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DETAILED DESIGN STUDIES OF THE HIGH ENERGY BEAM TRANSPORT LINE OF THE MINERVA PROJECT AT SCK CEN*

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Abstract

MYRRHA [1] will be a research infrastructure focussed on the construction of a first prototype of an accelerator driven sub-critical nuclear reactor (ADS). The driver accelerator will deliver a 600 MeV, 4 mA Proton beam to the reactor core. The first phase called MINERVA aims for the construction of a 100 MeV, 4 mA proton linear accelerator with a focus on reliability. Attached to this 100 MeV linear accelerator are a Proton Target Facility (PTF), which is essentially a high power Isotope Separation On-Line (ISOL) Facility, and a Full Power Facility (FPF) for fusion material research. This paper presents the status of the beam optic studies and overall layout of the Protons Target line towards the PTF, the Full Power line towards the FPF and the beam line towards an energy tuning beam dump.

THE MAIN ACCELERATOR

The MINERVA facility is a 100 MeV-4 mA Proton accelerator. The injector section, composed of a 176.2 MHz RFQ and 15 CH cavities, accelerates the beam from the ECR ion source up to 17 MeV and a main accelerator brings the beam to a final energy of 100 MeV with 60 superconducting spoke cavities [2]. To achieve a high reliability for the ADS, the injector will be duplicated in the final MYRRHA configuration and a fault tolerance strategy will be elaborated for the superconducting linac [3, 4].

TARGET FACILITIES

The High Energy Beam Transport (HEBT) lines deliver the Proton beam to 3 different target stations: (1) the 'energy tuning beam dump' (ETBD) at the end of the Target Selection (TS) line, (2) the 'Proton Target Facility' (PTF) and (3) the 'Full Power Facility' (FPF). The starting point of the HEBT is the exit of the last low beta LINAC cryomodule, which houses the last 2 cavities (see Fig. 1).

The PTF houses an Isotope Separation On-Line (ISOL [5]) facility sustains on average 0.2 mA of beam on actinide targets and 0.5 mA on non-actinide targets. Radioactive isotopes are extracted on line from these targets to experimental stations in the PTF.

The FPF houses an irradiation rig for fusion experiments. The FPF target can take up to the full 4 mA of beam.

The ETBD will be used during first commissioning of the accelerator and during beam tuning at reduced duty factor.

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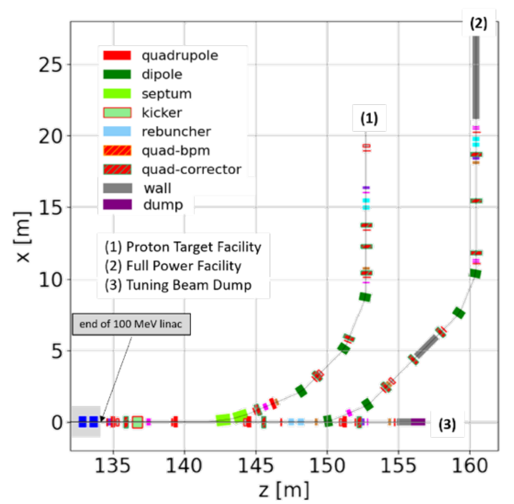

Figure 1: Layout of the high energy beam transfer lines (HEBT) in the MINERVA facility.

The beam intensity modulation to the different targets is based on a time modulation of the constant instantaneous beam current (4 mA). The overall cycle frequency is set to 250 Hz (4 ms period) and beam pulses as short as 0.010 ms can be delivered at this frequency to the targets [5]. Only the FPF target can handle beam pulses as long as 4 ms (i.e. constant beam) and the maximum pulse width to PTF is fixed to 0.490 ms.

Table 1 describes the beam distribution scenarios in the HEBT: (1) simultaneously to the ETBD and PTF, (2) both PTF and FPF receive beam (3) only the PTF and (4) only the FPF receives beam, which can go up to the full beam intensity (pulse width of 4 ms).

Table 1: Beam distribution scenarios in the HEBT

Target	(1)	(2)	(3)	(4)
ETBD	x			
PTF	X	x	x	
FPF		x (*)		x (**)

The HEBT lines have a common section of about 8 m starting at the end of the 100 MeV linac up to a point right in front of the septa magnets (see Fig. 1, in green).

