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Functional specification

LHC MODES

Abstract

The mode of an accelerator traditionally provides a summary status of operational activity. This mode is distributed for information and for conditioning sub-system response.
It is proposed that for the LHC machine there are two general modes: the accelerator mode and the beam mode. The accelerator mode provides a general overview of the machine activity (e.g. proton physics, access, shutdown, etc.), while the beam mode provides the state of the machine with regard to the machine cycle (e.g. injection, ramp, etc.).
A mode based on the LHC sectors is also proposed. This will reflect the sector based nature of the LHC and will be principally used to ease the conditioning of Role Based Access checks. For each sector an operational mode will be defined.

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History of Changes

Rev. No.	*Date*	*Pages*	*Description of Changes*
0.1	2007-04	All	Original version
	2007-04-12	All	Revision by Reyes
	2007-05	All	Revision by Mike after ABCIS discussion
0.2	2007-07	All	Revision by Mike after discussion with Stephen about RBAC requirements
	2007-08-31	All	Submission for engineering check
	2007-10-05		Comments from the Engineering Check round included. Additional people included in the "Checked by"
	2007-10-10	All	Submission for approval
	2007-11-19	Pages 4, 6 and 9; Tab. 2 and 4; Fig. 1 and 2.	Comments from the Approval round included
1.1	2010-03-23		Accelerator mode TOTEM PHYSICS changed to SPECIAL OPTICS PHYSICS. Figures 1 and 2 modified to include new mode transitions and remove the beam dump warning mode which does not exist anymore. Table 3 updated to include the modes where RF synchronization is allowed. Document text updated as well.
1.3	2010-09-04		Document Release
1.4	2010-11-14	Tables 1, 2 and 4; Section 7	Adding a new accelerator mode PROTON-NUCLEUS PHYSICS and an explanation about the circulating particle type.
1.5	2015-03-23		Added the possibility to use any BEAM MODE in the ACCELERATOR MODEs MACHINE CHECKOUT and MACHINE TEST. Table 4 updated.

Table of Contents

1. INTRODUCTION

This document provides an update of the first LHC mode proposal published by Robin Lauckner in 2003 [1].

The LHC modes are a synthesis of the more complex LHC State Machine and aim to provide a summary of the machine state to be used by systems such as Machine Protection, Front-end security (via Role Based Access [2]), experiments, etc. The modes are broadcast for information and for conditioning sub-system response.

This document is organized as follows. Section 2 describes the three types of mode proposed in this document:

- the **Accelerator Mode**;
- the **Beam Mode**;
- and the **Sector Operation Mode**.

The list of mode names and a description for each type is also given in Section 2. Section 3 explains the notion of mode concatenation. The users of the modes and the distribution methods are presented in Section 4 and 5, respectively.

Other possible modes, which will not be distributed by the timing system but are maintained by LSA and published mainly for information, are listed in Section 6. The last two sections are devoted to the logging and possible implementation of the modes.

2. TYPES OF MODES

In this document three main modes are defined, the Accelerator Mode, the Beam Mode and the sector Operation Mode.

The Accelerator Mode provides a summary of the LHC machine state; the Beam mode provides a description of the main phases of the accelerator cycle or sequence that is being played. Finally the Sector Operation Mode provides a binary flag per LHC sector to define whether or not it is operational. The Role Based Access system (RBAC) is the principal client, which will use the sector operational mode as part of the RBAC check.

Three modes might seem excessive, however, it reflects: one, the plethora of different users; two, the inherent complexity of the LHC. (One could imagine going even further and defining a mode per powering sub-sector but enough is probably enough.)

2.1 ACCELERATOR MODE

The Accelerator Mode provides with a summary status of the LHC machine state. Table 1 contains the, so far, foreseen Accelerator Modes and their description. Nevertheless, the list is not exhaustive since as we gain experience in the operation of the machine, most likely more Accelerator Modes will be needed, in particular in what concerns the physics programs.

