ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC31

ESTABLISHING A NEW CLASS OF HIGH-CURRENT ACCELERATOR-DRIVEN NEUTRON SOURCES WITH THE HBS PROJECT*

A. Lehrach[1]†, J. Baggemann, Y. Bessler, T. Brückel, O. Felden, T. Gutberlet, R. Hanslik,
J. Li, E. Mauerhofer, U. Rücker, A.Schwab, J. Voigt, P. Zakalek
Forschungszentrum Jülich, Jülich, Germany
K. Kümpel[2], O. Meusel, H. Podlech[2], J. Storch,
Johann Wolfgang Goethe-Universität, Frankfurt, Germany
W. Barth[3], R. Gebel[4], J. List[3], M. Miski-Oglu[3]
GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
[1]also at III. Physikalisches Institut B, RWTH Aachen University, Aachen, Germany
[2]also at Helmholtz Research Academy Hesse for FAIR (HFHF), Frankfurt, Germany
[3]also at Helmholtz-Institut Mainz, Johannes Gutenberg-Universität, Mainz, Germany
[4]also at Forschungszentrum Jülich, Jülich, Germany

Abstract

Accelerator-driven high brilliance neutron sources are an attractive alternative to the classical neutron sources of fission reactors and spallation sources to provide scientists with neutrons to study and analyze the structure and dynamics of matter. With the advent of high-current proton accelerator systems, a new class of such neutron facilities can be established referred to as High-Current Accelerator-driven Neutron Sources (HiCANS). The basic features of HiCANS are a medium-energy proton accelerator with beam energies of tens of MeV up to 100 mA beam current, a compact neutron production and moderator unit and an optimized neutron transport system to provide a full suite of high performance, fast, epithermal, thermal and cold neutron instruments.

The Jülich Center for Neutron Science (JCNS), together with partners, has established a project to develop, design and demonstrate such a novel accelerator-driven facility, called the High Brilliance neutron Source (HBS).

INTRODUCTION

The goal of the HBS project is to build a versatile neutron source as a user facility with open access and service according to the diverse and changing demands of its communities. Embedded in an international collaboration with partners from Europe and Japan, the Jülich HBS project offers the best flexible solutions for scientific and industrial users. The overall conceptual and technical design of the HBS as a blueprint for a HiCANS facility has been published in a series of recent reports [1, 2]. The full-scale HBS facility is characterized by the simultaneous operation of a suite of neutron instruments distributed around three target stations, each efficiently operated to deliver variable neutron spectra. During the development of the HBS concept, particular attention was paid to extreme flexibility and scalability in terms of beam energy, beam power, time structure and duty cycle.

This paper presents the status of the HBS project, focusing on the high-current linear accelerator and the proton beam transport system, including a novel multiplexer to distribute the proton beam to three different neutron target stations while adapting a flexible pulse structure.

DESIGN OBJECTIVES

One of the most important issues for high-power hadron linacs is the choice of technology with respect to superconducting or room temperature operation. The advantage of a certain technology depends on various top-level beam parameters. These include the RF duty cycle, the peak beam current and the final energy, summarized in Table 1.

Table 1: Top-level Beam Parameters

Parameter	Specification
Particle type	Protons
Beam current	100 mA
Final energy	70 MeV
Beam duty factor	6 (up to 20)%
RF duty factor	8 (up to 25)%
Pulse length	208/208/833 µs
Repetitions rate	96/96/24 Hz
Average beam power	420 (1400) kW
Peak beam power	7 MW

The design objectives for the HBS-Linac should aim for an accelerator system that is as efficient as possible in terms of length and RF power and as reliable as possible as a user facility. High reliability and availability can be achieved by implementing a modular design that allows easy access to all components for repair and maintenance. In addition, all components should be operated well below their technical

* Work supported by the Innovation Pool project on “High current accelerator systems for future HBS”, Research Field Matter of the Helmholtz Association (HGF), Germany.
† a.lehrach@fz-juelich.de

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC31

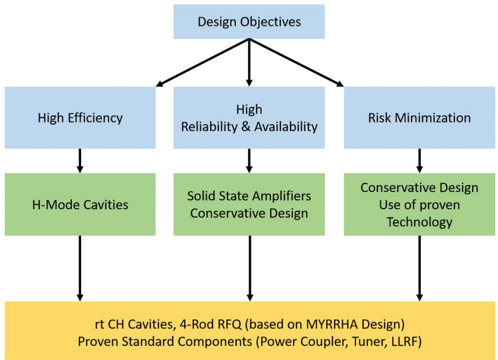

Figure 1: Design philosophy driven by obtaining high availability, risk minimization, high efficiency and cost reduction.

and physical limits. Redundancies in critical components can significantly increase reliability and availability. The overall design philosophy and final choice of technology is illustrated in the diagram of Fig. 1.

