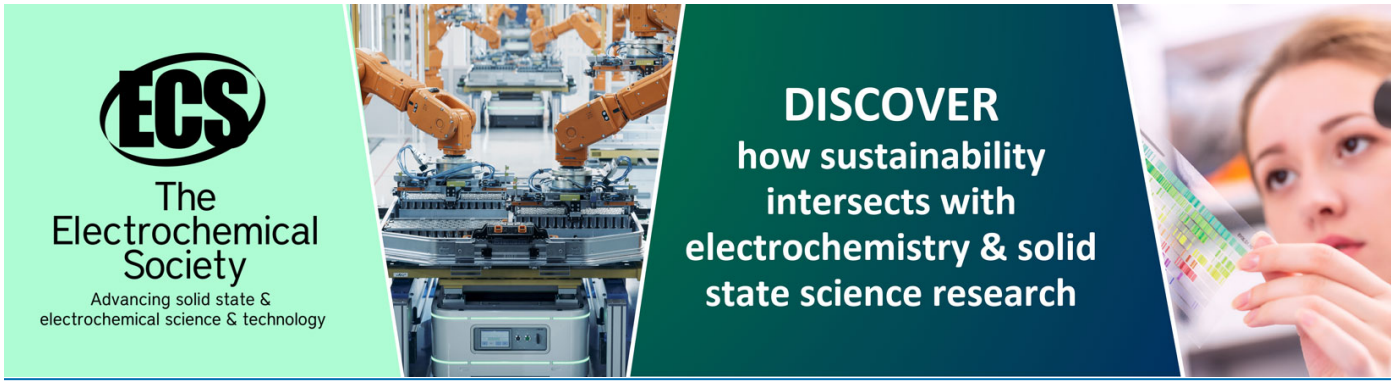
Positron beams from small accelerators and status of a novel positron storage project



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Positron beams from small accelerators and status of a novel positron storage project

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Abstract. Positrons are generated by an intense beam of deuterons. Deuterons with energies up to 3 MeV and 300 μA intensity or 1000 W power are guided onto a carbon target. The (d,n) reaction converts ^{12}C into the positron emitter ^{13}N. In one version a CVD diamond target is rotated behind a W foil moderator after irradiation. Rapid heating of the diamond and defect generation limits this method to deuteron power <100 W. At higher power ^{13}N molecules are released had must be condensed behind a moderator. Graphite is employed for higher power doses. External direct current or e-beam heating are used to reach temperatures in excess of 2000 K when nitrogen is released from graphite. Efforts to maximize the release of ^{13}N containing molecules as well as the goal to accumulate positrons in a novel trap design are discussed. Up to 75% of the activity was released at 2 MeV. This decreases with deuteron energy.

1. Introduction

In recent years a number of experiments have been carried out or are proposed which require very large numbers of positrons.[1] These include more ambitious positron-in-materials experiments, the formation of Ps_2 (Positronium) molecules,[2] Bose Einstein condensation of Ps, and the creation of anti-hydrogen atoms.[3] These are the stepping stones towards probing fundamental properties of antimatter and gravity.[4] Considerably more ambitious is the idea of using stored antimatter as a battery to deliver energy in remote locations such as outer space. At 1.8×10^{11} MJ/kg (including readily available electrons) positrons are more than 10 billion times as efficient per mass than chemical fuels. Less than a nano-gram of positrons contains sufficient energy to lift 1 kg of payload beyond the gravitational pull of Earth. Three challenges require solutions: Production, storage and conversion to accelerating forces. Here, a recently proposed concept to store positrons and a positron source based on a small van de Graaff accelerator to test this idea are discussed.[5,6]

The implementation of Penning-Malmberg trap enabled on-demand delivery of ~10^9 positrons in short bursts.[7] In typical cylindrical traps positrons are confined radially by a large homogeneous magnetic field of several Tesla strength. Electric repulsive potential barriers of about 1kV provide axial confinement. To retain larger numbers of positrons the required electric potential rises rapidly. Figure 1 shows an example (dashed line).

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Almost all positron sources utilize powerful accelerators and nuclear reactors or long lived radioisotopes. To a potential user of positrons for materials research or high energy physics it is desirable to have on-demand access to positrons sufficient for several experiments without the concern of longer lived radioactive materials or the need to travel to a large facility. Potentials on the order of less than 100 V are desirable for portable traps. These could be filled at a central location and delivered to users for positron annihilation experiments.

