MACHINE PROTECTION ISSUES FOR eRHIC *

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Abstract

eRHIC (electron - Relativistic Heavy Ion Collider) electron beams will be damaging both directly and as a result of synchrotron radiation. The machine protection and abort systems will be designed to prevent any equipment damage from the electron beams. In this paper we will review the requirements for the machine protection systems and the plans we have put into place to better evaluate the failure probabilities, beam abort systems designs, and overall machine protection systems designs. There are three systems associated with the machine protection and beam abort systems; the beam permit link, the abort kicker systems, and the beam dumps. We describe the requirements for these systems and present our current plans for how to meet the requirements.

INTRODUCTION

The eRHIC project will convert the existing Relativistic Heavy Ion Collider (RHIC) at BNL into an electron-ion collider. But there is even more to it than that. Since RHIC is the only polarized proton collider in the world [1], eRHIC would also become a polarized electron, polarized proton collider, as well as a polarized electron, polarized He-3 collider. The project will retain one of the existing RHIC rings, but add an electron accelerator into the existing RHIC tunnel. The electrons will be accelerated and decelerated using an energy recovery LINAC (ERL) [2]. More details on the eRHIC project and eRHIC Controls issues are reported in this conference [3].

ERHIC MACHINE PROTECTION

The eRHIC machine protection systems will be modeled on the design of the RHIC machine protection systems, although adapted to the eRHIC requirements. The main differences in the requirements come from the characteristic times of the eRHIC systems.

The machine protection systems will include a beam permit system that has inputs from loss monitors, power supplies, superconducting RF monitors, vacuum chamber heating monitors, water temperature, quench detectors, access controls systems, vacuum monitors, and longer term beam lifetime or slow loss monitors. Beam aborted from eRHIC will go into one of three beam dump systems, depending on the energy and what part of the acceleration/deceleration cycle a given beam is in. In general the eRHIC systems and the RHIC systems are independent. An interlock that dumps the electron beam does not need to cause the beam in RHIC to be aborted and a RHIC beam abort does not need to cause an electron beam abort.

There are three systems associated with the machine protection and beam abort systems; the beam permit link, the abort kicker systems, and the beam dumps. The beam permit link is the interface to the network of devices that participate in the beam permit. The kicker systems monitor the beam permit link and will abort the beam if the permit is dropped.

Machine Protection Requirements

Since eRHIC uses an ERL, the electron beam current in the ERL must remain balanced throughout the acceleration/deceleration process. So eRHIC will be brought on by slowly ramping the electron beam current until it meets the required intensities for operation. Once eRHIC is on and electrons are cycling through the systems, it remains on indefinitely. This is different from RHIC, which injects, ramps, stores, and then dumps the beams at the end of a store.

eRHIC beam losses can be classified into one of five groups [4], listed as

Ultra-fast	Losses occur in $<$ 6 turns, or 77 μsec
Fast	Losses occur in $>$ 77 μsec & $<$ 10 $m$sec
Intermediate	Losses occur in $<$ 10 sec
Slow	Losses occur in $<$ 100 sec
Steady State	Anything $>$ 100 sec

For Ultra-fast losses only passive components can protect equipment (e.g., absorbers). For eRHIC there will be collimation systems, which will mainly be intended to reduce experiment backgrounds but will also be the limiting aperture during collisions.

For Fast losses the Beam Loss monitors can be used to protect systems by triggering a beam abort when the losses exceed thresholds. Intermediate losses may not exceed Fast loss monitor thresholds but could still deposit too much heat into a cryogenic system, so the Quench protection system (QPS) will cause an abort when a superconducting magnet or RF cavity quenches.

When fault times are slow enough, preemptive systems, such as automatically reducing beam currents, are being considered, avoiding actual beam aborts all together. For Intermediate or slow beam losses, such systems can be employed.

Understanding how much damage a given amount of deposited energy can cause is strongly dependent on the energy density (Joules per unit volume) as well as the time to deposit that energy in some given material [5]. However, some fault scenarios for eRHIC have been evaluated,

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making it clear that the beams will have the potential to do significant damage.

