BNL-104799-2014-TECH

AGS/AD/Tech Note No. 383;BNL-104799-2014-IR

SOURCE OPTIONS FOR RHIC PREINJECTORS

J. Alessi

October 1993

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

DISCLAIMER

Accelerator Division
Alternating Gradient Synchrotron Department

BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, New York 11973

Accelerator Division
Technical Note

AGS/AD/Tech. Note No. 383

SOURCE OPTIONS FOR RHIC PREINJECTORS

J. Alessi, K. Prelec

October 25, 1993

SOURCE OPTIONS FOR RHIC PREINJECTORS

J. Alessi, K. Prelec

A. TANDEM AS THE PREINJECTOR FOR RHIC

In a multistage acceleration facility, such as RHIC, the acceleration scenario depends to a large degree on the availability and beam parameters of ions from 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. Two possible scenarios for acceleration of Au ions were then considered, the original, starting with a higher charge state of 33+ (Ref.1) and the revised, starting with a lower one, of 14+ (Ref.2,3).

The first RHIC scenario (Ref.1) envisaged a stripping of the tandem beam to a charge state 33+ before injection into the Booster, capture into <u>one bunch per cycle</u>, and one additional stripper to produce fully stripped ions for injection into AGS. This cycle would be repeated <u>57</u> times per ring. The recent experience with the acceleration of Au^{33+} in the AGS has shown that the overall efficiency between the injection into the Booster and the accelerated beam in the AGS is about 25%, in agreement with assumptions in Ref.1; this means that 4×10^9 ions have to be injected into the Booster to get 1×10^9 ions in a RHIC bunch (Table I, h=1). A long RHIC filling time is considered to be the main drawback of this scheme because of the effects of the intrabeam scattering in the coasting RHIC beam.

The present, revised RHIC scenario for acceleration of gold ions (Ref. 2,3) starts with the injection of ions in the charge state 14+ from one of the BNL tandems into the Booster, followed by stripping after the Booster to charge state 77+ for injection into the AGS, and finally, by stripping to charge state 79+ for injection into RHIC (Table I, h=3). The beam will be accelerated in batches of <u>three bunches per Booster/AGS cycle</u>, with the same final intensity of 10^9 per bunch when injected into RHIC. This cycle will be repeated <u>19</u> times per ring, providing the required 57 bunches. Although there is no experience with the acceleration of Au^{14+} in the Booster/AGS complex, it is assumed that the overall efficiency will not be much different from the previous case. Therefore, for 3×10^9 fully stripped ions injected into RHIC per cycle, there should be about 12×10^9 ions in the charge state 14+ injected into the Booster. Future tests will determine the best combination of the tandem current and pulse length to achieve this intensity.

B. A RHIC PREINJECTOR BASED ON A HIGH CHARGE STATE, HEAVY ION SOURCE

As a possible future improvement of the RHIC preinjector we have been considering to replace the tandems, including the 2000 ft transfer line, with a heavy ion source delivering high charge states of any ion up to uranium, followed by an RFQ and a short, possibly superconducting, linac. This preinjector would be located close to the Booster, eliminating the long transfer line. We feel that its performance should allow for future increases in RHIC luminosity and broaden the choice of available ion species. It should also be much simpler, is higher by about a factor of two than what the tandem has recently been delivering to the Booster (about 0.5 part. μA of 33+). However, one can expect that the injection interval for the ECR beam would also be shorter by a factor of 2-3, resulting in about the same injected and accelerated intensities as achieved now with the tandem. The beam intensity in the AGS, toward the end of the acceleration cycle, is presently about 3 x 10^8, which is a factor of three lower than needed for a single RHIC bunch or an order of magnitude lower than needed for three bunches per cycle; this is the performance one could expect from the best existing ECR sources (Table I).

