Reliability model of SNS linac (spallation neutron source-ORNL)

Adrian Pitigoi, Pedro Fernandez
Empresarios Agrupados, Spain

Abstract

A reliability model of SNS LINAC has been developed using risk spectrum reliability analysis software and the analysis of the accelerator system's reliability has been performed. The analysis results have been evaluated by comparing them with the SNS operational data. This paper presents the main results and conclusions focusing on the definition of design weaknesses and provides recommendations to improve reliability of the MYRRHA linear accelerator.

Introduction

The collaborative MAX (MYRRHA Accelerator eXperiment research and development programme) Project launched in February 2011 and co-funded by the European Commission under the Seventh EURATOM Framework programme for Nuclear Research and Training Activities (2007-2011), followed from the recommendations of the European Union's Strategic Energy Technology Plan for the development and deployment of sustainable nuclear fission technologies in Europe.

MAX participates in addressing the issue of high-level long-lived radioactive waste transmutation by pursuing the development of the high-power proton accelerator as specified by the MYRRHA accelerator-driven system (ADS) demonstrator project in Belgium.

The main goal of the MAX Project is to deliver an updated consolidated reference layout of the MYRRHA linear accelerator with sufficient detail and an adequate level of confidence to initiate its engineering design and subsequent construction phase in 2015.

In this context, the MAX team aims to develop an accurate reliability model of the MYRRHA accelerator (Task 4.4), using the methodology applied for nuclear power plants. For this purpose, a reliability model of an existing accelerator has been developed as part of the Task 4.2 MAX project activities. The reliability model development is described and the results of the performed analysis are presented in this paper.

Paper contents

The MAX Task 4.2 activities performed are presented in the paper:

- compiling and processing data needed for developing the model and performing the reliability study;
- development of a detailed reliability model of the SNS using a risk spectrum fault tree;

- performing reliability analysis of the SNS linac, the major critical issues related to the accelerator reliability have been identified,
- compiling and processing SNS logbook data available on the SNS website (recorded during the period October 2011-June 2012) for evaluation of the SNS risk spectrum analysis results.

Theoretical results from the model were compared with the operational data records (real operation data). It was concluded that the RS model can be considered a trustworthy tool to further build the model for evaluation of the MAX linac reliability.

As a result of performing the SNS system's reliability analysis, the systems and components with the strongest impact on overall reliability are identified. This paper presents the conclusions and recommendations for increasing the reliability of the MYRRHA linear accelerator and for design optimisation.

MAX Task 4.2 – Objective

It is essential to develop a reliability model and to provide a feedback on actual reliability performance of an existing accelerator in order to develop a more accurate MAX reliability model and to guide the MYRRHA accelerator engineering design.

One of the most important goals of the MAX project WP4 is therefore to perform a detailed reliability analysis of an existing accelerator, using the methodology applied in the current nuclear power plants. The goal of this reliability analysis is to draft preliminary conclusions and recommendations in order to maximise the reliability/availability and safety of the MYRRHA accelerator.

In view of these goals, the Spallation Neutron Source (SNS – Oak Ridge National Laboratory) was selected within MAX Task 4.2 for reliability modelling using risk spectrum in order to provide feedback on actual SNS accelerator reliability performance as a reliability modelling tool for Task 4.4 of the MAX project.

A model of the full MYRRHA linac will have to be built based on its existing design and taking into account all support systems, smart control strategies, fast beam shutdown and accelerator/reactor interface aspects.

Input data needed for modelling and reliability study

SNS design information and reliability data have been collected, organised and processed to be used as input data to develop the SNS reliability model and to reach the objectives of Task 4.2. The data obtained from different sources could be grouped as follows:

- SNS design data;
- SNS systems and functions data;
- SNS reliability data;
- SNS operating status.

The input data sources are:

- SNS design and technical parameters (SNS public information http://neutrons.ornl.gov/facilities/SNS/);
- SNS reliability data: SNS RAMI and BlockSim models data;
- SNS operation dat: logbook data (http://status.sns.ornl.gov/beam.jsp).

