PROGRESS UPDATE ON THE DEVELOPMENT OF THE ^{3}He LINAC FOR PET ISOTOPE PRODUCTION

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Abstract

In 1995, Fermilab and SAIC formed a collaboration with partners from the University of Washington (UW) and the Biomedical Research Foundation of Northwest Louisiana (BRF) to explore an innovative approach to the production of radioisotopes. The accelerator system that is being developed accelerates ^{3}He to 10.5 MeV and then delivers this beam to the target to produce the short lived radioisotopes of interest to the PET community (^{18}F, ^{15}O, ^{13}N, ^{11}C). Research is being conducted to investigate the contribution that this promising approach can make to clinical and research PET.

The accelerator system has several very interesting aspects. These innovations include multiple RFQ accelerators configured in series, a gas stripper jet to doubly charge the low energy (1 MeV) ^{3}He beam, and an isochronous matching section to manipulate the transverse and maintain the longitudinal profile of the beam (without the use of an RF buncher) in the charge doubler transition section between RFQ's. This paper updates the progress of the PET ^{3}He RFQ accelerator, the current status of the design, and some of the interesting ongoing research.

Introduction

The idea of using ^{3}He for the production of radioisotopes for PET is not new. Development work on this concept was conducted by SAIC and the University of Washington in the early 1990's.[1] When the original program was being formulated, the PET environment in which it could make a contribution was significantly different than it is today. The original development was based on the belief that ^{18}F labeled compounds would be favored by the PET community. Also important was a global shortage of ^{18}O which made the standard approach of producing ^{18}F using $H_2{}^{18}O$ expensive and potentially unpredictable.

Since that time things within the PET community have changed significantly. There is no longer a significant shortage of $H_2{}^{18}O$. Also, FDA policy has changed regarding regulation of PET radiopharmaceuticals (Federal Register, February 27, 1995). The new policy no longer gives an advantage to ^{18}F labeled compounds. This means that ^{11}C agents are now no more trouble than ^{18}F. Carbon opens up a much larger array of molecules to label. Furthermore, recent developments in radiochemistry for preparing the important precursor, $^{11}CH_3I$, avoid the use of liquid solvents and $LiAlH_4$ which are very air and moisture sensitive, and make the precursor directly in the gas phase and at substantially higher specific activity. This leads to a smaller yield (mCi) requirement of $^{11}CO_2$. But, to take full advantage of this new technology, higher specific activity is necessary (i.e. new PET machines must be good producers of ^{11}C as well as ^{18}F). In these several ways the environment in which ^{3}He RFQ technology can make a significant and meaningful contribution to the advance of PET has changed.

While there have been interesting developments of several new low energy accelerators over the last 2-3 years - the Cyclone 3D (IBA), the TR13 (EBCO), PETtrace (GE), the tandem cascades from SRI or the new deep valley machines (CTI Siemens) - all of these machines use essentially the same nuclear reactions and target chemistry. The RFQ using ^{3}He, on the other hand, is a different approach and thus holds significant potential and research opportunities for advancing the state of the art in PET isotope generation.

System Description

Before the radiochemistry and targetry for ^{3}He could be investigated, an accelerator was needed that would supply a beam with the desired characteristics and parameters. The accelerator that had been developed by SAIC and the University of Washington in the early 1990's was a good starting point but needed to be upgraded to provide a more powerful tool for researching ^{3}He in light of current information. Analysis and a series of discussions resulted in the baselining of new operating parameters as indicated in Table 1.

