THE CLIC MACHINE PROTECTION

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INTRODUCTION

The proposed Compact Linear Collider (CLIC) [1, 2] is based on a two-beam acceleration scheme. The energy of two high-intensity, low-energy drive beams is extracted and transferred to the two low-intensity, high-energy main beams. The machine protection has to cope with a wide variety of failures, from real-time failures (RF breakdowns, kicker misfiring), to slow equipment failures, to beam instabilities (caused by e.g. temperature drifts, slow ground motions).

Due to the many different types of accelerator components and the beams of various characteristics throughout the entire complex, the CLIC machine protection is an extensive subject. The machine protection has the mission to protect the various machine components from damage caused by ill controlled beams. The severity of the damage is given by the financial impact of the damage and the reduction in the operational availability of the facility. The risk equivalent is given by the product of the fault rate and the impact of the fault (i.e. in statistical terms: risk is the expectation value of the fault impact). This concept is illustrated by some examples for downtime in Table 1.

Table 1: Examples of Risks

Downtime	Frequency	Risk Equivalent (for 6 month running per year)
3 month	1 per 5 years	7.5%
1 day	10 per year	5.5%
2 years	1 per 10000 years	0.02%

The machine protection system should reduce the risk to a level were the risk becomes acceptable. An acceptable risk can be expressed by the notion that the total expected operational downtime from all risks terms should be smaller than a few percent and likewise, that the total expected financial impact is also less than a few percent of the operational cost.

BEAM POWER AND DESTRUCTIVE CAPACITY

The beam power – given by the product of the beam charge, the particle energy and the cycle repetition rate (50 ~ 100 Hz) – is impressive both for the drive beam (70 MW) and the main beam (14 MW) and this makes a sustained disposal of this power a challenging task. However, for the purpose of the definition of safe beam, the destructive potential is primarily determined by the charge density of the beams. Table 2 summarizes various beams: a single (one of 24) drive beam train (DBT), the main beam at the extraction of the damping rings (MB-DR) and the main beam at the betatron collimation section (MB-βcoll). The last two columns give the energy density in copper due to direct ionization loss by a) the incident beam particles and b) the shower core particles. The numbers show that the effect of the charge density of the incident beam is far more significant than the shower core. These numbers must be put in perspective with the level of structural yield in copper (60 J g^{-1}). Hence, the drive beam is two orders of magnitude above safe beam, while the main beam is up to four orders of magnitude above safe beam.

Table 2: Beam characteristics and energy density

Beam (see text)	Particle Energy [GeV]	Pulse Charge [μC]	Beam Size [mm^2]	Energy Density in copper [J g^{-1}] Incident Beam	Shower Core
DBT	2.4	25	1	3.4 10^3	40
MB-DR	2.8	0.20	125 10^{-6}	1.8 10^5	0.34
MB-βcoll	1.5 10^3	0.18	40 10^{-6}	6.7 10^5	120

FAILURE TYPES

According to their nature, we distinguish the following types of failure in CLIC.

Fast Failures

These failures occur at time scales corresponding to the beam passage through the accelerator complex. Because of the continuous beam line nature, it will be difficult, if not impossible to detect a failure and dump the beam. The major sources of these '*in flight*' failures are:

- RF breakdown. An RF breakdown could potentially produce enough transversal kick to send the drive beam or the main beam off trajectory into some accelerator component.
- Kicker misfiring. A misfiring of a kicker can send the beam off trajectory into the extraction channel (most critical element: the septum magnet).
- Klystron trip. A klystron trip in the drive beam linac may potentially disrupt the beam enough to provide large losses. N.B. the drive beam linac has the equivalent of 1.5 drive beam train in the pipeline: i.e. a beam of two orders above damage level.

Inter-Cycle Failures

These are mainly equipment failures that happen in the interval between two successive machine cycles (10 ~ 20 ms). The major sources of equipment failures are:

- Power supply failures
- Positioning system failures
- Vacuum system failures

Slow Failures

This last category contains the failures that develop at time scales larger than the repetition rate of CLIC. These are the failures that cause a slow onset of losses due to drifts in temperature, alignment or beam feedback saturations. Under normal conditions, the beam feedback system should keep these drifts under control. Any deviation of the expected behaviour should be considered as potentially dangerous.

