OBJECTS CAPABLE OF TOUCHING THE BEAMS

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Abstract

The beams in the LHC can be intercepted by many different types of objects moving into the vacuum chambers. These include devices designed for beam monitoring, machine protection and for data taking by the experiments. Moving these objects can only be permitted under certain conditions. Interlocks should prevent quenches or even damage in case of wrong actions. A complete inventory of such devices will be given along with the conditions under which they can be moved and the interlocks, or signals, that are required to ensure that they cannot be activated at other times. A particular issue concerns the optics imperfections which can change significantly the safe position settings for a given mobile device. Controlling the orbit and beta-beating errors is therefore an important pre-requisite to commissioning protection devices and the collimation system.

INTRODUCTION

Many objects to be installed in the LHC ring and transfer lines will be capable of moving into the beam aperture. Under the right conditions this should pose no problem to the machine. For some objects this implies that there is no beam in the machine when the element moves into the aperture. Interlocks must be used to protect both the equipment itself and the machine when activation of mobile devices occurs under the wrong machine conditions. Such interlocks must safely remove the beam from the LHC before it can pose any danger to either element, or the machine.

In addition to interlocks – which provide protection – vetos should also be provided to avoid unnecessary down time for the accelerator. A veto can be used to prevent an element being moved if the safe conditions are not met. This approach would avoid the interlock firing and the beam being removed.

Two major types of elements will be present in the LHC: IN/OUT and Mobile devices. In this paper an inventory of all such devices is made with the conditions under which they may and may not be used.

IN/OUT DEVICES IN THE TRANSFER LINES

The conditions in the transfer lines are somewhat relaxed with respect to the ring since circulating beam is not present and only single pass events can occur. Even so, the full SPS batch delivered to the LHC is dangerous and suitable steps must be taken to avoid extraction of the beam if any element is wrongly positioned. In this case the interlocks must be connected to the SPS interlock system, not the LHC.

Stoppers & Dumps

In each of the LHC transfer lines there are 2 beam dumps (TED), one at the upstream and one at the downstream end of the line. In the case of TI 8 an additional safety stopper (TBSE) is installed. The normal operating mode for these elements is either OUT – to allow beam to pass, or IN to obstruct the beam passage completely. They are therefore built to withstand a full SPS batch to the LHC. In the case of the TED the beam can be repeatedly fired onto it. The TBSE should never see beam since it is one of the access safety elements for the transfer line. It can, however, mechanically withstand the occasional impact of a full SPS batch.

These elements take some time to move from OUT to IN and visa versa. In the case of the TED, the movement takes up to 82 seconds. During this 'MOVING' period extraction inhibits must be provided to prevent beam passing through a reduced aperture. In the past the TED in the extraction lines of the SPS have been provided with a software interlock to prevent such an occurrence.

Screens

Each transfer line has 9 screen mechanisms installed. These are in addition to those installed in the extraction channels of the SPS and the initial part of the transfer lines (TT40 and TT60). These screens will be used to measure the transverse profile of the beam. Several screens together can be used to extract information on the optics in the line.

As with the TED, the screen mechanisms can be IN, OUT, or MOVING. The same arguments to providing an extraction inhibit during screen movement apply. However, for the case where the screen is in the beamline, additional constraints apply.

Each mechanism is provided with two different screens. The OTR screen is very thin and can withstand a full SPS batch. The Aluminium screens cannot. In the case where Al screens are in use an intensity limit must be applied before allowing the extraction. In addition, the use of several screens (of either type) could produce significant blow-up of the beam. In this case safe injection into the LHC is more difficult. A cross interlock is therefore required. Hence, above certain intensities, the screens cannot be used if the beam is to be injected into the LHC. This might require the kickers to be cut or, more likely, the downstream TED to be in the beam.

Vacuum Valves

Each transfer line has a total of 7 vacuum valves for sectorisation of the vacuum system. These valves are activated by compressed air, but mechanically locked into the open or closed position. This means that failure of the compressed air supply will not cause the valves to close. Each valve has end switches for the open and closed position. These are connected in series to the valve interlock chain. As soon as a valve leaves the open position, the chain is broken and an extraction inhibit is generated. More details of valve operation are given in the next section.

IN/OUT RING DEVICES

Several different types of devices are installed in the LHC rings including vacuum valves, stoppers and a variety of beam instruments: screens, mirrors and wire scanners. Some of the beam instruments can be used with circulating beam in the machine, albeit with restrictions. In all other cases the movement of an element must result in the activation of an interlock leading to an immediate beam abort.

