Title
High Intensity, Pulsed, D-D Neutron Generator

Author
Williams, D. L.

Publication Date
2009-08-01

IBT-23

High Intensity, Pulsed, D-D Neutron Generator

D. L. Williams, J. H. Vainionpaa, G. Jones, M. A. Piestrup, C. K. Gary, J. L. Harris, M. J. Fuller, J. T. Cremer
Adelphi Technology, Inc., 2003 E Bayshore Rd, Redwood City, CA 94063

B. A. Ludewigt, J. W. Kwan, J. Reijonen[1], K.-N. Leung, R. A. Gough
Lawrence Berkeley National Laboratory, 1 Cyclotron Rd. Berkeley CA 94720

ACKNOWLEDGMENT

This work was supported by the US Department of Homeland Security under Contract no. HSHQDC-08-C-00022 and the US Department of Energy under contract no. DE-FG02-04ER86177, and DE-AC02-05CH11231.

Manuscript ID: 525

Title: High Intensity, Pulsed, D-D Neutron Generator

Authors: D. L. Williams, J. H. Vainionpaa, G. Jones, M. A. Piestrup, C. K. Gary, J. L. Harris, M. J. Fuller, J. T. Cremer

Affiliation: Adelphi Technology, Inc., 2003 E Bayshore Rd, Redwood City, CA 94063

Authors: B. A. Ludewigt, J. W. Kwan, J. Reijonen[1], K.-N. Leung, R. A. Gough

Affiliation: Lawrence Berkeley National Laboratory, 1 Cyclotron Rd. Berkeley CA 94720

Abstract:

Single ion-beam RF-plasma neutron generators are presented as a laboratory source of intense neutrons. The continuous and pulsed operations of such a neutron generator using the deuterium-deuterium fusion reaction are reported. The neutron beam can be pulsed by switching the RF plasma and/or a gate electrode. These generators are actively vacuum pumped so that a continuous supply of deuterium gas is present for the production of ions and neutrons. This contributes to the generator's long life. These single-beam generators are capable of producing up to 10^{10} n/s. Previously, Adelphi and LBNL have demonstrated these generators' applications in fast neutron radiography, Prompt Gamma Neutron Activation Analysis (PGNAA) and Neutron Activation Analysis (NAA). Together with an inexpensive compact moderator, these high-output neutron generators extend useful applications to home laboratory operations.

Keywords: neutron generator, prompt gamma activation analysis, neutron spectroscopy, neutron source.

PACS codes:29.25.Dz, 28.20.-v, 14.20.Dh

Plasma Neutron Generators

RFI plasma neutron generators can produce intense neutron outputs of 10^{10} n/s or greater with the deuterium-deuterium (D-D) reaction [1]. Based on core technology originally developed at Lawrence Berkeley National Laboratory [1-3] and further developed by Adelphi, these generators provide many times greater neutron output than other portable/transportable systems and have proven to be reliable and easily serviced.

---

[1] Now at Schlumberger

As shown in Fig. 1, plasma ion source neutron generators are either simple diodes or triodes with an RF ion plasma source. This source generates the D^+ ions that are then accelerated across a potential of ~120 kV to a titanium target. In the triode, the ion beam can be gated as is the case in Fig. 1. The target is biased to a negative voltage, while the plasma is at ground. The negative potential will then 'attract' the positively charged particles to the target. The accelerated ions impinge onto a titanium coated copper target where 2.5-MeV D-D neutrons are generated through fusion reactions. The implanted deuterium ions form titanium hydrates in the titanium matrix, thus 'trapping' the deuterium atoms. 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, which is removed from the target by water-cooling it.

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 [1-4].

These generators use 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 between 1000-2000 hours, depending upon the maximum yield being used.

