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METHODOLOGY APPLIED FOR DEPENDABILITY STUDIES ON THE COMPACT LINEAR COLLIDER

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Abstract

The Compact Linear Collider (CLIC) presents many challenges in terms of reliability and availability. The goal of a dependability study is to assess the requirements for component availability and reliability, by identifying the major contributors to failures and their effects, and analysing different operational scenarios and system designs. Hence, a good knowledge on CLIC system structures, failure modes and failure effects is needed. This paper reports about the set-up of the studies from the definition of the CLIC failure catalogue to the implementation of the models and analysis of the results. Steps that need to be followed when performing such a study will be presented in detail. Finally, the CLIC Drive Beam Quadrupoles powering system will be presented as a use-case.

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Abstract

The Compact Linear Collider (CLIC) presents many challenges in terms of reliability and availability. The goal of a dependability study is to assess the requirements for component availability and reliability, by a) identifying the major contributors to failures and their effects, and b) analysing different operational scenarios and system designs. Hence, a good knowledge on CLIC system structures, failure modes and failure effects is needed. This paper reports about the set-up of the studies from the definition of the CLIC failure catalogue to the implementation of the models and analysis of the results. Steps that need to be followed when performing such a study will be presented in detail. Finally, the CLIC Drive Beam Quadrupoles powering system will be presented as a use-case.

INTRODUCTION

CLIC, the future accelerator project under study to collide electrons and positrons up to 3 TeV centre of mass collision energy, provides unique opportunities for the exploration of Standard Model physics [1].

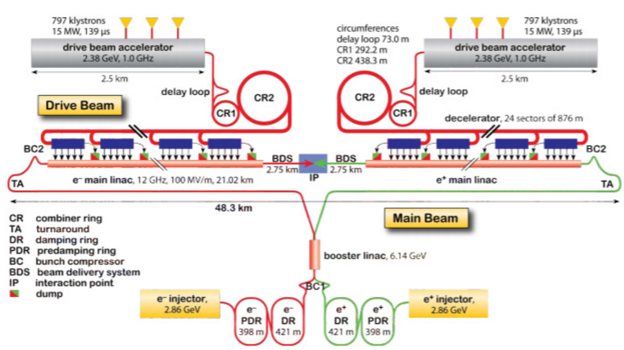

Figure 1: CLIC Layout at 3 TeV.

The layout of CLIC accelerator complex is presented in Fig. 1. The Main Beams will be generated and pre-accelerated in the injector linacs before being transported through the main tunnel to the main linacs. Using a classical approach, the linacs for the acceleration of the Main Beams would be powered by klystrons. In this novel acceleration scheme, the klystrons powering is replaced by using a second Drive Beam. The Drive Beam is produced in a low energy accelerator and subsequently decelerated in special Power Extraction and Transfer Structures (PETS). The generated RF power is transferred to the Main Beam accelerating structures providing an accelerating gradient of 100 MV /m. CLIC is designed to be built in stages of increasing collision energy, starting from 360 GeV to 1.4 TeV, up to a final energy of 3 TeV [2].

A dedicated availability study is crucial to demonstrate the applicability of the novel CLIC scheme. For all complex machines, but particularly for the case of CLIC, a stepwise methodology ensures the completeness and accuracy of the dependability simulation study.

The study begins with the definition of the CLIC failure catalogue, followed by the implementation of a corresponding availability model, model simulation, analysis of simulation results, model validation and sensitivity analysis.

The objectives of the stepwise method are to:

- obtain a complete picture of the machine design, failure behaviour and operational modes,
- identify potential contributors to CLIC failures and failure effects (e.g. downtime),
- provide guidelines for performance improvements in terms of maintenance strategies, system redundancies and operational schedules,
- analyse and compare possible operational scenarios and designs,
- provide requirements for spares and manpower.

The CLIC Drive Beam Quadrupoles powering system will be presented to illustrate the explained methodology.

STEPWISE METHODOLOGY

This section describes in details the proposed steps, presented in Fig 2.

Step 1. Definition of the problem. Definition of the specific questions to be answered by the study. Identification of the performance measures that will be used to evaluate the efficiency of the facility. This may be availability, reliability, costs and/or machine parameters.

CLIC efficiency will be demonstrated in terms of availability, reliability, integrated luminosity and power efficiency.

Step 2. Description of the machine. Definition of the different elements of the machine and the ways they interact. The machine could be defined as a hierarchy of systems, subsystems, assemblies and components arranged to a specific design in order to achieve desired functions. The level of detail is determined by the data available or the design-stage.

