at the focal plane of the phase space parameters (X_{foc}, Y_{foc}, θ_{foc}, ϕ_{foc})
2) Identification of the reaction ejectiles (Z, A) - crucial aspect for heavy ions

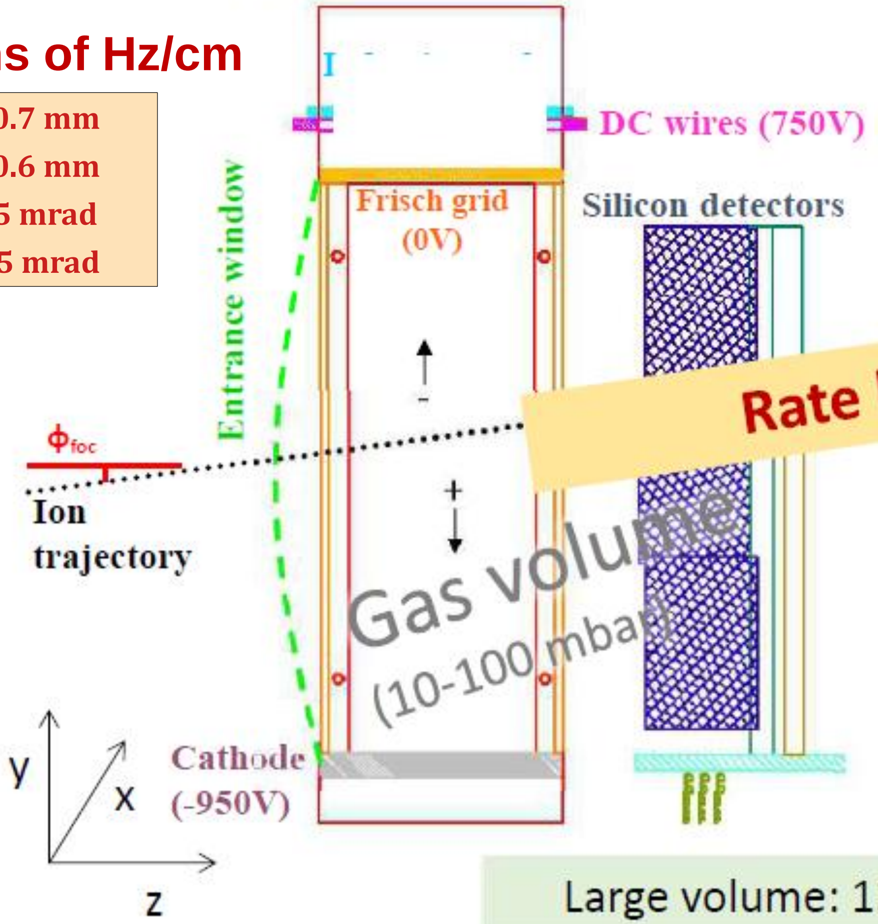
Hybrid detector:
Low pressure Gas section
proportional wires and drift chambers
\+
Stopping wall of **silicon detectors**

M. Cavallaro et al. EPJ A 48: 59 (2012)

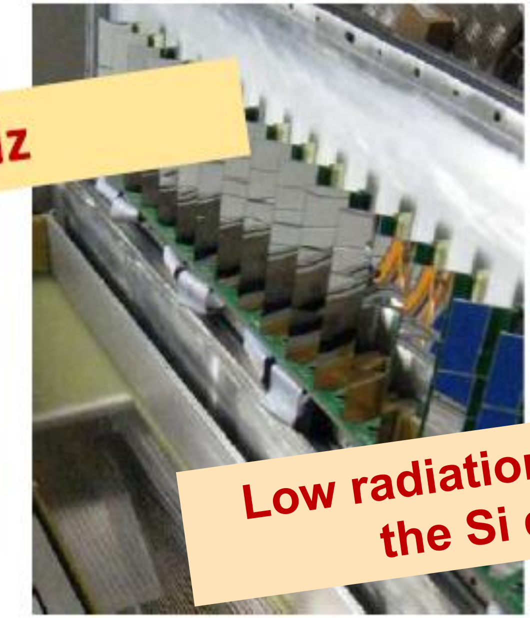
D. Torresi et al. NIM A 989 (2021) 164918

Up to few tens of Hz/cm

X resolution	< 0.7 mm
Y resolution	< 0.6 mm
θ resolution	< 5 mrad
φ resolution	< 5 mrad



Rate limit few kHz



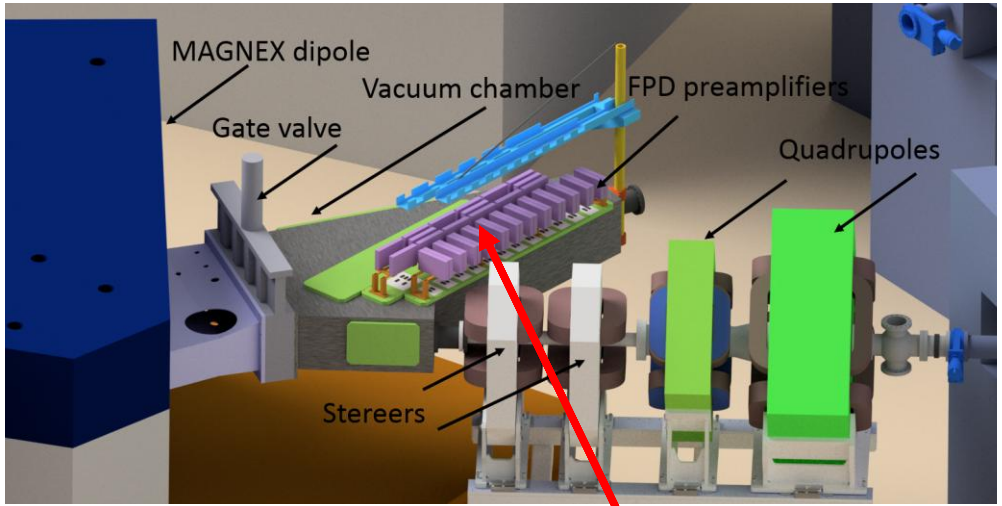
Low radiation hardness of the Si detector

Large volume: 1360mm X 200mm X 96mm

New Focal Plane Detector

Requirements for new PID system

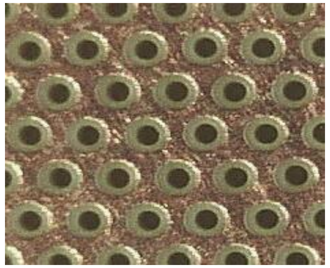
- **High count rate** up to 30-50 kHz/cm;
- **Radiation Hardness** of the order of 10^{11} ions/(cm^2/yr);
- Woking in **low pressure** (tens mbar) gas environment;
- Preserve a **high position and angular resolution;**
- Particle identification capability for identification of **Z ≈ 10 and A ≈ 20;**
- **Time resolution** better than 2 ns;
- **Double-hit** event probability **below 3%** in the whole FPD.



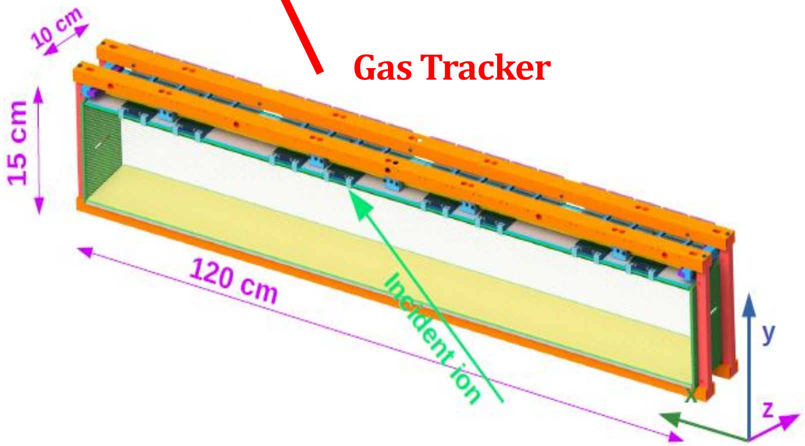
Wires → M-THGEM

- Large area and robust
- High rate (up to 1 MHz/mm^2)
- High Spatial Resolution (sub-millimetric)
- High gas gain
- Good timing properties (few ns)
- Flexible detector shape and readout patterns

M-THGEM



Gas Tracker



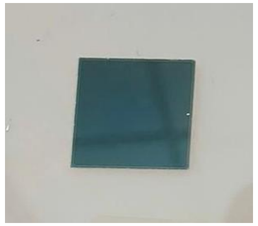
Silicon detectors → SiC + CsI(Tl)

SiC energy resolution comparable with silicon detector

Very good timing properties

High radiation tollerance for both SiC and CsI(Tl)

SiC



Tudisco et al., Sensor 2018, 182289

Focal Plane Gas Tracker: M-THGEM

A **proportional drift chamber** with a thin entrance window made of mylar, filled with **isobutane.** The **multiplication stage** is based on **3-layer thick GEM (M-THGEM) assembled together** each one being an insulator plane between two conductor layers with a large number of microscopic holes (multi-layer PCB technique) for 1.28 mm total thickness.

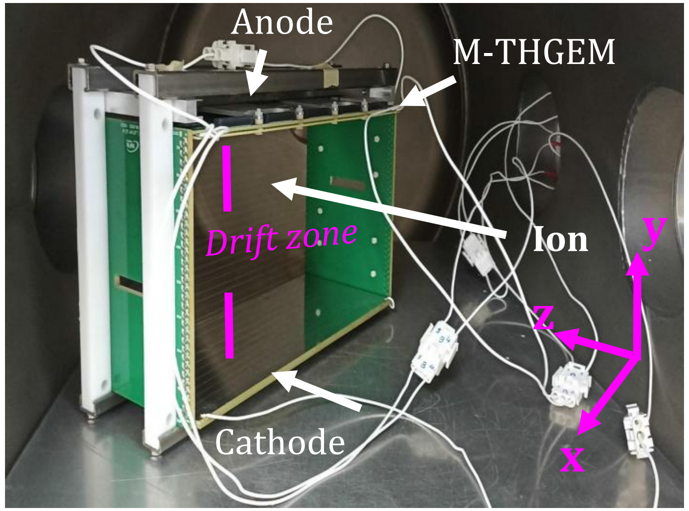
Requirements

Track heavy ions: O-Ne at 5-60 AMeV
Pressure: 10-40 mbar
X, Y resolution < 0.6 mm
θ, ϕ resolution < 0.3°
Rate: 3-5x10^4 Hz/cm

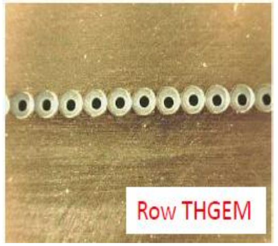
Electrons are guided by the high E of THGEM -> avalanche

Confined avalanche within holes ➔ Less photon-mediated secondary effects

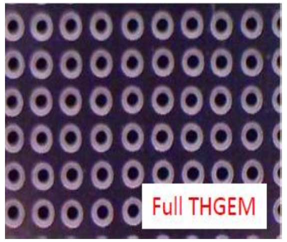
Electrons drift to anode, THGEM collects ions

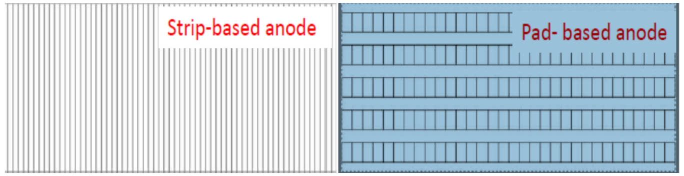


5 rows in z



Full THGEM



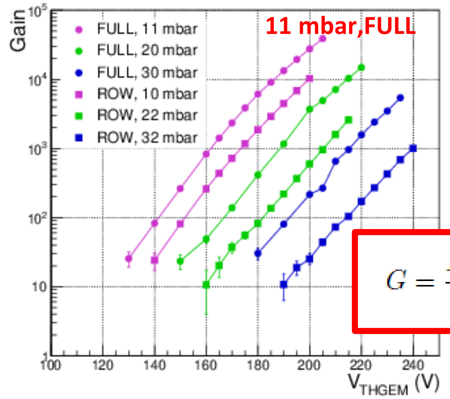


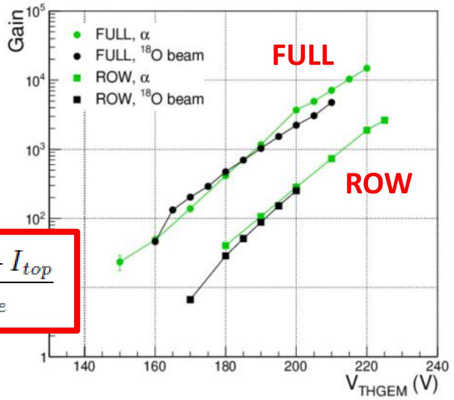
Gas tracker prototype characterization for different HVs, pressures and rates up to 3 kHz, done with a picoammeter with α-sources and ^{18}O at E=270 MeV at LNS.

FULL THGEM *vs* ROW THGEM configuration: better performances

I. Ciraldo et al. NIMA 1048 (2023), 167893

High gain at low pressure

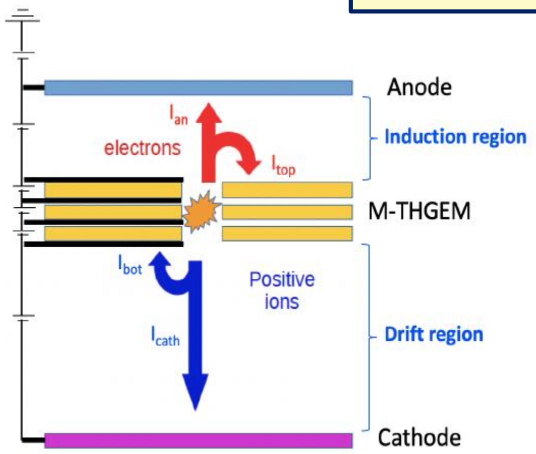




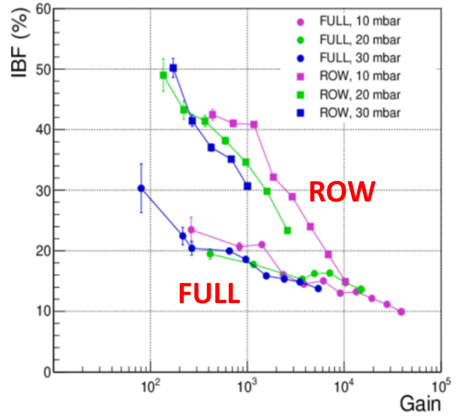
$$G = \frac{I_{an} + I_{top}}{I_e}$$

$$IBF = \left| \frac{I_{cath}}{I_{an} + I_{top}} \right|$$

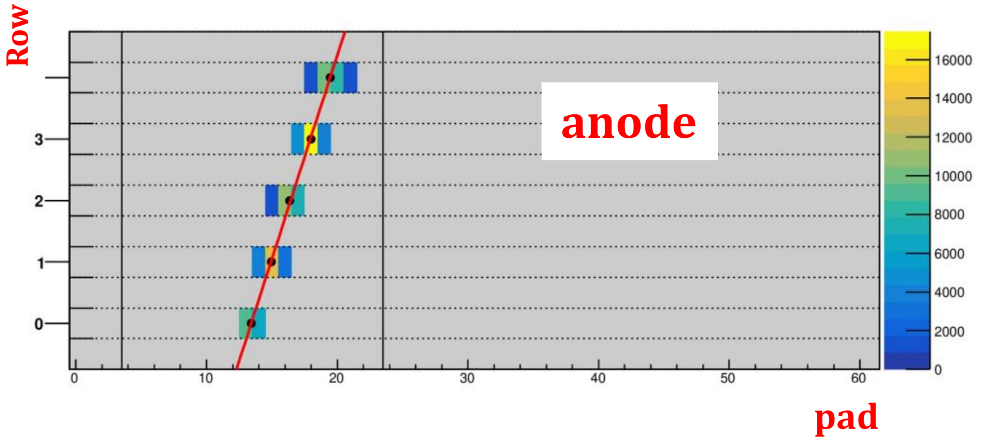
Ion Back Flow: its presence in the drift volume can induce severe distortions of the E in the drift region that may affect the position resolution and the drift time of the electrons.

