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`sara.benitez.berrocal@cern.ch`

SPS Fast Spill Monitor Characterisation and Evaluation Throughout 2023

S. Benitez , D. Belohrad, S. Burger, A. Goldblatt, M. Martín, S. Mazzoni, F. Roncarolo

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Summary

Monitoring the intensity of protons extracted from the CERN Super Proton Synchrotron (SPS) ring towards the North Area (NA) facility at a high rate is of utmost importance, with increasing challenges, for the the current facility operation, the ongoing NA consolidation, and the future Physics Beyond Colliders (PBC) projects.
Various instruments are being developed to measure beam current fluctuations across a broad range of frequencies, from a few hundred Hz to several hundred MHz.
This note is dedicated to discussing the design and initial implementation of a new Optical Transition Radiation - Fast Spill Monitor (OTR-FSM). It outlines the constraints identified during the early design phase, the first upgrades performed during the 22-23 YETS, and the results obtained during the 2023 operational period. Finally, it offers an improvement proposal for the YETS 23-24 to address the obstacles encountered so far.

Contents

1 Introduction

The continuous extraction of 400 GeV protons over several thousand turns from the SPS to the NA fixed target experiments involves the essential monitoring of the spill quality and fluctuations. This information is essential to optimise the extraction process [1, 2] and to successfully reach the fixed target experiments results. Table 1 summarises key parameters relevant for the spill monitors functional specifications [3].

Table 1: Key parameters of interest for the SPS spill monitors requirements.

Parameter	**Value or Range**	**Comment**
Spill Duration	4.8 [s] 1 [s]	present operation future, e.g. PBC
Beam Intensity	1-400 [1e11p]	
Spectrum Harmonics of interest	50 Hz,100 Hz 43.38 kHz 477 kHz 200 MHz 800 MHz 10 GHz	e.g. Noise, PC ripples SPS 1^{st} and 2^{nd} Harmonics* PS $1st$ Harmonic** RF capture RF long. blow-up Future, e.g. PBC

* the SPS circulating beam structure includes 2×10.5 µs injections, spaced by a 1.05 µs *abort gap* for the dump kickers rise.

** the slow extracted beam can still contain a time structure from the PS (the SPS injector).

The Beam Secondary emission Intensity (BSI) monitor is the current SPS operational spill monitor [3]. It relies on a Secondary Emission Monitor (SEM), that quantifies the secondary electrons produced as primary protons pass trough an extremely thin (around 12 µm) Titanium foil. The Secondary Emission Yield (SEY), defined as the number of secondary electrons produced per primary proton, measures in the range of a few 10^{-2}. However, this device is limited in terms of bandwidth, which reaches a few kHz. Attempting to cover a broader range by updating the electronics would be possible, yet the resultant signal would entail substantial noise, rendering it unfavourable. Apart from the BSI, three diamond Beam Loss Monitor (dBLM) are installed at the slow extraction area. They function as ionisation chambers, generating pairs of electrons and holes when loss particles cross the (Chemical Vapour Deposition) CVD substrate material ($10 \times 10 \times 0.5$ mm) depositing their energy on it, with 500 V of bias voltage [4]. They can operate as spill monitors under the condition that the time structure of losses aligns with the intensity of the extracted spill. Nonetheless, the present system implementation is characterised by a very low signal in comparison to the expected output[1] and high noise. Moreover, the data acquisition storage is limited to a 2.4 ms window [5].