FRONT-END AND DRIFT TUBE LINAC

The front-end of the HBS-Linac consists of a high-current proton source, a Low Energy Beam Transport (LEBT) and a Radio Frequency Quadrupole (RFQ) before the proton beam is injected into the Drift Tube Linac (DTL). This section has to fulfill several tasks. After the beam generation in the proton source, the beam has to be transported to the entrance of the RFQ. The LEBT has to match the transverse phase space to the acceptance of the RFQ. A chopper is used to convert the DC beam at the entrance of the RFQ into the required beam pulse structure. The beam energy at injection into the DTL is 2.5 MeV. At a frequency of 176.1 MHz, the RFQ would be impractically long. Therefore, it was decided to split the RFQ into two independently phased RF structures. To have maximum flexibility for longitudinal and transverse matching, a first medium energy beam transfer will be used between the two RFQ structures. After the second RFQ, the second beam transfer is matching the beam into the acceptance of the DTL. The front-end is a very critical section especially in terms of beam dynamics, because of the high space charge forces at these low energies. The design focus has been on minimizing emittance growth and only to a lesser extent on efficiency.

The DTL is based on a normal-conducting Crossbar H-mode (CH) cavity design and must accelerate the proton beam from 2.5 MeV to 70 MeV [3]. The design of the DTL is a complex process between beam dynamics and cavity design. There are a number of beam dynamics requirements for the DTL, including RF frequency, beam current, required maximum duty cycle, minimum emittance growth, and minimum particle losses.

The DTL beam dynamics design consists of 45 normal conducting CH-type cavities, of which the second, fifth and eighth act as rebunchers. The whole DTL section is 66.7 m long. The effective voltages of the accelerating cavities have been set to the maximum, while the voltages of the rebunching cavities are optimized to avoid over-focusing. The cavity design including simulation results for the outer surface temperature distribution are shown in Fig. 2 and the main cavity parameters in Table 2.

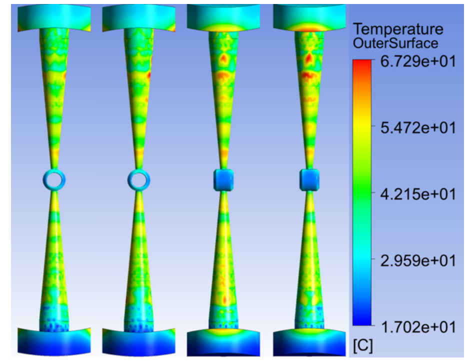

Figure 2: Normal-conducting Crossbar H-mode (CH) cavity design with simulated outer surface temperatures.

Table 2: Main Cavity Parameters

Parameter	Specification
Number of cavities	45
Aperture diameter	35 mm
Shunt impedance	19 - 51 MΩ/m
Voltage	0.5 - 2.4 MV
Gradient	1.5 - 2.5 MV/m
Total power per cavity	70 - 405 kW
Thermal load	8 - 25 kW/m

HIGH ENERGY BEAM TRANSPORT

The High Energy Beam Transport (HEBT) connects the linac to the individual target stations of the HBS, see Fig. 3 [4]. It includes the multiplexer system, which is part of the HEBT design, and a beam dump. To achieve full performance, this facility simultaneously operates three neutron target stations in parallel with several neutron instruments attached.

