# EBIS Option for the Relativistic Heavy Ion Collider - RHIC*

K. Prelec, J. Alessi, and A. Hershcovitch
Brookhaven National Laboratory, UPTON, NY 11973, USA

Abstract

The present RHIC scenario for acceleration of gold ions starts with the BNL Tandem injecting $Au^{14+}$ ions into the Booster. As a future alternative to the Tandem and its 840 m transfer line to the Booster, we are considering an EBIS followed by an RFQ and a short linac. Such a preinjector should be capable of delivering ions of any species up to uranium, with intensities as required by RHIC. This paper will first present a short review of the state-of-the-art of intense EBIS devices, followed by an estimate of parameters of a source for RHIC at BNL. We plan to proceed in two phases, first to develop a device with an electron beam current of 1-2 A to serve as a feasibility test, and then to continue with the design of the final device. The second part of the paper will describe an RFQ and a linac for ions with a charge-to-mass ratio of about 0.18. Finally, we shall mention a scheme to inject in a fast sequence up to four pulses into the Booster, running in an accumulating mode.

## 1. INTRODUCTION

The acceleration scenario in a multistage accelerator facility, such as BNL's Relativistic Heavy Ion Collider (RHIC), depends on the characteristics of the first stage, the preinjector. It was a fortunate situation that a Tandem existed at BNL and that the RHIC design could be matched to the Tandem performance. In the present scenario gold ions in the charge state 14+ will be directly injected [1,2] from the Tandem into the Booster, with the first stripper after the Booster producing $Au^{77+}$ to be injected into the AGS and the second one, for a full stripping, in the RHIC injection line. This scenario will allow formation of three bunches per cycle and shortening the RHIC filling time by the same factor of 3.

As a possible future improvement of the RHIC preinjector we have been considering to replace the Tandem, including the 840 m transfer line to the Booster, with a heavy ion source delivering sufficiently high charge states and intensities of any ion up to uranium, followed by an RFQ and a short, possibly superconducting, linac. This new preinjector would be located close to the Booster, eliminating the long transfer line. As a goal, its performance should allow for future increases in RHIC luminosity, broaden the choice of available ion species, and in principle, also be simpler, more reliable, requiring less maintenance and less staff to operate. However, heavy ion sources that would satisfy RHIC requirements are still not available, but will have to be developed by scaling up of existing devices. The rest of the preinjector, an RFQ and the linac, is a technology already adopted by industry; from the point of view of RFQ/linac design, it is preferable to get from the source a charge state as high as feasible so that the preinjector becomes more compact and efficient.

There are three candidates for a high charge state, heavy ion source that might be developed for RHIC needs. They are: Electron Cyclotron Resonance (ECR) ion source, Electron Beam Ion Source (EBIS) and a laser driven source. The chances that an existing device could be scaled up to RHIC parameters within a reasonable time is one of the most important considerations when deciding what approach to pursue. We feel that laser heavy ion sources are the least promising on this time scale, which limited our choice to the other two approaches: ECR and EBIS. Although ECR ion sources are much further in their development and applications, an improvement in the yield by an order of magnitude would be necessary to match the design performance of the Tandem for gold ions. There are no simple guidelines on how to scale up an ECR source (rf frequency and/or power, magnetic field, size) and projections about the future performance seem to be quite speculative. It is also true that the existing EBIS devices have yields lower than needed by at least an order of magnitude, but they offer a lower emittance, higher charge states, and straightforward scaling to the size as required for RHIC. Thus, we have concentrated our efforts on studies and development of EBIS devices.

*Work performed under the auspices of the U.S. DOE.

## 2. STATE-OF-THE-ART OF EBIS DEVICES

In an EBIS, multiply charged ions are produced by electron impact in a magnetically confined electron beam of proper energy. The ions are confined radially by the space charge of the electron beam and axially by potentials on trap electrodes. The duration of the ion pulse can be adjusted in a wide range, without sacrificing total charge in a pulse, and this is one of the advantages of an EBIS because the duration of the injection interval into the synchrotron can be optimized. The available number of ions N(q) in the desired charge state q will be

$$N(q) = k\times k(q)\frac{1.05\times10^{13}\times I(e)\times L}{\sqrt{V(e)}\times q}$$

where I(e) and V(e) are electron beam current and voltage, resp., L is the length of the trap, k is the neutralization degree and k(q) the relative charge abundance. Values for k up to and above 0.5 are routinely achieved, while the relative charge abundance for heavy ions in charge states of interest is usually between 0.1 and 0.2.

