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Intense Combined Source of Neutrons and Photons for Interrogation Based on Compact Deuteron RF Accelerator

S.S. Kurennoy*, R.W. Garnett, and L.J. Rybarcyk

Los Alamos National Laboratory,Los Alamos, NM 87545, USA

Abstract

Interrogation of special nuclear materials can benefit from mobile sources providing significant fluxes of neutrons (10^8/s at 2.5 MeV, 10^{10}/s at 14.1 MeV) and of photons (>10^{12}/s at 1-3 MeV). We propose a source that satisfies these requirements simultaneously plus also provides, via the reaction $^{11}B(d,n)^{12}C(\gamma_{15.1})$, a significant flux of 15-MeV photons, which are highly penetrating and optimal for inducing photo-fission in actinides. The source is based on a compact (< 5 m) deuteron RF accelerator that delivers an average current of a few mA of deuterons at 3-4 MeV to a boron target. The accelerator consists of a short RFQ followed by efficient inter-digital H-mode structures with permanent-magnet-quadrupole beam focusing [Kurennoy et al. (2012)], which suit perfectly for deuteron acceleration at low energies. Our estimates, based on recent measurements [Taddeucci et al. (2007)], indicate that the required fluxes of both neutrons and photons can be achieved at ~1 mA of 4-MeV deuterons. The goal of the proposed study is to confirm feasibility of the approach and develop requirements for future full-system implementation.

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Keywords: interrogation, source, neutron, photon, accelerator, IH-PMQ, deuteron

1. Introduction

Both neutrons and photons can be used as probes for interrogation of special nuclear materials (SNM). There are different ways to produce these probes, and the energies of interest vary depending on the preferred detection method. For example, 100-150 keV deuterons impinging on a tritium target very efficiently produce 14.1-MeV

* Corresponding author. Tel.: +1-505-665-1459; fax: +1-505-665-2904.
E-mail address: kurennoy@lanl.gov

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neutrons and can be provided by simple means implemented in commercially available neutron generators, e.g., [SODERN]. Photons are usually produced by bremsstrahlung of electron beams in metal targets, see an overview in Garnett (2014). However, having one universal source that delivers both neutrons and photons with energies ranging up to 15 MeV is an attractive option for interrogating the widest range of cargos [Gozani et al. (2010)] especially considering that 15-MeV photons are ideal for photo-fission production in actinides, cf. Fig. 1.

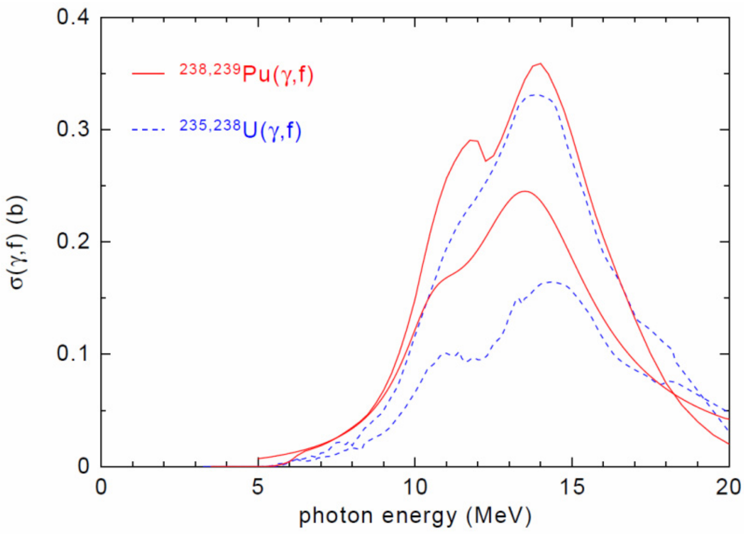

Fig. 1. Photo-fission cross sections for ^{235,238}U and ^{238,239}Pu (from ENDF/B-VII).

The reaction ^{11}B(d,nγ), known as a "prolific" source of 15.1-MeV gamma rays, suits the purpose of providing both neutrons and photons very well. It has been recently studied experimentally in detail; cf. Taddeucci et al. (2007). New cross section measurements at several deuteron beam energies E_d have been performed with both stopping-thickness and thin targets. For interrogation applications, the most relevant measurement results from Taddeucci et al. (2007) are neutron cross sections plotted in Fig. 2a and inclusive neutron-yield angular distributions shown in Fig. 2b, both for three different targets at deuteron energy E_d = 4 MeV and for neutron energies up to 20 MeV.