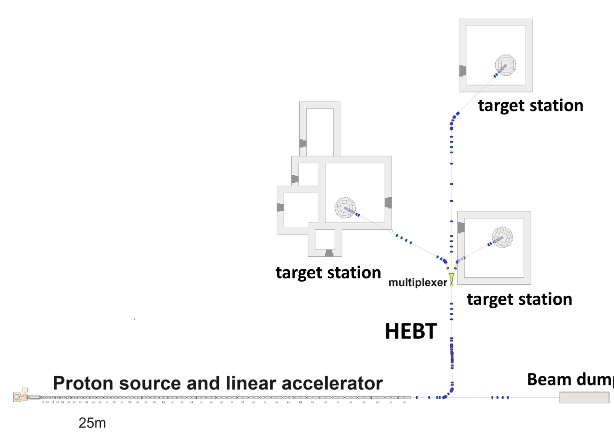

Figure 3: Schematic top view of HBS, including the front-end, linac and beamline to the individual target stations.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC31

Each target station is efficiently operated to deliver different neutron pulse structures, which is achieved by efficiently generating an interleaved proton pulse structure that provides three different proton beam timing schemes. The distribution of the different proton pulse sequences to the target stations is accomplished by a proton beam multiplexer system [5]. It consists of a kicker magnet and a three-field septum magnet (TFSM). The integration of the multiplexer system at HBS including the design of a septum magnet is based on dedicated developments using a 45 MeV proton beam of the JULIC cyclotron at Forschungszentrum Jülich [6] and scaled for the larger proton beam energy of 70 MeV at the HBS.

In conjunction with the HBS multiplexer system, the HBS High-Energy Beam Transport (HEBT) beamline was designed and the associated beam dynamics calculations were performed. The geometry of the HEBT is determined by the location and arrangement of the HBS target stations in the three experimental halls, based on the space requirements of the neutron targets, instruments and the corresponding building locations and dimensions.

The HEBT can be structured into different sections (see Fig. 3) [7]. The first section bends the beam horizontally by 90° from the linac to the experimental section. The second section then deflects the beam vertically by 90° from the ground floor into the basement in order to increase radiation safety. Both sections consist of two double-bent achromats, based on two 45° sector bending magnets, each equipped with five quadrupoles. In the basement, the beam is transferred to the third section of the straight HEBT beamline. Here, a quadrupole triplet with four quadrupoles is used to focus the beam into the multiplexer. In the straight beamline, the beam only passes through the first two quadrupoles of the multiplexer.

To guide the beam into the two outer field regions of the TFSM, a kicker magnet is used to apply an angle kick to the beam. The septum magnet separates the beams for delivery to the left and right target stations. The multiplexer section also provides an achromatic optics by adding three quadrupoles to the additional 45° bending magnet for the two outer beam lines. In the third section after the multiplexer, where the three beamlines are separated, a matching section consisting of a quadrupole triplet is used to match the beam into the three beam transport sections. The straight beamline consists of two FODO (focusing-drift-defocusing-drift) structures with a cell length of 5.6 m. The next triplet of the straight beamline focuses the beam into a 45° horizontal bending section, before the beam reaches the final achromatic section, which guides the beam vertically by 90° up to the neutron target station. In front of the targets, a quadrupole triplet is installed to adjust the focus of the beam on the target. Vertical and horizontal dipole scanner magnets are used to spread (beam painting) the beam evenly on the neutron target to optimize the heat distribution. From the last vertical bending section on, the three beamlines are identical again. Since the right and left beamlines to the neutron target stations are significantly shorter than the straight beamline, the FODO cells are removed. As an example, the straight beamline is shown in the Fig. 4.

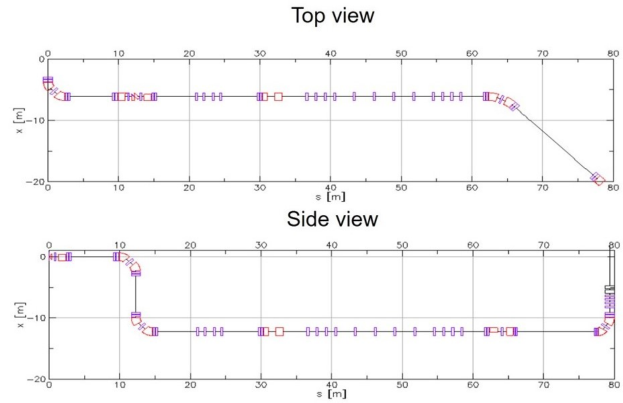

Figure 4: Top and side view of the straight HEBT beamline with quadrupoles (pink), dipoles (red), and scanner dipole magnets (black). The multiplexer is located at roughly 31 m.

