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Beam Dynamics Studies for the Target Beamlines of the High Brilliance Neutron Source

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Abstract. The High Brilliance Neutron Source (HBS) belongs to the class of High Current Accelerator based Neutron Sources (Hi-CANS). The driver Linac for the HBS must be able to reliably accelerate a 100 mA proton beam to an energy of 70 MeV [2, 1, 3]. The beam is sent pulse-by-pulse to three different targets via a multiplexer in the High Energy Beam Transfer (HEBT) section. Each individual proton pulse behind the multiplexer has a specific time structure in order to optimally serve the different instruments grouped around one target station. The main development steps of the HEBT are the development of a three-field septum magnet, which is an essential part of the multiplexer magnet system, the beam dynamics integration of the multiplexer magnet system into the beamline, and the ion-optical layout of the individual target beamlines.

1. Introduction

The High Brilliance neutron Source (HBS) project aims to develop a scalable Compact Accelerator-driven Neutron Source (CANS) that will enable neutron fluxes at the corresponding instruments comparable to existing fission-based or spallation neutron sources. 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 [1]. An appropriate beamline design has been worked out in detail. It will deliver proton beams of up to 100 mA and 70 MeV from the proton Linac via the target beamlines to the neutron production targets. To ensure the complex pulse structure of the proton beam, a multiplexer magnet system will be installed to generate and distribute the different proton pulse schemes to the target stations. The three individual target stations will be operated at different proton pulse frequencies, with the corresponding proton pulse length coupled via a fixed duty cycle.

2. Multiplexer System

The distribution of the different proton pulse sequences to the target stations is accomplished by a proton beam multiplexer system consisting of a bipolar kicker magnet and a three-field


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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 from the JULIC cyclotron at Forschungszentrum Jülich and scaled for the larger proton beam energy of 70 MeV at the HBS. In connection with the HBS multiplexer system, the HBS High Energy Beam Transport (HEBT) beamline was designed and the associated beam dynamics calculations were carried out [4, 5].

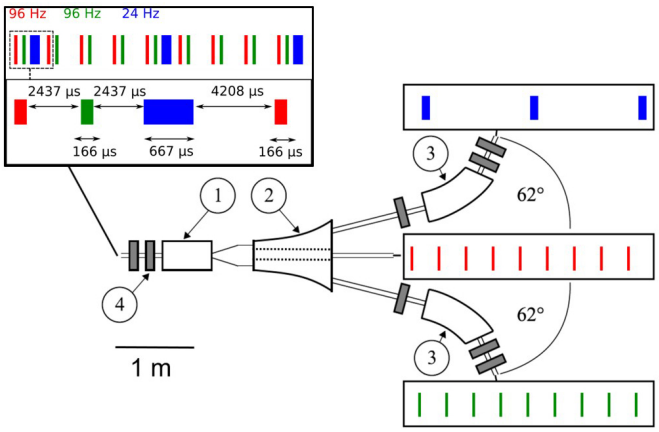


Figure 1. Conceptual layout of the multiplexer system for HBS as partly realized at JULIC. 1: Bipolar kicker magnet, 2: Septum magnet with three different field regions, 3: 45° sector bending magnet, 4: Quadrupole magnet (all in grey). After the multiplexer system, the proton pulses are split into three beamlines with a total tilt of 62°. The detailed timing scheme of the pulse sequence is also shown, with the two 96 Hz pulses of 166 μs length in red and green, and the 24 Hz pulse scheme of 667 μs length in red.

The focus was on the development of a new type of septum magnet based on permanent magnets with three different magnetic dipole field regions in close proximity. The conceptual layout of the multiplexer system is identical for both JULIC and HBS (Fig. 1).

3. High Energy Beam Transport

The HEBT is the proton transport beamline that connects the Linac to the individual target stations (Fig. 2). It includes the multiplexer system, which is part of the design of the HEBT.

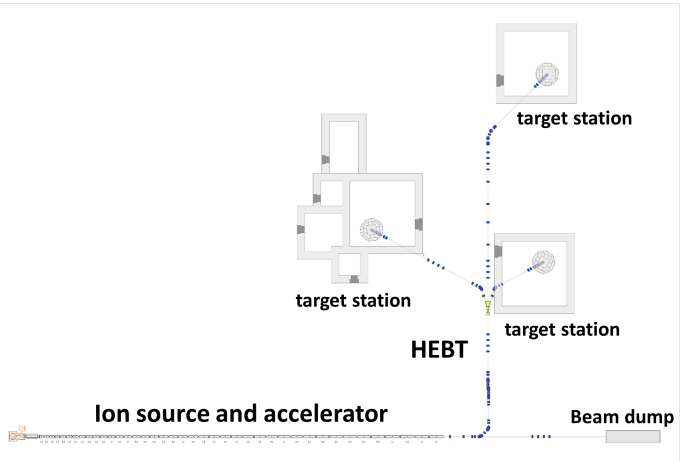


Figure 2. Schematic top view of HBS, including the front end, Linac, beam dump and HEBT beamline to individual target stations. The detailed location of the magnets is shown in Figs. 3 and 4.