Table 1 Accelerator Design Parameters

	Energy (MeV)	I_e (μA) average	Rep. Rate (Hz)	PW (μsec)
Existing Sys	8	300	360	55
New Sys.	10.5	200	360	70

Since the radiochemistry and targetry associated with pulsed high intensity ^{3}He beams was to a large extent unknown, it was decided that the system being developed needed to follow a conservative approach, i.e. it needed to be flexible and powerful enough to accommodate a wide range of targetry options. In particular it needed to be able to produce large quantities of ^{11}C since this isotope is likely to be used increasingly in PET. Table 2 indicates the beam required as a

Table 2: ^{3}He Current Required for PET RFQ

Radionuclide	mCi EOB in target	μA_e 8MeV*	μA_e 9.5MeV**	μA_e 10MeV**
^{18}F	600	333	207	177
^{11}C (low SA)	1000	202	140	125
^{11}C (high SA)	440	298	195	163
^{13}N	100	266	168	104
^{15}O (low SA)	800	517	360	318
^{15}O (high SA)	200	899	559	460

* 1 MeV energy loss in target window
** 1.5 MeV energy loss in target window

*Operated by the Universities Research Association under contract with the U. S. Department of Energy.

function of the final energy for the target quantities of the various PET isotopes. The requirements of Table 2 led to the accelerator current and energy requirements stated in Table 1. With this baseline information from our radiochemistry collaborators at UW and BRF, the existing 8 MeV ^{3}He accelerator was redesigned to meet the new requirements. The results of this redesign are shown in Figure 1. This layout makes the most efficient use of the existing equipment while solving some of the more challenging technical problems. Some interesting aspects of this accelerator system are:

Ion Source

Since one can achieve a much more efficient acceleration (length and power) with a doubly charged beam, a very attractive approach would be to make use of a doubly charged ion source. Unfortunately, nature works against this goal. With the second electron being bound with an energy of about 54.4 eV, common ion sources do not produce sufficient quantities of the doubly charged ion (15 mA required). As an alternative, the singly charged beam can be accelerated to an energy where it can be efficiently stripped (1 MeV). It is this approach that has been taken.

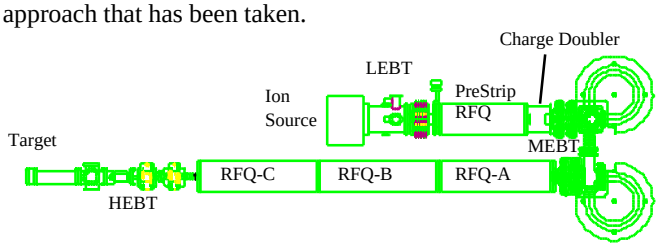

Figure 1. Layout of the BRF PET Accelerator.

Charge Doubler

At an energy of 1 MeV and a current of 400 μA_{avg} (20 mA_{peak}), carbon foil strippers could not survive the high power density. Both gas cells and gas jet strippers have been investigated. A jet stripper has been developed and tested with very promising results.

Medium Energy Beam Transport (MEBT)

The most difficult aspect of this accelerator system is the matching element between the prestripper and the post stripper RFQ's. This transition section needs to accomplish several things. It must provide sufficient space to accommodate the gas stripper (gas containment) while maintaining the longitudinal bunching of the beam and transversely matching the beam into the second RFQ. To overcome experimental realities, tunable components are desired. The longitudinal phase space of the beam must be maintained in order to eliminate the buncher/shaper section from the second RFQ (which at this beam energy would add about 1.5 m to the length of the second RFQ). Previous attempts to utilize an RF buncher to contain the beam longitudinally had been unsuccessful due to the very tight space constraints and the large number of free electrons (due to the proximity of the charge doubler). Based on this, it was decided to build an isochronous beam transport system that maintains the longitudinal and manipulates the transverse phase space of the beam.

Radio Frequency Quadrupole

The accelerator that had been developed under the earlier program had been designed for a final energy of 8 MeV. In order to achieve the higher energy requirements of the new system, it was decided that the most direct approach would be to add a third RFQ (manufactured by SAIC) to the high energy section to go from 8 MeV to the final energy of 10.5 MeV. This resulted in three RFQ's operating in series. The RFQ cavities are not resonantly coupled. Each cavity must be synchronized to and resonant at the same frequency. To accomplish this the resonant frequency of each cavity is controlled through adjustment of the temperature of the cavity cooling water. No mechanical tuners are used. Tests on this tuning system at full (2.5%) duty factor have been successful.

