NUMEN

Present outcome from the NUMEN R&D phase

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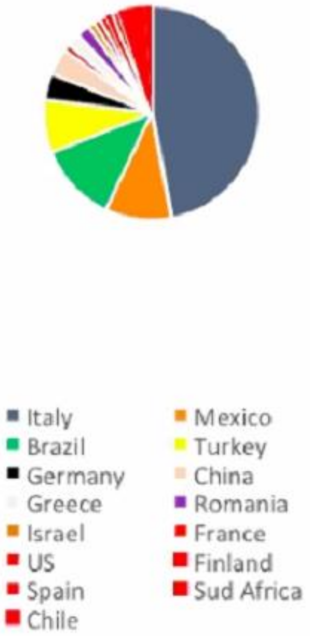
100 Researchers
40 Institutions
15 Countries



Istituto Nazionale di Fisica Nucleare

NUMEN (NUclear Matrix Elements for Neutrinoless double beta decay)

- The NUMEN experiment focuses on the measurements of the absolute cross sections of Heavy-Ion induced Double Charge Exchange (DCE) of nuclei of interest for the 0νββ decay (F. Cappuzzello et al. , Eur. Phys. J. A(2018), https://doi.org/10-1140/epja/2018-12509-3)

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

Beyond the standard model (Particle physics)

Phase-space factor (Atomic physics) PSF

Matrix elements (Nuclear physics) NME

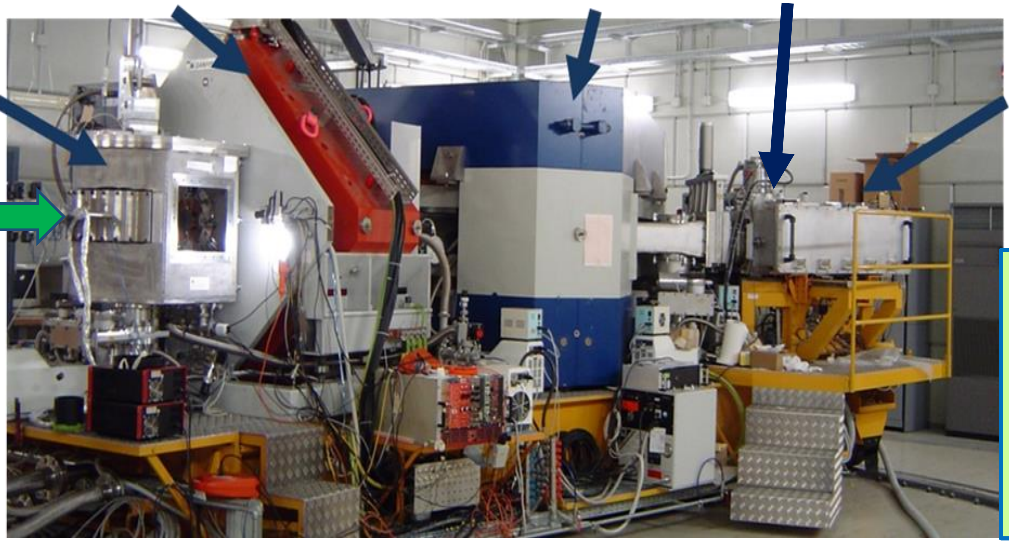
- In fact, information on 0νββ decay Nuclear Matrix Elements (NME) can be obtained using DCE reactions, because they present important similarities even if they are mediated by different interactions. One similarity is that initial and final nuclear states are the same.

- Two sets of measurements are planned, corresponding to $\beta^-\beta^-$ and $\beta^+\beta^+$ decays that feature the two directions of isospin lowering and raising operators, respectively (^{20}Ne, ^{20}O) and (^{18}O, ^{18}Ne) DCE reactions.

- 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

- **First pilot runs were performed using the existing large acceptance magnetic spectrometer MAGNEX with ion beams provided from the existing cyclotron at INFN-LNS**.

From existing magnetic spectrometer MAGNEX …



Ion beams from existing cyclotron (up to 10^{10} pps)

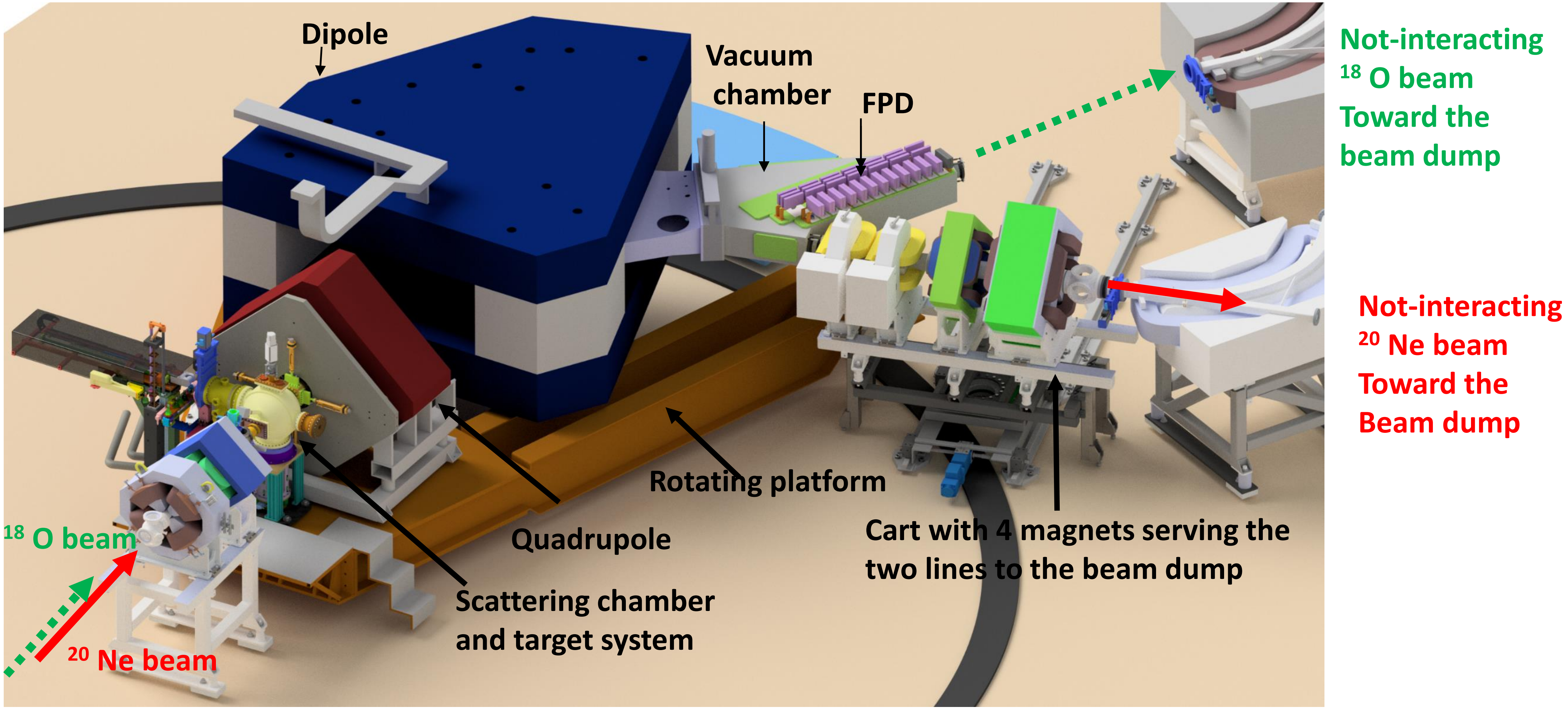
Figures of merit:

