COMPACT NEUTRON GENERATORS FOR ENVIRONMENTAL RECOVERY APPLICATIONS*

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ABSTRACT

New generations of compact neutron sources are being developed at the Lawrence Berkeley National Laboratory (LBNL). The D-D or D-T neutron generators can be used to perform precise elemental analysis by Prompt Gamma-Ray Activation Analysis (PGAA) in place of a nuclear reactor. The neutron generators will be composed of an ion source, from which a 1.5 A deuterium beam will be extracted and accelerated to about 150 keV onto a target loaded with deuterium. Based on the D-D nuclear reaction, the neutron generator will yield approximately 10^{12} n/s (10^{14} n/s. for D-T reaction). With this neutron output, thermal and cold neutron fluxes of 10^7 n/s. cm^2 and 6 x 10^6 n/s. cm^2 have been estimated using neutron moderators designed by the neutron transport simulation code MCNP.

Key words: environmental recovery, neutron generator, neutron flux, PGAA

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Introduction

Prompt Gamma-Ray Activation Analysis (PGAA)[1] is a nondestructive radioanalytical method capable of rapid, in situ, simultaneous, multi-element analysis involving the entire periodic table from hydrogen to uranium. PGAA can be used to quantitatively characterize the elemental composition of nearly any material without damaging the sample. The technique uses either thermal or cold neutron beams that produce a unique gamma-ray spectrum for each element. PGAA has been widely applied to material science, chemistry, geology, mining, archaeology, environment, food analysis, and other areas. It is also an ideal tool for environmental recovery applications.
PGAA application requires a detailed gamma-ray library that has been developed at LBNL in collaboration with the IAEA. The compact neutron generator developed by the Accelerator and Fusion Research Division at LBNL is expected to produce 10^{12} (D-D) to

10^{14} (D-T) neutrons per second, which is sufficient for PGAA. For the first time, it will be possible to do PGAA analysis without requiring that the work be done at a reactor, thus greatly extending its applicability. This article describes the development of compact and intense neutron generators at Lawrence Berkeley National Laboratory.

Neutron Tube Development

Compact neutron generators based on the D-D or D-T fusion reactions are being developed at the Lawrence Berkeley National Laboratory for explosive and mine detection, nuclear and non-nuclear waste characterization, neutron radiography and boron neutron capture therapy. The neutron generators will be composed of an ion source, from which a 1.5 A deuterium beam will be extracted and accelerated to about 150 keV onto a target loaded with deuterium. Based on the D-D nuclear reaction, the neutron generator will yield approximately 10^{12} n/s (10^{14} n/s. for D-T reaction). With this neutron output, thermal and cold neutron fluxes of 10^7 n/s. cm^2 and 6 x 10^6 n/s. cm^2 have been estimated using neutron moderators designed by the neutron transport simulation code MCNP.

