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Design status of the second target station cryogenic moderator system

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Abstract. The Second Target Station (STS) at Oak Ridge National Laboratory will be a 700 kW pulsed spallation neutron source optimized to deliver 20 high brightness cold neutron beams. To supply the optimum neutron performance, two compact liquid hydrogen moderators are located in the peak neutron production zones, immediately above and below the rotating tungsten spallation target, resulting in a nuclear heat load of over 400 W in each moderator. To simplify the Cryogenic Moderator System (CMS), the hydrogen loop will supply the two moderators in series with less than 20 K and greater than 99.8% para hydrogen fraction hydrogen at a constant flowrate of 0.5 L/s. An ortho-para converter will counteract the radiation driven backconversion of para to orthohydrogen in the moderators by driving the moderator supply parahydrogen concentration to near equilibrium as required for optimal neutron performance. Both the required performance of the ortho-para converter and the ortho-para diagnostics, monitoring the parahydrogen fraction, have been demonstrated at the Spallation Neutron Source. The layout of the hydrogen system, including the routing of the hydrogen transfer lines, has been determined. System temperatures and pressure drop have been shown to meet requirements by steady state analysis.

1. Introduction

The existing Spallation Neutron Source (SNS) accelerator has been upgraded from 1.4 MW to 2.8 MW through the Proton Power Upgrade (PPU) project, increasing the beam power delivered to the SNS target and allowing for a 700 kW, 15 Hz Second Target Station. The STS has been optimized to provide high brightness cold neutron beams to 20 beamlines by closely coupling two liquid parahydrogen moderators above and below the rotating tungsten spallation target [1].

The STS moderator designs have remained stable since they were optimized during preliminary design, while the surrounding structures have changed slightly. The upper cylinder moderator geometry has been fixed at 100 mm diameter with a 30 mm height. The lower tube moderator geometry has been fixed at 30 mm tube diameter with 170 mm tube length. The tube moderator features 3 tubes arranged in a triangular geometry, allowing for extraction of 6 beamlines. The cylinder moderator beam extraction ports have been modified during final design to allow for extraction of 14 beamlines from 4 ports [2].

2. Requirements

The requirements for the CMS are decomposed from STS requirements for neutron brightness, which is heavily dependent on the state of the hydrogen in the moderators. The hydrogen supply temperature to the moderators must be less than 20 K, as seen in Table 1, to ensure high density hydrogen and desired cold neutron spectrum from the moderators. Due to the 2 orders of magnitude lower neutron scattering cross section at desired neutron energies for parahydrogen compared to orthohydrogen, the spin state supplied to the moderators must be greater than 99.8% even while 394 W of ionizing radiation deposited in the hydrogen causes backconversion to orthohydrogen . The CMS must be able to remove the dynamic nuclear heat load deposited in the moderators, totalling 858 W, when the proton beam is active. Note that because this heat load is proton beam driven, the CMS must provide stable operation through sudden application and removal of the heat load thousands of times per year resulting from beam trips. Finally, to ensure safe operations, the hydrogen system will be designed to the requirements of the National Fire Protection Association Hydrogen Technologies Code, NFPA 2 [3].

Table 1. Second target station cryogenic moderator system requirements

Moderator	Max. Hydrogen Supply Temperature (K)	Minimum Parahydrogen Ratio	Hydrogen Heat Load (W)	Structure Heat Load (W)	Total Heat Load (W)
Upper Cylinder	20	99.8%	166	245	411
Lower Tube	20	99.8%	228	219	447

3. Hydrogen system

The STS CMS hydrogen system will be a single loop, forced flow, constant mass system operating above the critical pressure, as seen in Figure 1 [4]. The hydrogen will be supplied to the moderators in series to maintain simplicity and maintain the hydrogen inventory of 2 kg, below the NFPA 2 Maximum Allowable Quantity. A hydrogen circulator capable of providing up to 1 bar of differential pressure at the constant nominal flowrate of 0.5 L/s (0.037 kg/s) has been identified. A helium hydrogen heat exchanger allows heat deposited in the hydrogen to be rejected to the helium refrigeration system. While the hydrogen flowrate is constant, the helium flowrate to the heat exchanger is varied to compensate for the changes in proton beam driven nuclear heating. An accumulator, featuring a helium gas backed bellows, allows the hydrogen system to endure instantaneous heat load changes while maintaining constant system mass without large pressure variations. An ortho-para converter is located at the coldest point of the loop, driving the hydrogen quickly to equilibrium upon cooldown and maximizing parahydrogen fraction delivered to the moderators after cooldown.

