Double charge exchange reactions for neutrino physics

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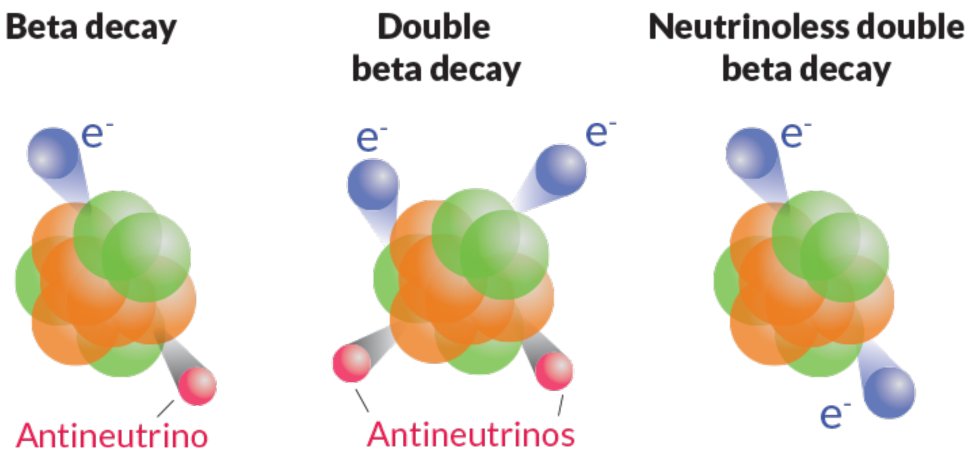
The double β-decay

$$ {}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z-2}X_{N+2} + 2e + (2\,\overline{\nu}) $$



The observation of the neutrinoless double beta decay will establish:

- Neutrino is a **Majorana fermion**
- Violation of the lepton number conservation
- A window into physics *beyond the* **Standard Model**
- **...**

The Decay Rate Expression for 0νββ

Two kinds of theoretical issues related to the double beta decay experiments.

1) Issues related to the **particle** physics deal with fundamental parameters entering the decay rate expression:
   - Neutrino masses
   - Coupling constant

2) Issues related to the **nuclear** physics: The decay rate is expressed in terms of NME that have **to be evaluated.**

$$[T_{1/2}]^{-1} = G_{0\nu} \cdot |M_{0\nu}|^2 \cdot |f(m_i, U_{ei}, \xi_i^2)|$$

Phase Space Factor

Nuclear Matrix Elements

Term containing a combination of masses m_i, the mixing coefficients U_{ei} and Majorana phases ξ_i

The Nuclear Matrix Elements

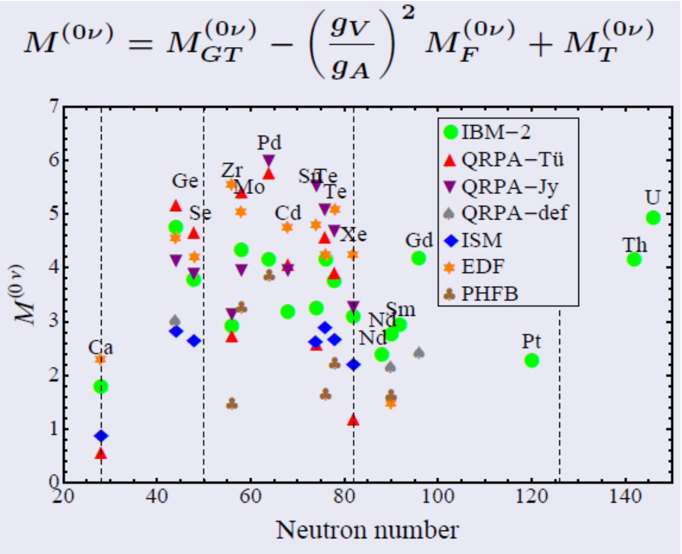
$$|M_{\epsilon}^{0\,\nu\beta\beta}| = |\langle \Psi_f | O_{\epsilon}^{0\,\nu\beta\beta} | \Psi_i \rangle|^2$$

The nuclear matrix elements evaluation up to date are based on:

Calculations: QRPA, Interacting Boson Model, Large scale shell model...

