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Compact Neutron Generators for Medical Home Land Security and Planetary Exploration

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COMPACT NEUTRON GENERATORS FOR MEDICAL, HOME LAND SECURITY AND PLANETARY EXPLORATION*

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Abstract

The Plasma and Ion Source Technology Group at Lawrence Berkeley National Laboratory has developed various types of advanced D-D (neutron energy 2.5 MeV), D-T (14 MeV) and T-T (0 – 9 MeV) neutron generators for wide range of applications. These applications include medical (Boron Neutron Capture Therapy), homeland security (Prompt Gamma Activation Analysis, Fast Neutron Activation Analysis and Pulsed Fast Neutron Transmission Spectroscopy) and planetary exploration with a sub-surface material characterization on Mars. These neutron generators utilize RF induction discharge to ionize the deuterium/tritium gas. This discharge method provides high plasma density for high output current, high atomic species from molecular gases, long life operation and versatility for various discharge chamber geometries. Four main neutron generator developments are discussed here: high neutron output co-axial neutron generator for BNCT applications, point neutron generator for security applications, compact and sub-compact axial neutron generator for elemental analysis applications. Current status of the neutron generator development with experimental data will be presented.

INTRODUCTION

Compact neutron generators are becoming an attractive alternative to nuclear reactors and radioactive neutron sources in variety of fields of neutron science[1], medical research[2] and various material analysis applications, ranging from coal and cement analysis[3] to various explosive detection schemes, from home-land security applications[4-6] to other explosive detection applications, like land mine detection[7]. Traditionally compact neutron generators have been used in oil well logging industry, using D-T fusion reaction for high energy 14 MeV neutron production. Currently the main commercial manufacturers of compact neutron generators are Thermo Electron, Sodern EADS and Sclumberger. These neutron generators generate D-T neutron yield in the range of 10^8 to 10^{10} n/s.

The Plasma and Ion Source Technology Group at the E. O. Lawrence Berkeley National Laboratory has been developing high power D-D neutron generators for various applications. These neutron generators are differentiated from the commercial manufacturers mainly by the method the plasma is generated and up to now by the use of D-D, instead of D-T, fusion reaction. The P&IST group has been pioneering in RF-induction discharge for different applications for more than twenty years[8]. These applications include H^- injectors for large accelerator systems[9] and for tokamak-fusion applications[10], positive ion sources for advanced focused ion beam systems[11] and for semiconductor applications[12]. This RF-technology with unique impedance matching circuitry and source designs capable of high power operation is now being used in various neutron generators. RF-induction discharge ion source has unique features that make it an excellent source type for high power, high yield neutron generators. These features include the high plasma density generation for high beam current extraction, extremely high atomic ion generation from molecular gases like hydrogen, and reliable, long life operation. These ion sources are currently used in three different types of neutron generators; axial, single ion beam neutron generator; co-axial, multi-beamlet, high current neutron generator; and point neutron generator with high instantaneous neutron yields. The latest addition to the line of neutron generators is a sub-compact, low yield neutron generator for sub-surface water/hydrogen analysis applications. These different types of neutron generators will be discussed in the following sections.

AXIAL, HIGH VOLTAGE SHIELDED NEUTRON GENERATOR

The axial, single beam neutron generator is a development from the sectioned insulator, single beam neutron source, which was developed mainly for pulsed beam applications. It's design and operation is described elsewhere[13]. The sectioned insulator neutron generator has been operated successfully for more than 500 hours. The external RF-antenna ion source has thus proofed the ability to provide long-life time operation with extremely stable operation characteristics.

In some applications there is a need for a neutron generators that do not have exposed high voltage elements. Thus the neutron generator can be placed close to various moderator materials or experimental devices. The latest axial neutron generator development has all the high voltage elements shielded by a grounded vacuum/target chamber. Figure 1 shows for a schematic drawing of the fully high voltage shielded neutron generator.

The main performance parameters of the shielded neutron generator are the following; D-D operation with vacuum pumping or semi-sealed operation, actively water-cooled target, external antenna configuration, few milli-amperes of extracted current, accelerator voltage 80 – 100 kV and estimated neutron yield of ~10^8 n/s. The RF-induction ion source has an aluminum outer cylinder for efficient RF-noise suppression. Ion current density and

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hydrogen atomic species distribution for the metal shield source design are shown in Figure 2.

