BNL-105157-2014-TECH

Booster Technical Note No. 113;BNL-105157-2014-IR

# An alternative injection scheme for heavy ions into the Booster

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March 1988

Collider Accelerator Department

**Brookhaven National Laboratory**

**U.S. Department of Energy**

USDOE Office of Science (SC)

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# AN ALTERNATIVE INJECTION SCHEME FOR HEAVY IONS INTO THE BOOSTER

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Section I - Introduction

At the present time, protons and heavy ions are injected and stacked in the booster phase space via two quite distinct techniques. For protons, an $H^-$ beam is first passed through a stripping foil, which converts about 100% of $H^-$ to protons. For this purpose, during injection the closed orbit of the synchrotron is locally moved to the injection orbit where the stripping foil is located. In this way the converging protons already stacked and $H^-$ beam merge tangentially at the foil location because of the exact but opposite nature of their charges. For a detailed description of the magnet geometry, see the Booster manual.[1] This technique is very efficient and preserves the "roundness" of the beam.

Unfortunately, for heavy ions the injection process is a little less quantitative. In Figure 1, the source of heavy ions and beam transfer line prior[2] to Booster injection are shown schematically as arrangement A. Of particular importance here is the fact that a stripping foil, $S_F$, is used to ensure a "charge equilibrated" state for the heavy ions on entering the Booster. This state simply reflects the experimental knowledge, that when a charged nuclear beam of a given velocity (provided by Tandem in this case) traverses a foil of a certain minimum thickness, a broad Gaussian distribution of charge states will result. The most probable charge state is the one injected into the Booster. We note, increasing the foil thickness will not change this charge distribution, only changing the initial velocity will allow this to alter.

Once the most probable charge state enters the Booster, it is stacked in betatron phase space via so-called multiturn injection. This involves a careful programming of the deformation of the closed orbit and the tune. Wei and Lee has simulated this process[3] and an injection efficiency of 80% for 20 turns was achieved. In another report[4], the actual intensity of heavy ions in the Booster was calculated for the h=1 mode using a variety of realistic source currents and pulse lengths from the Tandem. For this report[4] on eight turn injection with 100% efficiency and a 32 turn injection with 50% efficiency were assumed. Since a charge exchange takes place at least once when the ions cross the stripping target, we propose here an alternative method of multiturn injection for heavy ions in the Booster similar in spirit to the negative-ions charge-exchange methods used for protons. This method would be more reliable and efficient than multiturn injection, and would preserve the "roundness" of the beam. This method is also less sensitive to the length of the pulse from the Tandem. From the operation point of view the method is definitively more advantageous.

In this report we want to move the stripping foil $S_F$ to the injection point of the Booster, as shown schematically in Figure 1 (arrangement F), and in Figure 2. The actual geometry of the injection orbit will be worked out in a later publication, the question to be addressed here in some detail is "Do we gain in particle intensities in the Booster using arrangement F?" "How do these intensities compare with the results of reference 4?"

## Section II - Particle Intensities in the Booster

Let us make comparisons for $^{12}C$, $^{32}S$, $^{63}Cu$ and $^{197}Au$. Let Z be the fraction of heavy ions injected into the Booster for one revolution after initially passing through foil $S_F$ with the charge equilibrium value.

$$Z = N_T \times \frac{t_R}{P_L} \times S_F S_T \quad \text{where } t_R = \frac{2\pi R}{\beta c} \tag{1}$$

In this formula, $\beta$ is heavy ion velocity from Tandem[2] and $N_T$ is the number of ions produced at the Tandem for a given source strength and pulse length $P_L$.[4] $S_F$ and $S_T$ are the stripping foil efficiencies tabulated elsewhere[2,4] for different heavy ions species. Let $Z\sigma$ be the fraction of heavy ions that remain in the beam, with the charge equilibrium value, after the beam transverse the foil a second time. Hence after N turns, for a given pulse length, $P_L$, the total number of ions $N_{TOT}$ in the Booster is:

$$N_{TOT} = Z + Z\sigma + Z\sigma^2 + \,.\,.\; Z\sigma^{n-1} = \frac{Z(\sigma^n - 1)}{\sigma - 1} \quad (\sigma < 1) \tag{2}$$

The value for $\sigma$ is critical, but unfortunately unknown. For the purpose of this report we calculate $N_{TOT}$ as a function of $\sigma$, for various heavy ions species, and compare with the results of reference 4.

Let us tabulate the dynamical constants needed for this comparison for various heavy ion species. We note the quantity Z in equation (1) is a constant for a given Tandem source current. Changing $P_L$ only changes number of revolutions N that are possible.

