Testing and calibration of novel solid state HEH monitors for LHC Beam Dumping System

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1. Project description

The goal of the project is the development of a high sensitivity HEH monitoring system for the Large Hadron Collider (LHC) Beam Dumping System (LBDS). Higher sensitivity HEH measurements will allow for a more accurate estimation of Single Event Burnout (SEB) related failure rates within the LBDS whereas the acquired data will help to adapt the most appropriate mitigation measures for failure rate reduction. The testing, validation and calibration of the recently developed High Energy Hadron (HEH) monitoring system based on protected SEB phenomenon on high voltage Si diodes is a crucial step within the HEH monitor project. Testing of the system at the high altitude research station at Jungfraujoch started in December 2018 and is part of the monitoring system calibration campaign.

The LHC beam dumping system (LBDS) is the ultimate protection system for LHC and its reliable operation is crucial for the machine protection. The LBDS consists of 50 high voltage/high current generators and their associated magnets. Its role is to deviate two counter-rotating LHC beams onto their dedicated graphite blocks, which absorb the beam energy - up to 360 MJ per beam at 7 TeV. At nominal energy of 7 TeV the total current needed to deflect the beam is over 1 MA which requires to operate the generators at almost 30 kV. The LBDS pulse generators comprise altogether 800 HV thyristors and 480 IGBTs for HV trigger circuits, both sensitive to High Energy Hadrons (HEH) leaking from the tunnel via cable ducts to the galleries where the pulse generators are installed. HV semiconductor switches can hence experience a Single Event Burnout – a catastrophic failure that instantaneously damages a semiconductor. The sensitivity of a semiconductor to HEH is expressed as SEB cross-section (SEBc-s) which is the probability of the phenomenon expressed in effective area. Any SEB on the HV components inside the LBDS generators will provoke a beam dump not synchronised with the foreseen abort gap in the beam structure and is thus associated with beam losses and the risk of damage to downstream equipment, leading to significant machine down time for reparations and machine recovery. It is hence of crucial importance to reduce the probability of SEB related failure to a minimum reasonably achievable value (< 0.1 per year and beam).

Measurements of the SEBc-s dependence on applied voltage of HV thyristors and triggering HV IGBT were done at CERN using in house developed non-destructive method of SEBc-s measurement with the results shown in Figure 1. Based on these measurements, the SEB related failure rate probability was calculated under various present and future operation conditions, as shown in Table 1. The HEH fluency used in the table was calculated by a Monte Carlo simulation tool – FLUKA. Thanks to the shielding campaign performed during Long Shutdown 1 (LS1), the expected HEH fluency in galleries is now down to ~ 5e4 HEH/cm2.year, which is ~ ½ of the HEH (neutron) fluency from cosmic rays at earth level. This value is too low for the so far used HEH detection devices based on memory Single Event Upset (SEU) phenomenon with sensitivity of one count per 3e5 HEH/cm2: after 3 years of operation, 0 counts were observed. In order to improve the accuracy of the failure rate estimation, the new HEH monitoring system based on SEB phenomenon in HV silicon diode was developed. The diode type was chosen from several candidates according to the measured SEBc-s value. A high number of diodes (10 to 16 channels with 30 to 70 diodes per channel) are HV biased (~1.3 kV) and protected from destruction during SEB by a dedicated protection circuit. The voltage dependence of SEBc-s of the chosen diode is shown in Figure 2 together with measurement results at CHARM irradiation facility and at Am-Be source – both at CERN.

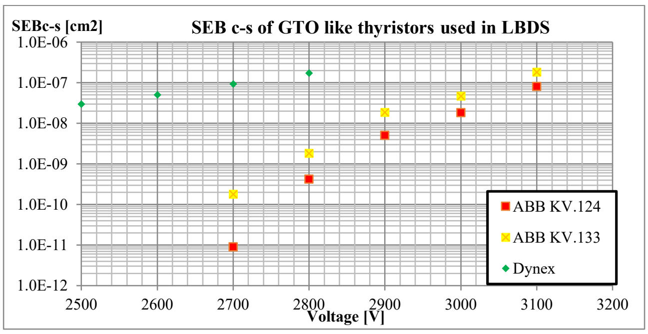

Figure 1. SEBc-s of 2 different GTO like thyristor types (both 4.5 kV rated) used in LBDS generators - Dynex and ABB made (two different production batches from ABB).

