Abstract

The neutron target station of the Compact Pulsed Hadron Source (CPHS) is tasked to generate neutrons through accelerating protons (13 MeV, 16 kW, 50 Hz, ~0.5 ms pulse width) onto a beryllium target. The neutrons are slowed down through multiple scattering with the moderator and reflector media-solid methane and ambient temperature water, respectively, to eventually the thermal- and cold-neutron energies. In order to optimize the target-Moderator-Reflector (TMR) performance for CPHS, we carried out Monte-Carlo simulations of the neutronics regarding to neutron production and moderation. Here, we report the design concepts of the TMR assembly.

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Keywords: Pulsed neutron source; Neutron target station; Neutronics.

1. Introduction

The CPHS project, currently under construction at Tsinghua university, Beijing, China, is designed to produce a primary beam of 13-MeV pulsed protons with a pulse width of ~0.5 ms and a peak/average current of 50/1.25 mA at a repetition rate of 50 Hz. This 16-kW proton beam impinging on a thin beryllium target (thickness=1.2 mm, the 13 MeV proton range in beryllium is 1.28 mm calculated by SRIM2008 [1]) will generate ~5×10^{13} primary neutrons over an energy range of 0.1-11 MeV, with an average energy about 3.3 MeV. These neutrons, slowed down to cold-to-epithermal energies by a solid methane moderator-light water reflector assembly, are transported via beam tubes to serve several neutron instruments for materials characterization. The CPHS neutron facility is similar to the Low Energy
Neutron Source (LENS) of Indiana University, USA in the infrastructure, operation and scientific mission [2, 3]. Both CPHS and LENS belong to a class of Compact, Accelerator-driven Neutron Sources (CANS) in the world that serves various purposes of education, research and development, as well as technological applications.

The neutron target station of CPHS must fulfill three requirements: i) the target must allow a sustainable operation (4 weeks under full beam power) in the practice of neutron generation, ii) the TMR assembly, while producing high fluxes of cold neutrons, must avoid as much as possible the leakage of fast neutrons into the beam lines, and iii) the shielding effectively protects personnel and the environment against radiation hazards as well as suppresses noises that may interfere with data acquisition. Regarding to requirement i) thickness of the target has to be adjusted according to the energy-dependent proton ranges in the target so that its Bragg peak falls outside into the coolant [4]. This reduces target fatigue due to the thermal load, beryllium atom displacements, and formation of hydrogen bubbles within the target body. Many related technical issues are addressed by authors of papers in this Proceedings. Here, we considered the neutronics of the TMR design for item ii above. We carried out Monte Carlo simulations to assess the neutron-production performance under different TMR configurations using the MCNPX Code, V2.5 [5]. The results lead to a proposed design of the TMR assembly of which the engineering and operation of the cold moderator system are described in an accompanying paper [6]. We point out that our design parameters complement those of the LENS well so that the basic engineering structures of LENS’ beryllium target, solid methane moderator, and shielding are readily adoptable to CPHS.

2. Monte Carlo simulations of the parameters in TMR configuration

The configuration of the coupled moderator with respect to the target and the reflector, as shown in Fig. 1, was chosen for CPHS. The materials choice for these components has been decided based on previous considerations of CANS [7, 8], especially from the experiences of LENS, and hence not a concern of the present study. We assume the proton-beam characteristics as given by the accelerator system [9] and the attainment of the beryllium target in heat removal, structural integrity and other technical issues. Our primary objective is to calculate the expected neutron intensity distribution over the energy intervals of cold neutrons (<10 meV) relative to fast neutrons (>0.1 MeV). This is achieved by Monte Carlo simulations of the neutron transport in a modeled TMR medium according to the kinetic theory formulated by the Boltzmann equation, executed by the computer code MCNPX. Starting from neutron generation based on the input probability distribution for the Be (13 MeV-p,n) nuclear reaction, the neutron trajectories are calculated according to the neutron-matter interaction cross-sections and scattering kernels of the TMR media (solid methane at 22 K, light water, beryllium, etc.). Eventually, the neutron intensity profiles are obtained by tallying the emerging neutrons of selected energy intervals. The reliability of the MCNPX code in use with cross-sections and thermal scattering kernels has been demonstrated by numerous neutron source studies [10-13].

In all of the simulations, the 13-MeV protons distribute uniformly over a circular cross section with a diameter of 4.5 cm on the target; the thickness of target is 1.2 mm; the cladding and structure material are the aluminum; the fixed dimensions of key components as well as those to be varied over the proper ranges permissible by space consideration, are shown in Fig. 1. The cold-neutron intensity and the ratio of fast neutron intensity over cold neutron intensity were used for the optimization of parameter \( l_t \), \( t_p \) and \( t_m \), where \( l_t \), \( t_p \) and \( t_m \) are the offset of the proton beam relative to the neutron beam the Z-direction, the thickness of light water pre-moderator, and the thickness of solid methane moderator, respectively. The total cold neutron intensity and the ratio of \( I_{t11} \) over total cold neutron intensity were used to optimize parameter \( r \), the radius of the reflector, where \( I_{t11} \) is the integrated intensity of cold neutrons under the full width at one-tenth of the maximum.
Fig. 1. Schematic illustration of the TMR configuration. (a) the side view, and (b) the top view. Parameter $l_z$ is the offset between the proton beam center line and neutron beam in Z-direction, the thickness of pre-moderator $t_p$ is the separation of the target plate and moderator slab in X-direction, parameter $t_m$ is the thickness of the moderator, and parameter $r$ is the radius of reflector.

