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Functional Specification

SAFE MACHINE PARAMETERS

Abstract

For safe operation of the LHC, several systems require machine parameters that must be generated and distributed around the LHC and to the SPS extraction interlock system with very high reliability. This specification defines the requirements for the generation and distribution of these parameters.

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INTRODUCTION

For safe operation of the LHC, a number of machine parameters must be generated and distributed around the LHC and to the SPS with high reliability by the **S**afe **M**achine **P**arameter (**SMP**) generation and transmission system.

The SMP system has to transmit the parameter "LHC ENERGY" to several systems, such as the beam loss monitors and the injection kickers. It is derived from the currents in the main dipole magnets in several sectors by a very reliable system installed in IR6 [1].

A limited number of Beam Interlock channels can be "masked" to ease the commissioning and setting-up [2]. The mask settings are only taken into account if the parameter "SET-UP BEAM FLAG" is .TRUE. The "SET-UP BEAM FLAG" is derived from the "LHC ENERGY" and measured beam intensity in the SMP system. An energy dependent intensity limit function has to be defined. Below this limit function the "SET-UP BEAM FLAG" is .TRUE., otherwise .FALSE. The name "SET-UP BEAM FLAG" replaces the up to now widely used name "SAFE BEAM FLAG".

Injection of high intensity beam is only permitted when there is already beam circulating in the LHC [3]. The presence of circulating beam is detected by beam current transformers [4]. A parameter, the "BEAM PRESENCE FLAG" is derived from the beam current and indicates if it is above a predefined threshold.

If there is no beam in the LHC ("BEAM PRESENCE FLAG" = .FALSE.), the intensity of the beam extracted from the SPS must be limited to avoid any damage to sensitive equipment of the LHC experiments. The extraction into an empty LHC ring is only permitted if the "PROBE BEAM FLAG" is .TRUE. (note probe beam intensity threshold < set-up beam intensity threshold @ 450 GeV).

As for the LHC, an "SPS SET-UP BEAM FLAG" is defined. If the flag is .TRUE., a number of input signals to the interlock system for extraction and transfer lines can be masked.

Fast extraction from the SPS towards LHC is only permitted at a specific energy (normally 450 GeV) and to CNGS at another energy (normally 400 GeV). Two parameters ("LHC CYCLE FLAG" and "SPS CYCLE FLAG" are used in the extraction interlock logic, in the so-called Master Beam Interlock Controllers (Master BICs), to ensure this condition.

Several LHC beam modes are defined in [5]. There are modes like Filling, Ramping, Adjust and Stable Beam / Unstable Beam for Physics. Movable devices from experiments (Roman Pots and LHC Velo) are only allowed to leave their switch position during mode Stable Beam. The SMP will have to derive two flags for the experiments: the "STABLE BEAM FLAG" and the "MOVING_IN_ALLOWED FLAG".

The SMP system should provide the flexibility to add more parameters if required later on. Parameters which do not have to be available from start-up are for example the four "SQUEEZING FACTORS". The factors are proportional to the $\beta_{squeeze}/\beta_{unsqueezed}$ per IP. The collimation system might use this information to guarantee adequate protection of the developing aperture bottlenecks during the squeeze.

This specification defines the different SAFE MACHINE PARAMETERS, their sources and usage. Several questions are addressed:

- What are the sources of the parameters?
- Which system uses the parameters and for what purpose?
- Which reliability and availability levels (SIL levels) are required?
- Which default value to take if an error is detected?

Table 1 summarises the different SAFE MACHINE PARAMETERS with their corresponding features. In appendix A the SIL levels are given according to the IEC norm 61508 [6].

The details of the generation of the parameters including protocols, format etc. are given in a technical specification [7]. A catalogue of failure scenarios is given in [8].