Table 1. Estimation of SEB related failure rate of LHC beam dumping generators based on SEBc-s measurement and HEH fluency simulation from FLUKA.

	6.5 TeV	7 TeV	HL-LHC@7 TeV without modif.	HL-LHC@7 TeV with modif.	7.5 TeV with modif.
	2.7 kV/GTO (MKD) 2.5 kV/GTO (MKBH)	2.9 kV/GTO (MKD); 2.7 kV/GTO (MKBH)	2.9 kV/GTO (MKD); 2.7 kV/GTO (MKBH)	2.65 kV/GTO (MKD); 2.4 kV/GTO (MKBH)	2.84 kV/GTO (MKD); 2.58 kV/GTO (MKBH)
ABB SEBc-s [cm^2]	2e-10	8e-9	8e-9	1e-10	2.5e-10
MKBH GTO SEBc-s [cm^2]	3e-8*	1e-7	1e-7	1e-11*	5e-11
IGBT SEBc-s [cm^2]	5e-9	5e-9	5e-9	3e-11*	3e-11*
HEH fluence est. [$HEH/cm^2.y$]	5e4*	5e4*	2e5 *	2e5 *	1e5 *
	Failure probability				
MKD (GTO) [y^{-1}]	6e-3	0.2	0.8	1.2e-2	1.5e-2
MKD (IGBT) [y^{-1}]	9e-2	9e-2	3.6e-1	2e-3	1e-3
MKBH (GTO) [y^{-1}]	0.12	0.4	1.6	1.6e-4	4e-4
MKB (IGBT) [y^{-1}]	3e-2	3e-2	1.2e-1	7e-4	3.5e-4
Total AD (MKD GTO+IGBT) [y^{-1}]	0.1	0.3	1.2	1.4e-2	1.6e-2
Total SD (MKB GTO+IGBT) [y^{-1}]	0.15	0.43	1.7	9e-4	8e-4

On December 4th, 2018, three prototypes of HEH monitors were installed at Sphinx laboratory with recording of the counts together with timestamp and complete telemetry into dedicated website. An "Alive" signal is recorded as well with various telemetric parameters: bias voltage measurement, total current consumption, ambient temperature measurement and voltage control status. From the very beginning we observed a count rate lower than expected. One of the possible explanations is the shielding effect of IGY monitor structure (lead + moderator) on the upper floor and the reinforced concrete building structure. For this reason, one monitor (MON1) was moved to the NM64 laboratory (wooden structure building) and installed on January 8th, 2019 in such a way, that the shielding effect of the IGY structure was excluded. The NM64 laboratory is at lower altitude (3450 m vs 3580 m for Sphinx laboratory) and may suffer from higher snow cover on the roof (not cleaned). The observed NM64 laboratory ambient temperature was approximately 4 °C higher compared to IGY laboratory, which is slightly reducing monitor sensitivity (negative temperature dependence of SEBc-s of ~ -1.2%/deg).

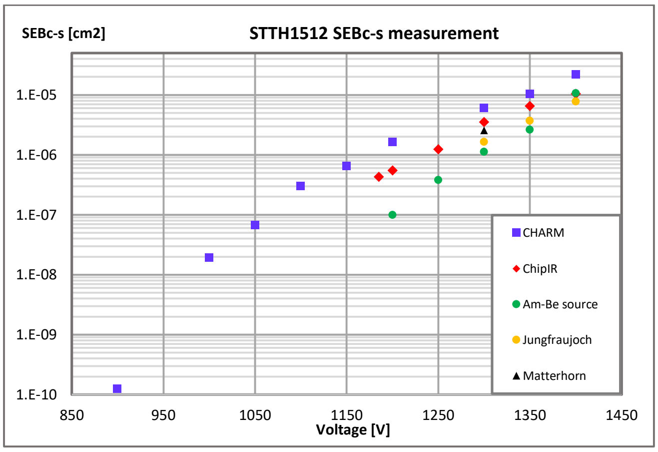

Figure 2. SEBc-s of the used HV diode (1.2 kV rated STTH1512) according to the measurements at CHARM (CERN), ChipIr (ISIS/UK), Jungfraujoch high altitude research station, Matterhorn (Project IGLUNA – Swiss and European space agencies) and at Am-Be source (CERN); the latter measurement indicates potential spectral dependence of SEBc-s of the diode on the applied bias voltage since the Am-Be source has limited spectrum energy of neutrons (<12 MeV) and observed SEBc-s voltage dependence is stronger compared to the ones observed on the other HEH sources.

