The High Brilliance Neutron Source Target Stations

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Abstract. High Current Accelerator driven Neutron Sources (HiCANS) are a cost-efficient alternative for future large scale neutron facilities. They excel in transforming neutrons released by the primary nuclear reaction into a spectral range usable for applications. In particular, the cost of a target station represents only a minor fraction of the overall construction cost due to the lower energy of the primary neutrons, which requires less shielding. They can be designed to provide optimized pulse and spectral properties for applications in neutron scattering, analytics and imaging experiments. For the High Brilliance neutron Source (HBS) project at Forschungszentrum Jülich, we have developed a modular design that meets the radiation protection requirements while providing sufficient space in its core to adapt the target-moderator-reflector assembly to the different applications. In the following, we present the basic target station design which will be used at HBS for three different realizations with their own instrument suite. All relevant components have been designed, built and tested at the JULIC Neutron Platform which has produced neutrons since December 12th 2022. The simulated performance of a target station shows that the brightnesses of the moderators are in the range of modern research reactors and sub-MW power spallation sources.

1 Introduction

Research reactors like ILL in Grenoble, FRM II in Garching or HFIR in Oak Ridge release neutrons in a single core that is surrounded by moderators providing neutrons for experiments in multiple experimental areas. Increasing the experimental area for instruments surrounding the research reactor is realized by complex neutron transport systems, providing identical source properties for a large group of instruments. At short pulse spallation neutron sources like ISIS in Didcot and SNS in Oak Ridge, different moderators were developed to provide dedicated pulse properties for different applications. As individual beam ports feed only individual instruments, the number of instruments per target station is limited. The upgrade with a second target station done at ISIS [1] and planned at SNS [2] is a significant investment due to severe shielding requirements against the high energy particles produced during the spallation reaction. Compact Accelerator-driven Neutron Sources (CANS) like LENS in Bloomington or RANS in Wako, which are mainly used for education and methods developments, release neutrons via nuclear reactions at low proton beam energy in the MeV range requiring less shielding than spallation neutron sources thus having a low price tag. They however serve only a limited number of in-house users at a time but can therefore adapt the proton pulse properties for a specific application.

High-Current Accelerator-driven Neutron Sources (HiCANS) benefit also from the lower radiation protection requirements but aim at a high availability for a large number of users. Therefore the provision of multiple target stations, whose cost represents only a minor fraction of the overall investment, is considered for projects like the High Brilliance neutron Source (HBS) project or the ICONE project [3] from the very beginning. This requires a target station design which is modular and adaptable to the specific requirements. This allows a further optimization of the target station and tailoring of the neutron beams to its instruments. In the following, the basic target station design for the HBS project is presented which is planned to be built in three stages.

2 High brilliance neutron source project

The HBS project team is developing a HiCANS concept which should serve as a national user facility in Germany. The proposed layout is shown in Figure 1 with three target