The Proton Target (PT) Line

In the common section, a kicker and a horizontally defocusing quadrupole steer the beam to the septa magnets. The kicker operates at a maximum repetition rate of 250 Hz and with a kicker strength of 7.7 mrad for 100 MeV protons.

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The kick duration is maximally 0.49 ms and minimally 0.01 ms, corresponding to the maximum and minimum pulse width which can be delivered to the PTF targets. Thanks to the additional quadrupole, the beam enter the first septum magnet at 70 mm offset from the straightforward beam line (the TS + FP line). Figure 2 shows the 6σ envelope and centroid position for the beam towards the PTF target and up to the straight beam towards the FPF target and beam dump at the end of the TS line.

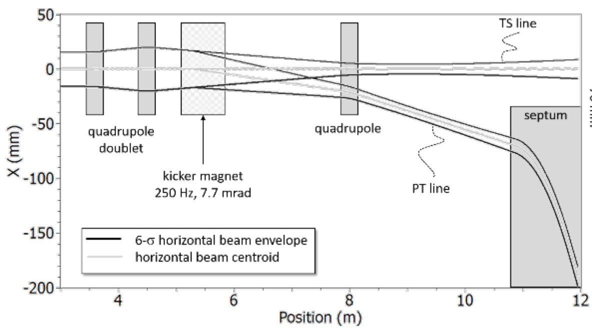

Figure 2: Detail of the kicker magnet, quadrupole and septum magnet in the PT line [7, 8]

The PT line is composed of two consecutive septa magnets and 3 static bending magnets of 22.5°. The beam optics in the PT line is shown in the middle part of Fig. 3. The overall beam pipe aperture of the HEBT lines is kept at 82 mm except at some locations (dipoles and septa). In the septa magnets, the vertical gap is reduced to 30 mm in order minimize its electrical power consumption. With help of the last three quadrupoles, the 1σ beam size on the PTF target can be can be tuned from 2 mm up to 20 mm.

Near the end of the PT line, two X-Y rastering magnets are located in front of the shielding wall in order to have a beam rastering on a circle of up to 30 mm radius. The combination of rastering radius and beam spot is always chosen to optimize the target irradiation and to reduce beam losses.

The Target Selection (TS) Line

The Target Selection line starts with the common section with the PT and FP line. In the subsequent section (common with the FP line), a space reservation is kept for a future rebuncher cavity required to inject into the 2nd part of the accelerator (MYRRHA facility). The rebuncher cavity imposes additional constraints on the vertical beam size, since the full aperture is limited to 56 mm.

The 1σ beam spot size at the ETBD is currently fixed at around 6 mm, but can be further optimized with the quadrupole doublet in front of the beam dump, depending on the beam dump requirements currently under design.

The Full Power (FP)Line

The unique part of the FP line starts after the common TS+FP line immediately after the rebuncher cavity (see Fig. 1). It consists of 2 pairs of 2 dipoles of 22.5° and a quadrupole triplet in between. A shielding wall is located in the deviation section. In the final straight line, a quadrupole triplet is foreseen to vary the 1σ beam size on the FPF target from 5 mm up to 25 mm.

The bottom part of Fig. 3 shows the 6σ beam envelopes in the FP line together with the beam pipe apertures. Near the end of the FP line, the aperture increases towards a total of 40 cm. The aperture variation is an optmization between beam optics and shielding design.