Accelerator mode name	**Description**	
SHUTDOWN	Usual winter status. Cold magnets floating.	NO BEAM
COOLDOWN*	Coming back from shutdown. The principal activity during this mode is cryogenics related, i.e. simultaneous cool down of several sectors.	NO BEAM
MACHINE CHECKOUT*	Check the simultaneous functioning of the various LHC sub-systems in the final configuration following the LHC hardware commissioning [3,4,5]. In subsequent years of LHC operation there will also be machine checkout periods following the yearly shutdown. The machine	NO BEAM

	checkout is the final test to take place before the injection of first beam. This would cover dry runs which aim to test all the application software and machine protection systems culminating in a complete machine cycle.	
ACCESS*	Access or preparation for said.	NO BEAM
MACHINE TEST*	Operations' tests without beam. Ad hoc tests without beam during normal running periods.	NO BEAM
CALIBRATION*	Power Converter calibration. No external interference with circuits. This mode is per sector and the equipment is in local state. The mode is used to condition RBAC.	NO BEAM
WARM-UP*	One or more sectors warming up for repair.	NO BEAM
RECOVERY*	Typically quench recovery, or recovery from cryogenics plant disturbance.	NO BEAM
SECTOR DEPENDENT	This Accelerator Mode tries to cope with the situation in which different sectors of the machine can be in different states at the same time (like for example during hardware commissioning and cool down). It indicates that in order to get the exact status of the machine one has to decode the Sector Mode (explained in Section 6.2).	
BEAM SETUP	Machine setup with one or both beams. This mode includes beam commissioning for the first time from the injection phase to the collision phase using different intensities with one and multi-bunch configuration. In this mode the equipment, the beam instrumentation, the machine protection and the beam parameters will be commissioned with each type of beam and within each relevant Beam Mode (INJECTION, RAMP, SQUEEZE, etc.). It also includes ad hoc test with beam during normal running periods, e.g. ramp development, absolute luminosity calibration, high beta commissioning, etc.	BEAM
PROTON PHYSICS	Beam based operation aimed at proton physics.	BEAM
ION PHYSICS	Beam based operation aimed at ion physics.	BEAM
SPECIAL OPTICS PHYSICS	Beam based operation with special optics, like for example the one for TOTEM.	BEAM
PROTON-NUCLEUS PHYSICS	Beam based operation aimed at proton-ion physics. The foreseen ions so far are: Proton, Lead 82+, Argon 18+, Deuteron and Xenon 54+	BEAM
MACHINE DEVELOPMENT	Beam based machine development.	BEAM

Table 1: Proposed LHC Accelerator Modes. The modes marked with an * are modes that might be different for different sectors. This possibility is discussed in Section 6.2.

2.2 BEAM MODE

Every LHC cycle is a sequence made of tightly coupled tasks that need to be carried out in strict order and have to be accomplished successfully to allow the LHC machine to make a transition from one state to another. The sequence execution will be done by a high level software application called the LHC Sequencer [6]. The tasks within a sequence that are related with a specific activity are grouped into what are called sub-sequences.

Thus, a LHC cycle like "Nominal LHC Operation" implies the execution of a sequence divided in several sub-sequences, for example: "pre-injection plateau", "ramp to injection plateau", "prepare for first pilot", etc. These sub-sequences, in turn, are made up of individual tasks.

Beam mode name	Description
SETUP	Possibly beam in transfer lines with transfer line dumps in. Includes pre-injection plateau and injection plateau - no beam in ring.
ABORT	Recovery mode following beam permit drop. This mode can be entered from any state if there is no beam in the machine.
INJECTION PROBE BEAM	If either ring 1 or ring 2 will be injected with or have safe beam circulating. In this mode a number of checks will be done for the different accelerator sub-systems before injecting higher intensities. The aim will be to establish a circulating safe beam with a given lifetime. An overview of the activities done within this mode can be found in [7]. A discussion on the beam intensities and filling schemes that would fit within this mode can be found in [8,9]. A detailed breakdown of the Nominal Injection Sequence can be found in [10].
INJECTION SETUP BEAM	During the INJECTION PROBE BEAM we will be able to make measurements with very limited precision. In order to make more precise measurements before filling for physics, a SETUP BEAM will be used. This beam will be wholly representative of the physics beam to follow, just with fewer bunches to stay below the damage threshold. As in the previous mode, more details can be found in [7-10].
INJECTION PHYSICS BEAM	At this stage the machine has been optimized. It proved to be able to have circulating beam with appropriate lifetime and it is ready to accept higher intensities needed for physics. Within this mode, prior to high intensity beam injection, a pilot beam will be injected since the accelerator will be empty when this mode is reached. As in the previous mode, more details can be found in [7-10].
PREPARE RAMP	Injection complete, preparing for ramp.
RAMP	Ready to ramp or ramping or immediate post ramp.
FLAT TOP	Ramp finished - pre-squeeze checks.
SQUEEZE	Preparing for or squeezing.
ADJUST	Preparing for collisions or adjusting beams after the squeeze. Possible to enter this mode from STABLE BEAMS. Possible to enter this mode at the end of STABLE BEAMS without the intention of going back into physics.
STABLE BEAMS	Stable conditions with collisions in the experiments, backgrounds and life time under control. Small adjustment of beam parameters permitted. In case of slow degradation all the experiments are warned and the ADJUST mode is entered when all the experiments have confirmed they are ready.
UNSTABLE BEAMS	Emergency mode entered from stable beams in case of sudden beam degradation. The UNSTABLE BEAMS mode may be entered without prior warning to the experiments. UNSTABLE BEAMS mode can be entered from ADJUST only if the accelerator mode is MD. This transition has been requested for Roman Pots calibration or special machine protection tests. In this case, a special key has to be turned in the control room of the

