A ^{3}He Radio Frequency Quadrupole Accelerator for Positron Emission Tomography

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Abstract

The feasibility of using Radio-Frequency Quadrupole (RFQ) accelerator to accelerate ^{3}He for use in Positron Emission Tomography (PET) has been demonstrated. The ^{3}He RFQ is extremely light weight in comparison to a cyclotron but can nevertheless produce all four radio-isotopes of interest (^{18}F, ^{13}N, ^{15}O, and ^{11}C) in more than adequate quantities. Due to the neutron-poor nature of ^{3}He, target reactions and collisions with the accelerating structure produce relatively small numbers of neutrons compared to proton and deuteron systems. As a result, the shielding requirements are reduced considerably. For example, there is no need for the radiation shielding around the accelerator. This reduced shielding results in a factor of 9 reduction in total facility shielding weight compared to a proton/deuteron cyclotron facility. The order of magnitude reduction in facility weight, the virtual elimination of the accelerator weight, and the relative lack of activated components gives rise to the possibility of a radiopharmaceutical production system which is cheaper than present systems and may ultimately be transportable. Such a system could make the PET technique far more accessible geographically and financially than it is at present. A patent application has been filed on the concept of using an RFQ to accelerate ^{3}He for radionuclide production.

1. Introduction

Although it has been some 25 years since the first cyclotron was installed in a medical center in the United States and some 15 years since the description of the first PET designed for human studies [1], PET is still largely a research tool. There are many reasons for the relatively slow transition of PET from research to clinical applications. One of the major reasons is that, due to the short half-lives of the positron emitting radionuclides, a PET facility necessarily requires a means to produce radioisotopes onsite. In almost all cases, this production is accomplished with a cyclotron particle accelerator. The specific design and capability of the cyclotron varies from facility to facility, but some common features exist, such as heavy magnets, high cost, and massive shielding.

Fairly recent developments in linear particle accelerators (particularly for Strategic Defense Initiative applications) have brought this technology to the stage where linear accelerators (linacs) can be profitably substituted for cyclotrons to alleviate some of the problems described above. Unlike cyclotrons, which have been in existence for many decades and been optimized for the radionuclide production role, small linacs for this application are possible only now, specifically because of the invention of the Radio Frequency Quadrupole (RFQ) [2]. Figure 1 is a photograph of a typical RFQ tank. For example, Hamm et al [3] have designed a compact proton linac for PET. The design requires the use of a Drift Tube Linac (DTL) structure after the RFQ in order to accelerate the protons from 2 MeV (their energy after emerging from the RFQ) to the full energy of 10 MeV. This design is over 4.4 m in length and requires a total peak power of 835 kW (8.4 kW average power).

RFQ's have proven to be among the simplest accelerators to operate. None of their adjustable parameters are critical. Control of the rf power to a few percent is adequate. Servo control of the RFQ temperature and, hence, resonant frequency is straightforward. Operationally, the accelerator system has three states; namely, "standby", "ready", and "run". Transition between these states are essentially push-button operations. The transition from "standby" to "ready" involves a five minute delay for component warmup. The other transitions are essentially instantaneous.

In addition to taking advantage of many of the new developments in RFQ technology, the concept described here includes the use of ^{3}He as the beam particle for production of all four of the radio-nuclides of interest (^{18}F, ^{13}N, ^{15}O, and ^{11}C). ^{3}He is commercially available and costs are estimated to be ~$2700/yr for weekly operations of 40 hrs. The design consists of a two-tank RFQ 3.5 m long which accelerates $^{3}He^{++}$ to 8 MeV. Due to the increased mass and charge of $^{3}He^{++}$ relative to protons and the nature of the RFQ accelerating process, no additional accelerating structure would be required to get the beam up to 8 MeV. This simplifies the construction and operation of the machine and will reduce the cost relative to a more complicated design involving a DTL. Estimates of the yield for this system show that more than sufficient amounts of all of the isotopes will be produced and will not require the use of enriched target materials.