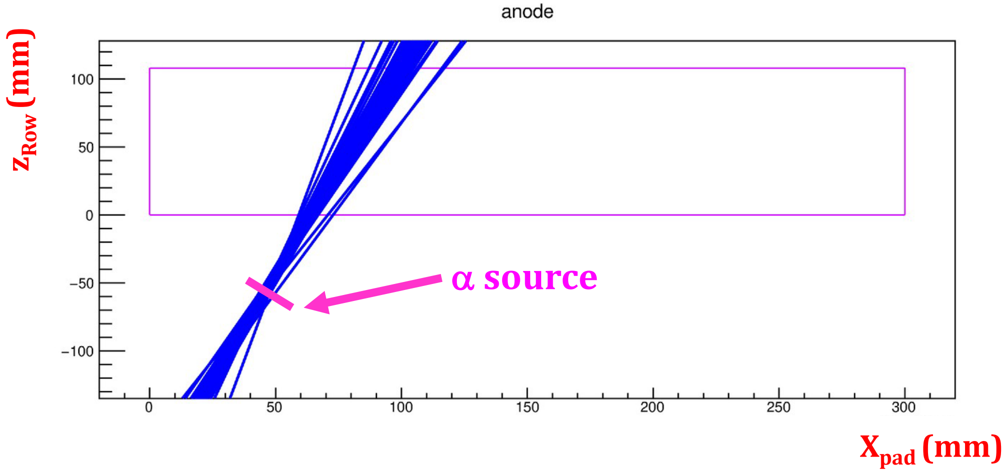


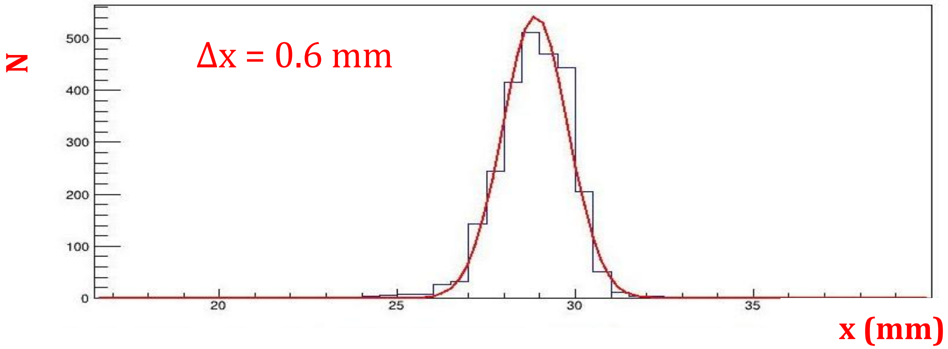
Low Ion Back Flow



Focal Plane Gas Tracker: Tracking performances



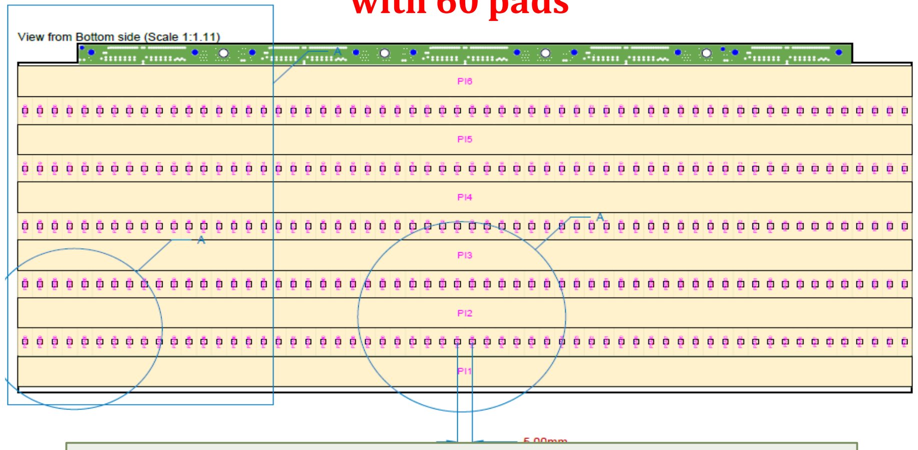


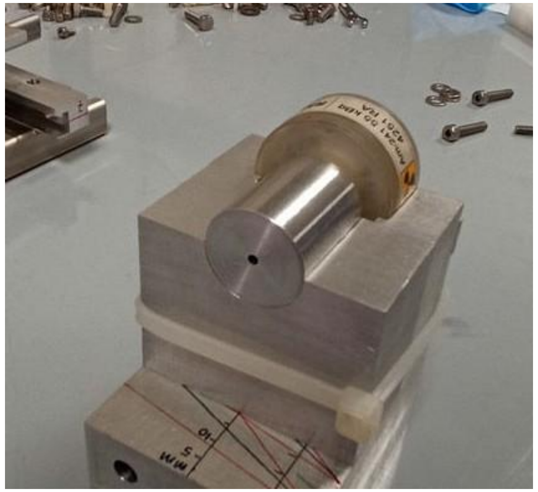


The charge distribution on the segmented anode provides the horizontal position (x, z) and the track angle θ, while the vertical position y and the angle ϕ are derived from the electron drift time.

For each cluster the centroid is extracted and a fit of the x position of the five centroids gives the track

Segmented anode: 5 rows (z-direction) each one with 60 pads





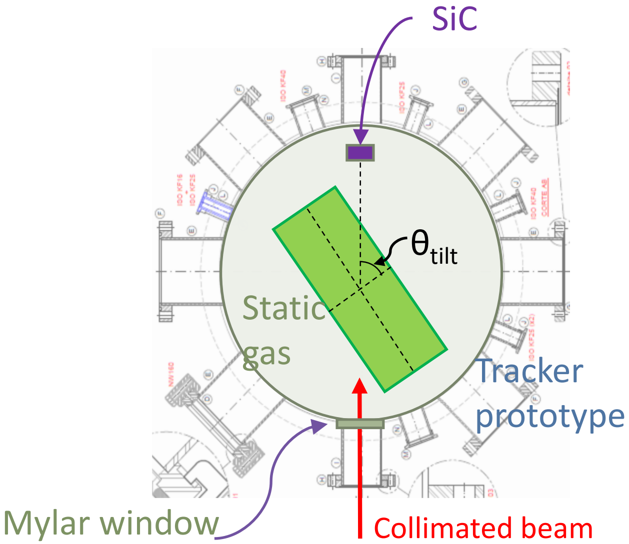
The trajectory of each alpha is tracked *back* to the alpha source position. The histogram of all the starting points of the trajectory must be compared with the collimator size: 1mm.

A preliminary resolution for the x coordinate 0.6 mm was obtained (after quadratic subtraction of the collimator dimension).
Run with smaller collimator (0.3 mm) are planned.

Focal Plane Gas Tracker: in-beam test at IF-USP (Brazil) and Safiira facility at 0° beamline

Pelletron beams ^{12}C at 45 and 37.5 MeV and ^{7}Li at 32 and 28 MeV (Pelletron beams of the Tandem facility)

To simulate the conditions of the typical NUMEN beams in terms of energy loss (charge distribution) in the low pressure gas volume.



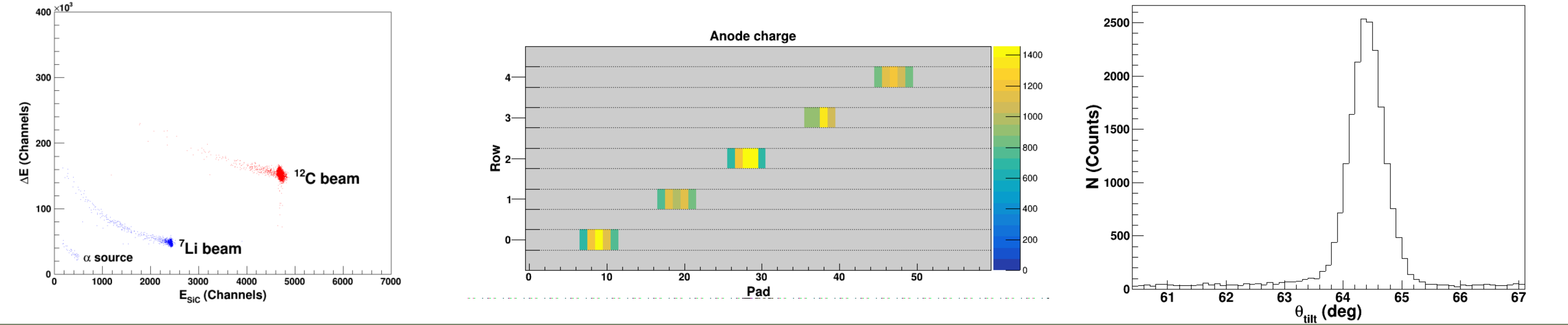
SAFIIRA beamline:

- Well collimated beam (0.3 mm diameter, divergence of 0.2° FWHM)
- Well controlled beam intensity (from 10 Hz to 3 kHz)

Tested:

- Position and angular resolution;
- Angle dependence of the tracking performances (changing the tilt angle);
- Rate dependence

On line spectra



Focal Plane Detector: the particle identification wall

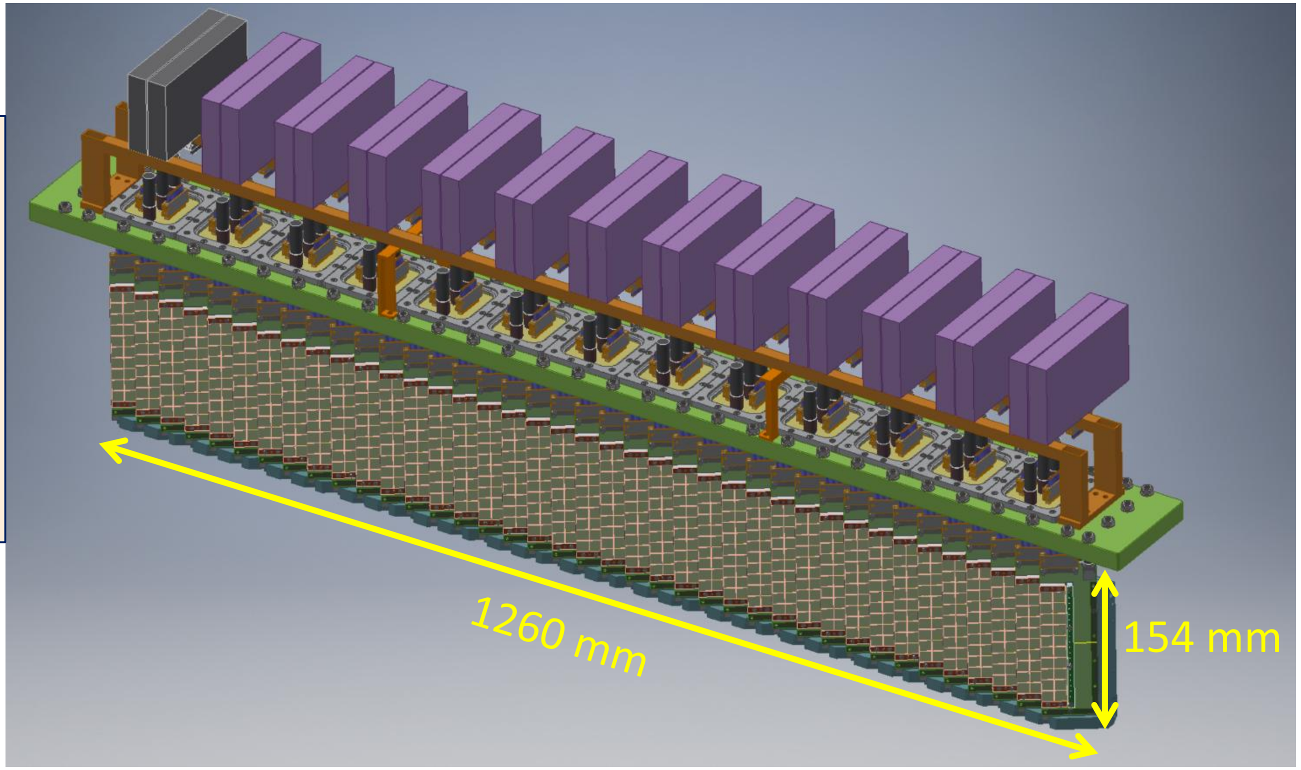
Determine the **atomic number (Z)** of the reaction ejectiles and provide, in connection with the gas tracker, the **isotopic species (A)** and its **atomic charge state (q)**

PID wall

720 SiC-CsI telescopes arranged in 36 towers

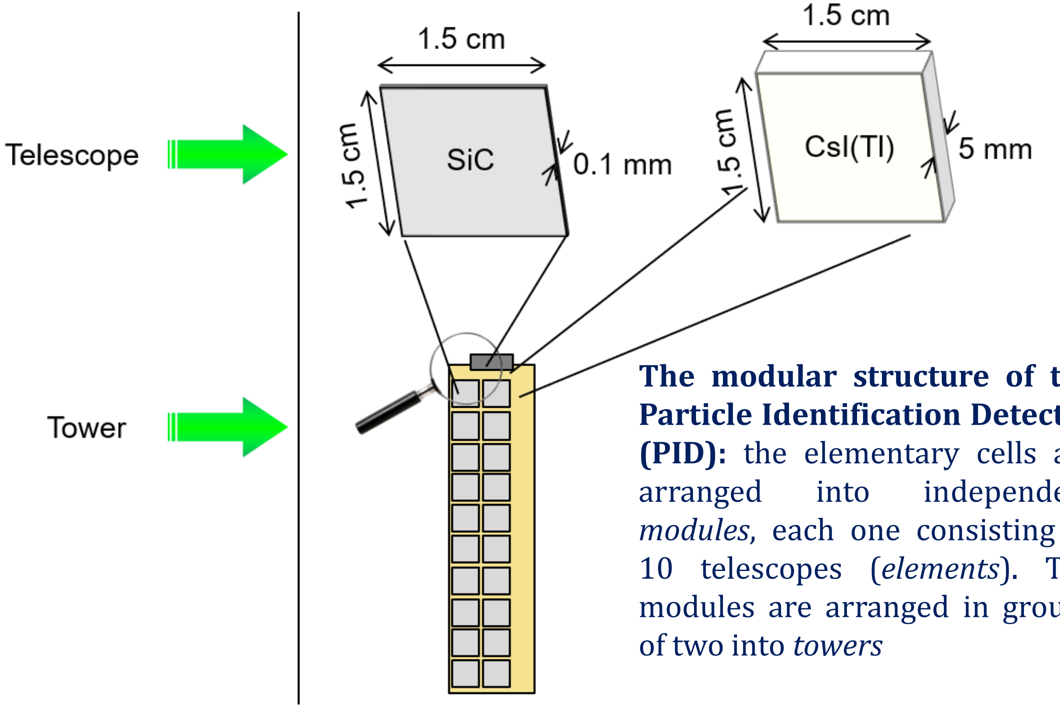
Obtained performances

- Radiation hardness **10^{13} ions/cm^2 for SiC**
- Radiation hardness larger than **7.5 x 10^{11} ions/cm^2 for CsI**
- **$\Delta Z/Z \approx 1/34$** and **$\Delta A/A \approx 1/47$**
- Time resolution hundreds of ps for SiC
- Double hit less than 2.5 % with the chosen granularity

