ACCELERATION AND TRANSPORTATION OF MULTIPLE ION SPECIES AT EBIS-BASED PREINJECTOR[*]

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Abstract

Electron Beam Ion Source (EBIS)-based preinjector was come into operation in 2010. Since than it has been delivering various ions to NASA Space Radiation Laboratory (NSRL) radiobiology program and Relativistic Heavy Ion Collider (RHIC) physics program. During the Run12, the EBIS-based preinjector provided U^{39+}, Au^{32+}, and Cu^{11+} ions for the RHIC physics program. The preinjector has delivered beams of He^{2+}, Ne^{5+}, Ar^{11+}, Ti^{18+}, Fe^{20+}, Kr^{18+}, Xe^{27+}, and Ta^{38+} for the NASA Space Radiation Laboratory radiobiology program for last three years. The performance and operational experience with multiple ion species of this preinjector is presented.

INTRODUCTION

In past Tandem Van de Graaff was providing heavy ions for NASA Space Radiation Laboratory (NSRL) radiobiology program and Relativistic Heavy Ion Collider (RHIC) physics program. Tandem preinjector is 40 years old and less flexible, for example it could not provide noble gas ions to NSRL radiobiology program and uranium for RHIC physics program. A new preinjector based on electron beam ion source (EBIS) was come into operation in 2010 [1]. This preinjector can produce ions of any species and able to switch between multiple species in 1 second to simultaneously meet the needs of both science programs. The main parameters for the preinjector are given in Table 1, and the layout of the preinjector is shown in Figure 1.

Table 1: EBIS-Based Preinjector Parameters

Ions	He – U
Q / m	≥1/6
Current	> 1.7 emA
Pulse length	10–40 μs
Rep rate	5 Hz
Output Emittance	0.14 pi mm mrad
Momentum Spread	±0.5%
Linac output energy	2 MeV/u
Time to switch species	1 second

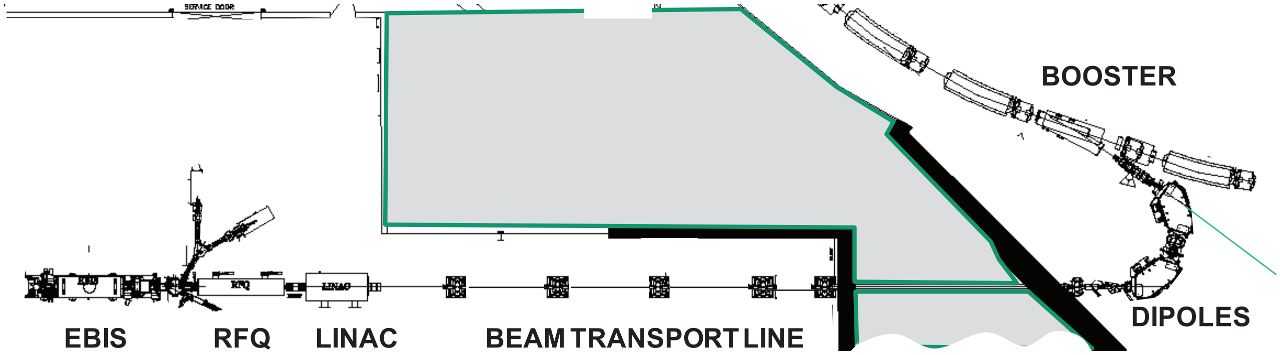

Figure 1: Schematic of the EBIS-based heavy ion preinjector

EBIS-BASED PREINJECTOR

The preinjector uses an EBIS source, a low energy transport line (LEBT), a Radio Frequency Quadrupole (RFQ), a medium energy transport line (MEBT), a linac and a 37 meter long high-energy transport line (HEBT).

The EBIS has a 5T superconducting solenoid which compresses an electron beam of up to 10A in a ~1.5 m long trap region. Ions of the desired species are injected, held in the trap, and stepwise ionized by the electron beam. When the desired charge state is reached, they are released from the trap in a short pulse.