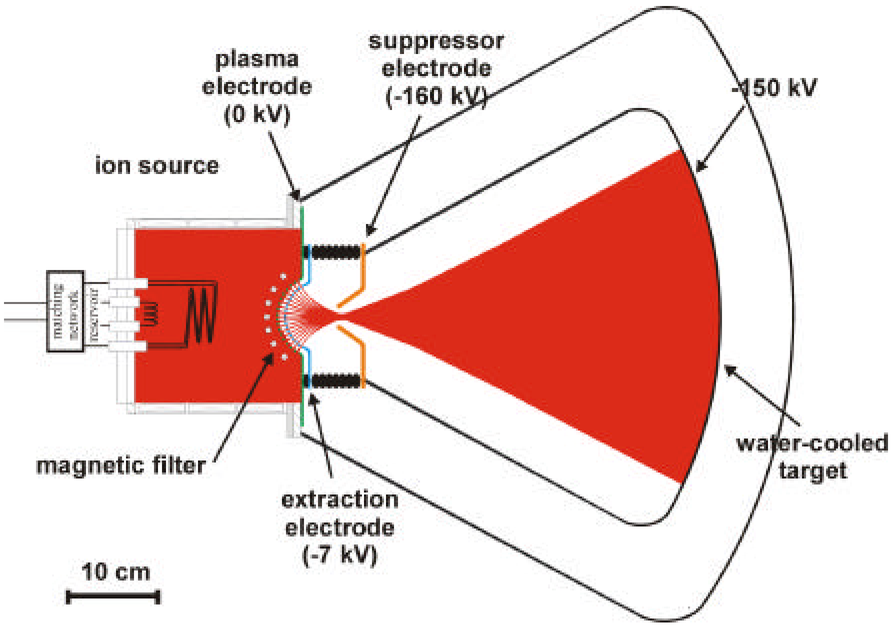

Figure 1. The RF-induction plasma source, beam extractor system, accelerator and target geometry

The RF-driven Ion Source

Figure 1 is a schematic diagram of the neutron tube designed and constructed at LBNL. In this neutron generator, a 30-cm diameter multicusp source is used to generate the plasma. The source chamber is surrounded by columns of samarium-cobalt magnets. The plasma is produced by RF induction discharge.[2] The RF power supply is operated at 13.5 MHz for CW or pulsed operation up to 5 kW or 2 MHz for high power (up to 90 kW) pulsed operation. The ion source, vacuum tank, vacuum pump and the high voltage feed through of the generator are shown in Fig. 2. The aluminum support structure around the neutron generator is used for lead and polyethylene shielding for the secondary-electron induced x-rays and for the neutrons.

The terminating impedance of the plasma typically ranges between 0.5 - 2 Ohms, whereas the coaxial transmission line and the output impedance of the RF-amplifier are both 50 Ohms. An RF-matching network is used to match the plasma and antenna impedance to the output impedance of the RF-amplifier and coaxial transmission line.

Figure 2. The neutron generator in the test-stand and layout of the set-up. From left, the high voltage feed-through is shown, the turbo vacuum pump unit on top of the vacuum vessel and on the right the 30 cm in diameter, multicusp ion source.

Conventional RF-antenna arrangement is used in the plasma generator. The coaxial titanium-quartz tube antenna is housed inside the plasma chamber. Very high hydrogen or deuterium atomic ion species percentage has been achieved (Fig. 3).

The high atomic species fraction in the beam is important so that higher neutron yields can be obtained (Fig. 4). The beam current density as a function of the RF power is shown in Fig. 5. The linear behavior of the obtainable, saturated beam current density as a function of the RF power is typical for RF induction ion sources[3]. The maximum obtainable current density depends also on the volume of the discharge vessel.

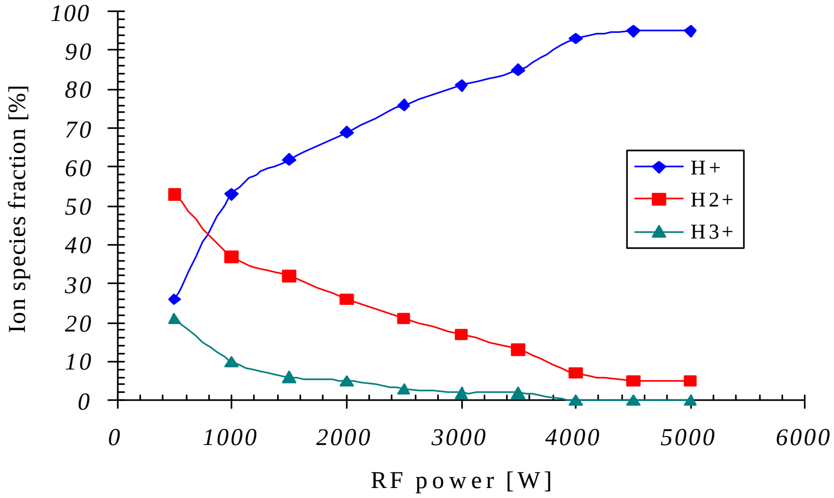

Figure 3. The hydrogen ion species fraction as a function of the RF power. More than 90% pure atomic species can be obtained at power > 4.0 kW.