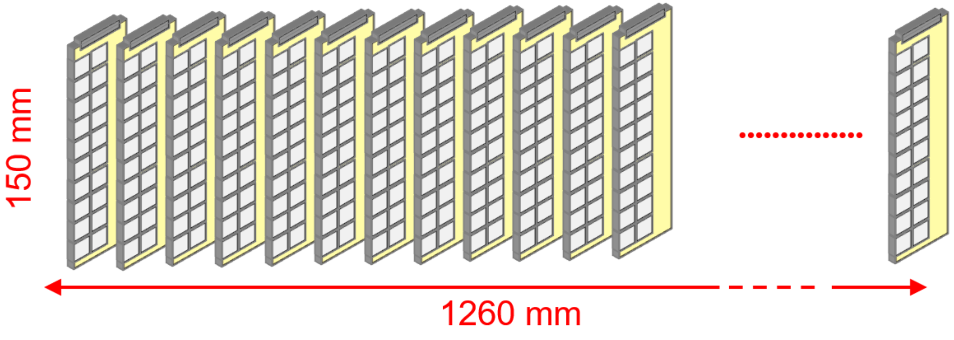


Focal Plane Detector: the particle identification wall

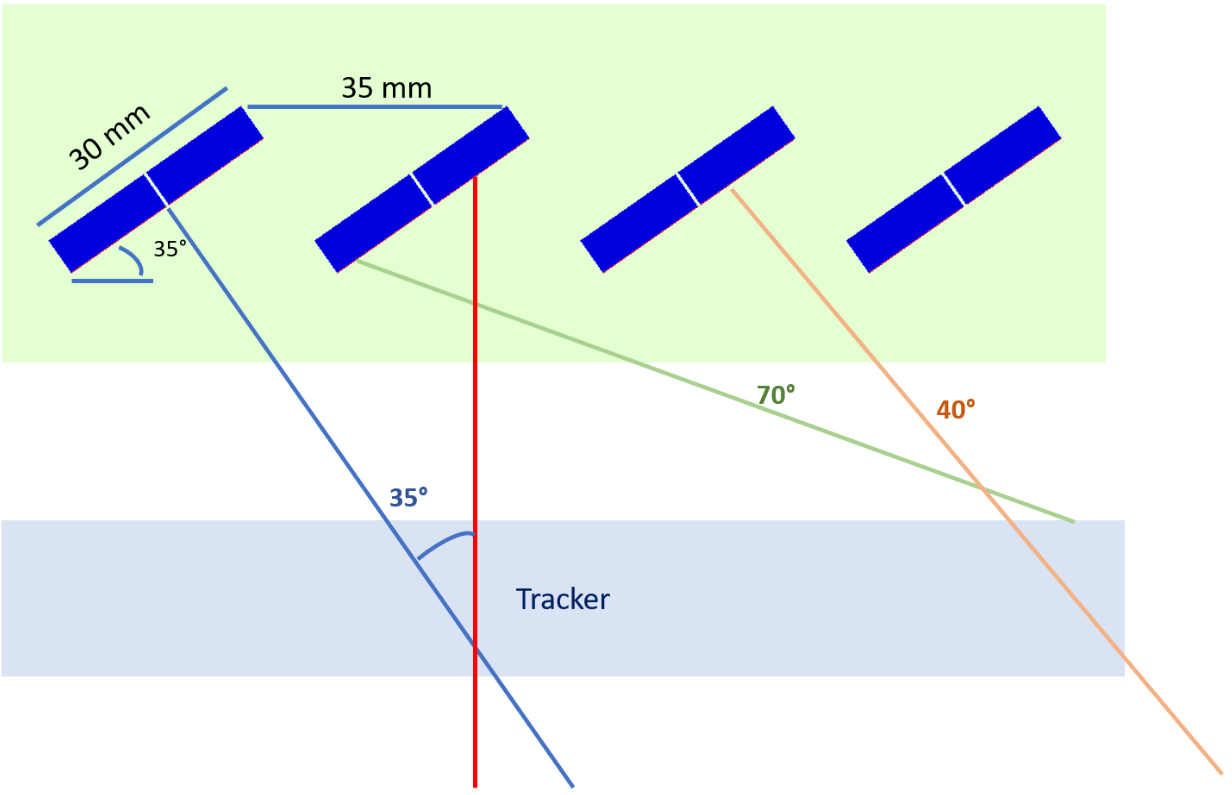
The PID tower



The modular structure of the Particle Identification Detector (PID): the elementary cells are arranged into independent *modules*, each one consisting of 10 telescopes (*elements*). The modules are arranged in groups of two into *towers*



36 towers
20 elements in each tower
35° angle of the towers



The full width of the MAGNEX focal plane, will be covered by 36 towers rotated by about 35° with respect to the vertical axis to partially compensate the tilting angle of the focal plane with respect to the dipole magnet optical axis.

The particle identification wall ΔE stage: SiC detectors

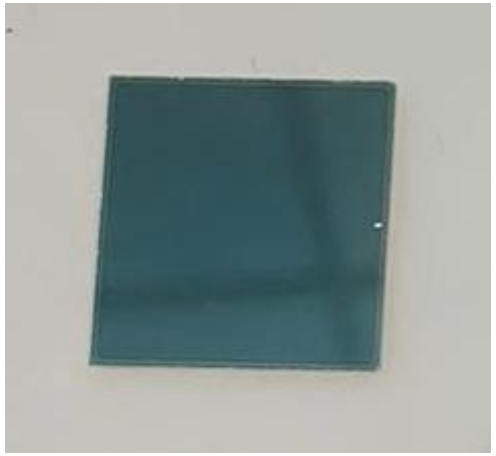
ΔE stage SiC
Epitaxial layer 100 µm
Dead layer on the back 10 µm
Area 1.54 x 1.54 cm^2
Edge structure 400 µm
Full Depletion Voltage -300/-1000 V

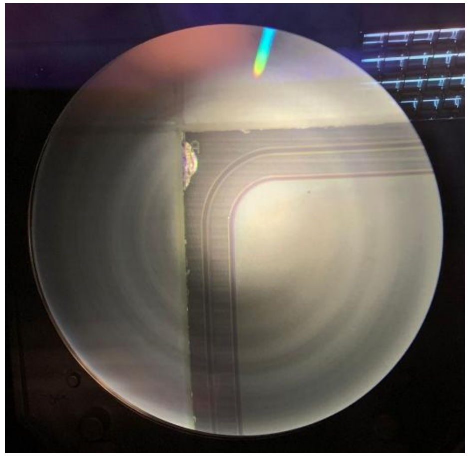
S. Tudisco, et al., ***SiCILIA****,*
Sensors 18 (7) (2018) http://dx.doi.org/10.3390/s18072289.

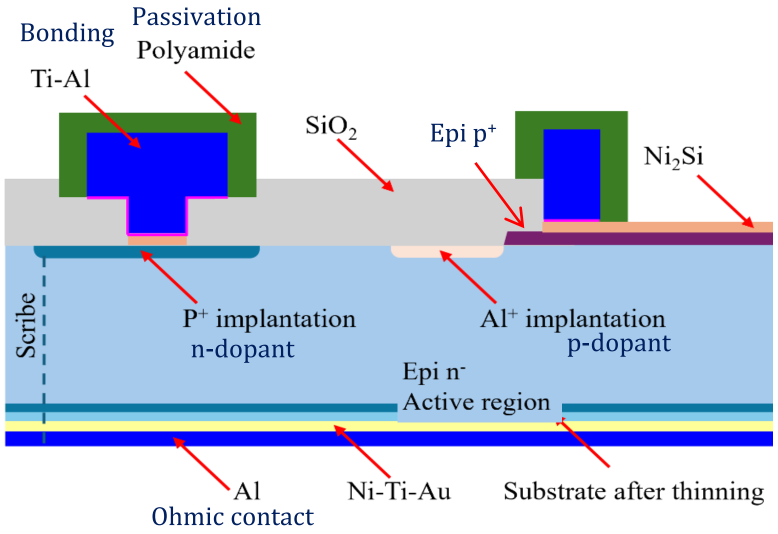
- Larger energy bandgap (3.23 eV) than Si detector (1.12 eV) -> **lower leakage current** but poorer energy resolution: not critical for NUMEN experiments where many primary charge carriers are created;
- Much higher threshold (25 eV) than Si for creation of defects in the lattice -> **radiation hard** ;
- High saturation velocity (2×10^7 cm/s) of the electrons and possibility to work near saturation since breakdown voltage is 10 times higher than Si -> **fast response (hundreds of ps)** ;

Requirements

- Need to work at **low pressure environment ->low depletion voltage to avoid discharge -> lower dopant concentration than 10^{14} atm/cm^3;**
- **Homogeneity** among different detectors in terms of depletion voltage, thicknessa, charge collection efficiency and energy resolution are required.







The particle identification wall ΔE stage: SiC detectors

➢Need to work at **low pressure environment ->low depletion voltage to avoid discharge -> lower dopant concentration than 10^{14} atm/cm^3**;

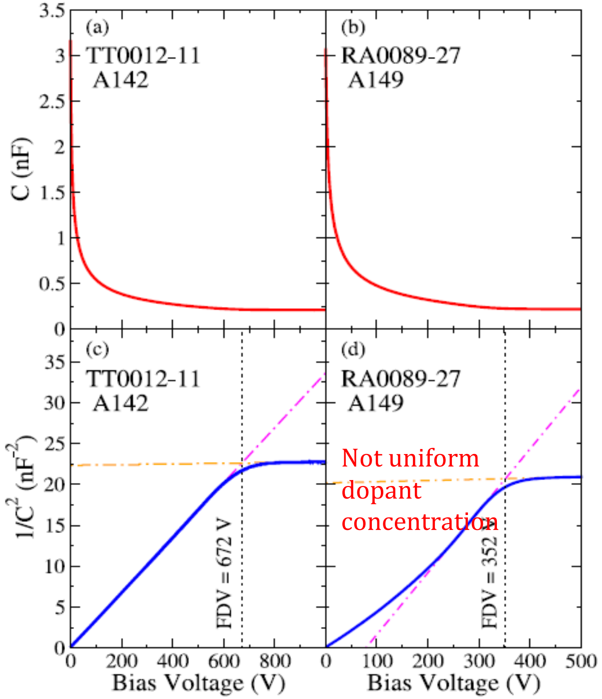
R&D program: production of two epitaxial wafers from the same bulk material with different **doping concentrations**

- $\approx 8 \cdot 10^{13}$ atm/cm^3 TT0012-11 (FDV ~ 770 V) well established (31% of good SiC)
- $\approx 3 \cdot 10^{13}$ atm/cm^3 RA0089-27 (FDV ~ 270 V) (21% of good SiC)

Several tests performed with sources and beams -> different performance for different dopant concentrations

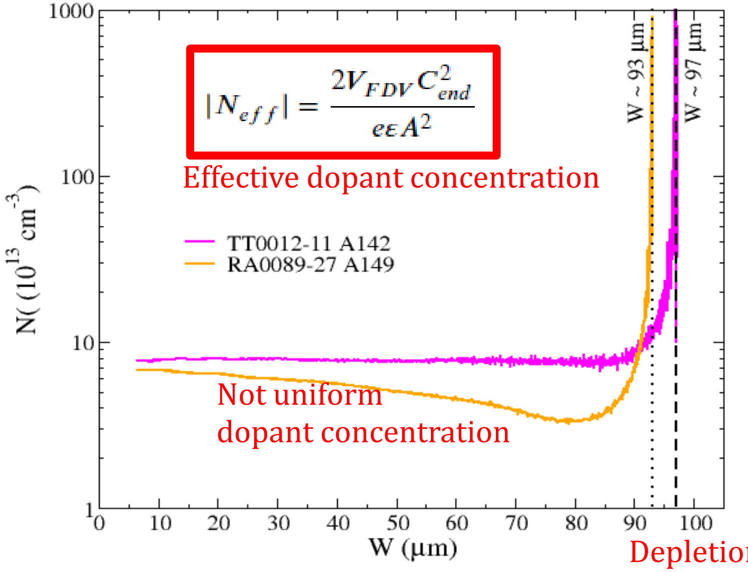
Not uniform dopant concentration and lower depletion depth than the nominal one for RA0089-27 SiC

Good sensors



The dopant concentration profile can be determined from the C-V characteristics

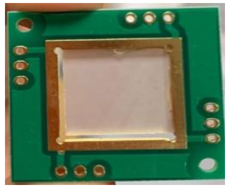
$$N = \frac{2}{e\varepsilon A^2 \frac{d(1/C^2)}{dV}}$$

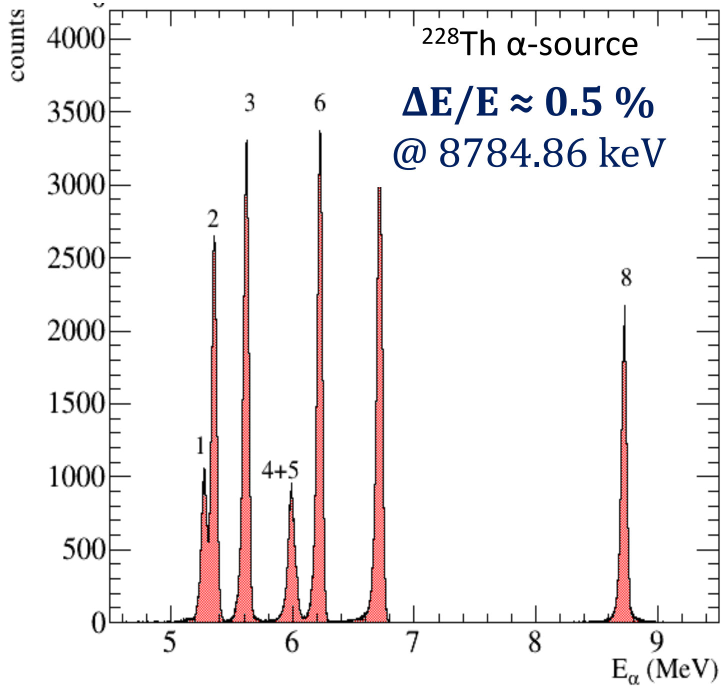


Depletion depth

Good energy resolution for both wafers

Front (ΔE resolution) **Back (Dead layer)**





D. Carbone et al., Nucl. Instr. Meth. A 1069, 169960 (2024)

SiC detectors: microbeam characterization

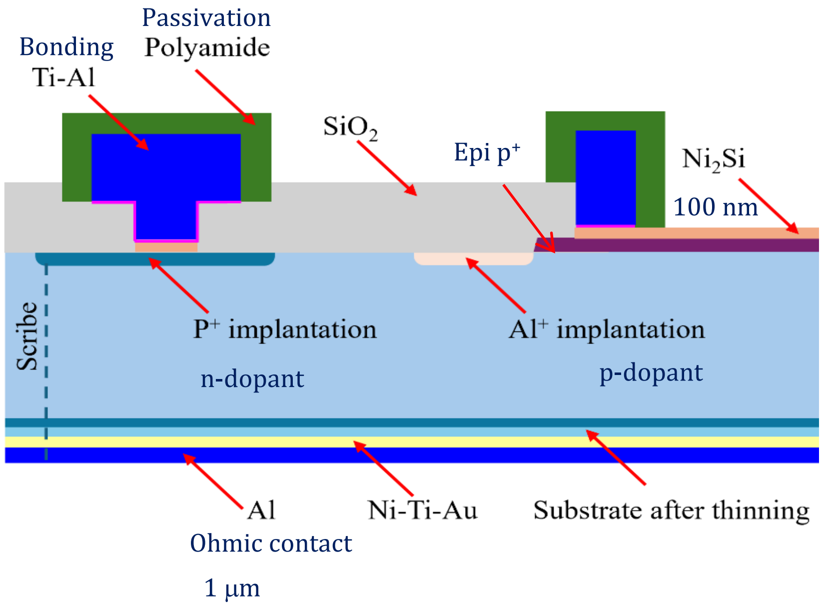
Ruđer Bošković Institute, Zagreb

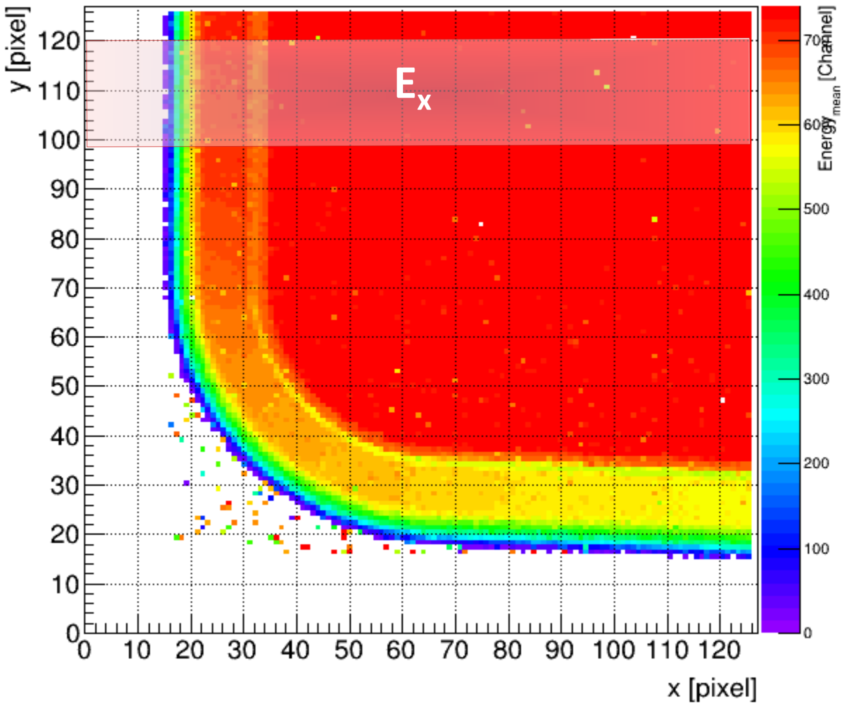
IBIC (Ion Beam Induced Charge) mode with proton microbeam (10 µm scanning pitch)