There are a number of EBIS (and its close relative, EBIT) devices in operation, but except for a few they all have been custom built for atomic physics studies of ions in high charge states. For that application the source need only produce a relatively small number of ions, but in charge states that go to fully stripped xenon and neon-like uranium. There are two operating synchrotrons where an EBIS serves as the source of ions in the injector: SATURNE at Saclay, France and CRYRING at Stockholm, Sweden. Unfortunately, SATURNE will be shut down in the near future and there will be no further experiments performed on DIONE, its EBIS source. The synchrotron source requirements for fixed target nuclear physics experiments (SATURNE) and even more so for atomic physics studies (CRYRING) are modest and no special efforts have been devoted to developing a device with an order of magnitude higher yield that would be needed for a Collider such as RHIC.

DIONE is the only one of them where production of heavy metallic ions has been tried; however, because until very recently there was no possibility to further accelerate those ions, the tests were very limited [3]. Table I shows some of the results of the test with gold ions; the total amounts of positive charges extracted from the source when operated with lead and uranium were similar but charge state distributions were not measured. The charge state distribution shows an optimum around $Au^{48+}$, with about $3.5x10^7$ particles in this charge state, which is about 11% of the total beam. Evaporative ion cooling would probably make the distribution narrower. As this was just the first and only test with high intensity gold ions, the result is very encouraging. The peak for lead was around $Pb^{52+}$ and for uranium around $U^{55+}$. The Stockholm EBIS was tested mostly with argon and xenon [4]; neutralization degree values up to 60% were observed. Their experience has been that a longer confinement time not only moves the peak of the charge state distribution toward higher values, but that the distribution becomes narrower as well. Some results are shown in Table 1; the optimum charge state was 23+, with 13.3% abundance. A longer confinement time resulted in an optimum charge state of 45+, with 23% abundance (ion cooling was applied in this case).

## 3. RHIC REQUIREMENTS

The RHIC design calls for 57 bunches injected per ring, with a filling time not longer than one minute per ring in order to avoid intrabeam scattering losses during the injection. The present scenario envisages acceleration of three bunches per AGS cycle, each with $10^9$ particles, requiring a filling time of about 38 s per ring.

At this stage of the source development, selection of the best charge state from an EBIS is still a free parameter (which was not the case for the Tandem beam). From the point of view of the rest of the preinjector (RFQ, linac) it would be preferable to select a charge state as high as possible because this would make the preinjector less expensive and more compact. However, the yield of an EBIS is to the first approximation inversely proportional to the charge state, while on the other hand the stripping efficiency will be better if the initial charge state and therefore the output energy of the Booster is higher. These basic considerations lead to a compromise, in which gold ions in a charge state of about 35+ and uranium ions of about 45+ seem about optimum.

In order to reduce the requirements of an EBIS for RHIC, we propose to inject four EBIS pulses in a fast sequence into the Booster. The pulses will be short so that each occupies a single turn; the Booster acceptance should allow for such a stacking [5]. The overall efficiency for acceleration, single stage stripping, and transfer has been estimated to be about 25%; this means that the source should deliver $3x10^9$ $Au^{35+}$ particles per pulse in order to fill three RHIC bunches per cycle.

## 4. DESIGN OF AN EBIS FOR RHIC

It is clear that the yield of existing EBIS devices is not satisfactory for use on a large hadron collider, such as RHIC. In order to reach yields of several times $10^9$ heavy particles it will be necessary not only to increase the electron beam current by an order of magnitude, but optimize other parameters as well. Although, at present, there is still not enough information available to proceed to the design of the final EBIS device for RHIC, one can still establish several guidelines for the design and determine tentative parameters for such an device.