Vacuum Valves (Normal)

The behaviour of the normal vacuum valves has already been described in the previous section. A ring interlock is provided which connects all vacuum valves in the LHC rings to the beam interlock controllers. A total of 249 vacuum valves are installed in the LHC [1]. This corresponds to 110 valves per ring and 29 valves common to both rings.

In the case where the valve control system detects a pressure rise the surrounding valves will be closed. However, before sending the command to close the valves a request to fire the beam dump will be made. The vacuum control system will then wait for an OK status from the beam dump before beginning the valve closing procedure. Once initiated, the valve takes around 3 seconds to completely close. Since moving the valve also breaks the valve interlock chain, a redundant interlock is therefore provided to reduce the chance of the valve closing onto a circulating beam.

Since any manipulation of the valves will provoke an immediate beam abort, a veto on such actions in the presence of circulating beam is suggested. This would have to make use of a measurement of the beam intensity distributed around the machine. Such information should form part of the safe beam parameters of the machine protection system [2].

Vacuum Valves (Fast)

A recent engineering specification [3] has described two fast acting vacuum valves to be installed around LHCb (point 8). These would be different from the normal valves in two fundamental ways:

- In case of a vacuum pressure rise the valve will immediately begin to close, instead of issuing a request to the beam dump and waiting for the OK status back. However, a trigger to the beam interlock system will occur once the valve begins to close.
- Once triggered, the complete closure time for the valve is 13ms (or ~150 turns)

These valves represent a very real danger for the machine since a redundant request for the beam abort is not provided. Such a redundant request is very difficult to achieve by other means. As it closes the aperture the valve edge is moving at approximately 1 beam sigma per turn. If the beam dump trigger fails to generate a beam abort then the first indication of problems would occur once the edge of the valve begins to intercept the beam at, say, 8 σ. A complete catastrophic loss of the total beam would then occur over the following ~10 turns. This would produce significant damage around the machine as well as the complete destruction of the valve itself. Very little reaction time is available for beam loss monitors and the like. A careful study of these devices and the means to redundantly protect the machine from them is needed before they are installed in the machine.

Vacuum Valves (Passive)

Two passive valves will be installed around the Alice detector. These valves can only be opened, or closed, manually. However, complete remote status information is provided. These valves are also attached to the vacuum valve interlock chain.

RF Stoppers and Safety Stoppers

Four RF electron stoppers will be installed in IR4. These will be used during RF conditioning (NO BEAM) to protect people accessing the adjacent regions of the machine. At the time of writing the plan is to install 2 safety stoppers in the machine at IR6. These so-called ‘sacrificial blocks’ are required by the LHC access safety system [4]. It is possible that the required functionality will be combined with that of the RF stopper, thus negating the need for a special installation in point 6.

The RF electron stoppers and safety stoppers will make use of standard valve mechanisms and their interlock behaviour will be similar. However, since they are also surveyed by the LASS, it will not be possible to re-open them if the access and safety conditions do not permit.

Injection and Matching Screens

Five screens are provided for each injection channel of the LHC. These are placed around the septa, kickers and TDI in point 2 and point 6. In addition 2 matching monitors are installed in point 4 (one per ring). An additional matching monitor is installed in point 3 for beam 2. The total is therefore 13 mechanisms. Each is provided with an OTR screen. Most of the injection screens will see the beam only on a single pass. The others, together with the matching monitors are designed to observe the beam over multiple turns. In all cases, their use is incompatible with a circulating beam. Moving one of these screens in should provoke an immediate beam abort.

Intensity limits exist for the matching monitors. The limit is based on the total intensity and the number of turns. The following hardware limits have been noted [5]:

300 turns with $1\text{x}10^{+11}$ protons
2 turns with $3\text{x}10^{+13}$ protons

A veto/interlock must therefore be provided based on these limits. It should be noted that the information on the intensity must be read from the SPS and that the veto should take the form of an extraction inhibit in the SPS.

Wire Scanners

Four wire scanners will be installed in the LHC (1 per plane and per ring). These can be used with circulating beam with the following limits on the total intensity [5]:

450 GeV: 8x72 nominal bunches: $6.62\text{x}10^{+13}$
7 TeV: 2x72 nominal bunches: $1.66\text{x}10^{+13}$

It should be noted that the above limits refer to the hardware itself. There is no guarantee that the use of the wire scanners with such intensities will not provoke a quench in the machine.

Alignment Mirrors

Each ring will have a BEUV telescope. An alignment mirror forms part of each mechanism. This must be dropped into the beam aperture in order to perform the fine alignment of the optics. A veto is required to prevent the mirror being put in with circulating beam. In addition an interlock is desirable to prevent beam being re-injected with the mirror in place.

