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THE SPS BEAM LOSS MONITORING SYSTEM RENOVATION PLAN

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Abstract

The Super Proton Synchrotron (SPS) beam loss monitoring (BLM) system at CERN, which has been operational for several decades, will be completely renovated during Long Shutdown 3 (LS3), encompassing detectors, cabling, and acquisition electronics. The upgraded architecture will adopt a design similar to the current Large Hadron Collider (LHC) BLM system, featuring front-end and back-end electronics housed in separate crates and connected via optical links, ensuring compatibility with the LHC upgrade scheduled around LS4. This paper presents an overview of the proposed architecture for the SPS ring and transfer lines, detailing the key components and expected improvements in performance, modularity, and reliability.

INTRODUCTION

The SPS, the second largest accelerator in the CERN accelerator complex, commissioned in 1976, has a rich and diverse physics programme, providing proton and ion beams to the LHC and to several fixed-target experimental areas such as AWAKE, HiRadMat and the CERN North Area [1, 2].

The BLM system at the SPS, operational for several decades, consists of 286 Ionisation Chambers (IC) distributed around the ring and an additional 144 more located along the various extraction lines (TT20, TT40, TT60) and experimental halls. The ageing and obsolescence of its components compromise maintainability and future operational performance. Consequently, a complete system upgrade is planned for LS3, encompassing detectors, acquisition electronics, and all associated cabling. The proposed architecture has been designed for compatibility with the LHC upgrade planned for LS4 and to optimise BLM system homogeneity across CERN machines. It will deliver substantial improvements over the legacy system, such as shorter acquisition periods, wider dynamic range and sensitivity, reduced beam dump request latency, enhanced remote diagnostics, and improved signal integrity through shorter cables and optimised cabling strategy.

DETECTOR RENOVATION

The legacy SPS detectors will be replaced by gas ionisation chambers based on the LHC design (Fig. 1). Both designs operate on the same principle but differ in dimensions, gas volume, and operating parameters.

The legacy SPS detectors are 278 mm long and 114 mm diameter cylindrical chambers equipped with 31 circular parallel plates spaced 5 mm apart. They enclose approximately 1.1 litres filled with air at room temperature and 1.1 bar pressure and biased at 800 V [3–5].

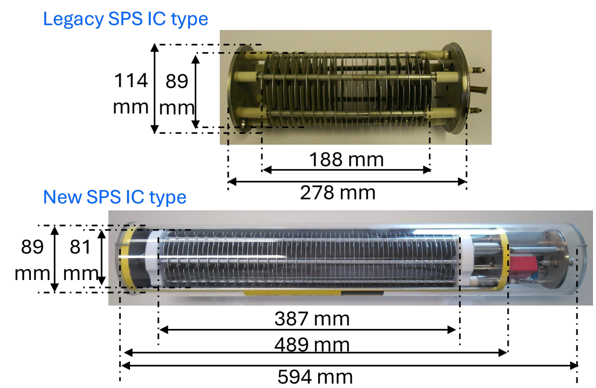

Figure 1: Comparison of legacy and new SPS detectors.

On the other hand, the new detectors are 489 mm long and 89 mm in diameter, with a sensitive volume of 1.5 litres filled with N_2 at 1.1 bar and operated at 1.5 kV. The internal structure consists of 61 parallel aluminium electrodes separated by 5 mm. The respective conversion factors are 36 µC/Gy and 54 µC/Gy [6], thus yielding an approximate 50 % increase in sensitivity, primarily from the larger gas volume.

Detector Distribution

To ensure a smooth migration of one of the SPS's most critical machine safety systems, it is proposed that both systems will operate in parallel until the complete commissioning of the new system. This strategy will enable a systematic comparison of the loss maps evolution, distinguishing between changes due to machine configuration and those attributable to the BLM system upgrade.

To achieve this, the new detectors will be placed on the existing supports using high-density polyethylene insulators to accommodate the detector size differences and enhance the insulation to the machine earth. The old detectors will be mounted on clamp kits, resulting in just a few cm displacement compared to pre-LS3 positions. These clamp kits (Fig. 2) can be easily deployed and removed, accommodate the diversity of existing supports, and do not require any additional drilling in highly activated regions.

However, this arrangement will not be feasible everywhere. In the legacy system, detectors in the arc regions are alternately positioned at beam height in the space between magnets, in front of the defocusing quadrupoles (QD), or beneath the first dipole downstream of the focusing quadrupoles (QF). The new detectors, being longer, will not fit below the dipoles. Moreover, this asymmetric layout causes measurements along the arcs to exhibit a triangular

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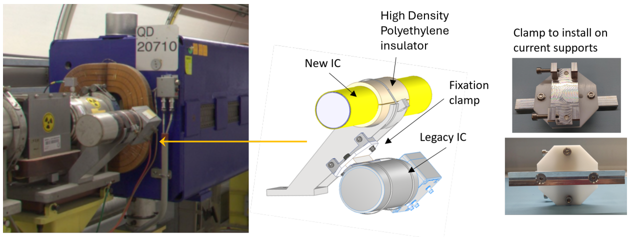

Figure 2: Installation of new and legacy detectors.

waveform, due to the shielding effect of the dipoles. FLUKA simulations suggest that placing the new detectors at beam height in the inter-magnet space before each quadrupole will improve measurements uniformity [7–10].