	experiment to disable, temporarily, the protection interlock, and has to be put back in position after the tests are finished.
BEAM DUMP	Requested or emergency dump. It will be verified that all the machine protection equipment performed correctly, together with the LBDS system via the XPOC analysis.
RAMP DOWN	Ramp down and cycling after programmed dump at end of physics fill.
CYCLING	Pre-cycle before injection following access, recovery, etc. The objective of this mode is to reset the magnetic history of the machine and prepare the machine for a new cycle.
RECOVERY	Following quench, emergency beam dump, post mortem, etc. Within this mode the reason of the abort, quench, emergency dump, etc, will be diagnosed by the post mortem analysis system.
INJECT AND DUMP	Dump after small number of turns following injection [11,12]. This mode may be used during first commissioning or for injection studies. In this scenario screens are allowed to be in the beam. This injection scenario will ensure that during the early commissioning the beam is properly disposed of. This is important whenever the beam does not immediately circulate in the machine due to improper settings of some machine parameters, or for setting up dampers, RF capture etc. This mode is also useful for injection steering of the transfer lines and the septa and kickers at the end of the lines. It also may be used for machine studies requiring less than 100 ms of circulating beam, e.g. aperture measurements in the injection/extraction channel. This mode will use dedicated hardware to trigger the beam dump via the BIS.
CIRCULATE AND DUMP	Dump after large number of turns following injection [11]. In this mode the screens are not allowed to be in the beam. It will use the timing system to trigger the beam dump via the BIS.
NO BEAM	In a machine mode where there is no beam or no preparation for beam.

Table 2: Proposed LHC Beam modes for proton and ion operation.

In general the successful execution of the tasks brings the LHC into the next state in the state machine diagram allowing the sequential execution of the machine cycle. The Beam Mode proposed in this document covers several states that are related to a particular activity. For example, the state in which the injection of pilot beam in ring one is taking place, and the state in which there is circulating pilot, in one ring say, are grouped into a summary mode called INJECTION PROBE BEAM.

Hence the Beam Mode provides with a description of the main phases of the accelerator cycle or sequence that is being played. The transition diagram for the, so far, foreseen Beam Modes is shown in Figure 1. The diagram corresponds to the nominal LHC Sequence and should be considered as a guideline; some variations are envisaged as we gain experience in the accelerator operation. The transition diagram covers protons and ions operation. The only difference between them is that for ion operation there is no need for an INJECTION SETUP BEAM mode. The reason being that the beam intensity per bunch is the same for INJECTION PROBE BEAM and INJECTION PHYSICS BEAM, which is already at the limit of the instrumentation sensitivity, the only difference is the number of bunches. An outline of the associated conditions can be found in Table 2. A more detailed, illustrative close up of the physics related modes is shown in Figure 2.

