

# Facility report on the Low Energy Neutron Source

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**Abstract.** The Low-Energy Neutron Source (LENS) at Indiana University is a new class of pulsed neutron source, whose cost and scale are compatible with a University environment. This smaller scale supports missions that are vital to the health of neutron scattering in an environment increasingly dominated by large user facilities focused, of necessity, on serving the scientific needs of a broad scientific community. These missions include student education and development of new technologies to play as well as scientific investigations that are compatible with relatively low neutron flux. Since LENS first started producing neutrons (in 2005), this idea has been taken up in a number of other locations throughout the world, as exemplified in the formation of the Union of Compact Accelerator-driven Neutron Sources, which has already held two international meetings. LENS itself is now operating regularly with two scattering instruments at a beam power of 4kW, and these instruments are producing scientific results, educating many students at all levels, and providing a center for innovation in neutron instrumentation. Over the last two years, we have implemented changes to the RF power systems and beryllium target at the facility, and these changes have significantly enhanced beam reliability. In this summary, we will describe these changes to the facility design, and highlight a number of the important results that have arisen from our research, innovation, and educational activities over the last two years.

## 1. Introduction

LENS was constructed as a new type of neutron scattering facility, one based on low-energy (p,n) reactions using a beryllium target. A facility such as this is relatively inexpensive to construct and operate (the total construction budget for the facility was on the order of \$15M, and our current operating budget is less than \$400K/yr), and yet it can provide a flux of neutrons sufficient for conducting targeted materials research. Moreover, the flexibility offered by such a facility (in terms of changes to beam time structure, source configuration, and instrumentation design) makes it an ideal tool for testing novel ideas in neutron instrumentation and an invaluable facility for education. Over the last two years, these features of this sort of source have produced a significant world community interested in similar facilities. In recognition of this, the Union of Compact Accelerator-driven

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Neutron Sources (UCANS) was born shortly after the ICANS-19 meeting in Grindelwald to enhance opportunities for technical exchanges among the various projects world-wide that involve similar facilities and two meetings of this new organization have already been held [1]. The LENS facility has two target stations, one with a solid methane cold source that is devoted to materials research and instrumentation development, and another that produces a fast and epithermal neutron beam for radiation effects and radiography research. At the present time, LENS is operated by Indiana University for internal and collaborative research, and operations funding is based on a fraction of the indirect costs generated by the research grants that make use of the facility. Therefore, access to the facility is primarily through collaborative research projects with scientists at the facility, as well as some beam-for-hire work (particularly on the fast-neutron target station). We encourage all with interesting research projects that could make use of our instruments to contact us to schedule suitable beam time.

Over the past two years, the reliability of the facility has been steadily increasing through the changes described below. Our SANS instrument has been used in a number of studies of material structure, and the SESAME instrument has completed its initial commissioning. We are in the middle of an extended (6 week) shut down during which we are taking a number of steps to increase the capabilities of the facility. The main vault for the cold moderator station was designed to accommodate up to 4 instruments, but to date we have only deployed two. We are exploiting this shut-down to modify the primary shielding enclosure in anticipation of the construction of future instruments. During this time we are also modifying the fast neutron target station to remove some undesired moderating material and to provide capabilities for exposing larger circuits to radiation with the facility.

## **2. Upgrades to the LENS source**

In operating LENS over the last 5 years, we have encountered two primary causes of beam down-time. We have experienced a number of target failures, and the legacy RF power systems used to drive the accelerator have been less reliable than one would have hoped for. Over the last two years we have taken significant steps to alleviate both of these issues.

### *2.1. RF power systems*

With assistance from experts at Los Alamos National Lab, we have replaced the original Litton L-3408 injectron switch tubes used to control our klystrons with CPI emac division Y-847B tubes. The former tubes are no longer being manufactured, and a number of them failed during use in LENS. Furthermore, as these tubes approached the end of their life, they could force RF trips at intervals as short as an hour or less. After the failure of the last of the Litton tubes we had in stock, we were forced to run the facility at 7MeV for several months while waiting for the first prototype of the new tube to be delivered. The collaboration with Los Alamos has also significantly increased our energy efficiency by reducing the switch-on and switch-off times for the power systems. Another source of trouble in the RF system has been water contamination in the oil in the HV tanks due to high humidity (as well as the occasional water leak). We have now purchased an oil purification system which has helped considerably. Presently we experience roughly two to three RF trips per day when operating at our standard power level of 3 to 4 kW, and beam recovery from one of these trips takes on the order of 20 minutes. We have established a sufficiently stable operating point for the accelerator, that these recoveries can be performed by properly trained instrument users (e.g. graduate students). We have not been able to determine a component responsible for these trips. In addition to the above-mentioned

modifications to the two target systems, our present 6-week shut down will be used to clean the oil and look into other aspects of the HV tanks in the RF in an effort to increase our reliability.

