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ABSOLUTE CALIBRATION OF BSI MONITORS IN THE SPS NORTH AREA AT CERN

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Abstract

Developments in current and future experiments in the SPS North Area (NA) and PS East Area (EA) fixed target beam lines at CERN, including the "Physics Beyond Colliders" (PBC) program, require accurate determination of the number of protons on target (POT). The re-calibration of Beam Secondary Emission Intensity monitors (BSI), recently completed in one of the NA branches, reduced the estimated uncertainty on the absolute POT to a few percent. The calibration is based on an activation technique, applied to metal foils (Al, Cu) installed in front of the BSI and irradiated with the nominal proton intensity for a short period. The number of protons is determined from offline gamma spectrometry analysis of the foils and compared to the total integrated signal of the BSI. A description of the method, data analysis and results, will be presented and followed by considerations intended to standardise the procedure for future regular use in all SPS NA beamlines.

INTRODUCTION

The fixed target experimental areas (EA and NA), receive slow extracted beams, which are split and sent towards different targets, before reaching the experiments. Fig. 1 shows the beamlines going towards different targets for the NA. The current of protons in these beamlines is de-bunched and distributed along spills that range between 1 to 5 seconds in NA and 400 ms in EA.

Beam Current Transformers (BCTs) are widely used at CERN for measuring beam current during operation, due to their less invasive nature and high precision. They can be directly calibrated using currents, but rely on high currents to have good signal to noise ratio [1].

The Beam Secondary emission Intensity (BSI) monitor (shown in Fig. 2) is used for measuring the beam intensity in slow extraction areas at CERN - where BCTs cannot be used - as it is able to measure lower currents, but it cannot be directly calibrated. It is one of the various types of Secondary Emission Monitors (SEMs) used in the North and East Areas. Other types can measure properties such as beam position and size.

The BSI consists of a metal foil, inserted in the beam for measurement. Charged particles pass through the foil, transferring a small part of their energy in the process. If sufficient, the energy can allow the electrons in the metal to exceed the Fermi level and escape from the surface [2].

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This process is termed Secondary Emission (SE) and its theory was developed by E. J. Sternglass [3].

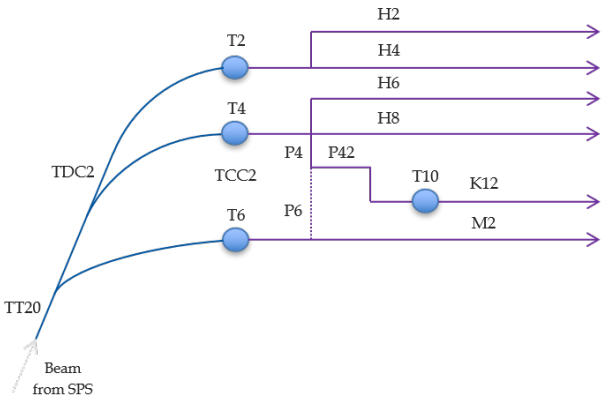

Figure 1: Schematic representation of layout of North Area beamlines. Circles mark the target locations [4].

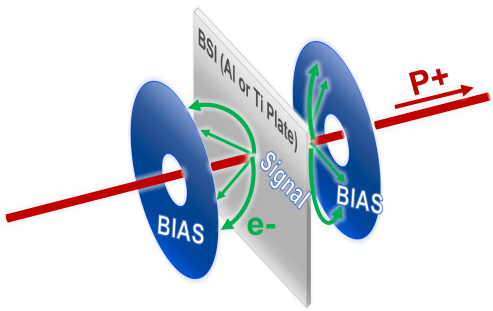

Figure 2: Schematic representation of BSI.

The quantity of electrons generated for each proton is called the Secondary Emission Yield (SEY) and can be expressed as [5]:

$$SEY = 0.01 L_s \frac{dE}{dx}|_{el} \left[1 + \frac{1}{1 + (5.4 \cdot 10^{-6} E/A_p)}\right] \quad (1)$$

This is defined by the kinetic energy of the projectile (E), the electronic energy loss ($\frac{dE}{dx}|_{el}$), the mass of projectile (A_p) and the characteristic length of diffusion of low energy electrons (L_s):

$$L_s = (3.68 \cdot 10^{-17} N Z^{1/2})^{-1}, \quad (2)$$

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which is related to the number of atoms per unit volume (N) and the atomic number (Z).