Table 1. Stripping Foil Efficiencies and Tandem Velocities of Heavy Ions.

| Species | $^{12}C$ | $^{32}S$ | $^{63}Cu$ | $^{197}Au$ |
|---|---|---|---|---|
| Atomic Number | 6 | 16 | 29 | 79 |
| $Q_T$ | 5 | 9 | 11 | 13 |
| $Q_F$ | 6 | 14 | 21 | 33 |
| $S_T$ | .39 | .36 | .27 | .19 |
| $S_F$ | .9 | .40 | .27 | .17 |
| $\gamma$ | 1.0075 | 1.0047 | 1.0029 | 1.0011 |
| $\beta$ | 0.1219 | 0.0966 | 0.0756 | 0.0462 |
| $t_R$ | 5.52 $\mu s$ | 6.96 $\mu s$ | 8.89 $\mu s$ | 14.56 $\mu s$ |

Using earlier results of reference 4), let us compare the number of ions per bunch (h=3) in the Booster using arrangement A of figure 1, with the more established 8 multiturn injection scheme, with the new arrangement F. For our comparisons here, it is not necessary to vary the Tandem source current. We compare arrangements A and F for different $P_L$ and take a source current of 110 $\mu$A throughout.

Table 2. Number of Ions/Bunch Injected into Booster, $^{12}C$.

| $P_L$ | No. of Revolutions | No. Injected in 8 multiturn | $\sigma$ | $N_{TOT}$ |
|---|---|---|---|---|
| 80 $\mu s$ | 15 | $.257 \times 10^{10}$ | .95 | $.357 \times 10^{10}$ |
| | | | .9 | $.264 \times 10^{10}$ |
| | | | .8 | $.160 \times 10^{10}$ |
| | | | .65 | $.095 \times 10^{10}$ |
| | | | .5 | $.066 \times 10^{10}$ |
| | | | .35 | $.051 \times 10^{10}$ |
| 110 $\mu s$ | 21 | $.252 \times 10^{10}$ | .95 | $.438 \times 10^{10}$ |
| | | | .9 | $.296 \times 10^{10}$ |
| | | | .8 | $.165 \times 10^{10}$ |
| | | | .65 | $.095 \times 10^{10}$ |
| | | | .5 | $.066 \times 10^{10}$ |
| | | | .35 | $.051 \times 10^{10}$ |
| 200 $\mu s$ | 37 | $.260 \times 10^{10}$ | .95 | $.565 \times 10^{10}$ |
| | | | .9 | $.325 \times 10^{10}$ |
| | | | .8 | $.166 \times 10^{10}$ |
| | | | .65 | $.095 \times 10^{10}$ |
| | | | .5 | $.066 \times 10^{10}$ |
| | | | .35 | $.051 \times 10^{10}$ |
| 500 $\mu s$ | 93 | $.257 \times 10^{10}$ | .95 | $.659 \times 10^{10}$ |
| | | | .9 | $.332 \times 10^{10}$ |
| | | | .8 | $.166 \times 10^{10}$ |
| | | | .65 | $.095 \times 10^{10}$ |
| | | | .5 | $.066 \times 10^{10}$ |
| | | | .35 | $.051 \times 10^{10}$ |

Table 3. Number of Ions/Bunch Injected into Booster, $^{32}S$.

| $P_L$ | No. of Revolutions | No. Injected in 8 multiturn | $\sigma$ | $N_{TOT}$ |
|---|---|---|---|---|
| | | | .95 | $.149 \times 10^{10}$ |
| | | | .9 | $.118 \times 10^{10}$ |
| | | | .8 | $.787 \times 10^{9}$ |
| 80 $\mu$s | 11 | $.144 \times 10^{10}$ | .65 | $.488 \times 10^{9}$ |
| | | | .5 | $.344 \times 10^{9}$ |
| | | | .35 | $.265 \times 10^{9}$ |
| | | | .95 | $.185 \times 10^{10}$ |
| | | | .9 | $.137 \times 10^{10}$ |
| | | | .8 | $.830 \times 10^{9}$ |
| 110 $\mu$s | 15 | $.145 \times 10^{10}$ | .65 | $.491 \times 10^{9}$ |
| | | | .5 | $.344 \times 10^{9}$ |
| | | | .35 | $.263 \times 10^{9}$ |
| | | | .95 | $.263 \times 10^{10}$ |
| | | | .9 | $.163 \times 10^{10}$ |
| | | | .8 | $.359 \times 10^{9}$ |
| 200 $\mu$s | 28 | $.141 \times 10^{10}$ | .65 | $.492 \times 10^{9}$ |
| | | | .5 | $.344 \times 10^{9}$ |
| | | | .35 | $.263 \times 10^{9}$ |
| | | | .95 | $.335 \times 10^{10}$ |
| | | | .9 | $.172 \times 10^{10}$ |
| | | | .8 | $.861 \times 10^{9}$ |
| 500 $\mu$s | 71 | $.139 \times 10^{10}$ | .65 | $.492 \times 10^{9}$ |
| | | | .5 | $.344 \times 10^{9}$ |
| | | | .35 | $.265 \times 10^{9}$ |