## *2.2. Beryllium Target*

Another frequent point of failure for LENS operations has been the target, and our target cooling system and the target itself have undergone major revisions in their design over the last two years. Our basic target design is a simple flat-plate geometry with water cooling on one side of the target, and the target itself acting as the window to the proton delivery system. In order to accommodate our then-anticipated ultimate power of a few dozen kW, the target was inclined at 45 deg to the proton beam, had an overall area of approximately 150 cm<sup>2</sup>, and was 4 mm thick (to withstand the static load imposed by the cooling water over this area). As discussed at the previous ICANS meeting, we experienced a number of target failures associated with the build-up of “gunk” on the back of the target which greatly reduced the heat transfer to the water and led to cracks in the target. This issue was overcome by simply adding sodium nitrate and a sacrificial element to the cooling loop. We also discovered that the soft aluminium vacuum seals we had originally chosen for the target tended to fatigue rather quickly, so these were replaced with elastomer seals. These elastomer seals have functioned very well thanks to the small radiation levels (compared to most neutron sources) near the LENS target.

Together, these changes increased the reliability of the vacuum system to the point where we could run for several hundred hours without difficulty. However, once we reached this level of reliability on the vacuum and cooling systems, another problem with the initial target design became apparent. After several hundred hours of operation at 4kW beam power, the front surface of the target was observed to crack and or blister as a result of hydrogen build-up (to a concentration of roughly 1%, far above the solubility in Be) in the Bragg peak at a depth of roughly 1 mm beneath the surface of the target. This problem was particularly acute when we were forced to run at 7MeV, since at this lower beam energy the Bragg peak is even closer to the surface of the target. This pointed to an intrinsic flaw with our original design, and to overcome this we reconfigured the design to employ a thinner target (1.2 mm) oriented perpendicular to the proton beam, so that the protons range out in the cooling water rather than in the target itself. Not surprisingly this change exacerbated the water chemistry problems, and consequently we have now revised our water loop to include an ion-exchange column (Pentek model BBF1-20MB). We now monitor the water resistivity and total dissolved solids and replace the exchange column whenever the resistivity drops below 1 M $\Omega$ -cm (in practice this amounts to every 4 months or so). We have experienced no target failures associated with water or hydrogen problems in the year since these changes were implemented. We did experience one failure of the elastomer seals (buna-N seals had been used), but these have now been replaced with viton seals and in this final configuration we have yet to experience a target failure (over approximately 1000 hours of operation at 3 kW).

The new target design is cheaper, more straight-forward to replace, and smaller than the original design. Like all operations at LENS, target exchanges can be performed with only modest exposure to the workers even without elaborate remote handling facilities.

## *2.3. Neutronic Performance*

The changes to the proton delivery and target systems over the past year have provided some interesting insight into the neutronics design of LENS-type sources. In figure 1 we show spectra

recorded by the beam monitor of the LENS SANS instrument for three different operating conditions of the LENS source (two different energies and two different target configurations). The change in target design involves at least two features that one might naively have expected to reduce the cold flux available to the instruments. First, there will be some reduction in primary neutron production since the target is no longer thicker than the proton range (although we endeavoured to minimize this by having the majority of the protons leaving the target after their energy fell below the 1.9 MeV threshold for neutron production), and second, the target was moved considerably further away from the moderator (which would be expected to reduce the geometric coupling between the two). Comparison of the two 13 MeV curves in figure 1 demonstrates that the target configuration change actually resulted in a slight increase (by roughly 25%) in cold flux at the instrument, presumably because the additional water between the target and moderator acts as a better premoderator to increase the neutronic coupling. We also note from looking at the same two curves that flux at energies above the cut-off imposed by the SANS instrument's Be filter is reduced slightly in the new target configuration (since the target itself has now been moved back out of the line of sight available to this instrument). Thus this target change resulted in a significant increase in the signal to background ratio for this instrument.

