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AUTOMATED OPERATION OF EBIS INJECTOR AT BNL*

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Abstract

The RHIC-EBIS pre-injector is a heavy ion pre-injector to deliver multiple heavy ion species at 2 MeV/u to the AGS-Booster at the RHIC accelerator complex. In addition to collider experiments at RHIC, multiple heavy ion species are used for the NASA Space Radiation Laboratory (NSRL) to evaluate the risk of radiation in space in radiobiology, physics, and engineering. A GCR simulator is one of the operation modes of NSRL to simulate a galactic cosmic ray event, which requires switching multiple ion species within a short period of time. The RHIC-EBIS pre-injector delivers various heavy ion species independently for simultaneous operation of RHIC and NSRL. We developed an automated scheme of the rapid species change and it is routinely used by NSRL or Main Control Room for daily operation without assistance of RHIC-EBIS experts. The number of species change exceeds one hundred. This paper describes the automated operation of the RHIC-EBIS pre-injector and the operational performance.

INTRODUCTION

At BNL, the RHIC-EBIS pre-injector has been operating to provide various heavy ion species for collider experiment at RHIC and NASA Space Radiation Laboratory (NSRL) at the same time since 2010. In addition to high intensity heavy ion beams for collider experiments at RHIC, the RHIC-EBIS pre-injector is required to switch heavy ion species rapidly for NSRL.

NSRL is an accelerator-based research laboratory for space radiation research [1]. One of the main sources of radiation in space is Galactic cosmic Ray (GCR), which is composed of high-energy protons and various heavy ion species coming from outside of solar system [2]. The energies of the ions are ranging from a few MeV/u to well above 1 TeV/u, with the peak of the distributions tend to be around 1 GeV/u, which is the energy that the AGS-Booster can supply. Evaluation of the risk of GCR is very important for interplanetary missions beyond Earth in the future. Heavy ions and proton beams from the AGS Booster synchrotron is transported to a target room at NSRL and used for this purpose. Available beam energy range is up to 1.5 GeV/u for heavy ions and 2.5 GeV for protons. The radiation environment of GCR is simulated by rapid change of beam energy and ion species. All heavy ion beams are provided from RHIC-EBIS and proton beam is supplied from either the 200 MeV Linac or Tandem Van de Graaff. A schematic of the RHIC accelerator complex is shown in Fig. 1 for better understanding the facility.

The RHIC-EBIS pre-injector has been developed to switch ion species for NSRL reliably and automatically using the sequencer without assistance of ion source experts. The sequencer also switches parameters of entire beam line for NSRL including the AGS Booster. The switch is done from either Main Control Room (MCR) or NSRL at their will and it is independent from operation for RHIC. This makes NSRL highly useful and distinguished for space radiation study. Typical available heavy ion species at a time is 10 for solid-state materials and 2 for gaseous species. Since the RHIC-EBIS pre-injector is very reliable, an EBIS operator does not generally need to be involved in routine GCR operation once operational parameters for each species are set up.

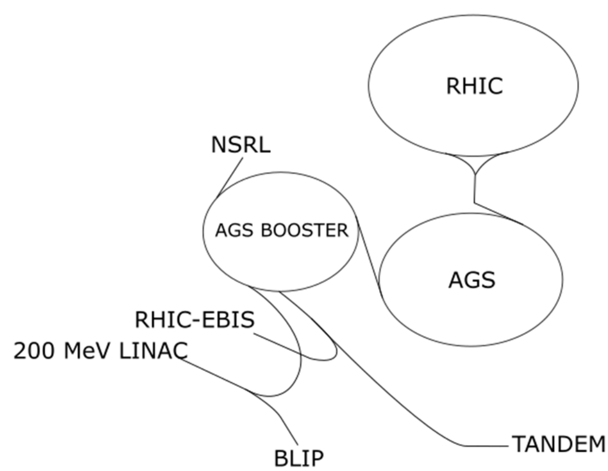

Figure 1: A schematic of RHIC accelerator complex. Heavy ion beams are provided from the RHIC-EBIS. NSRL uses ion beams of up to 1.5 GeV/u of heavy ions and 2.5 GeV of protons accelerated by the AGS Booster. Proton beam for NSRL is delivered from the 200 MeV LINAC or Tandem Van de Graaff. Tandem also serves as a backup for EBIS. For the isobaric collision program in Run-18, Tandem provided ^{96}Ru beam for RHIC and the RHIC-EBIS produced ^{96}Zr.

