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THE HEAVY ION INJECTION SCHEME FOR RHIC*

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Abstract

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven has a multi-component injection system. The Collider requires very heavy ions such as $^{197}_{79}Au$ to be injected fully stripped of atomic electrons, at a kinetic energy of approximately 10 GeV/nucleon. However, the heavy ions are produced initially at a negative ion source and accelerated first in a 15 MV Tandem. These partially stripped ions have a kinetic energy of approximately 1 MeV/nucleon on leaving the Tandem. In order to achieve the injection requirements for RHIC, the partially stripped ions are accelerated in the Booster (currently under construction) and pass through a stripping foil on their way to the Alternating Gradient Synchrotron (AGS), where they are further accelerated before injection into RHIC. Recent theoretical calculations have shown quite convincingly that very heavy ions with 2 electrons in the filled K-shell may be accelerated with negligible loss in the AGS.

I. Description of the Facility

I.1 Collider Performance

The complete RHIC facility will be a complex set of accelerators and beam transfer equipmment connecting them.[1] The final accelerator, the collider itself, has a circumference of 3883.8 m, and a magnetic field generated by superconducting magnets of about 3.45 T. With these parameters, the maximum energy is ~100 GeV/u for gold ions. The design specifications of RHIC call for ~1×10^9 ions per bunch for gold or ~6×10^{10} ions in 57 bunches in each ring of the collider.[1] For head-on collisions with gold beams at top energy, a luminosity of ~$2\times10^{26}cm^{-2}sec^{-1}$ averaged over a 10 h beam lifetime is expected.[1]

For heavy ion injection into RHIC, the rigidity values of the collider at injection ($B\rho$ = 96.7 T·m), and the desired beam lifetime of 10 hours within RHIC demand that fully stripped ions be injected at kinetic energies in excess of 10 GeV/u.

II. RHIC Injector Complex

II.1 Overview

The existing accelerator complex at Brookhaven (Figure 1) consisting of the Tandem Van de Graaff, the Heavy Ion Transfer line, the Alternating Gradient Synchrotron and the Booster Synchrotron will serve as the injector of heavy ions for RHIC. Operation of the AGS for heavy ion experiments started in October 1986 with the delivery of O^{8+} beams. Completion of the AGS booster synchrotron in 1991 will extend the mass range to the heaviest ions, typically ^{179}Au, with ^{238}U a definite possibility. In this paper, the multi-component injection mode of the collider will be discussed with special emphasis on the expected particle intensities.

The atomic electrons are stripped by passing the ions through foils S_T, S_B and S_A at various stages of acceleration. The location of these foils is shown in Fig. 2. After passage through the foils, a broad distribution of charge states results. Normally only the most probable charge state is accelerated at the next stage.