Figure 1 also demonstrates that the change in going from 7 MeV to 13 MeV in proton energy results in roughly a factor of 3 gain in the useful cold flux at the instrument (and this is essentially independent of energy within the range of energies employed by this instrument). This is comparable to, but slightly less than, the factor of 4 increase in cold neutron flux we anticipated from this increase in energy [2].

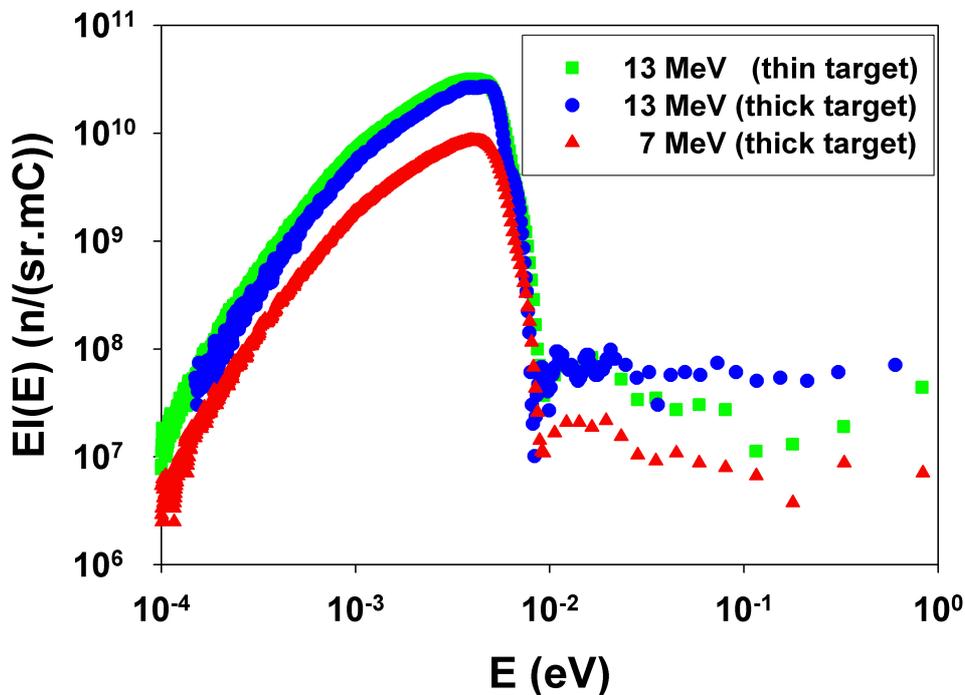


Fig. 1 Spectra delivered to the SANS instrument at LENS with three different target conditions (the original, thick target design with both 7 and 13 MeV proton beams, and the newer thin target design at 13 MeV). Note the thin target design provides an increase in cold flux associated with a slightly reduced flux above the cut-off of the Be filter on this instrument.

### 3. Instrumentation Development

#### 3.1. Moderator System Development

The LENS system was designed with a need to support an experimental neutronics program in mind, and such research has been a significant effort at the facility since its inception. The choice of materials in the target area, and the low energy of the proton beam allow us to extract the moderator system only a few days after full power operation (typically we shut beam down on Friday, and extract the moderator on Monday). As with the exchange of targets above, this is done without sophisticated remote handling, and contact dose rates at the are typically under 2 mSv/hr even at the most active locations on the moderator vacuum vessel at this point. In a typical experiment investigating moderator neutronics, we investigate 4 or 5 different moderator configurations within a two-week period. These experiments are typically performed with a beam power of a few hundred watts (e.g. 0.012 msec pulse widths at 45 Hz for emission time measurements, ~0.10 msec pulse widths at 10 Hz for spectral measurements) , and at these power levels, we can extract the test moderator after allowing roughly 12 hours of decay time.

