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SPS FAST SPILL MONITOR DEVELOPMENTS

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Abstract

The North Area facility (NA) receives 400 GeV proton beams through a slow extraction process, so-called spill, from the CERN Super Proton Synchrotron (SPS). To improve the quality of the SPS spill, it is crucial to monitor its intensity in the range between a few nA up to a few µA, with a bandwidth extending from a few Hz up to several GHz. The most promising measurement options for this purpose are the Optical Transition Radiation-Photomultiplier (OTR-PMT) and the Cherenkov proton Flux Monitor (CpFM). This document presents recent upgrades performed on both devices based on the operational experience gathered throughout the 2023 and 2024 runs. It includes a detailed analysis and discussion of the present performance, comparing the capabilities of each instrument.

INTRODUCTION

As part of the Accelerators and Technology Sector (ATS) within the Physics Beyond Colliders (PBC) study, numerous proposals for fixed-target projects in the North Area facility (NA) were previously presented [1]. The slow extraction process takes around 2×10^5 SPS turns, that is approximately 4.8 s, providing a spill (i.e. a continuous flux of protons) towards the NA fixed target experiments. Monitoring the current fluctuations of such spillis critical for optimising extraction and successfully carrying out experiments. A list of key parameters for the development of spill monitors is shown in Table 1 [2].

As discussed in [3], currently the SPS spill time structure is monitored by one *Beam Secondary Emission intensity Monitor* (SEM) installed at the beginning of the extraction line towards the NA (TT20). This type of instrument is sensitive to de-bunched beams (for which beam current transforms cannot be used), but is limited in bandwidth to below 2 MHz and signal-to-noise ratio (SNR). *Diamond Beam Loss Monitor* (dBLM) are under study. They can reach 500 MHz but have a low frequency cut-off (e.g. 50 and 100 Hz cannot be measured) and for the moment the measured signal amplitudes are only few percent of what expected from simulated losses and detector acceptance. This contribution will focus on the development, implementation and test updates of two of other techniques considered for fast spill monitoring, the *Optical Transition Radiation - Photomultiplier Tube* (OTR-PMT) and the *Cherenkov proton Flux Monitor* (CpFM).

Table 1: Key Parameters of Interest for the SPS Spill monitors

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

[a] the SPS circulating beam structure includes 2×10.5 µs injections, spaced by a 1.05 µs *abort gap* for the dump kickers rise.
[b] The slow extracted beam can still contain a time structure from the Proton Synchrotron (the SPS injector).

OPTICAL TRANSITION RADIATION-PMT MONITOR

The OTR-PMT system measures the extracted beam intensity by detecting OTR generated when the beam interacts with a titanium (Ti) foil inserted in the beam path at a 45-degree angle to the beam direction, facing upwards. The emitted radiation is captured by a fast PMT (R3377 series) with an anode pulse rise time of 0.8 ns [4], positioned vertically, approximately at 1 m from the interaction point. Next to the PMT, there is also an analogue camera (Watec WAT-902H3 ULTIMATE (CCIR)) installed to remotely visualise the centre of the screen and the presence of the OTR source. A motorised translation stage allows swapping between camera and PMT to image or integrate the OTR at the nominal measurement position. Both the PMT and the camera are protected by 15 mm thick lead shields for radiation protection. A rectangular cover surrounds the platform, ensuring that the entire setup is light-tight. In addition, an aluminium cylindrical tube is mounted on the beam pipe, featuring a door that provides easy access to its interior, where an optical lens (200 mm focal length, LA4984-ML series) system was installed to increase light collection efficiency. Finally, a ground-anchored bar supports the system, protecting the beam pipe tank from potential damage. Figure 1 shows the OTR-PMT design as described above. A new DAQ sys-

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Figure 1: Current design of the OTR-PMT monitor installed in TT20 transfer line in SPS.

tem [5] was recently developed and put into operation. It uses a VFC[1] platform equipped with a 4-channel 500 MSPS FMC form factor ADC module. It can store segments of data within the full 4.8 s[2] spill by using sequential triggering and its open hardware design permits to add a rear-transition module (RTM) in case of lack of FPGA internal memory.