PROTECTION STRATEGIES

The base line machine protection of CLIC consists of various strategies to deal with each type of failure.

Passive Protection

For *in flight* failures, where detection and beam abort are impossible, the protection will be based on passive protection in the form of masks and spoilers.

The passive protection must be made robust enough to provide full protection for the whole pulse. Many of the systems are already designed along this principle. As an example, the energy collimation is capable of withstanding a full beam impact of the main beam in case of an energy error [3].

Real-Time Protection

In cases where the geometry of the CLIC complex provides the possibility to take a short-cut in the signal path, a protection in real-time is an option that can be considered. Without detailing them all, the most obvious options are in the rings, the turnarounds and the drive beam linac (i.e. real-time source inhibit).

Beam Interlock System

In case of an equipment failure during the inter-cycle period, a Beam Interlock System (BIS) will assure that the next cycle is inhibited. Although there is a finite time for detection and treatment, the BIS will handle all failures up to 2 ms before the next cycle is set off.

Safe by Design

To cover the 2 ms blind period prior to the each cycle, all magnet circuits in critical beam transport structures must have enough inertia to remain within tolerance for 2 ms after a power converter fault. Here the required tolerance is determined by a safe passage of the beam. Preliminary studies have shown that tolerances at the level of ~10 % are acceptable, corresponding to magnet circuits with a L/R time larger than 20 ms.

The same principle of fault tolerance must be applied to all active equipment: vacuum, positioning systems, RF-HV, kicker-HV and beam instrumentation.

Next Cycle Permit

The repetition rate of CLIC allows for nearly 10 ms to analyse the performance of a cycle and to decide whether it is safe to commit the machine for the next cycle. After every cycle the next cycle permit is systematically revoked and is then only re-established if a predefined list of beam and equipment quality checks has passed.

The reliability of these quality checks, which can be implemented in a combination of hardware and embedded software, should be such that the number of false PASS decisions is lower than the requirements from the tolerable risks. The number of false VETO decisions should be low enough to limit the impact of the machine protection system on the total availability of the CLIC beam. Strict test procedures must be defined to certify the reliability of the post cycle analysis. These test procedures must revalidate the system every time a quality check implementation has been modified.

Although the results of all beam observation systems will be scrutinized for abnormalities, the workhorse of the system and the line of last defence for detecting any failure is the beam loss monitoring system [4].

Beam Interlock System Layout

The schematic layout of the BIS is shown in Figure 1. Conceptually it is based on the existing beam interlock system used in the LHC [5]. However, in this case there are four interlock chains (i.e. two for the drive beams and two for the main beams). The interlock chains follow the beam paths in both directions and are connected to a central interlock controller.

