RELIABILITY AND AVAILABILITY STUDIES IN THE RIA DRIVER LINAC*

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Abstract

The Rare Isotope Accelerator (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 facility should be as high as possible within design cost limitations. To make a realistic estimate of the achievable reliability a detailed analysis is required. The RIA driver linac is a complex machine containing a large number of superconducting (SC) resonators and capable of accelerating multiple-charge-state beams [1]. At the pre-CDR stage of the design it is essential to identify critical facility subsystem failures that can prevent the driver linac from operating. The reliability and availability of the driver linac were studied using expert information and data from operating machines such as ATLAS, APS, JLab, and LANL. Availability studies are performed with a Monte-Carlo simulation code previously applied to availability assessments of the NLC facility [2] and the results used to identify subsystem failures that most affect the availability and reliability of the RIA driver, and guide design iterations and component specifications to address identified problems.

THE DRIVER LINAC

An important measure of a successful RIA facility will be its ability to provide high availability of the radioactive beams for most experiments. The facility will utilize a wide variety of primary beams delivered by a driver linac that must accelerate beams of any ion, including uranium, at energies of 400 MeV/nucleon and a total beam power of 400kW. If we assume that the facility consists of the driver linac and all other systems with equal availability, then the availability of each sub-system must be larger than the facility as a whole. The driver is a complex and unique machine [3]. Assessment of the linac availability must take into account the large number of state-of-the-art SC resonators operating at relatively low frequency, the high-power beam, and the multi-beam capability. The accelerating field level in SC resonators can drop during long-time operation and the linac must be retuned to compensate for field level losses or even the total loss of a cavity. The high power of the beam requires extremely low levels of losses, ~ 1 w/m, so that hands-on-maintenance and high availability be attainable. The diversity of beams accelerated by the driver requires that tuning time from changes in ion species be minimized.

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BASIC CONCEPTS AND ASSUMPTIONS

Availability represents the average proportion of time when a *repairable* system is found operational over a long period. The availability characteristics of a system are determined by its reliability (failure rate), and maintainability (ease of maintenance). The RAM (reliability, availability and maintainability) of any given system is an inherent design characteristic that must be incorporated into the system at the design stage. In the pre-conceptual design phase, the objective of RAM analyses is to assist the designers in achieving an optimum design that balances the reliability and maintainability requirements among the subsystems and components. A system with high reliability can be unavailable most of the time if the repair time of its components is very long. High availability requires reduction of both rate and time duration of critical equipment failures.

Mean Time Between Failure (MTBF) is the expected length of time between two consecutive failures.

Mean Time To Repair (MTTR) is the sum of corrective maintenance time divided by the number of failures during a given time interval. Recovery from a failure has to take into account the time to repair and also restart time, staffing, and radiological and safety measures.

The mathematical model used in the availability analysis of the RIA SC driver linac assumes a constant failure rate, one for each component, and a reliability function described by an exponential distribution function. Failure events are described by *Poisson processes*, implying, in particular, that the probability of failure in a small time interval is proportional to the length of the interval, and there is zero probability of simultaneous events. Given the MTBF and MTTR, the availability of an accelerator component can be expressed as:

$A = MTBF / (MTBF + MTTR)$.

In general, the lifetime of a system of components can be described by the "bathtub curve", originally constructed to describe the mortality rate of a human population. In the "infant mortality" period, the failures correspond to a period of manufacturing tests or machine commissioning. The "end-of-life" period corresponds to a high failure rate or to a predetermined time. The failure rate for components-in-service derived from statistics is roughly constant. For the studies presented here we assume the machine is in its maturity.

Analysis of the RIA SC linac driver availability is based on simulations using a code developed at SLAC [2] to assess the impact of various technologies or configuration choices in the Next Linear Collider (NLC) performance.

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The code emulates failures in a Monte-Carlo process that uses real-time as the independent variable. It calculates the machine average availability based on:

i. given MTBF and MTTR values for each component,
ii. degradation of parameter affected by component failure,
iii. redundancy of components,
iv. number of repair people available for tunnel access,
v. recovery and tuning time, and
vi. total number of people available for repairs.

