Failure mode and effects analysis (FMEA) and development of an algorithm to assess reliability and availability of the RIA driver linac

Progress Report

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Overview

The RIA facility will include various complex systems and must provide radioactive beams to many users simultaneously. The availability of radioactive beams for most experiments at the fully-commissioned RIA facility should be as high as possible within design cost limitations, preferably close to 90%.The reliability and availability of the RIA facility must be carefully evaluated and incorporated into the design. In this project we proposed to identify the most probable failure modes of the facility operation as a global system and investigate the effects of those failure modes on the overall performance of the RIA facility. During FY04 we concentrated on failure mode and effects analysis of the driver linac, which is a complex and unique system.

The driver accelerator will produce beams of any ion, including uranium, at energies of 400 MeV/nucleon and a total beam power of 400 kW [1]. Except for the injector RFQ, the entire linac is based on SC accelerating structures. The driver linac is extremely complex and unique due to, among many factors, the use of large numbers of state-of-the-art SC resonators operating at relatively low frequency; the high-power beam of the driver linac requiring control of beam losses that cause radioactivation; and the multi-beam capability of the driver linac, requiring that accelerator-tuning time from one type of ion species to another be minimized.

FMEA is an integral part of engineering designs and should be applied to the RIA facility analysis to identify potential problems and to allow modification of the design in order to achieve the required availability goal for the RIA driver linac. The FMEA can be performed as either a hardware or functional analysis. The **hardware approach** requires parts identification from engineering drawings and reliability performance data, for example mean time between failure (MTBF) and mean time to repair/restore (MTTR), and is generally performed in a part-level (bottom-up) fashion. However, it can be initiated at any level (component/assembly/subsystem) and progress in either direction (up or down). The **functional approach** is used when hardware items have not been uniquely identified or when system complexity requires analysis from the system level downward (top down). A functional approach is applied to identify possible failure modes and their effects on the driver linac performance. Design deficiencies can be identified and improvements of the "baseline" design can be made. At the present pre-CDR stage of the RIA project we can identify two types of failure modes: 1) accelerator subsystem failures that can directly impact the beam quality and beam loss of the driver linac. This includes deviation of the accelerating field levels from the original settings, exceeding required rf field phase and amplitude dynamic error tolerances, and mechanical system failures that can result in beam loss, producing excessive radioactivation or even quenching the SC equipment; and 2) critical facility subsystem failures that can prevent the driver-linac from operating.

Accomplishments

The RAMI (reliability, availability, maintainability, and inspectibility) & FMEA studies for the RIA facility to date include: utilization of two approaches, those of the NLC/SLAC and the APT/LANL/AES. Significant effort has been invested to employ the NLC/SLAC method, collection of reliable data, creation of two models, ATLAS ECR, and RIA Front End, and initial studies for an optimization code.

1. The NLC/SLAC approach utilizes a Monte-Carlo simulation code to estimate the accelerator availability [2]. The code uses real-time as the independent variable and calculates the average availability based on given MTBF, MTTR and redundancy of components, and access required for repairs. It takes into account recovery and tuning time needed after a downtime, and the number of people available for repairs. These features are not available from commercial packages and are difficult to implement on spreadsheet-based methods.
2. The NLC/SLAC code has been developed specifically for the NLC accelerator RAMI/FMEA analysis, particularly, to compare the warm and cold designs of the NLC. All these features make the code extremely useful for the analysis of the RIA driver linac which includes both warm and cold sections. However, significant effort was required to adapt the MATLAB simulation package and to modify of macros for the RIA application. These tasks have been completed and the NLC/SLAC code has been applied to the ATLAS ECR and RIA Front End. The results are given below. Further effort from FY2005 funding will be necessary to run and analyze the whole RIA driver linac.

3 Another mathematical RAMI simulation is based on Markov models of the subsystems based on the topology of the system with a proper representation of the redundancies. This approach leads to a balanced design that makes full use of the resources offered by the current technology to identify the development needs for new technology in the most economical way, i.e., without unduly stressing the need to increase the reliability of any new component. The RAMI model will then be used to evaluate potential design alternatives through various trade-off studies.