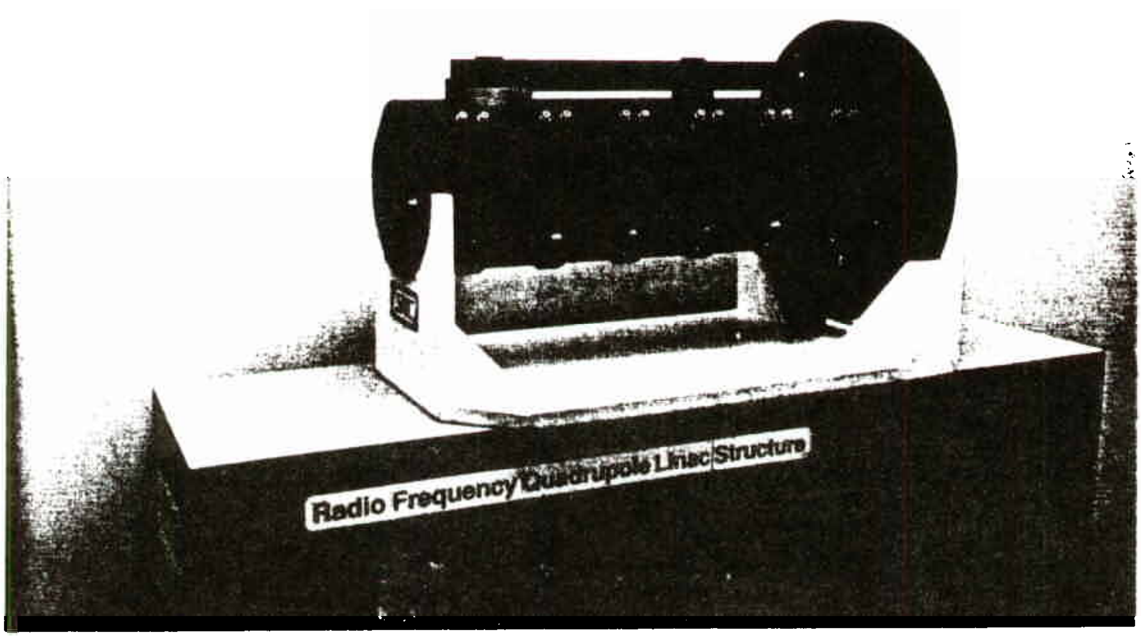

Figure 1. Typical RFQ Tank

Due to the neutron-poor nature of ^3He, relatively few neutrons are produced in interactions of the ^3He with most nuclei (either in the target itself or the accelerating structure). Coupled with the linear geometry of the RFQ accelerator, this leads to an order of magnitude reduction in the total facility shielding requirements (and hence, weight). In addition, all isotopes can be made with ^3He - there is no need to switch beam particles to make certain isotopes. Another benefit of using ^3He as the beam particle is that it will produce less activation of the accelerator and target hardware than a comparable proton or deuteron beam. This will result in lower radiation doses to maintenance personnel and, hence, more flexibility in the maintenance procedures.

Control and operation of the accelerator in a PET radiopharmaceutical production facility is a critical issue due to the fact that a major part of the cost of such a facility is the cost of the staff. If technicians instead of accelerator experts and radiochemists can be used to operate the system, substantial savings could be realized. By interfacing the simple to operate RFQ with already existing automated chemical synthesizers and targets, the important goal of a simple to operate radiopharmaceutical production system should be realizable.

2. General Design Description

The point design of the system was performed using the beam dynamic computer codes RFQSCOPE [4] and PARMTEQ [4]. RFQSCOPE is used to calculate parameters for the general description of the RFQ and input for the PARMTEQ code. The major parameters which are calculated with RFQSCOPE include the peak beam power, the peak surface field, the stored energy, and the quality factor of the RF cavity. PARMTEQ is used to study the beam dynamics of the RFQ. The code calculates the particle orbits using a table of geometric and electric field results calculated by RFQSCOPE. The input parameters to RFQSCOPE are:

Ion Species	=	$^3He^{++}$
RF Frequency	=	425 MHz
Aperture	=	.15 cm
Duty Factor	=	2%
Bravery Factor	=	2.24
Final Energy	=	8 MeV
Emittance	=	0.005 cm-mrad (rms, norm)
Peak Current (electrical)	=	15 mA

The RFQSCOPE output parameters are:

Current limit (electrical)	44 mA
Length	3.5 m
Peak RF Power	356 (kW)*
Average RF Power	7.2 kW

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* True cavity power consumption is assumed to be 50% higher than the code output.

The RFQ is about 3.5 meters in length and is enclosed in a 0.3 in. diameter vacuum tank. By comparison, a proton RFQ/linac design extrapolated from 10 MeV [3] to 12 MeV would be approximately 5.0 m long. A typical ^{3}He RFQ accelerator/target arrangement is shown in Figure 2.

The $^3He^{++}$ beam originates in a conventional duoplasmatron ion source. The ^{3}He passes through a low energy beam transport (LEBT) system that tailors the beam for injection into the RFQ. The ion source and LEBT combinations are attached to one end of the RFQ and are evacuated by a turbomolecular pump to an operating pressure of about 1×10^{-6} Torr. After acceleration to 8 MeV in the RFQ, the beam leaves the RFQ and drifts a short distance through a vacuum isolation valve, to the isotope-production target system. The RFQ beam transmission is 97%. The beam is allowed to expand during this drift to reduce the power density on the thin foils separating the accelerator vacuum from the target gas.

