Operation experience of LION and RHIC-EBIS for RHIC and NSRL

T. Kanesue, E. Beebe, B. Coe, S. Ikeda, S. Kondrashev, A. Lopez-Reyes, M. Okamura, R. Schoepfer, T. Rodowicz

Collider-Accelerator Department, Brookhaven National Laboratory, New York 11973, USA

Email: tkanesue@bnl.gov

Abstract. LION is a laser ablation ion source to provide singly charged heavy ions of various species for RHIC-EBIS. High charge state heavy ion beams from RHIC-EBIS are used for RHIC physics experiments and NASA Space Radiation Laboratory (NSRL) quasi-simultaneously. The demands for heavy ion beams are growing and more ion species are available and more NSRL beam time is used because of unique capability and flexibility of the sources. With the combination of LION and RHIC-EBIS, ion species can be switched on a pulse-by-pulse basis without the effect of previously used species. The present performance and operation experiences of LION and RHIC-EBIS are shown.

1. Introduction

LION and RHIC-EBIS are a part of the RHIC-EBIS pre-injector [1], which has been providing various heavy ion species for collider experiments at Relativistic Heavy Ion Collider (RHIC) and space radiation research at NASA Space Radiation Laboratory (NSRL) simultaneously in sequence since 2010. RHIC is one of two heavy ion collider accelerators, and the only polarized proton collider in the world. NSRL is an accelerator-based research laboratory for space radiation research to study the effect of Galactic Cosmic Ray (GCR) using mixed radiation of heavy ions and protons extracted from the AGS-Booster [2]. The available beam energy is up to 1.5 GeV/u for Fe and 2.5 GeV for proton. For the GCR simulator, ion species for NSRL is required to be switched rapidly while beams for RHIC is supplied.

A layout of the RHIC-EBIS pre-injector to supply 2 MeV/u of heavy ion beams (charge-to-mass ratio 1/2 ~ 1/6) is shown in Fig. 1. An electron beam ion source (RHIC-EBIS) is used as a charge bleeder and all primary ions are provided from the external ion sources to avoid "memory effect" of

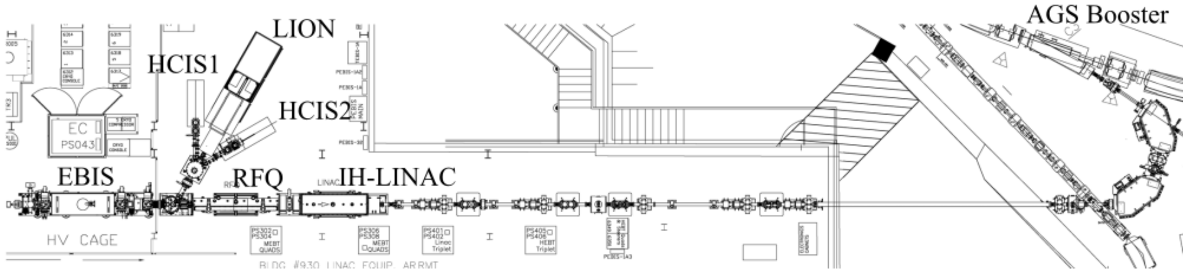

Figure 1. A layout of the RHIC-EBIS pre-injector.

previous species. A laser ion source, named LION, provides 1+ ions from any solid-state targets. Two hollow cathode ion sources (HCIS) produce 1+ ions from gaseous targets.

2. LION

LION is a key device to realize rapid species change. This is a laser ablation ion source and ions are generated by laser irradiation onto a solid target. At LION, low laser power density just above the threshold for plasma generation ($10^8 \sim 10^9$ W/cm^2) is used for 1+ ion production while a laser ion source in general is famous as an intense heavy ion source of highly charged ions using high laser power density above 10^{12} W/cm^2. At LION, the laser energy on a target is 200 mJ to 500 mJ with defocused laser spot of about 3 mm in diameter. Importantly, LION does not require warm-up, and full beam performance can be achieved from the first pulse though other ion sources typically needs 15 min or more to be stabilized. In addition, LION does not use working-gas, and vacuum pressure is kept below 10^{-4} Pa, which is very important to combine with EBIS. An ion beam out of LION produced by one laser shot is more than enough to provide ion yield required by users.

There are two target systems a target chamber. Each target system is driven by a dedicated laser so that beams for RHIC and NSRL are supplied independently. A rotating Au target is used for RHIC. A XY target supplies multiple ion species for NSRL. The XY target has a 254-mm-by-50-mm target holder driven by a two-dimensional linear stage. The number of species on the holder has been increased over the years, and recently 10~12 species are installed at a time. Typical target dimension is 25 mm by 50 mm or 25 mm by 25 mm except for Si (50 mm in diameter). Usually, NSRL run starts earlier than RHIC run from the end of September. If heavy ions are needed for RHIC, we provide beams later typically around January in the following year. Both NSRL and RHIC operations finish almost same time in July. The installed targets will last for the entire run. It takes 3~6 hours including pumping when new targets are needed.

