Feasibility Analysis and Intelligent Technologies for an Innovative Nuclear Reactor Enabling Waste Transmutation

Sampriti Bhattacharyya[†*], Rama K Yedavalli[†],
† The Ohio State University, Columbus OH 43210
**Fermi National Accelerator Laboratory, Batavia, IL 60510*
Emails: bhattacharyya.15@osu.edu, yedavalli.1@osu.edu

INTRODUCTION

A future application of linear accelerators (linacs) in Nuclear Energy is Accelerator Driven Subcritical Systems (ADSS, or Accelerator Driven Systems, ADS). ADS is a revolutionary concept where a proton linac produces energy from transmutation of conventional radioactive waste[1]. The major challenge in realizing this concept is combining high efficiency and high reliability in a proton accelerator. For use as a power plant, reliability of >99% is essential, whereas a superconducting linac such as SNS[a] has <85%[2]. A thorough understanding of reliability is imperative to ensure feasibility of ADS. This paper discusses the work performed on reliability analysis and use of intelligent controls for the proposed linac, Project-X at Fermi National Accelerator Laboratory, as the experimental test bed.

RELIABILITY AND ADS

ADS was proposed over 20 years ago but was rejected because a sufficiently efficient accelerator was not possible[3]. Since then development of superconducting accelerators has dramatically improved the efficiency. The major remaining concern is the reliability of such an accelerator. The field for which they were developed – basic physics research – does not require the >99% efficiency an ADS system would need. Reliability modeling is extremely challenging. There are

---

[a] Note the reliability numbers in [2] exclude weekly scheduled down time.

many and varied components in an accelerator with complex interdependencies. Components are often unique or first of their kind and have not been studied previously for reliability. Some initiative was taken by Oakridge National Laboratory to study their Spallation Neutron Source (SNS), and some work was done at SLAC[4] for the proposed International Linear Collider. The latter however could not be validated due to lack of real data. Until very recently these accelerators also did not attempt the extreme intensity a nuclear reactor would require, thus there was no working model with which to study reliability.

A new proposed superconducting linac, Project-X at Fermi National Accelerator Laboratory, is intended to have intensity approaching what an ADS system would need[5]. As it is still in the development stage, it is potentially suitable for testing different methods of improving reliability.

In our research we use commercial software, Availability WorkBench (AWB) by Isograph[6],[7], to develop a hierarchical method of reliability modeling for a linac. The model can give us the mean downtime and expected availability of the system. It helps us to identify the critical components and interdependencies between various subsystems. We structure the model for flexibility and ease of incorporating design changes. We develop a hierarchical method to allow exploring different scenarios at a minimal CPU cost. Future research will study ways to minimize downtime.

Reliability Model of the Linac

Reliability can be defined as the probability that a system will perform its intended function for a specified interval of time under the stated conditions. A meaningful understanding of reliability can be given through the following terms: Reliability $R(t)$, Availability $A(t)$, Failure Density Function $f(t)$, Cumulative Failure Density $F(t)$, Mean Time Between Failure (MTBF), and Mean Time To Repair (MTTR). These terms are defined in appendix A.

There are many ways to perform reliability studies, some of which are

1. Reliability Block Diagrams
2. Fault Tree Analysis
3. Markov Models
4. Simulation (Monte Carlo), often coupled with some of the above concepts

AWB uses (4): Simulation of a system described by a reliability block diagram.

In reliability block diagrams, components are connected in series, parallel, or as a *r*-of-*n* block, depending on the functional relationship *(Appendix A).*Since the accelerator has a large number of components, building and simulating the whole model in a single project takes a lot of computing time. Though we built such a model as well, we focus on a different procedure: dividing the system into subsystems, and representing subsystems as pseudo components. For this hierarchical method we simulate each subsystem and parameterize its failure and repair distribution. This subsystem can then be used as a single block (or couple blocks) for building the top level model of the accelerator. This enables us to form a simpler representation of the system, while allowing a systematic analysis.

For validating our idea, we use SNS data. Some of the subsystems of SNS are similar to that of Project X, both being proton linacs with superconducting RF cavities. We focused our validation on these common subsystems. Project-X has been divided into the following main subsystems at the top level.

1. Conventional Facilities
2. Beam Vacuum
3. Global Insulating vacuum
4. Global Controls

5. Global Cryogenics
6. LEBT (Low Energy Beta Transport)
7. RFQ
8. MEBT (Medium Energy Beta Transport)
9. HWR (Half Wave Resonator)
10. 325 MHz section
11. 650 MHz section
12. Magnet Package
13. Beam Instrumentation package

Note Project X continues with a 1.3GHz section, but the remainder is not relevant for ADS and has not yet been studied.

