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New energy calibration of the CMAM 5MV tandem accelerator

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Abstract

Ion accelerators are fundamental in the ongoing research on materials for future energy sources, being the primary tool for understanding the behaviour of different classes of materials (functional, structural, diagnostic) under e.g. the intense radiation expected in fission reactors or the critical thermal operational conditions in IV generation fission reactors. The relevance of ion accelerators research extends straightforwardly to the modification and analysis of materials to be used in future developments of diverse non-nuclear sources like photovoltaic, fuel batteries, etc. From the analytical point of view, the energy of the accelerated ion needs, in many cases, to be known with a precision higher than e.g. the width of reaction resonances that are used for controlling either the yield of a reaction or the penetration depth of the ion, imposing a calibration of the accelerator terminal voltage. This paper reports on the new energy calibration performed for the 5 MV CMAM tandem accelerator.

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Keywords: Ion Beam Analysis; Tandem Accelerators; Energy Calibration; Cockcroft-Walton

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1. Introduction

Ion accelerators are fundamental in the ongoing research on materials for future energy sources, being the primary tool for understanding the behavior of different classes of materials (functional, structural, diagnostic) under e.g. the intense radiation expected in fission reactors or the critical thermal operational conditions in IV generation fission reactors. The relevance of ion accelerators research extends straightforwardly to the modification and analysis of materials to be used in future developments of diverse non-nuclear sources like photovoltaic, fuel batteries, etc. From the analytical point of view, the energy of the accelerated ion needs, in many cases, to be known with a precision higher than e.g. the width of reaction resonances that are used for controlling either the yield of a reaction or the penetration depth of the ion, imposing a calibration of the accelerator terminal voltage.

The main facility of the Centro de Micro-Análisis de Materiales (CMAM) of the Universidad Autónoma of Madrid, Spain, is a 5MV terminal voltage tandem accelerator [1]. It was designed and constructed by High Voltage Engineering Europa B.V., HVEE [2], as the first coaxial high current Tandetron accelerator of 5MV using the Cockcroft-Walton power supply system (previously, terminal voltages were never higher than 3 MV with this system and the power supply itself was perpendicular to the acceleration stage). The accelerator is provided with two ion sources: a duoplasmatron source (model HVEE-358) and a negative sputter ion source (model HVEE-860C), which allow for almost any element from hydrogen to lead to be accelerated.

During commissioning of the accelerator [1], 10 year ago, terminal voltage of the accelerator was calibrated and the machine has been running routinely with voltages ranging from few hundreds of kV to 5MV.

2. Beam energy calibration

In a tandem accelerator, the beam energy is given by:

$$E_0 = E_{ext} + E_{acc} = q \cdot V_{ext} + (n+1)q \cdot TV_{Real} \qquad (1)$$

where E_o is the beam energy, E_{ext} is the ion source extraction energy, E_{acc} is the accelerator imparted energy, V_{ext} is the source extraction voltage, n is the charge state of the ion at the exit of the accelerator, q is the charge of electron, and TV_{Real} is the accelerator real terminal voltage.

To measure the terminal voltage, a Generating Voltmeter (GVM) is used [3]. The measured voltage, TV_{Nom} (nominal terminal voltage), is used as a feedback signal for the accelerator a.c. driver feeding the Cockcroft-Walton system. The GVM system can be accurately calibrated by using very well known energy beams.

The method proposed for calibrating the accelerator in energy is divided into two different parts. For low energies, we used the well-known resonances of the nuclear cross section for the reaction ^{27}Al(p, γ)^{28}Si at 991.7 keV and 1316.8 keV [4]. For higher energies, where it is harder to find well measured cross sections, we have used a method based in the measurement of elastic and inelastic proton scattering [5] to obtain a calibration constant with a moderate accuracy. When a thin (compared to the beam energy spread) target containing an isotope with well separated low energy excited states (e.g. ^{11}B [6]) is bombarded with protons at two different accelerator energies the information contained in the elastic and inelastic measured spectra is sufficient to find the spectrometer channel width and energy calibration constant as well as the beam energy.