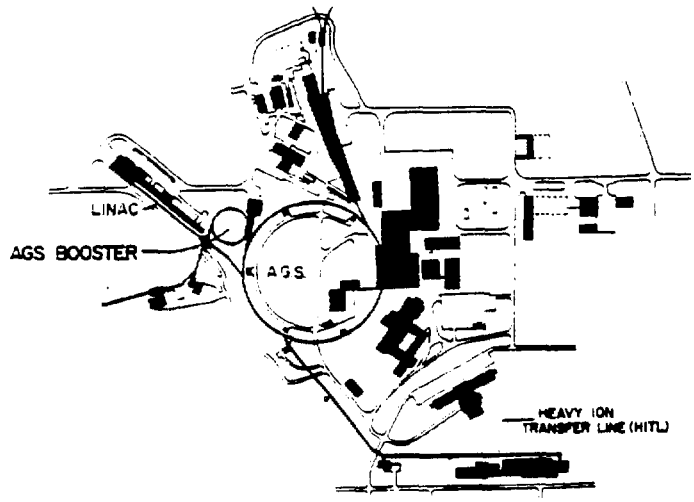

Fig. 1. Overview of RHIC Injector Complex

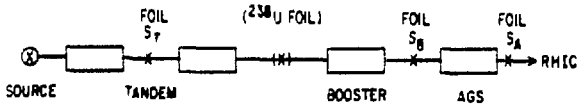

Fig. 2. Location of Stripping Foils

The design specifications of RHIC call for 10^9 particles per bunch of fully stripped ^{197}Au ions. In order to achieve this value, several limiting characteristics of the injection components must be respected.[2] These include the vacuum of the AGS (10^{-7} Torr at present, 10^{-8} Torr after upgrade program), which prohibits the acceleration of heavy ions with many atomic electrons, the lowest achievable frequency (215 kHz) of the Booster cavities, the stripping foil efficiencies, and the current technological limitations of heavy ion sources at the Tandem. Respecting these constraints, it is possible to achieve 10^9 particles per bunch for ^{197}Au. However, the wide variation of atomic structure across the periodic table prevents a simple uniform injection scheme for all heavy ion species.

II.2 The Tandem Van de Graaf

The acceleration of heavy ion beams will be started using one of two existing Tandem Van de Graaff accelerators. The construction of a transfer line from the Tandem to the AGS, located in a

*Work performed under the auspices of the U.S. Department of Energy

1800 ft long tunnel, was completed in 1986. Also shown in Fig. 1 is the extended heavy ion transfer line which will enable heavy ions to be injected into the Booster.

Up to 240 μA of usable ^{197}Au are now reliably available at the Tandem source.[3] More recently, a new experimental source has been investigated at Brookhaven, for which currents of up to 10 mA of ^{197}Au have been claimed elsewhere.[4] It remains to be seen how much of this current is available for injection into the small Tandem aperture.

Table II-1 shows the Tandem operation parameters for a high voltage terminal potential of 15 MV. S_T and Q_T are the stripping efficiency and most probable charge state after the negative ions have been accelerated to the high voltage terminal and stripped in the thin carbon foil inside the Tandem. The ions leave the accelerator with an energy $(1+Q_T)\times 15$ MV. For Table II-1, a source current of 200 μA and a pulse length of 110 μs was assumed. The transmission efficiency for the Tandem was taken to be 75%.

Uranium is shown as a viable species because of recent calculations showing that it is possible to accelerate ^{238}U in a charge 90$^+$ state within the AGS.[5] In the future, this nucleus will be of great interest for both fixed target (AGS) and RHIC operation because of the enormous electric fields generated in nuclear collisions. It is noted however, that at the present time an adequate source for Uranium does not exist at Brookhaven.

Table II-1. Tandem Operation Parameters

	Q_T	S_T	Kin. Energy MeV/u	β	Ions/Pulse*
Deuterium	+1	70%	15.0	0.177	7.2×10^{10}
Oxygen	+6	39%	6.56	0.118	4.0×10^{10}
Silicon	+9	30%	5.36	0.107	3.1×10^{10}
Copper	+11	27%	2.86	0.078	2.8×10^{10}
Iodine	+13	20%	1.65	0.059	2.1×10^{10}
Gold†	+14	12%	1.07	0.048	1.2×10^{10}
Uranium§	+35	3.4%	0.882	0.043	3.6×10^{9}

*75% transmission efficiency, 200 μA source current, 110 μs pulse length.
†Equilibrium Charge State 13$^+$.
§Requires Source Development and additional stripping foil at Tandem exit.

In order to accommodate Uranium in the Booster and AGS, a second stripping foil will be needed between the Tandem and Booster. This foil will produce Uranium in an equilibrium charge state of 35$^+$, and will deplete the number of ions per Tandem pulse to 3.6×10^9 (stripping foil efficiency = 17%).

II.3 The Booster as Preinjector to RHIC

This synchrotron will be commissioned in the summer of 1991 for heavy ions.

The extra kinetic energy provided by the Booster will enable additional atomic electrons to be stripped when passing through foil S_B (see Fig. 2) situated between Booster and AGS. Hence, nuclei heavier than ^{28}Si will survive acceleration in the AGS vacuum, and not be lost to electron capture or stripping reactions. The Booster vacuum of 10^{-10} Torr seems adequate for the survival of essentially all the heavy ion beam during the acceleration cycle.

The beam is injected horizontally into the Booster, and stacked in betatron phase space by filling the machine circumference with the Tandem pulse for some number of consecutive turns. The betatron acceptance is assumed to be 50 π mm·mrad in both planes.

