Target Manipulation in Nuclear Physics Experiment with Ion Beams

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Corresponding Author	Family Name	**Sartirana**
	Particle	
	Given Name	**Diego**
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	INFN, Section of Turin
	Address	10125, Turin, Italy
	Division	DIMEAS
	Organization	Polytechnic of Turin
	Address	10129, Turin, Italy
	Email	diego.sartirana@to.infn.it
Author	Family Name	**Calvo**
	Particle	
	Given Name	**Daniela**
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	INFN, Section of Turin
	Address	10125, Turin, Italy
	Email	
	ORCID	http://orcid.org/0000-0001-6006-7467
Author	Family Name	**Capirossi**
	Particle	
	Given Name	**Vittoria**
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	INFN, Section of Turin
	Address	10125, Turin, Italy
	Division	DISAT
	Organization	Polytechnic of Turin

	Address	10129, Turin, Italy
	Email	
	ORCID	http://orcid.org/0000-0002-4793-9408
Author	Family Name	**Ferraresi**
	Particle	
	Given Name	**Carlo**
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	INFN, Section of Turin
	Address	10125, Turin, Italy
	Division	DIMEAS
	Organization	Polytechnic of Turin
	Address	10129, Turin, Italy
	Email	
	ORCID	http://orcid.org/0000-0002-9703-9395
Author	Family Name	**Iazzi**
	Particle	
	Given Name	**Felice**
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	INFN, Section of Turin
	Address	10125, Turin, Italy
	Division	DISAT
	Organization	Polytechnic of Turin
	Address	10129, Turin, Italy
	Email	
	ORCID	http://orcid.org/0000-0002-2470-4315
Author	Family Name	**Pinna**
	Particle	
	Given Name	**Federico**
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	INFN, Section of Turin
	Address	10125, Turin, Italy
	Division	DISAT
	Organization	Polytechnic of Turin
	Address	10129, Turin, Italy
	Email	
	ORCID	http://orcid.org/0000-0002-2293-0044

Abstract	The NUMEN project at *Laboratori Nazionali del Sud* of INFN studies the nuclear matrix elements of Double Charge Exchange reactions between some particular nuclei. This information will be helpful in studying the Neutrinoless Double Beta decay. Because of the very low cross-sections of such reactions, high statistics must be acquired using very intense ion beams coupled with thin targets in order to get a good resolution in energy measurements. Since the target is irradiated with low energy and intense ion beams the crucial problems are the large amount of released heat and the activation of the material. To cope with the first problem isotopes are evaporated on a graphite substrate with high thermal conductivity that will be cooled down using a cryocooler. The second issue demands for an automatic system for the target handling during the data taking of the experiment. Positioning of the target-holder with appropriate precision and contact force is a special requirement, while all materials have to be selected to suit both the large temperature range and the foreseen radiation level. This work focuses on the automatic system for target manipulation, describing its design characteristics to cope with such particular working condition and to be integrated in the experiment.
Keywords	Automatic manipulator - Nuclear physics experiment - Hostile environment

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Target Manipulation in Nuclear Physics Experiment with Ion Beams

Diego Sartirana[1,2](✉), Daniela Calvo[1], Vittoria Capirossi[1,3], Carlo Ferraresi[1,2], Felice Iazzi[1,3], Federico Pinna[1,3], and for NUMEN collaboration

[1] INFN, Section of Turin, 10125 Turin, Italy
diego.sartirana@to.infn.it
[2] DIMEAS, Polytechnic of Turin, 10129 Turin, Italy
[3] DISAT, Polytechnic of Turin, 10129 Turin, Italy

Abstract. The NUMEN project at *Laboratori Nazionali del Sud* of INFN studies the nuclear matrix elements of Double Charge Exchange reactions between some particular nuclei. This information will be helpful in studying the Neutrinoless Double Beta decay. Because of the very low cross-sections of such reactions, high statistics must be acquired using very intense ion beams coupled with thin targets in order to get a good resolution in energy measurements. Since the target is irradiated with low energy and intense ion beams the crucial problems are the large amount of released heat and the activation of the material. To cope with the first problem isotopes are evaporated on a graphite substrate with high thermal conductivity that will be cooled down using a cryocooler. The second issue demands for an automatic system for the target handling during the data taking of the experiment. Positioning of the target-holder with appropriate precision and contact force is a special requirement, while all materials have to be selected to suit both the large temperature range and the foreseen radiation level. This work focuses on the automatic system for target manipulation, describing its design characteristics to cope with such particular working condition and to be integrated in the experiment. AQ1 AQ2

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1 Introduction

One of the hot topics in modern Nuclear Physics is the neutrino particle nature; Neutrinoless Double Beta decay fits in this context. Double Charge Exchange (DCE) reactions and Neutrinoless Double Beta decay share many similarities. NUMEN project [1] aims to study some DCE nuclear reactions. Some preliminary data have been already taken at *Laboratori Nazionali del Sud* (a INFN facility in Catania, Italy), using the spectrometer MAGNEX.

