FAST SPILL MONITOR STUDIES FOR THE SPS FIXED TARGET BEAMS

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Abstract

At the CERN Super Proton Synchrotron (SPS) the 400 GeV proton beam is supplied to the fixed target experiments in the North Area facility (NA) via a slow extraction process. The monitoring of the spill quality during the extraction, lasting 4.8 seconds with the present SPS setup, is of high interest for minimising beam losses and providing the users with uniform proton-on-target rates. The monitor development challenges include the need for detecting, sampling, processing and publishing the data at rates ranging from few hundred Hz to support the present operation to several hundreds of MHz to serve future experiments proposed within the Physics Beyond Collider (PBC) program. This paper gives an overview of the ongoing studies for optimizing the existing monitors performances and of the R&D dedicated to future developments. Different techniques are being explored, from Secondary Emission Monitors to Optical Transition Radiation (OTR), Gas Scintillation and Cherenkov detectors. Expected ultimate limitations from the various methods will be presented, together with 2022 experimental results, for example with a recently refurbished OTR detector.

SPS SLOW EXTRACTION

The main physics program at the CERN SPS relies on the delivery of 400 GeV protons to the NA fix target experiments. As illustrated in Fig. 1, this is achieved by a 4.8 s third integer slow extraction process [1] at the end of the SPS *fix target beam* cycle, lasting about 10 s from first injection to flat top. Among the parameters for assessing the spill quality, providing the experiments with a constant flux of protons on target during the spill is of paramount importance for the SPS physics program. For this purpose, the SPS 200 MHz RF system is disabled at the end of acceleration with the aim of extracting fully de-bunched beams.

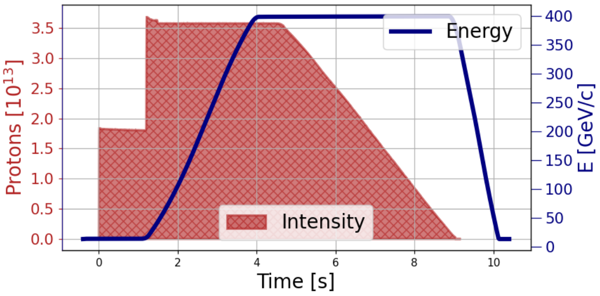

Figure 1: SPS Fix Target beams cycle.

Table 1: Key Parameters of Interest for the SPS Spill Monitors Requirements

Parameter	Value or Range	Comment
Spill Duration	4.8 s	present operation
	1 s	future, e.g. PBC
Beam Intensity	1 - 400 × 10^{11} p	
Spectrum Harmonics of Interest	50 Hz, 100 Hz	e.g. Noise, PC ripples
	43.86 kHz	SPS 1^{st} and 2^{nd} Harmonics*
	476 kHz	PS 1^{st} Harmonic**
	200 MHz	RF capture
	800 MHz	RF long. blow-up
	10 GHz	Future, e.g. PBC

* the SPS circulating beam structure includes 2×10 µs injections, the *abort gap* for the dump kickers rise

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

Therefore, measuring the beam current fluctuations at high frequencies during the spill in the transfer line from the SPS ring to the targets is of primary interest. Spill monitors can then provide signals for feed-back or feed-forward systems to equipment, such as RF cavities or magnet power converters, that are typically identified as possible sources of beam intensity fluctuations [2–4]. Table 1 summarises key parameters relevant for the spill monitors functional specifications.

SPS FAST SPILL MONITORS

From the parameters presented in Table 1, one can summarise the main challenges for spill monitoring as follows:

- monitoring beam currents ranging from few nA (1 × 10^{11} p in 4.8 s) to ≈1µA (4 × 10^{13} p in 1 s)
- by design the particles are un-bunched, standard electromagnetic beam position monitors and current transformers are not suitable
- to support the SPS slow extraction operation and optimisation, the overall monitor bandwidth must cover from very low frequencies to the several hundreds MHz, thus requiring *fast* spill monitors to identify the presence of (unwanted and normally relatively small) residual time structures from the SPS RF.

