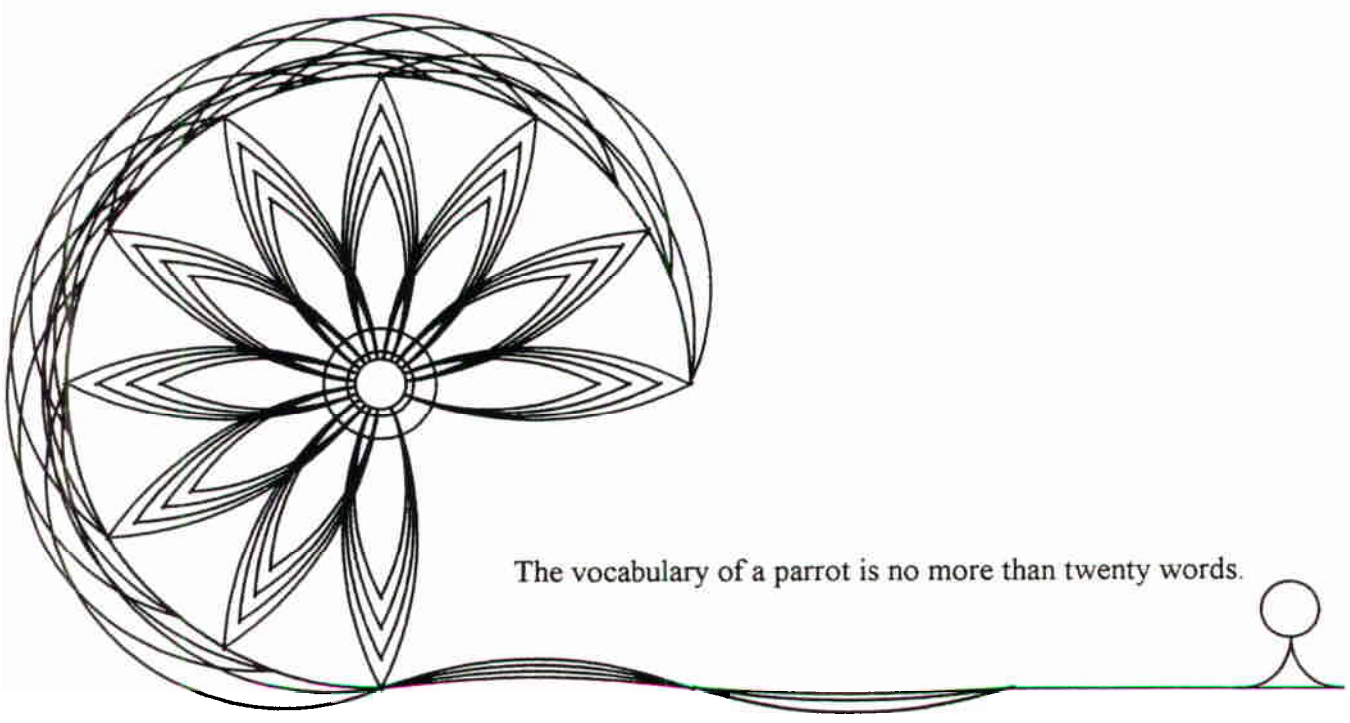
Session I.

Accelerators and Target Systems

Moderators: R. Shefer, R. Hamm



SESSION I: ACCELERATORS AND TARGET SYSTEMS

R. Shefer and R.Hamm, Co-chairs

During the past two years, a number of new approaches to radioisotope production have been demonstrated, including low energy linear and cyclotron accelerators and improved higher energy cyclotron designs. This session began with an overview of new accelerators for radioisotope production by Dr. Michael Welch, with particular emphasis on PET isotope production with low energy beams. He reviewed isotope production yields at beam energies below 4 MeV and described the experience of his group with the SRL tandem cascade accelerator which was installed in Washington University in the spring of 1993. Several new radioisotope targets have been tested on this machine and the target designs and yields achieved to date were discussed. Dr. Welch's introduction was followed by a presentation by Dr. Uno Zetterberg of GE Medical Systems. Dr. Zetterberg described the operating parameters and physical characteristics of the PET Trace cyclotron and discussed the advantages of the new vertical beam plane design.

On the topic of very high beam currents, Dr. Nigel Stevenson described the upgrades to the EBCO TR30 cyclotron at TRIUMF which allow this machine to operate with nearly 1 mA of beam at 30 MeV on two radioisotope targets. He described the detailed computer simulations which led to the design of both the solid and gas targets capable of surviving this high beam power load. The subject of RF linear accelerators was introduced by Dr. Robert Hamm of AccSys Technology. He discussed the principles of operation and characteristics of compact proton and deuteron RFQ linacs. These machines have been used as injectors for higher energy biomedical accelerators and AccSys Technology has designed several models specifically for PET radioisotope production.

The second part of this session continued with a summary by Prof. Ken Krohn of the results from the ^{3}He RFQ for PET isotope production. He described that new system, its advantages as well as its shortcomings and the experimental results achieved with the prototype. This was followed by a presentation with Dr. Robert Klinkowstein describing the compact electrostatic accelerator and target system under development at SRL for the production of [^{13}N]ammonia. This compact system will use a 1.25 MeV deuteron beam and a windowless graphite target to produce batches of [^{13}N]ammonia as a self-contained generator. All sub-systems of this unit are currently under development.

Dr. John Clark next described the experiences at Hammersmith and Turku with the IBA Cyclone-3 systems used for $^{15}O[H_2O]$ generation. He reviewed the history of the program and the problems encountered, as well as the present status of these two systems now in routine clinical use. Finally, Dr. Thomas Ruth reviewed the status of the development of the TR-13 cyclotron at TRIUMF, describing its design, expected performance, and present status.

In conclusion, this session covered a wide range of new accelerators and targets, all emphasizing the trend in this field toward very compact, simple systems to generate radionuclides for clinical use. Several of these machines, first described in Vancouver, are now complete and in operation, with most of the others expected to be complete in the near future.

Title: A New Versatile Target Design

Authors: Zetterberg, U., and Koziorowski, J,

Institution: GE Medical Syetems, Sweden

Abstract: The target presents a potential hazard with regard to radiation exposure to personnel during service and maintenance of the cyclotron.

To minimize the radiation hazard associated with target handling, our objective was to design a simple, reliable, long-time-between-maintenance, and easily serviced target.

This led to a modular concept where the targets consist of a limited number of standardized building blocks. No target is unique in its composition/structure. The targets are designed for manufacturing and assembly simplicity for instance by using an extruded aluminum hollow profile thereby providing a target unit with high reliability and reproducibility. The time for removing/attaching the target from/to the cyclotron is about 0.5 minutes. The time for assembling/disassembling is about 5 minutes. The short handling times reduces the personal dose appreciably.

PUSHING BEAM CURRENTS TO THE LIMIT

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ABSTRACT

One of the cyclotron systems running at the Nordion Int. radioisotope production facility at TRIUMF is the EBCO TR30. This cyclotron produces up to 250 μA on each of two beamlines simultaneously. Two solid (for the production of ^{201}Tl, ^{57}Co, ^{67}Ga and ^{111}In) and a gaseous (for producing ^{123}I) target station are in routine operation on this facility. Since future projections indicate a greater demand for reliable radioisotope production there is a program underway to increase the output of the facility to double the present level. One way that this is being achieved is through a careful thermal analysis of the the solid target system to maximize its performance. In conjunction with this we have developed and tested a 500 μA upgrade of our solid target system. Gas targets are being investigated for possible ways of increasing the efficiency of production via rotating/sweeping beams which allow higher beam currents. Finally, the TR30 cyclotron is being upgraded to deliver 50-100% more beam on target. By pushing both the cyclotron and target technology to the limit we will be able to produce significantly higher levels of radioisotopes than many other comparable facilities [1].

TR30 ISOTOPE PRODUCTION FACILITY

Isotope production at TRIUMF proceeds on all four cyclotron systems (520 MeV, CP42, TR30 and TR13) on site. The EBCO TR30 cyclotron, commissioned in July 1990, presently provides the most reliable high intensity beam for isotope production [2]. The TR30 cyclotron is a dual beam, variable energy (15-30 MeV) H^- machine that routinely provides over 200 μA at 29 MeV on each of two (solid) targets simultaneously. In addition to these two solid target systems an I-123 production (from Xe-124 gas) target is also located on the beamline systems of the TR30.

At present the TR30 isotope production facility runs near its maximum capacity of 450-500 μA on target at 30 MeV. Future business plans call for increased beam production and the desire of longer cool down periods for maintenance. To accommodate these requirements it is essential to increase the beam current in the TR30 and also increase the capacity of the targets to accept these higher power levels. A significant development program is underway to achieve our goals over the next 1.5 years. We will now describe some of the work we have undertaken towards those goals.

SOLID TARGET SYSTEMS

The solid target system [3,4] is based on a water-cooled silver face onto which target materials are electroplated and irradiated in vacuum. By placing the target at a 7° angle to the beamline the incident beam is spread out over the silver face to distribute the heat load. The wings of the double-gaussian beam are removed before the beam strikes the target by water-cooled graphite collimators placed immediately in front of the target face. Therefore, a well-defined rectangular beam (2.5 cm x 7.5 cm) strikes the target. Since the target materials are often enriched (and expensive!) it is normal to only plate this strike region of the silver face (to minimize losses during processing etc.).

This type of solid target system has been in use at TRIUMF on the TCC CP42 cyclotron for a decade. Except for minor refinements the system has essentially remained unchanged and has proven to be effective and reliable for radioisotope production from plated metals. Since the CP42 could only produce around 200 μA (i.e. the overall system was "cyclotron limited") there was little incentive to improve or increase the capacity of the targetry. However, the TR30 cyclotron can achieve up to 500 μA (usually split between two beamlines/targets). In addition, plans are under way (see below) to double this capacity. To avoid the situation of being "target limited" in our isotope production it became imperative that we increase the capacity of our targetry at least by a factor of two.

The most straightforward method of increasing the target's ability to accept more beam power is to increase the surface area, increase the cooling water flow rate, and spread the beam out more. Because the targets are transferred from the hot cells to the target stations in a carrier shuttle inside a pneumatic tube there are some size/geometry considerations and limitations. By optimizing the target design [5,6] we were able to produce a new version (see Figure 1) where the strike area is now (4 cm x 10 cm) about twice that presently used.

Figure 1. Target design.

There were very few changes required to our existing system (basically, only minor modifications to the mechanism that manipulates the target to/from the rabbit into the irradiation position were required). Of course the water flow must be proportionally increased. In addition, we will make some further changes in the choice of materials and minor construction modifications in the future [6,7].

Recent tests with our original targetry on the TR30 showed it could perform at routine currents of up to 250 μA at 30 MeV. Calculations using a thermal modeling finite element analysis computer program [8,9] for the new target design implied that double this current should be possible. In order to test this we set up a temporary "ultra-high" current target station on a spare TR30 beamline. Using some scintillating material pasted onto the surface of the target we were able to produce a defocused beam that was aligned on the outlined strike area. A special target which contained an imbedded K-type TC along with five plated Ni-Ag TCs on the silver face [10] was then tested with beam currents (29 MeV) up to 450 μA. With a water flow of ≈40 L/m through the target we monitored the temperature of the silver face during bombardment. Although not all TCs survived the ordeal we were able to extract sufficient information to conclude our confidence in the system at its design goal of 500 μA on target. Figure 2 shows the surface temperature measurements and indicates temperatures at maximum capacity (500 μA) which are below 140° -- our present operating conditions on standard targets.

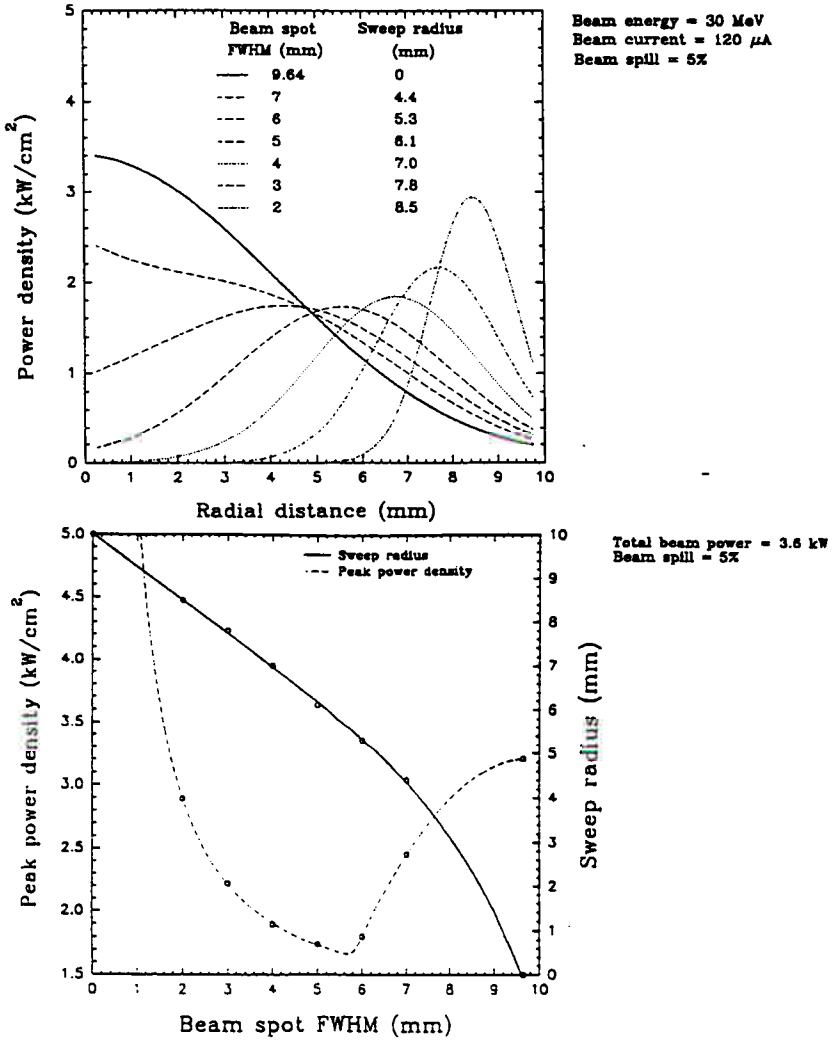

Figure 2.