The PMT signal is now distributed in two different paths. In the direct path, the signal is only amplified to match the used digital acquisition system (DAQ) characteristics. In the high-frequency path, the amplifier down-mixes the 800 MHz component of the PMT signal into the base-band. The signals are transmitted via four high-quality cables to the surface. The sampling frequency of the DAQ can be adjusted based on the acquisition mode, as outlined below:

- **Slow mode**: Storage of 5 seconds of the spill cycle data, when sampling at 800 kHz.
- **Fast mode**: Automatic and predefined sampling of data chunks throughout the entire spill cycle. The chunks are stored in the DDR memory and individually processed. The maximum sampling rate is 500 MHz.
- ***Ultra-fast* mode**: A bandwidth of 800 ± 100 MHz can be analysed using the same *Fast mode* acquisition digital processing.

The FFTs and spectrograms with higher temporal detail are produced in all cases.

During the early development of the OTR-PMT device, several uncertainties and issues emerged. These challenges prompted various modifications, resulting in the current design. The improvements included enhancements to the system design, upgrades to the electronics, and changes to the location of the device.

One of the most significant observations was how, with the Ti screen in the OUT position, beam losses generated relative high signals in the PMT. Figure 2 shows an example of measurements obtained during the operation in the early phase of the system. The sampling frequency was set to 100 kHz and an offline data integration was performed in 10 ms bins.

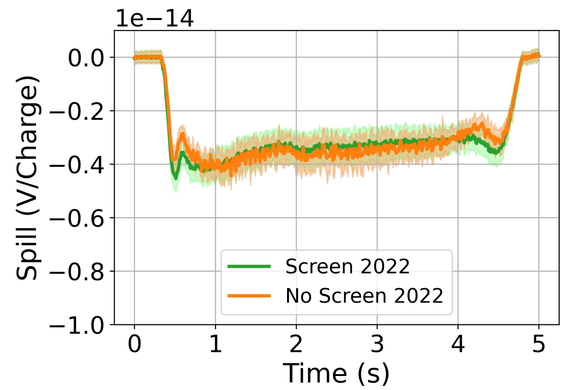

Figure 2: Spill signals recorded by the OTR-PMT monitor during the initial phase (2022). Signals were taken at 1300 V, and the traces are normalised by the SPS extracted intensity. The shaded areas indicate the standard deviation of the measurements.

As evident in Fig. 2, beam losses could be used to reconstruct the spill with the same SNR as with the Ti screen IN. This indicated at the same time high losses and low OTR detection efficiency. These findings motivated the relocation of the system to a new position with lower loss levels, moving it further downstream from the septa magnets, where the spill is extracted, from the SPS towards the NA. Besides, the installation of the analogue camera was another key change in the new design. It allows the visualisation of the OTR light (see Fig. 3), thus validating the system alignment and the effective collection of OTR photons by the photo-detector.

During operation, the PMT high voltage is kept to 1300 V, a level that provides on average about 0.2 mA output current. Combining this current with the PMT quantum efficiency (0.2), gain (4×10^4 at 1300 V) and the spill duration (4.8 s) one can estimate that about 7.5×10^{10} photons are collected at the PMT cathode. This is well compatible with what can be estimated using two different models [6, 7], i.e. from [4.2×10^{10} to 1.7×10^{11}] photons emitted by the screen.

By scaling from the spill length to the camera exposure time (20 ms), one can infer that about 3.1×10^8 photons generate the image of Fig. 3.

Figure 4 shows the average signal of 50 extractions normalised by the total extraction intensity, obtained during the 2024 run. The sampling frequency was set to 800 kHz. The set of measurements was taken during standard physics

[1] The VFC acronym comes from VME FMC Carrier, being VME = Versa Module Eurocard, and FMC = FPGA Mezzanine Card.

[2] It can be extended up to 10 s if longer spills are required during commissioning tests.

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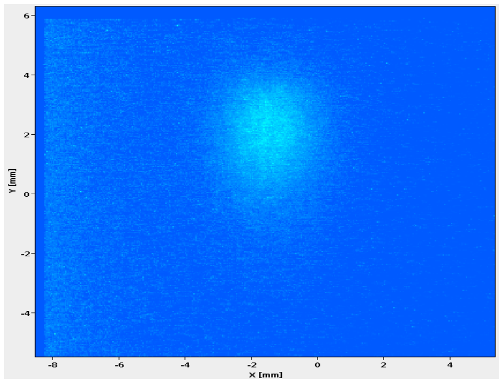

Figure 3: Image of the OTR light captured by the analogue camera, installed as a component of the OTR-PMT monitor. From this image, the beam horizontal and vertical size results to be approximately $\sigma_x = 1$ mm, $\sigma_y = 2$ mm.

operations, which involve more than 1×10^{13} protons per spill.