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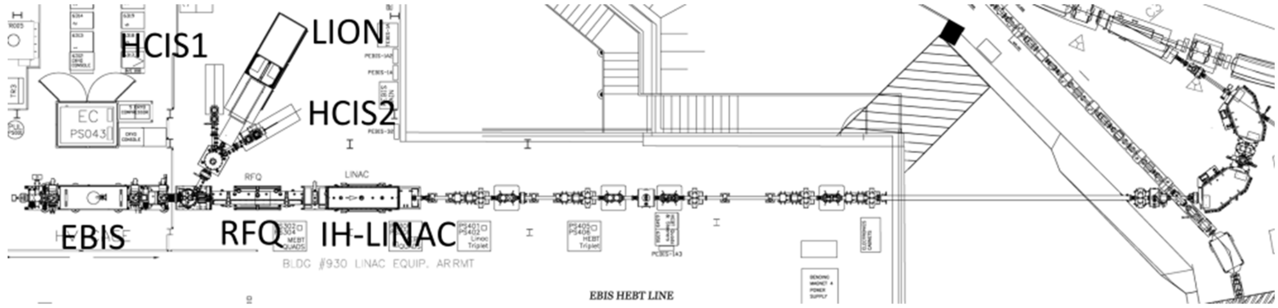

Figure 2: Layout of the RHIC-EBIS pre-injector.

RHIC-EBIS PRE-INJECTOR

Figure 2 shows a layout of the RHIC-EBIS pre-injector. For the rapid species change, an Electron Beam Ion Source (EBIS) is usually operated as charge multiplier and primary ions are injected from external ion sources to keep the ion trap clean. The primary singly charged heavy ions are produced from a laser ion source (LION) for all solid-state materials and two hollow cathode ion sources (HCIS) for gaseous targets. Highly charged ions such as Au^{32+} or Fe^{20+} from EBIS are accelerated to 2 MeV/u by a RFQ linac and a IH-Linac, both operating at 100.625 MHz. The 2 MeV/u heavy ion beams are injected into the AGS-Booster. The beam line after EBIS is designed to accelerate and transport heavy ions with charge-to-mass ratio more than 1/6 to switch ion species within 1 second.

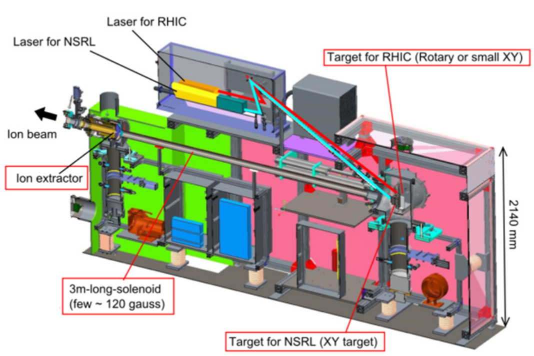

Figure 3: Layout of LION.

