# The Production of 13N Using Beam-Target D-3He Fusion Reactions

B.B. Cipiti and G.L. Kulcinski

September 2004

UWFDM-1235

**FUSION TECHNOLOGY INSTITUTE**

**UNIVERSITY OF WISCONSIN**

**MADISON  WISCONSIN**

# The Production of 13N Using Beam-Target
# D-3He Fusion Reactions

B.B. Cipiti and G.L. Kulcinski

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

September 2004

UWFDM-1235

# THE PRODUCTION OF $^{13}$N USING BEAM-TARGET D-$^{3}$HE FUSION REACTIONS

B.B. Cipiti & G.L. Kulcinski
Fusion Technology Institute, University of Wisconsin-Madison
1500 Engineering Drive
Madison, WI  53706
505-284-8757  bbcipit@sandia.gov

*The D-$^{3}$He fusion reaction has been used to produce medical radioisotopes using the University of Wisconsin Inertial Electrostatic Confinement (IEC) Fusion Device. The high-energy 14.7 MeV proton generated from the reaction can activate materials for isotope production. The traditional IEC setup has been altered to generate medical isotopes using beam-target D-$^{3}$He fusion. Beam target D-$^{3}$He reactions in a thin-walled, water-cooled, stainless steel tube were used to create $^{13}$N, an isotope used in Positron Emission Tomography. At a maximum ion energy of 85 keV, 1.0 nCi of $^{13}$N was created as a proof of principle experiment.  A scaled-up version of this concept may provide for a smaller, less expensive radioisotope generator for future commercial needs.*

## I. INTRODUCTION

The production of radioisotopes for medicine, industry, and research is fairly well-established today. However, the production methods have their limitations. Most of the isotopes in use come either from nuclear reactors, cyclotrons, or linear accelerators. These large and costly devices require isotope production in a lab, which limits both the availability of the isotopes and the minimum half-life than can be used.  It would be advantageous to have a small, portable isotope production unit.  The by-products of fusion reactions, namely high-energy protons and neutrons, can be used to generate isotopes[1].  A small fusion device then could be developed into a small radioisotope generator.

The University of Wisconsin (UW) Inertial Electrostatic Confinement (IEC) device uses spherically concentric, nearly transparent electrodes to radially accelerate ions to substantial fusion cross-sections.[2,3]  The experiment can run as high as 200 kV and so is able to achieve steady state D-$^{3}$He reactions.   The 14.7 MeV protons created from the reaction have enough energy for the production of radioisotopes.[4]   Recently, the proton

production rate of $5x10^{7}$ p/s has been high enough for proof of principle isotope production.[5]

The IEC device is small and relatively inexpensive.  It could be built for around $100,000 and could allow for portable isotope production.  For example, if the IEC device were placed on the back of a truck, isotopes could be used in more remote areas, and it would open the door to the use of much shorter-lived isotopes that could be produced on site.  The IEC project is focusing on producing the shorter-lived species.

The isotopes used in Positron Emission Tomography (PET) fall into the category of short-lived species.  PET is a medical imaging system that uses the decay of positron emitters injected into a patient to construct an image of the body.   The isotope $^{13}$N is a positron emitter with a ten-minute half-life.  It has been used for research in the past,[6] but its short half-live limits its use.  It can be created through the reaction $^{16}$O(p,α)$^{13}$N, using a target containing oxygen. Figure 1 shows the cross-section for this reaction.
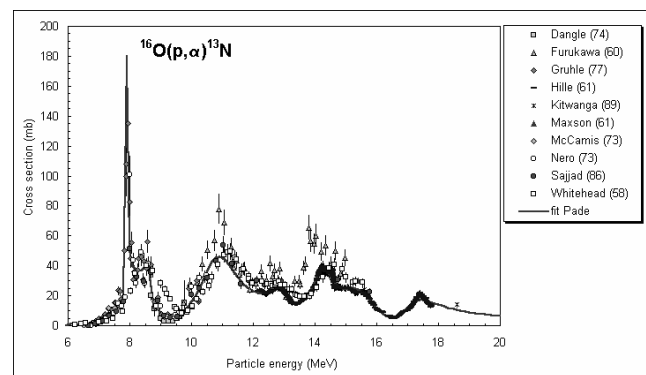


Figure 1: $^{13}$N Production Cross-Section[7]

The shorter-lived species are more desirable for medical imaging because they give a smaller residual radiation dose to the patient.  Their short half-lives would provide a smaller residual dose after the diagnostic

procedure is completed. These isotopes would be desirable for imaging of small children or pregnant women in which case the radiation dose is especially important.