Subsequent to a few further tests we will proceed with the assembly of a complete 500 μA target station and incorporate it into the TR30 system during the next year. This will allow us to run either single beam at currents up to 500 μA or a total of 750 μA when running dual beam. For the latter case, the TR30 upgrade (see below) will be necessary. Subsequent to the TR30 upgrade being proven successful we will consider a second ultra-high current target station in order to maximize the overall TR30 system's capacity and flexibility at 1 mA (30 MeV) on-target.

GAS TARGET SYSTEMS

The gas target system being used on the TR30 is based on Xe-124 for the production of I-123. This target contains the Xe gas within a cylindrical volume and has a double He-cooled havar entrance window. The present current limitation (30 MeV) of this target is 150 μA and it is routinely run at 125 μA for Nordion Int. in their commercial I-123 production program.

We undertook an examination of the performance of this (and similar PET) gas target under typical bombardment conditions by first making an analysis of the beam loss resulting from multiple scattering in the target. By varying such parameters as gas density and beam focus we were able to make some general conclusions with regard to the efficiency of the system under typical irradiation conditions. Typically, we found that the geometry of the target under normal operating conditions resulted in a make-rate loss of about 44% due to lost beam (as calculated from a standard production yield curve). By changing from a parallel beam to one that was slightly focussed we were able to reduce this to 37%. However, by far the largest effect was seen when the target length was halved and the pressure of the Xe gas was doubled. In this case our theoretical model predicted a loss of only 18%.

Of course, our model could not simulate one of the biggest effects we are aware of -- notably "hole punching" or depletion of gas in the path of the beam due to heating. To perform this analysis would require a complex finite element analysis modeling program. However, it should be possible to make empirical measurements of the effect if it can be removed or significantly diminished. This might be achieved either by an internal stirring system (fan) or, alternatively, by rapidly moving or oscillating the beam over the target window to avoid gas depletion at a particular location. The latter method is particularly advantageous since it also diminishes the effects of beam hot-spots and also reduces the maximum foil temperature. However, for this to be effective the appropriate beam parameters must be used e.g. the frequency of oscillation must be several hundred Hz in order to minimize potential thermal cycling effects in the long-term mechanical strength of the foil [11].

In a number of calculations we varied the beam distribution on the face of the gas target in terms of the sweep radius and width of the beam and assumed that the sweep frequency was rapid enough such that the temperature distributions on the window could be well represented by time-averaged values. We found that for a given beam current on target an optimum beam

size and sweep radius exists (for a particular target geometry) that results in a minimum peak foil temperature. Figure 3 highlights these conditions for our particular targetry. If peak foil temperature is the limit we have on our targetry then this method of distributing the heat load would also enable us to make a corresponding increase in the beam current.

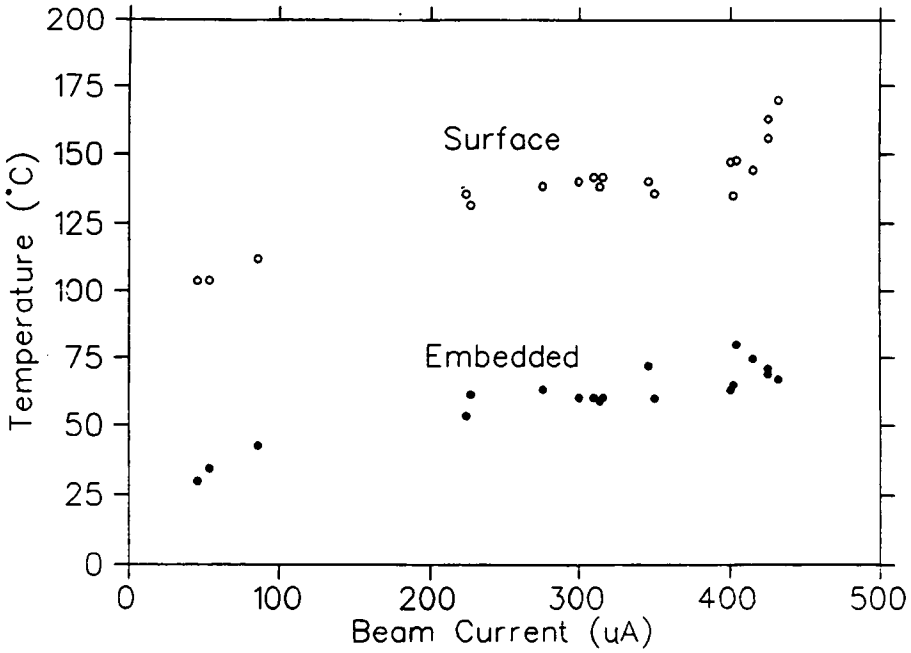

Figure 3. Dependence of foil temperature on beam intensity.

CYCLOTRON UPGRADE

The TR30 routinely produces over 400 μA on target and can achieve a maximum of 500 μA [2]. With suitable upgrades and changes we intend to double this capacity by the end of 1994. The major changes are :

Upgrading the RF system from 40 KW to 70 kW.

Upgrading the ion source and injection line. The present ion source delivers 5 mA DC. Some recent development work is indicating that this can be increased to 7 mA with few modifications.

Development work is also underway on a small (1 MeV) "central region model" cyclotron to improve the injection line by reconfiguring elements and adding a buncher to improve on injection efficiency.

Other services (power, cooling water etc.) must be upgraded. In addition solid target chemistry must accommodate the larger targets (discussed above) that will be prepared and processed. Beamline optics require minor changes (one interesting option [12] that has been suggested is incorporating octopoles to flatten the beam i.e. reduce the peak power density at the center of the target face).

The beam tests already performed at 450 μA on a single beamline prove the ability of the system (extraction foils, beamline and target components) to accept and transmit high power beams intothe target areas.

CONCLUSIONS

Our tests on the high current targetry together with our ongoing research into the improvements required on the TR30 show that much higher levels of radioisotope production are realistically achievable on this system. By 1995 we will have reached another interesting barrier where the existing cyclotron and targetry will seemingly have both reached their maximum capacities. In that case we will indeed have pushed beam currents to the limit -- or can we go even further?

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RF Linacs for Radioisotope Production

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Introduction

This paper is an update on the development of the rf linacs for radioisotope production first described in the accelerator roundtable presentations at the Third Targetry Workshop in Vancouver, Canada. These compact ion accelerators, now possible because of the development of the Radio Frequency Quadrupole (RFQ), can provide high currents of protons, deuterons, or helium ions from energies of a few MeV up to 100 MeV. Several of the rf linacs described in Vancouver have now been designed and developed for PET radionuclide production, showing their obvious advantages over other accelerator technology in size, weight and shielding requirements. Based on the results from these prototype systems, a design has now been completed for a 7 MeV proton linac that, when coupled to the new targets being developed, can supply all four PET radionuclides (^{11}C, ^{13}N, ^{15}O, and ^{18}F) in adequate quantities for clinical studies. This accelerator will require little or no shielding when the proton beam is delivered to a compact shielded target assembly, making it capable of being placed virtually anywhere in a hospital or clinic.

RF Linac Technology

The schematic layout of a typical rf linac for producing ion beams is shown in Fig. 1. The ion injector consists of an ion source to produce the required ion specie and an electrostatic extraction system to produce the ion beam at the correct energy for injection into the RFQ. The low energy beam transport (LEBT) is made up of either electrostatic or magnetic beam focusing elements placed in the beamline between the injector and RFQ. These lenses focus the high current beam from the ion source into the RFQ with the proper beam convergence and diameter for acceleration by the RFQ structure, shown in Fig. 2. Either positive or negative ions, or both simultaneously, can be accelerated in the RFQ due to the bipolar nature of the rf accelerating voltages. However, the RFQ will accelerate only the specie with the charge-to-mass for which it was designed, and will produce a fixed output velocity (energy) for these particles. The design and theory of the RFQ have been previously described in much detail[1] and this unique accelerating structure has now been proven in a number of practical applications.[2,3]

The RFQ is usually driven by an rf power system coupled to the resonant cavity through a coaxial line, and it uses a conventional vacuum pump (cryopump or turbomolecular pump) to maintain a vacuum of around 10^{-6} mbar. The resonant cavity of the RFQ is cooled to remove the heat generated by the rf power used to generate the accelerating voltages and to maintain the cavity at the correct operating frequency. The RFQ accelerator has been demonstrated as one of the simplest and most rugged high current ion accelerators. While it can simultaneously bunch, focus, and accelerate an intense ion beam, none of its adjustable input parameters are critical. The ion beam output current and energy are almost independent of the rf power level

after a threshold value has been achieved. The input beam energy has a large acceptance, with little reduction in performance, and the resonant frequency of this robust, symmetric structure is easy to maintain with a servo-driven tuner. The ruggedness and compactness of the RFQ has been best demonstrated by the BEAR program, where a 1 MeV H^- RFQ was operated aboard a rocket in sub-orbital flight.[4]

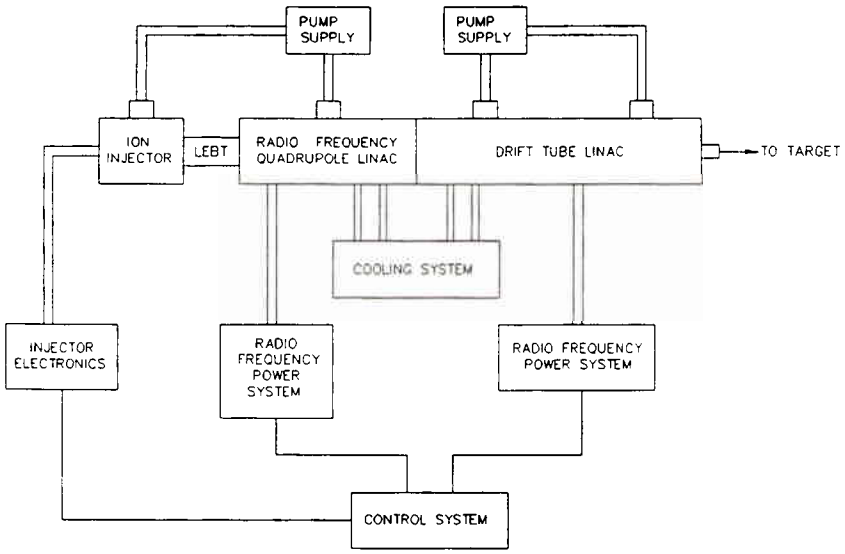

Fig. 1 - Schematic layout of rf linac system.

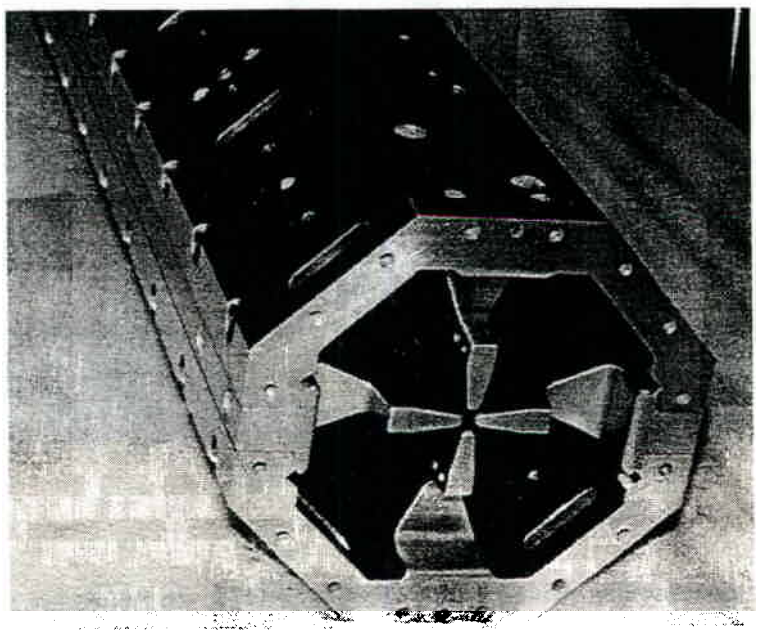

Fig. 2 - Four vane RFQ structure

The RFQ linac offers several advantages over other technology for the production of PET radionuclides, either as a stand-alone accelerator or as the injector to a conventional rf linac. The RFQ generates bunched high-current ion beams and produces high-quality beam outputs with respect to emittance and energy spread. At particle velocities above 8% of the speed of light (about 3 MeV for protons), the RFQ becomes an inefficient ion accelerator, but the beam is ideally suited for injection and further acceleration in a conventional drift tube linac (DTL) structure such as is shown in Fig. 3. This structure accelerates the bunched ion beam from the RFQ by high gradient rf electric fields in the gaps between the cylindrical drift tubes generated by rf power input to the cavity. The drift tubes shield the beam when the fields in the gaps are in the reverse direction, and also contain magnetic quadrupoles that focus the beam along the beam axis. Modern high frequency DTL structures can achieve accelerating gradients of more than 3 MeV/m, and are constructed in short sections that are easily joined to make a modular upgradable system. As with the RFQ structure, DTLs are inert metallic cavities with no moving parts, and are powered by external rf systems fed into the structure through easily replaceable vacuum windows. The resonant frequency is maintained with a servo-driven tuner coupled to the rf frequency generator.