The Laser ion source is a key to realization of automated operation and rapid species changes. It can generate ions by laser ablation from any solid-state targets using a high-power laser irradiated on the target surface in vacuum. After a laser is stabilized which takes ~15 min, no warming up is required to switch species and the full performance can be achieved from the first shot. The vacuum pressure at the target chamber is kept below 10^4 Pa. Species switch is achieved by mechanically changing a target position or by changing a laser spot to shoot a different target. Figure 3 shows a layout of the LION. There are two target systems and corresponding lasers to provide heavy ions for RHIC and NSRL at the same time. For RHIC, one or two ion species are required for the entire run in general. We use rotating disk targets or planer targets on a small two-dimensional translation stage depending on the conditions of the run. For NSRL, a two-dimensional linear stage, called the XY target, holds multiple targets with the movable range of 250 mm by 50 mm. Typical dimension of one target is 25 mm by 25 mm or 25 mm by 50 mm. About 10 different target species are mounted at a time. The switching time between species depends on the motion of the XY stage. With the current velocity of 1 mm/s, it takes at most 25 s to use the target located at the each end of the holder. In case faster switching is required, a laser spot on the XY target can be shifted by controlling a final mirror located in air, in addition to moving the XY stage, although the current target switching time is satisfactory. The XY target can be used for RHIC simply by switching triggers of laser and so the XY stage serves as a backup for the RHIC operation. These two target systems for RHIC and NSRL are mounted in the same target chamber in vacuum. The laser power density on the target is adjusted between a few 10^8 W/cm^2 and 10^9 W/cm^2 to optimize the charge stage in induced ablation plasma for singly charged ions. Typical laser energy on a target is between 200 and 500 mJ. The strength of a 3m-long solenoid magnet to transport the laser-produced plasma is adjusted between a few Gauss and 120 Gauss depending on ion species to provide optimum beam for EBIS injection for each species. Ions are extracted by a high voltage at about 19 kV at the end of the solenoid. Typical peak current of the extracted beam is a few hundred μA ~ 1 mA with a pulse with of ~200 μs.

Two HCISs are used to produce ions from gaseous species such as He, Ne, Kr, Ar, or Xe, and can also produce a metal such as Fe or Au simultaneously. Typical ion beam current from HCIS is 5~50 μA and long beam pulse of 10~40 ms in the operation scheme. The available number of gaseous species at a time is limited to one per source so EBIS experts need to replace gas in case more species are needed which takes about 30 min. The ions from LION and HCIS are transported through a common beam line toward an EBIS.

The EBIS utilizes 7~10 A of electron beam with 5 T of the maximum magnetic field at the center of a superconducting solenoid. The EBIS is operated as a charge multiplier, which means ions from external ion sources are trapped and the charge state is increased to the desired value by varying confinement time. Typical charge state of ions is listed in Table 1. The ion injection from

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LION uses fast injection scheme and that from HCIS uses slow injection scheme [3]. The different EBIS platform potential is provided for different ion species to match the injection energy of 17 keV/u of a RFQ linac. The EBIS can switch species faster than the basic control cycle of 200 ms.

Table 1: Example of Charge State from EBIS

	Charge State	Q/M	Confinement Time (ms)
He	2	0.500	17
Li	3	0.429	27
B	4	0.364	106
C	5	0.417	51
C	6	0.500	111
O	7	0.438	81
Si	11	0.393	118
Si	13	0.464	418
Ar	11	0.275	36
Ca	14	0.350	106
Ti	18	0.375	242
Fe	20	0.357	242
Fe	24	0.429	822
Kr	18	0.214	45
Xe	27	0.205	81
Ta	38	0.210	217
Au	32	0.162	85
Th	39	0.168	130

The highly charged heavy ions from the EBIS are accelerated by a 3.2 m long RFQ linac, followed by a 2.46 m long IH-Linac [4]. The parameters of the RFQ linac and IH-Linac are summarized in Table 2. The accelerated ions are transported and then guided by two 72.5 degrees dipole magnets for injection into the AGS-Booster. These magnets have 13.5 cm gap height, 1.3 m bend radius, and 1 T maximum field. There is a spiral resonator rebuncher cavity between the RFQ linac and the IH-Linac, and two spiral type debuncher cavities between the IH-Linac and the dipole magnet to reduce the energy spread of the beam for booster injection. The switching time between species is ~1 s, which is mainly caused by the bending magnet.

