

## The Low Energy Neutron Source-Status and Prospects

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### Abstract

*The Low Energy Neutron Source (LENS) at Indiana University uses a novel design for a neutron source that is suitable for operation on a university or industrial scale. The source is based on (p,nx) reactions in Be and it will operate in a long-pulse mode with a cryogenic moderator optimized for long-wavelength performance. It is being constructed to fulfill a three-fold mission of conducting materials research, educating the next generation of neutron scientists, and investigating new ideas in neutron instrumentation. LENS produced its first neutrons on 15 Dec. 2004, several months ahead of schedule, and is now embarking on a multi-year program of accelerator and power upgrades. Activities at the source have included spectral measurements from both room-temperature polyethylene and cryogenic methane moderators. The cryogenic system is capable of cooling the methane to temperatures as low as 3.6K. Tests of neutron radiation effects in transistors have also been conducted.*

### 1. Introduction

The Low Energy Neutron Source (LENS), which has been under construction at Indiana University since the Fall of 2003, produced its first neutron beam just before 11:00 PM on the 15<sup>th</sup> of December 2004. This facility is being constructed with money from the National Science Foundation, the State of Indiana's 21<sup>st</sup> Century Science and Technology Fund, the Department of Defense, and IU. LENS will run in a long-pulse mode, and will have a number of features that will allow it to fill a unique role in the world of neutron scattering. The facility has a three-fold mission for educating students and other researchers in the techniques of neutron scattering, conducting materials research with neutrons, and developing new technologies for neutron scattering. It will work closely with, and play a role that is complementary to, the Spallation Neutron Source (SNS) which will be starting operations within the next year.

LENS makes use of low-energy (<13MeV) (p,nx) reactions in a thick water-cooled Be target to produce neutrons with only limited build up of activity near the source. This approach is much less efficient in primary neutron production than the spallation process used at existing accelerator-driven neutron sources [1]. However, by making use of a high-current linear accelerator, operating in a long-pulse mode, and using a cryogenic moderator that is tightly coupled to the target, the facility can deliver a significant time-averaged cold neutron flux to its instruments. The limited activity built up near the source provides opportunities for conducting research into new materials and designs for neutron moderation, and its long-pulse mode of operation and low moderator temperature are attractive for exploring instrument designs suitable for future long-pulse spallation sources.

When complete, LENS will support a number of neutron scattering instruments, including a Small Angle Neutron Scattering (SANS) instrument, a neutron radiography station, and stations devoted to developing new neutron instrumentation concepts. Initially, one of these developmental beam lines will explore technology suitable for spin-echo scattering angle measurement (SESAME) [2]. This class of

techniques holds great promise for revolutionary improvements in instrument performance because it allows one to decouple the instrumental resolution from the incident beam phase space (thereby avoiding the trade-off between resolution and intensity that is inevitable with conventional neutron instruments). Similar techniques have been widely applied for increasing the resolution of inelastic scattering instruments, but the demonstration of these techniques for angular measurements has only been achieved recently and LENS will be the first facility to have a beam line devoted to these techniques on a long-pulsed source. Options for including additional instruments for neutron reflectometry, inelastic scattering, etc. are also being considered. A second target station to be devoted to studying neutron radiation effects in electronics [3] is also planned.

## 2. Novel Aspects of the LENS Design

LENS is presently making use of an ACCSYS PL-7 linear accelerator that had previously acted as the pre-injector for an electron-cooled proton storage ring (the Cooler) at IUCF [4]. This accelerator has been modified to accelerate protons (rather than the H<sup>-</sup> ions previously required for Cooler operations) with an increased duty factor compared to what had been required for its previous duties. With this accelerator and its extant RF system (with a peak power capability of roughly 700kW), LENS is able to operate at roughly 0.4% of its eventual power (average current of up to 18  $\mu$ A). Figure 1 shows the major components of the facility as it exists today. In the fall of 2005, we expect to commission a klystron-based RF system that will provide a roughly 20-fold increase in beam power. Installation of a new RFQ in 2006 will bring the facility to an operating power of roughly 17 kW by allowing a significant increase in peak current (7 MeV, 50 mA peak, 5% duty factor). Plans for the facility call for an eventual increase in beam energy to 13 MeV

