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ENGINEERING CHANGE REQUEST

Review of the Linac4 BCT Watchdog Interlocking Policy for High Loss Events

BRIEF DESCRIPTION OF THE PROPOSED CHANGE(S):

Currently every detected event of high loss, i.e., when measured intensity difference is above allowed threshold, results in interlocking of all users. However, in LINAC4 electromagnetic field breakdowns in its high gradient RF cavities is a natural phenomenon which happens once per couple of days, usually triggering the high loss interlock. This document proposes a change of the specification of the BCT WATCHDOG class, such that it can allow for occasional high loss events if they happen less often than the defined threshold. This shall reduce the machine downtime with a negligible increase of risk for the machine safety.

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SUMMARY OF THE ACTIONS TO BE UNDERTAKEN:

- Develop and deploy new version of BCTWD fulfilling the updated specification
- Define new Machine Critical Parameters corresponding to the new setting fields

1. EXISTING SITUATION AND INTRODUCTION

One of the machine protection systems in LINAC4 [1] is the BCT Watchdog interlock [2, 3, 4]. BCT stands for Beam Current Transformer, and it is a device that measures beam intensity. BCT Watchdog is implemented as a FESA class called BCTWD. For each beam pulse it computes beam losses between a pair of BCTs and beam transmission in percent. If any of those two values is out of a permitted range, then it enables an interlock via Beam Interlock System (BIS). While it tolerates that transmission is occasionally out of range (refer to as low losses Watchdog interlock), any occurrence of high loss stops all the beams.

Figure 1 shows 2024 statistics of high loss events. Only couple of them were related to hardware failures, another few with communication issue between BCTWD and BCTs. The experience gained from LINAC4 operation shows that most of the high loss events is because of breakdowns in RF cavities. Those events are inevitable in high gradient accelerating structures. When it