After 23 days of operation at NM64, the MON1 showed an increased count rate compared to the Sphinx laboratory operation (factor of ~1.13) contrary to the lower altitude (and lower cosmic rays originated neutron flux) and higher monitor ambient temperature related estimation (expected cumulative effect of lower altitude and higher temperature should result in a count rate reduced by a factor of 0.877 compared to Sphinx laboratory). The difference between expected and observed count rate (factor of 1.29 more at NM64 vs. expectation) can thus correspond most likely to the shielding effect of IGY monitor and Sphinx laboratory building structure. Since the snow layer on the roof of the NM64 building was not measured and considered, the shielding effect of our placement at Sphinx laboratory is most likely even higher.

To avoid the uncertainty of the influence of the uncontrolled thickness of the snow layer on the roof of the NM64 building and to approach the operational temperature in the LHC tunnel, the MON1 was moved back to Sphinx laboratory on January 31st, 2019 and two monitors (MON1 + MON2) readout electronics were modified according to the optimisation developed during an irradiation campaign performed in parallel at an Am-Be source at CERN. MON3 was exchanged and updated later at CERN and re-installed at Jungfraujoch on May 1st, 2019. Modifications consisted in separation of the 30 used diodes in parallel (per channel) into six branches of 5 diodes separated by small, low voltage and low parasitic capacitance diodes. In this way the capacitive load of the diode undergoing SEB is significantly reduced resulting in a higher sensitivity for SEB detection. Subsequent measurements showed the detection sensitivity (count rate) improvement by a factor of ~2.6.

Measurements were performed at three bias voltage levels – 1.4 kV, 1.35 kV and 1.3 kV. There is a certain statistical probability that HV diodes biased at such a voltage level experience an avalanche breakdown not related to HEH due to either semiconductor local defects or radioactive pollutant in the diode packaging material. In any case such a count can't be distinguished from nominal SEB. To determine this "background" signal frequency, all three monitors were removed from Jungfraujoch at the beginning of December 2019 and installed in the LHC tunnel 100m underground; hence well shielded from cosmic rays as the LHC is currently in long shutdown and without beam thus no HEH are present. This measurement of background count rate will allow more accurate evaluation of the measured data.

According to the SEBc-s measurement comparison summarized in Fig. 2, we are possibly missing a factor of ~2 compared to the single diode measurements at CHARM (supposed to be our most accurate SEBc-s measurement). Charm and ChipIr measurements were done in single diode setup but in case of ChipIr the fluency of neutrons per one spill was too high and due to the high diode sensitivity we observed measurement saturation and the measured data had to be corrected by a "de-saturation" function. All other measurements – at Matterhorn (project IGLUNA), Am-Be irradiation and the one at Jungfraujoch - were done on HEH monitors containing between 30 to 70 diodes per channel and some SEB detection "filtering" effect of the parallel diodes in the channel can still persist despite the effort to limit it.

The neutron spectrum of the Am-Be source at CERN is limited to less than 12 MeV with a majority of neutrons under 5 MeV - possibly involving stronger voltage dependence of the observed SEBc-s at lower voltages. Measurements at the Sphinx laboratory are very likely influenced by the shielding effect of the IGY detector above the monitor location and by the building structure made from reinforced concrete.

