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**J. Alessi, E. Beebe, C. Carlson, D. McCafferty,  
A. Pikin, J. Ritter**

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**Collider-Accelerator Department  
Brookhaven National Laboratory**

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# A Hollow Cathode Ion Source for Production of Primary Ions for the BNL EBIS<sup>a,b)</sup>

James Alessi<sup>c)</sup>, Edward Beebe, Charles Carlson, Daniel McCafferty, Alexander Pikin, John Ritter

*Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY, USA*

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A hollow cathode ion source, based on one developed at Saclay, been modified significantly and used for several years to produce all primary 1+ ions injected into the RHIC EBIS at Brookhaven. Currents of 10's to 100's of microamperes have been produced for 1+ ions of He, C, O, Ne, Si, Ar, Ti, Fe, Cu, Kr, Xe, Ta, Au, and U. The source is very simple, relying on a glow discharge using a noble gas, between anode and a solid cathode containing the desired species. Ions of both the working gas and ionized sputtered cathode material are extracted, and then the desired species is selected using an ExB filter before being transported into the EBIS trap for charge breeding. The source operates pulsed, with long life and excellent stability for most species. Reliable ignition of the discharge at low gas pressure is facilitated by the use of capacitive coupling from a simple toy plasma globe. The source design, and operating experience for the various species, is presented.

## I. INTRODUCTION

At Brookhaven National Laboratory, an Electron Beam Ion Source (EBIS) is now used for the production of highly charged heavy ions for use at the Relativistic Heavy Ion Collider (RHIC) and the NASA Space Radiation Laboratory (NSRL). In 2012 it operated for several months continuously for RHIC, delivering  $U^{39+}$ ,  $Au^{32+}$ , and  $Cu^{11+}$ . Since 2011, it has delivered 13 different ion species for NSRL. The EBIS, operating with a 10A electron beam, is followed by an RFQ and IH Linac, delivering 2 MeV/amu ions to the Booster synchrotron. When RHIC and NSRL are running concurrently, or RHIC is colliding 2 different species, the EBIS preinjector switches between species (presently 2) on a 1 second time scale. Details on EBIS performance are presented in Ref. 1.

## II. REQUIREMENTS FOR INJECTION OF PRIMARY IONS

Although occasionally ions are produced in EBIS by the feeding of a small amount of gas into the trap region (ex. for  ${}^3\text{He}^{2+}$  production), in most cases the EBIS acts as a charge breeder, in that 1+ ions are produced externally and injected into the trap region for further ionization. Operating in this way, the EBIS ions produced can be changed pulse-to-pulse by changing the injected ion species coming from multiple 1+ sources via an external “switchyard”.

Requirements for the 1+ source depend on the method used for ion trapping, either “fast” or “slow” injection. In either case, ions are injected from the electron collector end of EBIS, decelerated as much as possible as they enter the trap, and a voltage barrier created by an electrode at the electron gun end of trap reflects ions back towards the collector. For fast injection, one raises a voltage barrier at the collector end before the ions exit. One therefore efficiently captures ions contained in the time of a single “round trip”, which for the present case (3 meter round trip distance), is  $\sim 100\text{-}300\ \mu\text{s}$ , for light to heavy ions. In slow injection, one applies a fixed barrier at the collector end at a voltage just below incoming ion energy. If a 1+ ion is ionized one additional time by the electron beam during the round trip, it then remains trapped by this exit voltage (i.e. with twice the charge, it can no longer make it over the exit barrier). This method of ion injection is less efficient ( $\sim 5\%$  vs.  $\sim 50\%$ ), but injection can continue for a long time (wide injected ion pulse). To meet our requirement of  $\sim$ full neutralization of the space charge of the electron beam in the trap by ions once in the desired final charge state, fast injection requires  $\sim 30\ \mu\text{A}$  for heavy ions (ex.  $Au^{1+}$ ), but would need  $>500\ \mu\text{A}$  for light ions (ex.  $C^{1+}$ ) since the final charge state is much lower and the round trip time less. In contrast, using slow injection, if one has a source producing  $\sim 10\ \mu\text{A}$  of 1+ ions of any species, then one would need to inject ions for  $\sim 10\text{ms}$  (Au) to  $\sim 60\ \text{ms}$  (C). In our case, using the hollow cathode ion source (HCIS) described below, we typically use slow injection.

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<sup>c)</sup>alessi@bnl.gov

In addition to the above intensity and pulse width requirements, the source must operate at 5 Hz for RHIC, but need only operate at  $\sim 0.3$  Hz for NSRL. The  $1+$  source normalized emittance should be  $< 0.1\pi$  mm-mrad for efficient injection of ions into the trap. A schematic of the beamline connecting the external ion sources to EBIS is shown in Fig. 1. Two sources are used, to provide the rapid switching pulse-to-pulse, with pulsed electrostatic deflectors switching to inject ions from either source. The transfer line from the  $1+$  sources to the EBIS trap entrance is  $\sim 5.8$ m, and includes electrostatic quadrupoles, electrostatic steering, and several gridded electrostatic lenses to transport ions to EBIS. There is a Wien filter near the exit of each source that provides some modest mass separation of ions.

