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

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EXISTING SITUATION AND INTRODUCTION

Introduction

- One of the machine protection systems in LINAC4 is the BCT Watchdog.

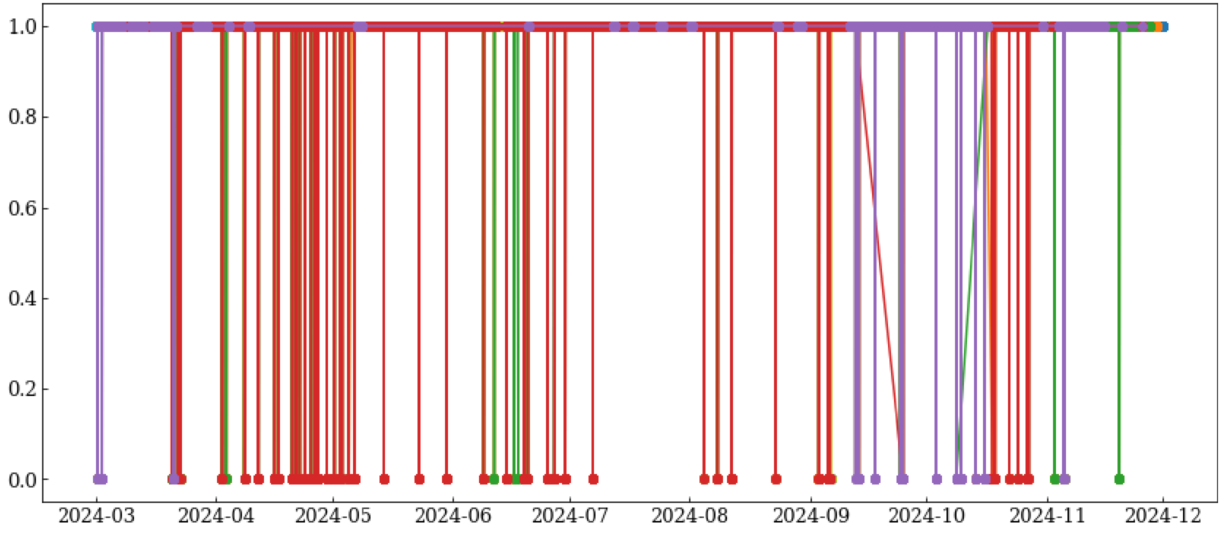
- BCT stands for Beam Current Transformer.
  - It is a device that measures beam intensity.

- BCT Watchdog is implemented as a FESA class called BCTWD
  - For each beam pulse it computes
    - Beam losses between a pair of BCTs.
    - 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).
    - It tolerates that transmission is occasionally out of range
      - Referred to as low losses watchdog interlock
    - **Any occurrence of high loss stops all the beams.**