The calibration factor (C_f) relates the signal measured by the BSI (N_{BSI}) and the number of protons (N_p):

$$C_f = \frac{N_p}{N_{BSI}}. \quad (3)$$

The calibration factor is also related to the SEY and the electronics gain, this is described in more detail in [6]. The material properties of BSI foils may change over time, affected by factors such as oxidation, radiation damage and vacuum conditioning. These changes impact the SEY and are difficult to predict or estimate accurately.

Studies on the status of beam intensity measurements conducted recently [7], indicated the importance and challenges involved in the absolute calibration. Direct calibration via a BCT is not possible, as the nearest BCT is in the SPS ring and the absolute losses during extraction are unknown. Historically the absolute calibration was performed using the activation method [6].

CALIBRATION VIA ACTIVATION

This method consists of temporarily installing a stack of metallic foils in the beam and irradiating for a short period of time. When crossing the foil, the protons from the beam generate spallation reactions, which result in the production of radioisotopes [8].

The foils are subsequently removed from the beamline and, after a cooldown period, they can be taken to the lab, where gamma spectrometry can be used to measure the activity generated by the radioisotopes.

From the activity measured in the foils it is possible to determine the particle flux ϕ' according to eq. 4.

$$\phi' = \frac{A}{N_x \sigma (1 - e^{-\lambda t_{irr}}) e^{-\lambda t_{wait}}}. \quad (4)$$

where A is the activity, σ is the cross-section, λ is the decay constant, t_{irr}, is the irradiation time, t_{wait} is the time elapsed between the end of the irradiation and the gamma spectrometry measurement and N_x is the surface atomic density, given by:

$$N_x = \frac{N_{av}}{M} \rho \Delta x. \quad (5)$$

Here N_{av} is Avogadro's number (6.022×10^{23} mol^{-1}), M is the molar mass, ρ is the density and Δx is the thickness of the foil. From the particle flux it is possible to determine the number of protons on target by multiplying ϕ' by the irradiation time.

Two reactions often used for this type of calibration are the $^{27}Al(p,3pn)^{24}Na$ and the $^{nat}Cu(p,x)^{24}Na$. The first reaction can generate high activity and has cross-sections documented over a wide energy range, but has a well known competing reaction:$^{27}Al(n,\alpha)^{24}Na$, which needs to be corrected for. The latter reaction has a lower cross section, but does not have any significant contributions from competing reactions [8].

In both cases nuclear recoil can occur, where the spallation process causes some of the nuclei produced to leave the foil. This is usually corrected for by using catcher foils, placed either side of a central foil. This puts the central foil in equilibrium. The activity measured in the central foil is used for the calibration calculations.

EXPERIMENTAL SETUP

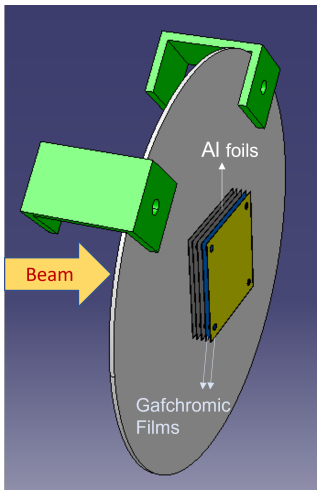

Figure 3: Experimental setup for first set of measurements.

Two activation measurements were conducted: on the 16th of September 2022 and on the 26th of October 2022, using different setups.

The first setup consisted of a stack of three 99.5 % purity aluminium, 100 µm thick foils, placed in front of the T10 target station in the NA, followed by 2 gafchromic films[1], as shown in Fig. 3. These were irradiated for approximately 26 minutes. After 2 days of cooldown the foils were retrieved and taken for gamma spectrometry measurements.

The second setup also used a stack of foils, made of three 99.999% purity aluminium, 100 µm thick foils and three 99.99% purity copper, 100 µm thick foils, as pictured in Fig. 4. Higher purity foils were used to avoid any possible contributions from impurities from the measurements and the metal screws and spacers (used in the first setup) were replaced with plastic ones.

Due to the addition of copper foils, more isotopes were produced. As some of these migrated to the aluminium foils, the cooldown period was longer.

