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Functional Specification

Interlocking of LHC BTV Screens

Abstract

Beam Television (BTV) screens will be used in the LHC for commissioning; injection studies and for monitoring the operation of the beam dump. The screens have limits on the circulating and single shot intensity which can be survived, given by thermal constraints. The interlocking of the screens must ensure that these limits are respected, while allowing the maximum flexibility for their diagnostic use. For the injection and matching screens their use will require a particular machine mode, 'inject and dump', where the beam is dumped shortly following injection, after a programmed number of turns. This document recalls the function of the different screens, defines the requirements for the interlocking and specifies the functionality required for the different related machine subsystems, including hardware and software interlocking and the LHC sequencer.

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1. SCOPE OF THIS SPECIFICATION

BTV screens will be used in the LHC for commissioning, injection studies and for monitoring the operation of the LHC Beam Dump System (LBDS). The screens have limits on the circulating and single shot intensity which can be survived, given by thermal constraints. The interlocking of the screens must ensure that these limits are respected, while allowing the maximum flexibility for their diagnostic use. For the injection and matching screens their use will require a particular machine mode, ‘inject and dump’, where the beam is dumped shortly following injection, after a programmed number of turns. This document:

- describes the different LHC screens and their functions;
- defines the limits on beam intensity for their use;
- defines the requirements for the hardware interlocking;
- defines the requirements for the software interlocking;
- specifies the functionality required for the other related machine subsystems, including the LHC sequencer and the new ‘Inject and Dump’ system.

2. BEAM PROFILE SCREENS IN THE LHC

2.1 INJECTION SYSTEM SCREENS IN LSS2 AND LSS8

A total of four BTVI monitors of three different types [1] are installed in each of the injection regions in LSS2 and LSS8, at the exit of the injection septa MSI, at the entry and exit of the injection kickers MKI, and in front of the injection collimator TDI. All the monitors are common to the circulating beam vacuum and are equipped with both Ti OTR and AL_2O_3 luminescence screens. For compatibility with high intensity circulating beam the screens must be retracted with the dummy chamber in place to ensure the continuity of the vacuum chamber, for impedance reasons.

The aperture available to the beam is reduced in the injection area. The measurement of the beam position and beam size is therefore required, for 450 GeV injected beam. In addition, the profile measurement offers an easy means of checking the kick angles of the injection magnets. These screens are only planned for use in single-pass mode.

2.2 FIRST ARC TRAVERSAL SCREEN FOR BEAM 2 IN LSS7

A profile monitor is installed in LSS7 between quadrupoles Q6 and Q7 to verify the traversal of the first arc for beam 2 with 450 GeV beam in single-pass mode [1]. The monitor is common to the circulating beam vacuum and is equipped with both Ti OTR and AL_2O_3 luminescence screens. For compatibility with high intensity (i.e. unsafe) circulating beam the screens must be retracted with the dummy chamber in place.

2.3 MATCHING MEASUREMENT SCREENS IN LSS3 AND LSS4

There are two BTVM monitors in LSS3 near Q7 and two in LSS4 near Q6, one for each beam in both insertions. These are equipped with both Ti OTR and AL_2O_3 luminescence screens, and are intended for the measurement of possible injection betatron or dispersion mismatch, over a number of injected turns with 450 GeV beam [1]. For compatibility with high intensity circulating beam the screens must be retracted with the dummy chamber in place.

2.4 LBDS SYSTEM SCREENS

For each of the two dump lines three types of screen monitors are installed [2]: the BTVSE upstream of the extraction septum MSD, which shares the circulating beam vacuum chamber, the BTVD after the dilution kickers MKD, and the large diameter BTVDD just before the dump block TDE. The BTVSE and BTVD screens are equipped with both Ti Optical Transition Radiation (OTR) and Al_2O_3 luminescence screens, while the BTVDD screen is equipped with a fixed Al_2O_3 screen. All screens are used in single-pass mode with 450 GeV to 7 TeV beams. For compatibility with high intensity circulating beam the BTVSE screen must be retracted with a dummy chamber in place.

The screens will be used to control and optimise the position of the extracted beam inside the extraction channel to ensure the best possible transmission efficiency. The swept beam position should be determined along the extraction line with the BTVD and BTVDD BTV screens. The BTVDD is used to determine the trace of the swept beam on the front face of the dump block TDE, over the full intensity and energy range, to verify the correct operation of the dilution kickers. The BTVSE and BTVD screens must be retracted at high intensity/energy.