The OTR-FSM (also labeled as OTR-PMT) aims to offer additional diagnostic insights into the frequency composition and internal structure of the extracted beam. This new

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[1] For instance, one of the devices is situated on the septa responsible for the beam extraction, where high level of losses is anticipated. In this case, only the 2.4% of the maximum expected signal is measured.

system evaluates changes in the extracted beam intensity by measuring Optical Transition Radiation (OTR) produced when the beam goes through a metallic foil (like Al, Ti, etc). The radiation is collected by a fast Photo-Multiplier Tube (PMT) [6] (anode with pulse rise time equal to 0.8 ns) and a wide BW (300 MHz) DC-coupled amplifier. The signal from the amplifier output in the tunnel is brought to the surface via 250 m CK50 cables, for which the specified attenuation is > 7dB/100 m at 200 MHz. Currently (2023), signal digitisation is done through a fast oscilloscope (500 MHz analogue BW, 5 GS/s, 2 GS of memory). The system is built upon a modified SPS Beam Imaging System (BTV). The camera normally installed to image the intercepting screen was replaced with a cone structure, approximately 1 m tall, that holds the PMT sensor (see Fig. 1).

Figure 1: Photo of the Fast Spill Monitor setup in SPS.

2 First Prototype Development And Measurements (2022)

Fulfilling the SPS NA Consolidation and PBC projects, the aim of this first prototype was to reestablish the potential use of OTR for monitoring the spill intensity at high rate, without optimised signal transport and data acquisition/processing. An obsolete spill monitor test device, located in TT20 at the functional position BSTL.210272, was refurbished during the 2021-2022 Year End Technical Stop (YETS). The old installation was based on multiple scintillation screens (remotely interchangeable) and an obsolete amplifier-PMT assembly. As described the Engineering Change Request (ECR) [7] the changes included:

- the installation of a Titanium foil at the place of one of the scintillation screens. This was meant to use OTR and thus increase the intrinsic monitor bandwidth.
- the PhotoMultiplier Tube (PMT) replacement for a new Hamamatsu Photonics H33780-50 model.
- a new -custom made- PMT head amplifier to maximise signal to noise and analogue bandwidth.

Tests conducted in 2022 showed a PMT signal upon inserting the Ti screen into the beam. For example, with a beam intensity above 1e13 p/spill and applying a voltage of 1300 V, it was already possible to well recognise the spill time structure. Measurements were taken at a 100 kHz sampling frequency and integrated offline in 10 ms bins, producing 500-point arrays. The final signal is the point-by-point average of more than 50 shots, normalised by the extracted intensity. However, the PMT signal was lower than expected, and there was also some signal obtained when the screen was not inserted (see Fig. 2), indicating simultaneously:

i) a possible misalignment of the titanium screen. A misalignment could result in the PMT acceptance not to be properly matched to the OTR cone angle emission.

ii) the high sensitivity of the system to beam losses or the presence of very high losses at the monitor location.

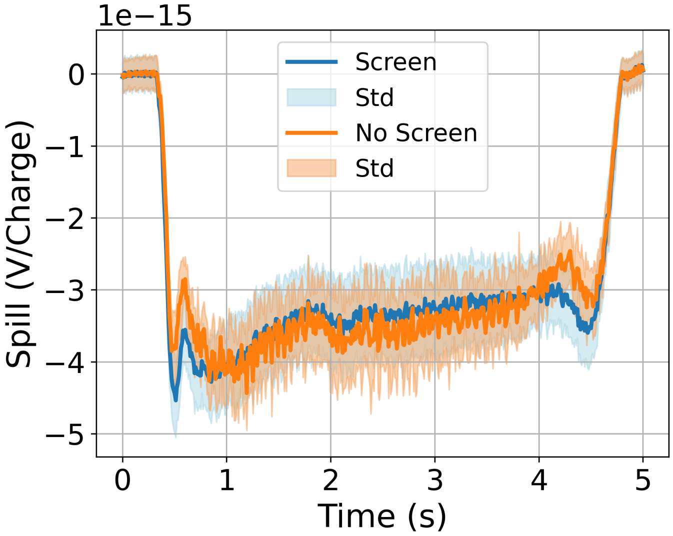

Figure 2: Spill signal measurement during 2022 tests. It presents the comparison between the signals obtained with and without screen. Signals are normalised by the SPS extracted intensity. The shaded areas indicate the standard deviation (std) of the measurements.