If the required source yield of gold ions in the charge state 35+ is $3x10^9$ per pulse, the corresponding number of positive charges is $1.05x10^{11}$. With evaporative ion cooling applied one can expect that the output ion beam will have about 20% in this charge state, so that the total number of positive charges extracted would be $5.25x10^{11}$. Neutralization efficiencies above 50% have been routinely achieved, which means that the capacity of the trap should be at least $1.1x10^{12}$ electron charges. First, we have selected L = 1.5 m as a reasonable limit for the trap length. The electron beam current is one of the most important parameters to determine the capacity of the trap; we have selected a value of I(e)=10 A as a realistic limit. The electron gun voltage of 20 kV is needed to reach a perveance value of 3.5 $AV^{-3/2}$, which is high but achievable. Such a voltage is not needed to reach the required ion charge states, and the electrons will be decelerated to 10 kV in the trap itself; a lower electron energy raises the trap capacity as well. The resulting design would have a capacity of 1.6 x $10^{12}$ charges, leaving a margin for the assumed value of the abundancy of the selected charge state. Table II shows a summary of parameters of this EBIS.

It is clear that the step from existing EBIS devices to the size required for RHIC is somewhat risky because of many questions to be addressed before embarking on the design itself (validity of scaling rules, high current electron guns, stability of high current electron beams, design of electron beam dump, etc.). Thus, we plan to first design and study a device of an intermediate size [6], with an electron beam current of 1-2 A, which should represent a step of about 5 above existing sources.

## 5. RFQ AND LINAC

Figure 1 shows the acceleration steps proposed for EBIS-based RHIC injection. As mentioned previously, our requirements for an EBIS for RHIC are $3x10^9$ $Au^{35+}$ particles per pulse. If these ions are extracted in 10 μs pulses, to allow single turn injection in the Booster, then the instantaneous current from the EBIS would be 1.6 mA of Au. These ions can be easily accelerated in an RFQ very similar to what already exists. The heavy ion RFQ built at LBL for the Bevalac comes very close to satisfying our needs. That 4-vane RFQ, operating at 200 MHz, accelerates ions with $q/m \geq 0.14$ from 8.5 keV/amu to 200 keV/amu[7]. The normalized acceptance of that RFQ is 0.5 π mm-mrad, larger than the expected EBIS emittance, based on the emittance of DIONE, of 0.1-0.3 π mm-mrad. With $q/m \geq 0.18$ from the EBIS, the source would operate on a high voltage platform of only < 50 kV to match the RFQ input velocity requirement. The only significant change from the LBL RFQ which would be desirable would be to increase the output energy to 300 keV/amu, to make the match to the linac easier.

To achieve a constant effective accelerating voltage over a wide range of mass and charge-to-mass ratios, the RFQ would be followed by a linac with independently phased cavities. Once again, a structure very close to our requirements already exists. The Atlas Positive-Ion Injector at Argonne uses a series of independently phased superconducting coaxial quarter wave resonator cavities to accelerate heavy ions with $q/m \geq 0.1$ from $\beta$=0.009 to 0.05 [8]. This linac, operating at 48 MHz, consists of 18 cavities, with 11 superconducting solenoids providing the transverse focusing. In our case, we envisage a similar number of cavities, operating at 200 MHz, to provide approximately 15 MV of acceleration voltage, giving > 2.5 MeV/amu. This keeps

Table I

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Au[a] | CHARGE STATE | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 |
| [5] | YIELD, $x10^7$ppp | 1.3 | 1.4 | 1.7 | 2.3 | 3.3 | 3.3 | 3.5 | 3.5 | 3.3 | 2.7 | 2.5 | 1.7 | 1.0 | 0.4 |
| | % | 3.6 | 3.9 | 4.8 | 6.6 | 9.4 | 9.7 | 10.9 | 10.8 | 10.8 | 9 | 8.3 | 5.9 | 3.3 | 1.5 |
| Xe[b] | CHARGE STATE | 20 | 21 | 22 | 23 | 24 | 25 | 26 | | | | | | | |
| [6] | YIELD, $x10^7$ | 5.3 | 7.3 | 10.4 | 13.3 | 12.7 | 8.5 | 3.5 | | | | | | | |
| | % | 7 | 10 | 15 | 20 | 19 | 14 | 6 | | | | | | | |

