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Technology and applications of neutron generators developed by Adelphi Technology, Inc.

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Abstract

A standard product line of high yield neutron generators has been developed at Adelphi Technology Inc. The generators use the D-D fusion reaction and are driven by an ion beam supplied by a microwave ion source. Yields of up to 5×10^9 n/s have been achieved, which are comparable to those obtained using the more efficient D-T reaction. The microwave-driven plasma uses the electron cyclotron resonance (ECR) to produce a high plasma density for high current and high atomic ion species. These generators have an actively pumped vacuum system that allows operation at reduced pressure in the target chamber, increasing the overall system reliability. Variations of these generators have been produced to increase the yield and total flux available. Several of the generators have been enclosed in radiation shielding/moderator structures designed for customer specifications. These generators have been proven to be useful for prompt gamma neutron activation analysis (PGNAA), neutron activation analysis (NAA) and fast neutron radiography. Pulsed and continuous operation has been demonstrated. Larger thermal neutron fluxes are expected to be obtained by multiple ion beams striking a central target that is filled with moderating material. Thus these generators make excellent fast, epithermal and thermal neutron sources for laboratories and industrial applications that require neutrons with safe operation, small footprint, low cost and small regulatory burden.

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Keywords: Neutron generators; ion sources; neutron activation analysis; electron cyclotron resonance.

1. Introduction

Neutron generators using the well-known D(d,n)He (or DD) fusion reactions have been available for use for over 50 years. These devices are relatively simple and inexpensive compared those using high acceleration energies. At present, most generators use the Penning ion source to obtain deuterium and/or

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tritium ions (D^+ or T^+) that are accelerated to a titanium target where the fusion reactions occur and neutrons are produced [1]. The Penning diode is simple and compact, requiring low power to operate. Unfortunately, the efficiency of gas conversion to ions results in a large component of molecular ions (D^+_2 or T^+_2), lowering the overall neutron yield of the generator. Their compactness, but lower neutron yields, have relegated them primarily to oil exploration.

Adelphi generators use microwave radiation to heat and ionize deuterium or tritium gas. Higher atomic conversion efficiencies are achieved using the electron cyclotron resonance (ECR) effect [2-8]. This source can also achieve plasma densities much higher than Penning or RF-driven ion sources while operating at lower gas pressures. Lower pressure operation prevents voltage breakdown in the acceleration region, resulting in more stable operation. Unlike RF plasma ion sources, ECR sources are easy to use with no complicated ignition procedures that require pressure or matching network adjustments. Since the microwaves are confined within the waveguide and the ion source cavity, no EMI noise, typical to the RF-driven ion sources, is present. With the ECR ion source the operation of the generators has become simpler and more efficient, making them more attractive for industrial and security applications.

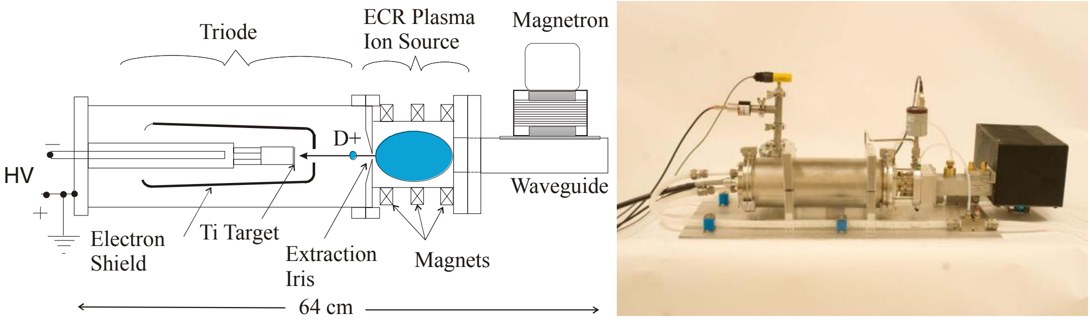
Both the DT and DD reaction have been manufactured by Adelphi. Major differences between the generators are the fusion reactions they use and the neutron yield provided. Generators utilizing D(t,n)He (DT generator) reaction are always sealed and cannot be refurbished after failure due to the contamination risk involved in handling of radioactive tritium. Generators utilizing D(d,n)He reaction (DD generator) are usually pumped, but some are also sealed. Pumped systems permit easy access and maintenance, which can be done at client site, resulting in long lifetimes since all generator components can be replaced. A sealed DD generator requires no expensive turbo vacuum pump; however, maintenance is more difficult if the generator head is opened for servicing or component replacement. This requires heating ("baking out") of the head in order to re-supply the gas and to prevent its contamination.

