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Accelerating Uranium in RHIC - I The Problems and Roles of an Intermediate Linac

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ACCELERATING URANIUM IN RHIC - I

THE PROBLEMS AND ROLE OF AN INTERMEDIATE LINAC

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Section I - Introduction

With the present design specification[1], ^{197}Au is the most massive heavy ion that will be accelerated in RHIC. There are several very sound reasons why nuclei heavier than ^{197}Au, i.e. ^{238}U, cannot be easily accommodated in the present design. In this report, I will focus on the problems associated with accelerating Uranium ions, and discuss the possible role to be played by an intermediate Linac in overcoming these difficulties.

There are several reasons to desire Uranium beams in RHIC. For the formation of a quark-gluon plasma energy densities in excess of 3 GeV/fm^3 and temperatures in excess of 200 MeV are required during the heavy ion collision. Assuming an extreme single particle model, the energy density in a nucleus-nucleus collision scales as $\epsilon_{AA} \approx \epsilon_{pp} A^{1/3}$ where ϵ_{pp} is the energy density in a p-p collision and A is the nuclear mass number. Hence, even in this extreme model we gain by a factor of 6.5% in the energy density for ^{238}U over ^{197}Au. In reality,[2] recent experimental evidence has shown a considerable amount of transverse energy flow, in contradiction to the extreme independent particle model. This result can only increase the attained energy density, and in general adds weight to be argument that the largest possible nucleus should be used for plasma formation. It would seem that the larger the nucleus, the more secondary particles will be produced in the initial collision, and hence the energy density reached will be larger.

In summary, both elementary theoretical considerations, and new experimental data on transverse energy deposition, point towards the advantages of accelerating the largest possible heavy ion.

Section II - Accelerating Uranium in the Present Mode of Operation

In Figure 1, the present mode of operation is shown schematically as arrangement A. Within this arrangement there are three overriding but related constraints that restrict Uranium operation for RHIC.

The first one is simply the size of the available Uranium source current. At the present time, only 10 nA are available for Uranium ions from the negative ion source[3] at the Tandem. This is a factor of 2 x 10^4 less than ^{197}Au currents,[3] and obviously too small for efficient RHIC operation.

The second constraint is the vacuum levels of the AGS. At the present time this is ~ 10^{-7} Torr,[1] as compared to 10^{-10} Torr in the Booster. The value of 10^{-7} Torr has led to the current result that only fully stripped heavy ions be accelerated in the AGS. This minimizes particle loss, for "pick-up" of an electron[4] has a much smaller probability at these intermediate energies than simple electron "knock-out".[5] As shown in Figure 1, the stripping foils S_T, S_F and S_B have to strip the electrons before injection into the AGS.

The third constraint for accelerating Uranium is the stripping foil characteristics as a function of energy. Published results[6] indicate that in order to achieve full stripping in 80% of Uranium ions, these ions must have a kinetic energy of ~ 830 MeV/A. However, assuming these ions enter the Booster with the same charge state as ^{197}Au, i.e. 13e, the present magnetic field strength of 1.2743 T can only result in a kinetic energy of 229.8 MeV/A. At this energy, published results[6] tell us that essentially no fully stripped Uranium ions will pass into the AGS after transversing foil S_B. This result is easily obtained from the formula;

$$B = \frac{A}{Qe\rho c} \left[\left(\frac{T}{A} + m_o c^2 \right)^2 - m_o^2 c^4 \right]^{1/2} \tag{1}$$

where ρ is the magnetic radius of the booster, and T is the kinetic energy.

Section III - Introduction of Intermediate Linac

Let us try a new strategy and assume an adequate source of Uranium exists. We introduce an intermediate Linac, shown in Figure 1 as arrangement G. In this new arrangement, the intermediate Linac provides sufficient kinetic energy, that after traversing the new foil S_L, the Uranium ions will enter the booster with a charge state that will ensure acceleration to ~ 830 MeV/A. The important question is; How large does this Linac have to be?

Using equation (1), and a magnetic field strength of 1.2743 T, we require a charge state of $Qe = 68e$ for $T/A = 830$ MeV/A in the Booster.

