

Final Report Phase II DOE STTR

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Project Title: “High Brightness Neutron Source for Radiography”

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Executive Summary

This research and development program was designed to improve nondestructive evaluation of large mechanical objects by providing both fast and thermal neutron sources for radiography. Neutron radiography permits inspection inside objects that x-rays cannot penetrate and permits imaging of corrosion and cracks in low-density materials. Discovering of fatigue cracks and corrosion in piping without the necessity of insulation removal is possible. Neutron radiography sources can provide for the nondestructive testing interests of commercial and military aircraft, public utilities and petrochemical organizations.

Three neutron prototype neutron generators were designed and fabricated based on original research done at the Lawrence Berkeley National Laboratory (LBNL). The research and development of these generators was successfully continued by LBNL and Adelphi Technology Inc. under this STTR. The original design goals of high neutron yield and generator robustness have been achieved, using new technology developed under this grant. In one prototype generator, the fast neutron yield and brightness was roughly 10 times larger than previously marketed neutron generators using the same deuterium-deuterium reaction. In another generator, we integrate a moderator with a fast neutron source, resulting in a high brightness thermal neutron generator. The moderator acts as both conventional moderator and mechanical and electrical support structure for the generator and effectively mimics a nuclear reactor.

In addition to the new prototype generators, an entirely new plasma ion source for neutron production was developed. First developed by LBNL, this source uses a spiral antenna to more efficiently couple the RF radiation into the plasma, reducing the required gas pressure so that the generator head can be completely sealed, permitting the possible use of tritium gas. This also permits the generator to use the deuterium-tritium reaction to produce 14-MeV neutrons with increases of yield of two orders of magnitude.

The first fast neutron radiographic images were obtained using neutron cameras and a new fast neutron generator. These early images demonstrated the feasibility of using fast neutrons for imaging and penetrating thick objects of high density and imaging. Fast neutrons can be used to image low atomic number materials (e.g. plastics, explosives, lubricants and ceramics) that are shielded by high density materials (e.g. lead, tungsten and uranium). Fast neutron radiography could be used as a means to screen weapons for flaws and chemical stability. X-ray radiography can not easily do this. Fast neutron imaging is technically difficult and, consequently, a completely undeveloped market. Two of the generators were designed to have small source size and high brightness, ideal for fast-neutron imaging. With these generators we successfully used two fast neutron cameras: one developed by us, and another developed by a collaborator, Commonwealth Scientific and Industrial Research Organization, CSIRO. We have successfully used these cameras to obtain low resolution images of various objects such as pipe fittings filled with water and other mechanical objects. Higher resolution and contrast images are expected by decreasing the source size and increasing generator yield.

1. Introduction

1.1. Success

This DOE STTR program has been a remarkably successful one, both as a research and development program and as a commercial development. Under the program LBNL and Adelphi have fabricated three prototype neutron generators (Table I), completed most of our original goals, and demonstrated fast and thermal neutron radiography. The yields of two of these generators have been successfully measured by us and three outside clients. Generators have been rented for various experiments, and purchase orders for three of these generators have been received along with partial payments. Commercial generators based on these prototypes are under construction at Adelphi's facilities in Redwood City California.

We have developed transportable neutron generators capable of imaging flaws in various materials that cannot be imaged by x rays or other methods. The source closely resembles a standard medical-imaging x-ray tube in that it is fundamentally a diode that requires a high voltage power supply, a chiller, and a vacuum system. An additional 3-kW RF generator is needed to drive a plasma ion source. As in a high power portable x-ray source, one would place the neutron source on site next to the object to be imaged. Assorted cabling, tubing, and vacuum hose would then be connected. A film cassette or other thermal-neutron imaging detectors would then be placed on the opposite side of the object. The source would then be energized and images taken. Large areas can be imaged, depending upon the film or detector size.

We have pursued radiographic imaging using either thermal or fast neutrons. In this pursuit we have developed two sets of imaging detectors and neutron generators: (1) a thermal neutron generator (model DD-108-T) with an accompanying thermal neutron imaging detector and (2) a fast neutron generator (model DD-109) with an accompanying fast neutron imaging detector. We have performed preliminary imaging experiments using the prototype imaging detectors developed under this program.

Table I: Neutron Generators Fabricated or Commercialized under this STTR program.

Model Number	Yield (n/sec)	Status	Primary Uses	Comments
DD-108*	10^8	In operation 12/2006	Radiography	Actively been used and rented
DD-109*	10^9	In operation 1/2008	Radiography; materials identification; IED detection	Actively been used and rented
DD-108-T*	10^8	In operation 7/2008	Radiography; materials identification	Thermal neutron generator
DD-110	10^{10}	Partial operation; Sale	Materials identification	First sale to IAEA
DD-109	10^9	In fabrication; Sale	materials identification	Sold to Heliocentric
DT-111	10^{11}	In fabrication; Sale	materials identification	Uses DT reaction, Sold to KSU

*Prototypes fabricated under this contract

1.2. Benefits

These generators produce a high yield of neutrons using the safe deuterium-deuterium reaction and an active pumping method wherein the deuterium is continually replenished to maintain continuous operation with no loss of neutron yield over many thousands of hours of operation. Other generators currently available on the market use radioactive tritium gas, are sealed, and have a lifetime of less than 1000 hours.

Advantages of using the RF-induction method compared to other types of discharge, like the penning and filament discharge, are (1) its ability to generate high plasma densities for a high intensity ion beam production, (2) its ability to generate a high percentage of atomic ion species, and (3) its long lifetime operation. A high atomic ion species fraction is important for the overall efficiency of the neutron generator. Neutron output increases by a factor of 3-4 if one uses a 100% atomic ion beam in comparison to a 100% molecular ion beam. The RF-induction discharge generates more than 95% of atomic ion species at about 2 kW of discharge power.

When the fast neutrons are moderated as we have done, the neutron generator mimics a research nuclear reactor, but is much less expensive and compact. Adelphi has enclosed three of their generators in polyethylene blocks and other moderating and neutron-absorbing materials. The moderated generator (DD-108-T) has an access port for the irradiation of materials. We have used these generators to identify materials using Prompt Gamma Neutron Activation Analysis (PGNAA) and Neutron Activation Analysis (NAA).

1.3. Commercialization Successes

We are actively pursuing the commercialization of the neutron generators developed under this STTR with LBNL. These generators have wide application in neutron radiography, homeland security, material identification and radiotherapy. We are currently fabricating three generators for customers. Sales have been made to International Atomic Energy Agency (IAEA), Kansas State University (KSU), and Heliocentric Inc. We are also in negotiation with Heliocentric Inc. for the distribution rights for these generators in the mining industry for materials identification.

The generator sold to the IAEA will be installed at the Centre National Des Sciences et Technologies Nucleaires (CNSTN) in Tunis Tunisia. Under its directive from United Nations, IAEA is making available neutron generators for non-reactor-based nuclear physics programs in developing countries. Adelphi will be participating in just such a program by this sale to IAEA and will be involved in the installation of the generator in Tunisia and has already trained a CNSTN graduate student to operate the generator. The model DD-110 generator will boast a yield of 10^{10} n/s, three orders of magnitude greater than the present commercially available technology. The generator has been assembled, tested and is currently being improved for delivery at CNSTN in November 2008.

Large volume sales are expected from collaboration with CMS Technology Inc. of Korea and the Lawrence Livermore National Laboratory (LLNL), who are collaborating in the identification of industrial material components. Adelphi has supplied these two institutions with neutron beam time and helped with the NAA identification of components of a proprietary material used in the mass production of a consumer product. Another possibility of large volume sales is with Heliocentric Inc. of Canada, who wish to develop a neutron generator capable of PGNAA analysis of mining materials. They have developed a business plan for this market that includes a minimum sale of 50 generators per year. They have purchased from Adelphi a model DD-109 which is now under construction and will act as prototype for their application.