Beam intensity out of LION is controlled by a 3m-long solenoid on expanding laser ablation plasma as keeping the laser poser density for 1+ ion production [3]. Laser is always shooting on the same spot and target position is changed to switch ion species. The switching time between species depends on the XY target motion and currently it takes 1~25 sec at LION. The beam current of lighter ions such as C and Si is hundreds μA to 1 mA with pulse length of 100 μs while that of heavier ions such as Au and Ta is about 100 μA with pulse length of 300 μs. These ions are injected into EBIS with fast injection scheme [4].

A laser ion source can produce plasma from any solid-state materials. Target purity and abundance of isotopes directly affects species and isotopes in laser produced plasma. A pure solid element with an isotope of 100 % natural abundance such as Au is an ideal target. In addition to pure materials, compound targets and alloys can be used as long as solid flat surface is available. With these targets, ions of all species and isotopes in a target are generated. Since a beam transport line between LION and EBIS uses all electrostatic components, all ions are injected into EBIS. Intended ion species is selected in rf linear accelerators, booster, and a beam line to NSRL target room after a stripper foil. We use alumina (Al_2O_3) targets for O beam [5]. Sintered enriched was ZrO_2 (42 x 3 x 2 mm^3) were used to provide ^{96}Zr beam (natural abundance of ^{96}Zr is low at 2.8 %) for isobar heavy ion collider experiment during RHIC Run-18 [6]. The isobar experiment was successfully completed with the enriched ZrO_2 targets [7]. Commercially available thoriated tungsten targets were used to provide Th and W. Recently in Run-21, we tested ZrO_2 targets for O beam at RHIC-EBIS because it has higher ratio of O compared to alumina. However, degradation of O beam intensity was quick within a week. This was different from Zr beam from the same targets, which lasted enough for RHIC operation. Eventually we used an alumina target to provide O beam for RHIC experiment. It is important to test and analyze the contents of plasma and target properties at test bench.

3. HCIS

Two hollow cathode ion sources (HCIS) are used to produce primary ions from gaseous species such as He, Ne, Kr, Ar, and Xe. Note that HCIS can also produce ions from solid materials though recently all ions from solid targets are provided from LION due to easy handling of the ion source. Each HCIS can provide one gaseous species. It takes about 20 min to replace gas when more gaseous species is needed. Typical ion beam current from HCIS is 5~50 μA and long beam pulse of 10~40 ms. This low current beam is accumulated by an EBIS ion trap using slow injection scheme.

4. RHIC-EBIS

The RHIC-EBIS is a state-of-the-art electron beam ion source. This EBIS has a 188-cm-long ion trap and utilized 7~10 A of electron beam with a 5 T superconducting solenoid. RHIC-EBIS can switch species at faster than 5 Hz (200 ms), which is the basic control cycle. Depending on the status of RHIC and NSRL, the number of pulses and ion species for NSRL change frequently. RHIC-EBIS is required to provide stable beams throughout the complicated operation mode.

RHIC is a collider accelerator. Once beams are injected in two rings, the circulating beams in opposite direction are used to take physics data at collision points until the beam quality became unusable to take data. The storage time can vary from more than 10 hours for nominal 100 GeV/n Au beam to less than 30 min for low energy experiments as low as 3.85 GeV/n. RHIC-EBIS provides typically 12 pulses separated at 5 Hz within a supercycle of about 6 seconds during RHIC injection and tuning for the injection typically 30 min before the injection starts. The supercycle is a repetitive cycle to accelerate ions to inject beam into RHIC. EBIS provides beams at earlier part of the supercycle, and the 12 pulses of EBIS beams become 2 bunches in RHIC. When RHIC-EBIS is not used for RHIC injection nor beam tuning, the number of EBIS pulses is reduced as standby mode to reduce load to ion sources and save lifetime of a cathode and a LION target. We keep at least 1 pulse to keep the system up and to realize any device failures. For short store such as 30 min, the number of the standby cycles is increased to 6 pulses to reduce thermal stress due to frequent change of the number of pulses. The short storage time was frequently used during Beam Energy Scan II (BES-II) started from Run-19 and successfully completed in Run-21 to investigate the first-order phase transition and determine the location of a possible critical point in a Quantum Chromodynamics (QCD) phase diagram with variable collision energy [8,9].

