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An Alternative Injection Scheme for Heavy Ions into RHIC

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I. Introduction

The most recent design performance of RHIC[1] is based on an h=1 radio frequency (rf) mode for the Booster component of the injector. This mode was selected in order to achieve the desired number of heavy ions per bunch for Au within RHIC, given the expected source currents at the Tandem,[1,2] and the constraint of only accelerating fully stripped ions[1,2] in the AGS. The desired particle intensity within RHIC is 1.0×10^9 ions/bunch for Au.

In contrast, a recent study on the feasibility of accelerating Uranium in the AGS and RHIC[3], showed that even with present day vacuum conditions (10^{-7} Torr in the AGS), it would be possible to accelerate Uranium in a charge 90^+ state and lose only a few percent[3] of the beam. This small loss is primarily due to the strong binding energy of the K-shell electrons.

In this paper, we extend the idea of accelerating ions with a filled K-shell to Au. In this way, it is shown that using a different arrangement of stripping foils, and accelerating K-shell ions in the AGS, an h=3 mode for Au is possible in the Booster. This new arrangement also satisfies required particle numbers per bunch for Au within RHIC. For completeness, the injection scheme and expected particle intensities for ^{12}C, ^{16}O, ^{28}Si, ^{32}S, and ^{127}I are tabulated, and the injection scheme for ^{238}U is also shown as a separate section.

Throughout the following discussion, we shall assume that the lowest rf frequency in the Booster is 215 KHz.

II. The Tandem and the Booster

In Figure 1, the injection scheme from the 1986 CDR manual[1] is shown schematically. The particle intensities for this scheme, with a variety of heavy ions, and a variety of Tandem currents, has been tabulated several times.[1,2] In Figure 2, the alternative injection scheme is shown. The intermediate stripping foil S_F has been removed, relative to Figure 1. In addition there is a new stripping foil S_A between the AGS and RHIC. Let us tabulate, amongst other things, the expected number of particles per bunch in the Booster, assuming an ion source current of 200 μA and a pulse length of 110 μs. This source current was recently achieved[4] for Au, at the Tandem.

We assume a transmission efficiency of 75% in the 15 MV Tandem[2] and a stacking efficiency of 100% for an 8 turn injection into the Booster.[2]

Table 1. Number of Particles per bunch in the Booster for Injection Scheme of Figure 2. A Tandem Source Current of 200 μA and a Pulse Length of 110 μs was assumed.

Species	^{12}C	^{16}O	^{28}Si	^{32}S	^{63}Cu	^{127}I	^{197}Au
Stripping Foil Efficiency at Foil S_T	39%	39%	30%	30%	27%	20%	12%
Charge at Foil S_T	5	6	9	9	11	13	14
Velocity on Entering Booster	β=.1261	β=.118	β=.107	β=.0999	β=.0781	β=.0595	β=.0478
Booster Synchronous Frequency at Injection	187 KHz	175 KHz	159 KHz	148 KHz	116 KHz	88 KHz	71 KHz
Booster Harmonic Number	2	2	2	2	2	3	3
No. of Particles per bunch in Booster	7.7×10^9	8.32×10^9	7.06×10^9	7.54×10^9	8.7×10^9	5.64×10^9	4.12×10^9
Booster Space* Charge Limit Per Bunch	3.3×10^{10}	3.85×10^{10}	2.44×10^{10}	2.44×10^{10}	1.8×10^{10}	1.0×10^{10}	1.0×10^{10}
Maximum Kinetic Energy at Booster	1350 MeV/A	1162MeV/A	926.2MeV/A	755.4MeV/A	345.2MeV/A	131.4MeV/A	65.5MeV/A
RF Frequency at Top Energy	2.71 MHz	2.66 MHz	2.57 MHz	2.48 MHz	2.03 MHz	2.15 MHz	1.5 MHz

*Based on standard formula[2] that relates space charge limit to tune shift.

This table clearly shows that for the light and medium mass ions (A=12-63), an h=2 mode in the Booster is desirable. For heavier masses (A=127,197) the h=3 mode is desirable. However, by removing the second foil a large increase in particle intensity is realized[2] (a factor of 5 for Au) and this more than offsets the reduction in the number of particles per bunch when going from h=1 to h=3. For the lighter ions (A=12,16), the gain in particle intensity by removing foil S_F is more limited,[2] and hence the overall number of ions/bunch in the Booster is a factor of .56 less for this new scheme of injection. Thus, for ^{12}C or ^{16}O, a source current of 360 μA would be required with h=2 and Figure 2, in order to be equivalent with h=1 and Figure 1.

