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THE USEFULNESS OF TANDEM ACCELERATORS AS INJECTORS TO HEAVY ION BOOSTERS

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Résumé. — Nous exposons les possibilités offertes par un accélérateur Tandem MP comme injecteur dans un post-accélérateur. Après avoir discuté les caractéristiques demandées nous concluons qu'un Tandem est bien adapté à cette tâche et surtout grâce aux possibilités des sources d'ions modernes.

Abstract. — We report about the possibilities of a Tandem MP accelerator as injector in a post-accelerator. After discussion of the required characteristics we conclude that a Tandem is well suited for this work and this owing to the possibilities of modern ion sources.

During the past few years a variety of proposals have been made to construct machines that would accelerate a broad range of heavy ions to energies of several MeV/nucleon. Frequently, these proposals have included the use of a tandem accelerator to produce high charge low emittance beams which are then directed into the final stages of acceleration which might be a cyclotron or linac. An example of such a multiple accelerator system is that being proposed at the University of Rochester. This facility will use the existing MP Tandem to produce positive ions that would be injected into a superconducting heavy ion cyclotron.

Figure 1 is a calculation carried out by Elmore ⁽¹⁾ which shows the energy/nucleon for particles as a function of mass for a tandem accelerating tube into a 500 MeV superconducting cyclotron. The following assumptions are made in the calculation:

1. The negative ion current from the ion source is 10 μ A.
2. The beam after pre-acceleration chopping is 2.5 μ A.
3. The overall transmission through the accelerator, excluding charge exchange branching, is 50 %.
4. Terminal charge exchange will be in gas and the charge exchange branching is calculated according to the paper of Betz [1].

Calculations are shown for two terminal voltages, 11 and 12 MV. The lower voltage, an ultra-conservative rating, is shown because today the machine operates for days on end without any disruptions at this voltage. 12 MV is shown as we expect equally reliable performance at this voltage with purified SF₆.

Whenever predictions of the type shown in figure 1

FIG. 1.

are made a series of questions arise in the mind of the reader about the basic suitability of a tandem as a booster injector.

1. Negative ions are not a usual state of matter. Can they be generated with sufficient intensity for most masses that the inevitable losses in the accelerator can be accepted?

⁽¹⁾ Elmore D. Private communication.

2. How serious are the losses from:
 - a. optical effects and lens aberrations?
 - b. charge exchange branching?
 - c. small angle scattering in the stripper?
 - d. vacuum conditions in the non-bakeable tubes?
3. Will the complex phenomenon of loading effectively prevent the acceleration of very high intensity beams?
4. Is charge state selection possible in existing machines to eliminate the need to accelerate unwanted positive ions?
5. Is the pulsed beam performance compatible with the injection requirements of a cyclotron?
6. Are tandems really reliable enough to be seriously considered as a positive ion source for a regional facility where predictable operations and the reliability of scheduling is absolutely essential to a successful laboratory?

I do not intend to address question 1. because Middleton has covered this point thoroughly previously [2]. Answers to the other questions can be given by describing some measurements that have been made at Rochester and Oxford.

1. Experimental data on transmission. — Measurements have been made at Rochester on the transmission efficiency of the MP tandem using 150 keV injection and beams of ^{32}S , ^{58}Ni , ^{197}Au from a refocused Middleton sputter source and ^{16}O from a duoplasmatron. I should point out that the Rochester tandem has several features that make it somewhat unique [3]. For the present measurements the most important features were the high capacity cryogenic terminal pumping and the non-aberrating spirally inclined field tubes.

Data was obtained which measured the intensity of individual charge states in a $ME/Q^2 = 300$ amu-MeV magnet system for terminal voltages between 8 and 10.5 MV. The upper limit to the voltage was set by the fact that the accelerator had been open only a few hours previously and had not been conditioned. The analyzed current was normalized to an equivalent particle current, corrected for known losses (due to a gridded lens), and compared to the particle currents that should be observed assuming 100 % transmission and the charge exchange branching of Betz [1].

Tables I to IV show the data for $V_T = 8$ MV. For ^{197}Au it can be seen that currents of ~ 2 μA were injected and that the transmission efficiency was between 25-30 %. Further measurements at the same energy where 4 μA was injected gave essentially the same transmission efficiency. At no time was there any evidence of loading phenomena and we believe that significantly higher currents could have been injected. Within the error of the measurements there was no indication that the theoretical charge state distribu-

tion had been distorted by stripping in the high energy tube. Such stripping would tend to remove low charge state components. Conversely, there was no indication of losses of high charge state components which would indicate small angle scattering effects. The data, which was taken at fixed stripper gas pressure, is consistent with the higher charge states being in equilibrium.