Beam operation for NSRL involves frequent change of species to simulate the effect of GCR. Before beams of multiple species are used for NSRL users, a set of parameters of all related devices is "archived" for each combination of species and charge state by EBIS experts and Main Control Room (MCR). To change species, the archived setting is restored, and ion species from external sources is switched by a sequencer without assistant from experts. When GCR simulator mode is used, a dosimetry system at NSRL automatically cut off beam in ~1 ms to control on sample, and initiate species change. The demand of NSRL beam has been increasing due to its unique capability. RHIC-EBIS initially provided beams for NSRL 5 days per week during day time. Recently we provide more time per day and 6 days per week routinely. The GCR simulator mode is routinely used, which increases the number of species change per day. More species have been added for LION to cover LET range without HCIS to make the source operation easier. The operation of the RHIC-EBIS pre-injector is getting more difficult compared to earlier time of the pre-injector.

Figure 2 shows time structure of the EBIS electron beam within a 6 sec supercycle when RHIC is at injection with NSRL running. We have a combiniation of beams for RHIC (full intensity or standby), and different species/charge state for NSRL. A duty cycle of the EBIS electron beam changes depending on the total number of pulses in a superccyle and confinement time of NSRL species. Cathode heater power needs to be high enough to keep electron beam current of 12 consecutive pulses for RHIC. However, increased heater increases the risk of cathode heater break, reduce cathode heater lifetime, and increase outgassing which can cause breakdown. We try to minimize cathode heater power without sacrificing beam intensity for reliable operation. In addition, electron beam current is affeccted by the duty cycle. The electron beam current decreases when the number of pulses for RHIC is increased or the confinement time for NSRL beam is extended because electron beam emission provides some cooling. This could change the electron beam trajectory, which can cause breakdown. Table 1 shows EBIS confinement time for different species to indicate the change of duty cycle. It takes about 10 seconds or less to respond to the duty cycle change. For reliable operation, we introduced software to automatically adjust cathode heater power depending on the total number of pulses in a supercycle and confinement time for NSRL beam to reduce the variation of the electron beam current.

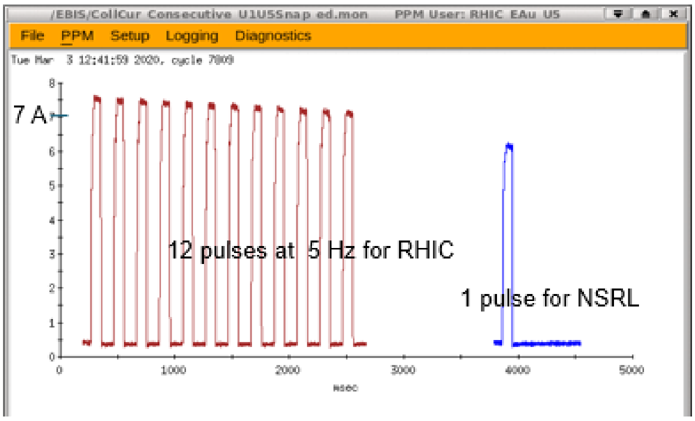

Figure 2. EBIS electron beam when EBIS is pulsing for RHIC injection and NSRL. Here, 5 sec out of 6 sec super cycle is shown.

Table 1. EBIS confinement time for different species

Species	Mass	Charge state	Q/M	Confinement time (ms)	**Species**	Mass	Charge state	Q/M	Confinement Time (ms)
He	4	2	0.5	17	**Fe**	56	24	0.429	822
C	12	5	0.417	51	**Nb**	93	19	0.204	70
O	16	7	0.438	81	**Ag**	107	29	0.271	386
Si	28	11	0.393	118	**Au**	197	32	0.162	70
Ti	48	18	0.375	242	**Au**	197	43	0.218	307
Fe	56	20	0.375	242	**Bi**	209	35	0.167	130

Figure 3 shows an example of dayly beam usage. As providing beams for RHIC, species change between He, O, Si, Fe from EBIS and proton beam from the 200 MeV Linac occurred more than 130 times as a GCR simulator mode. Stable heavy ion beams were delivered throughout the day. The species switching time at EBIS was about 40 sec. This is not limitting factor because it takes about 1 min to adjust Booster and a beam line to NSRL. Because the pre-injector is very reliable, the RHIC-EBIS pre-injector is unattended by experts for routine operation, and NSRL can change ion species at any time without notifying ion source experts.

5. Conclusion and Future plan

The operation of the RHIC-EBIS pre-injector including LION and RHIC-EBIS is getting more complicated with frequent RHIC injection as short as 30 min and more NSRL beam time and species. To increase the reliability, an active cathode heater control was introduced to compensate the effect of duty factor on electron beam current. The RHIC-EBIS pre-injector has been reliably providing various heavy ion beams under such operation mode. The pre-injector is unattended by EBIS experts for routine operation once a set of parameters for each species are “archived” by the experts. MCR can ramp up the number of EBIS pulses for RHIC injection and ramp down to the standby mode safely by a sequencer software. NSRL can change species without any assistance from EBIS experts and MCR.

