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A compact accelerator driven neutron source at the Applied Nuclear Physics Laboratory, Lund University

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Abstract

The Applied Nuclear Physics Group at Lund University has constructed a CANS (Compact Accelerator-driven Neutron Source). The CANS is based around a 3 MV, single-ended, Pelletron accelerator, which is used to impinge a 2.8 MeV deuterium beam into a beryllium target. The anticipated neutron production will be on the order of 10^{10} n/s in 4π sr, with future upgrades expected to increase neutron production to 10^{11} n/s. Neutron energy will be up to 9 MeV with peak emission at $\sim$5 MeV. Shielding and moderation will be provided by a large water tank surrounding the target, with exit ports to allow moderated neutrons to be directed to experiments. The thermal-neutron flux at the exit of the extraction ports is anticipated to be up to 10^6 n/cm^2/s. The CANS will be used to forward the activities of the group in the area of neutron-activation analysis, in addition to a broader range of neutron related applications.

Keywords: CANS; Pelletron; Deuterium beam; Beryllium target

1 Introduction

Since 2014, the Applied Nuclear Physics Group at Lund University has provided access to neutrons [1], with a well-established and user-focused infrastructure, emphasising expertise in nuclear physics and neutron-detection techniques. The use of these neutron has contributed to materials research [2] and detector development [3] related to the European Spallation Source [4, 5]. The Applied Nuclear Physics group also has a long history of accelerator-based research; from the development of PIXE [6] in the 1970s to advanced modern detector systems [7–9] more recently. In 2017, it was decided to combine these areas of expertise and construct a dedicated beamline for neutron production [10]. The new CANS (Compact Accelerator-driven Neutron Source) offers a significant increase in flux over the neutron sources currently used at the laboratory, with an initial neutron-production rate anticipated to be on the order of 10^{10} n/s in 4π sr and a further increase to 10^{11} n/s in 4π sr predicted [11]. The CANS is now entering the commissioning phase and, once fully realised, will be comparable to the Kyoto University Accelerator-driven Neutron

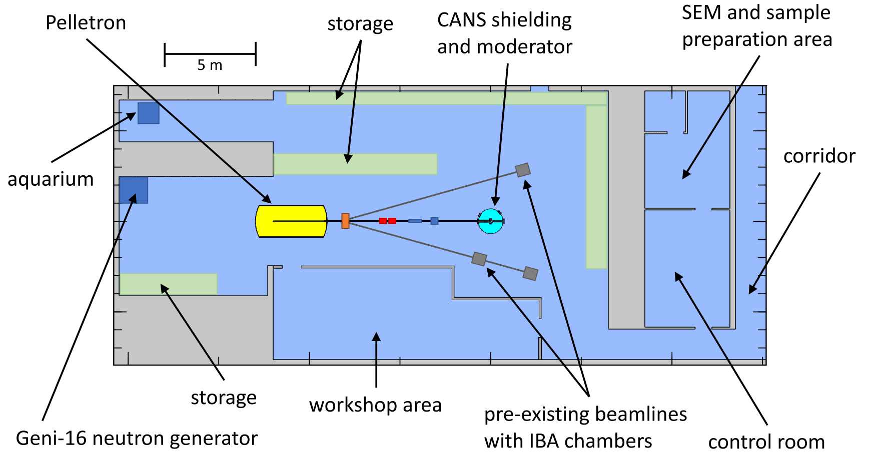


Figure 1 Floor plan for the Nuclear Applications Laboratory, Lund University, with key features of the layout, and major infrastructure components, labelled. The new CANS, which must compete for space in already busy laboratory environment, is place between the pre-existing IBA beamlines

Source [12]. A schematic overview of how the CANS fits into the pre-existing laboratory environment is presented in Fig. 1. The CANS will use a 3 MV, single-ended Pelletron accelerator to impinge a 2.8 MeV deuterium beam, with currents from 10 to 100 A, into a beryllium target. Resulting neutron energies will be up to 9 MeV with peak emission at $\sim$5 MeV. Pulsing of the neutron source will be made possible by periodic deflection of the beam into a tantalum beam-dump. Shielding and moderation is provided by a large water tank surrounding the target.

2 Infrastructure at the Nuclear Applications Laboratory

The primary workhorse of the laboratory over the past 30 years, has been a single-ended NEC-3UH Pelletron accelerator, commission in 1990 [13]. This machine has been used primarily for ion-bean analysis, with the application of PIXE, RBS, STIM, NRA, ERCS to a wide variety of fields. Examples of the work conducted are: geology [14–17], medicine [18, 19], biology and ecology [20–23], meteorology [24], detector development [8, 25, 26], characterisation of nano-structures [27] and astro-geological materials [28, 29]. It is this Pelletron that has been re-purposed as the CANS system.