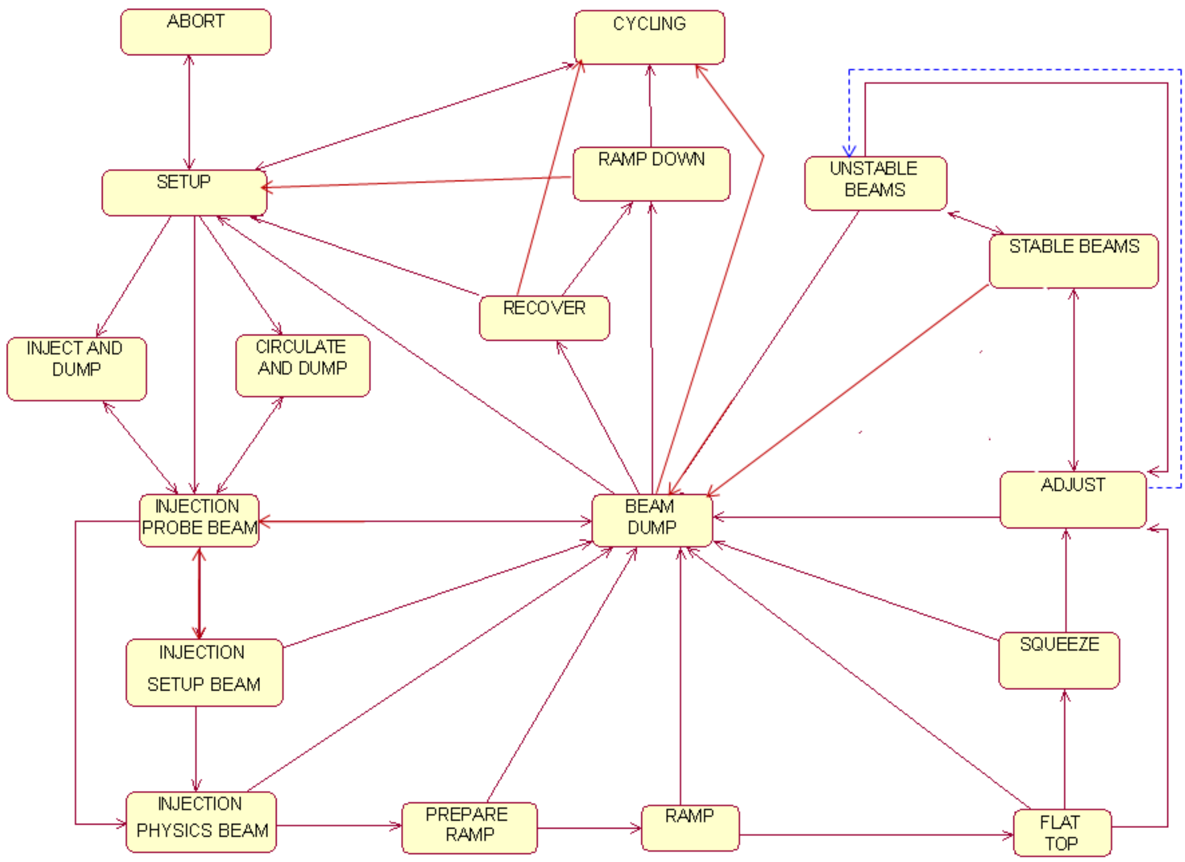

Figure 1: LHC Beam Modes diagram for the nominal sequence with protons or ions. Transition details suppressed for clarity. The dotted line indicates a special transition foreseen during Machine Development to be able to do Roman Pots calibration or Machine Protection tests.

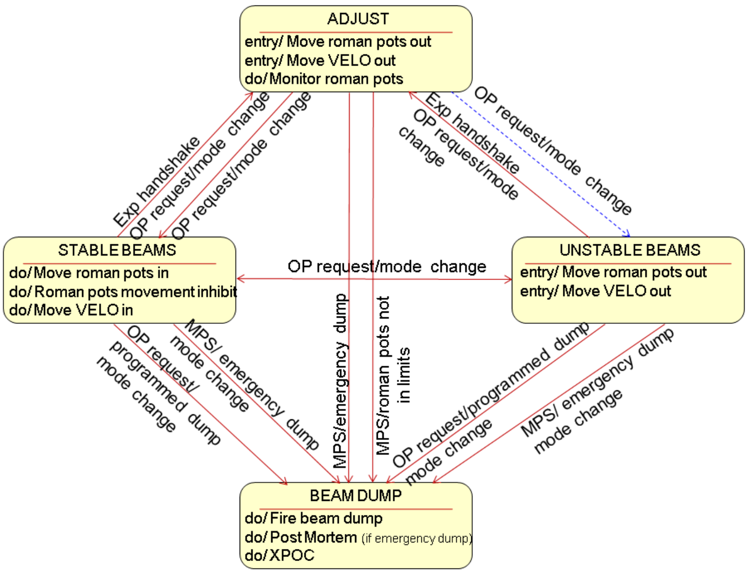

Figure 2: Illustrative close-up of physics related Beam Modes. The dotted line indicates a special transition foreseen during Machine Development to be able to do Roman Pots calibration or Machine Protection tests.