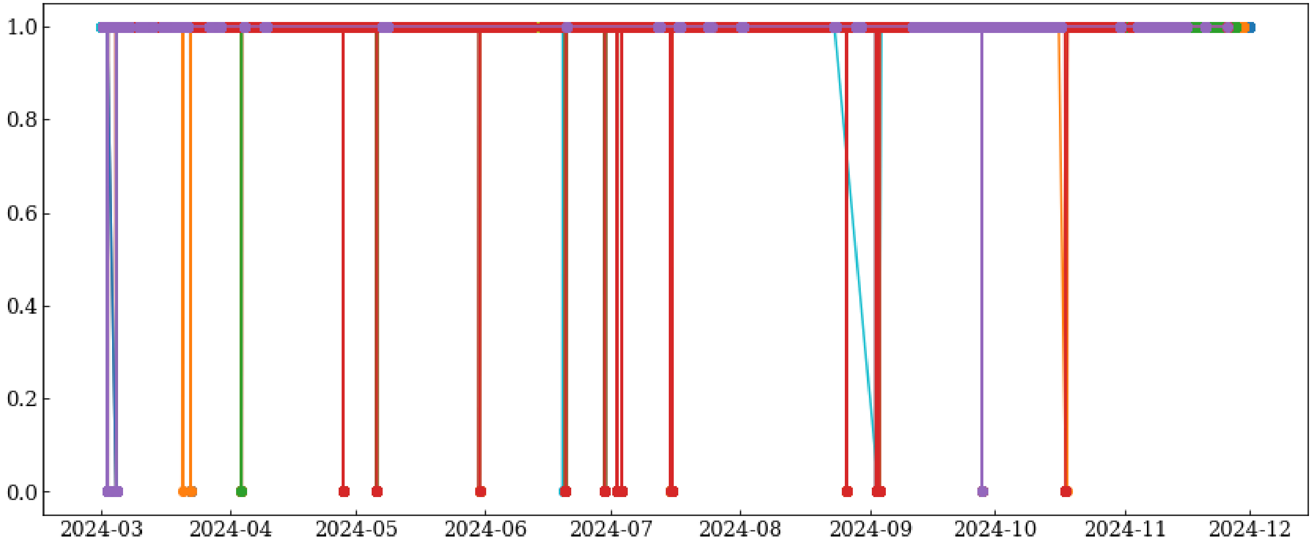
2024 statistics of high loss events

- The experience gained in operation shows that many of the high loss events is because of breakdowns in RF cavities.
- Only some of them were related to hardware failures or wrong settings, another few with communication issue between BCTWD and BCTs.

