A Cold Moderator For Sub-Thermal Neutron Flux Enhancement At The RPI-LINAC

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INTRODUCTION

The importance of high-quality thermal neutron scattering kernels coupled with a lack of accurate sub-thermal total cross section data prompted researchers at Rensselaer Polytechnic Institute (RPI) to design a cold moderation system to enhance sub-thermal neutron flux (defined as flux below 5 meV), for nuclear data measurements at the RPI Gaerttner LINAC facility. Using a series of neutronic and heat transfer simulations obtained with MCNP [1] and COMSOL [2], an optimized final design was produced. The final design exceeded current target sub-thermal neutron producing capabilities by a factor of 8 in the sub-thermal region and is easily configurable with existing neutron producing targets.

MOTIVATION

Nuclear criticality safety relies heavily on accurate neutronic computational tools to appropriately gauge the safety of a nuclear engineering design. Recent efforts to dramatically reduce the associated uncertainties imbedded in neutronic computational tools, such as MCNP, have increased an already heavy dependence on the underlying physics and nuclear data. In order to further improve these tools, experiments must be conducted to test the underlying physics and quantify the uncertainties in the nuclear data.

Criticality issues can easily arise from nuclear systems that rely on significant thermal neutron flux. In order to prevent these issues, the understanding of thermal neutron interactions needs improvement through accurate modeling and simulation. In the thermal region, a neutron's energy is on the same order of magnitude as molecular bond vibration and rotational energy, thus altering how neutrons scatter inside a medium. In order to account for these molecular effects, neutronic computational tools typically utilize a thermal neutron scattering kernel to complement the base nuclear data. However, these scattering kernels rely on accurate thermal neutron scattering measurements to inform the atomistic calculations of the phonon spectrum that the scattering kernel depends on. Scattering kernels start to heavily influence neutron scattering at 1 eV and only increase in importance as the neutron energy lowers. Therefore, accurate total cross section measurements encompassing the entire thermal region, quantified as 0.0005 - 10 eV, are vital for nuclear data evaluations to correctly represent the total thermal cross section. Accurate nuclear data evaluations of the thermal region are essential to criticality safety as this region can affect the neutron multiplication factor of a thermal system by upwards of 12%. [3]

Current accelerator and target configurations at RPI only generate very small sub-thermal neutron flux which corresponds with large statistical uncertainty. In order to enhance sub-thermal neutron flux, a cold moderator system is required. The idea of a cold moderator system was proposed before in a previous RPI study [4]. This study found that a cold moderator could enhance sub-thermal neutron flux by at least a factor of 5 over a moderator system at room temperature. The augmentation of sub-thermal neutron flux would result in significantly more accurate total thermal cross section measurements.

ENHANCED THERMAL TARGET

While the primary purpose of the cold moderator system is to achieve a large sub-thermal neutron flux, it is also intended to couple to an existing target as an augmentation attachment. The intended target is the RPI Enhanced Thermal Target (ETT) – a target that specializes in achieving copious amounts of thermal flux [4]. Displayed in Figure 1 is the front of the ETT from which neutrons emerge and travel to the detector. Here, an electron beam undergoes bremsstrahlung radiation inside a water-cooled tantalum target, producing neutrons via (γ, n) reactions. Surrounding the tantalum are graphite and lead bricks, with an opening for neutrons to emerge through a polyethylene plate before reaching the detector. The cold moderator system was designed to quickly couple to the side of the ETT when needed.

Fig. 1: ETT side view where neutrons leave in the direction of detectors.

PRELIMINARY EXPERIMENT

The first task in designing a cold moderator system was to select which moderator to use. A series of materials were investigated, including methane, hydrogen, mesitylene and water. Polyethylene was selected as the optimal material as it produced a good sub-thermal neutron yield and does not undergo phase change from room temperature to cryogenic temperatures. The latter point proved a major deciding factor for both consistency between measurements (i.e., different solid phases and crystalline structures forming) and safety to users. While polyethylene was believed to be the best candidate, an experiment was needed to validate neutronics calculations using the ENDF/B-VIII.0 thermal scattering kernel. [5]

Displayed in Figure 2 is the MCNP geometry of the setup used for the preliminary experiment. Placed in the neutron beam path is a piece of polyethylene surrounded by polystyrene. By taking this piece of polyethylene and cooling it down to near 77 K using liquid nitrogen, the impact on the neutron flux of the system could be explored.

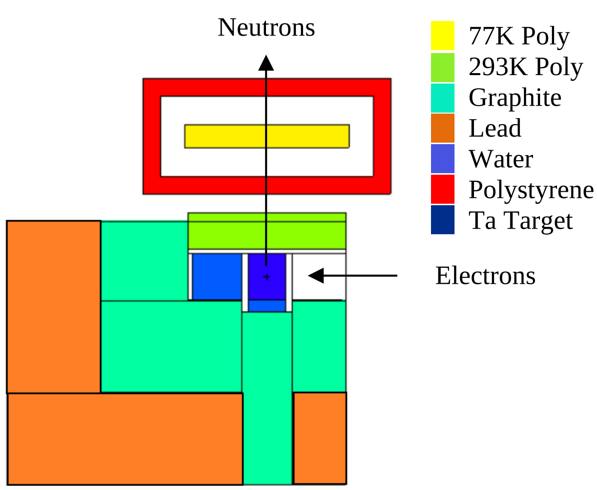

Fig. 2: Preliminary experimental setup to study the neutron flux shape from 77K polyethylene.