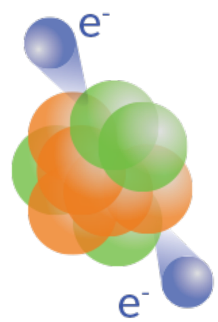
Measurements: early measurements not conclusive for 0νββ

- π-induced DCE reaction
- Heavy-ion induced DCE reaction
- Single charge exchange



A new experimental approach to extract the NMEs for 0νββ decay is based on the study of the heavy-ion double charge exchange reaction using **large-acceptance high-resolution spectrometer**.

Heavy Ion DCE and 0νββ



Differences

- ✗ DCE mediated by **strong interaction**, 0νββ by **weak interaction**
- ✗ DCE includes **sequential** transfer **mechanism**
- ✗ Dynamics of the process: **decay vs reaction**

Similarities

- ✔ **Same initial and final states:** Parent/daughter states of the *0νββ* decay are the same as those of the target/residual nuclei in the DCE
- ✔ **Similar operator:** Fermi, Gamow-Teller and rank-2 tensor components are present in both the transition operators, with tunable weight in DCE
- ✔ **Large linear momentum** (~100 MeV/c) available in the virtual intermediate channel
- ✔ **Same nuclear medium**: Constraint on the theoretical determination of quenching phenomena on *0νββ*
- ✔ **Off-shell propagation** through virtual intermediate channels

The NUMEN project

The aim of the project is to obtain *"data-driven"* information on **Nuclear Matrix Elements** for systems candidate for **0νββ**

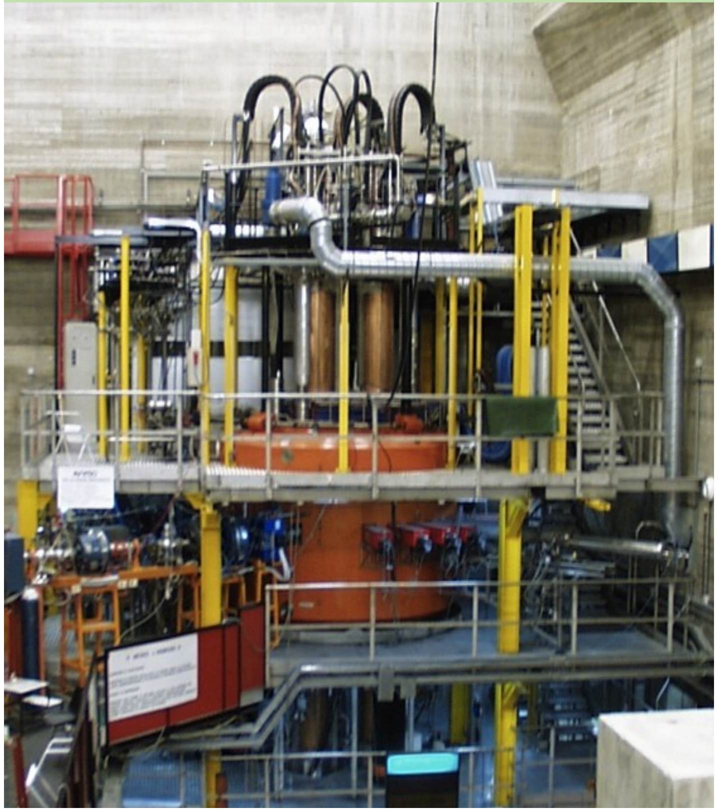
Additional aims:

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

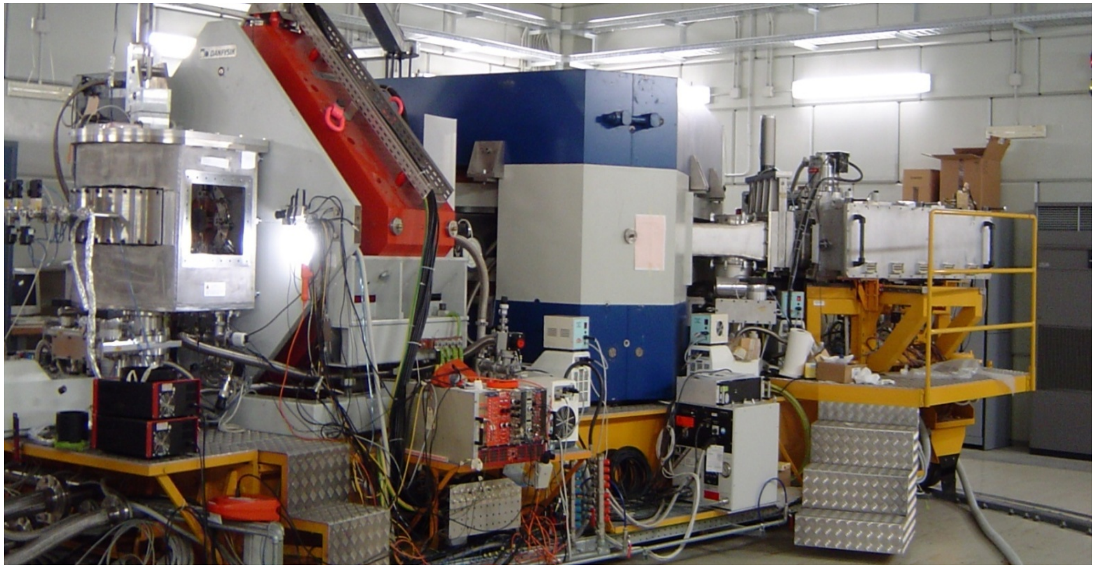
Big efforts required for the **theory developments**, see talks of M. Colonna e H. Lenske

