A Second Liquid Hydrogen Cold Source for the NIST Research Reactor

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ABSTRACT

The Center for Neutron Research has commenced an expansion project to add five neutron guides and several new instruments to increase our cold neutron research capabilities. One scattering instrument, MACS (Multi-Axis Crystal Spectrometer), will be displaced from an existing cold-neutron beam as a consequence of the guide installation. A second liquid hydrogen cold source is being fabricated for installation in a thermal beam port, BT-9, to provide a beam solely for MACS. The BT-9 cold source must be a rather small vessel, 11 cm ID by 4.5 cm thick (LH_2 dimensions), because the entire cryostat assembly must be inserted into a 15 cm ID beam port. Monte Carlo simulations using MCNP indicate that the brightness of the BT-9 source will be 50-80% greater than the existing source located in the cryogenic beam port. The calculated heat load of the new source is 160 W. This small load can be added to that of the existing cold source and the combined load will still be well within the capacity of our refrigerator. The new source will be operated independently, with its own condenser and hydrogen system. Thermal hydraulic tests on a mockup of the source, using R-134a as a working fluid, demonstrated that the source can be operated as a thermosiphon, with a maximum void fraction of about 13%. The source will be installed during the 2011 shutdown, when the new guides are installed.

Introduction

Neutron beam research has become an essential component of materials science, physics, chemistry, and biology in recent years, in large part as a result of the availability of intense beams of neutrons with low energy, or cold neutrons, and the instrumentation to exploit them. In the early 1990's, the U.S. had no competitive facilities for this type of research, and lagged far behind developments elsewhere in the world. With the commissioning of the cold neutron guide hall (1990) and the liquid hydrogen cold neutron source (1995) at the NCNR, cold neutron research in the USA developed rapidly. The number of research participants doubled after the guide hall opened, and nearly doubled again when the first liquid hydrogen source replaced the original solid D_2O source. In addition to this increase in participants, the quality of the research increased profoundly, as illustrated by the fact that the NCNR produces more high impact publications every year than any neutron source in the world except for the ILL in Grenoble, France. As part of the national American Competitiveness Initiative, an expansion of the capabilities at the NCNR was approved in 2007 on the basis of this proven relationship between cold neutron beams and scientific productivity. The proposed second cold source to be installed in BT-9 is an integral part of this expansion that will allow the world-leading MACS spectrometer to continue to operate at peak efficiency.

NCNR Expansion

The goal of the Expansion Project is to substantially increase the cold neutron measurement capabilities at the NCNR. A second guide hall is being built adjacent to the existing guide hall, and five new guides will transport cold neutrons from the existing liquid hydrogen source to 5-7 instruments. Optimization of neutron optics and space utilization will require that some instruments in the existing guide hall will be relocated in the new guide hall, as shown in Figure 1, but the net result will be at least the following new instruments:

1. Materials Diffractometer – A low-resolution, high-intensity diffractometer for rapid investigation of materials.
2. CANDOR – A 'white-beam' reflectometer/diffractometer.
3. vSANS – A very small angle neutron scattering diffractometer.
4. MAGIK – A multiple tagged-beam, off-specular reflectometer/diffractometer.
5. A multi-use fundamental neutron physics and imaging facility.
6. A modernized 10-meter SANS.

In addition to the new instruments, there are upgrades planned for the reactor, the NBSR, which was recently re-licensed by the Nuclear Regulatory Commission in July for 20 years:

1. A digital control console.
2. A new pump house for the secondary cooling system.
3. A new Thermal Shield cooling system.

Lying in the path of the new guides is the cold neutron spectrometer, MACS (Multi-Axis Crystal Spectrometer), located on the beam port CTW as shown in Figure 2. The new guides will be installed in CTW, in the same manner as are existing guides NG5-7 located in CTE. A new LH_2

cold source will be installed in the thermal-neutron beam port, BT-9, and MACS will be relocated there.

