Nuclear Instruments and Methods in Physics Research A 690 (2012) 102–105

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A hydrocarbon fluid-based deuteron ion source for neutron generators

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ARTICLE INFO

Article history:
Received 21 May 2012
Received in revised form
12 June 2012
Accepted 19 June 2012
Available online 5 July 2012

Keywords:
Neutron generator
Ion source
Electrical breakdown

ABSTRACT

A deuteron ion source based on a spark discharge between electrodes coated with a deuterated hydrocarbon fluid is investigated. In the prototypic example studied here ion currents extracted from the source were on the order of 0.5 A with a pulse duration of approximately 10 μs. Operation in a laboratory neutron generator provided a neutron yield of $\sim 10^5$ neutrons/pulse with the deuterium–deuterium fusion reaction at a deuteron ion energy of 65 keV. This approach to ion sources for neutron generators has the potential to provide a compact, long-lived, high-output neutron generator for homeland security applications.

1. Introduction

Neutron generators are required for a wide variety of national and homeland security field-based activities related to nuclear terrorism and nonproliferation. Despite a 2002 National Academy study [1] in which the need for improved compact neutron generators was noted, a compact generator with the required characteristics of neutron output, longevity, robust character, and reasonable cost does not yet exist.

Compact neutron generators are typically of the deuterium–deuterium (DD) or deuterium-tritium (DT) type, and fall broadly into two categories depending on the hydrogen isotope ion source used. The first type uses low pressure gas discharge-based ion sources, such as a Penning discharge. This type of generator can be compact with a long lifetime, but has a relatively modest neutron output of $\sim 10^3$ neutrons/pulse, or 10^6 neutrons/s using the DD reaction [2] due to the limited hydrogen isotope ion current density that can be extracted from a low-pressure-gas discharge. On the other end of the spectrum, spark or arc discharges provide relatively high-output (often of the order of or greater than 10^5 neutrons/pulse using the DD reaction) generators with limited lifetimes [3]. The high output is due to the ionization of, for example, deuterium stored at high density in metal deuterides and the significant ion current that can be extracted from what can be ampere-level, high-current density discharges. A factor limiting the lifetime of these sources is erosion of the metal hydride by the electrical spark or arc.

This paper reports on a study of an ion source that could enable a compact neutron generator with both high output and long-life. The ion source is based on the extraction of deuterium ions from a deuterated hydrocarbon fluid as a result of its dissociation and ionization in a spark discharge. Because the density of hydrogen in these fluids is close to that of hydrogen in metal hydrides, there is the potential to provide high pulsed deuterium ion currents; that is, high neutron output. Also, the hydrocarbon fluid is not permanently eroded from the electrodes over time by the electrical discharge used to ionize the material because the fluid is self-healing. Thus, this approach has the potential to also provide long-life.

The impact of the presence of hydrocarbons, or more generally insulators, on electrode surfaces during an electrical discharge in high and low pressure vacuum environments has been of interest for many years [4–6]. Aspects such as the influence of insulating material on the initiation field of a high voltage spark breakdown and continuation of a low voltage vacuum arc have been investigated. Of particular interest to the present work is the fact that it has been observed that once an arc spot is formed it tends to migrate toward the site of cathode 'contamination' such as grease or oil, and run on those locations until the contamination is removed [7]. This implies that, although a relatively short (up to ~ 3 μs) discharge was used in the present experiments, the ignition of a longer duration (> 10 μs) arc discharge could significantly increase the number of ions produced from a hydrocarbon fluid.

2. Experimental

The experimental chamber was a turbomolecular-pumped high vacuum chamber operating in the 10^{-7} Torr range within 30 min of evacuation from atmospheric pressure. The spark ion source consisted of two 0.02-in.-diameter tungsten electrodes ground to a wedge shape and placed with the axes of rotational symmetry aligned with one another. The spark-gap electrode

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http://dx.doi.org/10.1016/j.nima.2012.06.051

separation was ~0.5 mm and could be reliably triggered by applying ~12 kV between the electrodes using a Behlke 331–06 high-voltage switch. A resistance of 333 Ω was placed in series with the switch to limit the current. A 2.7-nF capacitor in parallel with the switch served as a voltage source. The voltage and current across the spark gap was measured using a Tektronix model 6015 high-voltage probe and a Stangenes Industries Model 2–0.1WA current transformer, respectively. The current on the target was monitored with a Stangenes Model 2–1.0 W current transformer.

The tungsten electrodes were coated with commercial Santovac 5^{TM} diffusion pump fluid [m-Bis(m-phenoxyphenoxy)-benzene; $C_{30}H_{22}O_4$] and a partially deuterated version of Santovac 5 [~$C_{30}H_{16}D_6O_4$]. The fluids were outgassed in high vacuum, vented to nitrogen and manually applied to the tungsten electrodes. Good wetting was evident by a visible contact angle of much less 90° between the fluid and the tungsten.

Mass analysis was conducted using a custom 90°, 7 cm radius electrostatic energy analyzer followed by a 1.2 m time-of-flight mass spectrometer. The energy analyzer was used as the ion energy spread in the spark source is on the order of 1000 eV [8]. The ion detector on the time-of-flight system was a 3-in. chevron channel electron multiplier array. The electron output of the CEMA was projected onto a P-47 phosphor screen and viewed with a Photonis XP2262B photomultiplier tube (PMT).