A test campaign was conducted to study the monitor signal while changing the beam position on the screen, however, no significant changes were observed.

Although general measurements showed that the *No Screen and Screen* signals were similar in amplitude, the BSI and OTR-FSM monitors have been compared while measuring the same extracted beam (at $\approx 3 \times 10^{13}$ p/spill). An example is shown in Fig. 3. During the 4.8 s spill, the sampling frequencies were set to 50 kHz for the BSI and 1 MHz for the OTR-FSM. Offline data integration was done in bins of 1 ms for both monitors. The upper plot illustrates the close alignment in capturing the spill intensity envelope. Meanwhile, the lower plot showcases the ability of both instruments to detect low-frequency harmonics such as the 50 and 100 Hz known to stem from noise in the magnet power supplies, which can influence the spill intensity [3].

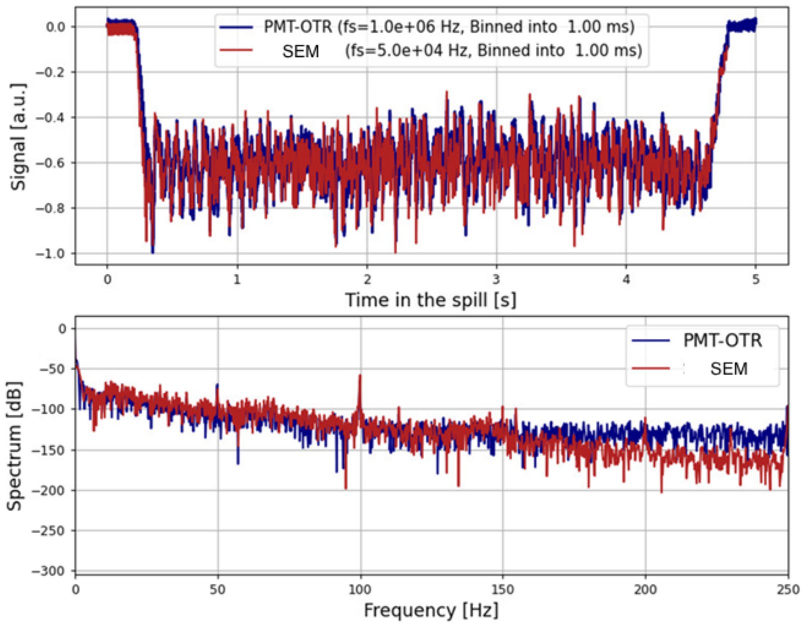

Figure 3: SEM and OTR-FSM detectors comparison in time and (low) frequency domain.

The very good agreement between the two types of instruments in terms of relative spill shape confirmed the suitability of the FSM as a beam intensity monitor, at least after digital integration in 20 ms chunks (50 kHz).

3 System Modifications during the 2022-2023 YETS

To evaluate the light collection of the OTR generated at the screen, a Zemax simulation model was developed. Zemax is a very powerful tool to visualise, analyse and optimise optical systems [8]. This model simulated the entire process from the generation of OTR light to its collection by the photomultiplier tube (PMT). Based on the simulation results, it was determined that a lens with a focal length of 200.0 mm (LA4984-ML series) should be included to focus the light onto the PMT. The schematic, shown in Fig. 4, was then used in the software to optimise the light collection on the PMT.

During the YETS 2022-2023, the optical line with the selected lens was installed inside the cone (see Fig. 5).