Present Adelphi Commercial Generators

Adelphi Technology produces high intensity neutron generators based on this technology. Adelphi currently makes devices with outputs of 10^8 (DD-108), 10^9 (DD-109) and 10^{10} (DD-110) fast neutrons per second (Figs. 2, 3). In addition, Adelphi has built a neutron generator specialized for the production of thermal neutrons for both prompt and delayed gamma neutron activation studies. The generators all have single ion beam sources and are contained in stainless steel containers. The current products can either be operated continuously or pulsed. Using both a foil activation technique and a neutron detector, the measured yield of the DD-109 generator is 2×10^9 n/s, while the maximum measured yield of the DD-108 is 1×10^8 n/s. These generators are supported by a single chiller and standard 24” rack of power supplies and controls. The entire system is computer controlled. At the time of this writing, the maximum measure yield of the DD-110 is also 2 x 10^9 n/s, but higher yields are expected soon. The original DD-110 has experienced some problems with high voltage breakdown because of its unusual rectangular beam optics (e.g. 2 mm x 30 mm). The full 10^{10} n/s are expected based on the expected beam current and voltage.

The neutron flux depends on the ion current and acceleration voltage. The voltage is easily controlled, and the current can be controlled by varying the plasma density (both by varying the excitation and gas density). This allows continuous and precise control of the neutron output, and if the output is measured, a feedback loop can maintain a constant output flux over extended times. Because the voltage, gas pressure and RF excitation can be computer controlled, the neutron generators have been equipped with software to allow their control remotely and even over an internet connection. Generators using the D-D reaction have the further advantage that the system can be opened and serviced, greatly increasing their lifetime. The generator head uses a serviceable stainless steel housing with conflate copper-gasket seals that can be easily removed, permitting most of the components in the generator head to be easily serviced and replaced (as long as these components have not become too radioactive). All high voltage and RF power are safely sealed away, permitting safe operation.

The compactness of the generators permits them to be safely housed in polyethylene moderators measuring roughly 60 x 60 x 80 cm^3 with additional lead and borated polyethylene. The moderators for the DD-110 and DD-109 are shown in Fig. 2 and 3a. The head is partially surrounded by 3 mm thick lead to shield the spurious x-rays generated by electrons emitted back to the plasma source from the primary ion interaction at the titanium target. Surrounding the polyethylene moderator is borated polyethylene to minimize any thermal neutrons and reduce the 2.2 MeV gamma emission from neutron capture in hydrogen. Additional ports can be machined into the polyethylene for the optimal placement of materials to be irradiated or for the extraction of either thermal or fast neutrons for example PGNAA. Such arrangements have been done for PGNAA by us and LBNL [4].

Pulse Generation

There are numerous applications that can benefit from the production of pulsed neutron sources, such as differential die-away measurements of special nuclear materials and, generally, the separation of thermal and fast neutron induced signals. A plasma neutron generator can be pulsed either by varying the excitation of the plasma or the acceleration field.

One means of pulsing the neutron generator is to pulse the RF power to the plasma. We have measured the pulse length using the RF plasma light output and the thermal and fast neutron output from the generator. A light pipe was used to gather light from the RF chamber so it could be measured with a fast photodiode. Using a BC-208 fast neutron scintillator made by ELJEN Technologies and a photomultiplier, we also measured the neutron flux per pulse and pulse structure. This is shown in Fig. 4, where we plotted the number of neutrons and photodiode signal (plasma light) as a function of time.

Following earlier research by LBNL [3], we achieved pulse lengths from 20 μs to 1 ms with duty factors as low as 7% as measured both by a photodiode observing the plasma and the neutron output. Using the photon plasma detector we observed 6 μs pulse fall times, and with the fast neutron detector a 8-μs fall-off time was measured. Again this is shown in Fig. 4. One can also see a plasma and neutron emission ("afterglow") after the RF pulse is extinguished that last 20 to 50 μs.

We also found that we could operate at low pressures and still reignite the plasma at each pulse. The minimum operating pressure depends on the duty cycle. The minimum pressure is around 10 mTorr at large duty cycles, but beginning below a 10-15% duty cycle the minimum pressure required to reignite the plasma dramatically increases. We also demonstrated that we could maintain plasma ignition between pulses by pre-igniting the plasma with short electrical pulses. We positioned a small arc electrode ("sparkplug") in the back of the RF plasma chamber. We reignited the plasma with a 10 kV, 10 μs pulse to the sparkplug electrode. This HV pulse was synchronized with the RF plasma pulse. This technique permitted us to have longer neutron pulses > 1ms with duty factors < 10 % while still maintaining pressures below 50 mTorr inside the plasma chamber.