The question now arises whether it is reasonable to expect a scaling-up of ECR source performance in beam intensity and charge states. The physics of such a plasma device is a complex one and does not allow simple projections of its performance when designing a new model; the experience with existing sources has shown that there appears a saturation effect when raising the rf power, and that the scaling with frequency does not follow expectations (Ref.5). In order to increase the yield one may have to increase the size of the source, which would probably result in an increase of the emittance, defeating in this way the objective. Our conclusion is that within a reasonable time of several years an ECR source may approach the performance as required by the original RHIC scenario (one bunch per cycle); any projection beyond that would be highly speculative because there are no simple guidelines for how to proceed with the design of an ECR source delivering an order of magnitude higher current, with the appropriate emittance. There are strong programs devoted to the development of ECR sources, both in this country and abroad, and it is preferable to follow their progress instead of embarking on a new program at BNL, waiting at the same time for the upcoming experience with the CERN ECR source of Pb ions.

3. EBIS

An EBIS is a magnetic solenoid in which ions are trapped radially by the space charge of a high current density electron beam, and axially by electrostatic barriers. It is most often a pulsed ion source although some operate steady state. The cycle begins with the injection of either atoms or singly charged ions into the trap. After the trap has been filled with a sufficient number of particles, the barriers are closed and the ionization process begins as a result of collisions with electrons in the electron beam. The ion charge state distribution tends to be narrow, evolving toward higher and higher optimum charge states as the confinement time increases. At the end of the cycle, when the desired optimum charge state has been reached, the trap is opened and a short pulse of ions extracted. Maximum number of positive charges that a trap could contain is equal to the number of electrons in the beam; this is proportional to the electron beam current and the length of the trap. Full charge neutralization cannot be achieved in practice, but values between 50% and 80% have been measured. The optimum charge state in the beam is a function of the product of the electron beam current density and the confinement time; depending on the ion species and its charge state it is possible to have from 20% to close to 100% in the optimum charge state.

In principle, an EBIS would be the ideal ion source for synchrotron and collider applications: it is a pulsed device, capable of delivering any ion, in requiring less maintenance and less staff to operate, resulting in a more reliable operation, at substantial savings. However, in order to optimize the design and do it at a reasonable cost, such a preinjector needs an ion source that is beyond what is presently available (Ref.4). Therefore, when considering any particular approach in the source design, one has to consider first, how close would an existing source, under best operating conditions, come to satisfying RHIC requirements, and second, what the prospects are for this source to be scaled up, so that eventually more than 10^9 fully stripped ions per bunch could be injected into RHIC. The rest of the system, an RFQ and the linac, is a technology already adopted by industry. However, from the point of view of the RFQ and the linac, it would be preferable to operate the source with as high a charge state as possible in order to make them more compact, efficient and less expensive.

1. Heavy ion source options

There are three candidates for a high charge state, heavy ion source, that might be developed to yield beams with parameters as required for RHIC now and in the future. They are: Electron Cyclotron Resonance (ECR) ion source, an Electron Beam Ion Source (EBIS) and a laser driven source. We shall only consider the first two approaches because laser sources are at present the least developed and seem to be the least promising. When comparing such different approaches as tandems, ECR sources and EBIS sources, we have to keep in mind that tandems and ECR sources are in principle constant current devices, while an EBIS is a constant charge per pulse device. Because of different modes of operation, the only valid criterion for comparison is the number of fully stripped particles delivered to RHIC.

2. ECR sources

An ECR source is a plasma device, with a minimum-B field configuration where a closed magnetic surface exists satisfying the electron cyclotron resonance condition at the frequency of microwaves used to produce the plasma and to heat plasma electrons. Ions are produced in collisions with energetic plasma electrons. ECR sources have initially been developed for steady state operation and there are many in use on cyclotrons and dc accelerators. This technology is mature, and sources can be obtained on a semicommercial basis. A few years ago, an "afterglow" effect was discovered when ECR sources were operated in a pulsed mode. After switching off the rf power, a short pulse ($\approx 1\ \mu s$) of high charge state ions appeared, with an intensity higher than the steady state yield by a factor of several (Ref.5). A source of Pb ions, operating in the afterglow, will be used at CERN because the beam intensity ($\approx 10^8$ per pulse) is satisfactory for fixed target experiments.