Status

The development of this system has taken place in two phases. A 1 MeV test stand was assembled from the accelerator components of the old system. Using this test stand, a number of the more difficult aspects of the system were addressed. Among the things that were studied are: low energy and medium energy beam characterization, ion source operation with He, charge doubler stripping efficiency, and charge doubler gas containment. The results of these tests have been incorporated into the design of the new components. Some of the information gained in the 1 MeV tests are summarized below.

Ion Source

He^+ ions are obtained from a fairly standard duoplasmatron ion source. The source operates at 360 Hz with a pulse length of 70 μs. It requires a gas consumption of 2-4 std cm^3/min (~ 1 liter / day of operation). Since ^{3}He is relatively expensive all attempts are made to minimize loss by reducing the source button (aperture) and pressure. Also the source is started and operated on ^{4}He except when ^{3}He is necessary. Because of the heavier ion and high duty factor, filament shielding is critical to prevent overheating and fast erosion. The filament is enclosed in a cylindrical shield with a sufficient opening to extract electrons while minimizing back-streaming ions. Several weeks of reliable and stable source operation have been obtained. A 25 mA beam is extracted at 20 kV from an ~ 1 cm plasma cup through a 0.8 cm grounded extraction electrode with an electron suppression electrode. Slightly after extraction the ~90% normalized beam emittance was measured to be 0.5 - 0.7 π mm mrad. One magnetic solenoid is used to focus the 20 keV beam into the RFQ. At the entrance of the RFQ, 0.7 m beyond the source, 75% of the beam is within ~0.5 π mm mrad emittance (normalized)[2].

Measured Emittance of the 1 MeV beam

After the Prestripper RFQ, at 1 MeV, the rms emittance has been measured to be 0.2 mm mrad (or ~34 π mm mrad unnormalized for 90% of the beam)[2]. This was measured with 5.5 - 7 mA at 1 MeV from the RFQ. Better matching and understanding of the RFQ transmission is needed. A maximum beam of 11 - 13 mA has been observed from the RFQ and appears to have similar characteristics. This was achieved with a larger solenoid in the 20 keV transport line.

Charge Doubler tests

A prototype stripper cell based on a pulsed gas jet was built to determine efficiency and gas flow in a realistic geometry. A mechanical injector (Nissan fuel injector) provided gas pulses to a converging-diverging nozzle. A directed gas jet of line density approximately 3-6x10^{16} cm^{-2} was created at the nozzle. It passed across the beam and was directed into a vacuum pump. The flow rate of the gas jet was sufficient to prevent excessive heating of the gas by the beam, and the injected gas was pumped out between beam pulses.

A magnetic spectrometer that bends the 1-MeV He^{+} and He^{++} beam ions into Faraday collectors at bend angles of 11.5° and 23.6° respectively, was used to test operation of the gas jet. Stripping efficiency was determined by measuring the relative distribution of beam current on the two collectors. Stripping efficiency for several gases is shown in Figure 2 as a function of back pressure on the injector.

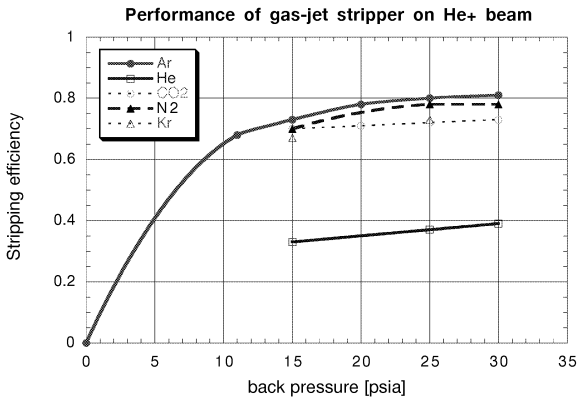

Figure 2 Performance of gas-jet stripper on He^{+} beam

The best performance was obtained with argon gas, which reached 80% stripping efficiency at a pressure of 25 psia. Pressure measured at the RFQ was 2.8x10^{-6} Torr for this operating point, at a repetition rate of 60 Hz. We expect to be able to operate at no less than 70% stripping efficiency at the design rate of 360 Hz by increasing pumping capacity. An operational version of the stripper cell is now in fabrication.