3 RF Power System

The rf power system for any accelerator is a critical system both in terms of performance and cost. As such, the rf power system for the ^{3}He RFQ will be discussed in some detail. The RFQ is configured as two 1.75 m long sections in tandem, each requiring about 180 kw of RF peak power. Table 1 presents the specifications for a 150 kW rf power source . The rf requirements were calculated with the PARMTEQ code. Conventional rf power systems are prohibitively expensive and heavy. The present design will instead employ a close-coupled, loop-driven scheme [5]. The close-coupled approach offers many advantages over conventional rf power systems:

- Eliminates the need for separate RF output cavities for each power supply
- Eliminates the need for transmission lines between the power supply and the RFQ, thus improving the power efficiency

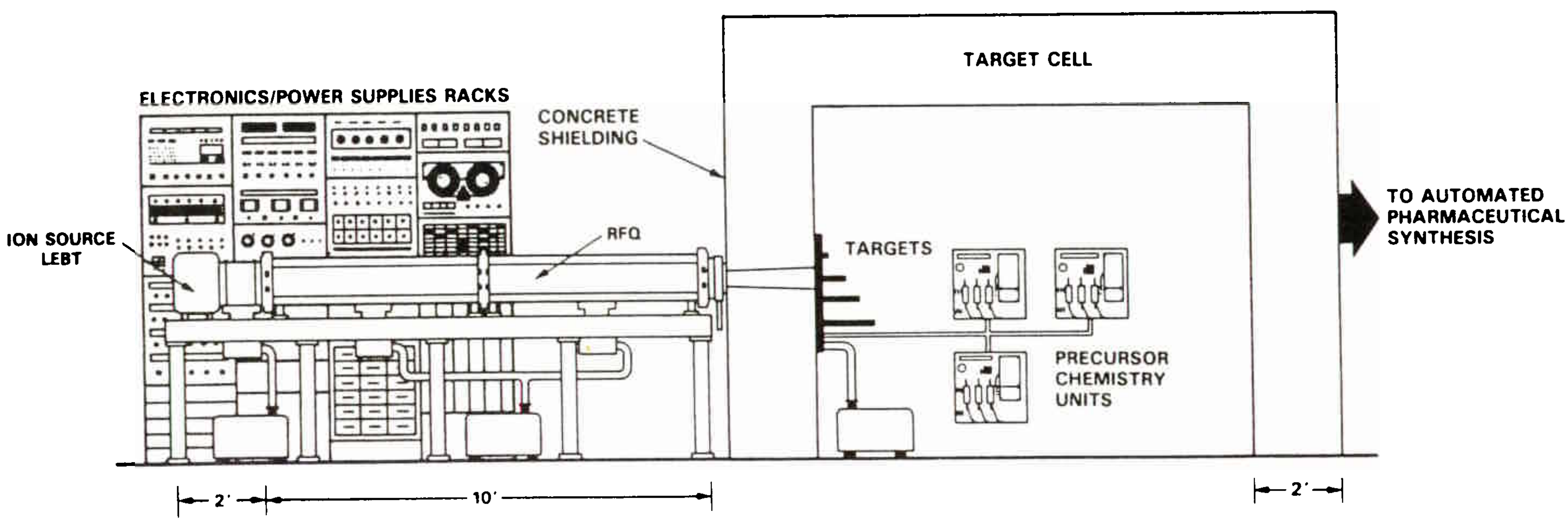


Figure 2. Typical Accelerator/Target Arrangement

- Eliminates the need for high-power RF windows for each transmission line

- Replaces the conventional RF drive loop with an integrated drive loop for each power source or cluster of power sources

- Provides a convenient, rigid, mechanical support for each power source.

Table 1. Conventional RF Power Source Specifications

Frequency	425 MHz
3DB Bandwidth	10 MHz min
Duty Cycle	5%
RF Pulse Width	60 μsec
Peak RF Power Output	150 kW min - 160 kW max
Phase Stabilities	+ .5°
AM Component	< 1.0 dB
Weight	1850 lb
Cooling	Cooling liquid, closed loop w/radiator and fans

Eimac Planar triodes are good candidates for producing rf power with high efficiency and high duty factors. For example, model YU-141, Y-176 can produce 30 kW of rf power with 2% duty factor and an efficiency of 60%. The planar triode operates well in a "grounded grid" configuration. This implies that the anode and the loop operate at an elevated potential (6-8 kV) and should have considerable capacitance to ground (200 pf or more). Using the required electrical insulation as the dielectric of the required rf bypass capacitor results in a compact and rigid configuration (Figure 3). Anode cooling water enters the anode bypass capacitor ring, passes through the loop to the anode cap, and then back through the loop and capacitor ring on the way out.