Our prototype generator is also being considered for the homeland security system being developed by Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO) for use in examining the contents of air cargo containers and luggage. Their program has been very successful and

is being considered for US airports. In June 2007 CSIRO personnel tested their detection electronics with Adelphi's neutron generator and measured the generator's yield. Their research has demonstrated the usefulness of fast neutrons for radiographic imaging, which can be adapted to industrial and power plant imaging.

1.4. Research and Development Successes

Under the program Adelphi and LBNL developed self-contained neutron generators that have their high voltage and RF power safely and ruggedly contained in a stainless steel housing. Previous generators developed at LBNL did not have this important feature that is necessary for commercial sale. We also developed techniques to increase the neutron yield by factors of up to 100X over those previous obtained by LBNL prototypes.

Under the program and beyond its original goals, we developed a new RF plasma source with a spiral antenna that gives higher efficiency production of ion species at lower gas pressures. Not only will this improve the efficiency of the device, but it will also allow us to use the D-T reaction, increasing the yield by two orders of magnitude. By operating at low gas pressures, we can completely seal the generator tube and use the radioactive gas tritium to operate the generator. This permits a whole host of other applications in both materials identification and homeland security.

A thermal-neutron generator that integrates a moderator around the fast neutron source was also fabricated. The moderator acts as both conventional moderator and mechanical and electrical support structure for the generator. This thermal neutron source can be used for thermal neutron radiography, neutron activation analysis (NAA) and prompt gamma neutron activation analysis (PGNAA).

2. Comparison of Accomplishments with Goals

2.1. Completion of Technical Objectives

The construction of the commercial prototype generators was the main objective of our Phase II effort. In this we were completely successful. Under this program we fabricated both a thermal and a fast neutron generator. Using these generators we began taking images of mechanical components using fast neutrons. This brings a completely new radiographic technique to compliment and enhance existing x-ray and thermal neutron methods.

We successfully completed most of our goals. We briefly discuss each goal.

2.2.1. Goal 1. Design and fabricate a compact RF matching network that can be made an integral part of the RFI-neutron generator head.

We completed this goal. The RF matching box is a key component of the neutron generator. We designed and fabricated two RF matching networks. LBNL first designed these matching networks and it is part of the intellectual property that Adelphi has obtained. For the case of the thermal neutron generator, we made the RF matching box integral to the generator. In our second generation design we reduced the cost and size of the components.

2.2.2. Goal 2. Based on our Phase I designs, fabricate fast neutron generator head. Purchase the 13.56 MHz, 3 kW RF Power supply and the 100 kV, 1 kW, DC Power supply. Assemble fast neutron generator head.

We completed all the tasks of this goal. We fabricated both the fast neutron DD-109 generator and the thermal neutron DD-108-T generator heads. These are shown in Figs. 3a,b and 6a,b,c. We purchased all the components and assembled them into standard racks. The Glassman HV power supply was at a higher power (120 KV at 4 kW) than the original selection. A diagram of the DD-109 system is shown in Figs. 4a,b, below.

2.2.3. Goal 3. Assemble generator system and install neutron source at the test chamber in Area 52 at LBNL. Test system for high voltage breakdown and cooling water and gas leaks.

We and our colleagues at LBNL completed all tasks of this goal. We assembled the DD-109 imaging generator at the test chamber in Area 52 at LBNL. At the time LBNL could not operate the generator with deuterium because of issues regarding radioactivity safety in the laboratory. LBNL tested the system for high voltage breakdown and cooling water leaks and gas leaks at LBNL. They also tested the RF plasma ion source measuring the ion species content of the beam. We then fabricated and built the generator's complete support system at Adelphi. This system was designed to be computer controlled. We developed software to operate the generators. LBNL also developed of a new RF plasma source using a flat spiral antenna. Two versions were fabricated and tested at LBNL. The spiral source has several advantages over that of the helical source. The source can operate at lower pressures and lower RF powers while obtaining the same ion beam current.

2.2.4. Goal 4. Measure the emission rate of the neutron generator in fast neutron mode. Using the ^{115}In neutron activation technique, measure the fast neutron flux. Correct for the back-scattered fast neutrons, by performing a MCNP (Monte Carlo n-Particles) model to calculate the neutron flux to neutron yield conversion ratio.

We measured the emission rate of the neutron generators using two methods. We used a Ludlum model 12-4 Neutron Detector and also the thin foil ^{115}In neutron activation technique. We also had outside groups measure the yield. The DD-108 generator was measured to have from 2×10^7 to 1×10^8 n/sec and the DD-109 was measured to have a 2×10^9 n/sec maximum yield.

2.2.5. Goal 5. Based on Phase I detector research and development, fabricate fast neutron detectors using capillary scintillators, tapered fiber optic and electronically cooled CCD detector.

We developed early detectors using CCD cameras, fiber optics and scintillators. We found that a Stanford Photonics CCD camera with MCP light amplifier and a thin plastic scintillator gave the best images using fast neutrons from the DD-109 neutron generator. In the last months of the program, images with this camera were obtained of various mechanical objects such as pipe fittings and metal tools. Higher quality images are expected when the conical target is used.

2.2.6. Goal 6. Fabricate a neutron radiation enclosure capable of permitting test imaging at ATI.

We developed compact moderators and shielding for all our generators. This required shielding for the x-rays generated from the back-streaming electrons (70 to 120 keV), for the γ -ray emission from neutron interaction mechanisms (0.5 to 10 MeV), and for the thermal and fast neutron emission from the primary D-D fusion event (0 to 2.5 MeV). We used a combination of Pb and Polyethylene shielding. This is shown in several of the figures below (Figs. 3b, 4a, 5b 6b,c).

2.2.7. Goal 7. Fabricate various phantoms for testing fast neutron imaging. Image these phantoms using the fast neutron generator at the new ATI neutron-radiation chamber.

We and our collaborators imaged a number of phantoms using both thermal and fast neutrons. We have done imaging with two sets of cameras developed by us and our colleagues. We have achieved fast neutron images of various mechanical objects (e.g. Figs. 7,8,9).

2.3. Supplemental funding Goals.

2.3.1. Goal 1 – Fabricate the thermal neutron generator with support power and cooling systems.

We completed this task. A complete thermal neutron generator was fabricated (Fig. 6). It combined the function of moderator and HV support into one generator.

2.3.2. Goal 2 - Measure the emission rate from the thermal-neutron generator using the ^{198}Ag neutron-activation technique and measure the thermal neutron flux. Demonstrate the ability to image using phantoms and available corroded aluminum components. Compare with images obtained using MNRC reactor.

We have not measured the thermal neutron flux using the activation technique. However, we measured the thermal neutron flux using the Ludlum Neutron Detector, model 12-4. We activated various foils to demonstrate the ability of these sources to be used in material identification. We have used the DD-109 extensively in Neutron activation analysis (NAA) and Prompt Gamma Neutron Activation Analysis (PGNAA) of materials.

2.2.3. Goal 3 - Complete fabrication of the 10^9 n/s generator and install vacuum system to recirculate deuterium gas.

We completed the fabrication of the DD-109 generator and measured its yield, which exceeded the expected yield by a factor of 2 X. Please see below and Fig. 3. We have not yet recycled the deuterium gas inside the generator to minimize the amount of deuterium used.

2.3.4. Goal 4 - Design a generator to operate with Tritium gas.

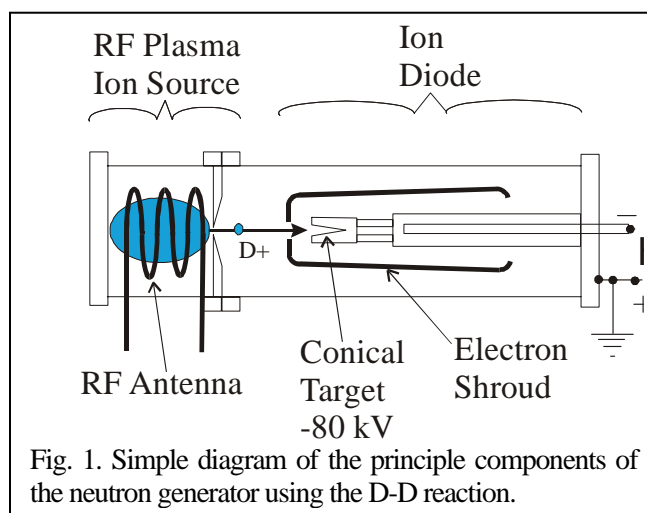
We have developed several designs for a DT generator using two plasma sources. Based on this design we are currently fabricating a DT source for Kansas State University. The external shell and the new ECR plasma source have been fabricated. We have also completed our research on the safe use of tritium gas. With LBNL we have also developed an inexpensive plasma ion source to operate with a sealed system and tritium. This source uses the electron cyclotron resonance effect to develop the plasma.