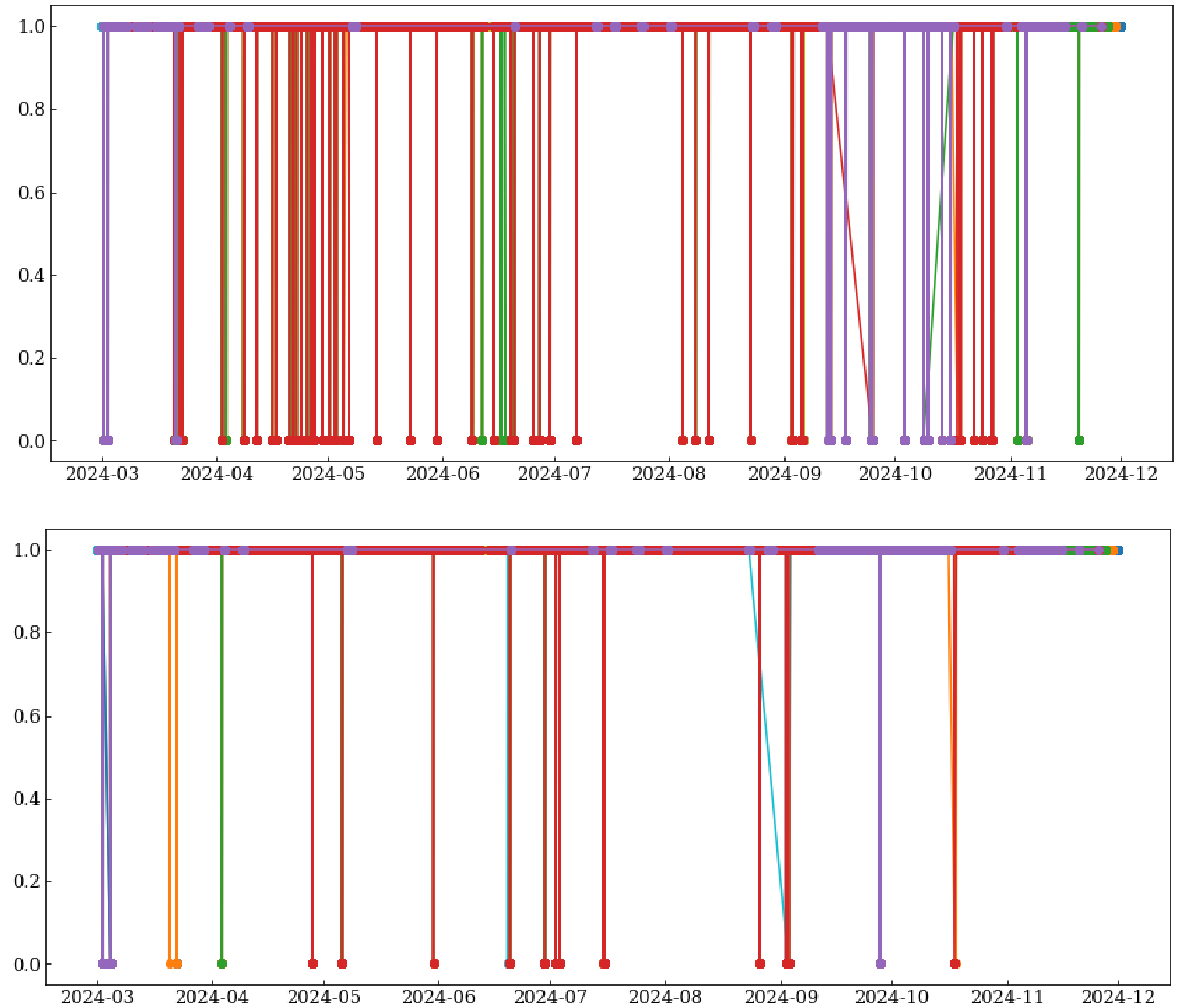

Figure 1: 2024 statistics of high loss events for L4L.BCTWD.L4T (top) and L4T.BCTWD.BI (bottom) for the operational beams (each colour corresponds to one beam type / telegram user). Zero means that the permit is removed.

happens the whole, or some part of the beam pulse is badly accelerated and focused. Having wrong energy, it is out of the acceptance of the transfer lines, and it is lost. In most of the cases the following pulse is fine. In some other cases, the control logic of given RF line detects the wrong state, and it inhibits the following pulse to assess its own integrity. If no issue is detected, then it continues normal operation. Otherwise, it interlocks the line.

However, since the BCT watchdog interlocks the beam, the operator needs to acknowledge and reset it manually. Normally, it takes a few minutes until the operator on shift realizes this event. Then, the operator needs to verify the reason of the interlock. However, with the gained experience that most of those interlocks are provoked by an event of RF breakdown or similar, usually the interlock can be cleared rapidly, and the beam is re-enabled to verify if the interlock persists.

2. REASON FOR THE CHANGE

The reason is to reduce machine downtime due to inevitable but not dangerous events, which happen regularly during beam operation.

We propose to update the BCTWD FESA class such that it could be configured to tolerate occasional high loss events, i.e. at least one in a certain period of time. Any uncontrolled beam losses should be avoided, however, events originating from RF breakdowns are inevitable and increasing somewhat their rate should not increase significantly the risk for the machine. We propose to start with a conservative number 1 event per 12 hours. Only if the system is proven effective and there is further potential gain in beam availability, upon Machine Protection Panel agreement it could be reduced to 1 event per hour.

2.1 Risk assessment

High-loss interlock protects against prolongated beam losses. By definition, high losses are detected only when an equipment failure or misconfiguration occurs. It can happen in the following scenarios

1. One power converter stops.
    a. Quadrupole: focusing is altered and beam being too large is scraped. The losses are distributed over sizeable area and therefore there is a low risk of damage. These power converters are monitored by SIS, which interlocks the beam when a power converter stops and from 2025 external condition will be present, such that the beam with given destination cannot be played.
    b. Dipole: beam has wrong trajectory. The losses are punctual, and in case impacting a sensitive location, for example a joint in a flange, they can lead to a vacuum leak. Considering beam parameters, this requires several consecutive pulses impacting the same location. However, these power converters are under surveillance of the FGC Interlock, that will not give the permit to BIS system until correct intensity is measured. Therefore, the related risk is very low.
    c. Trajectory correctors. Because they create relatively small angles to the beam trajectory, the induced losses are distributed over a certain area. In case impacting a sensitive location, for example a joint in a flange, it can lead to a vacuum leak. Considering beam parameters, this requires multiple consecutive

pulses impacting the same location. These devices are not directly monitored by any interlock system. The associated risk to damage any equipment with 3 bad pulses is low.

2. Incidental change of settings

   The effect is very similar to the described above scenario when a power convert trips. The impact depends on how much the new setting deviates from the optimum value: the smaller the change, the lower is the risk of a small area beam impact. In case of the dipoles, the FGC interlock has a relatively narrow window, therefore it will interlock when settings are outside of this window, thus this reduces the risk. There is no such protection for quadrupoles or trajectory correctors, because the risk that their failure provokes machine any damage is extremely low and the beam can be re-steered with given corrector off. The probability of incidental change is low a risk to damage any equipment with 3 bad pulses is low.