3. LIMITATIONS ON THE SCREEN USE

3.1 GENERAL LIMITS ON PROTON DENSITY

The limits for the proton beam density for the different screens have been estimated from temperature limits and rough thermal-stress analysis, assuming no safety margin:

- for the 12 μm thick Ti foils the limits are:
  - 10^{10} p+/mm^2 for a circulating beam (although probably limited by blow-up);
  - 10^{14} p+/mm^2 single shot;
- for 1 mm thick Al_2O_3 screens the limits are:
  - No use with circulating beam;
  - 10^{13} p+/mm^2 single shot;

The beam size scales inversely with the square root of the beam energy, which increases directly the density for a given beam intensity. Otherwise the limits above do not change with energy.

For use with a limited number of turns, for example for the mismatch monitors, it is assumed that the product of the turns and the single-shot density must be less than the limits given above for a single shot.

3.2 SPECIFIC OPERATIONAL LIMITS ON INTENSITY AND TURNS

3.2.1 INJECTION AND IR7 ARC TRAVERSAL SCREENS BTVSI

For nominal optics, the p+ density at the injection and IR7 screens for an injected nominal batch of ~3×10^{13} p+ is ~1×10^{13} p+/mm^2. Taking a factor of about 2 safety margin and the density limits given in 3.1, the product of the turns with the intensity at 450 GeV must therefore be at maximum:

- ~1.5×10^{14} [p+ $\times$ turns] for the Ti screens;
- ~1.5×10^{13} [p+ $\times$ turns] for the Al_2O_3 screens.

The BTVSI screens are only to be used for 450 GeV energy.

3.2.2 MATCHING SCREENS BTVM

The minimum beta functions are similar in amplitude to those at the BTVSI monitors. Therefore at 450 GeV the product of the turns with the intensity must be at maximum:

- ~1.5×10^{14} [p+ × turns] for the Ti screens;
- ~1.5×10^{13} [p+ × turns] for the Al_2O_3 screens.

The BTVM screens are only to be used for 450 GeV energy.

3.2.3 LBDS SCREENS

For the dump screens, used at different energies and with different beam sweeps, the maximum proton density is found by numerically superposing the distributions given by the local β functions using the calculated positions of the swept bunches and finding the maximum density [3]. The calculated proton densities at 450 GeV and 7 TeV are shown below in Table 1 for a single nominal bunch of 1.15×10^{11} p+. Table 2 shows the case of a sweep with a 2808 bunches with nominal intensity. Tables 3-5 show the p+ densities at the screens for the cases of MKBH, MKBV and total dilution failures.

Table 1. p+ densities at the TD line screens for a single nominal bunch.

bunches	**Single bunch density p+/mm2**	
1	450 GeV	7000 GeV
BTVSE	1.9E+10	2.9E+11
BTVD	1.3E+10	2.0E+11
BTVDD	8.2E+08	1.3E+10

Table 2. p+ densities at the TD line screens for nominal 2808 bunch sweep.

bunches	**Nominal sweep density p+/mm2**	
2808	450 GeV	7000 GeV
BTVSE	4.2E+13	2.9E+14
BTVD	3.1E+12	1.5E+13
BTVDD	4.2E+10	1.9E+11

Table 3. p+ densities at the TD line screens for 2808 bunch sweep with no MKBH dilution.

bunches	**No MKBH sweep density p+/mm2**	
2808	450	7000
BTVSE	4.2E+13	2.9E+14
BTVD	9.9E+12	4.9E+13
BTVDD	3.6E+11	1.5E+12

Table 4. p+ densities at the TD line screens for 2808 bunch sweep with no MKBV dilution.

bunches	**No MKBV sweep density p+/mm2**	
2808	450	7000
BTVSE	4.2E+13	2.9E+14
BTVD	1.5E+13	7.6E+13
BTVDD	4.6E+11	2.0E+12

Table 5. p+ densities at the TD line screens for 2808 bunch sweep with no dilution.

bunches	**No MKB sweep density p+/mm2**	
2808	450	7000
BTVSE	4.2E+13	2.9E+14
BTVD	3.7E+13	2.0E+14
BTVDD	2.8E+12	1.4E+13

Comparing the numbers in Tables 1-5 with the limits in 3.1, and allowing a factor 2 safety margin, the following conclusions can be drawn:

- All screens can operate safely with 3×10^{12} p+ at 7 TeV (17 ultimate bunches);
- BTVDD (Al_2O_3) monitors:
  - Fixed, so no interlocking;
  - Safe for nominal sweep up to ultimate intensity at 7 TeV;
  - Damaged for total dilution failure beyond 6×10^{10} p+/bunch (with 2808 bunches) at 7 TeV;
- BTVD monitors:
  - Ti screen;
    - Safe for nominal sweep up to ultimate intensity at 7 TeV;
    - Damaged for total dilution failure, beyond 4.2×10^{10} p+/bunch at 7 TeV;
  - Al_2O_3 screen;
    - Safe for nominal sweep for ultimate intensity at 450 GeV
    - Damaged for nominal sweep above 5.5×10^{10} p+/bunch at 7 TeV;
    - Damaged for MKBH, MKBV or total dilution failure;
- BTVSE monitors:
  - Ti screen;
    - Safe for nominal sweep at 450 GeV;
    - Damaged above 2.9×10^{10} p+/bunch at 7 TeV;
  - Al_2O_3 screen;
    - Damaged above 2×10^{10} p+/bunch at 450 GeV;
    - Damaged above 2.9×10^{9} p+/bunch at 7 TeV;

3.3 OTHER CONSIDERATIONS

All screens which share a common beampipe with the circulating beam must be in the out position for high intensity (unsafe) circulating beam operation, with the dummy chamber in place to ensure the continuity of the vacuum chamber, for impedance reasons.

4. INTERLOCKING REQUIREMENTS

4.1.1 INJECTION AND IR7 ARC TRAVERSAL SCREENS BTVSI, AND MATCHING SCREENS BTVM

The proposal is to only allow these screens to be used when the LHC is operating with safe beam (assumed to be less than 10^{12} p+), and in “Inject and Dump” mode, and with a number of turns requested from the “Inject and Dump” system which respects the safe limit depending on screen type given in 3.2.1. This means 150 turns with a Ti screen and 15 turns with the Al_2O_3 screen for a safe beam of 10^{12} p+. The actual interlocks required are:

- Hardware interlock from the screen crate to the BIS to inhibit the user permit if a screen is not in the OUT position. This interlock must be masked by the safe beam flag;
- A software interlock in the SIS system which checks the “Inject and Dump” turns requested, the SPS intensity and the screen type to allow or inhibit injection via the SW channel of the IR2 and IR8 injection BICs;

- A HW interlock using (the existing?) BLMs at each screen, with an interlock threshold at an appropriate integration time, to dump the beam if losses detected exceed the dangerous level;

Other related precautions which need to be implemented are:

- A sequencer check to ensure that: LHC mode = "Inject and dump", correct turns are loaded into the Inject and Dump crate, beam intensity requested = safe;
- Limit the maximum number of turns to 1000 in Inject & Dump hardware;
- While in "Inject and Dump" mode always include a "Dump Beam" timing event one ms after the hardware-counter dump should occur. This limits the number of unwanted extra turns to about 10-20, in case the counter-based system fails to trigger the beam dump.

4.1.2 LBDS SCREENS

The proposal is to prohibit any movement of these screens when beam is present in the LHC. The sequencer and the software interlocking system must combine to ensure that the screen type which can be used is consistent with the beam and energy conditions which will be used for the coming fill. The actual interlocks required are:

- Hardware signal to BIS from screen front-end to dump beam if any screen starts moving (before any movement happens);
- SW interlocking at the screen front-end to prevent moving with beam in the LHC, using the general beam permit distributed by the BIS;
- Software interlocks to beam dump if intensity / energy conditions are violated during a fill (note that this should be configured to the 7 TeV settings, so that dumps are not generated during the ramp – this means that when a screen is in, a beam may be dumped at injection if the intensity gets too high – possibly this constraint could be circumvented if required by allowing injection with higher intensity provided a programmed dump event is present in the ramp before the beam gets dangerous for the screen);
    - BTVSE;
        - Ti Screen: cannot use above an intensity of 5×10^{13} p+ at 7 TeV;
        - Al_2O_3 screen: cannot use above an intensity of 3×10^{13} p+ at 450 GeV, 3×10^{12} p+ at 7 TeV;
    - BTVD;
        - TI screen: no SW interlocking condition on intensity– can be used at all times;
        - Al_2O_3 screen: cannot use above an intensity of 1×10^{14} p+ at 7 TeV;

Other related precautions which need to be implemented are:

- The LHC sequencer to make explicit checks prior to injection, to ensure that the screen positions are coherent with the proposed fill intensity and maximum energy. It should be noted that this implies a set of target or run parameters for each fill.

