Journal of
Instrumentation

PAPER • **OPEN ACCESS**

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Published by IOP Publishing for Sissa Medialab

Received: *October 18, 2024*
Revised: *April 10, 2025*
Accepted: *April 30, 2025*
Published: *July 29, 2025*

Proton beam energy calibration of the 3 MV Tandetron™ at IFIN-HH

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https://doi.org/10.1088/1748-0221/20/07/P07051

ABSTRACT: The ELIGANT-TN long neutron counter, the ELISSA silicon strip array and the Mini-eTPC active gas target detector all represent nuclear physics research tools constructed at Extreme Light Infrastructure - Nuclear Physics (ELI-NP) for use in γ-beam experiments. Currently, these three setups are used at the charged particle accelerators of the "Horia Hulubei" National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), for performing reaction cross-section measurements. Accurate knowledge of the incident beam energy is of paramount importance for such studies, which is why in the present article we report on a new proton beam energy calibration performed using the following threshold reactions: ^{7}Li$(p,n)^{7}$Be, ^{13}C$(p,n)^{13}$N and ^{51}V$(p,n)^{51}$Cr. The measurements were performed by varying the projectile energy across the key range of $\sim$ 1600–3200 keV. The results demonstrate a linear dependence of the projectile energy on the terminal voltage.

KEYWORDS: Accelerator Applications; Instrumentation for particle accelerators and storage rings - low energy (linear accelerators, cyclotrons, electrostatic accelerators); Neutron detectors (cold, thermal, fast neutrons)

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1 Beam energy uncertainty in different applications

A 3 MV Tandetron™ accelerator produced by High Voltage Engineering Europa (HVEE) was installed at the "Horia Hulubei" National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH) and commissioned in 2012 [1]. The two types of ion sources provided with the Tandetron™ — a duoplasmatron and a negative-ion cesium sputtering source — allow for a broad range of elements to be accelerated. The 3 MV accelerator beamlines were thus designed to support a wide range of ion beam analysis (IBA) techniques, such as proton-induced X-ray emission (PIXE), particle-induced gamma-ray emission (PIGE), Rutherford backscattering (RBS), elastic resonance detection analysis (ERDA), nuclear reaction analysis (NRA), and μ-PIXE. Additionally, the 3 MV Tandetron™allows for cross-section measurements and provides external ion beams for applications in radiobiology, archaeology, and ion implantation. While most experiments conducted at this facility require only moderate energy calibration precision in some particular cases energy uncertainty becomes important and can introduce very large errors, such as when performing non-Rutherford backscattering spectrometry.

Similarly, nuclear reaction cross-section measurements exhibiting resonance structures are particularly sensitive to beam energy calibration. This applies to charged-particle induced reactions relevant to both astrophysical studies conducted with the ELI Silicon Strip Array (ELISSA) setup [2, 3], and nuclear safety investigations using the 4π ELI Gamma Above Neutron Threshold (ELIGANT-TN) detector [4, 5]. Precise energy calibration is equally critical for upcoming experiments with the Mini-electronic Time Projection Chamber (Mini-eTPC) [6], which will utilize quasi-monoenergetic neutron beams. These beams are produced by proton irradiation ($E_p > 1.88$ MeV) of natural lithium targets, requiring exact knowledge of the proton beam energy. Since accelerators typically provide only indirect energy information derived from operational parameters, a dedicated calibration procedure is essential to establish the correspondence between these parameters and the projectile energy.

In its basic configuration, the 3 MV Tandetron™ accelerator of IFIN-HH is not equipped with an analyzing magnet that could be used to precisely determine the ionic mass and energy by adding extra-focus to the beam. Instead, energy stabilization is provided by means of accurately measuring the terminal voltage (TV) using a generating voltmeter (GVM). The incident beam energy, E_{beam}, is thereby directly correlated to the extraction voltage (V_{ext}) and the charge state (q) of the ions as

$$E_{\text{beam}} = q \cdot [V_{\text{ext}} + (q + 1) \cdot TV], \tag{1.1}$$

The GVM system can be accurately calibrated using well-studied nuclear reactions and, in the case of α-particles, the associated beam energy calibration was recently performed using known resonances [7]. The aim of the present work was therefore to determine the proton beam energy within the range of 1.6 to 3.2 MeV using a set of well-known neutron threshold reactions [8, 9].