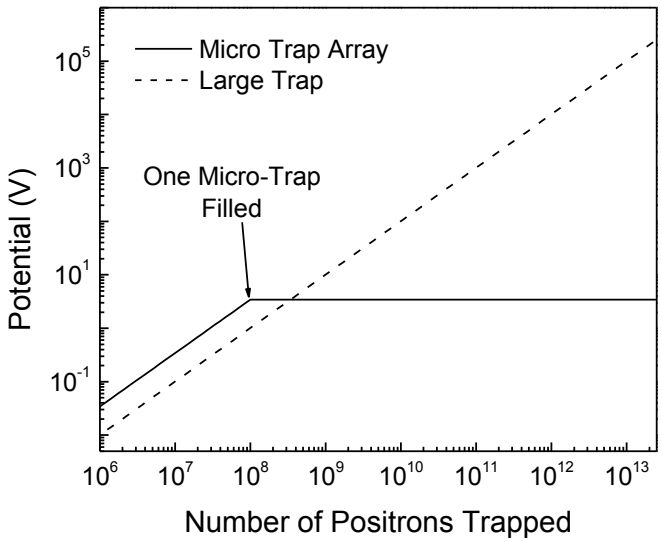

Figure 1: Retaining potential required to store positrons in a single trap (dashed) or an array of micro-traps (solid).

The novel concept would make portable traps practical allow for much larger numbers of stored positrons. It calls for separating the single cloud of positrons in 0.05 m diameter by 0.1 m long cylinder into N parallel cylinders. The conducting walls of each cylinder shields the repulsive fields from one cylinder to any other. The diameter of each cylinder is reduced to micrometer dimensions. The length to diameter aspect ratio is raised to about 1000 to maintain the overall length of each micro-trap. Adding more positrons requires filling more micro-traps at no added cost of increasing the confining potential (solid line in figure 1).

A "proof of principle" experimental project under way at Washington State University calls for storing $>10^{11}$ positrons in about 2×10^4 micro-traps of 100 μm ∅ and 0.1 m length each.[5,6] Each micro-trap will hold about 10^7 positrons.
A number of challenges need to be met for this project.

1) The trap will be assembled from 200 50 mm ∅ wafers of silicon. Microelectromechanical systems (MEMS) technologies are used to etch 20 000 holes into each wafer. The Bosch process and cryo-etching are refined to achieve straight hole walls and homogeneous etching rates across the wafers. The wafers will be gold coated and bonded together with micrometer precision to form the array of micro-traps.[8]
2) The array must be aligned to within 1 μm deviation over its 0.1 m length inside of a 7 Tesla superconducting magnet. Vibrations must be kept to less than 10 μm.
3) Vacuum conditions must be maintained well below 10^{-10} torr to minimize positron molecule collisions.
4) Monoenergetic positrons will be guided onto the magnet, trapped and stored. Electric potentials are applied to segments of the trap to facilitate the stacking more and more positrons to many micro-traps in parallel. To fill the micro-trap array with 10^{11} positrons in an hour or less the incident positron beam must deliver more than 3×10^7 positrons per second, not accounting for any inefficiencies.
5) Computer simulations are ongoing to determine the highest stable densities and ideal geometry.[9]

In the following, a beam concept to deliver sufficient positrons is discussed. The nuclear reaction $^{12}C(d,n)^{13}N$ has one of the largest cross sections to produce a positron emitting isotope.[10] ^{13}N decays

with a half-life of just under 10 min. 300 μA of 3 MeV deuterons suffice to generate a production rate of 1.2×10^{11} positrons/sec. With an overall of better than 2.5×10^{-4} efficiency to provide moderated positrons a filling time of 1 hour (not losses) can be reached.

2. Accelerator and positron production

The basics of positron production with a 3 MV deuteron accelerating van de Graaff machine have been described earlier.[11] The High Voltage Engineering (HVE) KN-3000 can deliver 0.5 to 3.0 MeV deuterons at currents from 30 to 300 μA. With a single focussing element and a pair of horizontal and vertical deflectors the beam is focussed onto a carbon target. The target is located in a 30 cm thick borated paraffin box within a 5 cm thick lead shroud to shield against neutrons and energetic gamma rays. Radiation detectors are installed to monitor the gamma rate and neutron dose at the deuteron target and at the cryogenic vacuum pump between the accelerator and the shielding igloo.

