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EDMS NO.	REV.	VALIDITY
2683896	**2.0**	**DRAFT**

REFERENCE
LHC-OP-MPS-0021

Date: 2024-01-08

MPS COMMISSIONING PROCEDURE

MPS Commissioning Aspects of the Beam Charge Change Monitoring (BCCM) System

ABSTRACT:

This document describes commissioning procedures for the **LHC Beam Charge Change Monitoring (BCCM) system**.

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HISTORY OF CHANGES

REV. NO.	DATE	PAGES	DESCRIPTIONS OF THE CHANGES
0.1	2021-07-20	20	First draft for discussion
	2021-11-19	21	Version presented to the MPP - BCCM intensity tolerance properly addressed - Added one beam test for the energy 0.5 TeV or more
	2022-01-21		Sent for approval
1.0	2022-02-09		Document released
2.0	2024-03-08	24	Document updated for the 2024 LHC startup

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1. INTRODUCTION

The LHC is protected against potentially dangerous beam losses by a distributed Beam Loss Monitoring (BLM) system, based on some four thousand detectors. To provide an additional level of safety, the LHC is equipped with a Beam Charge Change Monitoring (BCCM) system, which detects fast beam charge drops and triggers beam dumps for their potentially dangerous rates. The BCCM system is redundant for either LHC beam and based on signals from four beam sensors, so it is much simpler than the large and distributed BLM system.

The challenging beam dump threshold levels defined for the BCCM system and the required operational reliability proved to be difficult to satisfy at the same time. The Run 1 and Run 2 BCCM versions based on signals from Fast Beam Current Transformers (FBCTs) did not achieve the required performance to operate as an LHC protection system [1] [2] [3]. Because of these difficulties, a completely new system version based on signals from Beam Position Monitors (BPMs) was designed, prototyped and tested with beam at the end of Run 2. This document concerns only this new BCCM system, which has the following features:

- The BPM signals are much larger than the FBCT signals, giving more options for their analog processing and the sum of BPM electrode signals is still sufficiently independent of the actual beam position and bunch length.
- The beam synchronous ADC sampling rate is 40 MHz, four times lower than the one used in the previous systems, facilitating the digital signal processing.
- Chosen signal processing algorithms do not require the ADC sampling phase to be adjusted to the beam signal, which significantly increases the system robustness.
- The system bandwidth is controlled by analog low pass filters.
- The new algorithm of evaluating turn-by-turn beam intensity (1) changes is based on a simple concept of a one-turn (2) digital delay line: the beam signal changes are calculated for samples spaced exactly by one revolution period, allowing simple and efficient signal processing in the time domain.

Even with this new architecture achieving the required performance was difficult [4]. Necessary optimisations and their thorough testing in various beam conditions delayed the operational use of the BCCM by some two years.

This version of the BCCM commissioning procedures takes into account the updated dump threshold levels [5] and the experience gained during the 2023 LHC run, when the proper operation of the BCCM was systematically monitored.

2. SCOPE

This document covers tests which will be performed to validate the correct functioning of all the components of the BCCM system in relation with the Machine Protection

(1) In the document terms "beam intensity" and "beam charge" are equivalent.

(2) Term "turn" is used to denote one LHC revolution period, ≈ 88.9 μs.

System (MPS) for both LHC beams. The tests cover all the components of the BCCM system and its connections to the MPS.

3. PURPOSE

This document describes the procedures concerning the tests and their sequence, related to the participation of the BCCM system in the MPS.

Each described test is labelled with at least one of the letters listed in Table 1. The letters specify at which interval, or at which occasion the described test needs to be repeated.

Table 1: Labels for the test repetition scheme

Label	Repetition
S	To be repeated after every **s**hutdown
E	To be repeated after **e**nd-of-year stops
C	To be repeated after any significant **c**hange in the system
D	To be repeated after every beam **d**ump

This document is meant to be the reference document for the checklist, which will be used during the commissioning of the MPS.

All test results are reported by logged BCCM system parameters.

4. THE LAYOUT

The whole BCCM system consists of four systems, two redundant systems per each of the LHC beams, which are referred to as system B1-A and system B1-B for LHC Beam 1 and system B2-A and B2-B for LHC Beam 2 (3). The four systems use signals from the following BPMs:

- BCCM system B1-A: BPMYA.5R4.B1
- BCCM system B2-A: BPMYB.5R4.B2
- BCCM system B1-B: BPMYA.6R4.B1
- BCCM system B2-B: BPMYB.6R4.B2

The BPMs used by the BCCM system are shared with the standard BPM system, with the passive splitting of the electrode signals on the far end of the cables coming to rack BY05 located in UA47. The rack accommodates the whole BCCM system as well as the

(3) There are also development BCCM systems B1-C and B2-C [6]. They are used for hardware and software optimisations and their beam testing, impossible with the operational systems. Systems C do not have any interlock connections and are not used operationally, therefore do not require any beam commissioning.

BPM electronics of the shared BPMs. A photograph of all the BCCM electronics is shown in Figure 1.

Four signals of four electrodes of each BPM used in the system are processed by two identical BCCM front-ends. The BPM signals of systems B1-A and B2-A are processed by BCCM front-end A while the signals of systems B1-B and B2-B are processed with BCCM front-end B. The front-ends provide low-pass filtering of the signals, their summation, amplification and an envelope detection. The resulting four signals for BCCM systems B1-A, B2-A, B1-B and B2-B are sent to two VME acquisition cards, providing their 16-bit digitalisation at a 40 MHz rate, synchronously to the circulating beam. Each of the VME cards is equipped with an FPGA processing the ADC samples and providing all safety-critical functionality of the system.

