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ION COLLIDER PRECISION MEASUREMENTS WITH DIFFERENT SPECIES *

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Abstract

Precedent to electron cooling commissioning and collisions of Gold at various energies at RHIC in 2018, the STAR experiment desired an exploration of the chiral magnetic effect in the quark gluon plasma (QGP) with an isobar run, utilizing Ruthenium and Zirconium. Colliding Zr-96 with Zr-96 and Ru-96 with Ru-96 create the same QGP but in a different magnetic field due to the different charges of the Zr (Z=40) and Ru (Z=44) ions. Since the charge difference is only 10%, the experimental program requires exacting store conditions for both ions. These systematic error concerns presented new challenges for the Collider, including frequent reconfiguration of the Collider for the different ion species, and maintaining level amounts of instantaneous and integrated luminosity between two species. Moreover, making beams of Zr-96 and Ru-96 is challenging since the natural abundances of these isotopes are low. Creating viable enriched source material for Zr-96 required assistance with processing from RIKEN, while Ru-96 was provided by a new enrichment facility under commissioning at Oak Ridge National Laboratory.

INTRODUCTION

The Fiscal Year (FY) 2017 run with heavy ion (Au+Au) and polarized proton [1] operations concluded in late June 2017. Following this, preparations for a heavy ion run in FY 2018 (Run-18) proceeded. While the PHENIX experiment continued its upgrade to the sPHENIX collaboration [2], the STAR experiment prioritized an isobar heavy ion run at high energy, also including in their proposal [3] Au+Au collisions at multiple energies. Following from previous setup and testing [4], STAR desired additional dedicated runs of one Au ion beam ('Yellow' ring) on a fixed target in their detector.

Cryogenic operations commenced cooldown to 4K for the superconducting magnet system on March 5th. Following an initial setup period, the physics program commenced March 14th, with ^{96}Ru+^{96}Ru and ^{96}Zr+^{96}Zr collisions. This was followed with Au operations until the conclusion of Run-18 physics on June 11th, followed by a dedicated period devoted to the Coherent electron Cooling Proof of Principle (CeC PoP) [5]. The commissioning time for Low Energy RHIC electron Cooling (LEReC) continued through September 16th, as one sector of the RHIC 'Blue' ring cryogenics was maintained at 4K to continue supplying liquid He to superconducting RF systems for electron beam operations [6].

ION SOURCE PREPARATION

To best pursue observations of the chiral magnetic effect (CME), ^{96}Ru^{44+} and ^{96}Zr^{40+} were a suitable choice of isobar pair ions for the RHIC. However, with a natural abundance of just 5.5% and 2.8% respectively, enriched material was required for the ion sources.

Zirconium-96 was a commercially available substance, but ZrO_2 powder is not a viable material for laser irradiation at the laser-ion (LION) source line of the electron beam ion source (EBIS). With expert assistance from colleagues at RIKEN, Japan, a sintering process was used to compress and heat the oxide powder, as shown in Fig. 1, and create a number of solid targets acceptable for use with the laser.

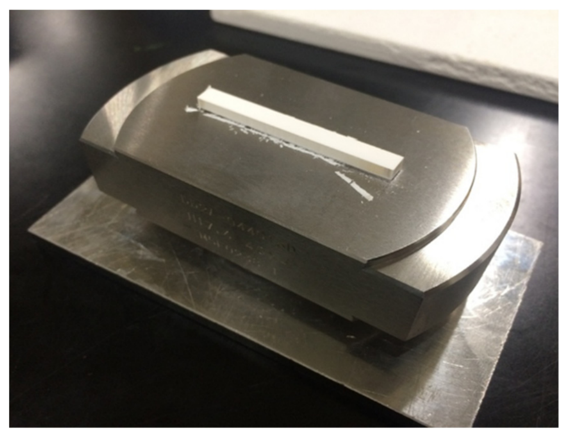

Figure 1: Zirconium oxide during sintering process to form targets at RIKEN, Japan. Image courtesy of RIKEN.