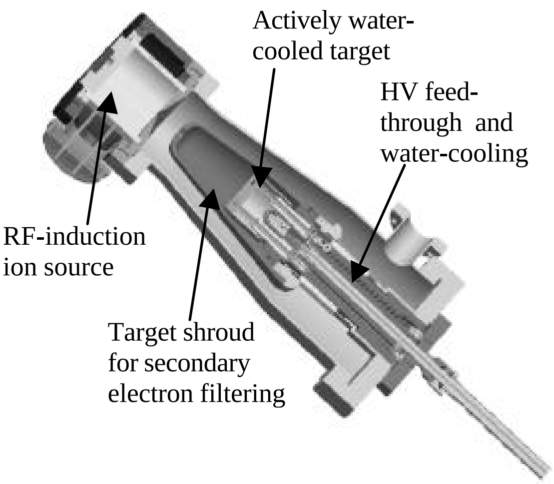

Figure 1: Fully high voltage shielded and grounded neutron generator design for medium neutron yield.

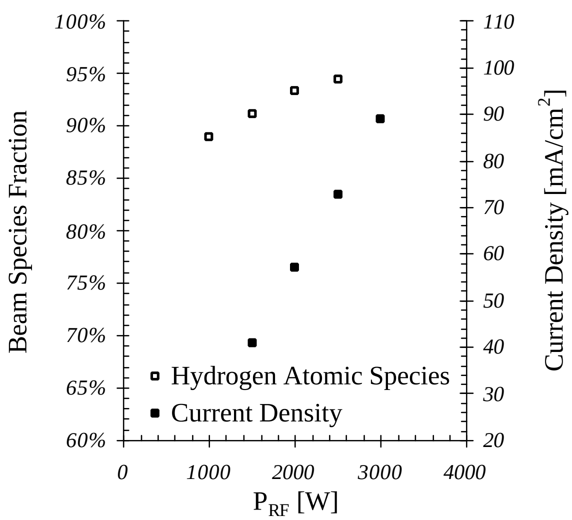

Figure 2: Hydrogen atomic species fraction and the extracted current density as a function of the RF-discharge power at 8 mTorr source gas pressure.

The neutron generator has a single gap extraction system. The geometries of the extraction system and the target shroud are simulated by using an IGUN ion extraction and transport code[14]. The design goal is to have a power load in the target of the order of 500 w/cm^2 or less.

The biasing voltage of the secondary electron filter shroud is generated by zener diodes. The biasing is necessary to minimize the potentially destructive high intensity secondary electron beam. These electrons are originating from the target surface and they can accelerate towards the ion source. The lower intensity electron beam formed in the gas at the accelerator and the beam transport section inside the filter shroud is dumped onto the water-cooled back-plate of the ion source. The target material is titanium-coated copper.

This neutron generator is fabricated for the Nuclear Engineering Department of the University of California Berkeley to replace the ^{252}Cf radioactive neutron source. The enclosed neutron generator will be tested during Summer 2005 and the performance will be evaluated in one the P&IST group's neutron generator test stands.

HIGH POWER CO-AXIAL NEUTRON GENERATOR FOR MEDICAL APPLICATIONS

As previously reported[15,16], studies has been made in determining the neutron yield required to achieve reasonable treatment time for NCT (Neutron Capture Therapy), either for brain or liver tumor treatments. It has been shown that a liver tumor treatment can be carried out in 45 minutes, if ~10^{13} n/s D-T neutron generator is used. For the first phase in developing a treatment system for liver cancer, a high power D-D neutron generator has been designed, fabricated and delivered to an Italian university and hospital consortium in Turin, Italy, see Fig. 3. The purpose of the neutron generator is to demonstrate the feasibility of operating a neutron generator at the power level required for treatments, using D-D reaction. The yield of this neutron generator is 10^{11} n/s. This is achieved, using 350 mA of beam current and 120 kV of acceleration voltage. The ion source performance and the neutron generator design is presented elsewhere[13].

Figure 3: The 10^{11} n/s D-D co-axial neutron generator mounted in one of the P&IST group neutron test stands. The neutron generator is 80 cm tall with the pumping chamber and 40 cm in diameter.

The neutron generator was delivered to a test stand in the, Physics Department of the University of Turin, Italy in November 2004. Currently the neutron generator is being operated for neutron production and the first experiments are being carried out.

POINT NEUTRON GENERATOR

Point neutron generator is developed specifically for PFNTS (Pulsed Fast Neutron Transmission Spectroscopy), an explosive detection scheme, developed by Tensor Technology Inc. The detection method is described in detail in ref.[17]. The requirements for the neutron generator are fairly demanding. The detection system requires a point neutron source for imaging, short neutron pulses for energy resolution and wide energy spectrum for elemental identification using absorption technique.

