DEVELOPMENT AND STATUS OF PROTECTION FUNCTIONS FOR THE NORMAL CONDUCTING LINAC AT ESS

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Abstract

The European Spallation Source faces a great challenge in succeeding with its ambitious availability goals. The aim is to construct a machine that allows for 95% availability for neutron beam production. This goal requires a robust protection system that allows for high availability by continuously monitoring and acting on the machine states, in order to avoid long facility downtimes and optimize the operation at any stage. The normal conducting section consists of the first 48 meters of the machine, and performs the initial acceleration, bunching, steering, and focusing of the beam, which sets it up for optimal transition into the superconducting section. Through a fit-for-purpose risk management process, a set of protection functions has been identified. The risk identification, analysis, and treatment were done in compliance with modern safety and ISO standards. This ensures that the risks, in this case downtime and equipment damage, are properly prevented and mitigated. This paper describes this process of defining the protection functions for the normal conducting linac at ESS.

INTRODUCTION

The high neutron production availability goals of ESS require the linear proton accelerator (linac) to produce, bunch, accelerate, steer, and focus the proton beam with high quality and reliability. The first 48 meters consist of normal conducting (NC) structures, and this is the most critical part of the accelerator as the options for retuning or adjustments are minimal. It is critical that the proton beam envelope as well as its beam energy are exact at the exit of the last NC structure to allow for further acceleration and transport, through the superconducting (SC) parts, to the tungsten target wheel. An overview schematic of the ESS linac is seen in Figure 1.

The NC linac, constituting the five leftmost blocks in Figure 1, consists of a 75 keV ion source, low energy beam transport (LEBT) structure, radio-frequency quadrupole (RFQ), medium energy beam transport (MEBT), and five drift tube linac (DTL) tanks. After leaving the last DTL tank, the beam energy is 90 MeV. The proton beam will, at nominal operation and upon exiting the MEBT, have a 2.86 millisecond pulse length with 14 Hz repetition rate [1].

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AVAILABILITY-DRIVEN MACHINE PROTECTION

Machine protection (MP) at ESS has been identified as an important driver for successfully reaching the availability goals of the facility [2]. The MP strategy is to identify and analyze systems and devices that play a role in this goal and, based on the outcome, adapt their functional behavior accordingly. MP is thus classified as a system of systems (SoS) [3], recognizing the complexity of and interactions between several systems that all need to fulfill their role for the overall MP-SoS to succeed.

In order to identify key functions of the MP-SoS, an ESS MP risk management process lifecycle has been developed that identifies and analyzes so-called *damage events* throughout the machine [4]. A damage event is an event that has a facility *downtime* (loss of neutron production) and a *cost* associated to it, whose combination creates a severity category. Based on that severity, the appropriate MP measures are taken. These damage events are then associated with a set of *hazards* that are to be prevented or mitigated by *overall protection functions* (OPF). The risk management process follows the IEC 61508 standard for functional safety [5], as well as the ISO 31000 risk management standard [6].

As the NC linac is found to be critical for the quality and availability of the proton beam, and in extension neutron production at ESS, this part of the machine has been analyzed by the ESS MP team together with the respective system experts to identify damage events, hazards, OPFs, and technology-specific *protection functions* (PF) where applicable. These PFs are then to be implemented into the MP-SoS by making use of the constituent systems as described below.

MP-RELATED NC LINAC SYSTEMS AND DAMAGE EVENTS

The MP-related systems in the NC linac are identified as the linac magnets, interceptive devices, vacuum system, and buncher cavities. In addition, the beam monitoring system is included in several PFs as it is able to monitor the necessary beam parameters, but it does not have any damage events associated to it. These systems are briefly described below.

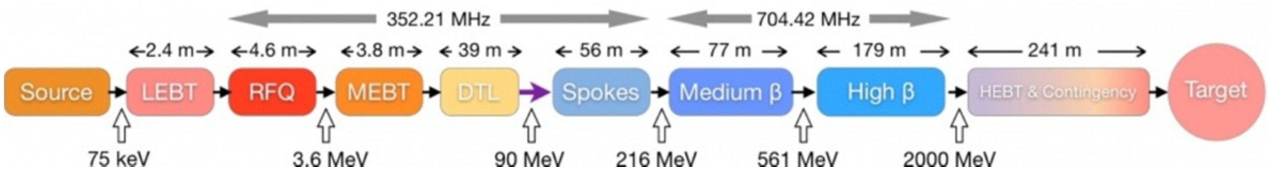

Figure 1: The ESS linac with its different sections, including lengths and nominal beam energies. Source: esss.se/accelerator.