IN/OUT DEVICES IN THE DUMP LINES

The devices in the dump lines are slightly special since they are within the beam dump system itself. This imposes slightly different conditions on the interlocks and vetos associated with them.

Vacuum Valves

Each beam dump line contains 2 vacuum valves. The behaviour of these is identical to that described earlier. It should be clear that even though the valve will not intercept the circulating beam, a beam abort must be issued if one of these valves begins to close. Since the valves act rather slowly and the beam abort request is issues immediately a trigger is received, there should be no problem extracting the beam past the closing valve.

Screens

Three screens are provided for each beam dump line. The positions are:

- Upstream of the extraction septum
- Immediately downstream of the dilution kickers
- In front of the beam dump block.

These screens are used to adjust the settings of the extraction equipment: the first screen for the MKD, the second for the MSD and the last for the MKB. As such, it must be possible to have the screens in with beam. The final screen is permanently in place. However, the first two can be retracted. Since the beam hitting these screens is not yet diluted by the sweep of the MKB, they cannot stand full nominal intensities at top energy. The following is therefore required:

- A veto on moving the screens in with the intensity/energy combination over a certain limit (roughly half nominal intensity at 7 TeV).
- An inhibit preventing the acceleration of the beams if the intensity is above the limit mentioned in the previous bullet.

It should be noted that, while the screens are actually moving, a beam abort would not be completely clean. In the worst case some beam would be scattered from the frame of the screen and could cause damage or activation in the downstream elements. A study is needed to determine if the screen movement can be allowed with circulating beam in the LHC.

MOBILE DEVICES

Collimation and Protection

In phase 1 of the collimation system a total of 108 collimators and protection elements will be installed in the LHC and transfer lines. The numbers are split as follows:

• Collimation System (including absorbers):	78
• Aperture Protection (for dump problems):	4
• Protection elements for injection:	6
• Transfer line collimators:	14
• Other elements (scrapers):	6

The above numbers refer only to fully mobile devices. Many additional fixed blocks and passive absorber elements will also be present around the machine.

The majority of the collimator and protection elements have two jaws and two motors per jaw. Each will have a maximum and minimum position and end stop switches to protect the equipment.

In the case of a motor failure, the collimators and protection elements will react differently. For the collimators, the affected will retract and a beam dump request issued. The idea here is to avoid leaving an object stuck in the aperture of the machine. Depending on the importance of the affected collimator, operation may continue, or be stopped for repair.

For the protection elements the opposite is true. In case of motor failure here the element must remain in position – since retracting it would leave the machine unprotected. In this case, it is not necessary to issue an immediate beam dump since the conditions for the machine are still perfectly safe. A warning, however, would have to be issued. Beam operation would have to be suspended only when movement of the device is required to maintain the required level protection.

Examples of this might be the retraction of the injection elements before acceleration, or the movement of the TCDQ to protect the cold aperture during the squeeze. Failure to move as requested therefore would have to result in an immediate beam abort.

Other Mobile Devices

Several experimental detectors are planned that will move close to the beam during stable data taking periods. These include:

- Totem Roman Pots: 24 initially (eventually 36)
- Atlas Roman Pots: 8
- LHCb Velo: 1 Detector (2 jaws)
- Alice ZDC: 2 Detectors not in the machine vacuum.
- BBLR : Not baseline, but eventually 8 wires.

In terms of aperture the Totem Roman Pots are the most critical. The plan is to run them during stable beam periods with settings at around 10σ from the beam axis. This places them rather close to the aperture protected by the collimators. Their position must therefore be well known and carefully controlled, since relatively small position errors could lead to the roman pots becoming the primary aperture of the machine. An issue for the experimental detectors concerns who and from where the control will be exercised. In fact, regardless of this the interaction between the LHC machine protection elements and these devices must be very strong. In addition, a detailed knowledge of the state of the LHC is needed before permission can be granted to move these devices.

Conditions for Moving Mobile Devices

The collimators are principally in place to provide the necessary level of beam cleaning in order to avoid quenches of the cold magnets. They play the additional role of providing some protection in the case of abnormal operation. Additional protection elements are provided to fill the protection holes left by the collimators. In order to function correctly all these elements must be carefully positioned with respect to each other around the beam. An example of the required settings for 450 GeV is given in Tab. 1.