2 Proposed proton beam energy calibration

The 4π ELIGANT-TN long neutron counter [4, 5] of ELI-NP was installed on the implantation beamline of IFIN-HH's 3 MV Tandetron™ [1] accelerator. ELIGANT-TN consists of 28 ^{3}He counters arranged in a 3 ring configuration, embedded in a high density polyethylene matrix that leaves a 4 cm hole opening for the beam line (see figure 1). The polyethylene matrix is surrounded by a cadmium layer that suppresses the environmental neutron background to a value of less than ~ 0.3 n/s. This arrangement ensures an almost constant high neutron efficiency of up to ~ 5 MeV. In the reported work, the $\epsilon_n = 37(1)\%$ efficiency of ELIGANT-TN was measured using a ^{252}Cf source placed in the target position. The ^{7}Li target was installed directly in the beam path, at the geometrical center of the array. Two active collimators, 5 and 3 mm in diameter, were installed sequentially upstream of the beamline, as shown in figure 1. The charge accumulated in the 3 mm collimator, the target and the beam dump was read using ORTEC 439 modules.

A fully digital data acquisition method was employed, based on the commercially available v1725 CAEN digitizers controlled via in-house developed Digital Extreme Light Infrastructure List-Mode Acquisition (DELILA) system [10]. DELILA was developed in-house at ELI-NP specifically for high-counting applications, in order to process data resulting from multiple kinds of radiation detectors. Thus far, this data acquisition system has already been successfully used with both the ELIADE γ−ray spectrometer [11], as well as the ELIGANT-GN array [12].

To perform the beam energy calibration, a proton beam extracted from the duoplasmatron ion source of the 3 MV Tandetron™ at an extraction voltage of 20 kV was delivered to the target installed at the center of the ELIGANT-TN array. The three different targets listed in table 1 were used to measure the neutron threshold. For a run at a given proton energy, figure 2 (left) demonstrates a typical pulse-height spectrum taken from one of the neutron counters. In a ^{3}He counter, a neutron is detected due to the nuclear reaction: $^{3}\text{He} + n \rightarrow {}^{3}\text{H} + {}^{1}\text{H} + 765\,\text{keV}$ where the emitted proton and triton deposit energy in the gas, generating the detector signal. The case when both reaction products deposit their energy within the active gas volume corresponds to the highest peak in the pulse-height spectra. The low-energy plateau corresponds to the wall effect when either ^{3}H or ^{1}H hits a wall of the counter before releasing all its energy. The stability of the proton beam intensity at the average value of ~ 100 enA is shown in figure 2 (right).

Table 1. The reactions and their respective thresholds measured through the current study versus the nominal values published in the literature [13].

Reaction	Target	Thickness	TV, kV		E_{thr}, keV	
		µg/cm^2	Measured	Nominal	Measured	Table
$^{51}\text{V}(p,n)$	^{51}V	~ 1000	756(4)	765(1)	1548(9)	1565.09(20)
$^{7}\text{Li}(p,n)$	^{7}LiF	~ 1000	915(3)	922.8(3)	1865(7)	1880.57(8)
$^{13}\text{C}(p,n)$	^{13}C	~ 30	1585(3)	1600.3(1)	3206(6)	3235.6(3)

Figure 3 shows a plot of the normalized neutron yield measured for each reaction in the vicinity of the threshold as a function of the terminal voltage provided by the GVM system (U_e). For the $^{51}\text{V}(p,n)$ reaction, the neutron integral for each energy was normalized to the measurement time, while for the $^{7}\text{Li}(p,n)$ and $^{13}\text{C}(p,n)$ reactions, the normalization was applied to the charge collected