The beam is captured at injection by an rf system of harmonic number h=2 for light and medium mass ions, and with h=3 for heavy ions such as Au.[6] After injection is completed, the rf voltage is adiabatically increased to produce a bucket area of ~0.07 eV·sec/u. Theoretical studies show that if the rf bucket grows to full size in 10 msec (approximately 10 synchrotron oscillation periods), 97% of the beam can be captured.[5,6] Following capture, the bunched beam is accelerated. The three particle bunches are ejected simultaneously (within one revolution) from the Booster.

In Table II-3, the expected particle numbers per bunch in the Booster are shown together with the rf frequency ranges, and the normalized emittance. The same Tandem pulse length and source current as in Table II-1 were used here. In Table II-3, the particle numbers per bunch were calculated assuming an eight turn injection of 100% efficiency.

Table II-3. Number of Heavy Ions per bunch in the Booster

Species	d	^{16}O	^{28}Si	^{63}Cu	^{127}I	^{197}Au	^{238}U	Units
Harmonic, h	1	2	2	2	3	3	3	
f_{rf} @ injection	2.62	350	318	232	264	213	190	kHz
f_{rf} @ top energy	1.40	2.68	2.60	2.08	2.23	1.66	2.85	MHz
Top kinetic energy	1857	1249	998	376	164	72	279	MeV/u
Ions/bunch†	19.9	8.32	7.06	8.7	5.64	4.12	1.2‡	$\times10^9$
normalized emittance	8.8	6.0	5.4	3.9	3.0	2.3	2.2	π mm-mrad
stripping effic. @ S_B	-	100	100	100	40	50	50	%
Q after S_B	1	8	14	29	53	77	90	
Ions/bunch after S_B	19.9	8.32	7.06	8.7	2.26	2.0	0.6	$\times10^9$
norm. emittance after S_B	8.8	6.1	5.5	4.1	3.6	4.0	2.3	π mm-mrad

†A Tandem Source Current of 200 μA and a Pulse Length of 110 μs were assumed.
‡Requires source development.

The normalized emittance after the stripping foil S_B was calculated from a standard multiple Coulomb scattering formalism.[7]

After extraction from the Booster, and on their way to the AGS, the ions pass through a stripping target. Experimental knowledge[8] indicates that for atomic number ≤ 63 the ions will be fully stripped with 100% efficiency. For ^{127}I, the fully stripped state is achieved with 40% efficiency[8] on passing through foil S_B. The heavier ions such as ^{197}Au or ^{238}U are stripped to a filled K-shell or two-electron atom. The stripping efficiency for ^{238}U in a charge 90$^+$ state is also known experimentally,[9] and peaks at 50% for a kinetic energy of 220 MeV/u. The stripping efficiency for 70 MeV/u ^{197}Au to a charge 77$^+$ state was deduced from theoretical work[10] on ^{208}Pb for the CERN SPS program. The result is considered reasonable, and will be known with more precision after a planned experiment[11] at Berkeley in the fall of 1989.

The stripping in foil S_B is accomplished with a foil of copper that, for gold, is 35 mg/cm^2 thick. If one does not allow more than 10% growth in the emittance of 50 π mm·mrad, the stripper foil must be installed in a location where the lattice beta function does not exceed 2.6 m in both planes. This condition is accomplished using two pairs of quadrupole doublets.

II.4 The AGS Component of the RHIC Injector Complex

Inside the AGS all heavy ions with A ≤ 127 will be fully stripped. Heavy ions such as ^{197}Au^{77+} and ^{238}U^{90+} will be accelerated with 2 electrons in a filled K-shell.

The present vacuum inside the AGS is 10^{-7} Torr, with improvement to 10^{-8} Torr expected in the very near future. For an AGS vacuum pressure of 10^{-7} Torr, the beam losses of heavy ions with A < 100 will be less than 1%. This loss mechanism is mainly due to electron capture from the residual gas ions (50% H_2, 50% CO). For the heavier ions with two electrons in a filled K-shell both electron knock-out and capture are possible. To estimate the depletion of these ions during the AGS acceleration cycle, the depletion rate λ(t) was calculated from the formula,[5]