Table 1: Beam Parameters for Different eRHIC Beams

	e-	p	$^2He^3$	$^{79}Au^{197}$	$^{92}U^{238}$	
E	10	250	167	100	100	GeV/n
n_b	180	111	111	111	111	
I_b	3.6	2.	6.0	6.0	6.0	10^{10}
E_d	62*	89	178	107	107	kJ

*Note: assumes 6 turns, each with 180 bunches.

Table 1 shows how much energy each of the different eRHIC beams will deposit when dumped. In this table E is the energy of the beams in GeV/nucleon, n_b is the number of bunches in a dump, I_b is the intensity per bunch in units of 10^{10} nucleons, and E_d is the amount of energy deposited, in kilo-joules, when these beams are dumped. The RHIC beams (p, $^2He^3$, $^{79}Au^{197}$, and $^{92}U^{238}$) are dumped at high energy at the end of a store as well as during a beam abort event. The electron beams will only be dumped at the high energies when there is a beam abort event. For normal operations the electrons are dumped at low energy. While the electron beams do not deposit as much energy as the hadron beams, they are still at levels that could be damaging to equipment. Note that the planned intensities for protons and ions for eRHIC are much lower than RHIC currently achieves.

Slow and steady state losses are not anticipated to be significant. Individual electron bunches only exist in eRHIC for 160 microseconds. Beam losses can come from the Touschek effect, in which intrabeam particles collide with large angle scattering. Intrabeam scattering from Coulomb interactions (both small and large angle scattering) will also occur in eRHIC, but this is more likely to change beam distributions and not cause beam loss. Losses can also occur from beam-gas interactions, which are predicted to be at tolerable levels. There are two types of these interactions, elastic scattering and Bremsstrahlung, in which particles scatter from nuclei.

Beam Permits

The eRHIC Beam Permit will be similar to the RHIC system, but with a single carrier link (or set of links) for all systems. In addition, certain systems will need to have faster and more sophisticated protection than the standard RHIC Beam Permit system can provide. Employing a dedicated National Instruments Compact RIO system, as used for the ERL test facility, will provide response times on the order of $8\mu sec$ [6]. The RIO chassis will communicate with each other and have their own interlock interface to the systems they are protecting. More evaluation is needed to work out the details of the interlocks and what systems need to interface to the abort kickers.

The RHIC beam permit system is conceptually very simple. A carrier signal is sent around to participating systems and if at any point the carrier is lost (a system ”drops” the permit) abort kicker modules that monitor the carrier signal send dump commands to the abort kickers. There are many systems that interface to the permit link, which is where the complexity comes in.

Systems that participate in the permit will define whether beam is or isn't allowed in RHIC. If the permit is down, beam cannot be injected into RHIC and if the permit drops while beam is in the machines, the beam will be dumped. Dropping the permit means not allowing the 10 MHz carrier to pass through to the next system, and within a well defined time interval the abort kicker modules will recognize that the carrier has been blocked.

Systems that participate in the permit include beam position and loss monitors, vacuum, power supply system status, and safety (e.g., entry gates). If any permit input or permit system connection fails, the beam permit system carrier gets dropped and the abort kicker modules send dump commands to the kicker systems. The abort kicker modules are also used when there is a controlled beam dump, at the end of a RHIC physics store.

There are actually three permit links, the main permit link that interfaces to the abort kickers and two quench links that interface from the quench detection system to the permit link and power supply emergency shutdown system. All three links use custom permit modules and each has its own 10 MHz carrier.

Dependability Analysis

A figure of merit for complex systems such as RHIC and eRHIC is high reliability. Reliability of a system is the probability that it will adequately perform its intended function for a specified period of time, and under specified environmental conditions. Reliability analysis involves the use of various techniques to calculate this probability within certain confidence limits. Reliability can be quantified in terms of SIL (Safety Integrity Level) [7], which defines the probability of failures in time. Another figure of merit is the Availability, which denotes the fraction of time for which the system performs its intended function. A system's dependability is the degree it is available given the level of reliability. It may sound like a subtle point, but a system may have poor dependability while still having high reliability. It may, for example, be poorly or inefficiently operated. This could be a function of system design and thus why it is important to look beyond failure analysis and consider efficiency in operability and maintainability.

The Machine Protection System (MPS) plays a key role in safeguarding against the anomalies developing in the collider during the run. It takes appropriate action to extract out the energy stored in various forms inside the system; for example, a beam abort or a superconducting magnet's power supply ramp down. The existing RHIC MPS will continue to serve the RHIC portion of the eRHIC facility, with possible improvements made based on dependability analysis, while a new MPS will be built for the electron systems.