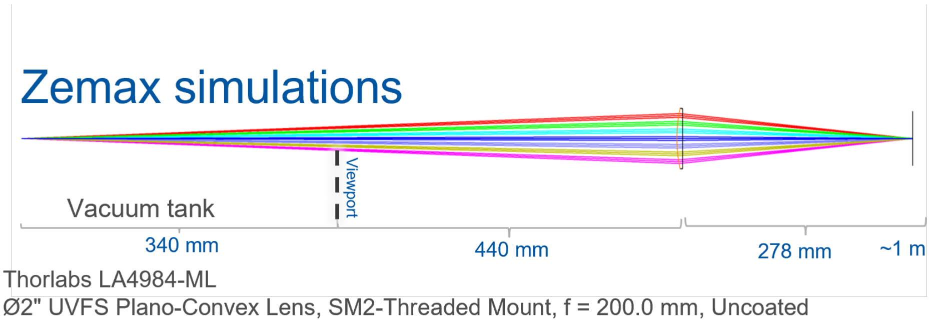

Figure 4: Schematics of the Zemax simulation to verify the optical line parameters.

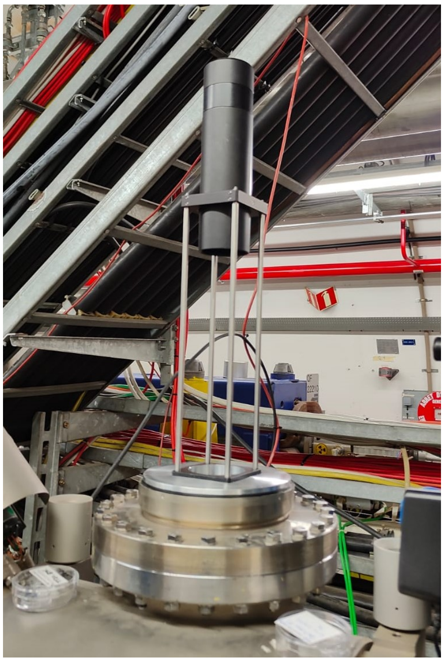

Figure 5: Optical line installed inside the cone for light collection.

3.1 OTR-FSM Measurements in 2023 Run

A comparison of typical signals measured before and after the system upgrade during YETS 22-23 is shown in Fig. 6. As in earlier examples, the signals are normalised by the total proton charges as measured by the SPS BCT before extraction. The PMT was powered with 1300 V in both cases. As observed, the signal amplitude increased by approximately a factor 3. However, data acquisition of the background noise collected by the PMT, without the Ti screen inserted, indicated that measurements were still significantly impacted by beam losses. Several scenarios were tested (see Fig. 7), both with and without the screen inserted, at various PMT high voltages to detect any visible differences. None were observed when the output current remained within the permitted limits, and even in cases where the limits were exceeded, the differences were minimal. Exceeding these limits could potentially damage the PMT.

At that stage, we suspected that the high losses at this location, directly hitting the

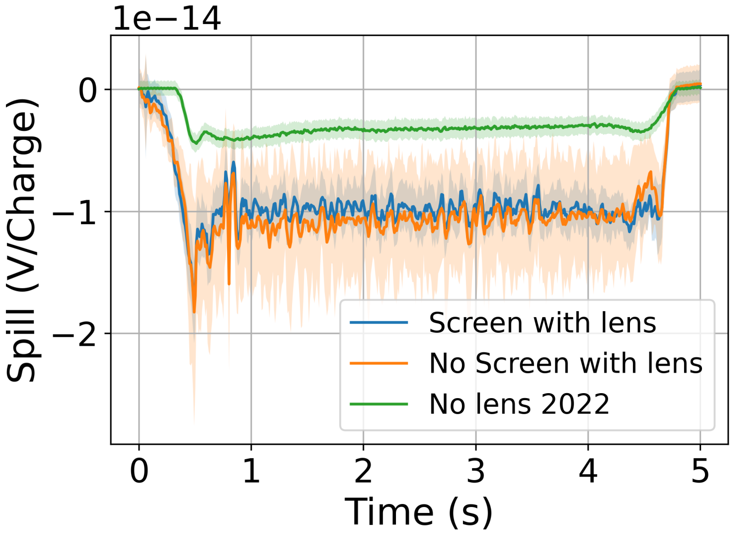

Figure 6: Signals before and after the optical line upgrade at the end of 2022. They are normalised by the SPS extracted intensity.