$$\lambda(t) = \beta(t)\, c \sum_i n_i\, \sigma_{ig}$$

where β(t) is the velocity of the ions, n_i is the density of gas ions in the AGS, and σ_{ig} is the interaction cross section for the accelerating ion on an individual gas species. σ_{ig} is the sum of the knock-out cross section σ^k_{ig}, and the capture cross section σ^c_{ig}. For the knock-out cross section we assume the theory of Bethe,[12] which has been teste , for Uranium by Gould et al. In this theory σ^k_{ig} is given by,[5,12]

$$\sigma_{ng}^{k} = 4\pi a_o^2 \left(\frac{\alpha}{\beta}\right)^2 \frac{R_\infty}{B_n} Z_i(1+Z_i)\, f_k \left\{ \ell n\left(\frac{2\beta\gamma\alpha R_\infty}{0.048\ B_n}\right)\right\}$$

where α is the fine structure constant, a_o the Bohr radius of the Hydrogen atom, Z_i the atomic number of the gas molecule, R_∞ the Rydberg constant, B_n the electron binding energy, and f_k an oscillator constant that takes the value 0.58 for ^{238}U in a charge 90^+ state. The kinematic factors, β,γ are given by the acceleration cycle. The capture cross section (Radiative Electron Capture) into the n'th shell is given by[5,13]

$$\sigma_{REC} = Z_i\left((\gamma-1)+B_n/m_e c^2\right)^2\ \sigma(\varepsilon)/(\gamma^2-1)$$

where m_e is the mass of the electron, and B_n is the binding energy in the n'th shell. $\sigma(\varepsilon)$ is the photoionization cross section, which is tabulated for various shells in a range of nuclei, and ε is the photon energy given by $\varepsilon = m_e c^2\ (\gamma-1) + B_n$.

Figure II-3 shows the depletion of ions for a 0.6 sec acceleration cycle. The depletion is defined by $D(t) \propto \exp(-\int_o^t \lambda(t')dt')$, and two values of the AGS vacuum were assumed (10^{-7} Torr and 10^{-8} Torr). It can be seen that the beam depletion is only a few percent.

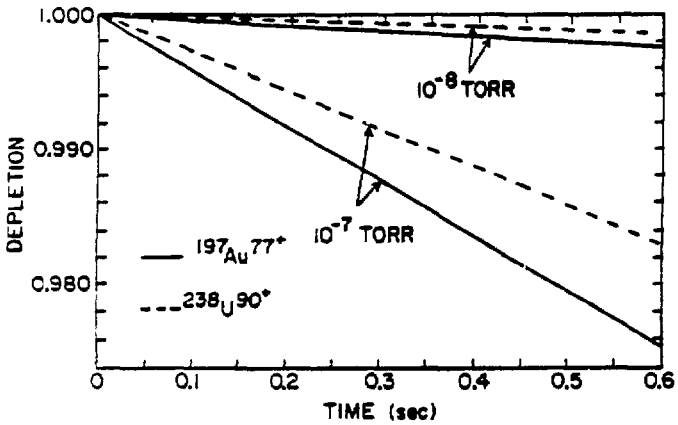

Fig. II-3. Depletion of beam in the AGS.

After acceleration in the AGS, the bunches are transferred into RHIC. For the heaviest ions, it is necessary to pass through the stripping foil S_A, to remove the last two electrons in the K-shell. The position of this foil is shown schematically in Fig. II-2. At the top AGS energies (10.4 GeV for ^{197}Au), a design beta function value of 50 m, and a rms scattering angle of 0.046 mrad for a 100 mg/cm^2 copper foil,[7] would correspond to an emittance growth of only 0.033 π mm·mrad. At these energies, negligible losses in particle numbers per bunch are expected during the final stripping process.

Taking into account the increase in the beam emittance due to the final stripping, the emittance values given in Table II-3 are just about those the beam would have when injected into the AGS. These emittances are considerably smaller than the ring betatron acceptance.

III. Discussion

The design criteria for RHIC demand that a range of species of ions be available for storage and acceleration. The wide variety of atomic properties associated with partially stripped heavy ions, together with the hardware constraints of the various preaccelerators of the injection complex severly limit the possible modes of injection into the collider. However, using properties of K-shell atomic structure, the luminosity demands of RHIC can be readily met, and indeed the range of ions available for acceleration can be extended to include Uranium.

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