As well as a comprehensive inventory of α-particle, β-particle and γ-ray sources, the laboratory also possesses a number of radioactive neutron sources: ^{252}Cf, AmBe, PuBe: with a neutron-production rates on the order of 10^6 n/s in 4π sr. A dedicated irradiation area, incorporating 2.75 m^3 water filled shielding-tank, is installed to utilise these sources. The shielding tank, or “aquarium”, has four ports to allow fast neutrons to escape. This set-up has been used extensively in work on γ-ray and neutron tagging [30–32], and neutron detector development [33–35]. In 2019, a GENI-16 neutron generator from SODERN [36] was installed to provide access to fast neutrons with a significant increase in neutron flux. The GENI-16, owned by SKB (Swedish Nuclear Fuel and Waste Management Company), has a neutron production rate of 10^8 n/s in 4π sr. It has been used in work related to nuclear safeguards [37], and also in the prototyping of a cyclic-NAA (Neutron-Activation Analysis) system [38, 39] which will ultimately be moved to the CANS.

The laboratory has and a triple γ-ray Ir spectrometer, which has been used in astrogeological research [40, 41], and can measure concentration of iridium in sample down to parts-per-trillion. In addition to the detector systems associated with the various experimental set-ups, a wide variety of infrastructure is available. This includes a range of scintillation materials and photomultipliers, HPGe detectors, ^{3}He tubes, a number of multichannel full digitisers and a 200 channel VME data-acquisition system.

3 Motivations for a CANS

Broadly, the motivation for the development of a CANS at Lund University is to expand the existing efforts in neutron related research, but the immediate application will be in the field of NAA. The Nuclear Applications Laboratory has a history in NAA, that has previously relied on reactor based irradiation of samples but a new, in-lab, cyclic-NAA system is now being developed. A prototype of the new NAA system is currently in operation, with the Genie-16 neutron generator used in place of the CANS which will drive the final configuration. High resolution γ-ray spectroscopy and γ-ray coincidence spectroscopy will be performed by an array of high-purity Ge detectors, positioned adjacent to the accelerator control room. Sample loading and unloading will be performed at the location of the measurement station to remove the necessity of having to enter the accelerator hall. The cyclic-NAA system will be used to monitor for the presence of specific radionuclides in environmental samples, taken from around the European Spallation Source [42, 43].

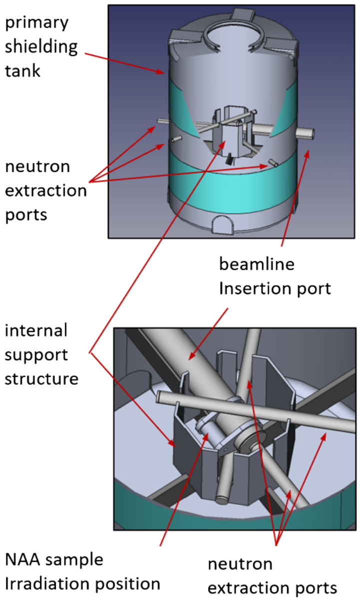
In addition to NAA, the CANS is intended to be used: in the develop novel state-of-the-art instruments and methods for the characterisation of spent nuclear fuel, with the purposes of nuclear safeguards; to test and categorise detectors for neutron scattering instrumentation; for work on thermal-neutron tagging; and as an educational platform. Further to these specific motivations, the commissioning of this CANS is part of a larger move towards a CANS network for Europe. At present, several CANS are either being designed or constructed with Europe, including HBS Jülich [44], ESS-Bilbao [45] and SONART [46]. For comparison, Japan boasts a wide a highly integrated network of neutron sources, with large spallation sources such as the Japan Spallation Neutron Source [47], reactor based sources such as JRR-3 [48] and a backbone of CANS facilities [49]. The move towards this network of CANS in Europe is becoming increasingly desirable as the available beam-time at conventional reactor facilities declines [50].

4 Compact neutron source development

The CANS will generate neutrons by the Be(d,n) reaction [51], using a 3 MV, single-ended Pelletron accelerator to impinge a deuterium beam into a thick beryllium target. Deuteron-beam energy will be up to 2.8 MeV with a current of 10 μA, although and upgrade to the ion source of the accelerator is planned which is anticipated to raise the current to 100 μA. At the presently available beam current, the anticipated neutron production will be on the order of 10^{10} n/s in 4π sr with peak neutron emission at an energy of $\sim$5 MeV. The experimental hall in which the Pelletron accelerator is stationed, was formerly used for an electron synchrotron accelerator. The control room for the experimental hall is therefore already well shielded, with a 2 m thick wall. Due to the existing neutron related research activities that take place in the experimental hall, the majority of the other licensing requirement with regards to radiation protection are already fulfilled.