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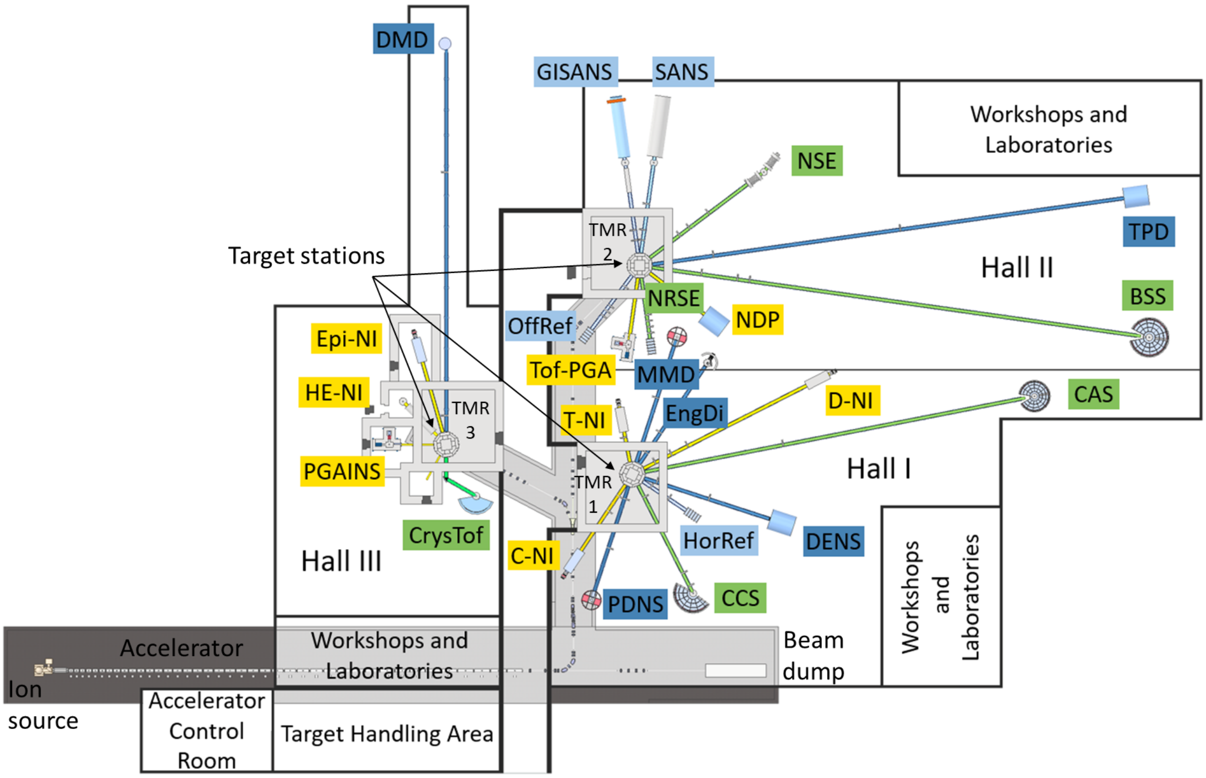

Figure 1. Proposed HBS facility with three target stations and 24 instruments.

Table 1. Main parameters for the HiCANS developed in the HBS project

Accelerator	70 MeV proton beam 100 mA peak current 20% RF-duty cycle
Target	Ta target with micro channel structure 100 kW average power deposiiton 10^{15} n/s source yield
TMR stations	3 individual TMR stations TMR 2: 24 Hz (667 μs pulse) TMR 1 + 3: 96 Hz (167 μs pulse)
Moderators	thermal moderator: light water cryogenic moderators: solid methane, solid mesithylene, liquid para-hydrogen
Instruments ´	TMR station optimized to instruments 6 - 12 instruments per TMR station scattering, imaging and analytics

stations and 24 instruments. The main parameters of this facility are summarized in Table 1.

The instruments are grouped regarding their requirements and built at optimized target stations. It was chosen to operate a target station (TMR-2) served by a 24 Hz proton beam with pulses of 667 μs length and two target stations (TMR-1 & TMR-3) served by a 96 Hz proton beam with pulses of 167 μs length. Instruments requiring a broad band of neutron energies are served by TMR-1 featuring a low frequency. The long neutron pulses of 667 μs makes it also the best choice either for low wavelength resolution applications, which can accommodate the full pulse, or for applications that require pulse shaping to perform very high resolution experiments. The other two target stations provide good resolution already using the full pulse of the target stations. The applications grouped around these target stations require typically a limited bandwidth. The difference between TMR-1 and TMR-3 is the focus on different applications and therefore energy ranges. TMR-1 serves mostly scattering instruments in the thermal and cold neutron energy range like diffractometers or direct geometry spectrometers and TMR-3 serves mostly analytical instruments in the epithermal and thermal energy range like imaging and PGNAA.

In order to minimize the development requirements for a facility with multiple target stations with different focuses, it was chosen to design a target station that can be used as a basis for different target station realizations.

