ACCELERATOR DEVELOPMENT FOR THE HIGH BRILLIANCE NEUTRON SOURCE (HBS-I)

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Abstract

Accelerator-driven neutron sources offer an attractive alternative to reactor- and spallation-based facilities for providing high-quality neutron beams for research and industry. With the availability of high-current proton accelerators, a new class of compact High-Current Accelerator-driven Neutron Sources (HiCANS) has recently become feasible. These facilities combine medium-energy proton beams in the tens-of-MeV range with beam currents up to 100 mA, compact target–moderator systems, and optimized neutron transport to deliver thermal, cold, epithermal, and fast neutrons.

The HBS-I project at Forschungszentrum Jülich is developing such a next-generation neutron source, designed as a flexible and cost-efficient research infrastructure. This paper presents the development and design of the 100 mA, 20 MeV pulsed proton linac, including the front-end, RFQ, CH-DTL, and the High-Energy Beam Transport (HEBT) system. The accelerator is optimized for high reliability, low beam losses, and uniform target irradiation through fast beam scanning, forming the technical foundation for a compact and high-briliance neutron source.

INTRODUCTION

Neutrons are an essential probe for investigating the structure and dynamics of matter across a wide range of length and time scales, making them indispensable for research in physics, chemistry, biology, and materials science. As capacities at conventional reactor-based neutron sources have declined significantly in recent decades, accelerator-driven neutron sources have emerged as a promising and sustainable alternative. These facilities use high-current pulsed proton beams in the tens-of-MeV range to generate neutrons in compact target–moderator systems, enabling efficient operation with significantly reduced shielding and cooling requirements.

The High Brilliance neutron Source (HBS-I), recently shortlisted by the German Federal Ministry of Research, Technology, and Space, is designed to provide high-quality neutron beams for a broad scientific and industrial user community. HBS-I employs a 100 mA, 20 MeV pulsed proton beam to produce small-diameter neutron beams suitable for experiments requiring high brilliance and small sample volumes. The facility will support research in energy materials, quantum materials, nanoscience, life sciences, and industrial applications.

Developed in collaboration between Forschungszentrum Jülich, Goethe-University Frankfurt, and Helmholtz-Zentrum Hereon, HBS-I represents a major step toward a new national neutron source [1]. Its compact design, modular accelerator concept, and flexible neutron instrumentation offer a forward-looking solution to the challenges currently faced by neutron research in Germany and Europe.

ACCELERATOR DESIGN AND KEY PARAMETERS

The HBS-I linac must provide a highly reliable, efficient and maintainable high-current proton beam for continuous user operation. To achieve this, the accelerator design follows several key principles. First, the choice between superconducting and normal-conducting technology is guided by the top-level beam parameters listed in Table 1, including beam current, duty cycle and final energy. For the required 100 mA, 20 MeV operation with an upgrade option to 30 MeV, a compact normal-conducting solution offers the most robust and cost-effective approach. Reliability and availability are central design drivers. All components are operated well below their technical and physical limits to minimize failure rates and simplify thermal management. A modular layout ensures straightforward access for maintenance and repair, while redundancy in critical subsystems further enhances operational stability. Together, these measures form the basis for a linac optimized for long-term,

Table 1: Top-Level Beam Parameters

Parameter	**Specification**
Particle type	Protons
Beam current	100 mA
Beam loss limit	1 W/m
Final energy	20 MeV
Upgrade option	30 MeV
Beam duty factor	2 to 4 %, DC
Pulse length	208 µs to 833 µs
Repetitions rate	24 to 96 Hz