A detailed list of machine components, and, for each component, its number, MTBF and MTTR are required. Availability data for individual components were based on data from different accelerator facilities, namely ATLAS, APS, JLab, LANL, and from reports of planned machines such as NLC and APT [2, 4]. Also required is an estimate of the degradation in the appropriate machine parameter caused by a component failure. For instance, we can tune around a failed resonator and degrade the beam energy by the resonator's accelerating field integrated over its length. Access requirement are divided in three categories: a) component failure brings the accelerator down but does not require access to repair, b) repair/replacement of the component requires access to the accelerator tunnel, or c) the component can be repaired while the accelerator is running ("hot repair"). Included in the category of "broken but no access needed" are failures of single resonators that require rephasing of neighboring resonators (retuning) and may degrade the beam energy, but repair can wait until a long access is required. The calculations take into account the constraints imposed by the number of people available for repair during an access.

For the availability analysis of the SC driver linac we imposed that a minimum beam power at the target be maintained, while, at this stage of the machine design, making assumptions about component failure effects. These assumptions were based on the performance of existing accelerators and experienced operators, and need to be validated with detailed Failure Modes and Effects Analysis (FMEA) studies. Listed below are some of the requirements and assumptions made.

- Some parameters have a minimum value that, when reached, cause the accelerator to be declared broken. The meaningful parameter for RIA is the beam power on the target, which will be specified as a percentage of the user requested beam power. As an initial assumption, the minimum acceptable beam power is set to 60% of the user requested power. Since beam power is proportional to its energy and intensity, both energy and current are used as "budget" parameters according to the criteria given below.
- Some component failures cause the machine to go down, such as failure of the Machine Protection System, and require immediate tunnel access to repair; others cause the machine to go down, but the machine can be retuned without tunnel access
- Each time a component breaks the intensity is decreased by the specified amount, and the component is scheduled for repair, immediately if it can be fixed hot, or at the next downtime. When the minimum allowed operational energy or intensity is reached the accelerator is declared broken, and many accumulated repairs are done.
- Downtime planning: after a budget parameter reaches its allowable limit, the code computes the time necessary to fix the components affecting the parameter. An additional time can be added to the downtime to repair other components.
- Except for the first cryostat in the low-energy section, where failures cause the beam to be lost, failure of a whole cryostat can be recovered by retuning.
- Amplifiers and other RF power equipment are situated in a separate utility building and can be replaced quickly , if there is sufficient redundancy.
- Solenoid failure increases beam losses by 10%. Beam can be retuned, with a MTTR of 4 hours. The driver is declared broken if losses are higher than twice the initial nominal setting.
- Quadrupoles are warm. Failure increases beam losses by 10%.
- Power supplies, water pumps, etc, are located in the support building and can be repaired hot.

For component identification and each component impact on the SC driver linac availability, the accelerator components were subdivided in systems: magnets, together with their power supplies, resonators, cryogenic system, RF power, vacuum, water distribution system, diagnostics, AC power, controls, and "site systems", which are distributed site wide and are not described in detail.

SIMULATION RESULTS

For the current design, with values based on the historical data and engineering expertise from many accelerator groups the SC linac availability is 96 %. The high availability comes from assuming an "universal spare" cold cryostat that can be used to replace a broken unit in eight hours, SC magnets run in persistent mode, high redundancy of power supply elements for the warm magnets and redundant amplifiers and klystrons. By assuming a support building, where power supply and controllers, and RF power sources are located, the number of tunnel accesses is reduced significantly. On the left of Fig. 1 is the percentage of downtime per region, including the low-, medium-, and high-energy SC linac sections, the front end, site-wide power, cryoplant facility, and site wide controls. The latter four are modelled as lumped systems, whereby only the downtime and recovery hours of those regions are assigned in the simulation.