The low proton energy employed at LENS provides a significantly different radiological environment near the source than is found at spallation sources. The target produces very few hard x-rays (essentially only target impurities or Bremsstrahlung from delta rays lead to x-rays of more than 120 eV), and the gamma field is dominated by capture in the reflector and shielding material rather than reactions associated with the primary neutrons. Efforts have been made to minimize the residual activity near the LENS target in order to facilitate changes in the moderator system and in keeping with a desire to minimize the need for remote handling of radioactive materials at a university lab. Toward this goal, aluminum alloys are used wherever possible in the construction of the Target and reflector assemblies. Neutron fluxes in the vicinity of the moderator, when operating at full power, are only on the order of  $10^{11}$  n/cm<sup>2</sup>/s (figure 2), and the peak neutron energy is less than 11MeV, so we believe that this will not cause significant operational problems.

The design of the LENS TMR is shown schematically in figure 3. The target is surrounded by a light water reflector that is 50 cm in diameter and 50 cm tall. This reflector is in turn surrounded by a 15cm thick high-purity lead gamma shield from which it is isolated by a flexible borated material (Thermo 227A) to reduce activation within the lead. The lead layer itself is surrounded by two additional layers of caramel corn bricks (polyethylene beads mixed with borax and epoxy [5]). In our case, the boundary between the two brick layers contains an additional layer of lead to further reduce the gamma field outside the TMR. This lead layer is formed by casting a lead and epoxy combination in the bottom of the molds when forming each of the caramel corn blocks.

The reflector has been designed to accommodate a variety of cryogenic moderators up to a size of 15x15x5cm for studies of moderator performance. Larger moderator designs could also be accommodated with a modified reflector and target assembly. For the initial tests of the facility we have chosen a relatively thin solid methane moderator of dimensions 12x12x1cm. The premoderation provided by the water reflector affords the opportunity to use a thinner moderator than normally found at spallation sources [6]. This feature simplifies its construction and greatly reduces thermal transport problems for the cryogenic system. We anticipate a thermal load on the moderator vessel of less than 2W when the source is running at 32 kW of beam power on the Be target. The cryogenic thermal budget contains significant contributions from both fast neutrons in the moderator material and gamma absorption in the moderator can and high-purity Al member that links the moderator to the second stage of a closed-cycle refrigerator (Cryomech PT-410). This solid thermal link is made from 5N pure Al with a cross section of 2x1cm near the moderator. The first stage of the refrigerator is used to cool a radiation shield that surrounds the moderator, the thermal link, and additional polyethylene that is used to minimize the neutron leakage along the reflector penetration used for the cryogenics. The cryogenic system has been tested inside the TMR and a base temperature for the moderator vessel of 3.6 K has been achieved. In earlier tests of the system, electrical

heaters were connected to the moderator vessel in order to evaluate the performance with a simulated heat load. With an input thermal load of 2 W on the moderator vessel, the vessel temperature remained below 10 K, and with a 5 W load the temperature was less than 13 K. Based on earlier work at IPNS [7], we expect this system to achieve neutron spectral temperatures below 30 K for moderator temperatures as high as 12 K.

Given the absence of neutrons with energies above 11 MeV (for our eventual proton energy of 13 MeV), and the limited number of x-rays and gammas, we anticipate having much less difficulty with radiation-induced damage in the methane than has been experienced at spallation sources. With a suitable protocol for periodic annealing of the methane, we are confident that this system at LENS can be run consistently at temperatures below 15 K (and most likely, less than 10 K). A residual gas analyzer has been incorporated into the moderator gas handling system to monitor for any breakdown in the methane induced by radiation during the commissioning phase of the facility. We also note that the limited heat load, and small thickness of the moderator are expected to produce a thermal gradient of less than 0.5 K through the thickness of the methane, so we do not anticipate needing the Al foam typically used in cryogenic methane moderators at spallation sources.