Superconducting Cyclotron and MAGNEX spectrometer @ LNS

- In operation since 1996.
- Accelerates from H to U ions
- Maximum energy 80 MeV/u.



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



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

Good compensation of the aberrations: Trajectory reconstruction

⇒

resolutions:
- Energy ΔE/E ~ 1/1000
- Angle Δθ ~ 0.2°
- Mass Δm/m ~ 1/160

The Phases of NUMEN project

European Research Council

✔**Phase1**: The experimental feasibility

✔**Phase2**: "hot" cases optimizing the experimental conditions, getting first results and developing reliable R&D for the upgrade (approved)

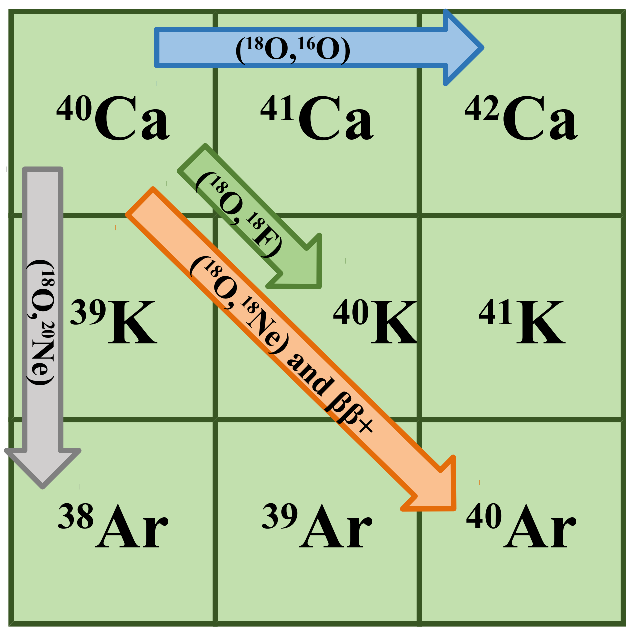
✔**Phase3**: The facility upgrade (Cyclotron, MAGNEX, beam lines, …..)

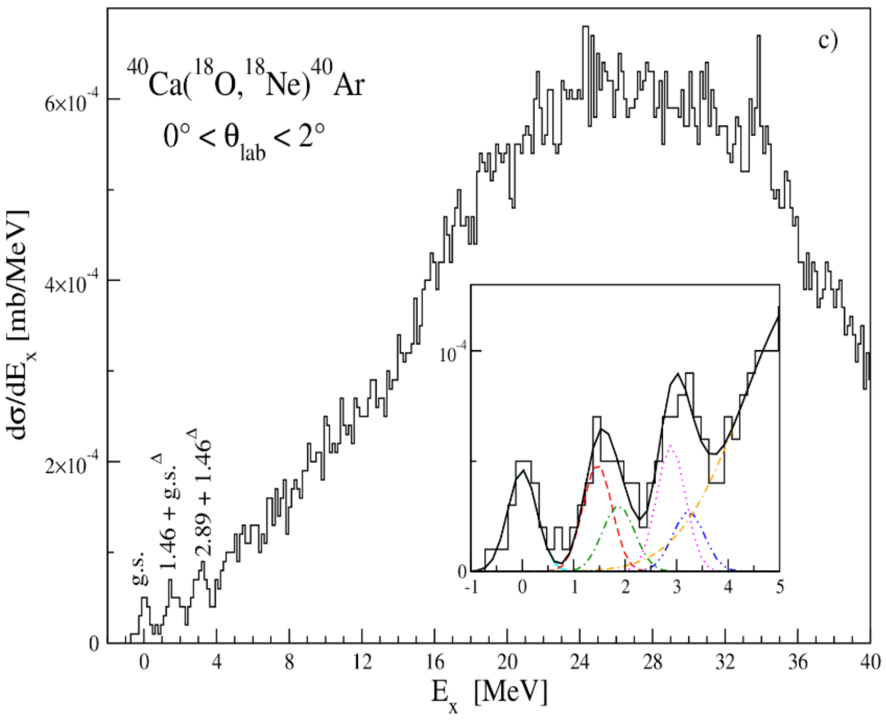
✔**Phase4** : The systematic experimental campaign