The power for each section will be supplied by 8 small planar triodes mounted directly on the RFQ cavity wall inside the RFQ vacuum enclosure as shown in Figure 3. This will provide ample power for normal operation, with sufficient reserve to survive the failure of two units. The 8 tubes would be mounted in pairs on each of the four quadrants of the structure. Each pair would be driven in parallel by one input cavity resonator. Figure 4 shows a close-up of a single close-coupled rf assembly mounted to an RFQ prototype.

Close-coupled, loop-driven, rf power sources, using the linac resonator itself as their output resonator and power combiner, offer substantial savings in the cost, complexity, weight and efficiency of rf power sources for linac applications. All problems associated with the extraction of the rf power from the power source, transmission of the rf power to the linac, and the injection of

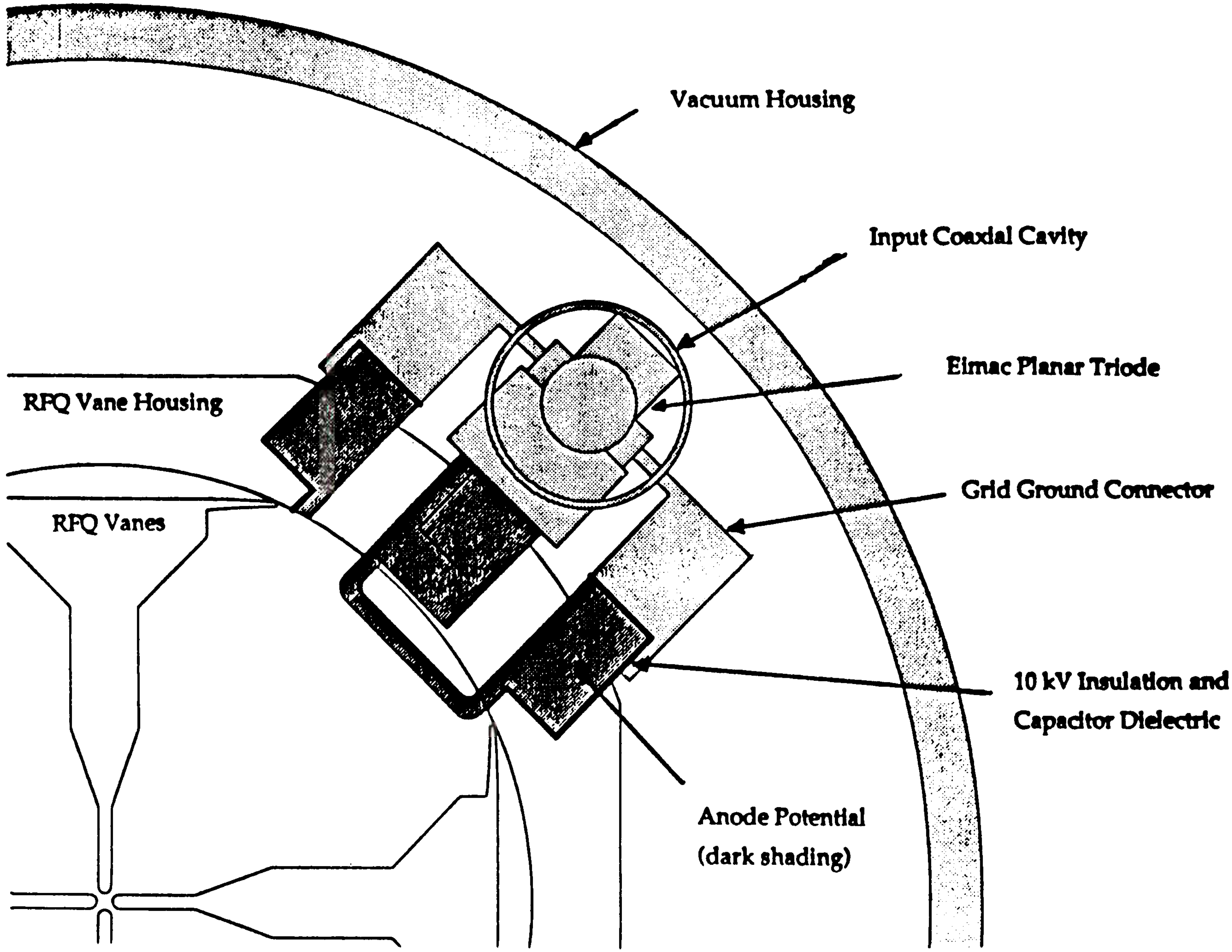


Figure 3. Anode Loop Insulation and Bypass Capacitor

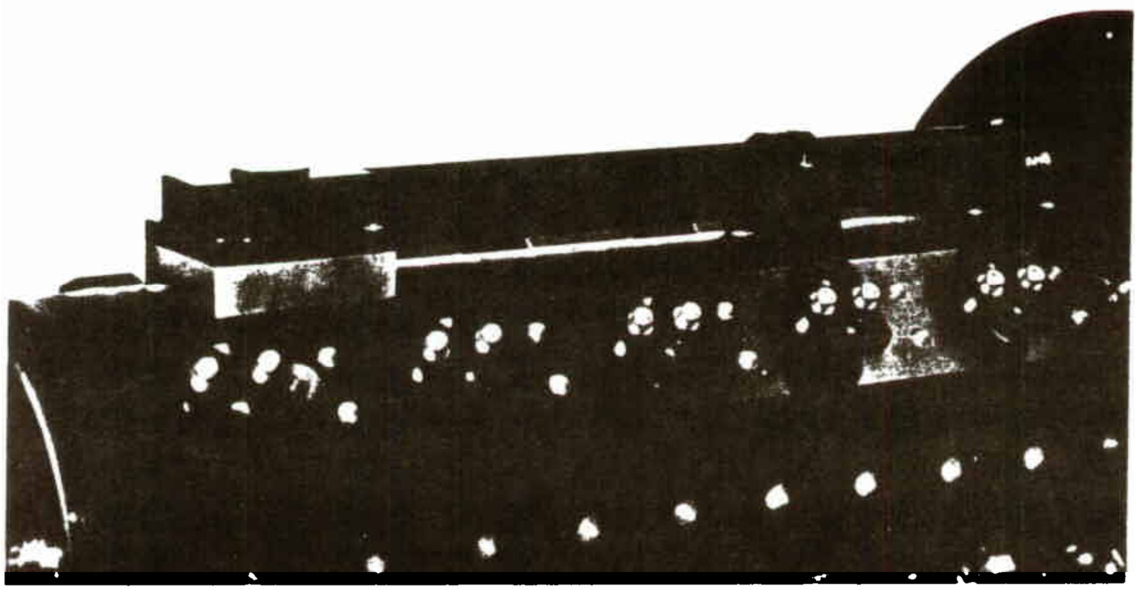


Figure 4. Close-up of Close-Coupled RF Assembly.