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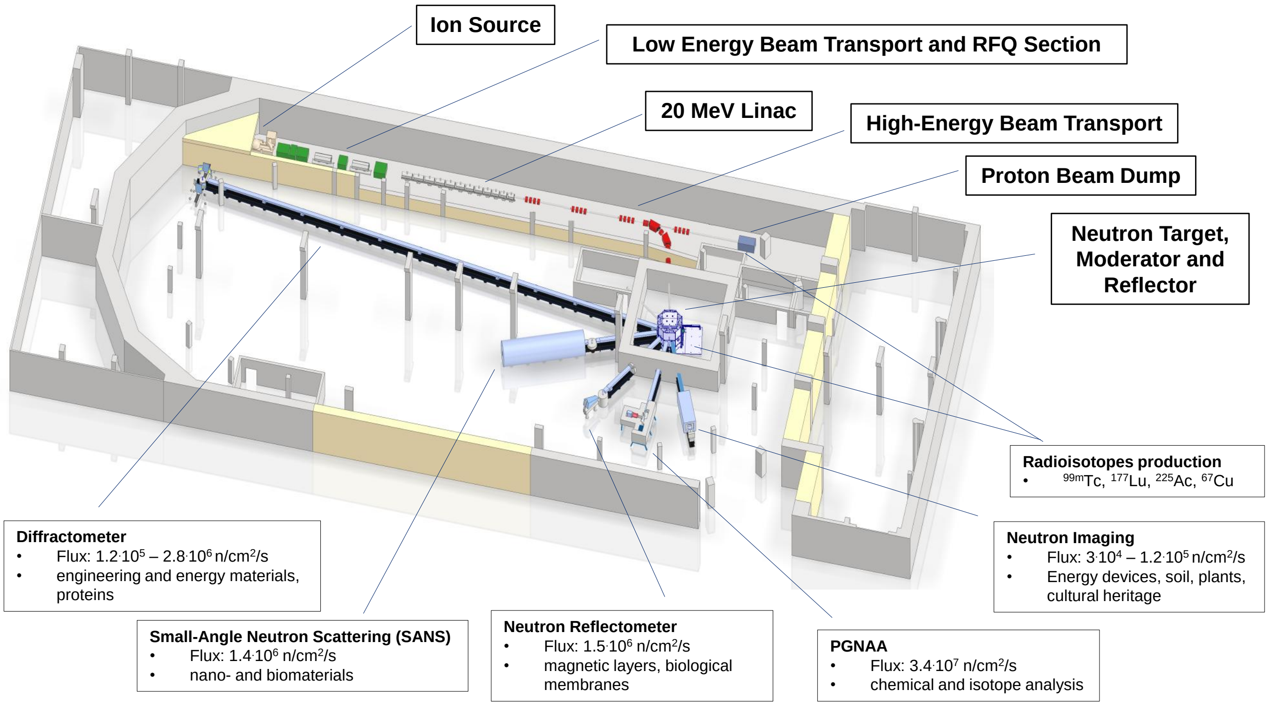

Figure 1: Planned layout of the HBS-I facility inside the former COSY hall, showing the ion source, LEBT and RFQ section, 20 MeV linac, the HEBT system, proton beam dump, neutron target–moderator–reflector assembly, neutron instruments, and medical radioisotope production stations. The figure also shows the expected neutron fluxes at the instruments and their corresponding application areas.

hands-on-maintainable operation in a user facility environment [2] .

After the decommissioning of the COoler SYnchrotron COSY [3] at the end of 2023, the existing experimental hall at Forschungszentrum Jülich became available for reuse. The HBS-I facility will be installed in this hall once the former accelerator components have been removed. The available floor space and infrastructure provide an excellent fit for the compact HiCANS layout, accommodating all accelerator components including the 20 MeV linac with a 30 MeV upgrade option, the neutron target–moderator assembly, and the associated neutron instruments and isotope production stations. Figure 1 illustrates the planned arrangement of the major subsystems within the former COSY hall.

FRONT-END AND LINAC

The front-end of the HBS linac consists of a high-current proton source, a Low-Energy Beam Transport (LEBT) section, and a two-stage Radio-Frequency Quadrupole (RFQ). Its main tasks are to generate a stable proton beam, match it into the RFQ acceptance, and minimize emittance growth at low energies where space-charge effects are strongest. A chopper converts the DC beam into the required pulse structure before injection into the RFQ.

To avoid excessive RFQ length at 176 MHz, the RFQ is split into two independently phased structures. A Medium-Energy Beam Transport (MEBT) section between them provides flexibility for transverse and longitudinal matching. The second transfer line matches the beam into the acceptance of the Drift Tube Linac (DTL).

Table 2: Main Cavity Parameters

Parameter	Specification
Cavity Type	MHz CH-DTL
Number of cavities	17
Aperture diameter	35 mm
Frequency	176 MHz
Shunt impedance	19 to 51 MΩ/m
Voltage	0.5 to 2.4 MV
Gradient	1.5 to 2.5 MV/m
Total power per cavity	70 to 405 kW
Thermal load	8 to 25 kW/m

The DTL is based on 17 normal-conducting CH-type cavities, accelerating the beam from 2.5 MeV to 20 MeV [4]. The cavity design parameter including simulation results for the thermal load are summarized in Table 2. Three cavities act as rebunchers, while the remaining structures provide acceleration. Beam dynamics design focuses on minimizing emittance growth and keeping particle losses below the 1 W/m limit required for hands-on maintenance. The effective voltages of the accelerating cavities are set to their maximum values, while the rebuncher voltages are optimized to avoid over-focusing. The full DTL section is approximately 25 m long.

HIGH-ENERGY BEAM TRANSPORT

The HEBT system guides the 20 MeV proton beam from the linac to the neutron target (see Fig. 2, left plot). A drift space of approximately 10 m behind the linac allows for a future energy upgrade (see Fig. 1) . Two quadrupole triplets provide transverse focusing through this section. Different neutron pulse structures can be provided by the generation of different interleaved proton pulse structures.

