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# Towards the integration of the NUMEN experiment

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# Towards the integration of the NUMEN experiment

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**Abstract.** The most promising probe to establish the Majorana or Dirac nature of the neutrino is the neutrinoless double beta decay and the effective neutrino mass would be evaluated by the knowledge of the corresponding nuclear matrix elements. Also measurements of the Double Charge Exchange (DCE) interactions of heavy ion beams can get information on them. The NUMEN experiment based on the pre-existing large acceptance MAGNEX spectrometer and integrated with new challenging components aims at measuring DCE cross sections using ion beams of unprecedented intensity ($10^{13}$ pps) on specific isotopes at INFN-LNS in Catania. Expected rate on the sensitive area of about 0.15 $m^2$ reaches up to about 5 Mpps, demanding for adequate detectors in measuring position, direction, energy, mass and charge of the ions produced by interactions. Gamma detectors surround a scattering chamber containing the target.

## 1. Introduction

The most promising probe to establish the Majorana or Dirac nature of the neutrino is the Neutrinoless Double Beta Decay ($0\nu\beta\beta$). If the $0\nu\beta\beta$ decay is detected, the effective neutrino mass would be evaluated by the knowledge of the corresponding Nuclear Matrix Elements (NME). Information on these NME can be obtained using Heavy-Ion Double Charge Exchange (DCE) reactions, because they present many similarities even if they are mediated by different interactions. One similarity is that initial and final nuclear states are the same.

NUMEN proposes to measure the absolute cross section of DCE of nuclei of interest for the $0\nu\beta\beta$ decay and investigate an overlap for the NME of two processes [1]. In particular, two sets of measurements will be performed, corresponding to $\beta^-\beta^-$ and $\beta^+\beta^+$ decays that feature the two directions of isospin lowering and raising operators, respectively. The first set exploits the ($^{20}$Ne, $^{20}$O) DCE reaction, the second set the ($^{18}$O, $^{18}$Ne) reaction. Competing channels to each of this reactions will be measured too. Examples of candidate isotopes of interest are $^{48}$Ti, $^{76}$Se, $^{116}$Sn with ($^{18}$O, $^{18}$Ne) reaction, and $^{116}$Cd, $^{130}$Te, $^{78}$Ge using ($^{20}$Ne, $^{20}$O) reaction.

The existing, large acceptance, magnetic spectrometer MAGNEX [2] has been used for pilot runs with some nuclei of interest for $0\nu\beta\beta$ and the ion beams (up to $10^{10}$ pps) provided from

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the existing cyclotron at INFN-LNS. The spectrometer features a scattering chamber with its target, a quadrupole, a dipole and a Focal Plane Detector (FPD) composed of a gas tracker and a silicon wall. Its figures of merit are as follows: $\Delta$E/E $\sim$1/1000, $\Delta\theta$ $\sim$0.2°, $\Delta$m/m $\sim$1/160.

However, to get significative values in the measurements 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 configuration is needed. A new superconducting cyclotron will be installed at INFN-LNS laboratory and new ion beam lines as well, highlights of this new accelerator are: 15 $\div$ 70 MeV/u, beam intensity up to $10^{13}$ pps [3], [4]. The upgrade of MAGNEX spectrometer is need to withstand the new ion beams and it is ongoing. An overview of the integration of its components is presented in the following two sections, the first one for the components upstream quadrupole and the second one for the magnetic components and the detectors.

## 2. The upstream part of the experiment

In the upstream part of the spectrometer a new chamber houses the target and gamma detectors are installed around it. Due to the new ion beams, a lot of heat, produced by beam-target interaction, must be quickly removed, and due to the high radiation level, the target has to be handled using an automatic manipulator. However the target must be thin to allow a good energy resolution. The custom solution foresees a uniform deposition of isotope of interest (some hundreds of nm) on Higly Oriented Pyrolitic Graphite (HOPG) few $\mu$m thin film featuring high thermal conductivity [5], [6]. The graphite sheet is pinched by a copper target-holder tightened to a cryo-cooler to making the cooling system.