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The faults occurring inside the MPS might adversely affect the uptime of the collider, and hence compromising its reliability and availability. The two major failures can be a False Failure (fail-safe condition) and a Blind Failure (ignoring a real anomaly). While the false failure imparts a downtime required to restart the collider, a blind failure is highly dangerous as it might actually damage the machine, imposing much longer downtime.

The aim of reliability analysis is to understand the importance of various components of the RHIC MPS. The RHIC MPS will be a segment of the future eRHIC MPS. More importantly, it will facilitate building a knowledge base for designing the eRHIC MPS. The basic advantages offered by this methodology will be documentation of knowledge, intelligent decision support, reasoning and explanation for the design of eRHIC MPS.

There are many parts to the MPS, from the detection of a fault from a loss monitor, quench detector, or some other piece of instrumentation, as well as the Beam Permit System (BPS), abort kicker system and dump system. Among these, the BPS is responsible to take active decisions regarding the system safety. The abort kickers and dump systems are comparatively more passive. Prioritizing its importance, we have first set our focus on the reliability analysis of the BPS. It concentrates the statuses of various collider support systems to allow beam entry and its presence.

As a first step we developed a Monte Carlo Simulation of the operation of the RHIC BPS. A modular multistate reliability model of the BPS has been developed, with a number of identical modules having exponential lifetime distributions [8]. The model utilizes the Competing Risks Theory with Crude Lifetimes, where multiple failure modes compete against each other to cause a final failure, simultaneously influencing each other [8]. The Monte Carlo iterations are done till a specific repeatability in results is achieved. The code is developed in Java and the results are analytically verifiable.

Next, we broke the module into various levels of hierarchy, and a Fault Tree Analysis (FTA) [9] helps tracing the top false/ blind failure of the module to a component level failure. This yields the exponential failure rates for the modules in the simulation. FTA is a deductive (top to down) technique to analyze an undesired top state combining a series of lower-level events. The lowest level event can be the basic component failures such as in ICs, resistors etc. The component failure rates have been calculated using MIL-HDBK-217F [10] and manufacturer's datasheets. The apportionment of failure modes of the component is calculated using FMD-97 [11].

Details on the Monte Carlo Simulation and the Fault Tree Analysis are reported in this conference [12, 13].

Fast Electron Beam Abort

A fast electron beam abort system is required to protect the ERL from damage. It is important to maintain the field in the super-conducting RF cavities during the beam abort process so that electrons do not deviate from the designed orbit, which requires the number of electrons in the decelerating phase be equal to the number of electrons in the accelerating phase throughout the abort process. Figure 1 illustrates the sequence of ERL turns encountered by the electrons for a case in which we have one ERL (one of the options investigated for eRHIC, which would take the beams up to 10 GeV). As the time of flight for the 10 GeV beam path is much longer than that of the 0.6 GeV returning path, a 10 GeV beam dump would be required for this situation. Regardless of the final design, it is clear that the eRHIC design will have some number of turns to get beam to full energy (whether it is 5 GeV, 10 GeV, 20 GeV, or higher) and will then require at least three beam dumps for the various beam dump scenarios. The main constraint driving this design is in balancing the beam current in the ERL's.

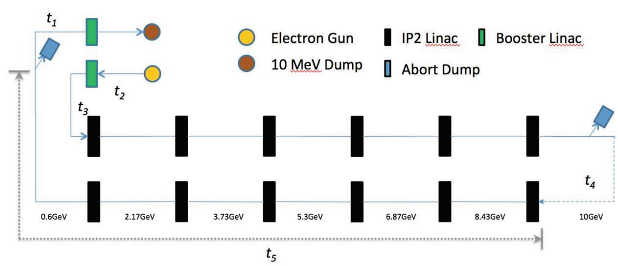

Figure 1: Beam path sequences for beam aborts. Electrons are accelerated by the Booster ERL (in green) and transported to the eRHIC rings at IP 2. After beam currents have been ramped up for operation there will be electron bunches in every part of this diagram, some being accelerated, some decelerated, some going into the 10 MeV dump, and some at the highest energy being put into collision with the hadron beams. If there is a beam abort event, beams being decelerated will be dumped into the low energy dump (blue box near Booster LINAC) and beams being accelerated will be dumped into the high-energy dump (at t_4), simultaneously.