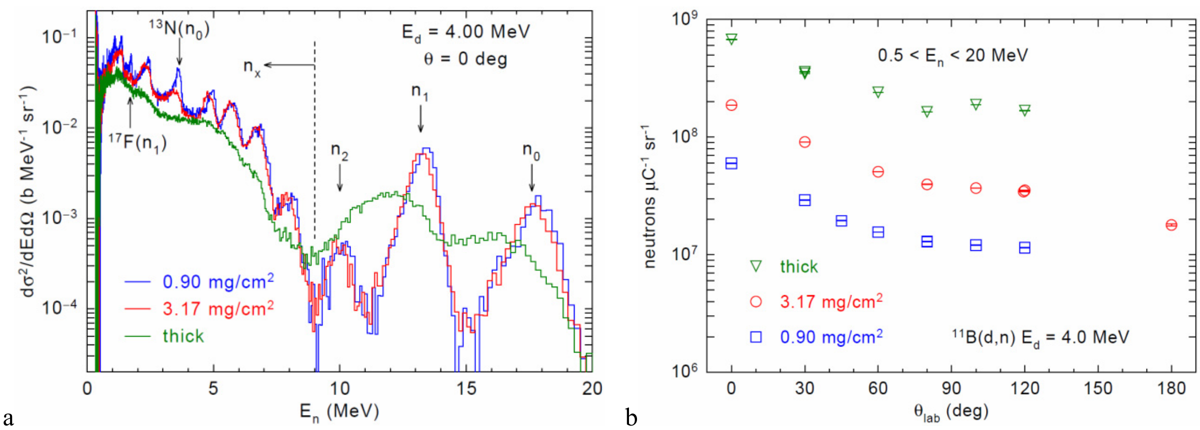

Fig. 2. Neutron cross sections (a) and inclusive neutron-yield angular distributions (b) for ^{11}B(d,n) from three target samples at 4 MeV.

We use data from Taddeucci et al. (2007) to estimate the flux values provided by 4-MeV deuterons delivered to a ^{11}B target. For a 1-mA deuteron current taken as a reference, the number of 15.1-MeV photons is estimated as $5 \cdot 10^{10}$ $s^{-1}sr^{-1}$ distributed isotropically. The flux of photons with energies in 1-3 MeV range is at least 1-2 orders of magnitude higher. The corresponding neutron flux estimate is $2 \cdot 10^{10}$ $s^{-1}sr^{-1}$ at 14.1 MeV with ΔE = 0.1 MeV, and significantly higher at lower neutron energies, below 5 MeV. We will return to the fluxes later in Sec. 2 after presenting an accelerator system that can efficiently accelerate deuterons to the required energy.

2. Compact deuteron RF accelerator

We propose to deliver a 4-MeV deuteron beam with a significant average current, up to a few mA, to a boron target using an RF accelerator based on the inter-digital H-mode (IH) structure with beam focusing by permanent-magnet quadrupoles (PMQ) inserted in the drift tubes. The IH-PMQ structures have been recently proposed and developed in Kurennoy et al. (2012) with a specific goal of efficient acceleration of light ions at low energies. They follow a Radio-Frequency Quadrupole (RFQ) linac that provides initial acceleration and bunching of the deuteron beam. The system, shown schematically in Fig. 3, also includes a deuteron ion source (IS) with a short electrostatic low-energy beam transfer / chopper section, and a boron target (^{11}B).