the rf power into the linac are solved, in the simplest way, by the close-coupled configuration. System control is simplified by eliminating any concern over reflected power and standing waves in the non-existent transmission lines. Such rf power sources are no longer a constraint on linac frequency since the major resonant element of the rf systems is the linac itself. The power efficiency is improved by eliminating the power dissipated in conventional rf power output resonators and transmission lines. The system reliability is improved by offering a "graceful degradation" condition on the failure of some power units.

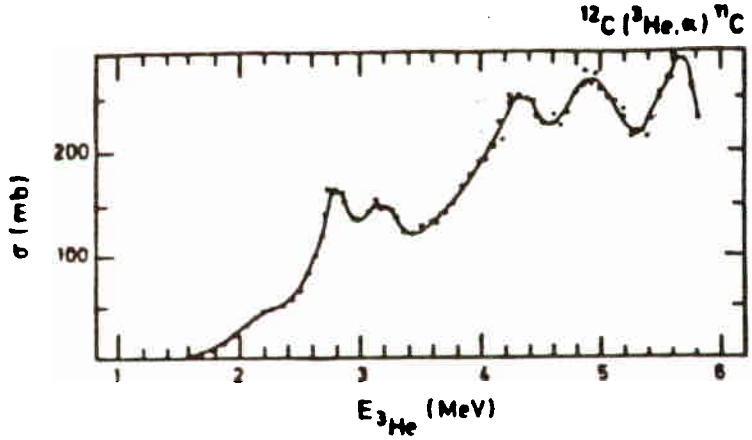
4. Radionuclide Yields

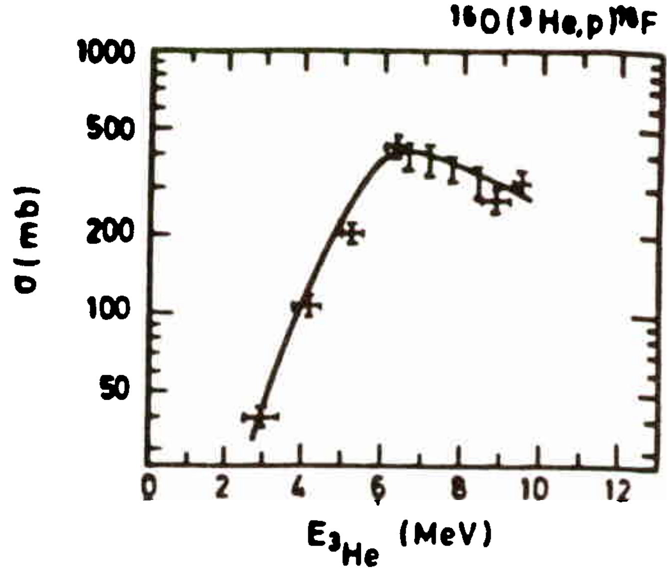
One of the most important aspects of any PET accelerator system is the radionuclide yield. The fundamental data underlying the concept of a ^3He RFQ for production of PET radiopharmaceuticals are the ^3He excitation functions (cross-sections vs. ^3He energy) in ^{12}C and ^{16}O as shown in Figure 5. The reactions, cross sections and half-lives for the isotopes of interest are shown in Table 2.