In order to determine the size of an intermediate Linac we need to know what velocity the Uranium ion needs to have in order to achieve charge state 67e after traversing foil S_L. Experimentally, very little is known at these intermediate energies about stripping foil efficiencies. However, in order to obtain a reasonable starting value, let us use the analysis of Betz[7] et.al., who fitted parameters of an empirical formula to charge equilibrium data at low energies. Betz et.al., said that for an incident velocity β_L, an ion of atomic number Z, will achieve a charge equilibrated state $\bar{q}$, of maximum probability, given by the formula

$$\bar{q} = Z \left[1 + \left(Z^{-\alpha} \beta_L / \beta' \right)^{-1/k} \right]^{-k} , \tag{2}$$

where $\alpha = .45$, $k = .6$, $\beta = .012$ and $Z = 92$ for Uranium ions. Inverting this formula, the β_L required for a charge state $\bar{q}$ is

$$\beta_L = \beta' \; Z^{\alpha} \left[\left(\frac{\bar{q}}{Z} \right)^{-1/k} - 1 \right]^{-k} \tag{3}$$

A word of caution is needed for this formula. Even at low energies, where experimental measurements are known, this formula is known to be inaccurate.[3] For instance, the charge state for ^{197}Au in foil S_F at Tandem energies is 33e. Equation (3) gives a value of $\bar{q} = 36$ for this β. However, for this initial study we will use formula (3); where we find for a $\bar{q}$ of 67 that we obtain a beta value of $\beta_L = .118$ for a Uranium ion leaving the Linac.

Let us use the result of an earlier publication[3] for the Linac β_L in terms of the Tandem β_T, i.e.

$$\beta_L^2 = \beta_T^2 \left\{ 1 + \frac{V_L \; Q_F}{V_T \left(Q_{T+1} \right)} \right\} , \tag{4}$$

where Q_T is the charge state after foil S_T, Q_F is the charge state after foil S_F and V_T is the Tandem voltage. We find for the Linac voltage,

$$V_L = \frac{V_T\left(Q_T+1\right)}{Q_F}\left[\frac{\beta_L^2}{\beta_T^2} - 1\right] \tag{5}$$

Assuming Q_T for Uranium is the same as ^{197}Au (i.e. 13e), and using the value of $\beta_T = .0435$, we arrive at the conclusion that a 40.7 MV Linac is necessary to achieve fully stripped Uranium ions in the AGS. This value corresponds to 5.64 MeV/A for the Linac.

Combining formulas (3) and (5), Figure 2 shows the Linac voltage V_L required to achieve an equilibrium charge state $\bar{q}$ in foil S_L. Measurements at Tandem energies have shown that formula (2) overestimates the value of $\bar{q}$, hence the value of <u>V_L = 40.7 MV should be considered an optimistic lower limit</u>. Crudely estimating the error in the Betz formula at Linac energies to be twice the error at Tandem energies, i.e. error ≈ 6e, Figure 2 indicates that a 70 MV Linac may be easily required to achieve a charge state of 67e in foil S_L. This corresponds to 9.71 MeV/A.

The expected steep dependence of V_L on $\bar{q}$, coupled to the general uncertainties in stripping foil characteristics at these energies, clearly indicate that more detailed experimental measurements must be made to focus on the value of V_L. <u>However, the results of this analysis clearly show that the Linac required is quite substantial, when measured by an standard</u>.

<u>Section IV - Particle Intensities and Role of Intermediate Linac</u>

The results of the last section assumed a stripping foil efficiency of ~ 80% at foil S_B, for fully stripped ions. This efficiency required an energy of 830 MeV/A for Uranium ions. However, stripping foil efficiencies are known[8] at lower percentage values. For instance, 50% of the ions may be considered fully stripped at energies ~ 480 MeV/A, and 20% of the ions may be considered fully stripped for bombarding energies ~ 425 MeV/A. In principle, if one can live with these lower yields, then a smaller intermediate Linac would be required.

There is also another question associated with the multiturn injection mechanism into the Booster. Earlier work[3,9] has told us that as the Linac voltage increases the stacking efficiency into the Booster will decrease. This section will focus on these questions, and draw conclusions on the optimal Linac size, and the source current needed for Uranium under these circumstances. Utilizing formulas (1) - (5), we obtain the following Table:

Table 1. Intermediate Linac Voltage as a function of Stripping Foil Efficiency for Fully Stripped Uranium Ions.

