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SPS BEAM DUMP SYSTEM (SBDS) COMMISSIONING AFTER RELOCATION AND UPGRADE

P. Van Trappen*, E. Carlier, L. Ducimetiere, V. Senaj, F. Velotti, N. Voumard, V. Namora
CERN, Geneva, Switzerland

Abstract

In order to overcome several machine limitations, the SBDS has been relocated from LSS1 (Long Straight Section 1) to LSS5 during LS2 (Long Shutdown 2) with an important upgrade of the extraction kicker installation. An additional vertical deflection kicker magnet (MKDV) was produced and installed while the high voltage (HV) pulse generators have been upgraded by changing gas-discharge switches (thyratrons and ignitrons) to semiconductor stacks operating in oil. Furthermore the horizontal sweep generators have been upgraded to allow for a lower kick strengths. The controls, previously consolidated during LS1, went through an additional light consolidation phase with among others the upgrade of the trigger & retrigger distribution system and the installation of a new fast-interlocks detection system. This paper describes the commissioning without and with beam and elaborates on the measured improvements and encountered problems with corrective mitigations.

PROJECT MOTIVATION

Relocation

As explained in [1], the pre-LS2 LSS1 internal high-energy absorber block (TIDVG) would not survive the nominal High-Luminosity Large Hadron Collider (HL-LHC) beam, due to an increased beam power and brightness, requesting an upgrade. Although multiple solutions have been investigated to try to design a completely external beam dump system for the SPS in view of the LIU operation, none of them was suitable for the improvements required within the technological limits. The retained solution is to displace the internal beam dump system from LSS1 to LSS5 since this location offers enough space to properly optimise the dump system to meet the activation, reliability and robustness requirements.

Upgrade

The SBDS was upgraded to increase its reliability and availability, with the main component being the addition of a third MKDV magnet to decouple the generators in case of a failure such as a magnet breakdown. Thanks to the upgrade from gas-tubes to semiconducter switches, the whole dynamic range of the SPS can be covered and there is no more need for two dump absorber blocks as in LSS1. Finally profiting of the displacement, several controls improvements were applied as described further in detail.

ADDITIONAL MKDV MAGNET

Construction

The additional MKDV magnet has been built according to the original design. It is a delay-line type magnet of 2.5 m length, made of 5 cells, and enclosed in a vacuum vessel. It features a characteristic impedance of 2 Ω and a beam aperture of 83 mm horizontal and 56 mm vertical. The yoke is made of ferrite blocks and the decoupling capacitance consists of lump capacitor boxes built outside the vacuum vessel.

Tests and Conditioning

The HV tests and conditioning of the magnet is performed in three phases. First a DC conditioning is carried out where a positive voltage is progressively applied up to 33 kV, followed by a negative voltage up to −25 kV. The micro discharges and final leakage current are monitored and logged for future reference. The second stage is pulse conditioning with a reduced pulse length (about 2 μs), in order to minimise the spark energy in case of flashover into the magnet. The pulse forming network (PFN) voltage is progressively increased up to 38 kV by steps of 100 V and with up to 1000 pulses per steps at 10 s repetition period. At the end, the time interval between pulses is elongated up to 2 hours to reproduce the real operation scenario. Eventually the pulse conditioning is repeated with the full pulse length.

NEW MKDV GENERATOR

Upgrade

Originally the MKDV generator used a combo thyratron/ignitron switch to combine fast switching of thyratron and high current conduction capability of ignitron. This setup, although working reasonably well during decades, suffered from complex triggering and biasing, risk of approaching obsolescence and potential environmental risks due to the mercury contained in ignitrons. It was decided to replace this combo switch by fast GTO-like thyristors while accepting an inferior commutation performance. In view of required magnet field rise time of 1.1 μs this commutation speed reduction is considered as acceptable. A so-called ring gate topology GTO 5STH2045H0003 from ABB with 4.5 kV rating, 20 kA/μs anode current commutation speed and peak current capability of 80 kA was selected. To maximise its commutation speed, we used the maximum recommended triggering current of 2 kA with more than 4 kA/μs triggering current slew rate. Triggering of 12 GTO in series is ensured by a coaxial architecture triggering transformer developed

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* pvantrap@cern.ch

at CERN with a common primary and 12 insulated secondaries. Voltage surveillance of the anode-cathode voltage on each GTO is done by a low-cost in house developed voltage controlled oscillator (VCO) with optical output fed into a surveillance system by optical fibres. Two GTO stacks are operating in parallel as such ensuring full redundancy and reducing overall inductance of the switch.