Table 1: Collimator and Protection Element Settings for 450 GeV Injection Conditions

a_{abs}	$10\ \sigma$	Active Absorbers
a_{sec3}	$9.3\ \sigma$	IR3 Secondary Collimators
a_{prim3}	$8.0\ \sigma$	IR3 Primary Collimators
a_{ring}	$7.5\ \sigma$	Ring Cold Aperture
a_{prot}	$6.8\text{-}7.0\ \sigma$	Protection Elements
a_{sec}	$6.7\ \sigma$	IR7 Secondary Collimators
a_{prim}	$5.7\ \sigma$	IR7 Primary Collimators
a_{TL}	$4.5\ \sigma$	Transfer Line Collimators (ring Protection at $6.9\ \sigma$)

The positions of each collimator computed from such a list forms a coherent set, or file, of settings. May datasets of this type can exist. In addition, different sets will be required at different points in the operational cycle of the machine; notably injection, acceleration, squeeze and physics.

Although the positions are known and can be set precisely, some room for optimization will be required. It is useful to think in terms of a window for moving each element around the position given in the file. Such optimization will be needed on a regular basis to take into account minor variations in the beam parameters, or settings. It should be noted that the change of any position must be done knowing the position of all other elements. The functionality of each element must always be maintained. The optimization window itself must vary as a function of the mode of the machine. In general the window will shrink as the intensity and energy go up and the β^* goes down. During stable data taking, essentially no freedom for optimization can exist.

The parameter space governing what can and cannot be moved is therefore rather complex. It is highly desirable that the control of all mobile elements is done from a single location – preferably using a single application.

The Effect of Optical Errors

Converting the sigma of Tab. 1 into millimetre positions at each element will initially be done based on the theoretical β at each location. In fact beta-beating can modify significantly the beam size at a given location. Beta-beating therefore imposes a strong limitation on the collimation and protection systems (more properly the collimation and protection systems impose a strong limitation on the tolerable amount of beta-beating). Two types of beta-beating can occur:

Static Beta-beating

This is not too much of a problem, up to a certain point. The collimator positions can be adjusted based on measured beta values rather than the theoretical ones. However as the amount of beta-beating increases the aperture of the machine is reduced as the beam size changes in the cold parts of the machine. This implies increasingly tight protection settings to avoid the cold machine becoming the aperture limit.

Transient or Dynamic Beta-beating

This occurs during acceleration (especially snapback) and squeezing and is a result of dynamic errors in the magnetic machine. With values above about 10% there is a strong risk of loosing functionality in the system (such as the secondary collimators becoming the primaries). With significant orbit offsets the problem is even worse. Transient beta-beating will severely limit the intensity and the ability to optimize the collimators until it is under control.

Machine Modes

Where the machine is within its operational cycle is an important constraint on the behaviour governing the movement of mobile devices. Certain elements are active only in a specific mode of the machine – such as injection, or stable data taking. Others must move as the mode changes. At present the different machine modes are not completely defined. However, the LHC modes are likely to be similar to those used for LEP and these can be used as a guideline. For this analysis the following modes are of significance:

- Setup : Injection optimization
- Injection : Accumulation of the physics intensities
- Acceleration
- Squeeze
- Physics: Stable data taking.

Setup

Before first injection the collimators and protection elements must be put into the positions determined during previous runs. All other objects must be moved out of the way. With a setup beam of low or intermediate intensity, the individual positions of the collimator and protection elements may be optimized. This may involve optimizing beam loss monitor signals, or repositioning the beam around measured beam profiles. The optimized positions must still comply with the functionality of each element.

Injection

During the process of injecting the main beam the chosen positions will probably be fixed – or at least the movement for optimization restricted. Once the injection process is complete, injection must be inhibited at the level of the SPS extraction and the injection protection elements moved out.

Acceleration/Squeeze

Whether the collimators need to move during acceleration is presently under discussion. This might be desirable to follow the shrinking beam size – especially with protection elements such as the TCDQ. The early part of the ramp, during snapback, is one of the most difficult periods since the available aperture is quite small and the level of transient beta-beating may be rather high. During the squeeze the aperture limitation in the LHC moves from the cold arc magnets to the inner triplet. Before the squeeze the cold aperture is at several 10's of sigma. At the end it is in the inner triplet at 8.4σ. To protect the inner triplet the collimators and protection devices must move in, either before or progressively during, the squeeze. Once again a window for adjustment around the optimum theoretical settings must be given.

Physics

It is necessary to distinguish between data-taking and non data-taking periods. Before stable physics begins it may be necessary to move the collimators once again - for optimization of background or increased cleaning efficiency. From this point onwards the allowed range for collimator position optimization must be very small.