The results of the preliminary experiment are shown in Figure 3. It is obvious that cooling the polyethylene dramatically shifts neutrons to lower energies. The sharp peaks in the experimental data below 0.01 eV are believed to be Bragg peaks from 2.22 cm (7/8") thick lead between the target and the detector. It should be noted that a Li-glass detector was utilized for this experiment 15 m away in the direction of the neutron beam indicated in Figure 2.

Polyethylene at 77 K shows a remarkable improvement over 293 K, achieving a gain of 6 at neutron energies of 2 meV. Here, gain is referring to the integral number of neutron counts at 2 meV when the polyethylene block inside the polystyrene enclosure is at 77 K vs. 293 K. In order to gauge the impact on the sub-thermal neutron flux from further cooling below 77 K, the same configuration was simulated at 25 K, producing a gain of 10 over 293 K at 2 meV. This shows that the colder the polyethylene, the higher the sub-thermal neutron flux. Additionally, this preliminary experiment proved the ability to accurately predict system neutronic performance using MCNP and NJOY [6].

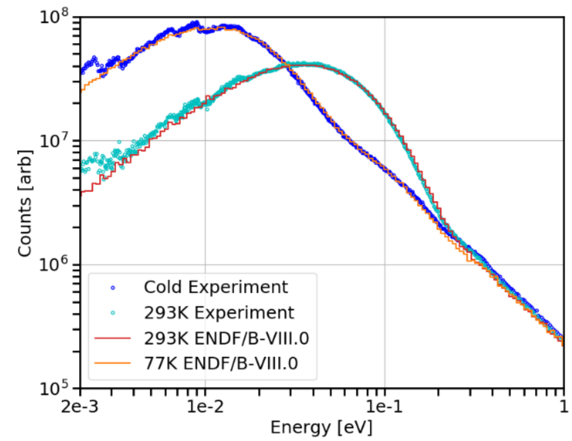

Fig. 3: Preliminary Experiment Results

NEUTRONIC AND THERMAL OPTIMIZATION

After the promising results of the preliminary experiment, the next logical step was to determine how to optimize the sub-thermal flux such that the gain, in terms of integral counts, over the ETT alone had a minimum factor of 3 in the 1-5 meV range. This essentially boiled down to deciding the correct size to create the cold polyethylene block and whether to include a pre-moderator. A 7"x7" polyethylene square block was selected as the smallest size for the polyethylene to completely cover the collimation system and provide adequate coupling to a cold finger. Displayed in Figure 4 is the neutronic optimization model used to determine ideal thicknesses of cold polyethylene and pre-moderator.

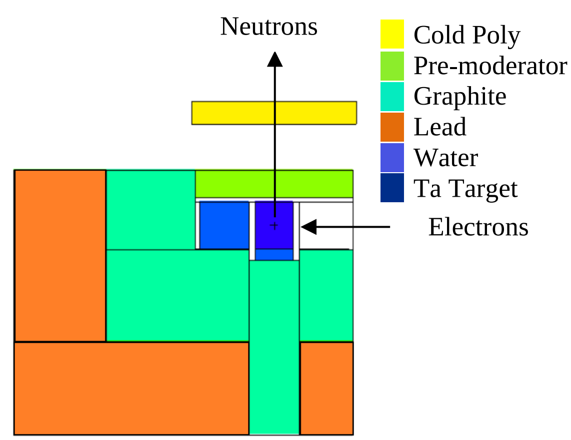

Fig. 4: Neutronic Optimization Model

The neutronics optimization indicated that 1” of cold polyethylene (yellow in Fig. 4) coupled with a 3 cm polyethylene pre-moderator (light green in Fig 4) was the optimal result. Polyethylene was selected as the ideal pre-moderator as it has a high hydrogen density and is a solid at room temperature – a key attribute that allows the cold moderator to be closer to the source of neutrons. Additionally, the neutronics optimization showed that the augmentation of the sub-thermal flux increases steadily as the temperature in the cold moderator drops but increases significantly the closer the cold polyethylene is to the neutron source. Therefore, a thermal optimization was needed to bring the cold moderator as close to the source of neutrons as possible while minimizing the temperature of the cold moderator.