1)Check of Ziegler energy loss tables (E_p= 6 MeV, SiC+ 300 µm-thick Silicon detector)
2)Depletion depth at FDV of the SiC (E_p= 3.4 MeV): in agreement with previous methods
3)Charge collection efficiency

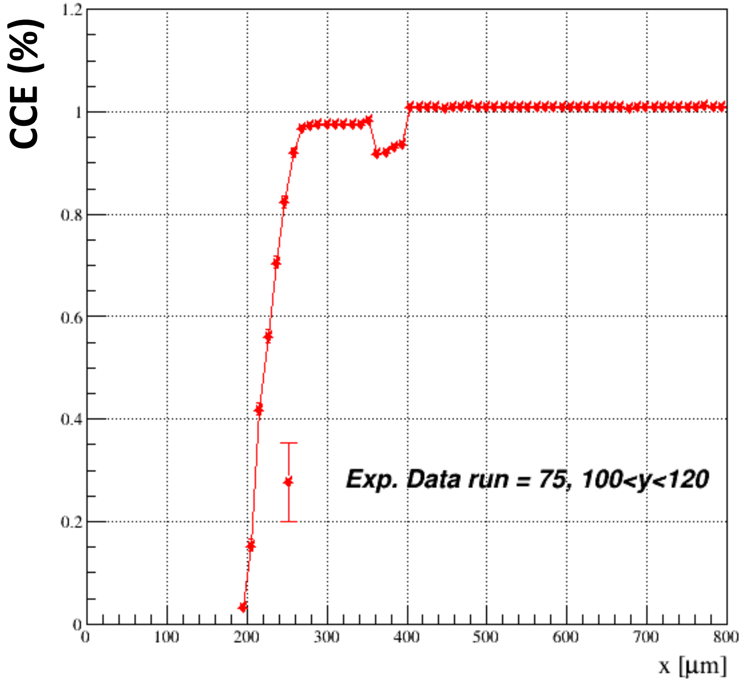
<u>Irradiation in the FRONT and BACK side:</u>

4 SiC devices
6 scanned areas
5 voltages FDV, FDV ± 15%, FDV ± 30%
4 proton energies: from 1.26 to 6 MeV
Different incident angles: 0° - 50°





- **Good uniformity** of the inner area
- **Edge effect** in the collection efficiency



A. Spatafora et al, NIM A (accepted 2025)

New production of improved SiC detectors with a low dopant concentration

Commissioning of the PID prototype at INFN-LNL

^{18}O beam @ 15 AMeV by Tandem + ALPI facility

- PISOLO chamber equipped with Au and C targets
- PID prototype (2 towers) placed at forward angles
- Readout:

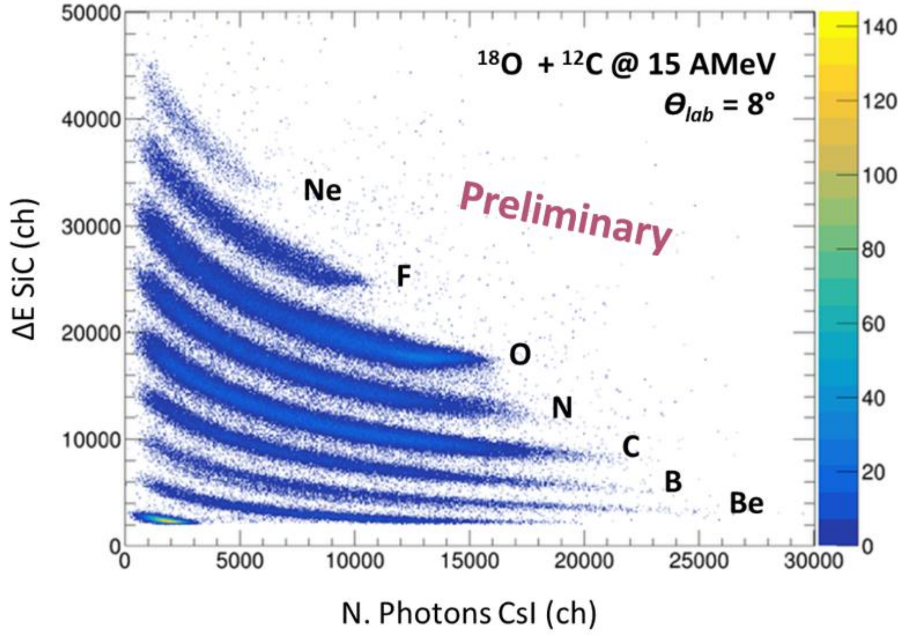
64 channels Preamplifiers (CAEN A1429) +

64 channels Digitizers (CAEN VX2745) +

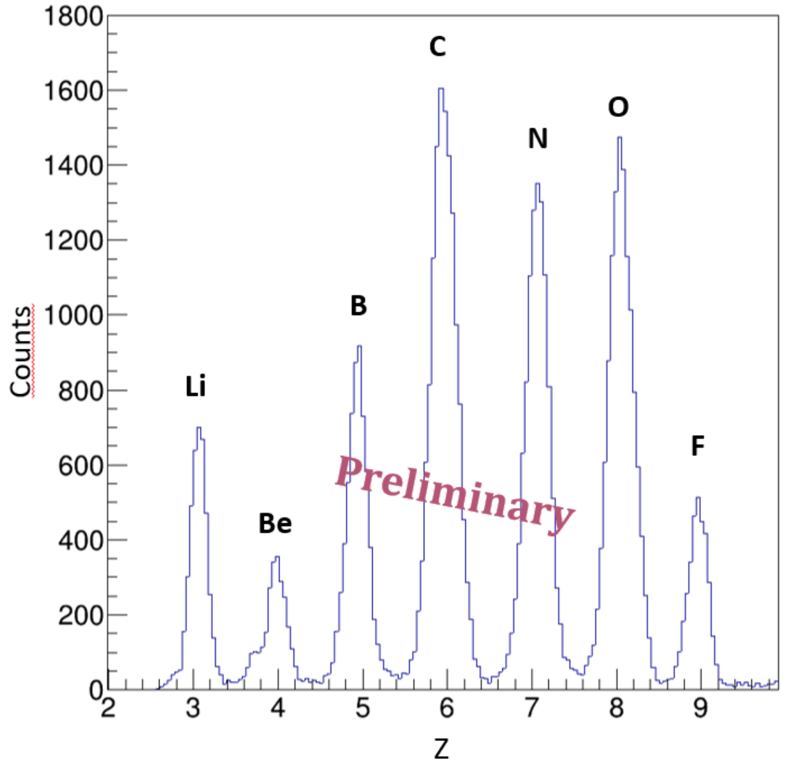
new DAQ program developed for NUMEN

Goals

- Z identification capabilities
- Validation of the readout + DAQ
- High rates effects
- Tilt angle effects



Particle identification capabilities
$\Delta Z/Z \approx 3$ %



Particle identification capabilities
$\Delta A/A \approx 2$ %

G-NUMEN: The γ array detector

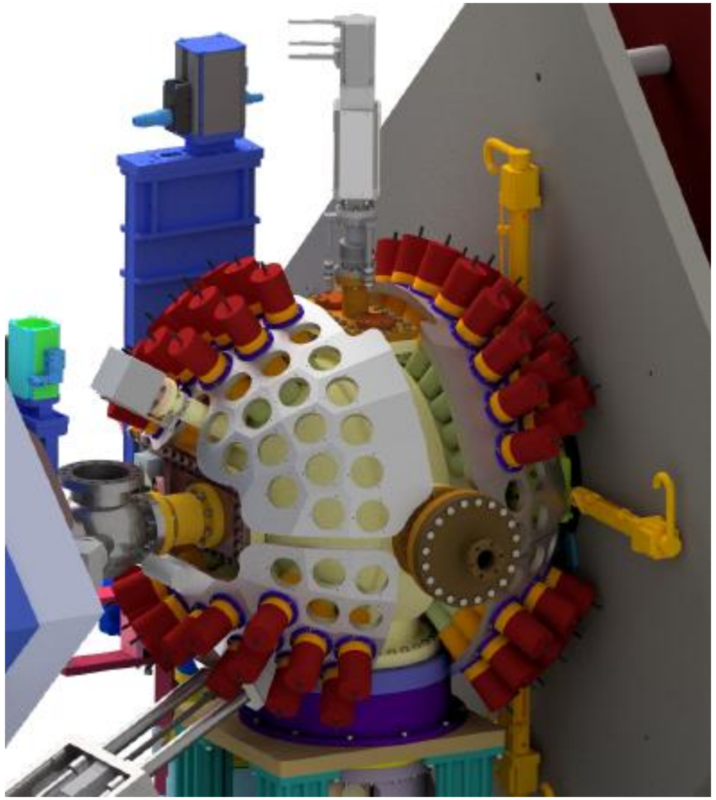
Mesurement of γ transitions in coincidence with DCE events in the Focal Plane Detector when the energy resolution in MAGNEX is not sufficient to resolve between states of the reaction products such as for deformed target-nuclei ^{110}Pd, ^{150}Nd and ^{160}Gd, and in all cases, at high reaction energies.

Requirements for **G-NUMEN**

- **Observational limit** $\sigma_{DCE}/\sigma_R < 10^{-8}$
- **Energy resolution** to separate g.s from excited states in DCE events
- **Time resolution** better than 2-3 ns
- **Radiation Tolerance** at 10^{11} fast neutrons/cm^2
- **Stability of the output pulse** with the **count rate** (up to 300 kHz)
- **Good linearity of the output pulse charge** with **energy**

G-NUMEN: 110 $LaBr_3$(Ce) scintillators coupled with Hamamatsu R6231PMT-type tubes purchased by the EPIC crystal company.

- Single crystal size 38 mm diameter and 50 mm length
- 24 cm distance from the target
- Total solid angle coverage = 20%



Expected performances

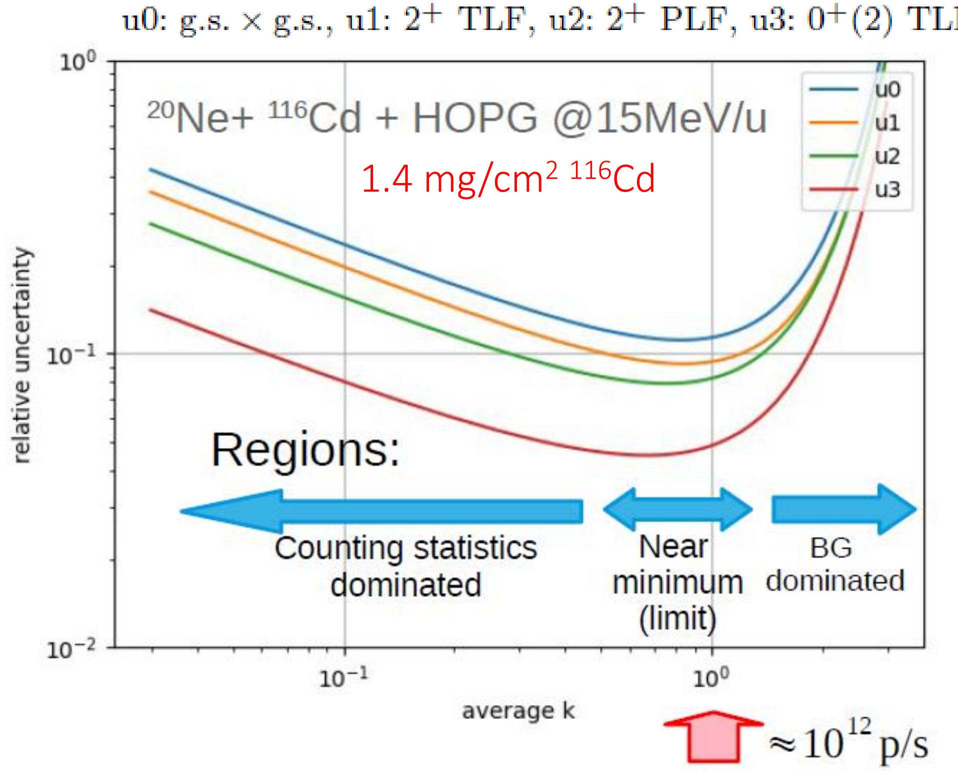
- Total photopeak efficiency of 4% at 1.3 MeV
- Energy resolution of 2.8% (6.4%) at 662 (122) keV
- Time resolution better than 1 ns
- Observational limit 0.3 x 10^{-9} (σ_{DCE} = 1 nb/state for σ_R = 3 b)
- Radiation tolerance up to 10^{10} neutrons/cm^2 (need of new data)

Challenge: distinguish γ rays from DCE events (very few) in the region of interest, in experimental conditions dominated by a **very high rate** of events coming from the projectile-target interactions-> **G-NUMEN demonstrator (15 detectors)**

G-NUMEN: Observational limit

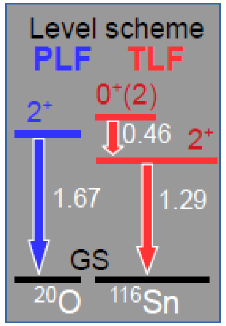
The **observational limit** is the lowest fraction of the signal reaction cross-section, which can be measured with an acceptable uncertainty by the spectrometer in a given experiment. It depends on characteristics of the nuclear reaction, of the γ spectrometer and on experimental conditions such as beam intensity and duration of the experiment.