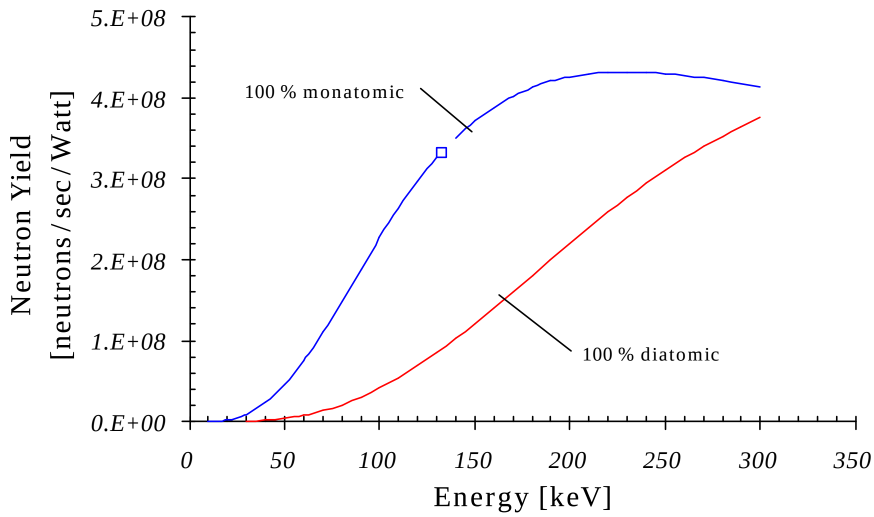

Figure 4. The comparison of neutron yields between monoatomic beam (the upper curve) and the molecular beam (lower curve). Neutron yields simulated using MCNP code.

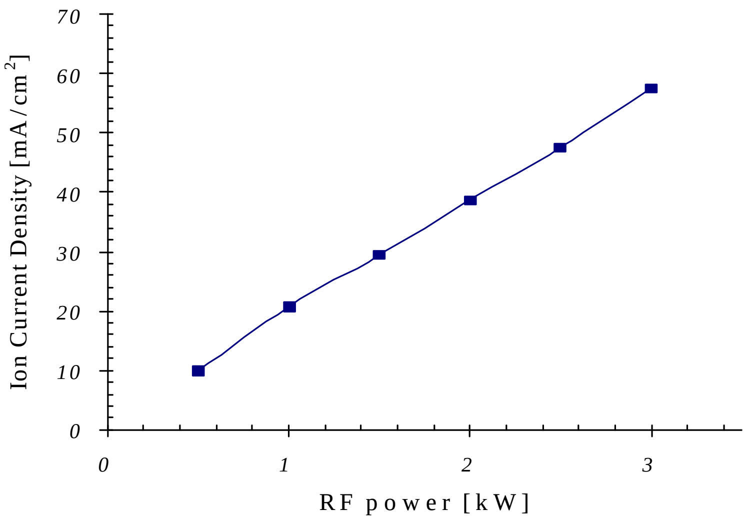

Figure 5. Ion beam current density as a function of the RF power. The source pressure in this measurement was 2 mTorr.

Accelerator Design

The beam extraction/accelerator system was simulated by using the IGUN[3] ion extraction simulation code. The beam is being extracted through a multi-aperture grounded plasma-electrode, extracted by low voltage and then accelerated to full energy with a third electrode. The target is biased at slightly higher voltage to suppress the secondary electrons created by the beam at the target. In this design the ion source is at ground potential and the target is at high negative potential. The design allows the beam trajectories to cross-over, which spreads the beam to larger area. A simulation of the beam behavior in the extraction gap is shown in Fig. 6. For the experiments described in this presentation, a seven hole extractor with combined area of 1 cm^2, was used. The target was placed 50 mm from the third electrode downstream.

Target and Moderator Design

The target is a copper substrate coated with a thin film of titanium. It contains water channels for cooling and thermodynamic stability of the target material. Deuterium (or deuterium and tritium) loading on the target is performed by the incoming beam. In this arrangement, the deuterium sputtered from the target surface is constantly replenished by the ion beam.

Moderators are developed in order to produce the thermal neutrons (~ 25 meV) for PGAA. Monte-Carlo code MCNP has been used to compute the moderated neutron flux and energy spectra. Different combinations of materials are used to produce intense thermal neutron beams. If the neutron generator produces 10^{12} n/s for D-D reaction (10^{14} n/s. for D-T reaction), thermal and cold neutron fluxes of 10^7 n/s. cm^2 and 6 x 10^6 n/s. cm^2 have been estimated using neutron moderators designed by the MCNP code.