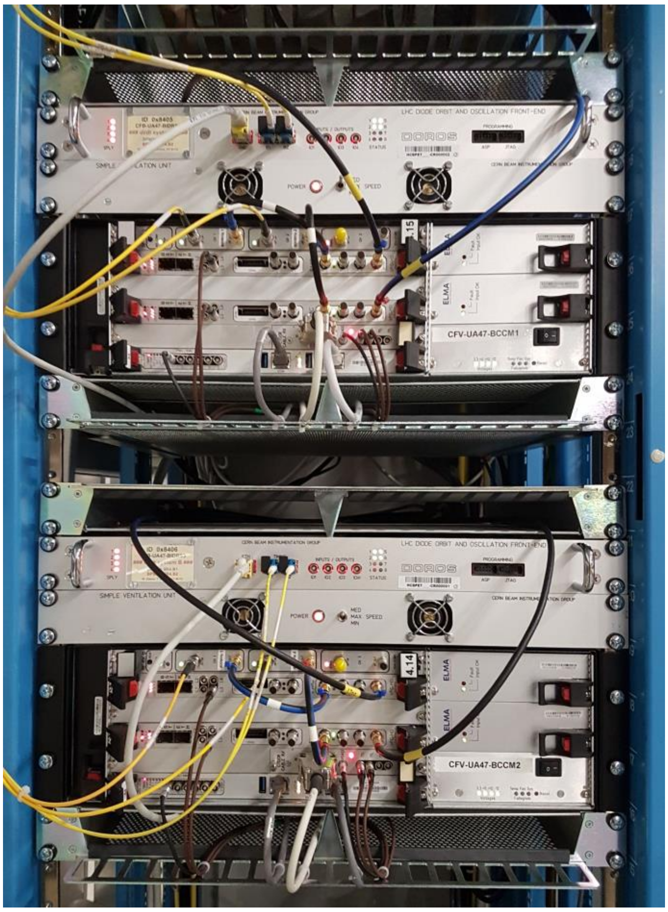

Figure 1: A photograph of BCCM electronics accommodated in rack BY05 in UA47. From top to bottom: BCCM front-end A, a ventilation unit, VME crate A, BCCM front-end B, a ventilation unit, VME crate B. Two CIBU modules for systems A and B are not visible in the photograph and are located at the bottom of the rack.

The beam signals of systems B1-A and B2-A are processed by the VME acquisition cards accommodated in VME crate A and the beam signals of systems B1-B and B2-B are processed by the VME acquisition cards accommodated in VME crate B. Each of the acquisition cards has a dedicated VME rear-transition-module providing the interface logic to a CIBU input. As only one maskable channel is available on the Beam Interlock

System (BIS) in UA47, the user permit outputs of the two BCCM systems A and B are combined (logical AND) using a dedicated interlock combiner module.

Each of the four BCCM systems evaluates turn-by-turn integrals of BPM sum signals proportional to the beam current and the resulting charges are scaled so that the results match readings of the LHC FBCTs. The BCCM operation is based on beam charges and the beam dump threshold levels are also defined in beam charges.

The beam charge change is evaluated by subtracting beam charges from two consecutive turns. The subtraction result is every turn compared to the one-turn dump threshold, which depends also on the actual beam energy. The actual beam energy is received from the General Machine Timing (GMT) decoded by the system FPGA. The one-turn charge changes are integrated in five other time windows and compared to the corresponding dump thresholds. If any of the beam charge changes is larger than its corresponding dump threshold, then the system removes its beam permit signal, which in turn initiates a beam dump through the CIBU channel.

The lengths of the integration windows and their corresponding dump thresholds for the two beam energy ranges are summarised in Table 2: Integration windows and their beam dump thresholds in units of 10^{11} proton charges (). [5].

Table 2: Integration windows and their beam dump thresholds in units of 10^{11} proton charges (4).

Energy [TeV]	1 turn	4 turns	16 turns	64 turns	225 turns (5)	1125 turns (5)
<0.5	6	6	6	6	6	10
≥ 0.5	3	3	3	3	5	10

Please note that the standard charge unit in the BCCM system is 10^{11} proton charges, denoted in the document as 10^{11} $p+$. This way the system can use fixed-point arithmetic. The system beam dump thresholds are set and logged assuming this convention.

All signal processing and dump generation is performed in the system FPGA. The system software (FESA class) provides only an interface to configure the system FPGA, monitor the system functionality and log system data and parameters.

All relevant system parameters are logged on change or once per hour if their values have been constant. The most important system data is logged at 1 Hz. Appendix A contains the list of most important logged quantities.

(4) This table containing updated dump threshold levels is the main reason for this new version of the document. The most important change with respect to the previous levels [7] is for the 6th integration window and the high energy range, for which the dump threshold got increased by factor 20.

(5) The lengths of the two longest integration windows are multiples of 20 ms to supress potential contributions from 50 Hz interferences and their harmonics.

5. TESTS PERFORMED DURING THE HARDWARE COMMISSIONING

Each electronic block of the BCCM system is tested for its full functionality in the laboratory prior to its installation. During hardware commissioning the system signal processing chain must be checked as much as it is possible without circulating beam, to detect potential anomalies as early as possible. The tests can only partially verify the system functionality and must be imperatively followed by beam tests described in Chapter 8.

All tests during hardware commissioning involve checking BCCM logged parameters and data. The parameters are logged “on change” or once per hour when their values have been constant, to make sure that their logging is operational. BCCM data is logged once per second. If data concerns minima, maxima, or standard deviations, then their values are calculated for 1 s periods.

All BCCM parameters and data have their corresponding software (FESA) fields and in principle their values can be checked at the software level. However, checking BCCM parameters in the logging database allows also verifying the logging itself.

Parameters of the BCCM front-ends are also logged, but this data is considered as auxiliary, not critical for the system operation and meant to be used only by the system experts for checking details of the system operation.

5.1 CONDITIONS REQUIRED TO START AND PERFORM TESTS

- Both BCCM front-ends are installed and operational, their beam signal inputs are connected to the BCCM BPMs and the RF outputs of the front-ends are connected to the respective ADC inputs.
- Both VME crates are operational with all their modules:
  - front-end computer;
  - card converting GMT signal distributed over RS485 (CTDCR card);
  - card converting 400 MHz RF clocks distributed over optical fibres to electrical signals, used to clock the system ADCs (RF RX D card);
  - VME FMC Carrier module hosting the ADC FMC mezzanine and the system FPGA;
  - CIBU interface rear-transition-module, interfacing the system FPGA to the current inputs of the CIBU modules.
- Distribution of the 400 MHz RF clock is operational.
- System software is operational.
- Logging is operational.

5.2 DESCRIPTION OF THE TESTS

Each test shall be done separately for each of the BCCM systems, namely B1-A, B2-A, B1-B and B2-B.