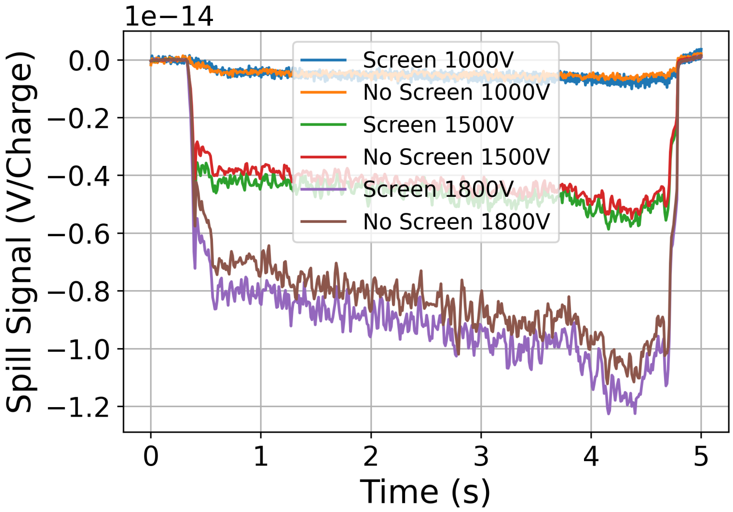

Figure 7: Comparison of the PMT signals with and without screen after diffuser removal. A small differentiation between them is observed with the PMT gain. Signals are normalised by the SPS extracted intensity.

PMT, were significantly adding to the OTR signal. This reduced the quality of the spill monitor measurements and caused damage to the photosensor (see Fig. 8).

4 Laboratory Tests

A laboratory setup was established to characterise the system's behaviour by evaluating its detection bandwidth, considering the entire chain, i.e., PMT-amplifier-long cable. In addition, we investigated the detection of light yield. For the tests, we used a spare PMT

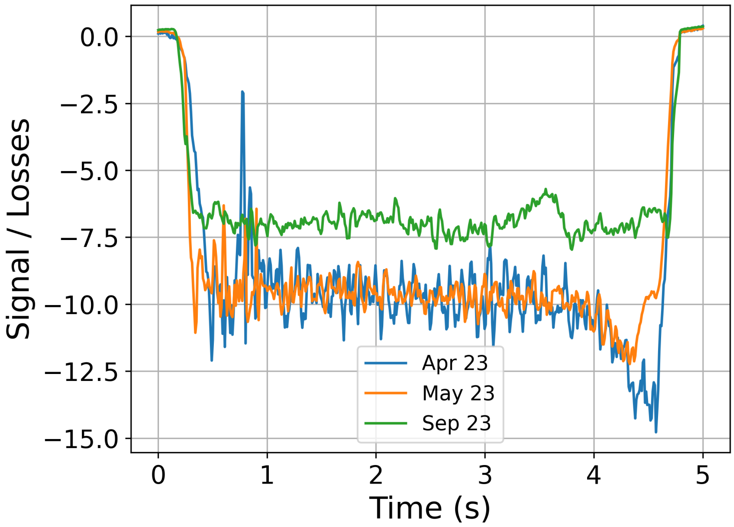

Figure 8: Evaluation of the PMT degradation along the beam RUN in 2023. The signals are normalised by the environmental losses measured by the closest BLM in the line.

from the R3377 series, a 300 MHz amplifier unit (C11184) with a gain of x25, and a cable approximately 180 meters in length.

The setup for the characterisation test of the PMT signal consisted of a pulsed laser (with a pulse duration of a few tens of picoseconds) configured at 200kHz, an optical filter with an OD=3 to protect the PMT from potential damage, and the PMT (in blue as PMT). In a second round of measurements, the output of the PMT was connected to the amplifier (in orange as 'AMP'), which, in turn, was linked to the long cable (in green as 'Cable') during the final test phase. In Fig. 9 it is possible to compare the final results of the three sets of measurements previously mentioned at 2000 V of high voltage[2].

