THE RHIC AND RHIC PRE-INJECTORS CONTROLS SYSTEMS: STATUS AND PLANS*

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Abstract

For the past twelve years experiments at the Relativistic Heavy Ion Collider (RHIC) have recorded data from collisions of heavy ions and polarized protons, leading to important discoveries in nuclear physics and the spin dynamics of quarks and gluons. BNL is the site of one of the first and still operating alternating gradient synchrotrons, the AGS, which first operated in 1960. The accelerator controls systems for these instruments span multiple generations of technologies. In this report we will describe the current status of the Collider-Accelerator Department controls systems, which are used to control seven different accelerator facilities and multiple science programs (high energy nuclear physics, high energy polarized proton physics, NASA programs, isotope production, and multiple accelerator research and development projects). We will describe the status of current projects, such as the just completed Electron Beam Ion Source (EBIS), our R&D programs in superconducting RF and an Energy Recovery LINAC (ERL), innovations in feedback systems and bunched beam stochastic cooling at RHIC, and plans for future controls system developments.

INTRODUCTION

The BNL Collider Accelerator Department (C-AD) facilities are shown in Fig. 1. The Tandem Van de Graaff (TVDG) accelerators provide heavy ion beams. The 200 MeV LINAC is the source of high-intensity and polarized protons. The Booster synchrotron acts as the second stage of acceleration for beams from both the TVDG and the LINAC. In 2011 EBIS was commissioned and used to provide ion beams to the NASA Space Radiation Laboratory (NSRL) that operates on a beam line off the Booster. Starting in 2012 EBIS will replace the TVDG as the source of ions to RHIC. The AGS acts as a third stage of acceleration before beams are delivered to RHIC. RHIC consists of two accelerators, with counter-rotating beams that can be put into collisions at six intersection points. For normal operations, beams are collided at the STAR and PHENIX experiments. In 2011 a third experiment (AnDY) began tests in the 2 o'clock interaction region. The 4 o'clock region contains the acceleration and storage RF systems for both rings. The 10 o'clock region contains the abort kickers and the beam dumps. The 12 o'clock region contains the polarimeters and hydrogen jet used for polarization measurement and calibration.

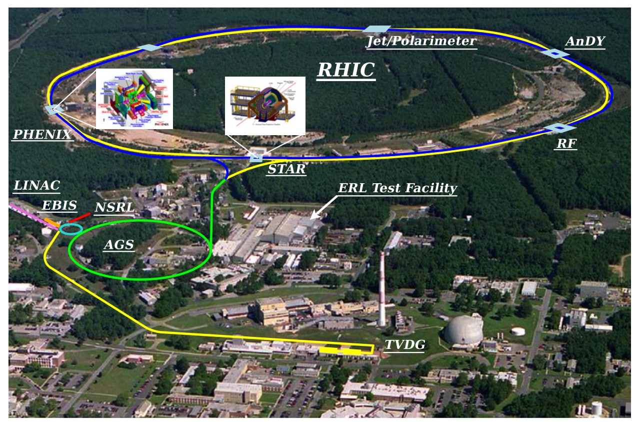

Figure 1: Accelerators at C-AD.

Since the pilot run in 1999 and through to 2011, RHIC has had 6 operating periods (runs) with Au+Au collisions [1, 2, 3]. The Au+Au runs alternated with a d+Au run in 2003 [4], a Cu+Cu run in 2005 [5], and another d+Au run in 2007/08 [6]. We also have run polarized protons, with the first run in 2001. Every year, with the exception of 2007 and 2010 we have had a polarized proton run [7, 8].

RHIC is the first accelerator capable of colliding ions as heavy as gold. As a result, the experiments at RHIC have made significant discoveries, setting the stage for developing a deeper understanding of the quark-gluon plasma (QGP) and the nature of the strong force [9]. The most significant discovery is a new state of hot, dense matter, composed of quarks and gluons, called a "perfect liquid". The properties of this matter can be described by the equations of hydrodynamics when the viscosity is nearly zero. The QGP has been seen to have unusual properties. Symmetry-altering bubbles have been observed, offering hints on the evolution of the early universe. The heaviest antimatter nucleus (an anti-helium-4 nucleus) was discovered at RHIC. RHIC is the world's only accelerator capable of colliding polarized proton beams. The RHIC polarized proton program aims to investigate the missing spin of the proton.

