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Upgrade of the MAGNEX spectrometer toward the high-intensity phase of NUMEN

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INFN LNS

European Commission

erc NURE

NUMEN

The NUMEN collaboration

https://web.infn.it/NUMEN/index.php/it/
F. Cappuzzello et al., Eur. Phys. J. A (2018) 54: 72

(NUclear Matrix Elements for Neutrinoless double beta decay)

96 Researchers
34 Institutions
12 Countries

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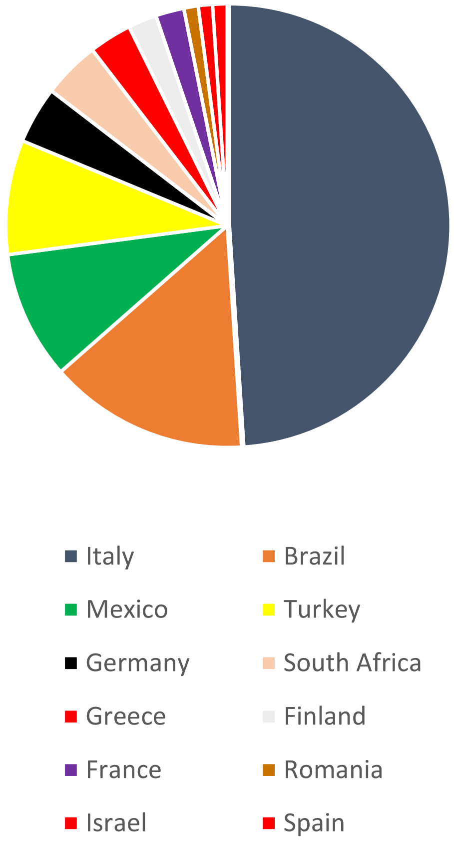


The MAGNEX facility at INFN-LNS

MAGNEX is a large acceptance magnetic spectrometer at INFN-LNS

LNS facility - Several users for different experiments with accelerated beams

see talk V. Soukeras

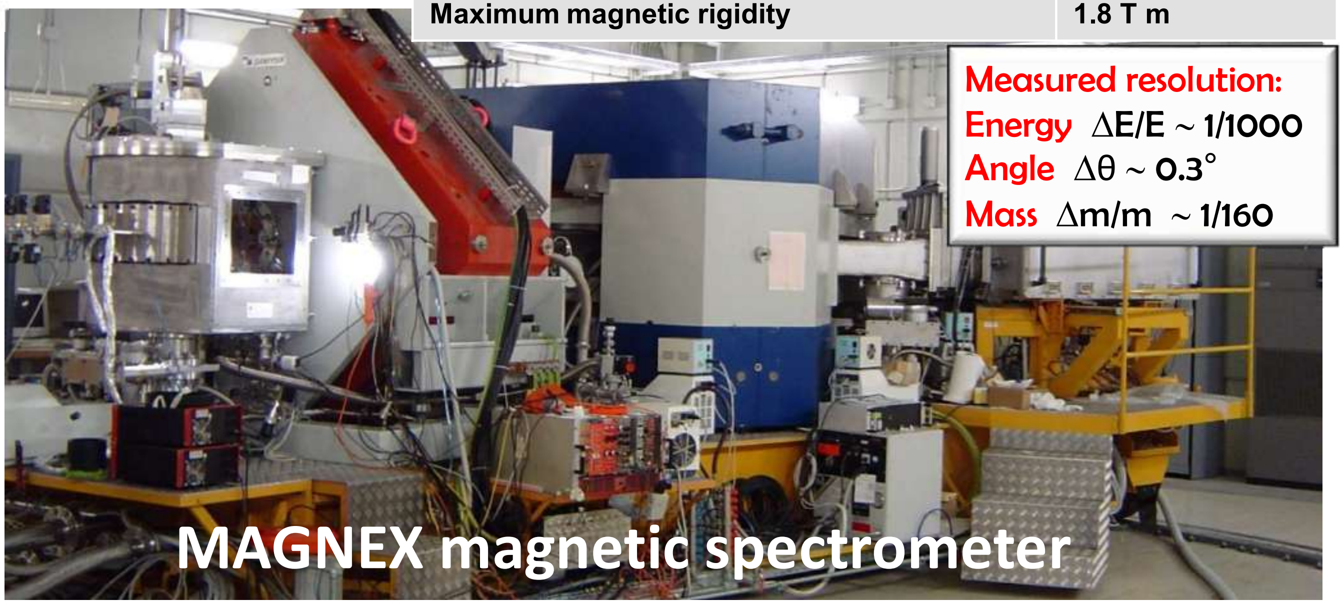
see talk S. Koulouris

Since 2014 it is the main facility for the **NUMEN** (Nuclear Matrix Elements for Neutrinoless double beta decay) project

F. Cappuzzello et al., EPJ A (2016) 52:167

Optical characteristics	Measured values
Angular acceptance (Solid angle)	50 msr
Angular range	–20° - +85°
Momentum acceptance	-14%, +10%
Momentum dispersion for k= - 0.104 (cm/%)	3.68
Maximum magnetic rigidity	1.8 T m

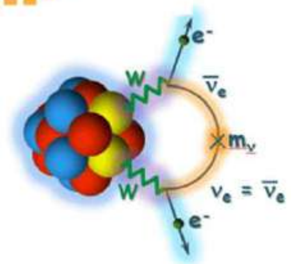
Scientific motivation for the **upgrade of the LNS superconducting cyclotron** and related infrastructures to deliver high intense beams (10kW)



PON(2014-2020) PIR01_00005

C.Agodi et al. Universe 2021,7(3),72

The physics case



0νββ is considered the **most promising approach to solve open problems in modern physics** (Neutrino absolute mass scale and nature)

0νββ decay **half-life**

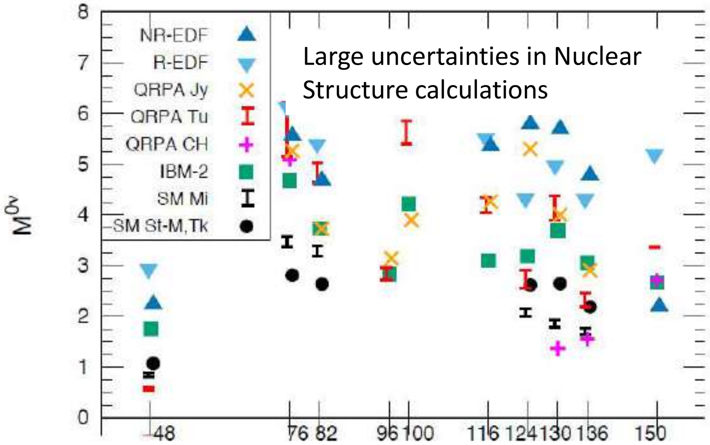
contains the average neutrino **mass**

$$\left(T_{1/2}^{0\nu\beta\beta}(0^+ \rightarrow 0^+)\right)^{-1} = G_{0\nu\beta\beta}\left|M^{0\nu\beta\beta}\right|^2 \left|f(m_i, U_{ei})\right|^2$$

Nuclear Matrix Element (NME)

$$\left|M_\varepsilon^{0\nu\beta\beta}\right|^2 = \left|\left\langle \Psi_f \middle| \hat{O}_\varepsilon^{0\nu\beta\beta} \middle| \Psi_i \right\rangle\right|^2$$

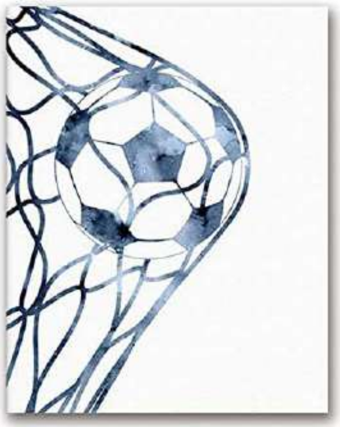
Transition probability of a **nuclear** process



Nuclear physics plays a key role!

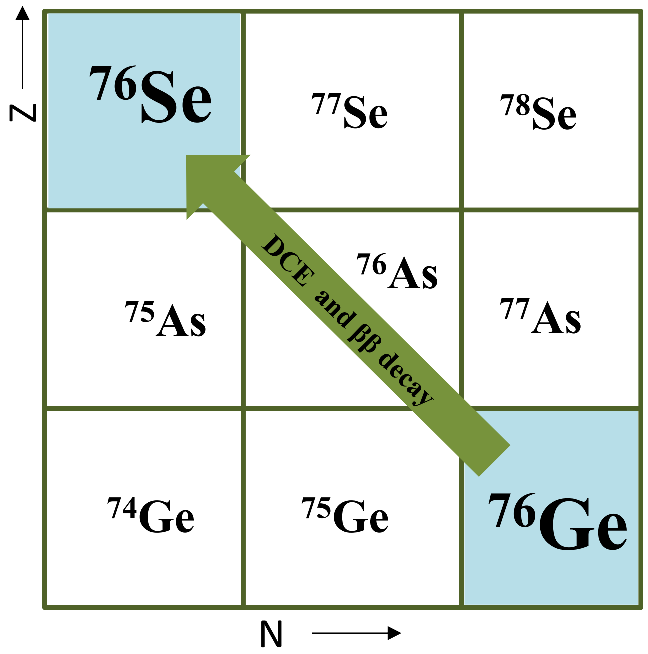
A new experimental tool

Heavy-Ion induced Double Charge Exchange reactions (DCE) as surrogate process of 0νββ to stimulate in the laboratory the same nuclear transition (g.s. to g.s.)