Table 1 also shows that the Booster is not space charge limited with this injection mode for 200 μA, and that future developments in source technology (approximately a factor of 2 increase) may be accommodated.

It is important to note that the charge state selected for ^{197}Au is the 14^+ state. This is one unit larger than the equilibrium value, and the stripping foil efficiency at foil S_T has been reduced from 19% for charge 13^+ to 12% for charge 14^+. This reduction is theoretical in nature, but is considered very reasonable[4] in view of known characteristics of charge distributions from a foil.

III. AGS Operation

Before discussing the AGS operation, let us tabulate the expected initial number of particles per bunch at the AGS, after the bunches from the Booster have traversed foil S_B in Figure 2.

Table 2. Expected number of particles per bunch in AGS, assuming injection scheme of Figure 2.

Species	^{12}C	^{16}O	^{28}Si	^{32}S	^{63}Cu	^{127}I	^{197}Au
Max. Kinetic Energy at Booster	1350.8MeV/A	1162.3MeV/A	926.2MeV/A	755.4Mev/A	345.2MeV/A	131.4MeV/A	65.5MeV/A
Stripping Foil Efficiency at Foil S_B	100%	100%	100%	100%	100%	40%	50%
Charge at Foil S_B	6	8	14	16	29	53	77
AGS Synchronous Frequency at Injection	339.3KHz	332.8KHz	321.6KHz	310 KHZ	256 KHz	179 KHz	133 KHz
AGS RF Frequency at Injection h=12	4.0 MHz	4.0 MHz	3.85 MHz	3.72 MHz	3.07 MHz	2.15 MHz	1.6 MHz
No. of Particles per bunch in AGS	$7.76x10^9$	$8.32x10^9$	$7.06x10^9$	$7.54x10^9$	$8.7x10^9$	$2.25x10^9$	$2.0x10^9$
Max. Kinetic Energy at AGS	13.51GeV/A	13.51GeV/A	13.51GeV/A	13.51GeV/A	12.36GeV/A	11.11GeV/A	10.35GeV/A

We see from this table that for all ions with A<197, only fully stripped ions will be accelerated in the AGS. Of course, this result is the same as the initial scheme in Figure 1. The stripping foil efficiences at S_B, for A=12-127, came from experimental results.[5] As mentioned in the last section, the particle intensity per bunch for ^{12}C or ^{16}O is less in Figure 2 than Figure 1 by a factor of .56. For ^{28}Si, ^{32}S and ^{63}Cu we would gain over the traditional arrangement. For ^{127}I, the 40% stripping efficiency[5] at foil S_B for fully stripped ions means we lose a factor of .667 overall in the number of particles per bunch.

For the more important Au ions the news is good. This scheme results in a factor of two increase in the particle intensity per bunch. This is a result of the 50% stripping foil efficiency at S_B to produce a charge 77^+

state of Au. This efficiency is soundly based on estimates for Pb,[6] to be used in the CERN injection scheme. However, an experimental measurement of this efficiency, at this energy will be carried out at Berkeley.[7] In a charge 77^+ state, Au has its K-shell filled. In Figure 3, we show the depletion of Au ions for two AGS vacuums (10^{-7} Torr and 10^{-8} Torr) using the theory developed before for depleting Uranium ions.[3] It can be seen that for an acceleration cycle of .6 seconds, only a few percent of the beam will be lost to electron knock-out or capture processes. The large binding energy of the K-shell electrons (93.5 KeV) ensures these ions will survive the acceleration cycle. It is noted that the AGS vacuum was taken to be 50% H_2 amd 50% CO.

It is important to note the low value of the rf frequency at injection (1.6 MHz) for Au. This is below the minimum rf value quoted,[1] and strongly suggests that the existing AGS cavity with a lower frequency (V=17,000 Volts f=1.6 MHz) be retained[8] for the initial acceleration of Au in the AGS.

The stripping of the two K-shell electrons at foil S_A takes place with 100% efficiency at the energies tabulated.

Overall, scheme 2 is better than the traditional one and allows very heavy ions such as Au to be accelerated at the initial Booster commission.

IV. Accelerating Uranium

There is considerable experimental interest in accelerating Uranium for both fixed target and collider modes. The extra Coulomb field strength will allow the study of non-perturbative QED effects.

