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SPS BEAM DUMP ENHANCEMENTS ON TRACKING AND SYNCHRONIZATION

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Abstract

During CERN's long shutdown 2 (LS2) at the Super Proton Synchrotron (SPS), the SPS Beam Dump System (SBDS) was displaced from point 1 to Point and at the same time further consolidated controls-wise. This made it possible to migrate the Beam Energy Tracking system (BETS) and the Trigger Synchronization system (TSU) already operational on the LHC beam dump (LBDS) towards the SPS. The challenge encountered in this migration was the change to a Pulse-to-Pulse modulation (PPM) with much faster cycles in the SPS in comparison to the LHC. This paper describes the modification of both as well as the automatic arming sequence put in place, including the interactions with the SPS injectors, the beam revolution frequency, and the Beam Interlock System (BIS).

BACKGROUND

SPS Beam Dump System (SBDS)

Uncontrolled beam loss in the SPS will cause thermal and radiation damages of machine components as well as induced radioactivity. For this reason an internal beam dumping system was designed and installed in the seventies [1]. It uses fast pulsed magnets (kickers) to dump the beam in one SPS revolution (23.1 µs) onto an absorber block (TIDVG). The kickers and absorber block are able to dump the beam at all momenta up to 450 GeV. The extraction system today consists of six kicker magnets which provide the beam extraction and the energy dilution 5 [2]. Three horizontal kicker magnets (MKDH) deflect the beam horizontally with a rise time of about one full SPS revolution. They provide a horizontal sweep which dilutes the beam energy across the dump block. Three vertical kicker magnets (MKDV) provide a vertical deflection and thus extraction. The short rise time of 1.2 µs of the MKDV is responsible for the beam extraction. MKDV oscillates at flat top current which provides dispersion on the absorber block (Figure 1).

Trigger Synchronization Unit (TSU)

The aim of the TSU [3, 4] is to centralize all dump requests from various clients and to synchronize them with the Beam Revolution Frequency (Frev), which allows to rise the dump kickers in the 1.44 µs Beam Abort Gap and avoid spraying the beam around the dump region during the 1.2 µs MKDV rise time. The TSU is a safety critical element in the SPS. The system is composed of two redundant cards in independent chassis which monitors each other and react to every discrepancy.

Dump requests can be triggered by the following clients: Beam Energy Tracking System (BETS), Beam Interlock System (BIS), SBDS State Control and Surveillance System (SCSS), direct triggering (Early Dump), Frev loss or instability.

An important additional feature in the SBDS is that the TSU generates an Injection Permit towards the SPS Injection BIS while armed and releases it 20 µs before issuing the actual dump trigger to avoid any possibility to inject beam after triggering and thus disarming the SBDS. The TSU also forces it User Permit to the Ring BIS during arming sequence.

Initially developed for the LHC Beam Dumping System (LBDS), the TSU system has been adapted and modified to fit to the SBDS requirements. The gateware has been reshaped by exchanging the initial PLL-based design with a less complex counter-based one for the regeneration of the Frev, because the initial LBDS design based on PLL was not adaptable to the SBDS Frev. This new gateware is compatible with both LBDS and SBDS. The TSU requires to be armed at every cycle.

Beam Energy Tracking System (BETS))

The aim of the BETS [5] is to continuously survey that the SBDS MKDV and MKDH generator charge with relation to the machine momenta tracks all along the ramps, from injection to flat top. The BETS is a safety critical system which generates a dump request whenever one of the SBDS generator strengths is out of tolerance. The BETS on SBDS required modification from its implementation on LBDS, i.e allowing jumps between 14 GeV and 26 GeV beams when arming. This requires the BETS to wait for the charge of the generators to reach nominal strength during the arming sequence. On the SBDS, the BETS and TSU systems are tightly linked, while not on the LBDS. The BETS in SBDS, unlike the LBDS, must generate the references to the MKDV and MKDH high voltage power supplies (HVPS) via a dedicated DAC card. On LBDS, the generation of the generators charge references is done via the slow control Programmable Logical Controller (PLC) system that has a slow cycle time (100 ms). This is not an issue with long ramp-up of the LHC, but becomes a problem in the SPS with ramp-up of < 2 s.