The SPS is now equipped with three *fast* spill monitors, based on independent measurement techniques and data

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acquisition systems, installed at different locations in TT20 beam line from the SPS to the targets.

Secondary Emission Monitor (SEM)

Apart for a limited number of beam imaging systems, all the diagnostics for beam position, transverse size and intensity in the NA primary lines is based on Secondary Emission Monitors (SEM)[1]. They consist of very thin (normally 12 µm) Titanium or Aluminium foils, or bands of different width and filling factor. The measurement relies on counting the secondary electrons generated by the primary protons traversing the foils/bands. The Secondary Emission Yield (SEY)[2] is few 10^{-2}.

One of the SEM monitors is equipped with a relatively fast amplifier (≈ 10 MHz BW). A low pass filtering (≈ 1 kHz) is necessary to minimise out-of-band noise and improve on signal-to-noise ratio. The amplifier output is digitised in the surface at a maximum rate of 200 kHz. This is the only *operational* system available so far in the SPS, and in the past it has been used as direct feedback to magnet power supplies, mainly to suppress 50 Hz magnet current ripples. At the moment, the monitor is exploited via SW in feed-forward mode to compensate for 50 and 100 Hz harmonics.

Diamond Beam Loss Monitors

For many years now, polycrystalline diamond detectors [6, 7] have been used as Beam Loss Monitors (dBLM) at CERN. They consist of synthetic diamond sensors, grown via a chemical vapour deposition (CVD) process, with a size of 10 × 10 mm and a thickness of 500 µm. They are normally placed few cm outside of the beam pipe, in strategic locations known to suffer from high beam losses, like beam injection and extraction regions. Assuming the losses time structure is the same as the slow extracted beam intensity, dBLMs can be very well exploited as fast spill monitors. In the past, they proved to be able resolving the 200 MHz structure of the SPS physics beam losses [8].

Recently, two dBLMs were installed in the first part of the TT20 beam line. The DAQ is based on analog 40 dB pre-amplifiers in the tunnel and 650 MHz ADCs in the service area. The analog BW has a lower limit at about 25 kHz (analog electronics cut-off) and a higher limit of 500 MHz (FMC ADC) [9]. Figure 2 shows how they were already successfully used to study the residual presence of the 200 MHz harmonic [10]. This was achieved by subtracting the power spectrum measured without beam to the one measured with beam. By moving the acquisition window of about 2 ms (which is at the moment the limit in amount of data that can be transferred per spill) along the 4.8 s, it was also possible to study the harmonic evolution along the spill[3].

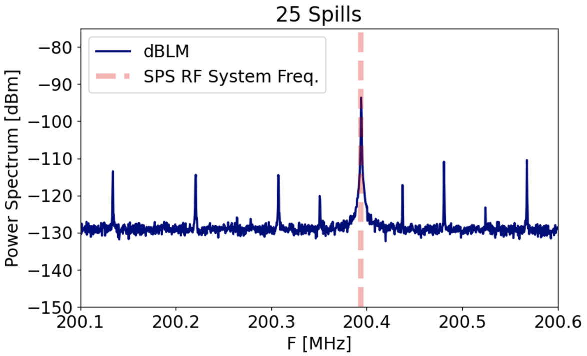

Figure 2: SPS beam power spectrum around the SPS 200 MHz nominal frequency, as measured by one of the TT20 dBLMs over a 2 ms chunk of the spill.

Optical Transition Radiation (OTR) - PMT System

The detection of OTR generated by charged particles traversing thin foils is very often implemented as an imaging system for transverse beam size measurements. When OTR was developed for the first time at the CERN SPS [11], OTR photons were measured by a Photo Multiplier Tube (PMT) and successfully served ed as *fast* spill monitor. Such a detector is intrinsically fast. The photon's emission can be considered as instantaneous, and the overall monitor BW would then be limited by the PMT rise and decay times and its readout electronics.