The HWR, 325MHz section, and the 650MHz section are made up of “cryomodules”: a package of superconducting cavities immersed in a liquid helium vessel. Repair or replacement of cryomodules takes weeks due to the cooling and warm up time, thus they are a key issue for reliability. From the standpoint of reliability, all cryomodules are the same, differing only in number of cavities and type of RF power.

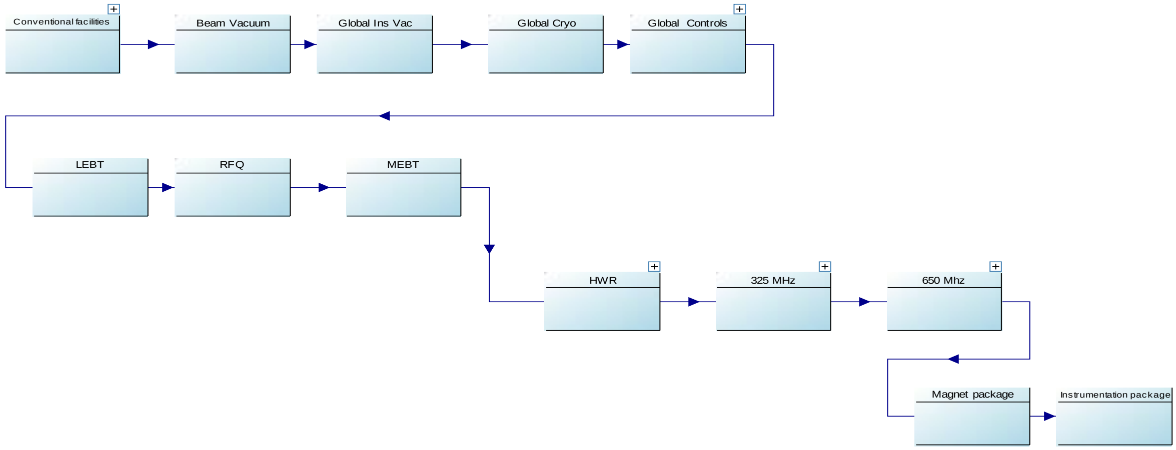

Fig.1

Figure 1 shows the simple top level reliability block diagram for Project-X consisting of 13 subsystems. A failure of any of these brings the system down. As mentioned, each subsystem has been studied and parameterized separately.

The model was built despite lack of data on constituent components. The actual failure and repair time distribution are therefore not known; but it is easy to insert meaningful data as it becomes available. The following assumptions have been made while developing the model:

1. AWB has the flexibility to use various failure distributions, but analogous to SNS analysis we are using only exponential for now.
2. No aging, dormant, or start up failures have been counted, though they can be easily included in AWB.
3. Labor, cost, inspection schedules have not been counted, but can be given as input if required.
4. Anything in the cold volume (cryomodule) has repair time ~400 hours.

5. Each cryomodule is a r-of-n system, i.e. it can take up to $n - r$ failures. For now, we assume, it can take at most 1 failure.
6. The magnet package is also a r-of-n system.
7. Load on any r-of-n system increases after each failure.

RESULTS OF RELIABILITY MODEL

In this section we will give some examples of the subsystems built. The MTBF computed for RFQ, Cryoplant, MEBT, Conventional Facilities, are within 1% of what SNS estimates using a Markov analysis. The Project-X ion source is, however, very different from SNS. It has redundancies which allow a longer lifetime. However, for the rest of the systems, models have been built, though as noted before, with many assumed rather than measured failure and repair properties. The goal of our research was to build the models so that data can be plugged in as and when available.

