AVAILABILITY STUDIES FOR LINAC4 AND MACHINE PROTECTION REQUIREMENTS FOR LINAC4 COMMISSIONING

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Abstract

Linac4 is one of the key elements in the upgrade program of the LHC injector complex at CERN, assuring beams with higher bunch intensities and smaller emittance for the LHC and many other physics experiments on the CERN site. Due to the demand of continuous operation, the expected availability of Linac4 needs to be carefully studied already during its design phase. In this paper an overview of the relevant systems impacting on Linac4 machine availability is given: the various system failure modes are outlined as well as their impact on the total yearly machine downtime. Machine Protection Systems (MPS) play a significant role in reducing the risk associated to each failure mode and are therefore important for reaching the target availability. The Linac4 MPS requirements, with particular focus on the different commissioning phases, are discussed.

INTRODUCTION

Linac4 is the new Linear accelerator which will replace Linac2 in the CERN injector complex to provide high-brightness beams to LHC experiments. It will accelerate H- ions up to 160 MeV for injection into the Proton Synchrotron Booster (PSB). Linac4 will be connected to the existing Linac2 transfer lines by means of a dedicated section during the Long Shutdown 2, foreseen in 2018. Linac4 is composed of an H- Source, a Low-Energy Beam Transfer (LEBT), a Radio-Frequency Quadrupole (RFQ), a Medium-Energy Beam Transfer (MEBT) and a series of accelerating structures (DTL, CCDTL and PIMS). At the end of the Linac the beam will be deflected to the transfer lines by a series of three dipoles during normal beam operation or sent to the dump line (Fig. 1).

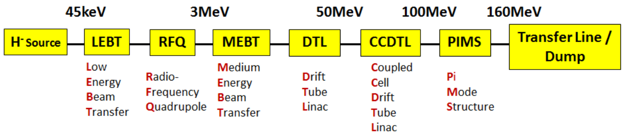

Figure 1: Schematic view of Linac4 layout.

By 2018 Linac4 will have to meet strict requirements in terms of availability to ensure continuous beam delivery to the CERN complex, possibly reaching the performance of Linac2 operation (98% availability). Contrary to Linac2, Linac4 will be equipped with a dedicated Beam Interlock System (BIS) to mitigate the consequences of beam losses on the accelerator equipment [1]. As shown in this paper, low-energy beams have the potential to cause some damage and downtime of delicate accelerator equipment, due to the very confined energy deposition on the surface of materials. The nominal LHC beam power in case of a beam dump amounts to 4 TW, for Linac4 the beam power is only 5.2 kW. Given these numbers, the LHC damage potential is clear, whereas for low-energy beams this is less intuitive, as it also strongly depends on other beam parameters (e.g. size, repetition rate). An example of low-energy beam-induced damage potential will be shown later in this paper.

The technology adopted for the Linac4 BIS is to a large extent inherited from the LHC BIS, which was designed in 2006 with much more stringent requirements in terms of safety and reliability. For all machines, but particularly for the case of Linac4, besides assuring the required level of safety, another important goal of the BIS is not to compromise the availability by triggering unnecessary beam stops.

An availability model based on the STPA [2] analysis carried out for Linac4 was developed and results are presented in this paper.

LINAC4 BIS COMMISSIONING

Linac4 has entered the commissioning phase in October 2013. The commissioning is currently being executed in energy steps (3 MeV, 12 MeV, 50 MeV, 100 MeV, 160 MeV). A low-energy machine as Linac4, which is designed primarily to produce high-brightness beams, needs a careful tuning of all systems to reach its design parameters and guarantee stability and reproducibility of beam operation. To reach such conditions and gain experience with the system, machine protection requirements during commissioning can be partially relaxed allowing for more flexible operation with safe beam settings. The availability of all foreseen hardware interlocks might not be guaranteed from the beginning of the commissioning, as the systems connected to the BIS need to design specific electronics for the interface. A study of the criticality of the different inputs as a function of the beam parameters and commissioning phase has been performed in order to decide the inputs to the BIS to be operational during the different commissioning phases.