The wide energy spectrum requirement is achieved by utilizing the T-T fusion reaction[18,19]. The overall cross-section is comparable to D-D reaction, except the reaction generates two neutrons per fusion. The energy distribution is from 0 to 9 MeV and is thus suitable for the PFNTS screening method.

The short beam pulses are generated by sweeping the beam across a collimator aperture with parallel plate beam sweeper and fast high voltage electronics switching system[20]. By utilizing this method, 15 ns beam pulses has been generated in a very compact device. The requirement for the point neutron generator is to have pulse duration of 5 ns at 0.25% duty cycle.

A new neutron generator concept is used to have a point neutron source with high intensity. In the point neutron generator design, the plasma is generated in a torroidal-shaped plasma chamber and the beam is extracted toward the middle of the generator to centrally located, small diameter target tubing. The pulsed point neutron generator will use 20 beamlets to produce total beam current of 1A. This generates 10^{12} n/s equivalent time-average yield during the pulse. Schematic drawing of the point neutron generator is shown in Fig. 4.

The ion source will be floating at +20 – +30 kV potential to ensure efficient and loss free beam transport through the beam extraction and focusing electrode system of the device. The collimator/beam dump will be at ground potential to facilitate straightforward water-cooling arrangements. The target will be biased to -100 kV.

The beam optics are modeled extensively with ion beam simulation codes, such as, IGUN[21], PBGUNS[22], SIMION 3D[23] and KOBRA 3D[24]. The beam sweeper operation has been simulated using KOBRA 3D and SIMION 3D. Some of the KOBRA 3D simulations are shown in Fig. 5.

Two prototype devices are build to gauge the requirements and the design of the RF-antenna and the ion source geometry and to verify the simulation results of the beam sweeper with real ion beam experiments. The ion source prototype has already been build. The fist experiments indicate The first results of the ion source prototype has indicated that, if run with a single RF-antenna configuration, the required discharge power level is fairly high. This is due to the size of the discharge vessel. Preliminary results of the 10 cm in diameter, 90 cm long prototype ion source are shown in Fig. 6. Other types of ion source options will be explored during summer 2005.

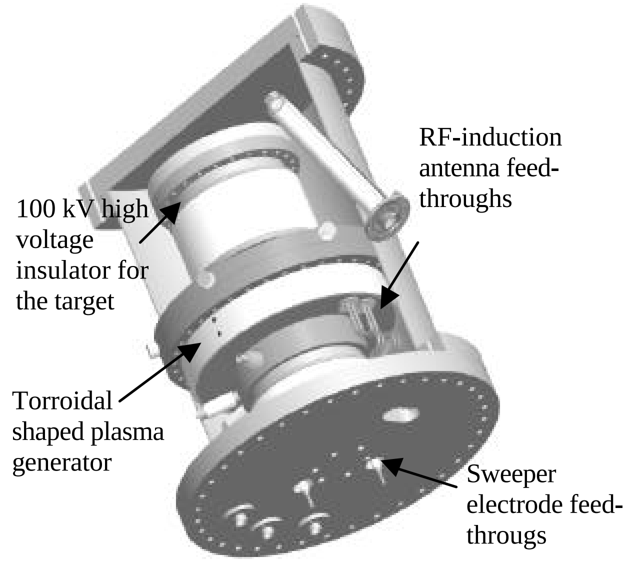

Figure 4: Cut-out drawing of the fast pulsing point neutron generator. The device is ~100 cm tall and ~50 cm in diameter.

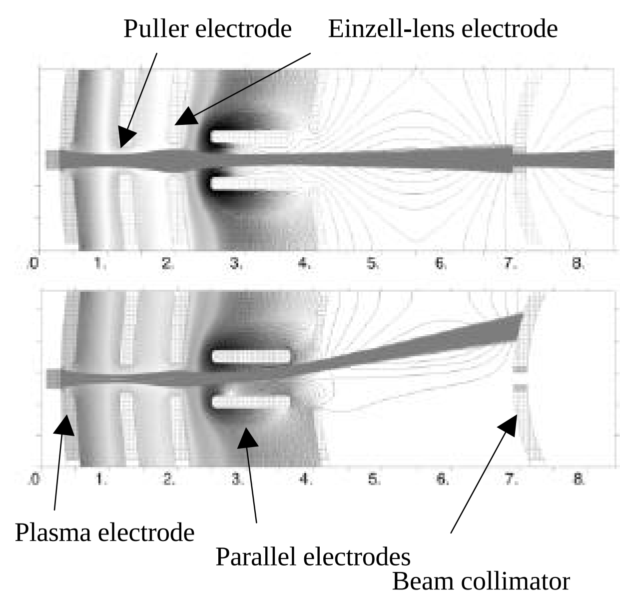

Figure 5: KOBRA 3D simulation of one of the 20 slit beam sweeper system of the point neutron generator. Beam optics in the case of non-deflection is shown in the upper simulation, beam sweep using +-1.5 kV potential in the parallel plates is shown in the lower picture. After the beam collimator the beam is accelerated to the full 120 kV energy.