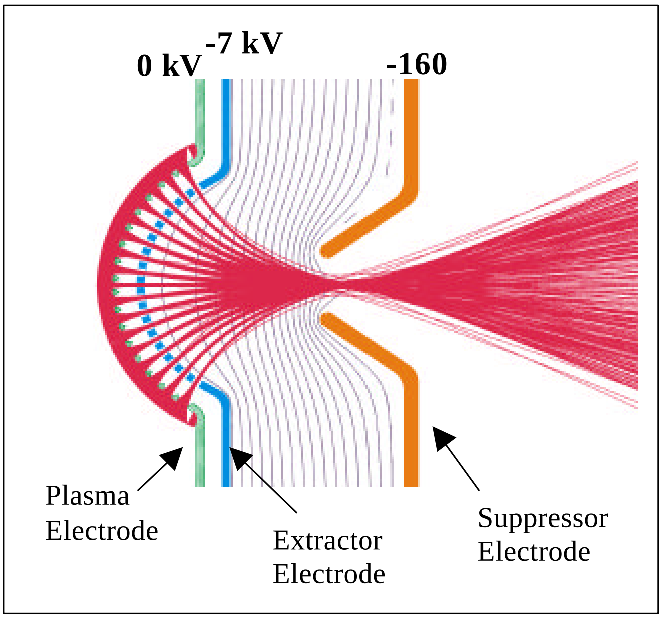

Figure 6. The IGUN simulation of the extraction area is shown on the right.

Experimental Results

The neutron tube has been operated at 80 kV acceleration voltage, 5 kW RF power at 1% duty factor and 10 mA of deuterium beam current. The target was not water-cooled during the initial measurements. Neutron measurement was performed by using several ^{3}He-detectors located inside the lead/polyethylene shielding. The neutron yield was ~ 3 x 10^{6} n/s, which is about a factor of three less than the yield produced at optimum TiD_2 target conditions.
Recently, the number of apertures on the plasma and extraction electrodes has been increased from 7 to 61. This gives approximately a factor of 10 increase in the extracted deuterium beam current. The measured neutron flux is observed to increase by approximately the same factor.

Next Generation Neutron Tubes

New steps are being taken to produce higher neutron flux with smaller neutron generators. Currently, simulations are being run on geometries such as the one shown in Figure 7(a). In this case, the neutron generator is a small cylindrical tube target and a single cylindrical multi-slit plasma electrode. The nature of the geometry allows the ion trajectories to expand naturally (Fig. 7(b)). The equipotential lines curve with the shape of the two electrodes. The design is simpler – in that it does not require as many electrodes, and produces a higher current at the target. This as well as other configurations are being studied and may be tested in the near future.