year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Phase1	done									
Phase2				Approved						
Phase3										
Phase4										

The phase 1: pilot experiment: $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$

- ✔ $^{18}O^{7+}$ beam from Cyclotron at 270 MeV (10 pnA)
- ✔ Most favourable case: low mass, high Q-value, high cross-section





The results of Phase 1 indicate:

Experimental feasibility: zero-deg, resolution (500 keV), low cross-section (μb/sr)

it is possible to extract valuable information cross section**.**

Phase 2: Moving towards hot-cases

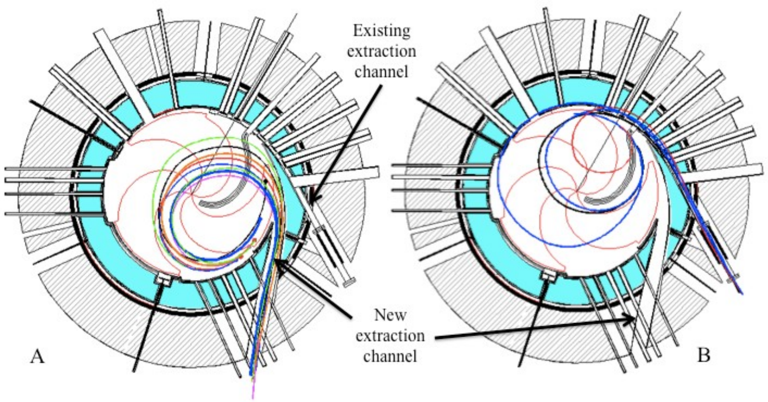
The results of **Phase 1** indicate that **it is possible to extract valuable information.** However, we the present set-up, it is difficult to **extend such studies to hot cases**. In fact:

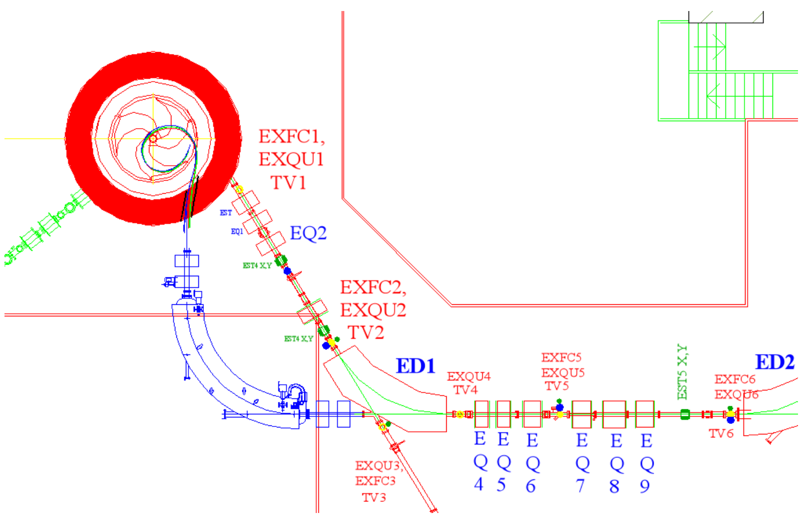
- The reaction Q-values are normally more negative and the isotopes of interest are heavier than in the ^{40}Ca case
- The DCE cross section is expected to decrease at higher bombarding energies since both τ and στ components of the nucleon-nucleon effective potential show this trend
- The (^{18}O,^{18}Ne) reaction is particularly advantageous, but it is $\beta^+\beta^+$;
- None of the reactions of $\beta^-\beta^-$ looks as favorable as the (^{18}O,^{18}Ne).
  - (^{18}Ne,^{18}O) requires a radioactive beam
  - (^{20}Ne,^{20}O) or (^{12}C,^{12}Be) have smaller *B*(GT)
- In some cases gas or implanted target will be necessary, e.g. ^{136}Xe or ^{130}Xe
- In some cases the energy resolution is not enough to separate the g.s. from the excited states in the final nucleus. γ-rays detection is required

Much higher beam current is required!