Table 1. Standard Model neutron generators using ECR ion source.

Product Model #	Nominal Yield (n/s)	Meas. Max Yield (n/s)	Max. HV Power	Ion Current
DD-108	1 x10^8 n/s	3 x 10^8 n/s	200 W	1.5 to 2 mA
DD-109	1 x10^9 n/s	3 x 10^9 n/s	2 kW	8 to 18 mA
DD-110	1 x 10^{10} n/s	6 x 10^9 n/s	6 kW	20 to 30 mA

2. Standard Models (DD-108, and DD-109)

Adelphi currently has three standard products listed on Table 1. These generators use a triode extraction geometry [6], wherein the last electrode acts as a target for the fusion reactions. A schematic drawing of the major components is shown in Fig. 1 (a) with a photograph of a model DD-108 generator head shown in Fig. 1 (b). The major components of this triode are the ECR plasma ion source, extraction

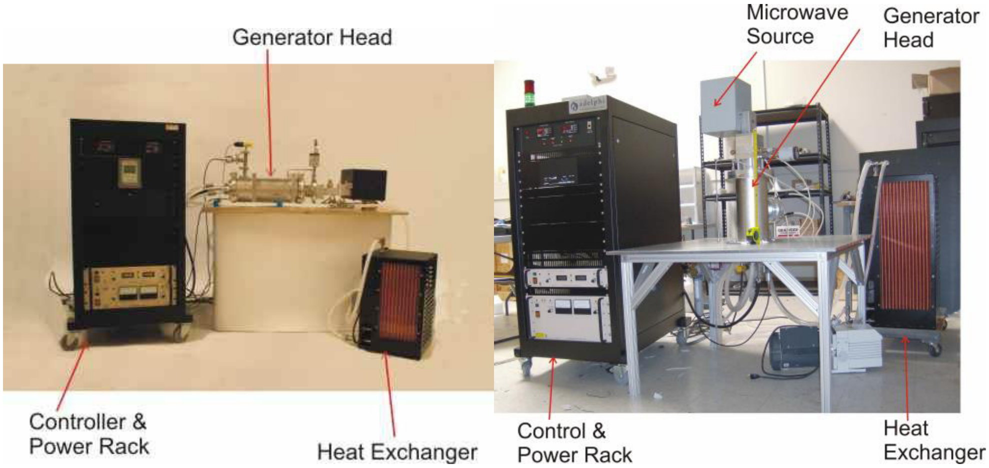


(a) (b)

Fig. 1. (a) A schematic drawing of the major components of the standard neutron generator (models DD-108 and DD-109). (b) A photograph of the model DD-108 generator head.

iris, electron shield, and titanium (Ti) target. The target is at a high negative potential (– 100 kV), while the ion source is at ground. Thus the deuterium ions (D^+) are accelerated from the ion source's extraction iris to the Ti target where the fusion reaction occurs. A magnetic field and a biased electron-shield electrode are used to prevent the back-streaming electrons from damaging the iris of the ion source. The acceleration region is housed in a 15.3-cm diameter pipe. Total length of the generator head is 64 cm, but this can be varied for customer needs.

The target is made from titanium-coated copper and is liquid cooled from behind the titanium. The incoming D^+ ions are trapped in the titanium lattice. Succeeding ions collide with these trapped ions, creating neutrons through fusion reactions. To maximize the neutron production and lifetime of the target, the titanium surface needs to remain cool in order to trap the maximum number of ions [9, 10]. Titanium temperatures are maintained by active cooling and shaping of the target surface in such a way as to minimize the power densities at the target surface. Both flat and "V" shaped targets are used. Flat targets are used for small neutron source sizes, and are limited in neutron yield due to target heating. The "V" shaped target distributes the head more uniformly.



