THE SAIC PET ISOTOPE TRACER ACCELERATOR FACILITY*

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Abstract

An accelerator has been developed for the production of radioisotopes for Positron Emission Tomography (PET) applications. This device uses a series of three radio-frequency quadrupole (RFQ) accelerators to produce 8 MeV ^{3}He ions. The ^{3}He reactions produce fewer neutrons than do conventional deuteron and (p,n) reactions, thereby reducing the radiation shielding required. In addition, the RFQ is a robust and relatively light-weight device. These factors result in substantial cost and weight savings over conventional cyclotrons. The design and performance of this accelerator will be discussed along with initial isotope production results.

Accelerator Facility

A line-drawing of the the SAIC PET accelerator is shown in Figure 1. The $^3He^+$ ions produced in an ion source are accelerated to 1 MeV by a 1.07 meter RFQ operating at 212.5 MHz. The 1 MeV ions are stripped of the second electron in the charge-doubler and further accelerated by a pair of 425 MHz RFQs (total length 2.81 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. Beam diagnostics consist of current transformers,[1] current-collecting aperture plates, and a removable beamstop immediately in front of the target. Beam steering is accomplished by steering magnets in the low energy beam transport (LEBT), medium energy beam transport (MEBT), and high energy beam transport (HEBT) sections. While not normally a part of the accelerator, a slit-and-collector emittance scanner can be installed wherever necessary for characterization of beam quality.

The duoplasmatron ion source produces up to 30 mA of $^3He^+$ ions. The "PreStripper" RFQ is designed to accelerate 20 mA of these 1^+ ions to 1 MeV. The charge-doubler strips 70-75% of these 1 MeV ions to the 2^+ state and the "PostStripper" RFQ accelerates 75% of these ions to 8 MeV. The design goal of the accelerator is to provide currents of up to 15 mA (electrical) of 8 MeV ions in a 2% duty factor (300 μA average electrical current). This level of performance is sufficient to produce at least 0.5 Curies (Ci) of ^{18}F and ^{15}O, 1.0 Ci of ^{11}C, and 0.1 Ci of ^{13}N.

To date the accelerator has been operated with 50 μs pulses at 180 Hz and has produced peak currents of 30 mA of 20 keV ions 14 mA of 1 MeV ions, and 2.5 mA of 8 MeV ions.

Ion Source/LEBT

Although direct acceleration of $^3He^{++}$ ions is desirable, no ion source has demonstrated sufficient 2^+ current and charge-state purity for this application. Therefore we produce a $^3He^+$ ion beam with a conventional duoplasmatron ion source and use the PreStripper RFQ to accelerate the 1^+ ions above 300 keV/AMU where the stripping cross sections are favorable for the production of the 2^+ ions.[2, 3] The duoplasmatron ion source operates at 20 kV above ground potential and has produced up to 30 mA of $^3He^+$ ions in 100-150 μs pulses at 360 Hz. The species content of the ion beam was measured with a magnetic analyzer and typically consists of 96% $^3He^+$ ions with approximately equal amounts of $^3He^{++}$ and H^+ ions.

The 1^+ ion beam is matched into the PreStripper RFQ using a solenoid magnet. The total ion current in the LEBT is measured by a current transformer while ion beam losses are collected on a washer plate located immediately in front of the RFQ entrance. The aperture of the plate matches the RFQ entrance aperture so that any beam current not focused into the RFQ is collected on the washer plate. The ion current injected into the RFQ is equal to the difference between the total current and the "lost" current.