Final calibration was obtained combining and fitting results from both parts to a linear equation:

$$TV_{Real} = A + B \cdot TV_{Nom} \quad (2)$$

2.1. Calibration through the ^{27}Al (p, γ) ^{28}Si resonances

The nuclear reaction ^{27}Al (p, γ) ^{28}Si has two sharp resonances determined with high accuracy at 991.74(2) keV and 1316.83(4) keV. The procedure consists in scanning the resonances in fine energy steps and determining the nominal terminal voltages corresponding to the resonance energies.

The integral of the gamma ray spectra collected from 3 MeV to the limit of ADC conversion (about 8MeV in our case) is measured and normalized to the collected charge [4]. The normalized total yield is plotted versus the nominal terminal voltage, TV_{Nom}, and fitted (see Fig. 1) using a Boltzmann function

$$Yield = A_2 + (A_1 - A_2) \cdot \left(1 - e^{\frac{TV_{Nom} - TV_{res}}{dTV}}\right)^{-1} \quad (3)$$

where A_1 and A_2 are the plateau heights before and after the resonance, TV_{Nom} is the nominal terminal voltage and TV_{res} is the nominal terminal voltage at the resonance energy.

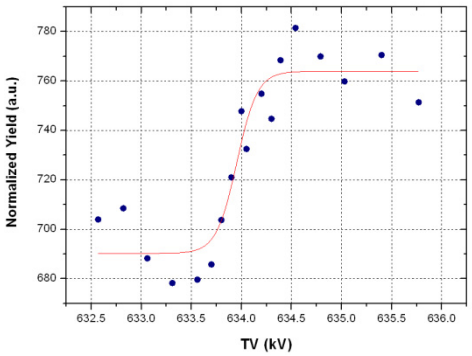

Fig. 1 The 1316.8 keV resonance scanned with the HVEE-358 source (ReGe detector)

Three runs for scanning the resonances were done using proton beams from the two ion sources at CMAM (see Table 1). A high purity (99.9%) thick aluminum target was used. The target had a gold capping layer to provide an independent measure of the dose through the counting of backscattered protons from gold and thus normalize the PIGE data to the RBS signal. Although this method was, eventually, not used, the energy lost by the protons when crossing this capping layer, E_{cap}, must be taken into account. Precise gold layer thickness was determined by RBS fitting the spectrum with RBX code [7]. The best fit of the spectrum is obtained with a gold layer $2.6 \cdot 10^{16}$ atoms/cm^2 thick and a contamination layer formed by H, C and O of approximately 10^{17} atoms/cm^2. The composition of the contamination layer cannot be exactly determined by RBS with protons: therefore, an average composition has been assumed and an average energy loss has been calculated.

Once TV_{res} is determined for each resonance, one can work out the calibration curve, taking into account the following equations:

$$E_{res} = q \cdot V_{ext} + (n+1)q \cdot TV_{Real} - E_{cap} \quad (4)$$

$$TV_{Real} = \frac{E_{res} - q \cdot V_{ext} + E_{cap}}{q \cdot (n+1)} = \frac{(E_{res} + E_{cap}) - V_{ext}}{2} = \frac{E_0 - V_{ext}}{2} = A + B \cdot TV_{Nom} \quad (5)$$

where E_{res} is the resonance energy. This sets values for establishing a calibration curve.

Two gamma detectors were placed at +/- 135 ° to the beam direction: a Reverse Electrode ultra-pure germanium (ReGe) detector and a Lanthanum Bromide ($LaBr_3$) scintillator, each with its corresponding electronic chain (preamplifier, amplifier, analog-digital converter, voltage supply, etc.). Detectors were mounted on sealing flanges and directly exposed to vacuum in the scattering chamber (only the detector window separates the detector crystal from the sample). The whole scattering chamber was electrically isolated (except from the detectors case) and was used as a Faraday cup for measuring the dose.