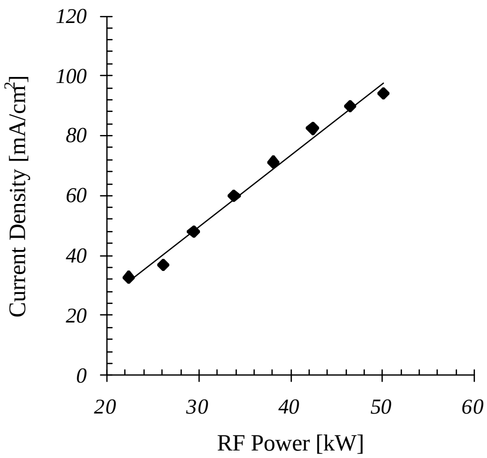

Figure 6: Extracted current density from the prototype ion source of the point neutron generator. The ion source was operated with 2 MHz RF-power supply at 8 mTorr gas pressure.

A second prototype system will be fabricated to test the beam sweeper system. This prototype will be built during spring 2005. In this prototype system the plasma generator has similar round geometry to the final device. This plasma generator will be operated either with a single, long antenna (like the current ion source prototype) or with multiple smaller ones. The prototype system can also extract three beamlets, to simulate the beam-beam interaction in the extraction and beam transport gap. The prototype system will be equipped with a 50 Ohm, matched faraday-cup for accurate beam pulse duration measurements. The prototype beam sweeper system is shown in Fig. 7.

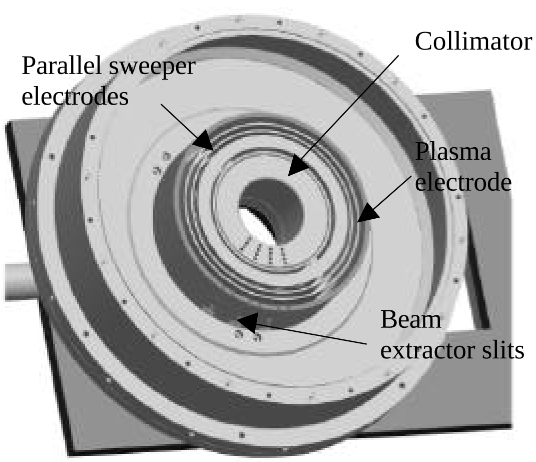

Figure 7. Cut-out view of the beam sweeper prototype. The prototype is built to test and verify the ion beam simulation results in a realistic geometry. The beam pulsing speed and the current will be measured from one extracteded beamlet, using a 50 Ohm impedance matched faraday-cup placed the target position in the middle of the device.

Based on the results obtained from the prototype systems, a final design, incorporating the tritium handling hardware will be performed. The first full test generator will be operated in a test stand during the summer 2006.

SUB-COMPACT MINIATURIZED NEUTRON GENERATOR

One of the latest fields of neutron generator technology, which the P&IST group is addressing, involves miniature, low yield neutron generator for applications, such as sub-surface ice/water and mineral analysis for planetary exploration or miniature high-energy gamma calibration device for high-energy gamma detector applications. The emphasis in these applications is the low power consumption, low weight, ruggedness and portability. To achieve these goals, some compromises have to be made. The miniaturized neutron generator will be operated at considerably lower neutron yield than the regular axial neutron generator. The neutron yield is in the order of 10^4 - 10^5 n/s for D-D operation and in the order of 10^6 n/s for D-T at ~40 kV of accelerator voltage and with a few microamperes of extracted beam current. The power consumption would be in the order of few watts. This enables fairly long operation time by using batteries or solar cells. The neutron generator would not be actively cooled. Figure 8. is a schematic drawing of a miniaturized neutron generator.

The ion source of this kind of neutron generator could be cold- or hot-cathode type, using high voltage discharges or electron emission from a filament. In certain applications, where the packaging of the neutron generator is less of a concern the ion source could also be driven with RF-induction discharge.