Ruthenium-96 material inventory was quite scarce worldwide. Fortunately, the Enriched Stable Isotope Pilot Plant (ESIPP) at Oak Ridge National Laboratory (ORNL) was beginning to reach the production stage of their electromagnetic isotope separator (EMIS) [7]. ^{96}Ru was made a priority for the first production isotope, as pictured in Fig. 2. ORNL delivered 500 mg of ^{96}Ru to BNL for our target production. Thorough testing of Ru beams, from the Tandem source through the injectors, showed that sufficient ion bunch intensity could still be achieved with 25% Ru-96 and 75% Al source targets, thus conserving valuable material. Ruthenium, however, could not be formed into a suitable solid target for the laser. Given prior expertise of Ru beam tests at the source and through the Booster and

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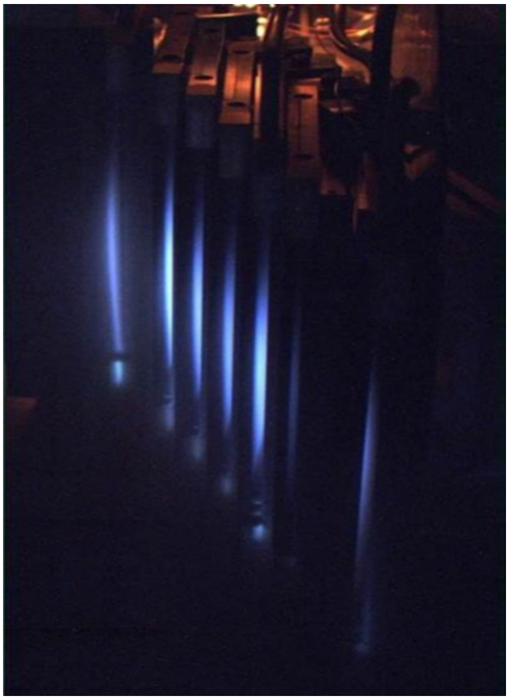

Figure 2: Electromagnetic separation of ^{96}Ru at ESIPP. Image courtesy of ORNL.

AGS, the Tandem Van de Graaf was chosen to produce Ruthenium-96 beams for RHIC [8].

MACHINE CONFIGURATION

While much of the setup and planning for the RHIC is based upon proven methods from previous runs, the unique nature of an isobar run required some additional consideration, and development of those previous methods. A few notable items are discussed below.

Setup Period

Normal operations involve multiple setup periods over the course of a Run for each change in species, energy, etc. In contrast, this run required multiple ion configurations (Zr, Ru) for the first days of physics. It was further determined that all anticipated running modes for the upcoming months of operations would be prepared and tested during the initial setup, including Au beam setups. Five different setups, as many as any other previous run, were required, as listed in Table 1. Additionally, a previously used setup was loaded first to inject Au beams, in order to test Collider systems after a long shutdown. This also avoided excessive use of enriched source materials during our initial efforts to establish adequate beam conditions.

Dedicated & Parasitic Beam Time

The CeC experiment needed development time throughout the run. At times only electron beam was required, and could operate parallel to our other daily ion operations. However, dedicated periods with electron beam acting on the ion beam in the Yellow ring were also needed. A schedule was developed to allow short Au beam operating periods at 26.5/n GeV for CeC, interleaved within the days of isobar running.

Fixed Target

In turn, the STAR experiment was able to make parasitic use of the Au beam. While running for CeC, beam in the Yellow ring was moved vertically at STAR's intersection point to place the beam halo incident on the detector's fixed target [9]. This allowed the experiment to take data at 7.15GeV/n center-of-mass energy when CeC was making use of Au at beam energy of 26.5 GeV/n. Additional days were dedicated solely to colliding low energy 3.85 GeV/n beam (2.98 GeV/n center-of-mass) on the fixed target for STAR.

SYSTEMATIC ERROR MITIGATION

The nature of the CME probe with isobars required special attention to systematic error reduction from the outset. With a charge difference of 10% between Ru and Zr ions, extra measures were taken to reduce systematic errors in the experiment's recorded data.

Mode Switching

Primarily due to their concerns with detector drift, temperature patterns, or evolving beam conditions, STAR requested (in advance of the run) regular switching between the isobar species. Thus, 3 weeks proposed for each element became one long run of the isobar pair, alternating between Ru and Zr on a regular basis. Changing RHIC components from one setup to another, however, was previously only executed as a complete shift in running mode, e.g. changing from polarized proton to heavy ion operations for the remainder of a run.