#	Rep.	Action
1	S C	Check that the logged dump thresholds correspond to the values listed in Table 2. The logged values for the low energy range below 0.5 TeV (encoded as A) should be as follows, in the "BCCM unis" of 10^{11} *p*+: – dump_Level_W1_A = 6 (window 1 → 1 turn) – dump_Level_W2_A = 6 (window 2 → 4 turns) – dump_Level_W3_A = 6 (window 3 → 16 turns) – dump_Level_W4_A = 6 (window 4 → 64 turns) – dump_Level_W5_A = 6 (window 5 → 225 turns) – dump_Level_W6_A = 10 (window 6 → 1125 turns) The logged values for the high energy range 0.5 TeV or more (encoded as B) should be as follows: – dump_Level_W1_B = 3 (window 1 → 1 turn) – dump_Level_W2_B = 3 (window 2 → 4 turns) – dump_Level_W3_B = 3 (window 3 → 16 turns) – dump_Level_W4_B = 3 (window 4 → 64 turns) – dump_Level_W5_B = 5 (window 5 → 225 turns) – dump_Level_W6_B = 10 (window 6 → 1125 turns) Please note that the above values are the maximal dump level values and they are hardcoded in the FPGA code and cannot be increased. However, for beam commissioning or other important operational reasons their values can be lowered to increase the system sensitivity at the expense of potential dumps at lower beam loss rates. During the hardware commissioning tests the beam dump threshold levels should have their default maximum values, unless clearly stated otherwise.
2	S C	Check that the presence flag for the 400 MHz RF clock is TRUE. The flag is logged as RFclkPresFlag and state TRUE is marked as 1.

5.3 STATUS OF THE SYSTEM AFTER THE TESTS

After these tests, the system is as much checked as possible with the minimal set of prerequisites, namely the 400 MHz RF clock, system software and logging.

6. LINK TO OTHER EQUIPEMENT

This chapter considers only interfaces of the BCCM system related to MPS.

6.1 INTERFACES WITH THE BEAM INTERLOCK SYSTEM

The interface with the BIS is described in more detail in the corresponding test specification [8] and shall be tested within the scope of the BIS tests.

6.1.1 SIGNALS BETWEEN THE BCCM SYSTEM AND BEAM INTERLOCK SYSTEM

Each of the four BCCM systems is linked to the BIS via a CIBU channel and is connected to a maskable input. The BCCM uses Beam_Info signal from the CIBUs during the commissioning of the User_Permit connection to the CIBU module [8].

6.1.2 CONDITIONS AND SEQUENCE FOR A BEAM DUMP

The BCCM USER_PERMIT (see Figure 2) of any of the four systems is set to FALSE if in that system:

- The detected beam intensity drop in one of the six integration windows is above the corresponding threshold limit for the actual beam energy range.
- An ADC sample does not fit to the system dynamic range.
- The 400 MHz RF clock, necessary to produce the 40 MHz clock for the system ADC, is missing, resulting in its presence flag to be in state FALSE.

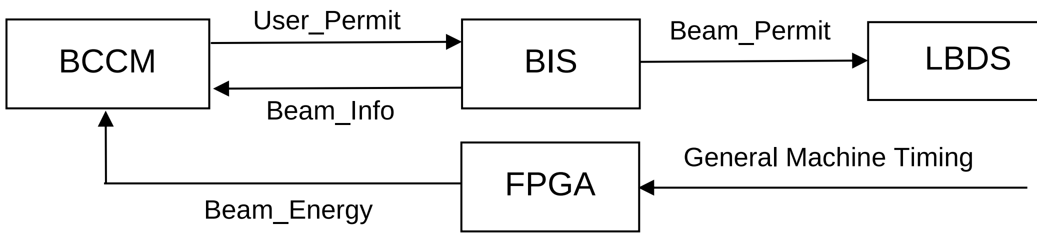

Figure 2: Schematic view of the signal flow for the Beam_Permit, Beam_Presence and Beam_Energy.

Please note that the actual beam energy distributed in the General Machine Timing (GMT) is decoded in the system FPGA and used to set the appropriate beam dump thresholds. However, this signal is not indispensable for system operation and therefore its lack does not cause a beam dump. Instead, in the absence of the beam energy information the system assumes that the beam energy is above 0.5 TeV and the lower dump threshold levels are used [7].

In order to remove dependencies which are not strictly necessary, once the beam energy becomes 0.5 TeV and the BCCM system switches the dump thresholds accordingly, the system stops checking actual beam energy [7]. The system starts checking the beam energy again after the beam has been dumped, upon execution of automatic procedures preparing the BCCM system for the next beam injection. At the same time all the system settings are initialised to their default values.

7. SYSTEM TESTS DURING THE MACHINE CHECKOUT

During this period the BCCM system will be checked as much as possible without beam in the machine. As one of the challenges of its reliable operation is potential interference originating in different LHC power systems, first checks are done on the values of the most important quantities measured by the BCCM system without beam, to confirm that they do not suffer from interferences.

7.1 CONDITIONS REQUIRED TO START AND PERFORM TESTS

- All BCCM hardware is operational.
- Distribution of the 400 MHz RF clock is operational.
- The system software is operational.
- Logging is operational.
- SMP beam energy distribution is operational.

7.2 DESCRIPTION OF THE TESTS

Each test shall be done separately for each of the BCCM systems, namely B1-A, B2-A, B1-B and B2-B.

#	Rep.	Action
1	S C	Check that the one-turn beam intensity values are published by the BCCM systems with no beam in the machine. Their 1 s logged minimum, maximum and average should be within the following limits: – int_1T_Min ≥ -0.1×10^{11} *p+* – int_1T_Max ≤ 0.1×10^{11} *p+* – |int_1T_Avg| ≤ 0.01×10^{11} *p+* (|x| denotes the absolute value of x)
2	S C	Check that the beam intensity change values for the first one-turn integration window are published by the BCCM systems with no beam in the machine. Their 1 s logged minimum, maximum and average should be within the following limits: – d_Int_W1_Min ≥ -0.01×10^{11} *p+* – d_int_W1_Max ≤ 0.01×10^{11} *p+* – |d_int_W1_Avg| ≤ 0.01×10^{11} *p+*
3	S C	Check that the beam intensity change values for the second four-turn integration window are published by the BCCM systems with no beam in the machine. Their 1 s logged minimum, maximum and average should be within the following limits: – d_Int_W2_Min ≥ -0.01×10^{11} *p+* – d_int_W2_Max ≤ 0.01×10^{11} *p+* – |d_int_W2_Avg| ≤ 0.01×10^{11} *p+*
4	S C	Check that the beam intensity change values for the third 16-turn integration window are published by the BCCM systems with no beam in the machine. Their 1 s logged minimum, maximum and average should be within the following limits: – d_Int_W3_Min ≥ -0.01×10^{11} *p+* – d_int_W3_Max ≤ 0.01×10^{11} *p+* – |d_int_W3_Avg| ≤ 0.01×10^{11} *p+*
5	S C	Check that the beam intensity change values for the fourth 64-turn integration window are published by the BCCM systems with no beam in the machine. Their 1 s logged minimum, maximum and average should be within the following limits: – d_Int_W4_Min ≥ -0.01×10^{11} *p+* – d_int_W4_Max ≤ 0.01×10^{11} *p+* – |d_int_W4_Avg| ≤ 0.01×10^{11} *p+*