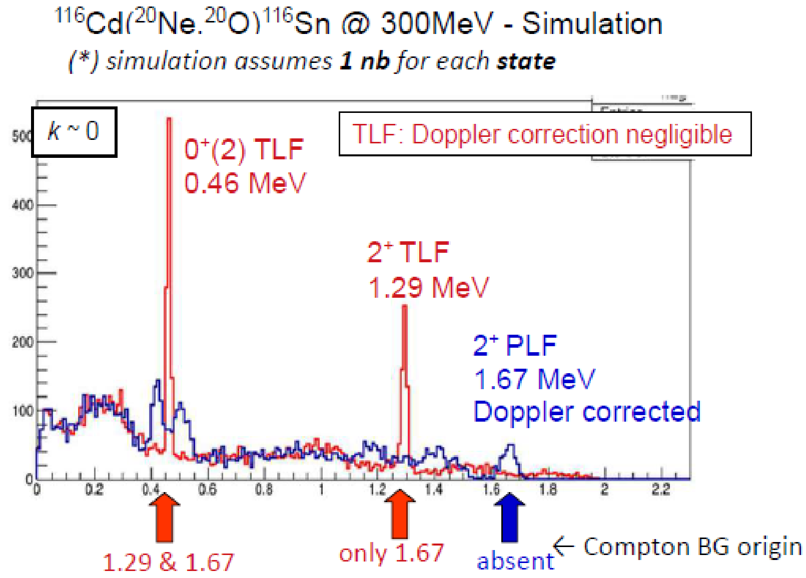
Relative uncertainty as a function of beam intensity in terms of the average k (number of reactions/bunch) for a cross section of **1 nb**/state (in a 1 month G-NUMEN experiment)



Number of reactions / bunch $k = n_{Targ}\,\sigma_R\,N_{Bunch}$

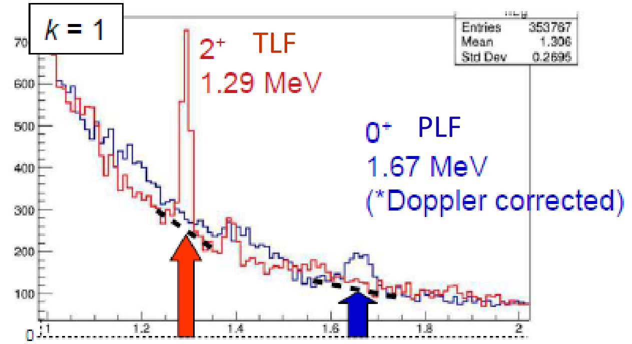
Compton BG in G-NUMEN + MAGNEX





At **low beam currents** the continuum BG (mostly Compton) is quite small

At **high beam currents** BG is dominated by growth of accidental coincidence events from other-than-DCE reactions



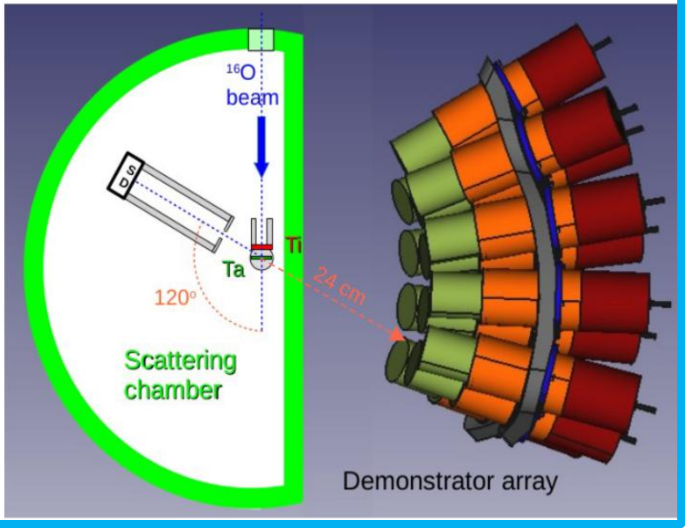
"The NUMEN technical design report",
F. Cappuzzello et al., International Journal of Modern Physics A 36, 30 (2021)

J.R.B. Oliveira, M. Morales et al., EPJ A (2020) 56:153

G-NUMEN: In-beam test of the Demonstrator under a high background at ALTO, IJCLab (Orsay, France)

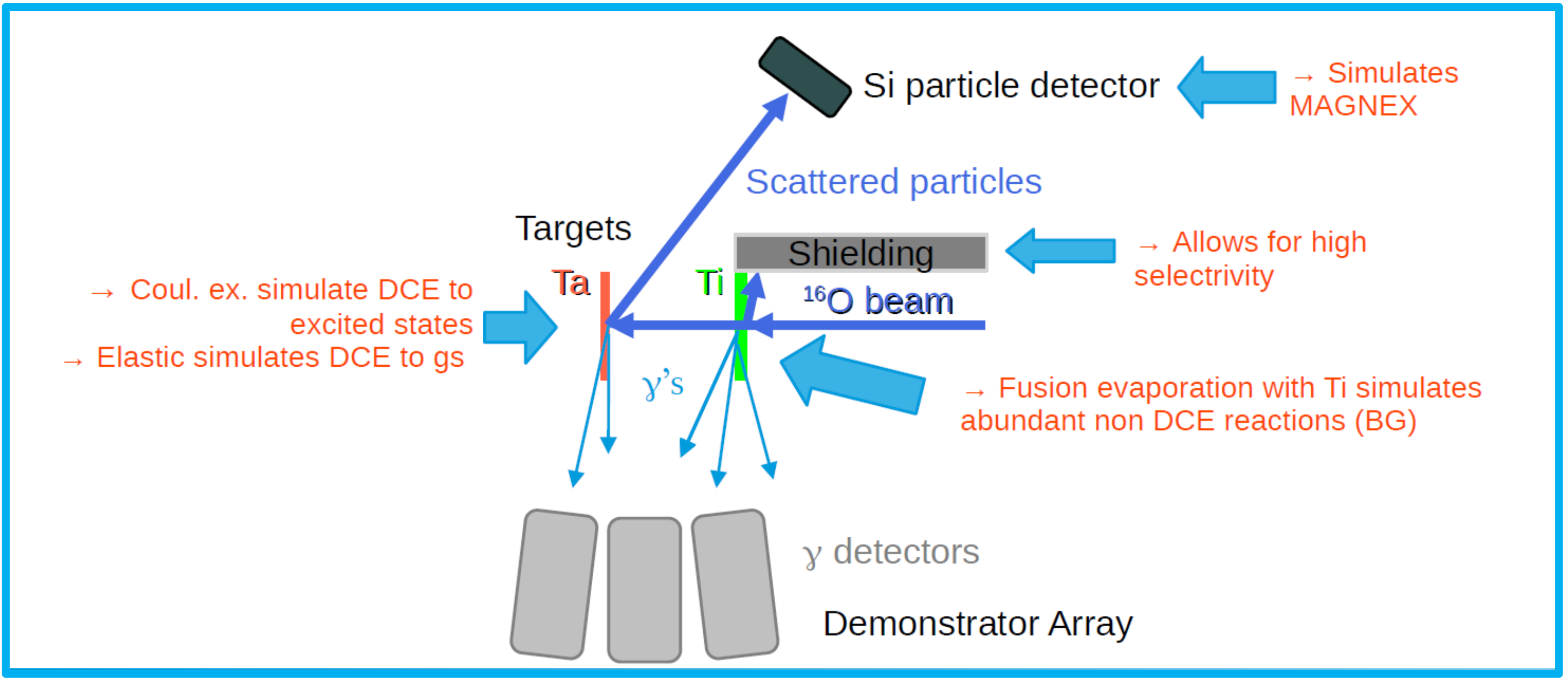
(Spokesperson J.R.B. Oliveira)

- ALTO (Tandem), IJCLab, Orsay
- ^{16}O @ 83.5 MeV
- 20 pnA, 2.5MHz
- Ti/Ta targets (4.4/2.5 mg/cm^2)
- Ti: Fusion Evaporation → BG
- Ta: Coul. Ex.→ Signal
- 14 LaBr3(Ce)
- p-γ Coincidence with Si detector (SD) @ 120°



Aim:

- Test of the γ spectrometer performance under the high background conditions of a NUMEN experiment
- Detection of γ-rays from the Coulomb excitation of a **Ta target** from the **^{16}O beam** in a very high background originated from γ-rays emitted in the fusion-evaporation of the beam with the **Ti target**
- Experiment designed with a signal to background similar to that of a NUMEN experiment



$$\frac{N_{gCoinc}}{N_{gBG}} = \frac{\sigma_{Coulex}}{\sigma_{Coulex} + \sigma_{Elastic}} \frac{\varepsilon_{Coulex}}{\varepsilon_{Average}} \frac{M_{Coul}}{M_{Average}} \frac{1}{k}$$

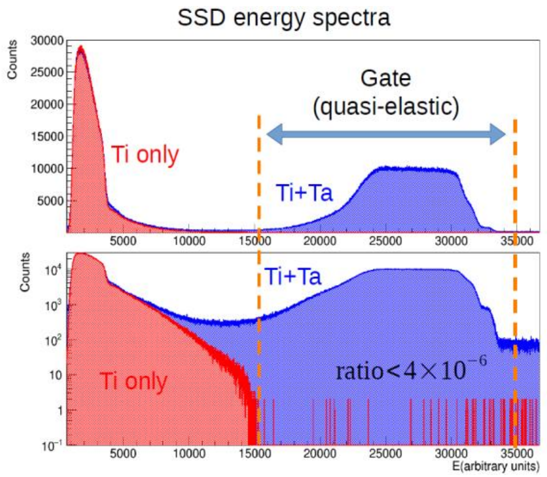
$$k = n_{Targ}\, \sigma_R\, N_{Bunch}$$

k, number of reactions / bunch

	Demonstrator	G-NUMEN
Beam intensity	1.2×10^{10}/s	1.0×10^{12}/s
Bunch Period	400 ns	50 ns
N_{Bunch}	5000	50000
k	0.5	1.0
n_{Targ}	8×10^{19}/cm²	7×10^{18}/cm²
N_{gCoinc}/N_{gBG}	0.2	0.2

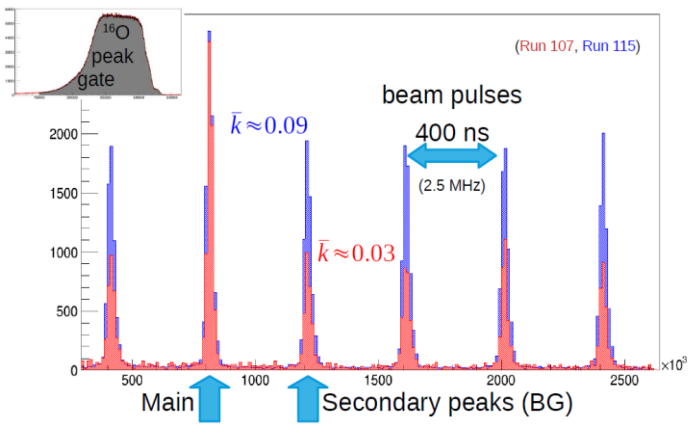
G-NUMEN: In-beam test of the Demonstrator under a high background

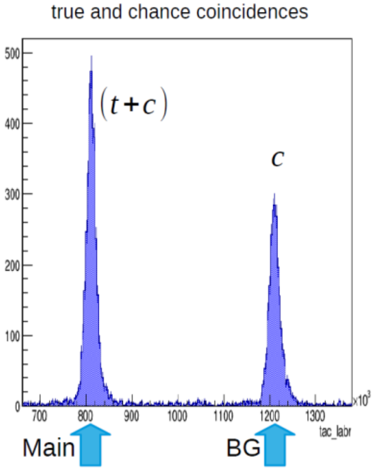
From preliminary analysis: Particle - γ coincidence allows successful selection of the signal (the energy peaks of interest) from intense background when good trigger selectivity is achieved (as with MAGNEX)



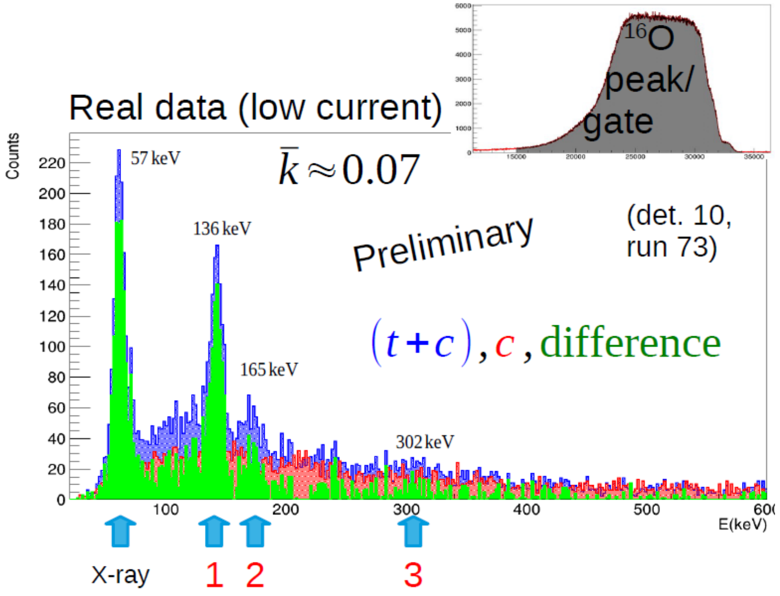
γ time spectra with respect to RF

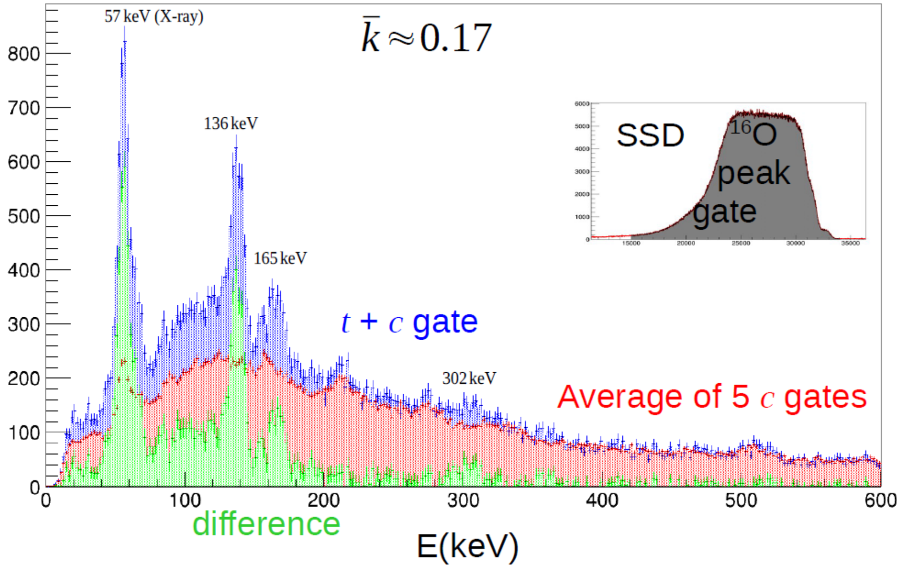
$\bar{k}$: average number of reactions per beam bunch

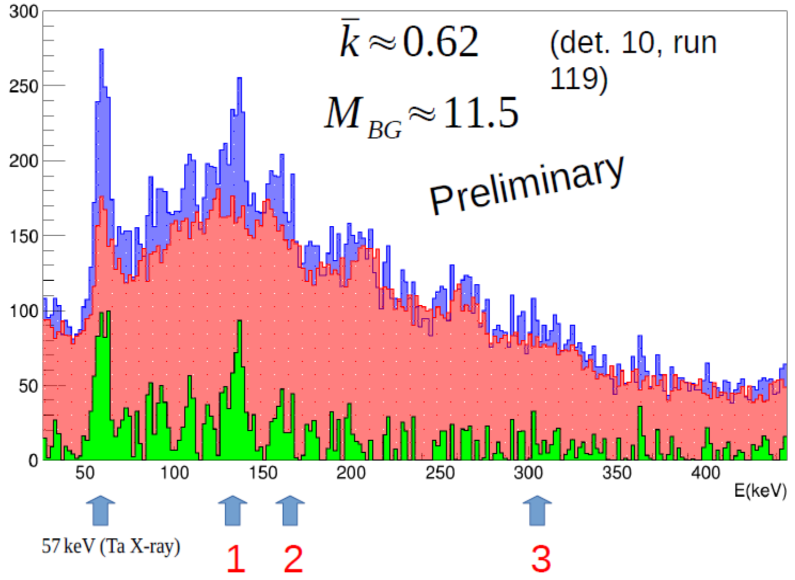




$$t/c = N_{\gamma Coinc}/N_{\gamma BG}$$







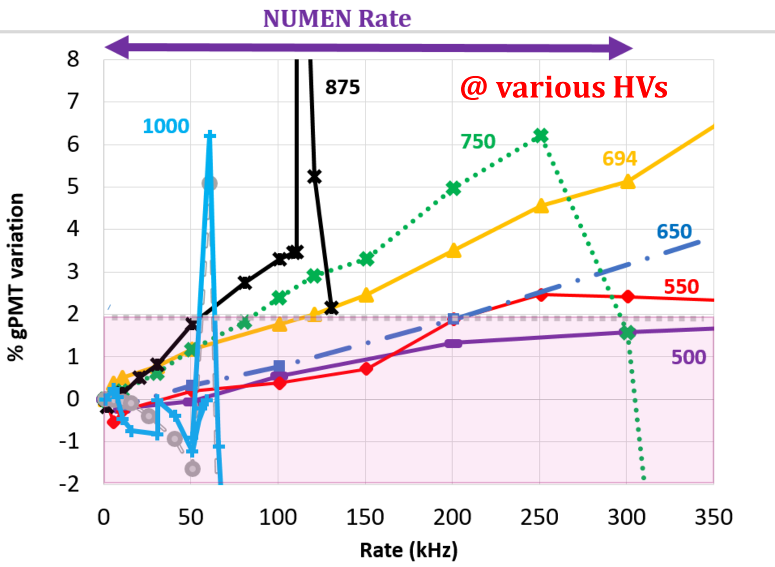
G-NUMEN: Gain stability with the EPIC voltage divider