Recent work at Wisconsin has shown that during normal operation, D-$^3$He fusion is dominated by beam-target reactions occurring in the cathode grid wires.[8] Over the 40-100 kV cathode voltage range at pressures around 2 mtorr, about 95% of the total D-$^3$He reaction rate is occurring in the grid wires. This result led to the idea of using beam-target D-$^3$He reactions to generate medical isotopes in the IEC device.

## II. EXPERIMENTAL OPERATION

The UW IEC experiment is shown schematically in Figure 2. A cylindrical, aluminum vacuum vessel with pumping system allows for base pressures in the mid $10^{-7}$ torr range. In normal operation, a 10 cm spherical cathode grid made from tungsten-rhenium wire is used. A high-voltage insulator allows operation down to −180 kV on the inner grid. A 50 cm anode (concentric to the cathode) is made from stainless steel wire and is kept at ground potential. The two grids form a deep potential well into the center of the device through which the fusion ions can re-circulate. The gridded construction makes the electrodes mostly transparent to ions.
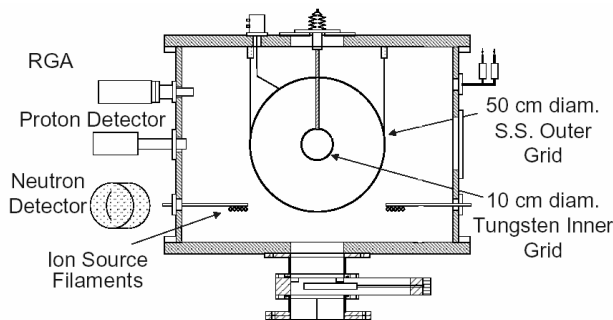


Figure 2: UW IEC Setup

Typically the device is operated at a background gas pressure of 2 mtorr. Three light-bulb filaments are used to ionize the background gas outside of the anode. The ions get accelerated towards the inner grid and may re-circulate a few times before being lost or fusing. A $^3$He neutron detector and solid-state charged particle detector are used to measure the neutron and proton production respectively. A residual gas analyzer keeps track of the gases and impurities present in the system.

For $^{13}$N production, the inner grid was replaced with a thin-walled, stainless steel tube with water flowing through it (See Figures 3 and 4). A strong negative potential was applied to the tube. With this solid cathode, the deuterium and helium ions were implanted into the outer surface of the tube wall. Further bombardment caused beam-target D-$^3$He reactions within the wall. The 14.7 MeV protons are generated isotropically, so roughly half travel deeper into the tube, and half leave the tube. The tube wall was designed to be thick enough to stop the deuterium and helium ions, but it was thin enough to allow the 14.7 MeV protons to penetrate to the water below. The protons then activated the oxygen in the water to produce $^{13}$N.
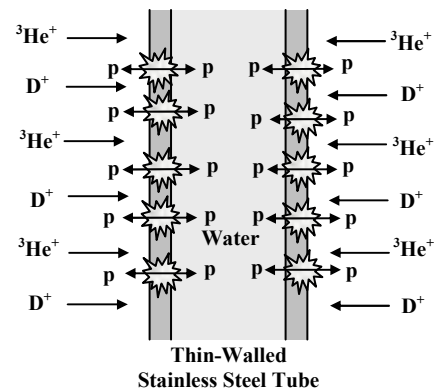


Figure 3: Beam-Target Isotope Production

The installation of the tube is shown in Figure 4. The main difference to the inside of the chamber is that the inner grid was replaced with the tube. Two boron nitride insulators were used to carry the tube into the system. This setup allowed for the water to re-circulate through the device.