Name	Format	Rate	Latency	Derived from (producer name)	Distributed to	Safety level
LHC ENERGY	2 bytes	10 Hz	0.1 second	Current in main LHC dipoles (BEM)	Beam Loss Monitors	SIL=2
					Injection Kickers	SIL=2
LHC SET-UP BEAM FLAGS	2 bits (SBF1& SBF2)	1Hz	0.1 second	LHC ENERGY (SMPG) and Beam Intensities (DCBCT)	LHC Beam Interlock System	SIL=2
					Master BICs in the SPS extractions	SIL=1
					Aperture Kickers	SIL=2
SPS SET-UP BEAM FLAG	1 bit	1Hz	0.1 second	Beam Intensities in SPS (BCT)	Master BICs in the SPS extractions and transfer line BICs	SIL=1
CNGS CYCLE FLAG	1 bit	1Hz	0.1 second	Current in main SPS dipoles	Master BIC in SPS extraction	SIL=1
LHC CYCLE FLAG	1 bit	1Hz	0.1 second	Current in main SPS dipoles	Master BIC in SPS extraction	SIL=1
PROBE BEAM FLAG	1 bit	1Hz	0.1 second	Beam Intensities in SPS (BCT)	Master BIC in SPS extraction	SIL=1
LHC BEAM PRESENCE FLAGS	2 bits (BPF1 & BPF2)	1kHz	1 ms	Beam Intensities in LHC (FBCT)	Master BICs in the SPS extractions	SIL=1
STABLE BEAM FLAG	1 bit	1Hz	1 second	Operator input and verification of consistency for some modes	Experiments	SIL=1
MOVING IN ALLOWED FLAG	1 bit	1Hz	1 second	Operator input and verification of consistency for some modes	Experiments	SIL=2
LHC SQUEEZING FACTORS	4 bytes	1Hz	1 second	Automatic process with operator input possible	tbd, possibly collimation system	tbd

Table 1: The above table summarises the main characteristics of the different SAFE MACHINE PARAMETERS.

1. DEFINITION OF THE LHC ENERGY

The LHC ENERGY is a parameter proportional to B·ρ and will be derived from the current in four main bend circuits around point 6 in the LHC. For proton operation it is about equal to the energy of a proton in the LHC. This parameter will be represented by a 16-bit value in order to allow a resolution of better than 10^{-4} on the maximum energy. One bit corresponds to 120 MeV. Thus 7 TeV corresponds to the hexadecimal representation '0xE3DD' and 450 GeV to the hexadecimal number '0x0EA6'. In case of a transmission failure, all payload bits are set ('0xFFFF') which corresponds to a (beyond design) energy value of 7.864 TeV.

1.1 GENERATION OF LHC ENERGY

The "LHC ENERGY" is generated by the energy tracking system of the LHC beam dump system installed in IR6 [1] and transmitted to the SMP system.

1.2 USE OF THE LHC ENERGY

- The Beam Loss Monitor System requires the energy since the thresholds for generating alarms and beam dump requests depend on the energy.
- The injection kickers installed in IR2 and IR8 use the energy from the safe machine parameters in their energy tracking systems. The injection kickers are inhibited if the energy does not equal 450 GeV.

The "LHC ENERGY" should be evaluated and distributed to the different users with a frequency of 10 Hz.

1.3 DEFAULT VALUE IN CASE OF ERROR

If an error is detected at any stage of the generation and transmission of the energy, the energy should be set to a defined value outside the possible range: 0xFFFF (corresponds to 7.8642 TeV).

<u>Example:</u> *if a receiver of the energy does not receive new values due to a failure, the energy is set to* 0xFFFF*.*

2. LHC SET-UP BEAM FLAGS

2.1 DEFINITION OF THE **S**ET-UP **B**EAM **F**LAGS (SBF)

The intensity limit threshold as a function of energy, below which the "SET-UP BEAM FLAG" becomes .TRUE., was defined as the damage[1] limit of Cu for transient beam loss based on simulation and experimental data [9]. Note that these intensity limits cannot be regarded as safe for beam loss under all conditions [10]. The originally proposed name of "SAFE BEAM FLAG" was therefore altered to avoid carelessness.