Another crucial aspect of the LENS design is the Be target itself. The facility design makes use of nonlinear focusing elements (two octupole magnets) in the proton transport line to transform a nominally cylindrically symmetric Gaussian-profiled beam into a rectangular beam with an approximately flat distribution over a 6x8.5 cm area. The precise performance of this system depends on the quality of the beam produced by the accelerator, which will depart somewhat from the Gaussian ideal. Tests of the system will be conducted over the course of the next year with the present accelerator, and again in 2006 after the new RFQ is installed. At full design power we expect an average thermal load on the target of roughly 650 W/cm<sup>2</sup> which presents a substantial, but manageable, heat transfer problem. To ensure tight coupling between the target and the source, and provide maximum flexibility in the design, we will cool the target with the hypervapotron (HV) technique [8]. A combination of simulation and experiments with Freon have suggested that this technique can achieve a critical heat flux (CHF) of over 1.5 kW/cm<sup>2</sup> with water at a pressure of only 3 atm. and a 2m/s flow velocity over the target. Even greater CHF is achievable at higher coolant pressure, but in the case of the pulsed beam employed at LENS the limitation on the target is more likely to be thermal stress problems rather than simply the average thermal load. A simple flat plate geometry for the vacuum side of the target leads to dynamic stresses in excess of 500 MPa (beyond the yield strength of Be). Finite element calculations indicate that a pattern of grooves on the vacuum side of the target (2 mm deep, 0.5 mm wide, and on a 4 mm pitch) can limit the dynamic stresses induced by the full-power beam to below 100MPa, however static stresses near the base of the resulting pins are considerably greater and design efforts are continuing to reduce this. The patterned Be target of approximately 3 mm thickness will be bonded to an Al or Cu plate into which grooves have been machined for HV cooling. Final design for the high-power target is expected by late 2005.

### 3. Results

Initial commissioning work for LENS has been underway since January of 2005. This has involved moderator characterization, optimizing the performance of the linac and proton transport beam line, and assessing the collimation, shielding, and detectors associated with the SANS and radiography instruments. The initial neutron production was characterized with both the 2-D SANS detector and a low-efficiency <sup>3</sup>He transmission detector. At present, the SANS and radiography beam lines have been constructed with crude prototype instruments to facilitate the characterization of the TMR. More sophisticated instruments will be installed during the Fall 2005 power upgrade.

The first tests of the facility were conducted with a simple room-temperature polyethylene moderator replacing the cryogenic system and moderator shown in figure 3B. The linac was run with a peak beam current of 6mA, a pulse width of 150 μs, and a repetition rate of 15Hz (average beam current 14 μA). A time-of-flight spectrum was collected using a low-efficiency ( $4 \times 10^{-4}$ ) <sup>3</sup>He detector positioned 5.7m from the source [6]. A representative thermal neutron spectrum is shown in figure 4. It is seen that the measured spectrum is within a factor of two of the simulation in this case. This agreement is reasonable given uncertainties in the detector efficiency, nuclear data, and details of the geometry of this preliminary setup. The MCNP model used for our predictions of the cryogenic flux available from the facility may be expected to be slightly less reliable than this due to the extra complications coming from the cryogenic utilities etc. and the absence of an MCNP kernel for methane suitable for temperatures below 22K. These

results do confirm, however, that our model should provide a reasonable representation of the facility's eventual performance.

In anticipation of future activities in the area of neutron radiation effects, we have also conducted preliminary measurements of radiation damage in transistors during the initial commissioning of the facility as described in greater detail in another contribution to this conference [3]. Associated with these tests we have measured the neutron flux within the water reflector cavity formed by the neutron beam lines using a combination of activation foils, sulfur pellets and changes in transistor  $H_{fc}$ . These tests suggest a neutron flux in this region of  $4 \times 10^7$  n/cm<sup>2</sup>/s (+/- 30%) for energies below 0.5eV and a total flux on the order of  $10^8$  n/cm<sup>2</sup>/s for our present maximum beam power of roughly 120W. These measurements are within a factor of three of the thermal flux predicted by MCNP for this configuration of the TMR and within a factor of two of the predicted flux above 1MeV [3].

