# DESIGN OF A LOW-FREQUENCY PROTON EXTRACTION LINE FOR HIGH-PULSED MAGNETIC FIELD NEUTRON SCATTERING AT ESS *

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*Abstract*

A dedicated low-frequency target station is recently proposed at ESS to support neutron-scattering experiments using >40 T pulsed magnetic fields [1, 2]. These experiments require isolated proton pulses at mHz rates, demanding a specialized extraction system that operates without disturbing the neutron production beyond the extracted pulse. This study evaluates the feasibility of such an extraction and transfer line. A new dipole integrated into the HEBT lattice enables single-bunch extraction, while a FODO-based transfer line ensures low dispersion and the required spot size at the target. Analytical estimates and preliminary simulations confirm that a dedicated low-frequency extraction system is viable and provides the basis for detailed magnet and operational design.

## INTRODUCTION

Neutron scattering under very high pulsed magnetic fields provides unique insight into the microscopic behavior of magnetic materials, enabling the study of field-induced phase transitions, quantum critical phenomena, and exotic magnetic states [3–5]. Such experiments require magnetic fields above 40 T, which can only be achieved using pulsed resistive magnets [3, 6]. Due to thermal and mechanical constraints, these magnets operate at very low repetition rates, typically one pulse every several minutes [7]. In contrast, spallation neutron sources such as the European Spallation Source (ESS) operate at much higher repetition rates, producing neutron pulses at frequencies of several tens of Hz [8]. As a result, only a small fraction of the available neutron flux coincides with the magnetic field pulse, significantly reducing experimental efficiency.

A dedicated low-frequency neutron source has been proposed to address this limitation by synchronizing neutron production with magnet pulses [1, 2]. This concept involves extracting selected proton pulses from the ESS linac at mHz repetition rates and directing them to a secondary target station. Parasitic extraction must preserve nominal beam delivery to the primary ESS target and avoid perturbing accelerator operation.

The implementation of such a source requires a dedicated beam extraction system integrated into the ESS High Energy Beam Transport (HEBT) line, as well as a transfer line capable of transporting the extracted beam to the secondary target while maintaining beam quality and minimizing losses. The extraction system must provide reliable single-pulse deflection with suitable magnetic field strength, timing characteristics, and field quality. The transfer line optics must ensure proper matching to the target requirements, including beam size and dispersion control.

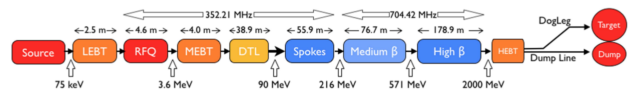


Figure 1: Schematic view of the ESS proton linac [9].

This paper presents a feasibility study of a low-frequency proton beam extraction and transfer line at ESS. The study includes integration of an extraction dipole magnet into the HEBT lattice, analytical estimates of magnet and timing requirements, and beam optics design of a transfer line delivering the required beam parameters to a secondary target station.

## ESS LINAC BEAM PARAMETERS

The ESS linac delivers high-power proton pulses with parameters summarized in Table 1. The accelerator is designed to provide a beam energy of 2 GeV, a repetition rate of 14 Hz, and a macro-pulse length of 2.86 ms, corresponding to an average beam power of 5 MW [9].

Table 1: ESS high-level beam parameters.

| | |
|---|---|
| Average beam power | 5 MW |
| Proton kinetic energy | 2 GeV |
| Pulse repetition rate | 14 Hz |
| Energy per pulse | 357 kJ |
| Average pulse current | 62.5 mA |
| Macro-pulse length | 2.86 ms |

The linac consists of a normal-conducting front end followed by superconducting accelerating structures, bringing the beam to its final energy. The High Energy Beam Transport (HEBT) section transports the beam to the target station and provides flexibility for beam distribution and future upgrades. The HEBT lattice includes drift spaces suitable for the installation of additional beamline components required for beam extraction.

Figure 1 shows a schematic overview of the ESS linac and HEBT system.

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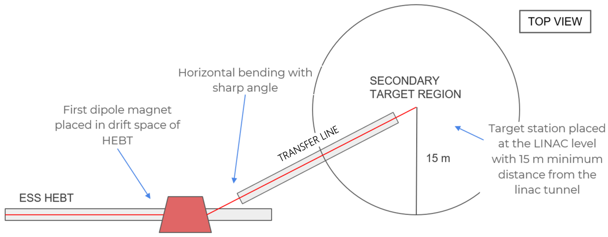


Figure 2: Schematic design of the transfer line.

## EXTRACTION CONCEPT AND LAYOUT

The proposed extraction system diverts selected proton pulses toward a dedicated low-frequency target station using an additional dipole magnet installed in a drift space of the ESS HEBT lattice. The extracted beam is then transported through a dedicated transfer line to the secondary target.