In 2021, an existing installation in the SPS TT20 line was refurbished with a new (movable) Titanium screen, a fast PMT [12] (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. At the moment the signal digitisation is done via a fast oscilloscope (500 MHz analogue BW, 5 GS/s, 2 GS of memory). The detector layout overlaid on a picture of the present installation in TT20 is shown in Fig. 3.

Table 2 summarises a simulation performed to estimate the expected number of photons at the PMT photo-cathode. For a SPS physics beam of 3×10^{13} protons/spill, the calculations yield to about 15 photons/ns collected at the photo-cathode, which is considered suitable for monitoring at high rate (e.g. at 200 MHz as proposed.

The new system was successfully commissioned in 2022. From the beginning it was possible to reconstruct the spill intensity (see section below for comparison to the SEM detector) and monitor the beam power spectrum at least up to 200 MHz (see Fig. 4) even with the OTR screen in the retracted position. This suggests that the PMT detector, placed at ≈ 1 m from the beam axis, is sensitive to beam losses. Indeed, preliminary studies based on scanning the

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[1] A recent, general, overview is included in [5]

[2] i.e. the probability of an electron to be emitted for a 400 GeV proton entering or exiting a Titanium or Aluminium surface

[3] A plot about this is included in the oral presentation associated to this contribution.

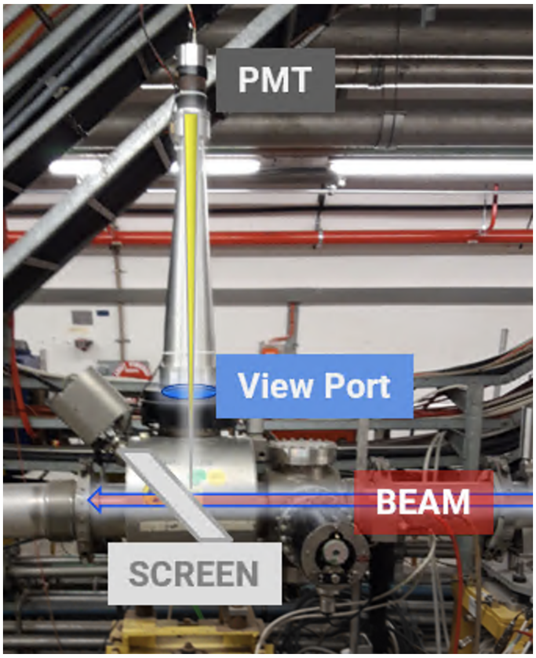


Figure 3: SPS OTR-PMT in the SPS TT20 beam line.

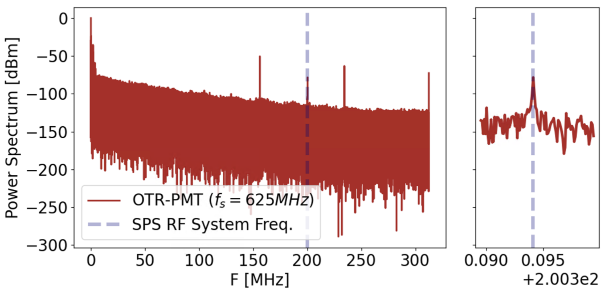
Table 2: Input parameters and main results of the simulation for the OTR-PMT optical system (see Fig. 3).

Input	
Protons Lorentz factor	$\gamma = 480$
OTR source ∅ (on foil)	5 mm
Source wavelength	550 nm
Foil - PMT distance	1 m
PMT photo-cathode acceptance (= top ∅ of the cone in Fig. 3)	40 mm
Output	
# of photons (500 nm$\leq \lambda \leq$600 nm)	3.78×10^{-3} ph/p
Photons collection at photo-cathode	61%

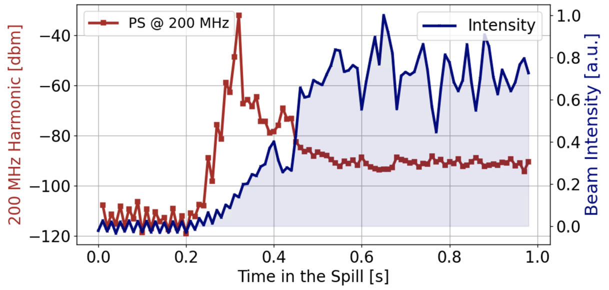
PMT voltage with the screen IN and OUT evidenced a signal gain with screen IN of only about 30 % to 40 %.