The source is followed about a meter long low energy transport line (LEBT), which facilitates injection of singly charge ions into the EBIS and transport and match into the RFQ for high charge state ions. Figure 2 shows the functional block diagram of the LEBT.

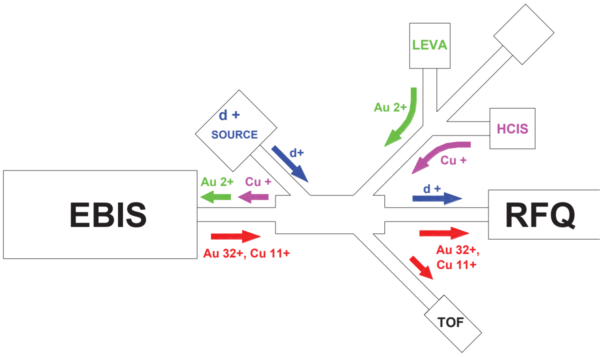

Figure 2: Functional block diagram of the LEBT.

The LEBT contains couple of electrostatic lenses, ~ 100 kV accelerating gap to provide energies of 17 keV/u, a solenoid to focus beam into the RFQ and current monitoring devices. About one-meter free space in the

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extracted beam line is needed to accommodate injection of singly charged ions from the external source.

The LEBT is followed by an RFQ, which accelerate ions up to 300 keV/u and operate 100.625 MHz. Table 2 show design parameters of the RFQ [2].

Table 2: Design Parameters of the RFQ

Frequency	100.625 MHz
Injection Energy	17 keV/u
Output Energy	300 keV/u
Electrode voltage	70 kV
Length	3.1 m
Cell number	189
Power	200 kW

An 81 cm long MEBT connects RFQ to linac and consists of four quadrupoles magnet, a four gap spiral structure buncher cavity and current monitoring devices.

The linac was design to provide low emittance and low momentum spread by using KONUS beam dynamics, it also include the possibility to shifting of phases of last two gaps to -90 degrees in order to achieve a lower momentum spread [3]. Table 3 show the design parameters of this linac.

Table 3: Design Parameters of Linac

Frequency	100.625 MHz
Injection Energy	300 keV/u
Output Energy	2000 keV/u
Internal triplet	1
Length	2.46 m
Accelerating gaps	27
Power	300 kW

The HEBT line from the IH linac to Booster injection includes is a ~17 meter section in the linac building, transport through a ~8 meter thick shield wall, and then inside the Booster tunnel a ~12 meter transport, including two dipoles, to inject beam into the Booster at the same location as beam coming from the Tandems. The two identical dipoles each have a bend angle of 73.4 degrees, a 13.5 cm gap, 1.3 meters bend radius, and 1T maximum field These magnets are laminated to allow the required 1 second field change time for different ion species. This beam line has several constraints in order to fit into the existing facilities. (1) It has to inject beam in the same location at the Tandem, which required a high bending angle, and since it had to fit inside the Booster enclosure, one had to make bend radius rather small compare to other focal lengths in the transport line. (2) It has spaces without any optics components and diagnostic to accommodate the 8 meters thick shield wall and 6 meters of space needed for the 200 MeV linac shield door. (3) The last element in the line is an existing inflector with horizontal aperture only 17 mm, designed for the Tandem beam, which has much lower emittance, and which is a bottle neck in this line. (4) The linac uses a triplet for transverse focusing while the rest of the line use FODO lattice. (5) The fact that ion species are not separated until the dipole makes tuning of the preinjector rather hard. To accommodate these constraints the resulting line has one quadrupole triplet, 8 quadrupoles, two bunchers, four horizontal steerers and five vertical steers. Diagnostics include phase probes, fast Faraday cup, adjustable slits, and three sets of multi-wire profile monitors, three current transformers, two Faraday cups, pepper-pot emittance monitor and two beam stops.

MULTIPLE IONS SPECIES

Time-of-flight measurements of the EBIS output beam generally indicate low (10-15%) impurities in the beam, but it is difficult for us to get a high-resolution measurement under our exact running conditions, so there is always some uncertainty. Figure 3 shows the output spectrum of gold ions from the EBIS for 7.6 Ampere of electron current.