* Work performed under Contract Number DE-AC02-98CH10886 with the auspices of the US Department of Energy.
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In some cases, the spins of the proton's constituent quarks (and antiquarks) only accounts for 30% of its total spin. RHIC experiments are the first to study the spin of gluons and the spin substructure of the proton.

The future of RHIC involves exploring the QGP. RHICs unique capabilities allow a detailed search for the quark matter critical point (the onset of deconfinement), collisions of deuterons or protons on heavy nuclei (so called cold colliding nuclei), collisions of highly deformed nuclei (U+U collisions, so called hot matter) and the exploration of chiral symmetry and thermalization studies. Further into the future is eRHIC, which will collide high energy, high intensity electron beams with ions, polarized protons, and polarized He-3. Such a collider will allow precision imaging of the QGP, determining the spin, flavor, and spatial structure of the nucleon. It will also allow probing more deeply into the nature of the strong force, something still poorly understood, and the properties of gluons, the particles that mediate the strong force.

Controls Systems at C-AD

The C-AD Controls Systems have evolved many times since first installing computer controls in the AGS back in the early 1970's. Today our systems consist of more than 13,000 modules, chassis, fiber optic components, PLCs, and specialty items. Together they combine to provide on the order of ~1 million setting and measurement control points. The primary Controls hardware platform is the VMEbus chassis, with 315 of these online throughout the facility. Each chassis contains a powerful processor card, and on average contains an additional 10 to 20 custom and commercial VME modules, providing a wide variety of functions and utilities. Some of the types of VME modules include Function Generators, Analog I/O boards, Digital I/O boards, Scalars, Motion Controllers, and specialty Timing boards. A detailed description of the C-AD controls for RHIC is given in ref. [10], although this reference dates back about ten years. Today's system is not much different, although we have many more chassis in the field and have upgraded the performance and bandwidth of our systems. Table 1 shows some of the system parameters for our controls.

The C-AD controls are distributed systems, as shown in Fig. 2. A C++ Accelerator Device Object (ADO) runs on a VME Front-End Computer (FEC) providing access to a power supply or device interface, along with timing and other links (e.g., a real time data link provides basic machine data, such a the main dipole ramp function, directly to FEC level software [11]). Data management consists of a number of servers that together manage data archiving, data logging, process control, and all the various interfaces needed in the main control room (MCR) - alarm managers, controls scripting, system support services, etc.

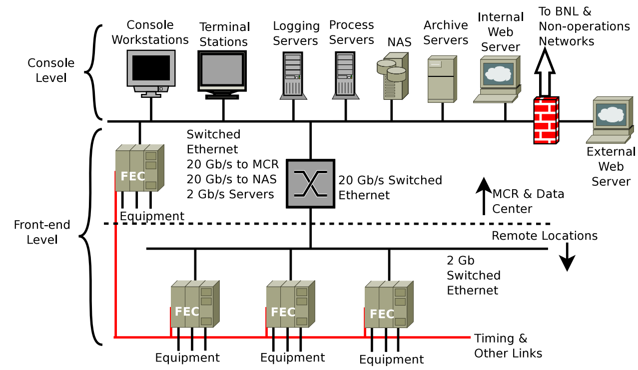

Figure 2: RHIC System Hardware Architecture, 2010.

IMPROVING RHIC LUMINOSITY

Improving the RHIC luminosity is a continuous process. Although RHIC was designed to meet a specific set of parameters, the needs of the experiments are always changing. We now operate RHIC well over an order of magnitude higher than its design. Improvements in the past include methods to make smaller beams through optics manipulations, avoiding processes that tend to increase the beam size, such as intra-beam scattering (IBS), increasing the source intensity, and reducing electron cloud buildup. We also focus on improving integrated luminosity by improving the uptime performance and reducing the time to perform various setup manipulations during the RHIC energy ramp and early part of storing the colliding beams. In the past couple of years we have seen significant increases in the luminosity through the development of bunched beam stochastic cooling. Other improvements include the development of tune, coupling, orbit, and chromaticity feedback [12, 13], correction of 10 Hz orbit oscillations using fast feedback [14], and the development of an all digital low level RF control system in RHIC [15, 16].