Two reports have already been written on accelerating Uranium within the AGS and RHIC.[3,9] The conclusions will not be repeated here, but for completeness we note that Uranium will require the second stripping foil to be in place in order to achieve the kinetic energy of 220 MeV/A in the Booster necessary for stripping to charge 90^+ in foil S_B. The enormous binding energy of Uranium K-shell electrons (132.5 KeV) ensures that the depletion rate in the AGS vacuum will be negligible. This depletion is shown in Figure 4 for AGS vacuum of 10^{-7} Torr and 10^{-8} Torr.

V. Conclusions and Suggestions

(1) As shown in this manuscript, a viable and robust method of injecting heavy ions into RHIC exists and this does not require the traditional h=1 mode of operation for the Booster rf. It is particularly important to note that the wide and individual characteristics of atomic structure dictate that a simple uniform injection scheme for all heavy ion species does not exist.

(2) For the all important Au ions, the scheme outlined here appears to produce a factor of two increase in the number of particles per bunch over the traditional injection scheme. Two stripping foil measurements need to be carried out to confirm this, and these measurements will take place in the near future.

<u>It appears that Au ions can be accelerated, via the scheme outlined here, using hardware components available on the initial day of Booster operation.</u>

(3) The "old rf system", (V=17,000 Volts, f=1.5 MHz) should be retained at the AGS for the acceleration of Au in this mode.

(4) Within the new acceleration mode outlined here, the source current at the Tandem could be increased by a factor of two before space charge limitations set in.

(5) The feasibility of accelerating Uranium strongly implies resources be made available for the development of Uranium ion sources at the Tandem.

References

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3. Accelerating Uranium in RHIC-II Surviving the AGS vacuum. M.J. Rhoades-Brown and H. Gould, RHIC Technical Note 38.

4. P. Thieberger, private communication.

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8. G. Raka, private communication.

9. Accelerating Uranium in RHIC - I The problems and role of an intermediate Linac. M.J. Rhoades-Brown, RHIC Technical Note 35.

<u>Figure Captions</u>

Figure 1 Schematic drawing of traditional injection scheme for RHIC.

Figure 2 Schematic drawing of new injection scheme outlined here.

Figure 3 Plot of depletion for Au ions in a charge 77 state in AGS vacuum.

Figure 4 Plot of depletion for U ions in a charge 90 state in AGS vacuum. The results shown here are different from reference 3 because of the vacuum gas constituents.