3 Basic target station design

A target station at a HiCANS has to provide tailored neutron beams with the requested energy spectrum and time structure to its instruments. Furthermore, it needs to shield the surrounding target room and its equipment from radiation leakage, both during operation and after operation, due to the activated components to enable access to the the target room. As multiple target stations are planned for a HiCANS, the basic design needs to be easily modifiable and adjustable to the instrument suite and the proton pulse structure. Finally, the number of instruments supplied with neutrons by the target station needs to be maximized.

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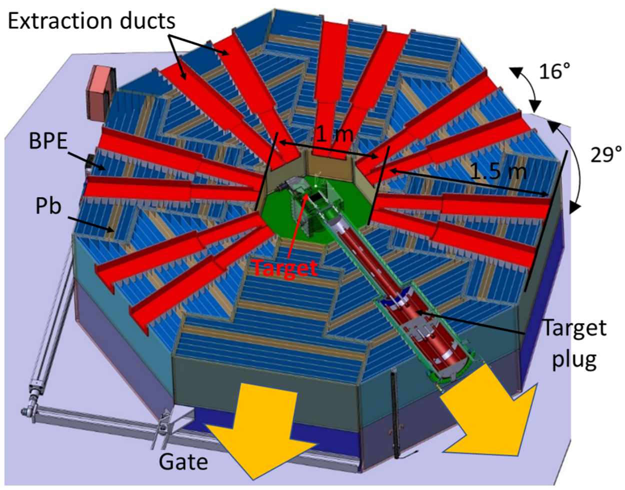

Figure 2. Basic design of the target station

In order to fulfill these requirements, the basic target station design has the following design features:

- Layered shielding of borated polyethylene and lead
- Vertical proton beam providing 360° for instrumentation and access to the target station
- Spacious inner core reserved for optimized moderator-reflector assembly to specific instrument suite requirements
- Large extraction ducts allowing an extraction of neutrons from different layers of the target-moderator-reflector assembly thus allowing fast, epithermal, thermal and cold neutron extraction
- Instrument specific moderators further tailoring neutron beams by optimized thermal or cryogenic moderator plugs
- Small neutron producing target resulting in efficient coupling of neutron production, moderation and extraction

The basic target station design for the HBS project is shown in Fig 2 which has an octagonal structure with a total width of 4 m and a height of 4.5 m. It features 4 double layers of borated polyethylene and lead with a total thickness of 1.5 m leaving an inner octagonal space with a width of 1 m for the moderator-reflector assembly. The octagonal structure is separated into 8 individual sections, one section dedicated for target access, one section that can be opened to allow access to the inner core and 6 sections usable for neutron extraction with two extraction ducts in each section.

3.1 Neutron producing target

The target is made of a single stationary structure consisting of tantalum as shown in Fig. 3. The total thickness is 21 mm, the width is 112 mm and the length is 120 mm with an irradiated area of 100 x 100 mm^2. In order to efficiently cool the 100 kW power injected by the proton beam in the small volume, the target is cooled with a micro channel

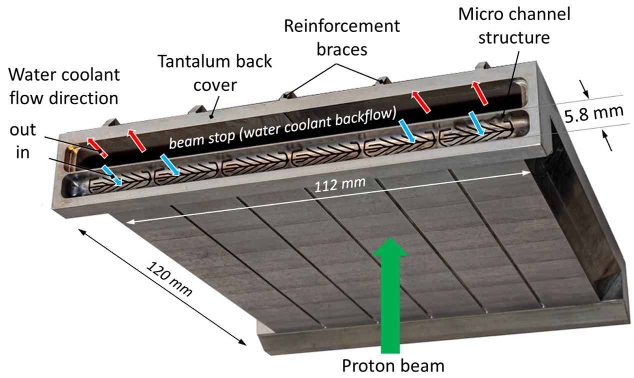

Figure 3. Tantalum target at HBS

cooling structure with a channel width of 0.35 mm inside the neutron producing layer allowing heat removal as high as 1 kW/cm^2. The neutron producing layer with the inserted cooling structure has a total thickness of 5.8 mm resulting in a neutron production within a volume of less then 100 ml thus maximizing the brightness and minimizing the activated amount of material. The exchange of the target is a standard operation that can be accomplished during regular maintenance periods. The time averaged neutron yield for a single target station is ∽ 10^{15} n/s.