4 The APT/LANL/AES approach utilizes the FMEA functional method, whereby a systematic process is applied to identify potential design and process failures before they occur, with the intent to eliminate them or minimize the risk associated with them. As an application of this approach, we studied the effects of resonator failure on the beam dynamics in the RIA SC Driver Linac.

5 One of the objectives of the RAMI analyses at the conceptual-design stage is to assist the designers in achieving an optimum design that balances the reliability and maintainability requirements among the subsystems and components. This is accomplished by developing a model incorporating the best available statistics for the state-of-the-art items. For technology-development items, where these statistics are not available, engineering judgment and expert opinion is used to define what in fact represents specifications. Collection of reliable data on existing machines is used to guide the budgeting process. Data was collected from mature accelerators that have direct experience with major systems that may also be used in the RIA project, such as ATLAS, and APS, and from JLAB, that have experience on SRF systems for acceleration. These numbers are intended to indicate the degree of design specifications necessary to achieve the desired availability goal for RIA.

6 Development of an automated retuning algorithm has been initiated. Preliminary studies have shown that the degree of difficulty involved in building such code was underestimated. There has been considerable interest by the heavy-ion accelerator operations community regarding the possibility of doing automated beam tuning. Beam tuning over a wide range of beam properties, beam species and charge-to-mass ratios appears to be a universally difficult task at currently operating facilities, as it will also be at RIA.

Examples of Simulation with the NLC/SLAC Code: The ATLAS ECR and RIA Front End

We chose to simulate the operational ECR providing heavy-ion beams routinely for the ATLAS SC accelerator and the front end of the RIA driver linac as a means of understanding the degree of complexity necessary to obtain meaningful results with the program. A detailed list of components, identifying possible causes of failure was established. Each component was assigned a MTBF and a MTTR. The simulation assumes the accelerator has reached a steady state after several years of operation. One year of operation is equivalent to 9 months actual time. The results give the total availability of the region depicted and the down-time, in %, of chosen component systems such as Magnets, RF, Main Power Supplies, Water Cooling, Cryogenic, etc. For instance, for the ECR simulation as a complete region, we divided the hardware components into 12 such systems, including the aforementioned systems plus Oven, Isolation Table, Vacuum, Extraction Tank, Controls, and Diagnostics. In this case, spares were assumed available for the main components, and the MTBF and MTTR input data were based on the ATLAS experience. For the RIA Front End data were collected from the sources mentioned before. A pie-chart of the simulation results is depicted in Fig. 1. As shown in the figure, the major contributing factor to down-time for the ATLAS ECR is the Radiation Safety System. RIA will have newer and more reliable radiation shielding monitors, which should reduce their contribution to down-time considerably. The total availability of the ATLAS ECR is 97.8%, and that of the RIA Front End is predicted to be 99.5%

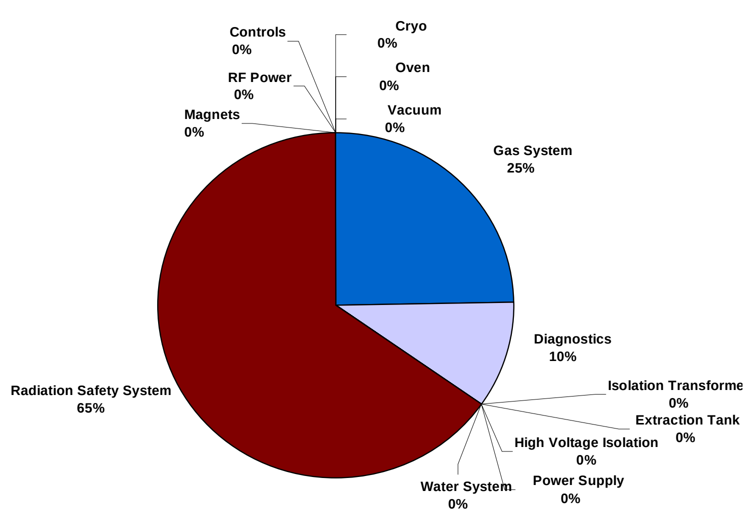

Figure 1 – ATLAS ECR Unavailability Distribution for a Ten-Year Run.