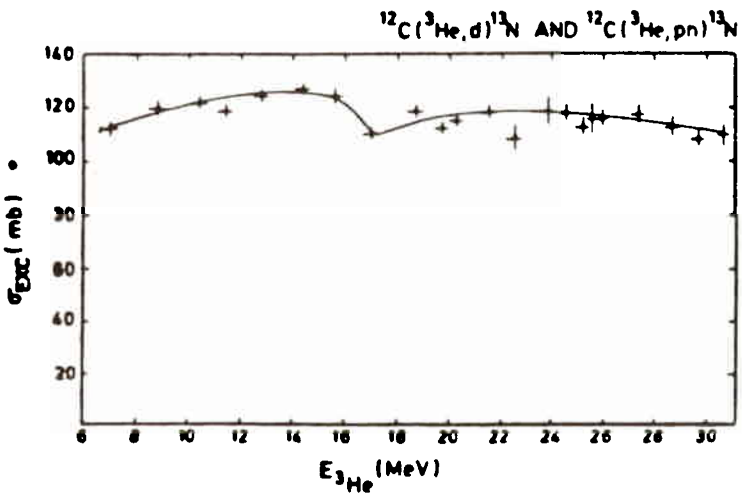
Table 2 Reactions, Cross Sections [6] and Half-lives of Interest

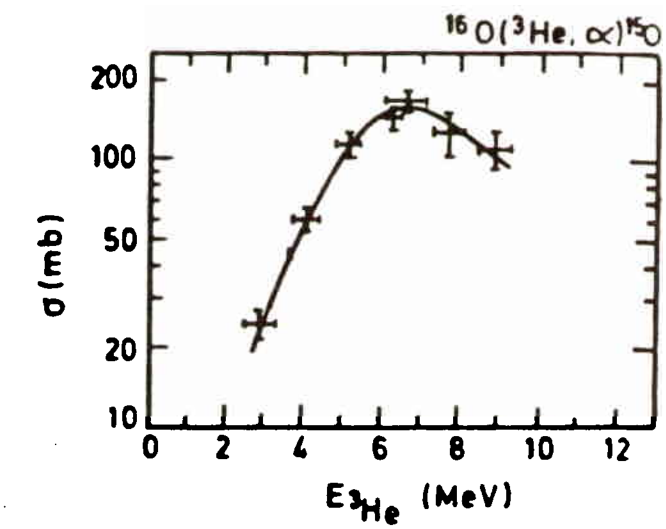
Reaction	Average (5-7 MeV) Cross-Section (mb)	Half-Life (min)
$^{12}C(^3He,\alpha)^{11}C$	250	20
$^{12}C(^3He,pn)^{13}N$ and $^{12}C(^3He,d)^{13}N$	110	10
$^{16}O(^3He,\alpha)^{15}O$	130	2
$^{16}O(^3He,p)^{18}F$	300	110

Allowing for a 1 MeV loss in the vacuum window foil separating the accelerator vacuum from the target, the cross section given in Table 2 is the average cross section for the energy range 5 - 7 MeV. Note that only one final state involves a neutron whereas most proton and deuteron based reactions involve neutrons which can lead to activation and shielding problems. Based on the cross-sections in Table 2, end of bombardment (EOB) yield estimates have been made and compared to the requirements for a single patient as shown in Table 3. For comparison, the reactions and yields for a small cyclotron are also presented in Table 3.









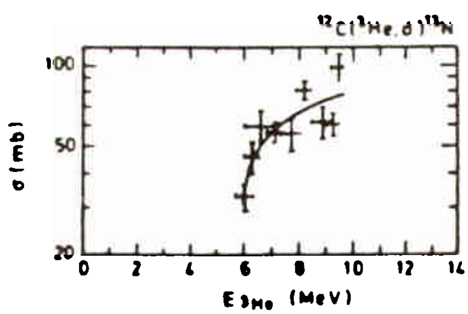


Figure 5. Relevant ^{3}He Excitation Functions.