In this scheme, it is essential to keep the timings of the following three events correct to avoid field variation in the two (or three) ERL's: shutting off the laser at the cathode of the electron gun, t_{gun}, aborting beam at the 0.6 GeV beam line, t_{d06}, and aborting beam at the 10 GeV beam line, t_{d10}. Maintaining the field of the Booster ERL requires

$$t_{gun} + t_2 = t_{d06} + t_1 \tag{1}$$

where t_1 is the time of flight from the entrance to the 0.6 GeV beam abort kicker to the entrance of the Booster ERL and t_2 is the time of flight from the electron gun to the Booster ERL entrance. To keep the field in the ERL's from changing during an abort (due to fluctuations in beam current),

$$t_{gun} + t_2 + t_3 = t_{d10} + t_4 \tag{2}$$

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where t_3 is the time of flight from the Booster ERL entrance to the IP2 ERL entrance and t_4 is the time of flight from the entrance to the high-energy abort kicker to the entrance of the IP2 ERL. If we choose the moment of shutting off the laser, t_{gun}, as a reference time to be determined by the detection of a machine failure, the times of aborting beam at the 0.6 GeV and 10 GeV beam dumps are given by the above set of equations. The time required for aborting all electrons in the ERL is about 77 μsec, i.e. the time of flight from the electron gun to the high-energy beam dump.

The location of the beam dumps has only been generally defined. We expect the high-energy beam dump will need to be located in the splitter/combiner section in the ERL straight section and located to avoid any beam-induced damage in the case of a dirty dump. For eRHIC a dirty dump can only occur if the kickers do not fire correctly and only provide a partial kick to the beams. The low energy dump will be located in a convenient place along the return transport to the Booster ERL.

Synchrotron Radiation

When an electron bunch goes through a bend, each electron emits synchrotron radiation. For radiation wavelengths longer than the bunch length, the radiation from individual electrons will add constructively, which is called Coherent Synchrotron Radiation (CSR).

Simple estimates of CSR effect for eRHIC shows that electron beams will have significant energy spread and energy loss if one does not take into account the shielding effect of beam pipe walls. When the walls of the beam vacuum chamber are conducting, induced charges will decrease the electro-magnetic fields created directly by bunches. This phenomenon is referred to as shielding and is stronger the closer the conductor is to the induced charges. Analytic theory of CSR shielding suggests that CSR can be suppressed if the beam-pipe dimension is small or the bunch length is large. For the eRHIC bunch length parameters (2-4mm rms) these analytic estimates show that CSR effects will be strongly suppressed for the present value of the vertical size of the vacuum chamber with a significant safety margin.

The electron beams will lose power in three possible ways: losses in the cavities from higher order modes, resistive wall losses, and synchrotron radiation. Contributions from wall roughness and CSR were estimated and are negligible compared to these three main sources. Figure 2 summarizes the power losses, which then defines the energy loss budget for eRHIC operations. Power losses will be limited to 10 MW total, by adjusting the beam current.

SUMMARY

The eRHIC machine protection systems are needed to protect the accelerator components from beam losses as well as from energy losses. The complexities of the systems are still not completely defined, but it is clear that many systems will be needed to monitor for faults and excessive deposited energy. We are studying the current

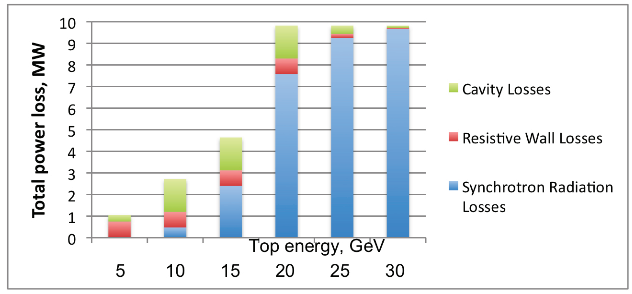

Figure 2: Energy losses from three primary sources.

RHIC machine protection systems, as well as those of similar accelerator systems around the world, in order to build a robust and dependable system for eRHIC.

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