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. 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 (Fig. 3).

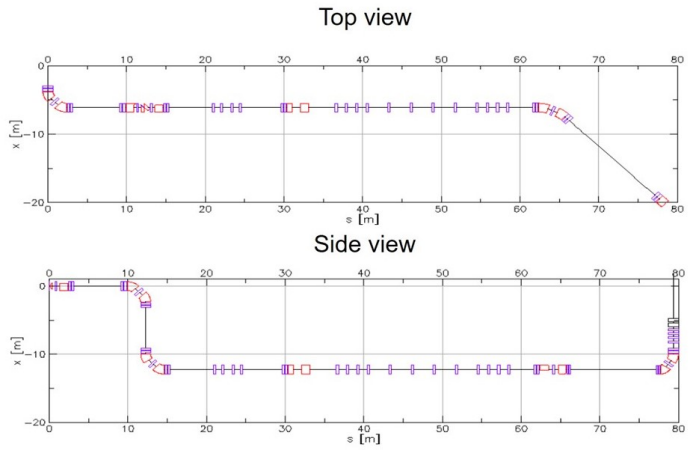


Figure 3. Top and side view of the straight HEBT beamline. The drawing shows the three different sections, the beam dump, and the respective quadrupole (pink), dipole (red), and scanner dipole magnets (black). The multiplexer is located at roughly 31 m in this representation.

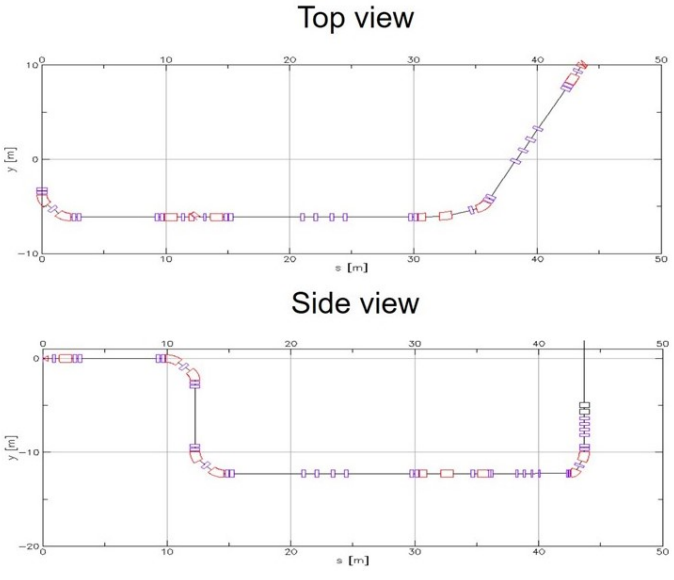


Figure 4. Top and side view of the left HEBT beamline. The drawing shows the three different sections and the respective quadrupole (pink), dipole (red), and scanner dipole magnets (black). The multiplexer is located at roughly 31 m in this representation.

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. The cell length of each FODO cell is 5.6 m, giving a total length of roughly 11.2 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 focusing of the beam on target. Vertical and horizontal dipole scanner magnets are used to spread (beam painting) the beam evenly on the neutron target to optimize heat distribution. From the last vertical bending section on the three beamlines are identical again. Since the right resp. left beamline to the neutron target stations is significantly shorter than the straight beamline (Fig.2), the FODO cells are removed. As an example, the top and side views of left beamline are shown in Fig. 4.

In the present arrangement of the neutron target stations (Fig. 2), the right beamline looks basically the same as the left one, except that the third section is shorter. Therefore, the triplet at the entrance of the third section can be adjusted accordingly to focus the beam into the vertical bending section. If the position of the neutron target needs to be shifted again to further optimize the experimental setup, the beamline can be easily be adopted by adding FODO cells in the third section and adjusting the final horizontal 45° bend in the straight beamline or the bending angle in the dipole behind the multiplexer in the two outer beamlines. The chosen beamline concept provides maximum flexibility to adopt to modified target positions.

The corresponding beam dynamics calculations for the different beam line sections have been performed using the Bmad library [6] to optimize the optical setting. The beam optics of the straight beamline and the left beamline including the magnet arrangement are shown in Figs. 5 and 6 respectively. For beam simulations, the following beam parameters were considered at the entrance of HEBT:

- Transverse beam size: $\sigma_{x,y} = 1.6\,\mathrm{mm}$,
- Beam emittance: $\epsilon^{g}_{x,y} = 2.54\,\mathrm{mm\,mrad}$ (rms, geom.), $\epsilon^{n}_{x,y} = 1\,\mathrm{mm\,rad}$ (rms, normalized),
- Momentum spread: $\Delta p/p = 0.5\,\%$,
- Optical functions: $\beta_{x,y} = 1.1\,\mathrm{m}$, $\eta_{x,y} = 0\,\mathrm{m}$.