The LaBr3(Ce) scintillator is coupled with a Hamamatsu R6231 PMT tube and an active voltage divider (EPIC crystal company)

Gain variation of the output pulse with increasing count rate was observed -> **restrictions** on the count rate sustainable by the detector

Loss of linearity of the output pulse charge with increasing the energy of the incident photon

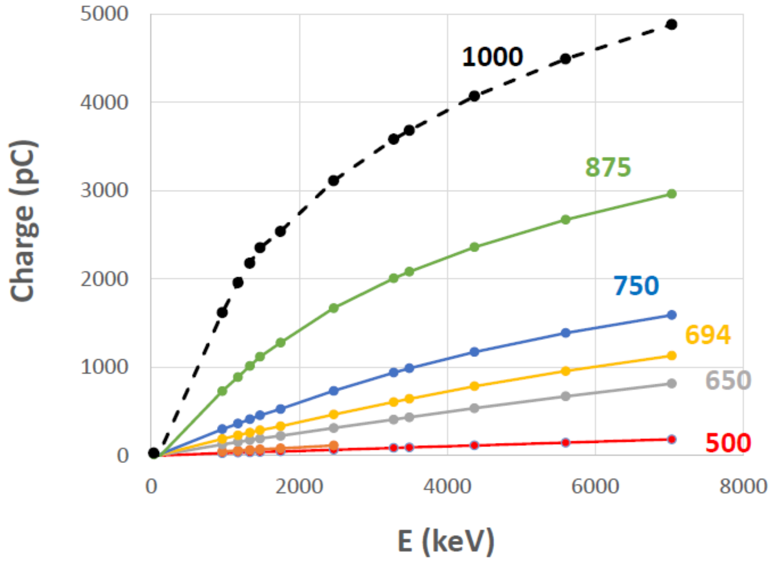
Gain variation with rate



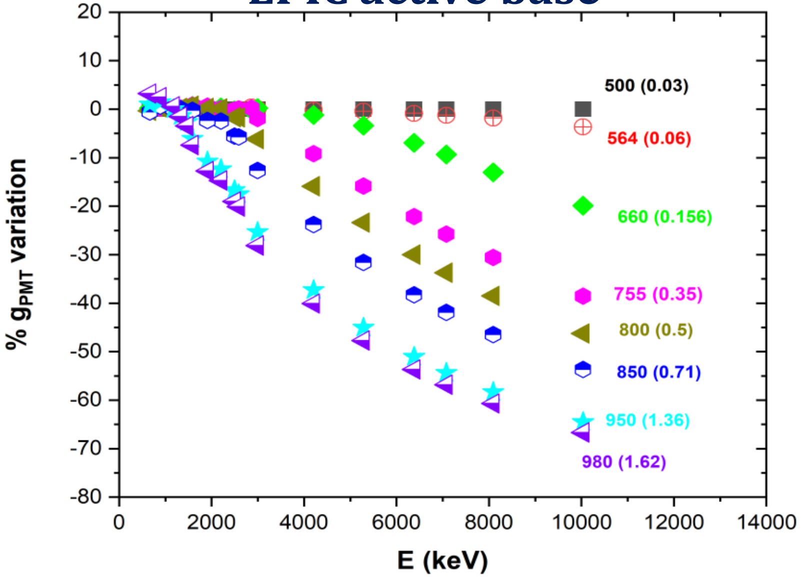
E.M. Gandolfo et al., Instruments ***2023****, 7, 28*

Loss of linearity with energy

EPIC active base



EPIC active base

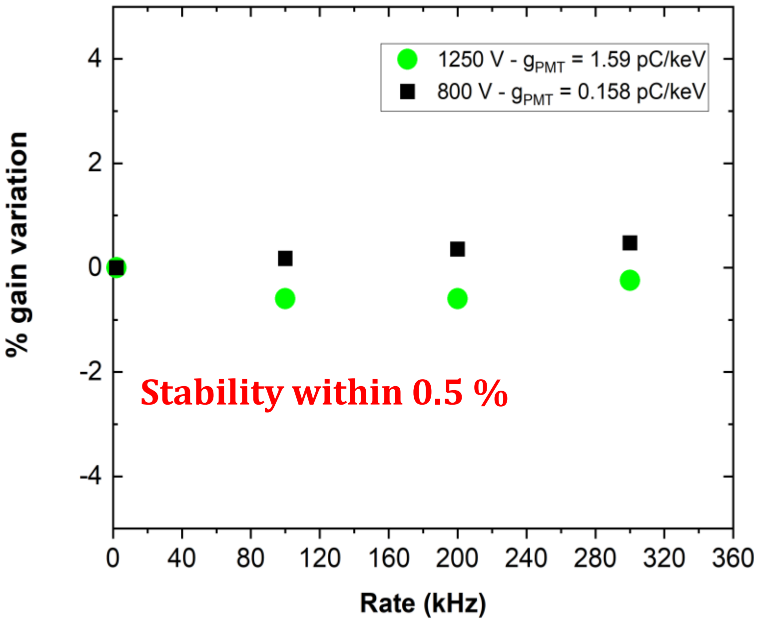


G-NUMEN: New full active voltage divider for high rate measurements

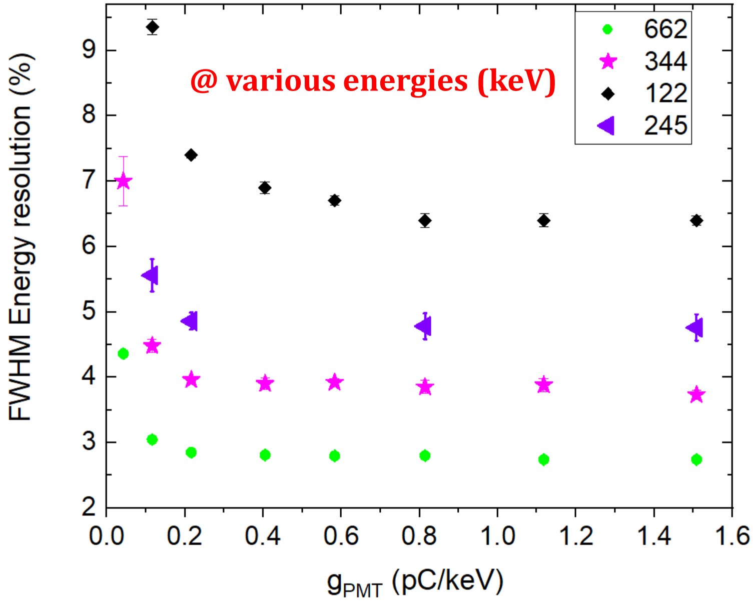
- A **new full active voltage divider** was developed that stabilizes the interstage voltage of the PMT dynodes by employing a transistor of PMOS type for each dynode.

- Highly stable gain (within 0.5 %) in the overall range of rate;
- Very good energy resolution (2.8 % FWHM at 662 keV) ;
- Very good time resolution (less than 1 ns FWHM) resolution;
- the best achievable output pulse linearity with energy with the considered PMT by employing a "tapered" version of the PMOS voltage divider

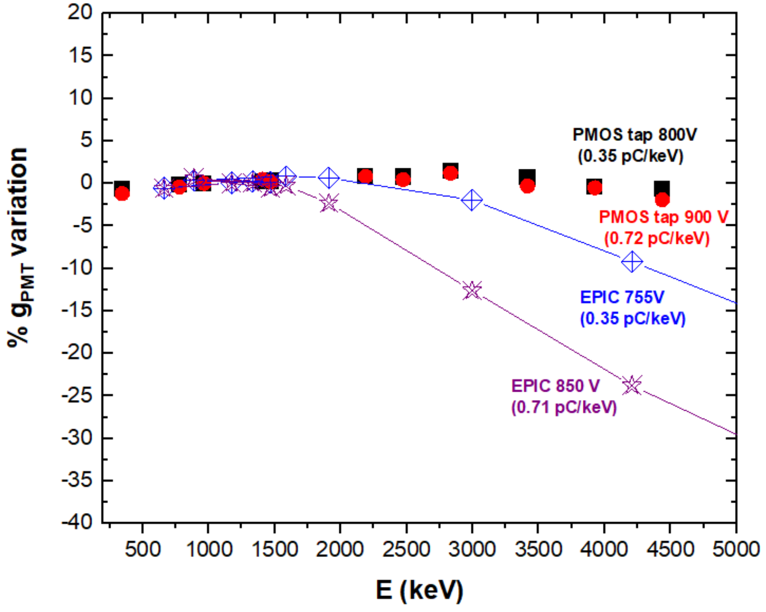
Gain stability with count rate



Energy resolution



Output pulse linearity with energy



D. P. et al., paper in preparation

G-NUMEN: Neutron irradiation at ALTO, IJCLab (Orsay, France)

Spokesperson: E.M. Gandolfo

^{18}O at 60 MeV/u I= 10^{12} pps
For a **typical 30 days-run**
at 40-50 deg
~1.4.10^{11} neutrons/cm^2
~4.10^{10} γ/cm^2

^{7}Li (p,n)^{7}Be
E= 16.7 MeV
E (^{7}Li) = 16.7 MeV
H cell length= 3.5 cm
H pressure = 1.1 –1.3 atm

Aim:

- **Evaluate the radiation damage induced by high fluence of fast neutrons on a LaBr$_3$(Ce) detector.** Experiment performed with the Tandem accelerator of the ALTO facility (IJC Laboratory) using the LICORNE source which provides a fast neutron flux exploiting the reaction ^{7}Li (p,n)^{7}Be in inverse kinematics (neutron fluxes up to 10^8 n/(s.sr))
- The characteristics of the LaBr$_3$(Ce) were studied before, during and after the exposure to a neutron fluence: the intrinsic background, the time resolution, the gain and the energy resolution.

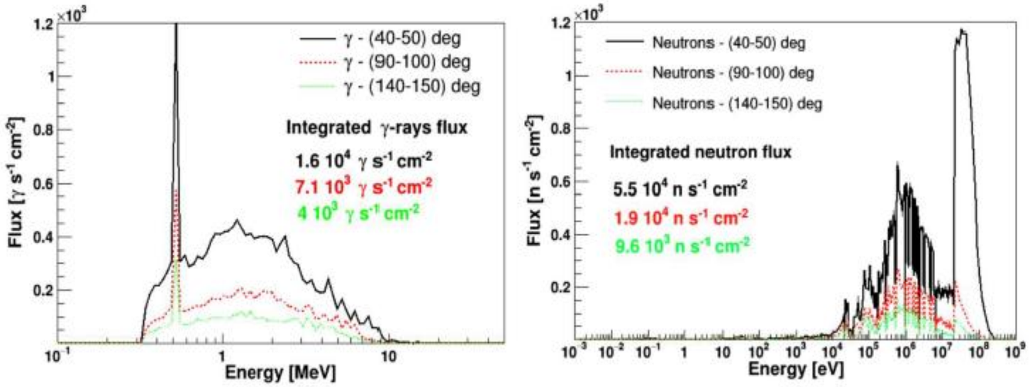
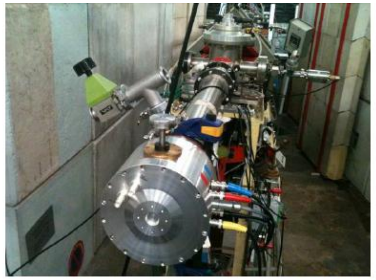
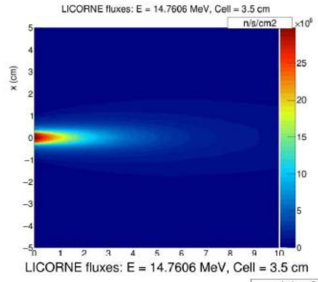
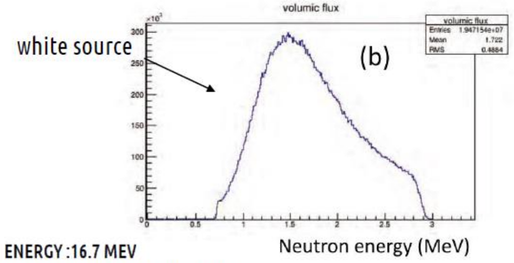


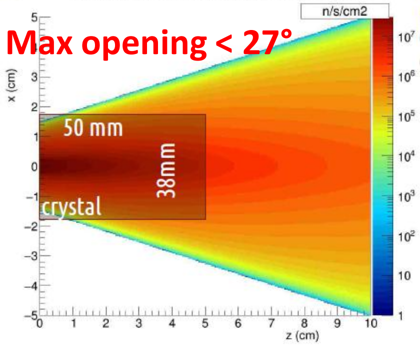
Figure 5.1 - FLUKA simulation of the gamma (left) and neutron (right) flux and energy in the array region for some angular slices of the array. The results refer to the reaction ^{18}O @ 60 AMeV on Sn 500 nm thick target with a beam flux of 10^{12} pps [O. Sgouros].

FLUKA simulations, O. Sgouros

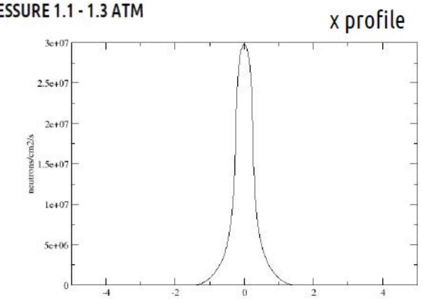








ENERGY :16.7 MEV
NOMINAL INTENSITY: 70 – 120 nA
CELL DIMENSION: 3.5 CM
CELL PRESSURE 1.1 - 1.3 ATM



E.M. Gandolfo, PhD Thesis , Naples 2022

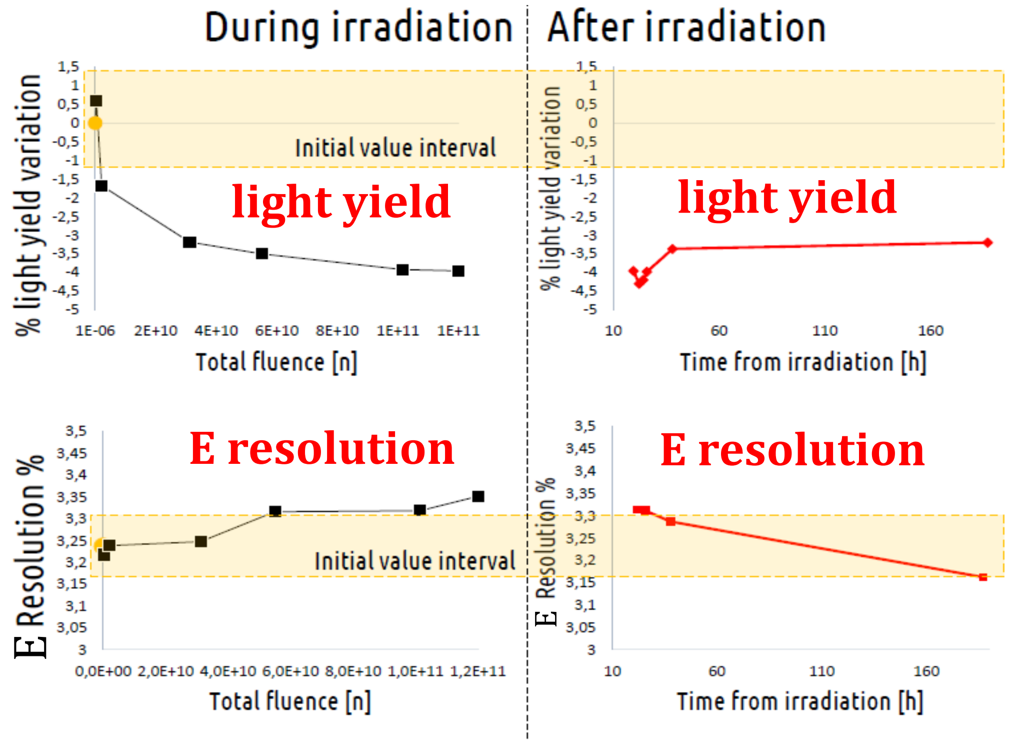
G-NUMEN: Neutron irradiation at ALTO

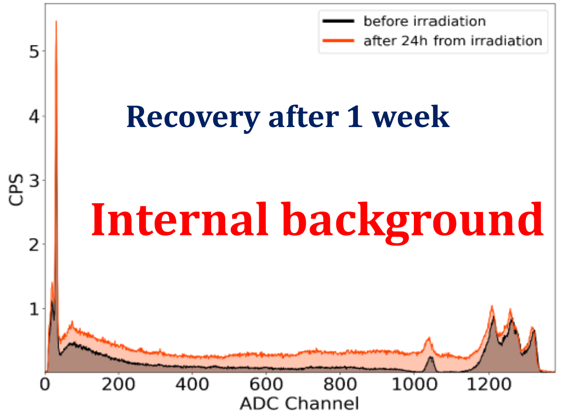
Irradation with a total fluence of **10^{11} neutrons [(1.1± 0.2)x 10^{10} n/cm^2]**