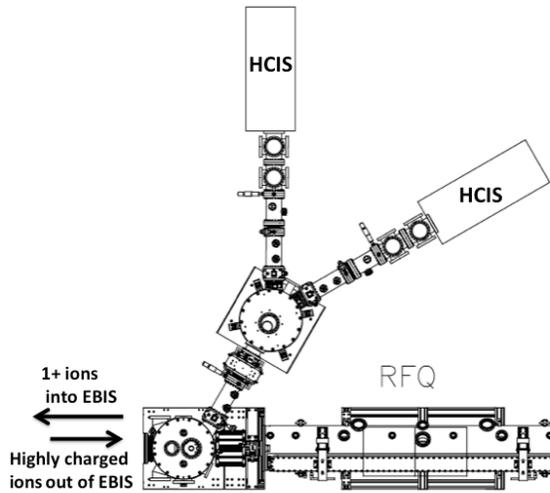


FIG. 1. Schematic of the beamlines connecting the  $1+$  sources to EBIS.

### III. HOLLOW CATHODE ION SOURCE

While in the past on the Test EBIS we have used several type sources for  $1+$  injection (ex. liquid metal ion source, metal vapor vacuum arc source, cesium emitter), on the EBIS used for accelerator operation we have so far used only hollow cathode ion sources. This type source was developed at Saclay for  $1+$  injection into the Dione EBIS<sup>2</sup>). Starting with the operation of one of the Saclay sources at Brookhaven, with good results, over time changes were made at Brookhaven that generally simplified the design while maintaining the good performance. The BNL version of the source is shown schematically in figure 2, and a photo of the source is shown in figure 3. The anode of the source is a copper or stainless steel rod, inserted into one end of a 25 mm diameter glass tube of  $\sim 50$  cm length and 2 mm thickness, acting as the insulator between anode and cathode. At the other end of the tube, the cathode is cylindrical, open on one end and closed except for the  $\sim 1.5$  mm diameter aperture on the other end.

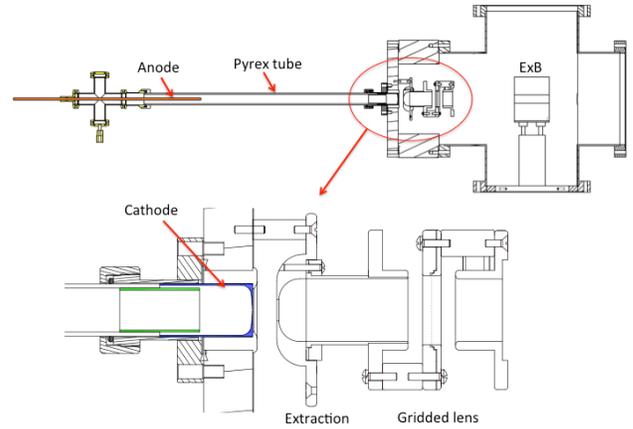


FIG. 2. Schematic of the BNL source, with a blow-up of the cathode and extraction geometry.



FIG. 3. Photo of the HCIS, anode on the left, cathode on the right, and plasma globe for ignition of the discharge.

The cathode is frequently made from the material of the desired ion, as will be discussed in the next section. A noble gas is fed in at the anode end through a pulsed or dc valve, with the pressure in the tube  $\sim 1$  Torr during the discharge pulse. With a pulsed voltage of 500-1000 V applied to the anode, a glow discharge is produced between the anode and grounded cathode. Discharge current when optimized for a particular ion can be 0.5-5A. Ions from the buffer gas are accelerated to the cathode, where they sputter cathode material. Ionization of the sputtered cathode material occurs in the discharge by electron impact, charge exchange with the buffer gas ions, and ionization by buffer gas atoms in metastable state. Further sputtering of the cathode by these metal ions is often much more effective than ionization by the buffer gas ions. Ions exiting through the 1.5 mm aperture are accelerated to 12-16 kV across an extraction gap of 11.5 mm, followed by a gridded lens for focusing of ions through the Wien filter, and then the remaining transport.

This source meets our modest intensity requirements, and is attractive due to its simplicity, reliability, and flexibility in type of ions produced. Changing cathodes can be done in  $< 30$  minutes, and the source is very easy to operate for most type ions. Source lifetime was typically limited to a couple weeks by gradual coating of the glass tube by metal from the cathode, resulting in transition to an arc discharge. However, after creating a shielded section

of the tube near the cathode by simply sliding a short section of smaller diameter glass tube in the glass-to-cathode interface region, source lifetime now can be several months. Measurements taken for  $\sim 10\mu\text{A}$  of  $\text{Cu}^{1+}$  and  $\text{Ne}^{1+}$  gave a normalized, rms emittances of  $\sim 0.02\pi$  mm-mrad.