Fully Stripped Uranium Efficiency at Foil S_B	Energy after Booster	Charge on Entering Booster	Velocity β_L After Linac	Voltage of Linac*
80%	~ 830 MeV/A	68e	.118	40.7MV(5.64MeV/A)
50%	~ 480 MeV/A	49e	.0633	7.12MV(.99MeV/A)
20%	~ 425 MeV/A	45e	.056	4.11MV(.57MeV/A)

*Lower limit.

In addition, let us expand on the results of reference 3, and calculate the expected particle numbers in the Booster (h=3) and the AGS. We assume stripping foil efficiencies at foils S_T and S_F to be the same[3] as ^{197}Au. We also extend the value for S_F to foil S_L. The transmission factor at Tandem[3] is taken to be .75 and .5 at the Linac. Only an eight turn injection scheme of 100% efficiency will be considered here.

Table 2. Number of Uranium Ions/Bunch in Booster (h=3) and AGS. Source Current = 110 μA. Pulse Length = 110 μs.

Linac Voltage MV	No. of Uranium Ions Entering Linac	No. of Revolutions in Booster	No. of Uranium Ions/Bunch in Booster (h=3)	No. of Fully Stripped Uranium Ions/Bunch in AGS
0	$.182 \times 10^{10}$	7	$.0607 \times 10^{10}$	0
40.7	$.182 \times 10^{10}$	19	$.0243 \times 10^{9}$	$.0194 \times 10^{9}$
7.12	$.182 \times 10^{10}$	10	$.0461 \times 10^{9}$	$.0231 \times 10^{9}$
4.11	$.182 \times 10^{10}$	9	$.0513 \times 10^{9}$	$.0102 \times 10^{9}$

The results of Table 2 are extremely interesting, for they show that the combination of multiturn injection efficiency into the Booster, and stripping foil characteristics at foil S_B dictate <u>that an optimum value of V_L exists. This value is around 8 MV</u> (~ 12 MV with errors in the Betz formula), <u>and is quite modest in size</u>. A large Linac, of the order of the one deduced in Section III, is simply not efficient in stacking particles into the Booster, and very little is gained in stripping foil efficiency at foil S_B (i.e. 50%-80%). Of course a Linac much smaller than 4 MV will produce no fully stripped U-ions in the AGS.

Finally, in order to achieve a particle number of 2.2 ions/bunch (h=1) in the Booster a particle source current of 5.25 mA is required for Uranium and a 7.12 MV Linac. Of course, in order to accommodate Uranium, smaller particle intensities will be torrelated.

Section V - Conclusions and Suggestions for Future Acceleration of Uranium

1) At the present time, because of particle source limitations, AGS vacuum considerations and stripping foil characteristics, it is simply not possible to acclerate Uranium ions in a collider mode. Unfortunately, most of the alternatives or improvements considered in this report require an independent effort to accommodate Uranium. The source development itself is a major project. If the Tandems are utilized, then an increase of ~ 2 x 10^4 in source current for Uranium would be required for acceptable intensities in RHIC. Assuming that it was possible to achieve acceptable currents, then a kinetic energy of ~ 830 MeV/A is required at the Booster for 80% full stripping of Uranium ions. Theoretically this would require a ring with a maximum field of 2.61 T.

2*) Once again, assuming source development will enable adequate currents of Uranium to be produced, an intermediate Linac would allow the existing Booster magnetic field strength to be utilized. Indeed, because of the efficiency of the Booster's multiturn injection,[2,9] it would seem that an optimal size of the Linac exists. In Section IV this was deduced to be (7-10) MV. The uncertainty in this figure reflects the uncertainty in the stripping foil formula of Betz. However, this Linac is quite modest in both size and cost, and would allow the RHIC facility to accelerate the full range of elements, i.e. protons to Uranium. This would give Brookhaven a competitive edge over CERN in both elements and energy.

