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OPERATION OF RHIC INJECTORS WITH ISOBARIC RUTHENIUM AND ZIRCONIUM IONS *

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Abstract

The FY18 RHIC physics program calls for Ru-Ru and Zr-Zr collisions at 100GeV using isobaric Ruthenium and Zirconium ions, each having 96 nucleons. In the injector chain, these two ions must come from Tandem and EBIS source, respectively. To reduce systematic errors in the detector, the luminosity for the two species is matched as closely as possible, and the species are switched frequently. Several bunch merges are needed in the Booster and AGS to reach the desired bunch intensity for RHIC. The setup and performance of injector chain with these ions are reviewed.

INTRODUCTION

It was found in previous RHIC runs that negatively and positively charged particles flow out of gold collisions differently. The theoretical hypothesis is that this is due to the effect of the magnetic field generated by the collision on the individual scattered particles. To test the hypothesis, isobaric nuclei, i.e. nuclei that have the same mass number but different numbers of protons, are needed. The chosen isotopes are Ruthenium-96 and Zirconium-96 both of which have 96 nucleons but have 44 and 40 protons, respectively.

To acquire reliable test results, a large number of Ru-Ru and Zr-Zr collisions have to be collected. To reduce the systematic errors, the collision species are switched on a day-by-day basis so that long term variation of factors such as temperature and detector condition do not affect the results. This requires to maintain the same running conditions for both species in the injectors, and a relatively quick switch between the two species.

The natural abundances of the desired isotopes are relatively low: just 5.54% for ${}^{96}_{44}$Ru and 2.80% for ${}^{96}_{40}$Zr. The enriched ${}^{96}_{40}$Zr is commercially available but the enriched ${}^{96}_{44}$Ru is not. It took several months effort of the Enriched Stable Isotope Prototype Plant (ESIPP) located at Oak Ridge National Laboratory (ORNL) to obtain 500 mg of ${}^{96}_{44}$Ru. This was done by heating and ionizing the natural material and electromagnetically separating the desired isotope.

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ZIRCONIUM PRODUCTION

To provide ^{96}Zr beam, the electron beam ion source (EBIS) [1] pre-injector is used. The EBIS pre-injector comprises laser ion source(LION) [2], two hollow cathode ion sources (HCIS), the EBIS charge breeder, a 300 keV/u RFQ and a 2 MeV/u IH DTL. The EBIS can switch between various highly charged ion species in ∼1s by selecting a particular external ion source system as an injector. In general, singly charged ions produced either by LION or HCIS are injected in ∼100μs or ∼10ms pulses, respectively into the EBIS. The EBIS captures and confines the ions in a high current density (∼300-600 A/cm^2) multi-ampere electron beam for a few to several hundred milliseconds. When the desired charge state is achieved, the ions are extracted from the EBIS in an intense pulse ∼10-40 μs with the proper energy for acceleration by the RFQ and LINAC. In order to meet the intensity goals for ^{96}Zr ion production, commercially available zirconium oxide powder was obtained, enriched to >50% ^{96}Zr, and fast injection from LION was used. The use of enriched Zr increased the ^{96}Zr/(^{96}Zr+^{90}Zr) ratio from 5% to 80%, allowing the use of ${}^{96}Zr^{16+}$ as the selected highly charged ion species with greatly reduced contamination from ${}^{90}Zr^{15+}$. The ability of LION to deliver sufficient amount of ${}^{96}Zr^{+}$ to EBIS in a 100μs pulse enabled EBIS to operate with a moderate 6A electron beam, and a 20ms confinement time for ${}^{96}Zr^{16+}$ production. During the period of Zr operation the EBIS continued to deliver beams such as He^{2+}, Kr^{18+}, Fe^{20+}, Ta^{38+}, and Au^{32+} to the NASA Space Radiation Laboratory and other RHIC users, often with 8 pulses of ${}^{96}Zr^{16+}$ at 5Hz and another highly charged ion species being delivered within the same ~6s machine supercycle.