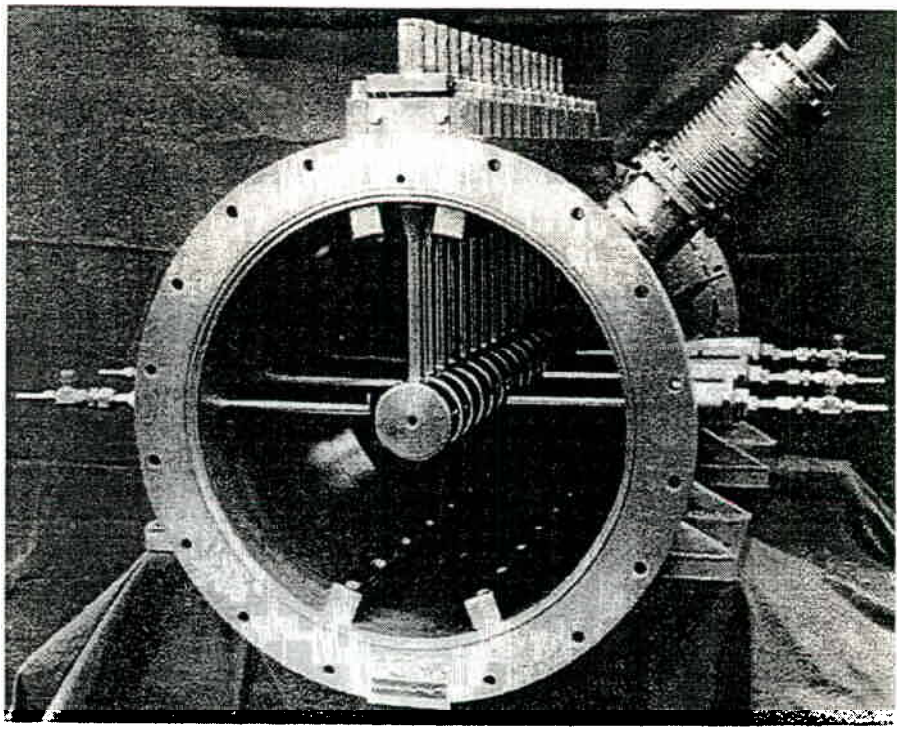

Fig. 3 - AccSys DTL structure.

The rf power systems that drive both the RFQ and DTL structures are reliable commercial units that are in use worldwide. The AccSys control system which operates the rf power, ion injector and vacuum systems, is based on a rugged interface unit developed at Fermi National Accelerator Laboratory,[5] that connects to a PC system. This modular control system can also be used to control the high energy beam transport elements required to transport the ion beam from the accelerator to the radionuclide production targets.

PET Radionuclide Production Linac

While several designs have been developed for rf linacs dedicated to PET radionuclide production,[6,7] none of these appears to be the ideal accelerator for a clinical setting. Recent work on small electrostatic machines[8,9] capable of accelerating both protons and deuterons has also pursued the goals required for this application: a rugged system, capable of making all four PET radionuclides, that can be placed in a small space near the patient handling area of a hospital or clinic at a fraction of the cost of existing systems. While none of these developments has yielded a final product that fulfills all of these requirements, they have prompted the development of unique targets that are capable of handling large beam currents at low bombarding energies. These new targets, including ones for pulsed beams, have now made it possible to define the ideal clinical PET radionuclide generator.

The ideal linac, shown schematically in Fig. 4, has an output energy of 7 MeV, is less than 4 meters long, weighs less than 5000 lbs, and requires less that 20 kW to operate. The bare accelerator is almost self-shielded because of the low beam spill, the low voltages used to accelerate the beam, and the steel vacuum chambers surrounding it. It utilizes an rf-driven H^- ion source for instant on/off operation with little maintenance, a proven RFQ section, and a short DTL section. The RFQ and DTL are each powered by a commercially available rf power system. The 7 MeV H^- ion beam that exits from the accelerator has very small transverse phase space dimensions (i.e. emittance) and is easily transported through small permanent magnet quadrupoles to a target system, which can utilize a removable neutron shield placed locally around the target during irradiation. The prototype of this system (with a 3.9 MeV proton output beam) is shown in Fig. 5. The radiation around the accelerator, both x-ray and neutrons, has been projected to be less than 10mR/hr for an output beam current of 100 μA, based on experimental measurements at 10 μA. Because the primary radiation is x-rays from the electrons in the accelerating gaps, this would not increase significantly with the 7 MeV version, as all of the accelerating gaps have the same voltage.

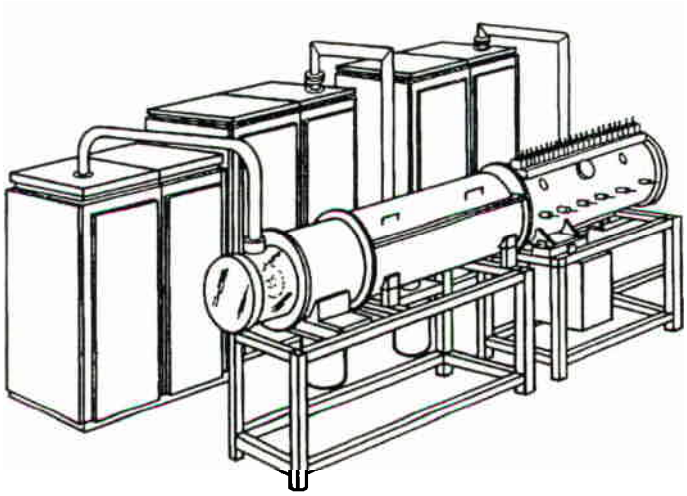

Fig. 4 - AccSys 7 MeV H^- linac.

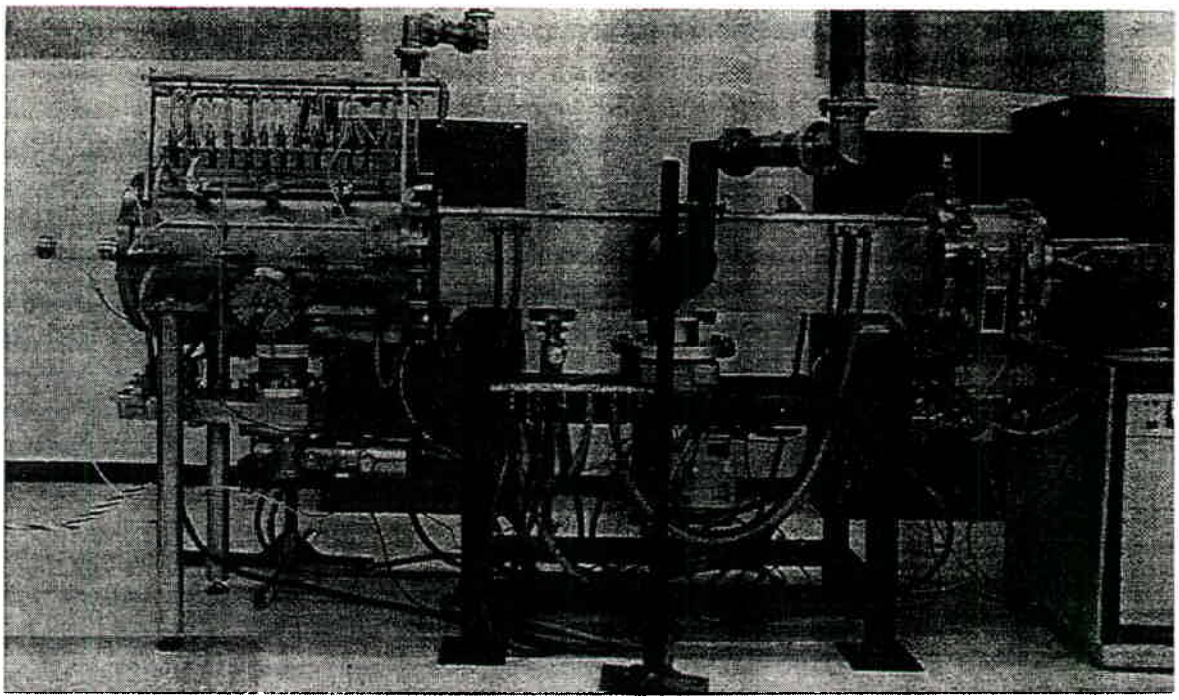

Fig. 5 - Prototype 3.9 MeV linac.

The proven components of this compact accelerator make it ideal for routine clinical PET radionuclide production. The rf-driven H^- ion source, now in routine operation at two accelerator laboratories, requires little maintenance and is quite easy to operate with an rf coil to excite the plasma instead of an electrical arc. The commercial rf power amplifiers developed by AccSys specifically for these linac structures require low operating voltages for the multiple tubes that are used in them and are low maintenance systems. The proven reliability of these components, combined with the ruggedness of the linac structures and the commercial vacuum and electronics systems, make this compact H^- linac comparable in operational simplicity to the ~6000 compact electron linacs in clinical use worldwide for routine cancer treatment. The efficient operation of the linac, coupled with the production of an H^- output beam, will allow simultaneous production of several PET radionuclides with appropriately matched targets and chemical synthesis modules.

The advantage of this compact linac over other low-energy PET accelerators is illustrated in Fig. 6, which is a calculated plot of the energy of the proton beam versus the beam current needed to produce enough radioactivity for routine synthesis of each of the four positron-emitting radionuclides with a bombardment time of only one half life (one hour for ^{18}F). These quantities have been chosen to be 1 curie of activity for fluorine-18 and carbon-11 and 500 mCi of activity for nitrogen-13 and oxygen-15. The energy range for typical electrostatic accelerators, as well as the energy for the AccSys PET linac system are indicated. Table I is a comparison of the parameters of the AccSys PET linac with those of the ^3He linac developed by SAIC and the electrostatic accelerator developed by SRL. Capital costs for these three systems are assumed to be comparable, with the electrostatic accelerator probably being the least cost system. Finally, Fig. 7 shows the AccSys PET linac layout in a typical clinical setting that would be required for any of these compact systems.

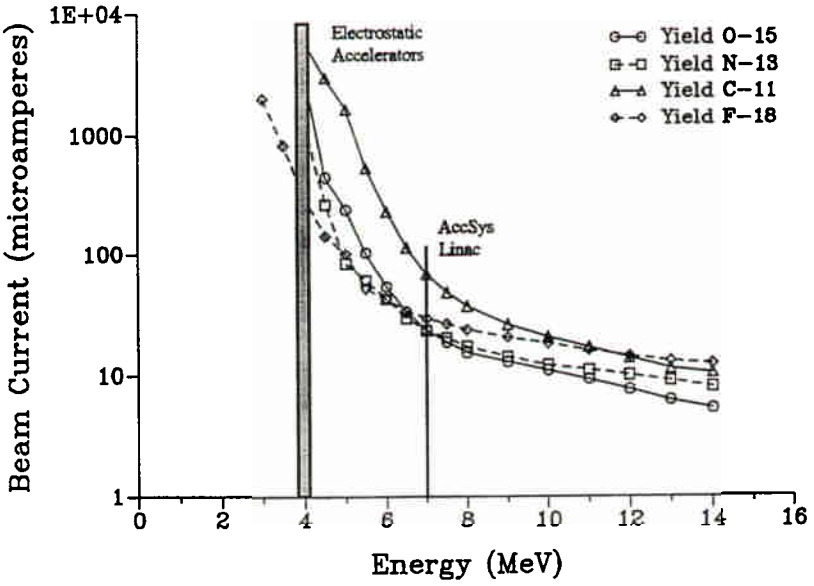

Fig. 6 - Proton current vs. ion energy for useful yields of PET radionuclides.

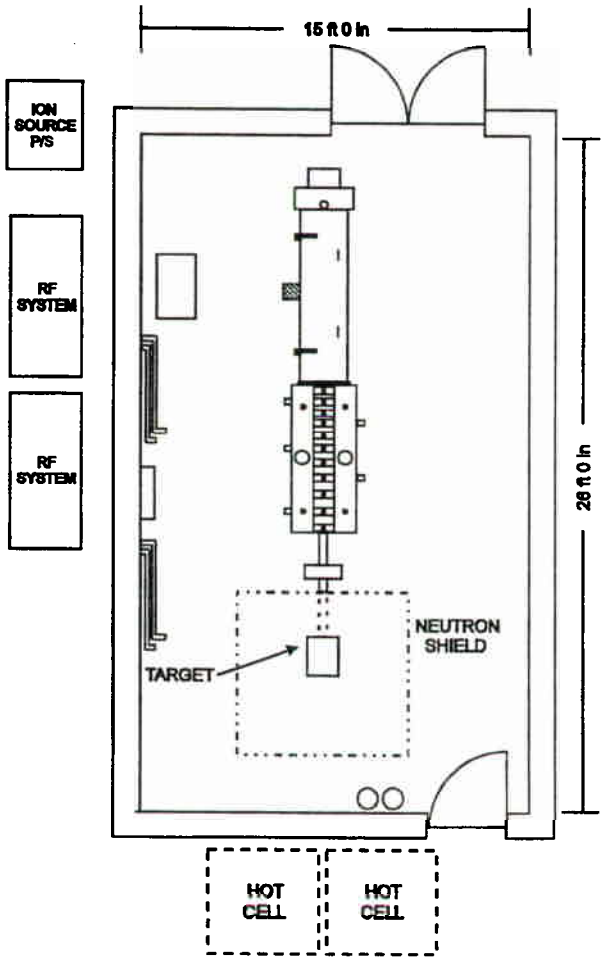

Fig. 7 - 7 MeV PET linac in typical "compact" accelerator vault.

Table 1. Comparison of Compact Linac Operating Parameters.