FIGURE 1

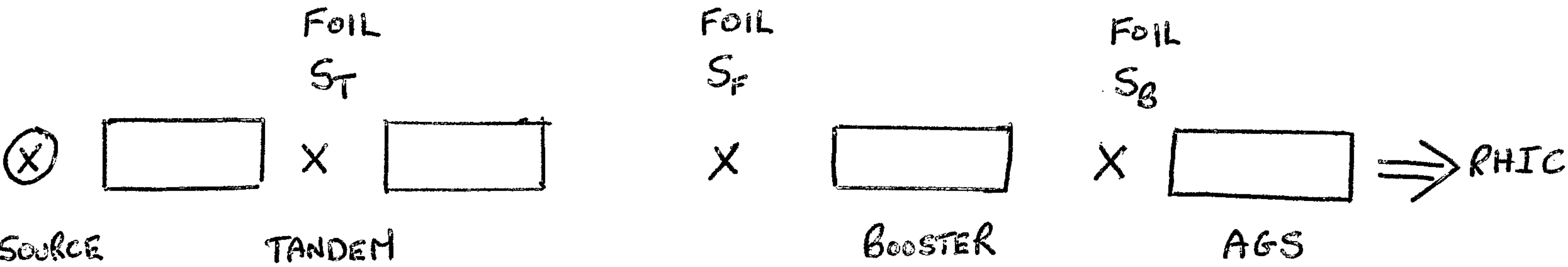


FIGURE 2

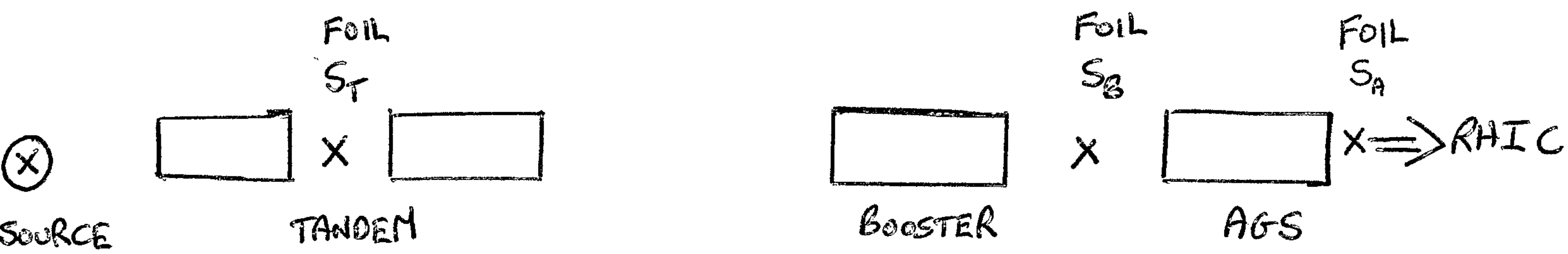
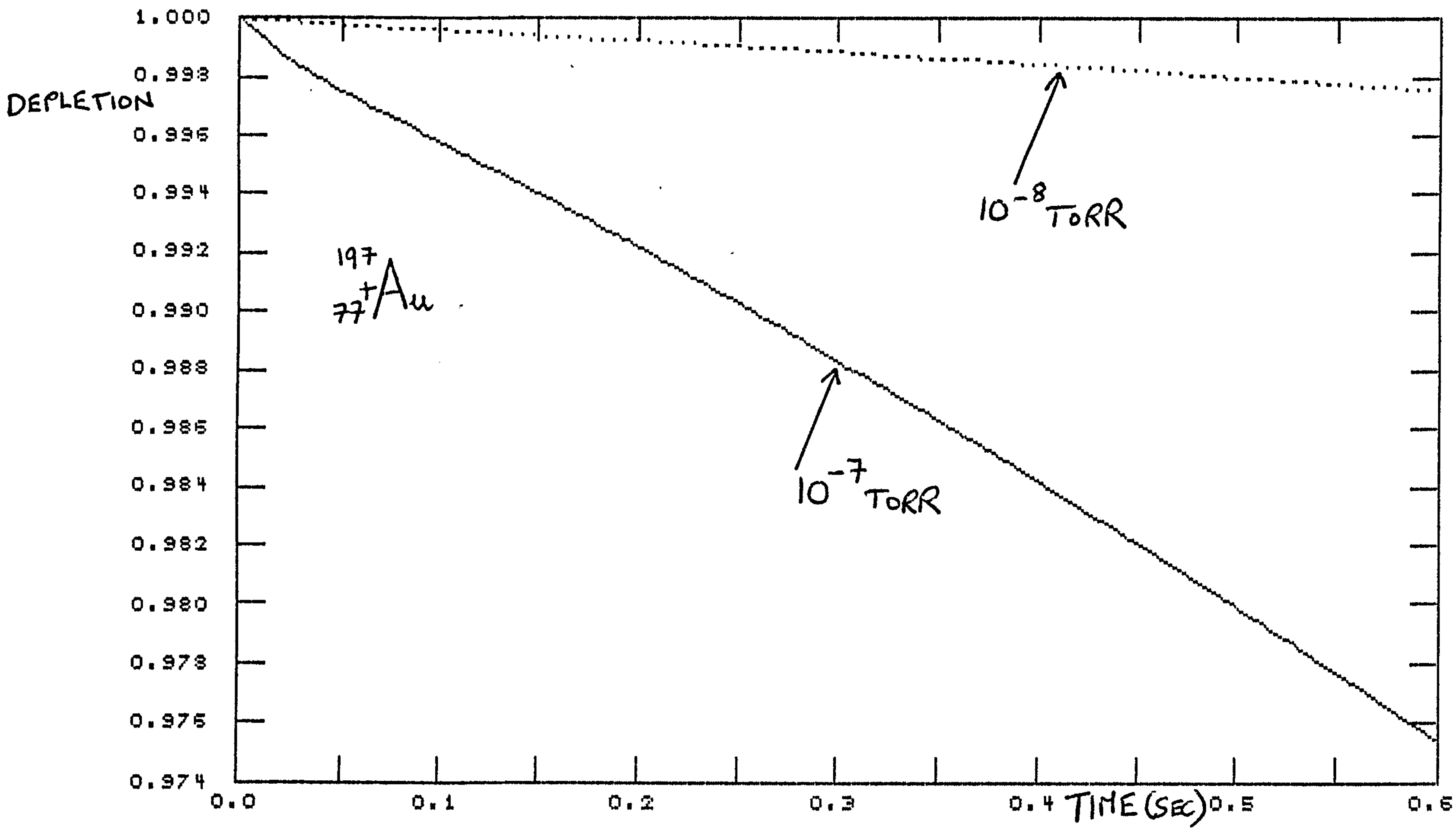