An example of such procedure for the 3 MeV phase of the commissioning is shown in Fig. 2, taking the so-called Master Source RF truth table as an example [3]. This table shows all the inputs of one part of the interlock system. The two different rows show the acceptable configurations to have beam in the Linac (1='TRUE', 0='FALSE', x='don't care'). This master device is capable of stopping beam operation in case an invalid

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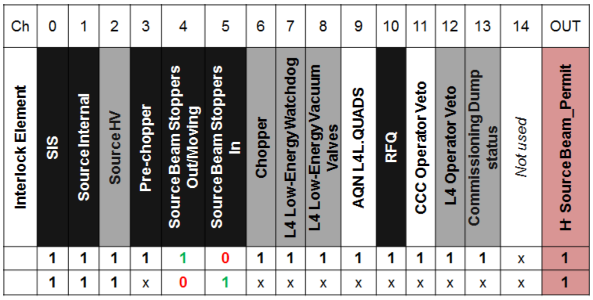
configuration is detected on the inputs, by turning the signal *H- Source Beam_permit* to FALSE, thus stopping the source. To classify their criticality, inputs in black are considered as mandatory, grey as recommended and white as not needed for the considered stage of the commissioning.

An additional possibility to address specific needs during commissioning is the use of the Software Interlock System (SIS), also inherited from the LHC. This also allows deploying a temporary replacement of hardware interlocks. The SIS is intrinsically less reliable than the BIS, but more flexible and suited to cope with commissioning needs. An example of the use of the SIS regards the Source High-Voltage monitoring, which has been temporarily implemented in the SIS, given the unavailability of the corresponding hardware interlock for the start of the commissioning.



Ch	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	OUT
Interlock Element	SIS	Source Internal	Source HV	Pre-chopper	Source Beam Stoppers Out/Moving	Source Beam Stoppers In	Chopper	L4 Low-Energy Watchdog	L4 Low-Energy Vacuum Valves	AQN L4L.QUADS	RFQ	CCC Operator Veto	L4 Operator Veto	Commissioning Dump status	*Not used*	H- Source Beam_Permit
	1	1	1	1	1	0	1	1	1	1	1	1	1	1	x	1
	1	1	1	x	0	1	x	x	x	x	x	x	x	x	x	1

Figure 2: Master Source BIS controller: truth table and criticality classification of inputs.

The 3 MeV commissioning up to the end of the Medium Energy Beam Transfer (MEBT) has terminated in April 2014. During this phase a temporary test bench was connected at the end of the line as an alternative destination to the dump line. The test bench was equipped with an emittance measurement slit and diamond detectors for measurements of unstripped H- ions, to study the operating conditions for the injection region in the PSB. Currently the first tank of the DTL has been connected for the 12 MeV commissioning. The definition of the criticality has been updated taking into account the new operating conditions and relevant failure modes.

Furthermore for the phases of the commissioning, starting from 12 MeV, activation of equipment should also be taken into account. Dedicated studies have been performed on the impact on equipment and maintenance strategies [4].

Table 1: Beam Parameters Causing a Damaged Stainless Steel Bellow during 3 MeV Commissioning

Beam Current	Repetition Rate	Pulse length	Beam Size
12.5 mA	1 Hz	300 us	13x1 mm

Low-energy Beams: Damage Potential

On December 12th 2013, a severe vacuum leak was detected in the MEBT line; the leak originated from beam impact at 3 MeV on a 200 µm thick bellow. Several unfavourable conditions contributed to the development of the vacuum leak. The beam parameters are summarized in Table 1 and resulted in an average beam power of 11.3 W. A very particular beam was being tested, with a very small size in the vertical plane (1 mm), compared to the horizontal plane (13 mm). A significant horizontal misalignment of the line (about 1 mm) was detected after the incident, most likely originating from the transport of the MEBT line from the previous test stand to the Linac4 tunnel. This misalignment further enhanced the shift of the beam towards the aperture limit. These circumstances resulted in the beam impacting on the stainless steel bellow for about 15 min. To allow for particular beam manipulations and analyses without risking stopping operation by the interlock system, no means of detecting beam losses were operational during this initial commissioning phase.

In the final BIS configuration a differential comparison of the beam current transmission in the RFQ is foreseen (so-called ‘watchdog’) since the beginning of the design, to detect possible losses before entering the MEBT. This interlock would have avoided the incident, but would have prevented necessary beam manipulations.

The replacement of the faulty bellow was necessary to restore operation and took a significant time to repair (~ 3 weeks). In this early phase of Linac4 this did not cause any further problem, but such mishaps should be strictly avoided when Linac4 will be an essential accelerator in the LHC injector chain. A target of 95% availability should be achieved to be able to provide beam to the different destinations. The careful analysis of the incident represented a useful lesson to gain experience with the machine and its parameters and assess the related damage potential, with a relatively low impact on the commissioning schedule and no impact on other machines.