Table 4. Number of Ions/Bunch Injected into Booster, $^{63}Cu$.

| $P_L$ | No. of Revolutions | No. Injected in 8 multiturn | $\sigma$ | $N_{TOT}$ |
|---|---|---|---|---|
| | | | .95 | $.0822 \times 10^{10}$ |
| | | | .9 | $.0681 \times 10^{10}$ |
| | | | .8 | $.0481 \times 10^{10}$ |
| 80 $\mu$s | 9 | $.088 \times 10^{10}$ | .65 | $.0311 \times 10^{10}$ |
| | | | .5 | $.0222 \times 10^{10}$ |
| | | | .35 | $.0171 \times 10^{10}$ |
| | | | .95 | $.102 \times 10^{10}$ |
| | | | .9 | $.0717 \times 10^{10}$ |
| | | | .8 | $.0517 \times 10^{10}$ |
| 110 $\mu$s | 12 | $.091 \times 10^{10}$ | .65 | $.0316 \times 10^{10}$ |
| | | | .5 | $.0222 \times 10^{10}$ |
| | | | .35 | $.0171 \times 10^{10}$ |
| | | | .95 | $.150 \times 10^{10}$ |
| | | | .9 | $.1 \times 10^{10}$ |
| | | | .8 | $.0552 \times 10^{10}$ |
| 200 $\mu$s | 22 | $.090 \times 10^{10}$ | .65 | $.0317 \times 10^{10}$ |
| | | | .5 | $.0222 \times 10^{10}$ |
| | | | .35 | $.0171 \times 10^{10}$ |
| | | | .95 | $.210 \times 10^{10}$ |
| | | | .9 | $.11 \times 10^{10}$ |
| | | | .8 | $.0556 \times 10^{10}$ |
| 500 $\mu$s | 56 | $.089 \times 10^{10}$ | .65 | $.0317 \times 10^{10}$ |
| | | | .5 | $.0222 \times 10^{10}$ |
| | | | .35 | $.0171 \times 10^{10}$ |

Table 5. Number of Ions/Bunch Injected into Booster, $^{197}Au$.

| $P_L$ | No. of Revolutions | No. Injected in 8 multiturn | $\sigma$ | $N_{TOT}$ |
|---|---|---|---|---|
| | | | .95 | $.0362 \times 10^{10}$ |
| | | | .9 | $.0328 \times 10^{10}$ |
| | | | .8 | $.0269 \times 10^{10}$ |
| 80 $\mu$s | 9 | $.044 \times 10^{10}$ | .65 | $.0202 \times 10^{10}$ |
| | | | .5 | $.0155 \times 10^{10}$ |
| | | | .35 | $.0123 \times 10^{10}$ |
| | | | .95 | $.0483 \times 10^{10}$ |
| | | | .9 | $.0417 \times 10^{10}$ |
| | | | .8 | $.0316 \times 10^{10}$ |
| 110 $\mu$s | 12 | $.0607 \times 10^{10}$ | .65 | $.0217 \times 10^{10}$ |
| | | | .5 | $.0159 \times 10^{10}$ |
| | | | .35 | $.0123 \times 10^{10}$ |
| | | | .95 | $.0820 \times 10^{10}$ |
| | | | .9 | $.0617 \times 10^{10}$ |
| | | | .8 | $.0382 \times 10^{10}$ |
| 200 $\mu$s | 22 | $.0633 \times 10^{10}$ | .65 | $.0228 \times 10^{10}$ |
| | | | .5 | $.0160 \times 10^{10}$ |
| | | | .35 | $.0123 \times 10^{10}$ |
| | | | .95 | $.133 \times 10^{10}$ |
| | | | .9 | $.0780 \times 10^{10}$ |
| | | | .8 | $.0400 \times 10^{10}$ |
| 500 $\mu$s | 35 | $.0633 \times 10^{10}$ | .65 | $.0228 \times 10^{10}$ |
| | | | .5 | $.0160 \times 10^{10}$ |
| | | | .35 | $.0123 \times 10^{10}$ |

In view of the results of Tables (2-5) let us calculate converged values of $N_{TOT}$ for $\sigma$ = .95 and .9, and the corresponding Tandem pulse lengths.