Two versions of delivering energetic positrons to a moderator have been tested. In the first case, the ^{13}N source isotope was trapped in the diamond or graphite targets and, after a suitable irradiation time, rotated behind a W thin foil moderator. In the second version, the graphite target is heated sufficiently to release the radioisotope. ^{13}N containing molecules can then be condensed behind the moderator. Nitrogen diffuses out of graphite at temperatures in excess of 2000 K.[12] In the case of positron emission tomography (PET) approaches to produce ^{13}N ammonia dissolved in water or to burn graphite by adding heat and oxygen were tested.[13]

2.1. Rotating source

The original concept of this positron beam called for irradiating diamond targets with the deuteron beam. Any ^{13}N activity would be trapped in the diamond while the generated heat is transported efficiently from the diamond surface to a water-cooled copper substrate. After irradiation times of 3 half lives the target was rotated 90 degrees behind a W thin foil moderator. Figure 2 shows a beam example where the intensity is monitored as a function of angular position behind the moderator. The data were corrected for the decay of the source. This concept works well at low power as was demonstrated originally by Xie et al as well as Cassidy et al.[14, 15]

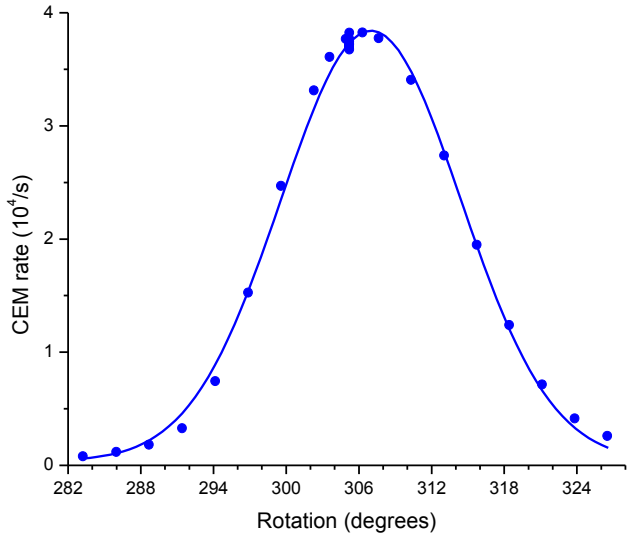

Figure 2: Positron beam intensity versus source rotation. At 307° the source is aligned with the moderator. The rates are corrected for source decay.

When the power of the deuteron beam was increased above approximately 100 to 200 W (50 μA at >2 MeV deuterons) and after longer operations the positron beam intensity degraded. The deuteron beam generated damage in the diamond targets to deteriorate the thermal properties of the diamond target. The target graphitized and eventually disintegrated due to thermal stresses. The vacuum in the accelerator and positron beamlines was maintained by cryopumps. The loss in positron beam intensity was accompanied by a build-up of radiation detected at the cryopumps. This was confirmed by replacing the diamond target with graphite of lower thermal conductivity. ^{13}N containing isotopes were released at lower deuteron beam power.

2.2. Thermal ^{13}N release and condensation

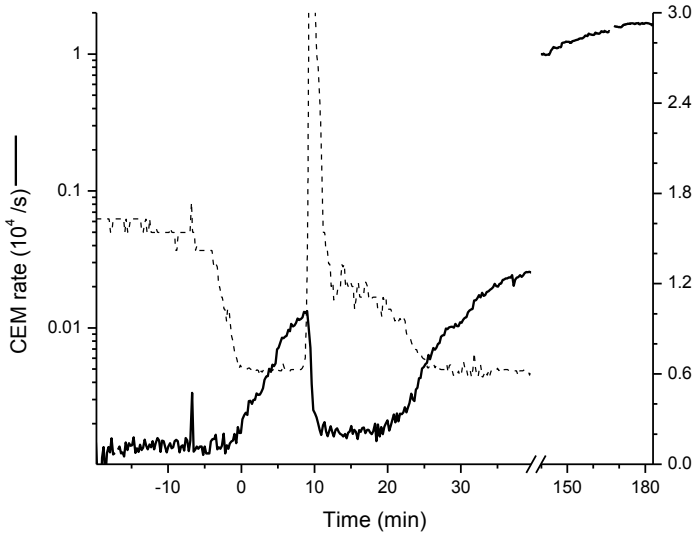

Figure 3: Positron intensity (solid line, left log scale) as the source cup is cooled below 20 K (near 0 min). The total pressure (dashed line, right scale) is also shown. Note the time step near 40 min.