3.1 Hydrogen System Layout

The layout of the hydrogen system has been determined during preliminary design. The hydrogen utility room, which features constant, redundant mechanical ventilation, will house the entirety of the hydrogen system with the exception of the hydrogen transfer lines which transport the hydrogen to the moderators, as seen in Figure 2. The hydrogen utility room has been located as close as possible to the moderators while remaining outside the crane coverage of the highbay. The hydrogen utility room houses the hydrogen coldbox, containing the hydrogen process equipment within a vacuum insulating vessel, the hydrogen refill system, and the hydrogen vent system. The hydrogen transfer line is routed from the hydrogen coldbox to the moderators within a covered trench to prevent mechanical damage. The helium refrigeration system is located adjacent to the hydrogen utility room, allowing a short helium transfer line run between the helium coldbox and the hydrogen coldbox.

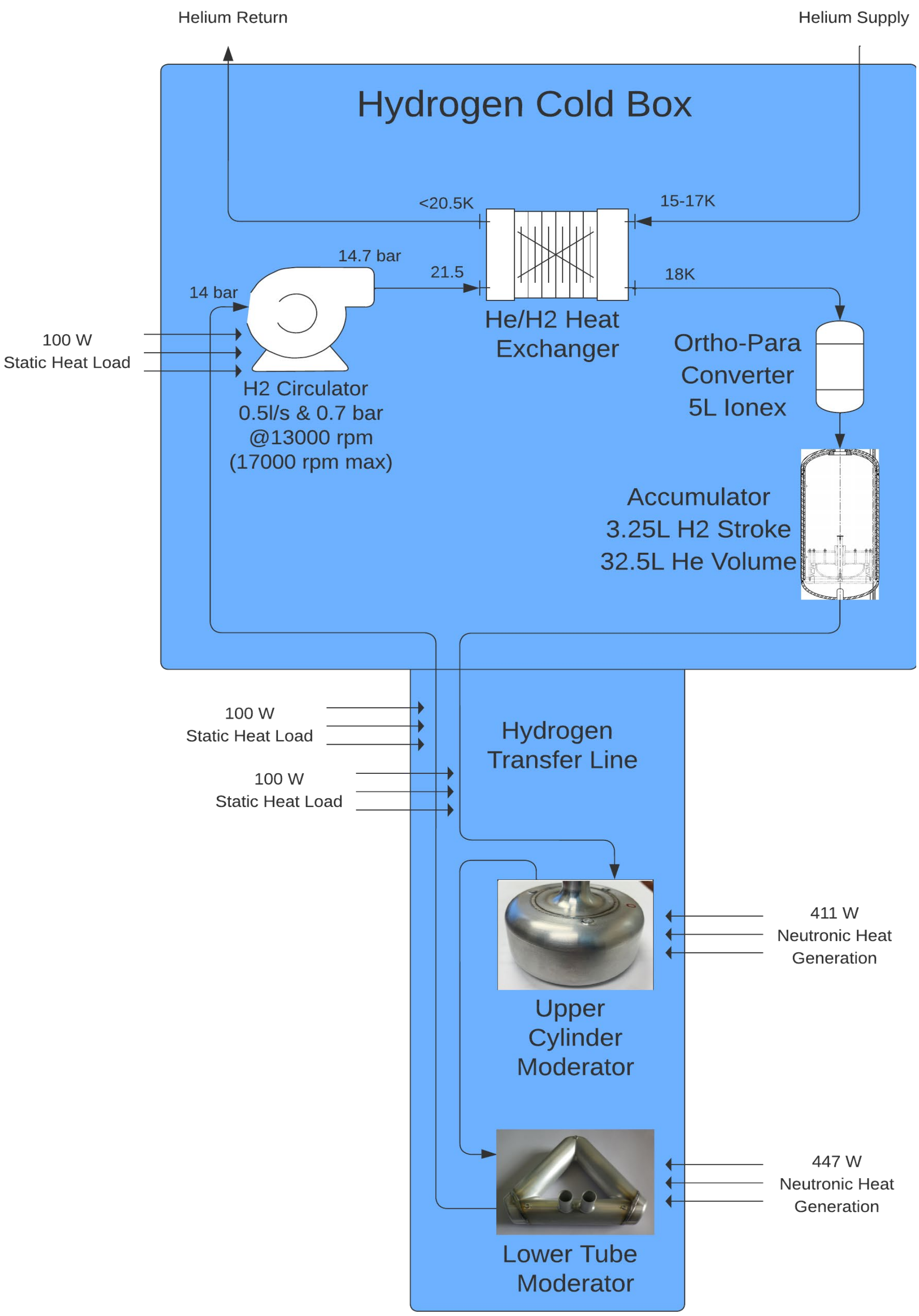

Figure 1. Hydrogen system process flow diagram.