SBDS ARMING SEQUENCE

The SBDS TSU and BETS require a tight arming sequence [6] which must consider all SBDS external and internal conditions, the SPS injection transfer line TT2 BHZ377 and BZH378 dipole magnets start and abort times, SBDS generators ramp-up to injection strengths, SPS beam revolution frequency (Frev) stability, SPS Ring BIS interactions and TSU injection permit to SPS Injection BIS [7] (Fig.2).

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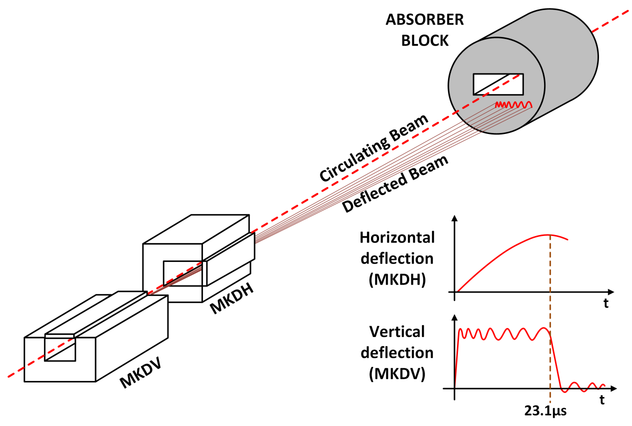

Figure 1: Principle of SPS Beam Dump.

The arming sequence is on-purpose not PPM (i.e. same timing/delays for all cycles) to simplify the configuration, diagnostics as well as post operation checks. SBDS being in ECA5 underground gallery is not easily accessible during operation and beam must be stopped if access is required for debugging. However, an SPS test mode has been created with all conditions but beam inhibited from PS.

Arming Sequence Considerations

The SBDS arming sequence must consider:

- All clients of the TSU (BIS, BETS, SCSS, Early Dump)
- The SPS Beam Revolution Frequency (Frev)
- TSU User Permit to the Ring BIS (TSU being actor and client of the SPS Ring BIS).
- Injection Permit to SPS Injection BIS to inhibit any possible injection if SBDS is not ready to pulse.
- Ramp-up of the MKDH and MKDV generators from lowest injection momenta (14 GeV) to LHC cycles injection momenta (26 GeV).

Arming Sequence Timing

The whole SBDS arming sequence is initiated by a single General Machine Timing (GMT) event, which is issued one second before the first beam occurrence. From calculations and simulations, the arming sequence must start at most 450 ms before first beam occurrence and lasts for 95 ms in total to give enough time for the BHZ to abort their ramp in time (350 ms before first beam occurrence) (Figure 3).

The TSU, BETS and BIS in the arming sequence are tightly interdependent; the BETS is both client and user of the TSU. When arming, the TSU forces to TRUE its "User Permit" (safe state input of critical equipment to the BIS) to the Ring BIS. Once the SPS Ring BIS loops are closed, the TSU releases its "inhibit tracking" signal to the BETS which in turn will start arming.

