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PERFORMANCE OF TITANIUM, TUNGSTEN, AND CARBON AS BEAM PROFILE MONITOR MATERIALS

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Abstract

This paper investigates the signal characteristics of titanium, tungsten, and carbon materials used in a secondary electron emission grid setup at CERN's North Area. Periodic scans were conducted to reconstruct beam profiles and assess the performance of these materials, configured as wires and bands, under slow-extracted 400 GeV protons. The study aims to inform the design and optimization of new secondary electron emission monitor systems for the NA consolidation project and future installations.

INTRODUCTION

At the CERN SPS, Secondary Emission Monitors (SEMs) in the form of titanium bands are key instruments for monitoring the transverse structure of high-energy proton and ion beams. Their working principle relies on the release of low-energy secondary electrons from the bands intercepting the beam, which are then collected and converted into spatially resolved signals [1]. These bands have demonstrated reliable performance across many years. They offer a high signal-to-noise ratio, and their minimal thickness helps reduce beam-induced heating while minimizing perturbations and particle losses due to scattering. However, titanium bands also present limitations. Their ultimate spatial resolution is constrained by the minimum manufacturable band width, approximately 300 µm for the devices used at CERN, which restricts achievable pitch to around 400 µm. In addition, the expertise required for their assembly may be more difficult to maintain compared to more conventional CERN wire grid systems.

In particular, carbon and tungsten wire detectors—currently standard across most of the CERN machines, are being considered as a viable alternative to titanium bands for monitoring the position and profile of the slow-extracted beam from the SPS to the North Area (NA) lines.

Thin wires, offering a well-controlled fabrication process, provide higher spatial resolution than bands. Their main limitation is signal strength, due to a smaller filling factor.

Considering both current and future operational scenarios for the SPS North Area, transverse profile monitors are required to operate reliably under a wide range of proton beam conditions [†], as summarized in Table 1.

TEST SETUP

One of the vacuum tanks hosting SEMs in the SPS beam transfer to the North Area (TT20 line), historically reserved for beam instrumentation tests, was modified to study the response of wire samples in comparison to that of titanium bands [2]. The tank was equipped with a detector head movable in steps across the beam pipe. The samples were mounted on a ceramic Printed Circuit Board (PCB)—shown in Fig. 1— installed on the detector head.

Table 1: Summary of Typical Beam Parameters for the SPS North Area

Beam Type	Unbunched proton beams
Beam Size (Gaussian σ)	From sub-mm to 3 mm
Spill Duration	1 s to 10 s[‡]
Total Protons per Spill	~ 10^{11} to a few 10^{13}

[‡] 4.8 s during present normal operation, including during the experiments discussed in this paper.

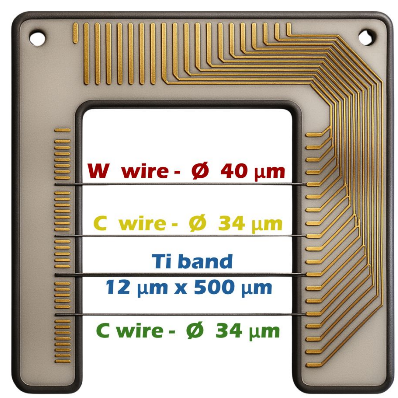

Figure 1: Design of the ceramic PCB used to test the 4 samples.

The setup consists of a titanium band, a tungsten wire and two carbon wires, as summarized in Table 2. The tungsten wire is coated with a thick layer of gold. As in the other CERN systems equipped with this wire type, the coating is required to facilitate the soldering of the wires on the PCB. The coating affects wire cooling because radiation cooling is a surface effect that dominates in vacuum and differs between tungsten and gold [3]. However, it has little impact on the signal, as both materials have very similar expected Secondary Emission Yield (SEY). The two carbon wires only differ in how they were mounted on the detector head: one is glued and the other soldered. In this case, soldering is facilitated by copper coatings deposited only on the extremities of the wire, which are never hit by the beam.

The titanium band, 12 µm thick, 0.5 mm wide is exactly as one of the types routinely used in the SPS NA.

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† The system should also be capable of detecting ion beams with a comparable total number of charges (proton-equivalent).

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Table 2: The samples under test. The last column, Pos., refers to the displacement of the detector head from its parking position to be programmed to position each sample on the chamber axis (ideal beam position).