EBIS

EBIS consists of a set of external ion sources that inject beam into a solenoid with an ion trap. An electron beam is injected into the solenoid, stripping off electrons bound to the ions. After providing enough time to build up the desired charge states the trap is opened and the ion beam transports to an RFQ and LINAC. The advantages of EBIS include the capability to produce any kind of ion beam (including noble gases and very heavy elements). This will allow RHIC to operate with Uranium beams as well as polarized He-3 [17, 18]. To date, EBIS has reliably provided $He^{+}, He^{2+}, Ne^{5+}, Ne^{8+}, Ar^{11+}, Ti^{18+}$, and Fe^{20+} to NSRL. In 2012 EBIS will provide Uranium and possibly Gold beam to RHIC.

Feedback in RHIC

The development of reliable feedback systems has improved the efficiency of ramp development and the repro-

Table 1: C-AD Controls Systems Parameters, Characterizing the Scale and Performance of our Systems

	2011
Number of front-end VME chassis	315
Number of read/write parameters (settings)	403,000
Number of read-only parameters (measurements)	502,000
Number of name server entries (devices & servers)	52,600
Total archive capacity	75 GB/day
Number of Named Items Archived	260,000

ducibility of the accelerator conditions. The added performance improvement has allowed RHIC to operate under more extreme conditions, helping to increase luminosities and beam polarization. For example, the tighter tune control that is accomplished allows operation close to resonances that would normally destroy the beam. Full descriptions of the various feedback systems can be found in ref.'s [12, 13, 14].

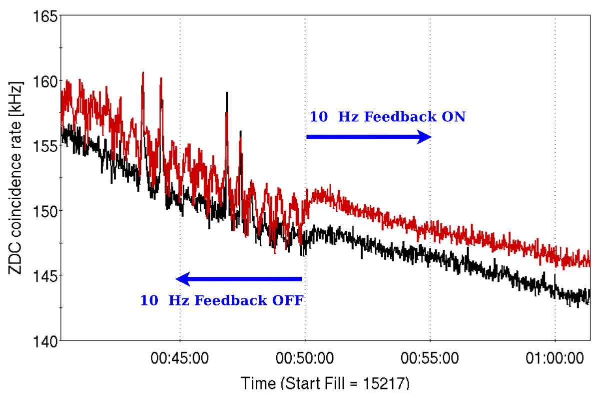

Figure 3: 10 Hz feedback improving the Luminosity at the Experiments. The ZDCs are the zero degree calorimeters used as luminosity monitors.

Stochastic Cooling

The most significant improvement to the heavy ion luminosity in RHIC has been the development of bunched beam stochastic cooling [19]. As can be seen in Fig. 4 the transverse emittance during a store can be reduced, making a smaller beam and maintaining high luminosity during the store. In the 2011 Au+Au run beam was cooled both transversely and longitudinally. This resulted in achieving average store luminosities of $30 \times 10^{26}\ cm^{-2}s^{-1}$ [20], well above the previous record of $20 \times 10^{26}\ cm^{-2}s^{-1}$ from the 2010 run, which included limited cooling, and over a factor of two beyond the $12 \times 10^{26}\ cm^{-2}s^{-1}$, achieved with no cooling in the 2007 run.

Electron Lens

The luminosity of polarized protons in RHIC is limited by head-on beam-beam effects. Beam interactions at the collision points can influence the betatron tunes and tune

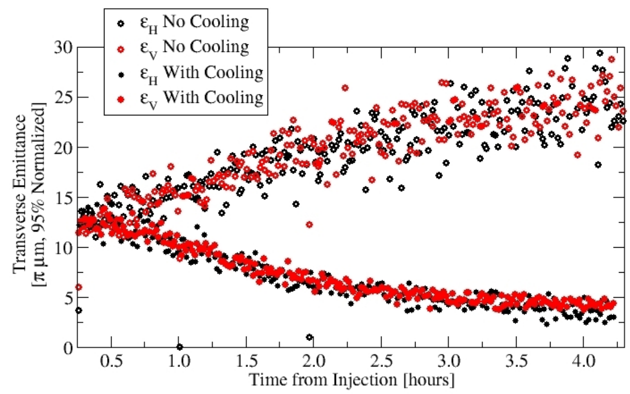

Figure 4: Horizontal and vertical emittances during two different physics stores. The open set of points show the normal increase due to IBS during a store. The solid points show decreasing emittances from transverse cooling. Measured using the RHIC IPM [21]

spreads of the beams. Beam-beam effects can be partially cancelled out by adding a third interaction between the proton beams and an electron beam. A set of electron lenses are being installed in RHIC next year and will be commissioned during the run in 2013. These systems, in combination with an upgrade of the polarized ion source, are expected to improve the polarized proton luminosity by a factor of two [22].