6	S C	Check that the beam intensity change values for the fifth 225-turn integration window are published by the BCCM systems with no beam in the machine. Their 1 s logged minimum, maximum and average should be within the following limits: – d_Int_W5_Min $\geq -0.01 \times 10^{11}$ *p+* – d_int_W5_Max $\leq 0.01 \times 10^{11}$ *p+* – |d_int_W5_Avg| $\leq 0.01 \times 10^{11}$ *p+*
7	S C	Check that the beam intensity change values for the sixth 1125-turn integration window are published by the BCCM systems with no beam in the machine. Their 1 s logged minimum, maximum and average should be within the following limits: – d_Int_W6_Min $\geq -0.01 \times 10^{11}$ *p+* – d_int_W6_Max $\leq 0.01 \times 10^{11}$ *p+* – |d_int_W6_Avg| $\leq 0.01 \times 10^{11}$ *p+*
8	S C	Check that the logged state of the actual beam energy read from the SMP is the low energy range below 0.5 TeV. This is indicated as beamEnergyFlag = 0.
9	S C	Manually turn off the reception of SMP energy information by setting filed forceBeamEnergyFlagRangeB = true in property ExpertCommand. The lack of this information switches the system to operate in the high energy range of 0.5 TeV or more. Check that this is indicated as beamEnergyFlag = 3.
10	S C	Manually turn on the reception of SMP energy information by setting filed forceBeamEnergyFlagRangeB = true in property ExpertCommand. With no beam in the machine this action switches the system to operate in the low energy range below 0.5 TeV. Check that this is indicated as beamEnergyFlag = 0.

7.3 STATUS OF THE SYSTEM AFTER THE TESTS

After these tests, the system is as much checked as possible with no beam in the machine.

8. TESTS WITH BEAM

A number of tests must be performed on the BCCM system with beam to validate its protection functionality under real conditions. Before these tests, the LHC Beam Loss Monitoring system must be fully commissioned with beam and must reach its full performance.

The BCCM tests should be done with the minimal beam intensities allowing checking the tested system functionality. For some tests the beam dump thresholds need to be lowered to force the system to provoke a beam dump for beam loss rates much lower than the ones used during regular operation. This way one can avoid exposing the LHC machine for risks related to important beam losses while still performing full system testing.

Please note that changing the beam dump threshold levels does not affect the safe operation of the system, as the settings can only be lowered below the limits hardcoded in the system protected settings. In the worst case, the changed settings left for regular operation will lead to a beam dump with abnormally small intensity change rates and the beam dump thresholds will be reset to their default values during standard procedures preparing the BCCM for the next beam injection.

Beam signals from the BPMs do not change significantly with beam energy, especially for the range 0.45 – 0.5 TeV. Therefore, in order to perform almost all tests at 0.45 TeV also for the second BCCM energy range of 0.5 TeV or more, the BCCM system can be manually switched to operate in the high energy range with the smaller dump thresholds. This is done by switching off the reception of the SMP energy information. Again, this feature does not affect the safe operation of the system, as in the worst case the system will operate with the lower beam dump thresholds, which may cause a beam dump with abnormally small beam intensity change rates.

As the BCCM operation is based on BPM signals, the BCCM beam intensity readings are not fully independent of the beam position, bunch length and in particular bunch number per batch. This requires that the BCCM intensity readings have tolerance with respect to the reference FBCT data.

To simplify the safe implementation of the dump threshold levels summarised in Table 2 and monitoring of the system proper operation, the BCCM never underestimates the beam intensity and whether the overestimation is within tolerances is checked only with production beam conditions, meaning operation with the largest number of bunches per batch and the intensity at least $600 \times 10^{11}\ p+$, corresponding to 10 % of the system full dynamic range of about $6000 \times 10^{11}\ p+$. For smaller number of bunches per batch and lower beam intensity the overestimation can be larger, which may result in the system triggering beam dumps at lower thresholds than specified in Table 2. Typically, the larger bunch spacing, the larger BCCM intensity overestimation, with the maximal error for a single bunch.

The tolerances of intensity readings provided by the BCCM should be tested before other tests, to assure a good scaling of the beam intensity measured by the BCCM with respect to the FBCTs and, by consequence, appropriate application of the dump threshold levels. Because of the required beam conditions, it may be difficult to perform the intensity tolerance test just after an LHC restart. Potentially the test can be moved to the end of the BCCM commissioning at the expense of accepting a larger tolerance with which the beam dump thresholds are executed during the whole run.

Proper operation of the BCCM is monitored every beam dump regardless of its cause. If during the dump the beam intensity is above the one-turn dump threshold for the energy of the dumped beam, then the BCCM system must also issue a beam dump request. The triggering of the system shall be independently checked by a post-mortem module.

8.1 CONDITIONS REQUIRED TO PERFORM TESTS

- All BCCM hardware is operational.
- Distribution of the 400 MHz RF clock is operational.
- The system software is operational.
- Logging is operational.
- SMP beam energy distribution is operational.
- Beam Loss Monitoring system is fully commissioned and operational.

- Beam operation has been commissioned at least to the intensity required for the performed test.
- Fast beam current transformers are operational and well calibrated.

Please note that almost all tests related to the BCCM operation for energies 0.5 TeV or more are performed at the injection energy, with the system manually switched to the sensitivities required for the high energy range. Only the last test is done for the energy above 0.5 TeV with the intensity of 3×10^{11} $p+$ and for the test the energy ramp must have been commissioned at least up to this intensity.