MKDV and MKDH generators references are generated by the BETS. The "inhibit tracking" from TSU, when active, sets the MKDV and MKDH references to the minimum injection momentum of 14 GeV. When released, the references are set accordingly to the machine momenta, which can be up to 26 GeV at injection for LHC cycles. The BETS must

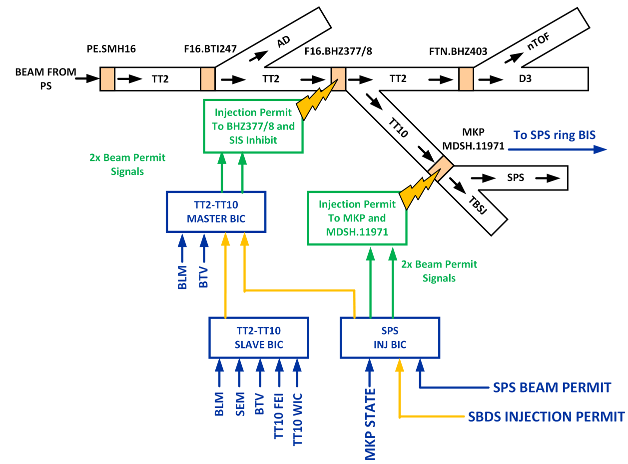

Figure 2: Architecture for the SPS injection BIS.

then wait 91 ms until the generators charge to the nominal strength before starting tracking. Once tracking, the BETS returns a permit to the TSU. At this time, if no interlock happened, the TSU finishes it arming sequence and the SBDS is armed. Injection Permit to SPS Injection BIS can then be asserted and beam injected in the SPS (Figure 4).

There are two sequence results possible:

- When Ring BIS and TSU User Permit are TRUE, the Inhibit tracking is released by the TSU and the BETS can be armed. After 91 ms, if no tracking fault is detected, the BETS returns its permit to the TSU which can be armed.
- In the case the BIS is opened, or the TSU User Permit is FALSE (e.g. no BRF, SCSS not ready), the Inhibit Tracking is not released by the TSU and the BETS cannot be armed and keeps the strength references at 14 GeV. The BETS permit to the TSU is not asserted and the TSU will not arm.

INTERACTIONS WITH OTHER SYSTEMS

SBDS Interactions with SPS Ring BIS

Unlike the TSU at the LBDS, the SBDS TSU is both client and user of the SPS Ring BIS, which does complicate the arming sequence of the TSUs. Once the arming event is received, the TSU system forces the User Permit to the BIS Ring to TRUE until the end of the arming sequence which lasts 95 ms. During this period, the BIS Ring loops close if no other user permit is false along the machine. At the end of the arming sequence, the TSU evaluates the Ring BIS. At this moment, two scenarios are possible:

- If Ring BIS is closed, TSU keeps its User Permits to TRUE if no other TSU client is faulty (BETS, BRF, SCSS) which results in the TSU to be kept armed until a fault or dump request occurs. In the case one of the TSU clients is faulty, but Ring BIS is closed, the TSU releases its User Permit which results in the BIS Ring to become faulty due to TSU at the end of the arming sequence.