3. Field breakdown in the accelerating structures.

   Such an event alters the amplitude and phase of the accelerating field. The beam is accelerated to a different energy, which changes the subsequent focusing and bending angles. Unless the breakdown occurs in the very last cavity of the linac, the effect of wrong focusing is such that the losses are distributed over a very large area of the beam chamber. In case it is the last cavity then the wrong angle received from the bends is the dominant effect and the losses can be concentrated in a narrow area. However, based on operational experience there is a relatively low probability that the following pulse will also suffer an RF breakdown, although this cannot be excluded. The exact moment of RF breakdown plays an important role of the criticality of this failure, because only the part of the pulse after the breakdown is affected.

In case the losses are localized in a small area, then Beam Loss Monitors have high chance detecting out of range radiation levels and stopping immediately beam production. This reduces the risk of having repeated full beam losses at the very same location. Linac4 is in a large extent resistant to a full beam loss and only some spots are more sensitive, like joints in the flanges.

2.2 Functional specification

The most intuitive approach would be to define a value with maximum number of events allowed within given period, for example, 1 event per hour or 3 events per day. However, its implementation is quite complex, because it requires to store in memory the list of the timestamps for each event and to compare them at every pulse with the current time. The already existing transmission efficiency counter of BCT Watchdog is implemented with counting down bad pulses from the threshold value down to zero, therefore high loss counters should be implemented also this way.

The first counter, highLossCounter, tracks the number of high loss events. It is initialized to with value defined by the **highLossCounterThreshold** setting. highLossCounter is reduced by one ay each high loss event. The watchdog removes the permit when this counter becomes zero. The second counter, highLossGoodEventCounter, monitors the number of consecutive pulses without high loss events. It is initialized with the value specified by the **highLossInterval** setting. BCTWD decreases highLossGoodEventCounter by one with each good pulse, and when it becomes zero, then it increases the highLossCounter by one and puts highLossGoodEventCounter equal to **highLossInterval**. Neither counter can become negative. Additionally, the highLossGoodEventCounter is reset to value of **highLossInterval** whenever a high loss event occurs.

Reset action will not set highLossCounter to **highLossCounterThreshold**. Instead. it should leave it unchanged if it is bigger than zero. If it is equal to zero, then reset action should set it to one. This is to avoid that resetting the watchdog allows multiple high loss events on the next occasion.

3. DETAILED DESCRIPTION

Two new setting variables, both protected with Machine Critical Setting RBAC role need to be defined BCTWD class

1. **highLossCounterThreshold**
2. **highLossInterval**

UML diagram of the algorithm to be implemented is depicted on Figure 2. For an example, we take **highLossCounterThreshold** = 2 and **highLossInterval** = 30000, meaning that 1 high loss event per 10 hours is accepted. Initially highLossCounter = highLossCounterThreshold = 2 and highLossGoodEventCounter = highLossInterval = 30000. Then we consider the possible scenarios:

1. **No high loss occurrence for an extended period.**

   Initially, highLossGoodEventCounter is equal to 30000 (defined by **highLossInterval**). It is decreased at each pulse until it reaches value of 0, corresponding to the green path depicted on Fig. 1.

   When it reaches this value, then it is set back to 30000. highLossCounter is not smaller than **highLossCounterThreshold**, therefore, it cannot be further increased. This corresponds to the blue path.

2. **Occurrence of 1 high loss event followed by extended period with no high loss event.**

   When high loss event is detected then highLossCounter is decreased by 1, meaning that it is set to 1. highLossGoodEventCounter is reset to 30000. highLossCounter is still bigger than 0, therefore highLossPermit is set to true and the operation continues. This corresponds to the magenta path depicted in Fig. 1.

   From now on only good pulses are encountered and at each pulse highLossGoodEventCounter is decreased until it reaches 0 (the green path).

   When highLossGoodEventCounter reaches 0, then highLossCounter is increased by 1, meaning that it is set to 2, and highLossGoodEventCounter is also set to 30000. This corresponds to the yellow path.

   Further the algorithm continues as described in point 1.