5. "INJECT AND DUMP" MODE FOR <1000 TURNS

This mode is used for injection setting-up and will use a hardware system to trigger the beam dump via the BIS: it is necessary to have the possibility to dump after less than one full turn of the LHC, in order to ensure that the injection setting up with the screens can be performed with a single beam impact. To protect the screens, the maximum number of turns possible in this mode should be limited to 15 or 150 (depending on screen type), assuming a safe beam limit of 1 10^{12} p+.

The mode will also be used for studies requiring less than 100 ms of circulating beam, for example aperture measurements in the beam dump extraction channel.

This mode can only be used with the Safe Beam from the SPS.

i. Machine mode is changed to "Inject and Dump" by the LHC sequencer;
ii. Number of turns selected between 0 and 1000 and loaded into the Inject and Dump hardware, requested by the LHC sequencer via the appropriate API;
iii. "Inhibit Post-Mortem request timing event set at 1 ms before the expected dump;
iv. "Programmed dump" Timing event delay set at 1 ms after the expected dump;
v. Checks are made by the LHC sequencer of injection screen positions, requested beam intensity, screen types and requested turns resident in the Inject and Dump hardware - injection is inhibited if:
    a. The screens are IN and the beam requested is not Safe;
    b. The screens are IN and the mode is not "Inject and Dump I";
    c. The number of turns requested exceeds the safe limit for the requested intensity.
vi. Beam is injected and the turn-counter triggered in the Inject and Dump hardware;
vii. 1 ms before the expected dump, an "Inhibit Post-Mortem request" timing event is sent out;
viii. After the programmed number of turns, the Inject and Dump Hardware triggers the beam dump by opening the beam permit loop;
ix. 1 ms later a "Request beam dump" timing event is sent out;

6. SUMMARY OF REQUIREMENTS ON OTHER SYSTEMS

6.1 LHC SEQUENCER

The sequencer [4] must provide the high-level management of the "Inject and Dump" machine mode. The following functionalities are required:

- managing machine mode changes;
- configuring all the systems to meet the entry conditions for the mode change;
- checking that the entry conditions are met;
- generating the timing events with the correct delays;
- setting the turn counter value;
- requesting checks before injection is enabled, in particular of the screen types, intensity, maximum fill energy, requested "Inject and Dump" turns and timing tables;
- requesting the correct beam from the SPS;
- arming and re-arming the LBDS;
- re-arming the BIS (tbc);
- inhibit the beam permit via the BIS to allow movement of screens without beam.

6.2 BEAM INTERLOCK SYSTEM

The BIS must have maskable inputs to allow the screens to be in beam with safe intensity. This is required for the BICs in IR2, IR3, IR4, IR7 and IR8. It is assumed that a separate non-maskable channel is not needed for each BIC for the "screen moving" input – it is assumed that the signal from the BTV front ends will be an OR of the "moving" or "in beam" condition of all the screens in one IR (in fact this is achieved if the "not OUT" signal is used).

6.3 SOFTWARE INTERLOCKING

The software interlocking will be needed to inhibit injection or dump the beam if the conditions are not correct. The requirements are:

- Injection, first turn and matching screens:
    - Inhibit injection if screens in beam and unsafe beam requested;
    - Inhibit injection if screens in beam and machine mode <> "Inject and Dump";
    - Inhibit injection if machine mode = "Inject and Dump I" AND SPS beam <> "Safe";
    - Inhibit injection if screens in beam and [turns × intensity] > 10^{13} (Al_2O_3) or 10^{14} (Ti);
- LBDS screens:
    - BTVSE;
        - Ti Screen: dump beam (at 450 GeV!) if proposed energy goes to 7 TeV at intensity $\geq 5\times10^{13}$;
        - Al_2O_3 screen: dump beam (at 450 GeV!) if intensity $\geq 3\times10^{13}$, or if proposed energy goes to 7 TeV at intensity $\geq 3\times10^{12}$;
    - BTVD;
        - Al_2O_3 screen: dump beam if energy goes to 7 TeV at intensity $\geq 1\times10^{14}$;

6.4 BEAM LOSS MONITORS

BLMs should be installed at the injection and matching screens, with interlock thresholds designed to dump the beam if the losses at injection indicate that the screen may risk damage. The threshold should be set to about 50% of the loss level corresponding to the assumed damage limit.

7. REFERENCES

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