Table 3 Yield Estimates

Isotope	Irradiation Time* (min)	Cyclotron+ Yield (mCi)	RFQ Yield (mCi)	Required Patient (mCi)
^{18}F	110	720 (p,n)	750	10
^{13}N	Saturation	600 (p,n)	290	10
^{15}O	Saturation	700 (d,n)	540	20
^{11}C	Saturation	2000 (p,α)	720	15

* After one T1/2 of irradiation the yield is 50% of saturation, after 3*T1/2 it reaches 87%.

\+ Japanese Steel Works 12/6 Baby Cyclotron

In all cases the yield of the ^{3}He RFQ exceeds the requirement. However, there are some targetry issues to be addressed for the ^{3}He RFQ system. The major one being the absolute yield and non-carrier free nature of the ^{11}C. Research is planned to improve this situation using innovative chemical synthesis and exploitation of hot atom chemistry to enrich in ^{11}C. ^{3}He targetry research in general is a planned part of the development of the ^{3}He RFQ PET accelerator and will be the subject of a forthcoming paper. Targetry related advantages of the ^{3}He RFQ system include the fact that all four isotopes of interest can be produced in adequate quantity without having to change beam particle type. This is a distinct advantage in efficiency and ease of operation and is unique to the 8 MeV ^{3}He RFQ. Low energy (12/6 MeV) proton/deuteron machines must switch beam particle type in order to produce all four isotopes. Also note that no enriched target materials are required, unlike the low energy proton/deuteron systems which must use ^{18}O to make ^{18}F, and ^{13}C to make ^{13}N.

5. Target System

The target mechanical system for the RFQ will be very similar to those used for cyclotrons. As such, the design will be based on an existing Scanditronix target handling system. The accelerated beam is extracted from the RFQ through a single beam exit port on which the target support frame will be mounted. The support frame will provide positions for mounting eight gas or liquid target chambers. The targets are mounted on guides which slide within the frame and can be remotely operated from the main console.

The beam enters the target chamber through a double-foil assembly mounted on the target flange. The thin foils are cooled by high-speed helium gas flowing between them in a closed-loop system. This system contains a recirculating pump, interlocks, interconnecting tubing, and controls. The foils facing the target and vacuum chambers are sealed with metal gaskets to minimize contamination. Organic seals are used elsewhere. Due to the high current, low energy nature of the ^{3}He RFQ, an alternate windowless beam/target interface is also being considered.

Target sequencing is fully automated and governed by the programmable controller. The operator selects the desired target at the control console by pushing a button. The controller initiates the change sequence by closing the beam exit vacuum valve and venting the small volume between the vacuum valve and the target. The support mechanism is tilted away from the beam exit flange. The selected target is indexed into position and the support mechanism is pressed against the beam exit flange. A mechanical fore-vacuum pump evacuates the volume between the target and beam exit valve to a preset pressure. When the vacuum level has been reached, the beam exit valve is opened. The time required for the target change is about three minutes.

6. Shielding and Activation

Unlike most reactions for proton and deuteron-based systems which involve neutrons in the final state, most of the ^{3}He-based reactions involve a charged particle in the final state. Such particles can be easily shielded by sheets of aluminum or the target casing itself. Further examination of the ^{3}He-based reactions reveals that although there are a few small secondary neutron production cross sections, neutron production in the targets will be greatly reduced relative to that in the proton and deuteron targets as shown in Table 4.

Table 4. Relative Neutron Production in Target (Neutrons/Radionucleus Produced)

Isotope	8 MeV ^{3}He	12/6 MeV Proton/Deuteron
^{18}F	0.08	1.00
^{13}N	1.00	1.00
^{15}O	0.20	1.00
^{11}C	0.50	0.50

Since ^{18}F is by far the most widely used PET isotope, the ^{3}He system is ideal because this reaction creates the fewest number of neutrons/radionucleus.

The neutron-poor nature of ^{3}He accounts for the relative lack of neutrons produced in the target nuclear interactions and also results in a relatively small production of neutrons in beam loss interactions of beam with the accelerating structure. Specifically, the cross section for neutron production for 8 MeV ^{3}He on natural copper (5 mb) is a factor of 100 smaller than that for 12 MeV protons on copper (430 mb) [7,8].

These facts have an enormous impact on the shielding requirement for the facility and, therefore, its weight. The capture efficiency of the RFQ is 97%. The beam dynamic calculations indicate that the 3% beam loss occurs equally at energy levels of .15, .6 and 1.5 MeV. If a conservative assumption is made that 1% of the beam strikes the accelerator at a point at full energy, the neutron dose rate one meter from that point would be only 0.3 mrem/hr. This is quite acceptable and, therefore, no neutron shielding is required around the accelerator.