3. Summarized Project Activities for the Entire Period

3.1. Machine operation

Based on the research and development of this STTR program, Adelphi now fabricates and sells a range of D-D neutron generators capable of fast neutron outputs from 10^8 to 10^{10} n/s. Four of the generators are illustrated and pictured in Figs.1-4.

These neutron sources employ plasmas generated by inductively coupled RF radiation to supply the deuterium ions. The main characteristics of this type of ion source are its high current density, $j \sim 100 \text{ mA/cm}^2$ at 3 kW of discharge power, and high atomic species, the H^+ fraction $> 90\%$ at RF power $\sim 1 \text{ kW}$. The ionized deuterium in the plasma is released into an acceleration chamber through an aperture in the wall of the plasma chamber. The size of this aperture determines the maximum beam current and, ultimately, the neutron flux of the device. The ions are accelerated and focused onto a titanium target where the deuterium ions collide, resulting in a nuclear fusion reaction that creates ^3He and a 2.5 MeV neutron. The RF-discharge yields a high fraction of monoatomic ion species in the ion beam. The ions are then accelerated to an energy of $\sim 100 \text{ keV}$ or higher to impinge onto a titanium coated copper or aluminum target where 2.45-MeV D-D, neutrons are generated through fusion reactions. Yields from 10^8 n/s to 2×10^9 n/s have been obtained under this program.



Key developments included automating the control of the system, improving beam optics and increasing the lifetime and reliability of the system. An important output of the STTR was the design and construction of the thermal neutron generator (DD-108-T).

As shown in Fig. 1, these generators are simple diodes with a RF plasma source that generates the D^+ ions that are then accelerated across a potential of ~ 100 kV to a titanium target. The main components of the generator are the (i.) *RFI plasma ion source*, (ii.) *accelerator diode*, (iii.) *conical target* and (iv.) *moderator*. These components are illustrated in Fig. 1. The (i) RFI plasma source produces deuterium ions that are (ii) accelerated across a diode structure to a (iii) Ti conical target, where the deuterium-deuterium reaction occurs, releasing fast neutrons (2.5 MeV). These neutrons are then slowed up in a (iv) moderator composed of water, which also functions to cool the conical target.

The plasma source uses a 13.56-MHz RF discharge to produce deuterium ions. Ions generated in the plasma source are accelerated toward the target using an electric field generated by biasing the target to highly negative potential. The negative potential will then ‘attract’ the positively charged particles to the target. After the ions are accelerated, they are impinged onto a target made of copper in which a thin layer of titanium is deposited. The implanted hydrogen ions form titanium hydrates in the titanium matrix, thus ‘trapping’ the deuterium atoms into the matrix. When the generator is operating, the titanium layer is initially being loaded with deuterium and the neutron output is increasing with time; then after some minutes of operation the target is loaded by the incoming ions and the neutron output saturates to a stable level. While the ions are implanted to the target, heat is also deposited to the target, which is removed by water-cooling.

A key innovation of the generator is the RF plasma D^+ ion generator. Previously, these sources were used in neutron generators with only moderate success. The prior RFI-plasma generators were made of quartz, and, although quartz is an excellent dielectric material, its heat conductivity is poor. Thus these sources were limited in operation power and were used only in a low duty cycle, pulsed mode. Our generator uses an alumina (Al_2O_3) discharge chamber that is actively water-cooled and, thus, can operate reliably in cw mode with more

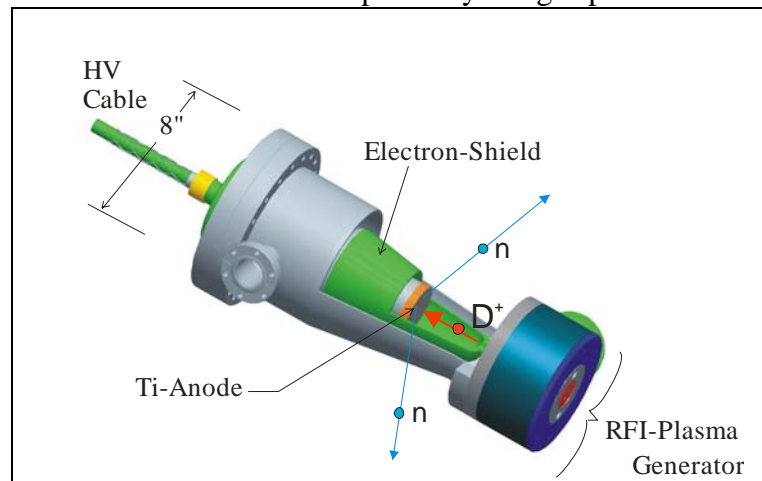


Fig. 2a. The Model DD-108 prototype fast neutron generator.

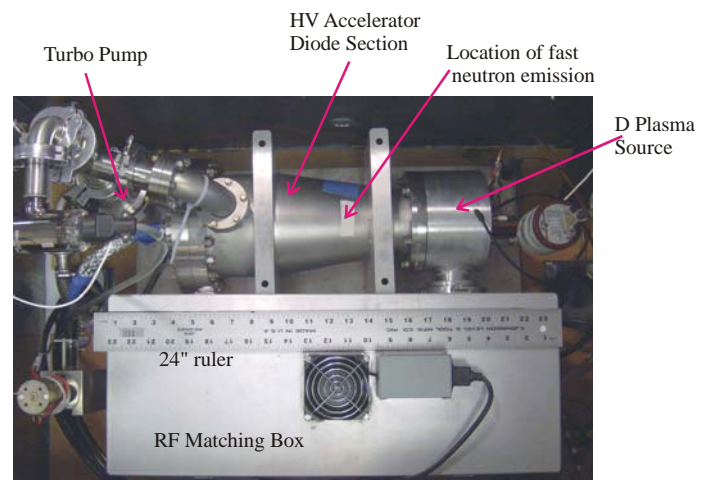


Fig. 2b. The DD-108 installed with supporting RF matching box and turbo pump.

than 3 kW of discharge power. The main characteristics of this type of ion source are its high current density, $j \sim 100 \text{ mA/cm}^2$ at 3 kW of discharge power, and high atomic species, the H^+ fraction $> 90\%$ at RF power $\sim 1 \text{ kW}$.

3.2. Adelphi's New Commercial Generators

Based on the core technology developed at LBNL and under this DOE grant, Adelphi now produces a product line of three fast-neutron generators, the Models DD-108, DD-109 and DD-110 each respectively producing 10^8 , 10^9 and 10^{10} fast neutrons per second. In addition, Adelphi has built a neutron generator specialized for the production of thermal neutrons for both prompt and delayed gamma neutron activation studies. These generators evolved from work sponsored by the Department of Energy to develop a source for non-destructive testing at nuclear power plants. The generators use the deuterium-deuterium (D-D) fusion reaction to produce 2.5 MeV neutrons and can be operated either in continuous-duty or pulsed mode. Brief descriptions of the four generators are given as follows:

3.2.a The Model DD-108 Generator

Adelphi and LBNL designed their first prototype tube to yield 10^8 n/sec . For safety of the operator, this tube was designed to have its high voltage and RF power internal to the tube. This was a major change from the early DD reaction generators created by LBNL which had the HV and the RF plasma source exposed. The DD-108 has a 2-mm diameter plasma extraction aperture which limits the ion current to 2 mA at 90 KV. This produces yields of $\sim 10^8 \text{ n/s}$. Three outside collaborators measured the yield of the generator. Yields between 2×10^7 to 1×10^8 were measured.