SNS risk spectrum reliability model development

A detailed risk spectrum fault tree model has been developed using the methodology currently applied for nuclear power plants taking into account the available SNS design information. The developed SNS risk spectrum model has been quantified using the reliability data obtained from the BlockSim model (failures data – MTTF and repair times data - MTTR).The risk spectrum model results have been evaluated with respect to the SNS logbook operational data (accelerator trip failures and overall availability) recorded during the period October 2011-June 2012.

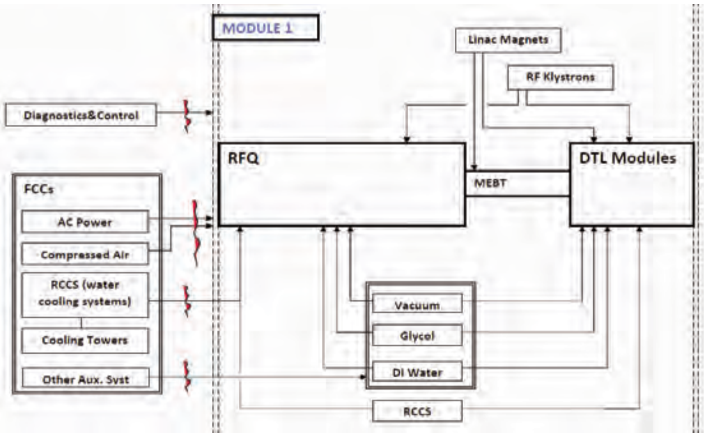
The following scenarios have been considered as the basis for developing the risk spectrum model of the SNS accelerator:

- Some of the SNS systems and components (i.e. stripper foil, ring and RTBT) have been considered as not relevant to the objectives defined for the MAX linac project, which is why these parts were not included in the reliability model.
- The "continuously monitored repairable component" - risk spectrum type 1 reliability model has been considered to model the failure behaviour of all SNS linac components. The risk spectrum type 1 reliability model is used to model a component failure which is detected immediately and which can be repaired.
- "Mean unavailability". This type of calculation is used to obtain the unavailability values of the basic events, the long-term average unavailability Q is calculated for each basic event.

The fault tree developed for SNS linac is a graphical representation of the functional structure of SNS systems, describing undesired events ("failures") and their causes. The fault tree is built using gates, basic events and house events. Generally, a fault tree can be subdivided into several fault tree pages, which are bound together using transfer gates. The level of detail for basic events was established corresponding to the availability of reliability data and the level of detail of the design information.

As a first step in the modelling of the SNS accelerator (linac), a "control volume" (Module 1) has been defined, consisting of the following SNS parts: RFQ, MEBT and DTL (DTL represents the first accelerating part of SNS linac).

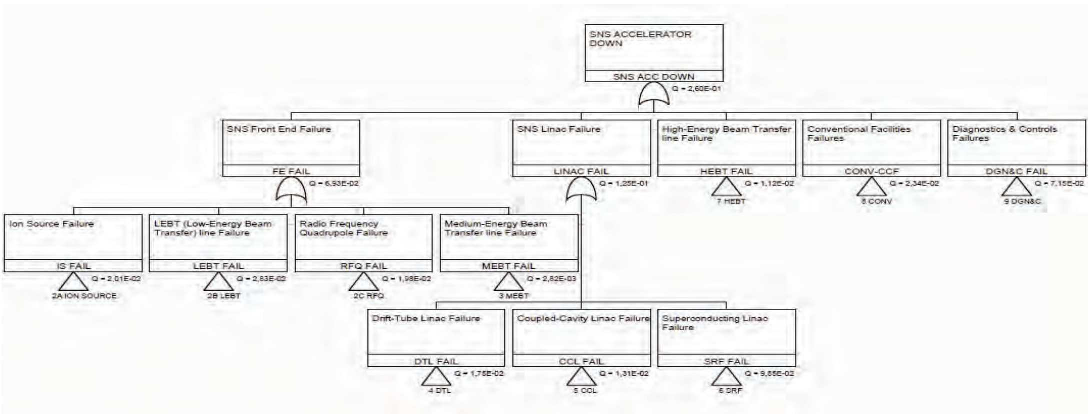
Figure 1. Module 1 functional block diagram



It was necessary to model parts of the technological systems (auxiliary systems) within Module 1, as they are important for RFQ-DTL functioning, i.e. the cooling systems (Glycol-DI Water, and RCCS for RFQ-DTL) and the vacuum systems. As a second step, all linac systems have been modelled and integrated into the SNS linac model, including LEBT, CCL, SCL, and HEBT. The rest of the auxiliary systems has also been modelled and integrated (compressed air, AC power, vacuum, cooling towers, RCCS general distribution, CHL, etc.).