To minimize infrastructure costs and simplify shielding requirements, the secondary target station is located at the same elevation as the linac tunnel, approximately 4.5 m below ground level. A minimum distance of 15 m between the linac and the secondary target station is maintained to ensure sufficient shielding and avoid interference with existing ESS infrastructure.

Figure 2 illustrates the conceptual layout of the extraction system, transfer line, and secondary target station.

## DIPOLE MAGNET DESIGN

The extraction dipole magnet must satisfy several key requirements:

- Fit within available drift space in the HEBT lattice,
- Provide sufficient magnetic field to deflect the 2 GeV proton beam,
- Allow controlled extraction of individual proton pulses without affecting adjacent pulses.

The required magnetic field is determined by the beam energy and bending radius [10]:

$$B = \frac{E}{0.2998\,\rho} \tag{1}$$

A bending angle of 13° and magnetic length of 5 m were selected, resulting in a bending radius of 22 m and required magnetic field of 0.3 T. Notably, the magnet's dimensions closely mirror those of the magnet designed and built in the SNS transfer line [11, 12].

A C-type dipole configuration was chosen due to its accessibility and suitability for beam extraction applications [13, 14]. The magnet gap was set to 105 mm to accommodate the ESS vacuum chamber.

Magnetic field simulations were performed using *Poisson Superfish* [15]. The magnet geometry and resulting magnetic field distribution are shown in Fig. 3.

The magnetic field profile along the horizontal axis is shown in Fig. 4, confirming that the required central field of 0.3 T is achieved.

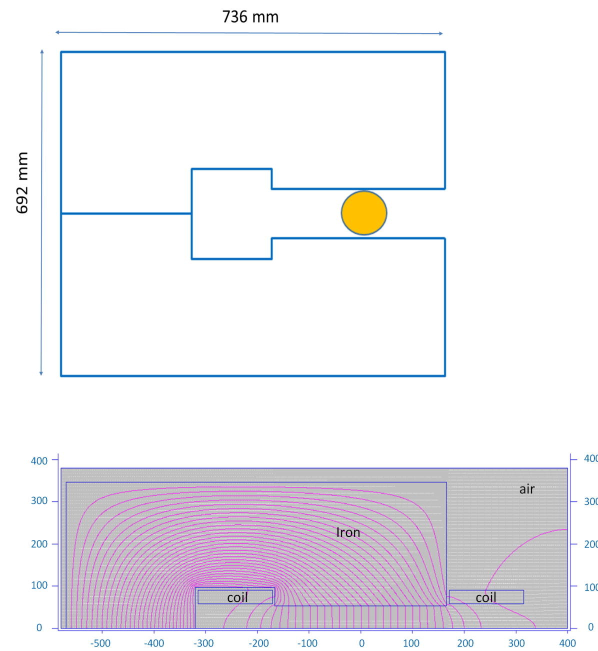


Figure 3: The schematic of the designed C-type dipole magnet with the yellow circle showing the linac vacuum chamber (top) and simulation of the top half C-type dipole magnet with *Poisson SuperFish* (bottom).

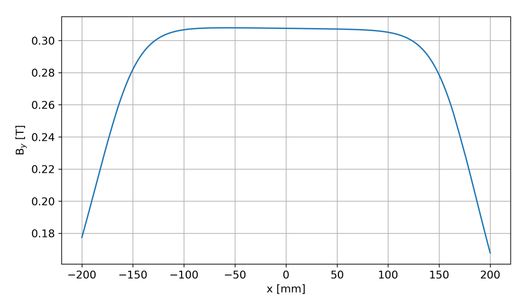


Figure 4: Magnetic field variation along the horizontal axis.

The field quality within the good field region is shown in Fig. 5. The field deviation remains below $10^{-3}$ within $\pm 35$ mm, satisfying beam transport requirements.

The total current of the magnet, calculated using Ampere's law,

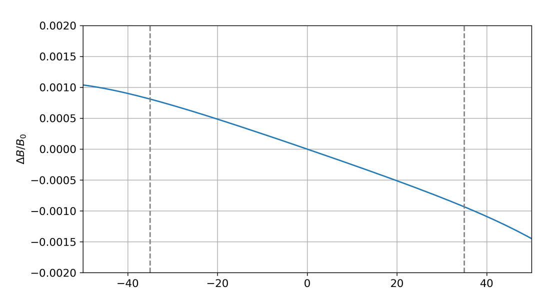


Figure 5: Field quality within the good field region.

$$NI = \frac{Bh}{2\mu_0} \quad (2)$$

corresponds to 13.3 kA per pole.