Table 6. Converged Values of $N_{TOT}$ for $^{12}C$, $^{32}S$, $^{63}Cu$ and $^{197}Au$.

| Species | $\sigma$ | Minimum N For Convergence | $N_{TOT}$ | $P_L(N)$ |
|---|---|---|---|---|
| $^{12}C$ | .95 | 135 | $.664 \times 10^{10}$ | 745.2 $\mu$s |
| | .9 | 85 | $.332 \times 10^{10}$ | 469.2 $\mu$s |
| $^{32}S$ | .95 | 135 | $.346 \times 10^{10}$ | 939.6 $\mu$s |
| | .9 | 85 | $.173 \times 10^{10}$ | 591.6 $\mu$s |
| $^{63}Cu$ | .95 | 135 | $.222 \times 10^{10}$ | 1200 $\mu$s |
| | .9 | 85 | $.111 \times 10^{10}$ | 755.7 $\mu$s |
| $^{197}Au$ | .95 | 135 | $.160 \times 10^{10}$ | 1965.6 $\mu$s |
| | .9 | 85 | $.080 \times 10^{10}$ | 1237.6 $\mu$s |

Section III - Conclusions and Suggestions for the Future

1. The traditional heavy ion injection mechanism into the booster, i.e., multiturn injection, is unfortunately limited in that particle intensities cannot be increased by accommodating longer pulse lengths. For an N turn injection, a pulse length of $Nxt_R$ only can be accommodated. Although for an eight turn injection, 100% stacking efficiency may be assumed; as N increases from 8 the stacking efficiency can be expected to fall.[3,4] This efficiency is unknown experimentally for heavy ions such as $^{197}Au$, but theoretically[3] 80% efficiency for N=20 has been calculated.

2. As an alternative, we suggest a stacking method analogous to the one employed for protons, but now passing two different charge states for the heavy ion through a stripping foil as indicated in Figures 1 and 2. The unknown experimental factor in this analysis is the fraction $\sigma$. This signifies how much of the most probable charge state from a "charge equilibrated" distribution will survive after this charge has made multiple passages back through the foil. The advantage of this scheme is that increased particle numbers associated with longer pulse lengths from the Tandem could be accommodated. <u>The overall critical quantity in this argument is the unknown factor $\sigma$</u>, for this dictates the rate of convergence of the series (2).

Although $\sigma$ is unknown, we may make reasonable qualitative arguments as to what happens during multiple passage of the foil. <u>For $^{12}C$ the situation is very promising indeed</u>. After first traversing foil $S_F$, $^{12}C$ is fully stripped. Hence, the fully stripped ions should be only slightly depeleted on passage through the foil again. This is because it is quite hard to pick up an electron (nuclei and electron have to be travelling at about constant relative velocity), and there is nothing left to strip. Hence for $^{12}C$ a $\sigma$ value of .9 or more may be reasonable. From Tables 2 and 6 we see that for $\sigma$=.9, a ~ 500 $\mu$s pulse of 110 $\mu$A will produce 3.3 x $10^9$ particles (h=3 mode) in the Booster, a factor of 1.3 more than an eight turn injection. If $\sigma$ turns out to be as high as .95, 6.64 x $10^{10}$ particles could be accommodated, a factor of 2.6 more than an eight turn injection. For $\sigma$=.9, $N_{TOT}$ is a factor of 1.58 <u>less</u> than a

32 injection scheme with 50% stacking efficiency,[4] but for $\sigma$=.95 we obtain a factor of 1.27 more.

For medium mass nuclei, $^{32}S$ and $^{63}Cu$, Tables 3, 4 and 6 show that if $\sigma$=.87 or greater this method is more efficient than a 8 turn injection. However, in this case it is very difficult to gauge the value of $\sigma$, for both $^{32}S$ and $^{63}Cu$ are not quite fully stripped (see Table 1). Because $^{32}S$ retains only 2 electrons in the most bound S-level after first traversing foil $S_F$, then $\sigma$ may also be large in this case too. Physically we may argue again that pick up is harder than stripping, and so unlike first passage through $S_F$ we would probably get a skew charge distribution after traversing foil. <u>An experimental measurement of $\sigma$ is essential here in view of the promising results</u>.