In order to shorten the fall-off further (< 1 μs) and eliminate the afterglow, we used a gate electrode to quench the plasma meniscus quickly. This blocks the ion extraction and eliminates the neutron production between pulses due to afterglow and pulse falloff. In Fig. 1 the gate electrode is shown positioned just after the plasma extraction iris . The gate works as follows: The ion source is at ground potential with positive ions streaming out of the extraction aperture. If the gate electrode is biased positively (+200V), it will repel the ions and prevent them from entering the shroud aperture and striking the Ti target. If the gate is biased to -2 kV the ions are accelerated to the target. We fabricated the gate electrode and placed it in an Adelphi neutron generator. The neutron counts increased with increasing gate voltage. Also, a +200V was sufficient to stop the beam entirely. With the gate electrode set to -2 kV, the generator produced a neutron pulse that matched the RF pulse structure. The neutron-pulse falloff was ~

10 μs in Fig. 4. When a 15-μs pulse reverse biases the gate to + 200 V, the neutron pulse is truncated and the afterglow neutrons are eliminated. This is shown in Fig. 5. The ion afterglow is eliminated and the neutron pulse falloff is truncated to < 1 μs. The afterglow is eliminated for the duration of the 15 μs pulse.

Applications

The high neutron yield offered by Adelphi's plasma sources offers a larger range of laboratory research opportunities, including neutron activation studies, explosives detection, detection of special nuclear materials, neutron radiography, and chemical analysis.

Detection of Conventional Explosives: Neutron interrogation is a valid method for determining the presence of concealed conventional explosives. There are several different techniques used, with effectiveness depending on the particular application. Whether thermal activation (measuring prompt or delayed gammas), fast neutron excited emission, or neutron radiography are used, increased flux will increase the range of detection – a critical parameter. Some of these projects have benefited from Adelphi high-output source technology. The research efforts should yield a viable solution for shipping containers in the next few years.

Special Nuclear Material (SNM) detection: Today, the detection and verification of SNM is an important challenge for the world community. The prevention of terrorists' smuggling of nuclear materials across boarders will employ new detection strategies. While advances in passive detection systems will enhance the probability of detecting non-shielded or weakly shielded radioactive materials, the detection of shielded SNM and in particular shielded HEU poses a significant challenge that is best addressed using active detection systems. These systems can be utilized to inspect cargo in shipping containers at seaports, border crossings, and air transport containers, or be deployed as mobile inspection systems. For the pulse-die away technique for locating SNM, pulsing with no neutrons between pulses, as demonstrated here, is important for detection of the resultant delayed fission neutrons [5].

Chemical Industry: PGNAA and NAA are established tools for elemental analysis and can potentially provide a complete picture of all contaminants in inorganic chemicals. Importantly, many applications require a higher neutron flux than currently possible with economically viable (much less than $1M) sources.

Acknowledgements

This work was supported by the US Department of Homeland Security under Contract no. HSHQDC-08-C-00022 and the US Department of Energy under contract no. DE-FG02-04ER86177.

10. Literature Cited

1. 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. A. Piestrup, "Development of Advanced Neutron/Gamma Generators for Imaging and Active Interrogation Applications," Proceedings of SPIE Vol. 6540-55 (SPIE, Orlando, FL, 2007).
2. J. Reijonen, F. Gicquel, S. K. Hahto, M. King. T.–P. Lou, K. N. K.-N. Leung, "D-D neutron generator development at LBNL" Applied Radiation and Isotopes, 63, 757-763 (2005).
3. J. Reijonen, K.N. Leung, G. Jones, "RF ion source development for neutron generation and for material modification", Rev. Sci. Instrum., **73**, 934 (2002).
4. J. Reijonen , K.-N. Leung, R. B. Firestone, J. A. English, D. L. Perry, A. Smith, F. Gicquel, M. Sun, H. Koivunoro, T. -P. Lou, B. Bandong, G. Garabedian, Zs. Revay, L. Szentmiklosi and G. Molnar, "First PGAA and NAA Experimental Results from a Compact High Intensity D-D Neutron Generator," Nucl. Instrum Meth. A **522,** 598 (2004).
5. D. Slaughter, M. Accatino, A. Bernstein, J. Candy, A. Dougan, J. Hall, A. Loshak, D. Manatt, A.Meyer, B. Pohl, S. Prussin, R. Walling, D. Weirup, "Detection of Special Nuclear Material in Cargo Containers Using Neutron Interrogation", Lawrence Livermore National Laboratory, UCRL-ID-155315, August 2003.

