Design and Performance of the Inter-RFQ Beam Transport and Matching Section for the SAIC PET Isotope Production Accelerator*

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Abstract

The SAIC PET isotope production accelerator is comprised of a 1 MeV $^3He^+$ radio-frequency quadrupole (RFQ) accelerator followed by a charge-doubler and pair of RFQ accelerators to produce 8 MeV $^3He^{++}$ ions. The inter-RFQ section consists of a stripper and a transport system in order to match the beam into the following RFQ. This inter-RFQ section is functionally equivalent to a single-sided beam funnel where the bend magnet has been replaced with a stripper cell. The operating frequency is doubled from 212.5 MHz to 425 MHz and the beam must be matched transversely and longitudinally to the 425 MHz RFQ acceptance. The transverse matching is accomplished using permanant magnet quadrupoles and the longitudinal matching is accomplished using a buncher cavity. Our particular design is unique in that the transverse x:y diameter ratio can be as high as 4:1. Initially this asymmetry was thought to complicate the transport, however the system can be designed to exploit the unique features of a large aspect ratio and has important implications at other facilities.

I. INTRODUCTION

The SAIC PET isotope production accelerator is illustrated in figure 1. The $^3He^+$ ions produced in an ion source are accelerated to 1 MeV by a 1 meter "PreStripper" RFQ operating at 212.5 MHz.[1] The 1 MeV ions are stripped of the second electron in the "charge-doubler" section and further accelerated by a 425 MHz "PostStripper" RFQ (2.8 meters) to a final energy of 8 MeV. The 8 MeV beam is focused into the isotope production target by a combination of quadrupole and multipole electromagnets to produce the four common PET isotopes.

The matching of the ion beam between the two RFQs is accomplished in the charge-doubler section using a combination of permanant magnet quadrupoles (PMQs)[2] and a buncher cavity. In order to simplify the transport and matching of the beam through this region, the final few cells in the PreStripper RFQ were modified.[1]

*Work sponsored by Strategic Defense Initiative Organization Contract Number SDIO 84-89-C-0046.

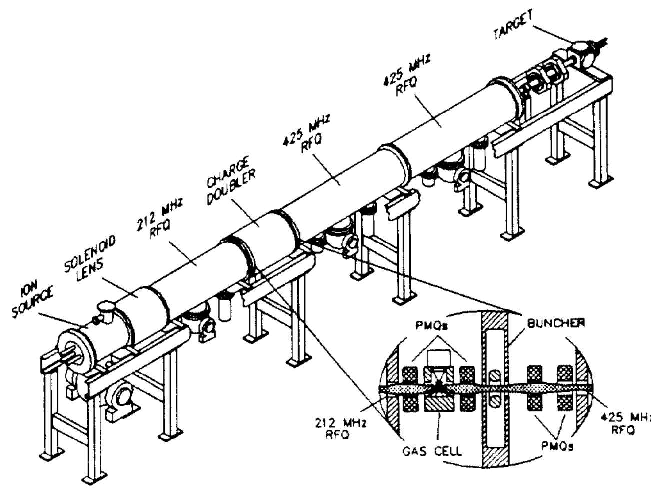

Figure 1. Line drawing of the PET accelerator. The $^3He^+$ ion beam is produced in a duoplasmatron ion source and accelerated to 1 MeV in the PreStripper RFQ operating at 212.5 MHz. The ions are stripped of the second electron in the charge-doubler and matched into the PostStripper RFQ. The PostStripper RFQ is divided into two segments by an aperture plate. The first segment accelerates the beam to 5 MeV and the second to 8 MeV. Upon exiting the PostStripper RFQ, the beam is directed into the isotope production target.

II. TRANSPORT DESIGN

In the charge-doubler region, the 1 MeV $^3He^+$ ion beam exiting the PreStripper RFQ, passes through the first PMQ and enters the gas cell where the second electron is stripped to make $^3He^{++}$ ions. These ions are focused through the buncher cavity and matched to the PostStripper RFQ acceptance using three additional PMQs.

A conventional pillbox cavity operating at 212.5 MHz would be very large and bulky. Also the small longitudinal distance available would result in a very inefficient cavity. Hence the PET buncher cavity was designed as a quarterwave stripline resonator. This design minimizes the longitudinal distance required and the drift-tube geometry provides two rf gaps, effectively halving the rf voltage required. The resonant frequency is controlled by moving a sliding short along the "stem" of the drift tube.