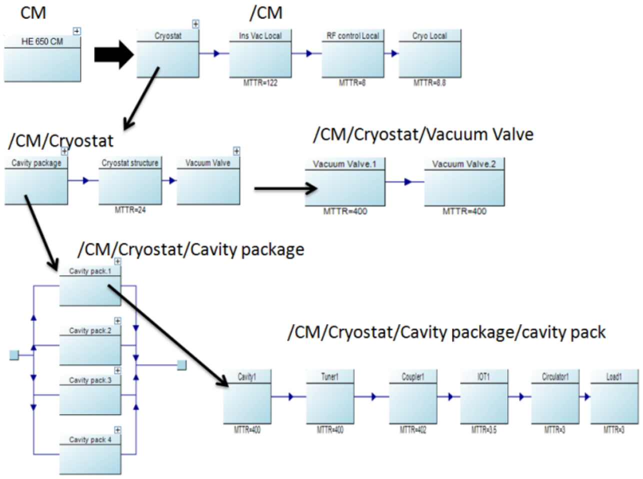

Fig.2

Figure 2 shows an example of a cryomodule. The main cryomodule (CM) block (top level) consists of the cryostat, local insulating vacuum, local cryogenics, and local RF control. The cryostat is further divided into the cavity package, cryostat structure and vacuum valves. The vacuum valves consist of two valves in series. The cavity package is a *r*-of-*n* system, consisting of *n* cavity packs. Each such pack further consists of a cavity, a tuner, a coupler, a RF power (IOT/solidstate/klystron), a load, and a circulator, all in series

This cryomodule model was then simulated, and we got data for failure and repair distributions. The cumulative failure distribution is shown in the figure 3, with a fit overlaid. The X axis gives the MTBF in hours and the Y axis shows the cumulative failure probability.

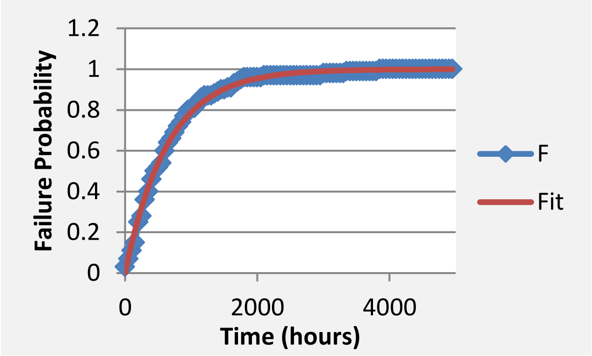

Fig.3

A similar fit is done for the Mean Time to Repair, shown in figure 4. In this case, we require a mix of Gaussian and exponential distributions since failure properties of the components vary widely, from a few hours to many days.

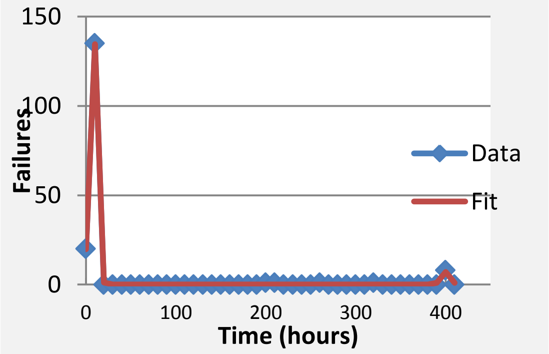

Fig.4

Such a repair distribution, parameterized by three distinct functions, can be reproduced using 3 sub blocks as shown in figure 4. The area under each of the functions in figure 3 is translated to an effective MTBF of each of the sub blocks so as to correctly populate the repair time distributions. This simplified description of the "HE650" cryomodule retains all the information relevant to simulating the system.

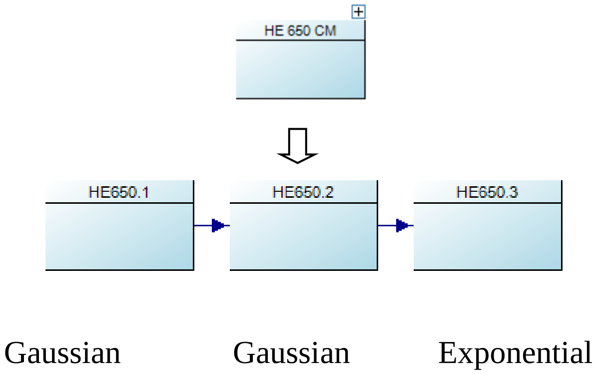

Fig.5

Similar procedures have been carried out for parameterizing magnet and beam instrumentation packages. Thus by simplifying the blocks, we make simplify representation of the massive accelerator system.

CONTROLS FOR ADS

The major challenge in ADSS is the downtime of the linac. The downtime of the linac can be contributed to the following causes :

1. Damage (→ replacement) of targets due to thermal and radiation stress.

- Targets are contained in stainless steel, beam interruption in sub second level can give rise to thermal cycles.

2. Ion source Replacement: Expected lifetime < 400 hours at 10% duty cycle

- Presently done manually, turning off the linac.