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Since high statistics is required to get good precision measurement, a more superconducting cyclotron has been designed, together with an upgrade of the whole MAGNEX spectrometer.

These ion beams will impinge on targets made of thin layers of specific isotopes (up to some hundreds of nm thick) generating heat, which has to be dissipated to avoid damaging the target itself [2].

To cope with the heat dissipation, the isotopes are evaporated on a HOPG (Highly Oriented Pyrolytic Graphite) substrate of about 2 μm featuring a high thermal conductivity. A target-holder (TH) made of copper clamps the target disk. In the current setup, the target is mounted on a sample-holder contained in a cylindrically shaped vacuum chamber (scattering chamber). The chamber is mounted on a rotating platform that hosts MAGNEX, a quadrupole and the detectors (Fig. 1). The rotating axis coincides with the target, which remains still.

A new chamber has been designed to fit the target cooling system, which is foreseen to be a cryocooler able to dissipate about 20 W by keeping the target at less than 40 K.

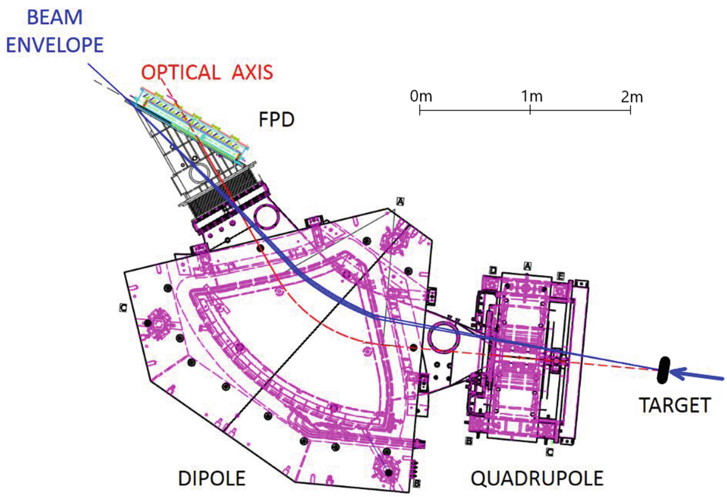

Fig. 1. Plan view of the principal structures of MAGNEX spectrometer. The ion beam first hits the *target*, then the results of this interaction are driven by a *quadrupole magnet* and a *dipole*, and reach the *focal plane detector* (*FPD*).

To guarantee a good thermal conductivity, the base of the target-holder must be accommodated to the cold finger of the cryocooler with an adequate coupling force of about 15 N. Moreover, the contact surfaces will be lapped to reduce the thermal resistance. With the above value of the coupling force, the temperature difference between the surfaces of cryocooler and target-holder has been estimated to be less than 0.3 K [3].

In addition, the target-holder must be shaped to accommodate a graphite sample disk for reference measurements, an empty location to study the background eventually generated by the copper frame itself around the target, and an alumina disk used to verify the alignment and the squeezing of the ion beam (Fig. 2). The alignment of each of these elements to the beam line asks for a linear vertical motion of 100 mm of the target-holder, which is achieved by using a linear actuator under the sustain of the cryocooler.

Besides, the angular error in the target-holder alignment to the ion beam must be less than 0.5° to avoid different path length of the particles inside the isotope layer and therefore affect the resolution in energy of the spectrometer.

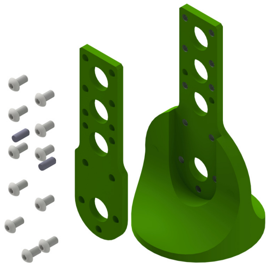

Fig. 2. Image of the target-holder (TH) exploded in all its components. The total height is 95 mm and the diameter of the circular base is 50 mm.

The ions will be transported to the NUMEN experimental hall by two different beam lines, the High Intensity (HI) line, that provides high intensity ion current, and the Low Intensity (LI) line, that allows using ion beams featuring lower currents. A relative 70° rotation of MAGNEX aligns the axis of the quadrupole along the two lines respectively, bringing it alternatively in the HI or in the LI configuration. Therefore, the connection between target-holder and cryocooler must respect these two different configurations by securing two different positions of coupling system, in order to maintain the target always perpendicular to the beam line. Since the scattering chamber is built-in with the rest of MAGNEX, each configuration requires proper connection to the corresponding beam line.