The SET-UP BEAM FLAG has two states:

- "SET-UP BEAM FLAG = .TRUE." ⇔ LHC is operating with a beam intensity and energy **below** the Cu transient damage limit.
- "SET-UP BEAM FLAG = .FALSE." ⇔ LHC is operating with a beam intensity and energy **above** the Cu transient damage limit.

[1] Damage in this context was defined as clear sign of deterioration of the material: discoloration, melting, holes.

There is one SET-UP BEAM FLAG per beam, for beam 1 (SBF1) and beam 2 (SBF2).

2.2 GENERATION OF THE SET-UP BEAM FLAG

The concept of "SET-UP BEAM FLAG" was introduced to increase flexibility during commissioning and setting-up. A certain number of interlocks can be masked if there is SET-UP BEAM in the LHC, see below for more information. The same concept was adapted in the SPS and transfer lines.

In the LHC the "SET-UP BEAM FLAGS" are derived from the "LHC ENERGY" and from the beam intensities measured in number of protons (for ions, number of charges). Their inputs are:

- The reliable energy tracking system installed in IR6 for the "LHC ENERGY"
- The DCBCT system installed in IR4 measuring:
    - Intensity of beam 1 (NBEAM1) required for SBF1
    - Intensity of beam 2 (NBEAM2) required for SBF2
- Threshold for beam 1: SBI_TH1, and for beam 2: SBI_TH2

Simulations and extrapolations from experiments [9] have shown that the damage potential for beam 1(2) is proportional to the beam energy and the number of particles in the beam and given by NBEAM1(2) × $(\text{Energy}/450)^{\mathbf{1.7}}$. NBEAM1(2) was found to be 10^{12} protons – the intensity above which damage can occur on Cu at 450 GeV. The SMP system must be implemented such that in principle the energy dependency can be updated in case further studies show that the damage potential varies differently with energy than assumed. Also, the initial value NBEAM1(2) should be modifiable in case it is required. Using the management of critical settings [11] could be envisaged for this task. Hard coding the values is the preferred solution.

An additional requirement for the SMP managing the LHC SET-UP BEAM FLAGS is that they have to be forced to "FALSE" via software for the safe handshake between the SPS extractions and LHC injections. The LHC sequencer would make use of that. High intensity beam can only be injected into the LHC from the SPS if the LHC SET-UP BEAM FLAG is "FALSE" (:= no interlocks are masked) [12,13].

If (NBEAM1 · $(\text{Energy}/450)^{\mathbf{1.7}}$ < SBI_TH1) then "SBF1 = .TRUE." (or is forced ".FALSE."), else "SBF1 = .FALSE."

If (NBEAM2 · $(\text{Energy}/450)^{\mathbf{1.7}}$ < SBI_TH2) then "SBF2 = .TRUE." (or is forced ".FALSE."), else "SBF2 = .FALSE."

To avoid a critical dependence on the BCTs, under normal conditions the SET-UP BEAM FLAGS will be forced to .FALSE. at the beginning of the energy ramp. If for certain conditions (e.g. for experiments using the aperture kicker) it is required to be able to mask and therefore not force it during the energy ramp, this can be requested by an EIC. The maximum allowed intensity should be limited to a lower value than the SET-UP BEAM Intensity Threshold, value to be decided.

2.3 SIL LEVEL FOR SET-UP BEAM FLAG

The correct evaluation of the SET-UP BEAM FLAGS depends on the measured beam current and the beam energy. For measuring the beam energy, a highly reliable system has been developed. The beam current is measured by Beam Current Transformers that have not been developed for the use in a highly safety critical system. Their safety integrity level needs to be addressed in the future.