Figure 2 shows a graph of all the data. It can be seen that the transmission varies from close to 100 % for ^{16}O to 25-30 % for ^{197}Au . The line that has been drawn through the data is consistent with vacuum losses of negative ions in the low energy tubes dominating the transmission. It is important to put this piece of information in perspective. It indicates that a rather modest decrease in vacuum pressure is all that is needed to improve the transmission so that it is constant at ~ 100 % over the whole periodic table. One single pump located in the middle dead section of the accelerator will provide a pressure/length product reduction of four. Such an addition is planned and is technically a comparatively trivial addition.

FIG. 2.

Table V shows transmission data at 10 MV. Here currents of 3 μA of ^{197}Au were injected into the machine. The same treatment of data was used to calculate transmission efficiency. It can be seen that the measured efficiency is at least 50 % of the theoretical maximum. Once again the machine showed no indications of loading phenomena. While the previous data at 8 MV was encouraging the data at 10 MV was conclusive; it is now possible to reliably predict that the injector accelerator is capable of handling currents that will result in 10^{11} particles per second from a superconducting cyclotron. With modest improvements in vacuum, injection optics, and charge state selection, 10^{12} particles per second appear quite reasonable as upper current limits.

TABLE I
¹⁶Oxygen at 8 MV

Charge state Q^+	Injected current $I_{LE} (\mu A)$	Analyzed current $I_{Q^+} (\mu A)$	Particle ratio	Predicted ratio	Predicted ratio after allowance for grid	Transmission efficiency
—	—	—	—	—	—	—
+ 2	.500	.056	.056	.004	.0036	—
+ 3	—	.275	.183	.101	.091	—
+ 4	—	.740	.370	.461	.415	.892
+ 5	—	.820	.328	.377	.339	.968
+ 6	—	.260	.087	.056	.050	—
+ 7	—	.004	.001	.002	.0018	—

TABLE II
³²Sulphur at 8 MV

Charge state Q^+	Injected current $I_{LE} (\mu A)$	Analyzed current $I_{Q^+} (\mu A)$	Particle ratio	Predicted ratio	Predicted ratio after allowance for grid	Transmission efficiency
—	—	—	—	—	—	—
+ 4	8.0	4.6	.1438	.2011	.1810	.794
+ 5	6.2	6.2	.2000	.3637	.3273	.611
+ 6	6.2	4.0	.1875	.2790	.2511	.747
+ 7	6.1	1.1	.0258	.0908	.0817	.316
+ 8	6.0	.32	.0067	.0125	.0113	.593
+ 9	7.8	.085	.0012	.0007	.0006	—

TABLE III
⁵⁸Nickel at 8 MV

Charge state Q^+	Injected current $I_{LE} (\mu A)$	Analyzed current $I_{Q^+} (\mu A)$	Particle ratio	Predicted ratio	Predicted ratio after allowance for grid	Transmission efficiency
—	—	—	—	—	—	—
+ 4	.600	.300	.125	.2269	.2042	.622
+ 5	.700	.460	.131	.2788	.2509	.522
+ 6	.700	.360	.0857	.2099	.1889	.454
+ 7	.650	.220	.0483	.0968	.0871	.555
+ 8	.650	.130	.0230	.0274	.0247	.931

TABLE IV
¹⁹⁷Gold at 8 MV

Charge state Q^+	Injected current $I_{LE} (\mu A)$	Analyzed current $I_{Q^+} (\mu A)$	Particle ratio	Predicted ratio	Predicted ratio after allowance for grid	Transmission efficiency
—	—	—	—	—	—	—
+ 6	1.80	.300	.0277	.1346	.1214	.228
+ 7	2.30	.380	.0236	.0840	.0756	.312
+ 8	2.20	.175	.0099	.0424	.0382	.259
+ 9	2.17	.070	.00358	.0173	.0156	.229
+ 10	2.05	.020	.00097	.0057	.0051	.190
+ 11	1.90	.005	.00024	.0015	.0013	.185

ADDITIONAL DATA WITH THE DEFINING APERTURE REMOVED

+ 7	4.00	.600	.0214	.0846	.0756	.283
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TABLE V
¹⁹⁷Gold at 10 MV