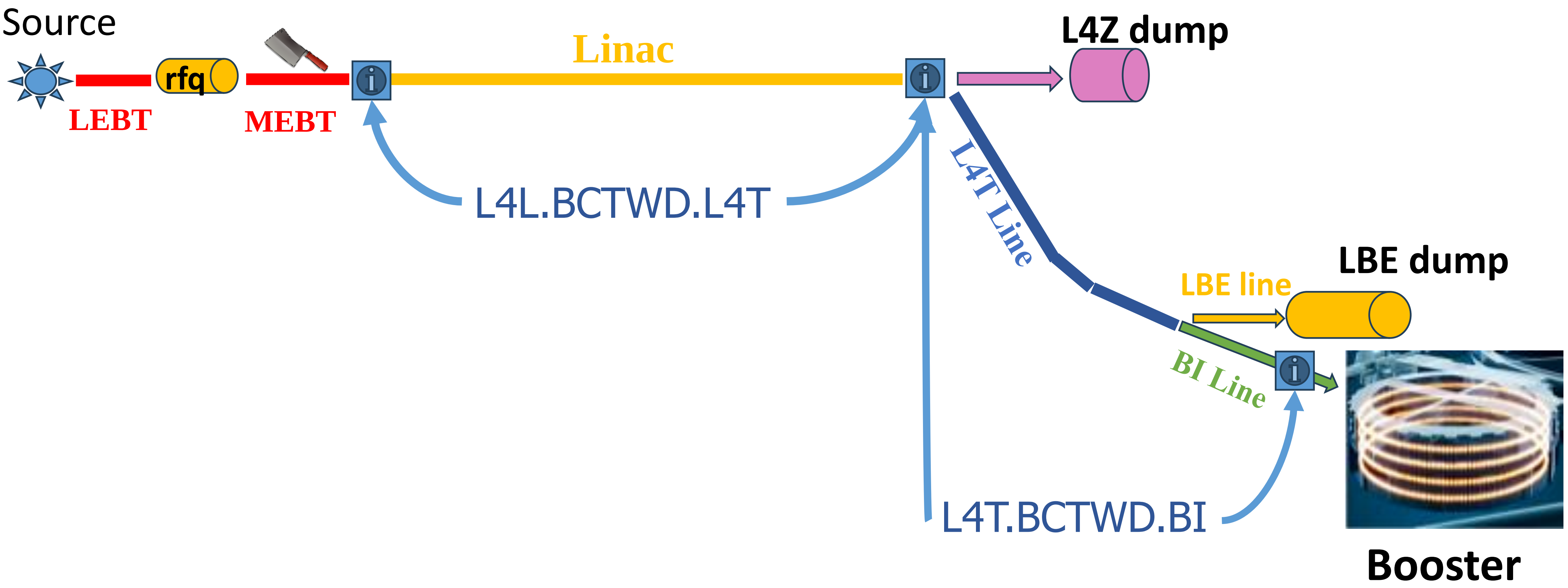
L4L.BCTWD.L4T: 222 events



L4T.BCTWD.BI: 31 events



The watchdogs in question



REASON FOR THE CHANGE

Reason for the change

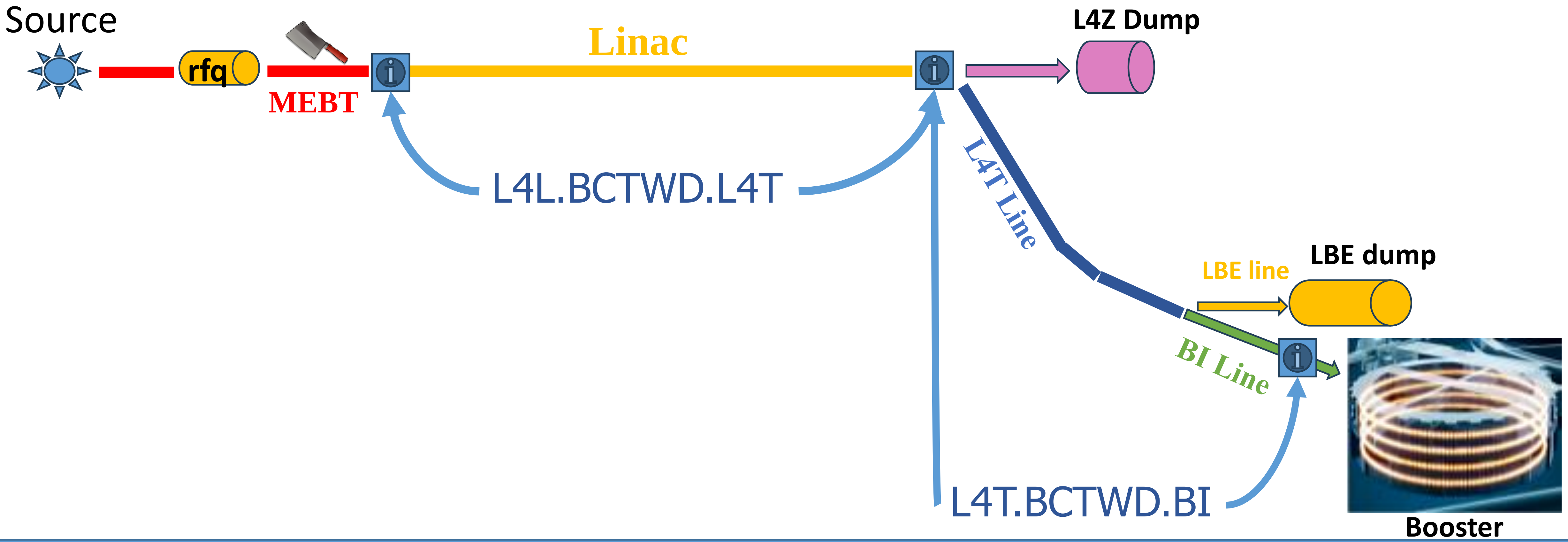
- Currently every detected event of high loss results in interlocking of all users.
  - i.e., when measured intensity difference is above allowed threshold

- Very often the high losses are a result of electromagnetic field breakdowns in the high gradient RF cavities of LINAC4
  - It is a normal phenomenon which happens once per couple of days.
  - Usually, they are one of events, however, sometimes the coming series.
- **We propose to 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.

The proposal

- We propose to permit 1 event per 12 hours in 2 BCTWD devices
  - L4L.BCTWD.L4T surveys the linac from DTL1 to PIMS12
  - L4T.BCTWD.BI surveys the transfer lines from the end of linac to PSB injection



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:

Risk assessment: Quadrupole power converter stops

- 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
- From 2025 external condition is configured such that the beam with affected destination cannot be played.
- Therefore, the related risk is very low.

Risk assessment: Dipole power converter stops

- 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.
  - SY-STI will perform simulations, the results are expected within February. No change will be implemented in operation until this statement is confirmed.
- However, these power converters are under surveillance of the FGC Interlock, that will not give the permit to BIS system until correct amperage is measured.
- Therefore, the related risk is very low.

Risk assessment: Trajectory correctors power converter stops

- 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.**

Risk assessment
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.

Risk assessment: 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.

Functional specification

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,
  - 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 using similar way.

Solution based on counters

- highLossCounter:
  - It tracks the number of high loss events.
  - It is initialized to with value defined by the highLossCounterThreshold setting.
  - It is reduced by one ay each high loss event.
  - The watchdog removes the permit when this counter becomes zero.
- highLossGoodEventCounter
  - It monitors the number of consecutive pulses without high loss events.
  - It is initialized with the value specified by the highLossInterval setting.
  - It decreases by one with each good pulse.
  - When it becomes zero, then
    - highLossCounter increases by one, if not bigger than highLossCounterThreshold
    - highLossGoodEventCounter is set back highLossInterval.
  - It is reset to value of highLossInterval whenever a high loss event occurs.
- Neither counter can become negative.