2.3 OPERATION MODE

This is mainly included to simplify the work of the Role Based Access system. It will be sector based and it will answer the question whether a LHC sector is operational or not.

For each sector, it will have two possible values TRUE and FALSE. The value will condition the restrictions applied by RBAC. When a sector operation mode is TRUE, the sector is in a state which implies that the CCC is the prime user of a given device. When FALSE, the sector's equipment can be controlled by equipment expert applications without restriction.

There is a global operational mode of the machine. If set to TRUE the sector's operational modes are overridden by the global operational mode.

Table 3 shows the accelerator modes which are declared as operational and non-operational. The accelerator mode BEAM SETUP will be set non-operational during the beam commissioning period with safe beam. When we will start commissioning with unsafe beam, however, the BEAM SETUP accelerator mode will be declared non-operational.

Accelerator mode	**OP MODE**
SHUTDOWN	NON-OPERATIONAL
COOLDOWN*	NON-OPERATIONAL
MACHINE CHECKOUT*	NON-OPERATIONAL
WARM-UP*	NON-OPERATIONAL
SECTOR DEPENDENT	NON-OPERATIONAL
BEAM SETUP	NON-OPERATIONAL (safe beam)/ OPERATIONAL (unsafe beam)
MACHINE TEST*	OPERATIONAL
PROTON PHYSICS	OPERATIONAL
ION PHYSICS	OPERATIONAL
TOTEM PHYSICS	OPERATIONAL
PROTON-NUCLEUS PHYSICS	OPERATIONAL
MACHINE DEVELOPMENT	OPERATIONAL
ACCESS*	OPERATIONAL
RECOVERY*	OPERATIONAL

Table 3: List of accelerator modes and the corresponding value for the operation mode. In dark grey there are the OPERATIONAL accelerator modes, in light grey the NON-OPERATIONAL. The BEAM SETUP mode value is conditioned to the commissioning of safe or unsafe beam.

The Operation Mode is distributed by the timing system, as a 16 bit mask with the first 8 bits representing each sector and the 9^{th} bit the global machine mode. In the LSA database there is a table called ACCELERATOR_MODES that contains, amongst other things, the name of the mode and a column indicating if it is operational or not. When the machine mode is changed, the corresponding operation mode is broadcast to all the CMW-RBAC servers. At the same time the telegram in the timing system is updated with the new operation mode. The telegram information is used by the LHC FGC (Function Generator Controller) to get notified about the current operation mode.

If the accelerator mode is operational, as already said, the LHC-Operator role or expert roles from the CCC location are the prime user of the LHC devices. If an expert needs to access a device outside the CCC, (s)he has to call the CCC and the Engineer In Charge (EIC) will add her(his) username to the appropriate role XX-LHC-piquet (XX stands for the abbreviation of the equipment type to be accessed). The role assignment is temporary and the EIC will set it to the interval of time the intervention takes. After this time, the username is automatically taken out from the role and no access to the equipment is possible anymore unless it is renovated.

3. CONCATENATION OF ACCELERATOR AND BEAM MODE

Concatenation of Accelerator and Beam Mode should give a reasonable full description of the state of the LHC e.g.:

- SHUTDOWN.NO-BEAM
- ACCESS.NO-BEAM
- PROTON-PHYSICS.INJECTION-PROBE-BEAM
- PROTON-PHYSICS.RAMP
- PROTON-PHYSICS.RECOVERY
- BEAM-SETUP.INJECT-AND-DUMP

Table 4 provides with a guideline of the possible combinations of Accelerator Mode and Beam mode.