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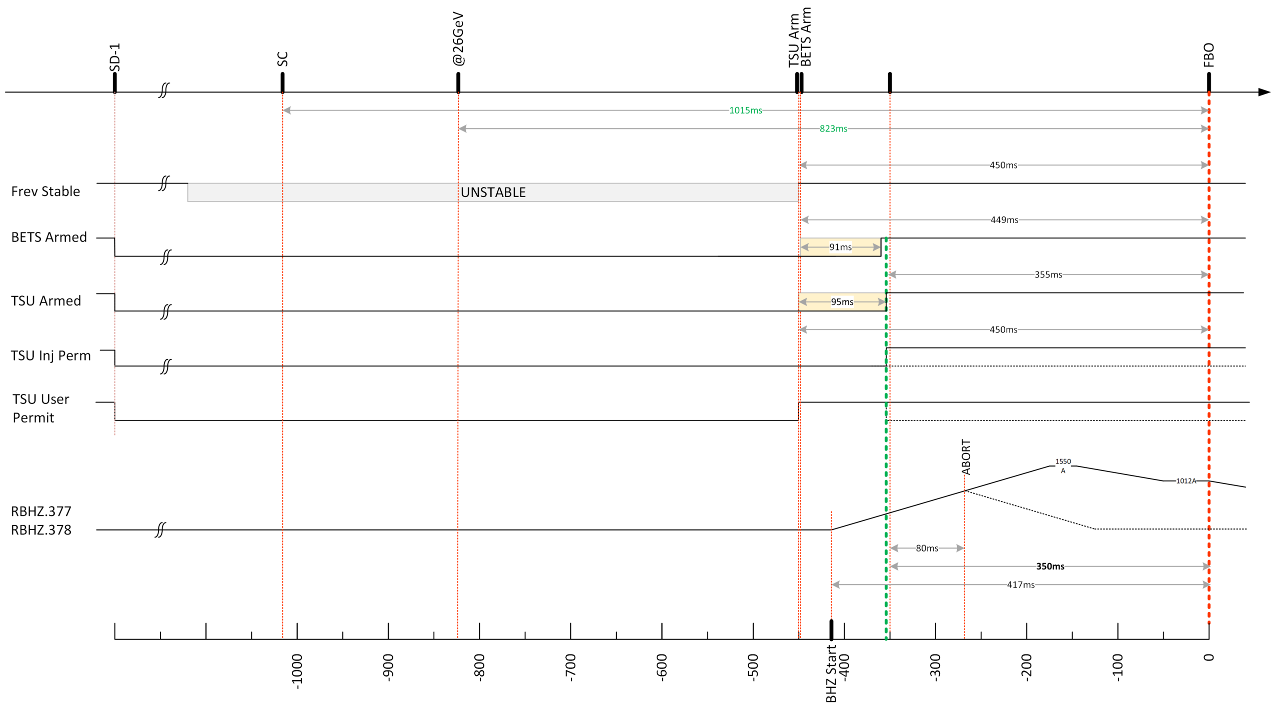

Figure 3: 26 GeV beams SBDS arming sequence.

- If Ring BIS is opened, TSU releases the User Permit to the BIS Ring at the end of the arming sequence.

SBDS Interactions with SPS Injection BIS

The beam transfer from the PS to the SPS is made through the TT2 and TT10 transfer lines. At the end of the TT10 line the SPS injection kicker (MKP) provides the final deflection for the injection into the SPS. During Long Shutdown 2 (LS2), the SBDS has been relocated from LSS1 to LSS5 [2] and the injection permit is now managed by a dedicated Injection BIS. In addition, after LS2 LIU beams can reach damage thresholds of the SPS Injection Beam Stopper (TBSJ) following repetitive shots. The SBDS Injection Permit is connected to this new Injection BIS via a dedicated Beam Interlock Controller Fibre board (CIBF) link [7]. For the TSU/BETS arming sequence, the situation is the same as for the Ring BIS, except that the Injection Permit sent by the TSUs are not forced TRUE during arming sequence but kept to FALSE state until the end of the arming sequence. At the end of the arming sequence, there are two scenarios:

- TSU Armed: the Injection Permit is set to TRUE until a fault occurs. The Injection Permit is released (FALSE) immediately when a fault or beam dump request occurs, but the beam dump event is issued at least 20 µs later by the TSU to avoid any possible injection before the SBDS pulses (20 µs delay + synchronization to Frev).
- TSU not armed: in the case the TSU cannot be armed due to internal or external factors, the Injection Permit is kept FALSE, inhibiting all possible injections. This will inhibit prepulses on SPS Injection Kickers (MKP), abort ramps on BHZ377 and BZH378 dipole magnets and release permit to MSDH.11971 corrector dipole magnet.

BHZ Ramp Abort

To dump the beam after the Proton Synchrotron (PS) at the TT2 transfer line level (dump D3) before entering TT10 transfer line, the F16.RBHZ377 and F16.RBHZ378 power converters will receive an injection inhibit signal from the TT2-TT10 Master Beam Interlock Controller (BIC) to set their reference currents to 0 A which avoid the beam to be deflected into TT10.