Linac Magnets

The linac magnets consist of quadrupole magnets for focusing and dipole magnets for steering the beam. These are placed together, where the dipoles are located inside the quadrupoles. The quadrupoles are located in FODO lattices for alternated focusing in the two transversal directions. In the NC linac, there are 11 magnet pairs, all located in the MEBT. The damage events associated with these magnets are overheating in case of insufficient water cooling or overcurrent from the power supplies, as well as degradation or damage from particle losses in the equipment.

Interceptive Devices

The category of interceptive devices (ID) includes everything that intercepts (goes into) the proton beam. At ESS, these are beam stops (BS), wire scanners (WS), emittance measurement units (EMU), beam scrapers (movable collimators), and an iris collimator. There is one BS in the LEBT, one in the MEBT, and two in the DTL. WS are located in three locations in the MEBT, and there is one EMU in the LEBT and one in the MEBT. The iris is located at the very beginning of the LEBT to adjust the beam current. All of these are designed to be able to take at least 50 µs of beam at 1 Hz pulse repetition rate, but the LEBT BS is able to take the full beam. The BSs, EMUs, scrapers, and iris are water cooled, and can thus break from lack of cooling, identified as a damage event. All of the IDs (except for the LEBT BS) have a damage event where they receive too much beam. As a last damage event, the scrapers and WSs can break mechanically by being crushed against each other in the beam pipe.

Vacuum System

The main role of the vacuum system is to keep high quality vacuum conditions in the beam pipe and other areas, such as vacuum shielding. In order to prevent extensive vacuum pollution and equipment damage in case of vacuum losses, or during maintenance periods, there is a set of vacuum gate valves that separate beamline sections from each other when needed. One is located before the LEBT and one after, one before the MEBT and one after, as well as one after DTL tanks 2, 3, 4, and 5. These valves, when located upstream of the beam destination, cannot be closed when beam is operating and the damage event of beam hitting a gate valve is included in the MP analysis. Additionally, a mechanical damage event of the valves is identified and analyzed.

Buncher Cavities

There are three buncher cavities at ESS, located in the MEBT. Their role is, as the name suggests, to bunch the proton beam in order to match the downstream radio frequency structures, such as drift tubes and superconducting cavities. The buncher cavities are water cooled and have the damage event of overheating due to lack of cooling. From beam physics simulations [7], it is also found that buncher cavity 2 and 3 can be hit by the proton beam and deform.

PROTECTION FUNCTION DEFINITION

The definition of PFs follow a process defined in [4], where the damage events are analyzed for the hazards that may lead to damage. Each hazard is then assigned one OPF, which is a generic function to prevent or mitigate the specific hazard. Depending on the severity level of the hazard, the OPF needs to fulfill a certain level of robustness. Up until the OPFs, no technology-specific systems have been identified to treat the hazards. This is instead done in the next PF step, in collaboration between the MP analysis team, integration team, and the system owners (e.g. the vacuum engineers in the case of the vacuum system) in order to define appropriate and implementable functions. The hierarchical analysis flow is seen in Figure 2, starting at the system level.

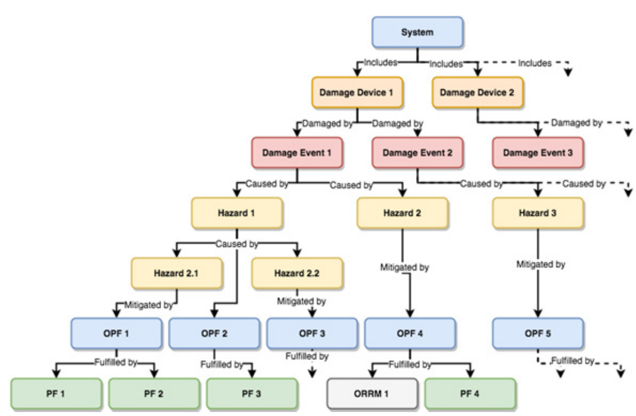

Figure 2: The MP analysis flow, from system, through damage device, damage event, hazards, overall protection functions (OPF), and protection functions (PF).

All of the PFs that are associated with stopping the proton beam to prevent damage will include the ESS beam interlock system (BIS) and a set of beam-stop actuators. The actuation consists in (a) inhibiting the timing system from generating a beam pulse, (b) activating the LEBT chopper and (c) MEBT chopper

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continuously, and (d) interlocking the ion source magnetron. In the case of an emergency beam interlock, also the (e) power for the plasma generation and (f) proton extraction mechanisms of the ion source are cut [8]. The protection for all systems described in this paper, except for the buncher cavities, is coordinated by dedicated local protection systems (LPS), controlled by a safety PLC.