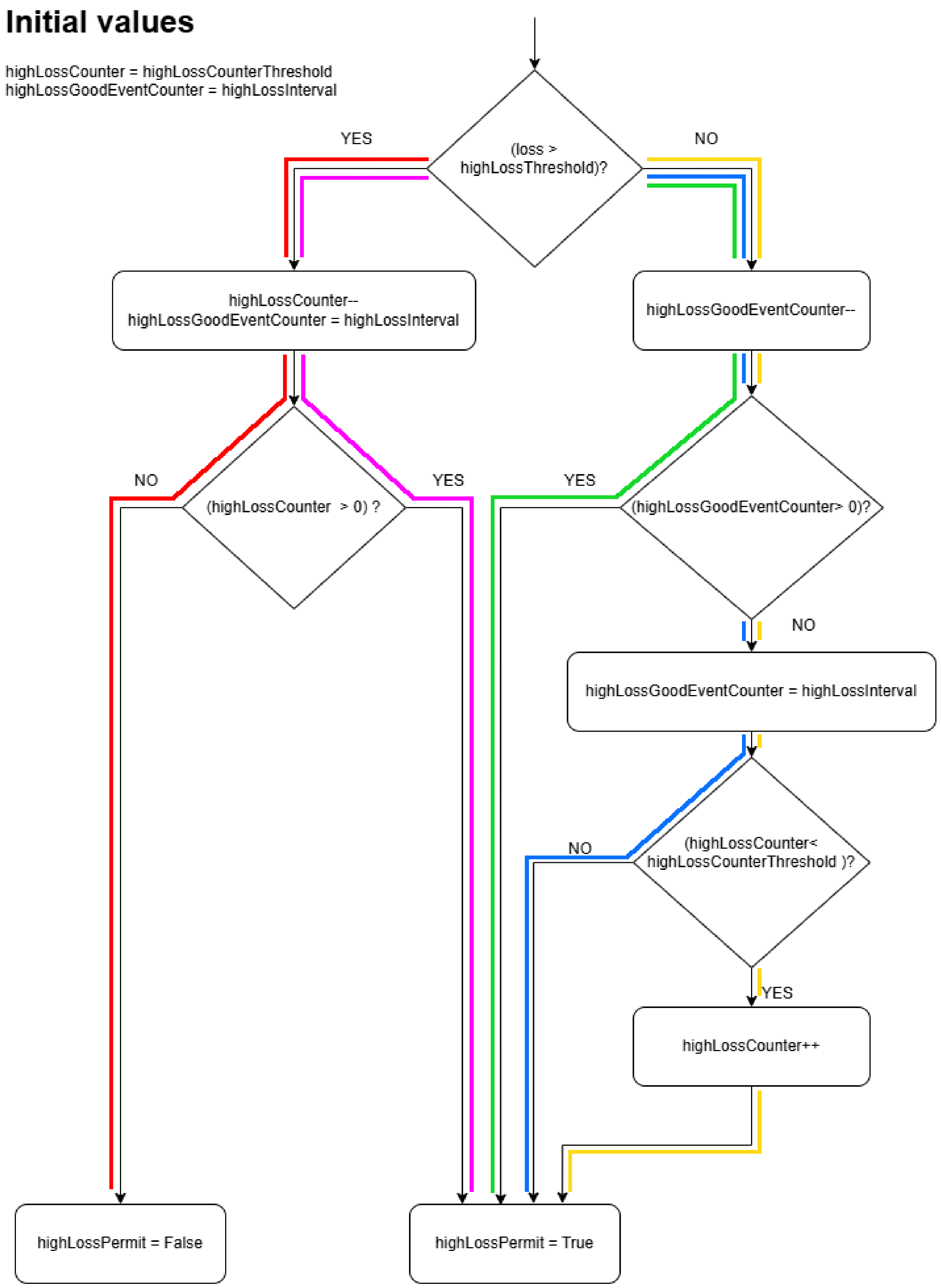

Figure 2: UML diagram of algorithm implementing the functional specification. The colours depict different paths through this logical tree.

3. **Occurrence of 2 high loss events in time interval smaller than 10 hours.**

   When the 1st high loss event is detected then highLossCounter is decreased by 1, meaning that it is set to 1. highLossGoodEventCounter is reset, meaning that it is set to 30000. highLossCounter is still bigger than 0, therefore highLossPermit is set to true and the operation continues. This corresponds to the magenta path on Fig. 1.

   Until next high loss event is encountered highLossGoodEventCounter is decreased at each pulse (the green path).

   Then, highLossCounter is decreased by 1, meaning that it is set to 0, highLossPermit is set to false and all beams are interlocked (the red path).

We propose to relax the high loss constraint only for 2 BCT Watchdog devices: L4L.BCTWD.L4T which compares L4L.BCT.4013 with LT.BCT30 and L4L.BCTWD.Dump which compares L4L.BCT.4013 with L4Z.BCT.0273. The values of the corresponding parameter should initially be highLossCounterThreshold = 2 and highLossInterval = 30000. This means that one high loss event per 10 hours will be allowed. All other watchdog devices are configured with highLossCounterThreshold = 1 and highLossInterval = 10000000. In particular, the watchdog monitoring the RFQ transmission is not going to be changed. Any further modifications of these parameters need to be approved by Machine Protection Panel.