The corresponding beam dynamics calculations for the different beamline sections have been performed using the Bmad library [8] to optimize the optical setting. The dynamic acceptance of the beamline needs to be further optimized, including multipole corrector fields. So far, only estimated multipole errors of the magnets have been implemented without any minimization of the average beam losses in the beamline. A straight forward approach to further reduce the average beam losses is to increase the aperture of the magnets, and to include a beam scraper at the entrance of the HEBT, which limits the beam size to 6σ, to reach a specified beam loss below $1\,\mathrm{W\,m^{-1}}$ for all three beamlines.

OUTLOOK

High-current accelerator-driven neutron sources (HiCANS) are an important step in the development of the next generation of neutron research facilities. The HiCANS concept, in which neutrons are produced by low-energy nuclear reactions using a high-current accelerator that directs a proton beam onto a metal target, is a new and cost-effective approach to accessing brilliant beams of thermal and cold neutrons at affordable construction and operating costs. Coordinated efforts are underway in several countries to develop such neutron sources. All these projects are part of the European Low-Energy Accelerator-based Neutron facilities Association (ELENA) [9], which promotes cooperation among the HiCANS projects.

The HBS with its 100ṁA beam at 70MeV belongs to the class of high-current compact accelerator-based neutron sources of HICANS. As other accelerator-based neutron sources will require different beam parameters in the future, the HBS design can be adapted to these local requirements. The HBS concept is extremely flexible and scalable in terms of beam energy, beam power, time structure and duty cycle, ranging from the size of a large laboratory for local university and industrial use to full-scale and highly competitive user facilities.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC31

REFERENCES

[1] T. Brückel and T. Gutberlet (Eds.), "Conceptual Design Report: Jülich High Brilliance Neutron Source (HBS)", in *Schriften des Forschungszentrums Jülich, Reihe Allgemeines/General*, vol. 8, 2021, ISBN 978-3-95806-501-7. doi:10.18154/RWTH-2021-01995

[2] R. Gebel, A. Lehrach, and H. Podlech (Vol. Eds.), "Technical Design Report HBS: Volume 1 – Accelerator", in *Schriften des Forschungszentrums Jülich, Reihe Allgemeines/General*, vol. 9.01, 2023, ISBN 978-3-95806-709-7. https://www.fz-juelich.de/en/jcns/jcns-2/expertise/high-brilliance-neutron-source/conceptual-and-technical-design

[3] H. Podlech *et al.*, "Conceptual Design of the Proton LINAC for the High Brilliance Neutron Source HBS", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 910–913. doi:10.18429/JACoW-IPAC2019-MOPTS027

[4] M. Rimmler, "Development of a Multiplexer System and Measurement of the Neutron Yield for a Low-Energy Accelerator-Driven Neutron Source", in *Schriften des Forschungszentrums Jülich. Reihe Schlüsseltechnologien/Key Technologies*, vol. 250, 2021. https://julib.fz-juelich.de/vufind/Record/866423

[5] M. Rimmler *et al.*, "Developments of a Multiplexer System for the High-Brilliance Neutron Source HBS", *J. Neutron Res.*, vol. 23, pp. 143-156, 2021. doi:10.3233/JNR-210009

[6] O. Felden *et al.*, "Recent Extensions of JULIC for HBS Investigations", in *Proc. Cyclotrons'19*, Cape Town, South Africa, Sep. 2019, pp. 195–198. doi:10.18429/JACoW-CYCLOTRONS2019-TUP019

[7] A. Lehrach *et al.*, "Beam Dynamics Studies for the Target Beamlines of the High Brilliance Neutron Source", *J. Phys.: Conf. Ser.*, vol. 2687, p. 042011, 2024. https://iopscience.iop.org/article/10.1088/1742-6596/2687/4/042011

[8] D. Sagan, "Bmad: A Relativistic Charged Particle Simulation Library", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 558, pp. 356–359, 2006. doi:10.1016/j.nima.2005.11.001

[9] ELENA: European Low Energy accelerator-based Neutron facilities. https://elena-neutron.iff.kfa-juelich.de