The initial ionization in LION by laser irradiation requires the seed target material to be a solid plate. The practicability of ZrO_2 powder as a laser target was tested using natural abundance material, but the compressed powder target failed after only a few laser shots due to local shrinkage under laser irradiation. To avoid the local shrinkage and to increase robustness of the target, compressed zirconium oxide was sintered. Using a rectangular shape die, 4 mm by 50 mm, the oxide powder was pressed at 3 to 4 tons and 1.5 g of the oxide powder was molded to about 2.5 mm of thickness. The compressed rectangular was sintered at about 1700 K. The

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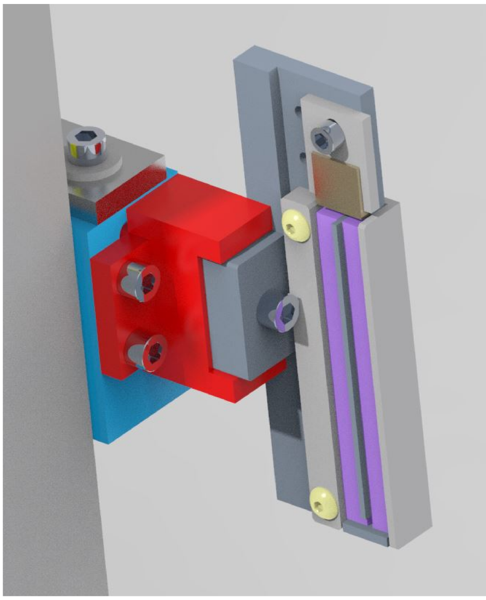

Figure 1: Laser targets and holders. The two mounted vertical purple strips show ^{96}Zr enriched sintered ZrO_2 laser targets. The small square piece above the Zr targets is gold which is used to provide Au beam to the RHIC.

dimensions were reduced by 12%. The sintering process was developed in RIKEN Japan.

The laser irradiation was optimized to minimize the consumption rate, of the enriched ZrO_2 target. The laser spot size was adjusted to be around 3 mm in diameter and the laser power density was chosen to be just above the ablation threshold. The laser energy used in the operation is from 130 mJ to 200 mJ. The beam current is regulated by adjusting the laser energy and the solenoid magnet which controls the diverging angle of the expanding laser plasma. The consumption rate achieved was measured and found to be around 1.1 μg per laser shot. Six rectangular enriched $^{96}ZrO_2$ targets were prepared to meet the needs of the entire RHIC run. The mounted rectangular targets are shown in Fig. 1. The $\sim$100μs beam of singly charged ions produced by the laser ion source and injected into EBIS includes all isotopes of zirconium and oxygen, as the transport line is primarily electrostatic. Due to time-of-flight effects, by adjusting the EBIS 1+ ion capture timing, the Zr output beam current was maximized and the oxygen contamination was reduced. The confinement time in the EBIS and RF amplitudes of the LINACs were adjusted to provide $^{96}Zr^{16+}$. The total charge from the EBIS pre-injector recorded after a bending magnet is typically 2.5 nC. Although, $^{96}Zr^{16+}$ and $^{90}Zr^{15+}$ cannot be separated at this point in the transport, since both ions have same charge to mass ratio, the purity of $^{96}Zr^{16+}$ in the beam from EBIS is estimated to be >75%.

RUTHENIUM PRODUCTION

The enriched ^{96}Ru was specially prepared for BNL by electromagnetic separation at the ESIPP at ORNL as shown in Fig. 2. Since only 500 mg was available, there was no