The target was a flat Ti-coated copper disc that was water cooled. Using imaging techniques, the neutron spot size was found to be 7-mm in diameter, which is well suited to radiography applications. In operation, one of our users, CSIRO, found "the generator to be stable and reliable."

3.2.b. The Model DD-109 Generator

Our most successful generator to date is the DD-109, which performed well beyond its design. It has operated in a stable and reliable manner since February 2008. The DD-109 has a 4-mm diameter plasma extraction aperture which limits the ion current to 12 mA at 120 KV. The tube was designed to yield 10^9 n/sec , but performed beyond our expectations, yielding $2 \times 10^9 \text{ n/sec}$.

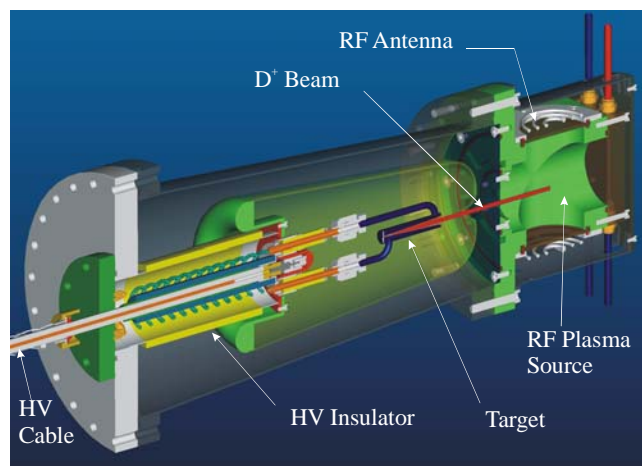


Fig. 3a. The DD-109 Fast neutron Generator.

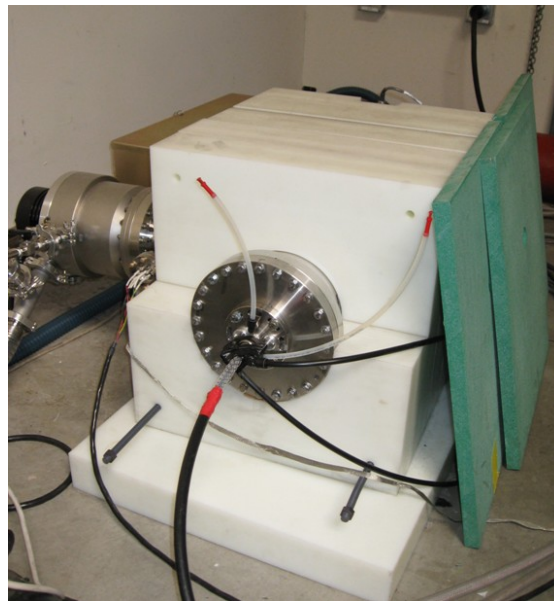


Fig. 3b. The generator head housed inside a polyethylene moderator and shield.

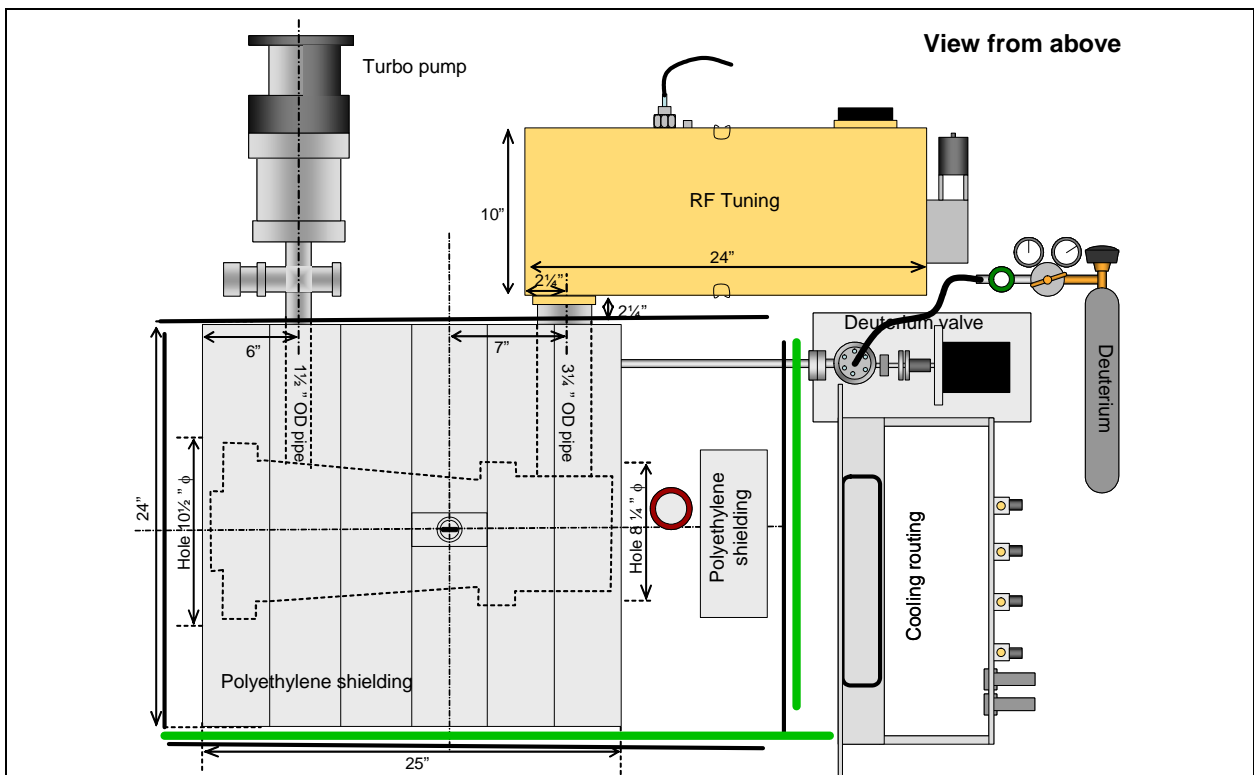
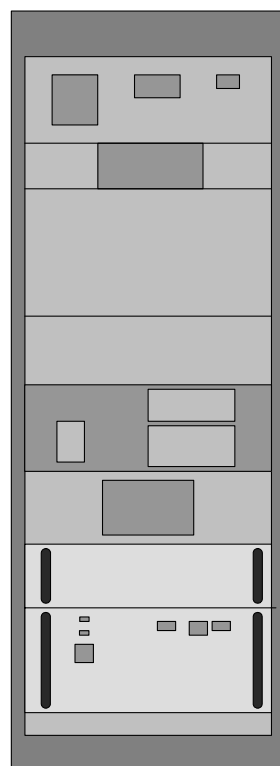


Fig. 4.a. The DD-109 enclosed in its polyethylene shield and surrounded by its support system of cooling water and deuterium gas delivery system.

Rack of electronics



Scale: 24"

Chiller

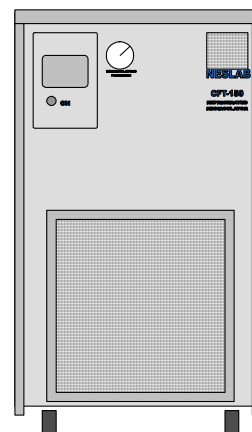


Fig. 4.b. The supporting power supply and chiller.

A section view of the generator is shown in Fig. 3a. As in the other DD-series generators,

water cooling to the target is brought up inside a high voltage column. The water lines spiral around the high voltage cable, allowing a high resistance path to the target. This permits cooling to the target without possible high voltage breakdown.