The high intensity of the ion beams together with the planned values of energy per nucleon poses a not negligible problem of radiation dose inside the chamber. The activation of the materials is not excluded; therefore, the replacement of an exhausted target cannot be done manually. An automated system capable of handling the target must be designed and built.

The following sections will present the design details of the whole target manipulation and storage system, as well as a description of the handling procedure.

2 The Target Handling and the Manipulator

The Fig. 3 shows the procedure that shall be adopted for placing the targets inside the scattering chamber, once the latter has been posed in communication with the ambient by opening a proper gate valve.

The sequence of events and phases is: 1) entry of manipulator end effector along a horizontal trajectory, with TH in horizontal position; 2) rotation of TH around a transversal axis, reaching the vertical position; 3) lifting of Cold Finger CF of the cry-ocooler to contact the base of TH; 4) rotation of TH to complete the bayonet coupling with CF; this last movement places the target perpendicular to the ion beam.

Subsequently, the manipulator will retract and the chamber will be sealed and de-pressurized for performing the experiment. The same movements, with different sequence, will be performed by the manipulator for extracting the target after the experiment.

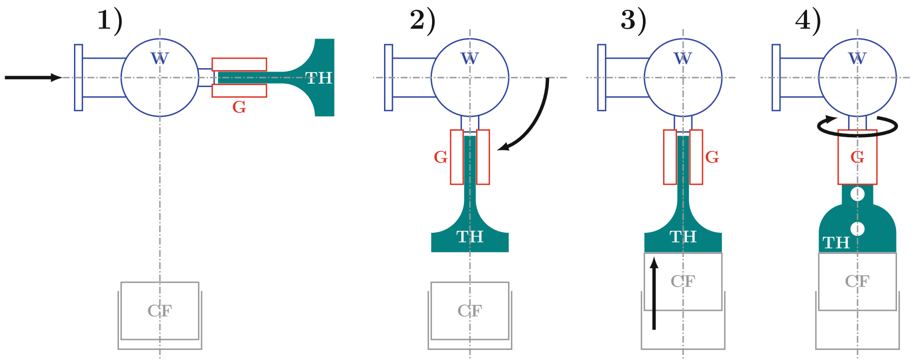

Fig. 3. Sequence for placing the target inside the scattering chamber. At the end, the target is placed perpendicular to the ion beam.

The design of the automatic system for target handling and storing takes into account the specifications required by the experiment. The system is composed by two main devices: the manipulator and the storage system.

The Fig. 4 shows an overall image of the manipulator, which is supported by a rigid structure TF fixed to the MAGNEX platform. The system has in the complex four degrees of freedom. The first DoF is a linear horizontal motion, provided by the pneumatic cylinder C (SMC mod. C96S-B40-800CJJ, 40 mm bore and 800 mm stroke), coupled with two linear guides LG (MISUMI mod. BSH2M-D30-L1150-M12) devoted to support any radial component of the external forces acting on the end effector. Two further DoFs are provided by the wrist unit W (IAI mod. WU-M), which can control the pitch and yaw motion of the end effector, consisting of the pneumatic gripper G (SCHUNK mod. KGG 60-20), devoted to grasp the target-holder TH by means of two specially shaped fingers F.

A series of adjustable limiters allows regulating with high precision the several movements of the manipulator, minimizing any possible positioning error.

The manipulation system is placed at a certain distance from the scattering chamber, i.e. far away from the target-holder during the beam collision: this is necessary to prevent damaging of the system from the radiations produced by the experiment. To this regard, the dose of radiations to this region is estimated to be around 2×10^6 *gray* as upper limit (as evaluated from Radioprotection Office of LNS). This value was an important reference for the choice of the system's components and materials. Particular attention was paid to the CERN documentation about mechanical behaviour in activated environments [4]. In particular, the most critical materials in these conditions are the silicone rubbers for the pneumatic components, which are not forbidden but require periodical check and maintenance.