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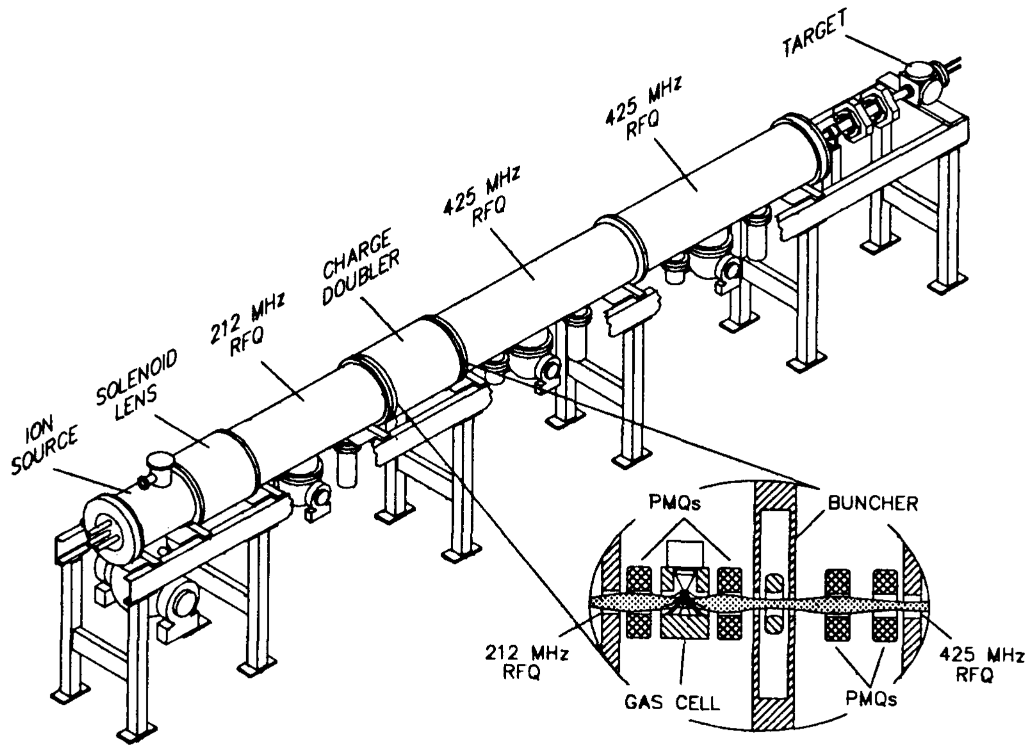

Figure 1. Line drawing of the SAIC PET Isotope Production Accelerator

PreStripper RFQ

The PreStripper RFQ operates at 212.5 MHz and accelerates the 1^+ ions to 1 MeV where the stripping cross sections are favorable for removing the second electron from the helium ions.[2, 3] Because RFQ focusing of $^3He^+$ ions is insufficient at 425 MHz, it was necessary to reduce the operating frequency of the PreStripper RFQ. The design of the PreStripper RFQ is discussed in detail elsewhere in these proceedings.[4] Frequency control is provided by adjusting the temperature of the cooling water and by a pair of rotary tuners. The rotary tuners use rotation of a flat paddle to shift the resonant frequency. The tuning range of the paddles was measured to be 170 kHz without exceeding 5% dipole field mixture. The position of the rotary tuners is controlled by a stepper motor. Typical startup rf operation of the PreStripper RFQ shows a decrease in resonant frequency due to heating of the vanes, followed by a return to the original frequency as the cylindrical RFQ housing heats up. This time delay is due to the difference in thermal mass and to the relative rf power deposited in the vanes and in the housing. Following the return to the original resonant frequency, the tuning range required of the tuners is relatively small, typically less than 10 kHz. Hence under normal operation, the effect of the tuners on the rf field symmetry and cavity Q is small.

Charge-Doubler/MEBT

Upon exiting the PreStripper RFQ, the 1 MeV beam ions are stripped of the second electron in a gas cell and matched into the PostStripper RFQ by a combination of permanent magnet quadrupoles (PMQs)[5] and an rf buncher cavity operating at 212.5 MHz. The stripper employs a gas cell rather than a foil stripper because of the high specific ionization rate of helium. A foil thin enough to not degrade the beam quality (1-2 $\mu g/cm^2$) would not survive the high energy deposition rate (5-10 mJ/pulse).

The 1^+ ion current out of the PreStripper RFQ is measured with a current transformer just prior to the stripper cell. The combined $1^+/2^+$ current is measured with a second current transformer just before the PostStripper RFQ and beam losses are collected on another washer plate located immediately in front of the RFQ entrance. The ion current injected into the PostStripper RFQ is the difference between the total current and the "lost" current. Separation of the 1^+ and 2^+ ion species is accomplished by the differential PMQ focusing of the 2^+ beam relative to the 1^+ beam.