- Beam is permitted: the normal function of the power converters F16.RBHZ377 and F16.RBHZ378 will be executed.
- Beam is not permitted: a "function abort" timing event will be issued. This will instruct the power converter to ABORT the existing function and go to 0 A current.

The BHZ (FT16.BHZ377/8) evaluates the Injection BIS 350 ms before first beam occurrence, including the 80 ms overhead to communicate the timing event to the FGC. The TSU and BETS must be armed at least at a milestone of 355 ms (considering a margin of 5 ms) [8]. If the TSU cannot be armed for any reason, the SBDS Injection Permit is never sent TRUE to the SPS Injection BIC and the BHZ aborts its ramp and falls back to 0 A before first beam occurrence.

Frev Stability Before Injection

The TSU requires the Frev to be stable at the start of the SBDS arming sequence. Thus, it has been required to have

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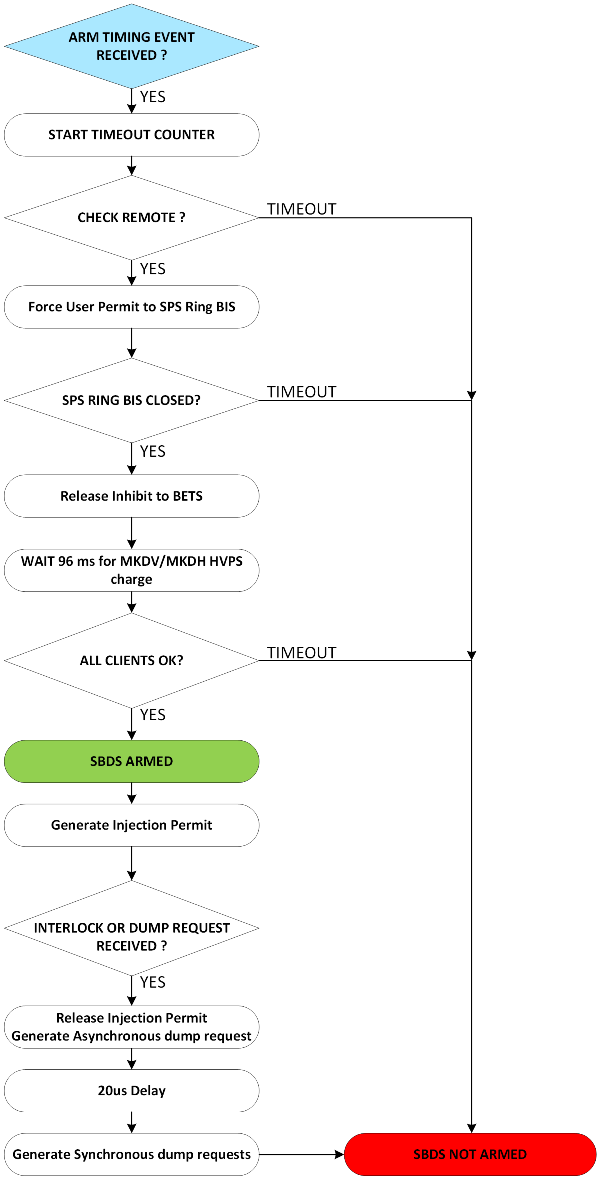

Figure 4: TSU Arming Sequence Flow.

a stable Frev after resynchronization at least 450 ms before first beam occurrence which is the minimum time to start arming to allow BHZ abort. The TSU regenerates internally the Frev using a counter-based system which uses a low pass filter to check for spurious jumps of the Frev as well as tight tolerances on the minimum and maximum values of the Frev, as well as tight timing interlock thresholds. The regenerated Frev (RBRF) is delayed internally in the TSU by an adjustable value to be synchronized with the beam abort gap (DRBRF). The DRBRF is the signal that issues the actual dump trigger upon request.