FAST SPILL MONITORS COMPARISON

The fast spill monitors based on Secondary Emission and OTR-PMT could be compared while measuring the same extracted beam, of $\approx 3 \times 10^{13}$ p/spill). A first example is shown in Fig. 5. While measuring the 4.8 s spill, the sampling frequency was set to 50 kHz. for the SEM and 1 MHz for the OTR-PMT. The data was then integrated off-line in bins of 1 ms for both monitors. The top plot demonstrates the excellent agreement in measuring the spill intensity envelope. The bottom plot highlights the capability for both instruments to identify low frequency harmonics, like the 50 and 100 Hz known to originate from noise in the magnets power supplies, and to affect the spill intensity. A second example, in Fig. 6, shows that the agreement between the two monitors is still excellent while looking at 50 kHz data.



(a) Left: Harmonics calculated over a 10 ms time window. Right: zoom around the SPS RF frequency at 200 MHz



(b) Evolution of the beam power measured at 200 MHz during the first part of the spill with the relative beam intensity extracted from the total PMT signal amplitude. Each point corresponds to a 10 ms integration time.

Figure 4: Example of SPS slow extracted beam power spectrum, measured with the OTR-PMT system.

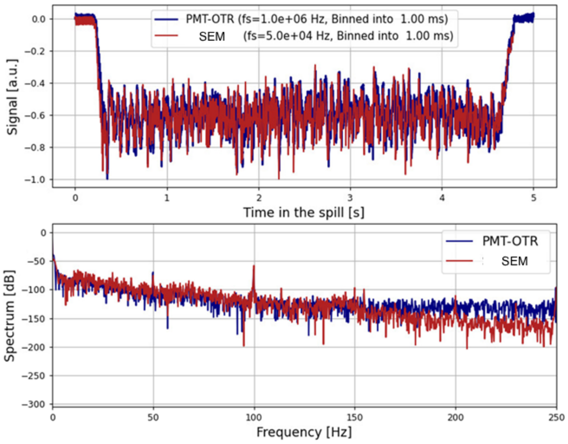


Figure 5: SEM and OTR-PMT detectors comparison in time and (low) frequency domain.

CONCLUSION AND OUTLOOK FOR FUTURE DEVELOPMENTS

Existing SPS Systems

Secondary Emission Monitor The SEM monitor at the beginning of TT20 is very robust and remains for the moment the only fully integrated spill monitor into the SPS control system and used operationally to minimise frequency ripple magnet power supplies. An upgrade of the in-vacuum parts of the monitor is foreseen, as this part is suspected to be a source of high noise in th system.. The DAQ will also

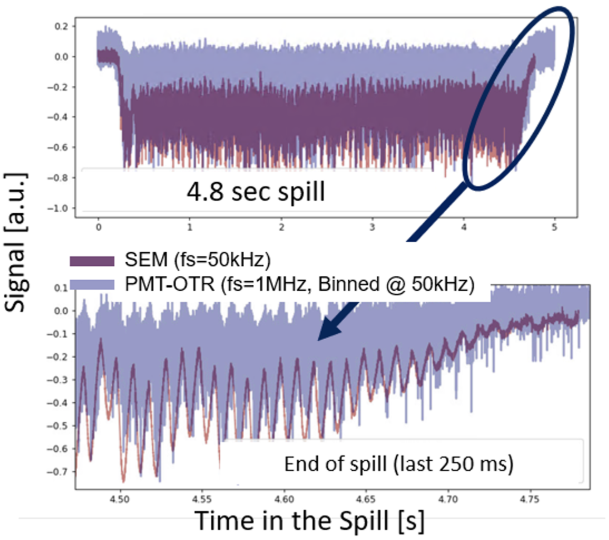


Figure 6: (top) SEM and OTR-PMT detectors comparison at 50 kHz acquisition rate, (bottom) zoom.

be upgraded to ensure higher analogue BW (~10 MHz max) and sampling rate.