Specification: Reset action

- To avoid that resetting the watchdog allows multiple high loss events on the next occasion, reset action **will not** set highLossCounter to highLossCounterThreshold.

- Instead, it should leave highLossCounter unchanged if it is bigger than zero.

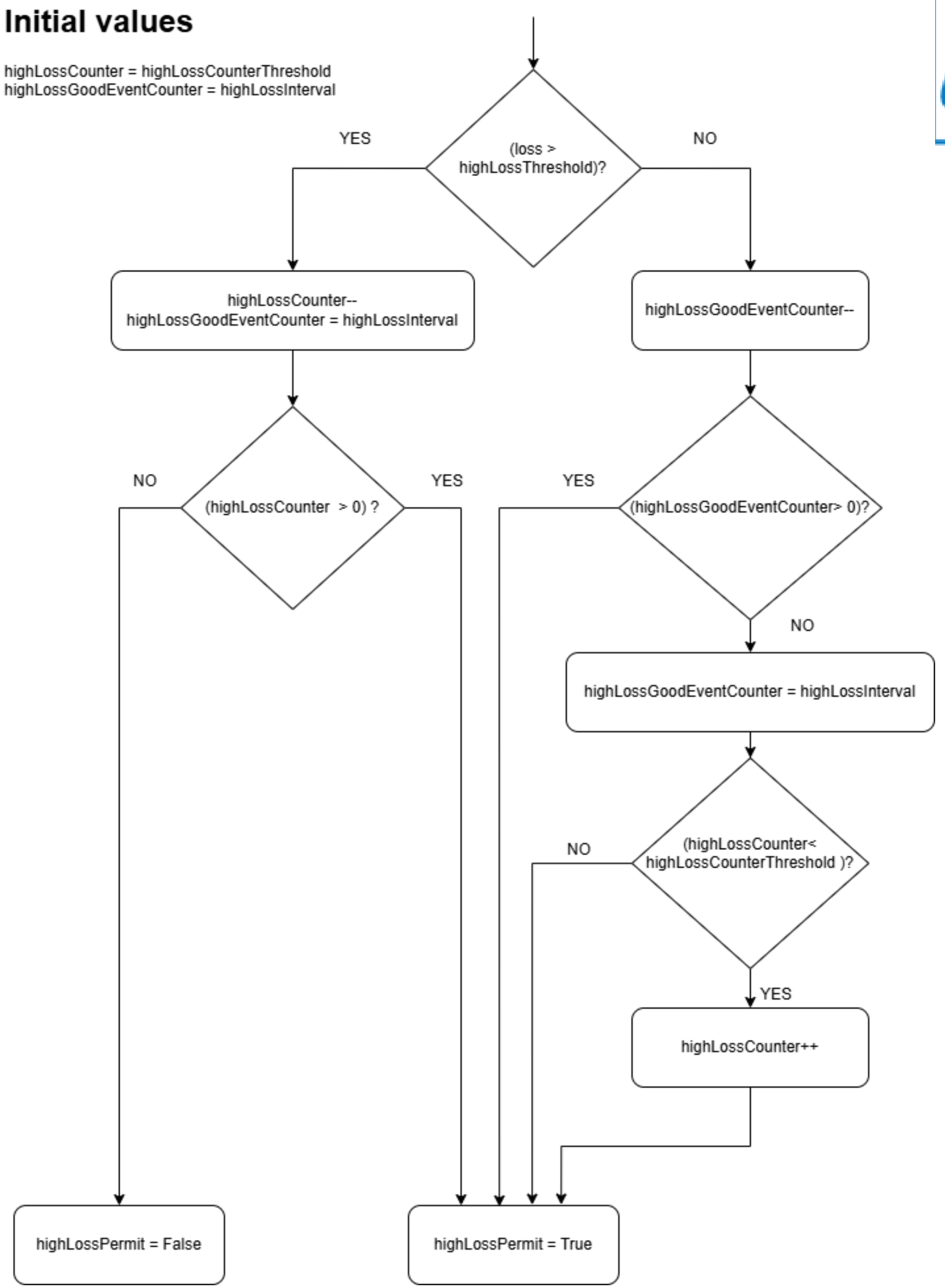
- If it is equal to zero, then reset action should set highLossCounter to 1.