3. Beam Tuning (as part of recovery)

- Low Level RF control and Magnet current control

4. Lack of autonomous intervention

5. Cryomodule Repairs and replacement (Contains the cold volume ~2K)

6. General unreliability of the machine.

As mentioned for ADSS to act as a power source a high reliability is needed (>99%) which is beyond the experience of the physics community. A part of the summer research, we analyzed the downtime reasons, the shortcomings in handling them, and explored probable approached using intelligent control and automation that can minimize the downtime to sub second scale.

Approaches

Remote Repair and Handling: We first discuss the application of autonomous controls and robotics for remote repair and replacement in ADS. The H- ion source has a very small lifetime. So, sufficient redundancy is proposed: i.e. there will be 3-4 hot spares available. As each breaks, we switch to the new one, and swap out the old one through train. An autonomous robotic arm can probably take care of precisely bolting the new spare to the beam line. Care has to be taken that air does not get inside the linac. For replacing Spallation and Fission targets, highly precise robotics is being explored. The challenge is making a reliable robot. If the robot fails, operation has to be halted or the plant has to be closed down, because human intervention in the high radiation area will not be possible. In case of Cryomodule, presently any repair or replacement is done by first warming up the whole module. This means a few days downtime. However cooling down the module after repair may take a week or more. Assuming we have a redundant linac which takes over, if the first one breaks, we still want a quick recovery of the failed one. The proposed idea is to have access panels to repair in the cold volume. Glove box can be mounted over the panels which will have a decent vacuum. Repairs can be done in the cryo system while still cold, and hence downtime can be minimized substantially since there would be no wait time. However this demands special gloves that are in more abundant application in space experiments.

Control and Optimization: There are three areas where the application of intelligent control can minimize downtime extensively. The foremost is beam focusing. The emittance of the beam is a measure of the spread of the beam and how fast it is growing. Higher emittance means lower intensity and lower energy. If the lateral emittance is high, it means the particles would hit the cavity walls or the detectors and damage the system. Presently the spread is controlled by observing it through the data from a laser scan and manually tuning the magnets. This means, the operation is performed at low intensity of the beam which also implies, the linac is essentially turned off (in case of ADS). This is not acceptable. To take care of the issues regarding thermal cycles such beam focusing must be implemented in sub second scale. The problem can be formulated as a minimization problem. We would define a cylindrical envelope and the goal would be to minimize the number of particles outside the cylinder.

An intelligent controller is proposed which can perform the following functions:

- Continuously implement corrective measure to ensure beam minimization outside the envelope
- After a major failure switch to low intensity and verify the new settings.
- Enable high intensity beam if the expected losses are reasonably low.

Fast Beam Tuning

Beam Control Challenges are:

- Usual particle accelerators tunes the beam manually, without any definite control technique/algorithm.
- Can take several hours to days: not feasible for ADSS.
- Estimation of the beam behavior is difficult- how big it is, and how much halo it forms.
- There are too many controls (magnets/currents in the magnets) and too few measurements- Over-determined system.
- Beam after control might look right at the measurement point but might blow up after it.
- Research on intelligent and smart control algorithms to determine quickest way to beam control.

We use the chi square minimization for beam control. We use a software, Tracewin® to simulate a part of the linac, and then randomly drift the magnet currents. We apply the chi square algorithm to bring the magnet currents back to optimal. Such a automated process is not currently used, and can help to reduce the downtime to a large extent.

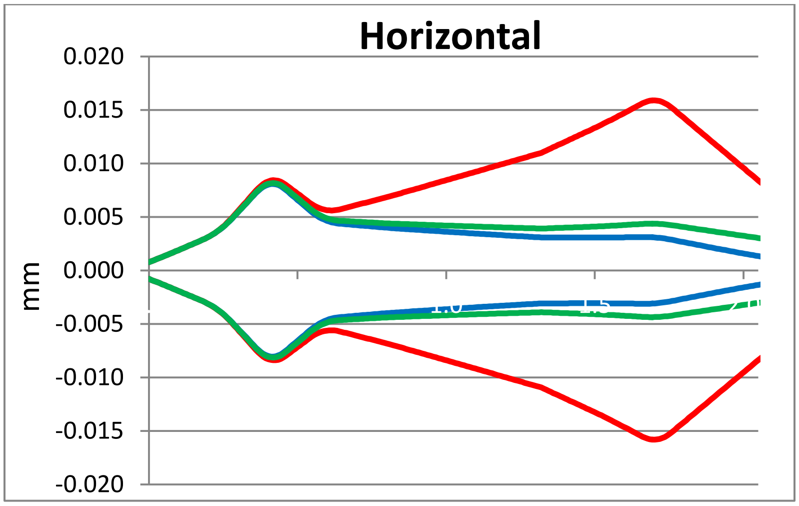

Fig 6

Fig6 shows the control of the beam in X, for example. The blue line is the nominal current, the red is the drifted and the green is the corrected one through chi-square.