The BT-9 Cold Source

The cold source for MACS has been designed for installation in a 15 cm ID beam port, and its geometry was specifically optimized for the largest possible diverging beam to illuminate its Double Focusing Monochromator. (The DFM, a crystal array approximately 30 cm x 30 cm, focuses a very intense monochromatic beam on a sample as small as 1 cm^2.) The source geometry approximates a disk, 4.5 cm thick and 11 cm in diameter, as shown in Figure 3. It was optimized by a series of MCNP calculations described below. The source must be simple to operate, very reliable, and, above all, passively safe. It will be cooled by a naturally circulating thermosiphon.

Neutron Performance and Heat Load Calculations

Monte Carlo simulations using the MCNP [1] code were performed to optimize the shape of the LH_2 vessel, and to determine the expected heat load in the source and the cryostat assembly. These calculations followed the methods described in a NIST Internal Report, "NIST Liquid Hydrogen Cold Source" [2]. Powerful variance reduction tools are required to obtain good statistics when the fraction of fission neutrons that ultimately reach the desired energy and direction is 10^{-7}. One tool, the DXTRAN feature of MCNP, is not compatible with the repeated structures in the reactor core model. A surface source surrounding BT-9 was generated during a lengthy criticality calculation to provide starting neutrons for the much shorter performance calculations in which only the CNS region is modeled. Small changes in the LH_2 thickness, density, and ortho/para ratio can then be easily studied. The optimum thickness for source brightness below E = 5 meV ($\lambda > 4$ Å) is 4.5 cm, but the brightness varies slowly between 3.5 and 5 cm. For these calculations, the void fraction was assumed to be 10%, and the ortho-LH_2 fraction was fixed at 65%, based on the performance of the existing source. The brightness as a function of wavelength for the BT-9 source and Unit 2 are shown in Figure 4.

The method used to calculate the heat deposited in the source at 20 MW is also described in Reference 2. The results of the heat load calculations for the cold source are given in Table 1. At 160 watts, the heat load should be easily removed along with the 1200 W load of the Advanced LH_2 Source, Unit 2, by the existing 3.5 kW helium refrigerator. The calculated heat load on the cryostat assembly is 1.8 kW, and it must be removed by the Auxiliary D_2O Cooling System which is currently used to remove about 45 kW from the Unit 2 assembly. The actual heat removal requirement on the D_2O may be twice that calculated due to the proximity of warm thermal shield components. The cryostat assembly is shown in Figure 5.

Design

The philosophy underlying the design of the BT-9 source is the same as that of the existing Unit 2 source [2]. The moderator vessel will be surrounded by insulating vacuum, a He containment, and a D_2O cooling jacket. These vessels must be considerably smaller for BT-9, however, as the assembly must be inserted through the thermal shield collar, 15.2 cm ID. Aluminum alloy 6061-T6 will be used for all of the in-pile components. All joints will be welded.

Moderator Vessel: The LH_2 vessel is 11.25 cm OD by approximately 4.5 cm thick, with a wall thickness of 0.127 cm. The liquid supply line is 0.95 cm OD, the vapor return line is 1.59 cm OD, and both have 0.9 mm wall thickness. The mass of the vessel is supported by thin titanium spacers minimizing thermal conductivity from the vacuum vessel. The working pressure of the hydrogen system is 0.5 MPa. A prototype failed (buckled) at 5 MPa, but did not leak.

Vacuum Vessel: The vacuum vessel is a 12.4 cm OD cylinder about 1 m long, with an elliptical head at the front (reactor) end. There is a hemispherical head at the back end with penetrations for the H_2 lines extending to the condenser. The cylinder wall thickness is 0.23 cm while the heads are 0.16 cm thick. It is designed to withstand an external pressure of 0.2 MPa. It is cooled indirectly by conduction through the He jacket, augmented by sheets of expanded Al in contact with the He containment vessel.