The required rise/fall time is 70 ms, which can be achieved through an optimized design of the coil as well as the power supply.

Key dipole parameters are summarized in Table 2.

Table 2: Dipole magnet specifications.

| | |
|---|---|
| Magnet type | C |
| Pole width | 332 mm |
| Magnetic length | 4.94 m |
| Bending angle | 13° |
| Bending radius | 22 m |
| Gap | 105 mm |
| NI (for one coil) | 13.3 kA |
| Field quality at x:(-35, 35) mm | $10^{-3}$ |
| B at center | 0.3 T |

## TRANSFER LINE OPTICS DESIGN

The transfer line transports the extracted beam to the secondary target while preserving beam quality and minimizing losses. Beam optics simulations were performed using *TraceWin* [16]. Figure 6 shows the transfer line layout. The design uses a FODO lattice consisting of eight quadrupoles and two dipole magnets.

The second dipole compensates dispersion generated by the extraction dipole, ensuring dispersion-free beam delivery at the target.

The quadrupole parameters were selected based on existing ESS components to simplify implementation and reduce costs. Table 3 presenting the specifications of the first seven quadrupoles.

Table 3: Specifications of quadrupoles.

| | |
|---|---|
| Length | 350 mm |
| Thickness | ~ 0.83 m |
| Gradient | 4 T/m |
| Aperture | 50 mm |

The field strength of the last quadrupole, positioned downstream of the second dipole, underwent specific tuning. This adjustment was made to increase the beam size and match with the desired value of 3.8 cm. The final field gradient corresponds to 1.2 T/m.

Figure 7 shows the dispersion, beam envelope, and beta functions along the transfer line.

Simulation results demonstrate that:

- Dispersion is effectively suppressed at the target location,
- Beam envelope remains within vacuum chamber aperture,
- Target beam size of 3.8 cm is achieved.

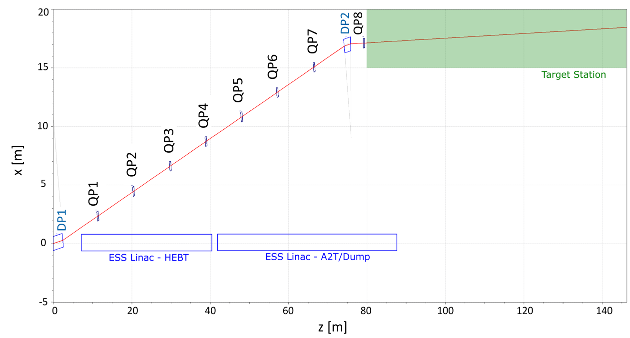


Figure 6: Schematic of the transfer line including quadrupoles (QP) and dipoles (DP) and the potential region for the target (shown in green).

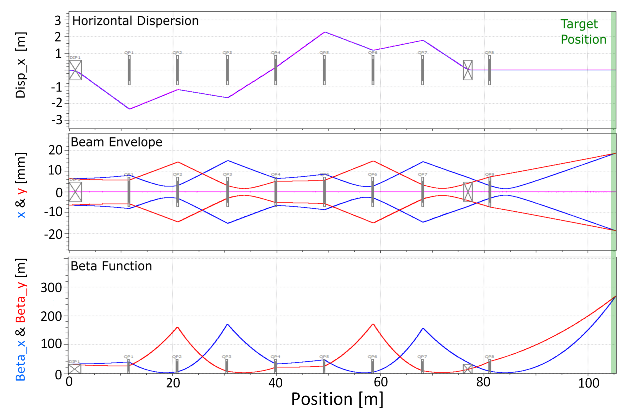


Figure 7: Horizontal dispersion, beam envelope and beta function in both transverse planes through the transfer line. The crossed rectangles represent the dipoles and the long rectangles represent quadrupoles.

Particle tracking simulations confirm that the required beam size and phase space characteristics are achieved at the target position (Fig. 8).

The final beam parameters at the target are summarized in Table 4.

Table 4: Required beam parameters at the secondary target station.

| | |
|---|---|
| Proton kinetic energy | 2 GeV |
| Pulse repetition rate | 3 mHz |
| Energy per pulse | 357 kJ |
| Average pulse current | 62.5 mA |
| Macro-pulse length | 2.86 ms |
| Beam size on target | 3.8 cm |

## CONCLUSION

A feasibility study of a low-frequency proton beam extraction system and transfer line at ESS has been presented. The proposed dipole magnet design provides sufficient field strength and beam deflection while maintaining acceptable field quality.