SBDS SUCCESSFUL ARMING AND DUMP SEQUENCE

On a successful arming sequence, the TSU gets armed and gives its User Permit to Injection BIS and keep it TRUE until a fault or dump request event occurs (Figure 5). In that case, the TSU outputs an synchronous dump request immediately when the event occurs. An external 50 µs hardware delay (more than two SPS turns) is added to this asynchronous dump request which is sent to the SBDS retrigger line for safety in the case of loss of the synchronous triggering path. The TSU does not trigger immediately on the synchronous dump requests. An internal 20 µs delay is added to the incoming dump requests so that the Injection Permit can be released, avoiding any injection after a dump. This delay corresponds to the time of flight of the signal plus delays in the hardware from SBDS (SPS point 5) to the injection BIC in BA1 (SPS point 1). The delayed dump requests are then synchronized with the TSU internally regenerated BRF, which may add up to 23 µs more delay. This means that the synchronous beam dump requests are issued between 20 µs and 43 µs after a fault or dump request event, depending on when this fault occurs w.r.t. the beam abort gap.

SBDS ARMING FAULT SEQUENCE

If the SBDS cannot be armed for any reason, the TSU must output a trigger to discharge the generators at the end of the arming sequence. The generators may be charged at 26 GeV and require a trigger to discharge to minimum injection momenta of 14 GeV for the next cycle. An output of the TSU is dedicated for this purpose (Arming Fault Trigger). This pulse is asynchronous to the Frev. When disarmed, the TSU sends to the BETS the Inhibit Tracking which sets the strength references back to minimum (14 GeV).

SBDS DIAGNOSTICS TOOLBOX

Tools were developed to help to identify and diagnose issues related to the SBDS TSU and BETS. Due to fast cycles transitions, such tools are of high importance. An Internal Post Operational Check (IPOC) digitizer [9] has been deployed to get all the important SBDS triggers and TSU signals at dump time. Using this tool, the experts can easily identify the source client of each dump, as well as spurious problems on TSU clients. As an example, in 2023 a weak BIS fiber optics was identified this way.

Python scrips have been developed to get statistics of the beam dumps sources as well as to identify possible issues on the SBDS and its components. In 2022, it identified a spurious problem on a Pulse Forming Network of MKDV out of $< 1\,\%$ of the total number of dumps.

An online cycle-to-cycle viewer, developped with PyQt displays the dump source and any dysfunction of the SBDS to help the operators and experts to diagnose faster.

CONCLUSION

Deployment of the BETS and TSU on the SBDS was complex and required several modifications and enhancements, principally due to the fact that the SPS is a PPM machine with much faster cycles than LHC. In the LHC, the arming of BETS and TSU is slow by design. The SBDS requires an automatic arming sequence with numerous factors to be taken into account, as the interactions with Injection and

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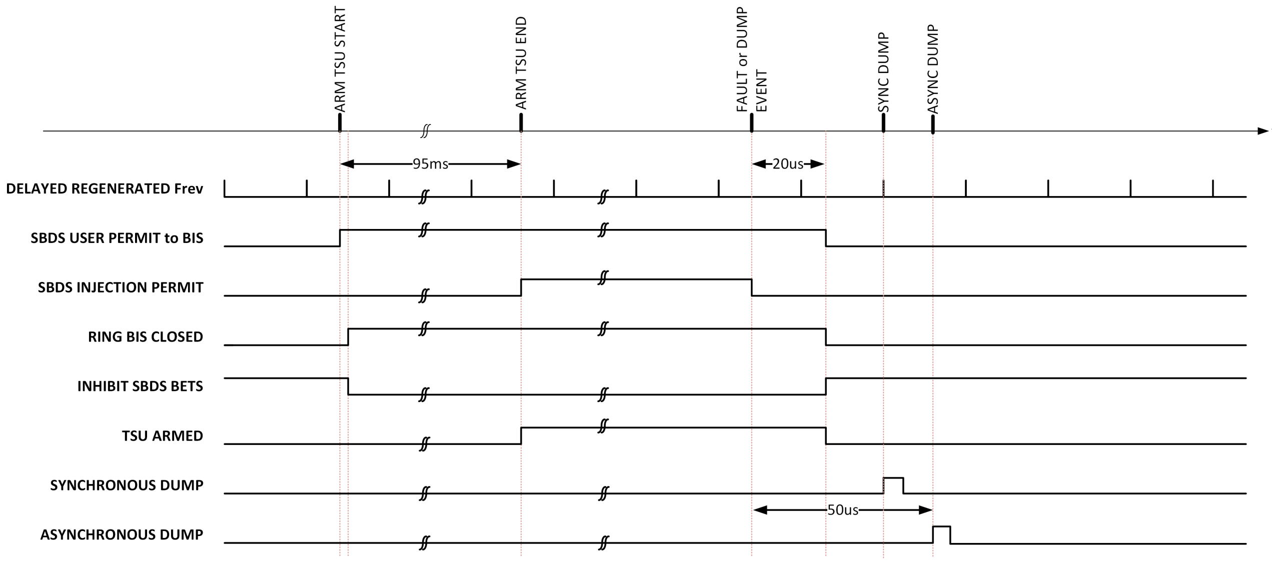