Detailed description

- Two new setting variables need to be defined BCTWD class
  - highLossCounterThreshold
  - highLossInterval
- Both need to be protected with Machine Critical Setting RBAC role.

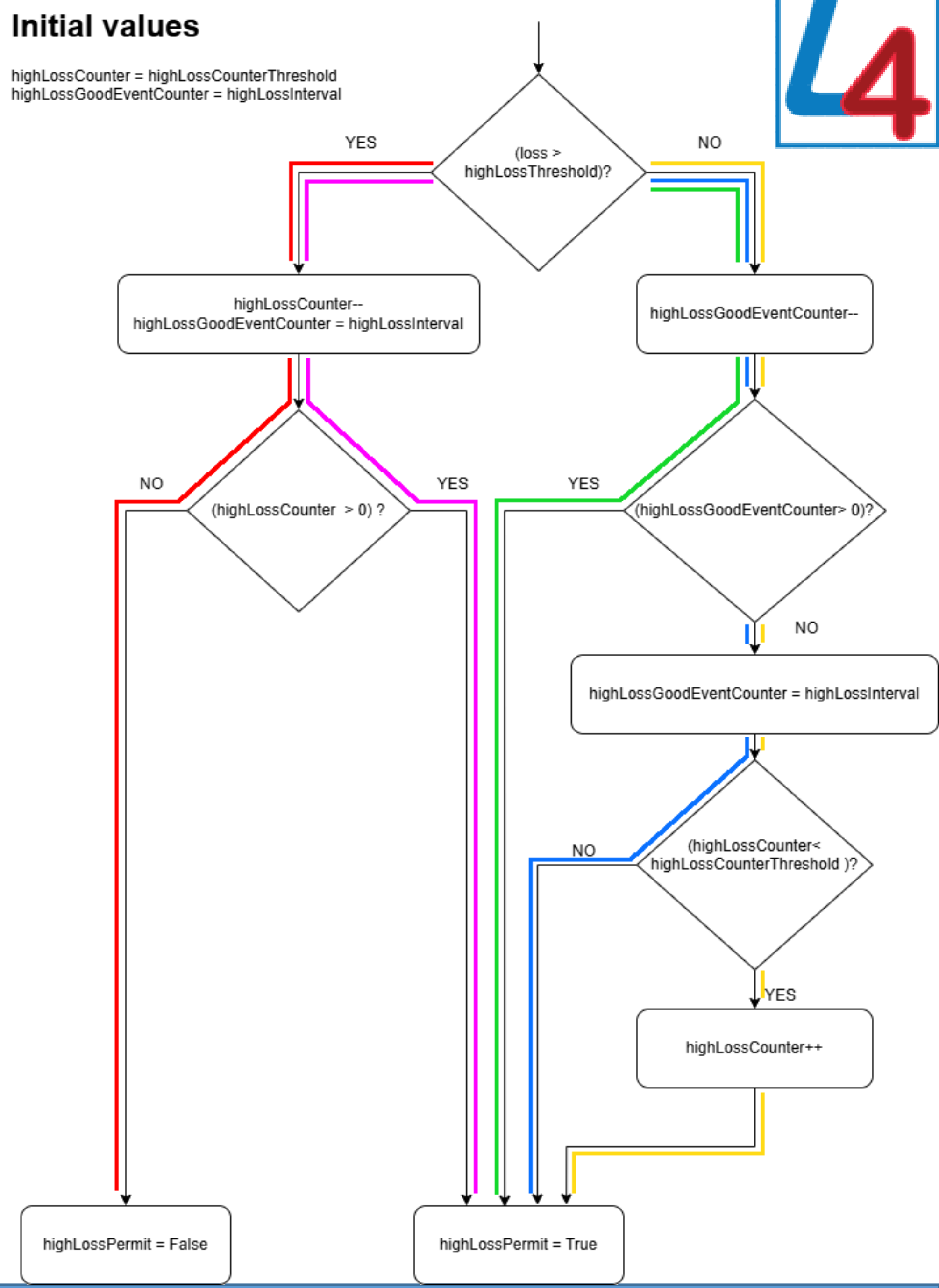
UML diagram of the proposed algorithm

- As an example, we take settings
  - highLossCounterThreshold = 2 and highLossInterval = 30000
    - meaning that 1 high loss event per 10 hours is accepted.
  - Initially both counters are zero, highLossCounter highLossGoodEventCounter.
- Then let's consider the possible scenarios