FIGURE 3



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0.1
0.2
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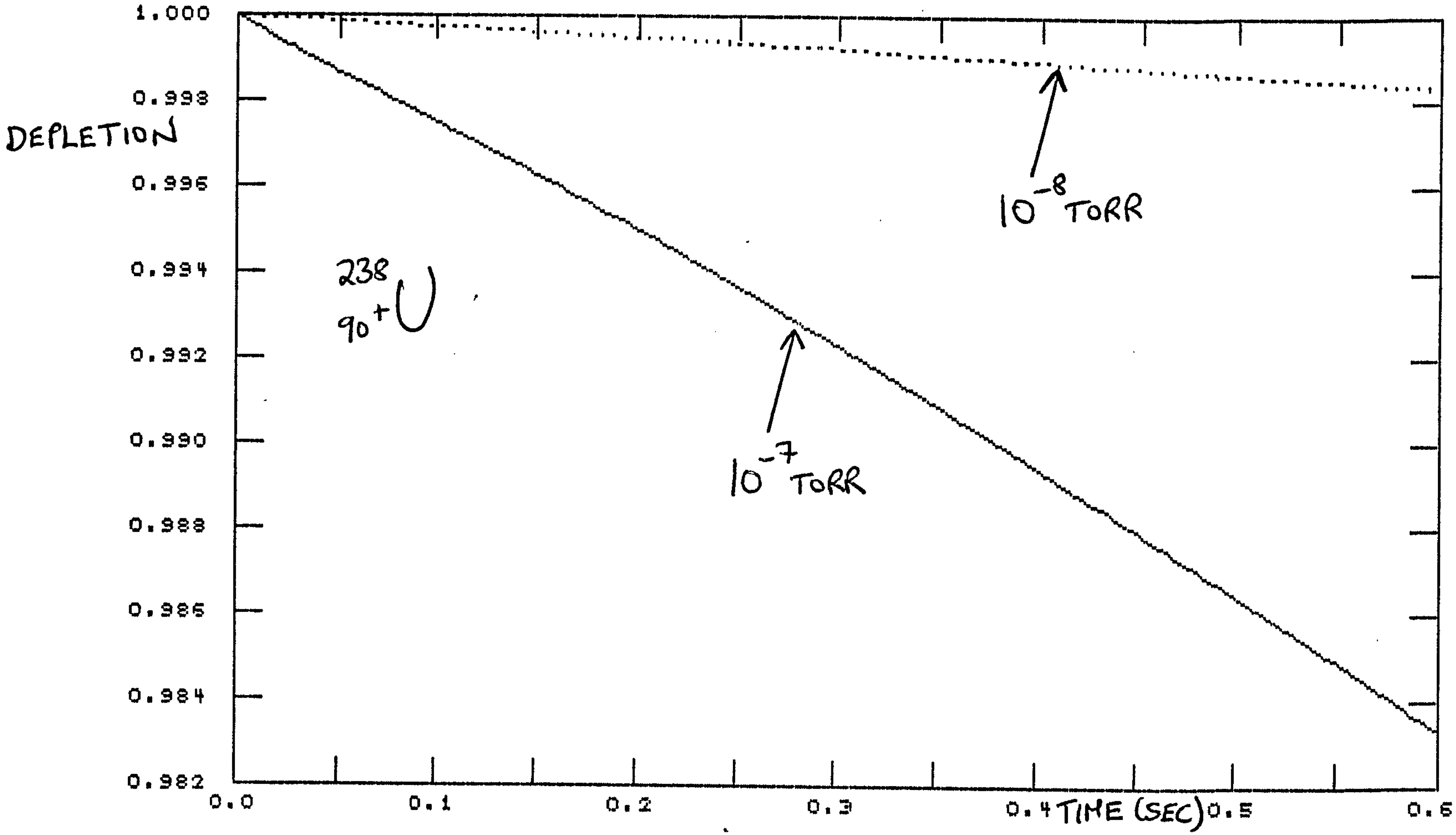
0.5
0.6
TIME (SEC)
197 77+ Au
10^{-8} TORR
10^{-7} TORR

FIGURE 4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