(a) (b)

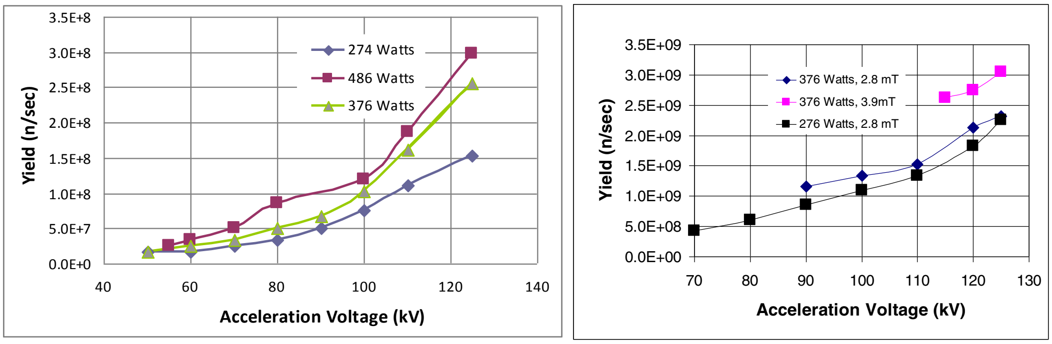
Fig. 2. (a) Model DD-108 capable is of producing 10^8 n/sec. (b) Model DD-109 is capable of producing 10^9 n/sec. DD-109 generator head is mounted vertically.

Deuterium gas is introduced continuously at low rates into the ion source. The desired internal pressure in the ion source and acceleration regions of the generator head is achieved by actively pumping the head, using a small turbo pump. Inherently the pumped systems are larger and more expensive, but have the added the benefits of increased lifetime and ease of maintenance.

Photographs of the two of the standard Adelphi generators (DD-108 and DD109) are shown in Fig. 2 (a) and (b). The three major components are the electronics (controller and power supply rack), the generator head and a heat exchanger. Fig. 1 (a) is a the model DD-108 generator with its head mounted horizontally; while in Fig. 1 (b) the model DD-109 generator head is mounted vertically. Both orientations are available for either model.

The neutron generator ion current and yield are both functions of deuterium gas pressure, magnetron power and acceleration voltage. Measured values are given in ref. [8]. Adjusting the acceleration voltage is the easiest way to change the yield. The generators are designed to operate with acceleration voltages between 70-125 kV. Magnetrons are usually operated continuous with input power between 200 to 400 watts. Gas pressures are between 2.5 to 5 mT in the plasma resonance chamber. There is a differential pumping effect between the plasma ion chamber and the acceleration region due to the plasma ion extraction iris (usually 1 to 3 mm in diameter). Thus pressures in the accelerations region are a low 10^{-4}

to 10^{-5} Torr, minimizing high voltage breakdown between the electron shield and other components. The measured neutron yields as a function of high voltage (kV) for selected magnetron powers are given in Fig. 3 (a) and (b) for both generators. As can be seen these generators deliver high yields of fast neutrons for the DD fusion reaction and rival that of the generators using the DT reaction and the Penning diode as their ion source.



(a) (b)

Fig. 3. (a) The measured yield as a function of acceleration voltage for the DD-108. (b) The measured yield as a function of acceleration voltage for the DD-109 for three magnetron powers.

3. Thermal Neutron Sources (Moderated Generators)

3.1. Moderated single beam generators (DD-109M)

We have fabricated moderators for our product line of neutron generators. These permit the generators to become useful thermal neutron sources for a variety of experiments and applications. Moderating to thermal energies permits activation of many isotopes and makes the generator useful for materials analysis and identification. The generator with an optimally designed moderator becomes a high thermal neutron flux source for Neutron Activation Analysis (NAA) and Prompt Gamma Neutron Activation Analysis (PGNAA). The moderated source closely mimics experimental research reactors, which have been the only sources of thermal neutrons that can be used for NAA and PGNAA. Furthermore, the fast neutron source can be pulsed or gated to minimize the noise background of the fast neutron source and its other activated products. This is especially true for delayed neutron activation analysis.

Moderation of the neutrons can be inexpensively done with hydrogen bearing materials. High density polyethylene (HPDE) has been shown by us and others to be an excellent moderator [8,12]. Since the fast neutrons are emitted roughly isotropically from the titanium target [1], the neutrons must be slowed down in the shortest distance in order to achieve the maximum flux of thermal neutrons. Monte Carlo Neutral Particle (MCNP) simulations demonstrate that HDPE does this best, achieving the maximum thermal flux at only 5 cm from the titanium target. Sanchez [12] has shown this to be the case for 2.5 MeV neutron emitted from the DD reaction.

Table 2. Moderated neutron generators.