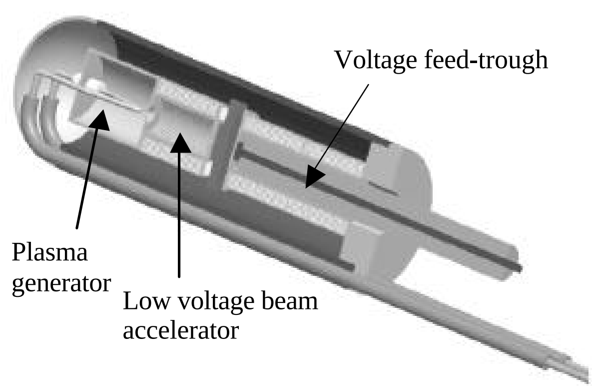

Figure 8. Low yield, miniaturized neutron generator. The diameter of the device is ~25 mm. Hot-cathode plasma generator pictured here.

The accelerator column design, and various types of ion source schemes are being studied at the P&IST group. Results will be presented in later time.

DISCUSSION

Multiple different types of neutron generators are developed and fabricated in the Plasma and Ion Source Technology Group at Lawrence Berkeley National Laboratory. These developments include; fully high voltage shielded axial neutron generator; high yield, D-D, co-axial neutron generator; point neutron generator and a miniaturized, low yield neutron generator. Purpose of these developments is to enable the use of neutrons in to new application areas unattainable before due to limited neutron generator designs, neutron output or cost.

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REFERENCES

[1] J. Reijonen, et. al., Nucl. Instrum Meth. **A522**, 598 (2004),

[2] J. J. Kehayias and H. Shuang, Nucl. Instrum Meth. **B79**, 555 (1993)

[3] G. Vourvopoulos, Nucl. Instrum Meth. **B56/57**, 917 (1991)

[4] L. Grodzins, Nucl. Instrum Meth. **B56/57**, 829 (1991)

[5] G. Vourvopoulos, Nucl. Instrum Meth. **B89**, 388 (1994)

[6] W. C. Lee, et. al., Nucl. Instrum Meth. **B99**, 739 (1995)

[7] Phillip C. Womble, et. al., Nucl. Instrum Meth. **A505**, 470 (2003)

[8] M.C. Vella, et. al., J. Vac. Sci. Technol. **A 3** (3), May/Jun 1985

[9] K. N. Leung, et. al., Rev. Sci. Instrum. **62** (1) 100 (1991)

[10] S. K. Hahto, et. al., Rev. Sci. Instrum. **75**, 355 (2004)

[11] Q. Ji, K.-N. Leung, T.-J. King, X. Jiang, B. R. Appleton, Proceedings of CAARI 04, October 10-15, 2004, Texas, USA, to be published in NIM B

[12] J. Reijonen, K. N. Leung, and G. Jones, Rev. Sci. Instrum. **73**, 934 (2002)

[13] J. Reijonen, et. al., to be published, Journal of Applied Radiation and Isotopes

[14] R. Becker and W. B. Herrmannsfeldt, Rev. Sci. Intrum. **63**, 2756 (1992)

[15] H. Koivunoro, et. al., Proceed. of the 10th International Congress on Neutron Capture Therapy for Cancer 8 - 13 September 2002, Essen, Germany

[16] H. Koivunoro, et. al., Proceed. of 6th International Meeting on Nuclear Applications of Accelerator Technology (AccApp '03), June 1-5, 2003, San Diego, CA.

[17] T. G. Miller and R. A. Krauss, Proceedings of the SPIE European Symposium on Optics for Environmental and Public Safety, Munich, 1995

[18] S. I. Warshaw, LLNL Report #UCRL-ID-144510

[19] T. Matsuzaki, et. al., Progress of Theoretical Physics Supplement, **154**, 225 (2004)

[20] S. Hahto, et. al., Rev. Sci. Instrum. **76**, 023304 (2005)

[21] R. Becker and W. B. Herrmannsfeldt, Rev. Sci. Intrum. **63**, 2756 (1992)

[22] J.E. Boers, Proceedings of the 1995 IEEE Particle Accelerator Conference, American Physical Society, 2312 (1995)

[23] D.A. Dahl, SIMION 3D 6.0 User's Manual, Idaho National Engineering Laboratory, INEL-95/0403

[24] P. Spädtke and C. Mühle, Rev. Sci. Instrum. **71**, 820 (2000).