Pulse Forming Network

A significant upgrade was done on the topology of the dumping system. In the past there were three PFNs with three switches supplying two magnets. A serious drawback of this topology was the fact, that in case of flash-over in one of magnets the other one was short-circuited as well via common switch. The proposed new topology consist of three independent PFN-switch-magnet units as such ensuring two-thirds of the kick even in case of breakdown in one magnet. PFN impedance was changed from original three to two Ohms i.e. the impedance of the terminated magnet. In addition a major part of PFN capacitance is implemented by self-healing capacitors and the whole is filled with silicone oil. To reduce the risk of damage to capacitors due to voltage reversal in case of magnet flash-over, the PFN contains a circuit for absorbing energy of reflected negative polarity pulse. Lastly, the new PFN contains a hydrophone for acoustic surveillance and detection of eventual capacitors or connection breakdown in oil and also a fire detection system.

CONTROLS UPGRADE

Several parts of the controls have been upgraded, below the major modifications are described.

Timing and Trigger Distribution

The timing and trigger distribution consisted of >20 years old modules of which obsolescence has become a problem. A modified version of the LHC Beam Dumping System's (LBDS) Trigger and Synchronisation Unit (TSU), which ensures a safe & beam-synchronised dump, was installed already in parallel before the LS2 consolidation to validate every dump of the relatively fast-cycled SPS. It has been installed as the sole trigger source post-LS2, as part of a new trigger distribution design, based on modern modules and peer-reviewed to ensure a guaranteed beam extraction.

Power Trigger Module (PTM)

The new semiconductor PFN GTO stacks require specific triggering where the triggering slew rate is paramount, as explained above. A specific PTM was thus designed for the MKDV switches while at the same time ensuring compatibility with the horizontal sweeper magnet (MKDH) generator modules, requiring consolidation. To ensure the high slew rate, four HV IGBTs (Insulated-gate bipolar transistors) in parallel discharge the pulse capacitors into the trigger transformer.

Knowing the double PFN switches configuration, dedicated reliability studies [2] were undertaken to ensure a high reliability (i.e. reducing failure mode *insufficient beam dump*) and high availability (i.e. reducing failure mode *too maintenance intensive*) of the system. The solution of a single PTM for each stack was retained as a result.

Fast-Interlocks Detection System and Retrigger

As found by the SBDS reliability studies [2], the highest risk failure mode is the *fast-interlocks failure detection or retrigger on erratic*. The suggested surveillance functionality to cover this is already existing at the consolidated, generic Fast Interlock Detection System (FIDS) [3] which lead to its installation at the SBDS. The FIDS offers in addition of the continuous surveillance, by detecting and counting nominal conduction events, more advanced diagnostics and a remote configuration ability.

HARDWARE COMMISSIONING

The hardware commissioning in Q1 2021 that heralded the end of LS2 started off without issues but as the magnet HV conditioning voltage went up, so did the issues with the newly produced MKDV1 magnet. The magnet current produced various vacuum breakdowns quite early in the conditioning process, at 33 kV while the nominal voltage is about 36 kV. Equally worrying was that there was no conditioning effect observed when the pulsing period was increased.

A decision was taken to keep MKDV1 installed, knowing that no better spare magnet was available until YETS21-22. To mitigate the harm-full full energy pulses after a period of no usage, a semi-automatic soft-start was introduced at the level of the controls (hardware + software). In addition, this decision was only made possible by a 25 % kick strength reduction - slightly compensated by increased strengths of MKDV2&3 - after careful study by SY-STI with 2021 beam parameters.

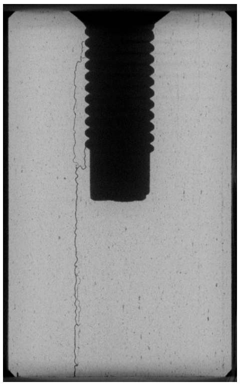

Figure 1: MKDV kicker magnet ceramic spacer tomography result with visible crack.