Helium Containment Vessel: Figure 6 is a sketch of the He containment vessel which is designed to withstand the internal pressure generated by the maximum hypothetical accident in the cryostat, protecting the BT-9 thimble. A prototype of this vessel broke at nearly 10 MPa. Ribs on its outer surface channel the flow of D_2O to the front end of the assembly, the location of the greatest heat load. The vessel wall is 0.38 cm thick, as are the ribs, and its OD is 14.29 cm. The flange at the rear of the He containment vessel mates with the D_2O cooling jacket, and includes plenums for the supply and return coolant flow. The front face of the flange has holes for alignment pins inside the BT-9 port, and has a mount for a lead gasket, replacing an existing CO_2 seal that must be removed to install the source.

D_2O Coolant Vessel: The interior surface of this vessel makes a contact fit with the He containment vessel restricting the flow to the channels. It has an OD of 14.6 cm, providing nominal radial clearance of about 3 mm with the smallest ID of BT-9. Its thickness is 0.16 cm.

The essential design philosophy calls for simple reliable operation, and this in turn requires the fewest possible active components. In order to meet this requirement, just as for the existing cold source, the BT-9 source will use a thermosiphon to remove the nuclear heat deposited in the moderator vessel. The design concept is to have a closed loop containing all of the hydrogen, consisting of a condenser, the moderator vessel, a ballast tank, and connecting piping. The condenser is cooled by a helium gas stream at approximately 14 K from a closed loop refrigerator. Heat is removed from the moderator vessel and hydrogen by boiling of hydrogen and the vapor is re-liquefied by the condenser mounted about 2 m above BT-9. The liquid is fed back into the moderator by gravity, and the loop is complete. The ballast tank serves as a buffer volume, and is sized to contain all of the hydrogen gas when the system is not operating.

The hydrogen system for the BT-9 source will be completely independent of the Unit 2 source. It will have its own ballast tank and condenser. A 0.38 m^3 ballast tank will be installed in a cavity of the MACS beam stop, in a location shielded from accidental contact with a load on the crane or a fork lift. The condenser will be mounted above BT-9 behind its own shield. The hydrogen lines will lie beneath MACS, or along the face of the reactor, behind the MACS shields.

Mockups

Because the size of the BT-9 vessel is so much smaller than Unit 2, with no room for a bubble-cap phase separator, thermal-hydraulic tests of the thermosiphon were required. Rather than using liquid hydrogen, the tests were performed with the commercial refrigerant R-134a as the working fluid. Several heaters were installed in the wall of the mockup, which had to be nearly surrounded by insulation. The mockup and piping had exactly the same dimensions as the planned source. When operating the mockup at 480 kPa and 287 K, the R-134a had the same liquid to vapor density ratio as the liquid hydrogen will have. The heat load was increased a factor of 7.5, to 1200 W, to obtain the same vapor volume flow rate, simulating the expected hydrogen thermosiphon behavior. Even at 3600 W, however, the thermosiphon removed the heat without the vessel emptying. The mockup was built with a section of Plexiglas to observe the filling of the vessel and the boiling characteristics. A piccolo-type phase separator was chosen as a result of these tests because with holes for the vapor return at the very top of the vessel, it resulted in the highest liquid level.

A second mockup allowed us to determine the void fraction by gamma-ray transmission measurements. An ^{241}Am source and a NaI detector were used to measure the increase in a tightly collimated beam of 60 keV photons, as the heat load was increased. The average void fraction at 1200 W was 13%, very close to the value used in the MCNP simulations.

A mockup of the coolant flow system, with a transparent water jacket, was also built and tested. By injecting dye into the coolant supply, it was easy to observe that an adequate flow reached the tip of the cryostat assembly.

Operation

It is expected that the Unit 2 and the BT-9 sources will be operated together for several years. The easiest way to operate both would be to install 'tees' in the existing load lines near the condenser for additional, smaller lines capable of supplying cold helium refrigerant at a rate of 25-30 g/s to the second condenser located above BT-9. It will require control valves in the load lines to each condenser, to independently maintain the desired operating pressure in each source. The new source will have its own instrumentation. The existing refrigerator PLC has the capacity for these additional parameters, and the necessary new subroutines in its software.