Effects of Resonator Failure on the Beam Dynamics in the SC Driver Linac

Effects of resonator failure on the beam parameters in the SC Driver Linac were studied and the lattice sensitivity to failures of one, two, and a whole cryostat were determined. Simulations were performed with the code TRACK[3]. The SC driver linac is divided into three major sections: a low-energy section, or prestripper, where the nominal U-238 energy increases from 0.19 MeV/u to 12.0 MeV/u, the medium-energy linac section, where the final energy is 85 MeV/u, and the high-energy section, where the energy increases from 85 to 400 MeV/u. For each of the sections, we examined the effects of resonator failure according to the number failed of resonators, and their location (beginning, middle, or end) within a particular linac section.

In the prestripper, failure of any one of the eight cavities in the first cryostat or failure of the first or middle cryostat affects severely the beam dynamics. Retuning is necessary to recover beam properties and avoid losses. In the medium-energy section the beam parameters are also strongly affected by failure of a cavity at the beginning of the section. For example, the normalized longitudinal emittance increases by 35% compared to the no-failure mode. Without retuning, failure of a whole cryostat at the section beginning causes 45% losses.

We also compared the effects due to cavity failure in the high-energy section for the baseline design, to the effects in the triple-spoke design [1]. A full cryostat off at the beginning or middle of the high-energy section of either design causes the normalized longitudinal emittance to grow by a factor of three. In both designs, the loss of a cryostat at the end of the high-energy section does not affect the beam parameters significantly. When the middle cryostat failed, we observed small oscillations in the bunch length for the triple-spoke option and high bunch-length oscillations for the baseline options. Fig. 2 shows the normalized longitudinal emittance when one cryostat, two cavities, and one cavity are off at several locations of the baseline high-energy section.

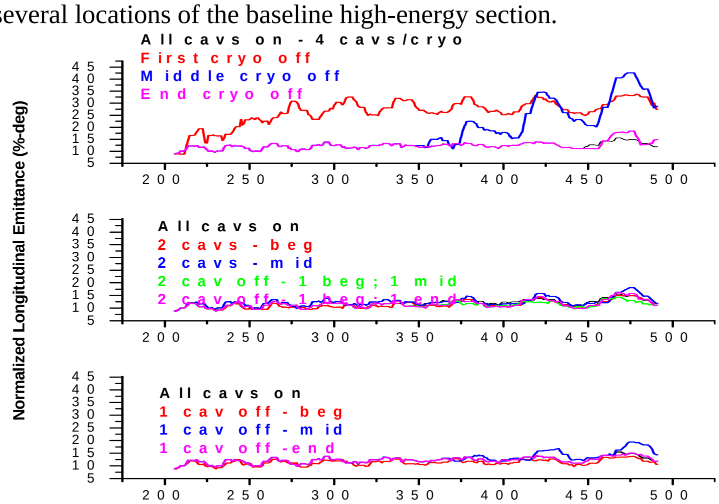

Figure 2: Effects on the normalized longitudinal emittance when one cavity, two cavities, and a whole cryostat fail at the beginning, middle, and/or end of the baseline high-energy section.

As seen in the figure, one or two cavities off in the high-energy section do not affect the beam dynamics. There are no losses when a whole cryostat fails, independent of its location in the section, but retuning is necessary to restore the beam quality. The retuning procedure requires development of the advanced optimization code that must be able to set new accelerating field phases in the resonators to maintain synchronous motion. Some adjustments of the focusing field are necessary to avoid beam emittance growth. The development of this optimization code has been started at LANL and will take one more year to complete.

In summary, the lower the energy, the higher the effects in beam parameters. The beam quality is more affected when the failures occur at the beginning of a section. In most cases, we can recover from resonator failures by choosing the appropriate phase and amplitude of neighboring cavities.

Work Completion

Major assembling of reliable data and model building was accomplished during FY2004. Application of the NLC/SLAC approach to the entire Driver Linac will be completed during FY2005 if the project is continued. The independent method based on Markov model will be simultaneously applied for the RAMI analysis of the driver linac. To date the full amount of allocated funds (0.5 FTE each) at ANL and JLAB has been spent. The LANL project allocation (0.35 FTE) for FY 2004 was $110K. To date, LANL has spent $59.8K. The LANL project members will extend their work on development of automated retuning over a wide range of beam properties, beam species and charge-to-mass ratios into FY2005.

Literature Cited

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