Rapid change to machine configurations, referred to as 'mode switching' at the Collider-Accelerator Department of BNL, has been an ongoing effort over the years to automate the necessary steps required to change the setup of an accelerator. This was concieved by the need to alternate work between multiple heavy ion species or polarized protons in the Booster and AGS accelerators [10]; its success led in turn to frequent changes of multiple Booster species and energies that became the engine for the Galactic Cosmic Ray (GCR) simulations at the NASA Space Radiation Laboratory (NSRL) [11,12].

With over a million parameters in the control system, rapidly saving and restoring an entire RHIC configuration is not feasible. However, expanding upon previous mode switching experience, we were able to narrow the parameter list down to the order of thousands of parameters that must be set when changing species. By identifying the specific tasks, eliminating manual hardware changes, and creating relevant files to save and restore each RHIC machine state, it became possible to rapidly execute a sequence of tasks while cycling the magnets down to injection energy. In this way a mode switch became possible with only ~5 additional minutes added to the cycle each time, which is well within normal variations of setup and beam tuning time alloted for refilling the RHIC rings.

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Table 1: Run-18 Machine Parameters for Multiple RHIC Configurations

Setup	No. of ion bunches/ring	Ions/bunch [10^9]	Beam energy	β* at IP [m]	Run length [days]	Time in store [% of allocated calendar time]	Comments
Ru+Ru	111	1.0	100 GeV/n	0.7@IP6	57	72%	Daily switch with Zr
Zr+Zr	111	1.0	100 GeV/n	0.7@IP6			Daily switch with Ru
Au+Au	111	2.0	13.5 GeV/n	3.0@IP6	24	58%	Medium energy Au
Au	12	0.6	3.85 GeV/n	6.0@IP6	4		Fixed target at STAR
Au	12	0.2	26.5 GeV/n	5.0@IP6	8		Fixed target, concurrent with CeC
				5.0@IP2			CeC PoP, interleaved with other modes
e$^-$	n/a	n/a	1.6 MeV	n/a	89	n/a	LEReC testing

Level Luminosity

Maintaining constant, optimal event data rates for the STAR experiment was preferential. Consistant beam conditions (transverse and longitudinal emittance, bunched beam intensity, etc.), for each store as well as between Ru and Zr, were also desired. This would further serve the experiment's desire to reduce systematic errors.

Previous experience has shown that stochastic cooling systems are effective in reducing beam emittances and maintaining high luminosity over the course of hours while colliding stored beam [13-16]. Additionally, slight position offsets between colliding beams have been used previously to lower collision rates to a requested level [17]. These methods were to be employed in combination to maintain beam conditions and event rates.

PERFORMANCE

Rapid Setup

Despite unscheduled interruption due to two snow events, the setup for Run-18 was complete in 6 days, when the physics program began for STAR. In a shorter time than any previous Run setup (using one species), this setup period completed Au, Zr, and Ru setup. This was also the first time RHIC had 3 different species circulating within the same 24-hour span. Mode switching was tested successfully and allowed Operations staff to change species at will in the RHIC, over 70 times through the course of the Run. Unprecedented in the history of colliders, a store-by-store switch of species became our daily routine.

100 GeV/nucleon Ru/Zr Operations

Source and accelerator setup provided sufficient beam intensity to achieve the RHIC luminosity that met or exceeded the requested collision rates of 10±5 kHz measured on the Zero Degree Calorimeters (ZDC) at STAR. Stochastic cooling systems maintained or decreased transverse and longitudinal beam emittance, and beam losses were low – a few percent per hour, quite close to the calculated "burn off" rate of annihilation by colliding beams [18].

With this level of performance, it became standard practice to fill the Collider at intensities slightly higher than required and offset the relative position of colliding beams at STAR to establish the requisite collision rate of 10 kHz. As rates declined over the course of the store, beams were periodically re-steered to maintain the 10 kHz rate.