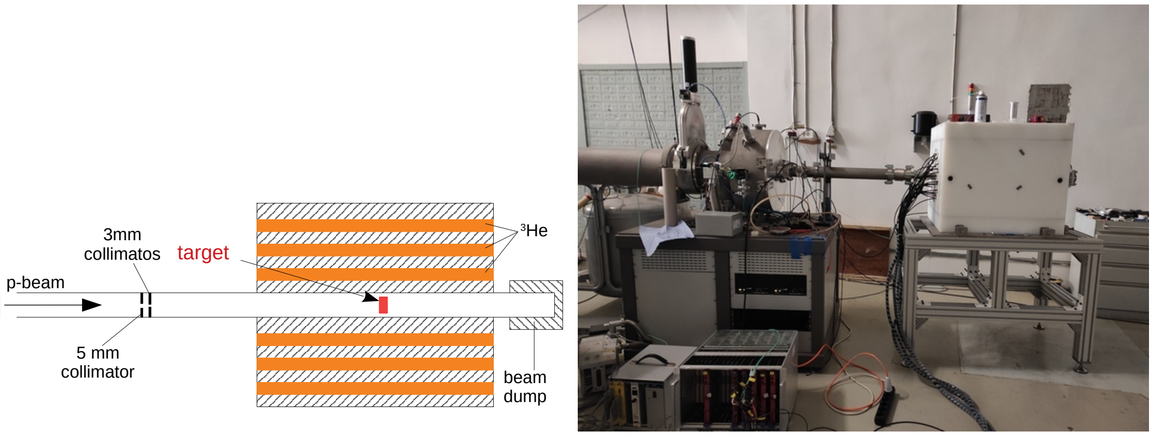

Figure 1. Schematic view (left) and photograph (right) of the ELIGANT-TN experimental setup installed on the implantation beamline of the 3 MV Tandetron™ accelerator at IFIN-HH.

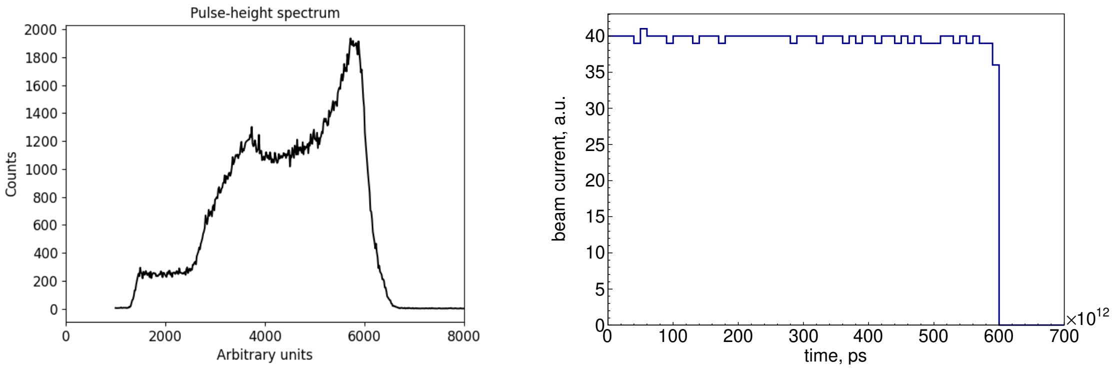

Figure 2. Example of a pulse-height spectrum recorded from one of the ^{3}He tubes during the measurements (left); beam current, expressed in arbitrary units, recorded during a typical 10-minute run (right).

by the target. The yield (Y) near the threshold was fitted using the logarithmic function, eq. 2.1.

$$Y = a \cdot \ln(x - c) + b \tag{2.1}$$

The threshold energy was calculated as the intersection between the function expressed through eq. 2.1 and the linear fitted background function depicted in figure 3. The nominal terminal voltage (U_n) was derived from the table of threshold energies reported in the literature for the selected reactions and corrected for the energy loss to the center of the target. The relation between U_n and the GVM values (U_e) displayed in figure 3 is as follows: $TV = (1.06055 \pm 0.00288) \cdot TV_{\mathrm{GVM}} - (-75.19 \pm 2.64)$ kV. The non-zero value of TV at $TV_{\mathrm{GVM}} = 0$ is caused by the extracting voltage uncertainty of ± 0.3 kV (according to the high-voltage source specification) and the GVM offset. No deviations from the GVM linearity were revealed.