BEAM MODE	ACCELERATOR MODE: Shutdown	Cooldown*	Machine Checkout*	Access*	Machine Test*	Calibration*	Warm Up*	Recovery*	Beam Setup	Proton Physics	Ion Physics	Special Optics Physics	Proton-nucleus Physics	Machine Development	Sector Dependent
No Beam	X	X	X	X	X	X	X	X							
Setup			X		X				X	X	X	X	X	X	
Abort			X		X				X	X	X	X	X	X	
Injection Probe Beam			X		X				X	X	X	X	X	X	
Injection Setup Beam			X		X				X	X		X	X	X	
Injection Physics Beam			X		X				X	X	X	X	X	X	
Prepare Ramp			X		X				X	X	X	X	X	X	
Ramp			X		X				X	X	X	X	X	X	
Flat Top			X		X				X	X	X	X	X	X	
Squeeze			X		X				X	X	X	X	X	X	
Adjust			X		X				X	X	X	X	X	X	
Stable Beams			X		X				X	X	X	X	X		
Unstable Beams			X		X				X	X	X	X	X		
Beam Dump			X		X				X	X	X	X	X	X	
Ramp Down			X		X				X	X	X	X	X	X	
Cycling			X		X				X	X	X	X	X	X	
Recovery			X		X				X	X	X	X	X	X	
Inject & Dump			X		X				X					X	
Circulate & Dump			X		X				X					X	

Table 4: Acceleration and Beam Modes concatenation. The modes marked with an * are modes that might be different for different sectors. The accelerator and beam modes during which LHC RF synchronization is allowed are indicated in dark grey. The modes where the synchronization is not allowed are indicated in light grey.

3.1 RF FREQUENCY SYNCHRONIZATION AND MODES

It is expected that the LHC clocks are stable during all the accelerator and beam modes indicated in Table 4 in light grey. In particular, no RF resynchronisation should be made during these accelerator and beam modes. In addition, during the beam mode Setup, the IMMINENT flag of the Injection handshake [13] gives an indication that an Injection beam mode (and thus a period with a guaranteed RF) will start after minimum 3 min, provided that the handshake concludes with a READY state.

The experiments automatically will switch to internal clocks (or support the possible event of a clock instability) when the accelerator and beam modes go outside the given list (modes indicated in dark grey).

4. HANDSHAKE VS ACCELERATOR AND BEAM MODES

During any of the Physics accelerator modes (Proton Physics, Ion Physics, Proton-Nucleus Physics or Special Optics Physics), handshakes are mandatory at every corresponding critical transition Injection, Adjust and Dump. When foreseeing a long no-beam period (two hours or more), CCC closes the handshakes and then sets appropriate accelerator/beam mode (e.g. Access.NoBeam, Recovery.NoBeam, MachineTest.NoBeam) This allows the experiments to freely carry out calibrations or tests with their detectors.

CCC initiates an Injection handshake after going back to a beam commissioning mode (either Beam Setup or Machine Development accelerator modes), or if the beam mode is changed to Setup. The handshake is left open with all experiments in "READY" state as long as needed by the machine. If one experiment's Injection Permit falls off, that experiment handshake state should indicate "PROBLEM". CCC calls that experiment and finds out about the situation. That experiment attempts a recovery for going back to "READY" such that CCC does not need to redo an Injection handshake. As long as no experiment goes to "VETO", a new Injection handshake is not needed. For a definition of the handshake procedures see [13].

5. USERS OF THE LHC MODES

As already stated, the modes are traditionally used to communicate to users the overall state of machine operations. The mode is distributed for information, and for conditioning sub-system response. The users of the LHC modes will include:

- The Safe Machine Parameters (SMP): among the different parameters managed by the SMP system, two flags: "Safe Stable Beams" and "Movable Device allowed in", are derived from the Beam Modes "STABLE BEAMS" and "UNSTABLE BEAMS". Both flags are going to be distributed by the Global Machine Timing (GMT). According to the first flag value, the experiments will move their detectors towards the beam. According to the second flag value, IF the detectors' movable objects are not in OUT positions, a beam dump request will be issued. More details in [14].
- Experiments: the modes are used for information and for conditioning the interlock of the movable devices [15] as explained before. The modes are also used by the Detector Control System (DCS).
- Role Based Access (RBAC): for front-end security and software application control rights, etc.
- Hardware: for conditioning sub-system response.
- LHC Control Software: for conditioning sub-system response (such as data acquisition) and publishing.