	AccSys	SAIC	SRL
Output Particles	$H^{\pm}$	$^{3}He^{++}$	H^{+}, D^{+}
Max Energy	7.0 MeV	8.0 MeV	3.7 MeV
Maximum Current	150 μA	300 μA (electr.)	750 μA
System Length	14.5 ft	16.5 ft	14 ft
Accelerator Weight	2 tons	1 ton	1 ton
Shielding Weight	4 tons	4 tons	5 tons
Total Electrical Power	20 kW	20 kW	15 kW
Floor Space	300 sq. ft	300 sq. ft	300 sq. ft
Current Required for 1Ci Production Yields:1Ci ProductionYields:			
^{11}C	70 μA (20 min)	275 μA (sat.)	420 μA (40 min)
^{13}N	100 μA (20 min)	2000 μA (sat.)	110 μA (20 min)
^{15}O	15 μA (5 min)	400 μA (sat.)	200 μA (sat.)
^{18}F	25 μA (60 min)	430 μA (110 min)	740 μA (110 min)

Conclusions

AccSys Technology, Inc. has developed the technology for a very compact 7.0 MeV H^- linac that can be used to produce clinically useful quantities of all four common PET radionuclides. Recent operation of a lower energy prototype of this accelerator has shown that only minimal shielding of the accelerator will be required. Because the target can be located up to two meters from the accelerator, total shielding volume is small. The recent work on targets for low energy beam systems can be utilized to develop PET radionuclide production targets matched to this accelerator's beam properties.

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^{3}He RFQ for PET Isotope Production
A UW/SAIC Progress Report

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A broad agency announcement by the Strategic Defense Initiative of the US Department of Defense ("Star Wars") in 1988 requested proposals to apply new accelerator technology being developed for the military for alternative uses in medical research. The proposals were to be evaluated on issues such as cost, weight, simplicity, control systems, and targetry. This report describes one such project proposed jointly by Science Applications International Corporation (accelerator design and development), the University of Washington (targetry development) and Scanditronix (manufacturing). SDIO funding for miniaturized accelerators for PET was awarded in November 1989. Two different projects were funded: Science Research Laboratories and Washington University (St. Louis) to develop the tandem cascade accelerator and ourselves to develop the 8 MeV ^{3}He RFQ.

Advantages of the RFQ

The SAIC/UW proposal was to develop an 8 MeV $^3He^{++}$ beam with 150 μA mean particle current (1). The anticipated reactions and yields for PET isotope production are given in the table below.

Nuclear Reaction	mCi Anticipated
$^{16}O(^3He,p)^{18}F$	685 (110 min)
$^{16}O(^3He,\alpha)^{15}O$	660 (sat'n)
$^{12}C(^3He,\alpha)^{11}C$	700 (sat'n)
$^{12}C(^3He,pn)^{13}N$	270 (sat'n)

Several advantages were suggested for RFQ linacs for isotope production. They are generally small, light weight, and thus more easily sited that PET cyclotrons. RFQs are inexpensive to manufacture, have low power requirements, and are simple and robust machines. None of their adjustable parameters are critical. Several additional advantages were gained by selecting a ^{3}He beam at 8 MeV. These targets do not require enriched isotopes. Both ^{18}F and ^{15}O can be made with a simple target to irradiate natural abundance water. Also, the neutron deficient nature of the irradiating particle results in a low neutron field and so only the targets need to be shielded. The initial proposal described a $^3He^{++}$ ion source with a system for efficient recovery of the ^{3}He and close-coupled RF power system to avoid problems of transmission lines and RF windows and to improve power efficiency.

Challenges for RFQ Targetry

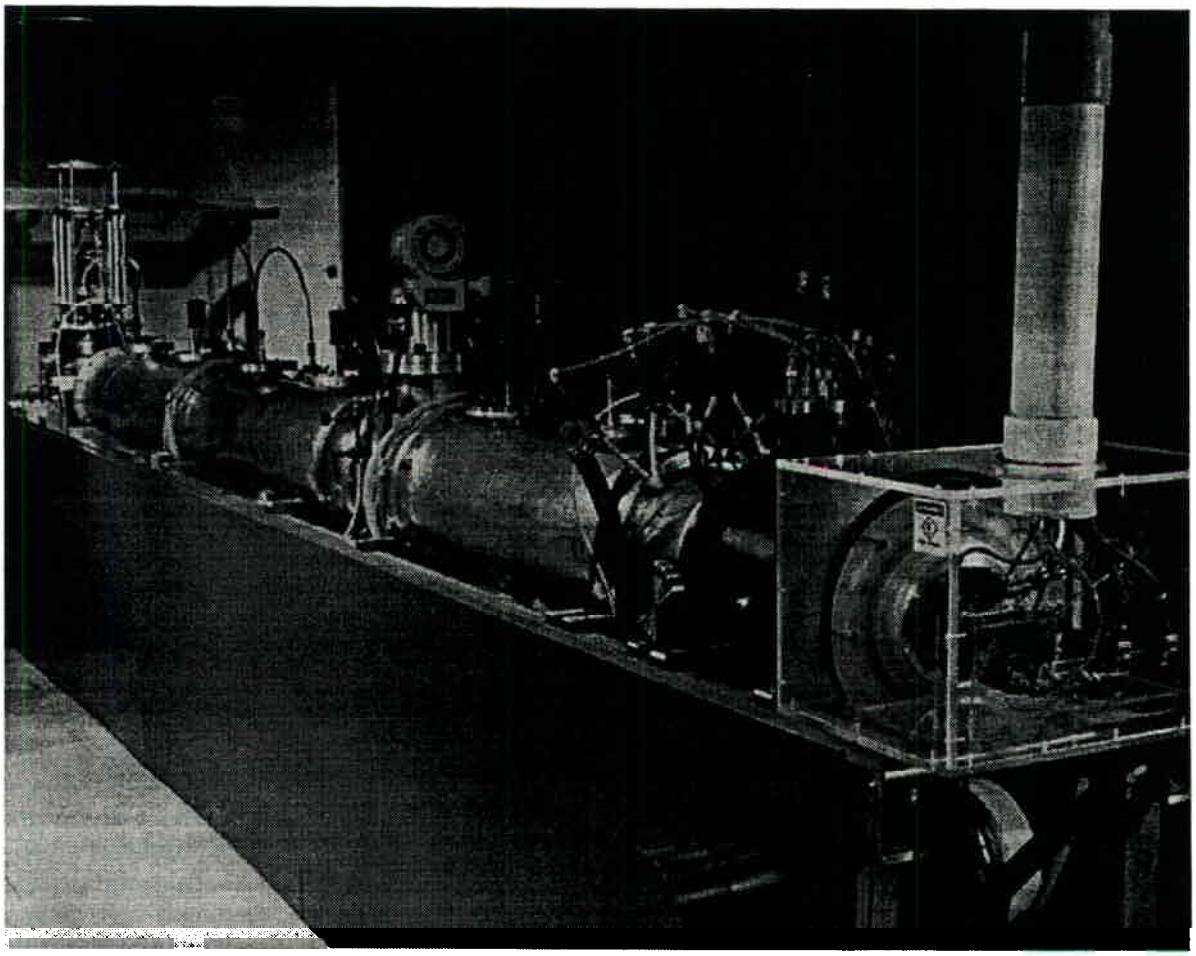
Several challenges were anticipated for the new RFQ targets. The average *beam current* that was needed for practical isotope yields was 150 μA particle (300 μA_e). This would result in 150 μA x 8 MeV, 1200 watts, of power deposited. However, the RFQ beam is pulsed with a duty cycle of 2% (360 Hz x 50 μsec). The pulses are essentially square wave with a peak current of 7.5 mA_p. Thus the more formidable issue was the 60 KW during the pulses. This power deposition was compared with that of other accelerators in a report (2) and windows of large surface area were anticipated to reduce the beam current density to about 5 $\mu A_p/cm^2$.

A second concern, common to all low energy accelerators, was that the *windows* could only be 1 MeV thick to achieve the required yields for routine PET. This corresponds to Havar windows of only 0.16 mil (0.004 mm or 3.3 mg/cm^2). The third targetry issue was one of *specific activity* for ^{15}O and ^{11}C, produced by (^3He,α) reactions on ^{16}O and ^{12}C, respectively.

RFQ Engineering and Construction

Design and engineering of the RFQ have been described (1,3). After some experience in developing close-coupled RF, it became apparent that this objective was too developmental for the time requirements and financial resources of the SDIO project and it was abandoned in favor of a standard RF power system consisting of several planar arrays of 6-8 vacuum tubes operating in parallel. Furthermore, the current output of ^3He doubly charged from the duo-plasmatron ion source was too low to meet the machine's needs. An ECR source was considered but was not consistent with the stringent weight requirements of SDIO. We therefore settled on using singly charged ^3He from the duo-plasmatron ion source, which was accelerated to 1 MeV with a 212.5 MHz RFQ, and then the second electron was stripped during passage thru a low pressure argon region. The 1 MeV He^{++} was then accelerated with two coupled RFQ tanks operating at 425 MHz, resulting in the desired 8 MeV terminal beam energy.

A picture of the RFQ as of January 1993 is given below. The accelerator portion from ion source (on the right) through to the beam stop (on the left) is 5.0 meters long.



Evaluation of Reaction Cross Sections and Preliminary Target Design

In order to critically assess the feasibility of 8 MeV ^{3}He for PET isotope production, we did a series of cross section measurements using the tandem Van de Graaff at the UW (tables below) and found excellent agreement with the literature for reactions on ^{16}O, but discrepancies for reactions on ^{12}C. Fortunately the ^{11}C yield is over twice what we had anticipated. The ^{13}N yield is only about one-half of that predicted from the literature, but should still be adequate for batch production of $^{13}NH_3$. Our results also showed that increasing the ^{3}He energy by 1-2 MeV increased the ^{11}C yield by ~3-fold but it did not substantially improve the ^{18}F yield. As part of these experiments we also measured the neutron yields at several angles for both targets.

Yields were also measured for ^{3}He reactions on natural-abundance boron as a potential route to high specific activity ^{11}C. Less than 1 Ci of activity could be made at full current and saturation. We have not persued boron targets.

$^{15}O/^{18}F$ Target Yields

Product	Anticipated[1]	From UW Expts[2]
^{15}O	660 mCi	690 mCi at saturation
^{18}F	685 mCi	860 mCi in 2 hrs
Neutrons		$4x10^7$ neuts/μcoul at 0° $1.7x10^7$ at >45°

$^{11}C/^{13}N$ Target Yields

Product	Anticipated[1]	From UW Expts[2]
^{11}C	700 mCi	1600 mCi from carbon (1 hr) 800 mCi from CO (1 hr)
^{13}N	270 mCi	110 mCi (20 min)
Neutrons		$3x10^8$ neuts/μcoul at 0° $2.7x10^7$ at >45°

[1] Predicted from literature. [2] Thick target yield below 7 MeV measured at UW

From these studies we concluded that a beam ≥7 MeV would be needed on target; any windows should be ≤1 MeV thick and, if a thicker window is needed for strength, then a higher energy ^{3}He beam should be designed. It was also clear that we should avoid using materials with Z<Coulomb barrier in the high energy end of the accelerator and in the targets in order to take full advantage of the low abundance of neutrons. This ruled out use of aluminum alloys.

Neutron Production

Neutron counts are less useful than neutron dose rates (rem/hr) for estimating shielding requirements for an accelerator installation. We therefore made numerous measurements with Bonner spheres to assess the rem dose axial to the beam and at several angles. Our results showed that the neutrons were distributed isotropically around the oxygen target but were highly forward-peaked for the carbon target because the latter involvess a stripping mechanism for one reaction channel. The results are summarized below and are compared with neutron production for ^{2}H and ^{1}H reactions calculated from literature data and normalized to production of equal amounts of radioisotope. These results show that reactions with "neutron poor" ^{3}He

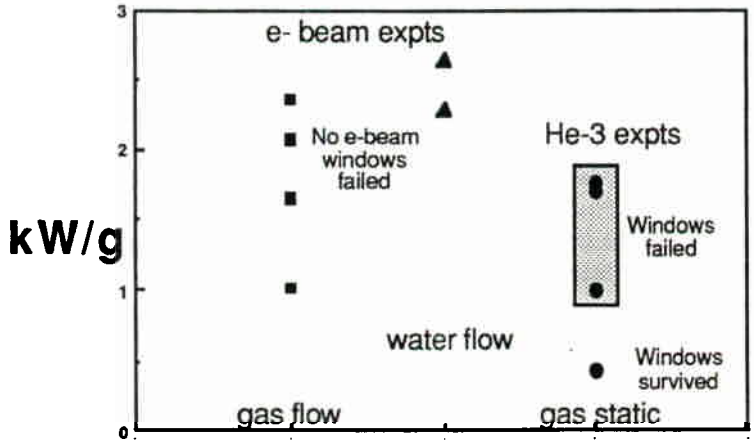
produce less radiation from the targets. The PET-RFQ requires only local shielding around the targets.

Target Material	rem/min (at 1 meter)		
	^{3}He	^{2}H	^{1}H
Carbon	0.49	24	1.6
Oxygen	0.31	19	0.45
Nitrogen	not measured	24	N/A

^{3}He: 8 MeV x 300 μA, thick targets. ^{2}H: 5 MeV x 100 μA, thick targets calculated from ref. 4.
^{1}H: 11 MeV x 100 μA, thick targets from ref. 5.

Evaluation of Thin Windows

Our preliminary studies with thin Havar windows used an electron beam welder and were reported at the Fourth Targetry Workshop (2). The electron beam was chosen to have the same thermal deposition profile as the 8 MeV ^{3}He beam. An 80 keV e-beam was used at a peak pulse current of about 18 mA; pulses were 200 μsec wide FWHM at a repetition rate of 360 Hz. The e-beam experiments demonstrated the capability of constructing target windows that would withstand the thermal stresses of the RFQ, although the gas target was operating near the limit of tolerance and some of these windows failed during equivalent ^{3}He bombardments with >1 kW/g when the gas was static. While this outcome is not too alarming, it emphasizes the need to continue window tests with full duty cycle, current and beam area.