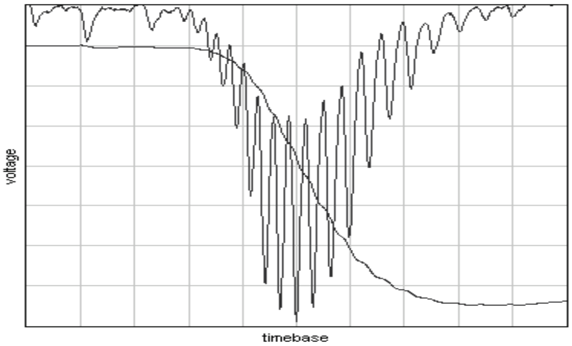

Figure 3: Gold ion spectrum from EBIS at 7.6 A electron current.

The total charge expected from EBIS at 75% neutralization of 10 A electrons beam is about 150 nC in about 10 microseconds i.e. about 15 mA. The maximum current that can be transport through drift space of length L with radius R is given by [4]

$$I_{max}(A)=1.166*(mc^2/(30*q))*\beta^3\ \gamma^3\ (R/L)^2$$

where m and q are the mass and charge of the ions respectively and β,γ are the relativistic parameters. Table 4 shows the maximum current which can be transported 1 meter with radius of 20 mm at17 keV/u for different ions.

Table 4: The Maximum Transported Currents for Different Ions with 20 mm Radius and 1000 mm Drift Space with Energy of 17 keV/u.

Ions	Maximum transported current
Au^{+32}	20 mA
D^{+1}	6 mA
${}_3He^{+2}$	5 mA

As stated in the previous section that about 1 meter drift space needed in the LEBT to facilitate injection. There was no margin to add charge separation system before RFQ without manipulation of ion energies. Figure 4 shows a conceptual alternate solution to accommodate charge separation in the LEBT with dispersion of about a meter, which is sufficient to separate charge state of gold ions. The charge separation system include two 241 mm long 90° gradient magnet with edge angle of 4° and gap 100 mm at 8 kG. Two accelerating column are 150 mm long at ±15 kV. Magnet has to float at 40 kV for $_3He^{+1}$ ions.

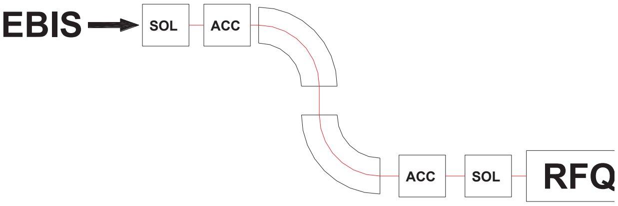

Figure 4: Concept for the charge separation system before RFQ. It consist of two 90° gradient dipoles sandwich between de-acceleration and acceleration column.

The TRACE output for Au^{+32} ions for 10 mA is shown in figure 5. First and last solenoids need 655 and 2285 gauss field respectively. Accelerating and de-accelerating column require 400 Volts.

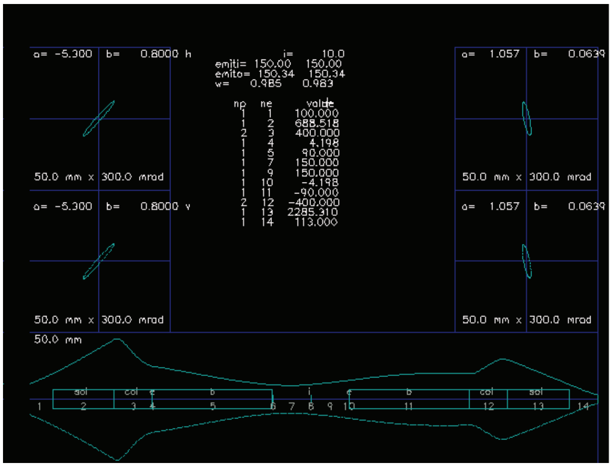

Figure 5: Conceptual LEBT with charge separation before RFQ for 10 mA of Au^{+32} ions.