The DD-109 generator was primarily designed to be a radiographic imaging tube. To keep the apparent spot size small, and thus minimize blurring, a conical target was fabricated. When viewed along the axis of the generator, the neutrons appear to be emanating from a 5-mm diameter spot. As in x-ray radiography, the blur, Δs , on the film plane caused by the finite source dimension, D , is given by $(D/L)i$, where i is the distance from the object to the image (film) plane and L is the distance from the source to the object. The " L/D " is a standard yardstick for discussing the merits of the neutron or x-ray source. Small D 's permit the film or detector to be close to the generator and maintain a high flux at the detector, resulting in short exposure times. The DD-109 conical target was designed to permit high ion beam currents with a small apparent source size.

For other applications (e.g. PGNAA and NAA) the generator is easily opened and the target can be replaced with other target geometries. We have made two other targets. These are a "V"-shaped target and a water cooled target surrounded by a polyethylene ring. The "V" target permits high current operation and is inexpensive to fabricate compared to the conical target. We have used this target in all our preliminary experiments. The second target is surrounded by a polyethylene ring. The polyethylene ring permits immediate moderation of the fast neutrons. All targets are Ti-coated copper.

3.2.c. The Model DD-110 Generator

A high-yield D-D generator capable of 10^{10} n/s (Model DD-110) has been designed and fabricated by Adelphi for the International Atomic Energy Agency (IAEA). It is scheduled to be delivered to the Centre National Des Sciences et Technologies Nucleaires (CNSTN) in Tunis Tunisia in December 2008. This generator is similar to the other two models, in that its ion beam is axial and its HV and RF voltages are safely contained in the generator housing. The generators produce a high yield of neutrons using the safe deuterium-deuterium reaction and the active pumping method, wherein the deuterium is continually replenished to maintain continuous operation with no loss of neutron yield over many thousands of hours of operation.

Unlike the lower yield generators, the DD-110 uses a rectangular ion beam that is designed to fit the aperture of the "V" target. The beam measures 2 mm x 30 mm at the exit aperture of the plasma source, resulting in beam currents as high as 55 mA to be delivered at the target. At 120 KV, the beam power is 6

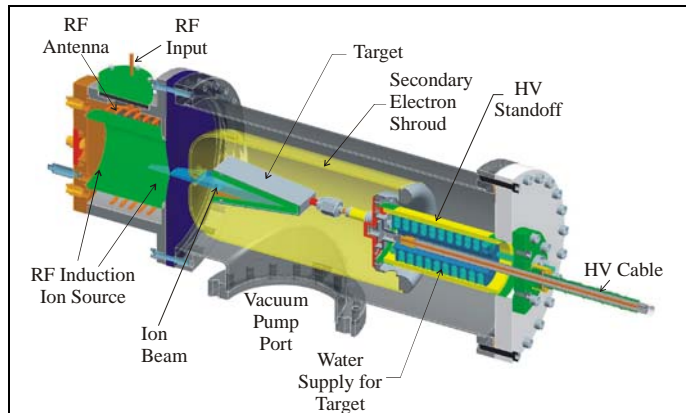


Fig. 5.a. The model DD-110 generator fabricated by Adelphi for IAEA. This generator is expected to achieve 10^{10} n/sec.

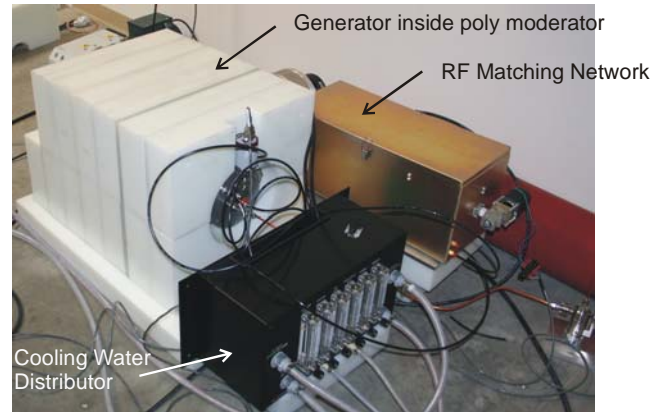


Fig. 5.b. The DD-110 surrounded by its support systems and enclosed in a polyethylene moderator.

kW and the expected yield is calculated to be 10^{10} n/s. As of this writing, the generator has been assembled and tested with yields of 2×10^9 n/s measured. The 10^{10} n/s yield is probably the highest attainable yield for a single beam D-D reaction generator.

The diagram of the generator is shown in Fig. 5a surrounded by its support systems and enclosed in a polyethylene moderator in Fig. 5b. As can be seen, the generator closely resembles the DD-109 and DD-108 generators. Since the large “V”-shaped target must handle greater ion beam power, a larger volume of water must be delivered to the target. Two 5/16”-diameter double-helix hoses deliver the water to the target, while a 6 KW Spellman HV supply delivers the 120 KV, 55 mA to the generator. The generator is housed in a polyethylene moderator; a RF-matching box is used to maximize the RF power to the plasma source; and a water distribution box directs cooling water to the generator target, plasma source, and plasma exit iris.

3.2.d. The Model DD-108-T Generator

Adelphi fabricated a thermal neutron generator composed of a D-D reaction fast neutron generator integrated with a compact moderator. The moderator, composed primarily of polyethylene, provides not only for the thermalization of the neutrons, but also for the structural support and the HV insulation of the generator. Other functions, including target cooling and active pumping of the deuterium gas, also take place within the moderator block. (see Figs. 6a,b,c). For example, cooling water is piped into the moderator to the conical target and fast neutron radiator. The water both cools and moderates the fast neutrons. The thermal source resembles a block of polyethylene and can be placed in any laboratory setting for active radiographic imaging of objects.

The small compact moderator permits us to maximize the brightness and modify the neutron spectrum for optimum imaging of specified components and munitions. Reactors, in comparison, are large and generate neutron spectra that are not necessarily optimized for penetrating the object or for producing the best image quality and resolution. Our neutron source spectrum (wavelength and bandwidth) can be optimized for the particular application. We can do this by selecting its mean neutron energy through proper design of the moderator. This is accomplished by our previously developed moderator-design program. The moderator is very small compared to ordinary reactor moderators because our fast neutrons are produced in a small volume (conical target). The moderator is located close to this small volume source, limiting the moderator’s size but improving its efficiency for producing thermal neutrons. To increase the thermal neutron yield and meet the desired image quality suggested by the solicitation, we have added a graphite reflector and a unique beam shaping aperture (BSA). These changes will increase the overall thermal flux by a factor of 2 X to 4 X. We will also increase the yield of the fast neutron generator by an order of magnitude.

With these improvements we calculate that we should achieve sensitivities and resolutions on the order of 0.25% for imaging times between 5 to 30 minutes depending upon the materials being imaged. Such a neutron radiographic system would be highly complementary to present x-ray radiographic capabilities. Indeed, it would permit imaging of objects that are inaccessible to x-rays (e.g. corrosion in aluminum)

A sectioned view of the existing thermal neutron generator is shown in Fig. 6a. Most of the generator support structure is modular and is composed of polyethylene, which functions as the moderator, support structure and high-voltage protection for the generator. Supported in the interior of the moderator is an RF induction-Plasma neutron generator¹ with a single target axial geometry. At the end of the column is a conical target suspended in the cooling water supplied via entrance and exit spiral tubing. Water-cooling around the fast neutron's conical target permits immediate moderation of the fast neutrons. The high-resistance cooling water at the target is at -120KV, and, thus, helical coils of plastic tubing are used to supply the cooling water with little current loss.

The moderator achieves its compactness by being designed into the structure of the fast neutron tube. By elastic scattering of the fast neutrons (2.5 MeV) in both water and polyethylene, the speed of the neutrons is reduced to thermal energies. The water functions both to cool the conical target and to immediately start moderating the fast neutrons. Further moderation occurs with the polyethylene surrounding the entire structure. The polyethylene both moderates and forms the support structure for the entire tube. Thus by moderating the fast neutrons as soon as they are emitted and having dual functions in many of the components of the tube, we are able to minimize the size of the thermal neutron source. The fast neutrons need only travel a few cms before they lose half their energy to the hydrogen molecules in the water. This results in a device that is portable and several orders of magnitude smaller than its only other competitor, the nuclear reactor. The conical anode is suspended in water that both cools it and immediately starts moderating the neutrons.