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



F. Cappuzzello et al., EPJ A (2018) 54:72

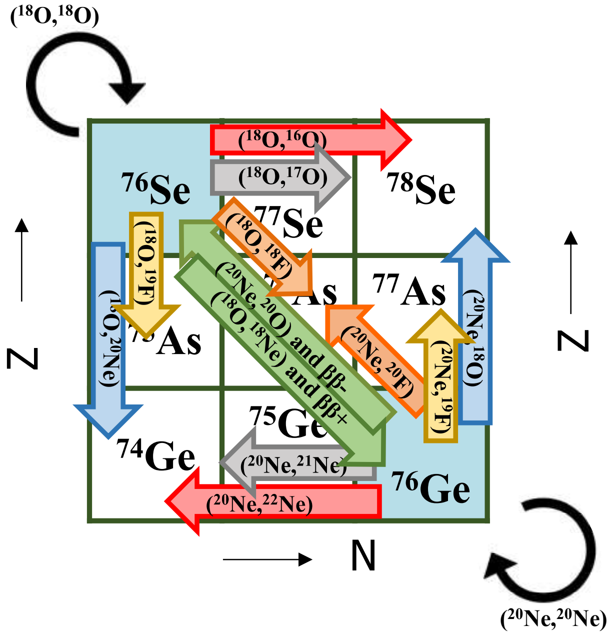
The NUMEN experiments

- **DCE on isotopes of interest for 0νββ** via **(^{20}Ne,^{20}O)** (ββ$^-$) and **(^{18}O,^{18}Ne)** ββ$^+$ from 15 MeV/u to 60 MeV/u

- **Complete net** of reactions which can contribute to the DCE cross-section: 1p-, 2p-, 1n-, 2n-transfer, SCE, (elastic and inelastic)

see talk F. Cappuzzello

see talk O. Sgouros



- ➢ Low cross sections of DCE (few nb)
- ➢ Only few systems have been studied in the present condition

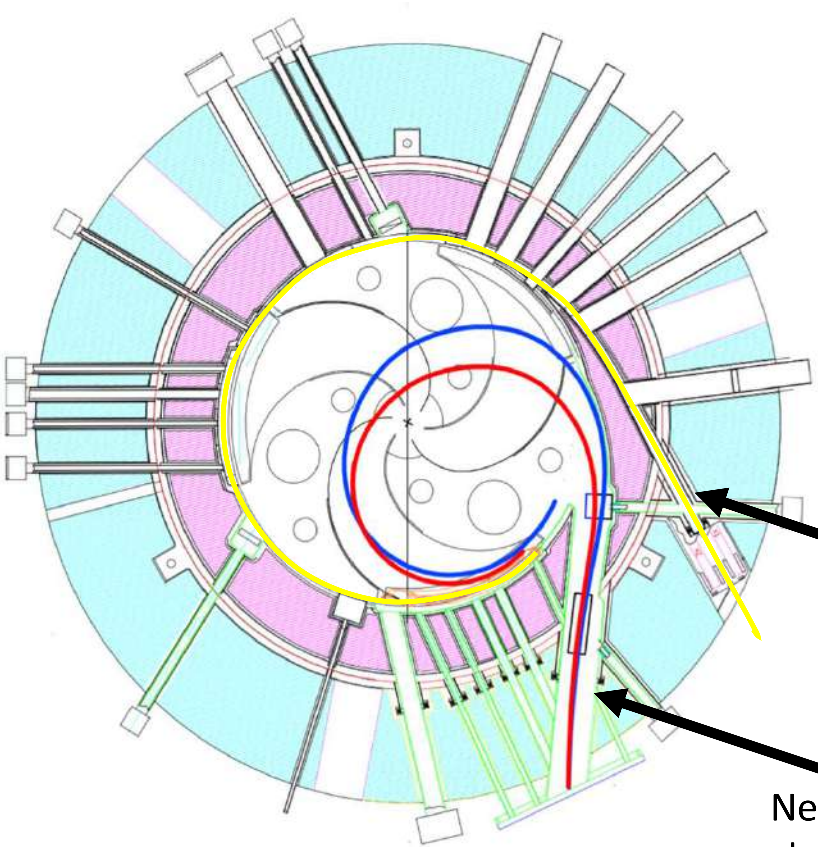
Much higher beam current is needed

Upgrade of the LNS Cyclotron and MAGNEX to work with two orders of magnitude more intense beam

NUMEN phases			
Phase 1	**Phase 2**	**Phase 3**	**Phase 4**
Feasibility study	Study of few cases + development of theory + R&D activity	Shutdown & Upgrade	Systematic study of all the targets
2014-2015	2015-2020	2020-2022	2023 - …

Upgrade of the LNS accelerator and beam lines

- **Superconducting Cyclotron** current (from 100 W to 5-10 kW);
- **beam transport line** transmission efficiency to nearly 100%
- Maintaining the present **beam quality**



Extraction by stripping

Extraction by stripping is based on the instantaneous change of the magnetic rigidity of the accelerated ion, when its charge state increases after crossing a thin stripper foil

For ions with A<40, and energies higher than 15 MeV/u, the abundance of q = Z exceeds 99%

Expected beam intensity

Ion	Energy	Isource	Iacc	Iextr	Iextr	Pextr
	MeV/u	eμA	eμA	eμA	pps	watt
^{12}C q=5+	30	200	30 (4+)	45 (6+)	$4.7 \cdot 10^{13}$	2700
^{12}C q=4+	45	400	60 (4+)	90 (6+)	$9.4 \cdot 10^{13}$	8100
^{12}C q=4+	60	400	60 (4+)	90 (6+)	$9.4 \cdot 10^{13}$	10800
^{18}O q=6+	20	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	3600
^{18}O q=6+	29	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	5220
^{18}O q=6+	45	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	8100
^{18}O q=6+	60	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	10800
^{18}O q=7+	70	200	30 (7+)	34.3 (8+)	$2.7 \cdot 10^{13}$	5400
^{20}Ne q=7+	28	400	60 (7+)	85.7 (10+)	$5.3 \cdot 10^{13}$	4800
^{20}Ne q=7+	70	400	60 (7+)	85.7 (10+)	$5.3 \cdot 10^{13}$	10280
^{40}Ar q=14+	60	400	60 (14+)	77.1 (18+)	$2.7 \cdot 10^{13}$	10280

Present performance $^{13}C^{4+}$ @ 45 MeV/u Pextr = 100 watt I= 1×10^{12} pps

Characteristics of the beam extracted by stripper

Energy spread FWHM 0.23%

Beam specification at the NUMEN experiment (expected at the exit of FRAISE separator)

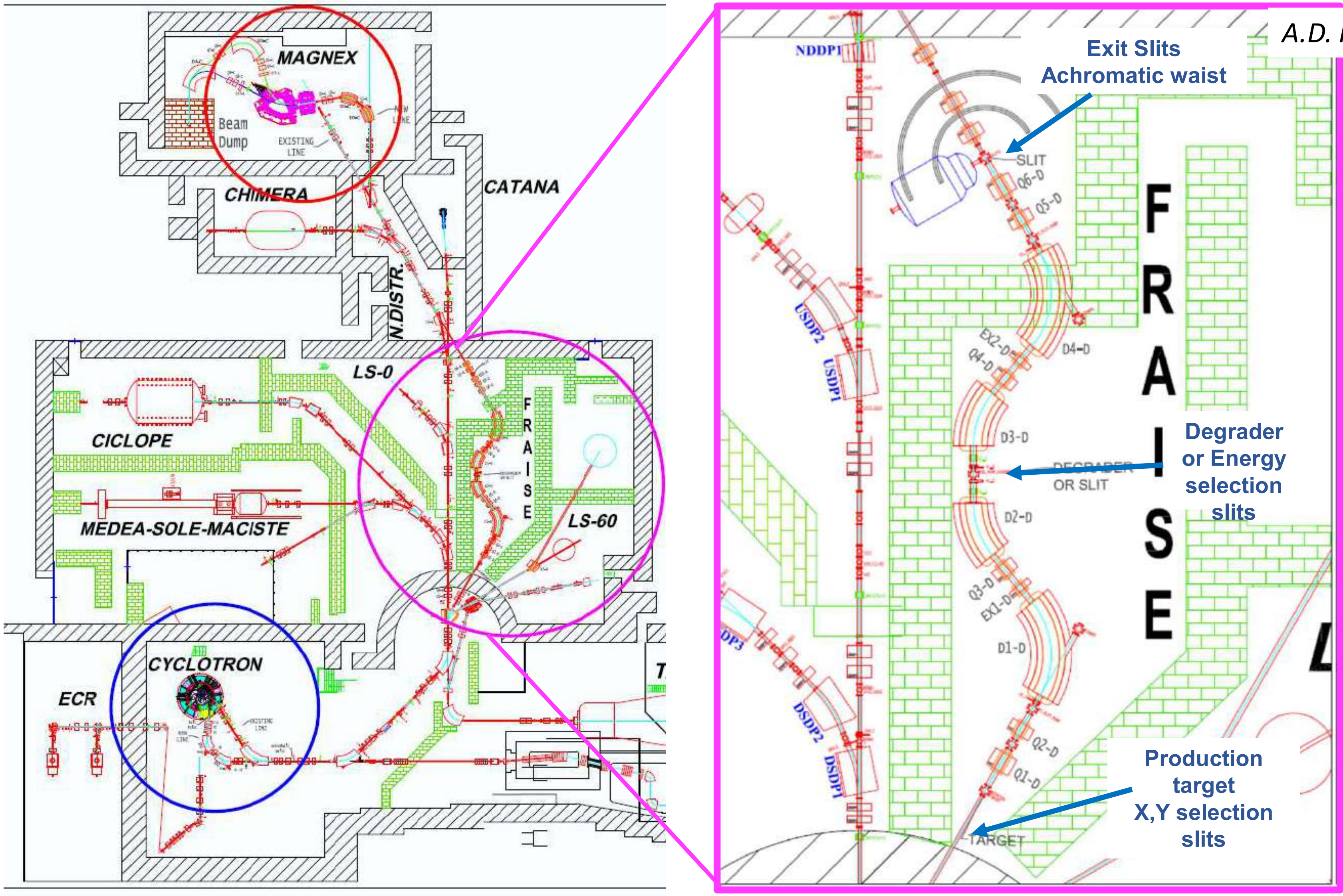
Radial Beam size FWHM 1.0 mm
Radial Divergence FWHM ± 4 mrad

Vertical Beam size FWHM 2.5 mm
Vertical divergence FWHM ± 7.5 mrad

Energy spread FWHM 0.1%

FRAISE:a new FRAgment In-flight SEparator

A.D. Russo et al., NIM B 463 (2020) 418



Main features:

- 4 dipoles and 6 quadrupoles, arranged in a symmetrical configuration
- maximum magnetic rigidity 3.2 *Tm*
- momentum acceptance ±1.2%
- solid angle acceptance ±2.5 *msr*,
- energy resolution 2500 for a beam spot size of 1 *mm*.

$$\mathbf{RP} = \left|\frac{R_{16}}{2x_0 R_{11}}\right| = \mathbf{2500}$$

(beam spot ±1 mm)