4. IMPACT ON OTHER ITEMS

4.1 IMPACT ON ITEMS/SYSTEMS

Layout Database and seq input file extraction for optics	None
Optics files, survey files and GEODE	None
LSA DB	Requires definition of 2 new parameters
CCDB (and any other controls related DBs)	None
Drawings and machine stickers/labels	None
Cablotheque	None
OP/CO applications	None
SY-ABT expert tools	None
TE-MPE	Possible impact on documentation

4.2 IMPACT ON UTILITIES AND SERVICES

Raw water:	No
Demineralized water:	No
Compressed air:	No
Electricity, cable pulling (power, signal, optical fibres…):	No
DEC/DIC:	No
Racks (name and location):	No
Vacuum (bake outs, sectorisation…):	No
Special transport/ handling:	No
Temporary storage of conventional/radioactive components:	No
Alignment and positioning:	No
Scaffolding:	None
Controls:	None
GSM/WIFI networks:	None
Cryogenics:	None
Contractor(s):	None
Surface building(s):	None
Integration:	Ni
Others:	-

5. IMPACT ON COST, SCHEDULE AND PERFORMANCE

5.1 IMPACT ON COST

Detailed breakdown of the change cost:	
Budget code:	

5.2 IMPACT ON SCHEDULE

Proposed installation schedule:	YETS 2024/2025
Proposed test schedule (if applicable):	
Estimated duration:	
Urgency:	None
Flexibility of scheduling:	-

5.3 IMPACT ON PERFORMANCE

Mechanical aperture:	Not applicable
Impedance:	Not applicable
Optics/MADX	Not applicable
Electron cloud (NEG coating, solenoid…)	Not applicable
Insulation (enamelled flange, grounding…)	Not applicable
Vacuum performance:	Not applicable
R2E impact on performance and availability:	Not applicable
Others:	

6. IMPACT ON OPERATIONAL SAFETY

6.1 ÉLÉMENT(S) IMPORTANT(S) DE SECURITÉ

Not applicable.

Requirement	Yes	No	Comments
EIS-Access		x	
EIS-Beam		x	
EIS-Machine		x	

6.2 OTHER OPERATIONAL SAFETY ASPECTS

What are the hazards introduced by the hardware?	In case a trip of power converter for corrector magnet or very unlikely event is repeated sparking in a cavity, more than one beam pulse will be lost in the machine.
Could the change affect existing risk mitigation measures?	Yes, BCTWD is a risk mitigation measure and this will relax its behaviour.
What risk mitigation measures have to be put in place?	-
Safety documentation to update after the modification	-
Define the need for training or information after the change	-

7. WORKSITE SAFETY

7.1 ORGANISATION

Requirement	Yes	No	Comments
IMPACT – VIC:		x	
Operational radiation protection (surveys, DIMR…):		x	
Radioactive storage of material:		x	
Radioactive waste:		x	
Non-radioactive waste:		x	
Fire risk/permit (IS41) (welding, grinding…):		x	
Alarms deactivation/activation (IS37):		x	
Others:			

7.2 REGULATORY INSPECTIONS AND TESTS

Requirement	Yes	No	Responsible Group	Comments
HSE inspection of pressurised equipment:		x		
Pressure/leak tests:		x		

HSE inspection of electrical equipment:		x		
Electrical tests:		x		
Others:				

7.3 PARTICULAR RISKS

Requirement	Yes	No	Comments
Hazardous substances (chemicals, gas, asbestos…):		x	
Work at height:		x	
Confined space working:		x	
Noise:		x	
Cryogenic risks:		x	
Industrial X-ray (*tirs radio*):		x	
Ionizing radiation risks (radioactive components):		x	
Others:			

8. FOLLOW-UP OF ACTIONS BY THE TECHNICAL COORDINATION

Action	Done	Date	Comments
Carry out site activities:			
Carry out tests:			
Update layout drawings:			
Update equipment drawings:			
Update layout database:			
Update naming database:			
Update optics (MADX)			
Update procedures for maintenance and operations			

Update Safety File according to EDMS document 1177755:			
Others:			

9. REFERENCES

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[4] A. Topaloudis and J. A. Santamaria, "MOPHA145-Evolution of the CERN LINAC 4 Intensity Interlock System Using a Generic, Real-Time Comparator in C++. EDMS 2707912.," [Online]. Available: https://edms.cern.ch/document/2707912.