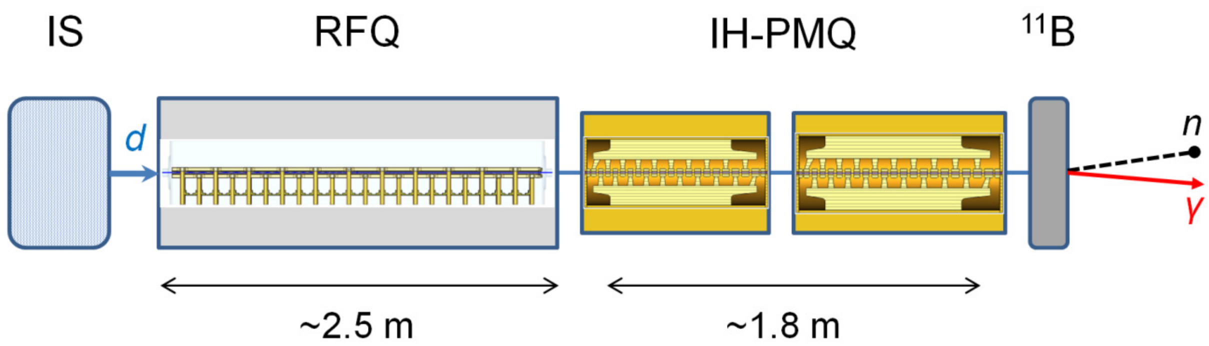

Fig. 3. Proposed RF accelerator system to provide 4-MeV deuterons for SNM interrogation.

Variable system parameters include the final deuteron energy, beam current, pulse structure, and RF frequency. The system size depends mainly on the final energy and frequency. One convenient frequency choice is 201.25 MHz, in part because RF power sources are available, but also because the accelerator structures under consideration – RFQ and IH-PMQ – either have already been developed or can be easily derived from existing designs. For example, the first tank of the IH-PMQ that is capable of delivering the peak current of 50 mA has already been designed: the structure accepts 1.5-MeV deuterons from the RFQ and accelerates them to 2.85 MeV, see Kurennoy et al. (2012) and also below, in Sec. 2.2. If the final energy is chosen to be 4 MeV, the accelerator will include one more IH-PMQ tank; approximate longitudinal dimensions for this case are shown in Fig. 3. The transverse sizes are ~0.4 m for a 4-rod RFQ, and 0.3 m for the IH-PMQ cavities. The final energy should be chosen as a trade-off between the neutron / gamma fluxes (higher beam energies lead to higher fluxes) and the full system size, which also defines its cost. From this viewpoint, E_d = 4 MeV is a reasonable choice in the proposed approach since the system is still compact and can be made mobile, and at the same time both the photon and neutron fluxes are already significant, see more in Sec. 2.3.

2.1. RFQ linac

RFQ linacs are commonly used in the front ends of modern ion accelerators. Classical 4-vane RFQs became almost standard, though they are more expensive to build and maintain than 4-rod RFQs. Based on recent commissioning results for the Fermilab 4-rod RFQ [Schmidt et al. (2014)], cf. Fig. 4, and our own recent experience in designing and building a proton 4-rod RFQ [Kurennoy et al. (2013)] for the LANSCE front end (see in Fig. 5), we prefer the 4-rod RFQ type for the proposed accelerator system due to its simplicity. While it would be possible, in principle, to use only one single RFQ to bring deuterons to the final energy of 4 MeV, such an RFQ would be prohibitively long. An estimate with the LANL RFQ design codes [LAACG] gives its length around 9 m. With other parameters fixed, the RFQ length depends on its design peak current: the higher the current, the longer the RFQ [LAACG]. Such a long RFQ would also be inefficient, significantly increasing the RF requirements for the system. An RFQ becomes less efficient as an accelerator at beam velocities above ~3% of the speed of light c, and 1.5-MeV deuterons already have velocity v = 0.04c. This is why we switch to more efficient IH-PMQ structures at the deuteron energy of 1.5 MeV.