- thanks to high energy dispersion value at the symmetry plane, it will allow to deliver stable beams with an **energy spread of 0.1 %**

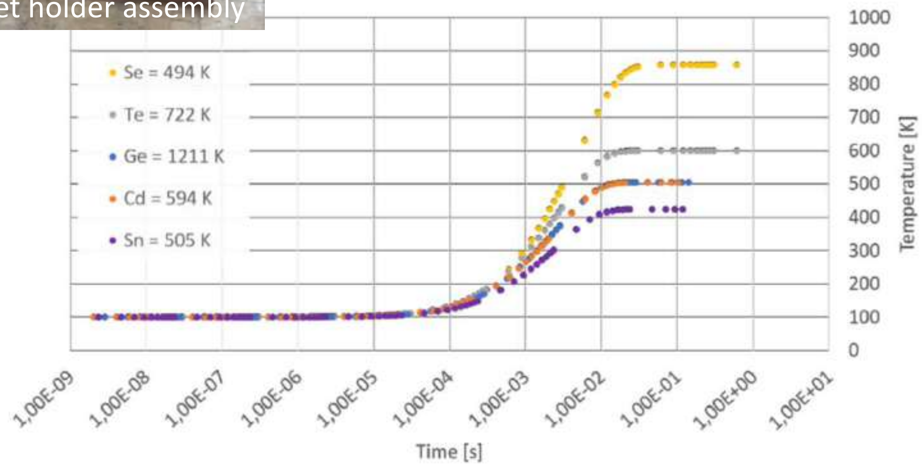
Upgrade of the MAGNEX target system

An innovative approach to high-intensity beams: evaporation on HOPG

F. Iazzi et al., WIT Trans. on Eng. Sciences 116 (2017) 61

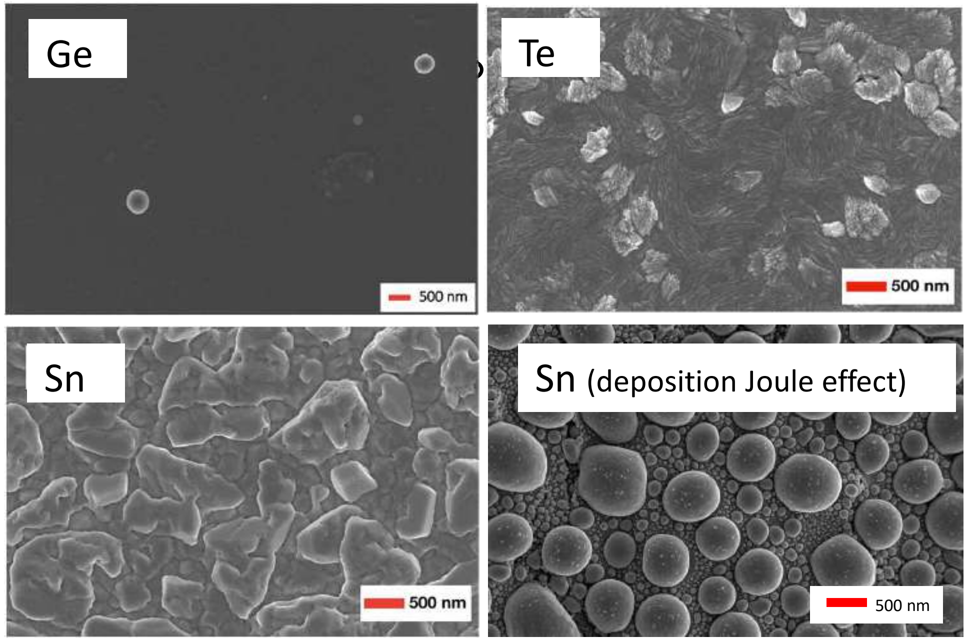
- Substrate made of Highly Oriented Pyrolytic Graphite(HOPG) featuring high thermal conductivity (1930 $Wm^{-1}K^{-1}$)
- Target encased in a Cu holder, mounted on top of a cryocooler and kept at 40 K
- Numerical codes for equilibrium temperature
- Tests with heavy-ion beams (radiation damage)
- Non-trivial evaporation technology to guarantee uniformity

Advantages:
- Thin targets (resolution issues)
- Small emcumbrance (γ detectors around target)
- Small quantities and reduced waste of isotopically enriched material



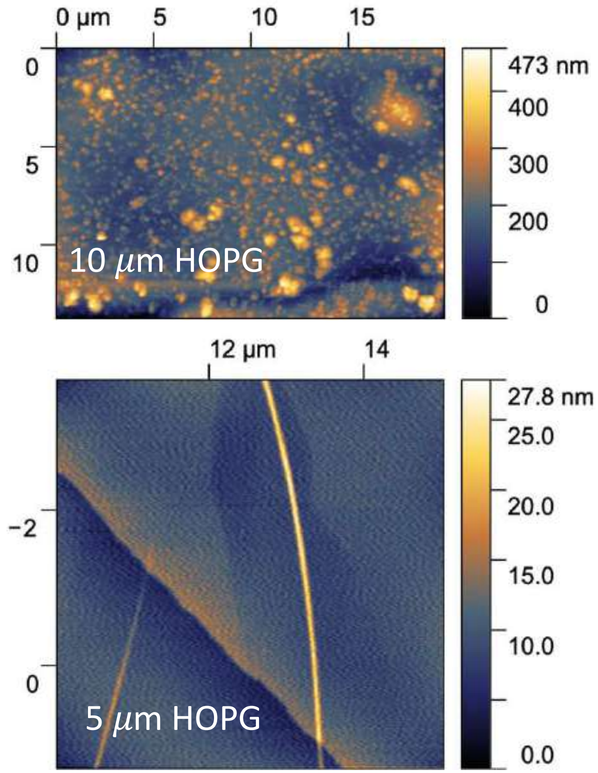
Target characterization: microscopy techniques

Field Emission Scanning Electron Microscopy (FESEM)



- Morphology (few nm resolution in the planar axes)

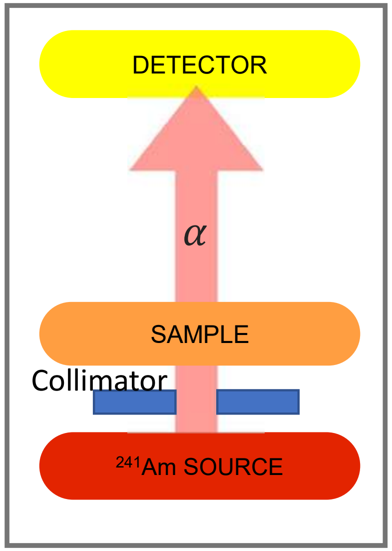
Atomic Force Microscopy (AFM)

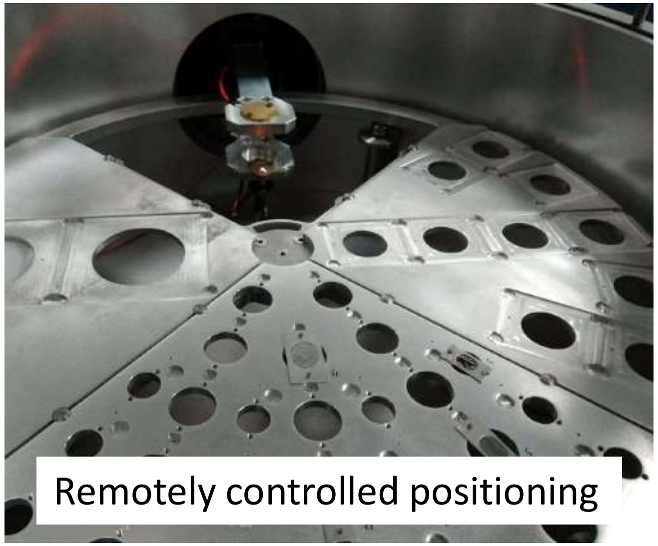


- Topography map with nm resolution in the z axis

Target characterization: Low-energy ion beams techniques

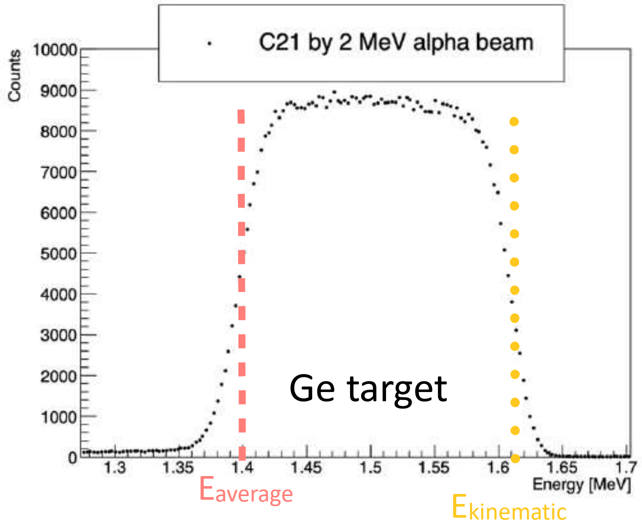
Alpha Particle Transmission





- Small experimental set-up (radioactive source)
- Thickness evaluation
- Thickness uniformity evaluation

Rutherford Backscattering (RBS)



- Large experimental set-up (accelerator)
- Thickness evaluation
- Elemental analysis

Upgrade of MAGNEX detectors

The present Focal Plane Detector (FPD)