Neutron spectra obtained after the installation of the cryogenic methane moderator are shown in figure 5. In this case the data were collected with high-efficiency <sup>3</sup>He detector behind a Cd mask with a 5x20mm hole in order to avoid saturation of the detector and yet facilitate rapid collection of data as the moderator was allowed to warm. Each spectrum was collected in 10 minutes with the detector held 5.7m away from the moderator face. The moderator vessel temperature rose from 3.6K to 130K (at which point all methane had been removed) over a period of 7 hours while these data were collected. For these data, the source employed a proton pulse width of only 50μs at a peak current of 9mA to provide modest time of flight resolution at energies greater than 100meV. Due to limitations with the heaters presently installed in the cryogenic system, the methane was originally condensed into liquid and then frozen only once; no attempt was made to cycle through the freezing point to enhance the uniformity or density. The spectrum with the empty moderator exhibits a single dominant peak consistent with a 290K Maxwellian below the Cd cutoff, as the detector is essentially viewing a reentrant cavity moderator formed by the water reflector. This peak is reduced in intensity and shifted to lower temperature (160K), but it is not eliminated, when the moderator is filled with methane and cooled to its base temperature. For these tests, the beam line was not lined so it is most likely that these warmer neutrons are coming indirectly from the reflector and scattering off the front surface of the methane. The presence of a warmer spectral component is consistent with MCNP simulations for the present geometry, although in the simulations the temperature of the warmer component is considerably higher and its spectral weight is lower [6]. The long-wavelength portion of the spectrum obtained with a filled moderator at 3.6K is consistent with a Maxwellian distribution at a characteristic temperature of 25K. Future studies will confirm the origin of all components of the spectrum and determine whether the presence of the warmer components will interfere with the instrumentation planned for the facility. Further characterization of this spectrum as well as its dependence on the design, physical temperature, composition, and thermal history of the moderator will continue throughout the commissioning phase of the facility.

#### **4. Conclusions**

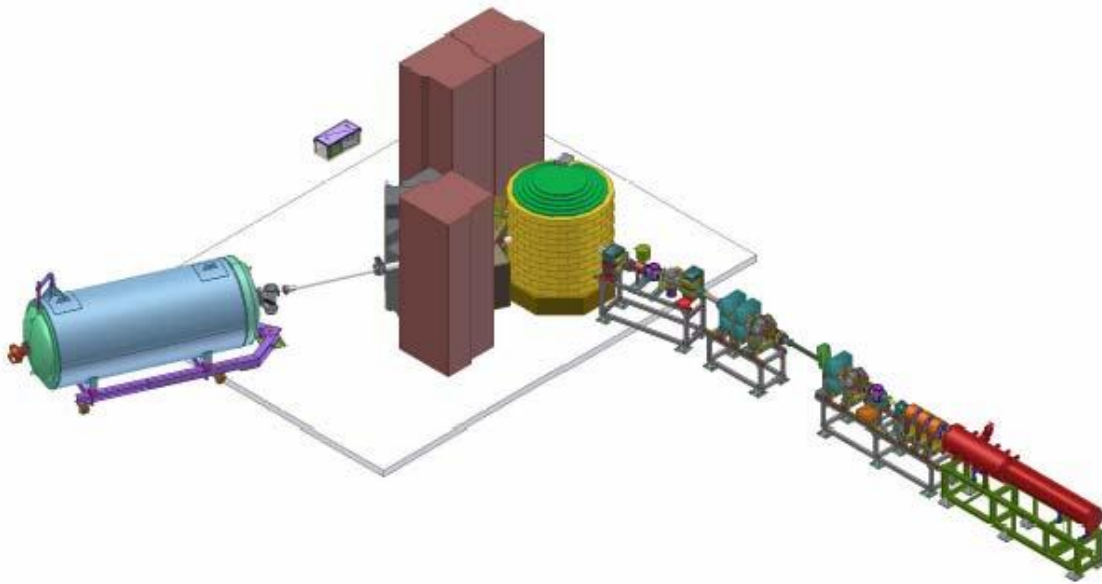
LENS has started its program of neutron scattering, education, and instrumentation development. Cold neutron spectra have been collected from its solid methane moderator and the results demonstrate an ability to cool the moderator to temperatures below 4K with a closed-cycle He refrigerator. Over the next several years the facility will undergo a series of power upgrades and improvements to its accelerator and neutron production target. To date the performance of the system is within the range of expectations and prototype radiography and SANS instruments have been constructed. The addition of a second target station devoted to studying radiation effects in electronics and the production of thermal neutrons is anticipated for the future as is the construction of additional instruments.