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III. EXPERIMENTAL RESULTS

The original transport solution performed poorly. Although the emittance orientation of the 1 MeV beam exiting the PreStripper RFQ agreed with the theory,[1] the transmission of the beam through the PostStripper RFQ was less than 20%. The reason for this poor performance was inadequate performance of the buncher cavity.

The difficulty with the original transport solution is that the rf defocusing produced by the buncher cavity must be within 3.4% of the theoretical value to maintain a transverse match. This means that insufficient bunching leads to not only a longitudinal mismatch, but a transverse mismatch as well.

Fortunately the features of the beam transport solution provide a simple means of measuring the degree of rf defocusing produced by the buncher cavity. Because the effective focal distance of the second PMQ is substantially altered by rf defocusing, the degree of defocusing can be derived from the change in quadrupole field required to refocus the beam ions on a viewer downstream of the buncher cavity. In addition it is not necessary to strip the beam ions to the 2^+ state to observe this effect. Therefore a relatively simple experiment can be performed to measure the degree of rf defocusing produced by the buncher and also calibrate the effective on-axis voltage as a function of rf power without requiring measurement of the longitudinal emittance, phase, or energy spread.

To measure rf defocusing, the PostStripper RFQ was replaced with a drift space and a beam viewer with an electromagnetic quadrupole between the buncher and the viewer. The $^3He^+$ beam was accelerated in the PreStripper RFQ and focused onto the viewer using the electromagnetic quadrupole. As the phase of the buncher was varied, the quadrupole magnet was adjusted to refocus the beam onto the viewer and the current required was recorded for a variety of rf power levels.

Figure 2 shows a typical result of quadrupole focusing current as a function of buncher phase at a fixed rf power level. The amplitude of the refocusing current was derived by fitting the data with a sine wave shown as the solid line in the figure. The effective rf defocusing produced by the buncher cavity was derived from the refocusing current and compared with results from TRACE3D.[3]

IV. THEORY

The theoretical rf fields were derived using electrostatic field codes to compute the electric field amplitude and fitting that amplitude with a time-varying Gaussian function. Although the electric fields are not precisely Gaussian, this difference does not lead to significant errors and the Gaussian expression can be integrated analytically to yield the effective rf gap voltage (E_0TL) used by TRACE3D. This effective gap voltage was used to generate rf defocusing according to the defocusing model internal to TRACE3D. The quadrupole gradients required to refocus the beam could then be derived from TRACE3D.

The original buncher drift tube had a 5 cm bore to reduce geometric aberrations. However analysis of this geometry indicated that a drift-tube voltage of 1.5 MV would be required to achieve proper performance. Reduction of the drift-tube bore diameter did not appreciably improve on this performance.

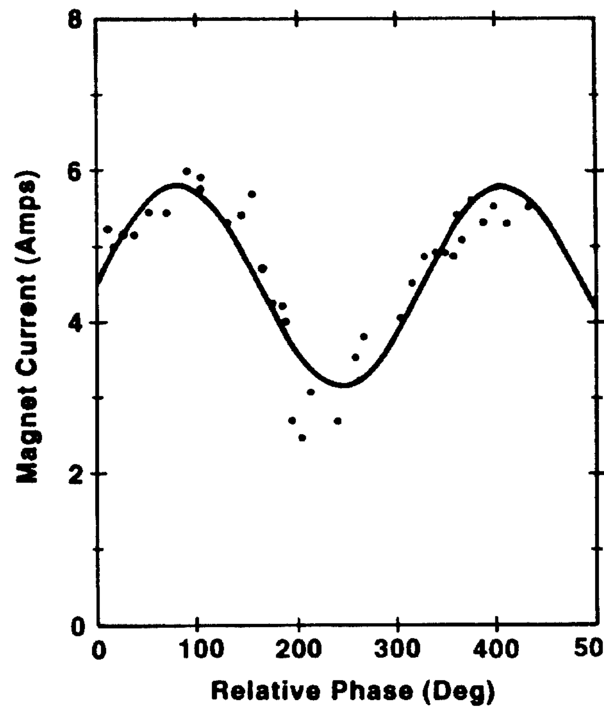

Figure 2. Typical data plot of quadrupole refocusing current as a function of buncher rf phase. The data were fit with a sine function. The resulting amplitude is the change in quadrupole magnet current required to refocus the beam onto the viewer and is proportional to the degree of rf defocusing induced by the buncher.

The solution to this problem is based on abandoning the circular-aperture geometry. Although this approach runs contrary to common practice, the key factor to consider is the necessity of increasing the effective on-axis rf voltage without sacrificing additional rf power. The on-axis voltage is very sensitive to the relationship between the rf gap and the inner diameter of the drift-tube. The narrow rf gap necessitated by the low-energy ion beam places severe restrictions on the inner diameter of the drift tube if high efficiency is to be maintained.