Improving Carbon-11 Specific Activity

The specific activity of ^{11}C from the ^{12}C(^{3}He,α) reaction could be increased by taking advantage of the nucleogenic event to form compounds that are chemically separable from and have less carrier than the ^{11}C retained in the target carbon. Calculations based on a simple model of the kinematics of the nuclear reaction and electronic stopping of recoil ^{11}C in elemental ^{12}C suggest that as much as 90% of the recoiling ^{11}C escapes from thin (100 μg·cm^{-2}) carbon foils. See reference (6), figure 2 for details. This loss decreases as the thickness of the foil increases, due to stopping of ^{11}C in the foil. We have tested this prediction by irradiating different thickness of C foils, both with and without thin silver wrapping, to measure the loss of recoil ^{11}C. About 8 mg C/cm^{2} is required for the full ^{11}C yield, but several thin foils will give

more volatile activity from recoil than 1 thick piece of C. The volatile $^{11}CO_2$ had a specific activity about 100-fold higher than was found in thick carbon.

Carbon Target[1] number/thickness	Separation between foils	Percentage of volatile ^{11}C [2]
1 foil of 1 mm	0 mm	1%
8x 0.6 mg/cm^2	9 mm	29%
4x 0.6 mg/cm^2	15 mm	39%
2x 0.6 mg/cm^2	35 mm	53%

[1]The target also contains 2 atm He plus 0.1 % O_2.

[2]The volatile activity was >99% $^{11}CO_2$, the most convenient form for subsequent radiochemical syntheses.

This approach to increasing the specific activity of ^{11}C appears promising. It combines the use of the physics of the nuclear reaction to separate the new ^{11}C atoms from bulk ^{12}C, and the chemistry of energetic atomic ^{11}C moderated by He to react with O_2, yielding $^{11}CO_2$. The target requires optimizing for geometric variables and gas composition and pressure.

Computer Modeling of Recoil Yields

The best target geometry to make ^{11}C and ^{13}N via $^{12}C(^3He,\alpha)^{11}C$ and $^{12}C(^3He,d)^{13}N$ appears to be a series of thin C foils separated by a gas that can be pumped off to extract the radioactive atoms as they are formed. The recoverable yields will be influence by the geometry of this target. In some simulation experiments each foil was divided into many thin lamina; the ^3He energy at the center of the lamina was determined and the cross section for the appropriate reaction was calculated. For each lamina the angular region in which the ^{11}C or ^{13}N nuclei stop in a specific gas space or foil was obtained. The yield of nuclei stopping in gas or in foils was obtained by integrating the cross section over this angular region and summing over all laminas, foils and gas spaces. In these simulations we aimed at 10% precision and ignored the effects of range straggling. We assumed that the ^3He, ^{11}C and ^{13}N all travelled in straight lines. The cross sections used for $^{12}C(^3He,\alpha)^{11}C$ were those of Cirilov (7) and for the $^{12}C(^3He,d)^{13}N$ reaction were those of Cochran and Knight (8). We assumed cross sections were isotropic in the CM frame of reference and that only reactions to ground states needed to be considered.

Validity of the calculations was checked by comparing predicted total thick target yield with our measurements. The yield for $^{12}C(^3He,\alpha)^{11}C$ from the calculation was 6.7 mCi/μA, in agreement with our measured value of 7.1. The calculated yield for $^{12}C(^3He,d)^{13}N$ was 0.45 mCi/μA, twice our measured value of 0.22, but consistent with the literature thick target yield.

For both reactions, the simulations gave two maxima for the yield as a function of foil thickness and spacing. One maximum is when the foil thickness approaches zero, but this is not a practical condition because the number of foils becomes too large. For the other maximum the optimum geometry at a He pressue of 1 atm is as follows:

^{11}C 0.55 mg/cm^2 separated by 3.4 cm predicted gas yield of 1.52 mCi/μA
^{13}N 0.30 mg/cm^2 separated by 1.8 cm predicted gas yield of 0.06 mCi/μA

The maxima were broad, decreasing roughly 10% when either the foil thickness or spacing was changed by 40%. Changing He pressure at a fixed geometry had a dramatic effect

on the yield of isotopes in the gas. However, if one varied the foil spacing but kept the same amount of gas between the foils, the yield remained the same.

Improving Oxygen-15 Specific Activity

We have also evaluated the potential role of the ^{15}O hot atom and its associated track chemistry in water to increase the specific activity of nucleogenic ^{15}O in a water target (9).

Target Material	Phase	[^{15}O]Oxygen* Yield	[^{15}O]Oxygen* Specific Activity
O_2	gas	690 mCi	<0.3 Ci/mole
H_2O + He	liquid	~535 mCi	<0.3 Ci/mole
(continuous He purging)	gas	~5 mCi	>1000 Ci/mole
H_2O + 100 mg/L H_2O_2	liquid	340 mCi	<0.3 Ci/mole
	gas	200 mCi	~200 Ci/mole
N_2	gas	400 mCi	>100,000 Ci/mole

*Calculated at sat'n for 150mA$_p$ 8 MeV ^{3}He on window, 7 MeV on target material.

A single target for production of both ^{18}F and ^{15}O is desirable and appears feasible with irradiation of $H_2{}^{16}O$. Our concern was the adequacy of the specific activity for $C^{15}O$, which we believe should be ≥5 Ci/mol. This value is sufficient that a single breath inhalation without bringing the carboxyhemoglobin saturation above 10%, the threshold for symptoms (10). To date our experiments have used low current ^{3}He, and we anticipate higher $O^{15}O$ yields with more than a 10-fold increased current, more radiolysis and less surviving H_2O_2. An N_2 target is still a viable second choice for the production of high specific activity $C^{15}O$.

Progress in Achieving Beam Goals

The progress in building the accelerator was interupted in January 1993 when our collaborators involved in commercializing the RFQ (General Electric Medical Systems) decided that the program should be cut in favor of other programs with shorter near-term business payoffs. In spite of this abrupt halt to the RFQ project, it is important to summarize the measurements and targetry design considerations that were completed.

^{3}He BEAM CURRENT

Location	mA$_e$	Duty Factor
Ion Source	18 of He^+	2%
1 MeV	16 of He^+	2%
8 MeV (beam stop)	4 of He^{++}	1.6%
8 MeV (targets)	2.5 of He^{++}	0.1%

Carbon-11 production from a 0.25 mm carbon target with a Havar window:

Peak mA	Ave μA	sec	mCi	150 μA$_p$ sat'n
2.54	10.2	411	7.51	1060
2.36	2.62	600	3.30	1310

Nitrogen-13 production from a 0.25 mm carbon target with a Havar window:

Peak mA	Ave μA	sec	mCi	150 μA$_p$ sat'n
2.54	10.2	411	1.01	78

Fluorine-18 recovery from the thick water target described below:

Peak mA	Ave μA	sec	mCi	300 μA_e sat'n
2.54	10.9	445	0.363	218
2.29	9.1	600	0.516	278

These preliminary measurements are all that were completed before the RFQ was mothballed. The ^{11}C and ^{13}N results are consistent with our predictions, but the ^{18}F yield was low. We expect that this was due to loss of ^{18}F in the targetry plumbing.

Measured Neutron Yields with the RFQ

Neutron yields were measured with calibrated Bonner spheres for both thick C with a Havar window and the water target illustrated below. The results given were in good agreement with those obtained from the Van de Graaff experiments and support the accuracy of our cross sections and the reasonableness of our anticipated yields.

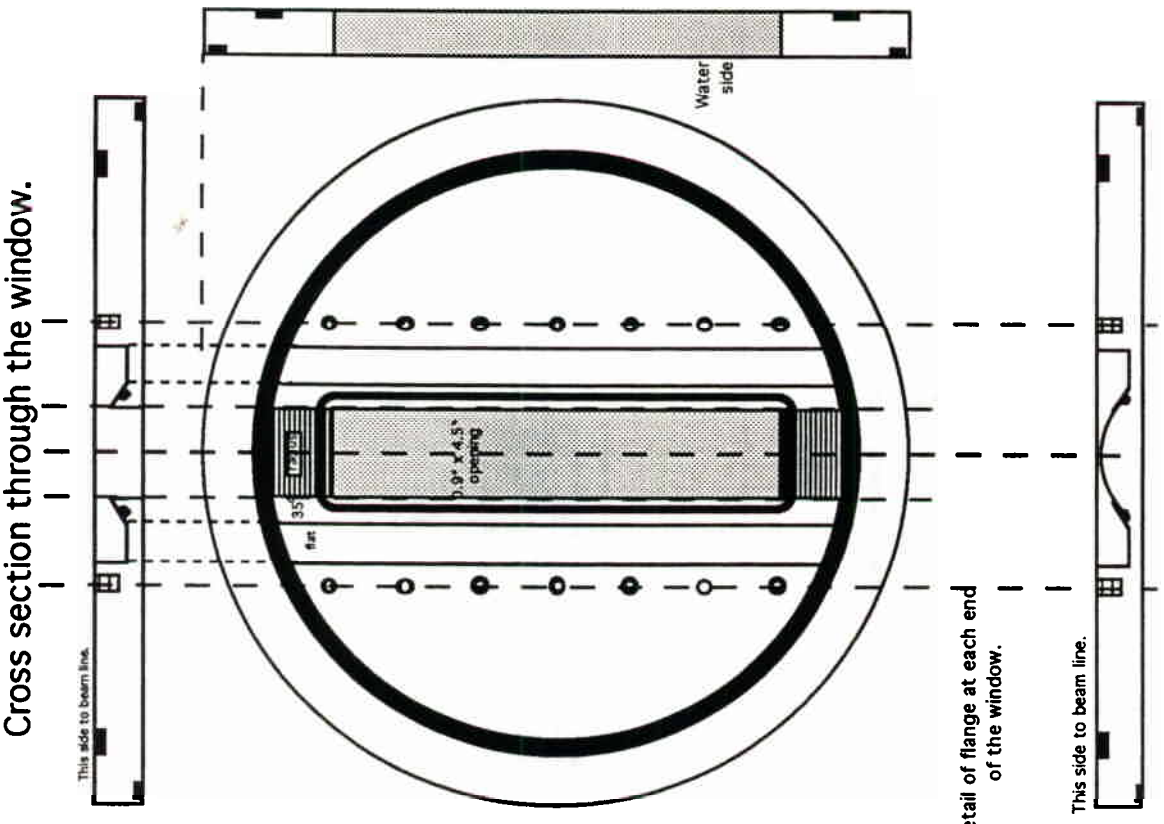
	rem/min (at 1 meter)	
Target Material	From cross sections	Actual RFQ performance
Carbon	0.49	0.44
Oxygen	0.31	0.31

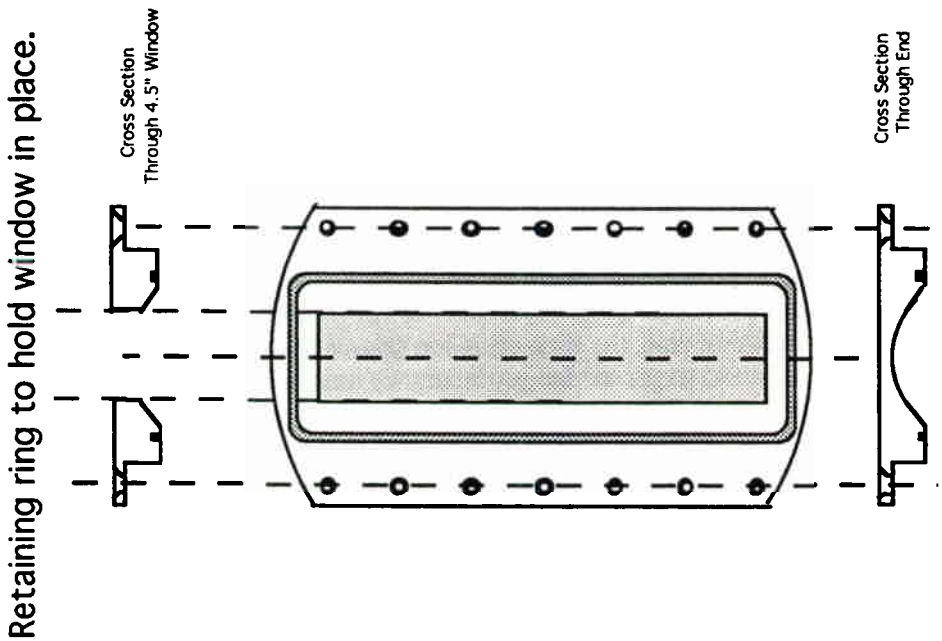
Experimental Conditions: ^3He at 8 MeV x 150μA_p, thick targets, measurements axial with the beam

Design and Construction of a High-Flow Water Target

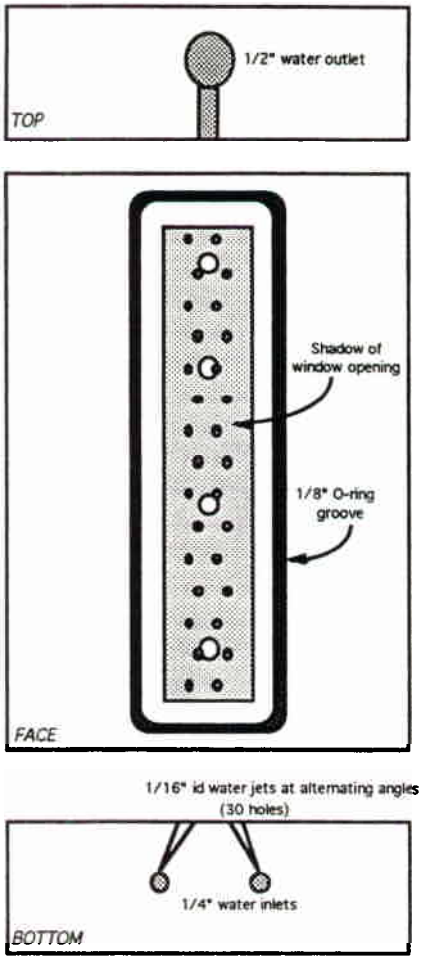
A recirculating water target has been designed and built and has been tested, but not with high beam current. It is shown schematically below and has a beam strike area of 30 cm^2 with a curved window of 0.004 mm Havar (~1 Mev thick). The radius of curvature around the long axis, 2.0 cm, was calculated to match the tensile properties of the foil. The window was not curved in the orthogonal axis but the corners were rounded to minimize tear at the corners. There was no deformation of the window from the curvature of the target body. In order to minimize the pressure drop across the window, the reservoir was maintained at vacuum. The surface area for the plumbing exiting from the target chamber was twice the inflow area. Under these conditions the high pressure side of the recirculating pump was at 0.4 to 0.7 atm when running at 4 L/min. The other side of the Havar foil faced the high vacuum of the beamline. The thin Havar windows withheld a pressure differential up to 2 atm and were robust to repeated start/stop cycles of the pump.