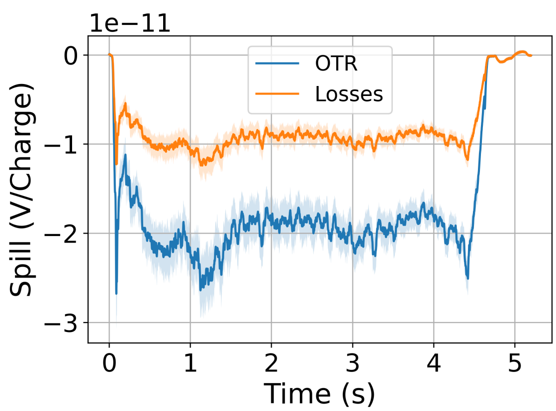

Figure 4: PMT-OTR signal (blue) during the 2024 run, after the system improvements. It is compared to the background from losses (orange). Signals were taken at 1300 V, and the traces are normalised by the SPS extracted intensity. The shaded areas indicate the standard deviation of the measurements.

The OTR signal is more than a factor 2 greater than the signal obtained from the losses. This represents a significant improvement regarding the *No Screen vs. Screen* signals issue, if compared to the initial measurements recorded in 2022. It should be noted that a direct comparison between the results presented in Figs. 2 and 4 is not feasible. This is due to differences in electronic systems, system locations, and the measured spills (and losses).

The results demonstrate that both losses and OTR photons are suitable for reconstructing the spill time structure. However, a fast spill monitor is crucial for commissioning and machine development periods when the extracted beam intensity can be two orders of magnitude lower. Scaling losses by the same factor, and considering that operational efforts consistently aim to reduce losses, justifies the continued study of OTR.

With respect to the other Fast Spill Monitors in the line, an interesting analysis could involve comparing the frequency spectra of the OTR-PMT with the one of the SEM. Figure 5 presents a comparison of the power spectrum distributions obtained from the OTR and SEM devices at the same extraction timestamp.

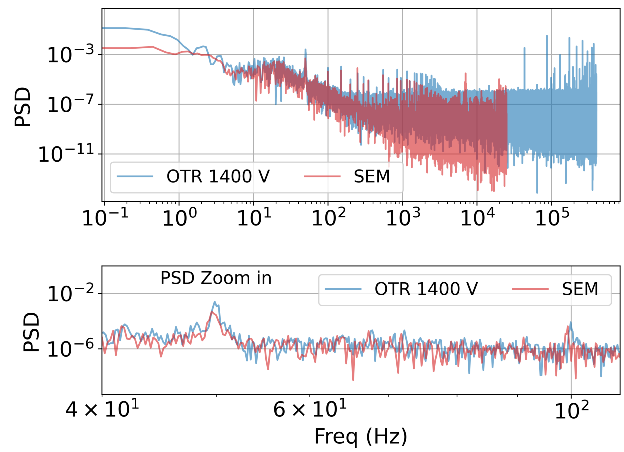

Figure 5: Power spectrum distributions of the OTR and SEM signals (upper plot). The lower plot provides a zoomed-in comparison of the low-frequency range, emphasising the 50 Hz and 100 Hz components. Both spectra are normalised to the DC component.

From the comparison of spectra, it is evident that the OTR-PMT monitor is capable of measuring a broader range of frequencies and exhibits improved performance in the 50 Hz range and its harmonics. Due to the nature of the tests conducted during operation, the sampling frequency was set to 800 kHz; however, the OTR-PMT is capable of measuring at much higher frequency ranges. Also, the performance of the OTR-PMT can be improved by adjusting the gain of the PMT.