Product name	Thermal flux (n/cm^2-s)	Meas. Max Yield (n/s)	System
DD-109M	1x10^6	4x10^9	Single beam
DD-110MB	7 x 10^7	6 x 10^9	Multi-beam

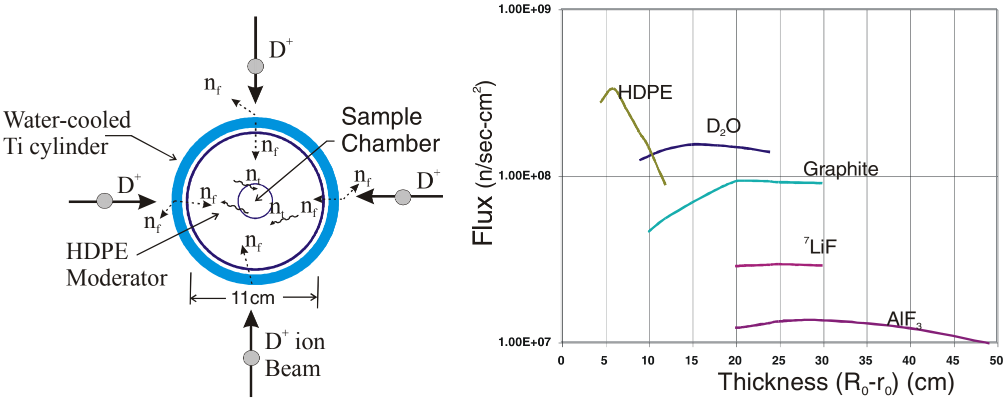
(a) (b)

Fig. 4. (a) Moderated DD-109. Moderation of fast neutrons is accomplished by using high density polyethylene. Top of HDPE moderator shell has been removed. (b) Shielding of thermal neutrons is accomplished by borated polyethylene surrounding the HDPE.

The DD-109M becomes a safe, compact nuclear reactor for demonstrations, experiments and research. This desired system would not be the size of a large two story building, cost $30 million dollars and require licensing from the governmental agencies. Indeed, the only fuel used is deuterium, readily available from most scientific gas suppliers. Generators using the deuterium-deuterium reaction require no licensing for export or operation. The generator with its moderator can be fit on a floor area of 122 cm x 182 cm and be made primarily of HDPE. The polyethylene can be easily machined to permit changes in the moderator and instrument placement. Adelphi has optimized detector and sample placement and moderator geometry for maximizing detection efficiency.

3.2. Multi-beam high thermal flux neutron source (DD-110MB)

The new DD110MB is expected to produce high fluxes of thermal neutrons (e.g. 10^8 n/cm^2-sec) at a centrally located sample chamber. This flux is achieved using four ion beams arranged concentrically around a cylindrical titanium target containing a R_o radius HDPE moderator with a small $r_o = 1.1$ cm radius sample chamber in the middle. This arrangement is shown in Fig. 5 (a). Fast neutrons are produced at the cylindrical titanium target. The thickness of the moderator R_o-r_o is selected to maximize

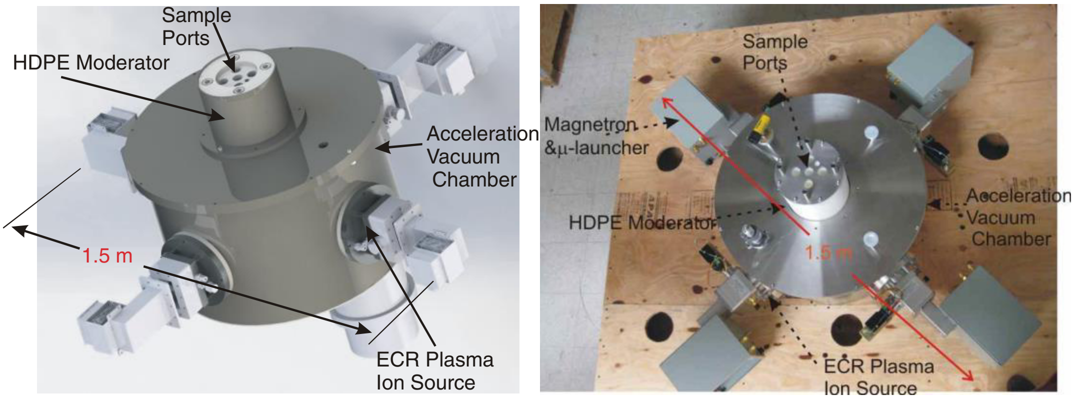


(a) (b)

Fig. 5. (a) Four ion beams directed toward cylindrical target filled with a HDPE moderator. (b) The thermal neutron flux (< 0.5 eV) as a function of moderator thickness.

the thermal neutron flux at the center. Thus the 2.5 MeV neutrons are quickly thermalized to energies below 0.5 eV and concentrated at the central sample chamber. Fig. 5 (b) shows the thermal neutron flux plotted as a function of moderator thickness (R_o-r_o) in cm.