Due to the irradiation with protons and the high radiation level inside the target station, the target will undergo irradiation-induced damage. The estimated life-time of the tantalum target is 2.6 years [4] mainly due to the high proton induced displacement per atom (DPA). For the HBS project, the target change is planned annually, to have a high safety margin.

3.2 Target extraction

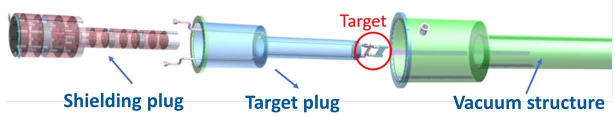

Figure 4. Target plugs

The exchange of the target is enabled by a plug-in-plug system as shown in Fig. 4. A vacuum structure made of aluminium is placed in one segment of the target station and shares the vacuum with the accelerator. This allows a windowless design preventing energy loss of the proton beam and minimizing radiation background. The target is placed at the front of the target plug made of aluminium with water pipes being fed through. The target plug closes the vacuum outside the target station which allows breaking the vacuum under safe radiation levels. A shielding plug is inserted into the target plug with the same layered structure of lead and borated polyethylene as the shielding of the target station.

The target plug together with the shielding plug can be extracted with an appropriate mechanism from the outside after the vacuum is broken. A mobile shielding is placed around the target during the extraction for transport to a storage or target handling area. The high activation of the Ta target decays with a half-life of Ta^{182} of 115 days, after which the target can be separated from the plug structure and decommissioned. This reduces the nuclear waste, that has to be decommissioned, to a mass of 3.5 kg.

3.3 Extraction ducts and moderator plug

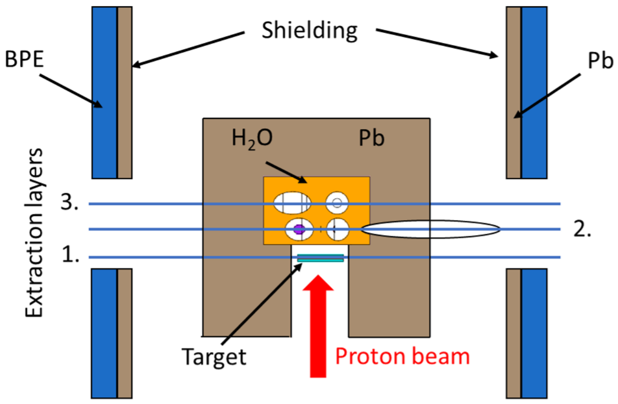

Figure 5. Target-moderator-reflector assembly with illustration of three extraction planes with a thermal light water moderator and a lead reflector.

The optimal extraction volumes for cold, thermal and epithermal neutron beams differ for each target station. Hence neutrons are extracted from different positions of the target-moderator-reflector assembly. This is realized by a large extraction duct through the shielding of the target station (Figure 2) with an inner width of 200 mm and an inner height of 400 mm, where the neutron guide can be placed to have an ideal view towards the extraction volume. The target is placed in the lower third of the extraction ducts height allowing to extract neutrons directly either from the target or from the moderator placed in front of the target as shown in Figure 5 with an example of three extraction layers.

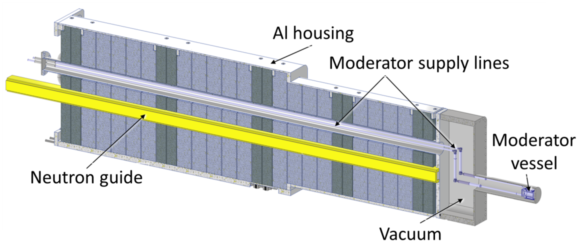

Figure 6. Moderator plug, which can be inserted into the extraction duct.