Diamond BLM monitor dBLMs proved to work well, especially to study high frequency (up to 300 MHz) spill fluctuations. Their main limitations are signal-to-noise ratio and the management of the data acquired at 650 MS/s, for which only a portion of the spill (few ms) can be stored during each SPS cycle. Diamond BLMs will certainly continue to be exploited operationally as fast spill monitors and for cross calibration of other instruments.

OTR-PMT Monitor The prototype OTR-PMT detector was successfully commissioned with beam in 2022 and its performance were fully bench-marked with the SEM monitor up to 50 kHz. The dtectioon seet-up will be modified moving the PMT away from the beam line such that it will not be sensitive to beam losses. In that configuration, it is expected that the PMTs bias voltages can be increased to further improve on signal-to-noise ratio.

With the present DAQ architecture, the overall BW is limited to ≈500 MHz. In order to explore the GHz regime interesting for the CERN PBC program, we are studying the options of the signal digitisation in the SPS tunnel, and usage of optical link to transfer the data to the front-end computer.

New developments

Cherenkov proton Flux Monitor (CpFM) In 2016 - 2019, a new proton flux detector was developed by the UA9 collaboration [13] in the framework of the *crystal-assisted* slow extraction studies. The monitor (see Fig. 7) is based on a fused silica bar inserted on demand into the proton beam. The bar, acting as Cherenkov radiation source and light-guide, is coupled via a vacuum tight view port to an optical fibre bundle, bringing the light to a photo-multiplier detector. A second bar, installed in the retracted position, was used for systematic background subtraction. The system was validated in the SPS ring, and later in the TT20 line. At this location, it was optimised to work as a fast spill monitor [14]. In 2018 the CpFM was successfully tested with a 2 GS/s, 500 MHz BW digitiser. The measured data were processed to extract the 200 MHz harmonic component from the beam signal.

As Cherenkov radiation provides a larger flux of photons compared to OTR, that system could be one of the candidates for very fast monitoring (e.g. in the > 1 GHz regime) required for future PBC experiments. The CpFM will soon be put back in operation equipped with a CERN standard detection systems similar to the one used for the OTR-PMT detector.

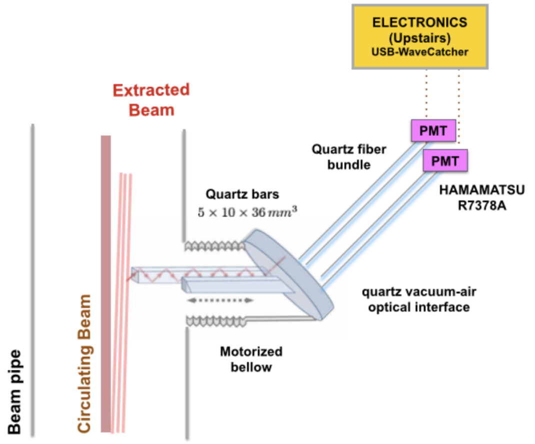


Figure 7: CpFM monitor layout (courtesy of F. Addesa).

Gas Scintillation detector For many years, the CERN Proton Synchrotron (PS) slow extracted beam to the East Area (EA) experimental lines is monitored by a gas scintillation detector. It is composed of a small chamber, separated from the upstream and downstream vacuum beam lines, fed with a constant flow of Nitrogen. The 24 GeV PS beam generates a gas scintillation (decay time ≈10 ns monitored by two PMTs (in coincidence to suppress background). The 10 ns analogue pulses are converted to NIM-standard (30 ns, −1 V) and sampled at 2 kHz. The suitability of this technique for the 400 GeV SPS beam is under investigation.