2.4 USAGE OF SET-UP BEAM FLAGS

- Beam Interlock System with 17 controllers around the LHC [2]: if the "SET-UP BEAM FLAG" = .TRUE. and a mask for a specific client is set, the USER_PERMIT of this client is ignored independent of the value of the USER_PERMIT. Only part of the user permit signals can be masked.
- Injection interlock system: the "LHC SET-UP BEAM FLAG" is transmitted to the SPS extraction interlock system. If the "LHC SET-UP BEAM FLAG" = .TRUE., no injection of high intensity beam into the LHC is permitted by the extraction interlock logic in the Master BICs. Extraction of high intensity beam is only permitted when the "LHC SET-UP BEAM FLAG" = .FALSE. In case intensity below the SET-UP BEAM Threshold is circulating in the LHC and the "LHC SET-UP BEAM FLAG" is .TRUE., it must be forced to .FALSE. to guarantee that the LHC is "ready" (no interlocks masked) for high intensity beam.
- Aperture kickers: operation of these kickers is allowed only if the "LHC SET-UP BEAM FLAG" = .TRUE.

The LHC SET-UP BEAM FLAG should be evaluated and distributed to the different users with a frequency of at least 1 Hz.

2.5 DEFAULT VALUE IN CASE OF ERROR

If an error is detected at any stage of the generation and transmission, the value should be set to SET-UP BEAM FLAG = .FALSE.

3. LHC BEAM PRESENCE FLAGS

3.1 DEFINITION OF THE BEAM PRESENCE FLAGS

The BEAM PRESENCE FLAG is .TRUE. when there is circulating beam in the LHC, and FALSE if there is no circulating beam. There is one BEAM PRESENCE FLAG per beam.

3.2 GENERATION OF THE BEAM PRESENCE FLAGS

Inputs to the "BEAM PRESENCE FLAG" are from the Fast Beam Current Transformers (FBCTs) in the LHC. The signal from the transformer will be compared with a threshold.

- For BPF1, the intensity (number of protons) measurement from the FBCT beam 1, is NB1
- For BPF2, the intensity (number of protons) measurement from the FBCT beam 2, is NB1
- Preset threshold value, minimum intensity: MINIMUM_BEAM_INTENSITY

If (NB1 < MINIMUM_BEAM_INTENSITY) then "BPF1=.FALSE.", else "BPF1=.TRUE."

If (NB2 < MINIMUM_BEAM_INTENSITY) then "BPF2=.FALSE.", else "BPF2=.TRUE."

The BCTs that determine the "BEAM PRESENCE FLAGS" are installed in IR4. The value for the threshold should normally be fixed. It must be possible to set it to a different value after receiving authorisation (e.g. through the Machine Protection Panel). The value of the threshold must be logged. If there is only coasting beam in LHC (no bunched beam), it is not possible to inject high intensity beam in LHC since the fast BCTs do not measure un-bunched beam.

3.3 USAGE OF THE BEAM PRESENCE FLAGS

The "LHC BEAM PRESENCE FLAGS" must be .TRUE. in order to extract high intensity beam from the SPS and inject it into the LHC. The flags are used in the Master BICs in the SPS extractions [12,13], one for extraction into TI 8 (flag for Beam 2) and one for extraction into TI 2 (flag for Beam 1).

In order to prevent failures that could appear at the very last moment before injection, the "BEAM PRESENCE FLAGS" should be evaluated and distributed to the Master BICs with a frequency of 1 kHz or higher.

3.4 DEFAULT VALUE IN CASE OF ERROR

If an error is detected at any stage of the generation and transmission of the flag, the value should be set to "BEAM PRESENCE FLAG" = .FALSE.

The "BEAM PRESENCE FLAGs" are used during the injection process (only "PROBE BEAM" can be injected if the "BEAM PRESENCE FLAG" is .FALSE.). The test injection mode where otherwise protected timing events important for the synchronisation between the SPS and the LHC can be sent out asynchronously also uses the "BEAM PRESENCE FLAG". It has to be .FALSE. to go into that mode. The mode is required for pulsing the injection kickers during shutdown and other injection equipment tests. For additional security the injection test mode also removes any possibility to produce LHC beams in the injectors and the switching to the mode is protected by a hardware key owned by the injection experts. The default value .FALSE. of the "BEAM PRESENCE FLAG" in case of error can hence be regarded as adequate.