A dedicated availability model is necessary to estimate the future availability of Linac4 and quantify the impact of failures of different systems on the overall expected yearly downtime.

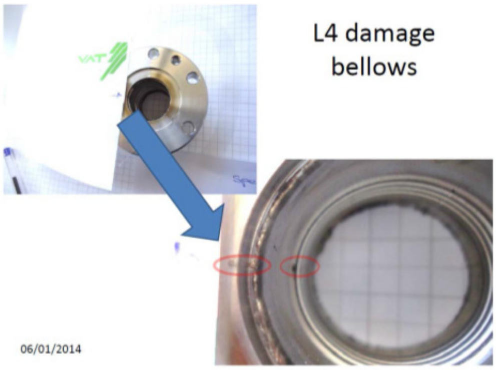


Figure 3: Detail of the damaged Linac4 bellow in the MEBT line.

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LINAC4 AVAILABILITY MODEL

An availability model was developed in Isograph [5]. It consists of a series connection of different blocks, indicating that a failure of any of such components can lead to a beam stop and therefore machine unavailability and downtime. Each block can be expanded and is composed of more blocks in different configurations (series/parallel), as shown in Fig. 4.

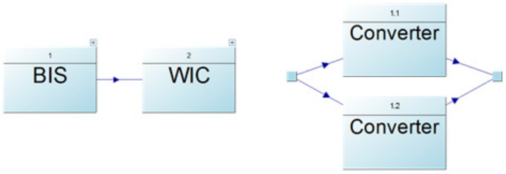

Figure 4: Linac4 component models using Isograph.

Basic failure modes are assigned to different blocks of the model; the exponential pdf (probability density function) is chosen for most of the component failures, under the assumption that these will be during future operation in the so-called region of ‘useful-life’ and therefore failures occurring for burn-in or wear out of components are negligible. This assumption is particularly well suited for electronic components.

Maintenance tasks need to be defined for each failure mode. The assumption is that maintenance is only corrective, namely interventions are only executed after a failure occurs. Several parameters have to be specified: mean time to repair (MTTR), personnel and logistic time, spare availability and cost. In the first version of the model, the cost analysis is not included.

The parameters of the pdf as well as maintenance tasks are set according to system experts experience and are therefore not calculated with dedicated procedures, as done for example in [6]. Conservative assumptions are made in case of machine protection systems. Since most of the hardware is inherited from the LHC, figures have to be scaled down to a less demanding machine, particularly in terms of radiation effects on the installed electronics.

The goal of the model is to derive estimates of Linac4 availability based on current experience at CERN with the different systems. To benchmark such approach, this work was extended also to the European Spallation Source (ESS) and results are presented in [7].

An example of selected pdf for failures and recovery for some Linac4 systems is shown in Table 2.

Table 2: Component Failure Probabilities and Parameters

System	Pdf	MTTF	MTTR
Power converters (global)	exponential	200 h	0.5 h
Klystron	exponential	$5*10^4$ h	48 h
Ion pumps (global)	exponential	8760 h	24 h

Based on the current model parameters the predicted Linac4 availability is 95%. This result is in agreement with the target availability of Linac4. It is nevertheless interesting to look at the main contributors to the yearly downtime of Linac4: the RF system is the main cause of downtime, accounting for roughly 50%. This is not surprising considering the dominance of RF systems in Linacs. In particular, the main contributions come from the powering chain, composed by modulators and klystrons. Also the vacuum system will play a significant role in the yearly downtime (~20% of the total).

Uncertainties regarding failure rates of particular systems, as for example the ion source, still need to be addressed in more detail to obtain final results. Nevertheless these estimates show that 95% is a realistic target to be achieved for Linac4 operation. It is expected that a conditioning effect could be observed over time and that maintenance strategies are refined with increasing experience with the machine.

CONCLUSIONS

Linac4 is one of the projects aiming at improving LHC performance providing high-brightness beams to the CERN injector chain. It has now entered the commissioning phase and will be ready to be connected to the PSB during the Long Shutdown 2.

The importance of this accelerator is crucial for what regards availability, as all the CERN accelerators will rely on beam from Linac4. A machine protection system was designed for Linac4, inspired by the corresponding LHC implementation. The scope of the machine protection is to prevent equipment damage and unforeseen stops, without compromising the operational flexibility and availability. A dedicated study on Linac4 availability was carried out and a model created in Isograph, based on expert’s estimates of component failure rates and repair times. The predictions show that the target of 95% availability is a realistic achievement to be accomplished, while gaining experience with the machine and its systems.

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