Two upgraded HEH monitors (MON7 and MON8) with reduced current consumption (= lower HEH monitor internal heating and hence reduced diode ambient temperature and increased SEBc-s) and with higher number of diodes (16 channels with 30 diodes each = 480 diodes) were built and used in the field campaign of the IGLUNA project: measurement of the attenuation of cosmic rays neutrons in the ice shelter - a key factor for the feasibility of the project of a shelter for potential inhabited mission on the Moon's recently discovered ice filled craters on the south pole. One monitor was placed on the glacier surface with full day exposure and with daily temperature variation of up to 50 °C whilst the second one was placed in the cavern in the glacier and shielded by up to ~20m of ice at constant temperature around 0°C but at close to 100% humidity. Both monitors were enclosed in hermetically sealed plastic boxes with silicon paste sealed feedthroughs for supply and LAN cables. Calibration measurements of the monitors used for IGLUNA project (MON7 and MON8) started at Sphinx laboratory on December 6th, 2019 and are performing well. Prior to installing them at Jungfraujoch, they passed more than a month in the LHC tunnel for background measurements and did 1.4 and 1 count per day (at 1.3 kV bias voltage) respectively.

HEH monitors with further increased sensitivity (16 channels with 70 diodes per channel = 1120 diodes) were built as well and are undergoing background measurement in the LHC tunnel.

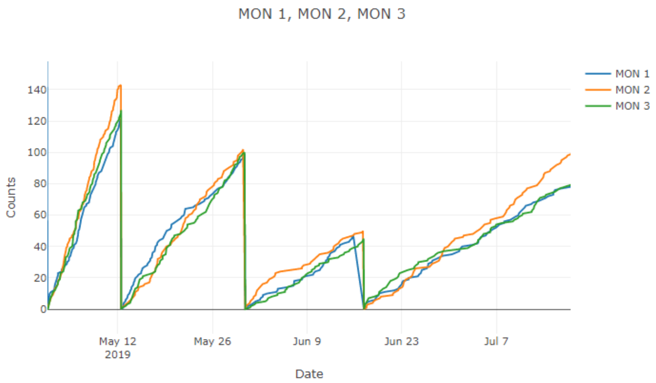

Figure 3. 3 HEH monitors cumulative counts at 1.4 kV, 1.35 kV and 1.3 kV respectively.

The HEH monitor system proved its reliability and its capability of autonomous and failure free operation even with multiple power cuts related to main grid maintenance at Jungfraujoch and during the IGLUNA field campaign. Measured counts on the three monitors at the bias voltage of 1.4 kV, 1.35 kV and 1.3 kV are shown in Figure 3. The slope difference of the individual curves corresponds to the HEH monitor sensitivity variation with the bias voltage. The latest configuration change illustrated in Figure 3 happened in late May – the visible reset of counters in mid-July corresponds to a power cut which caused the reset of the internal counters. To avoid such artefacts a battery backup or UPS has been identified as future upgrade option.

Results were presented at IEEE Pulse power and plasma conference (one poster and one oral presentation) another paper abstract has been submitted to IPAC 2020.

Internet data bases

https://dcabreri.web.cern.ch/summary_v2.php
https://dcabreri.web.cern.ch/mon1/m1v2/m1v2_alive_table.php
https://dcabreri.web.cern.ch/mon2/m2v2/m2v2_alive_table.php
https://dcabreri.web.cern.ch/mon3/m3v2/m3v2_alive_table.php

Collaborating partners / networks

S. Danzeca, R. G. Alia, M. Cecchetto, Ch. Cangialosi, J. Lendaro - Radiation to Electronic working group/CERN
Pirerre Carbonez - Radiation protection group/CERN
IGLUNA a habitat in ice, Swiss Space Centre and European Space Agency
ChipIr/ISIS - Neutron and Muon Source, Science and Technology Facilities Council, Rutherford Appleton Laboratory, UK

Scientific publications and public outreach 2019

Conference Papers

Cabrerizo Pastor, D., V. Senaj, T. Kramer, Data acquisition system for HEH monitor, 22nd IEEE International Pulsed Power Conference, Orlando, FL, USA, June 23-28, 2019.

Senaj, V., D. Cabrerizo Pastor, T. Kramer, High sensitivity HEH monitor, 22nd IEEE International Pulsed Power Conference – oral presentation, Orlando, FL, USA, June 23-28, 2019.

Senaj, V., D. Cabrerizo Pastor, T. Kramer, Testing of HEH monitor for LBDS, IPAC 2020, Caen, France, to be published.

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