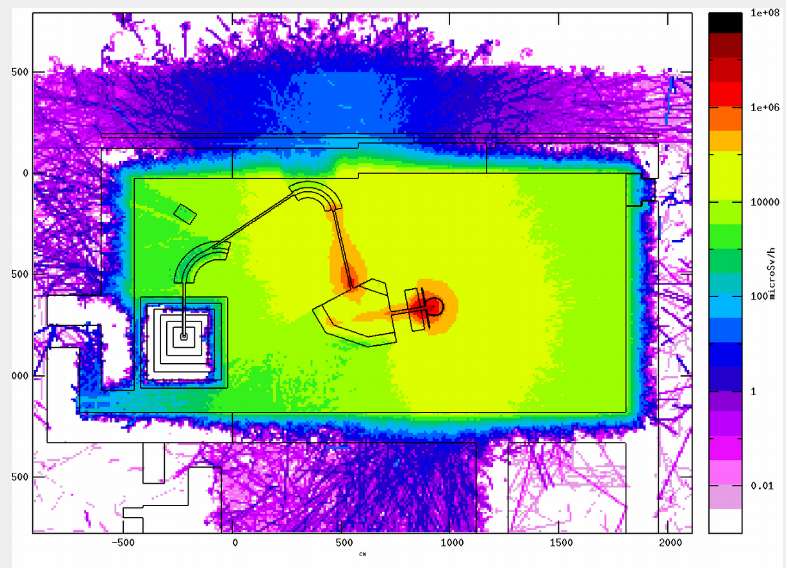
Phase 3 upgrades: cyclotron

- The **CS** accelerator current (from 100 W to 5-10 kW);
- Extraction by stripping





Radioprotection issues



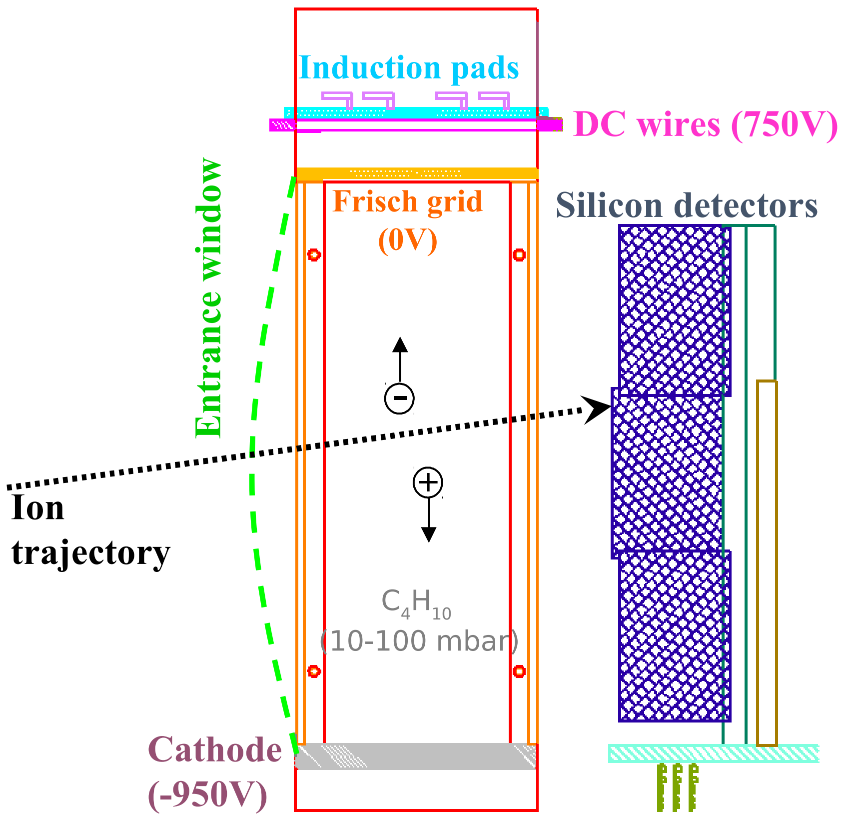
From S.Russo (LNS radioprotection service)