Acquisition was done using commercial software Genie 2000, which allows real time processing of measured data and the extraction of information (e.g. dead time, peak search, peak integral, spectrum stripping, spectra comparison, etc.) during the experiments.

Table 1shows a summary of the measurements and the reference resonance energies.

Table 1. The set of calibration measurements performed on resonant ^{27}Al (p, γ) ^{28}Si

Run	Source	Detector	TV_{Nom}(kV)	E_{res} (keV)	E_{cap} (keV)	E_0 (keV) ($E_{res}+E_{cap}$)
1	HVEE-860C	$LaBr_3$	467.97 ± 0.05	991.74	0.88	992.62
		ReGe	467.94 ± 0.04			
2	HVEE-358	$LaBr_3$	473.91 ± 0.04	991.74	0.88	992.62
		ReGe	474.5 ± 0.1			
3	HVEE-358	$LaBr_3$	633.83 ± 0.03	1316.83	0.78	1317.61
		ReGe	633.95 ± 0.04			

Taking into account the energy lost in the capping layer, it is possible to determine the initial energy of the beam when the resonance occurs, and to relate it to the calculated (see Eq. 1) terminal voltage for the resonance.

2.2. Calibration through non resonant nuclear reactions

The non resonant nuclear reaction calibration technique (NRC) [5] is based on the measurement of elastically scattered particles by two different masses and non elastic processes with positive Q-value.

Let's assume a nuclear reaction of the kind:

$$(E_0, M_1) + (E_2, M_2) \rightarrow (E_3, M_3) + (E_4, M_4) \quad (6)$$

where E_i and M_i are the kinetic energy and the mass of an i particle. Assuming E_2=0, and E_0 the energy of the beam, the kinematic equation, solved for particle 3 gives that:

$$E_3 = (E_0 + Q)B\left[cos\theta + \left(\frac{D}{B} - sin^2\theta\right)^{\frac{1}{2}}\right]^2 \quad (7)$$

being

$$B = \frac{M_1 M_3}{(M_1+M_2)(M_3+M_4)} \cdot \frac{E_0}{(E_0+Q)} \quad (8)$$

$$D = \frac{M_2 M_4}{(M_1+M_2)(M_3+M_4)} \cdot \left(1 + \frac{M_1 Q}{M_2(E_0+Q)}\right) \quad (9)$$

In an elastic collision $Q=0$ and, therefore, we can introduce the kinematic factor, k, defined as

$$k = \frac{M_1^2}{(M_1+M_2)^2}\left\{cos\vartheta + \left[\left(\frac{M_2}{M_1}\right)^2 + sin^2\vartheta\right]^{\frac{1}{2}}\right\}^2 \quad (10)$$

which allows to express the particle kinetic energy as

$$E_3 = kE_0 \quad (11)$$

The detector calibration can be expressed as

$$E = a \cdot N + b \quad (12)$$

N being the channel number.

We have used a MnSnO target for the elastic reaction and a BC target for the nuclear reaction $^{11}B(p,\alpha)^8Be$ at terminal voltages of 634, 635.4, 1267 and 2000 kV.
In the case of RBS on a MnSnO target, from (11) and (12) we have:

$$a \cdot N_{Mn} + b - k_{p,Mn} \cdot E_0 = 0 \quad (13)$$

$$a \cdot N_{Sn} + b - k_{p,Sn} \cdot E_0 = 0 \quad (14)$$

and for the reaction $^{11}B(p,\alpha)^8Be$

$$a \cdot N_{\propto,B} + b - (E_0 + Q)B\left[cos\theta + \left(\frac{D}{B} - sin^2\theta\right)^{1/2}\right]^2 = 0 \quad (15)$$

resulting in a system of three independent equations which has been solved, using *Mathematica* [8], in terms of a, b and E_0. As in the previous method (eqs. 4 and 5), the energy of the beam can be used to compute, from equation (2), the real terminal voltage which in turn can be expressed as a function of the nominal terminal voltage.