Table 2: Parameters of the RFQ Linac and the IH-Linac

	RFQ	IH-linac
Frequency (MHz)	100.625	100.625
Input energy (keV/u)	17	300
Output energy (MeV/u)	0.3	2
Charge-to-mass ratio	>0.167	>0.167
Cavity length (m)	3.2	2.46
Power (with beam loading) (kW)	~200	~300

BEAM OPERATION FOR RHIC

RHIC continuously runs from around January to the end of June in general. However, RHIC does not require ion beams from the RHIC-EBIS all time. RHIC is refilled by the injectors at about every 0.5~20 hours depending on the store condition. The store length could be shorter than 30 min for RHIC low energy run. For RHIC injection, the RHIC-EBIS pre-injector provides 12 pulses at 5 Hz within a supercycle, the overall repetitive sequence of the accelerator facility (about 6 s for AGS to use the bunch merge scheme of 12-6-2). Typically, it takes 30 min or more to complete RHIC fill including machine set up. The 12 pulses are also used during store for injector tuning. At times when EBIS is not used for booster, the number of pulses is reduced to one as standby mode to keep the system up and running. The chance of machine failure is increased during the transition between standby mode and operational mode when duty is increased by a factor of 12. The switch between operational and standby mode is automated by the sequencer, and the number of cycles is gradually increased over several minutes. MCR switches the mode at any time.

BEAM OPERATION FOR NSRL

There are three NSRL runs per years in general, and the run starts before RHIC run and end at the similar time as RHIC. High-energy beam from booster is supplied at about every 4 s when RHIC is in shut down. When AGS is running, beam cycles for NSRL are interleaved in the 6 second supercycle period for AGS/RHIC using the Pulse to Pulse Modulation (ppm) feature of EBIS and RHIC injectors. Variety of heavy ion beams is provided from the RHIC-EBIS pre-injector. The number of available species is typically 12 at a time, 10 from LION and 2 from 2 HCISs. For automated operation, EBIS experts tune the RHIC-EBIS pre-injector for different species. The optimized parameters are archived with a standardized name for each ion species and charge state. For NSRL, active and background ppm users are used for the automated species change. Each ppm user contains different machine parameters of different beam characteristics. The archived parameters of next species are restored on a background ppm, and the actual species change occurs by switching the ppm user. During the switch, important devices such as lasers, XY target, vacuum valves are controlled in proper orders by the sequencer. MCR or NSRL can switch species at any time without notifying EBIS experts, without causing any failure of EBIS or resulting in delay of RHIC operation. The species change sequencer checks important parameters of EBIS and external sources to avoid breakdown and missed ion injection into EBIS. The possibility of electron beam fault is higher without ion beam neutralization of electron beam though EBIS is very stable and reliable under the normal operating condition. In addition, the EBIS electron beam used for NSRL beam is suppressed at the moment of the switch to tolerate any possible glitch of timing. This scheme contributed a lot for reliability of the RHIC-EBIS pre-injector. Since 2016, the

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new mode of NSRL operation, GCR simulator, has been developed. This mode is used to simulate the mixed radiation of heavy ions and protons in space by sequences of exposures. A dosimetry system at NSRL precisely controls dose on samples and cut off ion beam about 1 ms and triggers the species change and energy change according to a pre-defined setup file. The number of beam pulse for each species is as low as one.

OPERATIONAL PERFORMANCE

The above-mentioned beam operations for RHIC and NSRL run independently. The number of pulses per supercycle varies from 1 to 13, and the condition of the machine changes frequently on the order of minutes especially during GCR simulator mode. Figure 4 shows an example of a supercycle with both RHIC and NSRL running. EBIS is triggered at 12 times with ET0 trigger at the beginning of the supercycle for RHIC injection, and later EBIS is triggered once for NSRL. The number of pulses for RHIC is reduced to 1 when EBIS is in standby mode and there is no pulse for NSRL when NSRL is in shut down. Despite the large variation of duty and rf power required for different species, Low Level RF systems (LLRF), which is very similar to that developed for the BNL 200 MeV Linac [5], regulate cavity voltage and phase and keep cavity matching by controlling tuner position very well for all rf cavities.