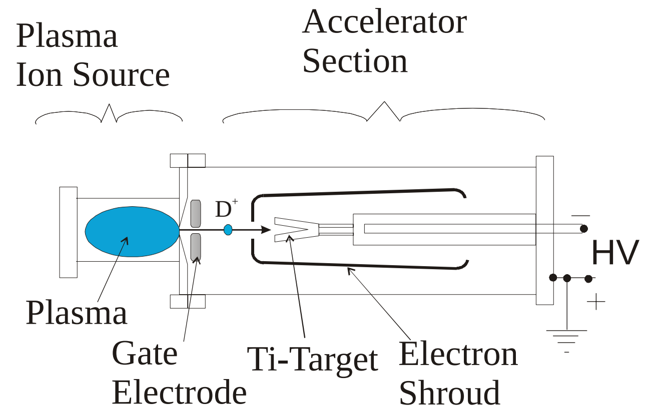


Fig.1. Simple diagram of the principle components of the neutron generator using the D-D reaction.

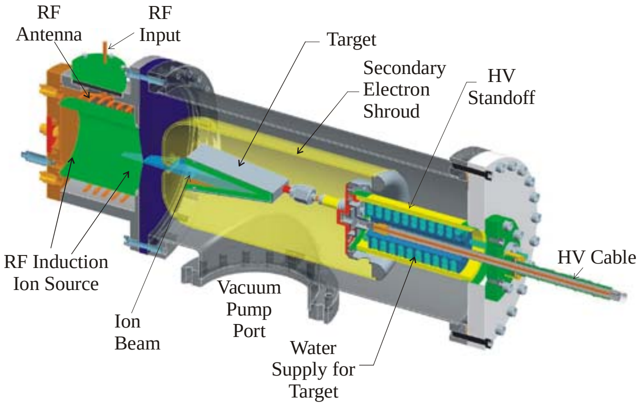


Fig. 2.a. The model DD-110 generator. This generator is expected to achieve 10^{10} n/sec.

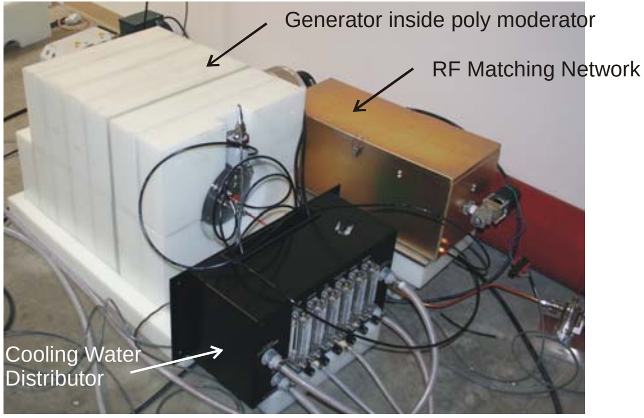


Fig. 2.b. The DD-110 surrounded by its support systems and enclosed in a polyethylene moderator.

1

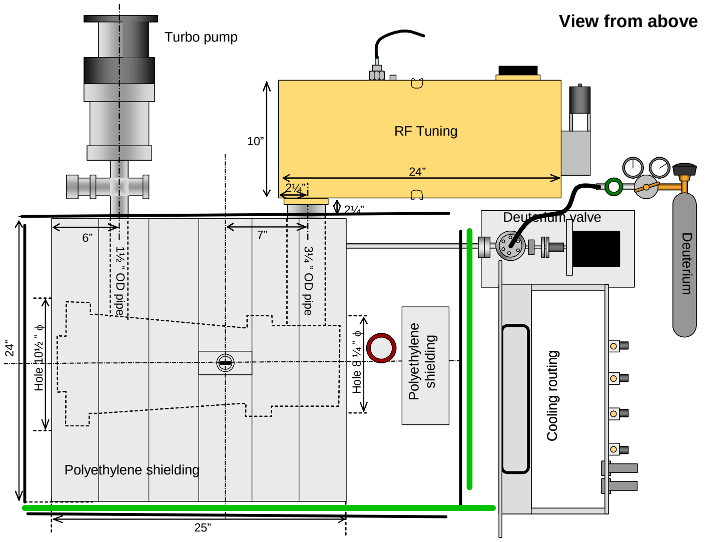


Fig. 3.a. The DD-109 enclosed in its polyethylene shield and surrounded by its support system of cooling water and deuterium gas delivery system.