Type	Material	Dimensions	Pos. [mm]
Wire	Carbon (glued)	34 µm dia.	30
Band	Titanium	12 µm × 0.5 mm	40
Wire	Carbon (soldered)	34 µm dia.	50
Wire	Tungsten (Au-coated)	40 µm dia.	60

EXPECTED SIGNALS

The electric charge generated in a SEM sample exposed to a proton beam depends on both geometry and material properties. From a geometrical standpoint, different sample shapes and dimensions (e.g., wires vs. bands) intercept different fractions of the beam even when placed at the same transverse position. This affects the number of primary protons interacting with the sample. We define a geometrical factor G_{fact} to account for this difference, depending on parameters such as wire diameter or band width. From a material standpoint, the signal also depends on the proton energy deposition and the resulting SEY, defined as the number of secondary electrons emitted per incident proton. The SEY can be approximated using Sternglass's empirical formula [4]:

$$\text{SEY} = 0.01 \cdot \left(\frac{A}{3.68 \cdot 10^{-17} \cdot N_a \cdot Z^{1/3}} \right) \cdot \frac{dE}{dx} \cdot \left(1 + \frac{1}{1 + 5.4 E_k} \right), \tag{1}$$

where $\frac{dE}{dx}$ is the stopping power [eV·cm²/g], E_k the proton kinetic energy [MeV], ρ the target density [g/cm³], A and Z the mass and atomic numbers of the target, and N_a Avogadro's number. The first term in parentheses represents an effective interaction length, inversely dependent on material density and atomic structure.

The expected signal ‡ from a sample of material X (e.g., carbon or tungsten wire), placed at the same beam position as a titanium band, is then:

$$S_{\text{X}} = S_{\text{Ti}} \cdot G_{\text{fact}} \cdot \frac{\text{SEY}_{\text{X}}}{\text{SEY}_{\text{Ti}}}. \tag{2}$$

This provides a direct prediction of relative signal amplitudes across different samples, summarized later in Table 3.

EXPERIMENTAL RESULTS

The tests were performed by scanning samples through the full vertical distribution of the slow-extracted proton beam. Several sets of beam scans were carried out in 2024 and 2025, under conditions representative of current commissioning and operational intensities, from ~1.3 × 10^{11} to ~1.7 × 10^{13} protons per spill, which we refer to as "Low" and "High" intensity, and which are displayed in Table 4. Measurements were taken during separate extractions, with intervals ranging from tens of seconds to several minutes. The relative signal response during each 4.8 second spill at the center of the wire or band is shown in Fig. 2

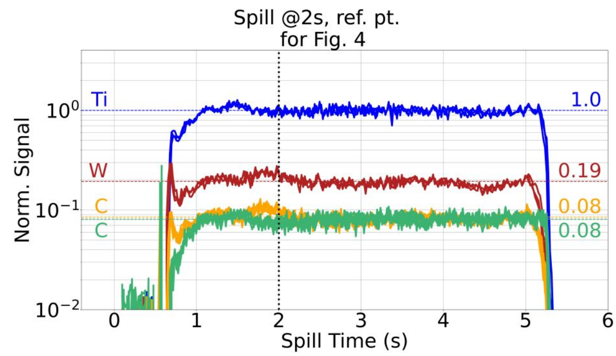

Figure 2: Wire sample signals during the proton spill from SPS to NA, when each wire is set at the vertical beam center, incident proton intensity 1.7×10^{13}.

Signal amplitudes were digitized at 50 Hz (one sample every 20 ms), enabling beam profile reconstruction either by integrating the full signal for each position (see Fig.3 and Fig. 4) or by taking a single digitized point in the spill as shown by Fig. 5.

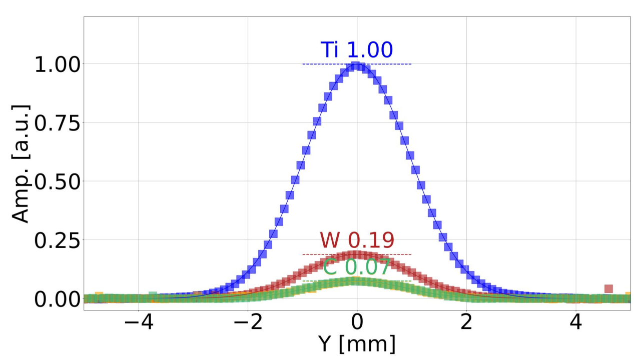

Figure 3: Profile for scan with incident proton intensity 1.2×10^{13}. Note that the carbon wire profiles are near identical.

For low-intensity proton tests (of the order of a few 10^{11} protons per spill), the limited signal-to-noise ratio renders the 20 ms reconstruction unreliable for carbon wire signals, although the titanium band signals remain adequate. In the case of tungsten wires, however, averaging over the full spill remains feasible and allows a reliable reconstruction of the transverse beam profile, as illustrated in Fig. 4.

‡ Before any analogue or digital electronics amplification and processing, assumed to be the same when comparing different SEM samples.