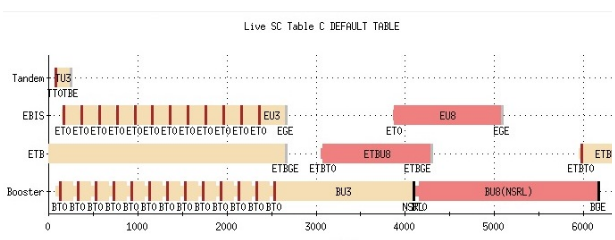

Figure 4: Supercycle when both RHIC and NSRL are running.

Figure 5 shows an example of daily beam operation with both RHIC and NSRL running. The top plot shows Au beam intensity at Booster injection for RHIC, and the bottom plot shows beam intensity at NSRL target room. The GCR simulator mode with proton from the 200 MeV Linac, He from EBIS/HCIS, O, Si, and Fe from EBIS/LION was used. As seen in the figure, beam operation for NSRL and RHIC did not affect each other. NSRL species was changed more than 130 times on that day without troubles on the RHIC-EBIS pre-injector, and stable heavy ion beam are delivered throughout the day without EBIS experts.

Figure 6 shows the details of the automated species change, where species was changed in the order of Si, He, O, Fe, then Si. The number of Au cycles was changed from 12 to 6 during that time (Fig. 6 (a)), but it didn't affect beam for NSRL. The Au target was mounted on a small 2D stage in LION dedicated for RHIC operation.

This sequence of species change involves the switch from LION-to-HCIS, HCIS-to-LION, LION-to-LION, LION-to-proton, and proton-to-LION. These all worked well. The switching time from the end of a species to the next species for the RHIC-EBIS pre-injector is about 40 sec (Fig. 6 (b)). The dosimetry system controls the exposure time, species and energy changes as shown in Fig. 6 (c).

Total days when EBIS provided beam for NSRL including setup and testing in Run-17 (NSRL 16C, 17A, 17B) and Run-18 so far (NSRL 17C, 18A, 18B) is summarized in Table 3. After the automated rapid species change became available, more species are used in a day. In addition to the listed species, B and Ca produced by EBIS/LION were delivered to NSRL earlier. Also, Cu, Pb, and U were delivered to RHIC with EBIS/HCIS.

For RHIC Run-17, the RHIC-EBIS pre-injector started to provide Au beam from EBIS/LION for injector tuning from April 14, 2017, then RHIC started Au-Au setup from May 30, 2017 after polarized proton program was finished. The Au-Au run ended on June 21, 2017. RHIC Run-18 was for isobaric collision program of ^{96}Zr-^{96}Ru from March 8 to and low energy Au-Au program after that which will continue until June 18, 2018. ^{96}Zr beam was provided from EBIS/LION and ^{96}Ru beam was delivered from Tandem Van de Graaf. The RHIC-EBIS pre-injector provided ^{96}Zr and Au throughout the isobaric collision experiment, and Au beam after that.