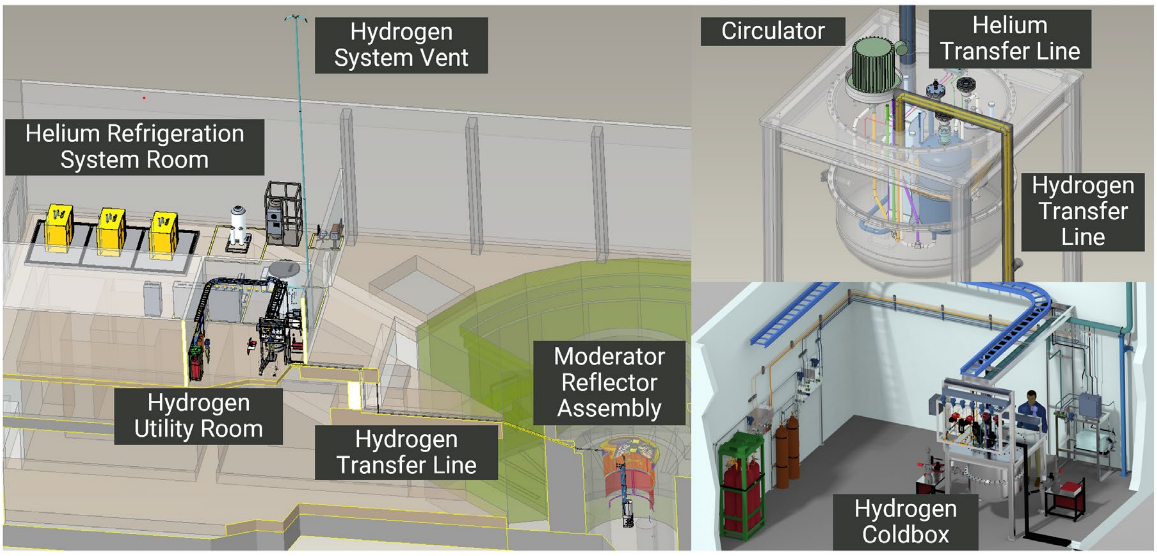

Figure 2. CMS layout within the STS target building (left), zoomed in to hydrogen utility room (bottom right), and zoomed in to hydrogen cold box (top right).

3.2 Hydrogen Transfer Lines

The hydrogen transfer lines serve two main functions: allowing hydrogen to flow to and from the moderators with acceptable static heat load and to ensure venting of the hydrogen back to the hydrogen utility room, and away from the spallation target, in any upset scenario. The hydrogen transfer line length has been reduced to 31 m due to the location of the hydrogen utility room. The hydrogen transfer line geometry will be parallel supply and return lines within a single vacuum jacket. Invar has been selected for the hydrogen line material to minimize thermal contraction and allow the transfer lines to function without any bellows. The inner diameter of the transfer line was chosen to be 14 mm, resulting in acceptable pressure drop while minimizing hydrogen inventory. The hydrogen transfer lines, and surrounding vacuum line, will be polished to reduce radiative heat transfer; however, no multilayer insulation (MLI) will be used due to the possibility of impeding hydrogen venting through the vacuum space in case of a hydrogen vessel or hydrogen line failure. The resulting static heat load to the hydrogen is estimated at 100 W each for the supply and return lines. While this heat load is substantially higher than could be achieved with MLI, reducing the static heat load as much as possible is not actually desired in the hydrogen system, as having a static heat load that is a reasonable fraction of the 858 W dynamic heat load will help aid system stability during beam excursions. The most significant downside to including no MLI in the transfer lines is higher heat fluxes during loss of vacuum scenarios. Loss of vacuum accidents are currently being analysed to ensure adequate venting of hydrogen from the loop.

3.3 Accumulator design

The accumulator features a 32.5 L static helium volume separated from the hydrogen process by a stainless steel edge welded bellows with a 3.25 L stroke. The bellows maintains pressure equilibrium between the hydrogen and helium while allowing volume exchange between the fluids. The helium volume is surrounded by the flowing hydrogen, so that the two fluids are in thermal equilibrium.