$\Delta E/E \sim 1/1000$
$\Delta\theta \sim 0.2°$
$\Delta m/m \sim 1/300$

To get significative values of tiny DCE cross sections and to speed up a systematic study of the large number of nuclei of interest for $0\nu\beta\beta$, a new set-up is mandatory and it consists in:

- A new superconducting cyclotron featuring ion beams of 15÷70 MeV/u and up to 10^{13} pps.
- A complete upgrade of the MAGNEX spectrometer, whose target and detectors will have to handle higher rates. For that, a R&D phase started for the following components:
  - Scattering chamber and Target system
  - Vacuum chamber and Focal Plane Detector (FPD) composed of the gas tracker and the PID Wall
  - Beam dump lines
  - Gamma detector array (G-NUMEN) around the scattering chamber

… to the new MAGNEX



The transport of high energy ions requires to have a higher magnetic rigidity of the quadrupole and dipole whose magnetic fields will be increased of 20% compared to the present values, up to 1.139 T and 1.380 T respectively.

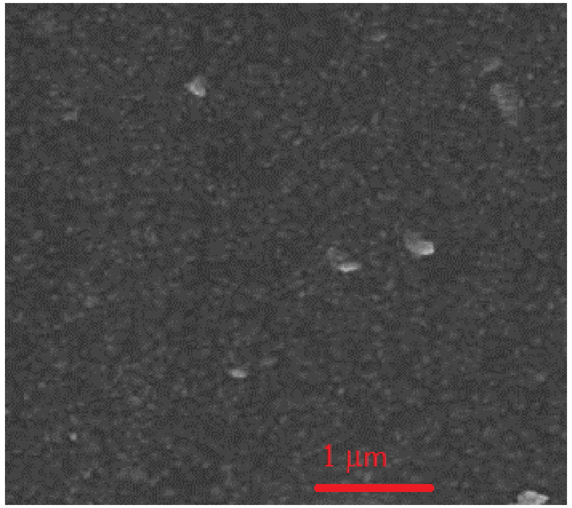
The target

Requirements:

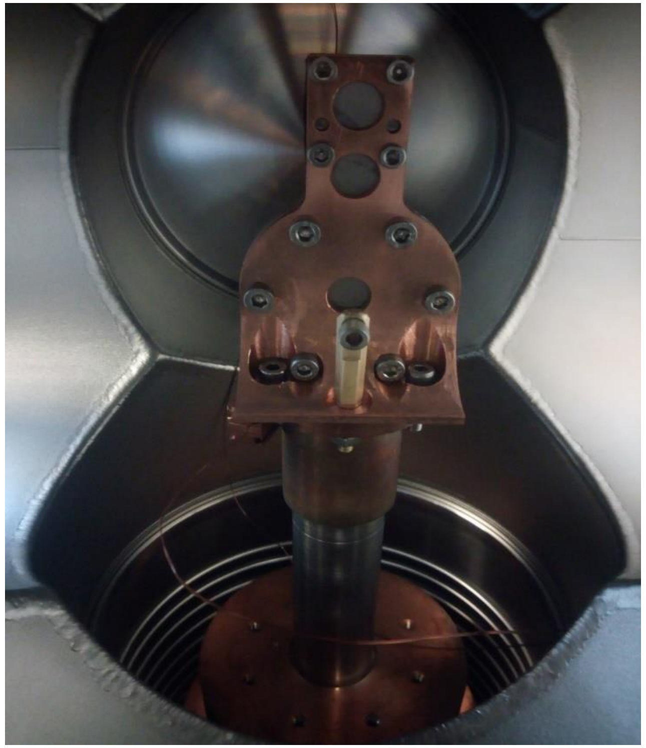
- Thin isotopic target to allow the ejectiles energy measurement with a good energy resolution
- Adequate holder for the target
- Heat, produced by the interaction of the intense beam and the target, must be draw toward a heat sink to avoid the material melting

Challenging solution

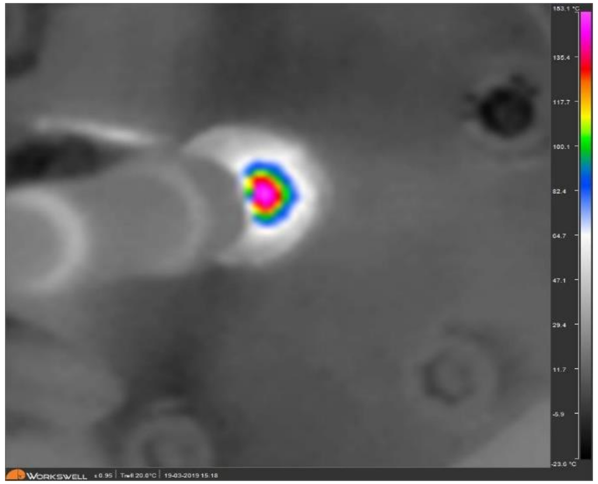
- Isotope deposition (PVD technique), some hundreds of nm thin, homogeneous and uniform.
- The substrate is a Highly Oriented Pyrolitic Graphite (HOPG) film (few μm thin) with high in-plane thermal conductivity (≈ 1900 W/m K) that acts also as post stripper layer
- The graphite sheet is pinched by a copper target-holder tightened to a cryo-cooler



Te deposition, 216 nm thin amorphous' (polycrystalline) layer Top view by FESEM analysis