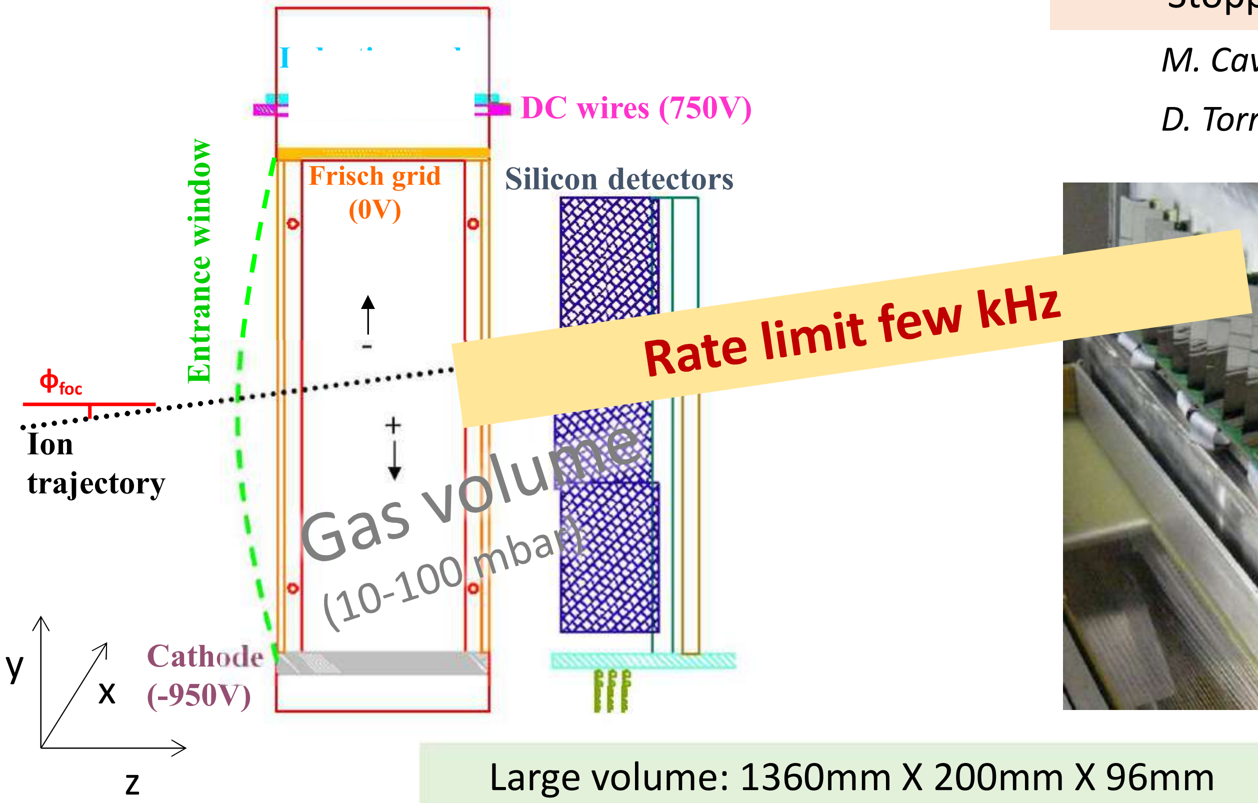
Two tasks to accomplish:

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

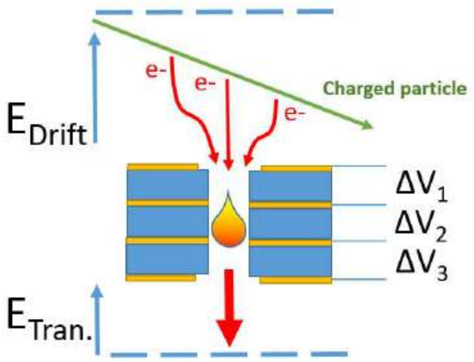


Large volume: 1360mm X 200mm X 96mm

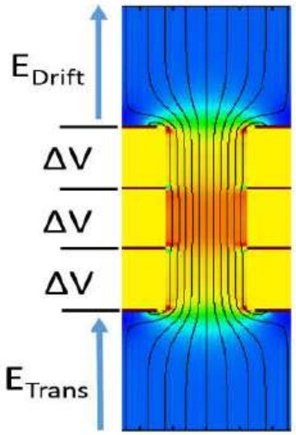
Upgrade of the MAGNEX detectors: The tracker

The new tracker

Rate
from few kHz to MHz
preserving low-pressure operation



3-layer THGEM



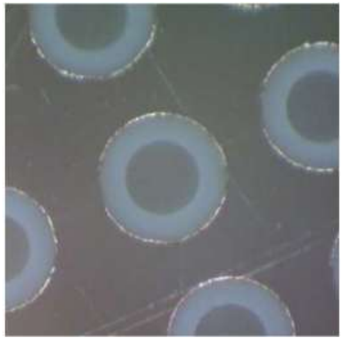
Thick Gas Electron Multiplier (THGEM)

Manufactured by standard PCB techniques of precise drilling in G-10/FR-4 (and other materials) and Cu etching

Multiple THGEM

→ Simple & Robust

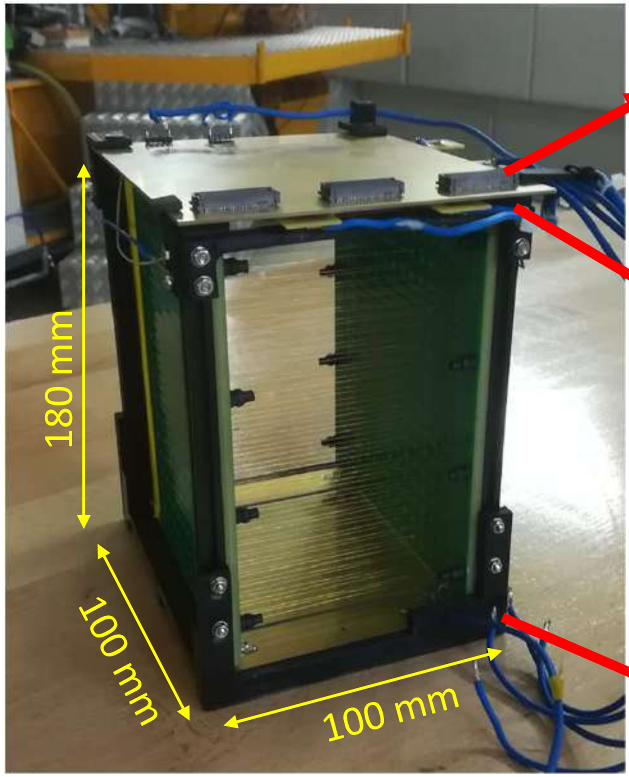
Assembly of several THGEM elements stacked together



Large achievable gain at low pressure due to:

1) Extended avalanche volume (larger than the e^- mean free path) ➔ high e^- multiplication
2) Avalanche confinement within the hole
   ➔ Lesser photon-mediated secondary effects