3.3. Other R&D: Spiral Antenna Coupling

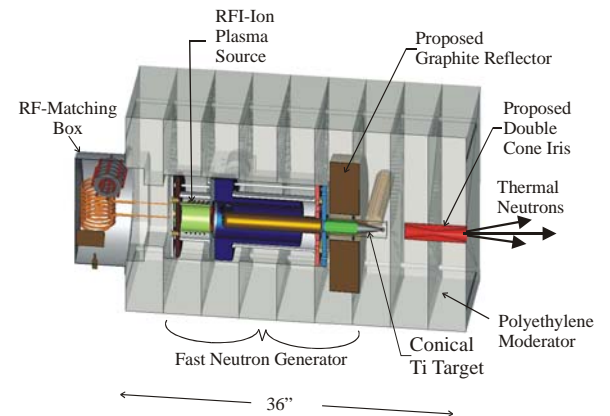


Fig. 6.a. The thermal neutron generator (DD-108-T) as fabricated by Adelphi. The fast neutron generator is integrated with a moderator and shielding structure. Water surrounding the D-ion target both cools and starts the moderation of the fast neutrons.

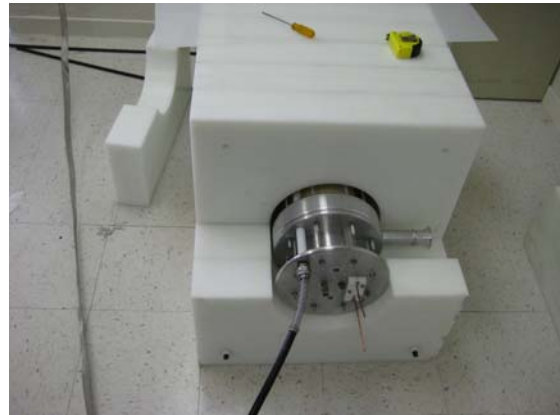


Fig. 6.b. The fast neutron source being assembled into the thermal neutron moderator.

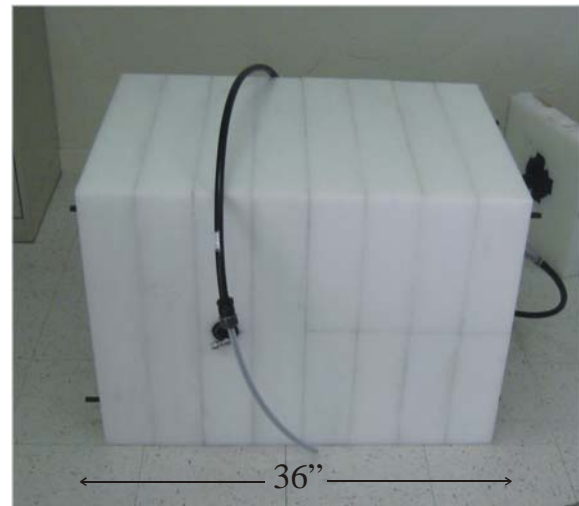


Fig. 6.c. The assembled thermal neutron generator.

¹ "RF-Induction Plasma neutron generator" will be abbreviated to "RFI neutron generator."

Another innovation is that the RF antenna is outside the plasma. This minimizes the possible loss of tritium and its mixing with the cooling water. Two RFI D-ion sources have been developed for the axial generators, one with (1) a solenoid-antenna coupling and another with (2) spiral-antenna coupling. In both cases, the RF power is coupled by an antenna that resides outside the plasma chamber. The RF is coupled either through a ceramic cylinder or through a dielectric window. Having the antenna outside the plasma chamber prevents corrosion of the antenna, which occurred previously even when it was dielectrically coated. In previous internal antenna designs, water leakage could occur since water was being recirculated inside the antenna. Water contamination would be particularly dangerous if radioactive tritium gas were being used and, if a leak occurred, absorbed into the water.

Tritium is a radioactive gas. There are certain safety precautions one has to take into account when tritium gas is used for a D-T fusion reaction based neutron generator. The most important of these is to design a system that does not allow tritium to be mixed with water or to be released to the atmosphere. Two of the most critical design areas are the RF-induction antenna window and the ion source cooling. The RF-window for D-T applications will be a sapphire disk oven brazed to a molybdenum frame, which is water-cooled to minimize the inductive heat-load. The antenna is wound in the shape of a spiral (Figs. 5 and 6). The spiral antenna has proven to be an efficient way of coupling RF-energy into plasma. In this context the high efficiency means low operation gas pressure, high atomic hydrogen and hydrogen-type gas atomic species fraction, and high output current density while operated at low RF-discharge power. This allows a design and fabrication of a sealed D-T or T-T neutron generator that has extremely high efficiency.

The spiral antenna design produces high ion current density at low RF-input power. The use of low input power lowers the cooling requirement of the windows. The spiral antenna also allows operation at low gas pressure. This is an important feature for sealed tube neutron generators using the D-T reaction. The lower the operational pressure of the source, the more reliable the high voltage holding at the target section of the generator. With a properly designed electrode structure, the accelerator system is stable at an operating pressure of less than 10 mTorr. The spiral antenna has also been shown to provide good ion species distribution. A typical atomic species fraction from an ion source is >80%. The more atomic-ion species are present in the plasma, the more efficient the neutron generator is.

3.4. Fast Neutron Imaging.

3.4.a. Introduction

Fast neutron imaging detectors up to the present have been constructed by only a few national labs and universities for specific applications such as the fast neutron imaging of imploding DT fusion pellets. Neutron radiography has traditionally been thermal neutron radiography, with many laboratories employing commercially based thermal neutron imaging systems based on film such as Kodak SR film, boron-doped microchannel plates (Nova Scientific), or the Fuji Film Gd-based photo-stimulable phosphor.

Presently, there are no established commercial vendors of high resolution, fast neutron imaging systems. Saint Gobain Crystals of Newbury, Ohio sells fast neutron Bicon scintillators and Bicon solid plastic scintillator fiber arrays with square fibers as small as 250 x 250 microns. However, for better resolution one requires liquid-scintillant-filled capillary arrays, which can have as small as 85 μm pixels. The liquid scintillant capillaries act as light guides, and are thus a pixilated fast neutron detector. Adelphi has tested a 1.5 inch x 1.5 inch x 5 cm thick capillary array. In addition Adelphi has tested a Bicon scintillant fiber array, another pixilated fast neutron detector, which is a 1" x 1" square bundle of 500 μm x 500 μm x 5 cm long plastic fibers, which act as light guides. The simplicity and lower cost of the Bicon solid fiber array provides Adelphi with a fast neutron imaging system quicker-to-market than the hollow, liquid scintillant filled capillary arrays. The actual resolution of the capillary arrays may be reduced from

its 85 micron pore diameter to the resolution of the solid fiber arrays, due to light production by a single neutron in 2 or more adjacent capillaries.

3.4. CSIRO Imaging Detector using the DD-108 Generator

CSIRO and Adelphi collaborated on making a low resolution fast neutron imaging array with the CSIRO Neutron Block Detector and the Adelphi DD neutron generator. This is a modified block detector used in PET scans. The imaging module comprises a 10×10 array of plastic scintillators that are read-out using 4 photomultiplier (PM) tubes. Auger camera logic is used to reconstruct the neutron interaction position on an event-by-event basis. A flat-field image is acquired first with no object in between the source and detector. The object to be imaged is then inserted and a second image taken. The ratio between the two images provides a measure of the neutron attenuation. The unique ratio of the light intensities in the 4 PM tubes determines which plastic scintillator pixel is emitting light. Hence 4 PM tubes and 64 pixels provide a resolution equal to the surface area of the plastic scintillant pixel.