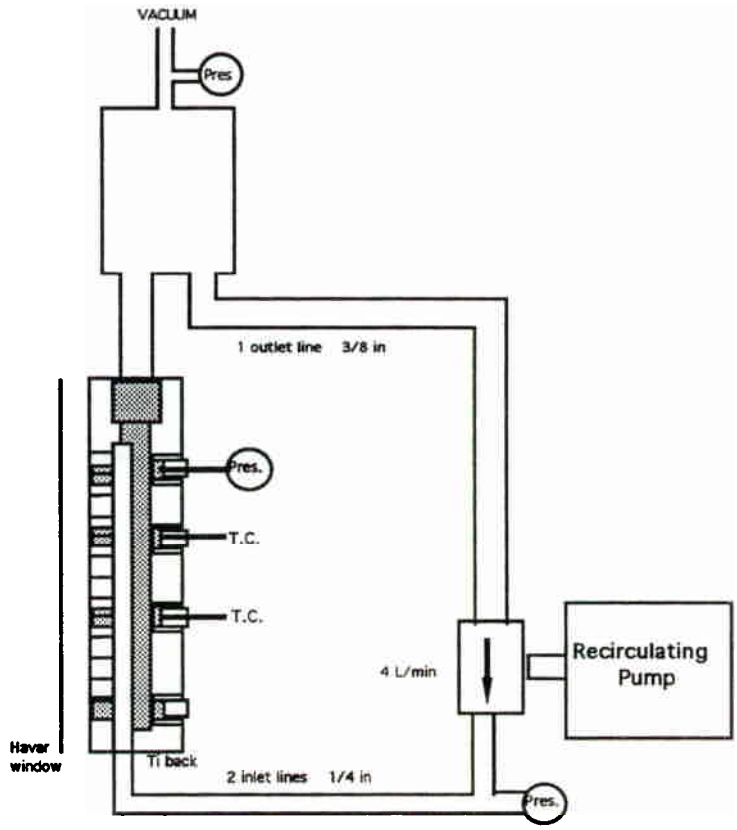
The front of the target was made from a standard stainless steel MF160 flange that was milled on a 4-axis computer-controlled machine to achieve the required concave radius. The window was held in place by 1/16" wide O-rings above and below the foil and by 14 closely spaced bolts tightened from the center toward the ends of the cover flange. Care was taken to break all edges in contact with the foil. The target back was made from 1.25" thick titanium. It was bolted to the MF160 flange with a 0.125" wide O-ring water seal between the two pieces. Two 0.25" id lines entered from the bottom of the target back, each supplying water to 15 jets of 0.065" id. One quarter of the jets were directed at 20° and 35° toward the midline from each supply channel. Water exited the target through four holes of 0.25" id to a channel 0.4" id that exited from the top. The target was monitored with pressure and temperature sensors. This target has been operated at 12 μA_p mean ^3He current with no rise in temperature.


Cross section through the window.
Water side
This side to beam line.
35°
flat
9" x 4.5" opening
Detail of flange at each end of the window.
This side to beam line.


Retaining ring to hold window in place.
Cross Section Through 4.5" Window
Cross Section Through End

View of the Titanium Target Back





Plumbing for the Water Target

Summary and Future for the ^{3}He RFQ

The RFQ has not yet operated at 8 MeV and 300 μA_e average beam current with 2% duty cycle. We have therefore not been able to test our windows or targets at full power. While there are many reasons to remain optimistic about the potential of RFQs to provide a practical source of isotopes for PET, this accelerator has not yet provided the anticipated demonstration. More than anything else, the lack of an ion source to deliver sufficient current of doubly charged helium (>20mA) triggered the problems we have encountered in producing the intended beam. Use of a 1 MeV RFQ and gas stripper as the ion source for $^3He^{++}$ introduced several technical complications, including the need to match three RFQs. This caused several problems in optimizing performance, especially at high duty factor, and in integration of subsystems, combining to give low beam current output. For example, the efficiency of the charge doubler stage was typically only 20%. And so, while at shutdown many of the subsystems of the RFQ were working better than ever before, there remain some important technical hurdles prior to testing the targetry. The PET community deserves a chance to critically evaluate the practical usefulness of RFQs and this machine is probably the closest to being able to provide that test. When the machine operates at one-half of full power, we should be able to make valid tests to evaluate the practical value of this accelerator for clinical PET. These tests may show that the energy should be increased by 1 or 2 MeV to increase radioisotope yields with lower currents and/or thicker windows. The cost will be a longer machine, but the benefit could be an appreciably more robust isotope production system.

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An Ultra-Compact ^{13}N-Ammonia Generator

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A dedicated, accelerator-based ^{13}N-ammonia generator capable of providing multiple 30 mCi batches of $^{13}NH_3$ for clinical use is under development at Science Research Laboratory, Inc. (SRL). The system utilizes a very low energy (1.2 MeV) coaxial cascade accelerator (CCA) to produce ^{13}N-ammonia via the $^{12}C(d,n)^{13}N$ nuclear reaction in a solid graphite target. The ^{13}N production target designed for this system is windowless and allows in-situ extraction of activity via combustion of the graphite, as described in an accompanying paper.(1) We have tested a prototype target using an existing deuteron accelerator at SRL and have shown that the target is reusable for multiple irradiation and extraction cycles. New target processing techniques developed at SRL and Washington University allow the extraction and conversion of target activity to ^{13}N-ammonia in under 10 minutes with a total decay-corrected efficiency of 44%.(2) Using these techniques, a batch yield of 30 mCi of $^{13}NH_3$ may be obtained from an EOB target yield of 136 mCi of ^{13}N-ammonia. We have measured the thick target yield from the $^{12}C(d,n)^{13}N$ reaction on graphite at low deuteron bombarding energies and have found that the saturated yield at 1.2 MeV is 0.85 mCi/μA.(3) A deuteron beam current of approximately 215 μA will therefore provide the required target yield in a 20 minute irradiation time.

The CCA is a compact, high current electrostatic accelerator based on a patented, power efficient high voltage power supply design which can deliver continuous milliampere currents. The operating parameters of the 1.2 MV CCA for ^{13}N production are listed in Table 1. A schematic of the ^{13}N-ammonia generator, including the CCA, graphite target and ^{13}N extraction system, radiation shielding, chemical synthesis system and controls, is shown in Figure 1. The high voltage power supply of the CCA is mounted directly onto the accelerating column and operates at the same voltage gradient as the accelerating tube. This results in a compact configuration and eliminates the need for an external power supply chassis. A power-efficient RF ion source, housed in the high voltage terminal, provides deuteron beam currents of up to 1 mA with a very high D^+ fraction. The accelerating column is SF_6 insulated and is housed in a pressure vessel of dimensions 1.5 m long by 0.7 m in diameter. The estimated weight of the 1.2 MV CCA is 600 lbs. Measurements indicate that approximately 17 cm of polyethylene neutron shielding and 1 cm of lead are required to the reduce radiation dose at 1.5 meter form the accelerator target to acceptable levels. The entire ^{13}N-ammonia radiochemical delivery system shown in Figure 1 is incorporated into a cabinet approximately 2.2 m long x 1.1 m wide x 1.4 m high.(3) This instrument is approximately the same size as a large office copying machine and twice the size of a $^{82}Sr/^{82}Rb$ generator plus infusion system.

Schematic drawing of the ultra-compact ^{13}N-ammonia generator using a 1.2 MeV deuteron coaxial cascade accelerator

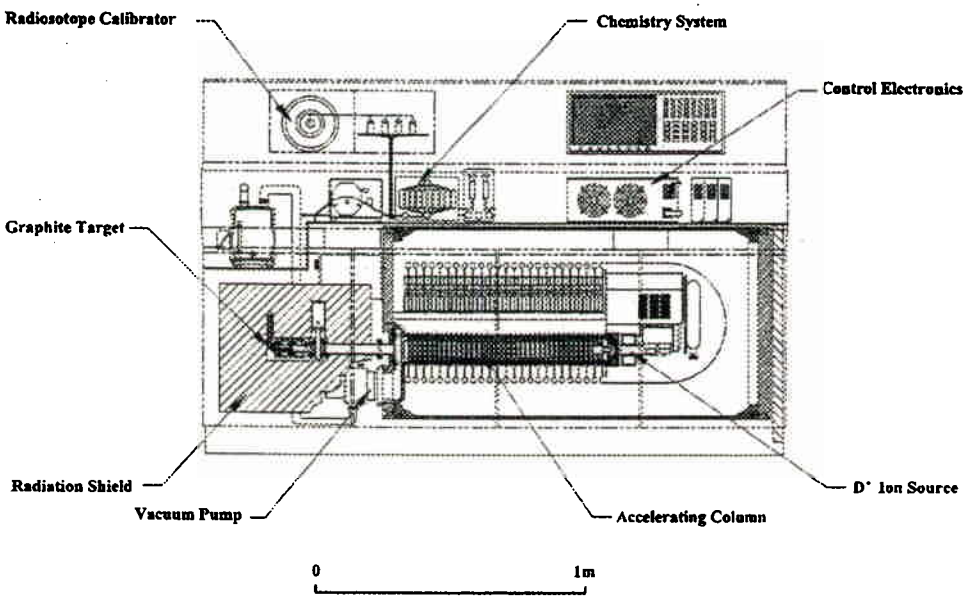

Figure 1

Table 1: Coaxial Cascade Accelerator Specifications

Maximum Terminal Voltage	1.25 MV
Maximum Current	1000 PA
Operating Current	225 PA
D^+ Fraction	95%
Total Electric Power	2 kW
Pressure Vessel	
Length	1.5 m
Diameter	0.7 m
SF_6 Pressure	95 psia
Overall Length	1.9 m
Approximate Weight	600 lb

The accelerator-based ^{13}N-ammonia generator described above will provide a convenient and cost-effective alternative to ^{82}Rb for PET myocardial blood flow studies. Preliminary cost estimates indicate Flat die capital outlay for this system will be comparable to die cost of a one year supply of ^{82}Rb plus an infusion system. The availability of a low-cost system for on demand production of ^{13}N-ammonia will increase the capabilities and reduce the operating costs of PET centers currently dependent on generator produced isotopes. Many cyclotron-based PET centers would also benefit from the additional flow agent production capabilities provided by a dedicated ^{13}N-ammonia generator. Because of its small size and low weight, this system could also provide isotope production capabilities to a mobile PET facility.

Acknowledgements:

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Progress Report on the TR13

Thomas J. Ruth and Kenneth Buckley
TRIUMF

The TR13 is a 13 MeV cyclotron is a developed jointly by TRIUMF and Ebco Technologies of Richmond, BC under a technology transfer agreement. The Cyclotron is designed as an integrated facility consisting of a cyclotron, target changer, targets, local shielding and product transfer systems. The design reflects more than eight years experience with the CP42 cyclotron facility, two years with the TR30 (another joint effort between TRIUMF and Ebco) and state-of-the-art cyclotron technology.

The main features that are responsible for high productivity and low radiation exposure are:

- The cyclotron has an external ion source capable of producing a much higher beam current than an internal source. The high gas flow, required to run the source, does not adversely affect vacuum in the cyclotron due to differential pumping between source and cyclotron. Therefore activation of the machine due to gas stripping is very low.

- Low beam energy to minimize reaction pathways causing parts activation.

- Localized modular shielding around most radioactive components. Because of the low energy and minimal beam loss the cyclotron and targets do not need a separate shielded vault when outfitted with the localized shielding.

The following sections describe the machine in some detail.

Accelerator

The cyclotron is mounted with the beam plane oriented vertically. This allows the magnet yoke to roll on rails for access. This configuration is space saving in that the foot-print is smaller and can fit in a room with a low ceiling.

The TR13 is a sector-focused H^- cyclotron with a maximum proton energy of 13 MeV and a nominal circulating beam current of 100 μA. Figure 1 shows a view of the cyclotron magnet opened and one target shield pulled back. Table 1 lists the cyclotron parameters.

The advantage of accelerating negative ions has been proven over the years in machines such as the TRIUMF 500 MeV cyclotron, the CP42 at TRIUMF and other radioisotope producing cyclotrons. Because negative ions can be extracted at virtually 100% efficiency, the need for internal targets disappears, thus eliminating an important source of machine activation.

Cyclotron Parameters

The magnet has four return yokes as shown in figure 2. This configuration eliminates any possibilities of second harmonics in the magnetic field, which might cause undesirable resonances.

There are four sectors so the Dees can be accommodated in two opposite valleys, thus reducing the magnet gap between the sectors and maintaining a very high hill-to-valley field ratio, which produces strong focusing.