The opposite approach was tested. The deuteron beam generates the ^{13}N isotope as well as provides sufficient heat to release the isotope. A copper coldfinger was installed behind the moderator to condense any gases. When the temperature drops below 20 K the positron beam intensity rises and a sudden drop in the pressure in the target chamber is observed as shown in figure 3. After about 10 minutes the temperature jumps up, the positron beam is lost before both recover. The required temperatures below 20 K suggest that a significant fraction of the ^{13}N molecules are $^{13}N^{14}N$.

Again, this concept shows promise at relatively low deuteron power, several issues remain to be resolved. Most importantly the thermal isolation of the deuteron target and the ^{13}N condenser must be improved. Second, some of the ^{13}N inventory never is released from the target or may condense elsewhere at higher temperature. In an environment rich in deuterium, carbon and residual water from the vacuum system ^{13}N tagged compounds such as NH_3, HCN or deuterated versions are possible.

3. Graphite target heating

The deuteron target was separated from the positron beam to evaluate and optimize the release of ^{13}N compounds. The heating of the target was separated from accelerator power heating by installing either direct current heating or electron gun heating. In the former thin graphite targets were heated with up to 250 A passing through the target. About 1000 W were provided into the target and target holder system. The electron beam system was operated with 9 keV electrons at up to 140 mA onto 0.025 m square graphite targets. In a separate test 110 mA at 7 keV (770 W) heated the graphite to 2000 K as measured with an optical pyrometer.

A residual gas analyzer (RGA) was used to observe the partial pressures to determine the released gasses. As expected, nitrogen (masses 14 and 28) was released at a power consistent with the 2000 K threshold. Other dominant gases were CO and argon as well as water, hydrogen and deuterium. Over time the partial pressure of argon and water dropped significantly. Of these, argon was not expected from graphite. However, the graphite sample was not selected for purity.

Target heating was carried out either together with deuteron bombardment or separately after the deuteron beam was shut down. The former combined the heat sources of the deuteron beam with the secondary heater and the latter permitted more careful monitoring of the ^{13}N isotope release from the target. Radiation monitors were installed in the paraffin and lead box and at the cryopump between the accelerator and the target. When the deuteron beam is shut down, almost all radiation is due to ^{13}N decays. About 1% of the initial dose is due to ^{56}Mn with a 2.58 hr half live. Figure 4(a) shows the sudden drop in activity on the target along with a rise of the radiation dose at the cryopump when the

heater is turned on. The deuteron beam is off during this measurement and the data were corrected for the 10 min half live of ^{13}N. In this case about 35% of the ^{13}N inventory was released after 3 MeV deuteron bombardment. Figure 4(b) shows the fraction of released radiation as a function of deuteron beam energy or implantation depth. Most tests were conducted at 2 MeV when the heater power was gradually increased. In both cases, by combined heating or after shutting down the deuteron beam the maximum released fraction was 75% to date. Estimates of the total positron flux generated are consistent with thick target yields for the ^{12}C(d,n)^{13}N reaction.

It appears that the ^{13}N containing molecules are released more rapidly by the direct current heating compared to e-beam heating from the opposite side of the target. The rise in radiation release precedes the observation of nitrogen (masses 14 and 28 on the RGA). In the initial experiments the accelerator deuteron beam power caused sufficient heating to release some of the ^{13}N inventory above a threshold power level. However, during the most recent experiments at even higher deuteron power this no longer occurs. The causes for these effects are under investigation.