a TOTAL POSITIVE CHARGE: $1.5x10^{10}$; CONFINEMENT TIME: 0.16 s

b TOTAL POSITIVE CHARGE: $1.5x10^{10}$; CONFINEMENT TIME: 0.04 s

us comfortably below the space charge limit at Booster injection. Since $\beta\lambda$ is similar for the two linacs, the dynamics of the two should be quite similar.

## 6. INJECTION INTO THE BOOSTER

The EBIS pulse width can be varied with the extracted charge remaining constant. Therefore, the source will be operated with a 10 μs pulse width to allow single turn injection into the Booster. In order to reduce the source requirements, a method of accumulating four EBIS pulses in the Booster, prior to acceleration, has been considered by Y.Y. Lee [5]. Stacking into the momentum space of the Booster is proposed, similar to what is done at the CERN ISR and MIMAS at SATURNE. In our scenario, the first pulse is injected at the outer edge of the horizontal admittance. In between EBIS pulses the Booster field is raised by ~0.5% to move the injected pulse to a smaller radius, and the linac energy is changed by ~1% by a slight adjustment of cavity phases, to put the next pulse on the outer edge again. It is estimated that up to 4 pulses can be stacked in this way based on the present Booster rf system voltage limit. The EBIS operating with a repetition period of ~ 100 ms, and the Booster vacuum of $< 3 \times 10^{-11}$ Torr, it is estimated that stripping losses during accumulation will be approximately 5%.

Ions could be easily injected into the existing Tandem-to-Booster heavy ion transfer line, at a point very close to the Booster.

References


[1] RHIC Conceptual Design Report BNL 51932 (May 1986).
[2] RHIC Conceptual Design Report BNL 52195 (May 1989).
[3] B. Visentin, A. Courtois, R. Gobin, F. Harrault, and P.A.Leroy, paper presented at the 6th Int. Symp. on Electron Beam Ion Sources and Their Applications, Stockholm, June 1994.
[4] L. Liljeby, et al., ibid.
[5] Y.Y. Lee, private communication.
[6] E. Beebe, et al., paper presented at the 6th Int. Symp. on Electron Beam Ion Sources and Their Applications, Stockholm, June 1994.
[7] J. Staples, R. Gough, H. Schneider, and E. Zajec, Proc. 12th Intern. Conf. on High Energy Accel., Fermilab (1983) 516.
[8] R.C. Pardo, et al., Proc. 1993 Part. Accel. Conf., IEEE 93CH3279-7 (1993) 1694.


Table II

| | |
|---|---|
| Electron beam current | 10 A |
| Electron beam voltage | 20 kV |
| Length | 1.5 m |
| Trap capacity | $1.1 \times 10^{12}$ |
| Yield, positive charges | $5.25 \times 10^{11}$ |
| Yield, $Au^{35+}$, design value | $3 \times 10^9$ |
| Yield, $Pb^{53+}$, design value | $2 \times 10^9$ |

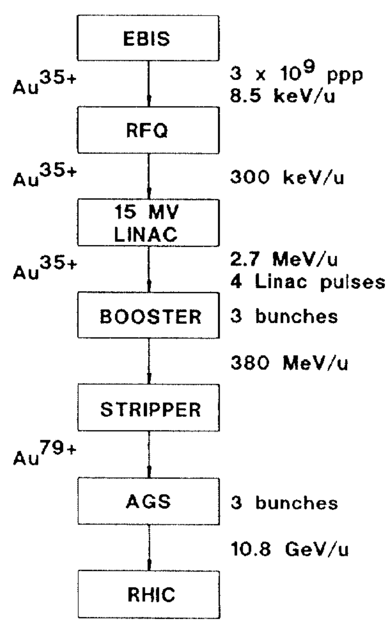


Fig. 1 - Block diagram of the acceleration stages for EBIS-based RHIC injection.