The cathode needed to be cooled due to the large ion fluence reaching it. A closed, primary water loop re-circulated through the system with a small pump. The water then acted as both the coolant and the material to be activated. A tube-in-tube heat exchanger used building cooling water to remove the heat from the primary loop. Applying voltage to the tube required using very pure and de-ionized water. An ion exchange resin column was used to keep the water ion free. It consisted of a mixed-bed resin that removed both positive and negative ions. The resin column also removed the $^{13}$N that was created in the water. A NaI scintillation detector was used to measure the $^{13}$N activity in the resin column.
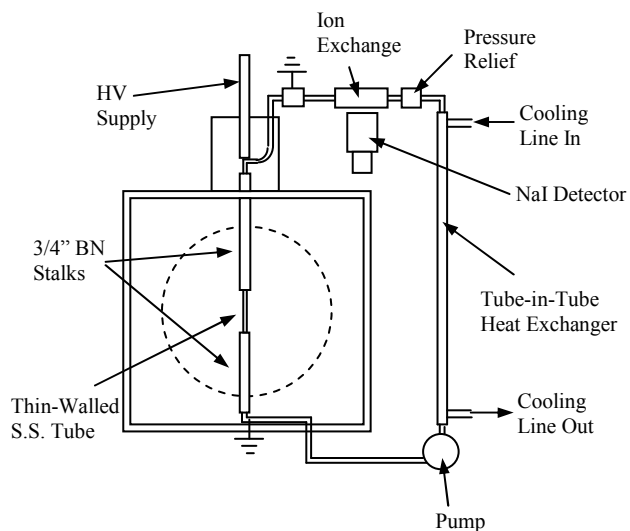
Figure 4: Cooled Water Target $^{13}$N Production System

## III. RESULTS

### III.A. Device Operation

The tubular cathode design represented a substantial change in the IEC operation, but the main difference was that it eliminated fusion ion re-circulation. The experimental difficulty was in containing the water system in the vacuum environment.

In initial experiments, there were various problems with electrical breakdown. These problems were mostly centered around the lower stalk which contained a transition to an insulating tube. Visible arcing was seen down the length of the lower insulator, so a few revisions to the design were installed. The best design consisted of an alumina tube to carry the water with insulating boron nitride discs around it to help block the breakdown path to ground.

Additional problems occurred with water leaking into the vacuum environment. All of these problems would probably easily be solved with a more professionally manufactured design. There were no problems with leaking of the thin-walled steel tube. The cooling system was able to handle the heat load, and the resin column kept the resistivity of the water to acceptable levels.

The best $^{13}$N production run achieved 85 kV on the cathode (running deuterium and helium-3), for a few minutes before electrical breakdown shut the device off. Figure 5 shows the D-$^3$He proton production rate as a function of run time for that experiment. This plot shows

the total D-$^3$He reaction rate occurring in the tube wall. The initial climb was due to a gradual ramp up in cathode voltage to 85 kV. The current into the tube was measured at 30 mA on the power supply during the entire run. The production peaked at about $4 \times 10^6$ p/s. The voltage was sustained at 85 kV for a few minutes before the machine shutdown. Roughly half of the protons generated were available for activation of the water. This proof of principle production run produced enough of a proton fluence to generate measurable $^{13}$N.
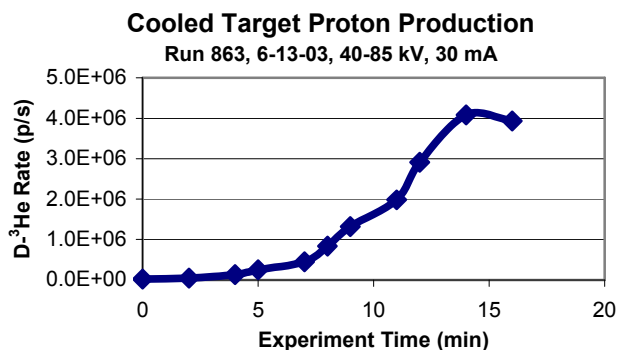


Figure 5: Proton Production Rate

### III.B. Isotope Production

After the 85 kV run was complete, the NaI detector was used to measure the $^{13}$N production. The spectrum showed a fair amount of scatter in the data due to the short counting time, but the counting time had to be short compared to the half life of the isotope. The background was subtracted out, and the 511 keV gamma peak was counted to determine the $^{13}$N activity.

A series of five counts were taken using the NaI detector after shutdown to determine the half-life of the positron emitter. Each was a 180 s count. Appropriate geometry and efficiency factors were calculated to determine the total collected $^{13}$N activity in the resin column. Figure 6 shows the activity as a function of time using the data from the five counts. An exponential decay curve was fit to the data to verify that the half-life was 10 minutes, verifying the production of $^{13}$N.