Once stable physics conditions are declared the experimental detectors can be moved into their data-taking positions. Each detector will need a small tolerance in the position to allow for fill-to-fill variations. If, for any reason, the machine drops out of stable physics mode, these detectors must be automatically moved out of the beam aperture. This might occur if the beam stability or lifetime drops and re-optimization of the machine parameters are required.

In this case there is a very strong link between the mode of the machine and the machine protection.

SUMMARY

A summary of all devices in the LHC capable of moving into the beam aperture is given in Tab. 2. A total of 476 objects are described. Over half are vacuum valves. In most cases the basic interlocks governing the object moving into the beam aperture is covered in the hardware design. Some objects need more special treatment – especially those that are designed to intercept the beams under certain circumstances.

The control of mobile devices which are meant to be moved close to the beam needs special attention. The settings of these devices will depend heavily on the mode of the machine together with the intensity and energy of the beams. The settings of all elements form a coherent set and the functionality of each object must be maintained under all conditions. Failure to do this might result in an object becoming the primary aperture in the machine, or the machine loosing its protecting aperture limits. Since no object can be moved in isolation, It is therefore recommended that the control of all mobile elements in the LHC is exercised by the same applications in the same control room.

The proposed fast acting vacuum valves around LHCb are of particular concern. A single level of protection is provided in the form of an end switch trigger. This will fire the beam abort if the valve begins to close. If, for any reason, the beam is not dumped immediately, a catastrophic loss of the beam on the valves will occur. More studies are needed to determine if an additional redundant means of ensuring the machine protection exists.

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[4] G. Roy, "*Bloc de Sûreté d'accès du LHC*" , LHC-Y-ES-0007-10-00, EDMS. 474026.

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Table 2: Inventory of Objects in the LHC and Transfer Lines

Name	Description	N^o.	Position	Type	Comment
TED	Stopper	4	TI8/TI2	IN/OUT	Needs extraction interlock while moving
TBSE	Safety Stopper	1	TI8	IN/OUT	Needs extraction interlock while moving
BTV	Screens	18	TI8/TI2	IN/OUT	Limitation on extraction intensity with Al screen. Needs extraction interlock while moving
VV	TL Vacuum Valves	14	TI8/TI2	IN/OUT	
TCDI	TL Collimators	14	TI8/TI2	Mobile	
VV	Ring Vacuum Valves	249		IN/OUT	Veto activation with circulating beam
VVX	Fast Valves	2	IR8	IN/OUT	Very fast acting
VVX	Passive Valves	2	IR2	IN/OUT	Mechanical action only. Remote Status available
BTV	Injection & Matching Screens	13	IR2/IR8/ IR3/IR4	IN/OUT	Veto movement with circulating beam Limit on the number of turns vs. injected intensity
BWS	Wire Scanners	4	IR4	IN/OUT	Limits on intensity vs. energy
	RF Electron Stoppers	4	IR4	IN/OUT	Linked to LHC Access Safety System
	Safety Stoppers	2	IR6	IN/OUT	Linked to LHC Access Safety System
BEUV	Alignment Mirrors	2	IR4	IN/OUT	
VV	Dump line Vacuum Valves	4	IR6	IN/OUT	Dump Circulating beam on activation
BTV	Dump Line Screens	6	IR6	IN/OUT	Veto movement with intensity above a threshold Veto acceleration with screens in above threshold
TCP	Primary Collimators	8	IR3/IR7	Mobile	
TCSG	Secondary Collimators	30	IR3/IR7	Mobile	
TCT	Tertiary Collimators	16	IR1/IR5/IR2	Mobile	
TCLP	Absorbers	8	IR1/IR5	Mobile	Absorbers for Physics regions
TCLA	Absorbers	16	IR3/IR7	Mobile	Cleaning region absorbers
TCSP	Scrapers	6	IR3/IR7	Mobile	For special use.
TCDQ	Protection Elements	2	IR6	Mobile	Protect cold aperture from bad dump.
TCS	Protection Elements	2	IR6	Mobile	As above
TDI	Injection Protection	2	IR2/IR8	Mobile	
TCLI	Injection Protection	4	IR2/IR8	Mobile	
XRP	Totem Roman Pots	24	IR5	Mobile	Set at 10s in during stable data taking
XRP	Atlas Roman Pots	8	IR1	Mobile	
VELO	LHCb Vertex Locator	1	IR8	Mobile	At around 5mm from beam axis during data taking
ZDC	Alice Detectors	2	IR2	Mobile	Outside the beam vacuum.
BBLR	Beam-Beam Compensator	8	IR1/IR5	Mobile	Not baseline
	Total	**476**			