Figure 5: TSU-BETS arming and dump sequence.

Ring BIS, synchronization with Frev and internal SBDS generator reference generation and tracking with the BETS. Another challenge was the tight relation with the SPS Injection BIS to avoid injections after dump and to dump the post-LS2 high intensity beams upstream from the SPS.

The SBDS arming and synchronization has been deployed during the LS2 and commissioned without blocking issues, thanks to the extensive studies before installing and commissioning.

REFERENCES

[1] P. Faugeras,C. G. Harrison, and G. H. Schröder, "Design study of the SPS beam dumping system", CERN, Geneva, Switzerland, Rep. CERN CDS CERN-LabII-BT-INT-73-5, Jul. 1973. https://cds.cern.ch/record/1035902

[2] P. Van Trappen *et al.*, "SPS Beam Dump System (SBDS) Commissioning After Relocation and Upgrade", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2530–2532. doi:10.18429/JACoW-IPAC2022-THPOST039

[3] A. Antoine, E. Carlier, and N. Voumard, "The LHC Beam Dumping System Trigger Synchronisation and Distribution System", in *Proc. ICALEPCS'05*, Geneva, Switzerland, Oct. 2005, paper PO2.020-2.

[4] N. Voumard, "SBDS Trigger Synchronization Unit system", CERN, Geneva, Switzerland, Rep. CERN EDMS 2061157, Feb. 2021. https://edms.cern.ch/document/2061157

[5] E. Carlier, R.A.Barlow, P. Bobbio, G. Gräwer, N. Voumard, and R. Gjelsvik, "The beam energy tracking system of the LHC beam dumping system", in *Proc. ICALEPCS'05*, Geneva, Switzerland, Oct. 2005, paper PO2.056-4.

[6] N. Voumard, "Arming sequence for SPS Beam Dump System (SBDS)", CERN, Geneva, Switzerland, Rep. CERN EDMS 2738576, Jun. 2022. https://edms.cern.ch/document/2738576

[7] I. Romera Ramirez "Beam Interlock System for SPS Injection" CERN, Geneva, Switzerland, Rep. CERN EDMS 1934839, Nov. 2018. https://edms.cern.ch/document/1934839

[8] D. Nisbet "Power Converter requirements for the SPS Injection (TT10) Beam Interlock System" CERN, Geneva, Switzerland, Rep. CERN EDMS 2091153, Feb. 2019. https://edms.cern.ch/document/2091153

[9] N. Magnin, E. Carlier, B. Goddard, V. Mertens, and J. A. Uythoven, "Internal Post Operation Check System for Kicker Magnet Current Waveforms Surveillance", in *Proc. ICALEPCS'13*, San Francisco, CA, USA, Oct. 2013, pp. 131–134.