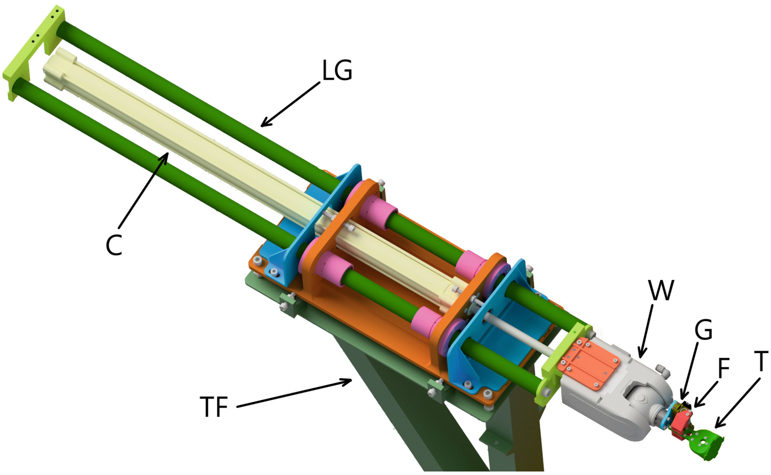

Fig. 4. Overall view of the manipulator.

3 Connection Between Target-Holder and Cryocooler

The connection between the target-holder TH and the cold finger CF of the cryocooler is achieved by a bayonet coupling, presented in Fig. 5. The base of the target-holder is provided with two pairs of wedge-shaped protrusions that mate with two proper seats obtained in a positioning cup PC attached to the CF. Since the MAGNEX must be able to operate both in LI and HI configuration, which correspond to two different orientations of the whole spectrometer shifted by 70° around the target vertical axis, the manipulation system shall couple the TH to the CF in one of both angular position required by the foreseen configuration, using the corresponding couple of wedges.

In order to provide the desired forcing between the contact surfaces of TH and CF, the rotary coupling motion forces the wedges under two flexural springs S, which provide the desired pre-load. The springs are fixed to the CF by a positioning cup provided with two equidistant protrusions. These latter also have the function of limiting the coupling movement, ensuring the precision of positioning.

The flexural springs have been dimensioned respecting the specific requirements of this application. The first request is a contact force greater than 15 N; the second condition is the maximum grip torque exerted on the target-holder: the chosen gripper in fact can provide a 50 N force for each jaw, which corresponds to a 20.7 N force to each wedge in use. It has also to be considered the friction between the two copper surfaces to couple (that shall be lapped to obtain a surface roughness of 0.25 μm) and between the steel spring and the copper wedge.

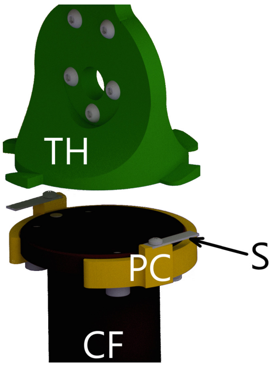

Fig. 5. The bayonet coupling between target-holder TH and the cold finger CF of the cryocooler. After lifting of CF to contact the base of TH, a 25° rotation engages one couple of TH wedges with the flexural springs S, bringing them in contact with the limiters on the positioning cup PC.

From the free-body diagram of Fig. 6, it is possible to derive the mathematical model of coupling between one spring and the wedge, expressed by Eq. (1):

$$K = F \cdot \sin\left(\frac{F \cdot l^2}{2 \cdot E \cdot I}\right) + (\mu_1 + \mu_2) \cdot F \cdot \cos\left(\frac{F \cdot l^2}{2 \cdot E \cdot I}\right) \tag{1}$$

Where:

K : is the maximum force on a single wedge given by the gripper (20.7 N);
F : is the normal force acting on the spring (greater than 7.5 N by requests);
L : is the length of the flexible part of the spring;
E : is the elastic modulus of the spring material;
I : is the moment of inertia of the spring cross section;

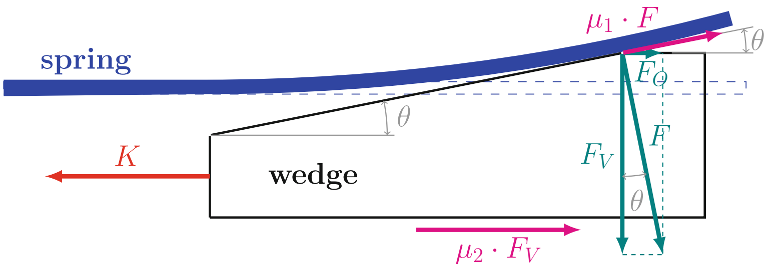

Fig. 6. Model of coupling between pre-load spring and TH wedge.

μ_1 : is the friction coefficient between the wedge and the spring;
μ_2 : is the friction coefficient between the target holder and the cold finger.

A special problem to consider is the operation at a cryogenic temperature around 40 K. The materials in the TH-CF joint, in fact, could undergo important variations in the characteristics: this could represent a problem in particular for the flexing springs, which are typically made of harmonic steel. While the variation of the Young modulus, which increases slightly at such a low temperature, is not a problem, more important is the considerable embrittlement that these materials undergo at such a low temperature [5]. This has led to the use of AISI 316 stainless steel, which maintains its characteristics constant even in cryogenic environments [6].