Prototype of the target and its cooling system in a test chamber

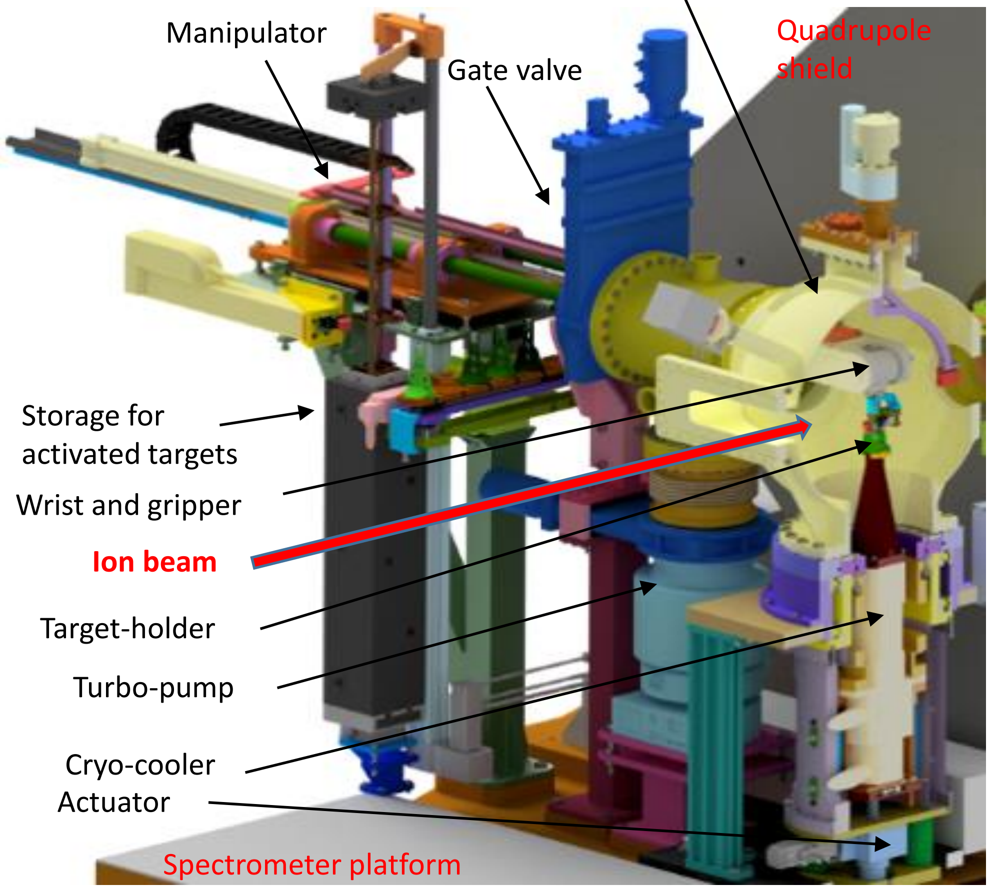


Thermal map of a Te-on-C target irradiated with a IR laser diode

The new target system inside the scattering chamber

Requirements:

- The target, inside the scattering chamber, is the rotation fulcrum of the whole spectrometer
- An automatic system to align the target to the beam
- An automatic manipulator to replace the degraded target, because of the high radiation level

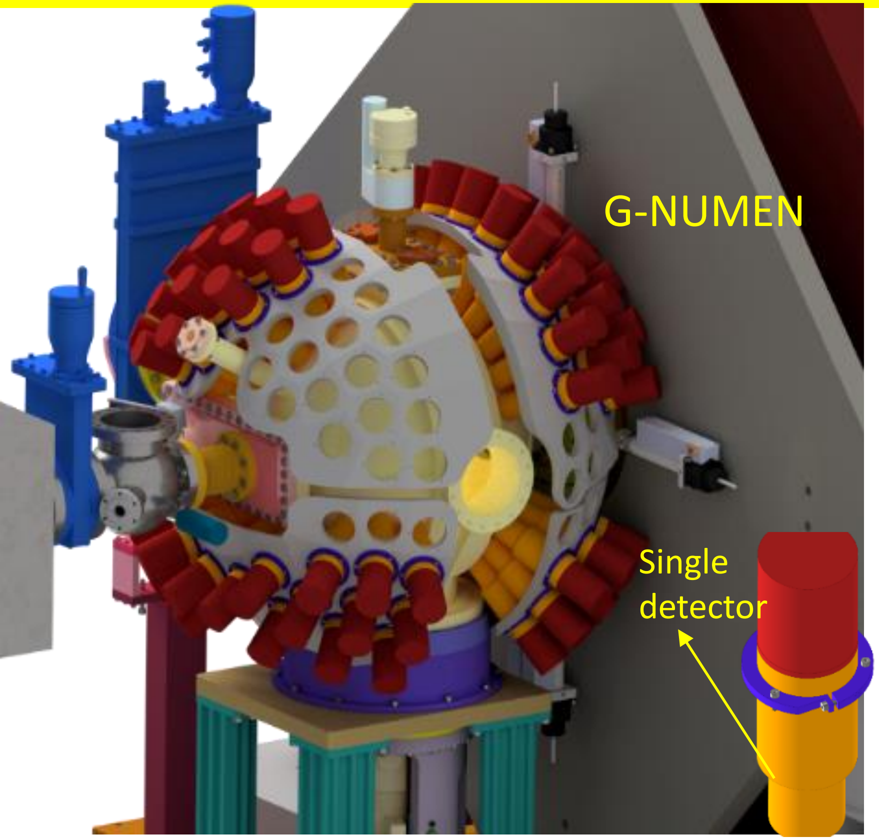


Custom solution:

- A spherical like shape scattering chamber, supported with a cylindrical structure wrapping the target cooling system, is fixed to the spectrometer rotation platform
- The target (and its cooling system) is bonded to the floor, and it is aligned to the beam with an actuator, a bellows sustains the needed stroke. Sealing allows vacuum operations
- An automatic manipulator is positioned on the side of the chamber. Its wrist with the gripper enters in the chamber through a gate valve and unlock the target-holder from the cold finger of the cryo-cooler. A vertical cylinder stores the activated targets till they are removed away

Wrist of the manipulator
The gripper tighten the target-holder

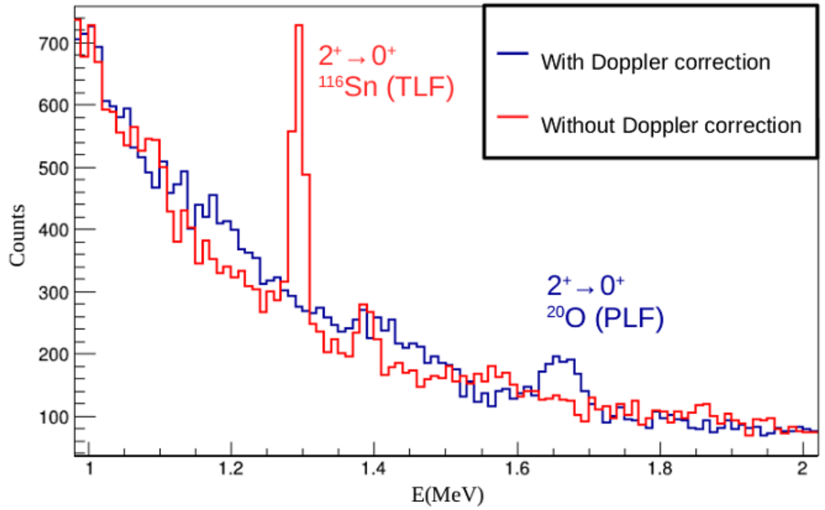
G-Numen, the gamma detector array



Requirements:

- Allow to separate the low lying DCE states of the projectile-like fragment and target-like fragment, in specific cases (deformed target nuclei, beam energies > 20 MeV/u)
- Energy resolution of 3-30 %
- Time resolution < 1 ns
- Detector able to handle high background (up to 10^5 cps)
- Tolerant to radiation

Support of the upstream octant (by courtesy of S. Belliardo)

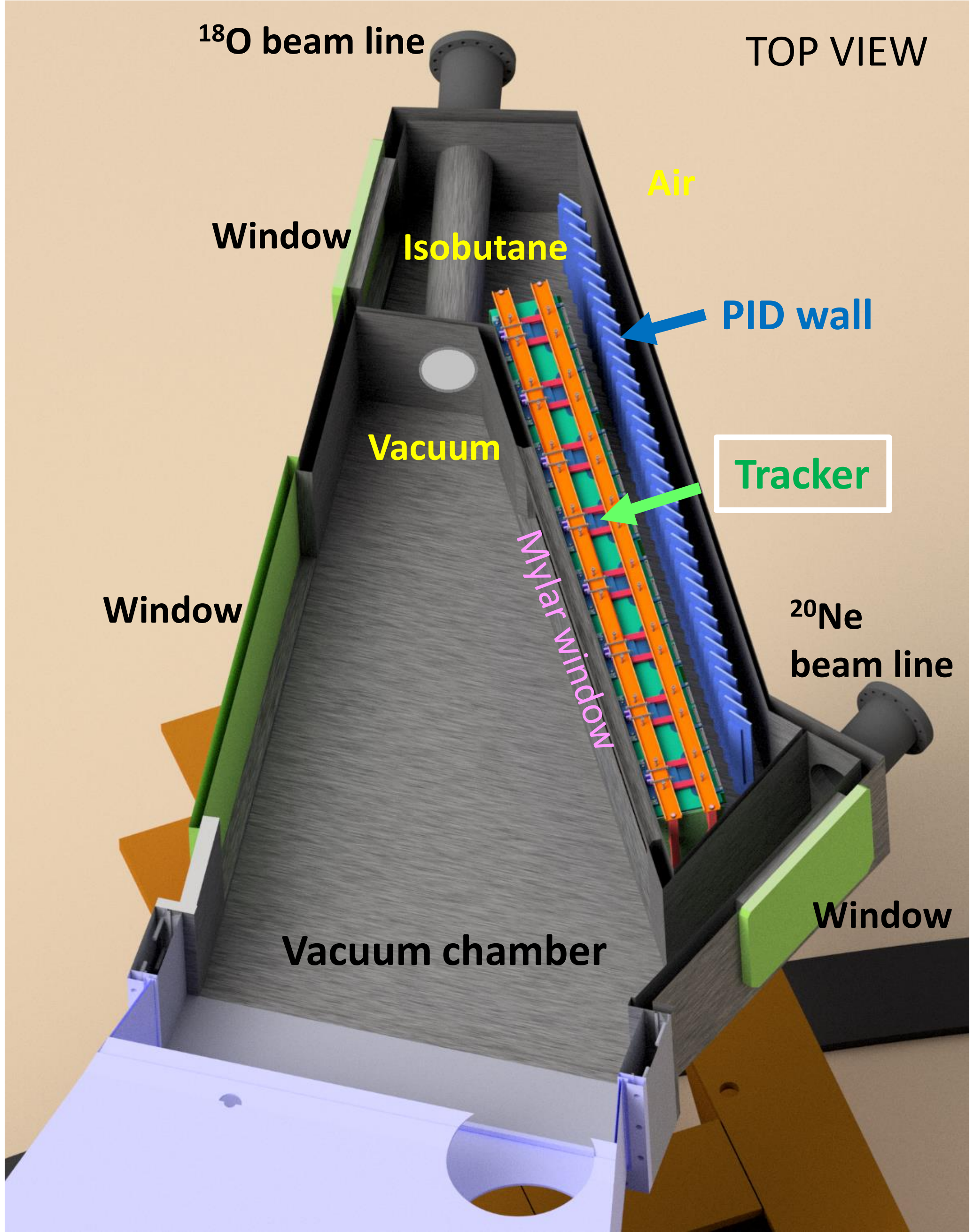


Simulation of the gamma ray spectra for transitions to low lying states of DCE measurements, with G-NUMEN
NUMEN Technical Design Report

G-NUMEN:

- 110 LaBr3 (Ce) scintillator detectors, each with its PM, are foreseen around the scattering chamber (5 mm aluminium thick)
- Coverage $\Delta\Omega \approx 50$ msr
- Total photo-peak efficiency near 4 % and energy resolution of $\approx 3\%$
- A spherical like shape support divided in some parts facilitate the gamma detectors handling. Semi-automatic systems are under design.

Vacuum chamber



- A very thin (few μm) mylar foil (920 mm x 150 mm) separates the isobutane-filled FPD region from the vacuum part
- The ejectiles from nuclear reactions are analysed by the dipole and they hit the Focal Plane Detectors
- The not interacting ions of beam (^{18} O or ^{20} Ne) move along the vacuum chamber and enter the corresponding beam lines
- The gas tracker and the PID wall are suspended to independent stainless steel rectangular flanges sealed to the chamber top to facilitate their insertion/extraction with a specific lifting system
- Additional sealed flanges allow the positioning of the mylar window and the installation of specific tools for the beam tuning