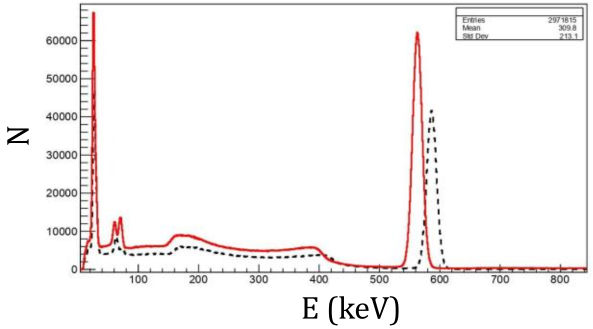
Monitoring of the effects of the radiation damage on:
- Energy resolution @662 keV
- Light yield
- Time resolution for ^{22}Na coincidence

^{7}Li Coulomb excitation peak for monitoring the ^{7}Li flux

Monitoring of neutron flux/fluence through:
- ^{7}Be decay
- Activation foil of natural Indium







E.M. Gandolfo, PhD Thesis, Naples 2022

Results from this first campaign:

- **Decrease** of **light yield** by 4%, slight recovery after one week: final value of decrease 3%
- **Energy resolution deterioration** by about 5%. Total recovery after 20 days
- Unaffected **time resolution**
- A factor 2 **increase** of the **internal background,** recovery after 1 week

The $LaBr_3(Ce)$ **still meets the NUMEN requirements** after irradiation with a neutron fluence of **10^{10} n/cm^2**, though **continuous energy calibration** is needed to correct light yield variations.

Data will be taken soon for a higher neutron fluence **10^{11} - 10^{12} n/cm^2** at IPEN Brasil

New target system

Goal: Produce targets of specific isotopes to be irradiated with intense ion beams

Candidates isotopes: *^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{124}Sn, ^{128}Te, ^{130}Te, ^{136}Xe, ^{148}Nd, ^{150}Nd, ^{154}Sm, ^{160}Gd, ^{198}Pt*

Idea: Deposition of few hundreds of nm of isotopic materials on **high in-plane thermal conductivity** (1600-2200 $Wm^{-1}K^{-1}$) substrates characterized by **low stopping power, high mechanical strength, high purity and low thickness**

***Substrate*:** Few μm of graphite foils like **Higly Oriented Pyrolitic Graphite (HOPG)** other **multi-layer graphene (MLG)** candidates.

- **Heat dissipation**
  Cooling system
- Target and cooling system **compact**
  Free solid angle around the target (γ-ray spectrometer)
- **Energy resolution** for the DCE products
  Thin and uniform targets

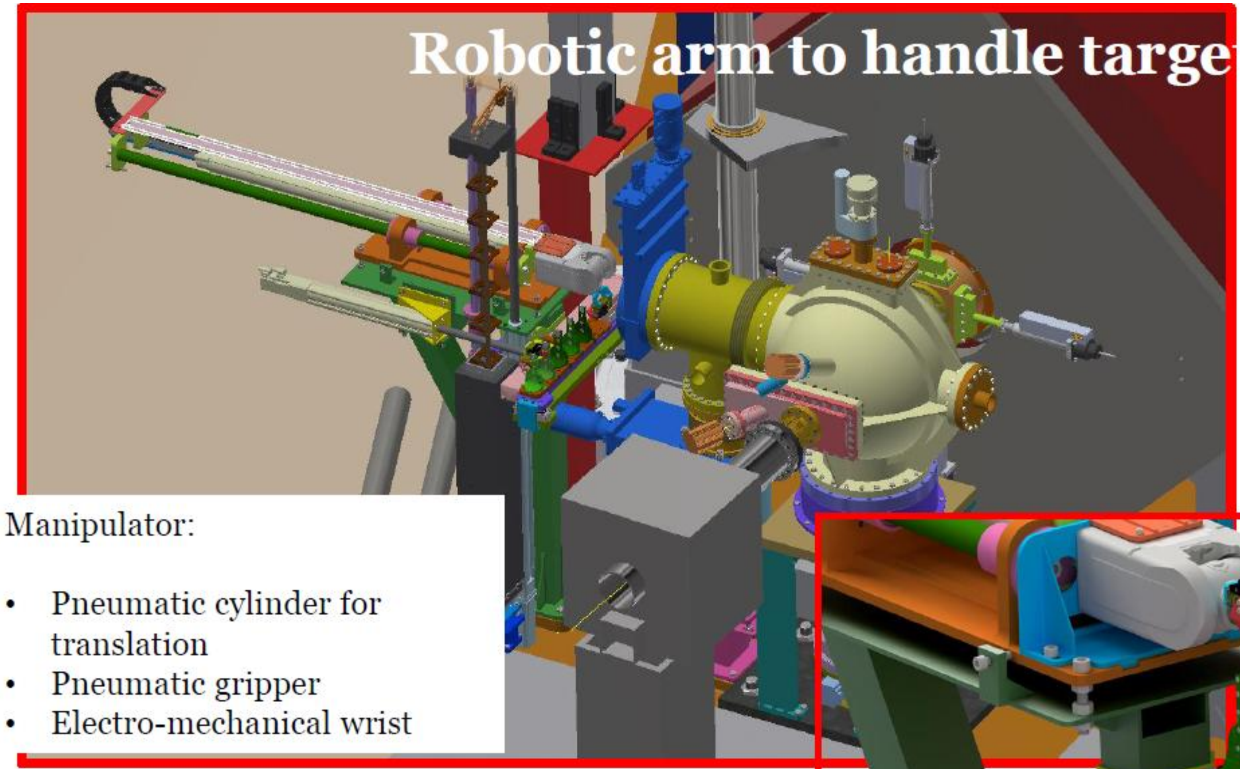
First attempts of target evaporation on HOPG (from Optigraph)

New target system: cooling and automatic manipulation

Cooling system to dissipate the heat from the beam spot: Target encased in a Cu holder, mounted on top of a cryocooler that can dissipate up to 20 W and kept at 40 K

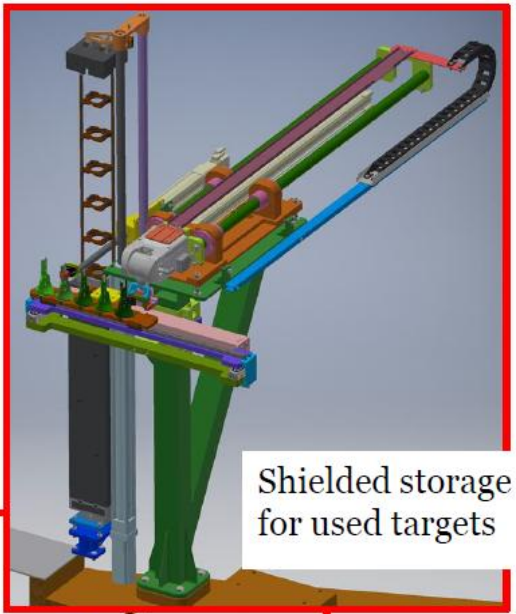
- **Numerical codes for equilibrium temperature:** Solves the time-dependent heat equation in target + HOPG substrate to determine the evolution in space and time of the temperature until steady state (*F. Iazzi et al, WIT Trans. on Eng. Sciences 116 (2017) 61)*

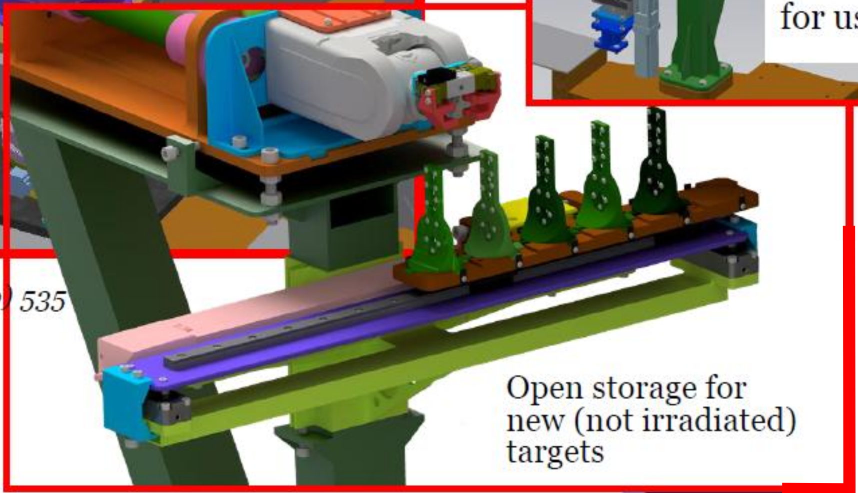
D. Calvo et al., J. Phys. Conf. Ser. 2374 (2022) 012029 and NIM A vol. 1041 (2022) 167336



Manipulator:

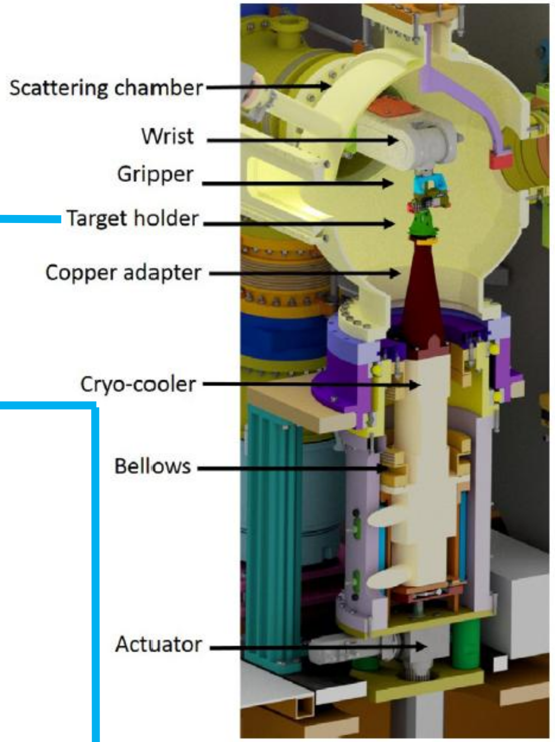
- Pneumatic cylinder for translation
- Pneumatic gripper
- Electro-mechanical wrist





D. Sartirana et al., Mechanisms and Machine Science 84 (2020) 535

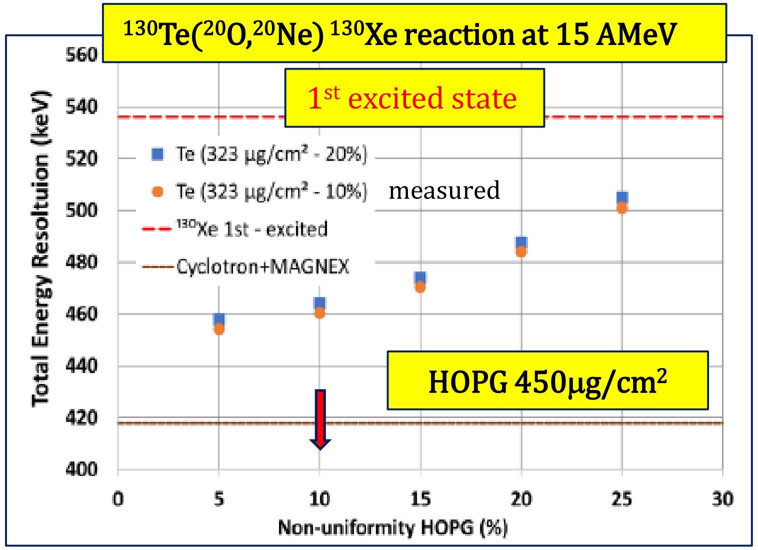
Automatic system to handle the targets and manage the target replacement avoiding human presence in the experimental hall



Targets development: energy resolution

Requirement: good energy resolution to separate DCE transitions to ground and 1st excited state -> **thin and uniform target and substrate -> a very complex process**

- **First depositions by electron-beam evaporation of Ge, Te, Se, Mo, Sn and Cd isotopes on HOPG** by: **varying** the evaporation rate, the substrate thickness and temperature, **with** and **without** a deposition buffer (Cr buffer)
- **Standard evaporation conditions** for Te, Ge, Se. Succesful **Mo target** depositions on **HOPG heated** at temperature 300°. More studies for Cd and Sn are needed (*M. Fisichella et al., submitted to EPJA, 2025)*
- **First implantation tests (UNAM, Mexico)** of ^{127}I and ^{81}Br ions electromagnetically selected on a 50 μm graphite substrate at E~1 MeV (at 200-300 nm depth). The protocol will be used to produce the noble gases implanted targets **Xenon** and **Kr** of interest for NUMEN (not easy to make thin targets as they do not produce solid compounds).