Next year from 2022 summer to the end of the year, the existing RHIC-EBIS will be replaced with the Extended-EBIS to increase beam intensity and to provide intense polarized $^3He^{2+}$ ions for the future electron-ion collider (EIC) [10,11]. The Extended-EBIS will provide Au beam to Run-25, which is the last year of RHIC operation, and transition to EIC will be started. NSRL operation will continue during the transition. EIC operation is expected to start from FY2031.

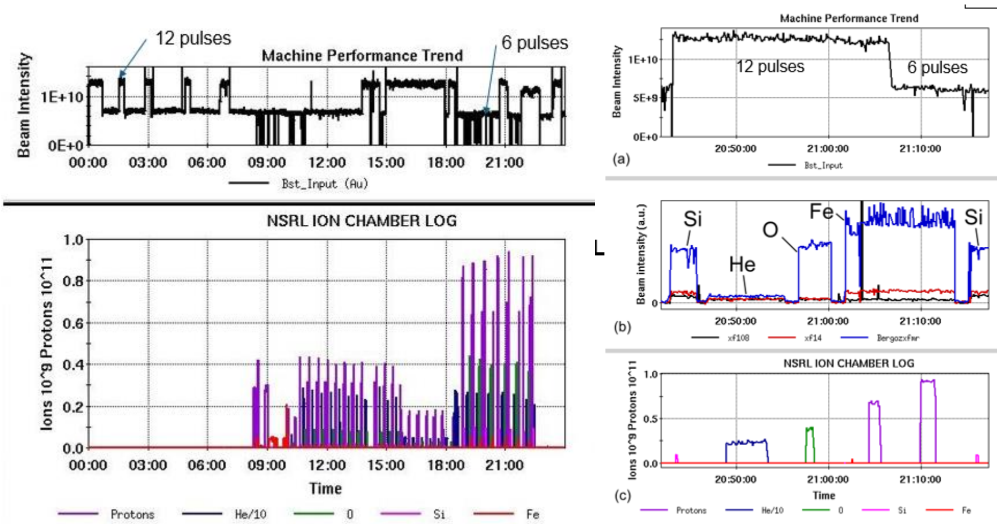

Figure 3. Beams for RHIC and NSRL when EBIS is providing beams for both facilities. Left plot shows beams during a day (Upper plot: total beam in a supercycle for RHIC at Booster input. Lower plot: beam at NSRL). Right plot shows 30 min period on the same day (Top: EBIS beam for RHIC. Middle: EBIS beam for NSRL. Bottom: Beam at NSRL).

Acknowledgement
This work has been supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy and by the National Aeronautics and Space Administration.

References

[1] Alessi J, et al. 2011 *Proc. 2011 Particle Accelerator Conference* (New York, NY, USA, March 2011) p 1966
[2] La Tessa C, Sivertz M, Chiang I, Lowenstein D and Rusek A 2016 *Life Sciences in Space Research* **11** 18-23
[3] Ikeda S, Kumaki M, Kanesue T and Okamura M, 2016 *Rev. Sci. Instrum.* **87** 02A915
[4] Beebe E, Alessi J, Binello S, Kanesue T, McCafferty D, Morris J, Okamura M, Pikin A, Ritter J and Schoepfer R 2015 *AIP Conference Proceedings* **1640** 5
[5] Saquilayan G Q, Ikeda S, Kanesue S, Wada M and Okamura M 2018 *AIP Conference Proceedings* **2011** 020013
[6] Okamura M, Beebe E, Ikeda S, Kanesue T, Raparia D, Muench L, Karino T and Haba H 2020 *Rev. Sci. Instrum.* **91** 013319
[7] Marr G, et al. 2019 *Proc. 10th International Particle Accelerator Conference* (Melbourne, Australia, May 2019) p 28
[8] Odyniec G, et al. 2019 *Proceedings of Corfu Summer Institute 2018 "School and Workshops on Elementary Particle Physics and Gravity"* (Corfu, Greece, August 2018) p 151
[9] Liu C, et al. 2019 *Proc. 10th International Particle Accelerator Conference* (Melbourne, Australia, May 2019) p 540
[10] Zelenski A, Atoian G, Beebe E, Poblaguev A, Raparia D, Ritter J, Maxwell J, Milner R and Musgrave M 2018 *Proc. 9th International Particle Accelerator Conference* (Vancouver, BC, Canada, April 2018) p 644
[11] Ikeda S, Beebe E, Kanesue T, Kondrashev S and Okamura M 2020 *Rev. Sci. Instrum.* **91** 013327