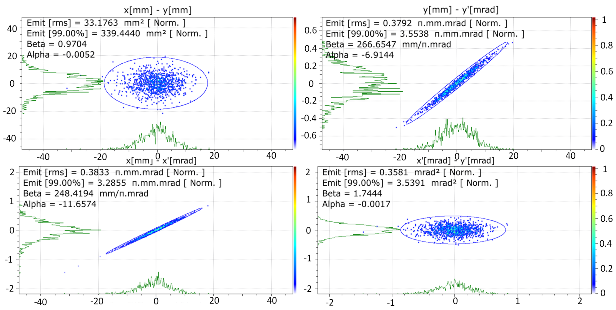


Figure 8: Particle distribution in four different planes. The corresponding values of emittance (the phase-space distribution of the proton beam), beta, and alpha, the phase-space ellipse parameters, are also reported.

Beam optics simulations demonstrate that the transfer line can deliver the required beam size and suppress dispersion at the target location with minimal losses.

The required rise and fall times can be achieved through further optimization of both the coil design and the magnet power supply. Overall, the results confirm that integration of a low-frequency extraction system into the ESS HEBT is feasible and provides a viable solution for supplying proton pulses to a dedicated secondary target station.

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## REFERENCES

[1] M. Akhyani, H. M. Rønnow, and L. Zanini, "A high brilliance low-frequency spallation source optimized for one single instrument", *EPJ Web of Conferences*, vol. 298, p. 05001, 2024. doi:10.1051/epjconf/202429805001

[2] M. Akhyani, P. Konik, D. Shapiro, A. Ioffe, L. Zanini, and H. M. Rønnow, "A dedicated target station for neutron scattering under very high pulsed magnetic fields: cold source optimization", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 1086, p. 171379, 2026. doi:https://doi.org/10.1016/j.nima.2026.171379

[3] B. Winn and M. Stone, "Neutron Scattering and High Magnetic Fields", Rep. ORNL/TM-2014/652, 1410956, Nov. 2014. https://www.osti.gov/servlets/purl/1410956/

[4] K. Ohoyama *et al.*, "Neutron diffraction experiments with 40T pulsed magnets", *J. Phys. Conf. Ser.*, vol. 51, no. 1, p. 506, Nov. 2006. doi:10.1088/1742-6596/51/1/115

[5] H. Nojiri *et al.*, "Neutron Diffraction Study of PrCo2Si2 in Pulsed High Magnetic Field", *J. Phys. Soc. Jpn.*, vol. 60, no. 7, pp. 2380–2387, Jul. 1991. doi:10.1143/JPSJ.60.2380

[6] H. Nojiri, "Pulsed high magnetic fields for neutron and x-ray scattering experiments", 2006, https://www.tandfonline.com/doi/abs/10.1080/10238160412331299438 (visited on 12/13/2023),

[7] F. Duc *et al.*, "40-Tesla pulsed-field cryomagnet for single crystal neutron diffraction", *Rev. Sci. Instrum.*, vol. 89, no. 5, p. 053905, May 2018. doi:10.1063/1.5028487

[8] S. Peggs *et al.*, "ESS Conceptual Design Report", Feb. 2012, http://esss.se/documents/CDR_final_120206.pdf (visited on 11/05/2023),

[9] M. Åberg *et al.*, "ESS Technical Design Report", European Spallation Source, Report 978-91-980173-2-8, 2013.

[10] K. Wille and J. McFall, *The Physics of Particle Accelerators: An Introduction*. Oxford ; New York: Clarendon Press, May 2001.

[11] J. G. Wang, D. L. Le Bon, R. McBrien, and T. Hunter, "Characterization of a SNS Transfer Line Dipole", 2002. https://cds.cern.ch/record/584824

[12] J. G. Wang and T. Hunter, "Measurements of SNS Magnets at ORNL", 2003. https://www.slac.stanford.edu/pubs/slacwps/wp02/slac-wp-029-ch06-Wang.pdf

[13] J. Bauche and A. V. Aloev, "Design of the Beam Transfer Line Magnets for HIE-ISOLDE", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 1289–1291. doi:10.18429/JACoW-IPAC2014-TUPRO104

[14] S. Fatehi, "Compact High-Temperature Superconducting magnets for Laser-Plasma Accelerator beam capture and transport", 2023, doi:10.5445/IR/1000158431, https://publikationen.bibliothek.kit.edu/1000158431 (visited on 01/04/2024),

[15] "User's Guide for the POISSON / SUPERFISH group of codes", Sep. 1992. doi:10.2172/10140823

[16] D. Uriot and N. Pichoff, "TraceWin", Mar. 2015, https://irfu.cea.fr/dacm/logiciels/codesdacm/tracewin/tracewin.pdf,