The 9 m long, high-vacuum line that will carry the deuteron beam to the target position is constructed at 0° to the exit of the accelerator. A total of five dipole magnets, four inside

Figure 2 Concept for the primary-shielding and moderator construction, based on a 3000 l tank of de-ionised water. The internal structure supports the ports for beamline insertion and neutron extraction, as well as providing a fixing point for sample irradiation for NAA



the accelerator pressure vessel and one at 2 m from the accelerator exit are used to position the beam. A pair of quadrupole magnets are positioned at 5 m from the accelerator exit, and are used to focus the beam to a diameter of 1 cm on the target. Following the quadrupole magnets, a fast electrostatic-deflector is positioned to allow the beam to be periodically deflected into a Tantalum beam dump. In this way the neutron source can be run in pulse mode with an adjustable duty cycle, and pulse widths down to 25 ns. A number of viewing ports with optical cameras are positioned along the beamline, each with an electrically isolated florescent screen that can be moved into the path of the beam to measure its current and view its profile. A movable Faraday cup is also positioned at 1.5 m from the target. The target itself is a 2 mm thick piece of beryllium, mounted to an electrically isolated flange, externally cooled with deionised water. Current measurement is also made from the target flange.

Shielding and moderation will be provided by a 3000 l water tank surrounding the target, with additional shielding provided by layer of layer of Mirrobor$^{\mathrm{TM}}$ [52] and high-density polyethylene. Illustrations of this construction can be seen in Fig. 2, the design being developed in collaboration with Cipax AB [53]. A total of four ports penetrate the tank, one to facilitate the insertion of the beamline and three for the extraction of neutrons. The three neutron-extraction ports are presently planned to be aligned at 0°, 30° and 150° to the incoming deuteron beam. The lower angle ports will extract a higher proportion of fast neutrons, while the higher angle ports will extract a greater proportion of thermal neutrons. Figure 3, shows simulation results, generated in PHITS [54–56], which illustrate the higher neutron flux and neutron energy produced from the target in the forward direction. Neutron flux at the NAA irradiation position is expected to on the order of 10^8 n/cm^2/s, this rising to 10^9 n/cm^2/s with the planned upgrade.

5 Summary and outlook

The Nuclear Applications Laboratory at Lund University already boasts a well-developed infrastructure, incorporating a variety of sources of ionising radiation, with a long history

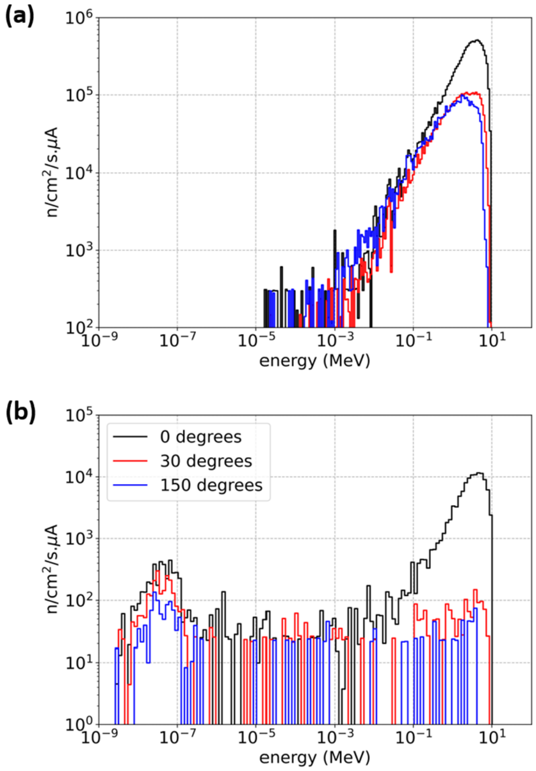


Figure 3 Simulated neutron energy spectra, with intensities normalised to units of n/cm^2/s·µA in reference to the deuteron beam current. Binning of the histograms is according to the CCFE-709 energy-group structure. (**a**) The source without shielding and moderation in place, for a 2.8 MeV deuterium beam. The influence of the forward momentum of the beam can clearly be seen in the increased neutron flux and neutron energy in the forward direction. (**b**) At the exit of each of the three neutron-extraction ports

of applied nuclear physics research. A CANS is soon to be added to the existing infrastructure, based on a deuterium beam and a beryllium target. The CANS is predicted to produce thermal neutron fluxes of around 10^4 n/cm^2/s, and fast neutron fluxes of around 10^6 n/cm^2/s, at the exit ports to the shielding assembly. The initial use of the CANS will be the implementation of a cyclic-NAA system, for which samples to be measured are expected to be irradiated with fluxes of around 10^8 n/cm^2/s. A future upgrade of the accelerators ion source is anticipated to increase all neutron fluxes by an order of magnitude over the aforementioned values. The new CANS is aimed at providing proof of principle for a dedicated CANS within Scandinavia, adding to the planned network of CANS for Europe.

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Availability of data and materials

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Competing interests
The authors declare that they have no competing interests.

Author contributions
All authors read and approved the final manuscript.

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