Each PF contains a sensor, logic element, actuator, timing requirement, and protection integrity level (PIL) [4,5]. The logic element for all functions is the LPS PLC (except buncher cavities and beam current monitoring) and BIS, and the actuators are as stated above. In the subsections below, the PFs for each system are mentioned and tabulated with their sensor, timing requirement and PIL.

Linac Magnets

The damage events from the linac magnets are handled by PFs that stop beam if the measured beam losses around the equipment are too high and that monitor the magnet temperature, supplied current, and cooling water flow to stop beam and power supply when necessary.

Table 1: Protection function sensor, timing, and PIL for the linac magnets.

Sensors	Timing	PIL
Differential Beam Current Monitors	30 µs	1
Neutron Beam Loss Monitors	-	0
Thermo-switches	100 ms	1
Current monitors	100 ms	0
Cooling water flow meters	1 s	0

Interceptive Devices

The hazard and risk analysis identifies that inserting a beam of too high current, repetition rate, or too long pulse length while an ID is in has to be prevented, just as inserting an ID if incompatible beam is already running. This can be handled through ID position switches and beam mode consistency checks by the BCMs during beam operation. The water-cooled IDs have the cooling monitored, and the EMUs and iris are also required to have temperature sensors. The scrapers monitor the charge deposition through a dedicated monitor. Finally, beam position monitors (BPM) check whether the beam is in the correct path.

Table 2: Protection function sensor, timing, and PIL for the interceptive devices.

Sensors	Timing	PIL
Position switch (out)	100 ms	2
Position switch (in)	100 ms	1
Proton Beam Mode Consistency	100 ms	1
Cooling water flow meters	1 s	0
Cooling water temperature meters	1 s	1
EMU temperature sensor	1 s	0
Iris temperature sensor	1 s	0
Scraper charge deposition monitor	30 µs	1
BPM	30 µs	0

Vacuum System

The vacuum valves cannot be in the pipe while beam is running, and thus have to be extracted before starting beam operation. Just as beam has to be stopped if they are inserted. This is handled by position switches on the valves and through monitoring the dedicated (vacuum interlock) signal that closes the valves.

Table 3: Protection function sensor, timing, and PIL for the vacuum system.

Sensors	Timing	PIL
Position switch (out)	100 ms	2
Position switch (in)	100 ms	1
Vacuum interlock signal	1 s	0
Fast valve controller	3 ms	1

Buncher Cavities

Protection of the buncher cavities is done through measuring the surrounding beam losses in the same way as for the linac magnets, monitoring the beam position fluctuations through BPMs, and monitoring the cooling water flow and temperature and stopping beam if these are wrong.

Table 4: Protection function sensor, timing, and PIL for the buncher cavities.

Sensors	Timing	PIL
Differential Beam Current Monitors	30 µs	1
Cooling water flow meters	1 s	0
Cooling water temperature meters	1 s	1
BPM	30 µs	1

CONCLUSIONS

The tough availability requirements on ESS has made machine protection an important tool for the success of the facility. By avoiding long downtimes and costly repairs, the facility can operate at a high power during extended periods of time. The machine protection risk management process that has been developed at ESS is found suitable for the analysis of damage events throughout the facility and ties those to custom protection functions. This paper has presented the protection functions associated to the normal conducting linac and briefly described the process behind their derivation. As the design of the facility is ongoing, the analysis and implementation of protection functions need to be flexible yet robust, and more iterations are foreseen before the complete set can be finalized.

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REFERENCES

[1] Peggs S. (ed.), *ESS Technical Design Report*, ISBN: 9789198017328, 2013.

[2] Hilbes C., Nordt A., Machine Protection - Systems Requirements and Architectural Framework, ESS Internal Document (ESS-0057251), 2015.

[3] Friedrich T., Hilbes C., Nordt A., Systems of Systems Engineering for Particle Accelerator based Research Facilities - A Case Study on Engineering Machine Protection, *SysCon 2017*, Montreal, Canada, 2017.

[4] Andersson R., Bargalló E., Hilbes C., Nordt A., Machine Protection Risk Management Process, ESS Internal Document (ESS-0095000), 2017.

[5] IEC 61508: *Functional safety of electrical/ electronic/programmable electronic safety-related systems*, 2010.

[6] ISO 31000: *Risk management - Principles and guidelines*, 2009.

[7] Miyamoto R., How to estimate the possible max angle for studies of BLM and MPS, https://jira.esss.lu.se/browse/BPWP-328 (access required, taken 2017-05-02), 2016.

[8] Rejzek M., Hilbes C., Fast Beam Interlock System (FBIS) Concept of Operations, ESS Internal Document (to be published), 2017.

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