Beam transport line transmission efficiency to nearly 100%

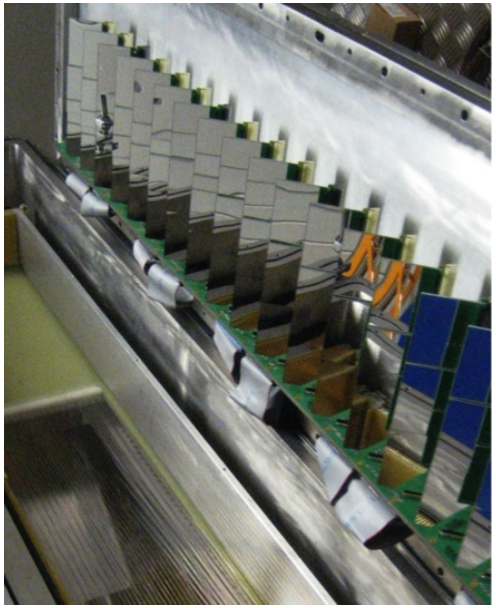
MAGNEX: the present Focal Plane Detector

The present focal plane detector is an hybrid detector:

- Gas section: **proportional wires and drift chambers (ΔE + tracking)**
- Stopping wall: **silicon detectors (residual Energy)**



Total volume: 1360 x 200 x 96mm^3



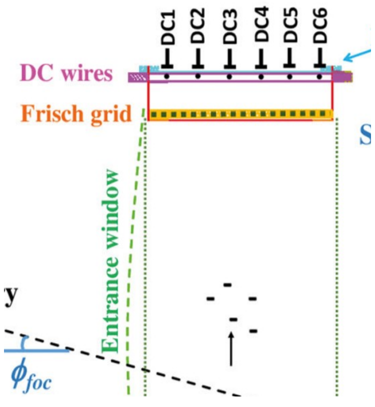
The FPD provides for each particle:
✔ full reconstruction of the **trajectory**
✔ **identification** in Z and M
✔ **energy** measurement

MAGNEX: the new focal plane detector

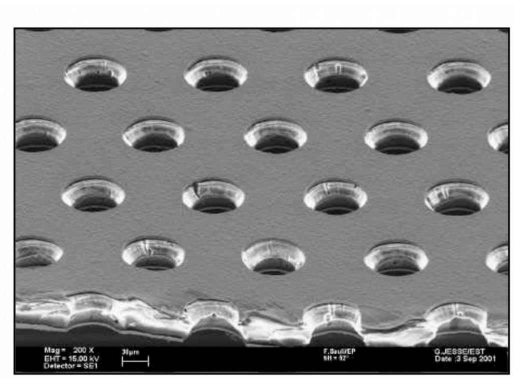
Main requirement:
High rate from 2kHz to 1MHz

Additional requirement
✔ Low pressure
✔ High dynamical range

From
multi-wire tracker



to
Micro pattern tracker

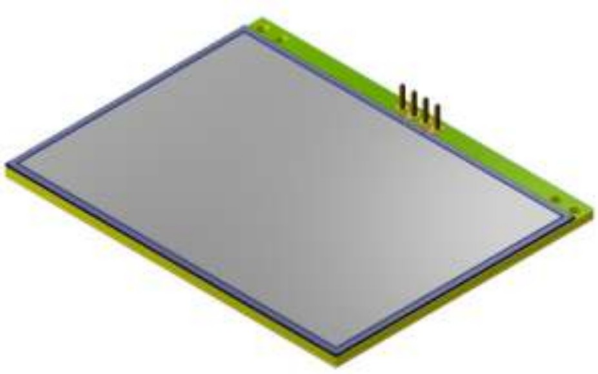


F. Sauli, Nucl. Instr. Meth. A 386(1997)531

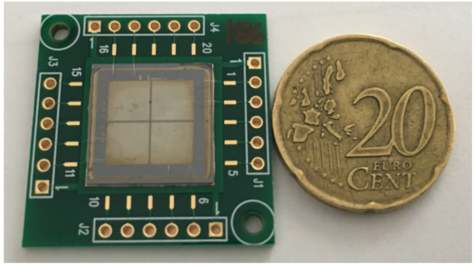
For the **energy** measurements and identification silicon detector are not suitable.