The emittance of ECR sources is larger than that of either the tandem or EBIS sources (from 0.5 to 1 π mm mrad for an ECR source, vs 0.1 to 0.3 π mm mrad for an EBIS and 0.04 π mm mrad for the tandem). The injection into the Booster would be a standard multiturn, one pulse per Booster cycle; however, the maximum injection interval will be shorter than is possible with the tandem because of the much larger ECR source emittance, resulting in fewer stacked turns. If we take the most recent data for Au ions from Ref. 5, one could expect in the afterglow mode about 30 μA in the charge state 27+ (1 part. μA). This intensity a beam with a good emittance. However, most of the existing devices of this type have been custom designed for use in atomic physics, where ions in the very highest charge states are needed, but where intensities as low as 10^5 particles per second are sufficient. The exception is the source DIONE at Saclay, providing very reliably many different ion species for the fixed target operation of the synchrotron SATURNE (Ref.6). Still, although the available charge states from EBIS devices are more than satisfactory for RHIC applications (e.g., Xe46+, Au69+), the highest intensity so far achieved is too low for RHIC. For example, the best result from DIONE was 2 x 10^{10} positive charges extracted in a pulse; however, the operation was limited to krypton and lighter elements because of the design of the RFQ (a program is presently underway to extend the available range of ion species to uranium, by producing U^{60+}). If this had been a beam of gold ions, and assuming that 20% of ions would have been in the optimum charge state of 33+, the number of particles would be only about 10^8 per pulse. However, by injecting multiple EBIS pulses it is possible to increase the Booster intensity easily by a factor of 3-4, as shown in Ref.7 (Table I). The pulse length from an EBIS can be adjusted down to ~ 10 μs, without changing the number of extracted charges. With such a short pulse it is possible to inject the ions during one turn in the Booster, recycle the EBIS and repeat the procedure several times. After filling the Booster with 3-4 pulses (the exact number will depend on EBIS beam parameters and on Booster acceptance), the acceleration cycle would begin. (This scheme is used at SATURNE, where a small synchrotron, MIMAS, is used to accumulate several pulses; such a scheme would be of no benefit with the tandem or ECR beams, which fill the Booster transverse acceptance through multiturn injection in a single pulse.)

One of the reasons that more powerful EBIS devices do not exist is the fact that there was little need for a high intensity, intermediate charge state ion source until the RHIC project. A few years ago the group at SATURNE, Saclay started a project to develop a next generation EBIS, called RHEA (Ref. 8), to serve as an improved source for SATURNE. The specifications for RHEA were within a factor of two from what would be needed for RHIC, but RHEA was recently terminated in view of the planned shutdown of the SATURNE accelerator.

When considering an EBIS as an option for the heavy ion source for RHIC, we were fortunate in that the scaling laws of EBIS devices are simple, in contrast to ECR sources. An EBIS for RHIC would require an increase by an order of magnitude in the electron beam current over existing devices; such current values have been reached and surpassed in other electron beam devices. With an electron beam current of 10 A and a length of the trap of 1.5 m, the source should deliver 5 x 10^{11} positive charges per pulse. Assuming again that the ions are gold and that 20% of the beam is in the optimum charge state of 33+, the number of particles per pulse would be 3 x 10^9. This number of particles, because of the pulse length of only 10 μs, corresponds to a current of 1600 el.μA or 48 part.μA. With the envisaged multipulse injection into the Booster the expected intensity of 10 x 10^9 particles per Booster/AGS cycle would be satisfactory for the three bunch per cycle operation. Of course, at this moment the selection of the best charge state from an EBIS is only tentative. One will have to optimize the whole system up to the AGS (source charge state, linac energy, Booster exit energy) to get the highest intensity for RHIC. In this respect an EBIS based system is more flexible than either the tandem or an ECR based system. For example, with a high enough charge state from an EBIS the acceleration time in the Booster may become shorter than presently required for the charge state 14+. If this results in a reduction of the Booster/AGS cycle as well, it may be possible to increase the intensity by compressing the Booster beam into only two bunches per cycle instead of three, without affecting very much the RHIC filling time.

C. CONCLUSIONS

It is our conclusion that it is prudent for BNL to continue the pursuit of the EBIS option for an advanced heavy ion source for RHIC, at least in the near term. The inherent flexibility of an EBIS based system, compared to the tandem, offers several advantages:

- any ion species,
- short transport line,
- lower operating costs,
- better injection efficiency if a higher injection energy is selected,
- a higher space charge limit at injection due to the higher injection energy,
- smaller Booster emittance due to a single turn injection,
- a higher Booster intensity by using multipulse injection,
- rapid and clean switching from one species to another.