The model of Eq. (1) has been implemented in Matlab® with an iterative algorithm, which led to an optimal solution for the system characteristics.

The calculation considering springs made of AISI 316 stainless steel and a contact force increased to 25 N corresponds to spring cross section of 0.6×4 mm and to 0.5 mm of spring deformation imposed by the wedge, the angle of the wedge is 2.8°. This solution limits to a minimum the quantity of material inside the chamber during the use of the beam, that is convenient to reduce the activation of material inside the chamber.

Another important design feature is the precision in angular alignment of the TH to the ion beam, determined by the geometric tolerances of the lower cup of the system that define the position of the limiters: the present solution limits the alignment error to a maximum of 0.3°, that is lower than the requested value.

4 The Storage System

The storage system is devoted to provide a given number of new target-holders for performing the tests as well as to collect, after the experiment, the exhausted and activated THs that must be handled and stored with particular precautions.

The Fig. 7 shows an image of the system, which is completely automated in order to control from remote the manipulation of the target-holders. A frame SF, which is in turn mounted on the triangular frame TF of the manipulator, supports the device. The latter is composed by a main plate SP, provided with a given number of slots, guided by a slide rail (Misumi mod. BJKSW-H20-L590) and driven by a linear actuator SA (IAI mod. RCA-SA6D-A-30-12-350). The movements to position the target-holders TH on the plate are: i) a vertical stroke of 5 mm, regulated by the limiters L and performed by two membrane actuators MC (Festo EV-20x75+DP) positioned under the sustain plate; and ii) a 90° rotation around the wrist pitch axis.

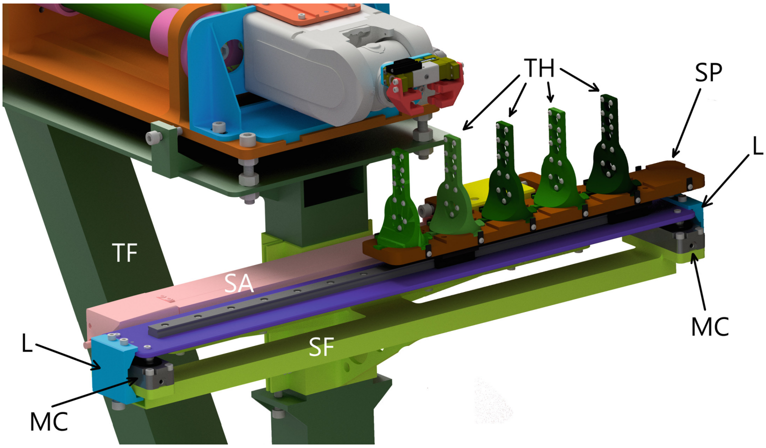

Fig. 7. Image of the automatic storage system.

5 Conclusion

A whole automatic manipulation system for targets that must be used in a nuclear physics experiment has been completely designed. The design had to cope with very particular conditions, which determined the search of non-usual solutions. The main issues are the operating temperature, around 40 K, the extreme precision and care required in handling the target of the experiment, and the activation generated during the tests.

The low operating temperature called for special attention to the materials of some elements, like the pre-load springs devoted to provide appropriate contact force between the target-holder and the cryocooler.

The precision and care requested in the manipulation are guaranteed by adopting accurate machining of all structural parts and by special elements for adjusting and regulating the motion of the several degrees of freedom.

To face the activation problem, it has been necessary to evaluate in all elements of the system the presence of materials possibly subjected to this phenomenon, and study their placement at safe distance from the source of radiation.

References

1. Cappuzzello, F., et al.: The NUMEN project: NUclear Matrix Elements for Neutrinoless double beta decay. Eur. Phys. J. A **54**, 72 (2018)
2. Capirossi, V., et al.: Study, fabrication and test of a special cooling system for targets sub-mitted to intense ion beams. Nuclear Inst. Methods Phys. Res. A **954**, 161122 (2018)
3. Xian, Y., et al.: Re-estimation of thermal contact resistance considering near-field thermal radiation effect. Appl. Therm. Eng. **157**, 113601 (2019)
4. Beynel, P., Maier, P., Schönbacher, H.: Compilation of radiation damage test data. PART III: Materials used around high-energy accelerators (1982)
5. Roesler, J., Harders, H., Baeker, M.: Mechanical Behaviour of Engineering Materials. Springer, Heidelberg (2007)
6. Ekin, J.W.: Experimental Techniques for low temperature Measurements. Oxford University Press, Oxford (2006)

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