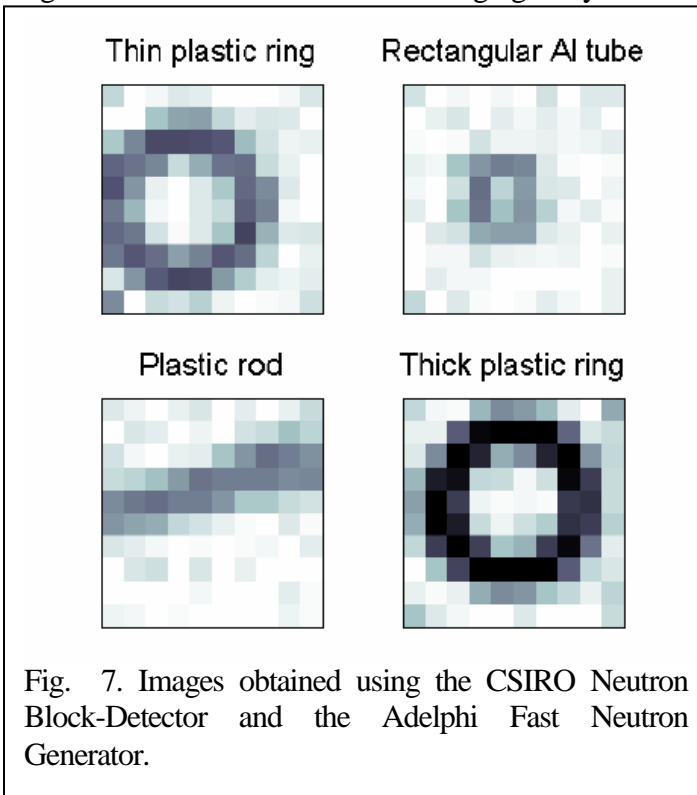


Fig. 7. Images obtained using the CSIRO Neutron Block-Detector and the Adelphi Fast Neutron Generator.

We imaged various pieces made of plastic and aluminum (thin plastic ring, rectangular Al tube, plastic rod and thick plastic ring, see Fig. 7). The images nicely demonstrate the performance of a single imaging module. In a practical scanning system, a large number of modules would be used together to provide a composite, high-resolution image of cargo and luggage items.

3.5. Adelphi's Fast Neutron Imaging Camera

Adelphi developed a fast neutron imaging camera (FNIC) under an NSF SBIR program, which we are using to successfully demonstrate the ability of our generators to image high density objects using fast neutrons. The detector consists primarily of a cooled CCD camera, a multichannel plate (MCP) light amplifier and a thin plastic scintillator.

The CCD camera is a Stanford Photonics XR/Mega-10Z CCD camera, which is a Peltier-cooled, GEN III CCD camera with an installed low noise, high gain dual MCP light amplifier and a 10-micron, mega-pixel resolution. This camera allows true photon limited imaging, in which the dark counts are virtually limited by photocathode cooling that allows integrated imaging times of up to 60 sec. with a 40-50% quantum efficiency, and light gains of 1 million via its dual multi-channel plate. Acquisition times ranging from minutes to hours are easily accomplished by adding 30 sec. integrated images. Each image is created by summing 450 frames, each a 66 ms exposure. The short frame times reduce the dark noise accumulation to 1 or 2 dark counts per frame, and the Piper software for camera control, image acquisition, and image signal processing further reduces noise by filtering out cosmic ray noise and spot noise from each of the incoming 66 ms frames. The 66 ms frames are integrated to produce a 30 sec.

image. These can then be added to produce images with equivalent exposure times of several hours. The camera has a controller, chiller and power supply, and is enclosed in a light-tight camera box.

The camera box allows the camera to be placed outside the neutron beam to prevent radiation damage to the camera. The camera is mounted inside in the top portion of the box, and the 10 cm x 10 cm area scintillator is attached to the inner surface of a removable plate at the base of the box. Inside the light-tight box the light emitted from the scintillator is turned 90 degrees by the mirror and focused by a large diameter lens (f -stop = 1.0) onto an dual micro-channel plate (MCP) image intensifier, which is a light amplifier with high gain – up to 1 million gain with low noise – 1 to 2 dark counts per frame. The light emitted from the MCP illuminates a bright phosphor that is imaged onto the CCD chip via a 1.6:1 tapered fiber optic. The effective resolution at the input plane of the Stanford Photonics camera is 10.35 microns. However, the neutron image resolution is limited by the thin sheet plastic scintillator thickness or alternatively by the pixel dimensions of the individual fibers of the plastic scintillator fiber array.

With the new, more powerful Adelphi DD-109 neutron generator, we found we could obtain better neutron images with a 10 cm x 10 cm x 1 mm or x 2 mm thick Bicron BC-408 plastic scintillator used in place of the Bicron BCF-20 fiber array scintillator. The success of the thin plastic scintillator in place of fiber scintillator arrays is an important result. The use of these thin, large area scintillant sheets greatly reduces the cost of the fast neutron imaging system in that high resolution (0.5 to 1.0 mm) images. Large area arrays are thus possible at relatively low cost and with simplicity, and yet can produce images of good contrast, sensitivity, and resolution.

The scintillator sheet is attached to the inside surface of the input plate of the neutron camera box. The relatively thin scintillator sheet is insensitive to thermal neutrons and high energy gammas. To stop low energy gammas and x-rays a 5 mm thick lead sheet is placed over the neutron aperture to stop the 80 to 120 KeV bremsstrahlung x-rays that are produced by the deuteron beam bombardment of the fusion target. There is only minor fast neutron scattering as the neutrons pass through the gamma/x-ray filter lead sheet.

The neutron-source size for determining resolution is somewhat complicated since the target is “V” shaped in our experiments. The DD neutrons emerge from a 1.9 cm vertical x 3.8 cm horizontal source aperture and pass through the 5 mm thick lead sheet, which is 34 cm from the source. The sample, which is attached to the outer surface of the camera box, is placed at two different distances from the source 50 cm and 126 cm. The vertical L/D is 25 and 63, and the horizontal L/D is 12.5 to 31.5. The expected resolution is primarily the product of the divergence of the neutron beam D/L with the object thickness t , or $\sigma = tD/L$. Thus the resolution of a 10 mm thick object is less than 1 mm in both the vertical and horizontal directions for these $L/D > 10$.

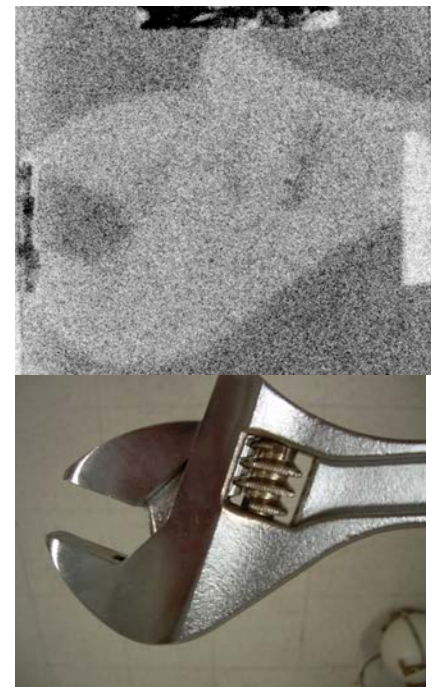


Fig. 8. A pixel-inverted fast-neutron image of wrench with photos of crescent wrench using the Adelphi DD-109 neutron generator. Collection time was 10 min. Distance from source to detector was 126 cm.

We took two images using two different scintillator thicknesses (1 and 2 mm) at two different distances ($L = 50$ and 126 cm). The neutron image of an adjustable wrench in Fig. 8 was obtained in 10 minutes. The DD generator was operated at a yield of 3×10^8 n/s with a source to detector distance of $L = 126$ cm and a scintillator thickness of 2-mm. This image is pixel-inverted so that darker corresponds to more neutron transmission and lighter corresponds to less neutron transmission. Fig. 9 shows the fast neutron image of a brass T-joint pipe half-filled with water. The source to detector distance was $L = 50$ cm and the scintillator thickness was 1 mm. This neutron image was obtained in 30 minute exposure with the generator producing a yield of 3×10^8 n/s. Again, the neutron image in Fig. 9 is pixel-inverted so that darker corresponds to more neutron transmission and lighter corresponds to less neutron transmission. The water appears as the white bottom horizontal layer, while the dark band above is air. The brass walls of the pipe and the water, which both attenuate neutrons compared to air, appear white, and the air appears dark. Inspection of two image showed that the 2 mm thick scintillator sheet created the shortest exposure time, higher resolution, and better contrast neutron image of the half-water-filled brass T fitting.