As a reference, signals from the single photons detected by a photon counter (in violet and brown as 'TDC1' & 'TDC2') and a PicoQuant photon detector (in red as 'Discriminator') were also recorded. We can observe from the graph that the frequency response of the system is above the 3 dB power level at over 200 MHz.

The second test performed at the laboratory aimed to study the signal quality of the PMT concerning its gain. Using a LED ($\lambda = 465\,nm$) as a DC light source, our aim was to reproduce the same OTR produced by the Ti screen in the TT20 detector [3]. The power used during the test was approximately 20 nW. It was measured at the cathode location with an optical power meter. With the provided light, the system exceeded the allowed output intensity limit for the proper operation of the PMT as indicated by the specifications (0.2 mA), even at minimum gain (1000 V). This indicates that the OTR-FSM is not receiving all the light produced by the OTR, suggesting a possible misalignment of the screen or unexpected light absorption by the window glass (unlikely). Figure 10 shows the setup used during the LED measurements as an example. The laser head also was included on the

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[2] Different voltages were used during the tests, with the case of 2000 V being selected as an example.

[3] The power of the LED was calculated based on the OTR photon yield formula [9] and the conversion equation: Power = (photons / time) x energy.

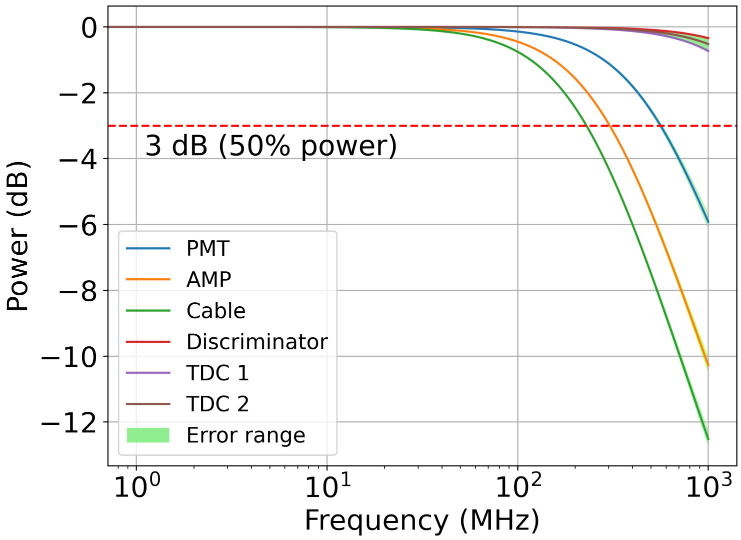

Figure 9: Frequency response of the system at 2000 V.

optical table for the photograph.