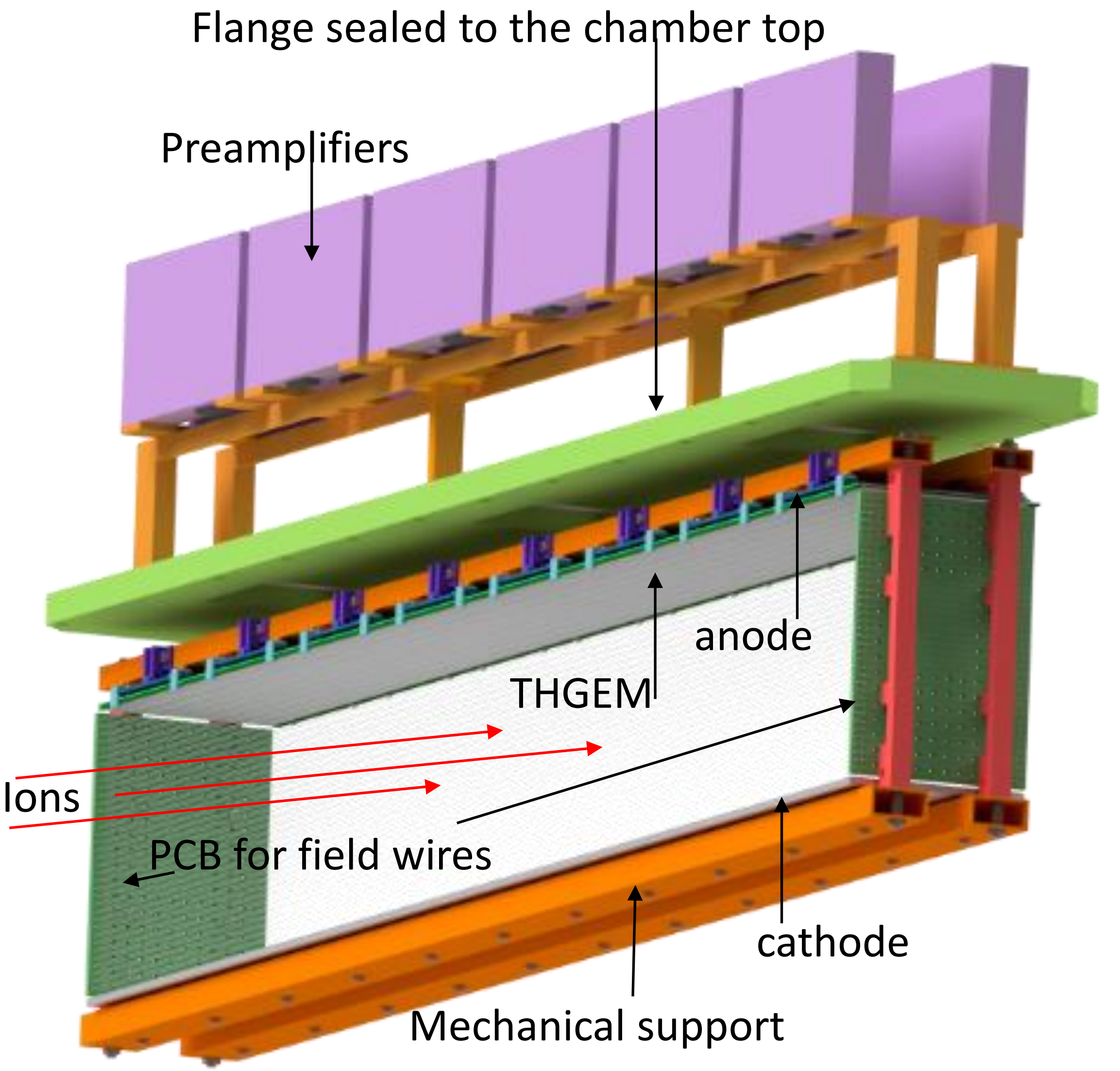
Tracker

Requirements:

- Heavy ion detection
- High resolution of the phase space parameters at the focal plane : < 600 μm for X_{foc} and Y_{foc} , < 500 mrad for θ_{foc} , ϕ_{foc})
- Capability to withstand a rate of ≈ 50 kHz/cm along the horizontal direction
- Time resolution of ≈ 1 ns

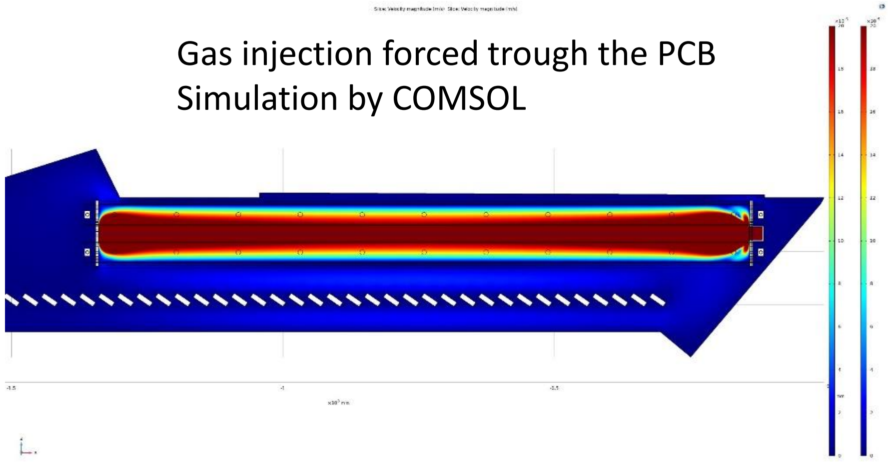
Tracker

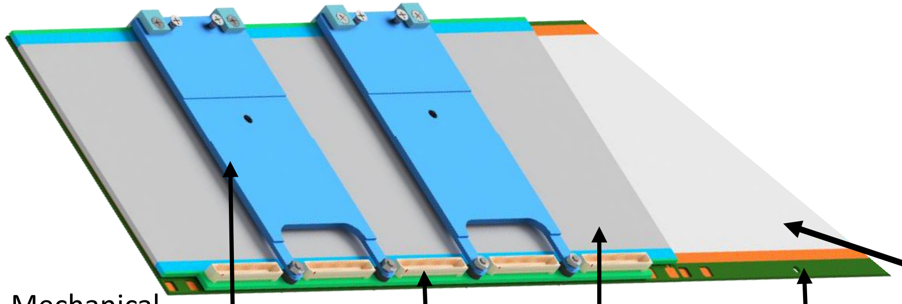
- A time projection chamber with electron amplification based on 3 THGEMs foils is under design
- The sensitive volume is 1200 x 116 x 108 mm^3
- This volume is delimited from the cathode and the THGEMs. Lateral PCBs support the drift wires arranged in two double rows to shape a uniform 50 V/cm electric field for defining the drift region. The wires are made of gold-plated tungsten with 50 μm diameter, 5 mm spaced
- The anode is segmented in 1200 pads arranged in 5 rows and spaced each other for the sampling of the ion tracks
- Isobutane gas (absolute pressure in the range 10 -100 mbar) fills the volume