To avoid the completions and extra cost it was decided not to adopt charge separation scheme before RFQ. In the present design charge separation occur in the HEBT between two dipole magnets where the resolution is about 500 at 2 MeV/u.

RESULTS

With impurities and multiple charge state it is very difficult to measure transmission of a particular charge state to be injected and accelerated in the down stream accelerator chain. To characterize the preinjector He^{+1} beam was tried with gas injection into the EBIS. Overall transmission from RFQ input faraday cup to Booster injection was about 78% (including some impurities in the RFQ input faraday cup). Table 5 show the transmission through preinjector for He^{+1}.

Table 5: Transmission Through Preinjector for He^{+1} (including some impurities (10-15%) in the RFQ input)

Location	Current (mA)
RFQ input (FC)	1.4
RFQ output (FC)	1.4
Linac output (CT)	1.1
Before bend (CT)	1.1
At Booster injection (CT)	1.1

Determining the transmission of a particular charge state of heavier ion through the preinjector is more complicated since EBIS produce several charge state and some ions of background gas (usually 10-15%) and ion species are not separated until the bend. Table 6 show the measured fractional charge state for gold ions produce by 7.5 A of electron current and simulated transmission of each charge state then compare total current with the measurements after each acceleration stage.

Table 6:Comparison of Transmission between Simulation and Measurement for the Gold Ions.

Charge State	**Frac. @EBIS (Meas.)**	**RFQ**	**LINAC**	**Booster Input**
26	0.0334	0	0	0
27	0.0448	0	0	0
28	0.0640	0	0	0
29	0.0929	0.0005	0	0
30	0.1082	0.0609	0.0442	0
31	0.1201	0.1076	0.1068	0
32	0.1281	0.1237	0.1237	0.1236
33	0.1201	0.0962	0.0915	0
34	0.1121	0.0714	0.0629	0
35	0.0761	0.0290	0.0216	0
36	0.0480	0.0158	0.0083	0
37	0.0320	0.0055	0	0
38	0.0200	0.0032	0	0
Total	1.0000	0.5137	0.4590	0.1236
Simu. (nC)	54.5	27.995	25.017	6.736
Mesu.(nC)	54.5	29.6	16.2	5.8

The design transmission of Au^{+32} for RFQ and Linac were 90% each. Assuming 10% impurities at RFQ input, the amount of Au^{+32} at end of preinjector should be 54.5*0.9*0.9*0.9=5.0 nC whereas measured and simulated values are 5.8 nC and 6.0 nC respectively.

In the presence of multi ion species it is very hard to tune the individual components of the preinjector. Generally, preinjector is tuned with maximizing beam current at Booster extraction. The beam is injected into the Booster through existing inflector. The inflector was design for tandem Van de Graaff beam that has order of magnitude lower emittance. The horizontal aperture of inflector was increase to 21 mm from 17 mm resulting transmission through inflector was increase to about 90% from about 70%. If one assumes Gaussian beam distribution, this increase in the transmission indicates the emittance of Au^{+32} is about 0.6 pi mm mrad (n,rms), which is about four times higher than the design value. Even this larger emittance, however, one would not expect any beam loss. The possible sources of emittance growth can be following; (1) since ion are generated in the solenoid field and are magnetised and (2) misalignment in the IH linac. There are indication that beam is misaligned in the IH linac. The measured emittances for helium and gold ions after MEBT are shown in figure 6. In case of gold ions neighbouring charge states are included in the measurements.

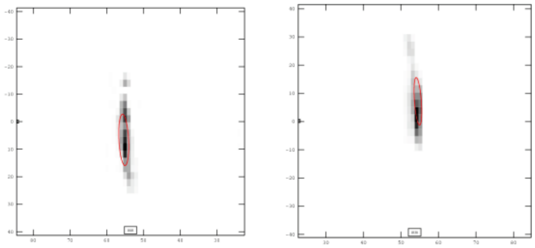

Figure 6: Matched condition into LINAC; Helium (left) ε(n,rms) 0.2 π mm mrad and gold (right) ε(n,rms) 0.26 π mm mrad

Figure 7 shows the measured and simulated real space beam footprint. Beam footprint is diamond shape, which is rather unusual.