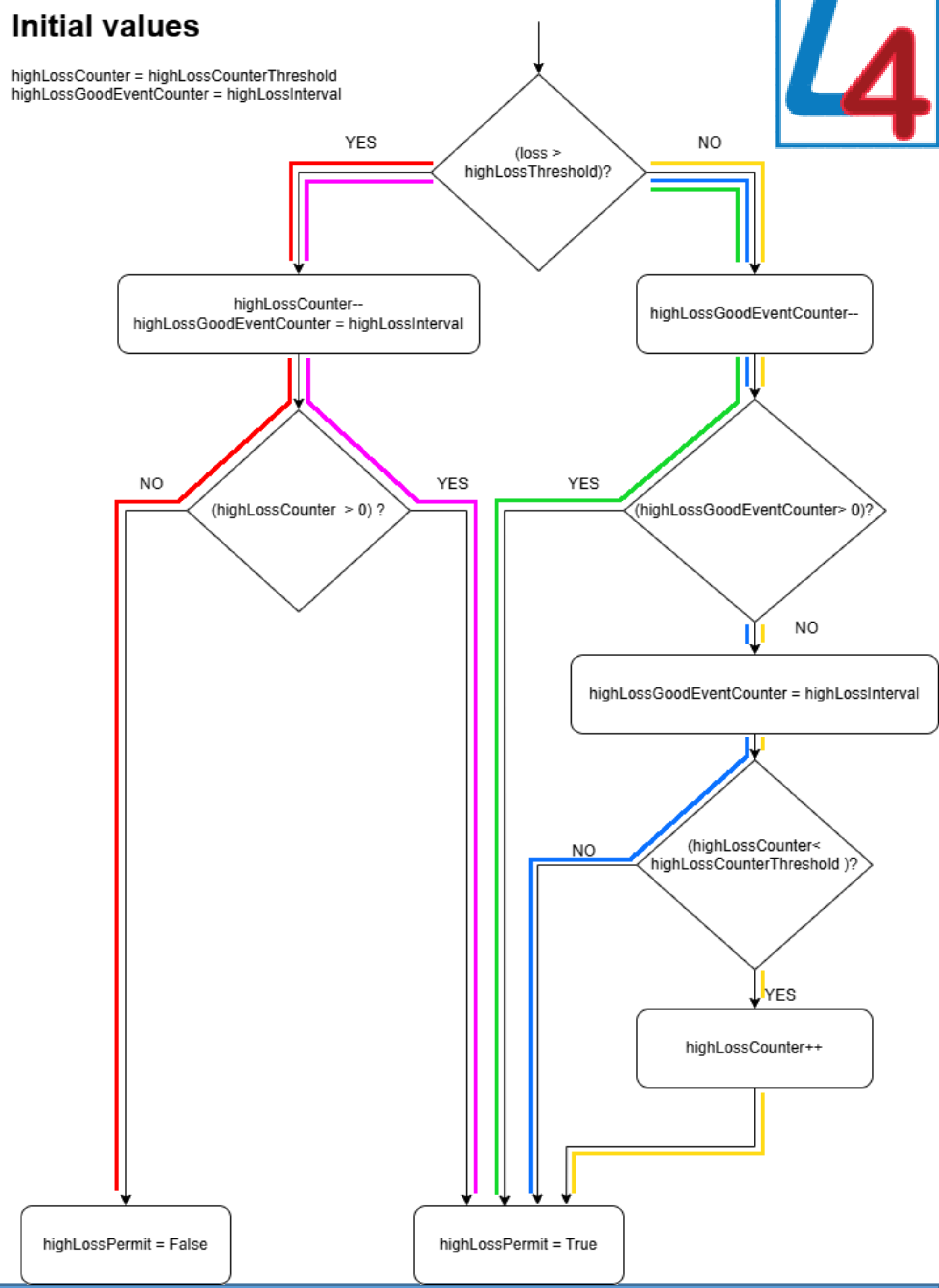
No high loss event for an extended period

- Initially,
  - highLossGoodEventCounter = 30000
    - defined by highLossInterval.
  - highLossCounter = 2
    - defined by highLossCounterThreshold.
- highLossGoodEventCounter is decreased at each pulse until it reaches value of 0.
  - This corresponds to the **green path**.
- When it reaches 0, 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**.