Fluence about 10^{12} cm^{-2} in a year of measurement

From Silicon



to SiC

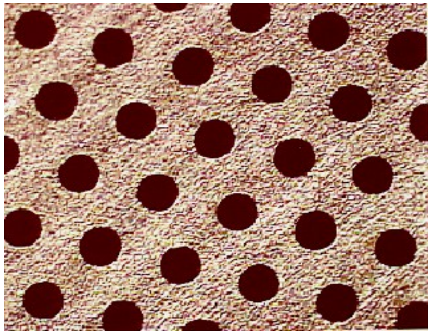


collaboration with CNR, STM, FBK for SiC detectors development

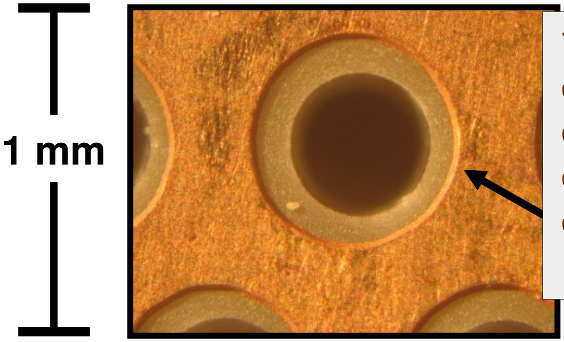
Tracker

Confined avalanche within holes, lesser photon - mediated secondary effects

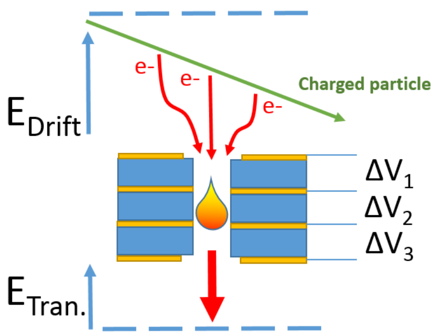
STANDARD GEM
10^3 gain in single-GEM



THGEM
10^5 gain in single-THGEM



THGEM geometry:
- ✔ Thickness 0.6 mm
- ✔ Hole Ø 0.5 mm
- ✔ Hole Pitch 1 mm
- ✔ 0.1 mm rim to Prevent discharges

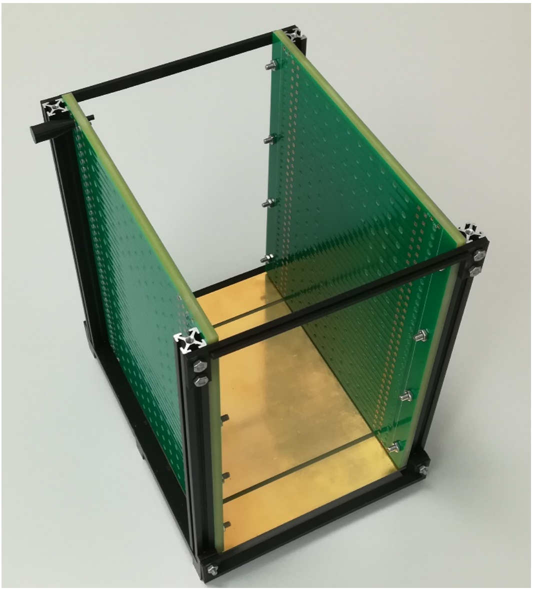


3-layer THGEM

M. Cortesi Review of scientific instruments 88, 013303 (2017)

- Effective single-electron detection
- High gas gain ~10^5 (>10^6) @ single (double) THGEM
- Few-ns RMS time resolution
- **Sub-mm position resolution**
- **MHz/mm^2 rate capability**
- Gas: molecular and noble gases
- **Operation pressure: 1mbar - few bar**

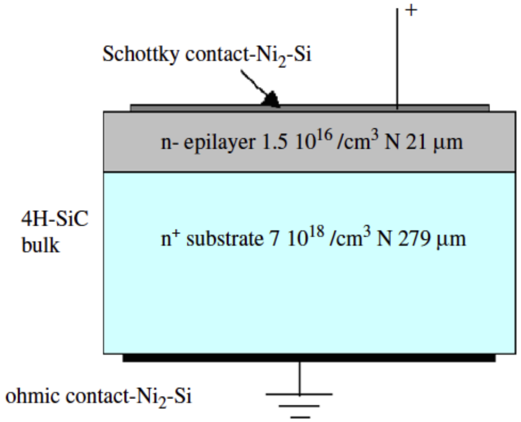
Reduced-size prototype
(10x10x20 cm^3)

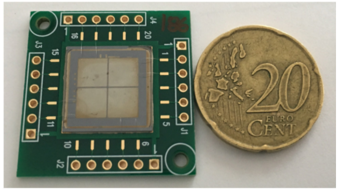


Particle Identification wall

Test on radiation hardness performed at LNS this year

The Schottky diodes are fabricated by epitaxy onto high-purity 4H–SiC n-type substrate.