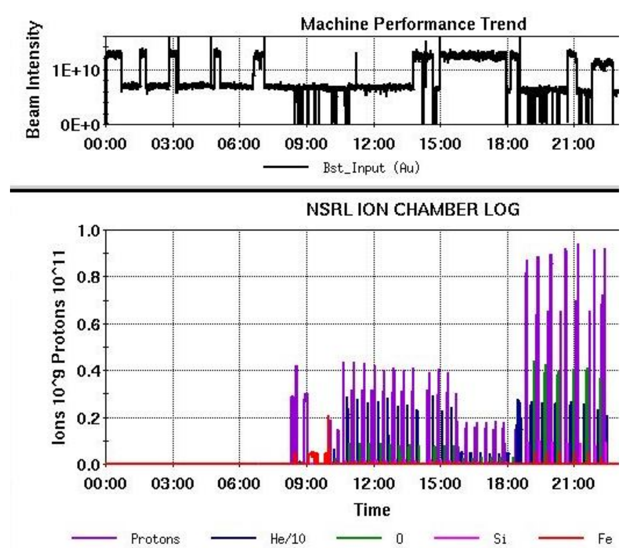

Figure 5: Example of beam usage with both RHIC and NSRL running for a day. Top plot shows Au beam for RHIC at Booster injection. Bottom plot shows ion species at NSRL target room with GCR simulator mode. Proton, He, O, Si, Fe were used on the day.

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Table 3: Heavy Ion Species and Number of Days used for NSRL during Run-17 and Run-18

	Species from LION											Species from HCIS				
	Li	**C**	**O**	**Si**	**Ti**	**Fe**	**Zr**	**Nb**	**Ta**	**Au**	**Th**	**He**	**Ne**	**Ar**	**Kr**	**Xe**
Run 17	5	14	20	38	12	51	1	1	5	7	2	35	0	1	4	11
Run 18 (as of 6/6/2018)	0	22	28	49	21	56	0	0	31	5	5	35	8	0	11	16

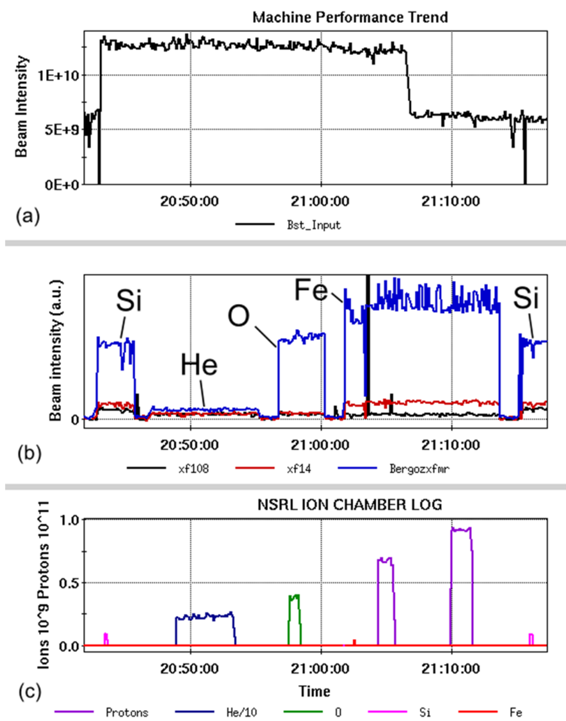

Figure 6: Au beam for RHIC and rapid species change for NSRL with GCR simulator mode. (a): Au Beam for RHIC. (b): beam at Booster injection (black), after IH-Linac (red), and EBIS output (blue). (c): Beam at NSRL target room.

CONCLUSION

At Brookhaven National Laboratory, the RHIC-EBIS pre-injector is providing heavy ion beams for both RHIC collider experiments and NSRL. Since 2016, automated rapid species change and the GCR simulator mode have been developed and now they are routinely used for NSRL. Available heavy ion species for NSRL at a time is typically 12 and NSRL can switch to any of them at any time without assistance of EBIS experts. The number of species changes per day is more than 100. The reliability of the RHIC-EBIS pre-injector is very high and for normal operation, no EBIS experts are needed. The key component of the fast species change is LION combined with EBIS.

At the RHIC-EBIS the switching time between ion species for RHIC and that for NSRL in a supercycle is about 1 s. The switching time to introduce a new species for NSRL is about 40 s with the automated species switching, and the full beam performance is available from the first shot without warm-up.

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