Neutron production measurements were made using a laboratory neutron generator consisting of a high-vacuum chamber in which the deuterated metal target and spark ion source were placed in essentially a diode geometry as shown in Fig. 1. The target-to-spark gap separation was 10 cm. The target was TiD_2 and operated at −65 kV relative to the grounded electrode of the spark ion source. The auxiliary electrode was placed ~1 cm behind the spark gap.

The plastic scintillator detector used for neutron detection measured 5 cm × 20 cm with a thickness of 13 cm. The associated PMT was a Hamamatsu R329-02. The scintillator-PMT combination produced 1.4 to 1.5-V signals (−2300 V on PMT) with a FWHM of ~6 ns on the Compton edge (~1 MeV) of a ^{60}Co source. The pulse height of this nearly 1 MeV gamma-ray signal was approximately equivalent to the maximum detector signal produced by a 2.5 MeV neutron generated by the DD fusion reaction [9]. The detector was determined to have a neutron detection efficiency of ~10% with a ^{252}Cf source. This was a reasonable efficiency for 2.5 MeV neutrons in the plastic scintillator [10]. and includes the attenuation of the neutron signal by a factor of roughly 3 due to the use of a 4-in. thick lead shield to suppress the gamma-ray signal from the ^{252}Cf (the relaxation length of lead for fast neutrons is ~9 cm[11]). This lead shield remained in place during neutron production measurements to maintain the efficiency calibration and suppress bremsstrahlung x-rays produced by secondary electrons leaving the target during generator testing. The neutron detector was placed 1 m from the target and its output was viewed directly with a Tektronix TDS 540D oscilloscope.

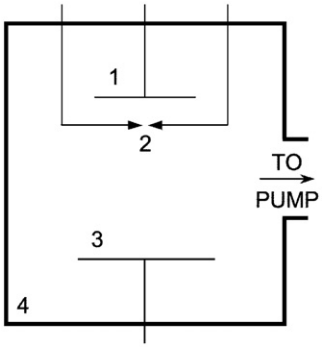

Fig. 1. Schematic of the laboratory neutron generator: 1. Auxiliary electrode; 2. Spark gap; 3. Target; 4. Vacuum chamber.

3. Results and discussion

Fig. 2 shows the mass spectrum obtained from commercial and partially deuterated Santovac 5. In the case of commercial Santovac 5, the dominant peaks in the mass spectra were always H^+ and C^+ The intensity of the C^+ peak was always much less than that of the H^+ peak. The essentially complete dissociation of the hydrocarbon species is to be expected and is part of the reason that spark sources, particularly of the energetic form employing an energy storage capacitor as in these studies, are not used for the study of hydrocarbons [8]. The appearance of the hydrogen and carbon peaks remained similar throughout the energy ranges selected with the electrostatic analyzer from ~50 V to 1000 V, ranges outside of which individual mass peaks were no longer observed. Over the course of greater than ~100 discharges other mass species could occasionally be seen, but the H^+ and C^+ peak intensities remained dominant and relatively constant.

The mass spectrum shown in Fig. 2b is typical when the partially deuterated oil is used to coat the electrode surfaces. Identical conditions (spark voltage, detector gains, analyzer deflection voltages) were used to collect the mass spectra in Fig. 2a and b. It is clear that now both H^+ and D^+ appear in the spectrum, again

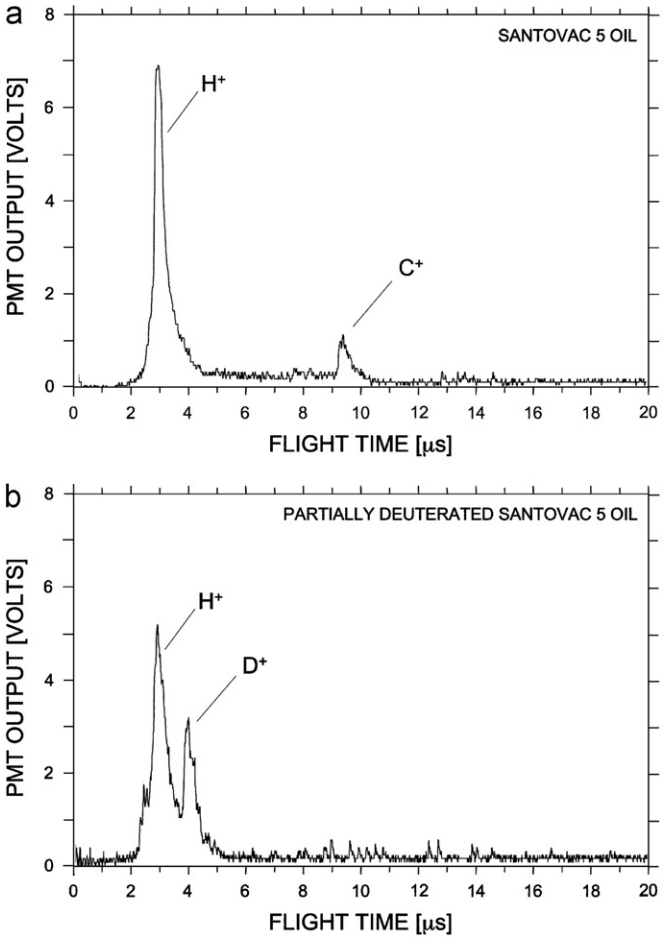

Fig. 2. Mass spectra from (a) commercial Santovac 5 oil and (b) partially deuterated Santovac 5 oil.