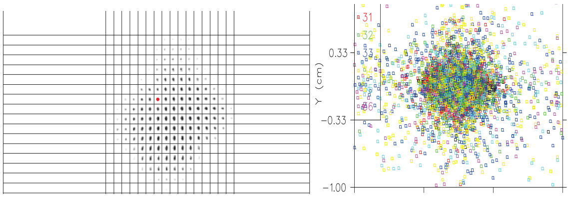

Figure 7: Diamond shaped beam footprint after the linac by pepper-pot emittance monitor (left). Simulated beam footprint at the same location (right)

Simulations revealed that diamond shaped associated with off energy synchrotron oscillation in the RFQ. In case of gold where RFQ is tuned for charge state 32, higher charge state say 35 will come higher energy than the synchronous particle and go through synchrotron oscillations. Figure 8 shows the x-y and $\Delta\Phi$-ΔW phase space at end of RFQ for charge state 35 of gold while RFQ is tuned for charge state 32.

Momentum spread was measured via measuring time taken by the circulating beam to debunch in the Booster. This gave a $\Delta P/P = \pm 0.03\%$, which is better than the design value ($\pm 0.05\%$).

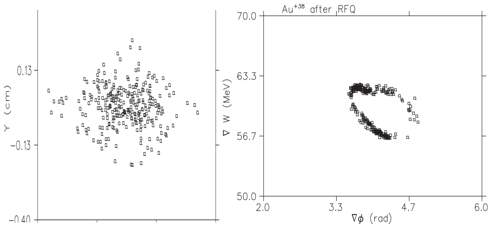

Figure 8: The x -y (left) and $\Delta\Phi$-ΔW (right) phase space at end of RFQ for charge state 35 of gold while RFQ is tuned for charge state 32.

Since EBIS also produce ions from background gases along with desired ion species with specific charge state distribution, some times q/m for the desired ions and ions from the background gas are so closed that even booster can not distinguee them. Some examples are He^{+2}, O^{+8}, & C^{+6} and Ne^{+5}, O^{+4}, & C^{+3} are seen in the NSRL beam line after Booster while delivering He and Ne ions to delivering to NSRL. Another example Ar^{+7} and Cu^{+11}, seen in the Booster to AGS transfer line while delivering Cu ion to RHIC program.

Table 7 shows the charge measured out of preinjector for Cu, Au, and U. The fraction making it to the Booster input comes from a combined effect of charge state distribution and impurities. These values, taken during the RHIC run, are ~80% of the best intensities seen at output of preinjector [5].

Table 7: Output of Preinjector

Electron Beam	**Ion**	**Preinjector output**	
		Ions	Charges
8.3 A	^{63}Cu^{11+}	6.1e9	6.7e10
9.5 A	^{197}Au^{32+}	1.5e9	4.7e10
9.6 A	^{238}U^{39+}	1.1e8	4.2e10

The measured current at the output of preinjector is about 70% of design value. Unfortunately it is hard to pin down the inefficiencies of the systems, because there is no ion (q/m) selection until bend in the HEBT. Therefore, the causes are still not understood; as this can be due to some combination of EBIS output charge state distribution, impurities, output emittance, possible misalignments, current measurement, etc.

SUMMARY

EBIS-based preinjector has delivered U^{39+}, Au^{32+} and Cu^{11+} beams with excellent reliability and stability. The preinjector supported RHIC physics program continuously for 2.5 months, plus ran additional time for machine setup prior to the run. While intensities for U, Au, and Cu, are still lower than our design values, with the addition of bunch merging in the Booster and AGS the RHIC program met their bunch intensity and integrated luminosity goals. Preinjector in the past year has also produced beams of He^{2+}, Ne^{5+}, Ar^{11+}, Ti^{18+}, Fe^{20+}, Kr^{18+}, Xe^{27+}, and Ta^{38+} for the NASA Space Radiation Laboratory radiobiology program.

ACKNOWLEDGEMENTS

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