4. FLAGS RELATED TO LHC BEAM MODES

4.1 LHC BEAM MODES

The LHC beam modes are defined in another document [5]. In this specification the beam modes are only discussed in the context of the SMP system.

In general, the LHC beam modes are not used by machine protection devices. However to derive the flags "STABLE BEAM" and "MOVING_IN_ALLOWED" it is required to know if the beam mode is either "stable beams" or "unstable beams".

4.2 GENERATION OF STABLE BEAM FLAG AND MOVING_IN_ALLOWED FLAG

Only an operator can judge whether one can enter into the LHC beam mode "stable beams". A software command is used for that purpose. Some verification must be performed by the SMP system:

- For a running period, a value of the physics energy is defined (e.g. 7 TeV). This value could be envisaged to be modifiable through the management of critical settings to have some flexibility during the first years of LHC.
- If an operator declares mode "stable" or "unstable beams" when the LHC is not at physics energy (in the example not at 7 TeV $\pm$ dE), the "MOVING_IN_ALLOWED FLAG" and "STABLE BEAM FLAG" should remain .FALSE.
- After the end of the fill the magnets are ramped down. If the magnets start to ramp down in the mode "stable beams" or "unstable beams", the SMP system will detect that the energy does not correspond to the physics energy and sets the "STABLE BEAM FLAG" and the "MOVING_IN_ALLOWED FLAG" to .FALSE.

- The beam must be dumped if the experimental detectors are not in OUT position and "MOVING_IN_ALLOWED FLAG" = .FALSE.

4.3 USAGE OF STABLE BEAM FLAG AND MOVING-IN-ALLOWED FLAG

- The experiments switch on their detectors only if the "STABLE BEAM FLAG" is .TRUE.
- The experiments are only allowed to move their detectors towards the beam (away from OUT position) when the "MOVING_IN_ALLOWED FLAG" = .TRUE.
- The experiments should not provide USER_PERMIT = TRUE to the Beam Interlock System if the experimental detectors are not in OUT position and the "MOVING_IN_ALLOWED FLAG" = .FALSE.

4.4 DEFAULT VALUE IN CASE OF ERROR

If an error is detected at any stage of the generation, transmission and reception, the value should be set to "STABLE BEAM FLAG" = .FALSE. and "MOVING_IN_ALLOWED FLAG" = .FALSE.

5. LHC SQUEEZING FACTORS

5.1 DEFINITION OF THE LHC SQUEEZING FACTORS

The "LHC SQUEEZING FACTOR" is a parameter proportional to the beta function at an IP with an experiment and is defined as $\beta_{squeeze}/\beta_{unsqueezed}$. This parameter will be represented by an 8-bit value for each of the 4 IRs for a resolution of about 10^{-2} to describe the squeezing process. Currently beta squeezing is foreseen only when the energy for physics is reached. If the energy is not equal to the physics energy, the squeezing factor should be set to one (one = not squeezed).

5.2 GENERATION OF LHC SQUEEZING FACTORS

The "LHC SQUEEZING FACTOR" will be derived from the current in the quadrupole magnets in the insertions. The currents of at least two quadrupole magnets are required to determine the factor.

5.3 USAGE OF THE LHC SQUEEZING FACTORS

The collimation system could make use of this parameter for the position interlock functions during the squeeze, where aperture bottlenecks develop around the experiments and special protection is foreseen.

The "LHC SQUEEZING FACTOR" should be evaluated and distributed to the different users with a frequency of 1 Hz.

5.4 DEFAULT VALUE IN CASE OF ERROR

If an error is detected at any stage of the generation and transmission of the squeezing factor, the factor should be set to a defined value outside the possible range. This value will be defined by the hardware designers.

5.5 SCHEDULE

It is acceptable that the squeezing factors are introduced in the second version of the SMP system.