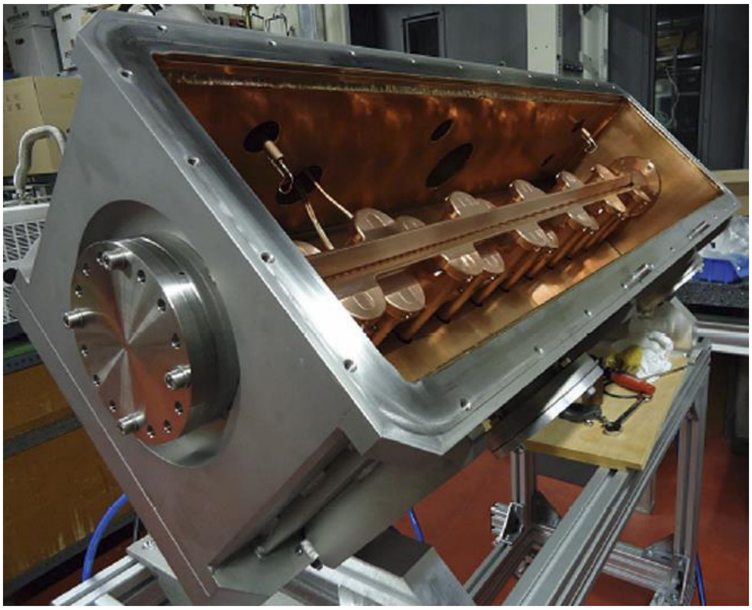

Fig. 4. Fermilab 201.25-MHz 4-rod RFQ for 60-mA H^- beam (2012).

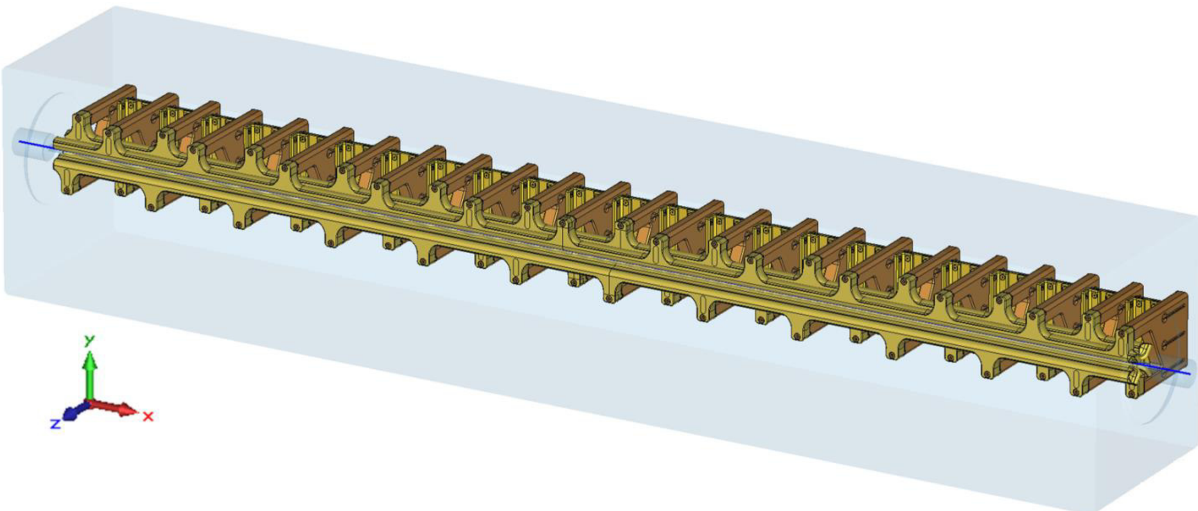

Fig. 5. CST Studio [CST] model of the LANL new 201.25-MHz proton RFQ with outer walls removed.

2.2. Inter-digital H-mode structures with PMQ focusing

The IH-PMQ structures are very efficient for accelerating particles with beam velocities in the range of a few percent of the speed of light: 10-20 times better efficiency compared to a conventional drift-tube linac (DTL), while their transverse size is 4-6 times smaller than for a DTL, see details in Kurennoy et al. (2012). The IH-PMQ cavity developed in the above reference is shown in Fig. 6. The cavity, which is 73.5-cm long, was designed to accelerate up to 50 mA of deuterons from 1.5 to 2.85 MeV with an average accelerating gradient of 2.5 MV/m. Such high currents require strong focusing that is provided by the PMQs inserted in each drift tube. For lower peak currents, the number of PMQs can be reduced. This cavity can serve as the first IH-PMQ tank in the scheme of Fig. 3.