Inputs (in terms of failures) from the auxiliary systems have been considered, some are included in the main linac systems fault trees, while some others function as CCFs in developing the fault tree of the "conventional facilities" event.

Figure 2. First level of the SNS RS model – SNS main fault tree structure



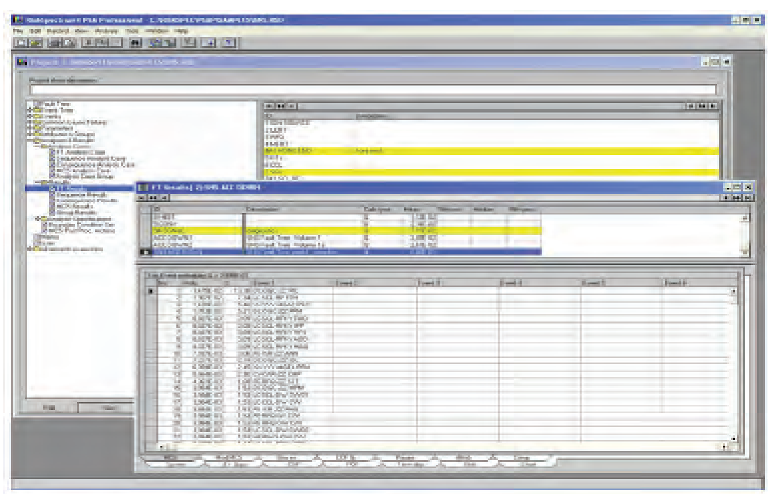
SNS linac reliability analysis

RS Model – MCS analysis

The SNS linac fault tree is a graphical representation of a Boolean expression. This Boolean expression can be converted by using Boolean algebra laws into a minimal cut set (MCS) representation.

The goal of the minimal cut set (MCS) analysis is to generate the minimal cut-sets of the fault tree and to perform a point-estimate quantification of the top event. The minimal cut-set (MCS) is that combination of events which causes the top event to occur. The term "minimal" means that if any of these events is removed from the set, the top event no longer occurs. The MCSs of the top event (SNS ACC DOWN) analysis case are presented below.

Figure 3. SNS ACC DOWN analysis case – minimal cut-sets list



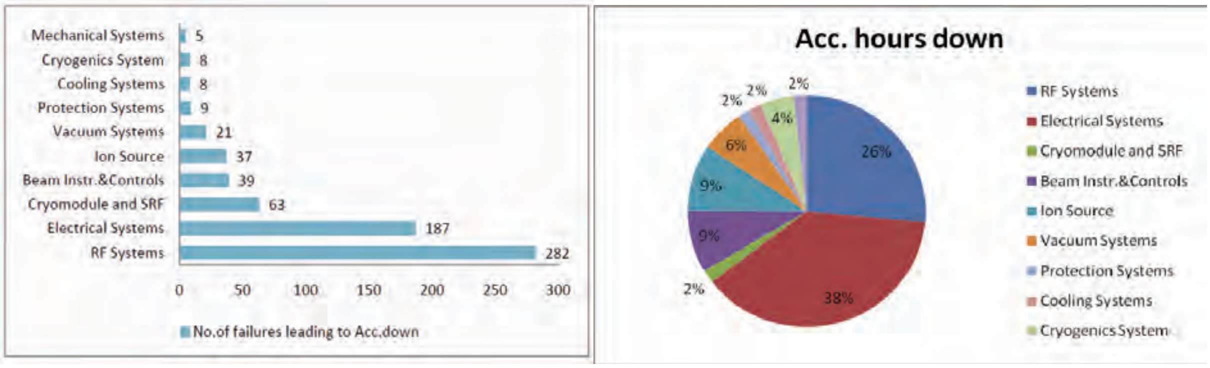
An MCS analysis has been performed for the complete SNS linac model as well as for different parts of the accelerator with the following conclusions:

- As the main result for the top event (SNS ACC DOWN) analysis case, the complete model running analysis has indicated a mean unavailability value of Q = 2.60E-01 = 0.26. Thus, Q = 26%, which results in a mean availability value of A = 1 - Q = 73% (the limit availability).
- The MCS analysis results indicate a wide range of failure modes (failures affect relatively all types of components.
- The linac (DTL-CCL-SCL) represents the system most affected by failures in terms of unavailability (Q=1.25E-01; A=87.5%).
- The highest values of unavailability are as follows:
  - SCL (Q=9.85E-02; A=90%);
  - DGN and C (Q=7.15E-02; A=93%);
  - Front-End (Q=6.93E-02; A=93%).
- The most affected part is the SCL, especially due to the malfunctioning of the SCL RF system (radiofrequency system of the superconducting linac) for which Q=6.33E-02 and A=94% (due to power supplies failures and klystron failures). The SCL usually fails as a consequence of cavities, cooling and vacuum malfunctions.
- The most affected parts of the front-end are the LEBT (Q=2.83E-02; A=97%) and MEBT (Q= 2.82E-02; A=97%), more specifically the magnets and the vacuum systems.

SNS reliability considerations (operating experience)

Reviewing the accelerator trips failure data from SNS logbook records from past operation experience, it has been concluded that the RF system and electrical system failures are the most frequent, while the failures in the electrical systems represent the most important contribution to total accelerator downtime (see Figure 4) in agreement with the conclusions from the SNS RS model runs.

Figure 4. Frequency of accelerator trip failures (by systems) and accelerator downtime contribution (by systems)



The pie chart above shows the distribution of breakdown hours by system. Accelerator trips caused by failures of components in the electrical systems represent 38% of the total accelerator downtime over the studied period. The second largest contribution is from the RF systems (26%), which are also the systems more often involved in failures leading to short accelerator trips (up to 0.2 hours).

According to the SCL risk spectrum analysis results, SCL-HPRF (Superconducting Linac – High Power Radiofrequency) and HVCM (High Voltage Converter Modulator) are the most affected subsystems of the SNS linac as far as failures leading to accelerator trips are concerned. SCL-HPRF is affected by frequent short failures, while HVCM is affected by long duration trips.

Figure 5. RF system failures

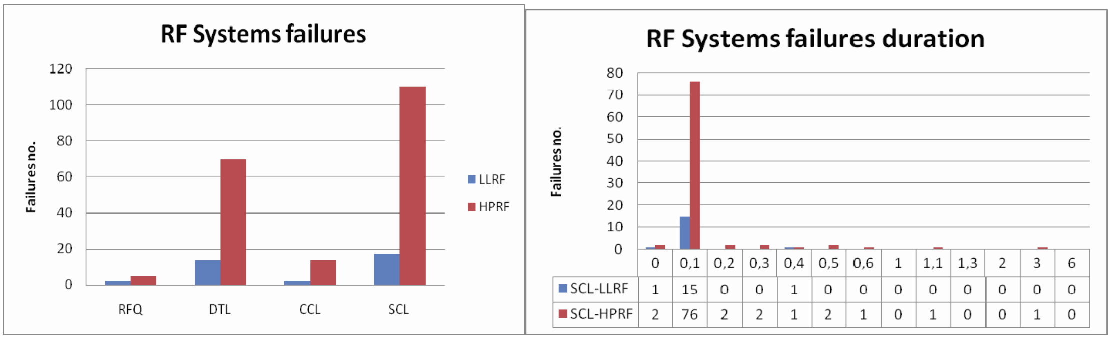
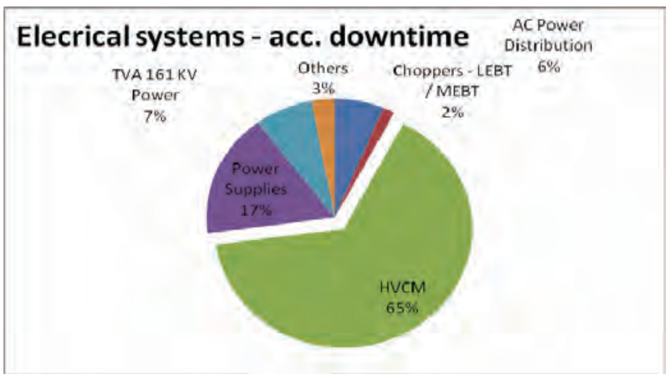
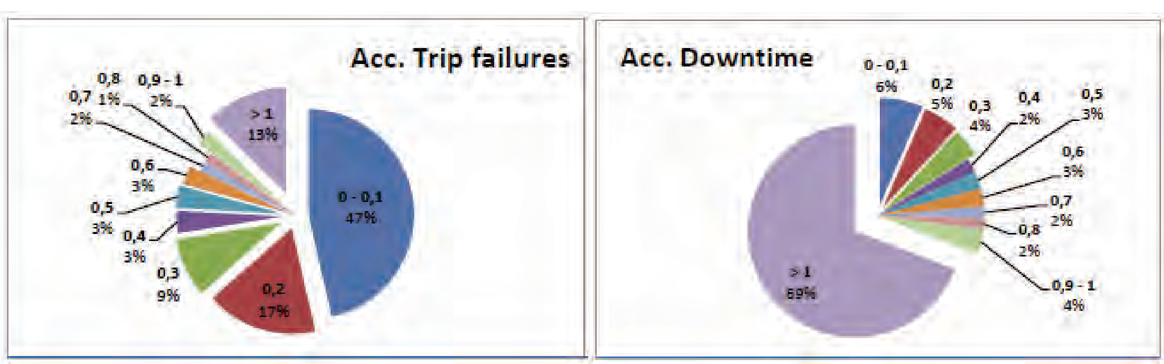