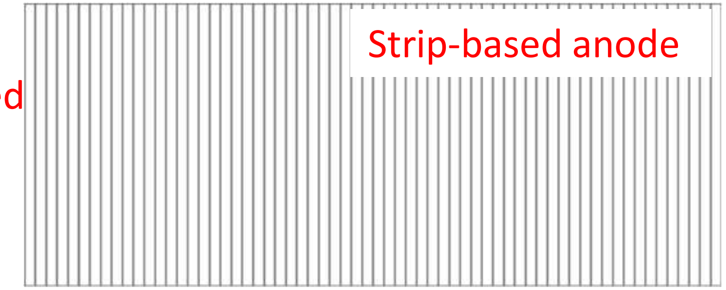
The tracker prototype

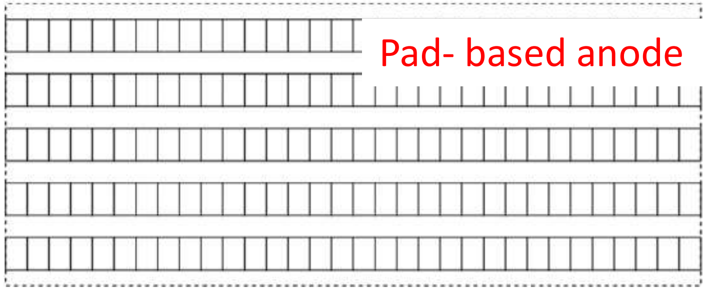


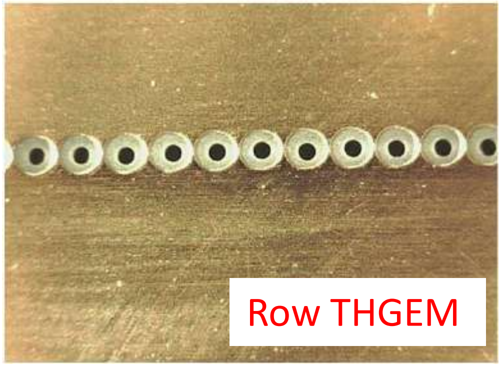
Stripped Anode

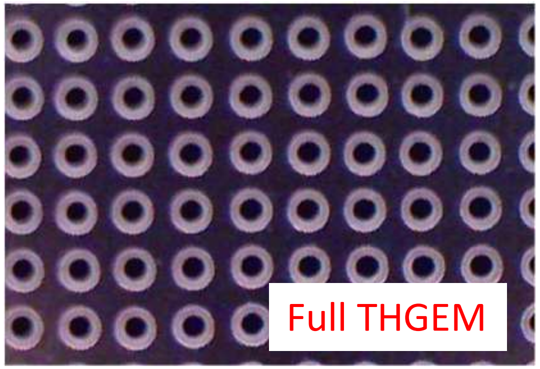
M-THGEM

Cathode

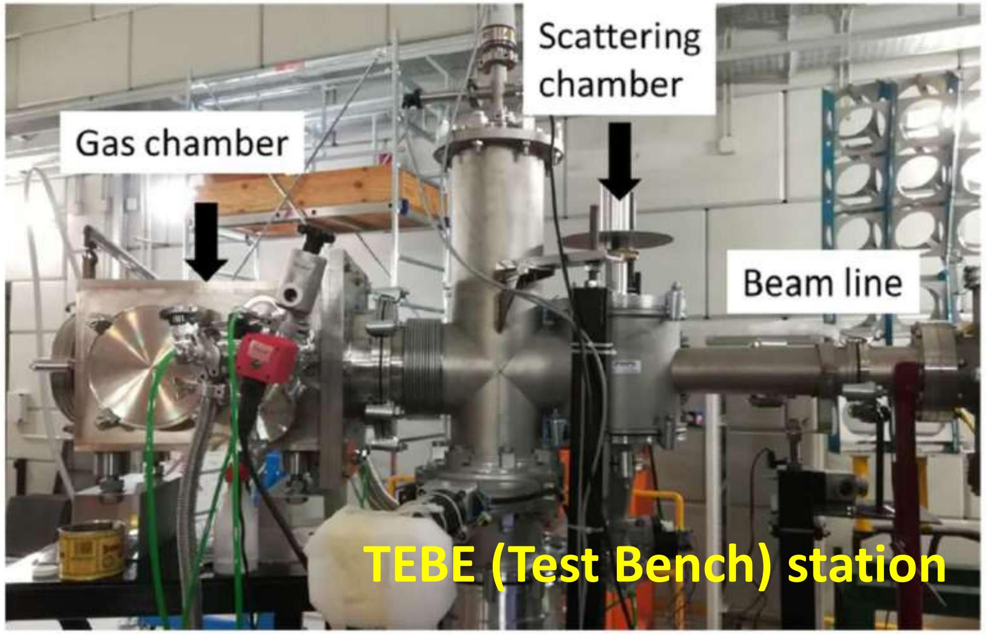


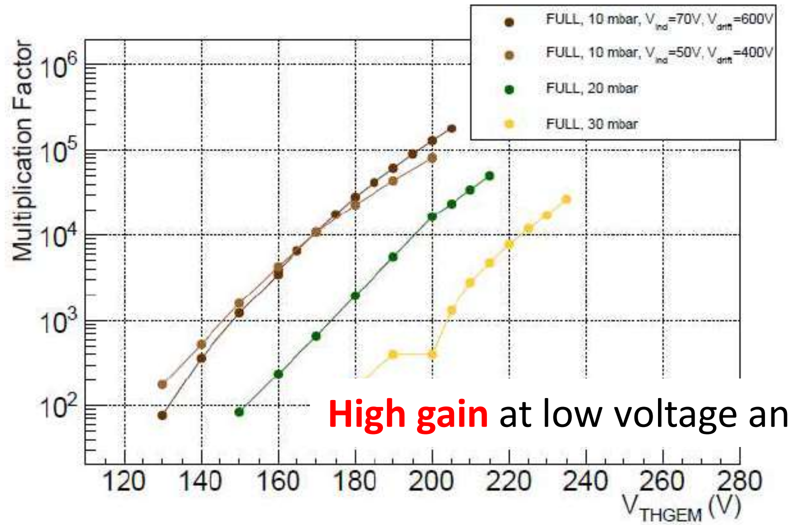




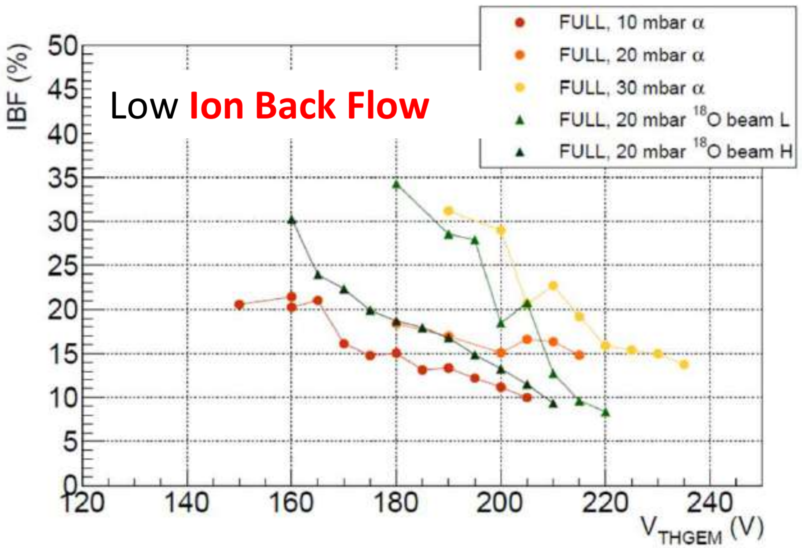


The tracker prototype



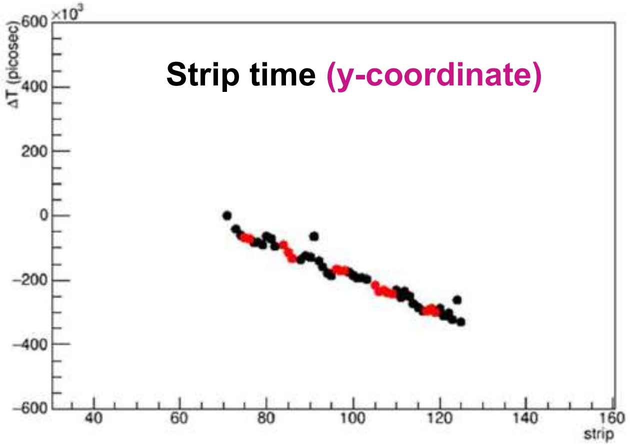


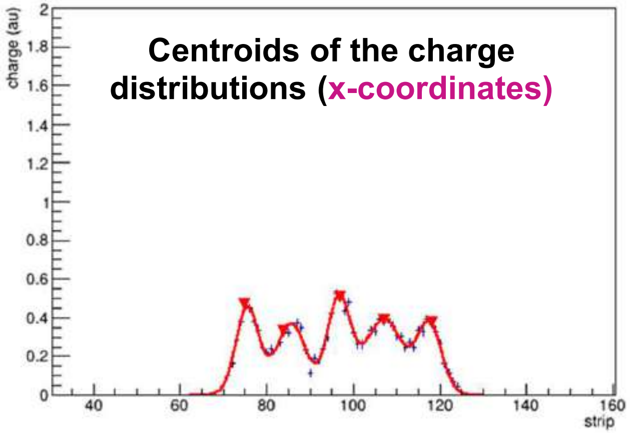
High gain at low voltage and pressure

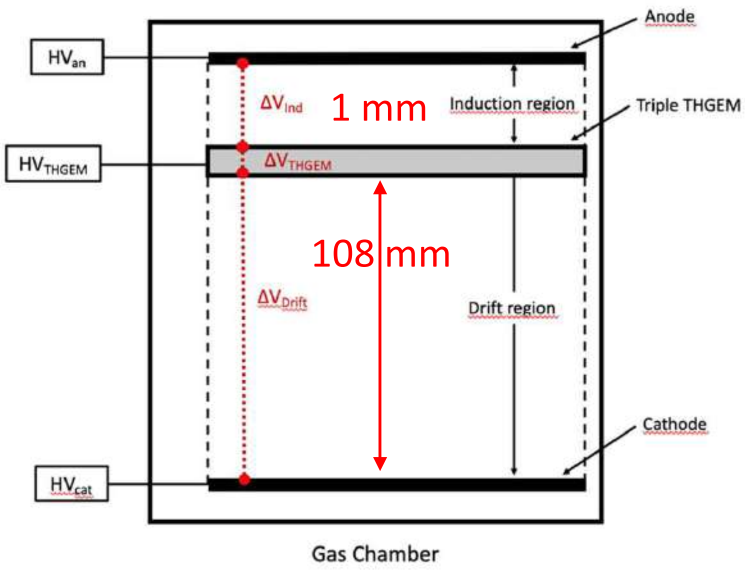


The tracker prototype

Example of the extraction of a track for a single event (strip-based anode)







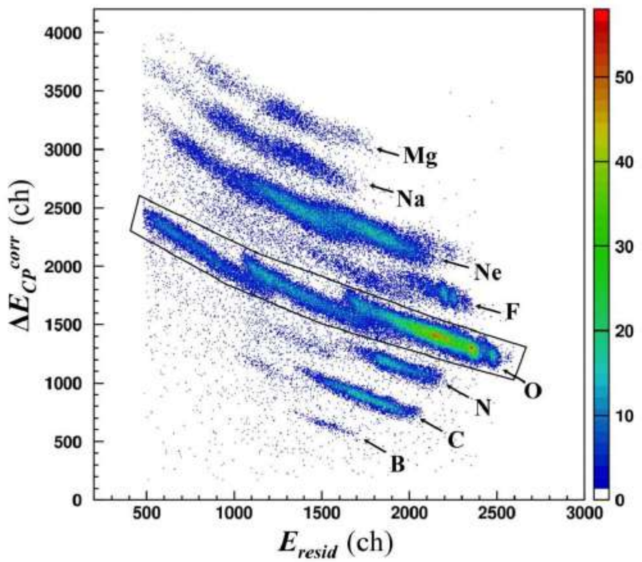
Upgrade of MAGNEX detectors: The PID wall

Present FPD PID (wire based gas detector + silicon detector wall)

- **Energy loss** in the active gas section
- **Residual energy** at the silicon detector wall
- **Position and angle** measured by the tracker

Radiation hardness
expected 10^{13} ions/cm^2 in 10 years activity (silicon detectors dead at 10^9 implanted ions/cm^2 heavy ions not MIP!!)

Z identification



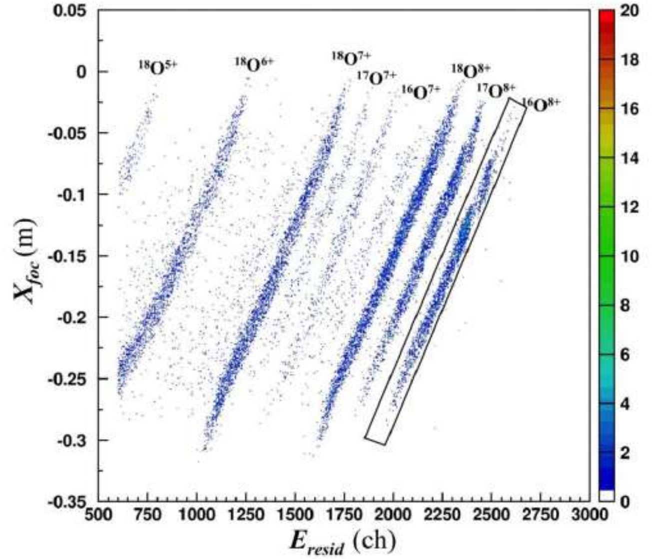
F. Cappuzzello et al., NIM A 621 (2010) 419

M. Cavallaro et al., NIM B 463 (2020) 334

S. Calabrese et al., NIM A 980 (2020) 164500

A identification

$$B\rho = \frac{p}{q} \rightarrow X_{foc}^2 \propto \frac{m}{q^2} E_{resid}$$



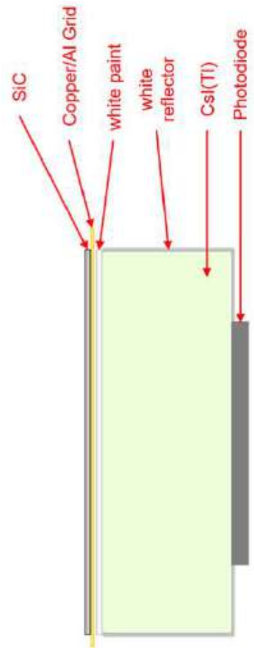
Upgrade of MAGNEX detectors: The PID wall