The accumulator is critical to the planned control scheme of the hydrogen loop. Rather than control the helium flow to the heat exchanger based on temperature, the flow will instead be controlled to maintain constant pressure in the hydrogen loop. Controlling based on pressure allows for the use of room temperature pressure sensors and allows control based off a ramped input function, as the hydrogen takes 10 s to flow from the moderator to the heat exchanger. When the proton beam is operating, 858 W of dynamic heat load is added to the hydrogen, warming and expanding the hydrogen in the moderators and the hydrogen between the moderators and the heat exchanger. In order to compensate for the expansion of the hydrogen in this region, another region of the loop must contract to maintain constant pressure. The accumulator, with a helium volume larger than hydrogen loop volume and with gaseous helium having a larger coefficient of thermal expansion at 18 K than liquid hydrogen, allows for offsetting contraction with minimal change in temperature. The 858 W of heat load in the moderators causes the hydrogen between the moderators and the accumulator to heat up by 2.6 K; however, the hydrogen exiting the heat exchanger, and thus the accumulator, must only drop its temperature by 0.15 K to maintain constant pressure in the hydrogen loop.

3.4 Ortho-para converter design

An ortho-para converter is required in the STS CMS hydrogen loop to hasten conversion to parahydrogen upon cool down and to counteract radiation driven back conversion to orthohydrogen to supply 99.8% or greater parahydrogen to the moderators. In 2023, an immersion Raman probe was implemented at SNS, offering realtime ortho-para monitoring in an operating neutron source hydrogen system [5]. At the time, SNS had no ortho-para converters installed in their hydrogen loops. The hydrogen system was cooled down 5 days before any proton beam operations, yet the parahydrogen fraction had only increased to 80 % during this time. Once the proton beam was ramped up to 1.5 MW, the quasiequilibrium parahydrogen fraction dropped to 60 % due to the radiation driven backconversion. While the SNS moderators were designed to be largely insensitive to parahydrogen fraction, a parahydrogen fraction of only 60% would be disastourous for STS moderator performance, reducing neutron output by about 70%.

In 2024 as part of the PPU project, SNS implemented window based Raman probes in their hydrogen loops, as well as ortho-para converters to increase parahydrogen fraction. The ortho-para converters caused the hydrogen to remain at equilibrium parahydrogen concentration for the cool down and greater than 99.9% parahydrogen fraction during beam operations up to 1.8 MW, as seen in Figure 3. In fact, the converion effect of the ortho-para converters was so strong, that when the beam was operated, the parahydrogen fraction in the loop increased because the hydrogen temperature dropped at the ortho-para converter, along with the accumulator as explained in the previous subsection, and the small increase in equilibrium parahydrogen fraction resulting from the temperature drop dominated any effect of backconversion.

The SNS installation of the ortho-para converters offered an ideal test bed for demonstrating STS ortho-para converter performance. The STS moderators will have a total of 394 W of energy deposited in the hydrogen, resulting in an estimated backconversion rate of 1.54 mg/s orthohydrogen production, which is also equivalent to the backconversion rate of an SNS downstream moderator operated at 1.7 MW. The SNS downstream ortho-para converters utilize 5 L of hydrous ferric oxide catalyst. While this catalyst volume is likely larger than required, STS will reuse this ortho-para converter design because STS moderator performance is highly sensitive to parahydrogen fraction and the design has been proven to meet requirements based on SNS operation.