8.2 TESTS AT THE INJECTION ENERGY, BEAM INTENSITY ABOVE 600×10^{11} AND THE LONGEST OPERATIONAL BATCHES

Tests described here are intendent to verify that the beam intensities provided by the BCCM system are within required tolerances with respect to the FBCTs and so are the beam dump thresholds.

The tests must be done with the largest number of bunches per batch used operationally. This condition assures that for shorter batches the BCCM system will never underestimate the beam intensity and, by consequence, the set dump thresholds will be never underestimated. The test involves only checking BCCM and FBCT readings. However, if the BCCM intensity readings are not accurate enough, then adjustments must be done to the factors scaling the BCCM raw intensity integrals to the absolute intensities in the units of 10^{11} $p+$. These factors are FPGA settings, copied from the corresponding FESA settings.

Longest operational batches may be difficult to use just after an LHC restart. Potentially the test can be moved to the end of the BCCM commissioning at the expense of accepting a larger tolerance with which the beam dump thresholds are executed during the whole run.

#	Rep.	Action
1	S E C	Check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading.
2	S E C	Check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not larger than the corresponding FBCT reading by more than 10 %.

8.3 TESTS AT THE INJECTION ENERGY AND INTENSITIES $3 - 10 \times 10^{11}$

Each test shall be done separately for each of the BCCM systems, namely B1-A, B2-A, B1-B and B2-B.

The tests will be done with beam intensities as measured by FBCTs corresponding to all dump threshold values appearing in Table 2, in the ascending order 3×10^{11}, 5×10^{11}, 6×10^{11} and 10×10^{11} $p+$.

The beam bunch configuration is not important for the tests.

The tests require 5 beam dumps.

8.3.1 TESTS WITH BEAM INTENSITY OF 3×10^{11}

The tests described in this section should be done with the FBCT beam intensity equal or greater than the smallest beam dump threshold value appearing in Table 2, namely 3×10^{11} $p+$ corresponding to the first four integration windows with respective lengths of 1, 4, 16, 64 turns and the high energy range of 0.5 TeV or more.

If the exact required beam intensity cannot be setup, then a larger value should be used.

Please note that the test is done at the injection energy and the dump thresholds are manually switched to the high energy range of 0.5 TeV or more.

#	Rep.	Action
1	S E C	Check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading.
2	S E C	Manually turn off the reception of SMP energy information by setting filed forceBeamEnergyFlagRangeB = true in property ExpertCommand. The lack of this information switches the system to operate in the high energy range. Check that this is indicated as beamEnergyFlag = 3.
3	S E C	Dump the beam with the operator switch. Check that the BCCM system has issued beam dump requests for windows number 1, 2, 3, and 4. Check that the beam dump requests are reported in the logging as dumpFlagW1 = 1, dumpFlagW2 = 1, dumpFlagW3 = 1 and dumpFlagW4 = 1.

8.3.2 TESTS WITH BEAM INTENSITY OF 5×10^{11}

The tests described in this section should be done with the FBCT beam intensity equal or greater than 5×10^{11} $p+$, corresponding to the dump threshold for 5th integration window with length of 225 turns and the high energy range of 0.5 TeV or more.

If the exact required beam intensity cannot be setup, then a larger value should be used.

Please note that the test is done at the injection energy and the dump thresholds are manually switched to the high energy range of 0.5 TeV or more.

#	Rep.	Action
1	S E C	Check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading.

2	S E C	Manually turn off the reception of SMP energy information by setting filed forceBeamEnergyFlagRangeB = true in property ExpertCommand. The lack of this information switches the system to operate in the high energy range. Check that this is indicated as beamEnergyFlag = 3.
3	S E C	Dump the beam with the operator switch. Check that the BCCM system has issued beam dump requests for the 5th integration window, as well as all the windows having smaller threshold levels at the high energy range, namely windows number 1, 2, 3 and 4. Check that the beam dump requests are reported in the logging as dumpFlagW1 = 1, dumpFlagW2 = 1, dumpFlagW3 = 1, dumpFlagW4 = 1 and dumpFlagW5 = 1.

8.3.3 TESTS WITH BEAM INTENSITY OF 6×10^{11}

The tests described in this section should be done with the FBCT beam intensity equal or greater than 6×10^{11} $p+$, corresponding to the dump threshold of the first five integration windows with respective lengths of 1, 4, 16, 64, 225 turns and the low energy range below 0.5 TeV.

If the exact required beam intensity cannot be setup, then a larger value should be used.

#	Rep.	Action
1	S E C	Check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading.
2	S E C	Check that the BCCM system operates in the low energy range, which is indicated as beamEnergyFlag = 0.
3	S E C	Dump the beam with the operator switch. Check that the BCCM system has issued beam dump requests for windows number 1, 2, 3, 4 and 5. Check that the beam dump requests are reported in the logging as dumpFlagW1 = 1, dumpFlagW2 = 1, dumpFlagW3 = 1, dumpFlagW4 = 1 and dumpFlagW5 = 1.

8.3.4 TESTS WITH BEAM INTENSITY OF 10×10^{11}

The tests described in this section should be done with the FBCT beam intensity equal or greater than 10×10^{11} $p+$, corresponding to the dump threshold of the last, 6th integration window with length of 1125 turns, and valid for both energy ranges. If the exact required beam intensity cannot be setup, then a larger value should be used.

Please note that for this intensity there are done tests for both energy ranges. Tests for the high energy range of 0.5 TeV or more are done also at the injection energy with the dump thresholds switched manually.

#	Rep.	Action
1a	S E C	Check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading.

1b	SEC	Check that the BCCM system operates in the low energy range, which is indicated as beamEnergyFlag = 0.
1c	SEC	Dump the beam with the operator switch. Check that the BCCM system has issued a beam dump request for the 6th integration window, as well as all the windows having smaller threshold levels at the low energy range, namely all remaining windows number 1, 2, 3, 4 and 5. Check that the beam dump request is also reported in the logging as dumpFlagW1 = 1, dumpFlagW2 = 1, dumpFlagW3 = 1, dumpFlagW4 = 1, dumpFlagW5 = 1 and dumpFlagW6 = 1.
2a	SEC	Refill the machine and check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading.
2b	SEC	Manually turn off the reception of SMP energy information by setting filed forceBeamEnergyFlagRangeB = true in property ExpertCommand. The lack of this information switches the system to operate in the high energy range. Check that this is indicated as beamEnergyFlag = 3.
2c	SEC	Dump the beam with the operator switch. Check that the BCCM system has issued a beam dump request for the 6th integration window, as well as all the windows having smaller threshold levels at the high energy range, namely all remaining windows number 1, 2, 3, 4 and 5. Check that the beam dump request is also reported in the logging as dumpFlagW1 = 1, dumpFlagW2 = 1, dumpFlagW3 = 1, dumpFlagW4 = 1, dumpFlagW5 = 1 and dumpFlagW6 = 1.