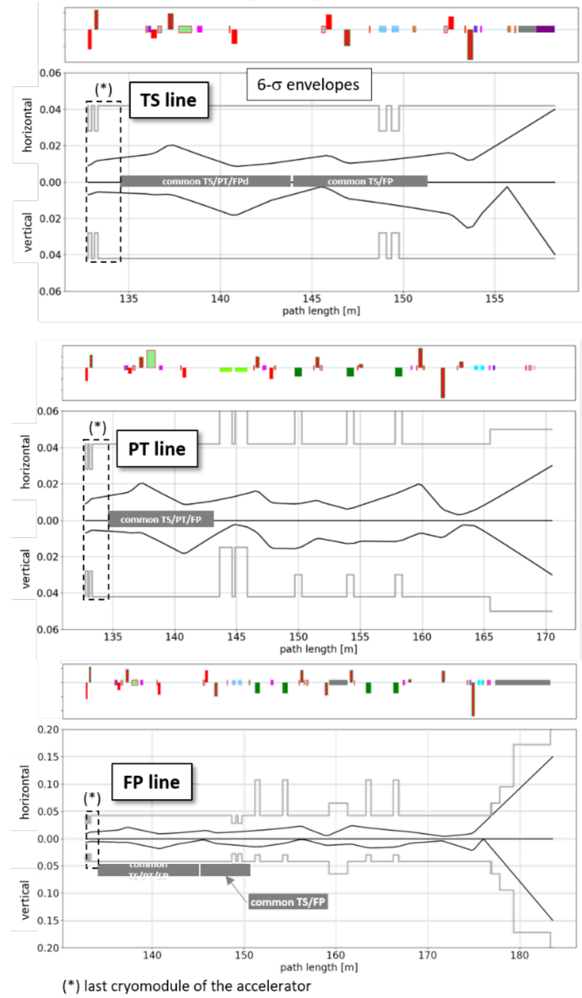

Figure 3: 6σ beam envelopes in the TS, PT and FP HEBT lines. The common sections are indicated with dark grey (common TS/PT/FP) and (common TS/FP). The colored symbols indicate the beam optical elements and a few diagnostics devices. A partial legend for the colored symbols is available in Fig. 1. The dashed rectangle indicates the last cryomodule of the accelerator containing one quadrupole doublet. In grey: the beam pipe apertures. Upper and lower envelops refer to the horizontal and vertical direction, respectively.

ELEMENT SPECIFICATIONS

For the HEBT lines (TS, PT and FP), 20 quadrupoles are placed with the following characteristics: magnetic length of 300 mm and minimum diameter of 42 mm. From error studies using the TraceWin code [9], a maximum tuning margin of about 0.9 T/m on the gradient should be foreseen for some quadrupoles. Taking this tuning margin into account and taking the maximum gradient from the nominal optics, the maximum gradient foreseen for the design is about 6.7 T/m.

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Orbit correctors will be incorporated in selected quadrupoles. Error calculations show that a maximum integrated field strength of 70 G.m should be foreseen. This is based on the 5σ value of needed corrector settings for 1000 different error cases. The errors are uniformly distributed : ±0.2 mm beam alignment in both planes was assumed, 1% error on the gradient, ±2 mrad roll angle on quadrupoles in the transverse plane.

7 rectangular dipoles of 22.5° angle and L_m=0.6 m (3 in the PT line and 4 in the FP line) bend the beam with a maximum field of about 1 T. In the error studies, an alignment precision of 0.1 mm was assumed for these dipoles.

The kicker magnet, designed by CERN via a collaboration, is currently foreseen to be 0.7 m long with an integrated strength of about 0.012 T.m. The timing properties of the kicker magnet are rather tight and are currently being assessed for technical feasibility. Rise and fall times for the kicker are set to 5 µs with a tolerated field stability during the flat top of 1% and 2.1% in the post-pulse ripple. These values are driven by the beam size and position tolerances on the PTF target and the ETBD. During the rise and fall times of minimally 5 µs, the beam is stopped in the low energy (30 keV) beam transfer section of the accelerator. As such, no beam is sent through the HEBT lines when the kicker is ramping up or down. The kicker is only needed for beam transfer to the PTF target.

The 2 septa magnets are currently under design by CERN with the following specifications: an effective length of about 1.0 m, resulting in an integrated field strength of about 0.28 T.m for a bend angle of 10.757°. The vertical beam envelope is kept very small at the position of the septa magnets (see Fig. 3) to keep the vertical gap size of the septa magnets minimal.

The rastering magnet system is currently under investigation and will adopt specifications based on the beam requirements put forward by both the PTF and FPF specifications for their targets.

BEAM DIAGNOSTICS

Figure 4 shows the location of 4 different types of beam diagnostics elements in the HEBT lines.

At the beginning of the HEBT (common section between the exit of the last LINAC cryomodule and the septum entry) the following beam diagnostics elements are incorporated. An ACCT BCM is placed immediately after the last cryomodule to assess the transmission through the accelerator. Subsequently, a BPM [7, 10] is placed inside the first quadrupole of the first doublet in the TS line (see Fig. 3), a halo monitor is placed immediately after the 1st quadrupole and space is reserved for a non-invasive profile monitor, which could also be replaced by a wire scanner, in between the two quadrupoles. The main function of these diagnostics elements is to detect any fault at the entry of the HEBT lines.