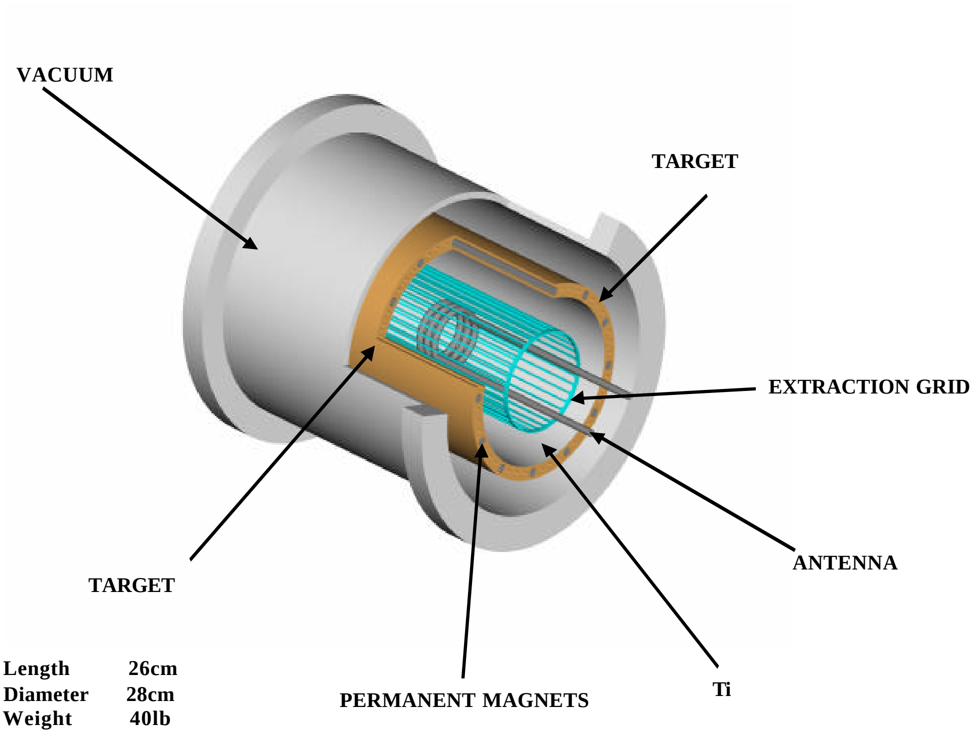

Fig. 7(a) The coaxial radial ion beam extraction neutron generator.

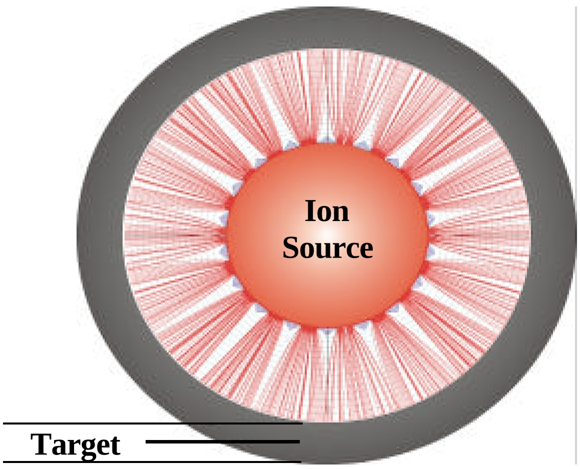

Fig. 7(b) Cross-sectional view of the coaxial neutron generator with ion beam trajectories computed by using the IGUN simulation code.

The PGAA Technique

The moderated cold or thermal neutrons can be used for environmental recovery purposes by using the neutron induced prompt gamma activation analysis (PGAA). PGAA is a non-destructive, self-calibrating radio-analytical method capable of simultaneously identifying nearly the entire periodic table. The method has been applied to material science, chemistry, geology, mining, archaeology environment, food analysis, medicine and other areas. Advancements in cold neutron technology make it possible to analyze materials in a low background environment by increasing PGAA sensitivity compare to thermal beams. PGAA has been limited mainly to reactor facilities. Development of a cold neutron beam on a portable neutron generator would expand PGAA capabilities to many areas.

Thermal or cold neutron capture produces a unique prompt gamma-ray signature for each element. Traditional cold neutron beam facility is associated with fission reactors. The thermal neutrons are moderated in liquid hydrogen and collected in a neutron guide tube that transports the neutron beam to the target. The gamma-ray spectrum can range from 0 to 11 MeV. Large, Compton-suppressed Ge detectors are used to minimize background and increase sensitivity. The spectrum is complex and a complete gamma-ray library is required. The PGAA database contains gamma-ray yields for about 80 elements and was developed in an LBNL led IAEA Coordinated Research Project. Short-lived decay gammas from Neutron Activation Analysis (NAA) of aluminum (2.25 min), sodium (20 min), and many other elements can also be used to enhance sensitivity.

A compact neutron generator provides a novel approach to PGAA analysis. Although the neutron flux is lower than that of a reactor, we can use a detector position much closer to the source because there is no intense radioactive core creating background. The expected D-D flux is at a distance of one meter from the generator is about 8×10^6 per cm2 per second. This exceeds the 2×10^6 flux originally available for PGAA at the Budapest Reactor. Conversion to D-T generation would increase the flux by a factor of ~100.

Acknowledgments

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