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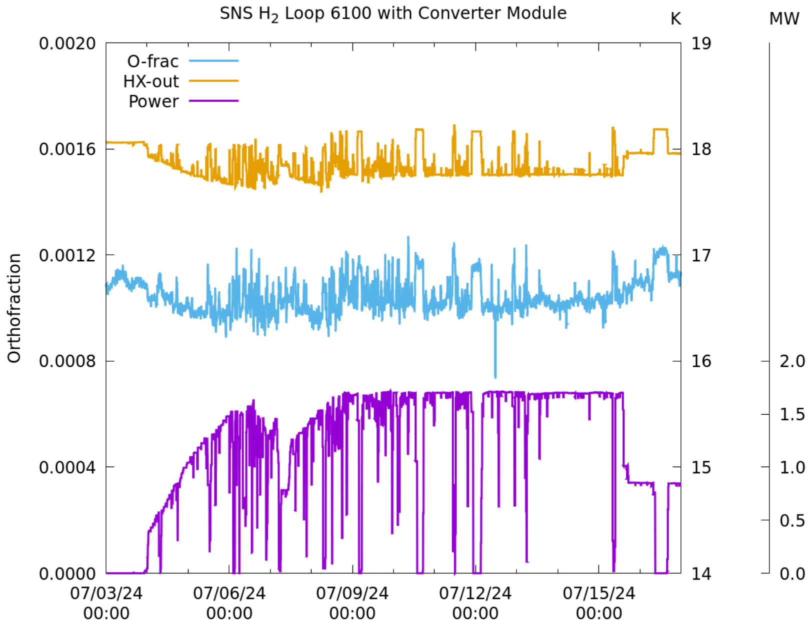
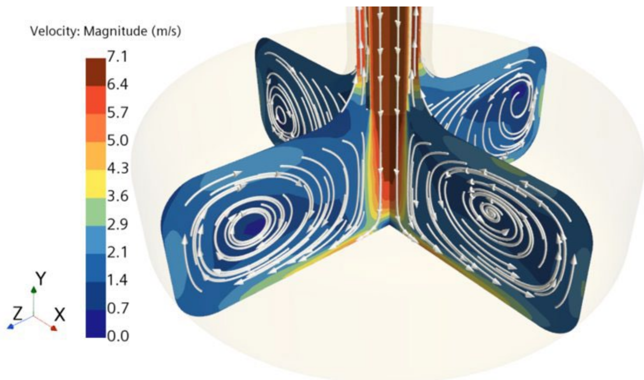


Figure 3. SNS hydrogen loop orthohydrogen fraction during summer 2024 beam operations correlates with the equilibrium at ortho-para converter (HX-out) temperature.

3.5 Hydrogen system analysis

Once the hydrogen system components were selected and arranged, steady state anaysis was performed to ensure that the hydrogen temperatures did not approach 33 K, where density rapidly drops, and that estimated pressure drop was less than the 1 bar maximum the selected circulator can deliver. Pressure drops for piping was estimated using empirical correlations while more complex components were analyzed with computational fluid dynamics software, as seen in Figure 4, as well as SNS empirical data. The results of analysis are shown in Table 2, revealing a maximum temperature of 21.55 K and a loop pressure drop of 0.67 bar and significant margin to both temperature and pressure drop limits. The accumulator and the transfer lines have been shown to be the largest sources of pressure drop in the loop. If additional pressure drop margin was desired, the pitch of the flow baffle which causes the spiral flow around the accumulator could be adjusted to lower flow speeds and pressure drop. At this time, only steady state hydrogen system analysis has been pursued; however, dynamic analysis is planned for later in final design.



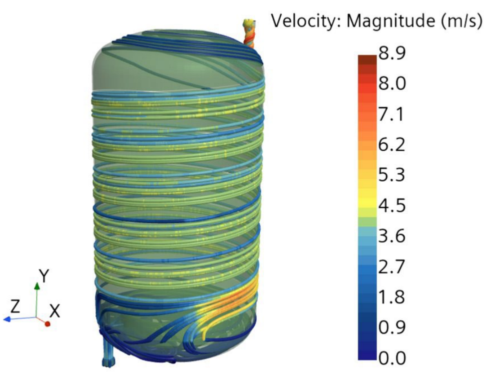


Figure 4. Velocity magnitude plots of the upper cylinder moderator (left) and accumulator (right).

Table 2. Hydrogen system steady state temperature and pressure drop with 700 kW beam operation

Component	Inlet T (K)	Inlet P (bara)	Outlet T (K)	Outlet P (bara)
Heat exchanger	21.55	14.67	18.00	14.64
Ortho-para converter	18.00	14.67	18.00	14.61
Accumulator	18.00	14.61	18.00	14.41
Hydrogen transfer line supply	18.00	14.41	18.35	14.23
Upper cylinder moderator	18.35	14.23	19.66	14.21
Lower tube moderator	19.66	14.21	20.98	14.19
Hydrogen transfer line return	20.98	14.19	21.28	14.00
Circulator	21.28	14.00	21.55	14.67

4. Conclusions

The latest design status of the STS CMS hydrogen system has been presented. The single hydrogen loop with the moderators arranged in series minimizes system complexity and hydrogen inventory. The CMS layout within the STS target building, including the hydrogen transfer line routing, has been determined. Based on recent operating experience at the SNS, the STS ortho-para converter design has been verified to meet STS requirements. Steady state system level analysis has been completed to show that hydrogen system temperatures and pressure drop are acceptable. The STS CMS design has matured steadily and is now ready for complex analyses such as dynamic hydrogen system analysis and loss of vacuum analyses as part of the final design phase of the STS project.

Acknowledgments

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