Materials to be irradiated are placed inside the sample chamber. The neutron flux can be used for neutron activation analysis (NAA) and prompt gamma neutron activation analysis (PGNAA) for determining the concentrations of elements in many materials. NAA and PGNAA allow discrete sampling of elements, as they disregard the chemical form of a sample and focus solely on its nucleus. In both techniques, samples are bombarded with thermal neutrons, causing the nuclei of the samples to form stable and unstable radioactive isotopes at differing decay and emission rates.



(a) (b)

Fig. 6. (a) Perspective view of the DD-110MB generator. (b) Photograph of the top of DD-110MB being assembled at Adelphi Technology Inc.

4. High flux fast neutron generator

The new model DD-109X neutron generator uses a minimum source-to-sample distance to provide the sample with a high flux of fast neutrons. This increases the reaction rate in the sample for diagnosis of content. Such active analysis is particularly useful for determining the material components of nuclear materials. Previously, samples were required to be placed a distance from the neutron source emitter where the flux of the fast neutron was small. The standard model generators of Adelphi have their titanium targets at high voltage potential (e.g. 120 kV) and are separated from the outside environment by an electron shield and a vacuum of 10 cm thickness. Since the neutrons are being emitted isotropically, the fast neutron flux (n/sec-cm^2) drops appreciably (~ 1/100) outside the generator head housing. The DD-109X changes all that by positioning the sample to be irradiated in the acceleration chamber next to the high voltage target that is producing the fast neutrons. Small samples (e.g. 1-10 cm^3) can be placed near the titanium target by inserting ceramic cups into the generator wall as shown in Fig. 7 (a). The cups permit the samples to be placed ~ 1 cm next to the "V" titanium target. This permits the sample to receive fluxes of $\sim 5 \times 10^7$ n/sec-cm^2. A photograph of the complete generator with two sample ports is shown in Fig. 7 (b).

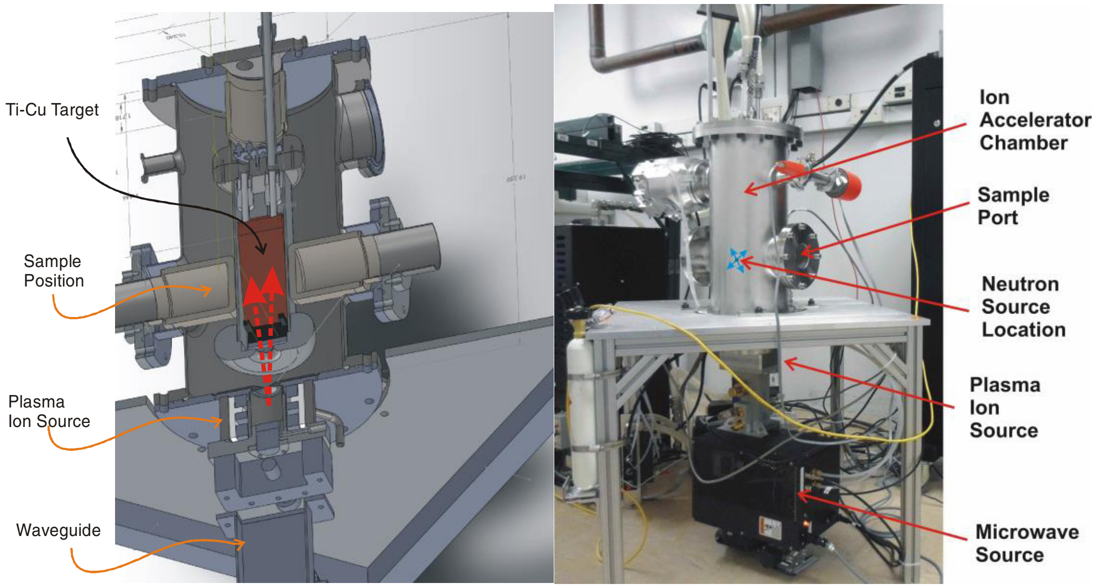
A "V" shaped titanium-coated copper target was used with a 16° apex angle. A schematic of the target is shown in Fig. 8 (a). Its length is 9 cm from the apex to the base. The incoming 3-mm diameter deuterium ion beam fills the target. This geometry distributes the heat on the surface, but with most of the ions striking the apex of the target. The total yield being emitted by the neutron generator is assumed to be 4×10^9 n/s. This is an estimated experimental value obtained from a 30 mA D^+ ion beam striking the titanium surface. The neutrons are emitted from the surface of the target (see Fig. 2) where the D^+

ions strike and fuse with those that are already embedded in the titanium matrix. As is the case for the standard generators, the ions deposit their energy into the titanium matrix resulting in a power density variation across the surface of the target. A simulated power density (watts/cm^2) of the ions as a function of the distance in meters along the surface of the target is shown in Fig. 3. The D^+ ions (Fig. 1) are exiting the plasma ion source from a 6 mm diameter extraction aperture.