R&D Programs

The C-AD R&D Division was formed at BNL in order to highlight and consolidate the significant accelerator R&D efforts occurring at C-AD. The R&D Division is focused on programs to perform accelerator-based experiments at BNL and to design and construct new facilities.

The main areas of R&D are in superconducting RF systems (SRF), the development of energy recovery LINACs (ERL), the design and construction of eRHIC [23], the development of electron beam sources (high quantum efficiency photocathodes), and to develop coherent electron cooling (CEC) in RHIC [24]. The R&D Division also is closely associated with Stony Brook University's Center for Accelerator Science Education.

The R&D division gets support from the C-AD systems groups, including the Controls Systems groups. The ERL facility is currently being constructed and the controls for the facility are being developed using the standard C-AD tools and systems (VME based with ADO interfaces).

FUTURE PLANS

Physics Programs

As outlined above, the future of RHIC is the electron-ion collider, adding electron beams, ERLs, and Coherent Electron Cooling to the systems in RHIC. There are three periods of upgrades in the RHIC long term planning. On the short-term (2011-2016) there will be ongoing upgrades to RHIC Luminosity, while the RHIC experiments focus on a well-defined program addressing key open questions in Nuclear Physics, dense matter and the spin structure of the nucleon. On a medium-term (2017-2022), the experiments plan further upgrades to focus on a quantitative pursuit of long-term questions on both cold and hot matter, the strong force, and spin dynamics. On the long-term (> 2022) we enter the eRHIC era adding a 5 GeV (upgradable to 30 GeV) electron accelerator composed of Energy Recovery Linacs inside the RHIC tunnel to facilitate e+Ion, e+p (3He) studies of gluon-dominated cold matter.

Controls Systems

There are many areas in the Controls Systems where we see a need for growth and improvements. These improvements are largely driven by improvements in technologies, but also by improvements in techniques and instrumentation.

Cyber Security is always a concern. The threats are becoming much more sophisticated. New cyber threats reach deeper into the controls hardware with attacks now aimed at PLC and VME level systems. We are actively engaged in instituting measures to protect our systems from these threats.

At C-AD we have a new MCR that is all digital. There are no oscilloscopes or multiplexed signals routed into the new MCR. This puts a greater demand on the software systems. For example, we have built interfaces to remote oscilloscopes that have local signal multiplexing and allow for remote scope control.

Machine protection is a major area of focus. New accelerator systems are coming into operation and new systems are being designed. In addition, there is always a desire to improve reliability and accelerator performance. With these things in mind, we are now working on developing detailed reliability analysis and looking at ways to improve our machine protection systems. We also have new energy sources that can damage components, such as high power synchrotron radiation and high power electron beams.

Accelerator physics online models are improving significantly, which translates into greater computation demands. We also are doing more online analysis (and automatic analysis) which leads to greater data volumes and bandwidth utilization. Techniques such as orbit response matrix measurements (ORM analysis) and online optics measurements are now being done in routine operations, also increasing the computation demands. As we are starting to see today, in the future we expect more physics based controls with parametric interfaces, auto-corrections, and model based corrections. For example, in RHIC, with 10 Hz orbit feedback, we use model derived transfer functions to determine the correct BPM to corrector gains.

More of our systems have all digital controls, such as the new LLRF and new instrumentation systems for feedback. This leads to more information and diagnostics, demanding greater data volumes and bandwidth utilization.

With new feedback systems coming online, we now see new controls paradigms developing. There is an evolution occurring from tuning knobs to adjusting gains, filters, and offsets. Auto-tuning systems are more prevalent as well as automatic parameter corrections. In RHIC we now have the ability to do automatic β^* squeezing during store, while beams are being cooled, to keep the luminosity as high as possible.

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