Medium Energy Beam Optics

As part of the design effort for the new MEBT (Figure 3), a number of options were investigated. It was recognized that folding the machine would accomplish the goal of keeping the length of the system manageable and could also do the longitudinal dynamics. Designs were investigated that included 180 degree bends, two 90 degree bends, three 60 degree bends, four 45 degree bends, and 30-60-60-30 degree combinations. In each case where multiple dipole designs were tried, quadrupoles were placed between the dipoles and varied in strength and position. Various internal gradients and edge angles were also tried. While it is possible to make a 180 degree bend which has the proper transition energy, it has not yet been possible to have a 180 degree bend design which is isochronous. For this and other reasons it was decided to use 2 x 270 degree bending MEBT which could be made isochronous.

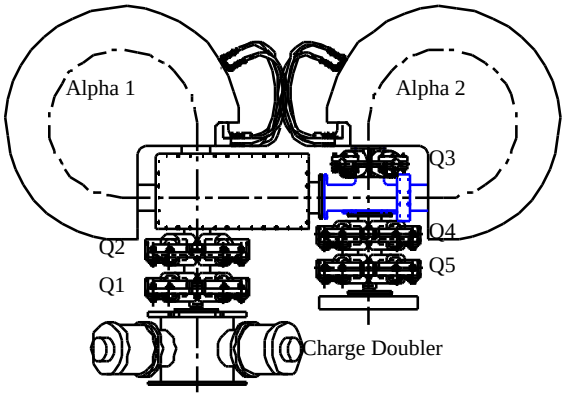

Figure 3 MEBT Mechanical Layout

The beam optics of the MEBT are shown in figure 4. The major magnets for this transport system have been fabricated and are being tested. The installation and commissioning of the transport system is scheduled to take place over the next two months.

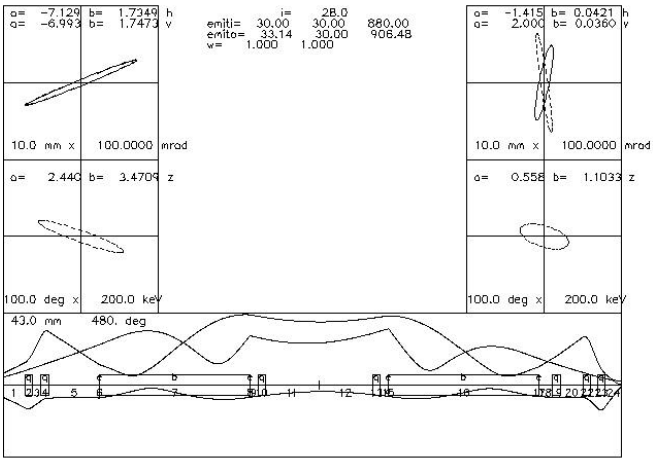

Figure 4 MEBT optics

Schedule

The modifications to the accelerator system are scheduled to be completed and tested in late 1996. Once completed, the accelerator will be run at Fermilab for 6 to 8 weeks in order to test shielding and do some initial targetry development. Following this run, the machine will be disassembled and shipped to the Biomedical Research Foundation. The accelerator system has been built in a modular fashion in order to facilitate moving. We anticipate that the move and commissioning will take about 8 weeks, after which the in-depth targetry and radiochemistry research will begin.

Reference

1. W. Hagan, et.al., "A Helium-3 RFQ Accelerator for PET Tracer Production", Proceedings of the Ivth International Workshop on Targetry and Target Chemistry, 1991, Pp 19

2. "Elliott McCrory, et.al. "Emittance Measurement Techniques Used in the 1 MeV RFQ for the PET Isotope Project at Fermilab". This Conference.