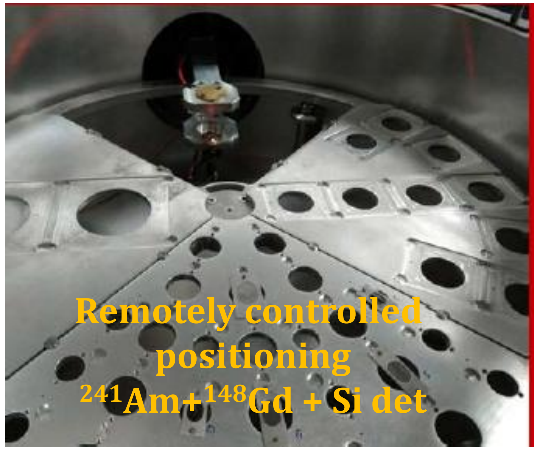


M. Fisichella et al., EPJ Web of Conferences 285 (2023) 01001

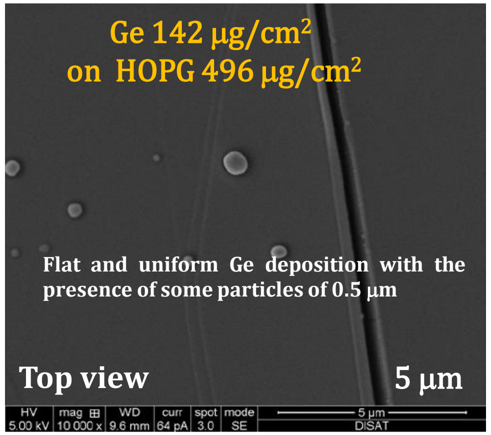
Relative non uniformity: $\delta(\rho x)/(\rho x)$ with ρx the thickness

Relative non-uniformity of HOPG is the highest contribution in ΔE: it should be < 10%

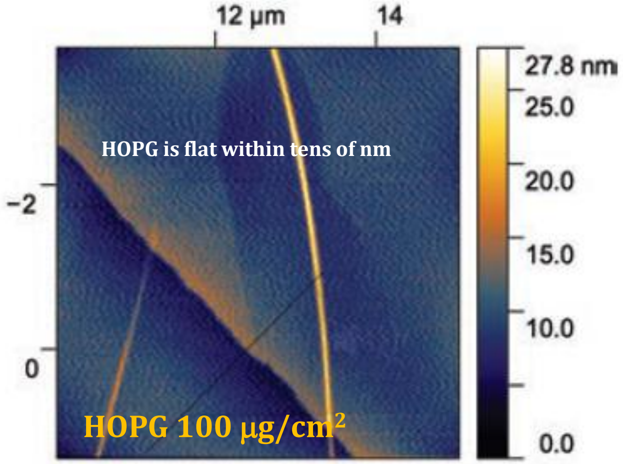
α-particle transmission (APT)
(CACTUS, LNS)
Mean energy-loss: thickness
width: non-uniformity



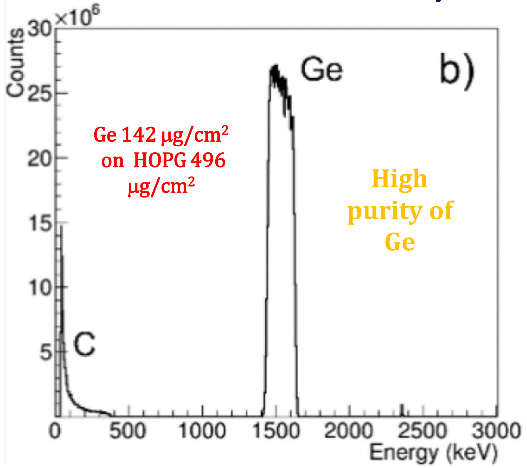
Field Emission Scanning Electron Microscopy (FESEM) (Politecnico, Torino, INFN Genova)
Surface morphology
(few nm resolution in the planar axes)



Atomic Force Microscopy (AFM)
Surface rugosity
(nm resolution in the z axis)



Rutherford Backscattering (RBS)
AN2000 INFN-LNL
Thickness, elemental analysis

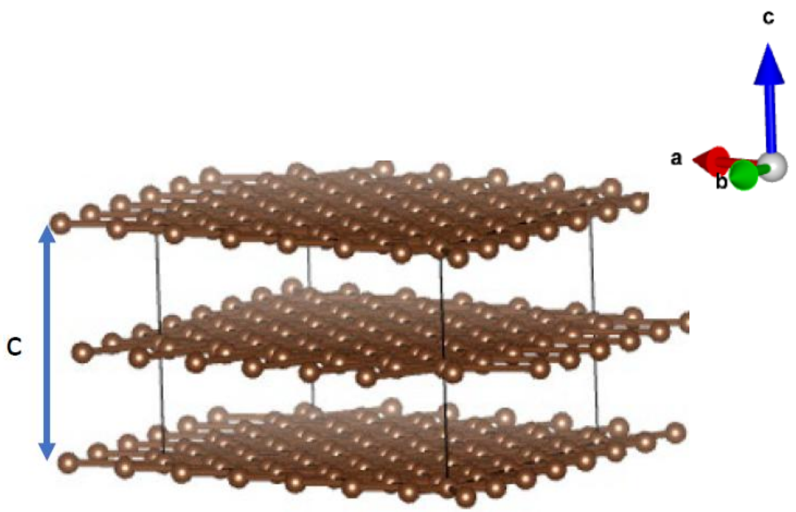


Targets development: MLG candidates

HOPG (Optigraph) non-uniformity > 10 %: not suitable as substrate of targets

New candidates to consider: Multi-layer graphene (MLG)

1)**High in-plane thermal conductivity** ($k_{//}$=1600-2200 W m^{-1} K^{-1}) to dissipate heat efficiently toward the cooling system
2) **Thickness** around 2 μm (450 mg/cm^2) and good **thickness uniformity** to minimize the impact on the energy resolution of the reaction products



Interplanar distances d = c/2

- HOPG (high oriented pyrolitic graphite) from Optigraph, Germany
- MLG (multi-layer graphene) from Kaneka, Japan
- MLG from ACF-metals, Arizona, USA (and Appl. Nanotech, Texas)
- MLG from Micromatter, Canada

- HOPG-Optigraph

CVD + HT HP annealing

- MLG-Kaneka

Pyrolisis of thin polyimide film

- MLG-ACF/Nanotech

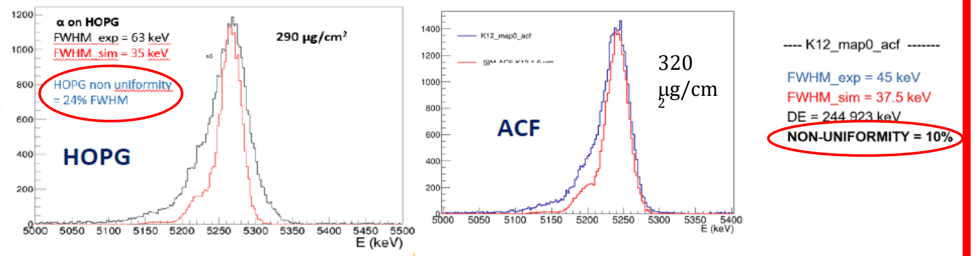
GO + rGO

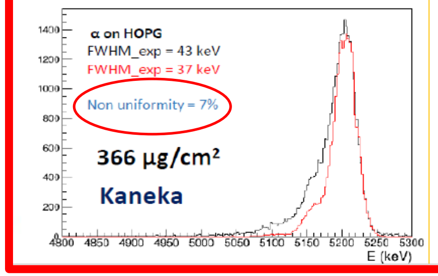
- MLG-Micromatter

Pulsed Laser Deposition (PLD)

Targets development : MLG candidates

- The **thermal conductivity K** was deduced from the density (XRD measurements done by INFN, Genova) and the thermal diffusivity (taken from literature) of the foils: $K = \alpha \rho C_p$ with α = thermal diffusivity, ρ = density, C_p = specific heat
- The **non-uniformity** obtained with α particle transmission (CACTUS, LNS)
- Raman measurements to study **defects** after irradiation (increasing the power of the laser)





Non-uniformity deduced comparing FWHM of data with that of a simulated spectrum of a uniform substrate (SRIM program)

Company	Calculated Density [g/cm³]	Purity degree/ crystallinity	Thickness [μm]	Thermal diffusivity [mm²/s]	Thermal conductivity [KWm⁻¹K⁻¹]	Tickness uniformity by APT
HOPG-Optigraph	2.265	99.9%/HO	2	1550	2.3	poor
MLG-Kaneka	2.272	99%/HO	1.6	1200	2.0 (*)	good
MLG-ACF/Nanotech	2.02	Fair	1-3	1308	1.93 (*)	good
MLG-Micromatter		amorphous			10^{-2}-10^{-1}	

(*) literature values

MLG foils (**ACF/Nanotech**) and **Kaneka** foils seem to be a **valid alternative** as substrates for NUMEN to pyrolitic carbon foils (HOPG): first tests of target evaporation

- **In addition,** on-going R&D program focused on the synthesis in-house and characterization of MLG foils with different techniques: low pressure filtration, pyrolysis of Kapton.

Final objective to create materials with a suitable structure (e.g. ordered, layered, smoothness, thermal stability, etc.) which can be adapted to a **variety of applications** as well as substrate for the **NUMEN targets**: **cost optimization, timely available and reproducible samples for experiments**

Targets development: substrate radiation damage

- **HOPG high thermal conductivity could be reduced after some time of beam irradiation**: experimental evaluation of radiation damage at the Sao Paulo Pelletron accelerator using **^{35}Cl at E = 70 MeV** to emulate the NUMEN target degradation conditions: analysis on-going

- **Neutron irradiation of HOPG foils** with a **14-MeV neutron beam up to fluences of 1.7x10^{10} n/cm^2** (SP, Brazil) shows significant damage to crystal structure and a 50% reduction of the thermal conductivity.

- Neutron generator (IEAv, São José dos Campos, SP, BRAZIL)
  14MeV

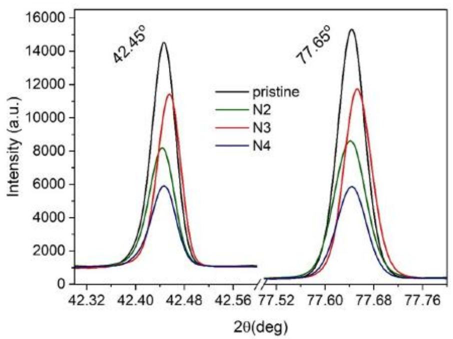
Table II - Irradiation time and neutron fluence incident on each HOPG foil.

SAMPLE	Irradiation Time (hours)	Fluence (n/cm^2)
N2	10.5	$5.18(13)\times10^{9}$
N3	24.4	$1.27(2)\times10^{10}$
N4	30.5	$1.7(3)\times10^{10}$

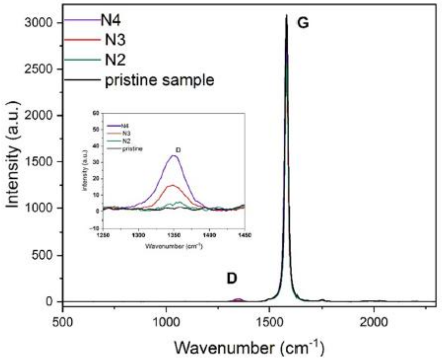
In-plane thermal conductivity κ(T) measured at 300 K for all samples.

SAMPLE	κ(T) (W/m.K)	κ(T) decrease (%)
Pristine	1249 (62)	–
N2	511 (31)	59.1
N3	602 (16)	51.8
N4	568 (11)	54.2

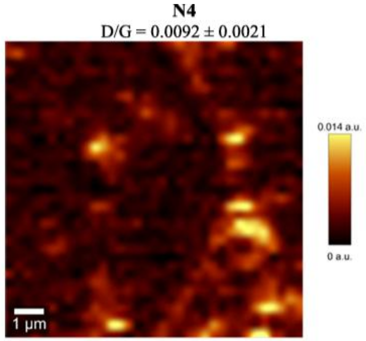
The intensity loss with increased irradiation is attributed to formation of defects

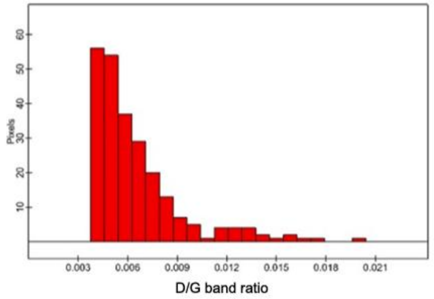


Micro-Raman spectra: a larger D peak represents more structural defects in the sample



Micro-Raman images of the 10 ×10 μm^2 regions for pristine N4 with the respective D/G peaks intensity ratio. The histograms represent the distributions of the D/G band intensity ratios in the area analyzed.





The max increase of D/G for the N4 sample evidences a decrease of crystallinity due to the higher neutron irradiation

M.A. Guazzelli et al., Diamond & Related Materials 151 (2024) 111803

- **Next step: Test** of the **complete target cooling system** in realistic experimental conditions using a ^{20}Ne ion beams at 14 MeV/n at 5.10^{11} pps. Evaluate the life expectancy of NUMEN targets, by investigating the substrate thermal conductivity drop due to radiation damages. Post-irradiation measurements on the substrate will relate the radiation induced lattice damages with thermal properties

Conclusions and perspectives

- The NUMEN project has an ambitious program related to the study of DCE reactions
- An extensive upgrade of the CS at INFN-LNS and of the MAGNEX spectrometer will give a unique opportunity for exploring all the nuclei candidate for $0\nu\beta\beta$
- Significant technological advancements have been required for the production of thin and uniform targets and for the development of novel detectors for use in high-radiation environments
- Several campaigns of characterization and radiation hardness evaluation of detectors and targets have been successfully completed and others are currently underway in order to be ready for the final phase of the project: start of the experimental campaign

Thank you for your attention !!!

The NUMEN collaboration

(NUclear Matrix Elements for Neutrinoless double beta decay)

Spokespersons: F. Cappuzzello (cappuzzello@lns.infn.it) and C. Agodi (agodi@lns.infn.it)

Proponents: C. Agodi, A. Anastasio, R. Babu, A. Boiano, S. Brasolin, G.A. Brischetto, M.P. Bussa, D. Calvo, F. Cappuzzello, D. Carbone, G. Castro, M. Cavallaro, K. Challa, I. Ciraldo, M. Colonna, A. Comite, G. D'Agostino, C. De Benedictis, G. De Gregorio, F. Dumitrache, C. Ferraresi, D. Gambacurta, C. Garofalo, A. Gargano, M. Giovannini, L. La Fauci, C. Lombardo, L. Neri, A. Pandalone, L. Pandola, R. Panero, M. Paterna, D. Pierroutsakou, A. Pitronaci, A. Rovelli, A.D. Russo, E. Santopinto, D. Sartirana, O. Sgouros, V. Soukeras, A. Spatafora, D. Torresi, S. Tudisco, I. Valinotto, A. Vanzanella, V. Izzo

Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Italy
Dipartimento di Fisica, Università di Torino, Italy
Dipartimento di Fisica e Astronomia "Ettore Majorana", Università di Catania, Italy
Dipartimento di Chimica e Chimica Industriale, Università di Genova, Italy
DISAT, Politecnico di Torino, Italy
Dipartimento di Matematica e Fisica, Università degli Studi della Campania Luigi Vanvitelli
DIMEAS, Politecnico di Torino, Italy

N. Added, V.A.P. de Aguiar, L.H. Avanzi, E.N. Cardozo, E.F. Chinaglia, K.M.Costa, J.L. Ferreira, M.A. Guazzelli, R. Linares, J. Lubian, S.H. Masunaga, N.H. Medina, M. Moralles, J.R.B. Oliveira, T.M. Santarelli, R.B.B. Santos, J. V. Schervenin, V.A.B. Zagatto

Instituto de Fisica, Universidade de Sao Paulo, Brazil
Centro Universitario FEI Sao Bernardo do Brazil, Brazil
Instituto de Fisica, Universidade Federal Fluminense, Niteroi, Brazil
Instituto de Pesquisas Energeticas e Nucleares IPEN/CNEN, Brazil

P. Amador-Valenzuela, R. Bijker, E.R. Chávez Lomelí, H. Garcia-Tecocoatzi, R. Gleason, A. Huerta-Hernandez, D. Marín-Lámbarri, J. Mas-Ruiz, S. Sandova, C. Valencia
Instituto Nacional de Investigaciones Nucleares, Mexico
Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico
Instituto de Fisica, Universidad Nacional Autónoma de México, Mexico
Instituto Tecnológico y de Estudios Superiores de Monterrey, Mexico

I. Boztosun, H. Djapo, A. Hacisalihoglu, Y. Kucuck, S.O. Solakcı, A. Yildirin
Department of Physics, Akdeniz University, Turkey
Ankara University, Institute of Accelerator Technologies, Turkey
Recep Tayyip Erdogan University, Department of Physics, Turkey

H. Lenske, N. Pietralla
Department of Physics, University of Giessen, Germany
Institut fur Kernphysik, Technische Universitat Darmstadt, Germany

L.M. Donaldson, T. Khumalo, R. Neveling, L. Pellegri
iThemba Laboratory for Accelerator Based Scienes, Cape Town, South Africa
School of Physics, University of the Witwatersrandy, Johannesburg, South Africa

S. Koulouris, K. Palli, A. Pakou, G. Souliotis
Department of Chemistry, National and Kapodistrian University of Athens and HINP, Greece
Department of Physics and HINP, University of Ioannina, Greece

H. Petrascu
Department of Nuclear Physics, Horia Hubulei National Institute of Physics and Nuclear Engineering, IFIN-HH, Romania

N. Auerbach
School of Physics and Astronomy Tel Aviv University, Israel

L. Acosta, J.A. Lay, Y. Ayyad, J. M. López González
Instituto de Estructura de la Materia. Consejo Superior de Investigaciones Científicas, Serrano Madrid, Spain
Departamento de FAMN, University of Seville, Spain
IGFAE, Universidade de Santiago de Compostela, E-15782 Santiago de Compostela, Spain

B. Urazbekov
Department of Nuclear Physics and Nanotechnology, L. N. Gumilyov Eurasian National University, Astana, Kazakhstan
Institute of Nuclear Physics, Laboratory of Low Energy Reactions, Almaty, Kazakhstan

97 Researchers
34 Institutions
11 Countries