The BT-9 source will be operated between 0.1 and 0.2 MPa, depending on the quantity of hydrogen loaded into the system. Most likely, it will be loaded with about 140 g of H_2, operating between 0.4 MPa (warm) and 0.1 MPa (cold). To protect the moderator vessel from overheating, there will be a high-pressure reactor rundown if the refrigerator fails, as is the case with Unit 2. There will also be a reactor rundown in the event of a loss of D_2O flow to the cryostat assembly. The reactor rundown signals protect the cold source, not the reactor.

Safety

Hydrogen safety is assured by protecting components from physical hazards, minimizing gas handling, and having at least two monitored barriers preventing the mixing of air and hydrogen. The system is passively safe; the H_2 simply expands into its ballast tank if the refrigerator fails.

All hydrogen containing portions of the system will be blanketed by at least a monitored layer of helium; components at cryogenic temperatures will also be surrounded by an insulating vacuum space (as shown in Figure 3 for the moderator cell). All joints inside the biological shield are welded, and the welds are radiographed. At each stage of assembly, the system is helium leak checked to ensure that the welds are vacuum tight (the actual specification is a leak rate < 10^{-9} STP cc/s; in practice, the standard is no detectable leak). This will provide complete assurance that the system is leak tight, and that there are at least two barriers to mixing of air with the hydrogen of the system. Piping containing hydrogen will be protected from damage by a variety of means, including routing through massive shields, protective barriers, and by administrative and physical restrictions on crane use in the area.

The closed nature of the hydrogen system minimizes gas handling. Once it is loaded with the proper H_2 inventory, the system is sealed and there will likely be no need to change it. There is no venting of hydrogen; pressure relief is to the ballast tank.

An accident analysis was prepared for the Engineering Change Notice (ECN) required to install the BT-9 source. The analysis included high probability events, such as a refrigerator trip and complete loss of off-site power, to the maximum hypothetical accident, in which a vacuum line is severed, air freezes on the moderator vessel, it fails, and a detonation follows. None of the scenarios compromised the reactor vessel or the containment building. The BT-9 source will have at most 25% of the allowed hydrogen inventory of Unit 2. The consequences of an accident lie within the envelope of the accident analyses described in Reference 2. It was determined that this source, like its predecessor Unit 2, can be installed under the provisions of 10 CFR 50.59; it poses no unreviewed safety questions regarding reactor operations.

Conclusion

A second cold source is being built for installation in BT-9 to accommodate MACS, and free CTW for neutron guides into the new guide hall. The cold neutron facilities at NCNR will be expanded significantly upon completion of the project in 2012.

References

1. "MCNP – A General Monte Carlo N-Particle Transport Code, Version 5", X-5 Monte Carlo Team, LA-UR-03-1987, Los Alamos National Laboratory, Albuquerque, NM, April 24, 2003.

2. P. Kopetka, R. Williams and J. M. Rowe, NIST Liquid Hydrogen Cold Neutron Source", NISTIR 7352, September 2006.

Acknowledgements

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Table 1. Nuclear Heat Load for the BT-9 Cold Source

	Liquid Hydrogen (27 grams)		Aluminum (141 grams)	
Radiation Source	Rate (W/g)	Heat (W)	Rate (W/g)	Heat (W)
Neutrons	1.21	33	0.00	1
Beta Particles	0.00	0	0.20	29
Gamma Rays	0.95	26	0.52	74
Sub-totals	2.16	59	0.73	104
Total	**163**	**watts**		