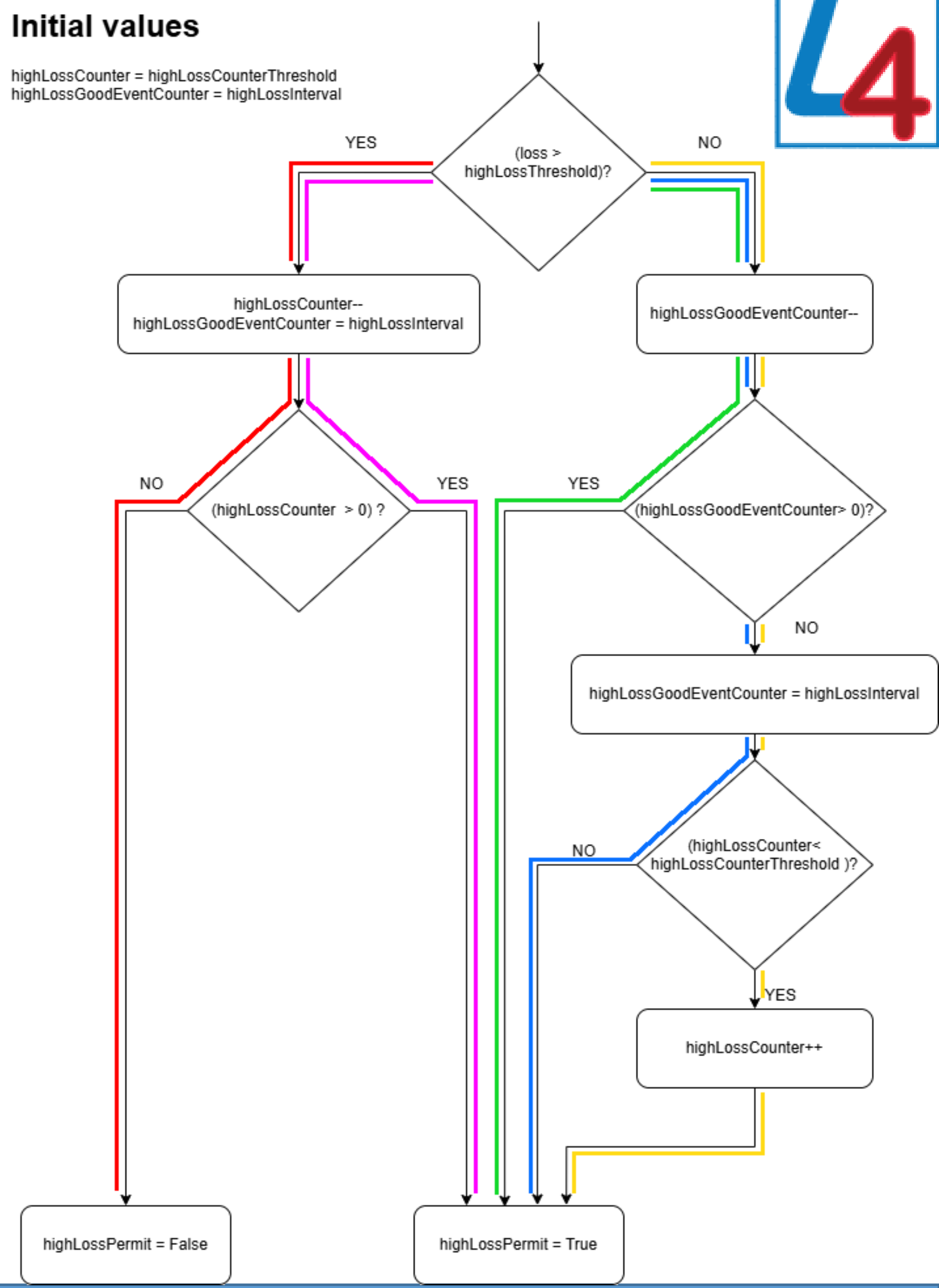
1 high loss event followed by extended period with no high losses