ACQUISITION ELECTRONICS

In addition to the differences in detector sensitivity and distribution, the most significant changes to be expected are due to the upgrade of the acquisition hardware.

In the legacy system, the currents generated by the ionisation chambers are transmitted via coaxial cables over hundreds of metres to analogue integration cards installed in 17 VME crates located in surface buildings. On each card, the current from up to 8 detectors is integrated through configurable capacitor values. A multiplexer then sequentially selects each channel, routing the signal to a variable-gain amplifier, whose output is digitised by a 12-bit ADC. Modules with different capacitors are used to adjust the sensitivity and dynamic range required at each machine location, and different gains can be configured per beam cycle. For standard arc channels, using 1 µF capacitors, the achieved resolution is approximately 4.88 nC/bit, and about 10 times coarser for channels optimised for higher dose rates. Effectively, only 11 bits are utilised, since detector currents are always positive, providing a maximum theoretical dynamic range of approximately 66 dB.

Each channel is acquired every 5 ms, and 5 parallel sliding window sums (a.k.a. running sums), using different lengths, are computed at software level and published periodically. If measured losses exceed predefined machine-protection limits, a beam dump request is issued. For that, two types of interlock logic are implemented: critical channels in some long-straight sections (LSS) use hardware comparators to trigger dump requests within microseconds, whereas less critical channels rely on software-level comparison of the sliding window sums, resulting in millisecond-scale latencies.

The new front-end electronic card, known as BLEIC, is based on a custom radiation-tolerant BLM Application Specific Integrated Circuit (BLMASIC) developed in cooperation with the CERN EP-ESE group. It implements a Fully Differential Current to Frequency Converter (FDFC), providing a very large dynamic range, complemented in parallel with a Wilkinson 9-bit ADC, which enhances the resolution between FDFC pulses with 10 µs periodicity up to 22-bits [11]. The principle of combining ADC values with FDFC pulses is already used in the BLM system deployed at CERN PS, PSB and Linac4, and is described in [12]. Preliminary characterisation measurements of the new design have demonstrated a resolution of 1.5 pA for slow varying currents; an accuracy error < 10 % in the range of 60.1 µA to 1 mA at the maximum sampling rate; and a deviation below 0.5 % at 3 kGy TID [13, 14]. This radiation tolerance allows placing the electronics in the proximity of the detectors, reducing the cable lengths and thus mitigating signal degradation, noise and interference issues.

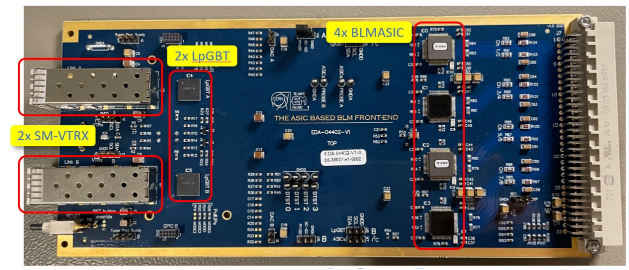

Figure 3: Prototype of the new BLM SPS acquisition card based on custom radiation-tolerant ASICs.

As shown in Fig. 3, each card is equipped with 4 BLMASICs, enabling acquisition of up to 8 channels in parallel. Two CERN Low Power Gigabit Transceiver (LpGBT) serializers connect to all the ASICs, providing redundant data transmission. Each LpGBTs interfaces with an optical VTRx transceiver [15], which sends loss measurements and system diagnostics via optical links to the surface for further processing. The bi-directional links also enable additional remote-control features.

SYSTEM ARCHITECTURE

In the SPS ring, the new infrastructure will adopt a more distributed structure than the legacy system: front-end crates will be located underground, while back-end crates will be placed in surface racks, both communicating through standard and radiation-tolerant fibres (Fig. 4).

To process the detectors in the arcs, 6 front-end mini-racks per sextant will be installed beneath dipole magnets, at positions selected to minimise radiation exposure, based on previous measurement campaigns. Crates processing the LSS detectors will be deployed in racks located at the bottom of the shafts, where radiation levels are lower. Four redundant radiation-resistant, single-mode (RRSM) fibres will connect each BLEIC card to an optical fibre star-point rack, also placed at the bottom of each sextant access point. From there to the surface back-end crates, conventional single-mode fibres will be used.

Each arc mini-rack houses an optical panel, a 19" three-fan cooling module, and a 19" Europa-format crate equipped with the following radiation-tolerant modules (Fig. 5):

- BLEIC: performs the acquisition of the ionisation chamber current, as described in the previous section.