Compared to an ECR based system, an EBIS based system has advantages as well:

- better injection efficiency due to the single turn/multipulse injection (EBIS) vs multiturn injection (ECR),
- a larger ECR beam emittance reduces the maximum number of injected turns compared to the tandem beam,
- higher charge states from an EBIS result in a smaller and less expensive RFQ/linac system,
- a straightforward scaling to the size as required for RHIC (in principle, there is need to scale up the electron beam current only, while values of most parameters, such as electron current density, source vacuum, and magnetic field, are at or below those in a typical existing EBIS; this is not true for scaling an ECR source where the rf power, frequency, magnetic field and size may have to be increased simultaneously).

D. BNL PROGRAM

At present, there is a low intensity EBIS being put into operation at BNL (obtained on a long-term loan from Sandia Laboratory where it was designed and built for atomic physics studies with ions up to U^{82+}); this part of the work was funded through BNL's Directed Research Program. It will serve as an intermediate step in the development and design of a source capable of delivering heavy ion beams as required for RHIC. The objective of the first phase, at a rather limited funding level over three years, is to modify the device by raising the electron beam current to 1 to 2 A and to check the yield compared to predicted values; several ion species would be investigated, including gold and uranium.

Should the results in the first phase warrant it, we would proceed to the design of the device for RHIC, together with the design of the rest of the preinjector (RFQ, linac), with 1999 as the goal for an operating system. We presently feel that the EBIS approach appears to be most promising for RHIC. Should, however, at the end of the first phase an ECR source prove to be a better choice, we could proceed with that option.

REFERENCES

1. Conceptual Design of the Relativistic Heavy Ion Collider RHIC, BNL-51932 (May 1986).

2. Conceptual Design of the Relativistic Heavy Ion Collider RHIC, BNL-52195 (May 1989).

3. H. Foelsche, et al. "The Relativistic Heavy Ion Collider, RHIC," in "Advances of Accelerator Physics and Technology," H. Schopper, ed., World Scientific Publishing Co., Singapore, 1993, p.104; also, BNL-47751.

4. K. Prelec, et al., Nucl. Instr. Methods A295, 21 (1990)

5. D. Hitz, et al., and G. Melin, et al., 11th ECR Workshop, Groningen, May 1993.

6. B. Visentin, et al., 5th Int. Conf. on Ion Sources, Beijing, August 1993, and B. Visentin, private communication.

7. Y.Y. Lee, AGS Tech. Note #362 (July 1992).

8. J. Faure, et al., Proc. 5th Int. Symp. on Electron Beam Ion Sources and their Applications, Dubna, USSR, Sept. 1991, p.76.

TABLE I

Estimates of RHIC Performance, for Several Options
(Au Operation)

	Q	I(pμA)	Normalized Emittance π mm mrad	# turns injected	$N_{Booster}$ (x10^9)	h	Booster bunch (x10^9)	RHIC[a] bunch (x10^9)	Filling[b] time (s) (1 ring)
Tandem (RHIC baseline)	33+	3	0.04	≥ 14	4	1	4	1	114
	14+	15	0.04	≥ 9	12	3	4	1	38
ECR	27+	1.1	0.5-1.0	10-15[c]	0.8-1.2	1	0.8-1.2	0.2-0.3	114
EBIS	33+	1.9[d] (1.2x10^8/ pulse)	0.1-0.3	1 turn, 4 pulses	0.48	1	0.48	0.12[e]	114
Proposed RHIC EBIS	33+	48[d] (3x10^9/ pulse)	0.1-0.3	1 turn, 4 pulses	12	3	4	1[e]	38

[a]Assumes 25% total efficiency for stripping, acceleration and transfer.
[b]Assumes 2 second cycle time for Booster/AGS.
[c]Estimated maximum based on previous AGS/proton experience.
[d]Current in pμA, assuming a 10 μs pulse length.
[e]For an EBIS, this value could be higher because of a higher Booster injection efficiency.