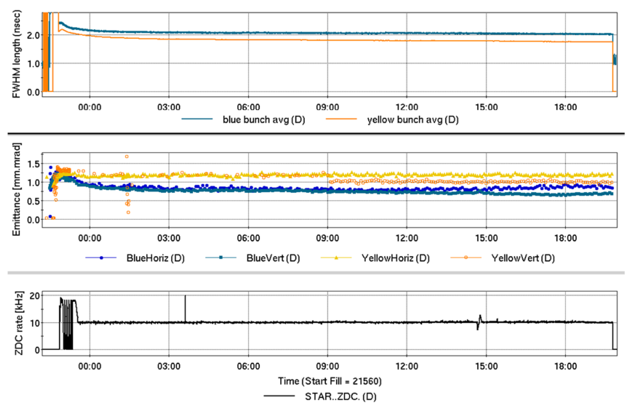

Figure 3: Bunch length, emittance, and ZDC collision rates at steady levels over 20-hour stores.

As seen in Fig. 3, the result of these methods was that Ru and Zr could be colliding for over 20 hours each at 10±*0.5* kHz rates. Level luminosity, daily species switches and nearly identical beam conditions all made great strides toward avoiding systematic errors. Consistent running in this configuration exceeded projected integrated luminosity goals for Run-18, as shown in Fig. 4.

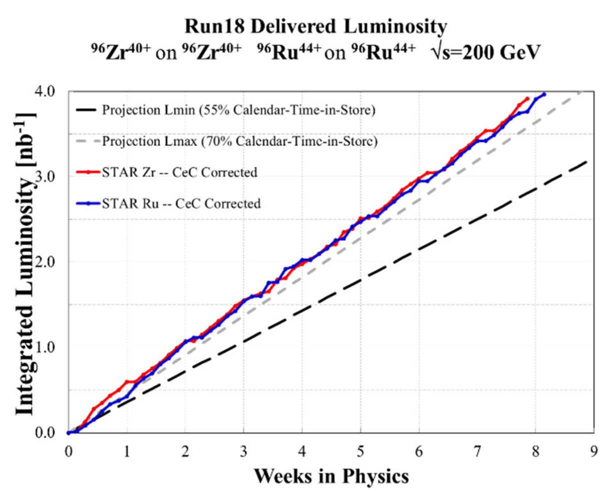

Figure 4: Delivered luminosity for the isobar portion of Run-18.

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In part the day-long RHIC machine cycles contributed to this success. Losses from beam-beam interactions were reduced, with beams only in collision at the STAR experiment. With lower intensity requirements compared to previous high energy Au runs, there was less strain on ion sources and injectors, and stochastic cooling systems were more effective on bunched beam in RHIC. Beyond the contributing factors to long and steady collision rates, failure rates (MTBF, MTTR) were at record lows amongst nearly all injector and collider subsystems. With a rigidity at store energy slightly lower than high energy Au, there was less stress on RHIC magnet systems, and magnet quenches induced by abort kicker misfires became extremely rare. Reduced secondary beams from collisions and lower off-momentum losses meant less radiation upsets in Collider control systems. Thus, availability averaged over 92% for the isobar portion of Run-18, a record compared to previous years at RHIC.

Mode switching allowed seamless changes to Au running for CeC, which made use of 53 hours of beam time throughout the isobar run.

Ultimately, conservative use of beam from the sources resulted in a surplus of source material. Zr-96 target consumption was lower than anticipated and spent target material could be reprocessed. The negative ion sputter source at Tandem was very efficient, consuming just 8% of the Ru-96, which allowed us to return most of the enriched Ruthenium back to the rare isotope inventory at ORNL.

13.5 GeV/nucleon Au Operations

Following the successful isobar portion of Run-18, we were able to transition and begin Au-Au collisions for STAR in 25 hours of setup time, as a portion of this setup was accomplished in the initial days of Run-18. This "medium" collision energy – above injection energy yet well below the typical 100 GeV/n stores – presented a different set of operational concerns. Store length was reduced to 1.5 hours, and stochastic cooling systems could not operate at this energy to mitigate emittance growth and lifetime issues. As luminosity was reduced at this medium energy, maximum experimental data rates were not a limiting factor, thus maximum Au beam intensities were favoured. This portion of the Run did present an opportunity to explore fractional tune working points near the integer, (Qx,Qy) = (0.10,0.08). While showing improved loss rates while colliding at store, losses during the short energy ramp were excessive and orbit control was limited by the resolution of the power supply interface [19]; the typical tunes (Qx,Qy) = (0.23,0.22) were restored for the remainder of the run. As in the isobar run, efficient mode switching afforded us the ability to allow dedicated shifts for CeC tests with Au beam in the Yellow ring, accumulating an additional 133 hours. In this mode STAR could also make use of its fixed target program, and sampled data while CeC was running. Performance for this part of Run-18 again exceeded projected goals, as seen in Fig. 5.