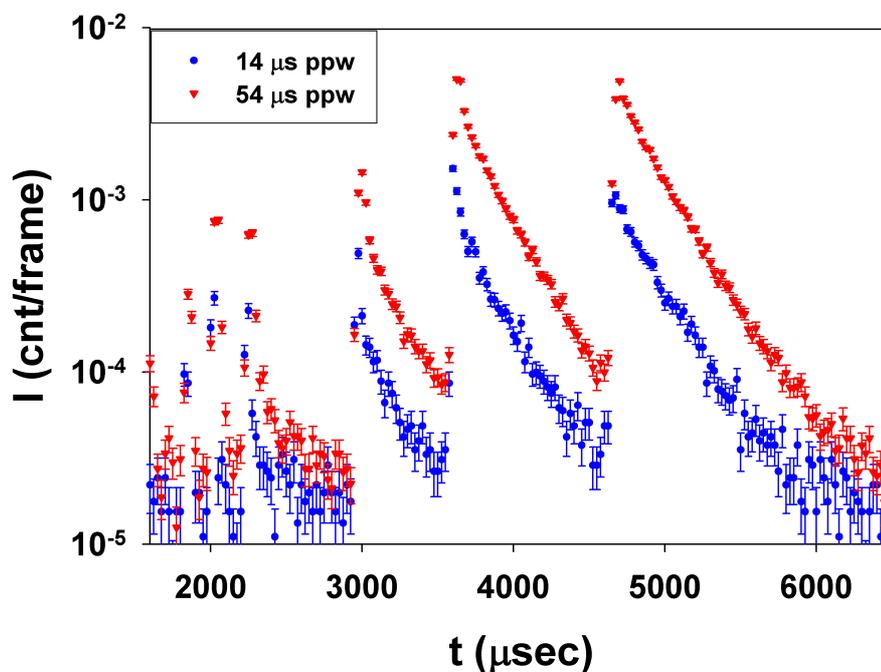


Fig. 2 Emission time measurements from the standard LENS methane moderator taken with a time-focused spectrometer using the (111) reflections from a Ge crystal held at 11K with two different

proton pulse widths and 25  $\mu$ sec time bins. In each case the data were collected over roughly a 5 hour period. Note that, not surprisingly, the shorter pulse width affords a better view of the short-time behavior of the moderator (leading edge in peaks at 90 and 140 meV). With the longer pulse width, and a data collection time on the order of 24 hours, the tails of the peaks could be explored over about 3 decades in intensity. Background count rate for this detector is roughly 0.42 cps ( $10^{-5}$  /frame.25msec bin) with the beam on, which is about 25% above the dark count rate for the detector.

This capability has been used to confirm calculations on the relative performance of Cd and Gd poison plates for the SNS and to investigate the spectrum from liquid hydrogen at different ortho to para ratios. In addition to measurements of neutron spectra, we are also able to measure the emission time distributions of candidate moderators as demonstrated in figure 2 (where we explore the emission time characteristics of the LENS methane moderator at two different proton pulse widths). For coupled moderators, we can study the tails of over up to three decades in intensity (at least near 4.5 and 40 meV). Presently, we are engaged in research on pelletized moderators and convoluted moderators in which a moderating material is interleaved with single crystals of silicon [3]. This latter program grew from an idea put forward by Stuart Ansell of ISIS (and first investigated at LENS), and is described in greater detail elsewhere in these proceedings [4]. The essential idea is to use the crystals as an extension of the concept of a grooved moderator by making it more efficient (by eliminating the need for extra vessel material to define the grooves) and flexible (since you have much more control over the thickness and distribution of the ‘grooves’). The presence of silicon in the grooves also affords an opportunity to exploit additional features beyond those available to the traditional design (such as refractive and Bragg effects for slow neutrons and nuclear scattering within the “grooves” for faster neutrons). Our results to date have demonstrated that the flux can be increased by an amount comparable to that seen in a grooved moderator, with a remarkable strong angular dependence, and that this gain in intensity is primarily seen in the peak flux, not simply in the tail of the emission time distribution [4].

### *3.2. Spin manipulation technology*

Another significant area of instrumentation development at LENS is devoted to the study of various techniques for manipulating the neutron spin, and exploiting the spin to encode useful information about material structure. This work, supported by an “Instrumentation for Materials Research” grant from the NSF, includes efforts to develop new components, such as spin-flippers and Wollaston prisms that incorporate superconducting thin films and/or magnets, RF spin flippers suitable for MIEZE techniques, and components suitable for spherical neutron polarimetry. We are particularly interested in demonstrating devices suitable for spin manipulation at pulsed neutron sources, and exploring the performance of such devices at long-pulse sources.