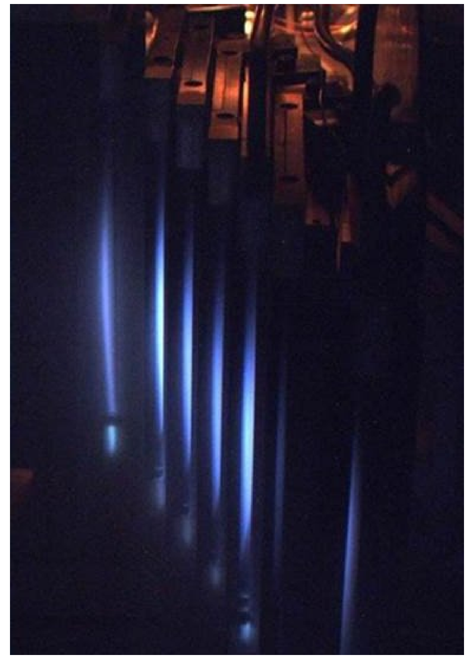

Figure 2: Ruthenium isotope separation at ORNL. Here the blue glow is due to photoemission as the ion beam interacts with background gas in the vacuum chamber. The glow furthest to the right is due to ^{96}Ru ions. With permission and courtesy of ESIPP at ORNL.

choice but to use one of the BNL Tandems (MP7) to take advantage of the large efficiency of the negative sputter ion source [3] operated in the pulsed mode [4]. A mixture of 50mg ^{96}Ru powder and 43mg ^{27}Al powder was pressed(1000 psi) into the cathode holder as shown in Fig. 3 (adapted from Fig. 1 in Ref. [4]). Steps were taken to minimize the loss of enriched material during the pressing process. The atomic concentration of the mixture is 25% ^{96}Ru and 75% ^{27}Al. Extensive ion-source intensity measurement with different mixtures of Al and not-enriched Ru powder showed that the intensity from 25% Ru targets is about the same as from 100% Ru targets. Therefore the percentage used is close to optimal to conserve enriched isotope without sacrificing intensity. Another advantage of the mixtures with aluminum powder is that the aluminum, being malleable, acts as a binder when compressed, thus forming a compact volume with a smooth surface. The actual ion production efficiency achieved will be determined at the end of the run. Currently, it is estimated that 350 mg will remain unused.

BOOSTER AND AGS OPERATION

Figure 4 shows the injector chain that provides ions for RHIC. Ruthenium ions ($^{96}Ru^{12+}$) from Tandem with a kinetic energy of 1.86 MeV per nucleon are injected into Booster over several tens of turns according to the multi-turn scheme described in [5]. The beam is then captured into harmonic 4 buckets and accelerated to a merging porch where the 4 bunches are merged into one as described in [6]. This single bunch is accelerated to a kinetic energy of 65.2

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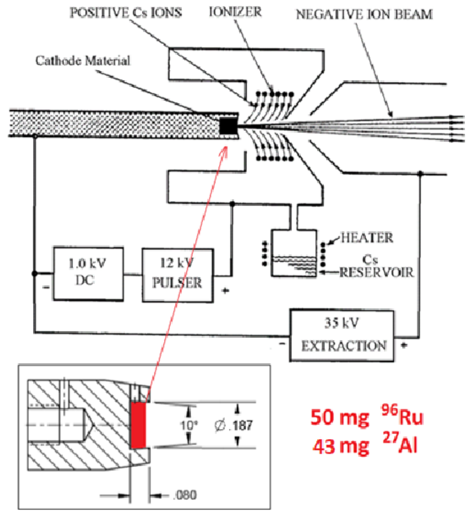

Figure 3: Schematic of the pulsed negative ion cesium sputter source system used for the ^{96}Ru injection from the MP7 BNL Tandem.