Other Operations

Amid the 13.5 GeV/n Au run, another mode switch was employed to run for STAR's fixed target at low energy, 3.85 GeV/n. This was accomplished in under 5 days. At low energies, moving beam position at the experiment cannot be made in increments by orbit correction dipoles; the resolution of 12-bit power supply controls were too coarse. One key innovation was the ability to accurately control the population of the beam halo, and thus collision rate with the fixed target, by exciting bunched beam with the base-band tune meter (BBQ) kickers [20]. In this way a fairly constant event trigger rate could be maintained over the course of a short (30-45 minute) store, as shown in Fig. 6. Ultimately, this afforded STAR over 3 times their original event goal.

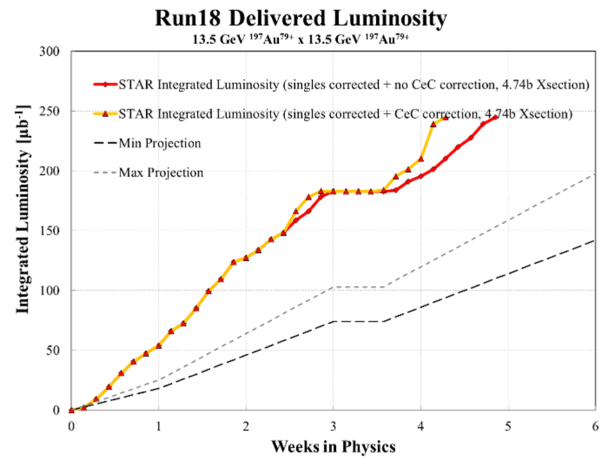

Figure 5: Delivered luminosity for 13.5 GeV Au+Au. The 3rd week ran a single beam on fixed target for STAR.

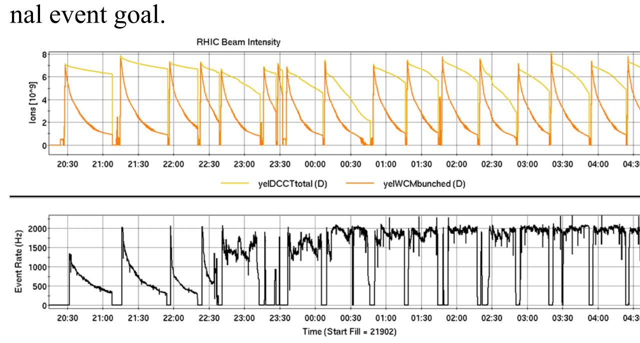

Figure 6: STAR event rate, at bottom, overcomes the bunched beam decay, top, with excitation of beam into the halo and incident on fixed target.

Further periods of machine development and accelerator physics experiments were undertaken to improve conditions during this Run and to plan for future runs and projects. This included tests of new hysteresis cycles to mitigate persistent current effects [21], hollow electron lens beams as collimators [22], ion beam circumference lengthening [23], and injection kicker effects on emittance growth [24].

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As previously mentioned, CeC made use of both electron-only and electron-ion beam time with results that will be used to plan further efforts towards coherent electron cooling [25].

To prepare for electron cooling of low energy ion beams in upcoming runs, cryogenic systems were maintained in one sector of the RHIC Blue ring, to keep LEReC superconducting RF systems in operation past the end of the physics run for STAR. LEReC continued for nearly 3 months to reach commissioning milestones, on or ahead of schedule.

CONCLUSION

The RHIC Run in FY 2018 was a great success. By making best use of past experiences and accumulated knowledge, it was possible to operate the Collider in an efficient and flexible manner and switch the RHIC operating mode daily, thus accomplishing many goals at or ahead of schedule. Along with special attention and planning for consistent beam conditions, this helped reduce systematic errors in recorded data between two isobar elements. Collaboration with experts worldwide helped innovate production of Ruthenium-96 and Zirconium-96 source material that ultimately exceeded collision rates desired by experimenters. In addition to this result, other Gold setups helped realize goals for the STAR experiment and future Collider-Accelerator Department systems were also tested and developed.

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