## **4. Materials Research**

The materials research mission at the LENS facility is primarily focused on large-scale structure of materials, but we also have an increasing interest in neutron radiation effects as well. We have three instruments dedicated to structural studies (SANS, SESAME, and high-energy radiography) and we

are currently reconfiguring our second target station to facilitate radiation effects research using neutrons with energies up to 11 MeV.

#### 4.1. SANS

The SANS instrument at LENS has a flux at the sample on the order of  $10^4 \text{ cm}^{-1}\text{s}^{-1}$  and a minimum  $Q$  of roughly  $0.005 \text{ \AA}^{-1}$ . One of the major areas of study on the instrument over the last two years has been the investigation of the structure of several fluids in meso-porous materials ranging from MCM-41 to coal. The scientific interests in this work range from fundamental studies of how confinement influences phase transitions and atomic structure, to more practical issues associated with the reactions between  $\text{CO}_2$  and geological specimens. This work has, for instance, confirmed the capillary condensation mechanism for fluid invasion in the coals, and has demonstrated a change in the fractal dimension of the coal upon invasion of  $\text{CO}_2$  [5]. In other work, the instrument has studied the evolution in shape of ellipsoidal micelles as a function of surfactant salt concentration and temperature [6]. We have also succeeded in characterizing the packing of RNA within the capsid of the Brome Mosaic Virus with this instrument [7]. We have found that the instrument is well suited to the characterization of mesoscopic structure in strongly scattering systems, and it is particularly useful in the case of parametric studies where sample equilibration times can be substantial.

We would also like to point out that this instrument also plays an important role in the our moderator development program, in that it provides a direct view of the moderator, can be easily modified into a time-focused spectrometer for emission time measurements, and can also measure total cross sections on candidate materials to energies as low as  $50 \text{ \mu eV}$ .

#### 4.2. SESAME(*Spin Echo Scattering Angle Measurement*)

The SESAME beamline at LENS is nearing completion, with an initial spin echo having been achieved on the beamline. The flux on sample is  $2400 \text{ cm}^{-2}\text{s}^{-1}$  and it has a maximum spin echo range of two microns. Initial measurements of nano-porous anodized alumina and depletion potentials in hard sphere polymers are already scheduled to begin by early summer.

Two major parts upgrades are also in progress for the beamline. As an alternative to the current 2D scintillating detector, an array of 24 linear  $\text{He}^3$  tubes, providing a resolution of 10mm by 4mm, has been built. The detector housing can be freely rotated to ensure that the finest resolution is in the direction of interest.

In addition to the spin echo work, the beamline has also worked as a test bed for polarized neutron measurements. RF flippers for the SNS have been measured on the beamline and measurements for a cryo-flipper have been scheduled for the spring.

The SESAME beamline has been an invaluable tool for education and R&D. Over the past 5 years, the beamline has created research opportunities for 5 graduate students and 3 post docs, who have worked on projects involving computer programming, power supply debugging, neutron detector design and debugging, motor control assembly and interface construction, and polarizer/analyzer efficiency measurements. We are currently in the process of designing and constructing the next generation of magnetic Wollaston prisms for use on the SESAME beamline at LENS and on other

beamlines across the country. The opportunity afforded to us through this beamline has allowed us to make advances in instrument development while avoiding the highly competitive beamtime application process at national labs. On the SESAME, we will be able to measure the effects of changing various geometric parameters of the Wollaston prisms on the neutron polarization. Of particular interest are the effect of wire shape and positioning in each prism.

## 5. Acknowledgements

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## 6. References

- [1] D. V. Baxter, "Proceedings of the first two meetings of the Union of Compact Accelerator-driven Neutron Sources," to appear in *Physics Procedia*, Elsevier, 2012.
- [2] C. M. Lavelle et al.
- [3] S. Ansell, first presented at the ACNS meeting in Ottawa Canada, (2010)
- [4] E. B. Iverson et al., elsewhere in this proceedings.
- [5] N. Das et al., unpublished
- [6] H. Cao, et al., accepted for publication in *Langmuir*
- [7] N. Das et al., unpublished,