The cold neutron intensity and the ratio of fast neutron intensity over cold neutron intensity as a function of $l_z$ are shown in Fig. 2. $l_z$ was chosen to be 9 cm, preventing the instruments from viewing the proton footprint on the target. This offset of the neutron beam is effective in reducing the fast neutrons along the proton forward direction going to the beam lines.

Fig. 2. The cold neutron intensity and fast neutron/cold neutron intensity ratio as a function of $l_z$, the relative error of the data are less than ±0.8%. ($r=25$ cm, $t_p=2.0$ cm, $t_m=1.8$ cm)
The parameters $l_p$ and $l_m$ were optimized together because they are deeply coupled together, both of them will affect the neutron moderation, thermalization, and absorption. The effects of $l_p$ and $l_m$ are shown in Fig. 3. Parameter $l_p$ and $l_m$ were fixed to 2.0 cm and 1.8 cm based on the results of the highest cold neutron intensity.

![Fig. 3. The cold neutron intensity and fast neutron/cold neutron intensity ratio with respect to different $l_p$ and $l_m$ values, the relative error of the data are less than $\pm0.8\%$. ($R=25\,\text{cm}$, $l_c=9\,\text{cm}$)](image)

A larger radius for the reflector ($r$) yields higher neutron intensity, but the ratio of $I_{0.1}$ over the total cold neutron intensity decreases (as shown in Fig. 4). Neutrons returning from the outer part of the reflector mostly contribute to the long tail in the neutron pulse. Aiming at high cold neutron intensity under full width at one-tenth maximum area and a moderate reflector size, $r$ was chosen to be 25 cm.

![Fig. 4. Comparison of the cold neutron intensity relative to the fast neutron intensity as a function of $r$, the relative error of the data are less than $\pm0.8\%$. ($l_p=2.0\,\text{cm}$, $l_m=1.8\,\text{cm}$, $l_c=9\,\text{cm}$)](image)
3. The predicted performance of TMR

After the TMR was optimized, the neutronics performances were evaluated by simulating i) the neutron flux at the cold moderator surface over different energy intervals, ii) the neutron spectra serving the neutron beam line, and iii) the full-width-at-half-maximum (FWHM) of the neutron pulse at the moderator surface. All of the results were normalized to $7.8 \times 10^{15}$ protons per second, and the proton pulse width was set at 500 µs.

The obtained neutron fluxes at the cold moderator surface for energies (in meV) $E_n<10$, $E_n<25$, and $E_n<1.1 \times 10^{10}$ are $8.75 \times 10^8$, $1.25 \times 10^9$, and $5 \times 10^9$, respectively.

The spectrum of neutrons in the beam line (diameter=10 cm) at 10 meters from the moderator surface was calculated and shown in Fig. 5. The jolting features in the 0.02-0.2 MeV range of the neutron spectrum are due to resonances in the aluminum scattering cross-section.

The time structure of the neutron pulse was simulated by tallying the neutrons emitted from the cold moderator surface over the instruments side in forward angles ($\theta < 15^\circ$) over different time intervals. Then the FWHM of the neutron pulse was calculated, yielding the temporal response, as shown in Fig. 5. The FWHM is constant (~560 µs) for the solid methane in the cold neutron region due to the dominant exponential decay from Maxwellian distribution; the FWHM will decrease with the increase of the neutron energy in the epithermal region because fewer collisions with the moderator are encountered; the FWHM is dominated by the proton pulse width (500 µs) for fast neutrons.

![Fig. 5. Simulated neutronics performance of TMR configuration. The intensity distribution is the neutron flux within beam line at 10 meters from the moderator surface. The FWHM line of neutron pulse was calculated from temporal response of TMR system with 500 µs proton pulse width.](image-url)
4. Summary

A series of Monte Carlo simulations were performed for a variety of TMR configurations. Suppression of excess fast neutrons relative to the effective cold neutron intensity was the main criterion for the optimization of the several important moderator-target parameters: i.e., the offset and separation, the moderator thickness, and the reflector diameter. Consequently, we show the predicted neutron spectrum and the FWHM of the neutron pulse from the cold moderator.

Acknowledgements

We are very indebted to D.V. Baxter, J.M. Carpenter, Q.K. Feng, M. Furusaka, W.Q. Guan, T. Kawai, Y. Kiyanagi, P.E. Sokol, and for their kind advice and constructive discussion during the course of designing the CPHS target station.

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