6. SPS FLAGS

6.1 DEFINITION OF THE SPS SET-UP BEAM FLAG

The "SPS SET-UP BEAM FLAG" has two states:

- "SPS SET-UP BEAM FLAG" = .TRUE. ⇔ SPS is operating with a beam intensity **below** the damage level of Cu for transient beam loss at top energy of the cycle.
- "SPS SET-UP BEAM FLAG" = .FALSE. ⇔ SPS is operating with beam **above** the damage level of Cu for transient beam loss at top energy of the cycle.

6.2 GENERATION OF THE SPS SET-UP BEAM FLAG

The SPS SET-UP BEAM FLAG is derived from the SPS beam intensity measured in number of protons (for ions, number of charges) after injection is finished, and before extraction. The intensity is measured with the high intensity BCT installed in LSS3. The BCT has a maximum range of 1.5 x 10^{14} protons with a bit resolution of 1 x 10^{10} protons.

- Intensity of the beam: NBEAM
- Threshold for beam: SPS SET-UP BEAM FLAG_TH
- If (NBEAM < SPS SET-UP BEAM FLAG_TH) then "SPS SET-UP BEAM FLAG" = .TRUE., else "SPS SET-UP BEAM FLAG" = .FALSE.

The values for the thresholds should be hardcoded. It could be envisaged to have them modifiable through the system for management of critical setting. Following [9] the SPS SET-UP BEAM FLAG_TH is 10^{12} charges for LHC beams.

6.3 DEFINITION OF THE PROBE BEAM FLAG

The "PROBE BEAM FLAG" was introduced to protect against single pass failure scenarios at injection involving sensitive equipment like the inner detectors of the experiments. The LHC (SPS) SET-UP BEAM intensity was considered too high to be injected into an empty machine in view of the possible failure scenarios.

The "PROBE BEAM FLAG" has two states:

- "PROBE BEAM FLAG" = .TRUE. ⇔ SPS is operating with LHC beam **as low as operationally possible**. The value of the threshold can be set remotely using the management of critical settings, but will always have to be below 10^{11}. For normal operation, it is expected that the threshold will be between 10^9 and 10^{10}.
- "PROBE BEAM FLAG" = .FALSE. ⇔ SPS is operating with beam **above** this threshold.

There is only one "PROBE BEAM FLAG" for both LHC beams.

6.4 GENERATION OF THE PROBE BEAM FLAG

The "PROBE BEAM FLAG" is derived from the SPS beam intensity measured in number of protons (for ions, number of charges) after injection is finished, and before extraction. The intensity is measured with the high sensitivity BCT system installed in LSS4. The BCT has a maximum range of 7 x 10^{11} protons with a bit resolution of 10^8 protons.

- Intensity of the beam: NBEAM
- Threshold for beam: PROBE BEAM FLAG_TH, must be smaller than PROBE BEAM FLAG_TH_MAX
- If (NBEAM < PROBE BEAM FLAG_TH) then "PROBE BEAM FLAG" = .TRUE., else "PROBE BEAM FLAG" = .FALSE.

The values of the actual and maximum thresholds must be logged.

6.5 DEFINITION OF THE CYCLE FLAGS FOR THE SPS

The SPS cycle for LHC injection ("LHC CYCLE") is defined to accelerate the beam to an energy of (normally) 450 GeV. No other cycle should accelerate beam to the same energy and extract beam to the TI2 or TI8 beam lines. The "LHC CYCLE FLAG" has two states:

- "LHC CYCLE FLAG" = .TRUE. ⇔ SPS is operating with beam accelerated to 450 GeV.
- "LHC CYCLE FLAG" = .FALSE. ⇔ SPS is **not** operating with beam accelerated to 450 GeV.

The SPS cycle for CNGS operation ("CNGS CYCLE") is defined to accelerate the beam to an energy of normally 400 GeV. No other cycle should be used accelerating the beam to the same energy and extracting beam into the TT41 beam line. The "CNGS CYCLE FLAG" has two states:

- "CNGS CYCLE FLAG" = .TRUE. ⇔ SPS is operating with a CNGS cycle and accelerates beam to 400 GeV .
- "CNGS CYCLE FLAG" = .FALSE. ⇔ SPS is not operating with a CNGS cycle or does not accelerate beam to 400 GeV.