The curve in Figure 6 was extrapolated back to find that about 1.0 nCi of $^{13}$N was present in the resin column at machine shutdown or end of bombardment. Using the measured D-$^3$He proton rates, a theoretical $^{13}$N production was solved to be 1.7 nCi. There was a fair amount of uncertainty in the data due to the low counting rates and high background counts. The difference in the production

may be within the uncertainty.  It also may be possible that the resin column did not capture 100% of the $^{13}$N produced.
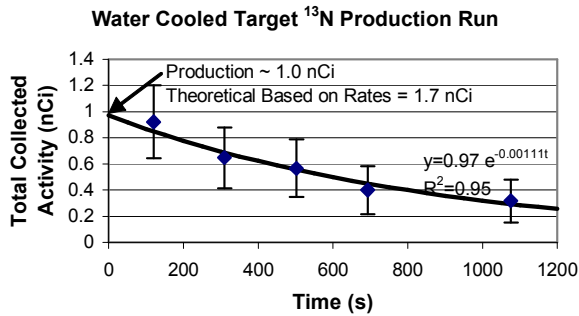
**Water Cooled Target $^{13}$N Production Run**



Figure 6: $^{13}$N Decay Plot

## IV. DISCUSSION

The activity needed for a typical PET diagnostic scan is on the order of 10 mCi.  Therefore the production of 1.0 nCi is about seven orders of magnitude away from what is needed.  A numerical model was used to extrapolate the power requirements needed to create a medical dose using this particular beam-target setup.

Using the maximum power supply voltage of 200 kV, and assuming a maximum embedded fusion ion density in the tube wall of a 1:1 ion to metal ratio, the maximum activity produced by this beam-target setup is 0.0012 mCi $^{13}$N/mA fusion ion current.  This number assumes an infinite irradiation time which is about equal to three or four half-lives of run time (30-40 minutes).  The numerical model takes into account both the fusion reaction cross-section and the $^{13}$N production cross-section.

This number means that about 8 A of current is needed to produce 10 mCi of $^{13}$N.  At 200 kV, the power supply requirements would be at least 1.6 MW, possibly more due to secondary electron effects.  This large power requirement would turn the IEC device into a non-portable unit and would increase the cost of the isotope production.

To turn the IEC Concept into a portable isotope production unit, a small size and reasonable power requirement must be maintained.  The research project at Wisconsin is currently investigating a low-pressure operating regime.  This new regime may allow for increased fusion performance, and thus higher reaction rates at a lower input power.  A parallel research path is investigating pulsing the IEC device to allow for much higher currents.  It is hoped that such higher performances will allow for a more feasible isotope production unit.

## V. CONCLUSION

D-$^{3}$He fusion has been used to successfully produce medical isotopes in a small fusion device.  Proof-of-principle experiments have produced about 1.0 nCi of $^{13}$N using beam-target fusion reactions.

This particular beam-target setup is very inefficient from an input energy standpoint.  Large amounts of power would be required to produce doses high-enough for medical scans, and these power requirements would increase the cost and size of this concept.  However, there are other regimes in the IEC concept that can be explored to increase the fusion reaction rate without increasing power requirements.  The experiments presented in this paper represent a first step and can be modified to be used for a different device configuration.

## REFERENCES

1.  G.L. KULCINSKI, "Near Term Commercial Opportunities from Long Range Fusion Research," *Fusion Technology,* **30**, 411 (1996).

2.  R.P. ASHLEY et al., "D-$^{3}$He Fusion in an Inertial Electrostatic Confinement Device," 18th *IEEE/NPSS Symposium on Fusion Engineering, IEEE #99CH37050* (1999).

3.  R.L. HIRSCH, "Inertial-Electrostatic Confinement of Ionized Fusion Gases," *Journal of Applied Physics,* **38**, 4522 (1967).

4. J.A. SORENSON & M.E. PHELPS, *Physics in Nuclear Medicine, Second Edition,* W.B. Saunders Company, New York (1987).

5. R.P. ASHLEY, G.L. KULCINSKI, J.F. SANTARIUS, S. KRUPAKAR MURALI, G.R. PIEFER, B.B. CIPITI, R.F. RADEL & J.W. WEIDNER, "Recent Progress in Steady State Fusion using D-$^3$He," *Fusion Technology,* **44**(2), 564 (September, 2003).

6. B.T. CHRISTIAN et al., "Improving the Radionuclidic Purity of $^{94m}$Tc for PET Imaging," *Applied Radiation & Isotopes,* **46**(2), 69 (1995).

7. Nuclear Data Services, International Atomic Energy Agency, www-nds.iaea.or.at/medical/O6p13N0.html (2003).

8. B.B. CIPITI, "The Fusion of Advanced Fuels to Produce Medical Isotopes using Inertial Electrostatic Confinement," Doctoral Thesis, University of Wisconsin-Madison, (2004).