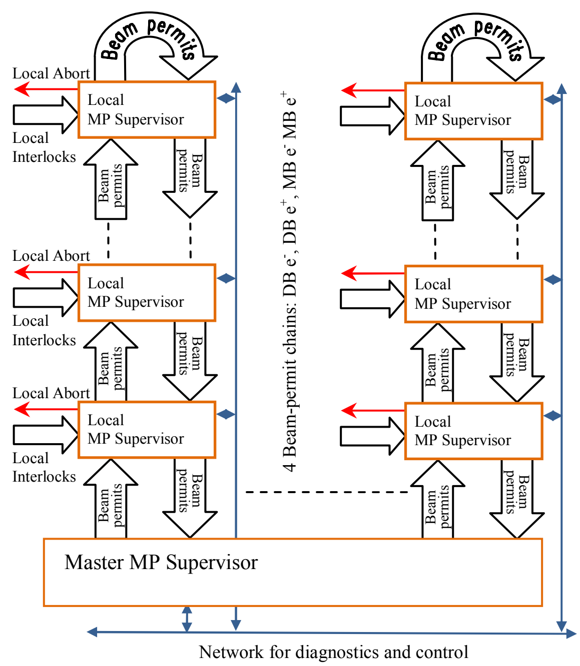

Figure 1. Schematic layout of the Beam Interlock System

FAULT ANALYSIS

For the technical design of the CLIC machine protection, a detailed analysis of all failure scenarios will be made in order to estimate the risks and to derive the required reliability of the system components. A full failure catalogue can be established by convoluting the component classes with the full set of failure classes. Combined failure scenarios (e.g. multiple breakdowns, collective power converter trips) must be considered as well. For every entry in the failure catalogue, the component multiplicity, expected failure frequency, direct damage, collateral damage and mean time to repair have to be obtained to complete the study. For those cases where the resulting risk is too high, or where the required reliability cannot be obtained, redundant solutions should be implemented.

Critical Case Studies

At the current conceptual design stage of the project, only the most critical failure scenarios are examined. Primarily this consists of simulating the most likely failures and evaluating the potential damage. Various studies have been undertaken already [6, 7]. This approach will be complemented by identifying the most critical accelerator components (usually aperture restrictions), determining which beam disturbance is required for reaching these components and then identifying those failures that may cause these disturbances.

OPERATIONAL SCENARIO

Safe operation of CLIC requires that potentially harmful beam must not be allowed into the machine. In this context, the qualification 'potentially harmful' depends on the knowledge on the current state of the machine. At a 'cold' start-up, i.e. when the machine is completely unknown, only beam that cannot cause structural damage to the accelerators components is safe. Once the machine is probed by such a safe pilot beam, the charge density of the beam can be increased in steps by the beam control system, as long as allowed by the post cycle analysis of every pervious step.

Drive Beam

The CLIC drive beam is produced in a 1 km long LINAC. For each cycle a sequence of a header (121 bunches) – to 'preload' the cavities of the fully loaded drive beam linac – followed by 24x24 sub-pulses (121 bunches), is accelerated to 2.4 GeV. The header is then dumped whilst the following 24x24 sub-pulses are recombined in the delay loop and combiner rings, into 24 "*trains*", of 24x121 bunches with a 12 GHz structure. The trains will be transferred to the 24 decelerating sectors where their energy is extracted and transferred to the main beam.

Starting with an unknown machine, all 24 distinct paths of the recombination complex will initially be tested with a safe pilot beam of 30 bunches. The schema to safely reach the nominal intensity will consist of gradually adding bunches to the end of the pulse: in sequence H+30b (header + pilot), H+60b, H+1SP+30b (header + one sub-pulse + pilot for next sub-pulse), H+1SP+60b, H+2SP+30b, etc. Once we have reached H+24SP+30b, we have produced the first train, plus a pilot for the second train. At that point the recombination complex and the first decelerator are fully tested. The test of each subsequent turnaround and decelerator sector will also start with a safe pilot beam, however, the intensity may now be increased exponentially.

Main Beam

To obtain a safe main beam for cold start-up, the brilliance needs to be reduced by four orders of magnitude with respect to nominal. The nominal main beam consists of 312 bunches spaced by 0.5 ns. The beam position monitors require a beam presence for at least 10 ns to measure the position. However, they should be able to measure the beam position – albeit with a degraded performance – with a reduced number of bunches e.g. 6-7 instead of 20.

Hence the reduction in the number of bunches from 312 to 6, reduces the brilliance by a factor 50. Decreasing the current per bunch will give another factor of 3. The missing factor can be obtained by increasing the emittance of the beam in the damping ring with a factor 3 in the horizontal plane and a factor 20 in the vertical plane.

The strategy will then consist of gradually reducing the emittance and increasing the bunch current and then the number of bunches, until the nominal beam is reached.

CONCLUSIONS

The machine protection of the CLIC complex is one of the key issues in the feasibility of the whole project. The study of the baseline, using passive, active and permit-based protection, is now well under way. The principles for bootstrapping both the drive and the main beams from safe to nominal values have been established.

To complete the conceptual design stage, all critical case scenarios will be analysed. Further studies will be made to validate that machine optimisation is possible taking into account the degraded resolution of the beam instrumentation under unfavourable beam intensity conditions.

The principles of the CLIC machine protection will be tested in the operational environment of CTF3 [8].

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