Similarly, during full current operation for ^{13}N production (worst case) only 2 feet of ordinary concrete placed one meter from the target is required to reduce the neutron dose rate to 1 mrem/hr at the surface of the concrete. Assuming a target cell (containing targets and precursor units) of dimensions 5'x10'x8', this results in a total concrete volume of 16 yd^3 or 32 tons. Since the accelerator only weighs 0.5 tons and is unshielded, this is close to the total weight of the entire system (through precursors). By comparison, in a typical cyclotron facility the weight of the shielding (including the vault) and the cyclotron (20 tons) is about 260 tons [9]. Thus, the ^{3}He RFQ weighs a factor of 40 less than the proton cyclotron and the total facility weighs less by a factor of ~8. This weight difference could be reduced even further through careful shielding design and use of administrative radiation protection procedures. For example, if the target cell contained only the targets, a reasonable goal, it could be reduced in size by a factor of at least 2-3. The precursor units could be outside the cell and shielded with lead for the 0.5 MeV annihilation gamma-rays. Such an approach would reduce the overall weight to approximately 15 tons.

The activation of accelerator components will be reduced by a factor of 10-100 compared to the activation of a proton machine because of the reduced neutron production. Because the machine is a linear device, no extraction mechanism is required, thereby completely eliminating a major source of radioactivity inherent to cyclotrons. This virtual elimination of activated components will result in reduced radiation exposures to maintenance personnel. The rigid rule of Monday maintenance at medical cyclotrons to allow weekend radioactive decay would not have to be carried over to the ^{3}He RFQ.

7. Comparison to Alternative Approaches

Competition for a light weight, small, low cost accelerator for PET will likely be in the form of superconducting proton/deuteron cyclotrons and room temperature proton/deuteron linacs. The ^3He RFQ approach avoids the technical risk and high operation cost associated with the superconducting cyclotron and the complexity of the coupled RFQ/Drift Tube Linac. In addition, the use of neutron-poor ^3He results in an average factor of 10-100 reduction in neutron production relative to proton/deuteron systems leading to smaller (therefore lighter) shielding requirements. A qualitative comparison of these systems is contained in Table 5.

Table 5. Comparison of Competing Technologies

	Superconducting Cyclotron	Proton/Deuteron Linac	^3He RFQ
Technical Risk	High	Low	Low
Reliability	Low	High	High
Single Particle	Maybe	No	Yes
Enriched Targets	Maybe	Yes	No
Beam Cross Section	Elliptical	Circular	Circular
Activation	High	Med	Low
Facility Size	70 m^2	~35 m^2	25 m^2
Facility Weight	~240 Tons	~150 Tons	~30 Tons
Capital Cost	High	Med	Low
Daily Operations Cost	High	Low	Low

8. Conclusion

A new, innovative accelerator system, borrowing technology developed in part for the Strategic Defense Initiative, has been proposed for producing radionuclides for PET. The design consists of a two tank RFQ to accelerate $^3He^{++}$ to 8 MeV. Advantages of this concept include small size, low weight, single particle type, no enriched targets, and low neutron production. The machine would produce all four isotopes of interest for PET (^{18}F, ^{11}C, ^{15}O, and ^{13}N) with ^{18}F being produced particularly copiously. Power consumption would be approximately 20% that of present cyclotron-based systems. These attributes give rise to the possibility of a radiopharmaceutical production system which is transportable. Such a system could make the PET technique far more accessible geographically and financially than it is at present.

References

1. M.M. Ter-Pogossian, M. E. Phelps, E. J. Hoffman, et al., "A Positron Emission Transaxial Tomograph for Nuclear Imaging (PETT)", Radiology, 114, 89 (1975).

2. R. H. Stokes, T. P. Wangler, and K. R. Crandall, Proc. 1981 Particle Accelerator Conference, IEEE Trans. Nucl. Sci., 28, 1999 (1981).

3. R. Hamm et al., Accelerator Technology Conference Proceedings, p. 141 (1986).

4. K. R. Crandall, et al., "RF Quadrupole Beam Dynamics Design Studies," 1979 LINAC Conference, Montauk, NY, September 10-14, 1979.

5. D. A. Swenson, "Close-Coupled RF Power Systems for Linacs", SAIC Memorandum, April 22, 1988.

6. Handbook on Nuclear Activation Cross-Sections, Technical Report Series No. 156, International Atomic Energy Agency, Vienna, 1974.

7. E. A. Bryant, et al., Physics Rev., 130, 1512, 1963.

8. R. M. Humes, Phys. Ref., 130, 1522, 1963.

9. "Scanditronix Positron Emission Tomography Systems", Scanditronix, Inc., 106 Western Ave., Post Office Box 987, Essex, MA 01929.