3)* As an alternative proposition, the vacuum of the AGS could be reduced. A detailed theoretical analysis of stripping and pick up of electrons, under current or improved AGS vacuum conditions, needs to be carried out. It may well be possible that for an order of magnitude reduction in the vacuum, that sufficient numbers of partially stripped Uranium ions could survive the AGS acceleration cycle. A complete analysis of this kind would involve the combination of the expected heavy ion acceleration energy, as a function of time, with known theoretical results for stripping and pick up. This analysis would have to be repeated as a function of vacuum pressure in the AGS. This will be discussed in detail in a separate report.

4) We note there is continuous source development under way at Brookhaven, Oak Ridge, Argonne and GSI. I understand Argonne will be injecting Uranium ions into a Linac from a positive ion source as soon as 1990, but the current will be a very low (≅ 10 nA). However, developments at Oak Ridge (J. Alton) may point the way to reliable and adequate Uranium sources in the near future.

5) The experimental results from CERN point towards the advantages of using the largest possible heavy ion in the relativistic collision. As the experimental program develops and source currents improve, the various options for accelerating Uranium should be pursued. Indeed, with improvements in AGS vacuum and source technology, accelerating Uranium with the present arrangement (A), also seems a strong possibility.

The author acknowledges stimulating discussions with P. Thieberger.

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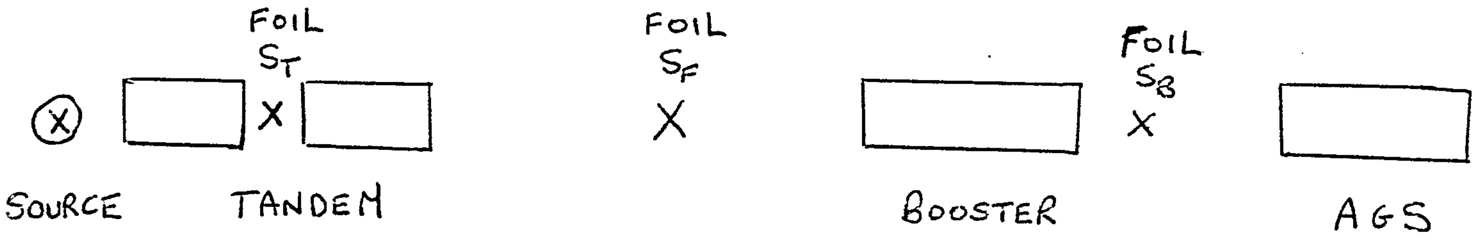
Figure Captions

Figure 1. Schematic representation of the RHIC front end. Arrangement A is the current arrangement, and arrangement E is the injection system incorporating an intermediate Linac.

Figure 2. Graph of required Linac voltage verses charge state at injection to Booster.

FIGURE 1

ARRANGEMENT A



ARRANGENT G

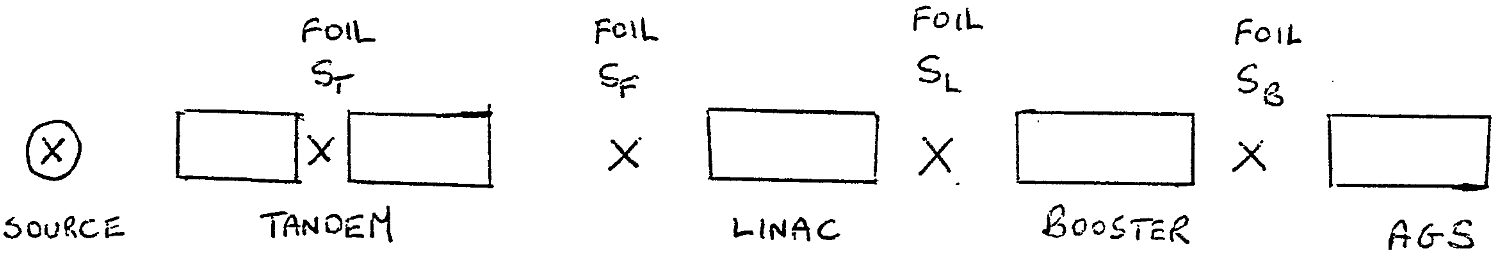


FIGURE 2

REQUIRED LINAC VOLTAGE VERSES CHARGE STATE $\bar{q}$
AFTER FOIL S_L