Figure 6. Electrical subsystems contribution to the accelerator downtime



In addressing all linac systems, beam interruptions of between 0 and six minutes (0 - 0.1 hours) represent 47 % of beam trips, i.e., 327 failures from the total of 705 failures recorded over the studied period of time. Failures whose duration exceed 1 hour represent 13% of the total. The latter contributes most to the total downtime for the same period, accounting for 308 hours, which represent 70% of the total (445 hours).

Figure 7. Statistics of accelerator trips by duration (hour fractions): a) failure frequency, b) contribution to the total downtime



The SNS RS model results have been evaluated compared with the above statistics and taking into account the assumptions formulated for the model development and the model limitations mentioned in Section 3.

Given the consistency of the SNS design information database and due to the conservatism of the reliability data used for model quantifying and to the fact that the human factor has not been taken into account (neither have improved operational reliability or the improvements of the maintenance programme), it can be concluded that the overall availability of the SNS linac (A=73%) resulting from the RS model is confirmed by the availability figures of the SNS from the first years of SNS operation.

The availability results obtained by MCS analysis run separately for the different SNS linac parts (IS, RFQ, MEBT, DTL, CCL, SCL, HEBT), have agreed very well with the SNS logbook availability records, although the global result is A=73%. This difference is attributable to the fact that the MTTF and MTTR values used for model quantification may be too conservative, and to assumptions and constraints of the model. The MTTF and MTTR data used represent a data mix from SNS registers including previous experience. Reliability input data used do not result from the statistical interpretation of logbook data over the entire operation period, which explains the differences between the values compared.

It should be noted that the results from the model agree substantially with what is indicated by the operational data, despite the model limitations and the fact that some parts are not considered and other parts are not developed in detail. As a consequence, the RS model developed for SNS linac is validated by the site operation data (data registered in the SNS logbook).

Conclusion

- The reliability results show that the most affected SNS linac parts/systems are:
  - SCL, front-end systems (IS, LEBT, MEBT), diagnostics and controls;
  - RF systems (especially the SCL RF system);
  - power supplies and PS controllers;

These results are in line with the records in the SNS logbook:

- The reliability issue that needs to be enforced in the linac design is the redundancy of the systems, subsystems and components most affected by failures.
- For compensation purposes, there is a need for intelligent fail-over redundancy implementation in controllers.
- Enough diagnostics has to be implemented to allow reliable functioning of the redundant solutions and to ensure the compensation function.

Acknowledgements

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