#### **Acknowledgements**

The LENS project is supported by the National Science Foundation (under grants DMR-0220560 and DMR-0242300), the 21<sup>st</sup> Century Science and Technology fund of Indiana, Indiana University, and the Department of Defense.

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*Figure 1: Overall schematic layout for LENS Phase I. Shown are the accelerator (right-hand of the picture), the TMR (vertical cylinder at the center of the picture), the SANS instrument, and the camera on the radiography station.*

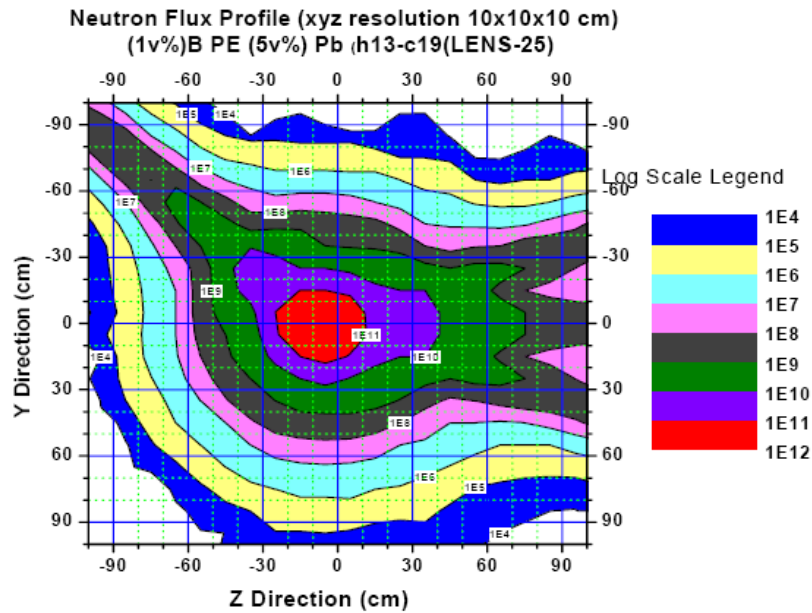


Figure 2: Displayed is the total neutron flux distribution in the equatorial plane of the LENS TMR when the source is operating at 13MeV and 32kW beam power as predicted by MCNP. In this view the proton beam enters in from the upper left corner and three neutron beams are extracted toward the right hand side. The methane moderator is centered at the origin and the Be target is positioned at  $z = -9\text{cm}$ ,  $y = 0\text{ cm}$ .

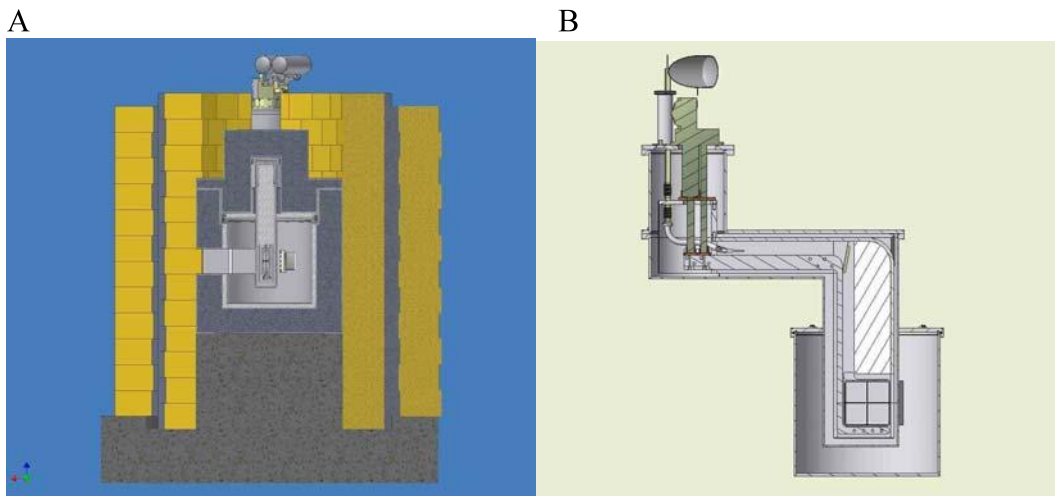


Figure 3: A,B Cross Sectional views of the LENS TMR assembly. The proton beam comes in from the right in figure A, and the neutrons are fed out to instruments on the left. Figure B shows details of the thermal connection between the closed-cycle refrigerator and the methane moderator at the center of the water reflector (which is 50cm in diameter). In B, the white hatched area is a polyethylene plug designed to limit neutron streaming upward and the high-purity Al thermal link is the gray hatched material to its left.