In parallel, the spare MKDV kicker magnet that was produced at the same time has been reopened to investigate the weakness. Significant electrical breakdowns have been observed on several insulating ceramic spacers. A few of them were submitted to a Computed Tomography (CT), which revealed several internal voids and a non-homogeneous density across the length, see Fig. 1. The voids, aligned in the extrusion direction, allowed the creation of electrical paths between the HV busbar and the ground supporting parts. To fix the issue new spacers have been specified, exclusively with isostatically pressed ceramic, and duly controlled by CT. As breakdowns were tracked up to the corner of the HV busbar, this latter has been remachined with larger radii all along the edges.

Electrical tests in a HV test cage before installation confirmed that the modified magnet had an improved behaviour, observed with the following parameters: direct current conditioning leakage current and sparks, vacuum spikes and breakdowns with short and long pulse pulsed conditioning.

BEAM COMMISSIONING

After the extensive hardware commissioning, a series of commissioning steps were defined and carried out with beam: I) verification of BTV installed just upstream of the absorber block (TIDVG), II) MKDH polarity assessment, III) kickers waveform scan for different beam types and energies, IV) validation of failure of MKDV and MKDH.

The first two commissioning steps could be addressed with the first beam dumped on the TIDVG. The first beam dump was carried out with RF cavities switched off, hence the dumped beam covered the whole MKDV and MKDH waveforms showing the correct polarity of the MKDH (deflection towards the external part of the SPS) and of course the BTV readiness.

The full waveform scan was performed using a single bunch of 1×10^{11} p and changing the injection bucket. In this manner a controlled and detailed scan of the full MKDs waveform could be done. In Fig. 2-top the overlap of all BTV images recorded is shown when dumping at 450 GeV. A similar scan was performed at 260 GeV and at 350 GeV on the same cycle (LHC type) and at 400 GeV on an SFT-PRO cycle. All the data was completely compatible with expectations, except for the horizontal deflection obtained by the MKDH. Further analysis and tests showed that the MKDH is performing about 30% less than expected.

Finally, the failure of both MKDV and MKDH kicker generators was emulated in the machine, removing one of the kickers at the time. Disconnecting one of the MKDV showed that the 450 GeV beam could be safely disposed on the TIDVG, as per design, regardless of which MKDV is not pulsing. In Fig. 2-bottom, the reconstructed image of the whole beam at 350 GeV on the BTV is shown when one MKDV is disconnected. The dumped beam reaches the screen, hence the TIDVG, as expected. The same measurement was repeated for the MKDH, showing that the first and third kicker tanks deliver roughly 50% the deflection of the second one. The reason behind the behaviour of the first and last MKDH are still under investigation.

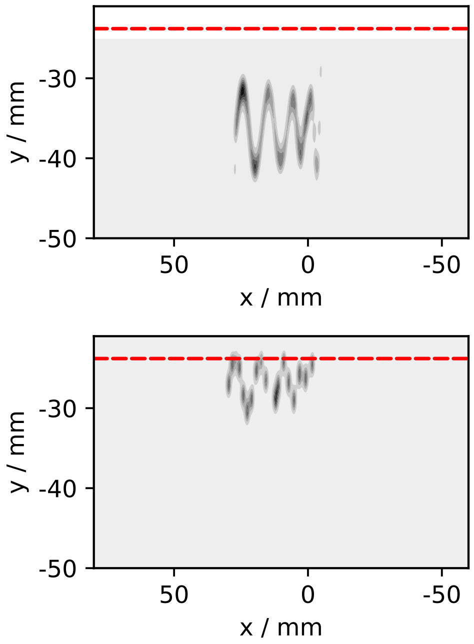

Figure 2: Reconstructed of full beam dumped on the BTV at the TIDVG from single bunch dumps. (Top) Nominal dump at 450 GeV. (Bottom) Dump with two out of three MKDV kickers at 350 GeV.

CONCLUSION

Years of specifying, designing, building and testing lead to a successful commissioning of the SBDS with, eventually, an improved reliability and availability. The upgrades at the level of the HV pulse generator, magnet production and controls consolidation were described. The commissioning went well initially but was then halted by the problem with the ceramic spacers of the newly built MKDV1 magnet which took a while to understand. The magnet swap during the YETS did go as planned and as a result the MKDV1 magnet is not a limiting element anymore.

Measurements with beam confirmed the kick strength as per specification although there were some surprises at the level of the MKDH magnets which remain to be investigated.

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