- Alarms: conditioning of Alarm processing.
- Access System: for conditioning sub-system response.

Some of the conditioning of system response is non-critical; however, the mode can be used to perform critical conditioning of sub-system behaviour like in the case of the modes used to calculate some SMPs. Therefore secure distribution of the modes becomes critical.

6. DISTRIBUTION OF THE MODES

The mode will be made available by a number of channels. These will include:

- high level publishing mechanism from LSA for clients such as page 1;
- via DIP [16], GMT (as Safe Beam Parameters, SBP) and BST (Beam Synchronous Timing) messages [17,18] for the experiments;
- via the GMT as SBP [14] for equipment and instrumentation.

7. PARTICLE TYPES USED ACCORDING TO THE ACCELERATOR MODE

The LSA RunControl project has implemented the sequencer tasks that will take care of defining the particle types to be used according to the accelerator mode. The tasks set explicitly the circulating particle type for each ring in the database and in the telegram to assure consistency. Those tasks are used were appropriate within the LHC sequences. Independently of those tasks the LSA RunControl project provides with a task to change the accelerator mode (as well as the beam mode) in the database, in the telegram and the in Safe Machine Parameter Controller to assure consistency of the mode all over the places before the mode is published. If the mode is PROTON PHYSICS the task automatically sets the particle type in both rings to PROTONS. If the mode is ION PHYSICS the task automatically sets the particle type in both rings to PB82. Only when the mode is PROTON-NUCLEUS PHYSICS or SPECIAL OPTICS PHYSICS, the particle type will have to be explicitly defined via the corresponding task in the sequencer.

The particle types foreseen so far are the following: Proton, Lead (Z=82, A=208), Argon (Z=82, A=208), Deuteron (Z=1, A=2) and Xenon (=54, A=209). As already said, they are distributed via two exclusive groups in the LHC telegram:

1. PARTY1 (Circulating particle type for ring 1), group number=23
2. PARTY2 (Circulating particle type for ring 2), group number=24

These groups (PARTY1, PARTY2) contain the following lines:

- PROTON, value=1
- PB82, value=2
- AR18, value=3
- D, value=4
- XE54, value=5

The following CTIM events are associated to them:

1. HX.PARTY1-CT
2. HX.PARTY2-CT

The following XTIM devices are associated to them:

1. HTX.PARTY1-XTIM
2. HTX.PARTY2-XTIM

The LSA database contains a table called PARTICLE_TYPES, with two columns, one for the particle type of ring 1 and the other one for the particle type of ring 2. It is from this table that the particle types are published to DIP. The names of the particle types are the same as in the telegram: PROTON, PB82, AR18, D and XE54. Those names can be seen with the same spelling in the DIP publication under dip/acc/LHC/RunControl/RunConfiguration[19] called PARTICLE_TYPE_B1 and PARTICLE_TYPE_B2.

8. OTHER MODES

Other modes can be defined. It is not planned, initially at least, to distribute these over the timing system. They would be maintained by LSA and published at the high level for information.

8.1 ACCESS MODES

The access modes are the operational modes of the LHC Access Control System [19]. When the Accelerator Mode is in Access, sub-access accelerator modes could be used to describe the state of the access system in more detail. There are three main access modes: Machine closed, Restricted access and General access; and two additional specialised modes: Patrol and Test.

8.2 SECTOR MODE

During hardware commissioning and cool down, the different sectors of the machine can be in different states. Thus, a Sector Mode is defined to cover the various possible states. The values of the Sector Mode are a sub-set of the previously defined Accelerator Modes (NB as distinct from the Sector Operation Mode) and are marked with an asterisk in Table 1. In this special situation, the Accelerator Mode will be called SECTOR DEPENDENT to indicate that one has to decode the Sector Mode to get the accurate status of the full machine.

Whether or not the Sector Mode is distributed by the timing system is open to debate, but it will be published at the high level from LSA.

9. LOGGING

All mode changes are time stamped and logged in the logging database.

10. DATABASE AND FINITE STATE MACHINE

The modes will be stored in the LSA database in an appropriate table. It is envisaged that a finite state machine will be responsible for maintaining the modes and for ensuring legal transitions between states and for initiating the distribution of any mode changes to the systems concerned.

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