8.4 TESTS AT THE INJECTION ENERGY AND BEAM INTENSITY ABOVE 300×10^{11}

Tests described earlier are performed with beam losses caused by standard beam dumps causing the whole beam intensity to be removed within one machine turn, so that they are relevant for thorough testing only the first window with the beam intensity integrated during one machine turn.

The tests described in this section aim at checking the protection action of the BCCM system for all remaining integration windows. Instead of generating beam loss rates as stated in Table 2, the beam thresholds will be manually lowered to provoke beam dumps upon the noise of the beam intensity measurement at the injection energy. In order to have a sufficient noise level, it is required to have in the machine circulating beam of the total intensity above 300×10^{11} $p+$ as measured by the FBCTs, corresponding to 5 % of the system full dynamic range of about 6000×10^{11} $p+$.

The beam bunch configuration is not important for the tests.

After each test a beam dump is generated and for the next test the machine must be refilled.

The tests will start from the high energy range of 0.5 TeV or more forced manually and windows number 2, 3, and 4 having in Table 2 the lowest dump threshold levels, followed by the cases with ascending dump threshold values.

The tests require 10 beam dumps.

#	Rep.	Action
1a	S C	Prepare circulating beam at the injection energy with the intensity above 300×10^{11} *p+* to test window number 2 at the high energy range.
1b	S C	Check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading.
1c	S C	Manually turn off the reception of SMP energy information by setting filed forceBeamEnergyFlagRangeB = true in property ExpertCommand. The lack of this information switches the system to operate in the high energy range. Check that this is indicated as beamEnergyFlag = 3.
1d	S C	By changing the value of parameter dumpLevelW2B, keep lowering the beam dump threshold for the 2nd integration window and the high energy range, until a beam dump is triggered. The operational value of the adjusted parameter will be automatically reset during preparations of the BCCM system for the next beam injection.
2a	C	Prepare circulating beam at the injection energy with the intensity above 300×10^{11} *p+* to test window number 3 at the high energy range.
2b	C	Check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading.
2c	C	Manually turn off the reception of SMP energy information by setting filed forceBeamEnergyFlagRangeB = true in property ExpertCommand. The lack of this information switches the system to operate in the high energy range. Check that this is indicated as beamEnergyFlag = 3.
2d	C	By changing the value of parameter dumpLevelW3B, keep lowering the beam dump threshold for the 3rd integration window and the high energy range, until a beam dump is triggered. The operational value of the adjusted parameter will be automatically reset during preparations of the BCCM system for the next beam injection.
3a	C	Prepare circulating beam at the injection energy with the intensity above 300×10^{11} *p+* to test window number 4 at the high energy range.
3b	C	Check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading.
3c	C	Manually turn off the reception of SMP energy information by setting filed forceBeamEnergyFlagRangeB = true in property ExpertCommand. The lack of this information switches the system to operate in the high energy range. Check that this is indicated as beamEnergyFlag = 3.
3d	C	By changing the value of parameter dumpLevelW4B, keep lowering the beam dump threshold for the 4th integration window and the high energy range, until a beam dump is triggered. The operational value of the adjusted parameter will be automatically reset during preparations of the BCCM system for the next beam injection.
4a	C	Prepare circulating beam at the injection energy with the intensity above 300×10^{11} *p+* to test window number 5 at the high energy range.
4b	C	Check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading.
4c	C	Manually turn off the reception of SMP energy information by setting filed forceBeamEnergyFlagRangeB = true in property ExpertCommand. The lack of this information switches the system to operate in the high energy range. Check that this is indicated as beamEnergyFlag = 3.
4d	C	By changing the value of parameter dumpLevelW5B, keep lowering the beam dump threshold for the 5th integration window and the high energy range until a beam dump is triggered. The operational value of the adjusted parameter will be automatically reset during preparations of the BCCM system for the next beam injection.

5a	S C	Prepare circulating beam at the injection energy with the intensity above 300×10^{11} $p+$ to test window number 2 at the low energy range.
5b	S C	Check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading.
5c	S C	Check that the BCCM system operates in the low energy range, which is indicated as beamEnergyFlag = 0.
5d	S C	By changing the value of parameter dumpLevelW2A, keep lowering the beam dump threshold for the 2nd integration window and the low energy range, until a beam dump is triggered. The operational value of the parameter will be automatically reset during preparations of the BCCM system for the next beam injection.
6a	C	Prepare circulating beam at the injection energy with the intensity above 300×10^{11} $p+$ to test window number 3 at the low energy range.
6b	C	Check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading.
6c	C	Check that the BCCM system operates in the low energy range, which is indicated as beamEnergyFlag = 0.
6d	C	By changing the value of parameter dumpLevelW3A, keep lowering the beam dump threshold for the 3rd integration window and the low energy range, until a beam dump is triggered. The operational value of the parameter will be automatically reset during preparations of the BCCM system for the next beam injection.
7a	C	Prepare circulating beam at the injection energy with the intensity above 300×10^{11} $p+$ to test window number 4 at the low energy range.
7b	C	Check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading.
7c	C	Check that the BCCM system operates in the low energy range, which is indicated as beamEnergyFlag = 0.
7d	C	By changing the value of parameter dumpLevelW4A, keep lowering the beam dump threshold for the 4th integration window and the low energy range, until a beam dump is triggered. The operational value of the parameter will be automatically reset during preparations of the BCCM system for the next beam injection.
8a	C	Prepare circulating beam at the injection energy with the intensity above 300×10^{11} $p+$ to test window number 5 at the low energy range.
8b	C	Check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading.
8c	C	Check that the BCCM system operates in the low energy range, which is indicated as beamEnergyFlag = 0.
8d	C	By changing the value of parameter dumpLevelW5A, keep lowering the beam dump threshold for the 5th integration window and the low energy range, until a beam dump is triggered. The operational value of the parameter will be automatically reset during preparations of the BCCM system for the next beam injection.
9a	C	Prepare circulating beam at the injection energy with the intensity above 300×10^{11} $p+$ to test window number 6 at the low energy range.
9b	C	Check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading.
9c	C	Check that the BCCM system operates in the low energy range, which is indicated as beamEnergyFlag = 0.