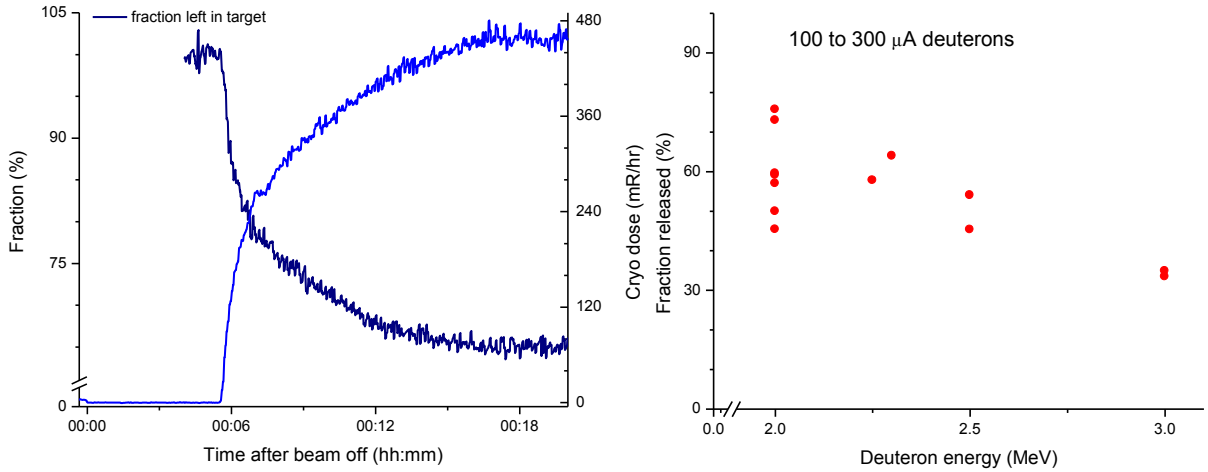

Figure 4: a) Source decay corrected fraction of ^{13}N radiation in the graphite target (left scale) and dose in the cryopump (right scale). 2 MeV deuterons were used. b) Fraction of radiation released from the target as a function of deuteron beam energy (red dots).

Conclusions

A small 3 MV van de Graaff accelerator was commissioned to generate the ^{13}N positrons source from bombarding graphite with deuterons. The graphite must be heated to about 2000C completely release the isotope which is then frozen near a thin film W moderator. An initial beam was observed, however, the compatibility of the high temperature generation of ^{13}N and freezing the isotope containing compound close to the moderator requires further improvements. Modifications are under way. Computer simulations indicate that space charge repulsion can be reduced dramatically by replacing a single large trap with an array of long but μm diameter tubes. A test bed is under construction.

Acknowledgments

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References

[1] Mills A P Jr 2011 *Rivista del Nuovo Cimento* **34** 151
[2] Cassidy D B and Mills A P Jr 2007 *Nature* **449** 195
[3] Amoretti M, Amsler C, Bonomi G, *et al Nature* **419** 456
[4] Holzscheiter M H, Charlton M and Nieto M M 2004 *Physics Reports* **402** 1
[5] Baker C J, Jennings J, Verma A, Xu J, Weber M H and Lynn K G 2012 *Eur. Phys. J.* D **66** 109
[6] Xu J, Weber M H and Lynn K G 2010 *CLXXIV Enrico Fermi School on Physics with Many Positrons* ed A Dupasquier A P Mills jr R S Brusa Societa Italiana de Fisica 481
[7] Murphy T J and Surko C M 1992 *Phys. Rev.* A **46** 5696
[8] Verma A, Jenning J, Johnson R D, Weber M H and Lynn K G 2012 *J. Vac. Sci. Technol.* B **31** 32001
[9] Narimannezhad A, Xu J, Baker C J, Weber M H and Lynn K G 2012 to be published
[10] Young F C and Rose D V 1996 *Atomic Data Nucl. Data Tables* **64** 223
[11] Hunt A W, Pilant L, Cassidy D B, Tjossem R, Shurtliff M, Weber M H and Lynn K G 2002 *Appl. Surf. Sci.* **194** 296
[12] Kohl W H 1960 *Materials and Techniques for Electron Tubes* Reinhold Pub. Corp. New York
[13] Dence C S, Welch M J, Hughey B J, Shefer R E and Klinkowstein R E 1994 *Nucl. Med. Biol.* **21** 987
[14] Xie R, Petkov M, Becker D, Canter K F, Jacobsen F M, Lynn K G, Mills R and Roellig L O 1994 *Nucl. Instrum. Meth. Phys. Res.* B **93** 98
[15] Cassidy D B, Canter K F, Shefer R E, Klinkowstein R E and Hughey B J 2002 *Nucl. Insrum. Meth. Phys. Res.* B **195** 442