Conclusion

Intelligent control techniques can help to overcome a lot of challenges in ADSS system. Smart control techniques can help in optimization of RF power in the superconductive cavities when a cavity fails. Use of decentralized control systems can help in RF phase adjustments in cavities. Research is ongoing in these areas. The use of controls for ensuring beam reliability, robotics for quick repairs, and advances in material science for improved targets, can make ADSS feasible in a near future. ADSS feasibility would be a breakthrough in energy domain since now we can use domestic and essentially free fuel, in a safe reliable way, accelerating us to energy independence.

APPENDIX A:

Mean Time Between Failures, MTBF: the average time between consecutive failures. In many cases (including in the SNS spreadsheet), MTTF and MTBF are used interchangeably; however, the more correct interpretation is MTBF=MTTR+MTTF.

Failure density function, $\boldsymbol{f(t)}$: the failure probability density function. The probability of failure between time t and $t + \mathrm{d}t$ is $f(t)\mathrm{d}t$. In the absence of repairs $\int_0^\infty f(t)\,\mathrm{d}t = 1$. With repairs, one can either take $f(t)$ as describing the first failure, or allow $f(t) \nrightarrow 0$ for $t \to \infty$ and therefore $\int_0^\infty f(t)\,\mathrm{d}t = \infty$.

Failure probability,$\boldsymbol{F(t)}$: the cumulative failure probability function giving the probability the system has failed at or before time t. $F(t) = \int_0^t f(t')\,\mathrm{d}t'$. The concept is of little value when including repairs; then Availability (below) is more informative.

Reliability probability,$\boldsymbol{R(t)}$: the complement of $F(t)$, $R(t) = 1 - F(t)$. Gives the probability the system has *not* failed at or before time t. As with failure probability, the concept is useful primarily when ignoring repairs.

Availability, $\boldsymbol{\mathcal{A}(t)}$: probability that the system is operating successfully at the time t. The concept is most useful when including repairs; without repairs, Failure Probability (above) is more informative.

Steady state availability, $\boldsymbol{\mathcal{A}_{SS}}$: availability after initial state conditions are washed out:

$$\mathcal{A}_{SS} = \lim_{t \to \infty} \mathcal{A}(t)$$

Without repairs, $\mathcal{A}_{SS} = 0$ i.e. the concept is only useful when repairs are considered.

Hierarchy/Hierarchical: A system arranged in different levels. The lowest level has components with defined failure and repair characteristics.

Series: System is functional only if *all* blocks are functional.

Parallel: System is functional as long as *any* of the blocks are functional.

$\boldsymbol{r}$ of $\boldsymbol{n}$: System containing n components and is functional if any r of them are functional. Note *Parallel* is the same as $r = 1$, *Series* is the same as $r = n$.

REFERENCES

1. Abderrahim *et al.*, "Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production", (2010)
2. J. GALAMBOS, “SNS Operational Experience at the MW Level,” *ICFA 2010*, Morschach, Switzerland, Sept. 27, 2010
3. NAS-NRC 1996 : National Research Council of the National Academy of Sciences, Nuclear Wastes: Technologies for Separations and Transmutation, Committee on Separations Technology and Transmutation Systems, Board on Radioactive Waste Management, Commission on Geosciences, Environment, and Resources, Washington, DC: National Academy Press, (1996).
4. T. Himel, J. Nelson, N. Phinney, M. Ross “Availability and Reliability Issues for ILC”, Particle Accelerator Conference (PAC 07), Albuquerque, NM, USA , June 2007
5. Yousry Gohar, David Johnson, Todd Johnson and Shekhar Mishra, “Fermilab Project-X Nuclear Energy Application: Accelerator, Spallation Target and Transmutation Technology Demonstration”, (2010). (indico.fnal.gov)
6. L. Sikos, J. Klemeš , “Evaluation and assessment of reliability and availability software for securing an uninterrupted energy supply” Clean Technologies and Environmental Policy doi:10.1007/s10098-009-0243-2
7. Isograph Ltd (2009) Isograph software suites, (www.isograph-software.com). Accessed 3 Jan 2009