9d	C	By changing the value of parameter dumpLevelW6A, keep lowering the beam dump threshold for the 6th integration window and the low energy range until a beam dump is triggered. The operational value of the adjusted parameter will be automatically reset during preparations of the BCCM system for the next beam injection.
10a	C	Prepare circulating beam at the injection energy with the intensity above 300×10^{11} $p+$ to test window number 6 at the high energy range.
10b	C	Check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading.
10c	C	Manually turn off the reception of SMP energy information by setting filed forceBeamEnergyFlagRangeB = true in property ExpertCommand. The lack of this information switches the system to operate in the high energy range. Check that this is indicated as beamEnergyFlag = 3.
10d	C	By changing the value of parameter dumpLevelW6B, keep lowering the beam dump threshold for the 6th integration window and the high energy range, until a beam dump is triggered. The operational value of the parameter will be automatically reset during preparations of the BCCM system for the next beam injection.

8.5 TESTS AT THE ENERGY ABOVE 0.5 TeV AND BEAM INTENSITY 3×10^{11}

To check the operation of the system for the higher energy range without manual switching the system sensitivity one test per system shall be performed at the energy above 0.5 TeV.

Each test shall be done separately for each of the BCCM systems, namely B1-A, B2-A, B1-B and B2-B.

The tests described in this section should be done with the beam intensity corresponding to the one-turn beam dump threshold for the high energy range of 0.5 TeV or more, namely 3×10^{11} $p+$. If the exact required beam intensity cannot be setup, then a larger value should be used.

The beam bunch configuration is not important for the test.

The tests require one beam dump.

#	Rep.	Action
1	S C	Check that the beam intensity as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading.
2	S C	Start the energy ramp.
3	S C	When the beam energy is at least 0.6 TeV, dump the beam with the operator switch. Check that the BCCM system has also issued a beam dump request for the first one-turn integration window. Check that the beam dump request is reported in the logging as dumpFlagW1 = 1. Check that the system switched to the high energy range when the beam energy was transiting 0.5 TeV. This is indicated in the logging by the beam energy flag beamEnergyFlag changing its state from 0 to 1.

8.6 TESTS WITH BEAM AT EVERY DUMP

Proper operation of the BCCM is monitored every beam dump regardless of its cause. If just before the dump the beam intensity is above the one-turn dump threshold, then the BCCM system should also issue a beam dump request.

#	Rep.	Action
1	D	Check that the beam intensity of 3×10^{11} *p+* or more as measured by the BCCM system and reported by parameter int1TAvg is not smaller than the corresponding FBCT reading. BCCM intensity readings below 3×10^{11} *p+* are not important for the system operation and therefore should not be systematically checked.
2	D	Check that the BCCM system has issued a dump request for the low beam energy range below 0.5 TeV if the intensity as measured by the FBCT was larger than 6×10^{11} *p+*.
3	D	Check that the BCCM system has issued a dump request for the high beam energy range of 0.5 TeV or more if the intensity as measured by the FBCT was larger than 3×10^{11} *p+*.

8.7 STATUS OF THE SYSTEM AFTER THE TESTS

After these tests with beam, the BCCM system can be used as an LHC machine protection system.

Please note that each beam dump is followed by automatic procedures preparing the BCCM system for the next beam injection. During the procedures all the system settings are initialised to their default values. Therefore, the system settings will automatically return to their default settings as long as the tests with beam described in this chapter are followed by a beam dump.

REFERENCES

[1] D. Belohrad et al., "The LHC Fast Beam Current Change Monitor", IBIC 2013, Oxford, UK, CERN-ACC-2013-0314, https://cds.cern.ch/record/1638370.

[2] E. Bravin et al., "Beam instrumentation for machine protection", 5th Evian Workshop on LHC beam operation, Evian-les-Bains, France, 2 - 4 June 2014, pp.171-176, https://cds.cern.ch/record/2295107.

[3] M. Krupa et al., "Summary of LHC MD 398: Verification of the dependence of the BCTF measurements on beam position and bunch length", CERN-ACC-Note-2015-0031, https://cds.cern.ch/record/2060850.

[4] M. Gasior et al., "Inclusion of Beam Current Change Monitor as part of LHC Machine Protection Backbone", LHC-BCCM-FS-0001, EDMS 2308155, https://edms.cern.ch/document/2308155.

[5] B. Todd and B. Puccio, "MPS Aspects of the Beam Interlock System Commissioning", LHC-OP-MPS-004, EDMS 889281, https://edms.cern.ch/document/889281.

[6] M. Gasior, T. Levens, "An LHC Protection System Based on Fast Beam Intensity Drops", 11th International Beam Instrumentation Conference (IBIC 2022), Cracow, Poland, 11 - 15 September 2022, pp.387-390, https://doi.org/10.18429/JACoW-IBIC2022-WEP06.

[7] C. Hernalsteens, "Proposal for adjusted BCCM thresholds", presented and endorsed at 230th Meeting of the Machine Protection Panel, CERN, 21 October 2022. Minutes in EDMS 3011789, https://edms.cern.ch/document/3011789.

[8] M. Gasior, T. Levens, "Installing A BCCM Development System During YETS 2022-2023", LHC-BCCM-EC-0002, EDMS 2817706, https://edms.cern.ch/document/2817706.

APPENDIX A: LIST OF LOGGED BCCM PARAMETERS

Each of the four BCCM systems, namely B1-A, B2-A, B1-B and B2-B has its own set of logged parameters. Their names are listed below.

Some comments to the logged parameters:

- Unit "FS" means "Full Scale" of the ADC and that the samples are normalised so that their values are in the range from 0 to 1.
- Unit "FS*T" means "Full Scale times turn" and is used for quantities related to one-turn sums of raw ADC samples, which is the measure of the integral of the beam current, before scaling it to the FBCT reading. ADC 40 MHz sampling is synchronous to the beam, so the sum is always calculated on 3564 ADC samples.
- Logging type "OC" means "on change". Such parameters are logged only when they change their values or if they do not change, once per hour, to make sure that the parameter is being logged.
- "1 s" logging means that the parameter is logged once per second.