Step 3. Failure analysis, data collection and operational modes definition. Quantities of interest need to be collected and the maintenance and repair strategies need to be defined. At component level, the following questions should be addressed:

- how can components fail? (Failure modes),
- how often does a given failure occur?,
- can a component fail when the facility is down due to other components failures?,

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- can a component fail when the facility is down due to maintenance works?,
- how does a failure affect the machine and its parameters? (e.g. reduction of output energy, reduction of luminosity, beam stop required, etc.),
- do any machine performance parameters affect other machine parameters? How?,
- what are the consequences of machine failure and/or machine parameters exceeding or decreasing below the threshold value?.

Given that a particular failure occurs, maintenance data and strategies should be defined by specifying:

- the time it takes to recover from a failure,
- the manpower needed to repair a failure and how much manpower is available,
- if the failure is repairable without accessing the location of the component (e.g. by a remote reset),
- if the recovery from the failure requires a spare part and how many spare parts of that type are available,
- the time in which a failure will be repaired: at the moment of failure, only when certain subsystems/parts of the facility are failed, or when the whole facility is down,
- if the repairs can be done simultaneously.

Accelerators are often operated in phases where only some components or subsystems might be required, i.e. can experience failures. Hence, the following questions should be addressed:

- which component is operating in each phase?,
- how could the component fail during the phase in which it is functional?,
- is planned maintenance foreseen? For how long? Will all failed components be repaired during planned maintenance or only the ones in specific locations?,
- during operational phases, which components are going to be repaired before restarting operation in case the system goes down due to component failures?.

The failure catalogue consists of all possible failure modes and their related information, i.e. failure effects, corrective actions, maintenance actions and operational phases, linked to the hierarchical description of the accelerator. Step 2 and Step 3 complete the failure catalogue. Close contact with system experts is crucial for the development of a complete and accurate failure catalogue. A failure catalogue template has been developed to support the data gathering.

Step 4. Model Implementation. Several commercial and custom software tools are used to model the performance of particle accelerators [3] [4].

The failure catalogue, as defined before, provides all the necessary information to implement a complete availability model to simulate realistic machine operation.

Step 5. Define and run the simulation. Determine the mission time and number of simulations to perform.

Step 6. Results analysis and model verification. Make sure the implemented model reproduces real machine operation by analysing the simulation results. Model verification can also be done by implementing the model in different software packages and benchmarking the obtained results.

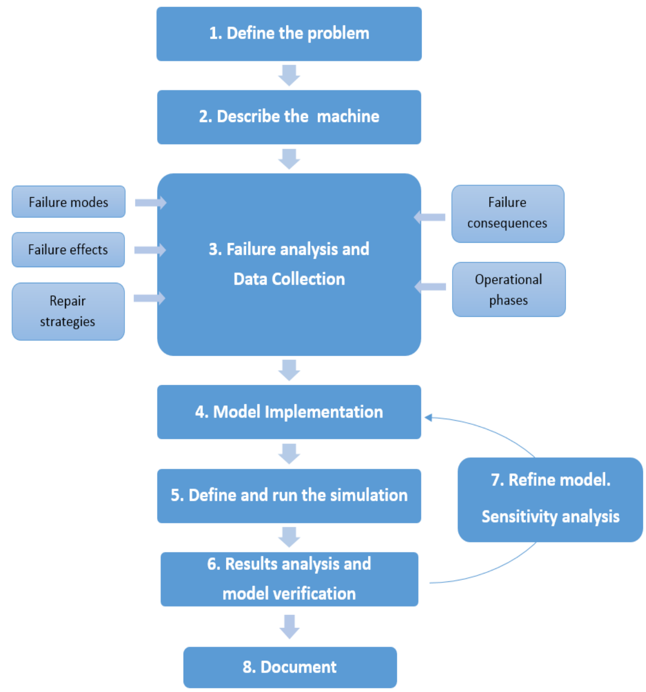

Figure 2: Steps for performing a complete availability and reliability study.

Step 7. Review and refine model including sensitivity analysis. Performing a parametric analysis on one input value, e.g. failure rate, or one assumption, e.g. repair strategy, while keeping the others at their nominal values, to see the effect on the simulation results. The resulting assessment of the impact of a given variable on the model output can be useful for decision making on redundancies, maintenance strategies and operational phases.