RESULTS

The gamma spectrometry measurements were used to calculate the POT, using eq. 4. Half-life values used in calculation were taken from [9]. Cross sections for the production of different isotopes, for protons in copper and aluminium, used in the calculation are summarised in Table 1. Only

[1] GAFChromic HD-V2 and FWT-60-20F

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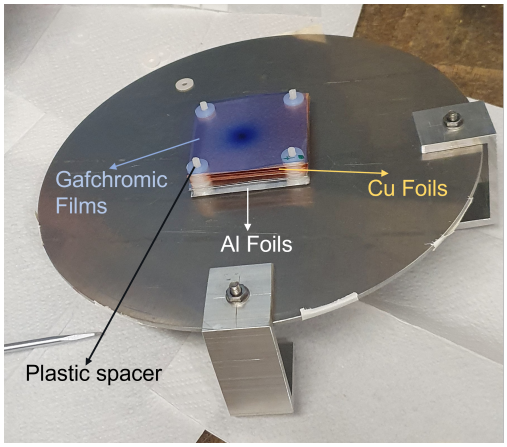

Figure 4: Experimental setup for second set of measurements

cross sections measured at similar energies to the SPS were included. These values, published from measurements at CERN and Fermilab were taken from [1, 10–12].

Table 1: Cross section values (including 1σ error) for production of isotopes from protons in Aluminium and Copper

Institution	Mat.	Isotope	E(GeV)	$\sigma(b)$
Fermilab	Al	^{7}Be	300	8.7± 0.7
Fermilab	Al	^{22}Na	300	9.4± 0.8
Fermilab	Al	^{24}Na	300	8.04± 0.58
CERN	Al	^{24}Na	400	8.82± 0.18
CERN	Cu	^{24}Na	400	3.96 ± 0.10
Fermilab	Cu	^{24}Na	30-800	3.59± 0.02
Fermilab	Cu	^{24}Na	400	3.90± 0.11

Not all cross-sections were directly comparable. At Fermilab the cross-section for ^{24}Na in aluminium was measured at 300 GeV and the values had already been corrected for the $^{27}Al(n,\alpha)^{24}Na$ reaction. At CERN the same cross section was measured at 400 GeV, but had not been corrected for the aforementioned reaction [11]. Corrections were therefore applied to the cross section for ^{24}Na in Aluminium, measured at CERN.

Because in the second setup, the copper foils were downstream from the aluminium foils (which are influenced by the $^{27}Al(n,\alpha)^{24}Na$ reaction), a correction was necessary. The copper ^{24}Na cross sections measured at Fermilab, had already applied this correction, but the one measured at CERN had not, thus a correction described in [13], for a setup of mixed copper and aluminium foils, was applied to the CERN value.

A calibration factor was determined for all measured isotopes, with a corresponding documented cross section. Each foil was precisely measured and weighed, to estimate the thickness. Errors included in the calculations are statistical errors on the gamma spectrometry measurements and measured thicknesses, systematic errors related to gamma ray intensities and geometry uncertainties related to gamma detector. In addition to these, errors on the half-life, and reported cross-section values were also included.

Fig.5 shows the different calibration factors calculated for each isotope during the two irradiation measurements, normalised to the previous calibration value (1.30e9), represented by the red dotted line.

There is very good agreement between the original value for the calibration factor (measured in the 90s) and the values calculated from this series of measurements. A weighted mean of all the calibration factors, gave an overall result of

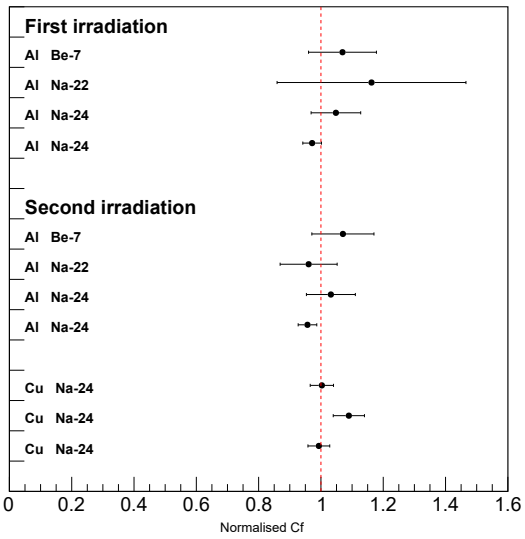

Figure 5: Experimental results for calibration factors, obtained from activation measurements for BSI in T10.

CONCLUSION

Driven by the interest in the fixed target experimental areas, which highlighted the need to understand the status of ageing equipment installed in these beamlines, a calibration campaign was carried out in the CERN NA. Two separate activation measurements were conducted at target station T10, in which a stack of foils was inserted in the beam, irradiated and subsequently collected for offline measurements.

Gamma spectrometry measurements of the activation foils allowed for the calibration of the BSI in T10, with experimental results within 2% of the original value. The success of this calibration has paved the way for a subsequent series of measurements, to be carried out at all target stations in the NA. Once completed, these new measurements will illustrate the status of the calibration at the different target locations, leading to the standardisation and documentation the calibration process for the whole NA and establishment of a time-frame for regular calibration of BSIs in the beamlines.

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