Due to the high efficiency of ELIGANT-TN, even small neutron yields can be detected in the vicinity of the reaction threshold and proper statistics can be collected within a reasonable timeframe. We may conclude, therefore, that the method presented herein provides a reliable and fast verification of the incident beam energy, which can be performed systematically before each reaction cross-section

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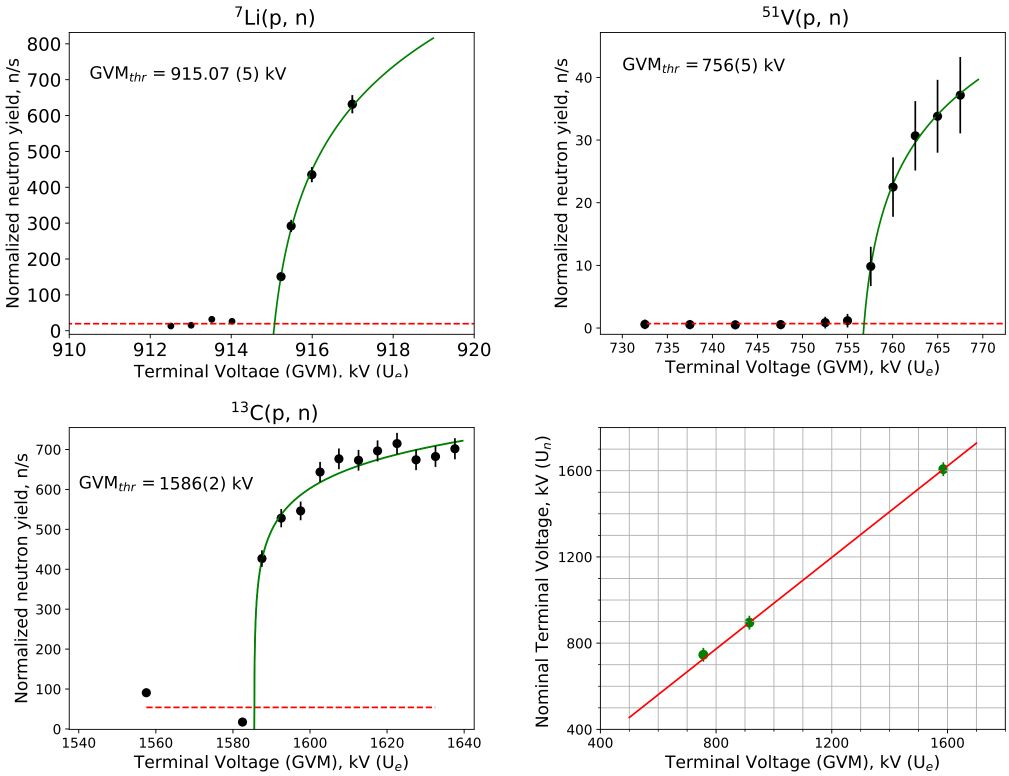

Figure 3. Variations of the normalized neutron yield as a function between the terminal voltage (error bars are inside the dots) and the fitted curves (red) for the measured threshold reactions: ^{7}Li(p,n) (top left), ^{51}V(p,n) (top right) and ^{13}C(p,n) (bottom left); results of the GVM linear calibration (bottom right).

experiment. A similar approach will be employed at the 9 MV Tandem accelerator of IFIN-HH in order to perform beam energy calibration using the ELIGANT-TN and Mini-eTPC setups.

Acknowledgments

This work was supported by a grant of the Romanian Ministry of Research, Innovation and Digitization, CNCS — UEFISCDI, project number PN-III-P1-1.1-TE-2021-1464, within PNCDI III and the research contract PN 23 21 01 06. The measurements performed at the 3 MV Tandetron™ of IFIN-HH are supported by the Romanian Government Programme through the National Programme for Infrastructure of National Interest (IOSIN). This research has been funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (grant # AP19680284).

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