Timepix detector A novel fast spill detector technique could be based on the design of Timepix ionisation profile monitors [15] with the addition of focusing electrodes[4]. The detector response time (≤5 ns) and preliminary calculations on the expected ionized electrons yield makes this technique potentially exploitable for measurements at least up to 200 MHz.

REFERENCES

[1] Y. Baconnier, P. Faugeras, K. H. Kissler, B. de Raad, and W. Scandale, "Extraction from the cern sps," *IEEE Transactions on Nuclear Science*, vol. 24, no. 3, pp. 1434–1436, 1977. `doi:10.1109/TNS.1977.4328969`

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[4] Inspired by the development described in [16]

[2] F. M. Velotti *et al.*, "Characterisation of SPS Slow Extraction Spill Quality Degradation," in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 2403–2405. `doi:10.18429/JACoW-IPAC2019-WEPMP034`

[3] M. Pari, F. M. Velotti, M. A. Fraser, V. Kain, and O. Michels, "Characterization of the slow extraction frequency response," *Phys. Rev. Accel. Beams*, vol. 24, no. 8, p. 083 501, 2021. `doi:10.1103/PhysRevAccelBeams.24.083501`

[4] V. Kain *et al.*, "SPS Slow Extracted Spill Quality During the 2016 Run," in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 627–630. `doi:10.18429/JACoW-IPAC2017-MOPIK049`

[5] F. Roncarolo, "Status and plans for beam instrumentation for SX at CERN," presented at ICFA Mini-Workshop on Slow Extraction. `https://conference-indico.kek.jp/event/163/contributions/3160/`

[6] H. Frais-Kolbl, E. Griesmayer, H. Kagan, and H. Pernegger, "A fast low-noise charged-particle cvd diamond detector," *IEEE Trans. Nucl. Sci.*, vol. 51, no. 6, pp. 3833–3837, 2004. `doi:10.1109/TNS.2004.839366`

[7] E. Calvo Giraldo *et al.*, "The Diamond Beam Loss Monitoring System at CERN LHC and SPS," presented at IBIC'22, Kraków, Poland, Sep. 2022, paper TU2C2, this conference.

[8] B. Dehning, E. Effinger, H. Pernegger, D. Dobos, H. Frais-Kolbl, and E. Griesmayer, "Test of a Diamond Detector Using Unbunched Beam Halo Particles," CERN, Geneva, Switzerland, Tech. Rep., 2010. `https://cds.cern.ch/record/1258407`

[9] E. Effinger *et al.*, "A Prototype Readout System for the Diamond Beam Loss Monitors at LHC," in *Proc. IBIC'13*, Oxford, UK, Sep. 2013, pp. 182–185. `https://jacow.org/IBIC2013/papers/MOPC45.pdf`

[10] P. A. Arrutia Sota *et al.*, "dBLMs first results and MD planning," presented at CERN SLAWG meeting, 2022.

[11] J. Bosser, J. Mann, G. Ferioli, and L. Wartski, "Optical transition radiation proton beam profile monitor," *Nucl. Instrum. Methods Phys. Res., A*, vol. 238, 45–52. 23 p, 1984. `doi:10.1016/0168-9002(85)91025-3`

[12] Hamamatsu PMT R3377. `https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/etd/R2083_R3377_TPMH1227E.pdf`

[13] UA9 Collaboration. `https://home.cern/science/experiments/ua9`

[14] F. M. Addesa, "In-vacuum Cherenkov light detectors for crystal-assisted beam manipulations," PhD thesis, Rome University, Rome, Italy, 2018. `https://cds.cern.ch/record/2661725`

[15] J. W. Storey *et al.*, "First Results From the Operation of a Rest Gas Ionisation Profile Monitor Based on a Hybrid Pixel Detector," in *Proc. IBIC'17*, Grand Rapids, MI, USA, Aug. 2017, pp. 318–322. `doi:10.18429/JACoW-IBIC2017-WE2AB5`

[16] The LHCb-RICH pixel hybrid photon detector. `http://tilde-gys.web.cern.ch/~gys/LHCb/PixelHPDs.htm`