The magnet can be opened for access to the inside of the machine. The vacuum chamber is of a very simple design. It is essentially a cylindrical wall that seals directly against the magnet poles. The material is aluminum, which avoids the long half-life activation associated with stainless steel. There are two O-ring seals between the vacuum chamber and the magnet poles.

To fit the Dees in the valleys, their width is limited to a nominal 45° which requires acceleration of the particles at the second harmonic. of the frequency of 73 MHz. This means that the voltages on both Dees are in phase. RF power is supplied by a commercial RF power amplifier, providing 50 kV at the Dees at 12 kW. The power supply is located adjacent to the cyclotron. A co-axial transmission line connects the power supply to the cyclotron. The transmission line is capacitively coupled to the Dees.

The cyclotron has a CUSP type external ion source, suspended on one side of the cyclotron. The source produces 1.5 mA H^- ions at 25 keV for injection into the cyclotron. Most of this current is lost at the inflector where the beam is bent into the median plane of the cyclotron. The source has one filament, expected to last roughly 6 months. The ion source has its own vacuum pumps that remove most of the hydrogen gas load before it reaches the cyclotron. The ion source filament is replaceable as one unit, a task which requires only 15 minutes.

The cyclotron vacuum chamber is evacuated by a cryogenic pump with a pumping speed of 4000 *l/s* for H_2O and 1500 *l/s* for air. This provides an operating pressure of 1 times 10^{-6} Torr. The ion source is pumped with a turbo-molecular pump and a cryopump.

The cyclotron is equipped with two fixed energy extractors that allow simultaneous extraction of beam currents variable in ratios from 1:100 to 1:1 at an energy of 13 MeV. The type of extractor installed is similar to that in the TR30. The extractors each carry a single foil carousel, that can be withdrawn from the vacuum chamber through a vacuum lock, to be changed when foils are spent. Based on the TR30 experience the foils are expected to last about six months.

Target Selectors

There are two target selector mechanisms which align targets with the extracted cyclotron beam. Both selectors are separated from the main cyclotron vacuum tank by vacuum valves. Each target selector accepts four targets mounted on each quadrant of a common flange. This flange is then mounted on dual gimbals with a metal bellows to form the vacuum envelope. In this way the target may be positioned in X and Y to align one target with the emerging proton beam.

Automated control is enabled with the current monitoring of a four quadrant slit arrangement in front of each target. Reference X and Y coordinates are used to for initial position of the desired target with minor adjustments done by PLC control system of the cyclotron based on the feedback of the beam current measurements on the four quadrant slit arrangements.

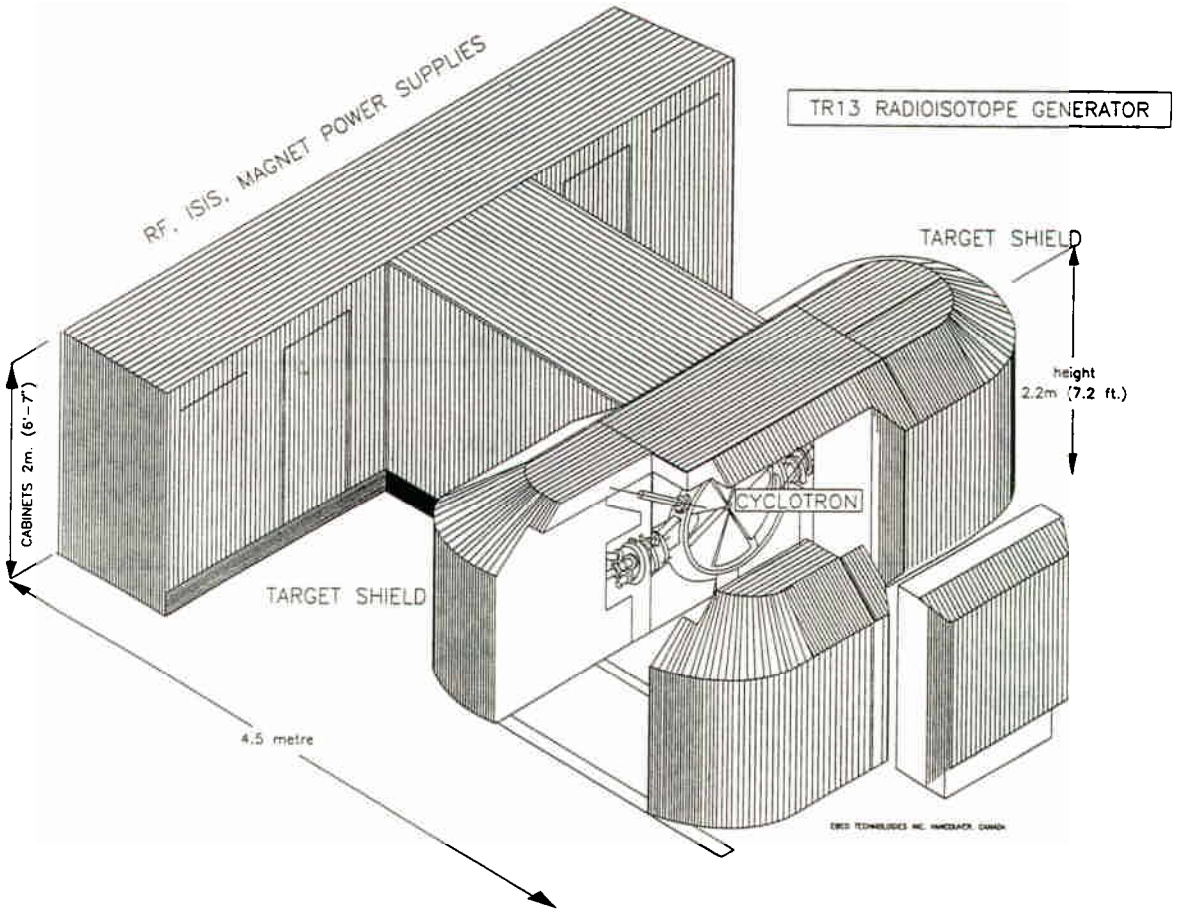

Figure: 1 Showing the Cyclotron and Shield open for access

TRIUMF 13 MeV H^- Cyclotron	
Magnet	
Average Field	1.2 T
Hill Field	1.90 T
Valley Field	0.55 T
Hill Gap	4 cm
Valley Gap	20 cm
Hill Angle	Variable (40° - 44°)
Iron Weight	22 Tonnes
Pole Radius	57 cm
Height	1 m
Outside dimension	1.7 m^2
Coil	
Coil Power	20 kW
Copper Weight	1.9 Tonnes
Ampere Turns	$7.2 * 10^4$
RF	
Frequency	73 MHz (nominal)
Dee Voltage	50 kV
Electrical Width	45° (nominal)
Harmonic	4th
Power	12kW
Vacuum	
Pressure	$1*10^{-6}$ Torr
Pumping	4,000 *l/s* (H2O)
	1,500 *l/s* (air)
Ion Source	
Type	H^- cusp
Output Current	1.5mA
Bias Voltage	25 kV
Extraction	
Energy	13 MeV (magnet large enough for 18 MeV)
Method	Stripping
External Beams	2

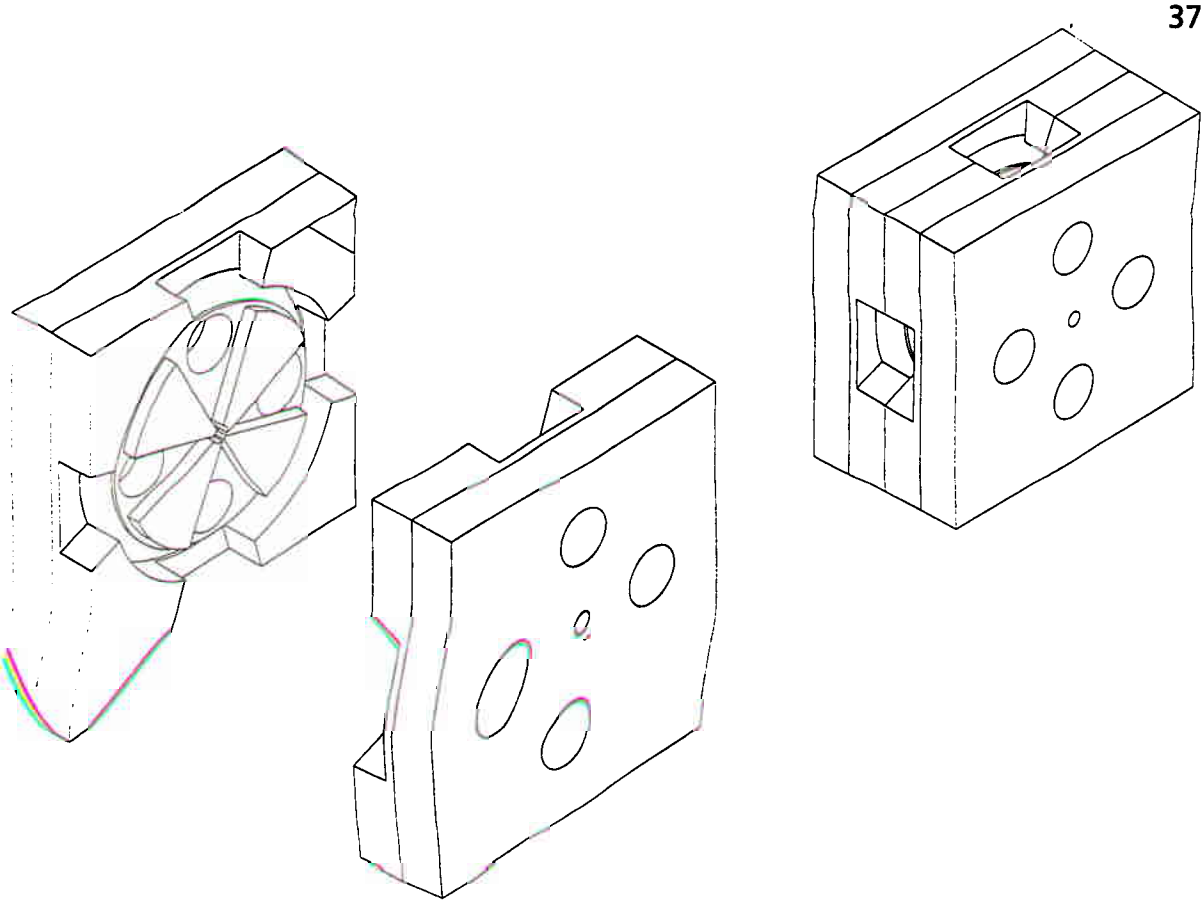

Figure: 2 Magnet Yoke Assembly

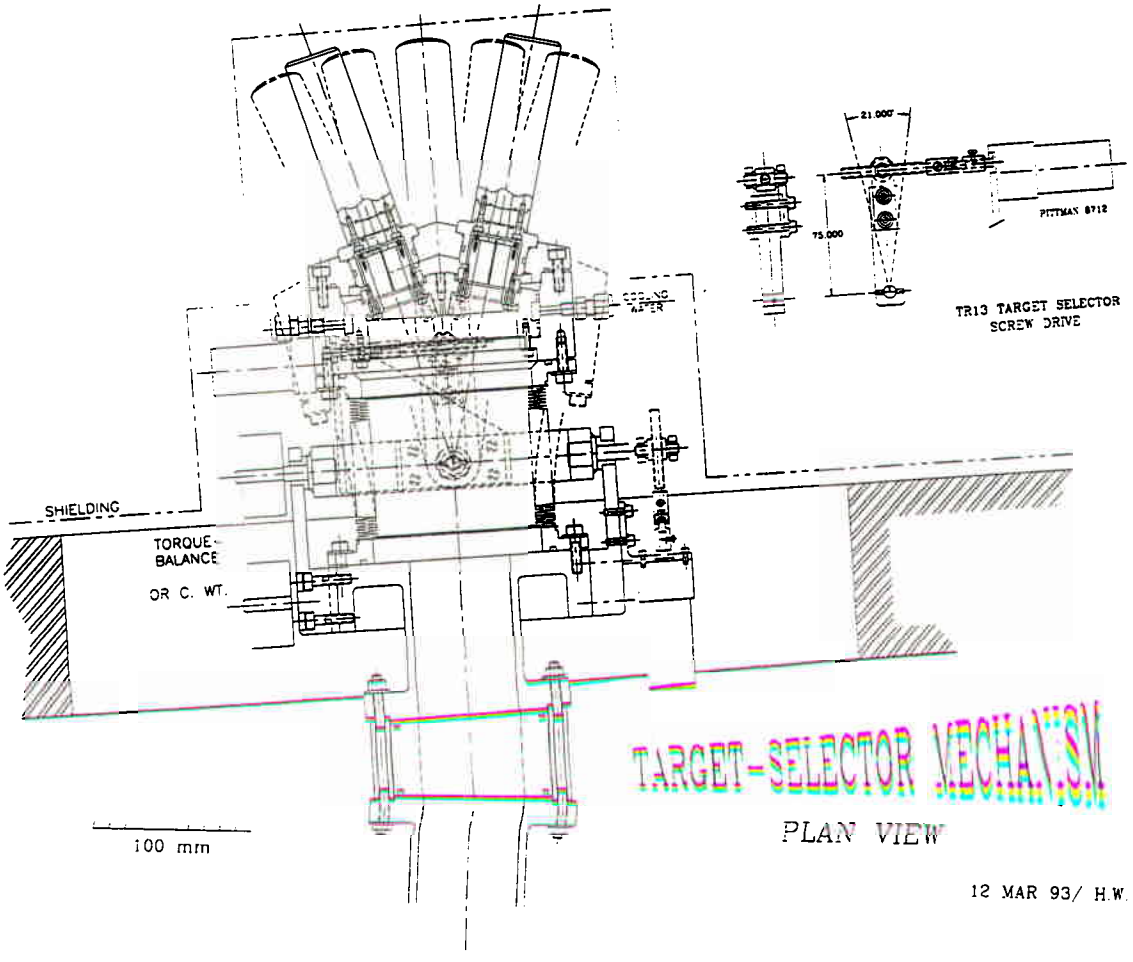

Figure: 3 Target Selector Mechanism. Plan View

Superconducting Cyclotron for Clinical PET

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Introduction

As PET has become more popular, there have been growing needs for an easily operational cyclotron and chemistry system. Not many hospitals want to keep a full set of operators: a cyclotron operator, a chemistry module operator and a scanner operator. When producing ammonia or fluoro deoxy glucose (FDG) for example, a cyclotron should be operated by a chemistry module operator. When performing an [^{15}O] gas study, it should be operated by a scanner operator or even by a doctor. Therefore our bases for developing the cyclotron, the targets and the chemistry modules have been:

(1) Simple operation
(2) High reliability
(3) Easy maintenance.