These extraction ducts are filled with instrument specific moderator plugs including the supply lines and neutron guides as shown in Figure 6. The guide has an undisturbed view to the moderator surface and the neutron spectra can be tailored to the instrument requirements as the moderator in the front can be changed. In such a design, the optical components like neutron guides can be placed as close as 400 mm from the moderator surface.

3.4 Moderator-reflector assembly

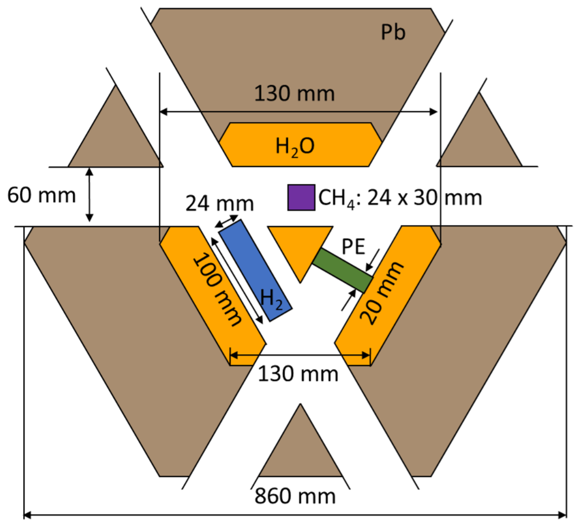

Figure 7. Example of moderator-reflector assembly with a cut through extraction plane 2 indicated in Figure 5 with a thermal polyethylene moderator and two cryogenic moderators, namely liquid hydrogen and methane.

In the core of the target station, different moderator-reflector assemblies can be tailored to the proton pulse structure and the instrument suite. In Figure 7, an example shows a cut through the second extraction plane of a moderator-reflector assembly. It uses a light water moderator to thermalize the primary neutrons coming from the target and to feed the moderators from the extraction ducts. A lead reflector around the thermal moderator feeds unmoderated neutrons back into the thermal moderator and acts also as the first shielding layer against fast neutrons and gammas. Three different moderators are used inside the extraction ducts, one polyethylene moderator to extract thermal neutrons and two cryogenic moderators (liquid hydrogen and methane) to extract cold neutrons.

The peak brightness for the different moderators calculated with MCNP6 is shown in Figure 8. It is in the range of 10^{13} $s^{-1}sr^{-1}Å^{-1}cm^{-2}$ which is comparable to modern research reactors and sub-MW power spallation sources. By choosing the moderator type, it is possible to shift the spectrum from thermal at 1.3 Å for polyethylene, cold at 3 Å for liquid hydrogen or a cold spectrum with a large number of thermal neutrons for methane due to its small volume.

3.5 Target test station

A mock-up of the target station for HBS was built at the JULIC cyclotron in Jülich as shown in Figure 9. It serves as a testbed for all critical components for the HBS like

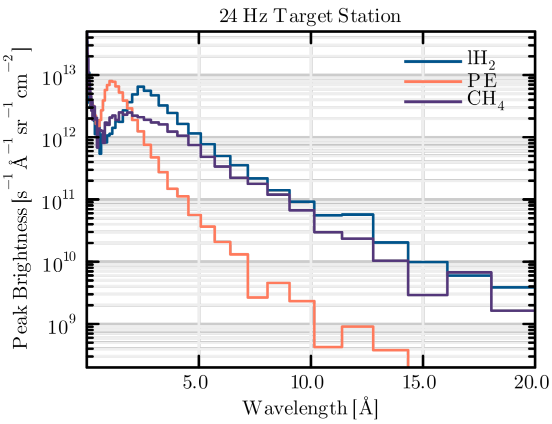

Figure 8. Simulated brightness for the moderator-reflector assembly for three different moderators.

target, cryogenic moderators, TMR assembly, target handling as well as the operation of a target station served by a low energy proton beam. The target station has reduced shielding dimensions compared to the HBS target station from 2 m to 1.5 m and the proton beam enters the target station horizontally instead of vertically.