6.6 GENERATION OF THE CYCLE FLAGS

The SPS ENERGY is measured with a system similar to the one used in the LHC. The value of the energy is transmitted to the SMP system. The SMP system requires two predefined parameters: SPS_ENERGY_LHC and SPS_ENERGY_CNGS. These energies must be different by at least 5 GeV.

If the measured energy is equal to the SPS_ENERGY_LHC within a tolerance of 5 GeV, the "LHC CYCLE FLAG" is set to .TRUE. If this is not the case, the "LHC CYCLE FLAG" is set to .FALSE.

If the measured energy is equal to the SPS_ENERGY_CNGS within a tolerance of 5 GeV, the CNGS CYCLE FLAG is set to .TRUE. If this is not the case, the CNGS CYCLE FLAG is set to .FALSE.

If the SPS ENERGY cannot be read by the SMP system, both flags should be set to FALSE.

6.7 USAGE OF THE CYCLE FLAGS

The cycle flags are used by the interlock system for LHC/CNGS extraction from the SPS, to determine if the beam is extracted towards LHC or towards CNGS. It also ensures that extraction is only possible at the specific energies corresponding to the settings of the transfer lines.

7. ERROR HANDLING

In order to achieve the required safety levels, the SMP system will be connected to the Beam Interlock System as User Input. The SMP system will itself read back the transmitted values of the different SMP parameters and compare them to the originally sent ones. In case of an inconsistency or other failure of the process, the beams will be dumped.

8. APPENDIX A: DEFINITION OF SIL LEVELS

SIL levels are defined in the norm IEC 61508. The following tables were taken from this norm, and adopted to the accelerator environment.

TABLE I: Category of accidents used for LHC consequences definition

Category	Injury to personnel		Damage to equipment	
	Criteria	**# fatalities**	**CHF Loss**	**Downtime**
Catastrophic	Multiple fatalities events	≥1	> $5 \cdot 10^7$	> 6 months
Major	Single fatality events	0.1	10^6 – $5 \cdot 10^7$	20 days to 6 months
Severe	Serious, but not fatal, injury events	0.01	10^5 – 10^6	3 to 20 days
Minor	Minor injuries events	0.001	0 – 10^5	< 3 days

TABLE II: Frequency table used for LHC risk definition

Category	Description	Frequency (per year)
Frequent	Events which are very likely to occur	> 1
Probable	Events that are likely to occur	10-1 - 1
Occasional	Events which are possible and expected to occur	10^{-2} – 10^{-1}
Remote	Events which are possible but not expected to occur	10^{-3} – 10^{-2}
Improbable	Events which are unlikely to occur	10^{-4} – 10^{-3}
Negligible	Events which are extremely unlikely to occur	< 10^{-4}

TABLE III: Failure rate (SIL) and Risk table used for LHC risk evaluation

Event Likelihood	Consequence			
	Catastrophic	**Major**	**Severe**	**Minor**
Frequent	SIL 4	SIL 3	SIL 3	SIL 2
Probable	SIL 3	SIL 3	SIL 3	SIL 2
Occasional	SIL 3	SIL 3	SIL 2	SIL 1
Remote	SIL 3	SIL 2	SIL 2	SIL 1
Improbable	SIL 3	SIL 2	SIL 1	SIL 1
Negligible	SIL 2	SIL 1	SIL 1	SIL 1

TABLE IV: Failure rate and SIL level		
SIL	Probability of a dangerous failure per hour	MTBF (years)
1	10^{-6} < PR < 10^{-5}	10 – 100
2	10^{-7} < PR < 10^{-6}	100 - 1000
3	10^{-8} < PR < 10^{-7}	1000 - 10000
4	10^{-9} < PR < 10^{-8}	10000 - 100000

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