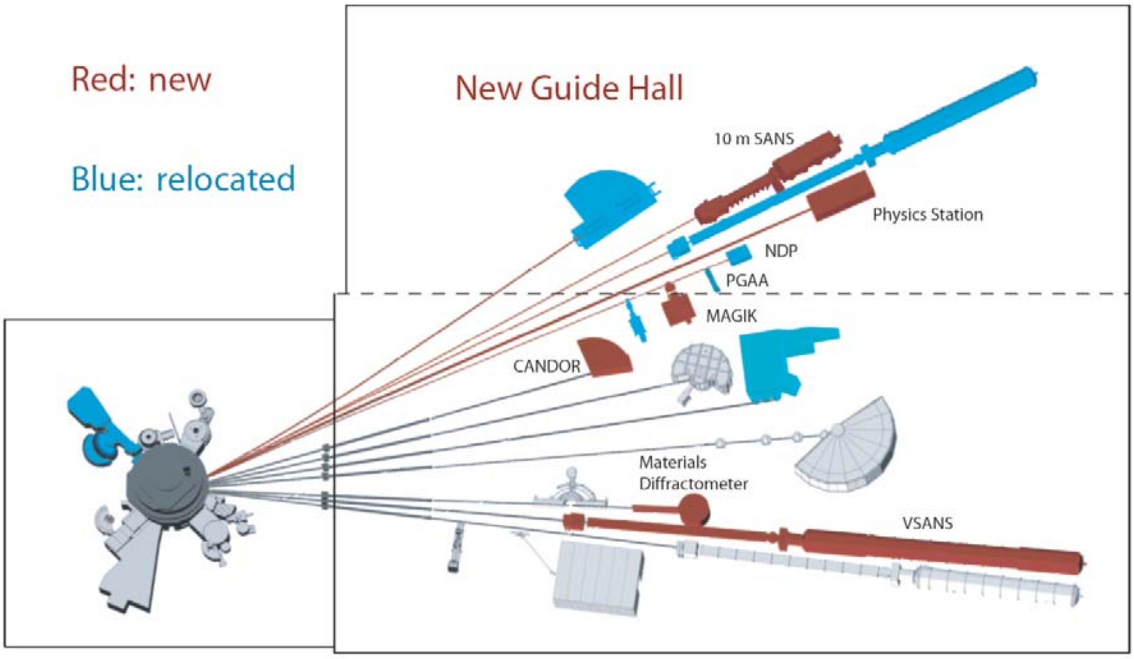

Figure 1. Anticipated layout of experimental facilities in the guide halls.