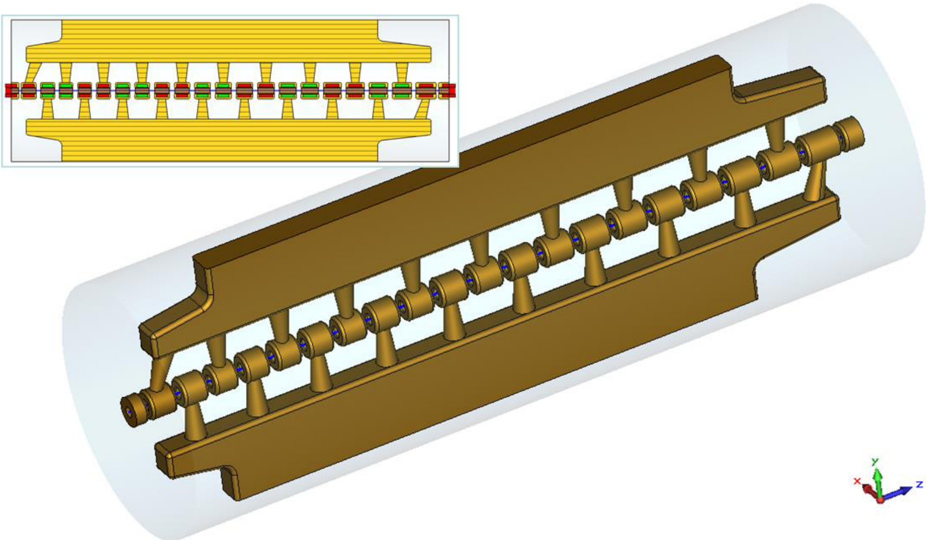

Fig. 6. CST model of IH-PMQ tank with the outer wall removed. The inset shows cross section with PMQs (quadrupole magnet configuration FFDD) inside the drift tubes.

Fig. 7. Drift tubes installed on the bottom part of the IH cold model. The top part is not yet inserted here.

The peak RF power for the above cavity is only 25 kW, and its thermal management at 10% duty is simple, by water cooling only in vanes [Kurennoy et al. (2012)]. Figure 7 shows a cold model built for the IH-PMQ cavity study. For the accelerator scheme in Fig. 3, a second IH-PMQ tank to bring deuterons to 4 MeV is required. It will be similar to the first tank shown in Figs. 6-7 but a bit longer, about 0.95 m, due to higher beam velocities after the first tank. The power required to run the second tank will correspondingly be somewhat higher than for the first one. However, due to the high efficiency of the proposed compact accelerator, RF power for the whole system can be provided by using only a few inductive-output tubes (IOTs).

2.3. Photon and Neutron Fluxes

The flux estimates based on data from Taddeucci et al. (2007) for a 1-mA current of 4-MeV deuterons on a ^{11}B target were already given in the Introduction: $5{\cdot}10^{10}$ $s^{-1}sr^{-1}$.15.1-MeV photons and 1-2 orders of magnitude more photons in 1-3 MeV range. For neutrons, the flux estimate is $2{\cdot}10^{10}$ $s^{-1}sr^{-1}$ at 14.1 MeV within ΔE = 0.1 MeV and significantly more below 5 MeV.

The preferred temporal structure of the deuteron current on target must be chosen from the detector requirements. Most likely, using multiple relatively short pulses, on the order of microseconds, would simplify actinide detection. The minimum pulse on/off time is primarily defined by an electrostatic chopper in the ion source transfer line before the RFQ and can be expected to be around 50 ns based on experience from the Spallation Neutron Source (SNS). The accelerator system can deliver duty factors up to 10% relatively easily; this would mean the peak beam current required for 1-mA average current is only about 10 mA. On the other hand, if higher instantaneous flux is required, the present system is capable of providing peak currents up to 50 mA. Such high currents would bring the instantaneous flux of 15-MeV photons into the 10^{12} $s^{-1}sr^{-1}$ range. The higher photo-fission cross section and better penetration for 15-MeV photons give advantages to the proposed system for SNM interrogation in comparison to the conventional bremsstrahlung approach.

3. Summary

The concept of an intense combined source of neutrons and photons for SNM interrogation is presented. The system is based on a compact RF accelerator of deuterons that consists of an RFQ followed by IH-PMQ structures. The accelerator delivers deuterons with energies up to 4 MeV to a ^{11}B target. The system can provide significant fluxes of both neutrons and photons with the energies of interest for interrogation. We have shown that the accelerator part of the system is feasible, however its design should be optimized based on the chosen detection scheme and detector requirements.

Acknowledgements

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