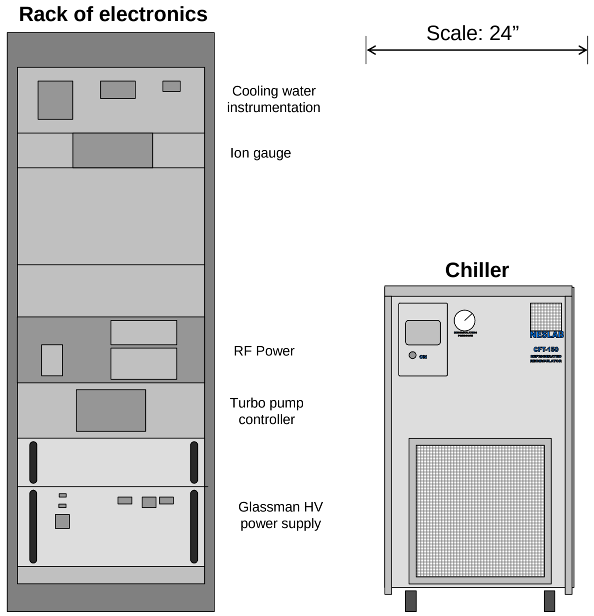


Fig. 3.b. The supporting power supply and chiller.

2

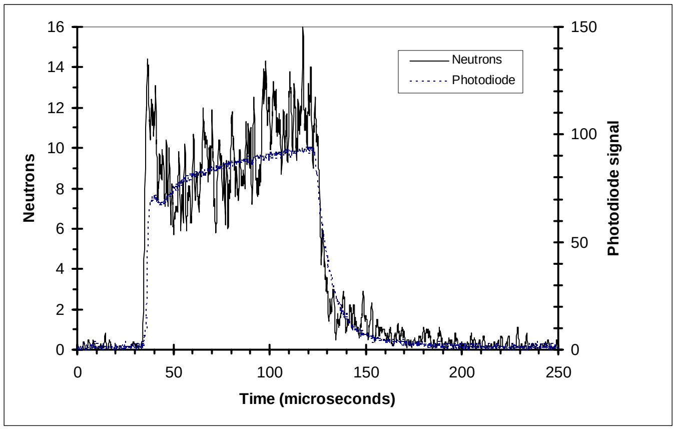
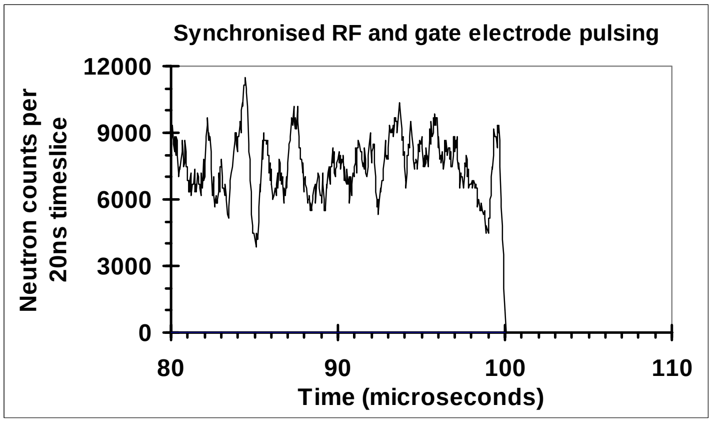


Fig.4. Measured fast neutron yield and plasma photon pulse as a function of time from the DD-108 for a 100 μs RF pulse.



1 Fig. 5. The neutron count as a function of time. The gate electrode was pulsed to +200 V at the end of the RF pulse at 100 μs.