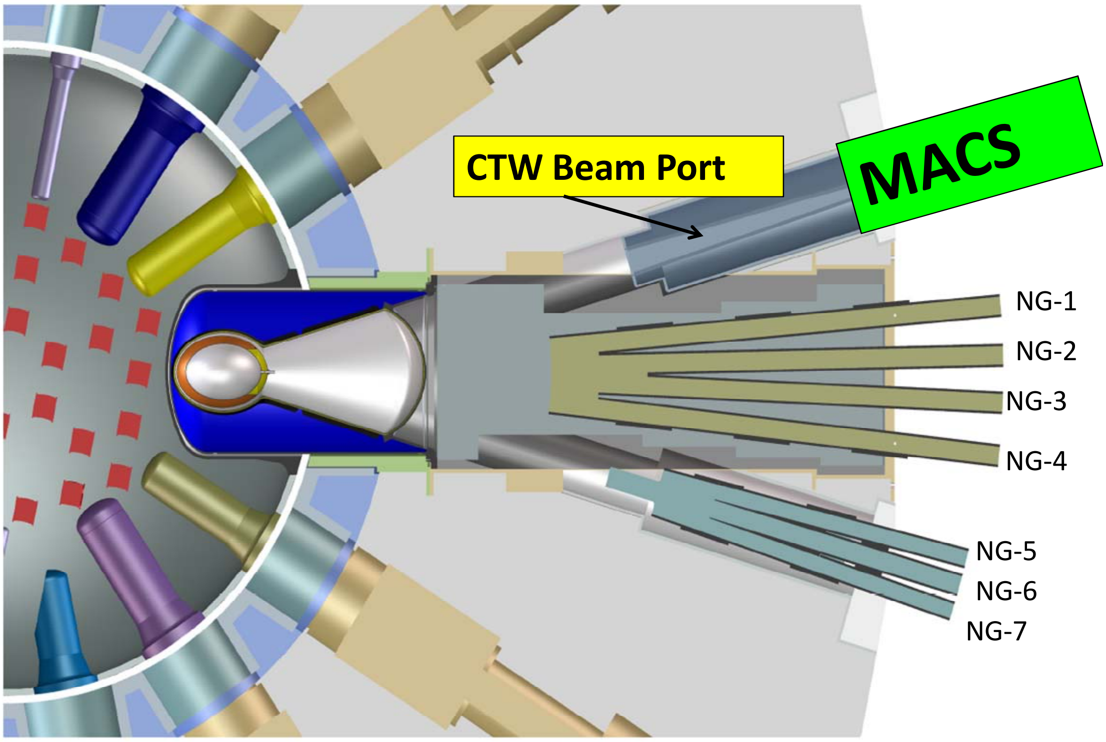

Figure 2. Existing cold source and neutron guides. The new guides will be installed in CTW, and MACS will be relocated to BT-9 (not shown), and have its own cold source.