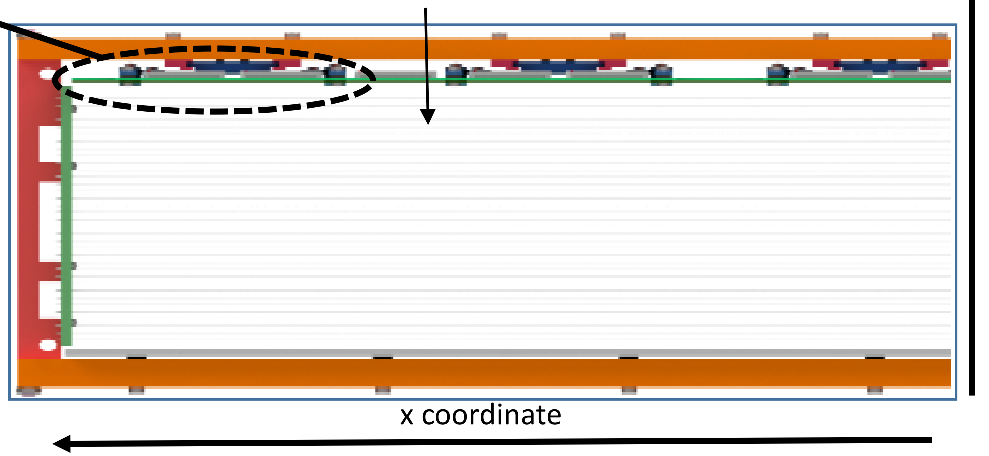
Tracker

Gas injection forced trough the PCB
Simulation by COMSOL





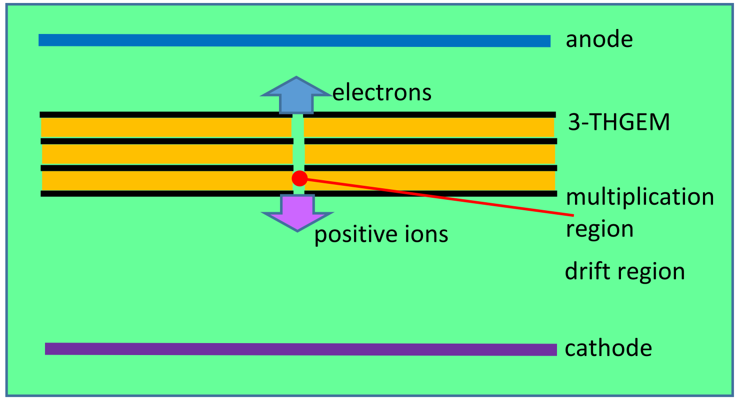
- The 3-THGEMs consists of a densely drilled (0.3 mm diameter holes) assembly of 3 insulating layers ($\approx 1\mu m$ thick) in an alternate configuration with the metallic electrodes
- The 3 – THGEMs assembly extends over the whole length of 1200 mm
- 4 anode circuits equipped with 300 pads each (in the figure one anode circuit is drawn) serve the THGEMs assembly
- Short cables wire the detectors equipped with SAMTEC multi-pin connectors, inside the chamber, and the preamplifiers positioned on the chamber top

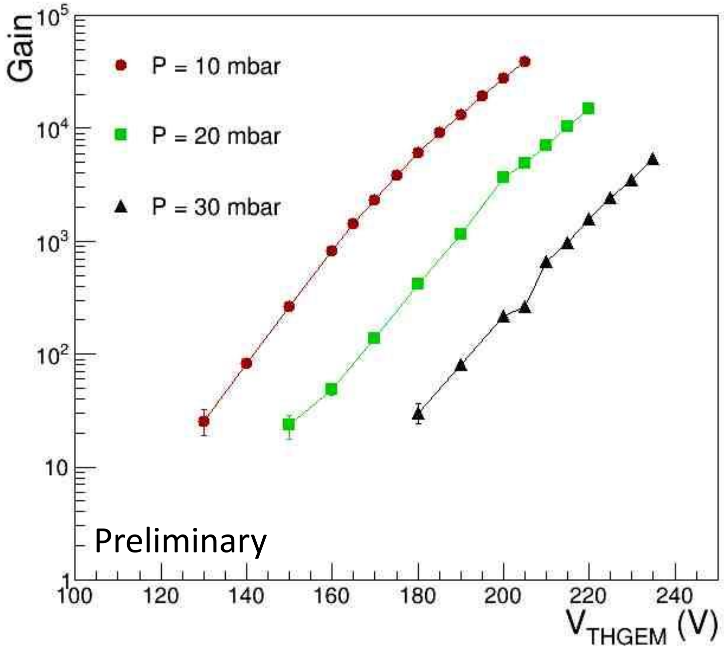


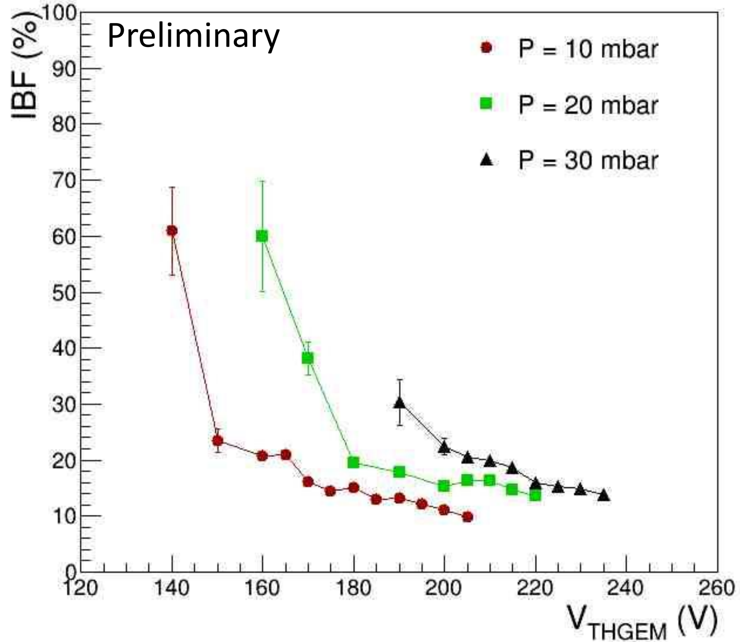
- The pads signals feed preamplifiers and then digitizers circuits
- The final information are the hit timestamp with a resolution < 1ns and the electrons collected by the pad
- x coordinate is evaluated with a centre of gravity calculation of the charge distribution
- Y coordinate is measured as arrival time of the electrons into the pads

Tracker prototype

- A reduced size prototype, 100 x 185 x 108 mm^3, has been built. It is smaller in the dispersive direction.
- The prototype has been tested and characterized with radioactive alpha source and with oxygen beam.
- THGEM prototypes have an area of 108 x 108 mm2, thickness of 1mm, and feature 0.3 mm diameter holes and 0.75 mm spacing. Samples substrates are Rogers 4350 and Ceramic SD103K.