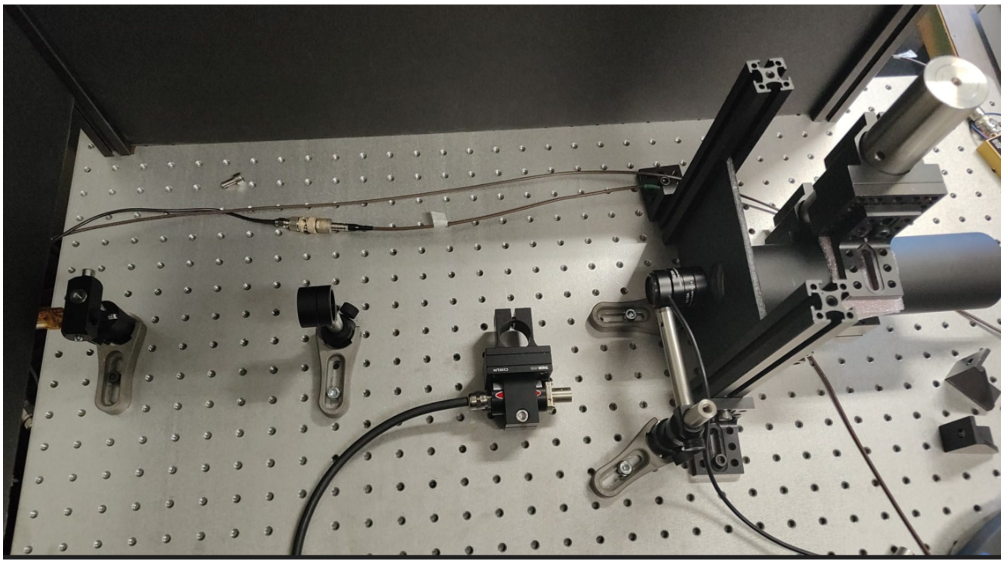

Figure 10: Setup of the optical line during the tests. From left to right, the elements are the LED, optical filter, laser (included for the photo), power meter sensor, PMT. The elements are housed inside a black box for light tightness.

5 Screen Reflectivity Factor Studies

The photon yield generated from the titanium screen depends on the reflectivity factor R. It refers to the efficiency of a surface or material in reflecting photons, measured as the ratio of reflected to incident photons. This metric is crucial in light reflection and absorption calculations. Our study considered replacing the titanium screen if its reflectivity (R value) was insufficient. Figure 11 presents the results from the CERN reflectometry laboratory, supervised by Thomas Schneider. Two different titanium screens (dark and light in the picture) were tested. Both screens showed a better R factor than expected, which did not help to explain the low OTR signal observed with beam measurements.

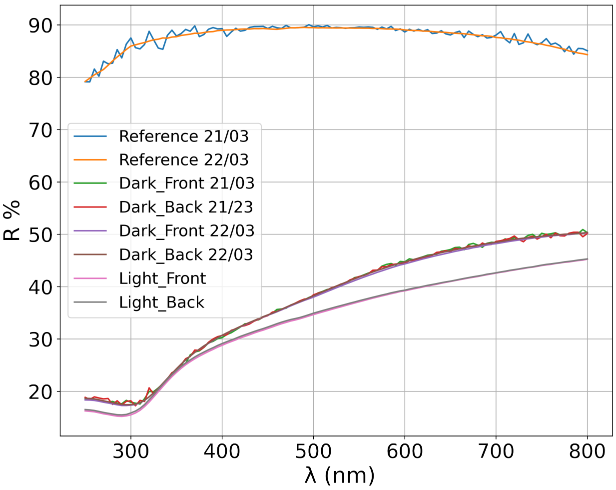

Figure 11: Results of the reflectivity factor tests conducted on the titanium screen depending on the wavelength range.

6 TT20 Radiation Survey

As a result of the inconclusive measurements in 2023 and the persistence of the *No Screen vs. Screen* issue, it was decided to investigate the losses around the system in more detail by creating a *radiation map* of the area and identifying the hot spots within the system. This *radiation mapping* was not only useful for visualising the dose the PMT was receiving but also for assessing the feasibility of installing an analogue camera to observe the OTR light and align the system.

However, LSS2 in SPS is an area highly activated by particle losses. The surroundings of BTV210272 (FSM location) and BTV210352 (the next BTV towards the NA) were surveyed by installing multiple dosimeters. They were installed during the YETS 22-23 and collected for dose measurements during the June 2023 TS. Figure 12 shows the total dose received at the points of interest over a period of 131 days of beam operation. Results indicated a reduction in the dose by ten times at the top of the BTV210352, making it a more suitable location for the FSM system. A new set of dosimeters was placed at the same points after the collection of the previous ones to continue the dose measurements until the YETS 22-23.