The HEBT consists of two main parts (see also Ref. [5]). In the first section, the beam is bent by 76° in the horizontal plane so that the target assembly fits precisely between two existing hall columns, while also allowing the reuse of available dipole magnets. A small vertical deflection of about 2° compensates for the height difference between the linac output (1.75 m above floor level) and the target position (1.35 m above floor level). A final quadrupole triplet focuses the beam onto the target. The resulting achromatic ion-optics, including the transverse betatron functions and the vanishing dispersion at the target position, is shown in Fig. 2 (right).

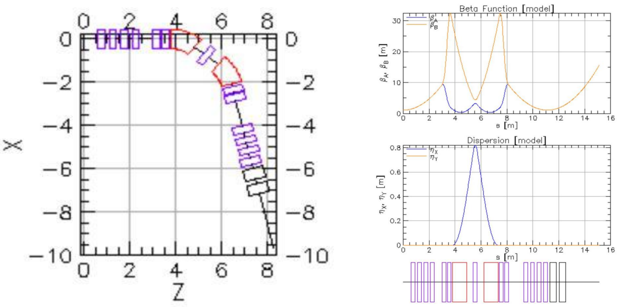

Figure 2: High-Energy Beam Transport (HEBT). Left: Beamline layout with quadrupoles (magenta), dipoles (red), and fast scanner magnets (black). Right: Transverse betatron functions (top) and dispersion (bottom) illustrating the achromatic ion-optics.

In order to evenly distribute the proton beam intensity across the target, beam scanner magnets will be employed. The beam scanning strategy is similar to the one applied at ESS [6] and has been intensively studied in Ref. [7] for a proton beam energy of 70 MeV [2] and the results of this study are shown in Fig. 3.

To achieve a uniform power distribution on the neutron target, the proton beam is deflected by two fast scanner magnets located upstream of the target. Each magnet is driven by an independent triangular current waveform, producing a Lissajous-type raster pattern on the target surface. The triangular waveform ensures a constant scanning velocity, preventing excessive dwell time at the edges of the target.

For a closed raster pattern within a single proton pulse, the horizontal and vertical scanning frequencies must be odd integer multiples of the inverse pulse length. This condition guarantees that the beam covers the entire target area uniformly during each pulse. Figure 3 (left) illustrates an example pattern for frequency indices (5,3) with a phase shift of $-\pi/2$ between the two planes. The resulting average power density distribution, shown in Fig. 3 (right), exhibits a maximum of approximately 1 kW/cm^2 [7].

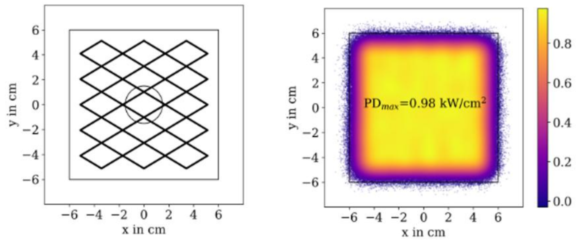

Figure 3: Left: Lissajous-type raster pattern generated by horizontal and vertical scanner magnets driven by triangular waveforms (example shown for frequency indices (5,3)). Right: Resulting average power density distribution on the target, demonstrating uniform irradiation for the chosen scanning parameters. Further information on the exact parameter for this setup can be found in Ref. [7].

The choice of scanning frequencies, beam width and target–moderator configuration is currently under optimization. As the target material and geometry are refined, the scanning parameters will be adjusted to ensure stable operation and optimal neutron yield for different proton pulse lengths.

SUMMARY AND OUTLOOK

The ongoing development of high-current accelerator-driven neutron sources represents a promising pathway toward compact and cost-efficient next-generation neutron research facilities. Within this framework, the HBS-I project develops a 100 mA, 20 MeV proton linac optimized for high reliability, low beam losses and flexible beam delivery. The design integrates modular normal-conducting RF structures, robust beam dynamics, and a scanning strategy capable of adapting to different target–moderator configurations.

An important subsystem of the facility is the High-Energy Beam Transport (HEBT) system, which employs an achromatic lattice and fast triangular-waveform scanning to achieve a uniform power distribution on the neutron target. This uniformity is essential for thermal stability, target lifetime, and maximizing neutron yield.

Current work focuses on refining the scanning strategy, optimizing beam width and frequencies, and adapting the system to different target–moderator configurations. These studies are essential to maximize neutron yield and ensure stable long-term operation.

In the next phase, engineering design and prototyping of key accelerator components will be carried out, together with integrated validation of beam dynamics and target performance. These developments will form the basis for a reliable, modular and scalable HiCANS facility, supporting a broad scientific and industrial user community.

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