CHERENKOV PROTON FLUX MONITOR

The Cherenkov proton Flux Monitor (CpFM) is a detector equipped with a 30 mm long fused silica bar ($5 \times 10\,mm^2$ transverse section, 5 mm in the longitudinal direction) that can be moved close to the beam on demand via a stepper motor. When the beam halo interacts with the material, Cherenkov photons are generated, and they travel along the bar to be collected by a PMT photodetector (R7378A series). Figure 6 illustrates the layout of the monitor.

The CpFM was developed by the UA9 collaboration over the course of 2016 to 2019 as part of their studies on crystal-assisted slow extraction [8]. As a second part of the study, the system was validated at the SPS, and later optimised to work as a Fast Spill Monitor in the TT20 line, situated at approximately 88 m from the septa, right before the first OTR-PMT location.

Given the expected Cherenkov photon yield, which is intrinsically higher than that of OTR (the expected Cherenkov yield is on the order of 10^{13}, according to [8]), the CpFM

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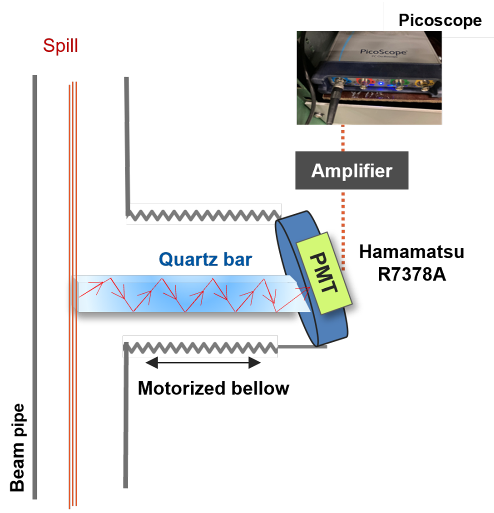

Figure 6: Layout of the CpFM installed in TT20 line.

emerges as an evident candidate for high-speed beam monitoring applications. Consequently, the system underwent fine-tuning and was commissioned for operation during the 2024 run.

Figure 7 presents the normalised signals recorded on the same day from the PMT-OTR and the CpFM, also compared to the SEM detector, when all binned in chunks of 20 ms.

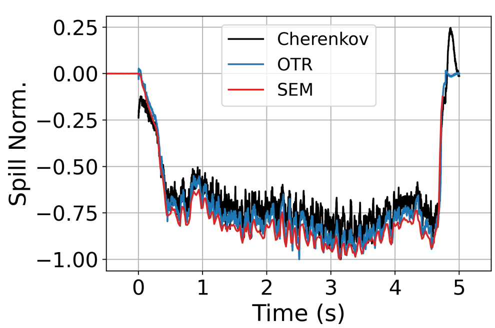

Figure 7: Comparison between OTR, Cherenkov, SEM and BSI normalised signals, during 2024 run measurements.

The three systems agreement in tracking the spill structure in time is well within 1 %.

Currently, systematic measurements are being conducted to evaluate the performance of the CpFM, in parallel with the OTR-PMT and SEM. However, a comparison of the OTR-PMT and CpFM signals with those from the dBLMs has not yet been possible.

CONCLUSION AND FUTURE WORK

Over the past two years of operation, significant efforts have been devoted to improving the performance of the Fast Spill Monitors to meet the requirements.

After improving its design, the OTR-PMT system underwent extensive beam testing in 2024 and is now continuously acquiring and logging spill data. This will enable a comprehensive performance assessment with abundant statistics under various beam conditions.

As of today, it's evident that the system aligns perfectly with the SEM at low frequencies and can measure spill harmonics up to a few hundred kHz with a better signal-to-noise ratio than the SEM. With high-intensity physics beams, which also results in relatively high losses, the system functions as a beam loss monitor even without the screen inserted.

The CpFM system was also recently tested, showing excellent agreement with OTR-PMT and SEM in tracking spill oscillations at low frequency. Given its higher photon yield and the limited time dedicated to its optimization so far, its potential for high-frequency measurements is significant.

Further tests are scheduled before the end of the 2024 run, involving heavy-ion beam measurements and validation of the OTR-PMT at higher bandwidths, specifically at 200 MHz and 800 MHz.

In the long term, methods compatible with an increased bandwidth up to 10 GHz are under investigation. In this context, Cherenkov measurements should be sufficiently fast offering a higher photon yield with respect to OTR, under the requirement of the design of a new -ultra-fast- DAQ.

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