These are preliminary imagines using our new fast neutron imaging camera (FNIC) developed under the NSF SBIR program, which is still in progress. The radiographic system combines two new technologies: the plasma driven fast neutron source, developed under this DOE STTR, and the FNIC. We expect to improve image resolution by reducing the source size and improve image contrast by optimizing the camera's parameters (e.g. scintillator thickness). Originally the DD-109 had a conical Ti target for minimize the apparent source size ($D = 6$ mm) along the axis of the generator. Unfortunately, the target leaked and had to be replaced with a "V" shaped target, which had larger apparent surface area, making the source rectangular and larger ($\sim 6 \times 12$ mm²) in the direction of the camera. We have another design that tilts the target in only one plane, increasing the surface area, but when viewed at the proper angle still gives a small source size. We also will use the DD-109 to imagine higher density objects.

4.0 Summary

In summary, Adelphi and LBNL have developed a series of high yield neutron generators that have immediate commercial application. The DD-109 and DD-108 generators have been successfully used for up to 2000 hrs without major servicing. As one important application, we have demonstrated fast neutron imaging of high density objects, achieving contrasting images with it and hydrogen containing materials (e.g. H₂O). We have also demonstrated that the generators can be used for materials identification using Prompt Gamma Neutron Activation Analysis (PGNAA) and Neutron Activation Analysis (NAA). Two generators are being fabricated for sales, and the existing generators

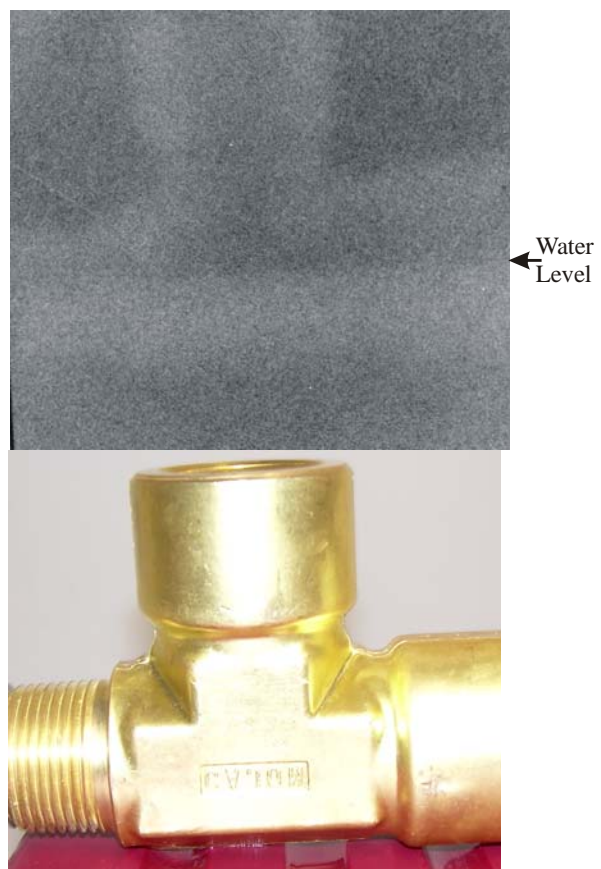


Fig. 9. A pixel-inverted fast neutron image of brass T-fitting in which the lower, horizontal pipe section is half-filled with water. Collection time was 30 min. Distance from source to detector was 50 cm.

have been rented by other companies for other research and development applications. These applications include the use of neutrons for the detection of explosives and special nuclear materials.

5. Identification of Products developed under the Award

5.1. Publications where this DOE contract is cited:

1. D. L. Williams, J. H. Vainionpaa, G. Jones, M. A. Piestrup, C. K. Gary, J. L. Harris, M. J. Fuller, J. T. Cremer, B. A. Ludewigt, J. W. Kwan, J. Reijonen, K.-N. Leung, R. A. Gough, "High Intensity, Pulsed, D-D Neutron Generator," CAARI Conference (2008).
2. J. Reijonen, N. Andresen, F. Gicquel, R. Gough, M. King, T. Kalvas, K.-N. Leung, T.-P. Lou, H. Vainionpaa, A. Antolak, D. Morse, B. Doyle, G. Miller and M. Piestrup, "Development of Advanced Neutron/Gamma Generators for Homeland Security and Imaging Applications," Optics and Photonics in Global Homeland Security III. Edited by Saito, Theodore T.; Lehrfeld, Daniel; DeWeert, Michael J.. Proceedings of the SPIE, Volume 6540, pp. 65401P (2007).
3. J. T. Cremer, M. A. Piestrup, X. Wu, "Fast and Thermal Neutron Radiography," Proceedings of SPIE, 5923-11, (2005).

5.2. Web site that reflects the results of this project.

Adelphi Technology Inc. has benefited enormously from this program. This is reflected in the products and services now presented on its website at:

http://www.adelphitech.com/products/neutrons_systemsMain.html

5.3. Technologies and Techniques.

Adelphi developed a line of neutron generators (e.g. DD-108, DD-109, DD-110) based on the research accomplished under this program. These generators are listed in Table I on page 3. In addition, early techniques of obtaining images from fast neutrons were developed under this contract. The use of fast neutrons is ground breaking work and promises imaging with high penetration of high density and high atomic number materials, and good contrast between hydrogenous materials (e.g. H₂O, and plastics) and high density materials.

5.4. Patent Submission

Title "Compact Neutron Source and Moderator," Inventors: Tak Pui Lou, Jani Reijonen, Melvin Arthur Piestrup. This is a joint patent between LBNL and Adelphi Technology Inc. This invention was made in the course of research under prime contract no. DE-AC02-05CH11231 between DOE and the University of California. PCT/US2007/013638, filed 6/11/2007, Ref: 014939-005200EP LBL Ref: IB-1240EPO Our Ref: P52791EP00 European Application No.: 07016419.9

5.5. Licensing Agreements

Specifically to this project, Adelphi licensed a large range of patents and patent applications from LBNL which has produced many of its neutron source designs. These are listed in Table II below. The term of the license is until the expiration of the patents.

Table II. LBNL Patents licensed by Adelphi on Neutron Source

Title	Patent Status	Date Issued	Application Serial Number	Patent Number
Porcelain-Coated Antenna for Radio-Frequency Driven Plasma Source	7.5 Yr. Maintenance Fees Paid	12/23/1992		5587226
Pulsed Source Ion Implantation Apparatus and Method	7.5 Yr. Maintenance Fees Paid	9/23/1992		5558718
Low energy spread ion source with a coaxial magnetic filter	3.5 Yr. Maintenance Fees Paid	7/24/1996		6094012
Focused Ion Beam System	3.5 Yr. Maintenance Fees Paid	8/30/1995		5945677
Glass Antenna for RF-Ion Source Operation	3.5 Yr. Maintenance Fees Paid	9/25/1996		6124834
Quartz Antenna with Hollow Conductor	Issued	4/22/1998		6376978
Matching Network for RF Plasma Source	Application Filed		10/060,026	
A Spherical Neutron Generator	Application Filed		10/100,955	
Ultra-short neutron pulse production	Application Filed		10/350,573	
Cylindrical Neutron Generator	Application Filed		10/100,962	
Neutron Tubes	Application Filed		10/360,245	
Compact Neutron Generator with a Small Source Size	Application Filed		10/410,623	
Ion Source with External RF Antenna	Application Filed		10/443,575	
Negative Ion Source with External RF Antenna	Application Filed		10/656,848	
Multiple Straight Antenna for RF Plasma Production	Provisional Filed			