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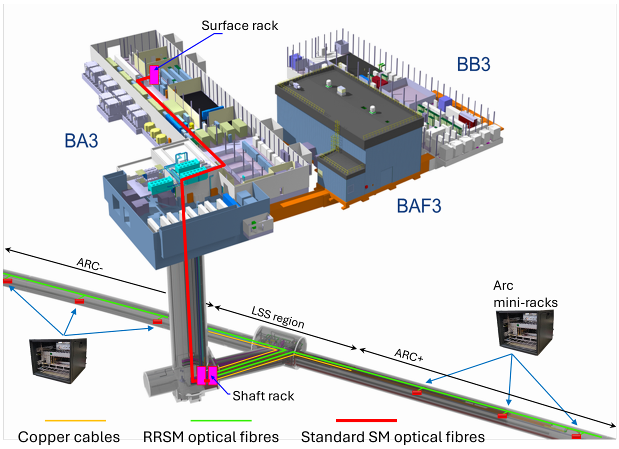

Figure 4: Electronics and cabling distribution of the SPS BLM system in one of the 6 SPS sextants.

- BLEACCM: provides local diagnostics via a portable tester device. In the LHC upgrade version, this card will be replaced by a BLEACCR, enabling remote diagnostics and control when connected to a WorldFIP fieldbus using a FMC-NanoFIP agent card [16].
- BLEIPU: contains the AC transformers and monitoring circuitry to survey the voltages of the detector bias feedback and the transformer winding outputs.
- BLEPSU: generates all the DC power supply voltages required for the acquisition and control cards [17].

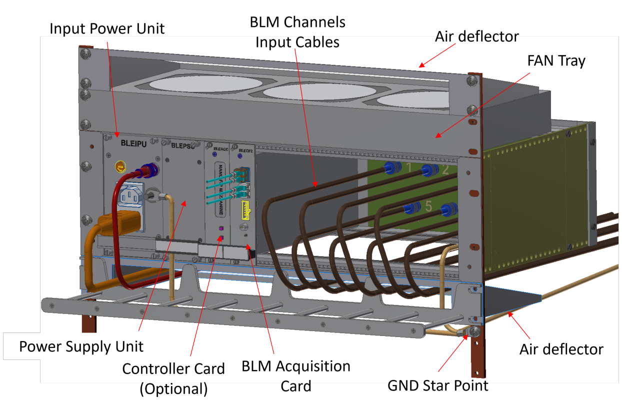

Figure 5: 3D model of the equipment installed at each arc mini-rack.

Surface electronics will consist of a Wiener VME64x crate equipped with the following modules:

- Up to 16 BLM Threshold Comparator cards (BLETC) implemented on the CERN Beam Instrumentation VFC-HD platform [18]. Each communicates with up to 2 BLEIC cards (thus up to 16 detectors), integrates the loss measurements of every channel over multiple parallel running sums (ranging from 10 µs up to several seconds) and compares the results against predefined interlock limits.
- A BLM Combiner and Survey (BLECS) card, which surveys and controls the high-voltage power supply, terminates the two backplane beam permit lines daisy-chained through the BLETC cards and triggers a beam interlock request to the Beam Interlock Controller User interface (CIBU) [19, 20] if any BLETC breaks the continuity of these lines.
- A MEN A25 Single Board Computer for running all the real-time services in charge of publishing the data and control.
- A timing receiver module based on a White Rabbit Event Node module (WREN) [21].

Surface racks will also house crates supplying the detectors bias voltage, via two redundant Heinzinger NCE 300 high-voltage cassettes [22]. The new system will make it possible to periodically superimpose a small modulation on the detector bias voltage. This technique, already used in other deployed CERN BLM systems, and applied in beam absence, allows the detection of misbehaving detectors and electronics or the degradation of cables and connectors, and has become a fundamental diagnostic tool [23].

Detectors in SPS extraction lines and experimental halls will be connected, instead, to the acquisition hardware deployed in the CERN injector complex during LS2 and described in [24]. As those front-end crates are not radiation-tolerant, they will be positioned exclusively in surface racks or galleries with negligible radiation exposure.

Cabling

Particular attention was given to cable routing with strategies tailored to each region. Where distances between detectors and electronics are long, as in the LSS, short coaxial cables connect detector signals to a nearby interconnect box, where they are grouped into a multi-wire cable that then extends until the shaft rack. Where electronics are in the vicinity of the detectors, as in the arcs, detectors are connected directly to the acquisition crate via short coaxial cables. In addition, radiation-resistant cables are used on the more exposed segments, while standard cables are employed for long distances. As for detector high voltage bias, it is distributed from surface via several trunks. Every 5 to 6 detectors, a junction box connects one of these trunks with a cable drop, linking the detectors in series, with the last connection routed back to the acquisition crate to enable remote bias voltage supervision and control.

CONCLUSIONS

During LS3, the SPS BLM system will undergo a complete renovation, significantly enhancing performance and maintainability. The upgrade will deploy several hundreds of 50 % higher sensitivity detectors, radiation-tolerant electronics offering 500 times faster acquisition rate and several orders of magnitude better resolution and dynamic range. It will also introduce advanced remote diagnostics and improved signal integrity transmission.

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