The resulting simulated distribution of the fast neutron flux emitted from the "V" target is shown in Fig. 8 (a). The neutron flux is plotted as a function of z for various values of $\boldsymbol{x}$, with $\boldsymbol{y} = 0$. $\boldsymbol{x} = \boldsymbol{y} = \boldsymbol{z} = 0$ is considered the origin and is clearly inside the "V" target. If the ceramic cylinders are placed along the z-axis, and $y = 0$ one would expect that the flux would be maximized. The simulation shows that at $x = -4$ cm, the point of maximum flux (from Fig. 8 (b)) is approximately1.9×10^8 n/cm^2-sec. Placing the rotational axis of the ceramic cup at $x = -4$ cm, $y = z = 0$ will deliver the maximum flux to the sample. As can be seen, the range of x of ± 2 cm around – 4 cm should not alter the flux more than approximately 10 %. Changing the parameters of the neutron generator and the target geometry will also alter the optimum position for placing the ceramic cup for the maximum flux. Thus, a maximum flux is delivered to the sample, resulting in a maximum rate of sample nuclear excitation.

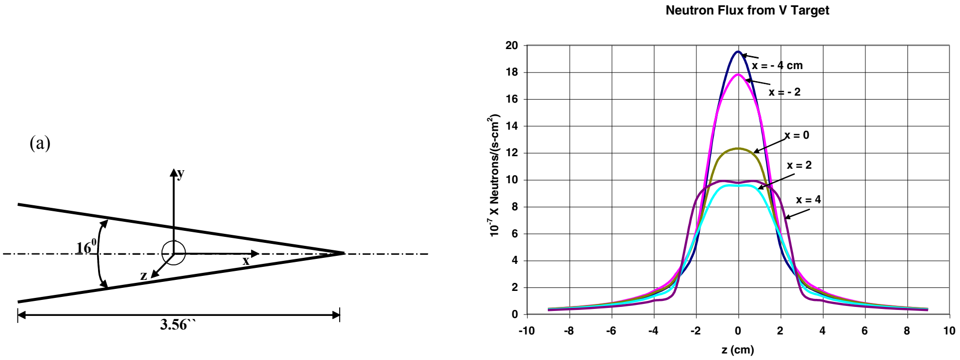
Small laboratories can now have neutron fluxes at a fraction of the cost of sources that are usually only available at national facilities and nuclear reactors. The generator can be operated both cw or pulsed. The advantage of pulsed operation, not found in reactors, allows analysis of delayed gammas and thermal neutrons without accompanied spurious noise from other radioactive components.

The new DD-109X generator permits the fast neutron irradiation of fissile materials such as spent uranium fuel rods to identify the various daughter components of the rod. The generator will be used to increase the accuracy of the delayed neutron group yield data and the corresponding uncertainties. This is important because it reduces the uncertainties in non-destructive assay techniques of spent nuclear fuel that utilize delayed neutrons. The precursors of the delayed neutron and gamma radiation are left in the fuel rod.



(a) (b)

Fig. 7. (a) Split view looking up from the plasma ion source. (b) A photo of the generator head mounted vertically.



(a) (b)

Fig. 8. (a) V-target with a 16° apex angle and 9 mm (3.56") length. (b) Calculated fast neutron flux a function of x along the axis of the V-target.

5. Conclusions

Adelphi makes neutron generators that produce fast neutron yields in the 10^8 to 10^{10} n/sec range. When the fast neutrons are moderated thermal fluxes between 10^6 to 10^8 n/cm^2-sec can be obtained. The generators can be modified to achieve geometries that increase the available fast neutron flux. Both horizontal and vertical positioning of the generator heads can be achieved. Thermal fluxes can be achieved by simple moderators made of high density polyethylene (HDPE). Larger thermal fluxes are expected from multiple ion beams striking a central target with an internal moderator. Use of these generators has applications in fast and thermal neutron radiography, materials identification and nuclear physics education.

Acknowledgments

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