On the 12th of December 2022, the first beam on target was realised with three experimental setups: a diffractometer setup at an extraction duct equipped with a cryogenic methane moderator, the HERMES reflectometer provided by CEA using a thermal extraction duct, which will be later upgraded with a liquid hydrogen moderator, and a detector test station looking at the thermal polyethylene moderator with a pin-hole camera with a width of 6 mm inserted into the extraction duct. The target test station together with the instruments is named JULIC Neutron Platform.

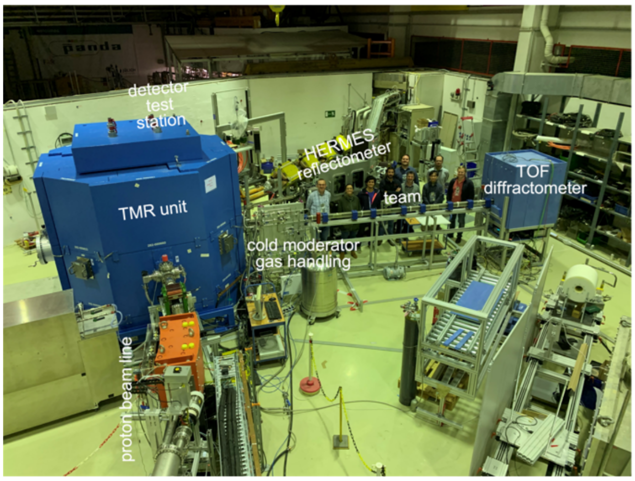

Figure 9. Target test station at the JULIC cyclotron.

Further optimization of the target test station with additional experiments are planned for 2023. It is planned to equip two extraction ducts with a thermal imaging station and an epithermal / fast imaging station. The planned experiments will allow to validate the simulation results obtained by Monte Carlo codes like MCNP, FLUKA, McStas or VITESS. Furthermore it will prove the feasibility of an accelerator-driven neutron source as the instrument performances can be scaled to the full fledged facility.

4 Summary, conclusion and outlook

The target station is the core of a HiCANS as it tailors the neutron beams to match requirements of specific instruments. The operation of multiple target stations at a HiCANS allows an unprecedented integral approach for the instrument design. At the same time, the modular design that is presented here allows the multiplexing of a whole target station including target, moderator-reflector assembly, shielding and moderator plugs at a cost of less than 10 M€. Dedicated target station setups can be derived from this basic design. It offers the flexibility by having a common outer shielding structure with an empty inner core. The inner core can be adjusted to the proton beam structure as well as the instrument suite optimizing the neutron beams to the instrument requirements. Large extraction ducts allow the extraction of the desired neutron beams from different positions of the moderator-reflector assembly and allow further tailoring of the neutron beams by inserting optimized moderators at the front of moderator plugs.

All components required for a target station have been designed, built and tested at the JULIC Neutron platform. The target test station allows further optimization of the critical components as well as to test the interplay between all of them. A much more detailed description will be published soon in a Technical Design Report (TDR). The performance of a HiCANS using such a target station was estimated for many instruments and will be published in a separate volume of the TDR. It shows that the flux at the sample position is comparable to modern research reactors or sub-MW power spallation sources with a very attractive price tag and a low background. Both the instruments and the facility allow an easy access thanks to the lower radiation levels.

The investigation of an accelerator-driven neutron source as well as the performed experiments indicate that a HiCANS is a valid option as a third corner stone of a healthy neutron landscape together with reactor neutron sources and spallation neutron sources ensuring neutron beam access for a large user community.

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