For the heavy nuclei $^{197}Au$, we are far from fully stripped when first traversing foil $S_F$ (see Table 1). In this case we may expect a smaller value of $\sigma$, for subsequent knock out of some of the 46 available electrons will surely occur. The results in Tables 5 and 6 once again show the virtue of this method of $\sigma > 80\%$. However, for $^{197}Au$, we do not expect $\sigma$ to be of this magnitude. However, once again we emphasize the advantages of a "round beam" in this case.

3. Obviously, multiple passage through the stripping foil will also cause emittance and momentum spread growth. This should also be investigated theoretically and experimentally. To minimize this effort, a foil with ions of higher nuclear charge would be better as the cross sections are higher and thus a thinner foil can be used. This could be very useful for energy loss does not increase with charge as fast as cross section increases.

The experimental measurement of $\sigma$ will be carried out by P. Thieberger and collaborators. The critical domain is expected to be for the medium mass nuclei such as $^{63}Cu$, where only six bound electrons remain.

The extremely promising results for $^{12}C$, $^{32}S$, $^{63}Cu$ and the positive implications for $^{197}Au$ strongly suggest that measurements of $\sigma$ must be carried out. It seems that for heavy ions two injection mechanisms should be available, where the one proposed here should be better, for light or medium mass nuclei, than the cumberson multiturn injection.

We acknowledge P. Thieberger for the idea of using a stripping foil in the way described here.

References

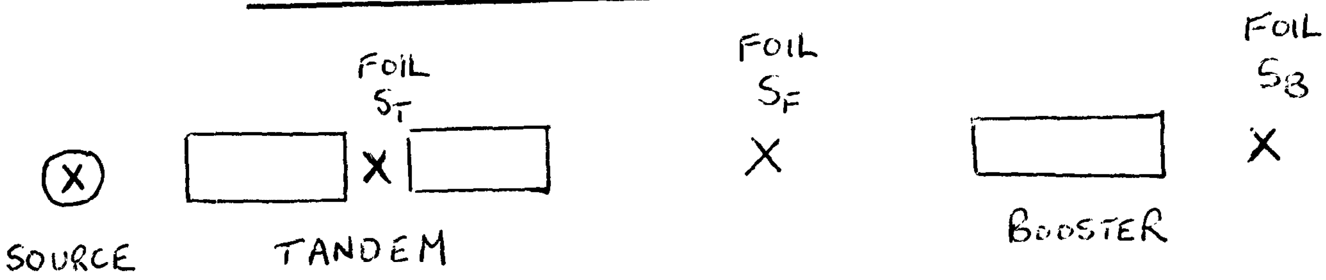
1) Booster Design Manual, Accelerator Development Department, Brookhaven National Laboratory.

2) "Conceptual Design of the Relativistic Heavy Ion Collider, RHIC", BNL 51932, 1986.

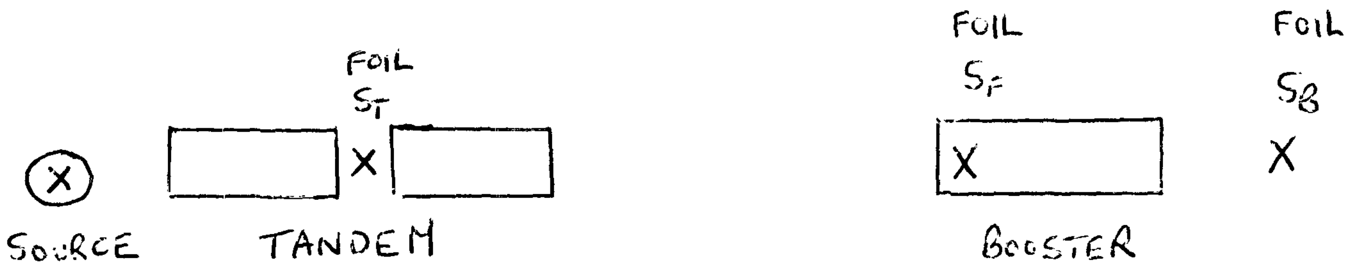
3) J. Wei and S.Y. Lee, "Simulation of Multiturn Heavy Ion Injection in the Booster. Booster Technical Note No. 102.

4) M.J. Rhoades-Brown and A.G. Ruggiero, "Source Current into the AGS, An Analysis of the RHIC Front End Injection System", RHIC Technical Note No. 32.

# FIGURE 1




ARRANGEMENT A




ARRANGEMENT F

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# FIGURE 2 (SCHEMATIC)