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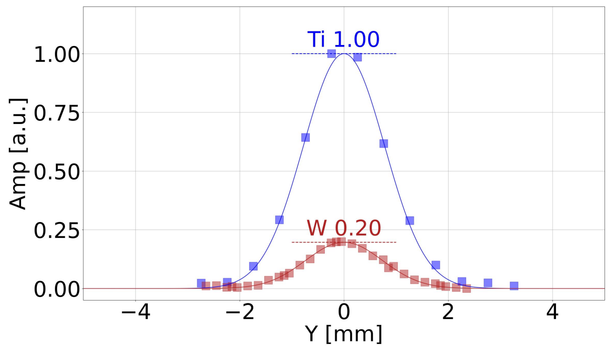

Figure 4: Profile for scan with incident proton intensity $3.2{\times}10^{11}$.

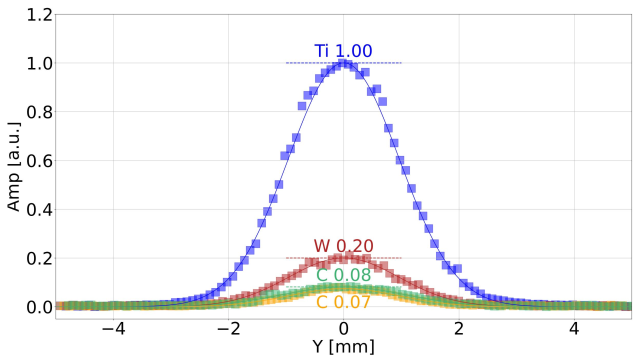

Figure 5: Profile at t=2 s for scan with incident proton intensity $1.2{\times}10^{13}$.

Table 3: Estimated and Measured Relative Signals for the Samples Under Test

Material	SEY [%]	G_{fact}	Relative signal	
			Estimated	**Measured**
Titanium	1.69	0.245	1.00	1.00
Tungsten*	3.61	0.020	0.17	0.20
Carbon	0.72	0.017	0.03	0.08

* Au coated

Overall, the extensive set of experiments—of which only a few representative examples are presented in this paper—consistently confirm the relative signal response of the four tested samples. The three approaches presented, namely the time evolution of the signal with the wire at the beam center, the profile amplitudes obtained by integrating over the full spill, and the profiles reconstructed from individual 20 ms samples, all converge to the same conclusion: tungsten wires yield approximately 20 % of the signal of the titanium bands, while carbon yields about 8 %. These results are summarized in Table 3, which also compares the measured ratios with the estimates discussed in the previous section—Eq. (2).

During the experiments, the measured distributions were fitted with a Gaussian function to determine the beam size and to verify the consistency across the different samples, despite their varying signal levels. The results, summarized in Table 4, indicate that even carbon wires—which provide only a few percent of the signal of the titanium bands—reproduce the beam size of the integrated spill to within 5 %. Tungsten wires reproduce the titanium band results within 2 %, even at low intensities. As an additional reference, Fig. 6 presents the beam size evolution during the high intensity experiment.

Table 4: Measured σ_y [mm] Values for Different Materials and Beam Intensities

Material	High Intensity		Low Intensity	
	Spill Integral	**At t=2s**	**Spill Integral**	**At t=2s**
Ti	0.97	0.96	0.76	0.75
W	0.97	0.96	0.78	0.78
C	0.94	0.95		
C	0.91	1.07		

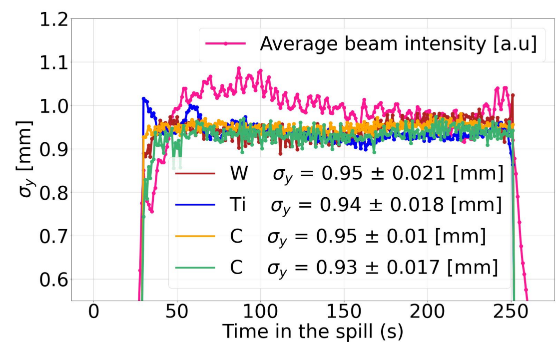

Figure 6: Beam size evolution from wires and Titanium band, plotted with the average beam intensity evolution during the tests.

CONCLUSION

Titanium bands remain the most effective material for SEMs in the SPS North Area, offering robust, low-noise signals for accurate beam profile characterization. Tungsten wires, yielding about 20 % of the titanium signal, reproduced beam size within 2 % and showed discrepancies of only 3 % relative to estimates, well within expected SEY uncertainties. This performance, combined with easier manufacturing, makes tungsten a viable alternative for future installations. Carbon wires, while capable of reproducing beam size within 5 %, consistently produced signals an order of magnitude lower than titanium, with 5 % deviations from estimates. Their limited signal-to-noise ratio at low intensity renders them unsuitable for most of the North Area commissioning phases. These findings inform material and design choices for the SPS NA consolidation project, confirming titanium as the reference standard, while validating tungsten as a practical alternative where fabrication constraints dominate.

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