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



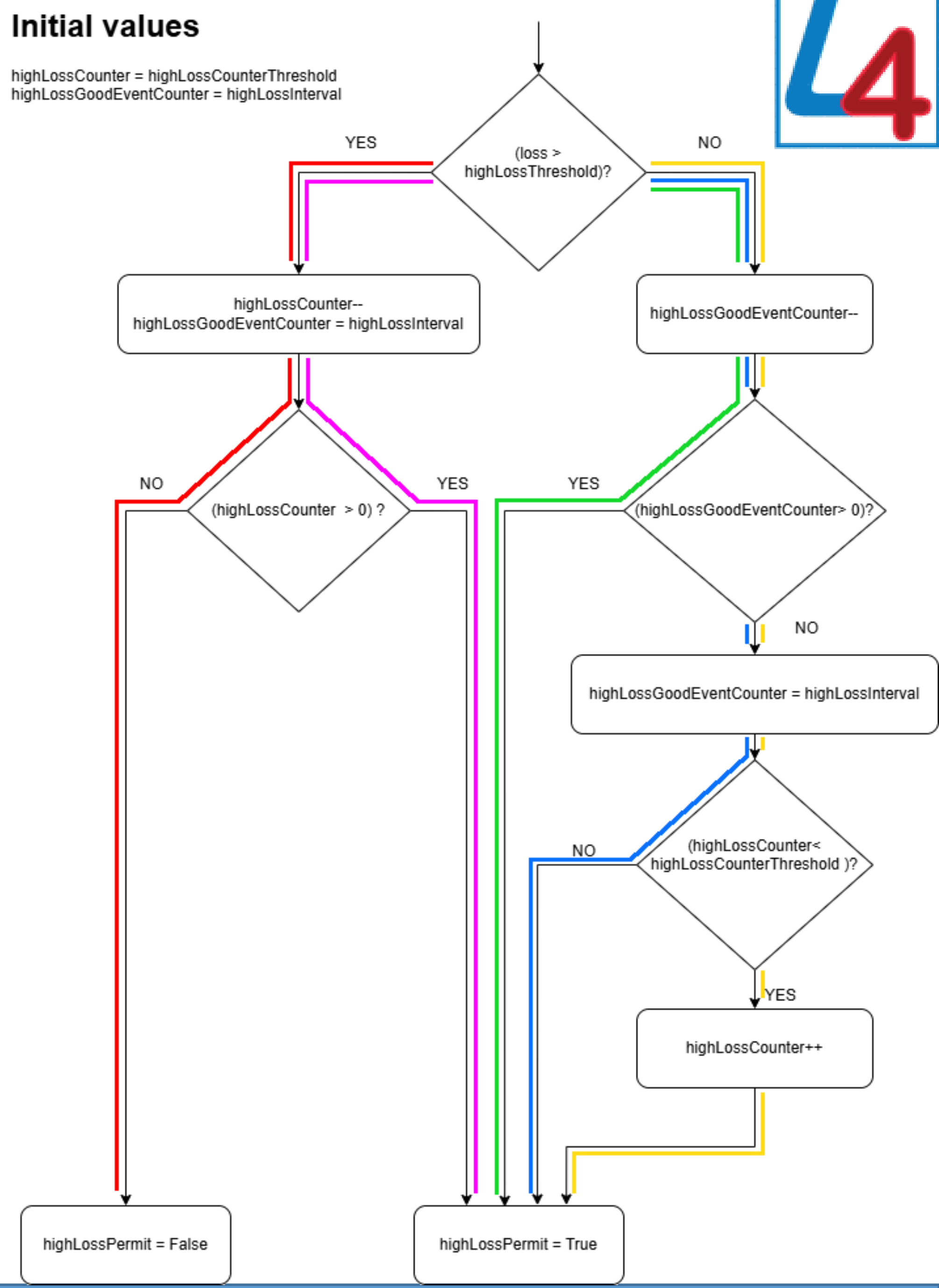
1 high loss event followed by extended period with no high losses

- From now on only good pulses are encountered
  - at each pulse highLossGoodEventCounter is decreased until it reaches 0 (**the green path**).
- When highLossGoodEventCounter reaches 0
  - highLossCounter is increased by 1
    - meaning that it is set to 2.
  - highLossGoodEventCounter is also set to 30000.
  - This corresponds to **the yellow path**.
- Further the algorithm continues as described in the 1st point.



2 high loss events within less than 10 hours

- When 1st 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**
- 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**)



Conclusions

- We propose to relax high loss policy for BCT Watchdog in Linac4 and to permit **occasional** high loss events
  - Only 2 watchdog instances would have the relaxed setting
    - In particular, the RFQ policy WILL NOT be changed
  - Start with 1 event allowed per 10 hours
  - If ever needed, this could be relaxed in the future under approval of MPP

- Increase of the risk for the machine safety is very small
  - Waiting for FLUKA simulations to confirm that even in the worst-case scenario of direct beam impact on metallic structures
    they should not melt with less then 10 pulses