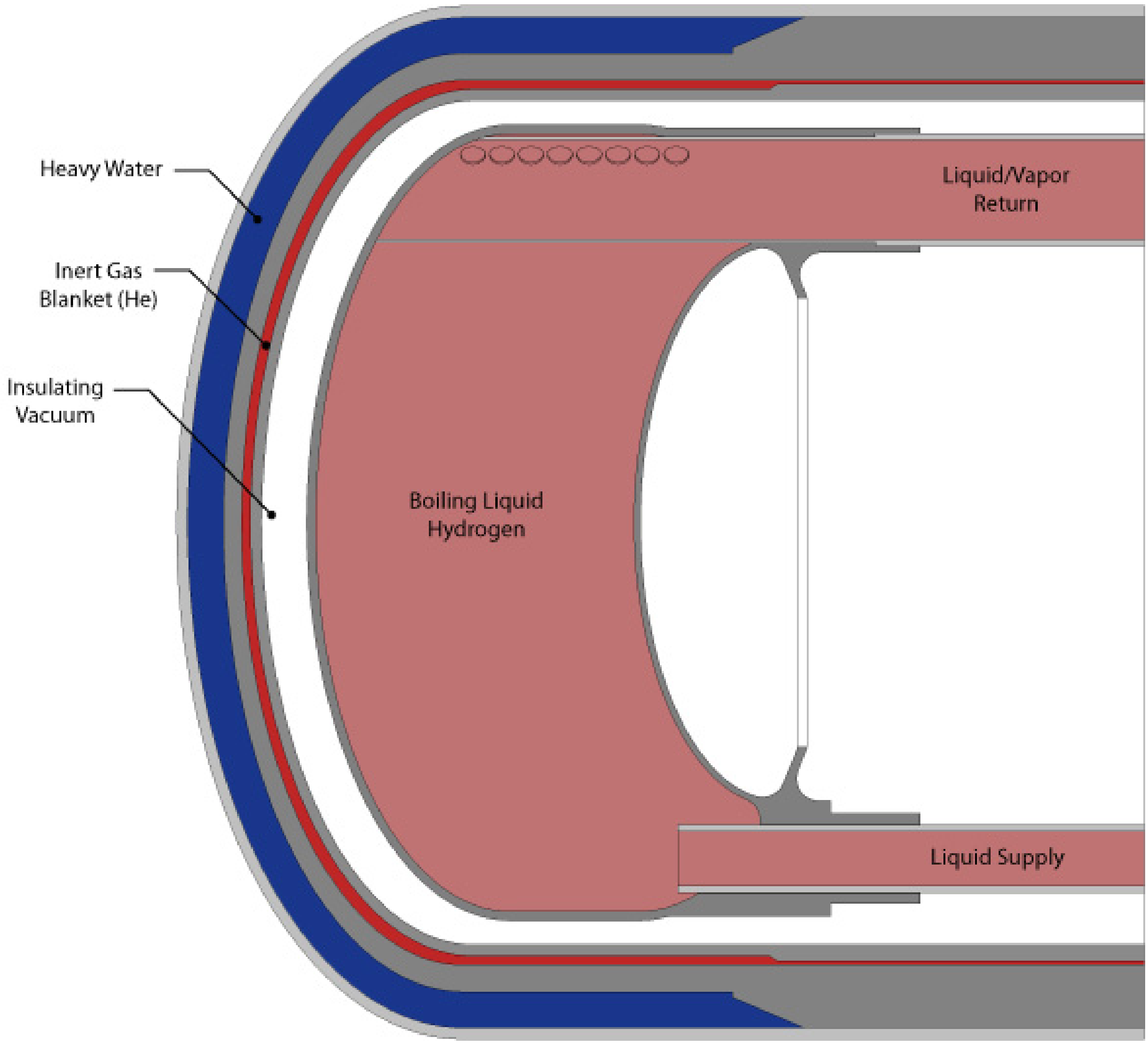

Figure 3. Cross section of the BT-9 cold source moderator vessel (nearly to scale; the LH_2 ID is 11 cm). The source is surrounded by insulating vacuum, a He containment, and a D_2O cooling jacket. At the top is a piccolo–like phase separator at the inlet of the vapor return line, to ensure the vessel is filled.

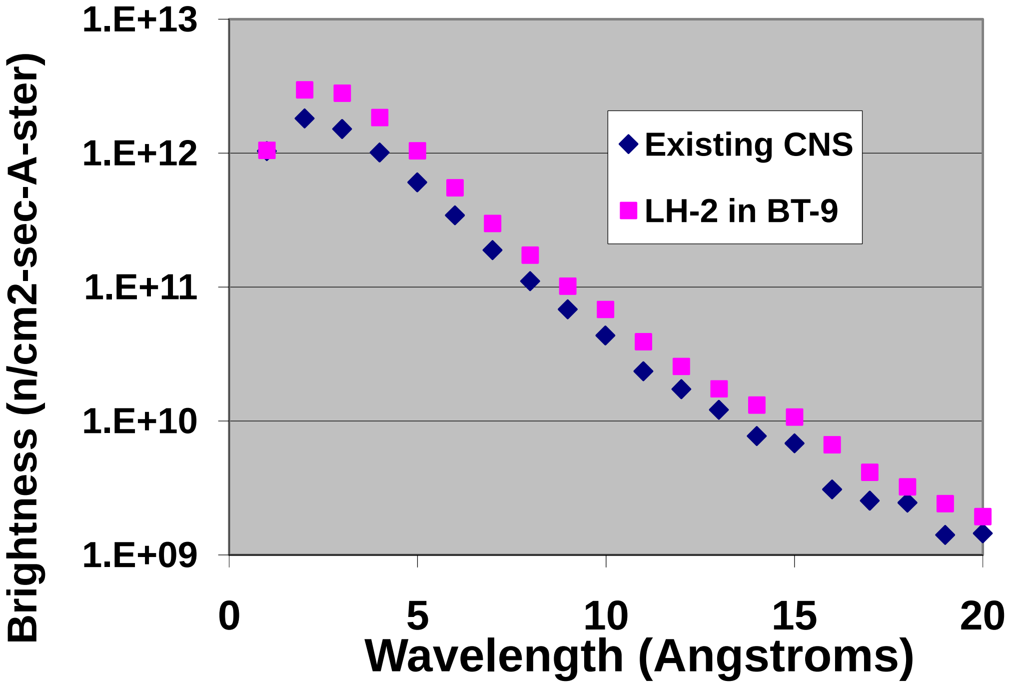

Figure 4. Brightness of the BT-9 source and the existing Unit 2 CNS. The intensity gain varies from 1.7 to 2.