The new FPD PID wall

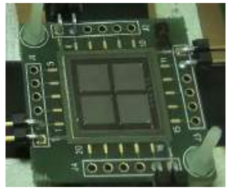
Radiation hardness

- PID capabilities for heavy ions
- Working in gas environment
- Large area
- High energy resolution (2%)
- Timing resolution (few ns)

➢ SiC-CsI telescopes



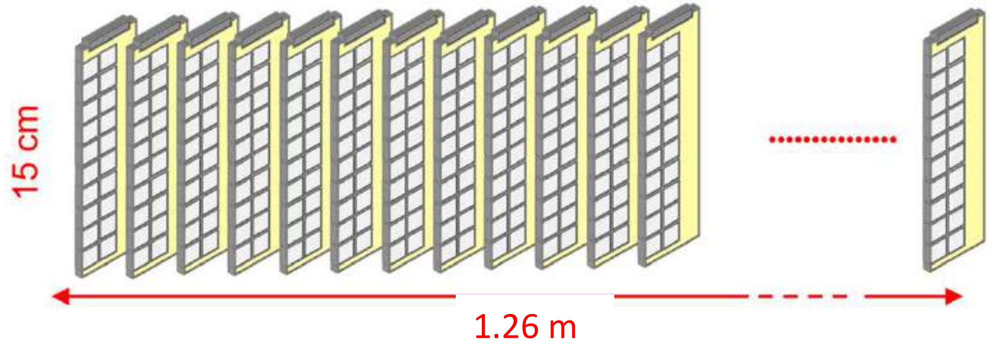
SiC
Thickness 100 µm
Area 1.54 x 1.54 cm^2
Bias -600/-1000 V



CsI (Tl)
Thickness 5 mm
Area 1.5 x 1.5 cm^2

Hamamatsu Photodiode S3590
Area ~ 1 x 1 cm^2
Bias -70 V

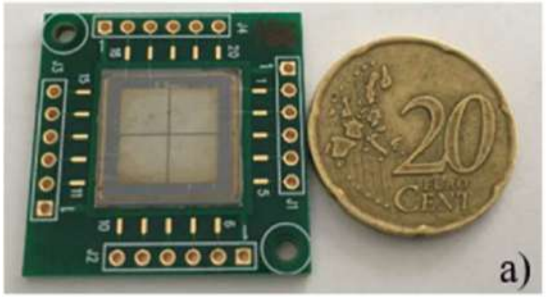
Total 720 telescopes



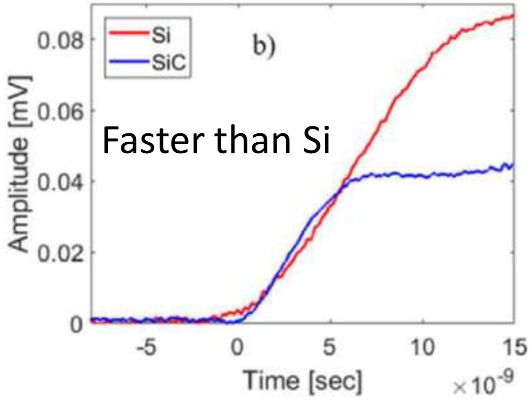
SiC detectors for NUMEN

S. Tudisco et al. Sensors, 18 (2018) 2289

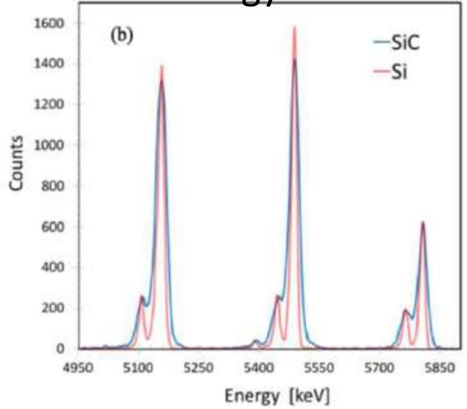
R&D performed within the SiCilia project (call of INFN CSN5)

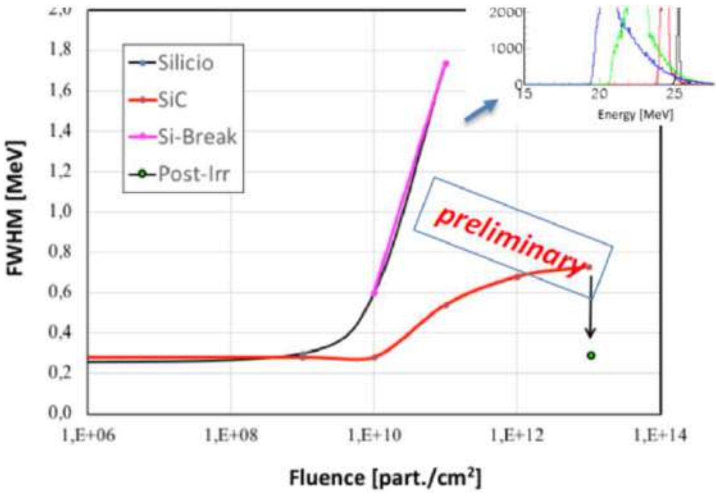


Faster than Si



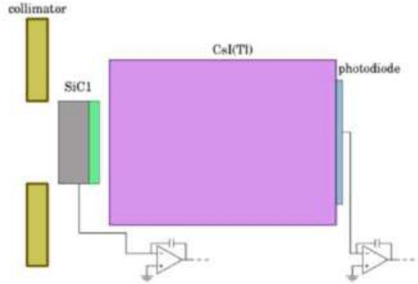
Good energy resolution

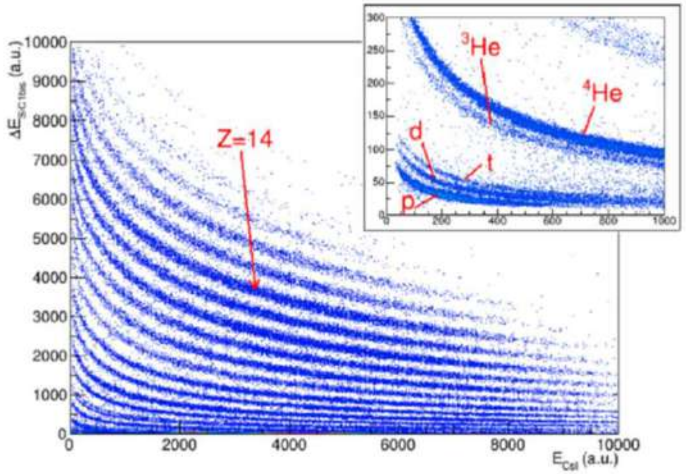




Excellent radiation hardness (> 1000 better than Silicon)

Good PID with **100 μm SiC** + CsI





Ciampi et al. NIM A 925 (2019) 60

The γ array (G-NUMEN)

Typical MAGNEX energy resolution for a NUMEN experiment ~500 keV (FWHM) at 15 MeV/u $\rightarrow$ enough for many systems.
For deformed nuclei and for all experiments at high beam energies energy resolution $\rightarrow$ array of γ-detectors

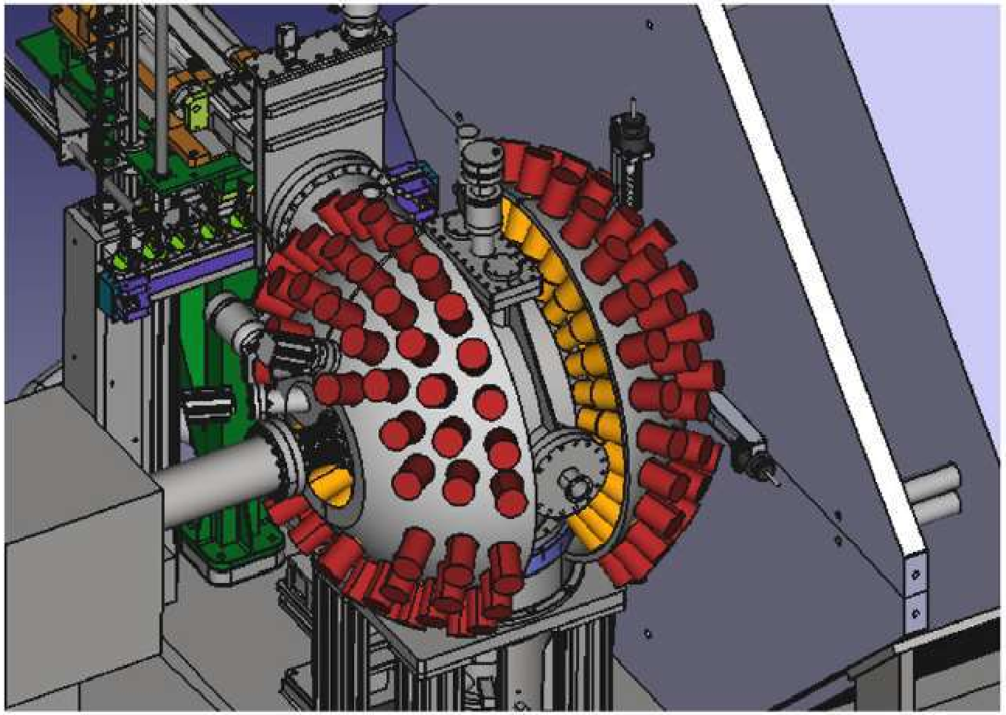
Requirements

- High photo-peak detection efficiency
- Gamma and neutron radiation tolerance
- High timing resolution (separate events from subsequent beam bunches)

Array of ~100 $LaBr_3(Ce)$ scintillator crystals coupled to standard **PM tubes** disposed in rings covering a total solid angle of 20% of the unit sphere

38 mm diameter, 50mm length, 245 mm distance from the target

Expected total photopeak efficiency of the array near 4%, energy resolution around 3%, at 1.3 MeV gamma-ray energy.
Expected timing resolution under 1 ns