Charge state Q^+	Injected current I_{LE} (μA)	Analyzed current I_{Q^+} (μA)	Particle ratio	Predicted ratio	Predicted ratio after allowance for grid	Transmission efficiency
—	—	—	—	—	—	—
+ 8	3.10	.950	.0383	.0639	.0575	.666
+ 9	3.02	.350	.0129	.0308	.0277	.466
+ 10	3.00	.170	.0057	.0122	.0110	.515
+ 11	3.10	.072	.0021	.0040	.0036	.586

2. **Confirming measurements.** — Confirming measurements on transmission properties of the EN tandem at Oxford have been supplied by Hyder (2). Oxford University has experience in the injection of medium mass ions into a similar spirally inclined acceleration structure. No significant loading has been observed for the following beams:

Ion	Current Injected	Voltage	Equiv. MP Voltage
—	—	—	—
¹² C	17 μA	4 MV	8 MV
¹⁶ O	5 μA	5.5 MV	11 MV
¹⁹ F	8 μA	6 MV	12 MV
³² S	6 μA	6 MV	12 MV
¹²⁷ I	2 μA	6.2 MV	12.4 MV

Transmission data for ions through the Oxford tandem are consistent with the U of R measurements:

Ion	Stripper	Transmission	Voltage	Equiv. MP Voltage
—	—	—	—	—
¹⁹ F	Gas	65 %	4 MV	8 MV
²⁸ Si	Foil	55 %	5 MV	10 MV
²⁸ Si	Foil	61 %	6 MV	12 MV
³² S	Gas	63 %	4 MV	8 MV

3. **Small angle scattering.** — Recent work of Hooton, Freeman and Kane [4], at AERE Harwell, on the scattering of heavy ions shows that the half angles introduced into the beam by multiple scattering are much less than those computed on the basis of the theory of Nigam, Sundareson and Wu [5]. Thus, transmission of multiply stripped heavy ion beams through tandem tubes is higher than some recent calculations have suggested.

4. **Pulsing.** — Nanosecond beam pulsing is an integral part of most booster proposals. For example, the superconducting cyclotron has rf frequencies that will lie between 27-84 MHz. The phase angle of acceptance will be approximately 15° for maximum intensity or 2° for best resolution. These specifications

translate into beam bursts with width and phase stability ~ 0.2 ns. Figure 3 shows the pulse beam performance of the Rochester tandem during ³He pulsing.

FIG. 3.

In practice the timing specifications of the previous paragraph are probably impossible to meet if all of the beam pulsing is done before the tandem accelerator. A *touch-up* buncher will be needed following the accelerator. The reason why bunching must be done after the machine is that small changes in the tandem terminal voltage, or the voltage gradients, produce significant variations in the transit time of ions through the machine compared to 1 ns. A very sensitive region is the injector drift spaces between the buncher and the machine; here the velocity of the particles is slow and the transit times long. For example, I⁻ particles injected at 2 MeV with an energy stability of ± 0.5 keV have time fluctuations at the target of ± 1.3 ns. Terminal fluctuations are less

(2) Hyder R. McK. Private communication.

critical but they must still be kept within a few kV. This is well within the normal operating range of an MP tandem at 11 MV.

FIG. 4.

It is important that the value of dE/dt , the rate of change of beam energy following the modulation, be moderately large for all ion species. Firstly, $dE/dt \times \Delta t$, where Δt is the desired time resolution, should be much larger than the natural energy spreads that are present in the ions leaving the source. Secondly, and in practice more important, is that $dE/dt \times \Delta t$ should be large compared to fast power supply fluctuations in the injector. High frequency ripples and fast voltage fluctuations of the order of hundreds of volts are common in existing injector systems and in practice are difficult to avoid. A practical solution which will operate reliably is to keep E and dE/dt high. There are other reasons for injecting at high energies one of which is that ions which travel along the axis have a slightly different time history than ions which travel at the edges of the tube. While all particles have received the same energy by the time that they reach the terminal, the time history of the extremum rays is different. At injection energies of hundreds of kilovolts these effects can be important if a focus is not located at the entrance to the first acceleration tube. They become of little consequence

FIG. 5.

at injection energies of 2 MeV even when conventional optics are used.

Figure 4 shows the high voltage performance of the Rochester MP tandem for experimental measurements. It should be emphasized that experimental programs are not commenced until long term reliability is assured at a particular level. It can be seen that 11 MV is a conservative rating. Figure 5 shows the range of heavy ions that have already been used in experimental programs at Rochester.

5. Summary. — When we examine the questions posed at the beginning of this talk we believe that in no case is the tandem excluded as a suitably heavy ion injector. Rather, the reliability and flexibility of modern ion sources make it an almost ideal machine for booster injection.

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