The target is inside a spherical like shape scattering chamber (460 mm of external diameter) (Figure 1) supported with a complex cylindrical structure that wraps the cryo-cooler. The entire spectrometer rotates around the target that presents its surface always orthogonal to the incident ion beam. In fact, the spectrometer angular position has to be optimized according to the O or Ne beams using two different connection plates, upstream chamber, with a surface inclined of +3° or -3° respectively and a bellows connected to the beam line will correct misalignment within ±1°. Since the target-holder houses also alumina for beam alignment purposes and graphite for reference, its vertical positioning is obtained by moving up and down the cryo-cooler with an actuator, a bellows guarantees the necessary stroke [7]. A thermo-camera maps the thermal field of the target signalling a degradation of the graphite itself. A Faraday cup measures the beam current on request, otherwise it is rotated by 90°. A pepperpot is inserted on demand along the beam for trajectory calibration purposes. An automatic manipulator [8] handles the target holder and replaces it when the target is degraded. Its wrist with gripper enters in the chamber through a gate valve and once positioned above the target-holder releases it from the cold finger of the cryo-cooler. A target storage houses the activated targets (up to 6) till they are removed from the experimental hall. Two pairs of motorized slits made of tantalum can model the acceptance of the spectrometer vertically up to ±7.5° and horizontally up to ±6.5°. In specific cases such as deformed target nuclei or beam energies $\geq$ 30 MeV/u, the MAGNEX energy resolution does not allow sufficient separation of the low lying DCE states of the projectile-like fragment and target-like fragment. To reach this task, an additional gamma-ray spectrometer composed of about 110 $LaBr_3$ (Ce) scintillator detectors, each with its photomultiplier (with a total length of $\sim$ 22 cm) will be installed around the scattering chamber (Figure 2) [9]. The PMTS signals of the gamma-ray detectors feed directly the VX2740 digitizer. The detectors cover the 20% of the total solid angle and feature a total photo-peak efficiency near 4% and energy resolution of about 3% FWHM, at 1.3 MeV gamma-ray energy. A time resolution better than 1 ns guarantees the capability to separate events of interest from the high background, up to $10^5$ cps. Since the expected radiation level around the target region is high and this part of experiment is highly crowded with mechanical components and instrumentation, it is very difficult to manually operate on the detectors. For this reason is under study a spherical like shape support divided in some parts to facilitate their handling.

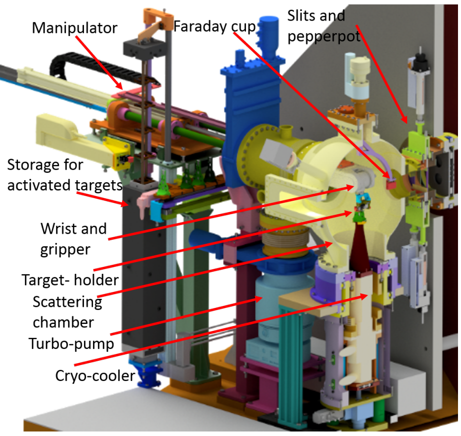


**Figure 1.** Scattering chamber.

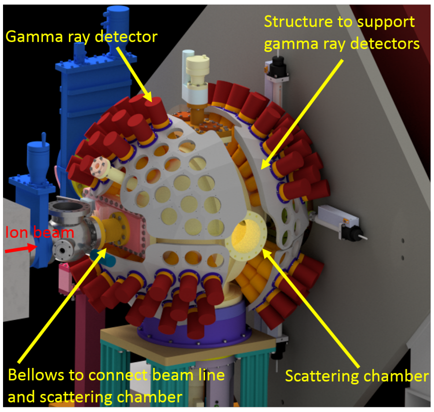


**Figure 2.** Gamma detectors.

## 3. Magnetic elements and new Focal Plane Detector

The transport of high energy ions requires to have a higher magnetic rigidity of the quadrupole and dipole, then their magnetic fields will be increased of 20% compared to the present values of MAGNEX, up to 1.139 T and 1.380 T respectively [9]. A new chamber is connected to the dipole vacuum chamber with a large rectangular valve and it houses the gas tracker and the PID wall, they form the Focal Plane Detectors (FPD). This new chamber cannot translate along the optical axis, as the current camera did to obtain a fine focusing of the ejectiles, due to the first magnetic elements of the beam dump lines positioned immediately downstream the chamber itself (Figure 3). The fine focusing of the ejectiles is then obtained with the upgraded dipole surface $\alpha$-coil [9].