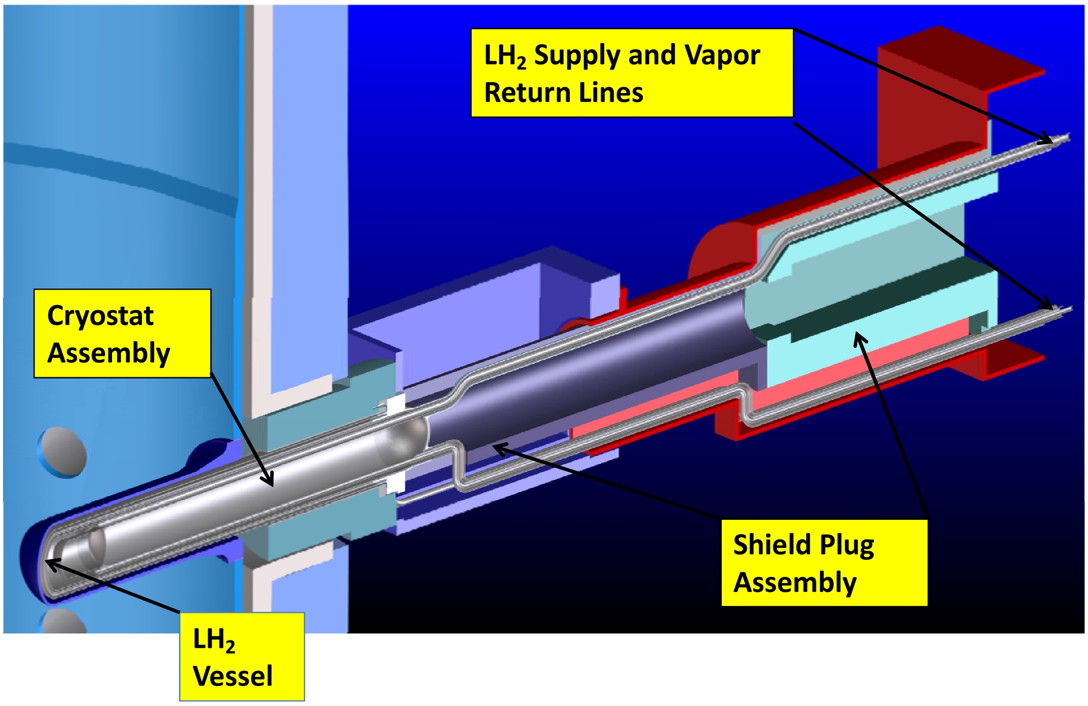

Figure 5. Cut-away view of the cryostat and shield plug assemblies to be inserted horizontally into BT-9.

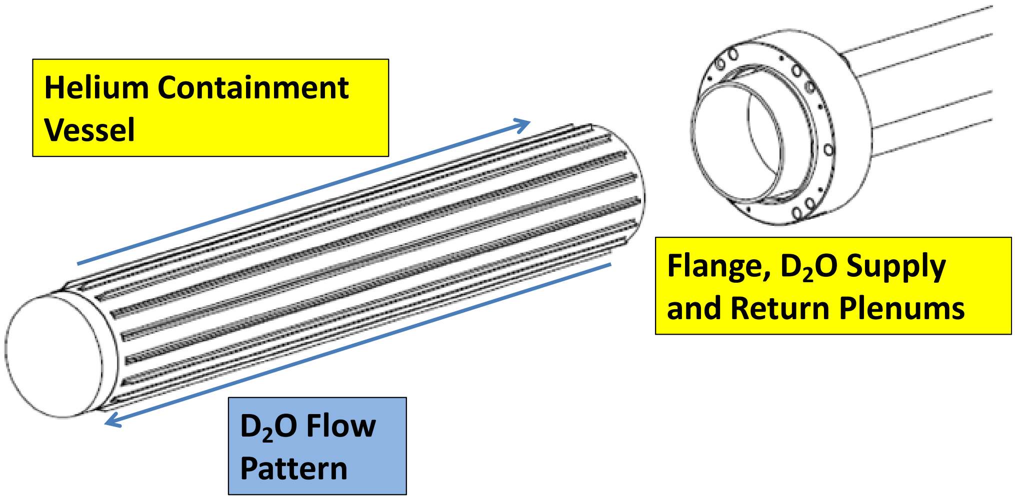

Figure 6. A portion of the assembly drawing of the He containment vessel and the flange that mates with the surrounding D_2O jacket.