Table 3: Names of most important logged BCCM parameters, which are identical for all four systems. In the logging database the names are preceded by a text identifying the system, namely LHC.BCCM.B1.A, LHC.BCCM.B2.A, LHC.BCCM.B1.B and LHC.BCCM.B2.B, respectively for systems B1-A, B2-A, B1-B and B2-B.

Name	Description	Unit	Type
sumRawNorm	factor normalising the BCCM intensity to the FBCTs	$10^{11}\,p+$	OC
sumRaw1TAvg	1 s average of 1-turn raw ADC sums	FS*T	1 s
sumRaw1TMax	1 s maximum of 1-turn raw ADC sums	FS*T	1 s
sumRaw1TMin	1 s minimum of 1-turn raw ADC sums	FS*T	1 s
sumRaw1TStd	1 s standard deviation of 1-turn raw ADC sums	FS*T	1 s
int1TAvg	1 s average of 1-turn intensity	$10^{11}\,p+$	1 s
int1TMax	1 s maximum of 1-turn intensity	$10^{11}\,p+$	1 s
int1TMin	1 s minimum of 1-turn intensity	$10^{11}\,p+$	1 s
int1TStd	1 s standard deviation of 1-turn intensity	$10^{11}\,p+$	1 s
rawMax	1 s maximum of raw ADC samples	FS	1 s
rawMin	1 s minimum of raw ADC samples	FS	1 s
RFclkPresFlag	presence flag for the 400 MHz RF clock	0 or 1	OC
beamEnergyFlag	0: low, 1:high, 2: high automatically, 3: high manually	0 or 1	OC
beamPresFlag	1 – beam present, 0 - no beam	0 or 1	OC
beamPresAmpl	raw ADC amplitude increase for BeamPresFlag =1	FS	OC
agRawMax	abort gap 1 s maximum of raw ADC samples	FS	1 s
agRawMin	abort gap 1 s minimum of raw ADC samples	FS	1 s
agLevel	abort gap average level of raw ADC samples	FS	1 s
agLock	ADC turn start synchronised to the abort gap	0 or 1	OC
intIIR	intensity from the system IIR filter	$10^{11}\,p+$	1 s
beamLT	beam lifetime	hour	1 s
	1-turn integration window (W1)		
dIntW1Avg	1 s average of the intensity change	$10^{11}\,p+$	1 s
dIntW1Max	1 s maximum of the intensity change	$10^{11}\,p+$	1 s
dIntW1Min	1 s minimum of intensity change	$10^{11}\,p+$	1 s

dIntW1Std	1 s standard deviation of the intensity change	10^{11} p+	1 s
dumpLevelW1A	dump threshold for the energy range below 0.5 TeV	10^{11} p+	1 s
dumpLevelW1B	dump threshold for the energy range 0.5 TeV or more	10^{11} p+	OC
dumpFlagW1	dump request flag	0 or 1	OC
	4-turn integration window (W2)		
dIntW2Avg	1 s average of the intensity change	10^{11} p+	1 s
dIntW2Max	1 s maximum of the intensity change	10^{11} p+	1 s
dIntW2Min	1 s minimum of intensity change	10^{11} p+	1 s
dIntW2Std	1 s standard deviation of the intensity change	10^{11} p+	1 s
dumpLevelW2A	dump threshold for the energy range below 0.5 TeV	10^{11} p+	1 s
dumpLevelW2B	dump threshold for the energy range 0.5 TeV or more	10^{11} p+	OC
dumpFlagW2	dump request flag	0 or 1	OC
	16-turn integration window (W3)		
dIntW3Avg	1 s average of the intensity change	10^{11} p+	1 s
dIntW3Max	1 s maximum of the intensity change	10^{11} p+	1 s
dIntW3Min	1 s minimum of intensity change	10^{11} p+	1 s
dIntW3Std	1 s standard deviation of the intensity change	10^{11} p+	1 s
dumpLevelW3A	dump threshold for the energy range below 0.5 TeV	10^{11} p+	1 s
dumpLevelW3B	dump threshold for the energy range 0.5 TeV or more	10^{11} p+	OC
dumpFlagW3	dump request flag	0 or 1	OC
	64-turn integration window (W4)		
dIntW4Avg	1 s average of the intensity change	10^{11} p+	1 s
dIntW4Max	1 s maximum of the intensity change	10^{11} p+	1 s
dIntW4Min	1 s minimum of intensity change	10^{11} p+	1 s
dIntW4Std	1 s standard deviation of the intensity change	10^{11} p+	1 s
dumpLevelW4A	dump threshold for the energy range below 0.5 TeV	10^{11} p+	1 s
dumpLevelW4B	dump threshold for the energy range 0.5 TeV or more	10^{11} p+	OC
dumpFlagW4	dump request flag	0 or 1	OC
	225-turn integration window (W5)		
dIntW5Avg	1 s average of the intensity change	10^{11} p+	1 s
dIntW5Max	1 s maximum of the intensity change	10^{11} p+	1 s
dIntW5Min	1 s minimum of intensity change	10^{11} p+	1 s
dIntW5Std	1 s standard deviation of the intensity change	10^{11} p+	1 s
dumpLevelW5A	dump threshold for the energy range below 0.5 TeV	10^{11} p+	1 s
dumpLevelW5B	dump threshold for the energy range 0.5 TeV or more	10^{11} p+	OC
dumpFlagW5	dump request flag	0 or 1	OC
	1125-turn integration window (W6)		
dIntW6Avg	1 s average of the intensity change	10^{11} p+	1 s
dIntW6Max	1 s maximum of the intensity change	10^{11} p+	1 s
dIntW6Min	1 s minimum of intensity change	10^{11} p+	1 s
dIntW6Std	1 s standard deviation of the intensity change	10^{11} p+	1 s
dumpLevelW6A	dump threshold for the energy range below 0.5 TeV	10^{11} p+	1 s
dumpLevelW6B	dump threshold for the energy range 0.5 TeV or more	10^{11} p+	OC
dumpFlagW6	dump request flag	0 or 1	OC