In order to achieve the specified values, the Linac must be adjusted accordingly. The beam emittance could eventually be reduced by a beam collimation system and the initial Beta functions and momentum spread adjusted by adding a matching section consisting of a quadrupole triplet and a bunch rotator between the Linac and the HEBT.

The optics in front of the multiplexer is similar for both beamlines. It includes a horizontal 90° bend from the Linac into the experimental section and furthermore two vertical bends to transfer the beam to the basement floor. The left beamline has an additional bend in the TFSM at about 50 m and the straight beamline has a 45° bend at roughly 79 m. The last vertical 90° bend at roughly 67 m (left beamline) and about 100 m (straight beamline) carries the beam from the basement up to the neutron target stations.

The geometric acceptance of the beamline can be estimated from the calculated Beta functions and dispersions along the beamline[4, 5] . The aperture of the magnets is planned to be 60 mm. In regions without dispersion ($\eta_{x,y} = 0$), the maximum Beta function is $\beta_{x,y} \leq 35\,\mathrm{m}$, giving a transverse beam size of $\sigma^{max}_{x,y} \leq 9.5\,\mathrm{mm}$ with a transverse emittance of $\epsilon^{g}_{x,y} = 2.54\,\mathrm{mm\,mrad}$ (rms). This corresponds to a 6σ beam that fits into the magnet aperture. In regions with maximum dispersion ($\eta_{x,y} \leq 0.8\,\mathrm{m}$), the maximum Beta function $\beta_{x,y} \leq 5\,\mathrm{m}$. With a momentum spread of $\Delta p/p = 0.5\,\%$, a 6σ beam also fits into the aperture of the magnets. The gap height of the TFSM is only $l_{gap} = 52\,\mathrm{mm}$, providing a safety margin for the 24 mm beam. The actual 6σ beam has an elliptical shape with an extent of 24 mm in the vertical plane and 8 mm in the

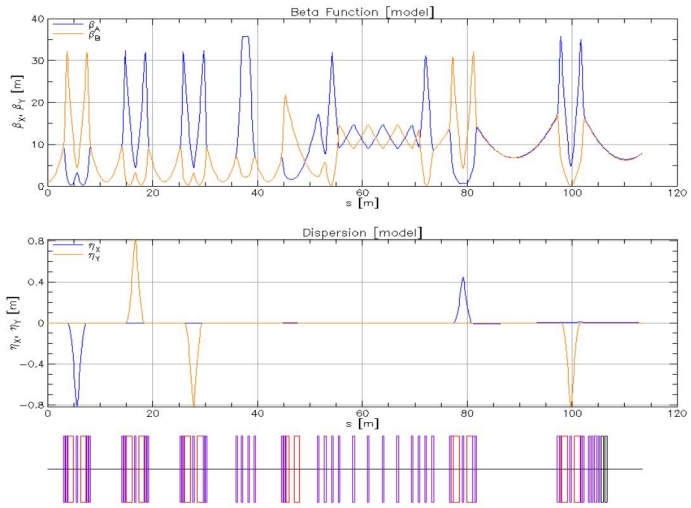


Figure 5. Horizontal and vertical Beta function $\beta_{x,y}(s)$ (upper plot), and dispersion function $\eta_{x,y}(s)$ (middle plot) versus longitudinal position s along the straight HEBT beamline. The lower plot shows the magnet arrangement with quadrupoles in pink, dipoles in red, and scanner dipole magnets in black. The multiplexer is located at roughly 50 m.

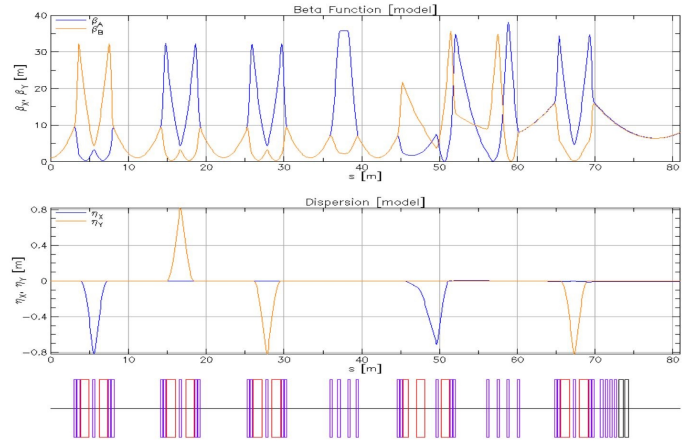


Figure 6. Horizontal and vertical Beta function $\beta_{x,y}(s)$ (upper plot), and dispersion function $\eta_{x,y}(s)$ (middle plot) versus longitudinal position s along the left HEBT beamline. The lower plot shows the magnet arrangement with quadrupoles in pink, dipoles in red, and scanner dipole magnets in black. The multiplexer is located at roughly 50 m.

horizontal plane. The effect of the field quality of the TFSM on the transmission through the HEBT has also been investigated in detail by particle tracking studies [4, 5]. The simulated beam transmission through all three field regions is close to 100 %.

4. Outlook

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.

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