The measurements were done using two implanted barrier Si detectors placed at a scattering angle of 170º and 165º respectively. Table 2 shows the summary of the obtained values.

Table 2. Nominal and real terminal voltages obtained from solving of the 3 equations for different beam energies

Angle [°]	TV_{Nom} [kV]	E_0 [keV]	TV_{Real} [kV]
170	474.74	1062.26	522.13
170	1267.61	2582.32	1282.16
170	1600	3280.83	1631.415
170	2100	4282.98	2132.49
170	1267.61	2582.32	1282.16
170	1600	3253.97	1617.985
170	2100	4280.74	2131.37
165	474.74	1016.99	499.495
165	1267.61	2568.68	1275.34
165	1600	3280.71	1631.355
165	2100	4298.58	2140.29
170	634	1386.11	684.055
170	635.4	1400.63	691.315
170	1267	2613.04	1297.52
170	2000	4282.98	2132.49
165	634	1348.71	665.355
165	1267	2614.86	1298.43
165	2000	4072.33	2027.165

3. Results and discussion

The combination of the results detailed in sections 2.1 and 2.2 allows us to produce a new calibration curve for the ion accelerator, shown in Fig. 2. Fitting of the data to a linear equation $TV_{Real} = A + B \cdot TV_{Nom}$, has been done weighting the data by their experimental error. The weights, used in the procedure of reducing Chi-square, are defined as $\omega_i = 1/\sigma_i^2$, where σ_i are the error bar for each experimental data.

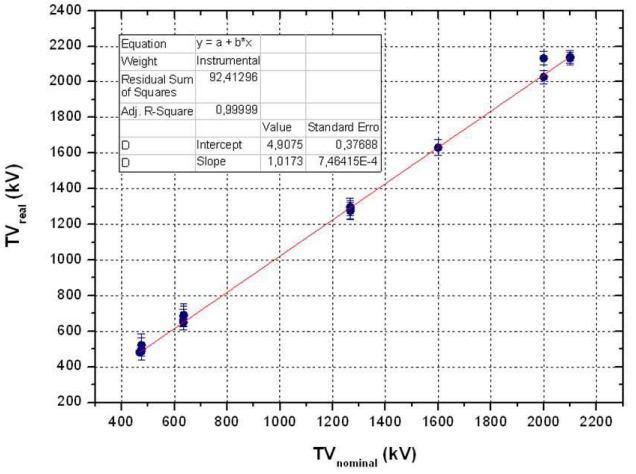

Fig. 2. Linear fit of terminal voltage obtained by the presented methods versus the nominal voltage set at the accelerator console.

The best fit is given for:

$$A = 4.9 \pm 0.4\ [kV]$$

$$B = 1.0173 \pm 0.0007$$

The previous calibration of the ion accelerator at CMAM was performed in 2002 using resonant cross sections of elastic reactions and the ^{27}Al(p,g)^{28}Si nuclear reaction [1]. Then, fitting of the calibration data gave $TV_{Real} = 4 + 1.0153 \cdot TV_{Nom}$ which differs less than 0.3% from the present results for terminal voltages higher than 1MV.

4. Conclusions

A new calibration of the tandem accelerator at CMAM has been done by measuring, in combination, well known resonant cross sections and non resonant nuclear reactions. This combination method, agreed by the participants of a IAEA coordinated research project [9] for the development of a reference database for Particle-Induced Gamma ray Emission (PIGE) Spectroscopy, has been shown to be adequate for a fast calibration in an extended range of voltages. The NRC method has been used up to only 2MV terminal voltage, but the easiness and rapidness shown make of it a possible routinely check prior to any measurement on which accurate beam energy calibration is needed.

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