PID Wall

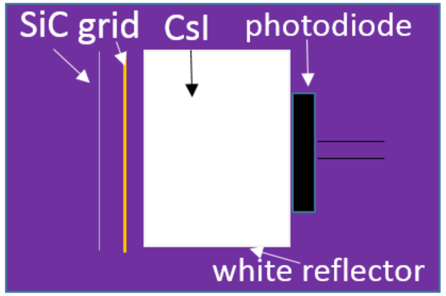
Requirements:

- Measurement of the energy loss of ions and of the residual energy of stopped ejectiles in the region of O, F, Ne atomic species in the incident energy range 15-50 MeV/u
- Energy resolution better than 2% to have $\Delta Z/Z \approx 1/48$ and $\Delta A/A \approx 1/160$
- Radiation hardness of 10^{11} ions/(cm^2 year) (120 days of irradiation)
- Double hit event probability less than 3%
- Time resolution less than 1 ns
- Installation in a low pressure isobutane atmosphere defined by the tracker.

PID Wall

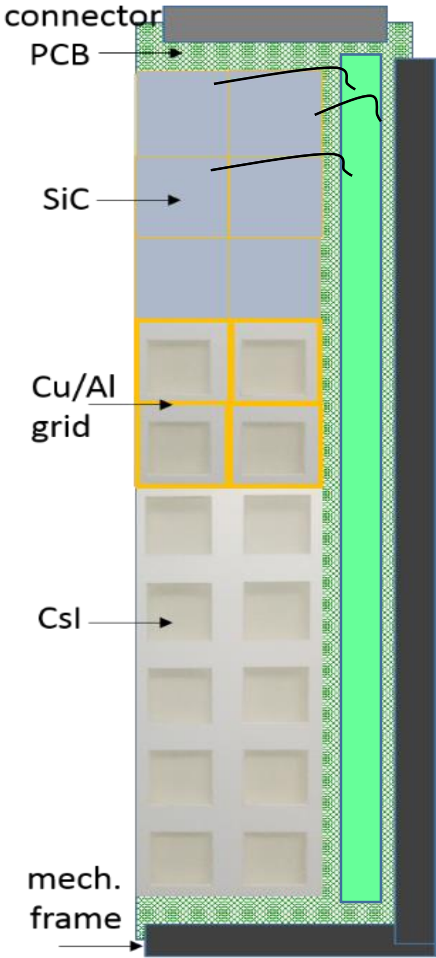
- The single unit is a telescope composed of SiC and CsI (Tl) sensors, the first one measures the ion energy loss and the second one the ion residual energy
- the 100 μm thin SiC sensor (15 mm x 15 mm) is glued to a Cu/Al grid on the top of a 5 mm thick CsI (Tl) read with a Hamamatsu photodiode S35590
- A custom PCB houses 20 telescopes arranged in 10 rows and 2 columns
- 36 PCB compose the PID Wall, each tilted of 35° angle with respect the tracker.

Scheme of a telescope

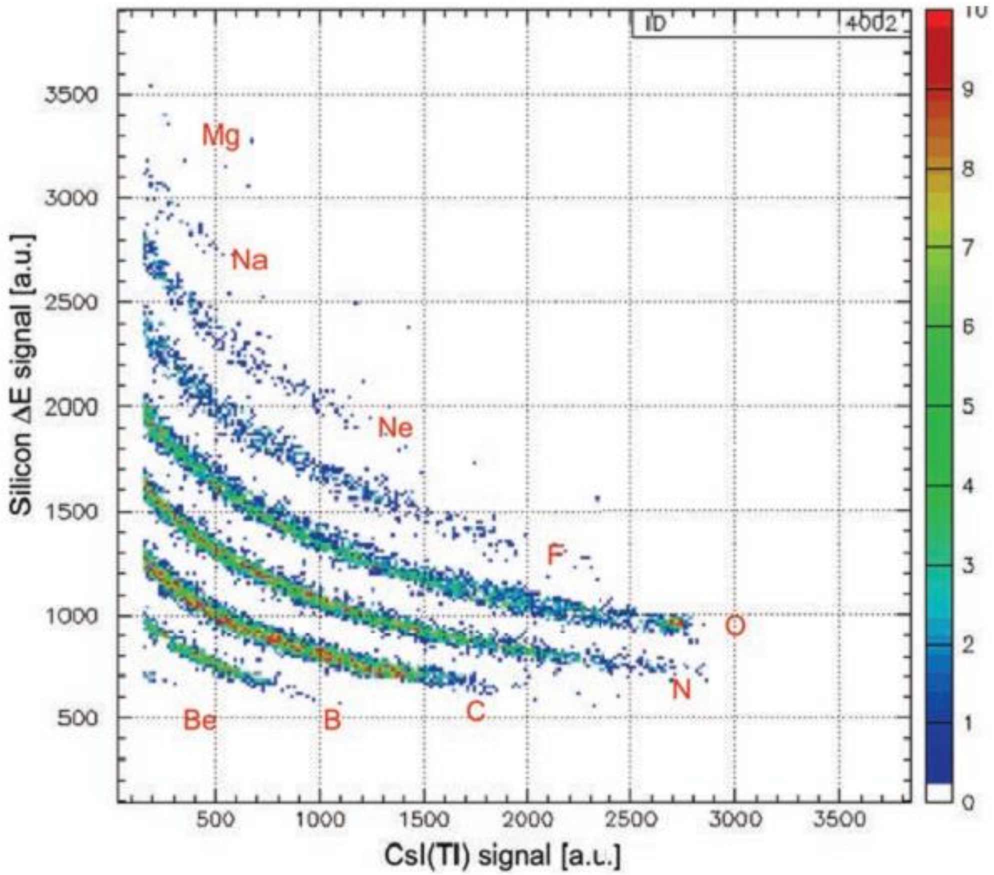


Prototype of 25 mm connections from Si sensor and PCB using wire bonding technique