Step 8. Documentation. Comprehensive documentation of all the followed steps is essential for the success of follow-up activities.

DRIVE BEAM QUADRUPOLES POWERING SYSTEM

Magnets Powering Strategy

A major concern regarding reliability and availability in CLIC was related to the Drive Beam Decelerators, which contains around 45000 quadrupole magnets. Individual powering of the magnets by highly reliable power converters still gives an average prediction of one failure every 7 hours. Moreover, to avoid a large number of very long cables in the tunnel, the magnets cannot be powered individually. As described in [5, 6], in the proposed powering strategy, one big converter supplies the current for several magnets (between 10 and 60), and small trimmers located close to the magnet adjust for the excess current. The power converters are implemented with redundant modules to allow for failure tolerant operation and eventual replacement during scheduled maintenance days. In case of a module failure, the probability (k) that the failure is transparently handled by the foreseen redundancy is estimated to be 80%.

Magnets Powering System Dependability study

The dependability study was performed following the steps described in the previous section.

Step 1. Definition of the problem. Determine if the proposed powering strategy improves availability and reliability of the Drive Beam Quadrupoles powering system with respect to individual powering.

A dedicated failure catalogue was developed for the powering system containing all the data defined in **Step 2** and **Step 3** with the information available in [5]. Regarding maintenance and operational modes the following was assumed:

- Components are not repaired until the powering system inhibits beam operation.
- Repairs can be done simultaneously.
- All the repairs must be finished before restarting the system.
- Components are as good as new after repair or maintenance, i.e., no aging is considered.
- Components cannot experience failures when systems are under repair or maintenance.
- An operational phase of 100 days is considered followed by 48 hours of scheduled maintenance.

Step 4. Model Implementation. An availability model for a powering sector was developed in Isograph [6]. The results were then extrapolated to estimate the availability and reliability of the 48 powering sectors that form the whole Decelerator Quadrupole Magnets powering system.

Step 5. Design and run the simulation. The mission time is set to 100 days and 100 simulations were performed.

Step 6. Results analysis and model verification. The results for one powering sector are presented in Table 1.

The results were compared to [7] for model validation. Both studies give similar results but are not identical due to the fact that different methods are applied in each study.

Based on the current model the predicted availability of a powering sector is 99.7%. Extrapolating the results to all 48 CLIC powering sectors, the simulations gives an average availability of 86%. The main contributors to the downtime of one powering sector are the power converter modules, accounting for roughly 87%. This is not unexpected, considering the large number of power converters and their limits in reliability.

Step 7. Review and refine model including sensitivity analysis. Various sensitivity analysis were performed (Table 1).

Up to 20 trimmers are allowed to fail out of the 830 trimmers per powering sector without affecting the beam dynamics, as explained in [5]. The analysis of trimmers' failure shows that tightening the trimmer redundancy requirement down to 10 failing trimmers, leads to a tolerable increase in downtime of 30%.

Table 1: One Powering Sector Availability Estimations

		Nominal parameters	10 trimmers failure tolerance	k = 95%
Mean Down Time (MDT)		2.16 h	2.8 h	0.96 h
Failures per operational year		0.54	0.7	0.24
Contribution to MDT (%)	Converters	86.5%	70.5%	75%
	Trimmers	0%	16.5%	0%
	Controls	13.5%	13%	25%

Furthermore, the study demonstrates that the probability of successfully handling a redundant power converter module failure plays a more important role: if power converters redundancy is ensured 95% of the times, the powering sector downtime will be decreased by a factor of two.

Step 8. Documentation. The process followed was documented together with the failure catalogue and including various presentations.

CONCLUSIONS

The CLIC novel acceleration scheme presents several challenges in terms of reliability and availability. For such complex machines, an adequate planning of the dependability studies is crucial to ensure realistic results. The proposed methodology gives clear and concise steps to achieve the objectives and reach the required deep understanding of the accelerator machine performance. The systematic approach reduces the likelihood to forget considerations that would lead to unrealistic machine performance simulation and wrong interpretation of results.

System experts' involvement in the process is extremely important in particular for the development of a complete and accurate failure catalogue, but also for the model validation and analysis of the results.

The described stepwise methodology was applied to the CLIC Drive Beam quadrupoles powering system dependability studies. This allowed quantifying the improvement in availability and reliability of the proposed powering strategy compared to individual powering. It furthermore showed that a substantial improvement is possible by making the power converter failover switching more reliable.

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