This situation is improved considerably by substituting a "slit" for the circular drift-tube aperture. In this situation, the effective on-axis voltage is determined by the geometry of the smallest dimension of the slit and can easily attain more than 90% of the drift-tube voltage. A significant additional benefit of this approach is that rf defocusing can be neglected in the direction parallel to the long axis of the slit.

Substituting a 0.9 cm by 3.5 cm vertical slit for the circular drift-tube aperture increased the effective on-axis voltage to 93% of the drift-tube voltage and reduced the required rf power to less than 20 kW.

This situation represents a considerable improvement in the stability of the beam transport solution because it virtually eliminates the sensitivity of the transverse beam matching to buncher operation. The horizontal beam transport was already insensitive to rf defocusing and, with the slit geometry, the vertical focusing is insensitive as well. Hence the new beam transport solution does not depend on achieving a precise rf-defocusing effect from the buncher cavity and the beam is always well-matched in the transverse planes reguardless of the status of the buncher cavity.

V. EXPERIENCE

The theoretical transmission of the original transport solution was 6% without an operating buncher cavity. The measured value was about 20%. The descrepancy is probably due to modelling the performance with TRACE3D rather than a more precise code like PARMILA.[4] Without an operating buncher, the debunching of the beam exiting the PreStripper RFQ is nearly complete by the time the ions arrive at the entrance to the PostStripper RFQ. Hence the tail and head of the leading and following bunches overlap the bunch in the middle. This overlap adds additional current to the central bunch that can be captured and accelerated but is not accounted for by the theory. Adding one-third of the ions captured from the overlap of the leading and following bunches to the beam captured from the central beam bunch boosts the theoretical transmission from 6% to 18% and is in much better agreement with the measured value.

The performance of the new transport design has not yet been quantified. Simulations indicate substantially improved performance, but these predictions have not yet been verified.

VI. IMPLICATIONS

The potential implications of the slit drift-tube apertures are very interesting. Abandoning a circular geometry could have a significant impact on design of accelerators. For example using a slit geometry in a conventional drift-tube linac (DTL) could significantly improve the performance at the low-energy end where the drift-tubes and rf gaps are "short" relative to the required apertures. The inlet end of DTLs has always been a design problem because the drift-tubes in this region can be too short to include quadrupole magnets. The invention of the RFQ accelerator partially solved this problem by boosting the injection velocity, but this solution is difficult to implement for heavy ions because the RFQs producing the required injection velocities get very long at the low frequencies required for heavy ion acceleration. Additionally it is desirable to increase the rf frequency to improve the effective acceleration gradient and to support beam funneling. Doubling the frequency halves the distance between drift tubes and halves the length of the drift tubes, effectively reintroducing the low-energy end problem.

Designing these DTLs could be simplified with slit-apertures because the rf defocusing can be neglected along the long axis of the slit. In this case one needs only relatively weak focusing to keep the edges of the "ribbon beam" confined. The strong focusing required in the other direction might be achievable by shaping the edges of the drift tube around the slit to produce the desired focusing components in the rf electric fields. The efficiency of "short" drift-tubes is also improved by the slit geometry because the effective gap voltage is a greater percentage of the rf voltage on the drift-tube. Transitioning from a ribbon beam to a circular beam could be accomplished at higher energies where the drift-tubes have sufficient volume to include magnetic focusing elements.

VII. CONCLUSIONS

The poor performance of the original charge-doubler section was traced to inadequate buncher operation. Transverse and longitudinal matching of the beam into the PostStripper RFQ required a precise degree of rf defocusing from the buncher. When this effect was not produced, the quality of the match was poor. Redesigning the buncher drift-tube with a slit aperture resulted in substantially improved theoretical performance and the rf power required by the buncher decreased by a factor of 13. In addition, the new transport solution always matches the transverse emittances regardless of the condition of the buncher. This solution decouples longitudinal matching from transverse matching and provides a much better solution to the inter-RFQ beam transport.

Acknowledgements

Successful operation of this accelerator facility is a result of the combined efforts of many people. In particular I want to acknowledge the efforts and contributions of Steve Schmidt, Mike Donovant, Russ Parker, Phil Young, Steve Ringler, John Klaus, and Don Young.

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[4]PARMILA (Phase And Radial Motion in Ion Linear Accelerators), Code available from the Los Alamos Accelerator Code Group, Los Alamos National Laboratory, Los Alamos NM 87545