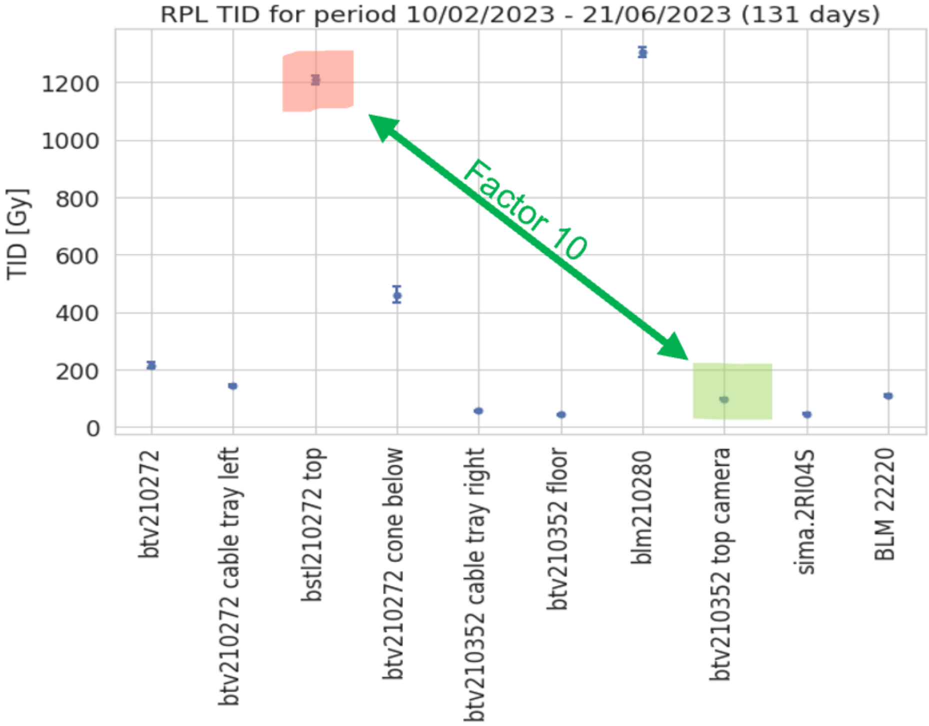

Figure 12: Total dose measured by the dosimeters at different points around BTV210272 (FSM location) and BTV210352 (the next BTV towards the NA). A factor 10 of reduction between the two locations was identified.

7 Conclusions

The OTR-FSM has proven to be an instrument with great potential in the field of fast spill monitoring. The latest measurements have verified its capability to analyse the spill spectrum for a low range of frequencies, aligning with what has been measured by other devices such as the SEM.

However, it has been observed that the performance of the system can be improved. The high level of background radiation not only complicates the interpretation of the obtained results but also damages the components of the system. Considering that the system has been refurbished, many improvements have been proposed for the upgrade of the OTR-PMT fast spill monitor during the 2023-2024 YETS:

- As reported in Section 6, a **change in the system location** from BTV210272 to BTV210352 is required. Both the cabling and the optical fibres required for the system operation will be purchased and installed.
- The new **structural design**, serving as support for the PMT, optical components, as well as **the new analogue camera**, will be installed. **Lead shielding** has been requested for the protection of the components.
- The **amplifier** will be upgraded based on the design of a local oscillator to be able to detect spill frequencies close to 800 MHz.

- For **data acquisition**, the Picoscope will be replaced by a system that allows much larger memory, enabling a higher sampling rate split in two frequency bands: a DC 300 MHz low frequency path for slow mode measurements up to 250 MHz and a 800 MHz high frequency path using a local oscillator [10].

The mechanical and location changes are documented in the Engineering Change Request, SPS-BTV-EC-0001 [11], and the upgrades in the electronics and data acquisition are reported in [10]. All these changes and future results will be documented in a forthcoming note, reporting on the 23-24 YETS system modifications, and measurements during the 2024 Run.

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