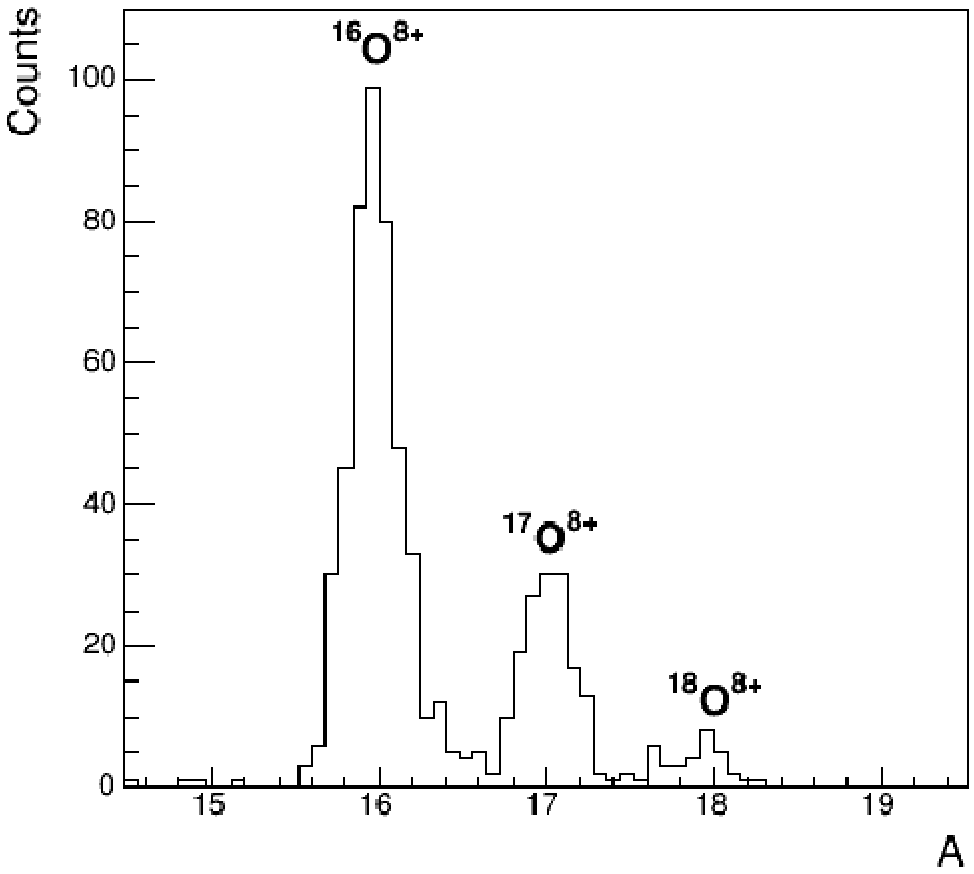
PID tower scheme



PID Wall



ΔE versus E with a single unit composed of Si and CsI (Tl) sensors.
The atomic number resolution is $\Delta Z/Z \approx 0.16$ in between 9 adjacent species
NUMEN Technical Design Report

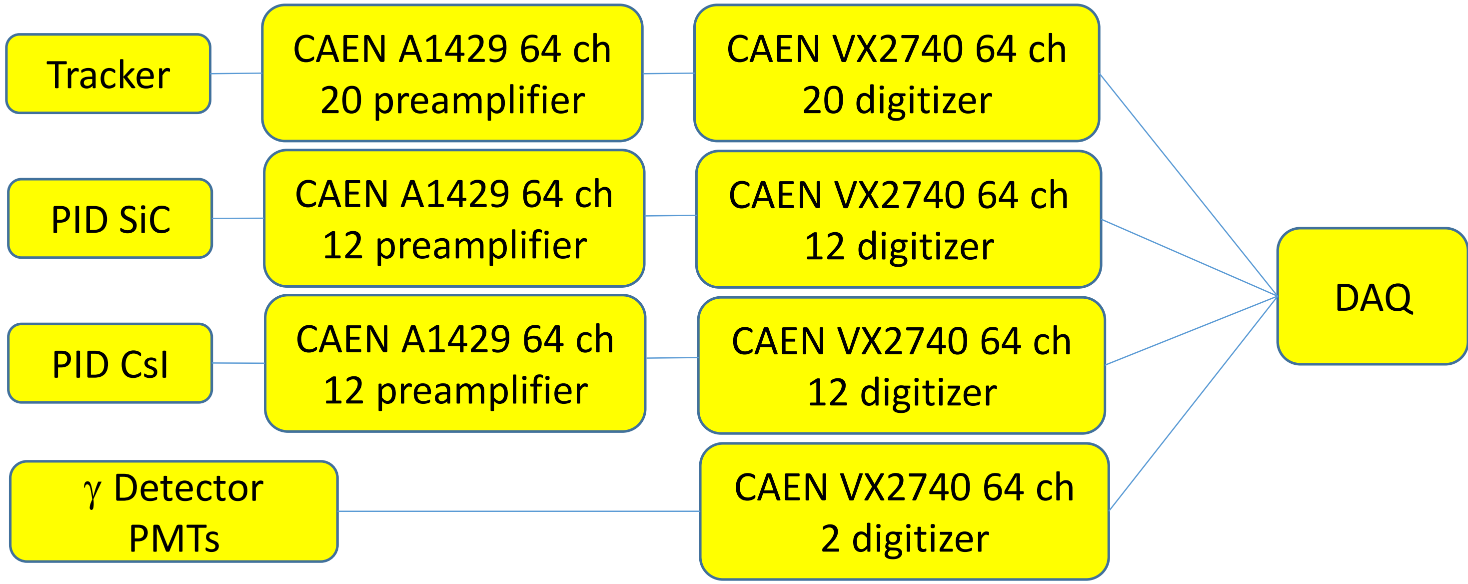


Mass spectrum obtained with a selection in the plot of X_{foc} -E correlation from a SiC – CsI telescope
NUMEN Technical Design Report

Readout architecture and DAQ

Requirements:

- Same readout components for the different detectors
- Signal digitalization and good time resolution
- Capability to withstand high rate, hundred kHz each tracker channel, few MHz for the γ–detector channel
- On –line processing for correlating the signals from both sensors of the PID telescope



Readout architecture:

- Tracker and PID Wall signals are amplified with CAEN A1429 charge-sensitive preamplifiers
- The CAEN VX2745 digitizers, with 125 MHz sampling rate, work with all the pre-amplified signals and PMTs signals of the γ-ray detectors
- The digitizer provide the timestamp of the event and a signal whose amplitude is proportional to the detector signal.
- The gamma-ray detectors (expected rate of few MHz/channel) will be used in coincidence with the FPD at lower beam intensity ($\approx 10^{12}$ pps)
- With dedicated algorithms the on-board digitizer FPGA selects correlated signals from the sensors of the PID Wall belonging to the same ion crossing the telescope

DAQ:

- The evaluated maximum data rate is of the order of 50-60 Mbytes/s
- A 9 byte data format stores the information of each hit
- The digitizers outputs feed the concentrators with 10 Gbit/s Ethernet links. A data storage follows.
- The DAQ works in free-running mode

Conclusions

- The R&D phase to upgrade the MAGNEX spectrometer is in its final part
- The production is ongoing.
- The integration phase started in laboratory since the experimental room of MAGNEX is in preparation.
- TDR has been published

The "NUMEN Technical Design Report", IJMPA, Vol. n° 36, Issue n°30, Article n°213001

- The installation at INFN-LNS of the new components for the MAGNEX spectrometer is foreseen in 2023