MeV per nucleon and then extracted into the Booster-to-AGS (BTA) transfer line where the ions are fully stripped to ^{96}Ru^{44+}. Eight single-bunch transfers to AGS are made per AGS cycle, with each bunch injected into a waiting harmonic 16 bucket on the AGS injection porch. The 8 bunches are then accelerated to a merging porch where the revolution frequency is high enough (some 196 KHz) to do the desired merges. The kinetic energy here is 164 MeV per nucleon. The bunches undergo a merge from 8 to 4 bunches followed by a merge of the 4 into 2 bunches. This puts 4 Booster loads into each bunch. Each of the 2 bunches is then sitting in a harmonic 4 bucket. These must be squeezed into harmonic 12 buckets for subsequent acceleration. The merging and squeezing processes are described in [6]. The two bunches are then accelerated to a kinetic energy of 10.254 GeV per nucleon and extracted into the AGS-to-RHIC (ATR) transfer line. The highest intensity achieved was 2.8e9 ^{96}Ru ions per bunch at AGS extraction. This in fact had to be reduced as only 1.0e9 ions per bunch were needed in RHIC. The measured single-bunch longitudinal emittance is 0.53 eV-s per nucleon. The normalized horizontal and vertical rms emittances are both 1.0 μm.

Similarly, Zirconium ions from EBIS are accelerated in a 300 keV RFQ and a 2 MeV per nucleon Linac and arrive at Booster with a kinetic energy of 1.97 MeV per nucleon. Both ^{96}Zr^{16+} and the contaminant ^{90}Zr^{15+} are present because they has very nearly the same charge-to-mass ratio. The pulse from EBIS amounts to approximately two turns around Booster. The beam is again captured into harmonic 4 buckets and accelerated to a merging porch where the 4 bunches are merged into one. This single bunch is accelerated to a kinetic energy of 113 MeV per nucleon and then extracted into the BTA transfer line where the ions are fully stripped to ^{96}Zr^{40+} and ^{90}Zr^{40+}. A bending magnetic downstream of

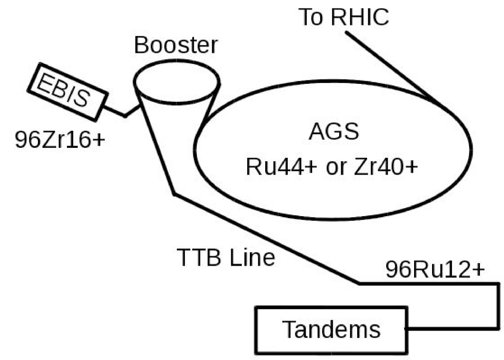

Figure 4: The injector chain of ion beams for RHIC.

the stripper then selects the ^{96}Zr^{40+} ions for injection into AGS. As before, eight single-bunch transfers to AGS are made per AGS cycle and one ends up with two bunches at AGS extraction with a kinetic energy of 9.244 GeV per nucleon. The highest intensity achieved was 2.5e9 ^{96}Zr ions per bunch at AGS extraction. This also had to be reduced as only 1.0e9 ions per bunch were needed in RHIC. The measured single-bunch longitudinal emittance is 0.56 eV-s per nucleon. The normalized horizontal and vertical rms emittances are both 1.0 μm.

For a brief period early in the run we used a setup in which there are 12 single-bunch transfers of Zr ions from Booster to AGS per AGS cycle. In this case the bunches must undergo RF quad pumping just before extraction from Booster so that they can fit into waiting harmonic 24 buckets on the AGS injection porch. On the injection porch the 12 bunches are merged into 6 and these are then accelerated to a merging porch where they are merged into 2 bunches. This puts 6 Booster loads into each bunch. This scheme was commissioned with Gold ions during the 2016 RHIC run and is documented in [7] and [8]. Although the scheme provides 50% more Zr ions per bunch, the increase was found to be unnecessary. The 8-4-2 merging scheme consumes less ^{96}ZrO$_2$ target material and reduces EBIS electron beam power requirements, so was therefore adopted for the rest of the run.

SUMMARY

The FY18 RHIC physics program required the RHIC injector chain to provide Ru and Zr ion beams and switch between them daily. To make it possible to accomplish the run with only 500mg of ^{96}Ru, the Tandem was used for this isotope and EBIS was used to deliver ^{96}Zr. To reduce systematic errors in the RHIC detectors, the beam conditions of the two beams were kept as close as possible on a daily basis. Special enriched source materials were provided and used to meet the desired intensity requirement. As RHIC store time is about 20 hours long, the daily switch of the species in the injector chains is not an issue.

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