In the Saclay version of the source, the anode voltage was applied to several smaller electrodes at various locations along the length of the discharge. In the BNL version with the rod anode and long glass tube, ignition of the discharge was first facilitated by pulsing rf through a coil wrapped around the outside of a section of the glass tube. Later it was found that a much simpler way of igniting the discharge was to merely place an inexpensive toy plasma globe in contact with the outside of the tube somewhere between cathode and anode. With this, one can see a glowing of the buffer gas even when no anode voltage is applied, and the glow discharge ignites easily.

#### IV. PRODUCTION METHOD FOR VARIOUS IONS

The ExB mass filter in the  $1+$  injection line gives only coarse mass separation, so optimization of the HCIS is typically based on final intensity after further ionization in EBIS and subsequent acceleration. Recently, studies of HCIS source performance have been done on a test bench where the current of mass analyzed ions can be measured after transport through a 90 degree analyzing magnet. The following are some comments on the production of various ions, based on our experience.

##### A. Ions from gases (He, O, Ne, Ar, Kr, Xe)

For these beams, the discharge is produced using the desired gas, with a stainless steel cathode to minimize production of other ions. Output can be 50-150  $\mu\text{A}$  in most cases. The only things of note here are for He and O ion production. For helium, only a very small amount of O mixed with the He causes a drastic reduction in the  $\text{He}^{1+}$  output, so one must be careful to avoid any leaks in the gas feed line. For oxygen ion production, we have found that a gas mixture of 5%  $\text{O}_2$  / 95% Ar gives more oxygen ions than when using a higher percentage of  $\text{O}_2$  in the mixture. With this mixture, the  $\text{Ar}^+$  output is much less than the  $\text{O}^+$  and  $\text{O}_2^+$  currents. Injecting  $\text{O}_2^+$  into EBIS is actually better than  $\text{O}^+$  injection, since the  $\text{O}_2^+$  current is three times higher than for  $\text{O}^+$ , which then means one can put six times more O atoms into the trap.

##### B. Ions from solids

For many solid ions, the cathode can be made from the desired material. We have done this for C, Ti, Ta, Fe, and U. To reduce the amount of material needed for Au and for isotopically enriched  $^{63}\text{Cu}$ , we instead use thin ( $\sim 100\mu\text{m}$ ) Au or Cu foils, crudely formed to fit on the

inside of a stainless steel or natural Cu cathode. For Ti, Ta, Fe, Cu, Au, and U we use neon as the buffer gas, since we've found that it performs as good or better than other noble gases in all these cases. For C we have found that helium works best as the buffer gas. The HCIS typically produced 10-20  $\mu\text{A}$  for these solids. There are no issues with the running of any of these beams, although with U care had to be taken to avoid the spread of any contamination from a small amount of uranium "dust" in the glass tube following a month of operation.

##### C. Silicon

Silicon has taken the most effort to develop. In our first attempt with a cathode of boron-doped silicon the conductivity was poor, so one could not establish a good discharge. With a thin layer of Au evaporated onto the cathode, we were able to use the cathode for a 5-day run, but operation became erratic as the coating was sputtered off. Hexamethyldisilane ( $\text{Si}_2\text{C}_6\text{H}_{18}$ ) is a volatile liquid that is non-corrosive and has low toxicity. It was used successfully in a Freeman source to make  $\text{Si}^+$ ,<sup>3)</sup> although at mass 28 it also produced  $\text{C}_2\text{H}_4$ , and  $\text{Si}^+$  was estimated to be 62% of the output at mass 28. On the HCIS, using a stainless steel cathode, we first established a discharge using Kr.  $\text{Si}_2\text{C}_6\text{H}_{18}$  was then introduced through a needle valve, and as the amount was increased, visible light from the discharge disappeared and the arc current dropped to a value too low for us to observe, but a good ion output was measured on the HCIS Faraday cup, and a good Si beam from EBIS was produced. We were able to run 5-10 days with this, but electrodes became coated, and extraction voltage holding became difficult. Finally, several alloys containing Si have been tried. An alloy of Si and Fe (14% Si) has been used for  $\sim 10$  days, but it has been difficult to get sufficient intensity. Most recently, on our test bench a Si-Cu alloy (80% Si) has looked very promising, and will be used in the upcoming run.

#### V. CONCLUSION

A hollow cathode ion source, based on one developed at Saclay, has proven to be a simple, versatile, and reliable source, providing all primary  $1+$  ions injected into the BNL EBIS. To date, 14 different ion species have been produced with this source. In the near future, we plan to add a Laser Ion Source for  $1+$  injection into EBIS,<sup>4)</sup> which will allow us to rapidly switch among many more species.

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