The new chamber features 230 mm height and its width increases, starting from the 800 mm of width of the gate valve, with a angular divergence of about 6° to allow the transport in vacuum of the unreacted ion beams up to the beam dump lines. The FPD, tilted with an angle of 59° with respect the gate valve shutter, is positioned in the middle and filled with isobutane at an absolute pressure of about 10 mbar. It offers a few $\mu$m thin mylar window (920 mm x 150 mm) to the entry of ions coming from the vacuum part of the chamber (Figure 4). 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 positioned on the MAGNEX platform and equipped with a suitable couple of grippers. The flanges houses intermediate PCBs equipped with multi-pin connectors, short cables wire the detectors, inside the chamber, and the preamplifiers positioned on the chamber top. Additional sealed flanges allow the positioning of the mylar window and the installation of specific tools for the beam tuning.

The required spatial resolutions for the gas tracker are less than 600 $\mu$m for the x and y coordinates (transverse coordinates to the beam) and less than 500 mrad for the horizontal and vertical angles, the time resolution is of about 1 ns. Further requirement is to withstand a rate of about 50 kHz/cm along the horizontal direction [9]. The implemented solution is a gas tracker based on 3 THGEM layers able to withstand the expected rate. The sensitive volume is of 1200 x 116 x 108 mm$^3$. On the bottom the cathode, and on the top the anode, 1200 pads are arranged in 5 rows and spaced each other to guarantee the sampling of the ion tracks. Drift fields along the x coordinate are supported with two lateral PCBs. A double mechanical frame houses the detector and connect it to the flange on the chamber top.

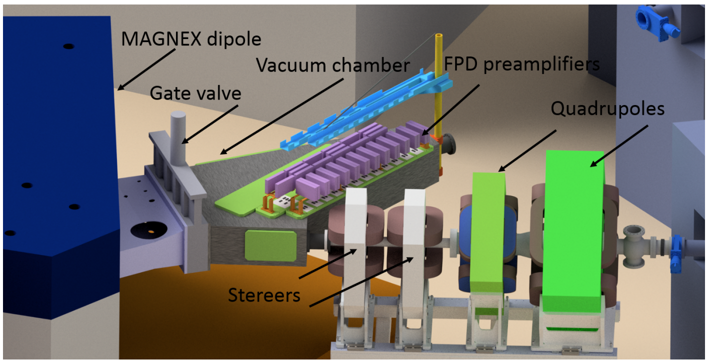


**Figure 3.** Vacuum chamber and first magnetic elements of the beam dump lines.

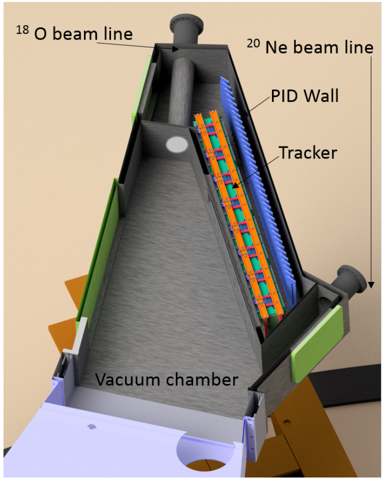


**Figure 4.** Top view of the internal of the vacuum chamber.

The PID wall has to provide the measurements of the energy loss of ions with different charge states in the 10 ÷ 25 mass region range and in the 4 ÷ 12 atomic number interval, and their residual energy. The request is of ∼2% energy resolution. Since a fluency of $10^{11}$ ion/(cm$^2$·year) is expected, a good radiation hardness is requested. Besides the PID measures the hit coordinate. Also for this detector the required time resolution is of ∼1 ns [9]. The implemented solution is a telescope composed of 110 $\mu$m thin SiC sensor (15 mm x 15 mm), to measure the ion energy loss, glued to a Cu/Al grid on the top of a 5 mm thick CsI (Tl) (for the measurement of the ion residual energy) read with a Hamamatsu photodiode S35590 (10mm x 10mm). A custom PCB houses 20 telescopes, 10 row and two columns. It is equipped with a metallic frame to allow its positioning with a 100 $\mu$m precision in a dedicated mechanical support hang to the chamber flange. 36 PCBs build the PID wall, each tilted of 35° angle with respect the tracker.

The readout architecture foresees to amplify the tracker and PID Wall signals with the CAEN A1429 charge-sensitive preamplifier circuit, its output feed the CAEN VX2740 digitizer [9].

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