PostStripper RFQ

The PostStripper RFQ operates at 425 MHz and accelerates the $^3He^{++}$ beam from 1 to 8 MeV. The injected ion beam is already bunched so that no buncher-shaper section is required. The PostStripper RFQ is mechanically divided into two separate resonators by an aperture plate. This aperture plate facilitates RFQ tuning by sectioning the relatively long RFQ (3.98λ) into two shorter segments. The penalty paid for this division is 10-15% additional beam loss at the interface. In the future, we plan on replacing the aperture plate with a washer plate that would resonantly couple the two RFQ sections[6] and eliminate this beam-loss penalty. As in the PreStripper RFQ, frequency control is provided by the temperature of the cooling water and by a pair of rotary tuners in each RFQ section.

HEBT/Target

The 8 MeV beam out of the PostStripper RFQ is directed into the isotope production target by a combination of quadrupole and multipole electromagnets. The multipole fields are primarily quadrupole and octupole in character and make the ion beam spatial distribution on the target window more uniform, thus reducing the peak power loading of the target window. The target is separated from the vacuum by a thin HAVAR[7] window. The range of the ^{3}He ions in the target material (primarily water) is only 80 μm, so the cooling of the target window and the thermal management of the heat within the water target must be carefully considered. The interaction of the ion beam with the target system was simulated with an electron beam welder and the results were presented elsewhere.[8]

The accelerator is protected from target foil ruptures by a valve that closes within 10 ms of losing vacuum pressure.[9] In the event of a foil rupture, closure of this valve, coupled with turning off the mechanical vacuum pumps, confines any radioactive material within the vacuum system and eliminates personnel exposure. Decontamination of the accelerator system is not an issue because of the relatively short half-lives of the isotopes produced (<2 hours). Also, experience has shown that pinholes developing in the target foil usually lead to degradation of the vacuum well before catastrophic foil rupture occurs.

Conclusions

The SAIC PET isotope production accelerator is currently in the debugging and commissioning stage. At present, the overall accelerator performance is limited by poor performance of the buncher cavity and by operation at less than the full 360 Hz duty factor. The ion source typically produces 22 mA of $^3He^+$ ion beam at the required duty factor and the transmission of the PreStripper RFQ is 50-80% depending on quality of the match. The stripping efficiency of the 1 MeV ions is 30-75% depending upon the gas parameters. Typical accelerator operation produces 10 mA of 2^+ ions at 1 MeV. The transmission of the PostStripper RFQs is limited by the buncher cavity and is approximately 20%. Therefore we routinely produce 2-3 mA of 8 MeV ions (in good agreement with PARMTEQ).

The RFQs have operated at the full 360 Hz duty factor, but are routinely run at 120-180 Hz. Operation at the reduced duty factor is primarily administrative in order to reduce rf tube stress because spare tubes have not been readily available. Preliminary ^{11}C and ^{18}F isotope production experiments have demonstrated yields somewhat lower than electrical beam current measurements would predict, but are in agreement with calorimetric beam current measurements. We are working to resolve this discrepancy between the electrical and calorimetric current measurements and to improve the operation of the buncher cavity.

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[1] Pearson Model 2500, Pearson Electronics, Inc., Palo Alto, California.

[2] Nikolaev et al., Sov Phys JETP 12 (11961) 627.

[3] Stier, et al. Phys Rev 96 (1954) 973.

[4] W.D. Cornelius and P.E. Young, Design of a 1 MeV $^3He^+$ RFQ for the SAIC PET Accelerator Facility, these proceedings.

[5] Field Effects, Inc., Acton, Massachusetts.

[6] M.J. Browman and L. M. Young, in Proc, 1990 Linear Accelerator Conference, Albuquerque, NM, Los Alamos Conference Proceedings Number LA-12004-C, p. 70.

[7] HAVAR is a trade name of Hamilton Precision Metals, P.O. Box 3014, Lancaster, Pennsylvania 17604.

[8] M.E. Schulze, et al., Fourth International Workshop on Targetry and Target Chemistry Villigen PSI, Switzerland, September 9-12, 1991.

[9] VAT Inc., Woburn, Massachusetts 01801