The primary challenge from a thermal optimization standpoint is how to minimize the energy being deposited inside the cold polyethylene from particles escaping the target. Since the idea of the pre-moderator would entail a smaller piece of cold moderator, and thus a smaller heating load, this idea was selected as the optimal route. The basic concept behind the cooling of the polyethylene was to surround the polyethylene in two layers of a neutron-transparent material to make radiative heat transfer the only form of heating from the surrounding environment. The first layer encloses a layer of vacuum, the best insulator, to effectively cut off conductive and convective heat transfer between the cold polyethylene and the surrounding air. The second inner layer immediately encases the polyethylene to dramatically reduce the radiative heat transfer from the outer layer to the polyethylene. Therefore, the two layers also need to be composed of a material with a very low emissivity in order to minimize the amount of heat ‘leaking’ into the system.

In order to determine the level of energy being deposited in the polyethylene and surrounding components, MCNP energy deposition (EDEP) studies were performed. These EDEP values were then transferred to COMSOL Multiphysics to determine the average temperature of the polyethylene. While a variety of design concepts and variations were explored, the most optimal design was selected as a 1” piece of polyethylene with a 1/16” plate of aluminum inside to provide optimal cooling.

RESULTS – FINALIZED DESIGN

The optimization process yielded a final design that effectively cools the cold moderator, while keeping it as close to the source of neutrons as possible. Displayed in Figure 5 is the entire cryostat design alongside a side cross section, where the internal aluminum plate is clearly shown inside the polyethylene block.

Differences between polyethylene and aluminum in terms of the thermal coefficient of expansion were accounted for by placing the aluminum inside the polyethylene. A worst-case scenario was performed where the thermal contact between the polyethylene and aluminum was reduced by 40%. Despite this drastic reduction, the average temperature in the polyethylene only reached 25 K. This average temperature corresponds to a gain in the sub-thermal region up to 8 in the 1-5 meV region over the ETT alone. It should be noted that the cold moderator could very well reach temperatures below this during operation, but the worst-case scenario was investigated to conservatively estimate the sub-thermal neutron flux gain.

The neutron spectrum emitted from the final design, displayed in Figure 6, clearly indicates the peak shift from the thermal region to the sub-thermal region. The ETT coupled with the cold moderator begins to significantly improve over the ETT alone starting at 0.02 eV, increasing the rate of improvement as the neutron energy lowers.

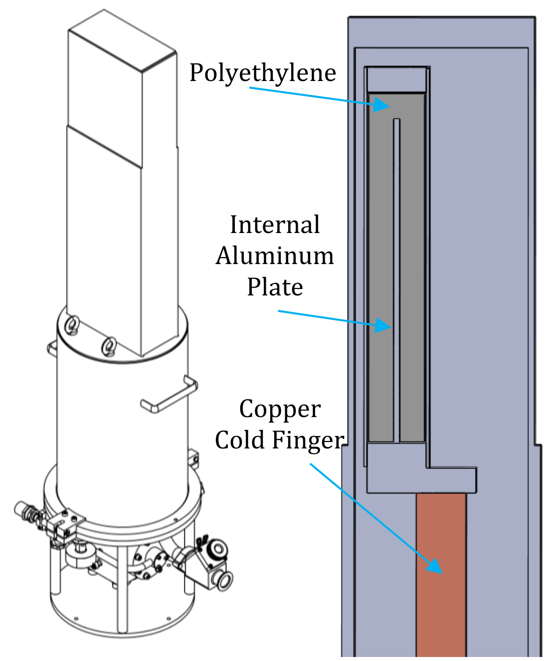

Fig. 5: (A) Entire Cryostat Design. (B) Cryostat Side Cross Section.

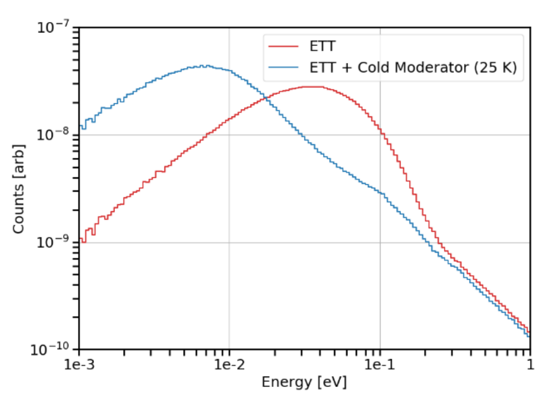

Fig. 6: Shifted Neutron Spectrum.

CONCLUSIONS

The coupled neutronic and thermal optimization for a cold moderator design was shown to produce a system that well exceeded the target specification of minimum required gain, while meeting all other constraints. Assuming the worst-case scenario, the cold moderator reached an average temperature of 25 K. This corresponds to a gain of 8 reached over the existing ETT alone for integral counts in the 1-5 meV energy range. The cold moderator system is easily portable, simply rolling in front of the ETT when a higher sub-thermal flux is desired.

Future work involves the testing of the system to ensure adequate cooling of the cold moderator under various LINAC beam loads. Additionally, total thermal cross sections measurements from 0.001-10 eV are planned for materials that require more accurate data in the sub-thermal regime and for materials which require a measured total thermal cross section. Currently, the primary material of interest is polystyrene, where a need for sub-thermal transmission measurements exists to support ORNL's thermal scattering library evaluation.

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