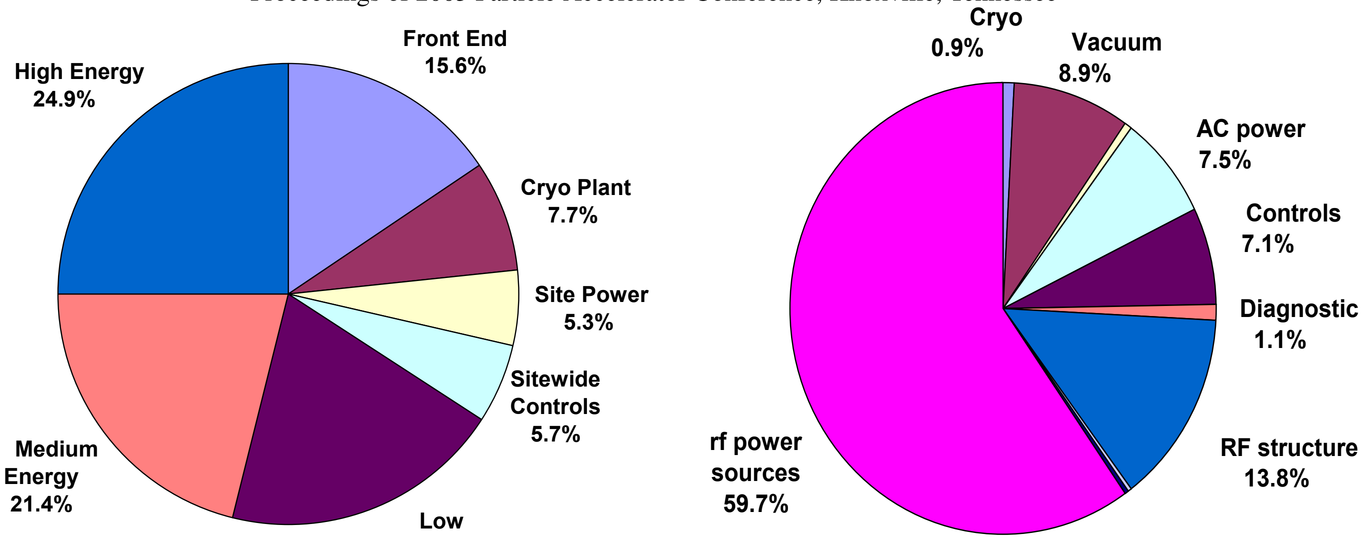

Figure 1: The distribution of downtime per region is shown on the left. Distribution due to systems contributing more than 0.4% of the SC linac downtime is shown on the right.

The right of Fig.1 displays the percent distribution per system for the sections of the SC linac, modelled in great detail. The availability for all the regions together is 94 %. The values adopted for the cryogenics plant and site power were consistent with values obtained from existing facilities. For the 20-year run presented, the monthly average tunnel access is 1.0; not including scheduled maintenance accesses. For this simulation, the required maximum number of people needed for simultaneous repairs is 8.

Detailed statistics of subsystem components show that amplifiers are responsible for the greatest number of failures, as depicted in Fig. 2.

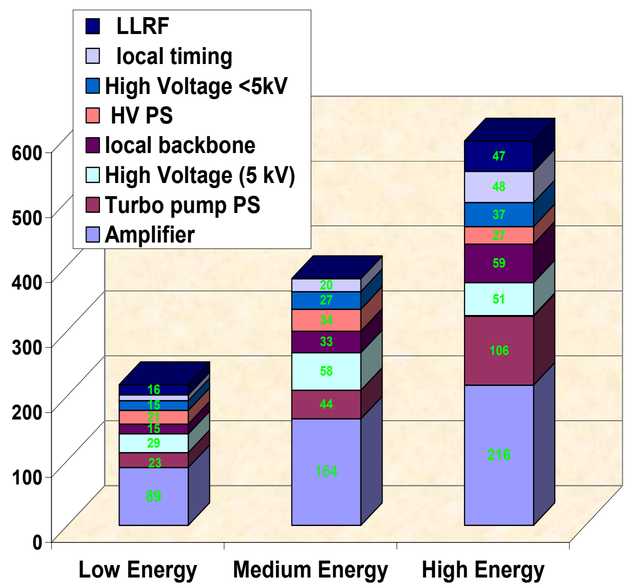

Figure 2: Failures per subsystem components causing more down 0.4% downtime, for a 20-year simulation.

SUMMARY

Availability studies were applied to the RIA SC driver linac to identify potential problems and guide the design so that the highest possible beam availability be achieved. With data collected from many laboratories, and engineering advice from many accelerator groups we established a database adapted to reflect as close as possible the complexities of the RIA machine at this design stage. The high availability obtained in the simulations comes from using the many already built-in fault mitigation factors in the design, such as large acceptance, independent resonator controls, and the possibility to run the SC magnets in persistent mode. These studies are to be used in an iterative process between designers and engineers to achieve the best design in the most cost effective manner.

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