3 BCM's are located at the end of each line: one in front of the shielding wall towards the PTF target, one in front of the rastering magnets for the FPF target and one in front of the beam dump at the end of the TS line.

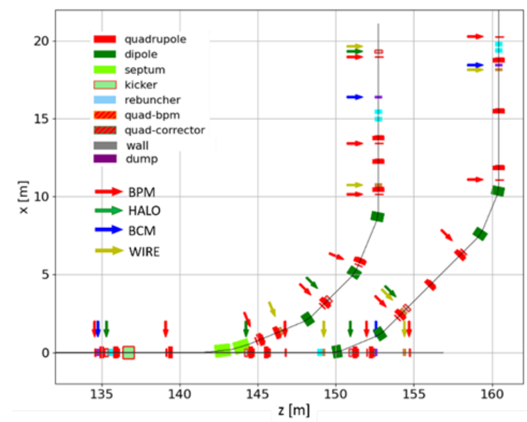

Figure 4: Beam diagnostics position in the HEBT lines. Beam Position Monitor (BPM), Halo monitor (HALO), Beam Current Monitor (BCM), Wire scanner (WIRE).

Currently, 14 BPM's are positioned close (or inside) to a few selected quadrupoles. 5 halo monitors are positioned to assess the presence of beam halo which might lead to beam losses. A total of 7 wire scanners are present: in the PT line immediately after the septa magnets, after the last dipole and in front of the PTF target. In the FP line, there is a wire scanner after the first bending dipole and in front of the last quadrupole. The reason why the BCM and wire scanner are placed before the last optical element in the FP line is driven by space constraints since the last 2 optical elements (1quadrupole and 2 rastering magnets) are very close to the wall, which is about 6 m long and a large beam size should be reached on the FPF target. The wire scanners after the 1st dipole towards the PTF and FPF serve as well as diagnostics for any beam energy deviation during beam tuning. 2 wire scanners are foreseen in the TS line towards the beam dump.

CONCLUSION

The HEBT lines of the MINERVA facility have gone through a number of design iterations and magnet specifications have been deduced for all optical elements. The beam diagnostics layout has been established. In the coming years, the current layout and optics settings might still go through some additional iterations during the detailed design studies.

REFERENCES

[1] MYRRHA, https://www.myrrha.be/

[2] MYRRHA Accelerator eXperiment, research and development programme, https://cordis.europa.eu/project/id/662186

[3] D. Uriot et al., "Beam simulation code development, global coherence - Start to End Model of the 100 MeV MYRRHAlinac", MYRTE D2.6

[4] A. Plaçais and F. Bouly, "Cavity Failure Compensation Strategies in Superconducting Linacs", in Proc. LINAC'22, Liverpool, UK, Aug.-Sep. 2022, pp. 552-555. doi:10.18429/JACoW-LINAC2022-TUPORI04

[5] A. Obertelli et al., Modern Nuclear Physics, Chapitre 6, Section 1, Springer, 2021

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA011

[6] H. Kraft and L. Perrot, “Beam Dynamics and Diagnostics for the High Energy Beam Transport Line of MINERVA Project at SCK•CEN”, in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 2304-2306.
doi:10.18429/JACoW-IPAC2019-WEPMP003

[7] H. Kraft, “Etudes de la dynamique faisceau et d’un diagnostic de position pour les lignes de haute énergie du projet MINERVA”, Ph.D. thesis, ED PHENIICS, Université Paris-Saclay, Orsay, France, 2021

[8] U. Dorda *et al.*, “Optimized Beam Optics Design of the MINERVA/MYRRHA Superconducting Proton Linac”, in *Proc. LINAC'22*, Liverpool, UK, Aug.-Sep. 2022, pp. 337-340. doi:10.18429/JACoW-LINAC2022-TUPOJO03

[9] TraceWin code, https://www.dacm-logiciels.fr/

[10] M. Ben Abdillah, P. Blache, F. Fournier, and H. Kraft, “Development of a Low-beta BPM for MYRTE Project”, in Proc. IBIC'19, Malmö, Sweden, Sep. 2019, pp. 504-507. doi:10.18429/JACoW-IBIC2019-WEPP002