We have installed the cyclotron and chemistry systems at Hyogo Institute for Aging Brain and Cognitive Disorder and Osaka City University. This paper introduces the outline of the system with a detail of [^{13}N] ammonia production.

Superconducting Cyclotron

The NKK-Oxford cyclotron is the first superconducting cyclotron for clinical PET. Figure 1 and Table 1 show the outline structure and the major specification of the NKK-Oxford cyclotron, respectively. It accelerates negative hydrogen ions for higher beam efficiency and low activation of the cyclotron.

Superconducting Magnet.

The superconducting magnet of the NKK-Oxford cyclotron operates in 'permanent current' mode. The power supply is connected to the magnet only during installation and annual maintenance. That makes the system highly stable and ready to run at any time. The cyclotron weighs only four tons and can be transported into the cyclotron room on wheels for installation.

Ion source.

The NKK-Oxford cyclotron has an externally mounted ion source to make service easy. The ion source is a multicusp H- ion source with two filaments. One of them is a spare. Each

filament has a life time of 200 running hours or longer. At an event of filament break, the system automatically switches over to the spare filament. No tools are needed to replace filaments.

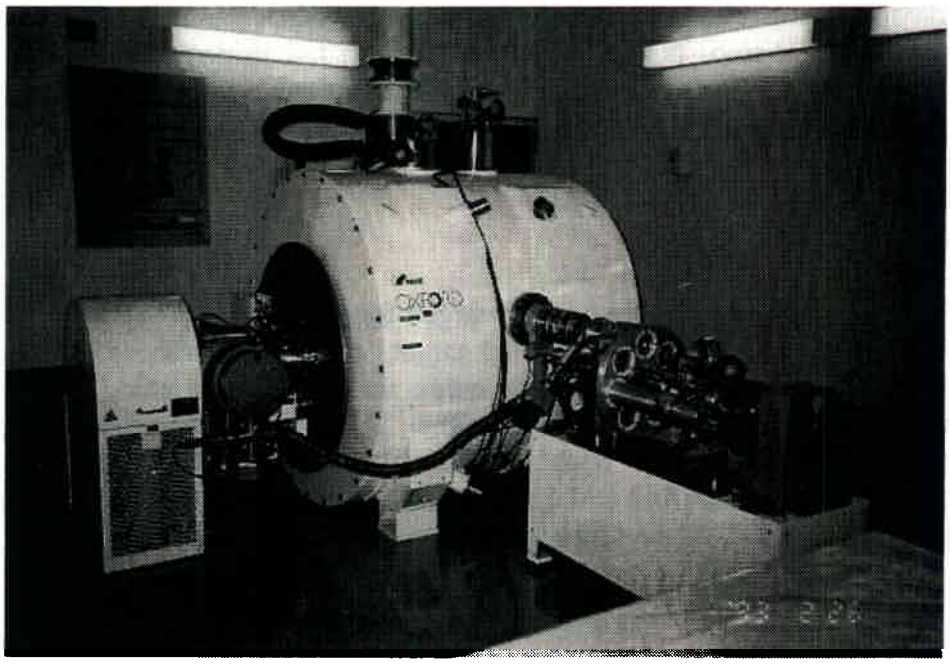

Figure 1. The outline structure of the NKK-Oxford cyclotron.

Table 1: Specification of the NKK-Oxford cyclotron

Accelerating Particle	H^-
Energy	12 MeV, Fixed
Maximum Beam Current	100 μA, Maximum
	50 μA, Guaranteed
Ion Source	Multicusp with 2 Filaments, External
Ion Source Service Interval	> 400 Running Hours
Extraction Radius	220 mm
Extraction	Carbon Foil Stripping
Extraction Foil Service Interval	> 4,000 Running Hours
Magnet	2.36 Tesla, Superconducting
Helium Boiloff	160 ml per Hour, Typical
RF Frequency	108 MHz
Overall Dimensions	^{W}1.4 m x ^{D}1.9 m x ^{H}1.9 m
Weight	4 Tons
Electrical Power Consumption	< 40 kW
Time Required to Startup	< 5 Minutes

Extraction System.

The extraction system consists of 20 carbon foils and a beam catcher placed just outside the extraction radius. The beam hits the beam catcher when the present foil breaks. Then the cyclotron controller stops the beam, pushes the next foil in position, and restarts the beam within a few minutes. Each foil has a life time of 200 running hours or longer. Therefore the extraction system has a service interval longer than 4,000 running hours and does not require operator's service.

Target Systems

The NKK-Oxford cyclotron has four targets for production of ^{11}C, ^{13}N, ^{15}O and ^{18}F. Table 2 shows our target systems. For the ^{15}O target, we have developed special fittings with minimized dead volume and applied a quick transfer system using a vacuum pump to minimize the usage of [^{15}N] nitrogen gas. The ^{18}F target has an internal water cooled heat exchanger. The [^{18}O] target water is circulated through the heat exchanger during bombardment to minimize void in the target chamber and then maximize yield at higher beam current. More than 95% of the target water is recovered and reused.

Table 2: The NKK target sustem

Nuclides	Reaction	Target material	Chemical form of extracted activity
^{11}C	$^{14}N(p,\alpha)^{11}C$	Nitrogen gas	[^{11}C]CO_2
^{13}N	$^{16}O(p,\alpha)^{13}N$	Water	[^{13}N]NH_4^+, aqueous
^{15}O	$^{15}N(p,n)^{15}O$	[^{15}N]Nitrogen gas	[^{15}O]CO_2
^{18}F	$^{18}O(p,n)^{18}F$	[^{18}O]Water	[^{18}F]F^-, aqueous

Chemistry Modules

Table 3 shows our chemistry modules that have been fully developed and commercially available. Conventional chemistry modules use time sequence control. Because of the nature of chemical reactions, however, time taking for a synthesis step may vary depending on

Table 3: The NKK chemistry modules

^{11}C	Carbon dioxide / Carbon monoxide Hydrogen cyanide Methyl iodide Methyl spiperon / Methionine
^{13}N	Ammonia
^{15}O	Oxygen / Carbon dioxide / Carbon monoxide Water
^{18}F	Fluoro deoxy glucose (FDG)

temperature, condition of reagents, etc. This fact results unstable synthesis yield and longer synthesis time to give longer time margin to each step. The NKK modules use feedback control by applying various sensors including specially developed one-chip gamma-ray monitors. The feedback control enables stable synthesis yield and shorter synthesis time.

Control

The cyclotron, targets and chemistry modules are fully computer controlled and has two operator's terminals, which we recommend to install in the scanner operator's room and in the chemistry room. The operator can activate one of the terminals by turning the selection key and run the cyclotron by using a 'mouse' with a graphic display of the terminal. Figure 2 shows the main graphic screen for radiopharmaceutical production.

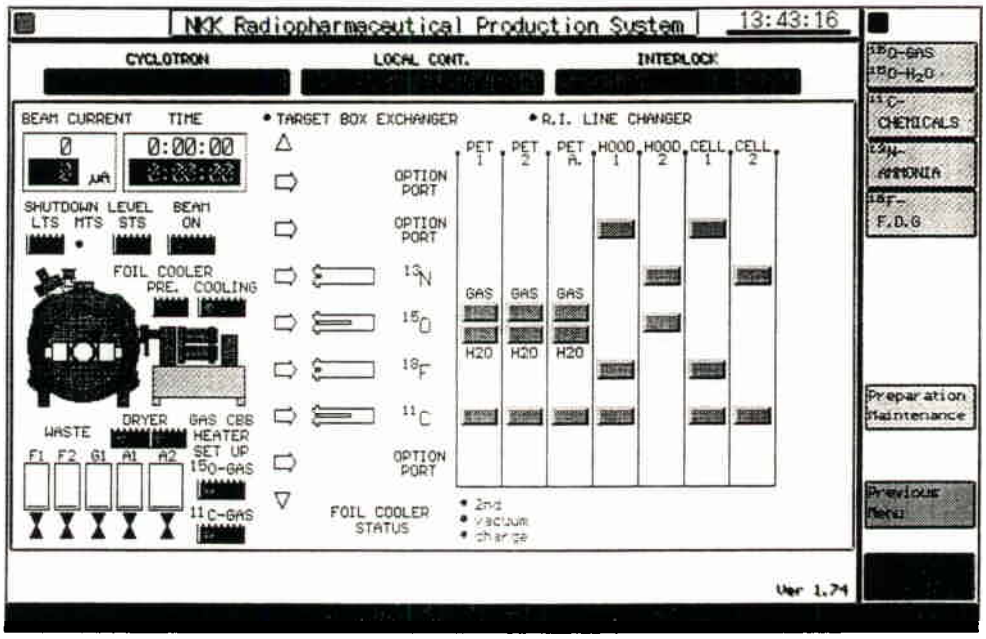

Figure 2. The main graphic screen for radiopharmaceutical production.

[^{13}N] Ammonia Production

Table 4 shows specifications of the NKK [^{13}N] ammonia target. The ^{13}N target directly produces [^{13}N] NH_4^+ in it. This is the reason that target water is bubbled with hydrogen gas and cooled through the internal heat exchanger for suppressing the target water boiling off during bombardment.

Figure 3 shows the schematic diagram of the [^{13}N] ammonia production system. The syringe AC1 on the chemistry module injects sterilized water into the feed line to the target. Then hydrogen gas pushes the water into the target box. The chemistry module charges

hydrogen gas up to 1.5 kg/cm2. Circulation makes a mixture of target water and fine bubbles of hydrogen gas in the target chamber. ^{13}N is produced in the form of NH_4^+ in the target water by bombarding with 12 MeV protons. After irradiation the target water is transported to the chemistry module by hydrogen gas. [^{13}N] NH_4^+ in the target water is trapped in the cation exchanger resin, then is swept to the vial with saline.

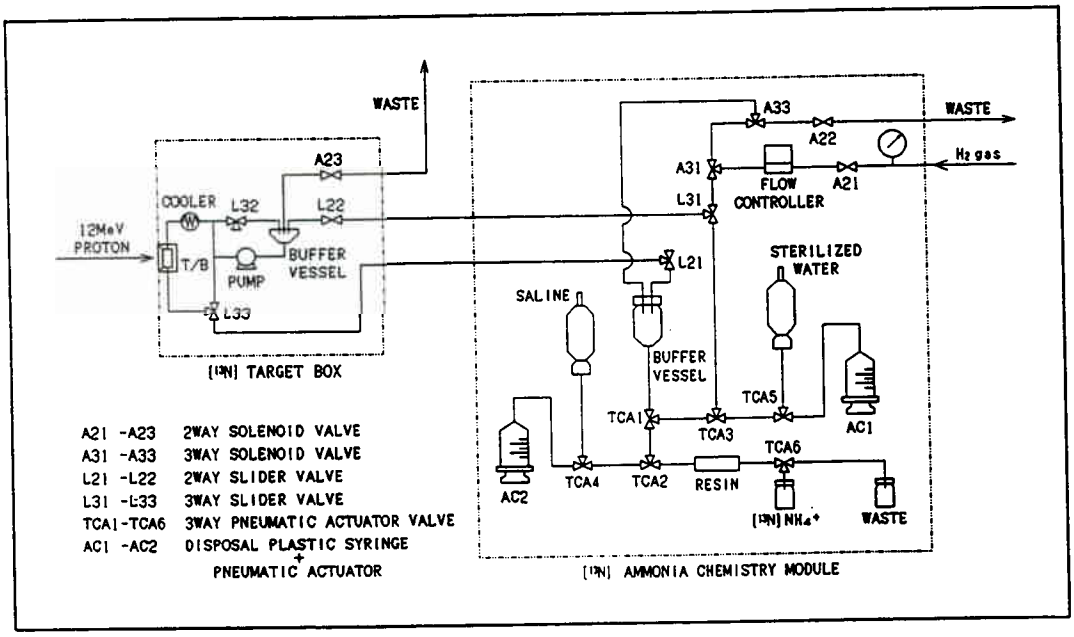

Figure 3. Schematic diagram of the [^{13}N]-ammonia production system.

Table 4: Specifications of the NKK [^{13}N] target box

Target	Water, 4 ml
Target body	Titanium, 16 mm ϕ x 5 mm
Foil	Titanium, 0.025 mm thick
H2 pressure	1.5 kg/cm^2

Table 5 shows the irradiation conditions, yield and efficiency of the NKK [13N] ammonia production system. The system produces 50 mCi of ammonia with a 20 μA x 10 minute irradiation and a 5 minute synthesis.

Table 5: Irradiation conditions, yield and efficiency

Beam energy	12 MeV
Beam current	20 μA
Time	10 Minutes
Yield (EOB)	70 mCi
Yield (EOS)	50 mCi
Synthesis Efficiency	>70 %
Synthesis Time	<5 Minutes

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