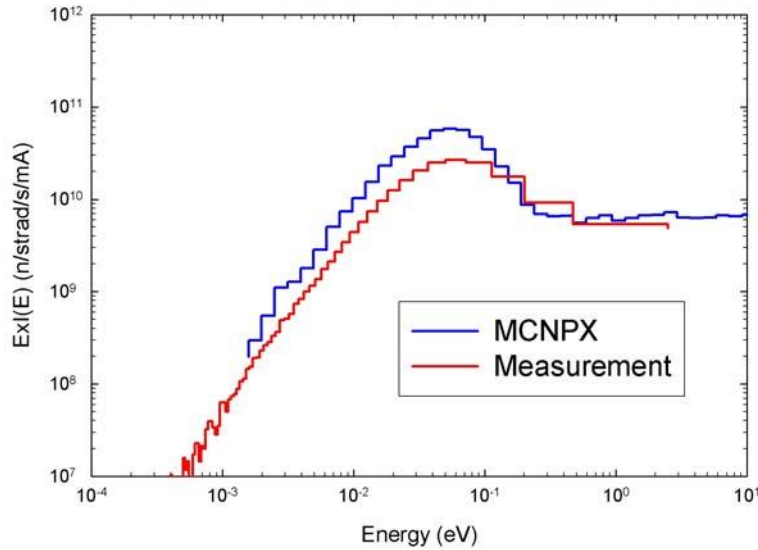


Figure 4: Comparison of a thermal neutron spectrum measured at LENS when operating at 7MeV with that predicted from MCNP calculations. The measurements were taken for a simple room-temperature polyethylene moderator and the measurements made with a flat geometry, low-efficiency  $^3\text{He}$  detector positioned 5.7m from the source and normalized with a set of bare and Cd-covered In activation foils positioned 1.4m from the source.

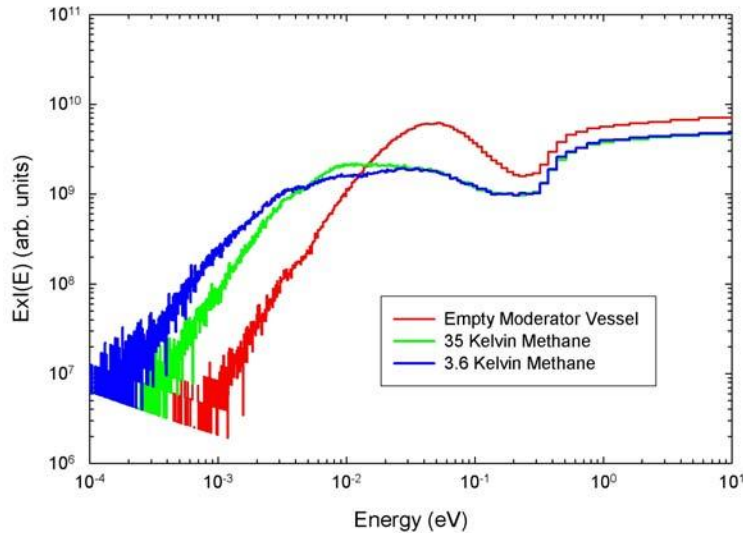


Figure 5: Neutron spectra collected after the installation of the cryogenic methane moderator. These spectra were taken with a high-efficiency  $^3\text{He}$  detector that viewed the source through a 5x20mm hole in a Cd mask in order to avoid saturation effects. The empty moderator spectrum was collected with the moderator vessel at a temperature of 130K after all methane had been removed. The 3.6K spectrum was collected with the moderator filled with methane and a small amount of liquid helium (the latter used to enhance thermal contact to the vessel). The intermediate curve was collected at a time when the moderator vessel temperature had risen to 35K. In this case, the actual temperature of the methane may be somewhat lower, as the methane was probably decoupled thermally from the vessel after the helium was removed.