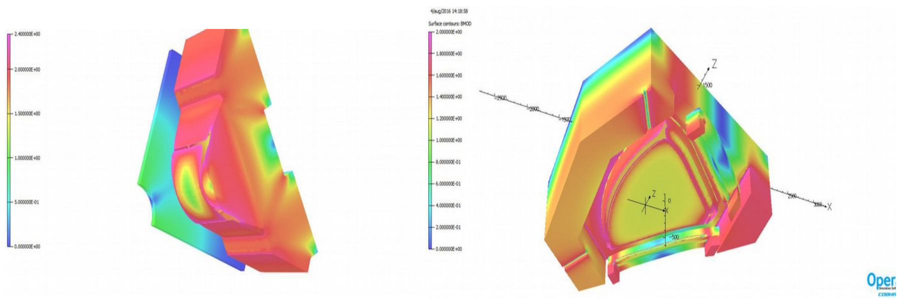
Requirement:

- **Active area** 1 cm^2
- ΔE stage **thickness** 100 μm

  E stage SiC thickness 3000 μm or Scintillator
- To tolerate **fluence** larger than 10^{12} /cm^2 (an year of measurement)
- High **energy resolution** (2%)
- **Timing resolution** (few ns)

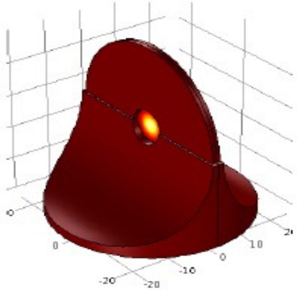
Other upgrades

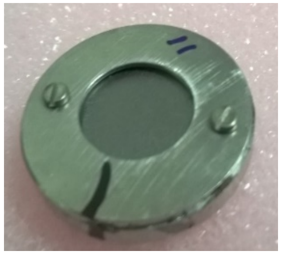
- The **MAGNEX** maximum magnetic **rigidity** (from 1.8 Tm to 2.5 Tm)



- An **array of scintillators for γ-rays ($LaBr_3(Ce)$ or Lyso)** measurement in coincidence with MAGNEX

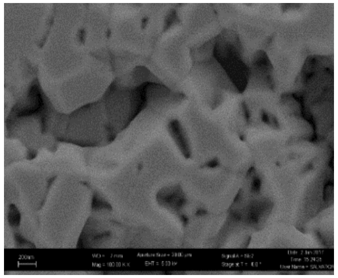
- The **target** technology for intense heavy-ion beams





Evaporation of target material on a **Pyrolitic Graphite** backing

Cooling system. Test next week at UNAM (Mexico)



Target uniformity studies

Conclusions and Outlooks

- ✔ **NUMEN** is a challenging project for the understanding of 0νββ-decay physics.
- ✔ **The project** rely on the upgrade of MAGNEX spectrometer and Cyclotron toward high intensity
- ✔ Relevant results for 0νββ-decay physics already achieved in the initial campaigns

A big challenge for the development of **technology and nuclear theory**

The NUMEN collaboration

Spokespersons: F. Cappuzzello and C. Agodi

Proponents: C. Agodi, J. Bellone, D. Bonanno, D. Bongiovanni, V. Branchina, S. Brasolin, O. Brunasso, S. Burrello, S. Calabrese, L. Calabretta, D. Calvo, V. Capirossi, F. Cappuzzello, D. Carbone, M. Cavallaro, M. Colonna, G. D'Agostino, N. Deshmukh, P. Finocchiaro, M. Fisichella, A. Foti, G. Gallo, U. Garcia-Tecocoatsi, F. Iazzi, R. Introzzi, G. Lanzalone, F. La Via, F. Longhitano, D. Lo Presti, P. Mereu, L. Pandola, F. Pinna, S. Reito, D. Rifuggiato, A.D. Russo, G. Russo, G. Santagati, E. Santopinto, O. Sgouros, V. Soukeras, A. Spatafora, D. Torresi, S. Tudisco, R.I.M. Vsevolodovna

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