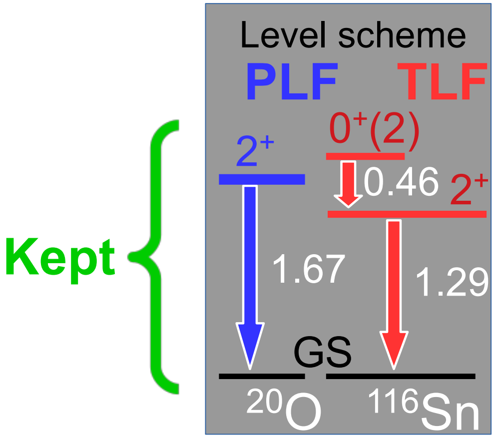
F. Cappuzzello et al., Front. Astr. Space Sc. 8 (2021) 668587

The γ array (G-NUMEN)

- *Spectrum is simple - few transitions are present, no need for very high resolution*
- *Level scheme and transitions are well known, objective is not searching for new ones*

PLF E* spectrum @ FPD

Selection of PLF energy range in γ-p coincidence confines gamma decay scheme to few low lying level transitions

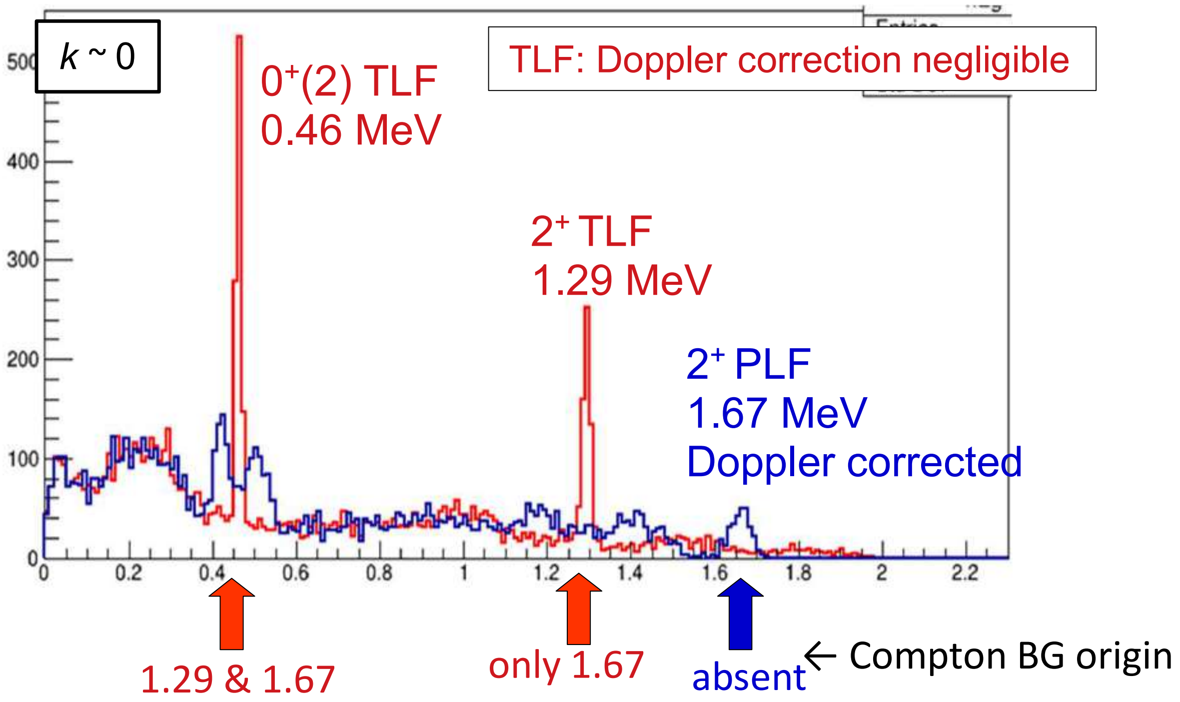


J.R.B. Oliveira et al., EPJ A (2020) 56:153

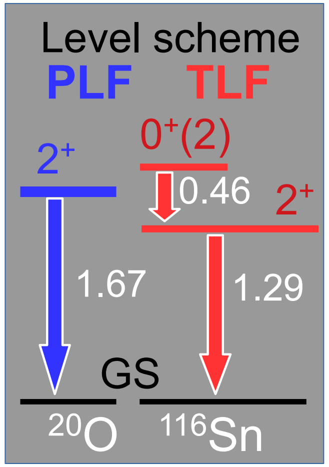
Compton BG in G-NUMEN + MAGNEX

^{116}Cd(^{20}Ne,^{20}O)^{116}Sn @ 300MeV - Simulation

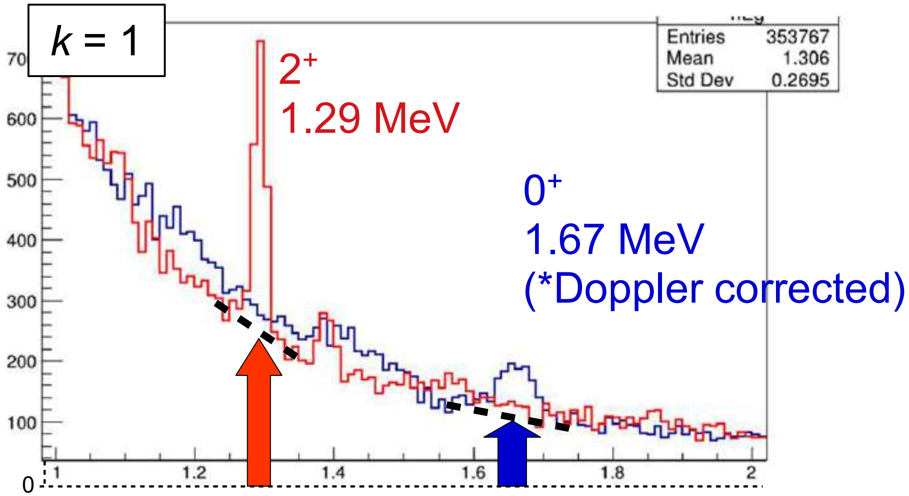
*(*) simulation assumes **1 nb** for each **state***



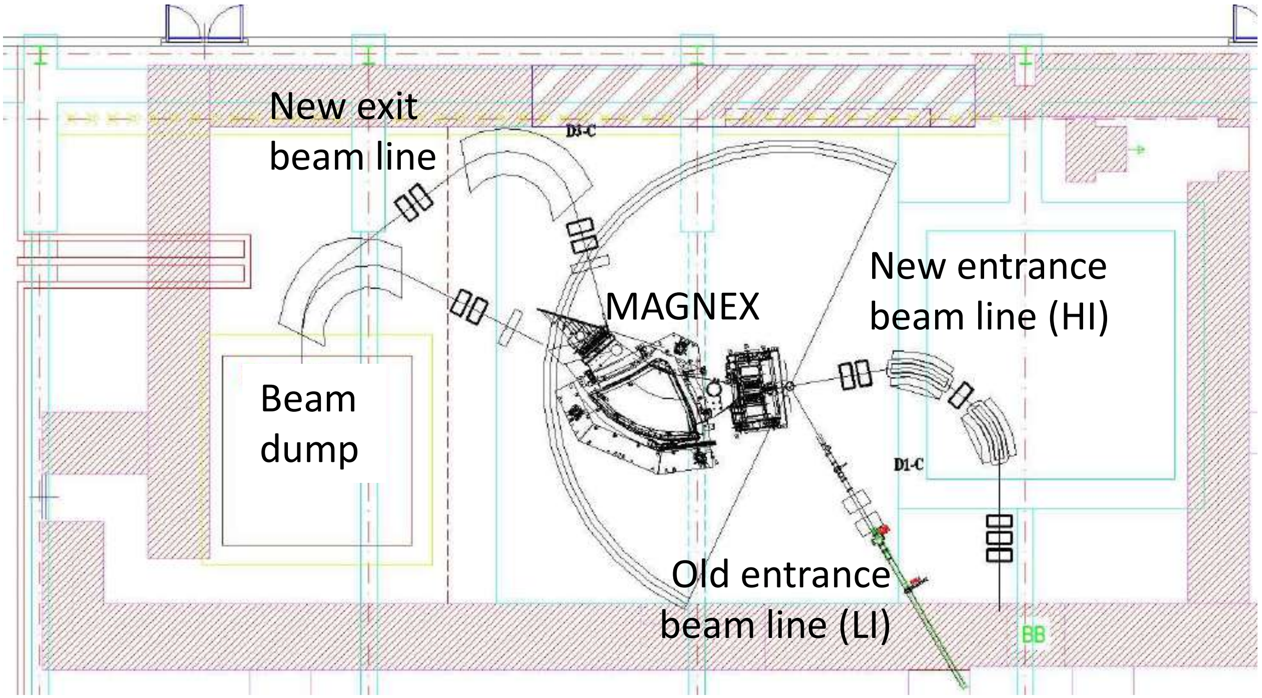
At **low beam currents** the continuum BG (mostly Compton) is quite small



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



Upgrade of the LNS facilities:
The MAGNEX hall



Engineering challenges:

- Integrating **the new entrance and exit beam lines** to the existing MAGNEX platform
- **High radiation** environment ($7 \cdot 10^4$ n s^{-1} cm^{-2})

see flash talk
O. Sgouros

- **Robotized systems** to minimize human access

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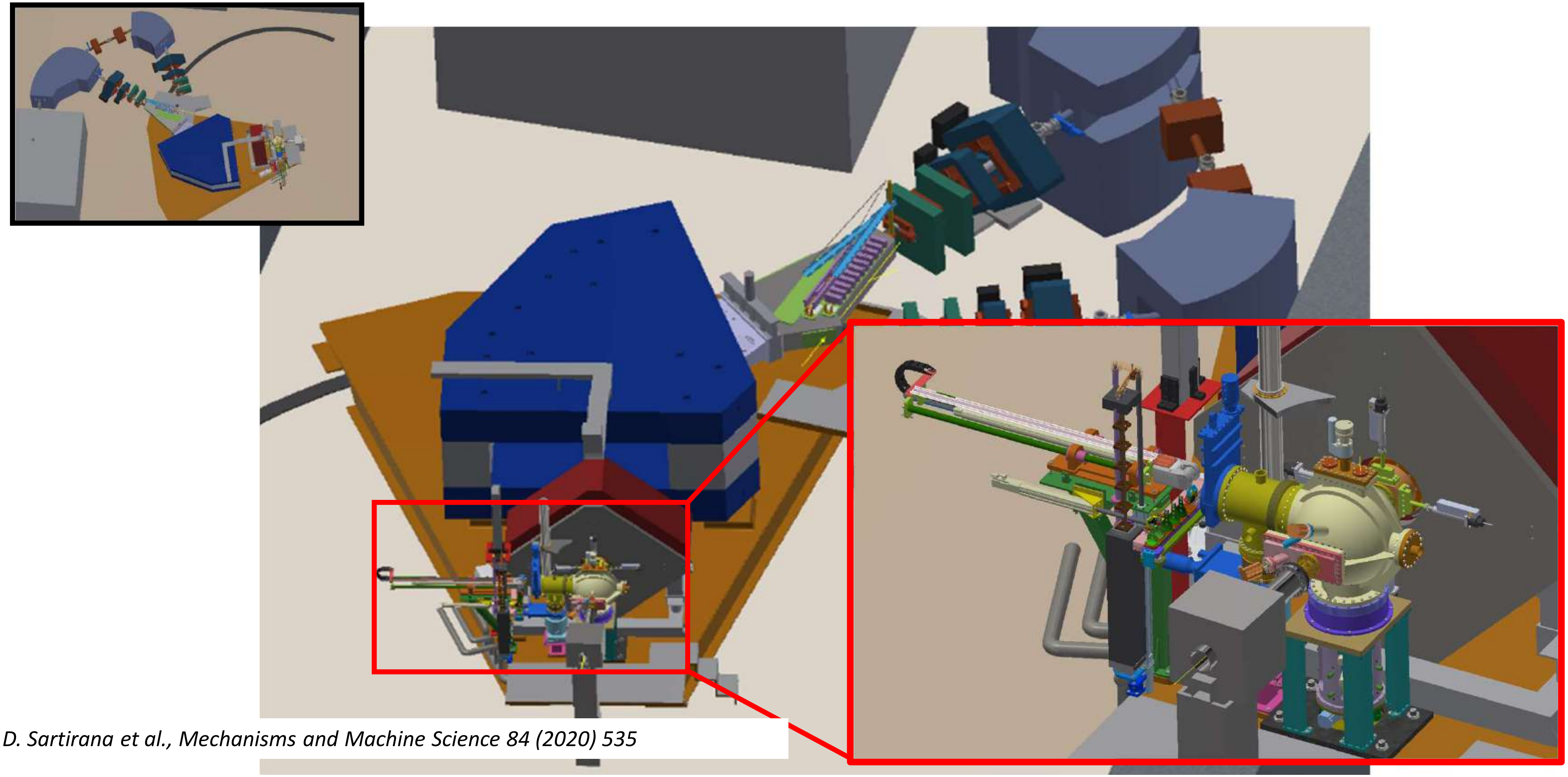
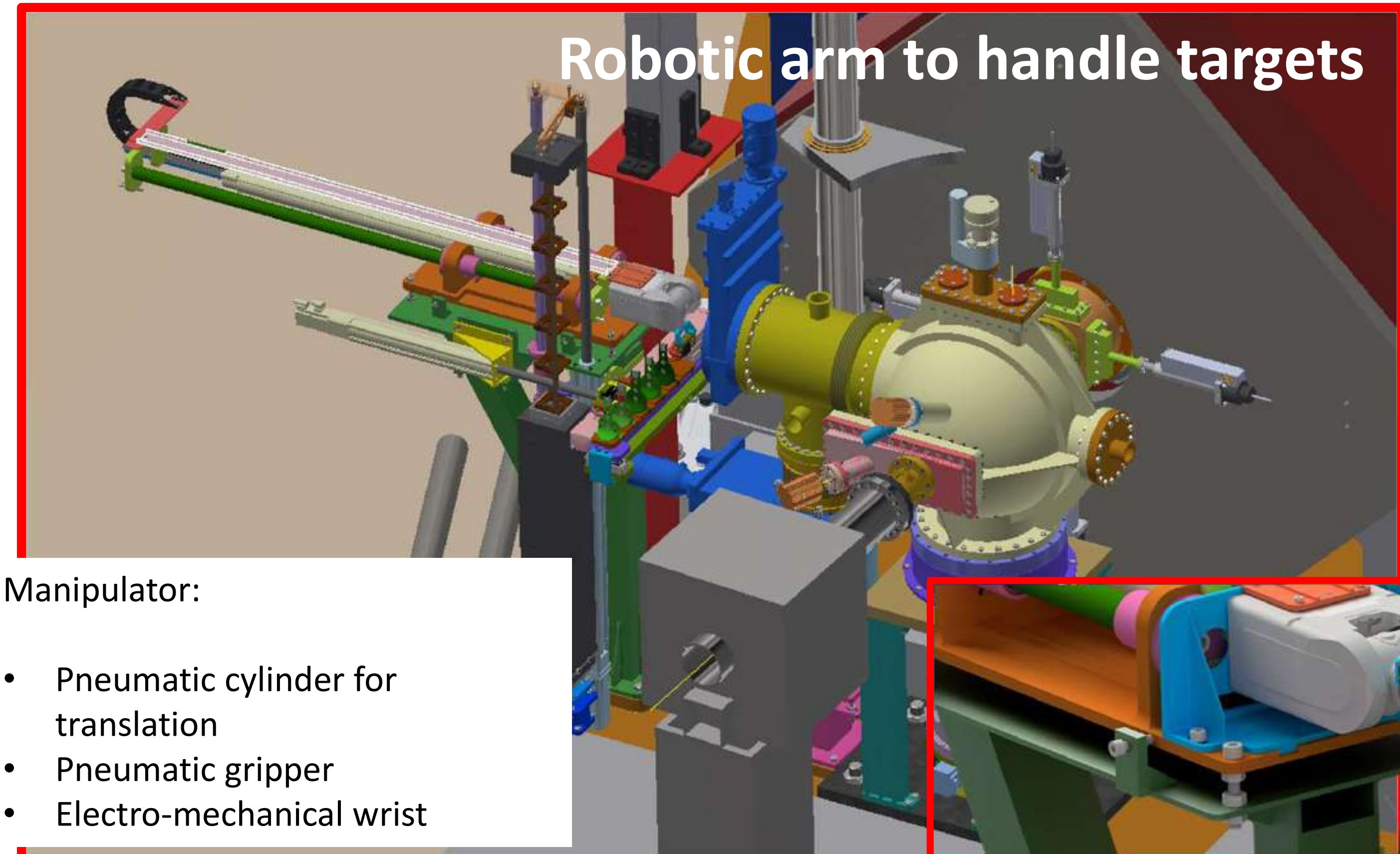
Upgrade of the LNS facilities: the scattering chamber



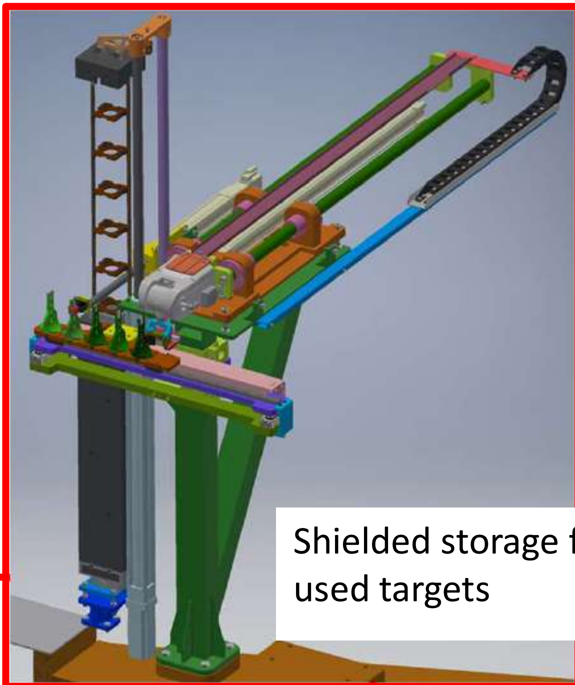
D. Sartirana et al., Mechanisms and Machine Science 84 (2020) 535

Upgrade of the LNS facilities: the scattering chamber

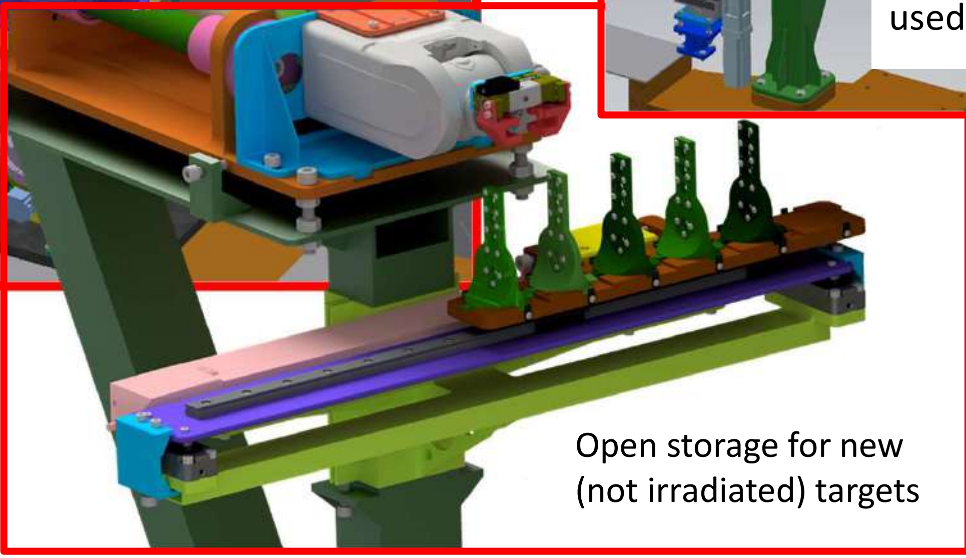


Manipulator:

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



Shielded storage for used targets



Open storage for new (not irradiated) targets

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

Conclusions and Outlooks

- Challenging project on DCE is on-going at INFN-LNS
- The upgrade for the INFN-LNS cyclotron and MAGNEX will allow to build a unique facility for a systematic exploration of all the nuclei candidate for $0\nu\beta\beta$
- A big opportunity not only for $0\nu\beta\beta$ physics applications but also for genuine nuclear physics (including technology for high radiation environment)
- High-intensity beams facility at INFN-LNS for many users

Thank you!